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New insights into the marine minerals and energy resources of the Chilean continental shelf with an environmental approach

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A B S T R A C T

Chile is the world's leading producer of many terrestrial mineral resources; however, the potential of the country's marine mineral resources has been largely overlooked. Within its continental shelf (up to 200 nautical miles from the baselines from which the breadth of the territorial sea is measured), Chile has favorable geological characteristics for hosting and forming marine minerals and energy resources.

During the last decades, several novel studies have demonstrated the potential of gas hydrate reservoirs in Chile (between 33° and 56°S) as an energy resource and source of greenhouse gases, which has attracted the attention of the Chilean scientific community. In addition, some studies have highlighted the potential value of marine minerals in the Chilean continental shelf, mainly due to the increasing demand for minerals for low-carbon energy production, such as cobalt-rich ferromanganese crusts, polymetallic nodules, and massive sulfides on the seafloor.

The goal of this study is to review all information on the non-conventional energy and mineral resources of the Chilean continental shelf. Furthermore, we provide data (e.g., core samples, seismic profiles, or research from related papers) on marine deposits in the Chilean seabed. Here, we show unpublished seismic images of a previously unidentified massive hydrate deposit in the southernmost part of the 1960 Valdivia earthquake rupture zone, which was the largest earthquake recorded in history. We also present geological data that suggests the presence of nodules, sulfides, and crusts on the Chilean continental shelf. Collectively, these findings represent the most important but least explored resources for critical elements and base metals in the country.

This study provides a primer for policymakers to apprise them of future research needed to develop potential mineral and energy resources within prospective deep-sea areas. It also includes advice on developing an environmental baseline for future environmental impact assessment. The new understanding of mineral and energy resources presented here greatly expands Chile's position beyond that as a source of terrestrial minerals to include potentially vast marine-based energy and metal resources, which are highly valued by industry. Based on these considerations, we encourage decision makers to promote and support studying marine deposits to further protect and evaluate future exploration.

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1. Introduction

The mineral rights of Chile extend across the Chilean continental shelf up to 200 km beyond its territorial water (United Nations Convention on the Law of the Sea, Article 76), covering an area five times larger than its land territory and extending from the seabed into the subsoil of these submarine areas. It is also one of the few Latin American countries that has a comprehensive understanding of the geophysics and tectonics of its seabed, mainly because significant earthquake and tsunami hazards generated by the subduction of the oceanic Nazca plate under the South American plate along the coast of Chile have driven extensive offshore studies. Chile has several geomorphological features within its continental shelf, such as a long submarine trench filled with carbon-rich sediments (Völker et al., 2013; Contreras-Reyes et al., 2013); oceanic ridges (Bello-González et al., 2018); more than a hundred significant seamounts on the Nazca plate (Contreras-Reyes and Carrizo, 2011); the center Chile Rise active seafloor spreading center, which is actively colliding with the South American continental plate; numerous oceanic fracture zones on the subducting Nazca plate (Maksymowicz et al., 2012; Contreras-Reyes et al., 2013; Villar-Muñoz et al., 2021); an accretionary prism associated with an active margin south of Valparaíso at 33°S (Contreras-Reyes et al., 2010, 2017); a surface upwelling of cooler, nutrient-rich waters that contribute to the formation of a minimal oxygen zone, which acts as a reservoir for dissolved Manganese (Mn) and its associated metals (Hein et al., 2013); and extensive abyssal plains (see Fig. 1 illustrating the different types of marine environments that are ideal for reservoir formation).

Despite the diverse geological features, mainly related to mineral and energy deposits, a more detailed description of the marine resources on the seabed of the Chilean continental shelf is required to fully assess their economic potential. Chile is the world's largest exporter of copper and other terrestrial mineral resources worldwide (World Economic Forum, 2022) and has a long list of terrestrial minerals mined in its territory (e.g., lithium, tellurium, arsenic, and molybdenum). Historically, terrestrial mining has been the primary focus over exploration of marine resources.

In Chile, several new projects related to minerals for the energy transition (e.g. electric batteries, wind farms, photovoltaic solar cells) are being explored (NDC, 2020), pitting the government and large mining companies (e.g., lithium) against local communities living near these projects. There is evidence of poor management of polluting waste (tailings) from the mining industry that can have a negative impact on human health and biodiversity (e.g., Castilla, 1983, 1996; Castilla and Correa, 1997; Leiva González and Onederra, 2022). Land mining tends to exacerbate the pre-existing vulnerabilities of the host community, which then continues to fall short on fundamental social foundations such as justice, human rights, equity, health, and education (e.g., Smart, 2017; Gankhuyag and Gregoire, 2018). The negative impacts of Chilean terrestrial mining include deforestation, erosion, pollution, human rights violations, contamination of coastal waters, displacement of communities, conflicts over land, and water allocation (e.g. Castilla, 1983, 1996; Castilla and Correa, 1997; Correa et al., 1999; Urbina et al., 2021; Klubock, 2021; Leiva González and Onederra, 2022).

In the last decades, the scientific community has discovered a vast abundance of a potential hydrocarbon energy resource called gas hydrate (GH), which is also common along the Chilean coast and has extensively studied its characteristics. GH has an ice-like structure, with a low-density gas molecule, mainly methane (CH_4), surrounded by a cage of water molecules. The stability of the GH depends on pressure and temperature conditions, which are met to a high degree on the seafloor and shallow subseafloor, where ocean depths are > ~400 m along continental slopes (Collett, 2002). The energy potential of hydrates is vast because 1 unit of gas hydrate contains 160 units of natural gas at atmospheric pressure (Kvenvolden, 1993; Sloan, 2003). Furthermore, GH is also a greenhouse gas that has significantly impacted the Earth's climate history (Dickens et al., 1995), as CH_4 is 84 times more potent as a greenhouse gas than CO_2 in the short term (IPCC, 2013). Understanding the origin and evolution of the Earth's methane budget is a relevant problem in Earth sciences, especially in the current global climate crisis (IPCC, 2021). To study CH_4 stored as GH, a prominent reflector called bottom-simulating reflector (BSR) is identified in seismic reflection profiles (Hyndman and Spence, 1992). BSR are the most widely used reflectors to identify natural GH and mark the base of the gas hydrate stability zone (GHSZ). Analysis of the seismic data using advanced techniques includes mapping the seismic velocity, which directly indicates the CH_4 concentration stored in the marine sediments (e.g. Tinivella and Carcione, 2001).

Seabed mineral deposits represent the most important but least explored resources of critical elements and base metals, which are

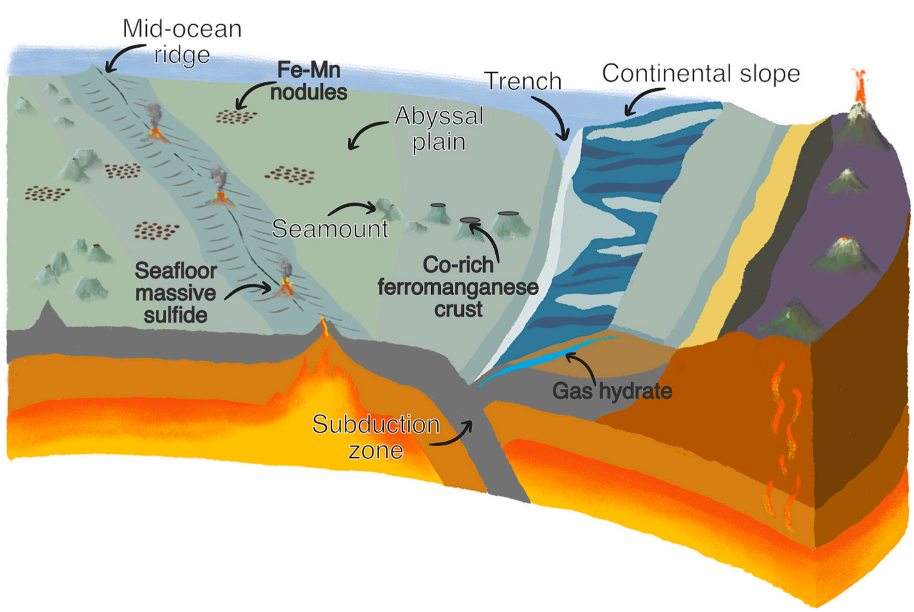

Fig. 1. Geomorphological features within the Chilean continental shelf, where hydrocarbon energy deposits (e.g., gas hydrates) and mineral deposits, including polymetallic nodules, cobalt-rich crusts, and seafloor massive sulfides, are found (figure not scaled and modified from Lusty and Murton, 2018).

Fig. 2. Marine minerals studied in this article (edited from the TMC Impact Report, 2021). Credits: Polymetallic Nodules, TMC; Co-rich ferromanganese Crusts, Hino et al. (2023), and Seafloor Massive Sulfides, Ishikawa et al. (2016).

crucial for low-carbon energy production, electronics, and new technologies (Hein et al., 2013). As shown in Fig. 2, the most abundant global marine mineral deposits worldwide are Polymetallic Nodules (PN), which are sources of Ni, Cu, Mn, and Co as well as other metals (e.g. Mo, Zn, Zr, Li, Pt, and Ti). PN are found on the surface of soft sediments at abyssal depths in all oceans and are expected to become an economically important source of mineral resources (Hund et al., 2020). Other types of abundant deep-sea mineral resources are cobalt-rich ferromanganese crusts (CRC) from seamounts (between 500 and 2000 m depth), which contain Co, Ni, Te, rare earth elements (REE) and Pt (Hein et al., 2013; Hein and Koschinsky, 2014). Also, polymetallic massive sulfides (SMS), which are deposited near hydrothermal vents (e.g. black smokers) in submarine volcanic chains or mid-ocean ridges (2000 to 4000 m depth) containing Cu, Zn, Au, Ag, Cd, As and Ga (Hein et al., 2013). Metalliferous sediments are mainly found in volcanic belts and on the ocean floor. Finally, phosphorite occurrences are found along the shelves, submarine plateaus, and banks (Rona, 2008). Metalliferous sediments and phosphorites are a significant mineral resource but are not the focus of the discussion here.

It is worth noting that globally only 19% of favorable areas for PNs, 42% for massive sulfides, and 54% for CRC are located on the continental shelf of coastal States, with the rest in international waters (Petersen et al., 2016). Knowing the location of favorable regions for these mineral deposits in Chile will provide guidance for promoting future exploration on the Chilean continental shelf and assist environmental impact studies in these little known areas.

Over the last decades, many countries have promoted deep-sea mining to satisfy the increased demand for critical metals needed for new green technologies and renewable energies. However, the extraction of deep-sea mineral deposits in the Area (defined as the seabed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction) is suspended until the multiple legal, technological, economic, and environmental challenges are resolved. This is due to the provisions of Part XI of the United Nations Convention on the Law of the Sea (UNCLOS), which classifies deep-sea mineral resources beyond the continental shelf as the "common heritage of mankind." It is important to note that UNCLOS is the principal international instrument dealing with key legal issues relating to the delimitation of boundaries, archipelagic status and transit regimes, jurisdiction over the continental shelf, deep seabed mining, exploitation regime, protection of the marine environment and dispute settlement.

Although some studies point out that the reserves of primary metals on land will not be depleted within half a century (e.g. Jowitt et al., 2020), Gilbert (2023) states in his prediction that "commercial mining of the sea floor could soon get the green light." This, along with the escalating global demand for cobalt, tellurium, nickel, lithium, REE, copper, and other rare and critical metals, combined with the rapid decline in the quality and quantity of deposits mined on land (Petersen et al., 2016), has positioned the seafloor as a promising new frontier for mineral resource exploration.

It should be noted that deep-sea mining has not yet commenced, and many environmental concerns are associated with correctly assessing the risks and impacts associated with the transition to mining (e.g. Durden et al., 2017; Clark et al., 2020). Recently, several studies have shown that it is possible to assess the environmental impacts of deep-sea mining in an interdisciplinary manner (e.g. Washburn et al., 2023; Fukushima and Tsune, 2019).

Chile has mineral and energy resources on land, but it also has potentially large but poorly-known resources hidden in the seabed of its continental shelf. The most studied marine resource in the sediments of the Chilean margin is gas hydrates (e.g. Vargas-Cordero et al., 2022), which have attracted the attention of the scientific community for a long time because, in addition to their potential as an energy resource, they are also associated with geohazards from landslides following hydrate dissociation, and an important greenhouse gas (Ruffine et al., 2023). The frequent earthquake activity along the entire Chilean margin makes this margin particularly prone to gas hydrate dissociation and slope instability, leading to submarine slides and associated tsunamis along the coast.

Marine mineral deposits in Chile are still poorly understood, but they are now gaining in importance as Chile moves toward a transition to carbon neutrality, where electricity will be generated mainly from non-conventional renewable energies (e.g., NCRE, 2018; Moreno-Leiva et al., 2017; Osorio-Aravena et al., 2020; Mattar et al., 2021; Leiva González and Onederra, 2022), which require mineral resources for generation, transmission and storage. Potential deep-sea mineral deposits along the Chilean continental shelf include: a) polymetallic nodules (PN), b) cobalt-rich ferromanganese crusts (CRC), c) polymetallic massive sulfides (SMS), and the geological formations associated with these mineral deposits (e.g. abyssal plains, seamounts, and mid-ocean ridges) are common across the Chilean seafloor (see Fig. 1).

Therefore, the main objective of this study is to review the state of knowledge regarding these marine mineral deposits (i.e., PN, CRC, and SMS), compile all existing literature on Chilean energy reservoirs, and identify potential reservoirs (mineral and energy) on the Chilean continental shelf to have a better and more accurate basis for future exploration. In this way, this study can contribute to the creation of new legislation, as all regulations and management of resource exploitation and extraction from the seabed would fall under national jurisdiction. Finally, we have also included environmental knowledge that will help to establish environmental baselines prior to any mining activity on Chile's continental shelf.

2. Energy resource

2.1. Gas hydrates

Recent studies discovered natural GH hosted in Chilean sediments and linked their presence and stability to favorable pressure and temperature conditions through extensive study of seafloor conditions (e.g., Grevemeyer et al., 2006; Loreto et al., 2007; Polonia et al., 2007; Vargas-Cordero et al., 2010, 2016, 2017, 2018, 2020, 2021a,b, 2022; Villar-Muñoz et al., 2014, Villar-Muñoz et al., 2018, Villar-Muñoz et al., 2019, Villar-Muñoz et al., 2021). Further studies of CH_4 emission sites are therefore poised to elucidate the stability of these reservoirs and potential pathways for methane emissions into the atmosphere (Bohrmann and Torres, 2006). It is generally recognized that GH destabilization and subsequent methane release in the past may have been one of the strongest influences on abrupt climate changes in the Earth system (e.g., Dickens et al., 1995; Sloan, 2003) and needs to be incorporated into climate models. However, methane release from GH is hardly considered in model calculations for climate studies, as there is little information on the magnitude and distribution of methane release from marine hydrate deposits (Ruffine et al., 2023). The triggering of temperature changes is still under debate, and the role of possible methane release by destabilizing marine GH (Fisher et al., 2003) is not yet understood well enough to attribute it to a triggering mechanism. Nevertheless, its effects as a greenhouse gas are well accepted, as described below.

GH are of particular interest when they occur near the seafloor (<700 m depth), as the gas released into the aquatic environment could reach the ocean surface and even escape into the atmosphere. Previous studies have shown that there are several areas in Chile where methane gas leaks from the seafloor (e.g., offshore Concepcion, El Quisco, Isla Mocha, and Taitao peninsula), but the potential for such vents to leak methane into the atmosphere is well demonstrated with data showing gas release at the sea surface offshore Isla Mocha (Vargas-Cordero et al., 2018, 2020).

Large areas of concentrated methane hydrates (methane hydrate concentration zones - MHCZ) have been found along Chilean margins (e.g., the Patagonia region has a CH_4 budget of 3×10^{13} m^3 under standard conditions; Villar-Muñoz et al., 2018), which could be affected by the production processes. Furthermore, warming seafloor waters above MHCZ could potentially release large volumes of CH_4 into the marine

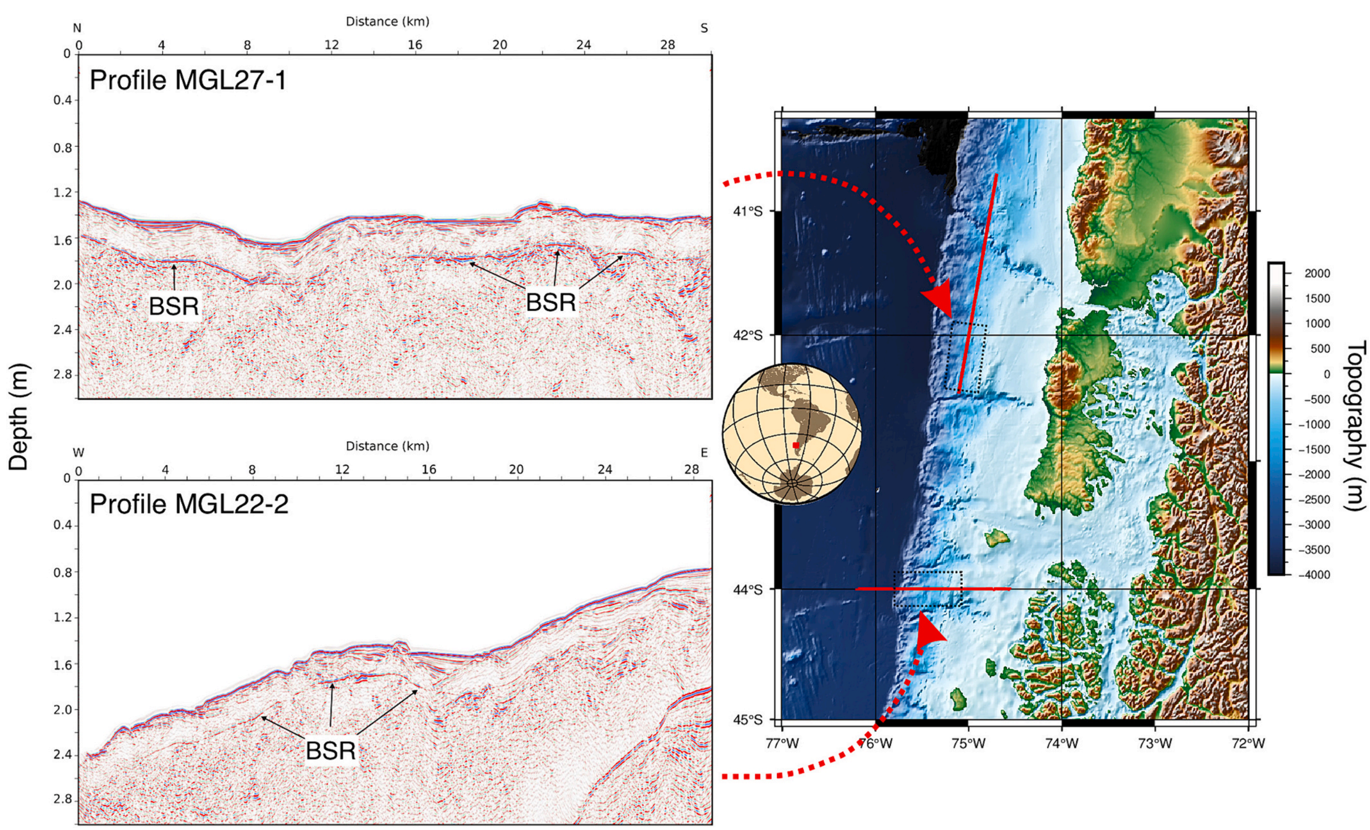

Fig. 3. Left side: New seismic profiles showing the BSR in the Chilean continental margin. Profile MGL27–1 is in the northern sector of the study area, and profile MGL22–2 is located perpendicular to the continental margin. Right side: Location of the profiles.

environment. Broadly speaking, GH deposits in the Chilean continental shelf represent a promising energy source for the future once the technology required for the industrial production of GH at water depths of >500 m is further developed.

In 2015, the Chilean government signed part of the Paris Agreement (NDC, 2020) to achieve the objectives outlined in Article 4.1, which has the following goals:

1. begin a decline in greenhouse gas emissions as soon as possible;
2. begin an equal balance between anthropogenic emissions and natural absorption in the second half of this century.

In this context, the exploitation of GH in Chile would violate the Paris Agreement and Goal #14 of the United Nations Sustainable Development Goals (UN-SDG, 2015), which aims to conserve oceans, seas, and marine resources through sustainable use. It is therefore suggested not to refrain from interfering with marine sediments for the purposes of exploitation.

Here, we present new information on a GH reservoir that has not been reported in previous studies. The new information is crucial because it addresses whether GH in central Chile will become unstable in current global warming scenarios. One potential factor exacerbating the methane release to the atmosphere is the limited knowledge of the nature and distribution of significant hydrate accumulations along the Chilean margin. New seismic profiles were acquired during the CEVICHE (Crustal Experiment Valdivia to Illapel to Characterise Huge Earthquakes) project in 2017 onboard the US R/V Marcus G. Langseth off the coast of central Chile (Bangs et al., 2020; Olsen et al., 2020; Vargas-Cordero et al., 2021a,b), reveal a continuous BSR with high amplitude and broad extent across the accretionary prism along the lower continental slope. These data imply a large volume (Villar-Muñoz et al., article in prep) of gas stored within hydrates along south-central Chile (Fig. 3).

3. Mineral resources

3.1. Polymetallic nodules

Polymetallic nodules (PN) were discovered approximately 150 years ago and occur throughout the global ocean, and they predominantly lie on the surface of sediment-covered abyssal plains at water depths of about 3500 to 6500 m (Thomson and Murray, 1895; Madureira et al., 2016; Kuhn et al., 2017; Hein et al., 2013; Hein et al., 2020). PN are common in abyssal zones with oxygen-rich bottom waters, low sedimentation rates (<20 mm per thousand years - mm ky^{-1}), and where sources of abundant cores (such as shells of small marine organisms or fragments of clams) occur (Glasby, 2000). High-grade PN occur in areas of moderate primary productivity in surface waters (ISA, 2022).

PN grow by accumulation of Mn and Fe oxides around a nucleus (Hein et al., 2013). They are formed by metal precipitation from a) ambient seawater (hydrogenetic formation), b) pore waters in sediments (diagenetic formation), c) hydrothermally derived fluids (Bonatti and Nayudu, 1965; Bau et al., 2014; Kuhn et al., 2017), and d) formation processes that represent a mixture of these different end processes. Hydrogenetic PN grow at an extremely slow rate of approximately 1–10 mm per million years (mm My^{-1}), whereas diagenetic PN grow at rates of several hundred mm My^{-1}. Most PN are formed by a combination of hydrogenetic and diagenetic precipitation and thus grow at average rates of several tens of mm My^{-1} (Hein and Koschinsky, 2014).

Deepwater PN are traditionally considered potential sources of Ni, Cu, Mn, and Co (see Fig. 4). However, recent investigations have shown that they contain a wide variety of metals, such as Mo, Zn, Zr, Li, Pt, Ti, Ge, Y, and REE (Hein et al., 2000; Hein et al., 2015), which increases the combined value of deep-water PN as an alternative supply for expanding economies and emerging green energy technologies (Abramowski and Stoyanova, 2012). Thus, PN are now positioned as potential deepwater mineral resources, with nickel being the most valuable component in the PN, followed by Mn (ISA, 2020).

In addition, PN deposits occur directly on the seafloor and cover a large part of the deep-sea surface sediments (Hein and Koschinsky, 2014). In contrast to deposits on land, deep-sea mining of PN does not require extensive overburden removal to reach the ore deposits. PN mining is much more akin to potato harvesting than to more conventional open pit or strip mining of ores (Morgan et al., 1999). In contrast, massive sulfide and cobalt-rich ferromanganese crust deposits on the seafloor are an integral part of the seafloor, and they would need to be mined conventionally by fracturing or cutting hard rock, respectively.

PN are found in many marine regions. Studies have reported the occurrence of PN along the Peru Basin, with an average PN abundance of almost 10 kg m^{-2}, with mainly Mn concentration (Von Stackelberg, 2000; Hein et al., 2013; Kuhn et al., 2017). However, the greatest abundance to date has been discovered in the Clarion-Clipperton

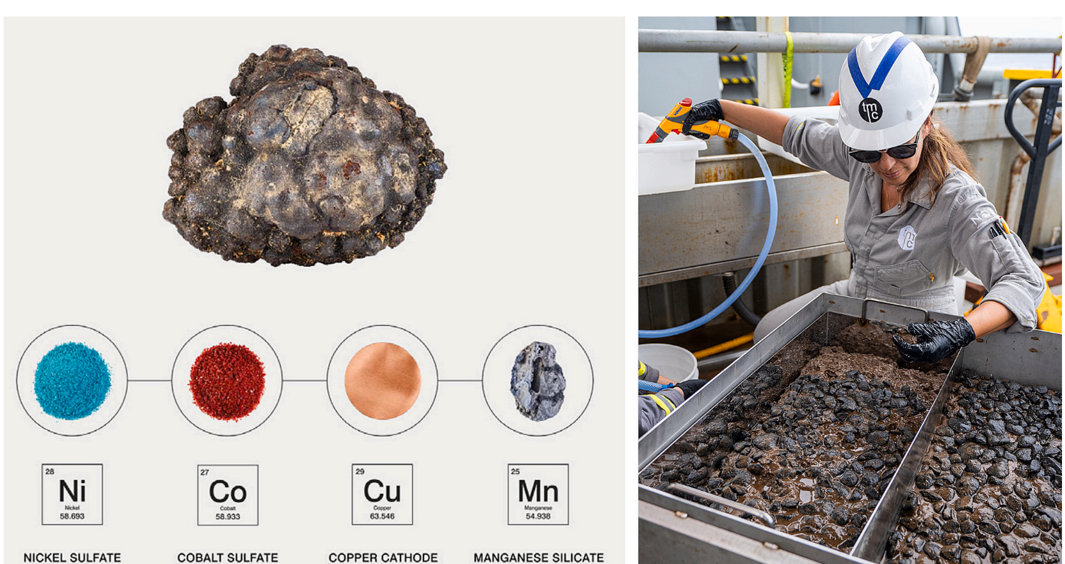

Fig. 4. Left side: Polymetallic nodules (PN) sample and its four major components. Right side: A scientist inspects seafloor PN collected by a box core in the CCZ (Credits: Richard Baron, TMC).

Fracture Zone (CCZ) in the Pacific Ocean, which extends from the west coast of Mexico to Hawaii.

On average, 1 m^2 of the CCZ contains about 15 kg of PN, and up to 75 kg can occur in rich zones (Bollmann et al., 2010). The PN resources in the CCZ contain 1.1 times more Mn, 1.85 times more Ni, and 3.2 times more Co than the total global land reserves for these metals (Abramowski and Stoyanova, 2012).

Moreover, CCZ PN metals have abundances of 22% Cu, 63% Mo, 21% W, 19% Li, 13% Nb, and 11% REE of their respective terrestrial reserves (Abramowski and Stoyanova, 2012). Therefore, PN have the potential to become a significant source of metals required by electronics and emerging technologies such as battery systems, electric cars, wind turbines, and other renewable green energy technologies, which require increasing amounts of Ni, Co, Cu, and Mn. This makes it a strong competitor for Chilean terrestrial mining of copper, which represents a large fraction of the Chilean national economy, and quantities of all of these metals are sufficiently large to affect global prices.

Vergara (1999) recognized several potential PN mining areas in the Chilean continental shelf. For example, PN occurrences with concentrations of 1.38 Cu + Ni were found on the outer elevation opposite from the mouth of the Loa River (~21°S) and at a depth of about 4000 m. In addition, PN occurrence were found near the volcanic arc, between Salas y Gómez and San Ambrosio islands, and around Rapa Nui island (also known as Easter Island). A high PN manganese content (mean concentrations of ~36%) was also observed around Juan Fernandez Ridge (García et al., 2020). An area of high probability for PN occurrence was also proposed by Gallegos (2000) around the northern continental shelf of Easter Island (21°-30°S and 110–115°W) and surrounding the Salas y Gomez Ridge (27°-35°S and 95°-106°W), based on superficial sediments that were found to have high Zn (>400 ppm), Cu (>900 ppm), Mn (>6%), and Fe (>15%) content in water depths exceeding 2500 m, which are sufficiently deep for PN formation. Finally, PN samples from the ISA database within the Magallanes (a Marine Protected Area, or MPA) samples have been collected at depths ranging from 3700 m to 4000 m, with Mn grades that vary between 8% and 17%, Cu + Ni grades between 0.3% and 0.6%, and Co grades between 0.2% and 0.5% (Vergara, 1999; Völker and Koschinsky, 2010) and one area very close to the Salas MPA (see location in the graphical abstract).

All these areas are located near or within MPA, which are specific and defined areas for ecological units of scientific interest that ensure the conservation and diversity of aquatic species and species associated with their habitat. For this reason, future mining of PN on the Chilean seabed would be prohibited in the areas designed so far, which motivates research to find new areas with PN deposits without such restrictions.

Recently, researchers from Chile and Japan working aboard the Japanese Research Vessel MIRAI found PN near the Chilean continental shelf (Kinoshita, 2019) between San Ambrosio Island and the Chile Trench (26°05′ S 75°57′ W at 3982 m depth). The PN samples appear to be large (Fig. 5).

3.2. Cobalt rich crusts (or Fe—Mn crusts)

Cobalt-rich ferromanganese crusts (CRC) precipitate from the cold (hydrogen-containing) bottom waters on the surface of seamounts, ridges, and plateaus as pavements and coatings on rocks in areas that have remained sediment-free for millions of years (Hein et al., 2013; Fig. 6). Crusts are typically found at water depths of 400–7000 m, with the thickest and most metal-rich crusts occurring at depths of around 800–2500 m (Hein et al., 2013). The distribution of crusts and the characteristics of the seamounts they form on indicate that mining operations would occur at depths between 1500 and 2500 m (Hein et al., 2009). Crusts also occur on polar ocean ridges, but their distribution is poorly understood. The thickness of the CRC ranges from 1 to 260 mm and tends to be thicker on older seamounts (Usui and Someya, 1997).

CRC are a promising resource on the seafloor as they contain large amounts of Co, Ni, Mn, and other metals that could exceed the quantities in terrestrial deposits (e.g., Bollmann et al., 2010; Hein and Koschinsky, 2014; Vysetti, 2023). The metal Te is also comparatively abundant in the CRC and is primarily required for the production of highly efficient thin-film photovoltaic cells. Metal extraction requires machines to separate the material from the substrate (e.g., ripping or drilling; Bollmann et al., 2010). However, geological formations with high potential for deep-sea mining are limited to guyots, i.e. old seamounts whose tops have eroded to form flat-topped undersea mountains (Staudigel and Koppers, 2015).

CRC have a very high porosity (average 60%), an extremely high specific surface area (average 325 m^2/g), and grow at prolonged rates of 1–5 mm My^{-1}, allowing the adsorption of considerable amounts of metals from seawater (Hein et al., 2000). Adsorbed metals include Co, Ni, Cu, and Ti and minor elements such as Mo, Te, Pt, Zr, Nb, Bi, and the REE. This makes CRC a potential resource for metals used in emerging high-tech and green technology applications. Fe and Mn are the main constituents of CRC and occur in roughly equal amounts. Co is a minor element but of greater economic interest, as it is present in concentrations typically exceeding 0.5% by weight of Co (Petersen et al., 2016).

As hydrogenetic crusts are slow-growing sedimentary deposits derived from normal seawater, the occurrence of the deposits is usually controlled by the following factors: a long-term stable bedrock outcrop, a continuous supply of oxygenated seawater, and very little or no sedimentation (detrital, volcanic, or biogenic; Okamoto and Usui, 2014). In

Fig. 5. New core samples of polymetallic nodules (PN) offshore San Ambrosio (~26°S). Left side: vertical view of the core-7. Right side: top sight of the core-4 showing the samples (Credits: Kinoshita, 2019).

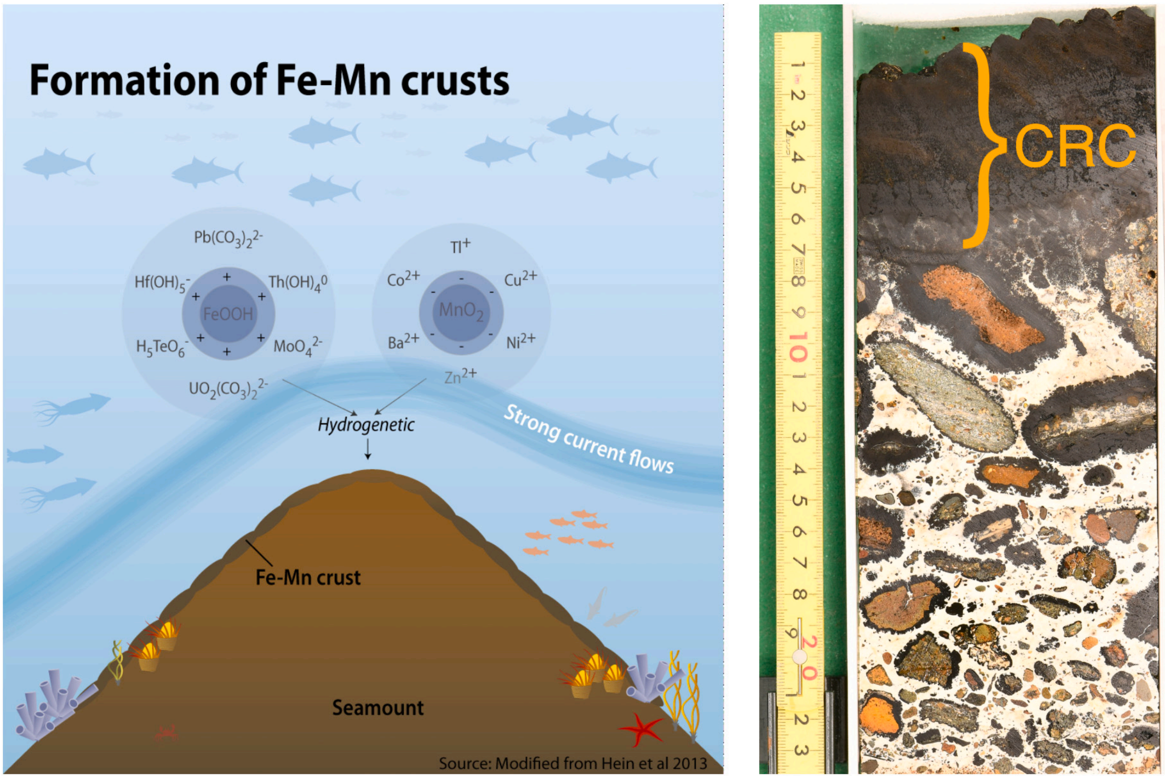

Fig. 6. Left: formation of ferromagnesian crusts (CRC), in which a wide range of metals and elements dissolved in ocean water are adsorbed in large quantities on the manganese and iron oxides deposited on the surfaces of the seamounts (credits: GRID-Arendal, modified from Hein et al., 2013; https://www.grida.no/resources/8000). Right: in the cross-section, the black CRC, several centimeters thick, is easily recognizable against the light-colored base rock (conglomerate). This sample comes from a seamount in the north-west Pacific Ocean, which is one of the most promising areas for CRC (Credits: Hino et al., 2023).

addition, the bedrock must be geologically stable (e.g., guyot). The stability of the seamount basement is one of the most critical parameters for determining the economic potential of the CRC.

Thus, seamounts, ridges, and primarily guyots have features that contribute to CRC development and metal extraction (Hein et al., 2013). For example, obstructive upwelling along the flanks of seamounts creates turbulent mixing along the flanks and over the ridges that help keep seamounts free of sediment, and this upwelling adds nutrients to the surface water that are utilized for primary production. Organic matter from primary production sinks and oxidizes in the water column, creating an oxygen minimum zone, which acts as a reservoir for dissolved Mn and its associated metals, slowing the growth rates of the CRC and allowing the maximum possible time for the precipitation of metals from the ocean water.

On the Chilean continental shelf, CRC and metalliferous sediments have been described in the volcanic belt and on the ocean floor around the islands of Salas y Gómez and Easter (Valenzuela, 1986). Corvalán et al. (1996) also describe this deposit around the San Félix and San Ambrosio islands. According to Vergara (1999), the most promising mineral deposits offshore of Chile seem to be the volcanic belt, which includes the Salas y Gómez, San Félix, and San Ambrosio islands, as well as the sedimentary basins surrounding Easter Island, which contain CRC.

The Salas y Gómez and Nazca Ridges are two chains of seamounts, comprising >110 seamounts that collectively extend over >2900 km in the southeastern Pacific and originate in the southeastern Pacific (Gálvez-Larach, 2009; Yáñez et al., 2012; Contreras-Reyes et al., 2022), representing approximately 41% of the seamounts found in the southeastern Pacific. The ecosystems of this region are isolated by the Atacama Trench, the Humboldt Current System, and an extreme oxygen minimum zone, which has led to a unique biodiversity (Wagner et al., 2021). The waters surrounding the Salas y Gómez and Nazca Ridges are mainly located outside national jurisdiction, with smaller portions in the Chilean continental shelf. As seamounts represent the most unique marine biodiversity hotspots on Earth, Chile has already protected all ridges within its jurisdiction (i.e. MPA).

In this study, recent bathymetric data in Chile (Diaz-Naveas et al., 2015) show the presence of ancient seamounts, guyots, and plateaus that peak between 300 m and 3000 m depth. One of the most important guyots in the Chilean continental shelf is the O'Higgins seamount (8.5–9.3 My) off Valparaiso (33°S), which represents the eastern component of the Juan Fernandez Ridge (Bello-González et al., 2018) and appears to be CRC-prone (Fig. 7, left). The western seamount is a larger edifice with an elevation of 3540 m and a flat top at ~500 mbsl (Lara et al., 2018). During its geological evolution (i.e., the formation of the seamount into a volcanic structure, the end of volcanism, erosion, subsidence, deformation, and sedimentation), the later stages of the seamount history are conducive to ferromanganese oxide deposition.

This seamount has a high biodiversity described as a benthic community consisting of an assemblage of four species of deep-sea corals at the margin of the O'Higgins seamount plateau (Cañete and Häussermann, 2012). Furthermore, the same study shows that this deep-sea coral assemblage represents a critical habitat for the nylon shrimp (Heterpus reedi), a crustacean of fishery importance. The presence of this crustacean and some fishes, such as the alfonsino (*Beryx splendens*) and orange roughy (*Hoplostethus atlanticus*), could draw industry attention to these fragile, unique, and unexplored Chilean benthic communities. Further west, along the same chain of seamounts of the Juan Fernández Ridge, we find the guyot JF5, which has an elevation of over 2000 m (Fig. 7, right). Further west, 70 km west of Robinson Crusoe Island, is Seamount Duke, which has a flat-top and star-like shape with a summit at about 500 mbsl and an elevation of about 3500 m from its base (see Fig. 2b in Lara et al., 2018). These guyots are also presented as possible candidates for a CRC deposit; however, there is no direct evidence from the surface of these seamounts. For this reason, these areas

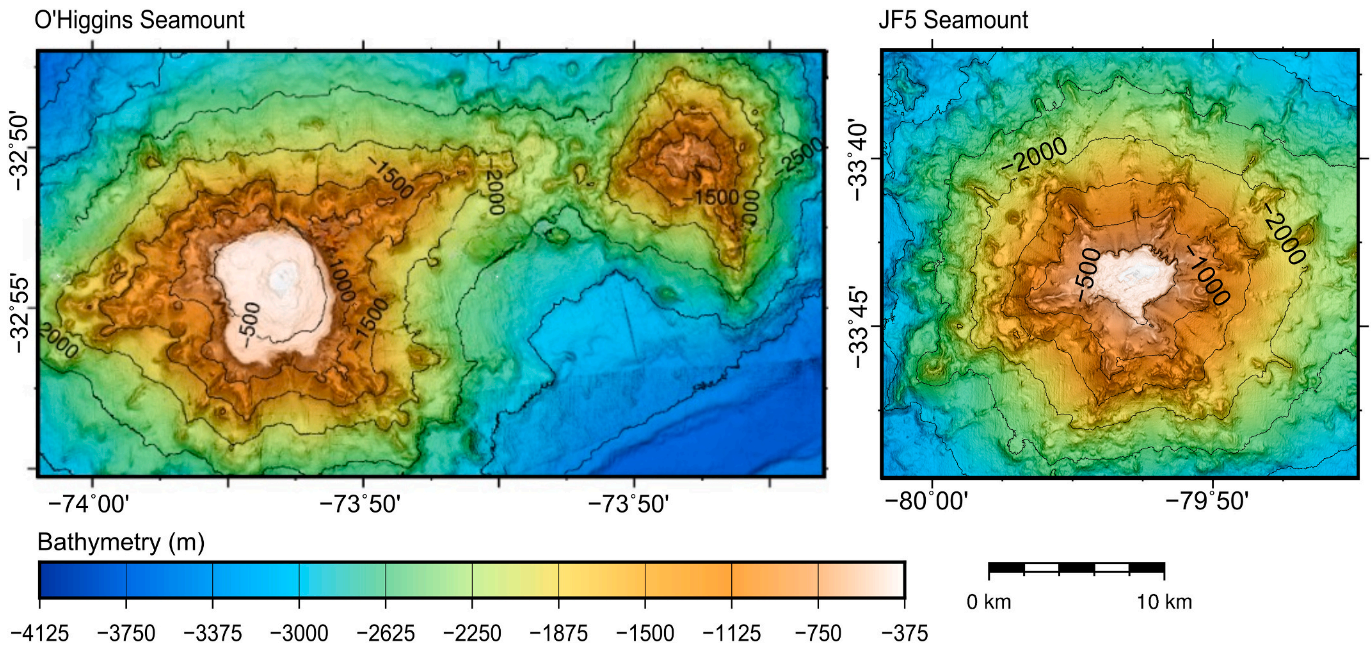

Fig. 7. Bathymetric data showing the guyots that may be prone to CRC formation. Left: O'Higgins seamount offshore Valparaiso. Right: JF5 seamount close to Juan Fernandez Island.

are ripe for geological and geophysical studies to determine the age and possible minerals deposited on these guyots.

The JF5 and Duke seamounts are within a multi-use MPA established in 2017. The coastal multiple-use MPA in Chile involves the creation of an environmental management system that conserves ecosystems and biodiversity while promoting sustainable activities such as artisanal fishing and tourism. Consequently, any mining would be outside the legal framework and incompatible with the kind of protection required in these areas.

However, the area near the guyot O'Higgins is outside of an MPA. It exhibits conditions that may be conducive to CRC deposits and future mining, but it is also a highly sensitive environmental area. This important flat-top seamount is close to the continental coast (Valparaiso); it hosts unique species, such as cold-water corals, and is a habitat for other species, including cetaceans. We encourage further studies of marine ecology to improve our understanding of this setting and determine appropriate protection of this important flat-top seamount, which could include a new MPA to prevent the degradation or loss of this habitat. A habitat that could take centuries to restore.

3.3. *Seafloor massive sulfides*

Seafloor massive sulfides (SMS or polymetallic sulfides) are the third type of metalliferous mineral resource found offshore. They were discovered in the late 1970s during an expedition to the East Pacific Rise (Bollmann et al., 2010). SMS form on and beneath the seafloor from high-temperature hydrothermal fluids seeping from vents along ridges, island arcs, and in fractured back-arc basins (Petersen et al., 2016), where sulfur-enriched water rises from the seafloor. They are found along active plate boundaries and at submarine volcanoes, where heat and elemental exchange occurs between crustal rocks and the ocean due to interactions between magmatic activity and seawater. The seawater penetrates several thousand meters deep into the crust through fissures in the seafloor. At these great depths, the intense magmatic activity heats the temperatures to >400 °C (Hannington et al., 2005). This high temperature environment facilitates the dissolution of metals and sulfur from the surrounding volcanic rocks. The heated water rises rapidly and flows back into the sea due to the lower density of this hot and mineral-rich fluid. In the ocean, the warm water column rapidly cools again, causing the dissolved metals to coalesce into tiny sulfide particles and sink as fine precipitants to the bottom.

In total, 58% of the known SMS are found at mid-ocean ridges, 26% in arc extension zones, 16% in island arc volcanoes, and 1% in intraplate volcanoes (Bollmann et al., 2010). However, the total quantity of SMS deposits is uncertain because the extent of hydrothermal vents globally is unknown. Estimates of the Earth's geothermal heat flow imply that extensive SMS deposits are yet to be discovered. The minerals that form SMS include iron sulfides and major minerals of economic interest, such as copper sulfide, zinc sulfide, and indium, as shown in Fig. 8.

Geological studies have shown that large deposits can form near offshore mid-ocean spreading ridges when the plates separate at a slow rate. Mid-ocean spreading ridges are volcanic ridges in the ocean where oceanic plates form and then separate. Fast spreading creates new fissures too frequently to establish long-term vent systems, and numerous small vents created by fast spreading would prevent the formation of a single deposit with large amounts of sulfide enrichment. Understanding the mechanics of spreading ridges is critical for SMS assessment.

It is essential to mention that hydrothermal vents provide us with ecosystem services of medicinal benefits. For example, unicellular organisms have been discovered that help in testing for COVID-19, and other microbes are currently used as antibiotics (e.g., Harden-Davies, 2017; Degnarain, 2020; Pettit, 2011). In addition, we find extensive biodiversity in the active hydrothermal vents, with many species living only in specific hydrothermal systems and nowhere else on the planet (endemic species; Van Dover et al., 2018; Goffredi et al., 2017). This is the case of the scaly-legged snail, which lives only in the hydrothermal vents of the Indian Ocean, or in the giant tubeworms that surround only the vents of the Pacific Ridge, or the Yeti crab, which lives in the vents near Easter Island at depths of >2000 m. Uninformed exploitation of any of these places could, therefore, lead to the extinction of one or more critical species before they become known to science. For example, the scaly-foot snails or mussels that inhabit these sources could easily become extinct, as their physiology makes it impossible for them to escape or live in other habitats (Hunter Jr et al., 2017).

On the Chilean continental shelf, García et al. (2020) have found several seamount chains and volcanic islands, such as the Salas y Gómez and Juan Fernández ridges, and three Quaternary hotspots near oceanic islands (Sandwell et al., 2005) that have a high potential to host SMS

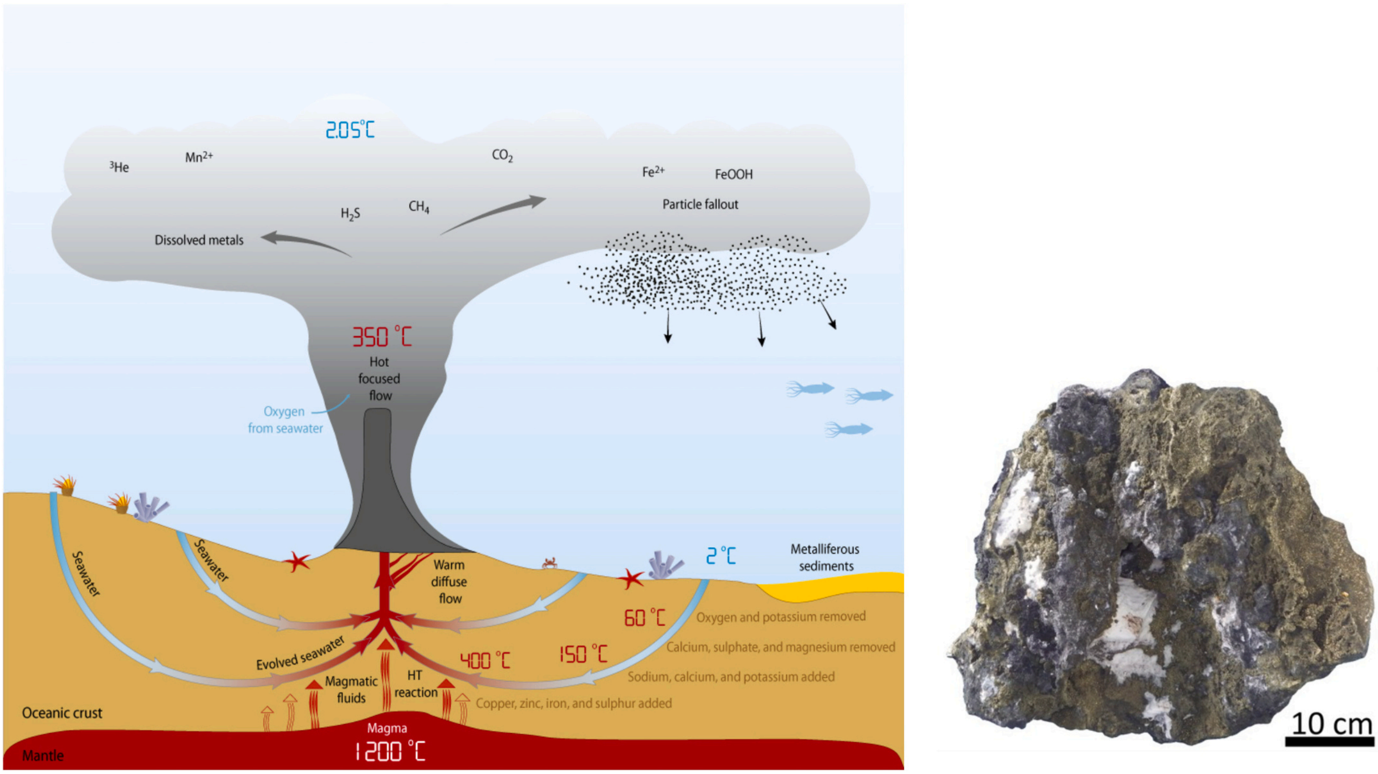

Fig. 8. Left: Basic components of a hydrothermal vent (or black smoke); see text for details (credit: GRID-Arendal; https://www.grida.no/resources/8166). Right: a hydrothermal vent block with a copper sulfide intrusion. This sample comes from the southern Japanese EEZ (Credits: Ishikawa et al., 2016).

occurrence. Furthermore, there are over a hundred seamounts (Yañez et al., 2009) that are yet to be explored, and the area around the hotspots that generated these seamounts could also host young polymetallic mineralization of SMS type.

Sitting in the trench along the southern Chilean margin at ~46°S is the Chile Ridge, which is an active seafloor spreading center that creates the Nazca Plate (to the north) and the Antarctic Plate (to the south) and could be forming SMS. The Chile Ridge is currently subducting to the east under the South American Plate, with southern portions already subducted. This peculiar zone is called the Chile Triple Junction (CTJ), where an important gas hydrate reservoir is also located on the continental margin (Villar-Muñoz et al., 2019). Although there is no direct evidence of SMS near the CTJ within the Chilean continental shelf, some studies have identified small chains of submarine volcanoes (Blackman et al., 2012; Villar-Muñoz et al., 2021), and results are indicative of sediment-hosted venting at the CTJ (German et al., 2022). Moreover, other studies have estimated high heat flow anomalies in the area close to the subduction (e.g., Villar-Muñoz et al., 2019, 2021), suggesting high and vigorous hydrothermal activity that could be the source of as yet undiscovered SMS deposits (Fig. 9). Although the physicochemical and geomorphological characteristics are favorable for the formation of SMS, it is essential to note that there are currently no known samples of SMS on the Chilean continental shelf.

Finally, regarding Chile's marine resources, our compilation here includes geological information related to the presence of GH, PN, SMS, and CRC in the Chilean continental shelf (see Table 1), which adds to the information already available.

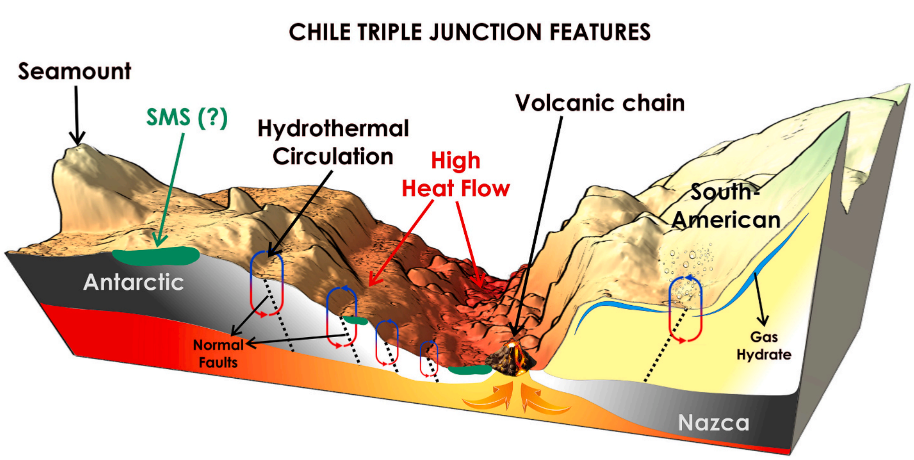

Fig. 9. Main features that can affect the thermal regime and favor the formation of SMS (in green) at the Chile Triple Junction area (modified from Villar-Muñoz et al., 2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Mineral and energy occurrences identified in the Chilean continental shelf during the last decade.

Name	Location	Type	Data From
JF5	−33.75°S/−79.92°W	CRC	Diaz-Naveas et al. (2015)
O'HIGGINS	−32.91°S/−73.92°W	CRC	Diaz-Naveas et al. (2015)
DUKE	−33.44°S/−79.55°W	CRC	Lara et al. (2018)
MUC02	−26.08°S/−75.96°W	PN	Kinoshita (2019)
MUC05	−25.70°S/−88.92°W	PN	Kinoshita (2019)
MGL27–1	−40.70°S/−74.70°W −42.47°S/−75.12°W	GH	Bangs et al. (2020)
MGL22–2	−44.00°S/−74.56°W −43.10°S/−76.20°W	GH	Bangs et al. (2020)
CTJ (INFERRED)	−46.20°S/−75.81°W	SMS	Villar-Muñoz et al. (2021)

4. Environmental impact

4.1. Environmental Impact of gas hydrates exploitation

Securing energy is a critical objective of any national development and security strategy. Within the framework of energy transition and carbon neutrality goals, the general trend in hydrocarbon policy worldwide is to increase the share of natural gas and decrease oil consumption.

In this context, shallow gas hydrates in the deep sea have attracted the attention of researchers as described above. However, hydrate well drilling is still associated with many unknowns and challenges due to technological barriers, complex in-situ working conditions, and unique physicochemical properties (Wei et al., 2020).

The most significant environmental impact of gas hydrate exploitation is the release of methane into the marine environment and the atmosphere, which can be triggered by drilling to extract gas from the seafloor and inadvertently destabilizing the sediments (Collet et al., 2000).

Although Chile has signed the Paris Agreement (NDC, 2020) to move away from fossil fuels and we do not condone disruption of marine sediments to extract this energy resource, it is important to note that irresponsible exploitation of this resource could cause disruption and release of methane from the deep sea: Gas production from a marine GH reservoir risks mechanical stability if hydrates cementing the pores of unconsolidated reservoirs are removed (Lee et al., 2011). Production processes relying on thermal stimulation pose a risk of production-induced instability to the slope (Tan et al., 2021), which could collapse and cause a slide or slump. As Tan et al. (2021) suggested, it is necessary to search for the overall optimal production strategy, as the economically optimal option likely carries risks from production-induced geological hazards.

The potential consequences of hydrate decomposition in near seepage areas depend on the magnitude and duration of hydrate decomposition. This is because the amounts of methane released may affect the seafloor and the microbial communities that support the methane cycle, thus varying methane transfer from the sediment to the water column (Ruffine et al., 2023). We suggest that policymakers also promote studies to identify these zones of methane leakage from GH (or cold seeps) to monitor what we assume will be increasing CH_4 release due to global warming of the oceans, as well as feedback effects from the transfer of this greenhouse gas into the atmosphere.

4.2. Environmental impact of mineral exploitation

A fundamental advantage of exploiting marine mineral resources is that it has no direct impact on established communities, which only exist on land. The extraction of marine mineral resources does not require social resettlement or loss of livelihood and eliminates the need for many legal restrictions related to environmental protection or social disruption that generally occur in communities impacted by large mining projects.

However, the mining industry must conduct investigations to improve our understanding of the dispersion and dilution of waste plumes (Fig. 10), the metals they contain, their toxicity, and, in the case of the benthic plume, the impact of sedimentation on poorly studied deep-sea habitats and species as the plumes settle.

Biodiversity loss is inevitable in mined areas, as seabed mining directly destroys habitat and indirectly affects large parts of the water column and seabed regions by creating metal-enriched sediments or plumes (Van Dover et al., 2017). This has prompted several scientists and authorities to demand more data before approving any deep sea mining project from ISA (e.g., Drazen et al., 2020).

As PN deposits are located directly on the seafloor, no extensive pre-extraction or overburden removal to access ore deposits is required. According to Paulikas et al. (2020), producing metals from PN would significantly reduce the impact on climate change compared to terrestrial mines. Moreover, metal production from PN would avoid the generation of solid waste and substantially reduce ecotoxicity, eutrophication potential, and SOx and NOx emissions. The social impact would be significantly lower in the case of metal production from PN, with substantially fewer anticipated deaths, injuries, illnesses, impacts on vulnerable populations, and potential for human toxicity.

However, as CRC are adhered tightly to the substrate rock and it is crucial to collect the crust without collecting the substrate (Hein and Koschinsky, 2014). Crust removal operations may include

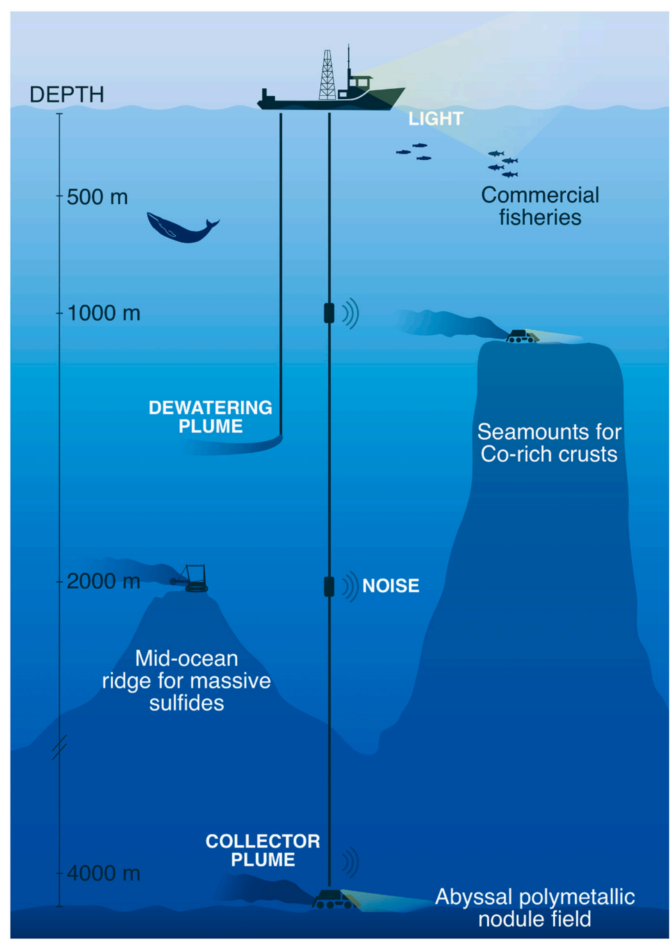

Fig. 10. A view of the environmental impacts (e.g., sediment plume, noise) caused by deep-sea mining of polymetallic nodules (PN) on abyssal plains, seafloor massive sulfides (SMS) on hydrothermal vents and cobalt-rich crusts (CRC) on the surface of seamounts (illustration without scale; modified from Drazen et al., 2020).

fragmentation, crushing, lifting, picking, and separation (Hawaii Department of Planning and Economic Development, 1987). Therefore, crust extraction is likely to have a greater impact on the environment than PN collection. In terms of environmental protection, there are as yet no technical solutions for economic extraction, as it is not yet known to what extent the extraction of CRC harms deep-sea habitats. Undoubtedly, CRC mining will have a local negative impact on benthic communities, but the impact of deep-sea mining will be much less than that of bottom trawling due to the limited area that will be affected (Pitcher et al., 2010; Hein et al., 2010).

The extraction of SMS requires the use of excavators (equipped with seabed crawlers) weighing several tons to remove many meters of sediments and substrate (Van Dover et al., 2018), similar to some land-based mining activities (Washburn et al., 2023). The extracted rock mixture is pumped from the collecting machine into a large container that will be raised and lowered between the ship and the seabed. The container is filled with huge blocks of massive sulfides at the bottom, then lifted onto the ship, emptied, and lowered back to the seafloor (Bollmann et al., 2010). All of these processes still have unknown environmental impacts.

In general, the main environmental issues from mineral mining are related to:

- Substrate removal: PN, CRC, and SMS provide a hard surface habitat to which some sessile invertebrates attach. Mineral collection will permanently remove most substrates and destroy the organisms attached to them.
- Benthic plume: As the collector vehicle moves across the seafloor, it will mobilize sediment. Most of the sediment will be discharged to the seafloor a few meters from its source, generating a plume. This plume could spread to other areas, and the fine sediment could clog the feeding and respiratory structures of filter-feeding organisms.
- Return water plume: Wastewater accumulated during the harvesting of the deposits would be discharged back into the ocean. This would also produce a sediment cloud in the water column, forming a plume composed of a suspended and a dissolved phase, often referred to as a mid-water plume.
- Noise pollution: Harvesting machines, pumping, and cleaning the crust material would create noise and vibrations, disturbing and scaring away fish and cetaceans.
- Light pollution: Lights from boats and collection machines could disturb birds, fishes, and mammals.

5. Future directions

In order to gain an understanding of the organisms affected in potential mining areas, comprehensive environmental studies are required prior to any mining operation to measure the subsequent impacts of mining on a site. Such studies should assess the marine environment in and around the proposed mining site, include suitable reference sites to observe mining impacts as part of a monitoring program, and assign protected areas to mitigate the effects of mining (Boschen-Rose et al., 2022).

Baseline environmental data is currently being collected using video footage of the seabed and sampling of benthic biota from the hard mineral component and soft sediments. This data will be used to develop an understanding of the distribution and structure of the benthic communities. Additional environmental parameters, such as depth, backscatter, roughness, aspect, and slope, are also characterized by multibeam echosounder data. Other environmental parameters in the water column include current measurements (ADCP), temperature (CTD), total organic carbon (rosette), fauna (video, hydrophone), plankton (net), met-ocean surveys (moorings), and sediments (trap) (Fig. 11). In addition, geophysical parameters are also relevant, such as gravity and magnetometric measurements; bottom and sub-bottom acoustic profiling; seismic reflection; and heat flow (e.g., device attached in a piston core). A summary of the equipment used for the exploration and environmental baseline is shown in Fig. 11.

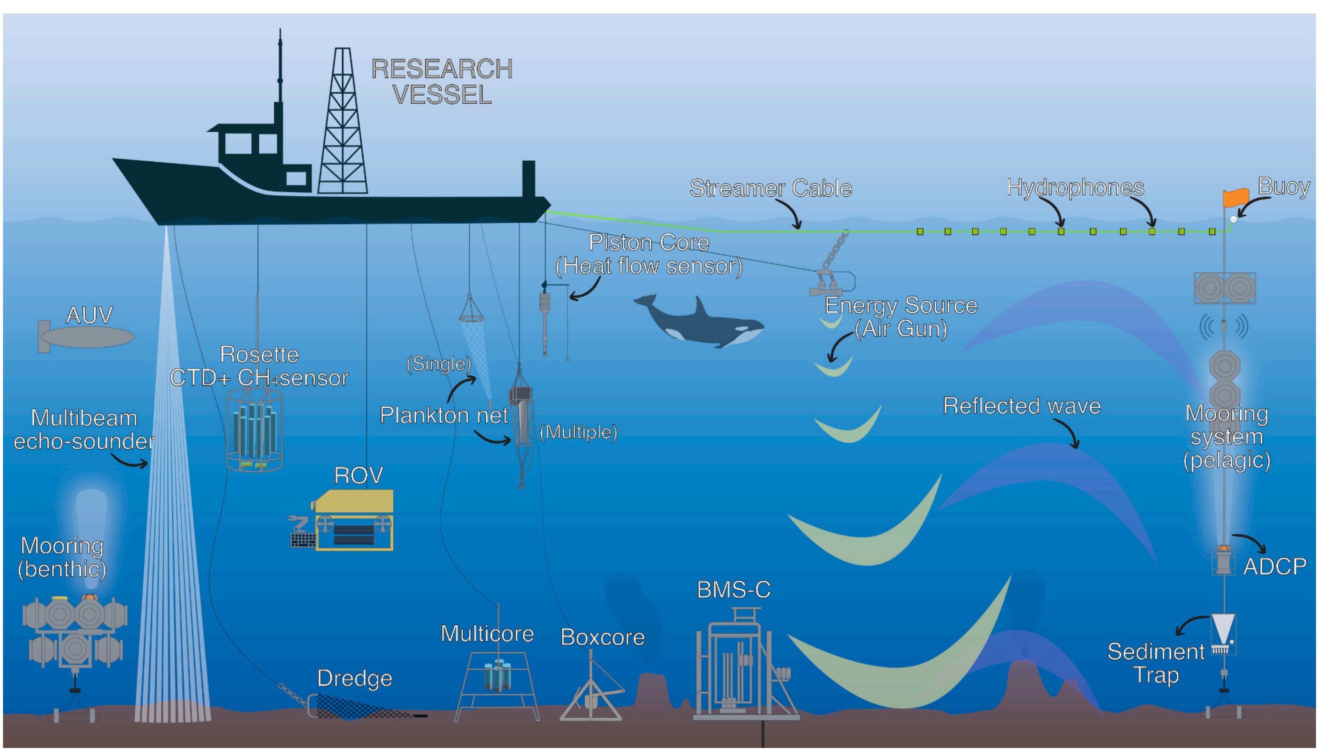

Fig. 11. Main reservoir exploration and environmental survey equipment suggested as a minimum on board a scientific vessel. Acronyms: i) ADCP: Acoustic Doppler Current Profiler; ii) ROV: Remote Operated Vehicles; iii) AUV: Autonomous Underwater Vehicles; iv) BMS—C: Benthic Multicore for Crusts; v) CTD: Conductivity, Temperature, and Depth; and vi) CH_4 sensor: methane sensor.

GH is a widespread energy resource in Chile that could be destabilized not only by mining operations, but also by the increase of the bottom temperatures (<700 m depth) due to global warming, releasing trapped methane in some areas (Ketzer et al., 2020). Therefore, future research related to GH must also focus on estimating seafloor sequestered methane gas and potential leakage zones that will be affected by the bottom temperature in future climate scenarios. For this research, high-resolution bathymetric and seismic surveys in conjunction with sonar data studies are crucial and should be carried out along the Chilean margin, from 33° to 56° S. Equipment should include a multibeam echosounder, a sub-bottom profiler, a seismic deployment and high resolution bathymetry (e.g. AUV), data which should be accompanied by sediment sampling (e.g. piston core) to study the characteristics of hydrates, if present, in shallow areas (see Fig. 11).

Furthermore, exploration of CRC is still in its infancy, and technologies to evaluate and recover crusts have yet to be developed or tested. Concerning SMS, much more research is needed in Chile to assess exploitation schemes because occurrences are rare and extraction schemes are untested. It should be noted that there may be larger deposits on the Chilean seabed that could be visualized in the near future. This optimism stems from the ongoing developments in advanced technologies that are currently being developed for the explanation of SMS far from the axis of the ridges and/or under the sedimentary cover that could be applied offshore Chile.

6. Conclusion

In this review, we present for the first time a comprehensive description of the mineral and energy resources in the Chilean continental shelf, adding data on new reservoirs obtained during recent research cruises off the coast of Chile. We also include exploration guidelines for these marine resources and suggest a plan for conducting environmental impact assessments, which represent significant advances in this area. These contributions provide a basis for future national policy and legislative decisions related to deep-sea mining and the designation of marine resources outside the boundaries of marine protected areas. These provide both environmental protection and sustainable economic benefits.

Currently, the best studied and evaluated mineral resource is the PN in the CCZ. We can therefore conclude from results of research on PNs:

i. advantages: PN contains all the metals we need for developing renewable energy sources (e.g., the manufacture of electric batteries) such as Ni, Co, Cu, Li and Mn. The biggest difference between PN mining and conventional mining is that these nodules contain a broad range of metals in a single nodule while terrestrial sources are broadly scattered. Cu, for example, is extracted in Chile or Peru, Co comes from the Congo, Mn is extracted in South Africa and Ni comes from Indonesia, where there are various problems with slavery, child labor and a great loss of biodiversity in the exploited area. In addition, the grade of these critical metals in PN exceeds most onshore sources, making deep-sea deposits a major competitor to conventional mining. The environmental impact studies carried out in the CCZ, show that the total amount of carbon stored in the deep sea that is at risk of being released into the atmosphere is 90% lower when deep sea PN are used compared to land-based mining, due to the fact that seabed sediments contain much lower amounts of carbon than on land, and very little can reach the ocean surface. Furthermore, due to the low grade of metals on land, four times more material must be removed to extract the same amount of metal, and many of these mines are located in places with high biodiversity, such as the Congo or Indonesia, which will release a large amount of sequestered carbon into the atmosphere. Finally, land-based operations (such as smelters or refineries) have the advantage that the processing plants are flexible in terms of location and can be sites in areas with minimal vegetation, for example, which would mitigate the environmental impact.
ii. disadvantages: the disadvantages of PN deep-sea mining are related to the environmental impact of the extraction of metals, such as the impact of the sediment plume left by the collector vehicle when mining the nodules in the deep sea or the mid-water sediment plume. Furthermore, the noise of the machines (such as ships or the collector vehicle) could affect the fauna, especially the animals that communicate by echolocation, such as cetaceans, and the light pollution, also caused by the surface vessel and the underwater collector vehicles, could affect the marine fauna. In addition to the disadvantages of PN-mining, a conflict in the mining exploitation of CRC is foreseeable as there are also commercial fishing areas around seamounts due to their high biodiversity and species richness. It is therefore likely that the fishing industry will be severely impacted by deep-sea mining of CRC. Moreover, if deep-sea mining is authorized in active hydrothermal vents, where SMS deposits are found, there is a high risk that one or more species endemic to these extreme areas will face extinction. This is due to the fact that active hydrothermal vents harbor great biodiversity, and many species are only found in certain vents and nowhere else on Earth (e.g. scaly-legged snail, giant tube worms or the Yeti crab).

In relation to energy resources in Chile, one of the most striking revelations of this study is the significant occurrence of GH deposits that extend along most of the Chilean continental margin from near Valparaíso at 33°S to the southernmost regions of Patagonia. Notably, the discovery of a highly concentrated deposit off the coast of Chiloe Island, clearly detected by seismic data analysis (MGL27–1, MGL22–2 in Table 1), underlines the importance of this study. However, the potential release of methane, a potent greenhouse gas, due to ocean warming, poses a concerning threat. To address this threat, it is necessary to continue to focus on research to pinpoint the locations of these deposits, particularly at depths <700 m, and to identify areas where methane is escaping into the marine environment and the atmosphere.

The mineral resources are crucial as sources of critical elements and base metals for the development of low carbon energy, electromobility and emerging technologies, which are part of Chile's Nationally Determined Contribution (NDC) to achieve inclusive and sustainable development. In particular, PN samples were collected near San Ambrosio Island at approximately ~26°S (MUC02) and in the vicinity of the Pearl seamount (MUC05). Moreover, the presence of a dozen guyots along the Nazca plate, that have not yet been subducted (e.g., JF5, O'Higgins and Duke seamounts), presents a promising source of CRC. In addition, our research indicates the potential presence of SMS near active hydrothermal vents, especially near to the subduction of the Chile Rise at approximately 46°S (CTJ in Table 1).

Our new discoveries of mineral and energy resources make Chile not only an established source of terrestrial minerals, but also a potential source of marine energy (i.e., methane gas) and metal resources (e.g. Co, Ni, Cu, Mn) that are highly prized by today's high-tech industry. Based on the information gathered in this review, we encourage decision-makers to continue exploring marine resources, either to further protect the deep sea (e.g., by establishing new marine protected areas) or to assess responsible future deep-sea mining exploration, and study the environmental impacts associated with this emerging industry.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

HIKARI HINO reports a relationship with Japan Organization for Metals and Energy Security that includes: employment. MICHAEL CLARKE reports a relationship with THE METALS COMPANY that includes: employment. JOAQUIM P. BENTO reports a relationship with THE METALS COMPANY that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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