Research Status and Strategies on Deep-Sea Extreme Environments and Life Processes (Postprint)

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Abstract

As an important component of the ocean system, the deep sea involves national strategy and territorial expansion, and has consistently constituted a strategic focus contested by maritime powers. The extreme deep-sea environment shapes unique life processes and harbors tremendous resource potential, with its exploration and research representing the international frontier of Earth sciences. Comprehensive investigation of marine extreme environments—including seamounts, hydrothermal vents, and cold seeps below 1,000 m water depth—and the unique life forms inhabiting these environments encompasses deep-sea geological, chemical, and physical environments as well as special ecosystems; it involves the development of specialized equipment for extreme deep-sea environments and the construction of integrated platforms for deep-sea exploration and research; it further entails the establishment of research vessels, submersibles, specialized equipment, methodological frameworks, and technical systems, thereby representing a manifestation of national comprehensive strength. This article summarizes international research progress on deep-sea extreme environments and life processes, and based on an analysis of the current status of China' s deep-sea research, proposes future strategies for China' s research on deep-sea extreme environments and life processes.

Full Text

Abstract

The deep sea constitutes a critical component of the marine system and represents a strategic focus for maritime nations in terms of national strategy and territorial expansion. Extreme deep-sea environments have fostered unique life processes with tremendous resource potential. Comprehensive exploration of marine extreme environments below 1,000 meters depth—including seamounts, hydrothermal vents, and cold seeps—and the specialized life forms inhabiting them requires multidisciplinary investigation spanning geology, chemistry, physical oceanography, and ecology. This endeavor necessitates the development of specialized equipment for extreme deep-sea environments and integrated platforms for exploration and research, encompassing research vessels, submersibles, specialized instruments, and methodological frameworks. Such capabilities reflect a nation' s comprehensive strength. This paper reviews international research progress on deep-sea extreme environments and life processes, and proposes future strategies for China' s research in this domain.

Keywords

deep-sea, extreme environment, life process, research status and strategies

A nation's maritime rights and interests concern its core interests. Following the division of global landmasses, the 12-nautical-mile territorial sea, 200-nautical-mile exclusive economic zones, and continental shelves surrounding land have been claimed. Attention has now turned to the deep sea and open ocean beyond national jurisdiction. The global ocean averages over 3,500 meters in depth, with more than 90% of deep-sea regions exceeding 1,000 meters in depth. The vast majority of these areas constitute international waters as defined by the United Nations Convention on the Law of the Sea, accounting for approximately 49% of Earth' s surface. Due to their unique political and legal status, as well as their diverse resources, international waters have become a new frontier for nations to extend their controllable boundaries and secure maritime rights.

As a vital component of the marine system, the deep sea encompasses special environments such as abyssal plains, seamounts, hydrothermal vents, and cold seeps. These features cause dramatic variations in seafloor topography and physicochemical parameters, thereby influencing deep-ocean dynamics, thermal conditions, and other environmental factors. This fosters unique ecosystems and life processes, potentially affecting heat dissipation in the upper ocean and directly influencing global climate change. Consequently, deep-sea research occupies a crucial position in Earth sciences and global change studies. However, human understanding of the deep sea remains extremely limited—actual measurements of basic deep-sea topography are even less comprehensive than explorations of Mars or the far side of the Moon. Therefore, exploration and understanding of deep-sea environments and ecosystems represent a frontier field in contemporary Earth science.

Furthermore, the deep sea harbors abundant mineral and biological resources. From polymetallic manganese nodules discovered in the Pacific during the 1960s–70s, to cobalt-rich crusts on seamounts and metal sulfides at mid-ocean ridge hydrothermal vents, to recently discovered rare earth resources on the deep Pacific seafloor—these will gradually become focal points for deep-sea resource development among nations. Simultaneously, deep-sea benthic biological diversity is remarkably rich, with an estimated 10 million unknown taxa inhabiting the deep ocean. Living in extreme physical, chemical, and ecological environments, deep-sea organisms have developed extraordinarily unique physiological structures and metabolic mechanisms, producing specialized bioactive substances including various extremozymes. These hold significant theoretical and applied value for biological resource development, new energy exploration, and novel biomaterial research, demonstrating tremendous resource potential.

The formation processes and material composition of seamounts reflect the transfer of matter and energy from Earth' s interior. Rock alteration processes on seamounts constitute important energy exchange mechanisms that shape distinct geological environments. Additionally, seamounts can generate internal waves, promote mixing of deep waters, and drive deep circulation. Observations from the Brazil Basin in the South Atlantic show that deep turbulent mixing triggered by a 4,000-meter seamount can influence upper ocean regions at 400-meter depth. Furthermore, blocked bottom currents create vortical structures known as Taylor-Hogg topographic eddies, facilitating exchange between oxygen minimum zone waters and mid-deep waters, causing variations in marine environmental parameters and forming pelagic fisheries. These processes also trigger important redox reactions, leading to precipitation of various metal elements and phosphorus. The Seamount Ecosystem Research Program (CenSeam) conducted integrated studies across multiple ocean regions, revealing that seamount ecosystems are complex and variable—contrary to conventional assumptions of high productivity and biomass, some seamounts exhibit low biological abundance. However, they demonstrate clear seamount effects in hydrodynamics, biogeochemistry, and biology compared to surrounding oceans. For instance, biodiversity on individual seamounts is typically high, yet varies considerably among seamounts, with species endemism rates differing significantly. Therefore, seamount ecosystems may be influenced by current patterns, particulate flux, topography, substrate type and distribution, water depth, and oxygen content, though systematic data on these aspects remain lacking.

Deep-sea hydrothermal activity continuously transports matter and energy to surrounding deep-ocean environments. Taking the Manus back-arc basin in the western Pacific as an example, magmatism generates high-temperature (>1,100°C), volatile- and metal-rich fluids that inject into seafloor hydrothermal circulation systems. This causes significant anomalies in turbidity, pH, and chemical composition within hydrothermal plumes and diffuse flow regions. Back-arc basin hydrothermal systems can form plumes rising 300 meters above the seafloor and diffuse flow areas extending hundreds of kilometers, creating unique biogeochemical environments and ecosystems while profoundly altering surrounding deep circulation and water masses. Consequently, hydrothermal plume transport is hypothesized to drive mid-depth ocean circulation and potentially influence marine environments and global climate change to an even greater extent.

The discovery of unique biological communities at hydrothermal vents represents one of the most significant scientific findings of the late 20th century.

Related resource and environmental issues, as well as "dark food chain" life processes, constitute current focal points in deep-sea research. A thermophilic bacterium isolated from hydrothermal vent samples exhibits a growth temperature of 121°C—the highest temperature tolerance known for life. Hydrothermal biological communities represent vital components of deep-sea chemosynthetic ecosystems, with biodiversity and productivity rivaling terrestrial tropical rainforests. Tubeworms, bivalves, and crustaceans based on chemosynthetic bacteria inhabit various types of hydrothermal zones, reproducing through chemosynthesis—fundamentally different from terrestrial and shallow-water life forms. Hydrothermal vent chemistry significantly influences biological community distribution. The Deep-Sea Chemosynthetic Ecosystem Biogeography Program (ChEss) has identified numerous new species from hydrothermal systems, preliminarily delineated global biogeographic patterns of deep-sea chemosynthetic ecosystems, and developed new ecological subdisciplines. At the genomic level, researchers have recognized novel adaptive strategies to special environments characterized by anoxia, sulfur enrichment, and metals. Hydrothermal activity is dynamic and discontinuous in both temporal and spatial dimensions, with biological communities and ecosystem characteristics varying significantly among different types or developmental stages of vents. However, the key factors causing these differences remain unclear.

Cold seeps represent another important "window" for upward transport of seafloor matter and energy. The decomposition of gas hydrates at cold seep sites supports chemosynthesis-based cold seep biological communities, while methane plumes can rise to considerable heights, exerting important influences on surrounding environments. Although cold seeps are widely distributed in the deep sea, present at oceanic plate subduction zones and hydrocarbon seepage outlets, human understanding of them has only just begun.

The deep sea constitutes the habitat for vast microbial communities of the deep biosphere and represents Earth's most biodiverse region. Up to two-thirds of Earth's microorganisms may be buried deep within seafloor crust and sediments. Extreme deep-sea environments, including hydrothermal vents and cold seeps, have fostered cellular structures, gene functions, physiological capabilities, and characteristics unparalleled by terrestrial organisms. Systematic investigation and comparative analysis of microbial resources and their diversity in deep-sea extreme ecosystems are of paramount scientific significance for revealing life's origins, evolution, and adaptive mechanisms to special environments. Moreover, surveys of marine microbial diversity facilitate exploration of microbial ecological functions in marine environments and elucidate material cycling processes. Marine microbial resource development will provide valuable materials for biomedicine and industrial enzymes, holding important exploitation value. The International Seabed Authority has incorporated deep-seabed biological genetic resources into its management agenda, making marine microbial resources—particularly deep-sea microbial resources—a hotspot in international marine scientific research and technological strategic planning.

Naturally, progress in the aforementioned scientific research depends on deep-sea technological equipment. It was precisely deep-sea exploration based on the Alvin submersible that led to the discovery of hydrothermal vents, driving transformative advances in deep-sea environmental and life process research. Currently, ship-based visual sampling equipment such as TV-grab systems, underwater towed vehicles equipped with various sensors and acoustic/optical devices, human-occupied vehicles (HOVs), remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), and seafloor observatory networks have become mainstream technical means for studying deep-sea extreme environments and life processes. The deepening understanding of the deep sea represents concrete embodiment of deep-sea technological advancement. Meanwhile, urgent scientific research demands drive rapid development of deep-sea technological equipment, making the construction of an integrated "vessel-submersible-in-situ-long-term" comprehensive deep-sea exploration technology system an important component of deep-sea extreme environment and life process research.

1 International Research Progress

Since the British HMS Challenger' s first global oceanographic expedition in the late 19th century, the deep sea has remained at the forefront of international marine science research and a cradle for major scientific discoveries. Particularly after World War II, world powers led by the United States attached great importance to "blue ocean strategy," substantially increasing investment in deep-sea research and catalyzing a series of breakthrough scientific advances. For example, seafloor spreading discovered in the late 1960s confirmed plate tectonics theory and established the new discipline of paleoceanography. Hydrothermal vents and the "dark biosphere" discovered in the late 1970s demonstrated upward transport of matter and energy from deep within Earth' s crust, sustaining vast biological communities independent of photosynthesis, thereby opening entirely new fields for marine science development. Entering the new millennium, relevant nations have accelerated their deep-sea exploration efforts, constructing new scientific research vessels and detection equipment and launching major deep-ocean exploration programs such as the Census of Marine Life (CoML, 2001-2010), Integrated Ocean Drilling Program (IODP, 2003-2013), EU Deep-Sea Program (IN-DEEP), and International Mid-Ocean Ridge Program (InterRidge). These initiatives have conducted comprehensive detection and research on hotspot areas including seamounts, hydrothermal vents, and cold seep ecosystems, yielding many new insights.

2 Domestic Research Status

Constrained by backward deep-sea exploration equipment, China has long remained in a position of "gazing at the ocean with sighs" in deep-sea exploration and research—a status inconsistent with its position as a major maritime nation. Prior to 2000, work mainly involved partial surveys of geological structures and seafloor mineral resources centered on polymetallic nodules. Since entering the

21st century, with strengthening national power, China’ s deep-sea research has gradually achieved a strategic transformation from single-resource investigation to integrated scientific exploration combining detection and research. In 2005, China discovered its first hydrothermal vent in the Southwest Indian Ocean; in 2007, it confirmed extensive gas hydrate deposits in the South China Sea and subsequently launched the “South China Sea Deep Process Evolution Program.” Follow-up initiatives including the 973 Program projects “Hydrothermal Mineralization Processes and Sulfide Deposit Prediction on the Southwest Indian Ocean Ridge” and “Hydrothermal Activity and Mineralization Mechanisms in Typical Back-Arc Basins” have propelled China’s deep-sea research development. The successful development of the Jiaolong 7,000-meter HOV marked China’ s enhanced capabilities in deep-sea research. Particularly, the commissioning of the comprehensive research vessel Kexue and implementation of the Chinese Academy of Sciences’ Category-A Strategic Priority Program “Material and Energy Exchange in Tropical Western Pacific Ocean Systems and Their Impacts” have enabled leapfrog development in China’ s deep-ocean research capabilities. This is primarily manifested through: independent exploration and practice establishing, for the first time domestically, a deep-sea environmental detection technology system combining macro- and micro-scale, underway and fixed-point, gradient and in-situ approaches; breakthroughs in key technologies including 10,000-meter deep-sea fixed-point detection, 7,000-meter deep-sea sampling, 4,500-meter deep-sea precision detection and sampling, 1,000-meter water column underway profiling, 30-meter deep-sea sediment coring, and 20-meter rock coring; and capabilities for comprehensive synchronous three-dimensional detection and sample collection of deep-sea topography, seafloor environments, and water column properties. To date, China has completed the first shipboard full-ocean-depth multibeam topographic survey of a 50 km × 50 km area over the Okinawa Trough hydrothermal zone (Figures 1 [Figure 1: see original paper]–3 [Figure 3: see original paper]), obtained the first high-precision deep-sea topographic map with 1-meter resolution for the Manus Basin hydrothermal area, discovered four new deep-sea hydrothermal vents, and for the first time internationally acquired temperature gradient distributions around hydrothermal vents. In South China Sea cold seeps, Okinawa Trough hydrothermal areas, Manus Basin hydrothermal areas, and Yap seamount regions, China has collected over 3,600 specimens representing more than 220 macrofaunal species, including 1 new family, 3 new genera, and 23 new species, achieving new understanding of deep-sea environments and resources.

3 China’ s Strategies for Deep-Sea Extreme Environment and Life Process Research

Deep-sea exploration and research encompass vast areas and complex processes involving geological environments, chemical environments, and special ecosystems; the development of specialized equipment for extreme deep-sea environments, establishment of technical systems, and construction of integrated deep-sea exploration and research platforms; and the organic integration of science and technology. International trends in deep-sea extreme environment and life process research can be summarized as: (1) research focus shifting toward different habitats in the global deep ocean, including seamount ecosystems, deep-sea chemosynthetic ecosystems, hadal ecosystems, and mid-ocean ridge ecosystems; (2) research content and methods trending toward multidisciplinary intersection, integration, and synthesis; (3) research approaches trending toward international cooperation and platform data sharing; and (4) research methods continuously adopting high technologies and developing toward full coverage, three-dimensional, automated, and information-based directions.

Currently, although China possesses world-class integrated deep-sea exploration platforms and basic conditions for comprehensive deep-sea detection and research, deep-sea scientific research remains in its infancy. Therefore, in response to current international deep-sea research trends and characteristics, China must highlight distinctive features and achieve breakthroughs in key areas to secure a position in the competitive international deep-sea science arena and meet major national marine strategic needs.

Figure 1. The Institute of Oceanology, Chinese Academy of Sciences uses the ultra-high-definition camera equipped on the "Faxian" ROV to conduct in-situ observation of the Lion hydrothermal vent (black smoker) in the Okinawa Trough.

Figure 2 [Figure 2: see original paper]. The Institute of Oceanology, Chinese Academy of Sciences uses the ultra-high-definition camera equipped on the "Faxian" ROV to conduct in-situ observation of chemosynthetic biological communities near the JADE hydrothermal vent in the Okinawa Trough.

Figure 3. The Institute of Oceanology, Chinese Academy of Sciences uses the self-developed deep-sea laser Raman spectroscopy detection system (RiP) to conduct in-situ detection of hydrothermal fluids at the Dragon vent in the Okinawa Trough, showing a temperature of 290°C and obtaining in-situ concentrations of dissolved methane, hydrogen sulfide, carbon dioxide, and sulfate ions in the fluid.

(1) **Highlight Regional Characteristics**: Although current deep-sea exploration and research show global trends, study areas concentrate primarily in the Atlantic and eastern Pacific, with the western Pacific remaining relatively understudied and lacking systematic investigation. However, the western Pacific seafloor exhibits extremely active geological processes, hosting over 70% of the world' s back-arc basins and representing the most concentrated distribution of seamount systems globally. This makes material and energy exchange processes in the region particularly complex, while harboring massive polymetallic sulfide and cobalt-rich ferromanganese crust resources and nurturing a global center of marine biodiversity. The western Pacific thus constitutes a uniquely advantageous geographical position for Chinese scientists to enter international deep-sea science frontiers. Through exploration of seamount, hydrothermal

vent, cold seep, and trench systems in this region, new discoveries and understanding regarding material-energy exchange processes with the water column and deep-sea life processes will fill research gaps in this area, making China the nation with the most comprehensive deep-sea data for the region and enhancing China’ s discourse power in international deep-sea affairs.

(2) **Focus on Scientific Questions**: Centering on current frontiers in deep-sea research and regional characteristics of the western Pacific, priority should be given to: subduction processes and resource-environment effects; seafloor topography and tectonic structures of hydrothermal vents, cold seeps, seamounts, and trenches and their geological conditions, processes, distribution patterns, and detection technologies; biological community characteristics, origins, and evolution in chemosynthetic ecosystems under extreme environments, analyzing deep-sea biological adaptation mechanisms to extreme conditions; material-energy transport dynamics in hydrothermal and cold seep systems and their support for and interaction with seafloor ecosystems; life processes, influencing factors, and roles in mineral formation of stratigraphic microorganisms in extreme environments; and hadal-specific physical oceanographic and geochemical phenomena, elucidating coupled evolution mechanisms between hadal environments and extreme life.

(3) **Emphasize Interdisciplinary Integration**: Deep-sea special geological, physical, and chemical environments have shaped unique ecosystems and life processes that result from comprehensive interactions among physical, chemical, geological, and biological processes. Research on deep-sea extreme environments and life processes requires comprehensive consideration from a marine systems perspective, with multidisciplinary intersection driving systematic, integrated outcomes that enhance China’ s academic standing in deep-sea science.

(4) **Emphasize Science-Technology Integration**: Bottlenecks in deep-sea research primarily concern detection technology. Every breakthrough in deep-sea research has resulted from new technologies and equipment applications. Therefore, strengthening deep-sea technology and equipment development guided by scientific objectives, with emphasis on enhancing capabilities of deep-sea autonomous observation platforms such as ROVs and AUVs, advancing development of deep-sea precision positioning and information communication, in-situ detection, and in-situ experimental technologies, constructing long-term observation systems for deep-sea environments and ecosystems, and developing deep-sea resource exploration and utilization technologies will enhance China’ s independent innovation capabilities in deep-sea research.

(5) **Strengthen International Cooperation**: Actively conducting international cooperation, participating in and leading major international deep-sea programs broadens research perspectives and expands research fields.

Opening deep-sea observation and research platforms promotes internationalization of technical systems and research teams, enhancing China' s international visibility, contributions, and influence in deep-sea research.

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Note: Figure translations are in progress. See original paper for figures.