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Deep-sea sampling techniques ranging from traditional methods to future perspectives

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Abstract. In the current trend of deep-sea exploration, deep-sea sampling technology has become a core tool for marine scientific research. However, the extreme environment of the deep sea has a great impact on sampling technology, such as the reliability of sampling equipment working in the high-pressure environment of the deep sea and the difficulty of long-distance operation. In recent years, however, deep-sea sampling technology has made significant progress in the intelligence and automation of equipment. The development of the Isobaric Sampler has enabled researchers to maintain the in-situ pressure and temperature of samples during the recovery process in order to avoid damage to the samples due to changes in environmental conditions, which significantly improves the accuracy of deep-sea biology and geology research. In addition, the widespread use of Remotely Operated Vehicle (ROV) and Autonomous Underwater Vehicle (AUV) has further reduced human error and improved the efficiency and reliability of sampling. However, deep-sea sampling still faces many challenges, and future development will focus on improving the intelligence of the equipment so that it can automatically adapt in the complex and changing deep-sea environment and enhance the quality of sample preservation and operational efficiency.

Keywords: deep-sea sampling, Remotely Operated Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs), mineral, deep sea exploration

1. Introduction

In the current resource constraints, the unknown deep sea with abundant resources has become the main exploration direction, and the exploration of the deep sea is of major significance to the development of society. In deep-sea exploration, due to the complexity and unknown nature of the environment, sampling technology for the deep sea is the core tool for marine scientific research.

Early deep-sea sampling relied on mechanical equipment, such as trawls and grabs, which could obtain samples, but were prone to mechanical damage and could not maintain in situ environmental conditions. In the mid- to late-20th century, Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) have become the main tools to improve the sampling depth, accuracy, and application range [1]. In recent years, deep-sea sampling technologies have made progress in intelligence and automation, such as isobaric samplers that can maintain in-situ pressure and temperature of samples to improve research accuracy, and ROVs and AUVs that have reduced human error and improved efficiency and reliability [2]. However, deep-sea sampling still faces many challenges, such as the durability of equipment in extreme high-pressure environments and the stability of long-range operations [3]. Future development will focus on improving the level of equipment intelligence to adapt to the complex deep-sea environment, and enhancing the quality of sample preservation and operational efficiency. Deep-sea sampling technology has a wide range of applications in marine science and multidisciplinary fields, and provides scientists with key data for understanding the adaptive mechanisms of deep-sea organisms and the potential for resource exploitation.

2. Application of deep-sea sampling techniques in multidisciplinary research

Deep-sea sampling techniques are diverse and constantly evolving. Sampling techniques for different types of items, such as sediments, biological samples, water and suspended matter, have their own strengths and challenges, such as sample fidelity and operational complexity. However, there are some shortcomings in real-time monitoring and control techniques, such as dependence on environmental factors, limited communication, high research and development costs, and existing techniques need to be optimized for the deep-sea environment.

2.1. Marine biology

Deep-sea sampling techniques are crucial in marine biology research, enabling scientists to obtain valuable biological samples for in-depth analyses of marine ecology. The rapid development of deep-sea sampling techniques in recent years has strongly promoted the progress of marine biology research. For example, Loke et al. developed a benthic invertebrate sampling method, Wang et al. designed an isobaric sampling device, and Licht et al. proposed a soft-bodied robotic grabber and other innovative technologies. Each of these methods has its own advantages and has provided some assistance in the exploration of the deep sea. In addition, the monitoring method proposed by White and the ROV storage device developed by Reis et al. not only improve the sampling efficiency and quality, but also enhance the comprehensive understanding of the deep-sea ecology, which opens up new possibilities for research [4-7].

2.2. Geology and mineral resources

Existing devices and techniques for deep-sea sampling technology are functionally classified into three main categories: sediment sampling, biological sampling and environmental monitoring, which are uniquely designed to meet the needs of different deep-sea studies. Sediment sampling devices include isobaric samplers that maintain in-situ pressure and temperature of samples, and multi-tube sediment samplers for large-scale geological studies and mineral exploration. Biological sampling devices such as the ROV storage unit provide stable sample preservation and the SyPRID plankton sampler collects high-resolution, high-capacity plankton samples. Environmental monitoring devices can measure environmental parameters on the seafloor and provide data support for research [8-9].

2.3. Climate science

Deep-sea sampling techniques are used in climate science research to obtain climate data over millions of years by analysing sediment and biological samples to provide relevant clues for research on the evolution of the Earth's climate, with isobaric samplers and ROV storage devices playing an important role. In addition, techniques such as the SyPRID sampler are of vital relevance to the study of changes in ocean heat content, microbial distribution and changes, gas hydrates, etc., and can be used to infer changes in ocean temperature and the global carbon cycle. Recent advances in deep-sea sampling technology have enabled climate studies to obtain more accurate and extensive data, and in analysing past patterns of climate change, such as multi-parameter analyses, it is possible to reconstruct the history of climate and identify the impacts of sudden-onset events [8,10-11], thus contributing to the accuracy of predictions of future climate and other environmental issues.

2.4. Environmental monitoring and protection

Deep-sea sampling techniques are key to monitoring the deep-sea environment and protecting the deep-sea environment, such as isobaric samplers to preserve sample characteristics, ROVs and AUVs to collect samples and monitor parameters, new sampling devices, such as ROV storage devices, to enhance monitoring capabilities, and plankton samplers to assess ecological status. Sampling technologies are also used for marine resource management and policy development. Deep-sea sampling techniques have greatly contributed to the development of deep-sea environmental monitoring and protection, improving data accuracy while providing appropriate technical support so that future monitoring will be more accurate and comprehensive to ensure the sustainability of the deep sea [10].

3. Challenges and future directions

3.1. Extreme circumstances in deep-sea environments

The extreme harshness of the deep-sea environment, with its high pressure, low temperature, lack of oxygen, extreme darkness and complex chemical conditions, poses a serious challenge to sampling technology. Underwater pressure increases dramatically with depth, by about 1 atmospheric pressure for every 10 metres, and the high pressure in the deep sea affects the performance and structure of sampling equipment, which can change the characteristics of the samples. At the same time, the low temperatures and lack of oxygen in the deep sea require equipment that is resistant to cold and has the ability to stabilise temperature and oxygen concentration. Dark working conditions complicate the operational processes and requirements of sampling activities. In addition, the complex chemical conditions are highly susceptible to damage to detection equipment, which requires highly corrosion-resistant and intrusion-resistant designs. While the challenges of deep-sea exploration are enormous, these issues also present opportunities for technological advances, such as the development of isobaric samplers. In the future, with the development of material science and intelligent control technology, deep-sea sampling equipment will continue to be optimised, and intelligent and multifunctional equipment will be better adapted to the deep-sea environment and promote new achievements in deep-sea research [8,10].

3.2. Limitations of sampling equipment

Deep-sea sampling technology has advanced significantly over the past decades, yet sampling equipment for practical applications still faces numerous challenges and limitations. The extreme environment of the deep sea is a great technical challenge, with its extremely high pressure, low temperature and complete darkness, which requires very high requirements for equipment materials and structural design. Sampling accuracy and efficiency are also challenges. The accuracy and efficiency of the equipment, which is usually required to complete the task within a limited time, determines the success of sampling, and He et al. reviewed that the operational stability and sampling success rate of many equipment in extreme deep-sea environments, especially in complex terrains and dynamic currents, have been dramatically reduced [11]. Sample preservation is difficult. While modern equipment can maintain in-situ pressure and temperature during sampling, samples may still be irreversibly altered by temperature and pressure changes when recovered to the surface, and Reis et al. discuss innovations in ROV storage devices, but also point out that it is difficult to avoid sample contamination and damage during prolonged deep-sea operations [10]. Complex operation and high maintenance cost are the bottlenecks, and Chen et al. introduced the multi-tube sediment sampler, mentioning that although it can improve the efficiency, it is complicated to operate, requires professional technicians, and increases the cost of use, which restricts the popularity of the application [8]. With the increased demand for deep-sea resource development, the sustainability of equipment has become an important research direction. Future sampling equipment should focus on material sustainability and energy efficiency, reduce environmental impact, and improve durability and reusability. In conclusion, although deep-sea sampling technology has progressed, there are still challenges in many aspects, which should be addressed to support more in-depth research in the future.

3.3. The need to improve sampling efficiency and sample quality

In the development of deep-sea sampling technology, the improvement of sampling efficiency and sample quality are central challenges. Challenges to sampling efficiency are the difficulty of operating equipment in extreme deep-sea environments and the high cost of sampling mission time. For example, traditional mechanical sampling equipment is prone to malfunction and has long preparation and execution cycles, which are limited by equipment durability and personnel experience. The direction of enhancement is to develop automated and intelligent sampling equipment, like remotely operated vehicles and autonomous underwater vehicles that have advanced to improve operational flexibility and precision, and multi-tube sampling techniques that can significantly reduce sampling time. The challenge of sample quality is that the deep-sea environment affects the physical and chemical integrity of samples, and traditional sampling methods have difficulty in maintaining in-situ pressure, which affects subsequent analyses. Improvements such as isobaric samplers can maintain in-situ pressure and temperature of samples, and new ROV storage devices can reduce sample damage and contamination. In the future, the development of deep-sea sampling technology relies on the improvement of automation and intelligence and breakthroughs in material science. Adapting equipment to the deep-sea environment can improve efficiency, developing advanced materials and technologies can ensure quality, and multidisciplinary integration and collaboration will bring innovative opportunities. In conclusion, deep-sea sampling technology is advancing in overcoming challenges [5, 11].

4. Conclusion

Deep-sea sampling technology has progressed dramatically, from simple mechanical devices in the early days to advanced, intelligent systems. traditional sampling methods such as trawls and grabs laid the foundation for marine science in the late 19th and early 20th centuries, but were too limited to be adapted to the deep ocean. in the mid-20th century, the emergence of multi-tube sediment samplers and other devices improved sampling accuracy and sample integrity. in the 21st century, the frontiers are in intelligence and automation, with devices such as isobaric samplers improving the quality of sample preservation and accuracy of research. In the 21st century, the frontier development is in intelligent and automated, isobaric sampler and other equipment to improve the quality of sample preservation and research accuracy, ROV and AUV technology to improve the sampling efficiency and research capacity. Despite these breakthroughs, we still face challenges in extreme environments such as high pressure and low temperature, which require high stability and durability of equipment. Future development will depend on advances in material science and automation control technology to improve efficiency and sample fidelity. Deep-sea sampling technology continues to innovate, providing support for multiple disciplines such as biology and geology, and deep-sea resource development and conservation and ecosystem research will be important directions in the future.

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