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REVIEW

Deep seabed mining: Frontiers in engineering geology and environment

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Abstract
Ocean mining activities have been ongoing for nearly 70 years, making great contributions to industrialization. Given the increasing demand for energy, along with the restructuring of the energy supply catalyzed by efforts to achieve a low-carbon economy, deep seabed mining will play an important role in addressing energy- and resource-related problems in the future. However, deep seabed mining remains in the exploratory stage, with many challenges presented by the high-pressure, low-temperature, and complex geologic and hydrodynamic environments in deep-sea mining areas, which are inaccessible to human activities. Thus, considerable efforts are required to ensure sustainable, economic, reliable, and safe deep seabed mining. This study reviews the latest advances in marine engineering geology and the environment related to deep-sea mining activities, presents a bibliometric analysis of the development of ocean mineral resources since the 1950s, summarizes the development, theory, and issues related to techniques for the three stages of ocean mining (i.e., exploration, extraction, and closure), and discusses the engineering geology environment, geological disasters, in-situ monitoring techniques, environmental protection requirements, and environmental effects in detail. Finally, this paper gives some key conclusions and future perspectives to provide insights for subsequent studies and commercial mining operations.

Keywords Deep seabed mining · Marine engineering geology · Geological disasters · Environment · Techniques

1 Introduction

Ocean mining has been developed since the 1950s, and deep seabed mining has seen a boom in the last decade. Many high-value deep-sea minerals have been discovered in a vast deep-sea area of 360 million km^2 with a water depth of more than 200 m (Miller et al. 2018). As the most valuable mineral resources of this century, deep-sea minerals are critical for high-tech industries related to the low-carbon economy (e.g., new forms of transportation, aerospace components, electric vehicles, renewable energy, and electrical storage).

Deep-sea minerals mainly include gas hydrates, which is a crystalline solid formed of water and gas, and polymetallic nodules, cobalt-rich crusts, polymetallic sulfides,

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and rare earth elements, which are rich in Mo, Mn, Se, Ni, Au, and Cu, have the potential to replace terrestrial metallic resources and have high commercial exploitation value (Pak et al. 2018; Liu et al. 2021a). Figure 1 presents the global sea distributions of polymetallic nodules, cobalt-rich crusts, and polymetallic sulfides along with their occurrence states and representative images. Polymetallic nodules are distributed in deep-sea plains at water depths of 4000–6500 m or fully or partially buried in sediment. The main industrial exploration areas of polymetallic nodules include the Eastern Pacific, the Peruvian Basin, and the Northern Indian Ocean Center (Pan and Hua 1996; Sharma 2017). Cobalt-rich crusts are distributed on the tops, flanks, and broad saddle structures of seamounts with water depths of 800–3000 m and connected to the hard bedrock surface. These crusts are mainly concentrated in the West and Central Pacific (Sharma 2017; Wei et al. 2017). Polymetallic sulfides are widely distributed in the hydrothermal zones of mid-ocean ridges, volcanic arcs, and back-arc spreading centers with water depths of 1000–3500 m. These sulfides occur in the Red Sea and Western Pacific (Ding et al. 2009; Liu et al. 2022). Given their areas of distribution, it is not easy to exploit these mineral resources.

Driven by the combination of industrialization and new energy development, companies from many countries have been scrambling to conduct mining trials on the ocean floor to obtain high-value minerals. In the 1950s, the United States, West Germany, United Kingdom, France, Union of Soviet Socialist Republics, and Japan began to investigate polymetallic nodules. In the 1970s, the multinational companies Ocean Mining Inc., Ocean Mining Associates, and Ocean Minerals Company, which are composed of several companies from the United States, Germany, the Netherlands, Belgium, and Italy, carried out polymetallic mining tests from 1978 to 1979, resulting in great progress (Chung 1998; Xiao et al. 2000). In 1994, the International Seabed Authority (ISA) was established to organize all mineral-related activities in the international seabed area for the joint management and development of resources. ISA approved "Regulations on prospecting and exploration for cobalt-rich ferromanganese crusts in the Area" in 2009, "Draft regulations on

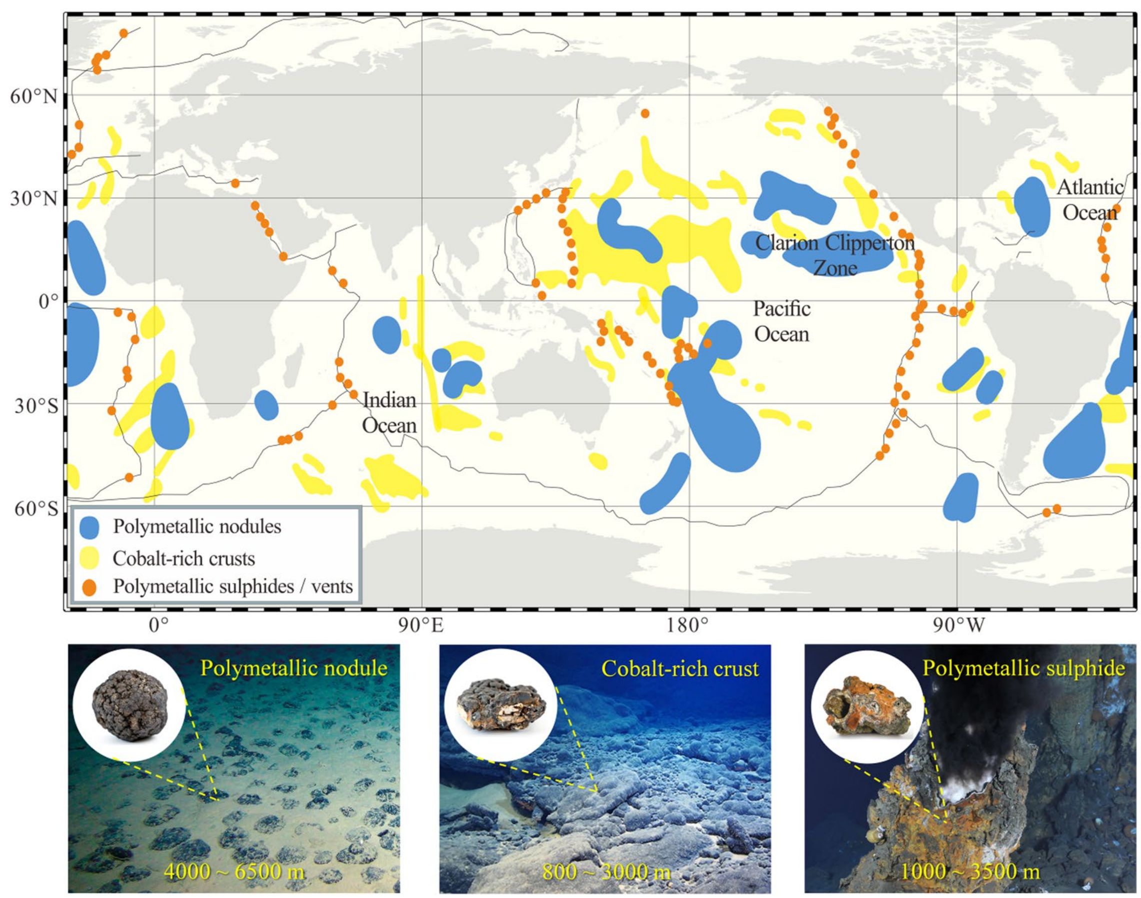


Fig. 1 Global distribution, occurrence state, and representative images of three major deep seabed mineral resources (modified from Miller et al. 2018; Cuyvers et al. 2018; photos taken by ROV KIEL 6000 during cruise M78/2, Jan Steffen/GEOMAR, and GEOMAR/Schmidt Ocean Institute/CSSF)

prospecting and exploration for polymetallic sulphides in the Area" in 2010, and "Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area" in 2013 (International Seabed Authority 2009, 2010, 2013; He et al. 2016). In 2020, the American Bureau of Shipping issued the "Guide for Subsea Mining," the first seabed mining guidelines for the marine industry. This guide provides requirements for the design, construction, installation, and survey of mobile offshore mining units. Along with increasing environmental awareness, the impact of mining activities on the environment has attracted increasing attention. The Legal and Technical Commission of ISA issued "Draft Regulations on Exploitation of Mineral Resources in the Area" in 2017, with subsequent revisions released in 2018 and 2019 (Wang et al. 2022). In 2021, the China Association of Oceanic Engineering approved the "Guidelines for the Environmental Protection and Preservation of Deep-sea Mining Activities (China Association of Oceanic Engineering 2021)," which describes general principles for deep-sea mining activities. Table 1 lists mining trials of deep seabed minerals and operational tests for mining equipment from 1978 to 2019.

While deep seabed mining has great potential, it remains in the exploratory stage, with the associated technology still being developed. Unlike mining operations on land (Sasaoka et al. 2016; Lian et al. 2020; Zhang et al. 2022), deep seabed mining is complicated by high-pressure and low-temperature environments with complex engineering geology and hydrodynamics. Deep-sea areas are not reached by human activities, thereby requiring the simultaneous development of science (technologies) and human cognition. Because deep seabed mining systems involve complex scientific backgrounds (e.g., multi-disciplinary) and challenging engineering problems, this study discusses the engineering geology and environmental issues related to deep seabed mining to support subsequent studies and commercial mining operations.

The remainder of this paper is organized as follows. Section 2 presents a systematic bibliometric analysis of the development of ocean mineral resources. Section 3 discusses the development, theory, and issues related to the three stages of ocean mining activities (i.e., exploration, extraction, and closure) in detail. Section 4 provides an in-depth discussion of the engineering geology environments and geological disasters at deep seabed mining sites along

Table 1 Mining trials of deep seabed minerals and tests of some mining systems (modified from Thiel and Schriever 1990; Ding et al. 2009; Yang et al. 2020; Su 2020)

Time (year)	Country/Company	Water depth (m)	Project content
1978	Ocean Management Inc (OMI)	5500	A
1978	Ocean Mining Association (OMA)	4570	A
1979	Ocean Mining Corporation (OMCO)	5000	A
1989	Germany/the former Ministry of Science and Technology of the Federal Republic of Germany	4140–4180	B
1990	Russia/Moscow Institute of Geological Exploration	79	C
1996	India/National Institute of Ocean Technology (NIOT); Germany/University of Siegen	500	D and E
1997	Japan/Polymetallic nodules Mining system research and development project	2200	F
1998	Japan/the Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (GSJ-AIST)	1600	G
2002	Japan/Japan Oil, Gas and Metals National Corporation (JOGMEC)	1600	D
2006	India/NIOT	450	F
2009	Korea/Korea Institute of Geoscience and Mineral Resources (KIGAM)	100	H
2012	Japan/JOGMEC	1600	E
2013	Korea/Korea Institute of Ocean Science and Technology (KIOST)	1370	F
2015	Korea/KIOST; Korea/Korea Research Institute of Ships and Ocean Engineering (KRISO)	1200	C
2016	China/Changsha Research Institute of Mining and Metallurgy	300	H
2017	Japan/JOGMEC	1600	C and E
2018	China/Changsha Research Institute of Mining and Metallurgy	500	E
2018	Netherland/Royal IHC	300	D
2019	China/Institute of Deep-sea Science and Engineering, Chinese Academy of Sciences (IDSSE,CAS)	2500	F

Notes: A, Mining trial for polymetallicnodules; B, Disturbance and recolonization experiment for deep seabed sediments; C, Test of the hydraulic lifting system; D, Test of the travel performance of the mining vehicle; E, Test of the acquisition performance of the mining vehicle; F, Test of the mining vehicle; G, Economic and technical feasibility study of polymetallic sulfide mining; and H, Test of the delivery system of the mining vehicle with the corresponding in-situ monitoring techniques. Section 5 discusses the requirements for environmental protection along with the environmental effects of deep seabed mining with a focus on the sediment plume. The summary and conclusions are presented in Sect. 6

2 Bibliometric analysis of ocean mineral resource development

Through bibliometric analysis, the development trends of some key information (e.g., literature numbers, authors, and keywords) from research literature can be assessed in a more objective and reliable way using mathematical and statistical theories. Here, the bibliometric analysis tool, CiteSpace-6.1.R2 (Chen 2004, 2006), was employed to summarize the overall status of the research relevant to ocean mineral resources and investigate the research development trends. The research literature data were retrieved from the Web of Science (WOS) database and the China National Knowledge Infrastructure (CNKI) database. Original data, including titles, authors, keywords, abstracts, etc., were output from these databases. The subject words used in the retrieval were "Ocean (or marine, undersea, underwater) + Mineral resources (or mining)". As a result, a total of 5838 effective literature records were obtained, including 4986 literature from the WOS database and 852 literature from the CNKI database, in a range of publication years from 1957 to 2022. The time of data retrieval was July 2022. The information from that 5838 literature was imported into the tool CiteSpace-6.1.R2 as basic data for bibliometric analysis.

2.1 Trends in the number of literature

The number of literature published in a certain time can reveal development trends in a research field to a certain extent. Figure 2 shows the variation trends of 5838 relevant literature in the field of ocean mineral resources over 65 years from 1957 to 2022 (where two databases are displayed separately). The time period of the analysis was divided into 12 time spans, with one span consisting of five years (except for the first and last spans).

Overall, the number of published literature related to ocean mineral resources gradually increased over time from 1957 to 2022. According to the variation trends, the development in the field of ocean mineral resources can be roughly divided into three stages: Stage I (1957 to 1988), Stage II (1989 to 2008), and Stage III (2009 to 2022). In Stage I, the average number of literature in each time span was approximately 19 for the WOS database and 22 for the CNKI database. These low literature numbers indicate that ocean mineral resources did not attract wide interest from experts and engineers during that time. Besides, the

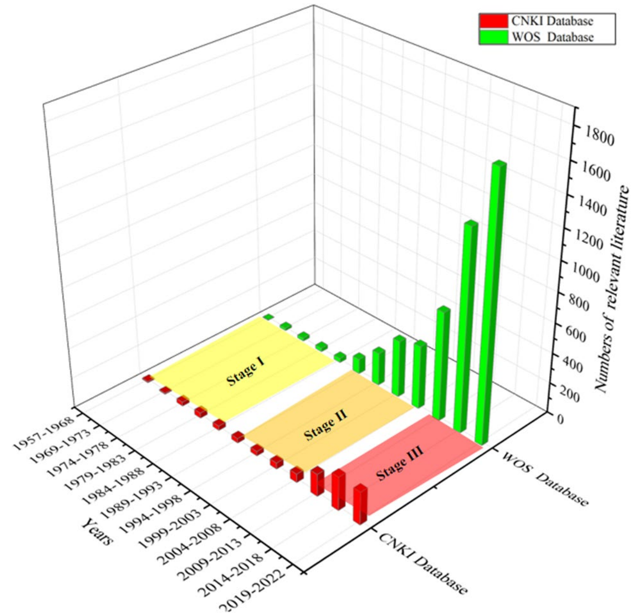


Fig. 2 Trends in the number of relevant literature published from 1957 to 2022

low literature numbers are also related to the economic and social development status at that time. In Stage II, the research situation had greatly improved, with ~ 280 studies in each time span for the WOS database and ~ 40 for the CNKI database. Compared to Stage I, the number of WOS database literature was nearly 15 times higher in Stage II. In Stage III, the number of relevant studies again increased substantially, with the average number of literature in each time span reaching ~ 1256 for the WOS database and ~ 195 for the CNKI database. Those trends highlight how ocean mineral resource development has become a hot research topic in the more than past 10 years. In addition, the trends could herald that this research topic will remain popular for a long time in the future.

2.2 Degrees of national concern and international cooperation

The institutional information extracted from research literature can inform the concern and cooperation between countries or regions in a research field to a certain extent. According to the data extracted from 4986 literature in the WOS database, a network graph of national concern and cooperation in research on ocean mineral resources was constructed (see Fig. 3). The clusters in the figure represent the countries of the institutions conducting the research, and the links between the clusters represent cooperation between institutes in different countries. Statistical analysis revealed 135 clusters and 163 links (not all clusters and links are displayed in Fig. 3 due to interface limitations).

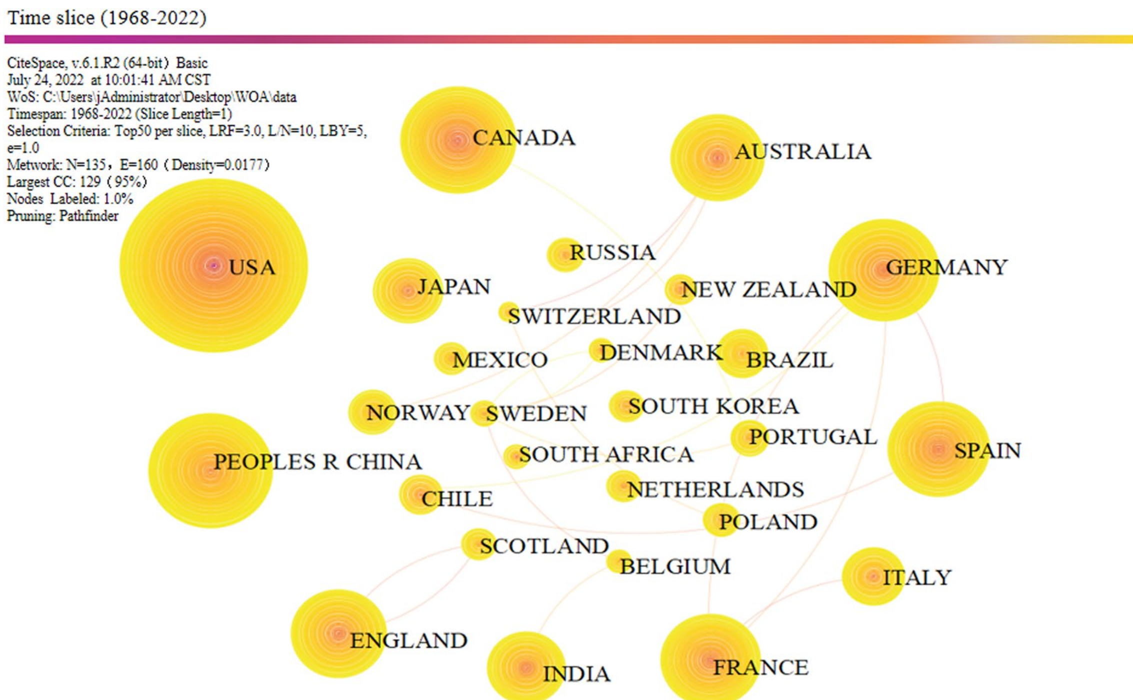


Fig. 3 Network plot of national concern and international cooperation based on the WOS database

The results in Fig. 3 indicate cooperation from 135 countries or regions on the topic of ocean mineral resources, and the degree of cooperation was high (the ratio of links to clusters was 163/135 = 1.21). The three countries with the most relevant literature are the United States, China, and Germany, which show large clusters. Those highly concerned countries or regions often have longer shorelines and need sufficient research to support their ocean mineral resources development, as shown in Fig. 4 (here, the data from all countries were grouped into continents, and the number of published studies is plotted with shoreline length by continent; The shoreline length data are based on Liu et al. (2015)).

2.3 Trends in literature keywords and hotspots

Literature keywords can intuitively reflect the theme of a study and affect the findings of literature searchers and whether the reader is interested in reading the study. Figure 5 shows clusters representing the literature keywords for studies on ocean mineral resources from the WOS and CNKI databases. The clusters represent the occurrence frequency of one keyword in all literature data, and the links between the clusters represent the correlations between keywords. As shown in Fig. 5a, the five most common literature keywords from the WOS database were “heavy metal”, “sediment”, “trace element”, “contamination”, and “rare earth element”

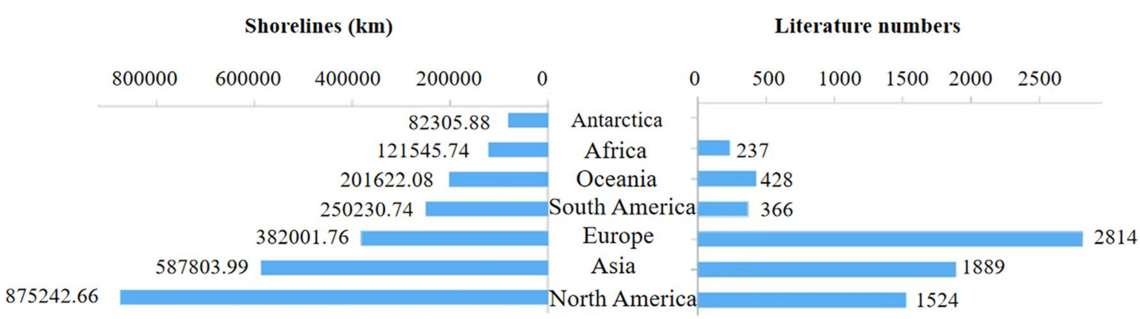


Fig. 4 Number of relevant literature versus shorelines by continent

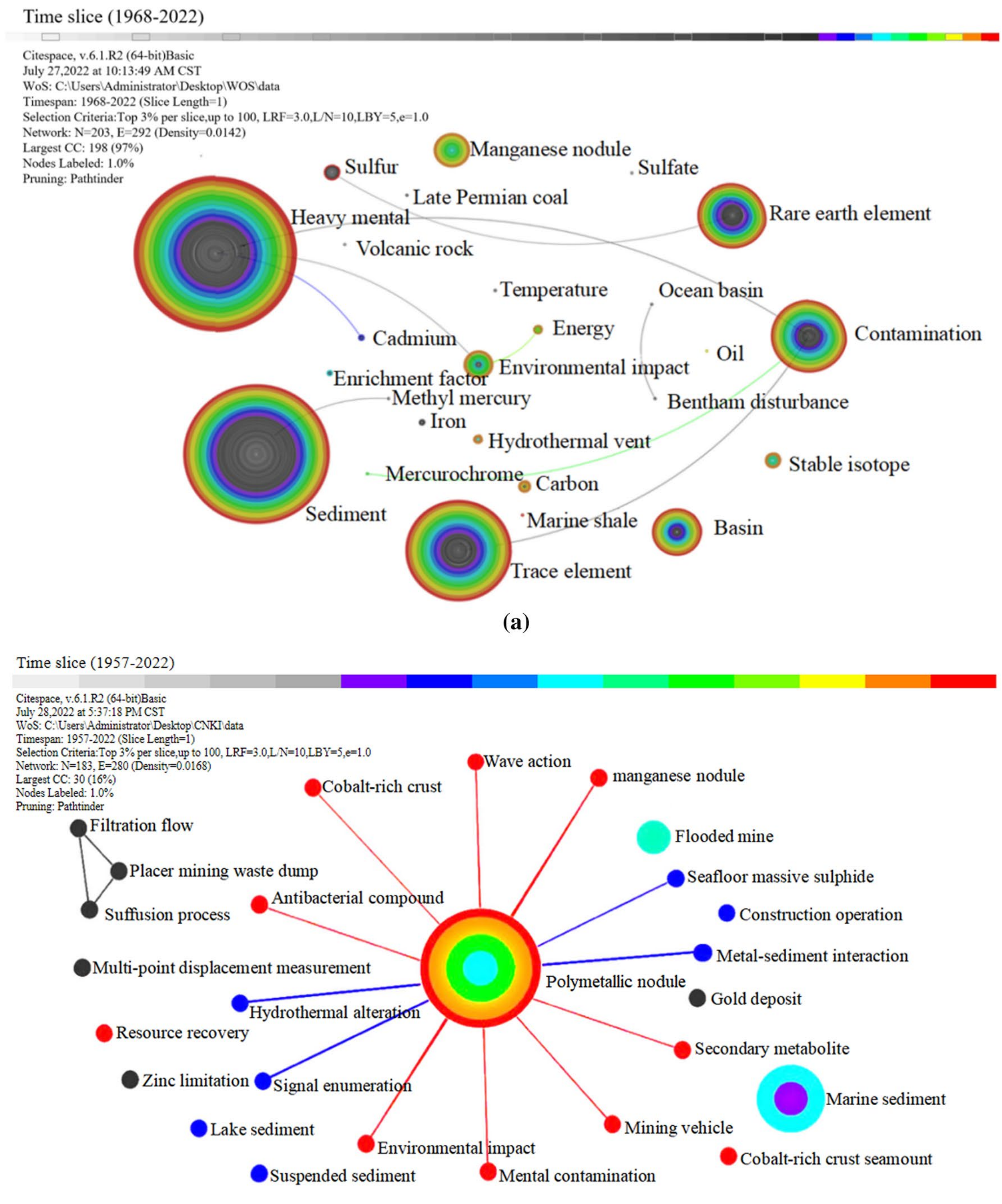


Fig. 5 Literature keywords on ocean mineral resources from the **a** WOS database and **b** CNKI database

(sorted from more frequent to less frequent); the five most common literature keywords from the CNKI database were "polymetallic nodule", "marine sediment", "flooded mine", "mining vehicle", and "environmental impact" (Fig. 5b). The popular research directions indicated by the keywords from the two databases are similar and include the mineral resources themselves (e.g., metals and nodules), resource development approaches, and the environmental effects of resource development. Those research directions clearly align with the full research process from identifying resources to safely developing the resources. In addition, some keywords were often mentioned together, forming the keyword links in Fig. 5. For example, "heavy metal" and "contamination" are linked in Fig. 5a, while "polymetallic nodule" and "mining vehicle" are linked in Fig. 5b.

To further investigate the frequencies of literature keywords used over time, the top 10 hotspots in the literature on ocean mineral resources over time are shown in Fig. 6. Through bibliometric analysis, the hotspots were counted in a way that a keyword in a certain period suddenly increases by a big margin. The larger the degree of increase, the higher the "strength" value in Fig. 6. In addition, the total time period of 1957 to 2022 was also divided into three stages (Stage I, 1957 to 1988; Stage II, 1989 to 2008; and Stage III, 2009 to 2022) as introduced in Sect. 2.1. As shown in Fig. 6a, for the WOS database, no obvious hotspots were found in Stage I. In comparison, Stage II had more hotspots, and they remained for a long time. Among the keywords in this stage, "sediment" had the largest strength value of 24.85. This indicates that the formation, distribution, and development of ocean mineral resources are inseparable from the study of seabed sediments. While in Stage III, the hotspots in this stage were related to the process of deep-sea resource development (e.g., extraction techniques and extraction effects on biosynthesis). The CNKI database also shows a similar development trend as the WOS database, as shown in Fig. 6b.

3 Techniques for ocean mining

In general, ocean mining activities have three main stages according to their order of implementation: exploration, extraction, and closure (China Association of Oceanic Engineering 2021). The exploration stage refers to the period of an ocean mining project after an exploration permit has been granted but no mining permit. The geologic and hydrologic environmental conditions, geotechnical properties of the seafloor soils, potential hazards, and relevant suggestions for the project should be provided during the exploration stage. After the mining permit is granted, the project enters the extraction stage, and mining extraction activities can be organized and carried out. When the mining task is completed or stopped, the project enters the closure stage, in which the ecosystem of the mining area is restored. The subsequent sections introduce the techniques involved in each phase of ocean mining.

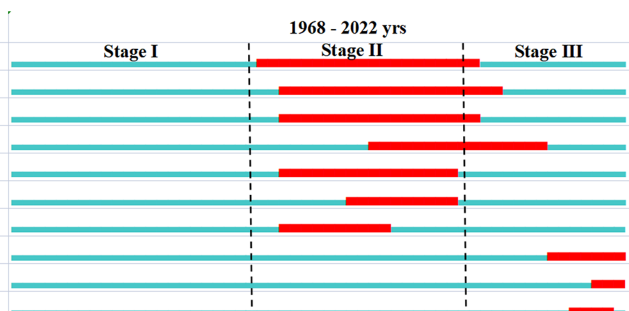
3.1 Techniques for the exploration stage

Comprehensive exploration of an ocean mining project should cover the ocean life, meteorology, chemistry, and geology based on techniques from fields including engineering geology, geotechnical engineering, and biology. This study focuses on techniques related to geological exploration, which primarily include geophysical exploration and geotechnical exploration.

3.1.1 Geophysical exploration techniques

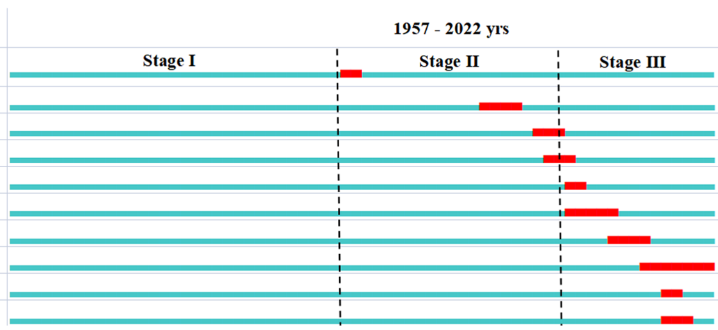
Geophysical exploration can reveal the geological characteristics (e.g., geological background, stratigraphic substance

Keywords	Year	Strength	Begin	End
Acid mine drainage	1968-2022	10.17	1990	2009
Sediment	1968-2022	24.85	1992	2011
Sulfur	1968-2022	9.17	1992	2009
Speciation	1968-2022	12.54	2000	2015
Geochemistry	1968-2022	12.79	1992	2007
Heavy metal	1968-2022	12.07	1998	2007
Evolution	1968-2022	7.49	1992	2001
Deep-sea mining	1968-2022	10.12	2016	2022
Extraction	1968-2022	8.26	2020	2022
Biosynthesis	1968-2022	6.86	2018	2021



(a)

Keywords	Year	Strength	Begin	End
Deep-sea mining	1957-2022	1.31	**1988**	1989
Mining waste	1957-2022	1.28	**2001**	2004
Submarine mine tailing	1957-2022	1.25	**2006**	2008
Marine sand mining	1957-2022	2.4	**2007**	2009
Law of the sea	1957-2022	1.7	**2009**	2010
Climate change	1957-2022	1.62	**2009**	2013
Marine sediment	1957-2022	2.11	**2013**	2016
Polymetallic nodule	1957-2022	2.27	**2016**	2022
Ocean science	1957-2022	2.34	**2018**	2019
Critical metal	1957-2022	1.56	**2018**	2020



(b)

Fig. 6 Top 10 hotspots in the literature on ocean mineral resources during different time periods **a** WOS database and **b** CNKI database composition, and geological structures) of the project area based on the local variation in geophysical fields. Geophysical exploration mainly considers the features of subsea stratigraphic substances (e.g., the density, elasticity, magnetic permeability, electrical conductivity, thermal conductivity, and radioactivity) to elucidate and explain the variation in geophysical fields. Thus, geophysical exploration is an indirect method. According to the features being detected, common geophysical exploration techniques include gravity exploration, seismic exploration, magnetic exploration, and electrical exploration.

(1) Gravity exploration

The principle of gravity exploration is based on the local variation in the gravitational acceleration fields of the seafloor caused by the density differences of various rocks and ores, as shown in Fig. 7. The local variation of the gravitational acceleration field (i.e., gravity anomaly) can be explored by gravity devices, mainly shipborne equipment (e.g., gravimeters and torsion balances). The plans and sections of the gravitational acceleration field can then be obtained and used to infer the position of mineral resources. Gravity exploration can be performed using fixed-point surveys or regional continuous surveys.

The gravity exploration technique was developed in the early twentieth century. Baron Roland von Eotvos made the first gravity field measurement in 1901 in a subaquatic environment (Balaton lake) using a self-developed torsion balance for measuring gravity variation (Vajk 1949).

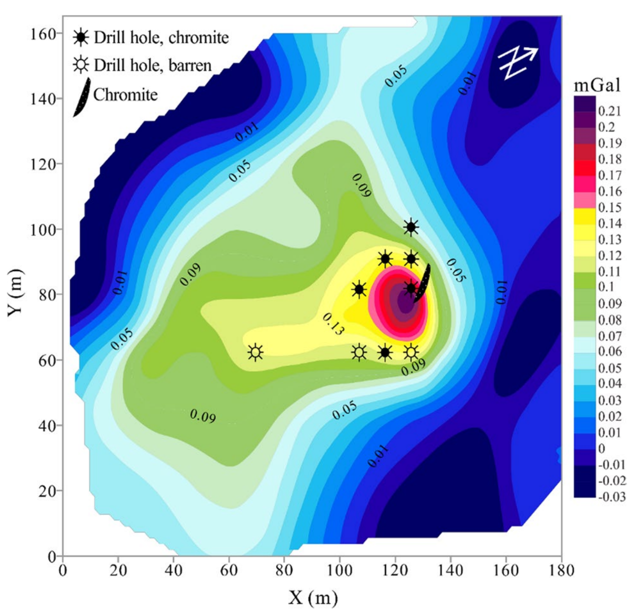


Fig. 7 Example of the gravity exploration technique (modified from Essa et al. 2020)

Subsequently, the torsion balance was employed at sea by Hecker in 1903 (Torge 1989). A gravity device was first attached to a submarine for exploration by Vening Meinesz in 1923 (Fujimoto et al. 2000). revealing changes in gravity in different oceanic regions; in particular, a large gravitational effect was found near the Indonesian Java Trench. Later, in the 1950s, gravity exploration approaches were widely applied in many countries, and the exploration efficiency was continuously improved. Some instruments used for gravity exploration include the pendulum ocean gravimeter of Graf-Askania and LaCoste & Romberg and the vibration ocean gravimeter of the University of Tokyo and the Massachusetts Institute of Technology (Forsberg et al. 2015; Shinohara et al. 2015). Since the development of global positioning system (GPS)-based 3D positioning, the gravity exploration approaches have been greatly improved. The gravity anomalies caused by resource storage can be detected more accurately with the support of GPS. Recently, some undersea remotely operated vehicles (ROVs) or autonomous underwater vehicles with gravity exploration functions have been developed (Ballu et al. 1998; Gilbert et al. 2007; James et al. 2013).

(2) Seismic exploration

The principle of seismic exploration is based on the propagation of seismic waves in strata with different elasticities. First, the seismic waves are artificially excited (e.g., by an explosive source, air gun, spark detonation gas, or resonator). The reflected or refracted waves at the interfaces between different elastic strata are received and recorded by hydrophones. Finally, the strata are identified by the different wave travel times and spectra. Seismic exploration is often used to explore oil and gas reservoir layers, coal fields, salt rock deposits, and some metallic mineral deposits. This technique can be used for continuous observation at sea and reach exploration depths of over a thousand kilometers, resulting in high efficiency.

In 1845, Mallet used artificially excited seismic waves to measure the propagation speed of elastic waves in the Earth's crust, which is considered the birth of seismic exploration (Graziano and Anita 2005). Regarding the application of seismic exploration, a team of physicists and geologists (William P. Haseman, J. Clarence Karcher, Irving Perrine, and Daniel W. Ohern) first recorded clear reflection waves produced by an artificial seismic source in Oklahoma (United States) in 1921 (Schriever 1952). Three oil storage fields were then discovered in the area through reflected seismic exploration in 1930 (Schriever 1952). During the same period, many salt domes were discovered along the Gulf Coast using refracted seismic surveys (Sussman and Stallman 1975). In the 1950s and 1960s, the spot photography technique of seismic exploration was replaced by analog tape recording, thereby improving the signal recording quality (Luo 2009). Later in the 1970s, analog tape recording was replaced by digital tape recording, resulting in a complete system based on high-speed digital computers that combined digital recording, multiple overlay techniques, and seismic data processing. In the 1990s, a new seismic exploration technique, seismic imaging, was proposed. The method utilized the characteristics of no surface wave interference in water and forms color digital soil sections by means of densely displaying wave impedance (Mora and Tarantola 1989). Recently, broadband seismic exploration techniques have been proposed for exploration in areas with large variations in water depth, rugged seabeds, and developed fractures (Moldoveanu et al. 2012).

From the perspective of testing dimension, seismic exploration approaches have developed from 1D to 4D (i.e., from the exploration of a point, to a line, to an area, and to multiple areas at different times). Time-varying 3D stereoscopic seismic images of the seabed layers can now be obtained using 4D seismic exploration approaches. In addition, hydrophone units have been placed on the seabed for long-term exploration, a technique known as ocean bottom seismometers (OBS) (Jocobson et al. 1991), as shown in Fig. 8. The OBS exploration technique allows the seabed reception of seismic waves, thus avoiding the large amount of absorption and attenuation of seismic wave energy in seawater and improving the accuracy of the results (Zhang 2015).

(3) Magnetic exploration

The principle of magnetic exploration is based on the local anomalies in the geomagnetic fields caused by various magnetic rocks, ores, and other objects (Fig. 9a). A magnetic field detector (e.g., proton precession magnetometer and gradiometer) is first fixed on a subsea drag body. The body is then dragged within a certain distance behind

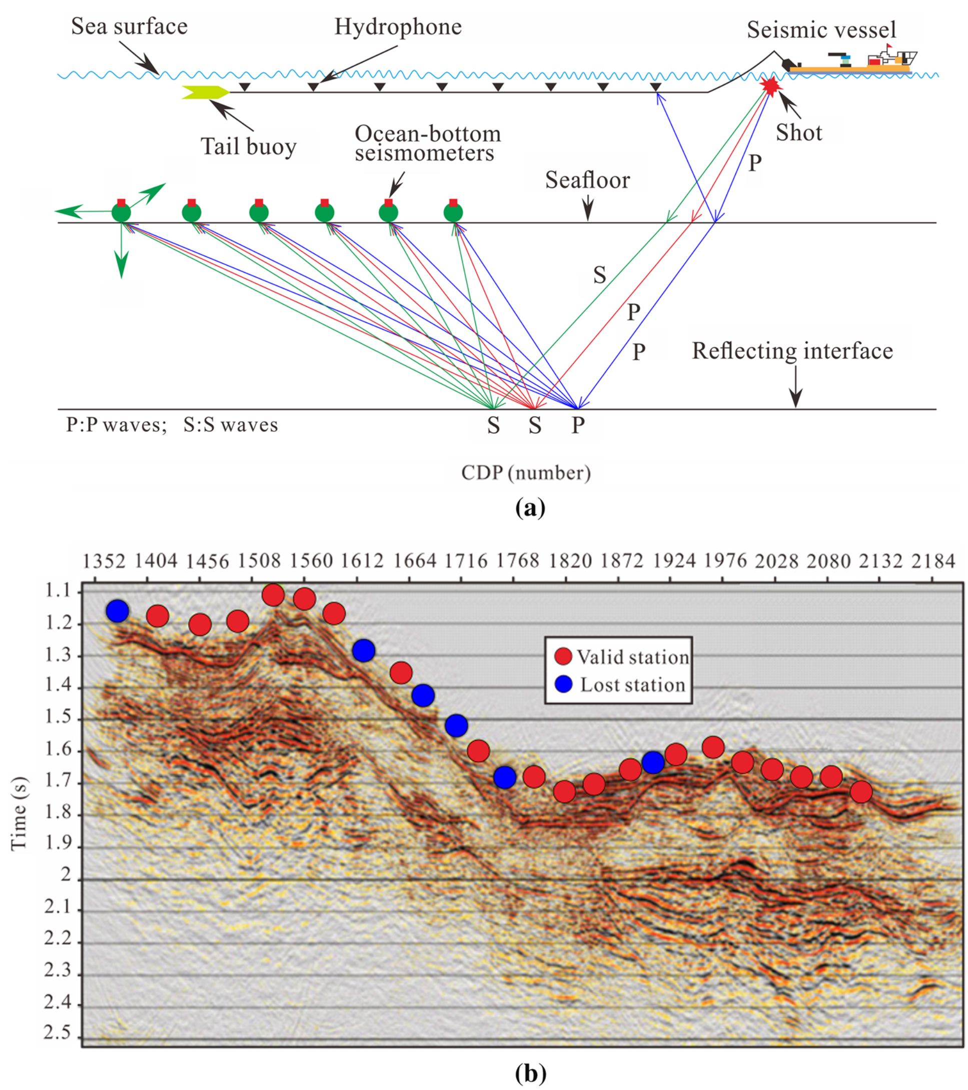


Fig. 8 **a** OBS principle and **b** example output (modified from Sha et al. 2015)

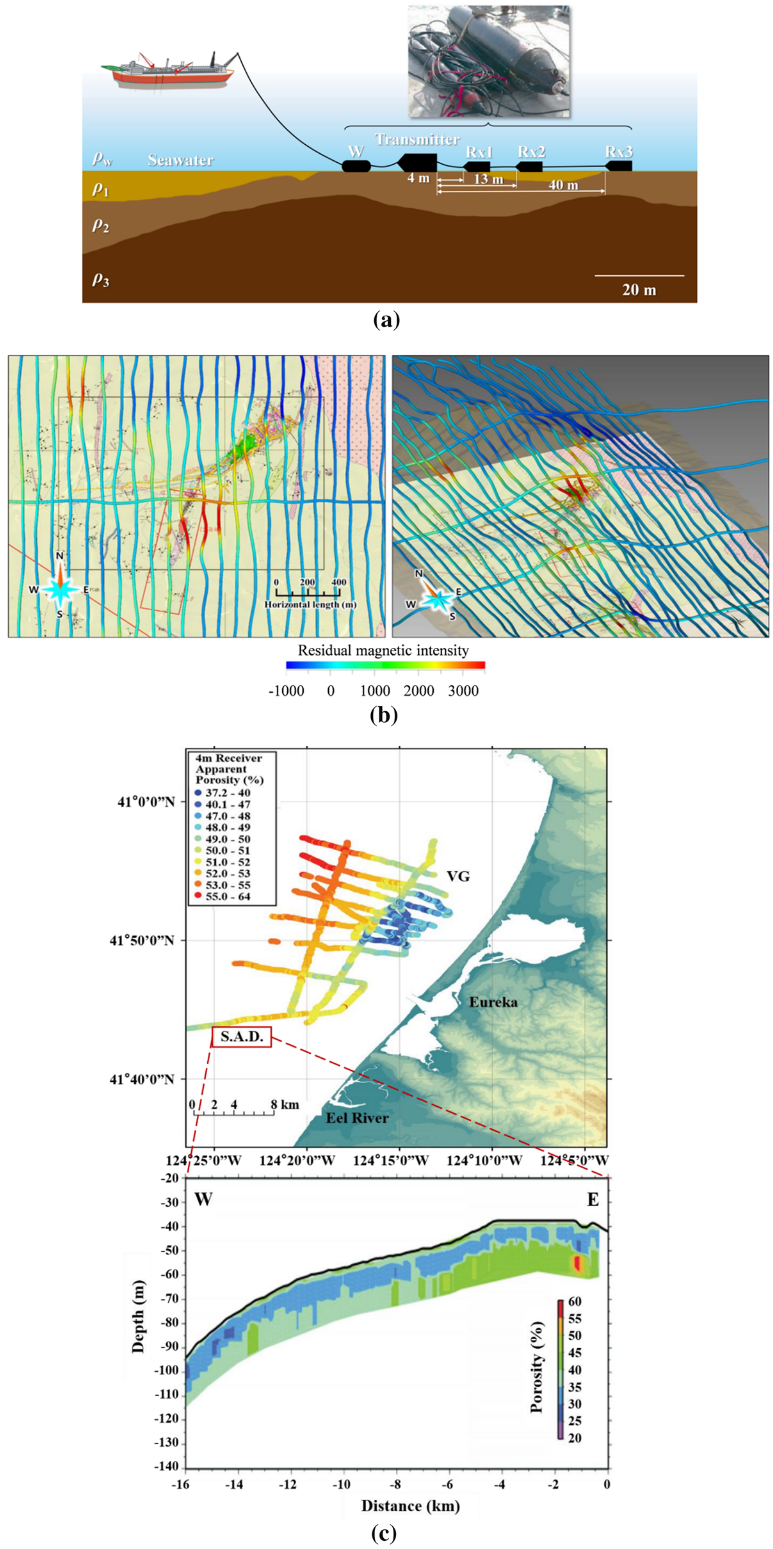


Fig. 9 Magnetic exploration **a** Working principle (modified from Hsu et al. 2014), where W is the weight as a depressor unit (The towed electromagnetic transmitter composed of 3 receivers (Rx1, Rx2, and Rx3, tuned to measure these magnetic fields different frequencies) and a transmitter (a horizontal magnetic dipole) forming an array with a total length of 40 m on the seafloor generates harmonic magnetic fields over a range of frequencies (Hsu et al. 2014)) **b** Example output on land (modified from Kim 2021) and **c** Example output on the exploration of underwater natural gas resources (modified from Evans 2007)

a moving ship, and the local magnetic anomalies of the stratum are recorded. This technique is suitable for exploring ore resources (e.g., iron ore, lead–zinc ore, and copper ore), Fig. 9b presents a example output on land, and Fig. 9c presents a recorded example on the exploration of underwater natural gas resources. However, this technique involves intermittent measurements, and the survey sensitivity is relatively low.

Magnetic exploration is the earliest developed and most widely used among all geophysical exploration approaches, and some magnetite can be easily found using a magnetic compass. In 1870, Thaln and Tiberg constructed a universal magnetometer, and the magnetic exploration approach was formally proposed (Zhang 2011). Schmidt invented a quartz blade magnetometer to find minerals other than iron ores in 1915. In the 1950s and early 1960s, magnetometers were installed on ships to conduct magnetic surveys of oceans (Howland-Rose et al. 1980). Later, a transient electromagnetic approach was developed with a deeper exploration depth and strong penetration in high-resistance layers. In the 1980s, the rapid development of various computer technologies and high-precision magnetometers promoted the development of magnetic exploration based on high-precision and automatic interpretation (Chen 2015). The inversion visualization technique for interpretation has been developed and realized (Zhang 2011).

(4) Electrical exploration

The principle of electrical exploration is based on the differences in the electrical properties (e.g., electrical conductivity, electromagnetic induction, and dielectricity) of rocks and ores (Fig. 10). Here, fields are of purely radial geometry and able to generate galvanic effects when they intersect subhorizontal, tabular bodies (Constable 2010). The implementation of this technique is similar to the implementation of magnetic exploration, except that the field sources in electrical exploration are electrical signals with different frequencies and waveforms. The spatial distributions of the electric and electromagnetic fields on the seafloor are then recorded and analyzed. Based on the current properties of the field source, the electrical exploration technique can be further divided into the direct current method and the alternating current method.

In the early twentieth century, Schlumberger conducted offshore measurements of direct current resistivity, marking the beginning of electrical exploration in the ocean (Allaud and Martin 1977). Corwin (1976) discovered a 300-mv self-potential anomaly in Penobscot Bay, Myanmar using the self-potential method (a type of direct current method) and found a sulfide sedimentary deposit. Goto et al. (2008) developed MANTA, an ocean direct current resistivity measurement system for probing the top boundaries of methane hydrate fields; MANTA was successfully used to detect methane hydrate resources near Okinawa in Japan. Recently, using statically placed electrodes and drag electrode techniques, Simyrdanis et al. (2016) performed 2D and 3D direct current inversion to image the seafloor layers near the coast of northwestern Greece.

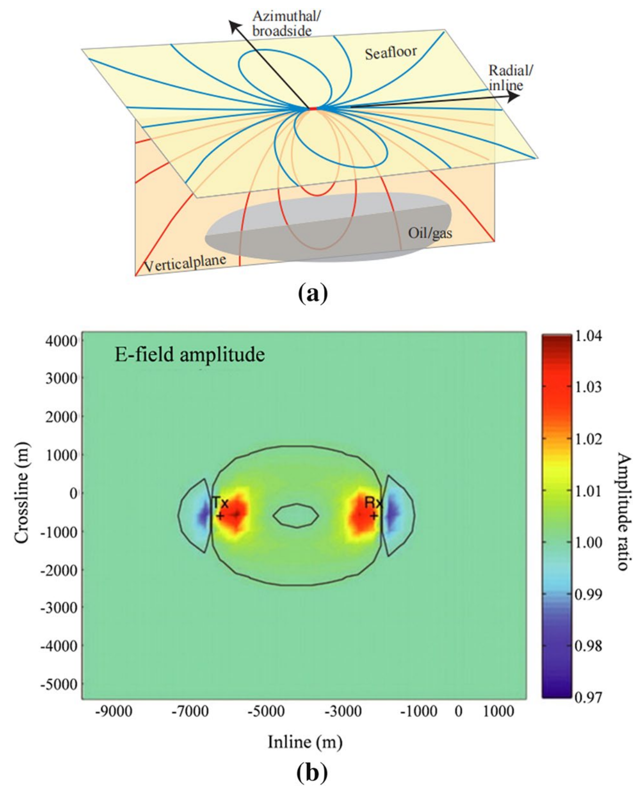


Fig. 10 Electrical exploration **a** Working principle (i.e. the dipole geometry of a near-seafloor transmitter, here the maximum vertical electric fields (red) are below the transmitter in the inline direction, and fields are of purely radial geometry and able to generate galvanic effects when they intersect subhorizontal, tabular bodies such as oil and gas reservoirs (Constable 2010)) and **b** Example output (Constable 2010), where Tx and Rx represent transmit and receive, respectively

3.1.2 Geotechnical exploration techniques

Compared to the large-scope survey of geophysical exploration, geotechnical exploration is based on a fixed-point survey. Geotechnical exploration mainly serves to test and evaluate the geological conditions (e.g., composition, structure, formation age, and genetic type of each soil layer along with adverse geologic actions) and the geotechnical properties of the seafloor soils (e.g., particle size distribution, void ratio, liquid and plastic limits, compression modulus, cohesion, and internal friction angle) in the project area. This information can be used to judge the stability and suitability of the project site. Geotechnical exploration is a direct method. According to the test site, the techniques for geotechnical exploration include in-situ and laboratory testing.

(1) In-situ testing

In-situ testing is carried out directly on the seabed of the project area, where the data are closer to the real state.

In-situ testing techniques for geochemical exploration are relatively simple and depend on the working ocean environment. The in-situ testing process typically involves the vertical penetration of various probes (e.g., cone type, cross-plate type, dish type, pillar type, T-bar type, and ball type) into the seafloor soil layers. The soil layer information is then inferred according to the penetration resistance or rotational torque force. Implementing the test relies on diving devices (e.g., cabled work platforms and ROVs) and power devices (e.g., chain-driven penetration systems and gear-driven penetration systems). Figure 11 shows some common in-situ testing techniques.

There are many types of in-situ testing techniques. According to current engineering survey reports of ocean wind farm projects and oil and gas pipeline projects, commonly used testing techniques include cone penetration test (CPT), standard penetration test, dynamic penetration test (DPT), vane shear test (VST), and full-flow penetrometer test (e.g., using T-bar and ball probes). VST, the first technique to be used in ocean areas, was first applied over 100 years ago (Cadling and Odenstad 1950; Briaud 2013). The principle of VST is relatively simple, and few influencing factors are involved (Zhang et al. 2021a). While VST allows the shear strengths of seabed soils to be obtained quickly, it cannot achieve continuous testing along the depth direction of the soil layers. In the 1930s, the concept of CPT was developed, with the most representative CPT device being the Dutch cone (Stanton et al. 1939; Seed and De Alba 1986). Begemann further developed CPT in the 1950s (Begemann 1953) to obtain the frictional resistance of the penetration bar. CPT then began to be used for the engineering classification of soils. CPT was first used for underwater testing in the 1960s and extended to deep-sea testing in the 1980s (Hanzawa and Tanaka 1992). In 2010, MARUM developed GOST, a commercial CPT system that functions in water depths up to 4000 m. Current CPT probes can carry numerous functional sensors, including pore pressure sensors, resistivity sensors, and wave transceivers (Lunne et al. 2009; Zou et al.2020; Liu et al. 2021b).

Unlike CPT, DPT requires additional penetration power; thus, free-fall DPT penetrometers are mainly used for ocean soil testing. The first ocean free-fall DPT penetrometer was

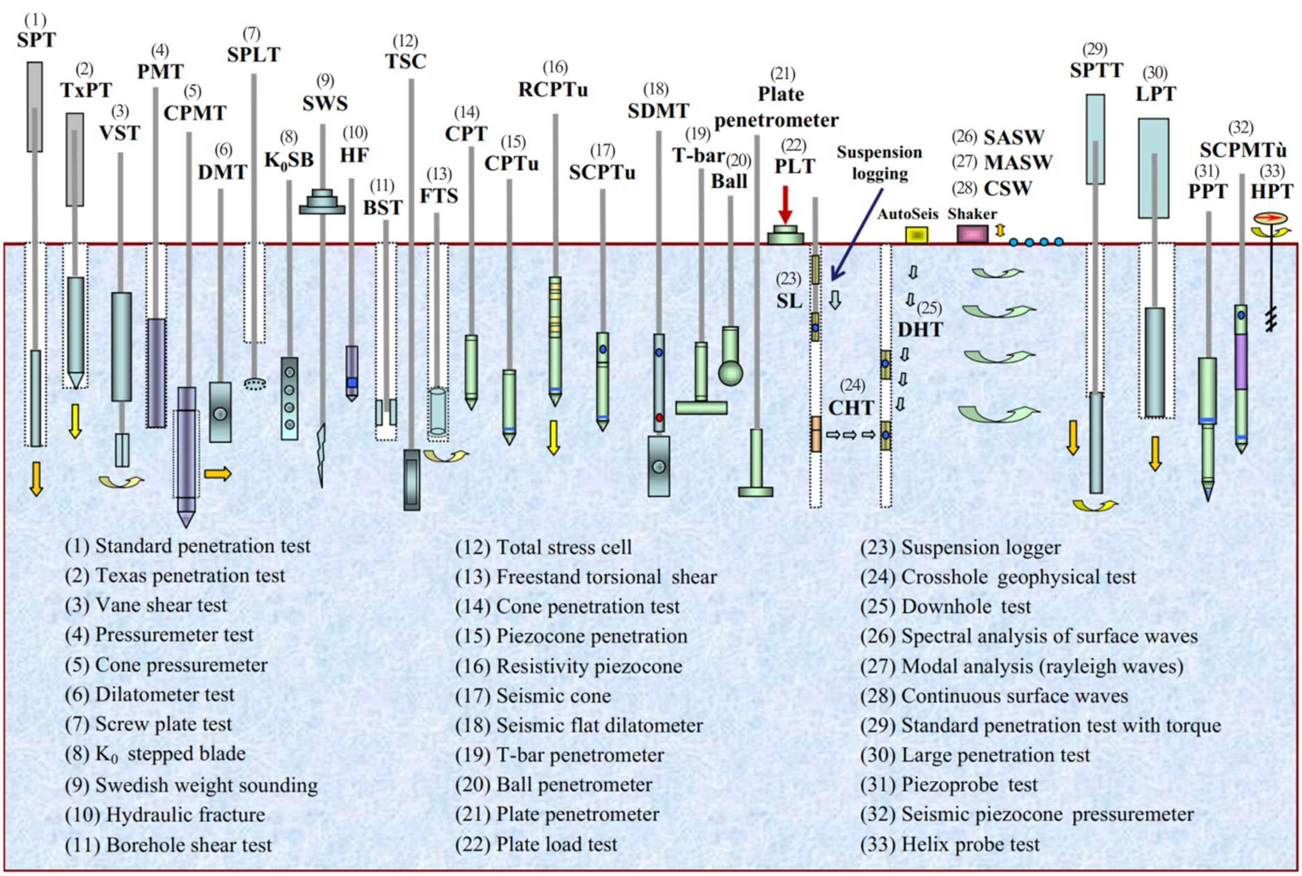


Fig. 11 Common in-situ testing techniques (modified from Mayne et al. 2009)

developed by the Memorial University of Newfoundland in 1973; this device had a limited testing water depth of 180 m and soil penetration depth of 4.5 m (Dayal and Allen 1975). In 2006, MARUM also developed a DPT system (DWFF-CPTU, Deep Water Free Fall Piezocone penetration Testing) (Lykousis et al. 2007). The maximum working water depth reached 4000 m, allowing the system to support deep-sea exploration. Full-flow penetrometer testing represents an improvement on CPT. The probes adopt T-bar and ball shapes, providing more accurate soil strength results. The full-flow penetrometer technique was first proposed and developed in the early 1990s by scholars at the Centre for Offshore Foundation Systems (Stewart and Randolph 1991; Fan et al. 2020a). Subsequently, Low et al. (2008) proposed a new manually operated full-flow penetrometer system that is easy to use on board. Recently, Guo et al. (2022a) developed a comprehensive seabed soil testing system equipped with full-flow penetrometers (i.e., ball and streamline probes), CPT, and VST probes. This system was used to evaluate the mechanical properties of sediments in the South China Sea (Guo et al. 2021a, b, 2023a; Gu et al. 2022).

(2) Laboratory testing techniques

To eliminate interfering factors from the project site, representative soil samples from the project site can be tested in the laboratory (sometimes directly in the ship laboratory) using more precise and sensitive instruments than can be applied in the field. It should be noted that the quality of the soil samples directly affects the value of the test results. Subsea sampling is generally conducted by gravity sampling or drilling sampling. In gravity sampling, the samplers (e.g., surface grab samplers, which are generally used for sampling depths < 1 m, and open-column samplers, which are generally used for sampling depths < 6 m) freely drop to the seabed under the influence of gravity and are dragged back using a cable. In drilling sampling, holes are first drilled in the seabed, and a thin-walled sampler is then used to extract soil samples from the drill hole. The sampling depth for drilling sampling can reach ~ 60 m. Laboratory testing can then be used to obtain the geotechnical properties (i.e., physical, chemical, mechanical, and microcosmic indexes) of the seabed soils based on soil mechanics theories. Figure 12 shows some common laboratory testing techniques.

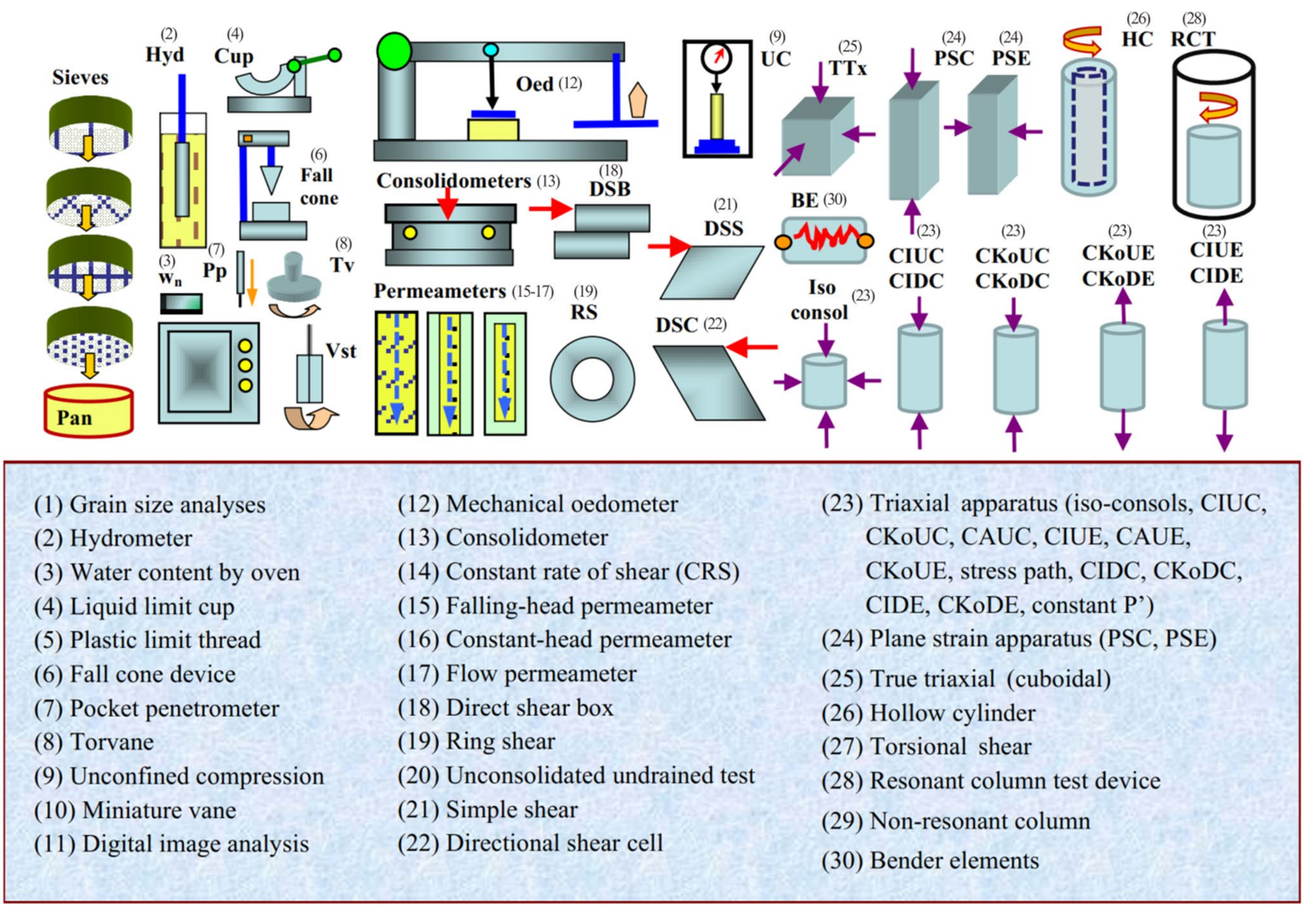


Fig. 12 Common laboratory testing techniques (modified from Mayne et al. 2009)

Most laboratory testing techniques for marine soils follow traditional soil tests, which are not introduced here. It is worth mentioning that the construction and development of submarine laboratories have accelerated in recent years. Submarine laboratories are designed according to the principle of saturation diving and can be moved or fixed. The working water depth of submarine laboratories has reached more than 300 m (Su 2020). If submarine laboratories become commonplace, geotechnical exploration with laboratory testing techniques will become even easier.

Regulations covering ocean engineering usually require geophysical exploration and geotechnical exploration to be conducted simultaneously so that comprehensive seafloor geological and geotechnical information can be obtained. Thus, there are many examples of applications that combine these two exploration techniques. For example, holes can be drilled first to obtain soil samples for laboratory testing followed by geophysical exploration (e.g., electrical and magnetic tests) in the drill hole.

3.2 Techniques for the extraction stage

The extraction stage is the primary component of ocean mining and requires various devices and systems to work together, including the mining ship or platform, launch and recovery systems, resource collection systems, dewatering and subsea mining cargo handling systems, and subsea mining control and monitoring systems (American Bureau of Shipping 2020). The techniques applied in the extraction phase often differ based on the physical form and depth of the resources being extracted. Overall, extraction techniques for ocean mineral resources can be divided into two types according to the systems used: mobile extraction techniques and fixed extraction techniques.

(1) Mobile extraction techniques

Mobile collection techniques are generally used for seabed surface resource extraction (resources with granular or nodular shapes, like polymetallic nodules). These techniques rely on ship-dragged collection devices (e.g., chain buckets, crab buckets, and pipe-suction ends) or self-propelled collection devices (e.g., subsea mining vehicles and miniature submarines) for ocean resource mining. The collection devices are recovered after the temporary storage devices are filled. Some common mobile collection techniques are summarized in Fig. 13.

The development of mobile extraction techniques is related to the water depth of the mining operation. For shallow sea resource mining (e.g., placer), most extraction techniques are derived from land mining techniques and use mining vessels such as chain bucket vessels, crab bucket vessels, and pipe-suction end vessels. The technical

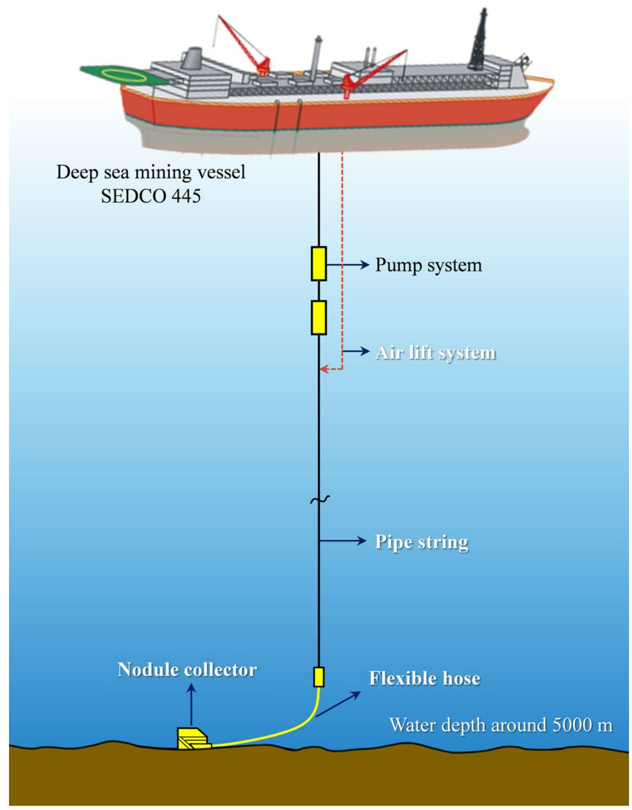


Fig. 13 Example mobile extraction techniques (modified from Bath 1989)

principle of these techniques is relatively simple. Mineral resources are collected under the action of these dragged collection or suction devices. The cost of these extraction techniques increases as the water depth increases. The large-scale extraction of deep seabed resources (e.g., polymetallic nodules) began in the 1970s (Bath 1989). In this system, the bucket is freely dropped from the vessel, and the worker on the vessel receives a signal when the bucket reaches the seabed. The bucket is then dragged using cables for collection. The continuous line bucket mining system was improved for use in deep-sea mining (Masuda et al. 1971). However, the system cannot adapt to the complex seabed topography, and the cables easily wind, resulting in low mining efficiency. In the 1980s, a shuttle vessel deep-sea mining system was developed by the AFERNOD in France (Gauthier and Charles 1979; Lenoble 1981; Du et al. 2016). This system requires a submarine to dive into the seabed for collection and can work at seabed depths up to 6000 m, with the daily collection amount reaching 2000 t. However, the continuous power issues in this system were difficult to solve. During the same time period, a pipeline lift mining system developed in the United States began to be used in deep-sea environments (Chung 2003), resulting in large-scale mining and high mining efficiency. Subsequently, Grebe

(1997) proposed a cooperative mining system based on a flexible transfer pipe and ore collector to adapt to the complex seabed terrain. More recently, subsea mining vehicles have emerged as a valuable tool for deep seabed resource extraction (Hong et al. 2019). These vehicles provide a flexible system with high mining efficiency and do not require a lifting system.

(2) Fixed extraction techniques

Fixed extraction techniques are required for some resources in deep seafloor layers or bedrock (e.g., oil, natural gas, combustible ice, brimstone, and coal). Fixed collection techniques first drill through the seabed to the resource storage area and reinforce the drill-hole wall to form stable extraction wellheads. Working tunnels may be further dug in some projects. The extraction devices (e.g., centrifugal pumps, boring bits, and jet devices) then provide flow pressure, shaking force, or high-temperature melting to release the resources, which are then transmitted to the platform or ship through conveyor belts, pipelines, or risers (Nian et al. 2018; Fan et al. 2022).

Fixed extraction techniques can be categorized based on their primary system and platform (see Fig. 14). The world's first offshore extraction well was drilled off the coast of California in the United States in 1897 (Silcox et al. 1987; Pan 2006) for the extraction of offshore oil. A wooden drilling platform with a large size and shallow operating level was first employed. Steel offshore platforms began to be used in the 1950s and 1960s, resulting in the rapid development of offshore oil and gas resources (Nian et al. 2022). By the late 1960s, the operating water depth had exceeded 200 m. In 1973, the first concrete platform was built in the Ekofisk oilfield in the North Sea (Aitcin and Houle 1986). In the 1980s, with the further development of deep-water oil and gas extraction, tension leg and guyed tower platforms were developed with working deeps of 600 m. At present, semi-submersible platforms are mainly used for mining in deep-water areas and can be used to extract multiple resources (e.g., oil, natural gas, combustible ice, brimstone, and coal). Representative systems include the Aker H-6 system from AKER Solutions in Norway, the DSS50 system from GustoMSC in the Netherlands, and the GVA7500M system from GVA in Sweden (Ted 2014).

3.3 Techniques for the closure stage

To decrease the impacts on ocean ecological environments as much as possible, environmental restoration remains critical during the closure stage after the mining activities are finished. The regulations on ocean mining in many countries put forward clear requirements for closure activities (American Bureau of Shipping 2020; China Association of Oceanic Engineering 2021). In addition to controlling the mining scale, the environmental impacts of mining, and the carbon footprint of extraction, the mine tailings (ore waste resulting from mining, typically a mud-like material) must

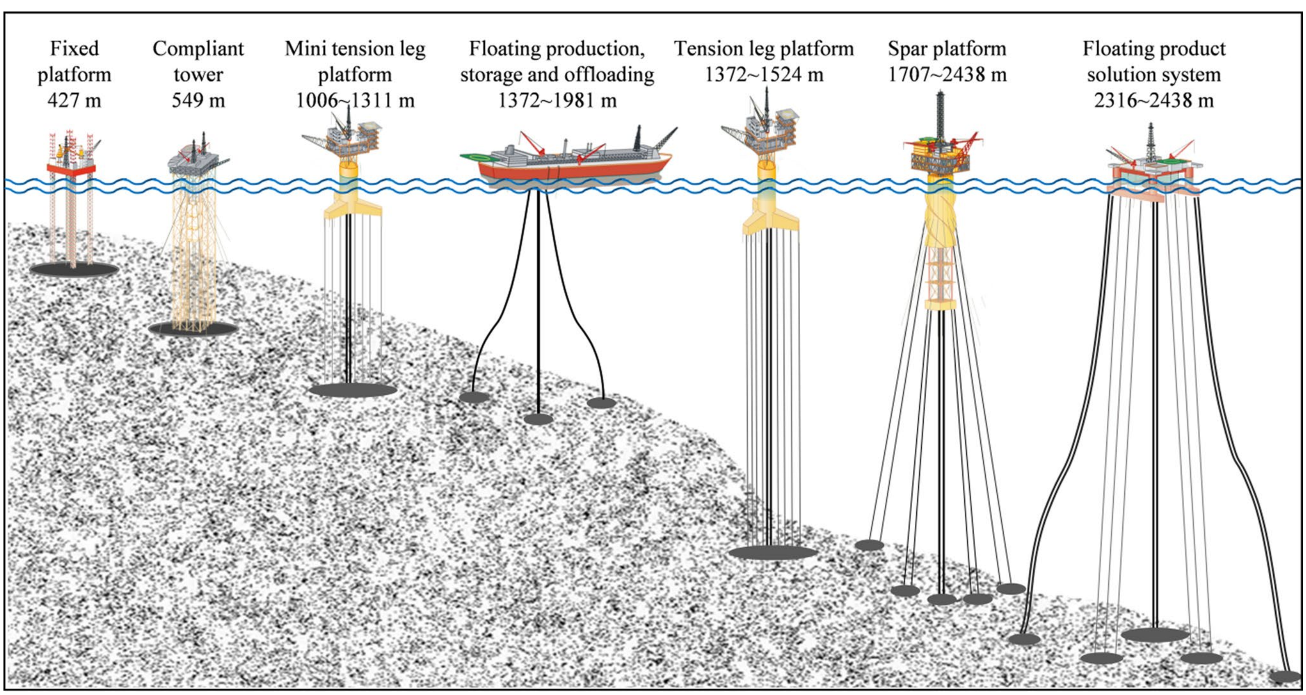


Fig. 14 Examples of resource extraction platforms (modified from Yu et al. 2015 and https://worldoceanreview.com/de/wor-3/oel-gas/wie-und-wo-gefoerdert-wird/)

be controlled and dealt with (e.g., by returning mine tailings back to the depth required by ISA or coastal states using the subsea mining downcomer and pumping system and returning tailings pipes for transporting seafloor mines from the seafloor to a mobile offshore mining unit).

After extraction, common ocean ecosystem restoration approaches include the construction of artificial algae farms, the planting of mangroves, and the placement of artificial reefs. Large-scale seaweed farming is one of the best ways to improve the marine ecological environment. Many algae (e.g., sargassum and stone lily) accumulate heavy metals and thus can purify seawater polluted with heavy metals (Phaneuf et al. 1999). Similarly, mangrove plants can absorb heavy metals in seawater and sediments through their roots, reducing the content of heavy metals in seawater (Ke et al. 2005). Artificial reefs can create a good environment for fish to inhabit and help restore sea areas with ecological imbalances and severe resource deficits (Fisher et al. 2015).

4 Engineering geology issues in deep seabed mining

4.1 Evaluation of the engineering geology environment

Evaluating the engineering geology environments of deep seabed mining sites is of great significance for preventing and controlling geologic hazards, protecting the environment, selecting the mining machinery and equipment, and designing the mining system (Sharma 2017). However, there are no mature procedures for the evaluation of the engineering geology environments of deep seabed mining sites. This section provides a comprehensive discussion of the engineering geology and environmental characteristics of mineral sites and briefly summarizes the process of evaluating the engineering geology environments of deep seabed mining sites.

In general, evaluating the engineering geology environment requires an on-site investigation, collection of corresponding data (including historical data), and development of an evaluation report (Guzzetti et al. 2005; Fell et al. 2008; Shano et al. 2020; Xie et al. 2022; Guo et al. 2023b, c; Shan et al. 2022; Dong et al. 2022, 2023). The evaluation report should describe the characteristics of the regional engineering geology environment as well as identify and evaluate geologic disasters and the corresponding mitigation measures (Aurelio 2004). On-site investigations should cover the regional structure, topography, landform, stratigraphic composition, physical and mechanical properties of sediments, hydrodynamic environment, site stability, and geologic hazards (Campbell 1997; Price 2008; Griffiths 2019; Nian et al. 2019; Guo et al. 2020a; Fan et al. 2020b; Shen and Shen 2022; Nian et al. 2022). Based on the above, and with reference to the mature evaluation process for onshore engineering geology environments, which has been implemented for decades, this study identifies a method to evaluate the engineering geology environments of deep seabed mining sites. Figure 15 presents the two aspects of the evaluation process: (1) The quantification and (2) The grading evaluation of the engineering geology environment.

According to the data of the engineering geology environment obtained in the exploration stage (the structure of the mining area, the deep-sea topography and landform, the stratigraphic composition, the physical and mechanical properties of the sediment, the occurrence forms of minerals, and the hydrodynamic environment), the engineering geology environment of the site is evaluated using a combination of qualitative and quantitative methods. The evaluation is typically based on the construction of an evaluation index system, identification of screening evaluation indicators, determination of appropriate evaluation models, and quantitatively grading the evaluation results (Crosta et al. 2006). Because many factors affect the evaluation results, and different factors interact, fuzzy mathematics and artificial intelligence methods are used at this stage (e.g., the gray evaluation model and pattern recognition) to quantitatively evaluate the engineering geology environment (Corominas et al. 2014; Chen et al. 2019). Subsequently, based on the quantitative evaluation results, the conditions of the engineering geology environment, the development level of geologic disasters, and the degree of influence of mining activities on the engineering geology environment are evaluated hierarchically. Table 2 presents the specific evaluation criteria.

To intuitively show the evaluation process of the engineering geology environment of deep seabed mining sites, Weaver et al. (2022) is used as a case study of polymetallic nodule sites, which are most likely to be the first deep-sea minerals that can be commercially exploited. However, the data from Weaver et al. (2022) are not sufficient to support quantitative calculations; thus, this study provides only a preliminary evaluation here. Polymetallic nodules are distributed in abyssal plains with water depths of 4000–6500 m; they are located within 0.3 m of the surface and are fully or partially covered in seafloor sediments (Sharma and Kodagali 1993; Kuhn et al. 2017, 2020). The seabed sediments around polymetallic nodules generally exhibit high porosity, high water content, and low shear strength (Cochonat et al. 1992; Sharma 2001; Sun et al. 2021). These sediments are clearly stratified, and the upper layer is composed of water, sediments, and polymetallic nodules, making the travel of mining vehicles difficult. The underlying layer is composed of sediments and polymetallic nodules that can provide support for mining vehicles (Grupe et al. 2001; Fan et al. 2021). As an abundant area of polymetallic nodules

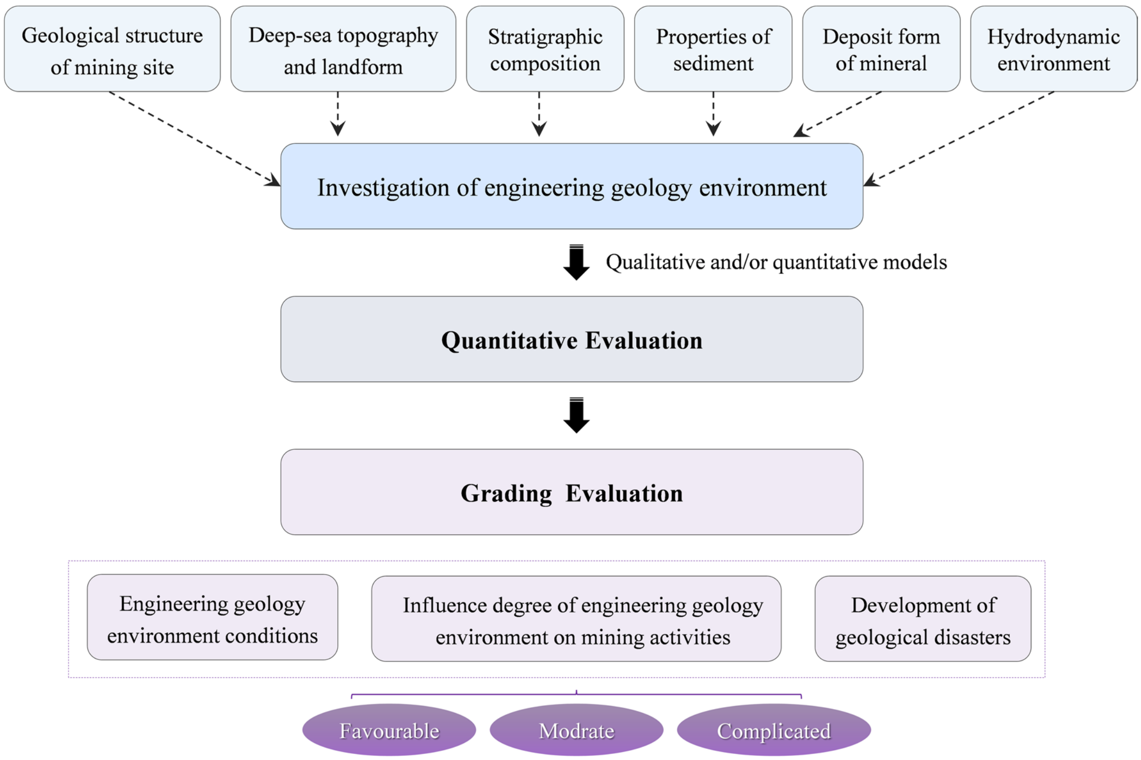


Fig. 15 Evaluation of the engineering geology environment of a deep seabed mining site

Table 2 Grading evaluation of the engineering geological environments of deep seabed mining sites

Type	Favorable	Moderate	Complicated
Engineering geological environmental conditions	Simple	Relatively simple	Complicated
Development of geological hazards	No development	Moderate development	Extensive development
Degree of influence of mining activities on the engineering geological environment	Almost no effect	Moderate effect	Serious effect

(Sparenberg 2019; Hein et al. 2020), the Clarion-Clipperton Zone (CC zone) is located south of the Clarion fault zone, east of the Lane fault zone, north of the Clipperton fault zone, and west of the East Pacific Rise, as shown in Fig. 16. There are also secondary fault structures developed between these major structures (Liu et al. 2009; Kuhn et al. 2020). The overall hydrodynamic environment in the area is weak (Aleynik et al. 2017; Fan et al. 2021). Some exploration work carried out in the CC zone (Kotlinski and Stoyanova 2007) has shown that polymetallic nodules are most abundant in depressions between hills and in the plains at the tops of the mounds. The abundance of polymetallic nodules is positively correlated with the slope gradient in the range of 0° to 3.6°. Sampling tests indicated that the penetration resistance of sediments within 20 cm in the surface layer was 0–15 kPa (Liu et al. 2014). Roughly speaking, the engineering geology environment of this polymetallic nodule site is relatively simple, geologic disasters are moderately developed, the mining activities have had a moderate impact on the engineering geology environment, and the overall grade of the engineering geology environment in the CC zone is moderate.

4.2 Geologic disasters at deep seabed mining sites

Geologic disasters in deep seabed mining sites may be caused by the deterioration of the geologic environment (e.g., the disturbance of sediments brought by mining activities), which changes the physical and mechanical properties of the sediments. In the absence of the influence of mining vehicles, geologic disasters may occur in seabed mining sites due to the instability of the seabed under the action of

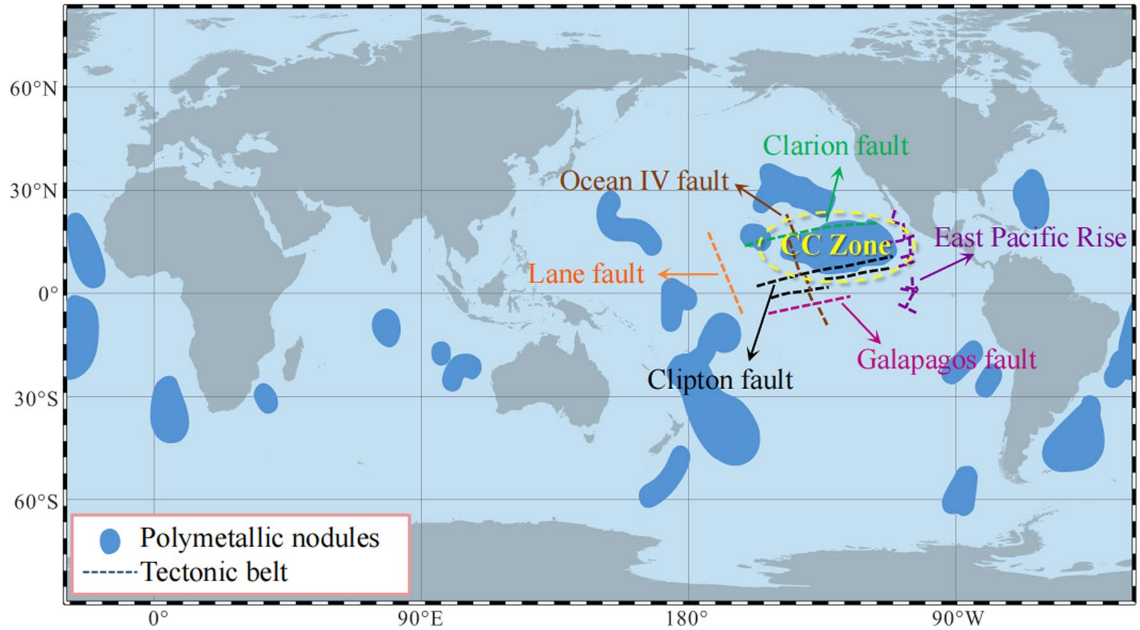


Fig. 16 Tectonic belt surrounding the CC zone (modified from Zhang et al. 2001; Li 2008; Liu et al. 2009; Hein 2016; Miller et al. 2018)

external loads. These loads include tectonic action, gravity, hydrodynamic action, gas release, and changes in pore pressure (Song 1993; Rahman 1994; Jeng 2001; Cochonat et al. 2002; Basilone et al. 2014; Zhang et al. 2021b). The influence of tectonic action is closely related to the distribution and occurrence forms of minerals (e.g., polymetallic sulfides), which are formed by cooling hydrothermal eruptions and are widely distributed in tectonically active areas (e.g., mid-ocean ridges, intraplate volcanoes, and post-arc basins) (Herzig and Hannington 1995; Hannington and Monecke 2009). The CC zone is located between the Clarion and Clipperton faults in the North Pacific and is affected by the fault tectonics developed there (Kuhn et al. 2020). Unlike polymetallic sulfides and polymetallic nodules, cobalt-rich crusts are mostly found on the sides and peaks of seamounts, plateaus, and abyssal hills far from tectonically active zones (Keating 1989; Hein et al. 2017) and are generally consolidated on bedrock. As the maturity of the crust increases, the porosity and moisture content decrease, leading to the dehydration of water-rich sediments along with the shrinking, cracking, and slipping of cobalt-rich crusts and bedrock (Keating 1989; Hein et al. 2017). Simultaneously, the crust sites are strongly affected by hydrodynamics (Shi et al. 2021), which exacerbate crustal shedding and result in

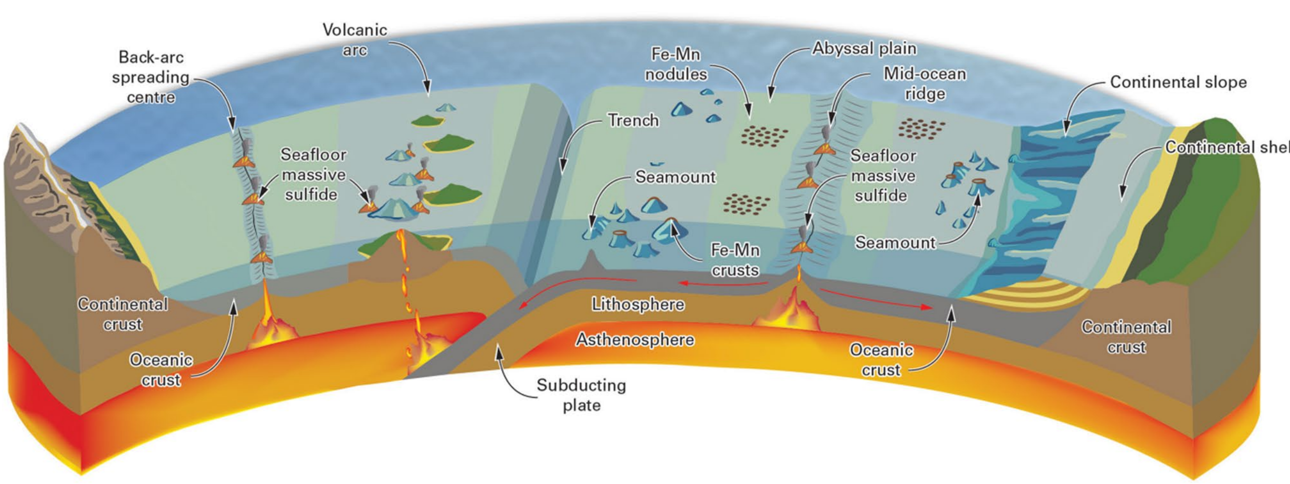


Fig. 17 Comparison of geological conditions of different deposit areas of deep seabed minerals (modified from Lusty and Murton 2018)

geologic disasters. Figure 17 compares the geologic conditions of different deep seabed mineral deposit areas.

Mining activities can disturb sediments via the travel of mining vehicles and the dragging of the ground-touching part of the conveying hose. Seabed sediments at polymetallic nodule sites have high fluidization, poor shear resistance, large porosity, and high water content with obvious stratification (Song 1999; Gillard et al. 2019). Under these conditions, seafloor sediments may subside when subjected to gravitational loads from mining vehicles (Grupe et al. 2001; Dai 2010). In addition, the travel of mining vehicles and dragging of the ground-touching part of the conveying hose can compact the sediments at the rut, and the sediments on both sides are turned over before redeposition (Miller et al. 2018). This leads to large changes in the physical and mechanical properties of the sediments (Fan et al. 2021), as shown in Fig. 18.

4.3 Technological advances for the in-situ monitoring of geologic environments

Deep seabed mining is a complex activity that requires the long-term, real-time monitoring of various parameters to ensure sustainable, economic, reliable, and safe operations. However, the complex and dynamic geologic environment requires the appropriate selection of in-situ monitoring techniques to minimize losses during mining activities. Techniques for monitoring the contents of the geologic environment of deep seabed mining can be divided into three categories: the monitoring of external loads, internal changes, and macroscopic deformation of geologic masses. However, few in-situ monitoring techniques have been developed specifically for the geologic environment of deep seabed mining activities. Thus, monitoring techniques for marine geologic disasters are summarized here to encourage the development of new monitoring techniques or apply existing techniques for the long-term or even ultra-long-term monitoring of deep seabed mining activities.

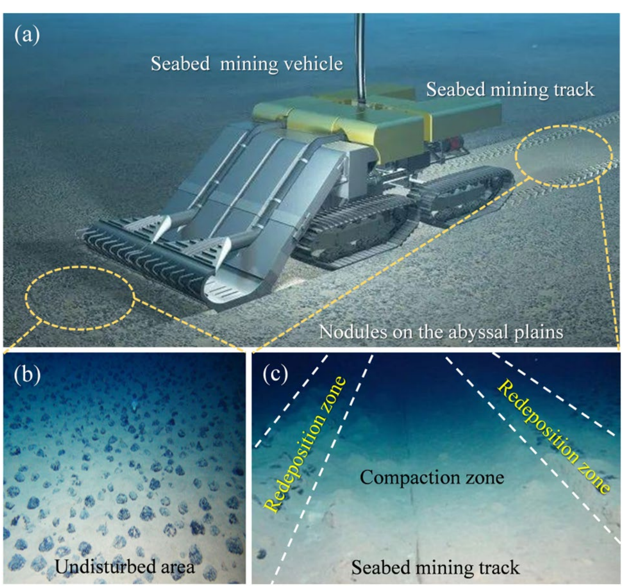


Fig. 18 Compaction zone and redeposition zone of the seabed mining track (modified from Miller et al. 2018; Cuyvers et al. 2018)

The external loads at deep seabed mining sites can be monitored by evaluating seismic action, tectonic movements, and the external dynamic environment (Jia et al. 2022). Figure 19 presents some technologies for monitoring external loads. Seafloor seismic action and tectonic movements can be monitored using an ocean bottom seismograph (OBS) (Gohl 2003; Jia et al. 2022). Seafloor tectonic movements, plate subduction, and magmatic activity can be reflected by the shallow heat flow and temperature changes with depth, which can be monitored over the long term by seafloor heat flow probes (Davis et al. 2003; Hamamoto et al. 2005). Monitoring the external dynamic environment of deep seabed mining sites refers to monitoring the hydrodynamic environment. Acoustic Doppler velocimetry can be used to measure the 3D instantaneous flow velocity and concentration (Hosseini et al. 2006). Ji et al. (2022) developed an in-situ observation system for the bottom boundary layer in the Abyssal Sea. This system can measure dynamic changes in the physical and chemical parameters of the seawater and the seabed boundary layer (e.g., temperature, salinity, pressure, and redox potential).

Monitoring the internal changes in sediments involves monitoring the pore water pressure, water content, density, and temperature. Figure 20 presents some tools for monitoring the internal changes in sediments, which include pore pressure probes and temperature sensors (Jia et al. 2022). Pore pressure can effectively reflect the external loads and geological processes of the sediments, and the in-situ observation of pore pressure plays a pivotal role in the prediction and prevention of geologic disasters (Schultheiss 1990; Liu et al. 2015). Changes in the internal temperatures of sediments can reflect the movement of fluids in pores and can be used to judge the stability of the seabed (Jia et al. 2022). Sun et al. (2022) developed a complex in-situ long-term monitoring system that can monitor certain parameters (e.g., acoustics, resistivity, and excess pore pressure) to provide early warning of submarine geologic disasters.

The monitoring of the macroscopic deformation of geologic bodies focuses on changes in the seafloor topography (Jia et al. 2022). Monitoring the seabed topography is important for determining whether a geologic disaster exists. While multibeam sonar has been applied to monitor

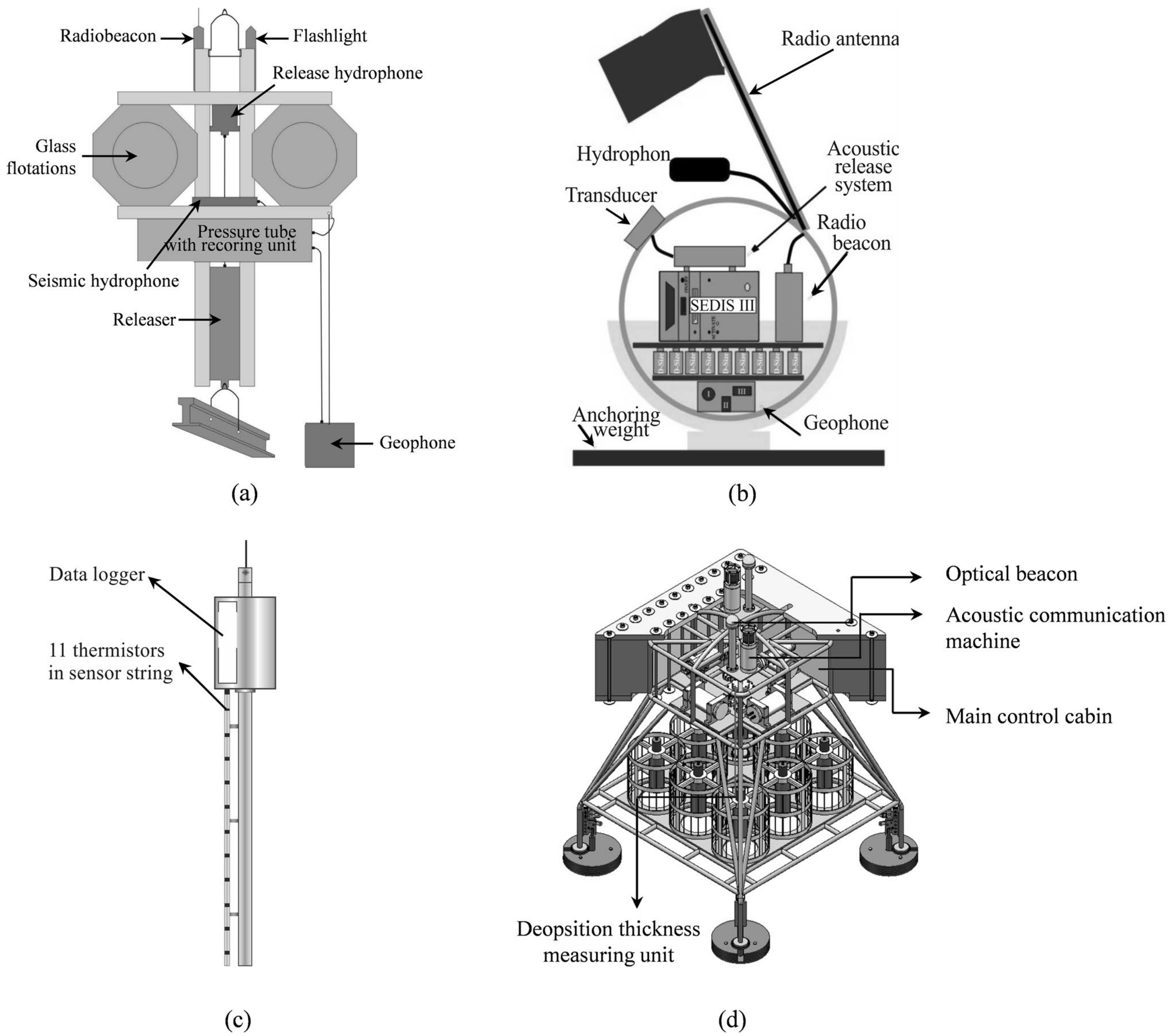


Fig. 19 Systems for the in-situ monitoring of external loads at deep seabed mining sites **a** Ocean bottom seismograph from the University of Hamburg (modified from Gohl 2003) **b** Ocean bottom seismograph from GeoPro (modified from Gohl 2003) **c** Seafloor heat flow probe (modified from Nagihara et al. 2002) and **d** In-situ observation system for the bottom boundary layer of the Abyssal Sea (modified from Ji et al. 2022)

seabed topography (Mayer 2006), it is difficult to achieve real-time, long-term monitoring using this approach (Zhu 2019). High-precision pressure gauges and three-axis accelerometers enable the long-term, in-situ monitoring of seabed deformation. Currently, microelectromechanical systems (MEMS) accelerometers and inclinometers are widely used to monitor subsidence and landslide deformation (Ge et al. 2022). Zhu (2019) designed a device that uses MEMS sensors and microcontrollers to monitor seafloor topography changes.

5 Environmental effects related to deep seabed mining

5.1 Environmental protection requirements at different mining stages

Potential environmental issues caused by deep seabed mining activities are important reasons for restricting commercial development (Collins et al. 2013; Jones et al. 2020). ISA clearly stipulates that evaluations of environmental

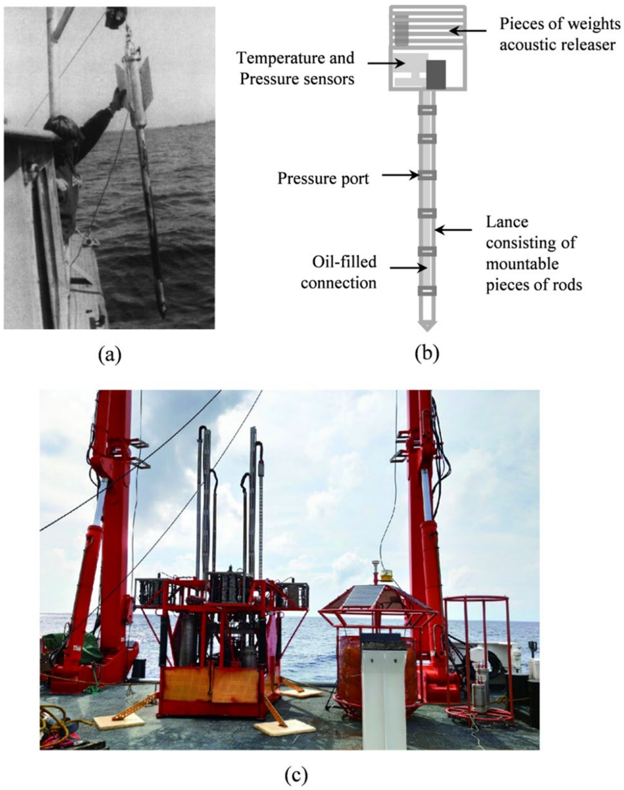


Fig. 20 Tools for the in-situ monitoring of internal changes in geologic bodies **a** Pore pressure probes (Piezometer probes) (modified from Harvey et al. 1997) **b** IFREMER Piezometer V2 (Stegmann et al. 2011) and **c** In-situ long-term monitoring system (Sun et al. 2022)

disturbance and environmental impact reports are necessary for deep seabed mining (Bräger et al. 2020). Therefore, in-depth investigations are required to identify and predict the environmental impacts of mining activities. This section elaborates on the environmental protection requirements at different mining stages.

(1) During the exploration stage, deep seabed mining sites need to be investigated to clarify the range of natural variations in the environmental baseline parameters and distinguish the anthropogenic disturbances from the natural environmental conditions (Clark et al. 2020; CAOE 2021). The evaluation should consider the diversity of deep-sea organisms, particularly sedentary organisms and macrobenthic organisms with poor mobility (Craik 2008; CAOE 2021). According to the results of the environmental investigations, the impacts of mining activities on the environment, society, and economy are predicted using a combination of qualitative and quantitative methods and incorporated in subsequent reports (Perez and Sanchez 2009; Durden et al. 2018).

(2) During the extraction stage, the environmental considerations focus on the mining process and tailings. The mining sites should be monitored using the latest techniques under the guidance of theory (Weaver et al. 2022) over a long time period to analyze the impacts of mining activities on the environment (ISA 2009, 2010, 2013), ensure that sensitive environmental parameters remain within acceptable ranges, and verify the rationality of the predicted environmental impacts (CAOE 2021).

(3) During the closure stage, the main task is to restore the environment of the mining site, particularly with respect to the original species (CAOE 2021). Although the specific impacts of mining activities are not fully understood, the following aspects should be considered: the proportion of the area affected by mining activities out of the total area of the water body; the impacts of mining activities on surface and bottom flows in different seasons; the proximity of coastal zones and residential areas to the affected areas; and the fishing potential or value for other commercial activities in the affected areas (Sharma 2015).

5.2 Effects of deep seabed mining on marine environments

Despite the scarcity of available data, some studies (Heffernan 2019; Weaver et al. 2022) have shown that mining activities can have direct, significant, and even devastating impacts on marine ecosystems (Fig. 21). Thiel and Schriever (1990) simulated the travel of mining vehicles on the seabed of the Pacific Ocean and found that a large amount of marine life could be destroyed even when no minerals were collected; the simulated area did not recover until 2015 (e.g., the tracks left by the mining vehicles were visible, and seabed creatures including sponges, soft corals, and anemones had hardly returned) (Heffernan 2019; Vonnahme et al. 2020). The marine environment is evaluated based on the physical, chemical, geological, and biological compositions of the marine ecosystem and water along with the properties of the seabed and sediments (ISA 2009, 2010, 2013). Different stages of deep seabed mining can impact the marine environment.

Seabed mining activities have two direct environmental impacts: harm or death to organisms (Mestre et al. 2017) and far-reaching or even permanent damage to their habitats (Birney et al. 2006; Gollner et al. 2022). Marine life is still abundant at deep seabed mineral sites that receive almost no light and have temperatures close to 0 °C. The travel of mining vehicles can crush the deep-sea organisms (e.g., polychaete worms and tiny sediment-dwelling creatures growing in seafloor sediments at polymetallic nodule sites

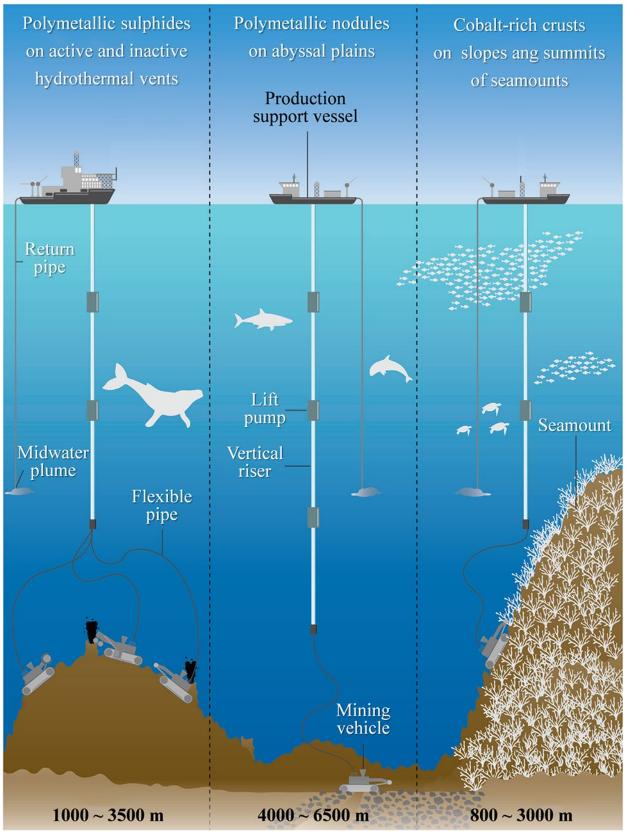


Fig. 21 Schematic diagram of the seabed mining process and its interaction with the ecological environment for the three main deposit types (modified from Miller et al. 2018)

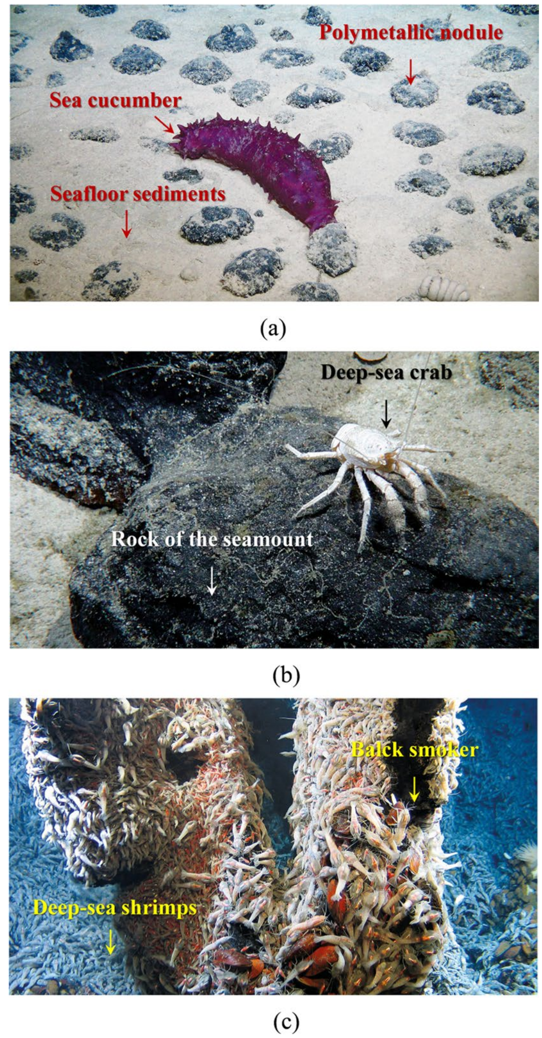


Fig. 22 Organisms living in areas where deep seabed mineral resources are found (photos taken by ROV KIEL 6000 during cruise M78/2) **a** Sea cucumber in a polymetallic nodule field **b** Deep-sea crab on a seamount **c** A dense population of deep-sea shrimps at a black smoker

and sponges and other filter feeders; Fig. 22) (Heffernan 2019). In addition, the scraping and cutting of the seabed sediments by mining vehicles along with the pumping of bottom water can injure or kill deep-sea fish and zooplankton that have poor mobility and are unable to escape interference (Koschinsky et al. 2018). The light emitted by seabed mining devices can affect bioluminescence, an important ecological function, and damage the eyes of living organisms (Lukoseviciute 2022).

Mining activities also damage the seabed ecosystem (Van Dover et al. 2017); for example, the exploitation of polymetallic sulfides may destroy the unique benthic ecosystem, which is entirely chemically synthesized, and lead to the acidification of the surrounding seawater (Hallgren and Hansson 2021). Moreover, the jets used to loosen the minerals disturb the sediments and form a seafloor sediment plume; these jets may permanently clear minerals and their surrounding sediments, leading to multifaceted impacts on the fragile ecological environment (Weaver et al. 2018; Paulus 2021). Seabed mining activities also have many indirect impacts that require attention (Birney et al. 2006). The operation of mining vehicles and the movement of seabed minerals through pipelines or chain barrels transmit noise in all directions. The low-frequency noise can travel a distance of 600 km, which negatively affects the normal life activities of marine organisms and may interfere with the communication and navigation functions of some equipment (Williams et al. 2022; Gross 2022).

5.3 Effects of plumes from deep seabed mining

In deep seabed mining activities, the collection of minerals, the beneficiation on the ship, and the discharge of underwater tailings have serious impacts on the marine environment, especially plumes (Fig. 23) (Muñoz-Royo et al. 2022; Peacock and Ouillon 2022). The mining of 3×10^6 t of polymetallic nodules per year is estimated to result in a total volume of 5×10^9 m^3 of resuspended sediment (Sharma

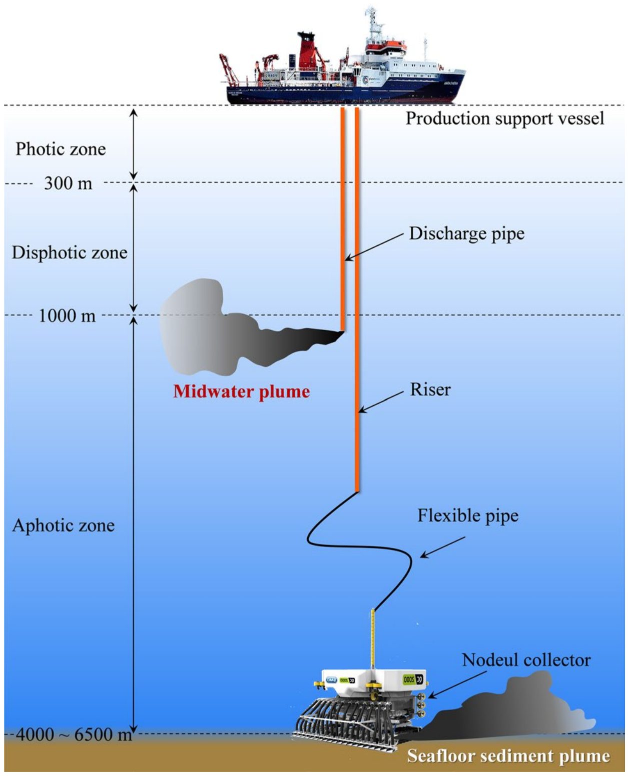


Fig. 23 Schematic diagram of a deep seabed mining system and plume (modified from Muñoz-Royo et al. 2021; photos taken by JAGO team/GEOMAR and QC2000 Nodule Collector developed by SMD)

2005). A high plume concentration can cover and bury the seabed fauna, causing suffocation and death of the organisms (Heffernan 2019). In addition, organisms located in deep-sea areas have adapted to conditions with low turbidity and low food supply; thus, very low plume concentrations can also affect the ecology of the mining site (Weaver et al. 2022).

There can be two stages of plume generation: the seafloor sediment plume discharged during extraction and the midwater plume discharged during beneficiation and the treatment of underwater tailings (Sharma et al. 2017; Muñoz-Royo et al. 2021). During the extraction stage, the travel of mining vehicles and the dragging of the ground-touching part of the pipelines disturb the seabed sediments and form the seafloor sediment plume (Peacock and Ouillon 2022). The composition of the midwater plume is diverse and includes tailings, sediments brought to the production support vessel, and effluent from mineral cleaning. The evolution and fate of the sediment plume are determined by the transport process, which operates on multiple spatiotemporal scales (Peacock and Ouillon 2022). The propagation range of the plume depends on the duration, velocity, volume, concentration, particle size distribution, and emission depth along with the state of the ocean in the discharge zone (Gillard et al. 2019; Fan et al. 2021). The scale of the sediment plume is underpinned by transport phenomena and fundamental fluid mechanics and depends on the design of the mining system and rheology of sediment-laden flows (Guo et al. 2020b, 2021b), the flocculation and settling behavior of the sediments, and the process of ambient flow (Spearman et al. 2020; Peacock and Ouillon 2022). For a 12×12 km^2 nodular mining site, the diffusion distance of particles larger than 0.1 mm is estimated to reach 50 km in one year (Ding et al. 2021). The most direct way to reduce the environmental impact of plumes is to release midwater plumes as close as possible to the seafloor (Muñoz-Royo et al. 2021) or in the low disphotic or aphotic zone; this reduces the vertical migration of plume material to minimize the impact on photosynthesis (Muñoz-Royo et al. 2021). ISA intends to introduce regulations to control the impacts of plumes on the deep-sea environment (Weaver et al. 2022). While the extent and specific impact of plumes have received considerable attention, simulating and predicting the propagation of large-scale plumes remain important issues to be addressed (Fan et al. 2021; Muñoz-Royo et al. 2021). Studies involving physical model tests, long-term in-situ monitoring, and advanced numerical simulation are needed to reveal the migration mechanism of plumes and assess the spatial extent of their impact.

6 Summary and conclusions

The commercial exploitation of deep seabed mineral resources is gradually approaching reality, and efforts are underway to ensure that deep seabed mining activities are sustainable, economic, efficient, and safe. In this study, the development of ocean mineral resources, the techniques used for ocean mining, the engineering geology issues related to deep seabed mining, and the environmental effects of deep seabed mining are analyzed. A brief summary and key conclusions are presented as follows.

(1) A bibliometric analysis was conducted on the development of ocean mineral resources based on 5838 studies from the WOS and CNKI databases. The numbers of relevant studies in this field gradually increased from 1957 to 2022, and the development trend can be roughly divided into three stages: Stage I (1957 to 1988), Stage II (1989 to 2008), and Stage III (2009 to 2022). Based on this trend, the topic "ocean mineral resources" has been a research hotspot in more than past 10 years and will continue to be for a long time in the future. Moreover, the continent with the most research in this area is Europe, and international cooperation on this research topic is frequent. A cluster analysis on the keywords of the research studies indi-

cated that the most popular research directions include mineral resource characteristics, resource development approaches, and environmental effects.

(2) According to the three stages of ocean mining activities (i.e., exploration, extraction, and closure), the development process, theory, and issues related to the main techniques involved in each stage were introduced. In the exploration stage, ocean mineral resources are mainly found based on differences in geophysical field features (e.g., density, magnetic permeability, electrical conductivity, and radioactivity) or by geotechnical testing using in-situ and laboratory techniques. These geophysical and geotechnical exploration techniques are usually used simultaneously. The techniques applied in the extraction stage can generally be divided into mobile and fixed extraction techniques. Subsea mining vehicles, which provide a high level of control and high mining efficiency, are the latest tool developed for the mobile extraction of deep-sea resources. Fixed extraction in deep-sea environments is primarily conducted using semi-submersible platforms that can be used to extract multiple resources (e.g., oil, natural gas, combustible ice, brimstone, and coal). Finally, techniques applied during closure are still in the exploratory stage and include the construction of artificial algae farms, the planting of mangroves, and the placement of artificial reefs. However, these techniques are receiving extensive research attention and show good prospects for the future.

(3) Based on data from an in-situ engineering geology investigation, a method for evaluating the engineering geology environment of a deep seabed mining site was proposed. The CC zone located in the Eastern Pacific Ocean, which is surrounded by tectonic belts, was used as a case study, and data were obtained from the published literature. The overall hydrodynamic environment in this area is weak, the penetration resistance of sediments within 20 cm of the surface layer is 0–15 kPa, the engineering geology environment is relatively simple, geologic disasters are moderately developed, and the impact of mining activities on the engineering geology environment is moderate; thus, the overall grade of the engineering geology environment is moderate. Geologic disasters at deep seabed mining sites may be caused by the disturbance of sediments by mining activities and the instability of the seabed under the action of external loads. Accordingly, techniques for the in-situ monitoring of the geologic environment are required to prevent and/or minimize losses. The different monitoring objects can be divided into three categories: external loads, internal changes, and macroscopic deformation of geologic masses. Various corresponding monitoring techniques and tools have been developed, including OBS, seafloor heat flow probes, acoustic Doppler velocimetry, and pore pressure probes. However, few in-situ monitoring techniques have been developed specifically for the geologic environments of deep seabed mining sites. Thus, the development of monitoring techniques or application of existing monitoring techniques for the long-term and ultra-long-term monitoring of deep seabed mining sites is encouraged.

(4) The environmental protection requirements during the three stages of deep seabed mining and the environmental effects of deep seabed mining were elucidated through an investigation of existing regulations and literature. Each mining stage involves different environmental considerations for the mining process, tailings treatment, and the restoration of the environment. Deep seabed mining activities have both direct and indirect impacts on the marine environment, including damage to deep-sea organisms and their habitats, noise transmission in seawater, and the formation of sediment plumes. Predicting the migration mechanism and controlling the propagation of large-scale plumes remain important problems to be solved through physical experiments, numerical simulation, and in-situ monitoring.

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Authors' contributions XG: Conceptualization, Methodology, Investigation, Visualization, Writing—Original Draft. NF: Methodology, Investigation, Visualization, Writing—Original Draft. YL: Investigation, Visualization, Writing—Original Draft. XL: Project administration, Methodology, Resources, Supervision, Writing—Review & Editing. ZW: Visualization, Writing—Review & Editing. XX: Visualization, Writing—Review & Editing. YJ: Project administration, Writing—Review & Editing. XG and NF contributed equally to this work.

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Declarations

Competing interests All the authors of this manuscript have approved the submission of this article for publication, and there are no conflicts of interest to declare. This paper has not been published elsewhere and is not under consideration by another journal.

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