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Deep Sea Unknown: A Review and Outlook on the Discovery of New Marine Species in the Early 21st Century

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Abstract At the beginning of the 21st century, with the rapid progress of deep-sea exploration technology, scientists discovered many previously unknown new species in the deep-sea environment. These discoveries not only challenged people's understanding of the limits of life, but also provided new perspectives for biodiversity research. The aim of this study is to comprehensively review the discovery of new deep-sea species during this period and explore their impact on biodiversity understanding, deep-sea ecosystem function research, and environmental protection and sustainable utilization. By analyzing the progress of deep-sea exploration technology, the discovery of iconic new species, and the contributions of these new species to scientific theory and environmental policies, this study emphasizes the importance of deep-sea research in promoting biodiversity conservation and understanding the complexity of life on Earth. The purpose of the research is to raise public and decision-makers' awareness of deep-sea environmental protection, promote a balance between scientific exploration and environmental protection, and emphasize the crucial role of international cooperation in deep-sea research and protection. By looking forward to the possible directions and challenges of future deep-sea research, we provide scientific basis and policy recommendations for deep-sea exploration and protection, to ensure the sustainable development and protection of the deep-sea, the last frontier of the earth.

Keywords Deep sea exploration; Biodiversity; Deep sea technology; Environmental protection; International co-operation

In the history of exploration in the 21st century, the deep sea has been one of the last frontiers studied by scientists. The deep sea, the most mysterious area on earth, covers more than 70% of the earth's surface, but more than 80% has not been explored by humans. In this vast and unknown deep blue, there are countless secrets and undiscovered lives hidden. In the early 21st century, people 's exploration and understanding of the deep sea have made a qualitative leap, especially the discovery of new species, which not only expanded the understanding of biological diversity (Ramirez-Llodra et al., 2010), but also provided The study of biological evolution and ecosystems provides new perspectives and data.

The discovery of new species in the deep sea not only satisfies human curiosity and desire for exploration, but is also of great significance to scientific research. Every discovery of a new species may subvert people's current understanding of biology, ecology and even earth science. These creatures survive and thrive in extreme deep-sea environments, demonstrating the resilience and diversity of life. Their existence not only enriches biodiversity, but may also hold biochemical substances with potential application value in modern medicine, new material development and other fields (Lins and Brandt, 2020).

This study aims to review the discovery process of new deep-sea species since the beginning of the 21st century. By sorting out the important discoveries and research results of the past two decades, it shows the progress of deep-sea exploration technology and how these advances help scholars understand unknown organisms. At the same time, this study will also explore the contribution of new species discoveries to the understanding of deep-sea ecosystems, and how these studies have affected people's overall understanding of the earth's biodiversity. In addition, this study will also discuss the technical, environmental and ethical challenges encountered in deep-sea research, and how to address these challenges through international cooperation and promote the healthy development of deep-sea research. Through this research, we hope to provide new ideas and directions for deep-sea scientific research and future exploration, and promote humankind's sustainable exploration of this unknown field.

1 Advances in Deep-Sea Exploration Technology

1.1 Application of remotely operated unmanned vehicle (ROV)

The development of science and technology has made progress in the field of deep-sea exploration particularly significant, especially the application of remotely operated unmanned vehicles (ROV). ROV technology allows scientists to conduct detailed observations and studies of the deep-sea environment without diving directly (Hudson et al., 2005). These equipment are equipped with high-definition cameras, sensitive control arms and various scientific research instruments, enabling precise operation and data collection in extreme deep-sea environments (Correa et al., 2015).

In the hydrothermal vent area of the deep Arctic Ocean, scientists used ROV to discover a new tubeworm species. These tube worms can survive in extreme environments with no sunlight and high sulfide concentrations, relying on a symbiotic relationship with bacteria to obtain energy from chemicals. This discovery not only enriches people's understanding of the diversity of deep-sea ecosystems, but also provides new clues to the origin and evolution of life. Through high-definition videos and pictures taken by ROV, scientists can intuitively observe the living habits of these creatures, providing valuable direct evidence for the study of deep-sea biology.

1.2 Deep sea drilling and sampling technology

Advances in deep-sea drilling and sampling technology have opened up new paths for the study of deep-sea biodiversity. These techniques allow scientists to obtain rocks, sediments and other geological samples directly from the deep sea bottom, which contain important information about early life forms on earth.

Taking the deep-sea drilling project “Deep Sea Life Exploration” as an example, scientists successfully drilled core samples from the depths of the South China Sea, which contained a large number of fossils and DNA of ancient microorganisms. By analyzing these microbial remains, researchers discovered several previously unknown microbial species that demonstrate the adaptability and diversity of life in extreme conditions. These deep-sea drilling technologies also reveal the complexity of microbial communities in deep-sea sediments (Mu et al., 2017), providing important information about the history of life on Earth and biogeochemical cycles.

1.3 Application of gene sequencing technology

The application of gene sequencing technology in deep-sea biological research has greatly accelerated the identification and classification of new species. By extracting genomic DNA from individual cells, scientists can quickly identify species of deep-sea organisms and analyze their genetic information.

During an exploration in the Mariana Trench, researchers discovered an extremely pressure-tolerant single-cell organism. By genetically sequencing it, they found that this organism has a unique set of genetic codes that allow it to survive extreme conditions. Survive under pressure (Kumar et al., 2018). This discovery not only challenges people's understanding of the limits of life, but also provides a new perspective for studying the adaptation mechanisms of organisms in extreme environments. Gene sequencing technology has also revealed the complex evolutionary relationships among deep-sea organisms, providing new clues for understanding the evolution of life.

2 Review of the Discovery of New Marine Species in the Early 21st Century

2.1 Overview of new species discovered: number, distribution and types

The widespread use of equipment such as remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), and deep-sea drilling, providing scientists with access to A pass to the most inaccessible areas on Earth. Since 2001, scientists have described more than 5,000 new marine species in deep-sea environments around the world, including tubeworms endemic to hydrothermal vents, according to the World Register of Marine Species (WoRMS), a variety of unknown crustaceans, and some strange deep-sea fish and molluscs, through research and discovery of the diverse survival strategies of new species that adapt to the extreme environments of the deep sea. These new species have been discovered at different depths and geographical locations across the oceans (Figure 1), from cold-water coral reefs and deep-sea mud bottoms to extreme hydrothermal vents and cold seep areas.

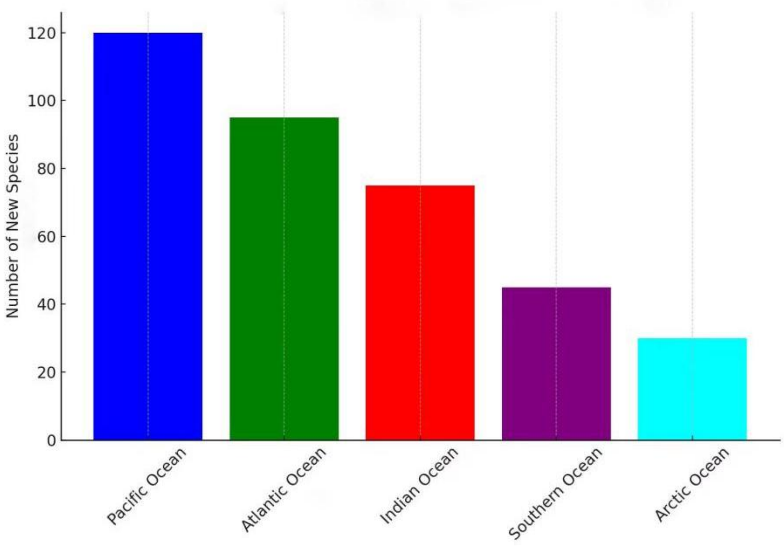

Figure 1 Distribution of new species in global oceans

In 2006, scientists discovered a new species of worm called Pyrodesmia flamea in the hydrothermal vent system of the South Pacific Ocean. This type of worm can survive in high temperature environments exceeding 350 ℃, and its body is covered with special structures that can resist extreme heat (Zhang et al., 2021). In addition to the discovery of a single species, deep-sea exploration has also revealed complex biological communities. In the cold water coral reefs of the North Atlantic, scientists have discovered dozens of previously unrecorded marine organisms that collectively build a complex ecosystem.

2.2 Iconic discovery cases: giant creatures and microorganisms in the deep sea

At the beginning of the 21st century, an international scientific research team used deep-sea submersibles to explore a remote area of the Pacific Ocean. When the submersible descended to a depth of about 2000 meters, scientists successfully discovered a new deep-sea giant fish-Megamouth. Megamouth fish live in the dark, high-pressure environment of the deep sea and are usually solitary, only gathering during the breeding season. Megamouth fish feed on other deep-sea creatures such as fish, crustaceans, and invertebrates. In addition to hunting, megamouth fish spend most of their time swimming, possibly in search of food or to avoid predators. As apex predators, they help control the populations of other organisms and prevent certain species from overpopulating and disrupting the ecological balance.

Deep-sea microorganisms may be more overlooked than giant creatures, but they are one of the most fundamental and important components of deep-sea ecosystems. In the deep-sea exploration of the 21st century, scientists have discovered a large number of deep-sea microorganisms that exist in environments such as seafloor sediments, hydrothermal vents, and cold-water corals (Shen, 2023). Deep-sea microorganisms live in extreme environments of high pressure, low temperature, low light, and lack of nutrients (Reysenbach and Shock, 2002). In order to survive in such conditions, they must possess special physiological and metabolic mechanisms (Figure 2). Some deep-sea microorganisms can use chemical substances (such as hydrogen sulfide, methane, etc.) released from hydrothermal vents on the seafloor as energy and nutrients through chemical synthesis to grow autotrophically. Other microorganisms rely on the remains or excreta of other organisms for heterotrophic growth. Because nutrients are limited in deep-sea environments, microorganisms must reproduce quickly to maintain populations. At the same time, they adapt to changing environmental conditions through continuous mutation and evolution. This high degree of adaptability and reproductive ability allows deep-sea microorganisms to maintain strong vitality in extreme environments.

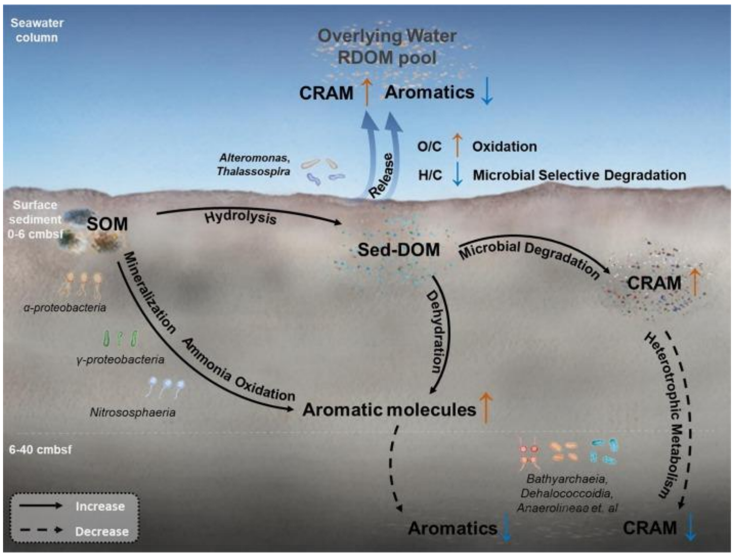

Figure 2 Chemical cycling of microbial sediments in deep-sea cold spring areas (Adopted from Chen et al., 2023)

Deep sea microorganisms possess unique metabolic pathways and high levels of biosynthesis ability. They can utilize special compounds that are difficult to obtain on land as energy and carbon sources, as well as synthesize bioactive substances with special functions, such as antibiotics, enzymes, and biotoxins. This provides new resources and application prospects for the research and development of marine drugs and biotechnology.

2.3 Analysis of the adaptation mechanism of new species to the deep sea environment

The discovery of new species in the deep sea has inspired scientists to conduct extensive research on their ecological roles and adaptive mechanisms, revealing how life survives in some of the most extreme environments on earth. The challenges faced by these organisms include hypoxia, high pressure, low temperature, and scarcity of food resources. The adaptive mechanisms they exhibit not only demonstrate the resilience of life, but also provide a new perspective for understanding the limits of life.

A key adaptive feature is the adaptation of deep-sea organisms to extreme stress. The pressure of the deep-sea environment far exceeds that of the Earth's surface, which poses a huge challenge to the integrity of cell structures and biomolecules. In order to adapt to this high-pressure environment, the cell membranes of some deep-sea organisms contain special fatty acids. These fatty acids can maintain the fluidity of the membrane under high pressure (Tamby et al., 2023), ensuring the normal performance of cell functions. Proteins in these organisms also exhibit unique stability and are able to maintain their three-dimensional structure and function in high-pressure environments, often through the substitution of specific amino acids in the protein sequence.

In order to survive in anoxic and low-temperature environments, some deep-sea microorganisms have developed chemical energy synthesis pathways that rely on inorganic compounds such as sulfide or methane as a means of obtaining energy. This metabolic strategy allows them to thrive in deep-sea environments that lack photosynthesis. There are also many deep-sea organisms that contain antifreeze proteins, which prevent body fluids from freezing and protect cells from ice crystal damage. The existence of these microorganisms is not only an important primary producer in deep-sea ecosystems, but also plays a key role in the global carbon cycle and energy flow.

3 Scientific and Environmental Significance of Discovering New Species

3.1 Contribution of new species discovery to the theory of biological evolution

The discovery of new species occupies a central position in the study of biological diversity and evolutionary theory, and is of immeasurable value in revealing the distribution and evolution of life on earth. Taking the new species of Squatiniformes discovered in the deep-sea environment as an example, this discovery not only expands people's understanding of the biodiversity of deep-sea ecosystems, but also provides important clues for understanding the adaptive changes of fish in the evolutionary process.

Lepidopoda are a group of ancient fish that live on the bottom of the deep ocean, and their discovery is particularly illuminating for theories of biological evolution. These fish exhibit a unique set of physiological and behavioral characteristics adapted to the extreme conditions of the deep-sea environment. They have specialized sense organs that allow them to detect prey and avoid predators in the dark depths of the ocean. The skeletal structure and musculature of lepidopoda also show significant differences compared with shallow-sea fish, and these differences reflect the long-term evolutionary adaptation to life in the deep sea.

By analyzing the genomes of new species of lepidopoda, scientists have revealed where these creatures fit on the evolutionary tree and how they are related to other fish. This study not only confirms the unique position of lepidopoda in the evolutionary history of fish, but also provides valuable genetic information for understanding how vertebrates adapt to extreme living environments. The discovery of new species of lepidopoda challenges traditional taxonomic views and forces scientists to reassess the classification and evolutionary history of certain fish groups.

3.2 The role of new species in deep-sea ecosystems

Research on deep-sea ecosystems has revealed the key role they play in earth's life-support systems, especially the contribution of deep-sea microorganisms in the global carbon cycle. These microorganisms participate in the fixation, transformation and storage of carbon through various biochemical processes, which are of great significance to maintaining the ecological balance of the earth.

Chemosynthetic microorganisms in deep-sea hydrothermal vent areas use inorganic compounds (such as hydrogen sulfide) as energy (Adam et al., 2020) and fix inorganic carbon into organic matter through chemosynthesis, which provides the basis for the deep-sea food chain. This process does not rely on solar energy, making it possible for life to survive in a deep-sea environment without light. This unique way of obtaining energy not only demonstrates the diversity of life's adaptation to extreme environments, but also provides a new perspective for people to understand the origin and evolution of life on earth.

Microorganisms in deep-sea sediments participate in the recycling and storage of deep-sea carbon by decomposing organic matter (Figure 3). These microorganisms can decompose dead organisms and other organic carbon deposited to the seafloor, convert some of the carbon into carbon dioxide and release it back into the seawater, while storing the other part of the carbon in a more stable form on the seafloor, thereby slowing down the increase in carbon dioxide in the atmosphere. This process plays an important role in regulating the earth's climate and mitigating global warming.

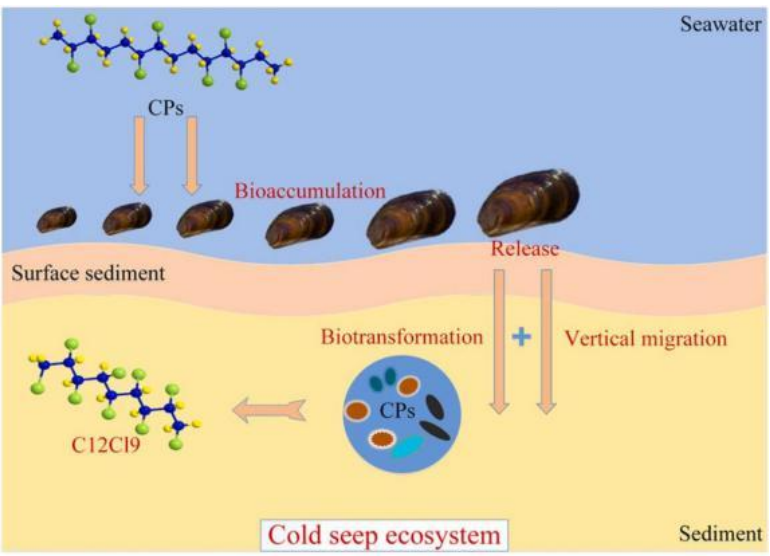

Figure 3 Deep sea carbon cycle and storage processes (Adopted from Lyu et al., 2023)

In addition, some deep-sea microorganisms are able to convert inorganic nitrogen into organic nitrogen and participate in the nitrogen fixation process, which reveals their role in the global nitrogen and sulfur cycles, further proving the importance of deep-sea ecosystems in the biogeochemical cycles of the Earth.

3.3 The impact of the discovery of new species on deep-sea environmental protection policies

With a better understanding of new deep-sea species and their ecological roles, the public and policymakers have become significantly more aware of deep-sea conservation. The distribution and ecological characteristics of deep-sea organisms provide a scientific basis for assessing the potential impacts of human activities, especially deep-sea mining, bottom trawl fisheries, and deep-sea energy development, on the deep-sea environment. For example, deep-sea mining may destroy precious ecosystems and lead to the loss of newly discovered species and their habitats (Liu et al., 2022). Therefore, it is particularly important to formulate and implement targeted management policies and conservation measures based on in-depth scientific research and understanding to ensure the integrity and long-term survival of these unique ecosystems.

The discovery of new species in the deep sea also reveals potential economic value, including the possibility of developing new drugs, biological materials, etc. Many deep-sea organisms possess unique bioactive substances due to their adaptation to extreme environments, which provides new resources for the fields of medicine and technology. However, this also brings sustainability challenges, how to utilize these precious resources while protecting deep-sea biodiversity and preventing over-exploitation and destruction.

Therefore, this requires the international community to cooperate to guide policy formulation through scientific research and implement ecosystem-based management methods to achieve sustainable use of deep sea resources. Limit negative impacts on the deep-sea environment through the development of effective international regulations and agreements.

4 Challenges and Development Prospects

4.1 Technological innovation and financial support

With the rapid development of science and technology, deep-sea exploration technology has made significant progress in the past few decades, from early reliance on manned submersibles for deep-sea exploration to modern and widely used remotely operated unmanned vehicles (ROVs) and autonomous underwater vehicles (AUV). Advances in these technologies have greatly broadened humanity's ability to explore the deep sea, enabling long -term, large-scale observations and data collection into previously unreachable ocean depths. However, the extreme conditions of the deep-sea environment, such as high pressure, low temperature, strong corrosiveness and complete darkness, place higher requirements on exploration equipment and also increase the cost of research.

In order to overcome these technical and financial obstacles, future technological innovation needs to make breakthroughs in materials science, remote sensing and telemetry technology (Wu et al., 2020), and energy technology. The development of new pressure-resistant materials, technological advances in real-time high-speed data transmission, and more efficient energy systems are all key to furthering the development of deep-sea exploration.

At the same time, the role of financial support from the international community and the private sector in promoting deep-sea research cannot be ignored. Through the public-private partnership model, cooperation projects between governments and enterprises, and funding from international multilateral institutions, resources can be effectively pooled to promote the research, development and application of deep-sea exploration technologies. In particular, encouraging the private sector to participate in deep-sea resource development while investing in scientific research will not only bring about technological innovation, but also provide new sources of funding for deep-sea exploration.

4.2 Environmental protection and sustainable management

With the development of deep-sea exploration technology and the increasing utilization of deep-sea resources , environmental protection and sustainable management have become the focus of scientists and policymakers. The fragility of the deep-sea environment and its important role in global ecosystems require people to find a balance between exploration and protection. This requires not only innovation at the technical level, such as developing low-impact detection technologies and improving the efficiency of data collection, but also adjustments at the management level to formulate and implement a series of conservation measures and guiding principles for sustainable use.

The International Seabed Authority (ISA) has developed a series of environmental management measures, including environmental impact assessment procedures, the establishment of protected areas, and strict monitoring of mining activities. These measures are intended to mitigate the potential impacts of deep-sea mining on ecosystems and protect the integrity of the deep-sea environment.

In terms of technological innovation, some more environmentally friendly deep-sea detection and sampling technologies have emerged in recent years (Feng et al., 2022). For example, a new soft-bodied sampler can collect samples of deep-sea organisms without disturbing seafloor sediments. This sampler reduces interference to the deep-sea environment and is an important advancement in the study of deep-sea biodiversity. Strengthening research on the functions and service values of deep-sea ecosystems is another key strategy to achieve deep-sea environmental protection. By in-depth understanding of the carbon fixation, nutrient cycling, and biodiversity maintenance functions of deep-sea ecosystems, scientists can more accurately assess the potential impact of human activities on the deep-sea environment and provide scientific basis for formulating conservation strategies.

4.3 Strengthen international cooperation

Strengthening international cooperation plays a vital role in deep-sea research and conservation, especially in sharing knowledge, technology and resources. A typical reference experience is Norway's international cooperation in Arctic deep sea research and protection. Norway, as a country rich in deep-sea resources and attaches great importance to marine environmental protection, its deep-sea research and protection activities in the Arctic provide a case worth learning from.

The Norwegian government has jointly promoted a series of deep-sea scientific research projects and environmental protection plans in cooperation with other Arctic Council member states. These cooperative projects include investigation and research of deep-sea ecosystems, monitoring of the impact of climate change on the deep-sea environment, and protection of deep-sea biodiversity. Through this kind of transnational cooperation, participating countries share research vessels, submersibles and other expensive deep-sea exploration technologies, as well as research data and results, greatly improving research efficiency and cost-effectiveness.

In jointly formulating and implementing relevant policies and management measures, Norway actively participated in the negotiations of the Arctic Marine Biodiversity Conservation Agreement, which aims to coordinate the actions of Arctic countries in the protection of deep-sea biodiversity and formulated a series of protection measures. Guiding principles and specific measures for deep-sea ecosystems. This multilateral cooperation mechanism not only helps protect the fragile Arctic deep-sea environment, but also provides an important reference for the sustainable utilization of global deep-sea resources.

Norway’s experience with international cooperation in deep-sea Arctic research and conservation emphasizes the importance of cross-border cooperation. This kind of cooperation can not only promote the exchange of scientific knowledge and the sharing of technology, but also form unified deep-sea environmental protection standards and policies on a global scale to jointly address the challenges brought about by deep-sea exploration and resource utilization. In the future, as deep-sea activities increase and environmental pressures rise, international cooperation will become even more critical, requiring more countries to participate in this global effort to jointly protect and sustainably utilize the deep sea, the last frontier of the earth.

5 Summary and Outlook

This study comprehensively explores the discovery of new deep-sea species since the beginning of the 21st century and its impact on the understanding of biodiversity, research on deep-sea ecosystem functions, and environmental protection and sustainable utilization. By reviewing advances in deep-sea exploration technology, examples of new species discovered, and the implications of these discoveries for scientific research and environmental policy, insights are gained into the current state of deep-sea research and possible future directions.

The discovery of new species in the deep sea has significantly enriched people's understanding of the earth's biodiversity, revealing complex ecosystems and the unique ways in which organisms adapt to extreme environments. These findings are of great significance for understanding biological evolution, ecosystem functions and services, and pose new challenges and opportunities for global biodiversity conservation. In addition, advances in deep-sea exploration have also brought new requirements for the protection of fragile deep-sea environments, emphasizing the need for sustainable management in resource development and scientific exploration.

Based on the findings of this study, it is necessary to strengthen investment and research and development in deep-sea exploration technology to reduce exploration costs and reduce the impact on the deep-sea environment (Ros et al., 2019). Develop strict environmental impact assessment and supervision mechanisms to ensure that deep-sea resource development activities will not damage the integrity of the ecosystem. Strengthen deep-sea research and protection through international cooperation, share data and resources, and develop global deep-sea protection strategies and management measures.

For future deep-sea research, it is expected that more unknown deep-sea creatures will be discovered, which will bring new breakthroughs to biodiversity research and life sciences. At the same time, in-depth research on the functions of deep-sea ecosystems and the mechanisms of biological adaptation will help people better understand the complexity of life on Earth and the stability of ecosystems. However, the fragility of the deep-sea environment and the potential threats posed by human activities will also be important considerations in future research and policy making. Therefore, achieving long-term sustainability of deep-sea research and protection will require the joint efforts of the global scientific community, policymakers, and the public.

Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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