Advances in Geo-Energy Research

Vol. 14, No. 1, p. 12-24, 2024

Original article

Application prospects of deep in-situ condition-preserved coring and testing systems

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Keywords:
Deep mining
deep in-situ rock
in-situ condition-preserved coring
in-situ condition-preserved transfer
in-situ testing

Cited as:
Xie, H., Gao, M., Zhang, R., Zhou, H., Gao, F., Chen, L., Peng, X., Li, X., Ju, Y. Application prospects of deep in-situ condition-preserved coring and testing systems. Advances in Geo-Energy Research, 2024, 14(1): 12-24.
https://doi.org/10.46690/ager.2024.10.04

Abstract:
Shallow resources are becoming increasingly depleted, deep resource exploration has become a global strategy. The design and testing of deep in-situ core samples are prerequisites for exploring deep resources; however, no in-situ condition-preserved coring and testing techniques and tools have been reported yet. Here, the first deep in-situ condition-preserved coring system (with the preservation of pressure, temperature, substance, light, and moisture) was developed that considers the effects of high water pressure and formation dynamic loads, along with an in-situ condition-preserved testing system. A pressure-preserved controller was designed, achieving the ultimate capacity of 140 MPa and 150 °C. A temperature-preserved coring system combining active heating and passive insulation was constructed, realizing temperature preservation from room temperature to 150 °C. Three generations of film-formation principles and methods were designed, achieving an excellent quality preserved rate, moisture preserved rate, and visible light barrier rate. Moreover, a deep in-situ condition-preserved coring system, and a simulated coring platform for large cores under in-situ environments was fabricated. A non-contact testing system was derived to cut and prepare specimens under in-situ environment and to perform non-contact non-destructive testing and true triaxial testing. The research findings can be successfully applied to deep coal and gas development, deep oil and gas resources assessment, and deep-sea sediment prospecting, achieving excellent application outcomes. This study provides important theoretical, technical and hardware support for deep in-situ rock physics and mechanics research and deep resource exploitation.

1. Introduction

As shallow resources become gradually exhausted, the exploitation of further resources continues to deepen. Accordingly, the accurate detection and efficient exploitation of deep resources need a comprehensive understanding of the occurrence of target resources, rock mechanics and other trends. However, compared with shallow resources, deep rock masses are in complex in-situ environments with high ground stress, temperature and osmotic pressure, leading to

Yandy Scientific Press

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Received June 23, 2024; revised July 15, 2024; accepted August 1, 2024; available online Aughst 5, 2024.

strong engineering disturbances. Deep in-situ rock masses have prominent nonlinear behaviour, which directly affects the safety and efficiency of deep resource development (Tomac and Sauter, 2018). To date, little basic research has focused on deep resource development, and uncertainties remain (Yang et al., 2022b). Coring to obtain deep rock samples, followed by subsequent testing, is a widely utilized strategy for investigating the physical and mechanical properties of deep rock formations (Tian et al., 2016; Liu et al., 2020). However, in conventional sampling, the core will be affected by factors such as stress release, temperature change and other factors, resulting in changes in its physical and mechanical properties (Xie et al., 2023). Furthermore, variations in the in-situ environment of the core will lead to the dissipation of oil and gas components within the rock and the killing of microorganisms (Alkan et al., 2020). Conventional rock mechanics testing methods also have certain limitations, as they use ordinary core samples. Regardless of the depth of the sample, these samples are loaded from zero to failure in the laboratory, and the obtained parameters, models and equations are depth-independent. Physical and mechanical parameters such as elastic modulus, compressive strength, Poisson's ratio, and porosity are treated as constants. However, these demonstrate linear or nonlinear variations with depth (Zhang et al., 2015; Beloborodov et al., 2024). Therefore, traditional coring and testing techniques can no longer meet the needs of deep earth science research. There is an urgent need to acquire deep cores with the retention of in-situ properties and carry out testing and analysis on them under in-situ conditions to form a new theory of rock mechanics for deep environments and provide support for the exploration and development of deep resources.

The most established and widely applied technology is in-situ pressure-preserved coring (IPP-Coring). (Kvenvolden and Cameron, 1983; Peterson, 1984; Dickens et al., 2000; Abid et al., 2015). However, the current IPP-Coring technologies are primarily designed for deep-sea natural gas hydrates (NGHs) in low-temperature and high-pressure environments where the pressure-preserved capacity is mostly in the range of 20-35 MPa. As a result, they are unsuitable for deep environments characterized by high-temperature, high-pressure, and high-disturbance conditions (Fang et al., 2023; Guo et al., 2023). Besides, compared to IPP-Coring technology, in-situ temperature-preserved coring (ITP-Coring) poses a greater challenge. The existing ITP-Coring technologies are largely immature and are mainly applied to deep-sea NGHs, enabling only low temperature preservation, which is unsuitable for high-temperature deep-rock environments (Abid et al., 2015). In addition, achieving comprehensive in-situ substance-preserved coring (ISP-Coring), in-situ moisture-preserved coring (IMP-Coring), and in-situ light-preserved coring (ILP-Coring) under high-temperature and high-pressure conditions remains challenging because of disparities in the mechanical, physical, chemical, and microbiological characteristics of rock samples compared to their in-situ conditions. In terms of testing in deep in-situ environments, only the Pressure Core Characterization Tools (Santamarina et al., 2012; Santamarina et al., 2015), the Pressure Core Non-destructive Analysis Tools (Nagao et al., 2015; Yoneda et al., 2015), and the Pressure Core Analysis and Transfer System (Inada and Yamamoto, 2015; Priest et al., 2015) can perform sample transfer and storage and achieve both non-contact and contact testing under reconstructed temperature and pressure conditions. However, the temperature and pressure specifications of these three systems are also designed for deep-sea NGH, enabling sample coring, transfer and testing under low-temperature and low-pressure conditions (≤ 35 MPa). As such, they are not capable of preparing, transferring or conducting mechanical tests on standard samples of rock under the in-situ high-temperature, high-pressure conditions found in deep terrestrial environments.

Traditional IPP-and ITP-Coring and testing technology is mostly aimed at deep-sea hydrate exploration, hence it has great limitations: it fails not only to meet the geological conditions of high temperature and high pressure in deep drilling but also to obtain key information such as that on in-situ pore pressure, temperature, humidity, and the microbial environment. This greatly reduces the research value of deep cores (Xie et al., 2021). In view of the above challenges, our team previously proposed the principle and technology of In-situ Condition-Preserved Coring (ICP-Coring) (pressure preservation, temperature preservation, substance preservation, moisture preservation, light preservation) for deep in-situ conditions, acquired preserved samples from the deep Earth and carried out In-situ Condition-Preserved (ICP) testing and analysis, revealing the differences in the in-situ physical and mechanical parameters of deep rocks at different occurrence depths. Thus, we established a new scientific theory of deep engineering and improved the ability to acquire deep resources (Xie et al., 2021). This paper introduces in detail the development of a deep ICP-Coring system and presents an in-situ condition-preserved test and analysis system, with the aim to provide important theoretical, technical and hardware support for the research of the physical and mechanical behaviour of in-situ deep rock. The findings of this study aid the advancement and utilization of deep resources and further development of the principles, technology and equipment available for deep in-situ rock mechanics research.

2. Deep in-situ condition-preserved coring system

2.1 Deep IPP-Coring technology

Existing studies on the physical and mechanical properties of deep rocks are mostly based on ordinary cores extracted under pore pressure release conditions, neglecting the influence of the initial pore pressure on rock properties. The deep IPP-Coring technique aims to maintain the initial pore pressure of the core during recovery, thereby providing a more realistic understanding of the in-situ stress environment of the strata (Schultheiss et al., 2017). Pressure-preserved controllers are the core components of in-situ pressure-preserved coring equipment in deep environments. In recent years, these controllers used internationally primarily include ball valves (Kvenvolden and Cameron, 1983; Kubo et al., 2014; Schultheiss et al., 2017) and flapper valves (Burger et al., 2003; Hohnberg et al., 2003; Kawasaki et al., 2006;

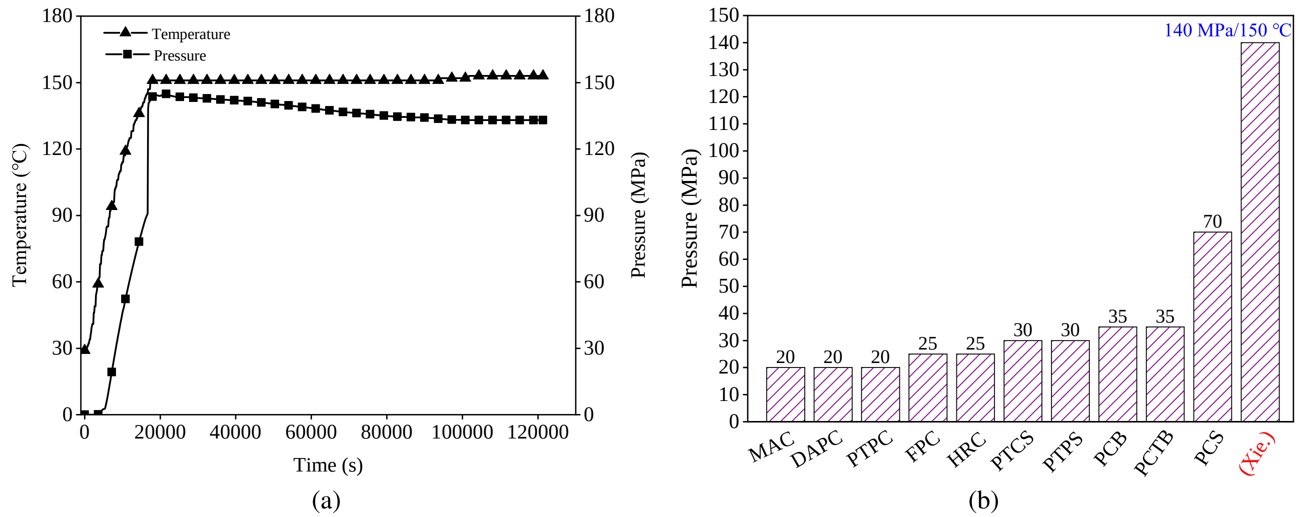


Fig. 1. (a) Ultimate pressure-bearing capacity test results under high temperature and ultrahigh pressure and (b) comparison of the ultimate pressure-bearing capacity of the main pressure-preserved corers used domestically and internationally.

Chen et al., 2006). Among them, the ball valve as part of the Pressure Core Sampler (PCS) has proven to show the best pressure-preserved performance of nearly 70 MPa. However, according to technical reports on PCS, over 30% of pressure core samples either cannot retain pressure or only maintain the original in-situ pressure partially. As the exploration depth increases, core sampling often faces challenges such as high-temperature and ultrahigh-pressure environments, as well as restricted apertures, where the existing pressure-preserved controllers cannot meet the demands of deep exploration.

In the face of the current technical difficulties in pressure-preserved core sampling, we innovatively proposed the principle and method of self-triggered pressure-preserved core sampling (the Steinmetz solid principle) and optimized the design of five configurations of pressure-preserved controllers (Li et al., 2021; Shi et al., 2024), greatly improving the maximum ultimate pressure-bearing capacity of the controllers (exceeding 140 MPa). In this paper, to address the problems of low initial sealing pressure and poor sealing performance in the scenario when the pressure-preserved controller relies solely on gravity for initial sealing, a self-triggered sealing mechanism for IPP-Coring was innovatively designed, significantly improving the success rate of pressure preservation. The pressure resistance characteristics of pressure-preserved controllers under the coupled effects of temperature and pressure was investigated, revealing the sealing failure mechanism of pressure-preserved controllers under high-temperature and ultrahigh-pressure environments (140 MPa, 150 °C), which is crucial for understanding how to improve the durability and reliability of pressure-preserved controllers under extreme conditions. The sealing structure parameters of the pressure-preserved controller were optimized and the ultimate pressure-bearing capacity of the pressure-preserved controller under 140 MPa and 150 °C environments was tested. The test results, shown in Fig. 1(a), indicate that the leakage rate of the pressure-preserved controller under 140 MPa and 150 °C environments approaches zero, maintaining stability for more than 24 h and demonstrating excellent pressure-preserved effects, far exceeding the current highest level achieved by the leading pressure-preserved corer (PCS; 70 MPa) (Fig. 1(b)).

2.2 Deep ITP-Coring technology

The ITP-Coring of deep rocks presents a significant technical challenge. Currently, only few corers are capable of temperature preservation in the low-temperature environments of seafloor sediments, which rely solely on passive temperature preservation. Additionally, there is a lack of research on temperature-preserved coring for deep rocks under high-temperature conditions (Xie et al., 2021). To maintain the in-situ temperature of deep rock cores, a new coring system was designed that combines active and passive temperature preservation. This active temperature-preservation control system integrates temperature acquisition, feedback and control and is capable of operating at 150 °C and 140 MPa, along with an underground power supply scheme for the corer. A structure for the passive insulation system was designed, and a sixth-generation independent fully closed-cell passive insulation material was also effectively developed. Successful operation has been demonstrated at 150 °C and 140 MPa (Xie et al., 2021). Achieving in-situ intelligent temperature control for deep rocks requires measuring the in-situ core temperature with sensors to determine the target temperature. Then, using the control module and heating module, intelligent temperature control and precise temperature replenishment can be achieved (Xue et al., 2023). In active temperature preservation, it has been confirmed that the heating module efficiently converts electrical energy into thermal energy at 150 °C and 140 MPa (He et al., 2022) to provide real-time heat compensation for the core. For passive temperature preservation, high-strength materials with low thermal conductivity have been developed to effectively reduce heat exchange between the core and the external environment (Yang et al., 2022a). As demonstrated

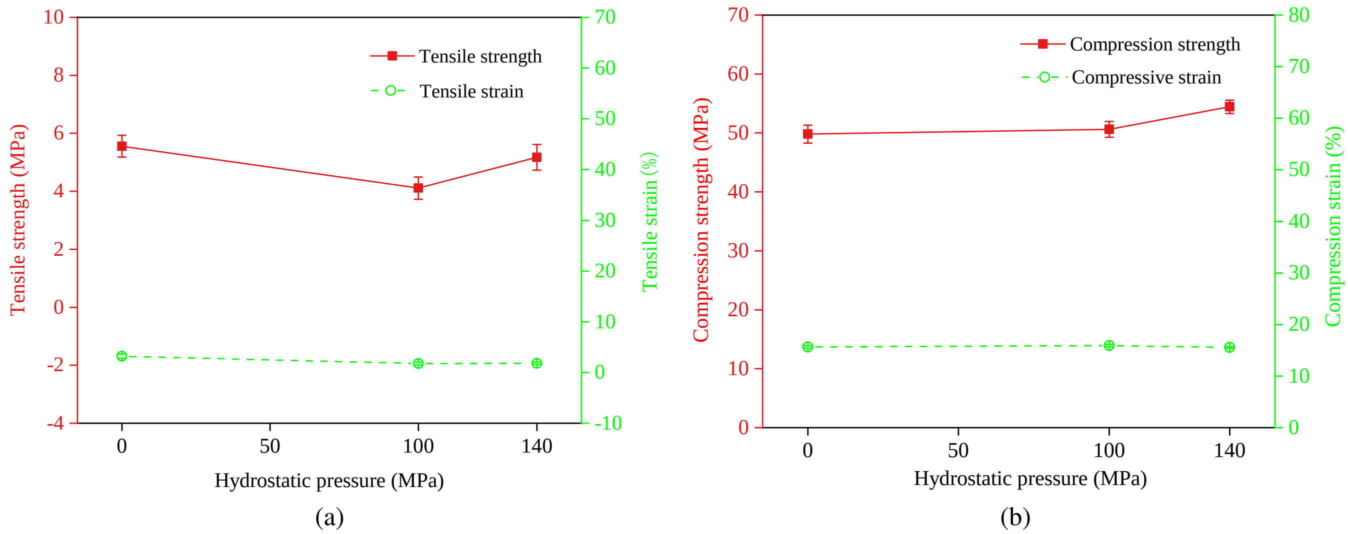


Fig. 2. Mechanical properties of the temperature-preserved materials under different pressure conditions and 150 °C: (a) Tensile strength under different hydrostatic pressures and (b) compressive strength under different hydrostatic pressures.

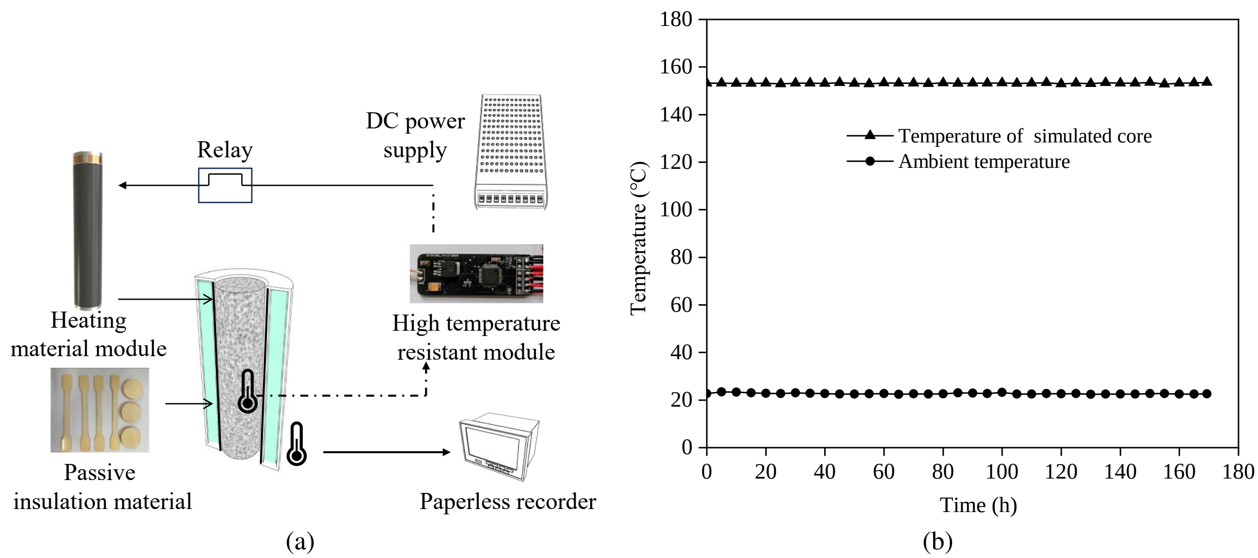


Fig. 3. Temperature preservation experiment of the ITP-Coring: (a) Experimental system and (b) experimental result.

in Fig. 2, hydrostatic pressures of 100 MPa and 140 MPa at temperatures up to 150 °C did not significantly affect the mechanical properties of the materials. The results indicate that an ITP-Coring system combining active and passive temperature preservation is suitable for deep coring in environments with a temperature of 150 °C and pressure of 140 MPa.

In order to verify the temperature preservation capability of the combined active and passive temperature preservation system, temperature preservation tests were conducted. These tests utilized an active temperature preservation setup, including a high-temperature-resistant control module, heating modules, and passive temperature-preserved materials (Yu et al., 2023). As illustrated in Fig. 3, the simulated core temperature remained at 153.2 °C, with a maximum fluctuation range of only 0.24%. The temperature was maintained for up to 169.3 h, which meets the project's requirements of 150 °C ±3% F.S. This indicates that the active and passive temperature preservation systems can operate for an extended period.

2.3 Deep ISP-, IMP- and ILP-Coring technology

Xie et al. (2018) first proposed the frontier concept of substance-preserved, moisture-preserved, and light-preserved coring by solid film. In the process of deep coring, physical or chemical methods are applied to generate a solid film layer on the core surface while drilling to maintain the three phases of solid, liquid and gas inside the core, in order to obtain information from the core that more closely reflects the in-situ conditions.

The key to realizing the preservation of substance, moisture and light during coring by a solid film lies in the innovation of the in-situ film-forming method, the development of film materials and the film-forming process. Owing to continuous exploration, substance-preserving, moisture-preserving, and light-preserving coring technology has significantly matured (Xie et al., 2021; Yang et al., 2023), forming a complete technical system from film-forming principles and film materials to film-forming processes while drilling. To improve the substance, moisture and light preservation efficiency and engineering implementation ability of solid-state film coring technology, three generations of film-forming principles and methods were developed, namely, adaptive phase transfer (first-generation), self-triggered in-situ crosslinking and curing (second-generation), and tough and high-barrier membrane forming (third-generation) principles and methods. Among them, the improved third-generation membrane (Generation 3-2) is an epoxy composite film utilizing multifunctional graphene nanosheets, which effectively elongates the diffusion path and blocks visible light. It demonstrates outstanding efficacy in preventing oxygen and water vapor loss while maintaining opacity to visible light. The oxygen transmittance and water vapour transmittance were reduced by over 99.99% and 96.17%, respectively, compared with those of the first-generation membrane, as shown in Fig. 4(a). By comparing the difference in material loss behaviour between the coated and uncoated core samples, the substance preservation efficiency and moisture preservation efficiency of the coated samples were obtained. The coated core achieved a 99% substance preservation rate, 99% moisture preservation rate and 100% visible light blocking rate (Xie et al., 2023; Yang et al., 2023). The excellent ability of Generation 3-2 as a barrier is expected to realize the efficient preservation of cores obtained under in-situ conditions and lay the foundation for cutting-edge scientific research, such as resource assessment and life detection. At the same time, to meet the tough and high-barrier membrane-forming principle, three types of film-forming processes were developed for drilling, namely, the plunger liquid storage process (Zhu et al., 2022), the double-spiral hose liquid storage process (Xie et al., 2023), and the double-parallel flexible hose liquid storage process, as shown in Figs. 4(c)-4(e). The plunger liquid storage process achieves the proportional discharge of A/B liquids through relative movement between cylindrical reservoir chambers and push rods, providing the advantage of stable liquid discharge. However, the reservoir chambers and push rods have a fixed space occupation after the discharge of liquids, making integration within the corer challenging. The double-spiral hose liquid storage process utilizes the annular space between the center rod and the inner wall of the core barrel and installs double spiral hoses for storing A/B liquids separately. During drilling, the spiral hoses are squeezed, leading to the discharge of A/B liquids. Due to the significant compression of the spiral hoses after coring, this structure effectively shortens the space occupation after liquid discharge. However, the uniformity of discharge of A/B liquids is greatly affected by their viscosity differences, and maintaining the consistency of A/B liquids' viscosity poses significant challenges and limitations. The double-parallel hose storage process can achieve both low space occupancy and uniform discharge, thus optimizing the integration capability in the corer. The double parallel hoses separately storing A/B liquids can be simultaneously flattened to a small volume through a diameter reduction mechanism and achieve uniform discharge of the A/B liquids regardless of the viscosity differences. This process achieves stable storage, rapid movement and efficient generation of the film-forming liquid, resulting in effective film formation during the coring process to preserve the core sample under in-situ conditions (Fig. 4(b)).

2.4 Integrated design of an ICP-Coring system

In this paper, based on the requirements of the functional integration of an in-situ condition-preserved coring system, an in-situ condition-preserved coring system was built. This system retains in-situ conditions, including the pressure, temperature, substances, light, and moisture content of the original cores. Under the conditions of the highest pressure of 140 MPa and the highest temperature of 150 °C, after more than 24 h of experimental research, the performance of the in-situ condition-preserved coring system was good, proving its ability to obtain and maintain the core under high temperature and pressure (Fig. 5).

In order to verify the reliability of the coring function of the in-situ condition-preserved coring system in practical engineering applications, a coring test was conducted on the proposed system. The in-situ condition-preserved coring system was lifted from the bottom of the well to the surface to obtain a 610 mm core. The valve cover of the pressure-preserved controller was turned over and closed to realize pressure-preserved coring. The test circuit of the temperature-preserved cored module was enabled, and the heating output power reached 190 W, meeting the requirements of the in-situ temperature-preserved coring function. The film-forming liquid solidified on the surface of the core to form a film, filling the 0.2 and 4 mm gaps between the core and the core tube and realizing the coring function of preserved substances, light and moisture. Thus, it was demonstrated that this coring system can successfully realize the ICP-Coring function in the actual drilling process. Compared with traditional coring exploration methods, this system can maintain information on the pressure, temperature, oil and gas, and the bedding state of rock samples in deep in-situ occurrence states and avoid the distortion of reserve evaluations, which is highly important for the accurate evaluation of deep reserves and exploring deep in-situ rock mechanics.

3. Deep ICP storage displacement and test system

3.1 Deep ICP displacement storage technology

After obtaining the in-situ condition-preserved rock core using the proposed in-situ condition-preserved coring technology, it is essential to systematically study the relationship between the physical and mechanical properties of rocks under deep in-situ environmental conditions and their occurrence depth and engineering response. To achieve this, it is im-

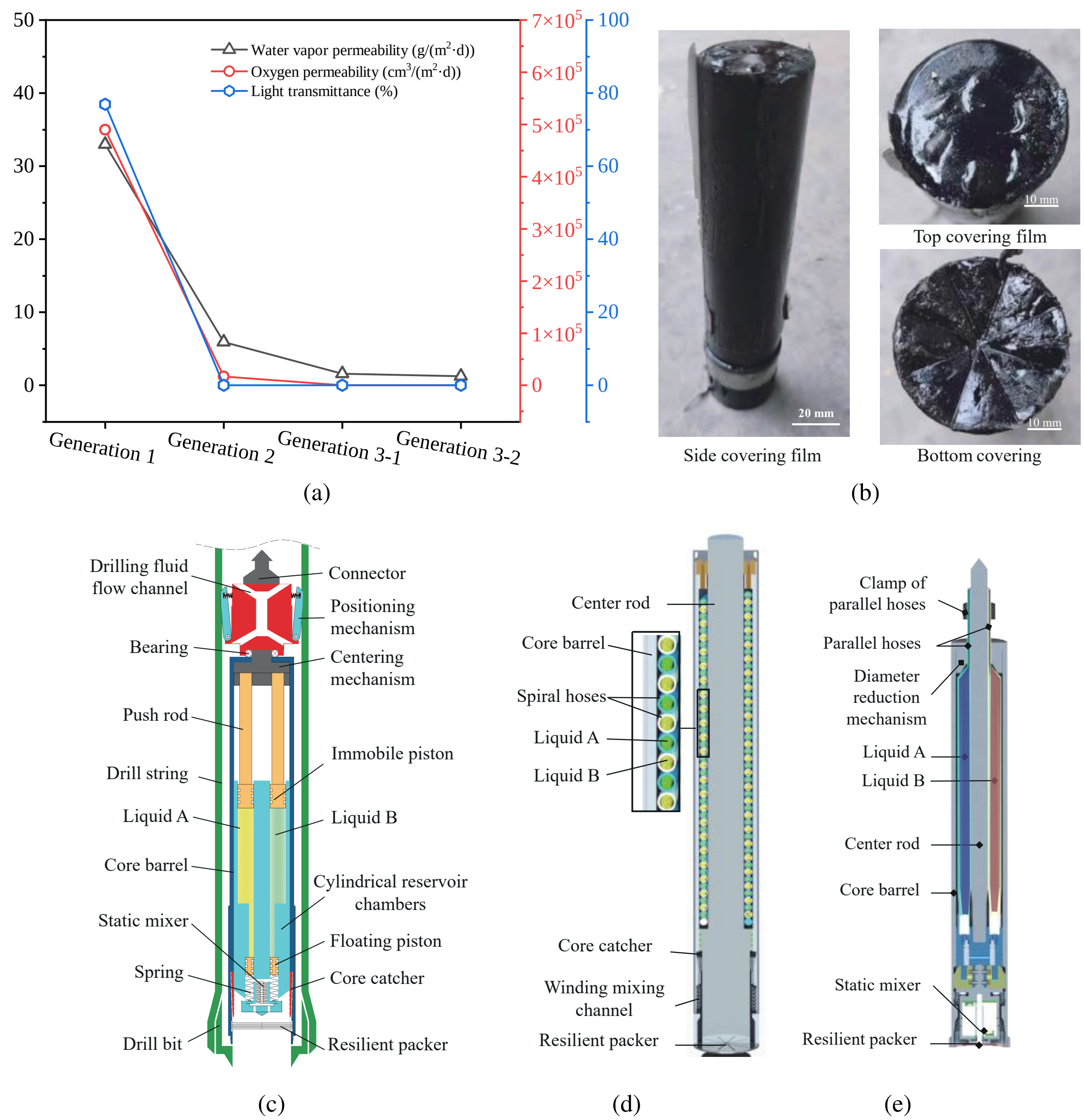


Fig. 4. Previously established films and processes: (a) Comparison of the water vapour permeability, oxygen permeability and light transmittance of films, (b) core of film formation while drilling during the simulated coring process, (c) plunger liquid storage process, (d) double spiral hose liquid storage process and (e) double parallel flexible hose liquid storage process. The data in (a) are from the literature (Xie et al., 2023; Yang et al., 2023).

perative to explore deep in-situ condition-preserved testing technology and analysis methods, which involve core transfer, core storage, specimen preparation, non-contact testing, and mechanical testing under an in-situ condition-preserved environment. As a kernel technology, a temperature-pressure interpolation decoupling control algorithm has been proposed to maintain the in-situ condition-preserved environment. This algorithm realizes the independent control of temperature and pressure based on the isodensity curve of water. The detailed mathematical model and implementation steps of the temperature pressure interpolation decoupling control algorithm can be found in Peng et al. (2023). A core storage and transfer system was developed accordingly, and experiments on temperature preservation, pressure preservation, and core transfer were conducted on this system for performance verification.

The temperature and pressure of the system controlled by a temperature/pressure control cabinet were increased to 150 °C and 140 MPa, respectively, as shown in Fig. 6. To evaluate the heat and pressure maintenance performance of the system, temperature and pressure were maintained for a maximum of 72 h. During this process, the pressure fluctuation was within ±2 MPa, and the temperature fluctuation was within ±2 °C, meeting the accuracy requirements.

After reaching the target temperature and pressure environment (140 MPa, 150 °C), a core transfer (push and pull) test was performed. As shown in Fig. 7, the system can effectively push and pull the core in an environment with a temperature as high as 150 °C and an ultrahigh pressure of 140 MPa. During

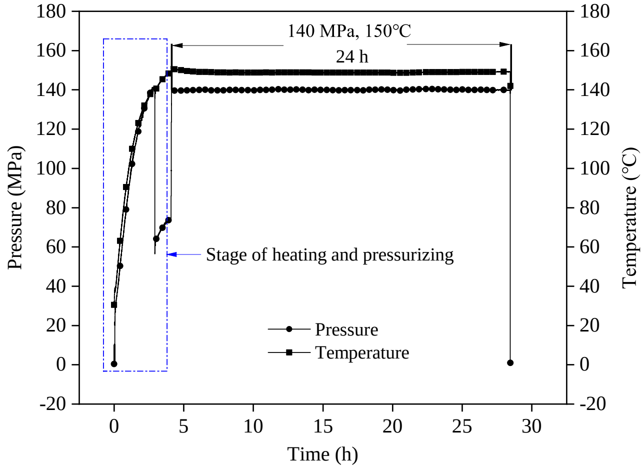


Fig. 5. Temperature and pressure test curves of the coring system.

the core transfer test, the pressure fluctuation was within ±2 MPa, meeting the accuracy requirements.

3.2 Deep ICP testing technology

The deep in-situ condition-preserved test system is divided into three parts: Specimen preparation system, acoustic-electric-magnetic non-contact system, and real-time triaxial loading test system. By integrating with the deep in-situ condition-preserved displacement system, the system reconstructs a high-temperature and high-pressure environment, allowing the core specimen to be transferred into the non-contact test chamber within the in-situ condition-preserved environment to carry out acoustic-electric-magnetic non-contact tests and physical parameter analysis. Then, the core specimen is pushed into the cutting chamber under the in-situ condition-preserved environment and cut into a specimen with dimensions of $\phi 50 \times 100$ mm. Finally, the prepared specimen is pushed to the real-time loading test system to obtain the real deep in-situ rock mechanics parameters.

3.2.1 Deep ICP environment specimen preparation system

The proposed deep in-situ condition-preserved environment specimen preparation system overcomes a series of challenges, such as rotary sealing, long-distance pushing, core pipe removal, and core mechanism docking in a high-temperature and ultrahigh-pressure water environment at 140 MPa and 150 °C, and has achieved success. Currently, there are no similar instruments equipped internationally that can complete the preparation of rock specimens in such extremely narrow high-temperature and ultrahigh-pressure water media.

The main functions and indexes of the specimen preparation system for a deep in-situ environment include the following:

1) A high-temperature and ultrahigh-pressure temperature and pressure system, that can achieve a maximum working pressure of 140 MPa and a maximum working temperature of 150 °C. Through high-temperature and ultrahigh-pressure water flow and cascade valve control, accurate and stable simulations of deep in-situ temperature and pressure environments can be realized.
2) An ultralong-distance push rod system, which utilizes a worm gear reducer to drive the lead screw. The push rod has a length of 4,935 mm, a maximum stroke of 3,600 mm and a displacement accuracy of ±0.2 mm, which can accurately position and push the core specimen under high-temperature and ultrahigh-pressure water environments of 140 MPa and 150 °C.
3) A realistic-environment rock specimen preparation system, which drives a double-blade parallel structure diamond grinding wheel through a servo push rod and motor. The specimen is cut into a specimen with dimensions of Ø50×100 mm, and the cutting accuracy is ±0.5 mm.
4) The rotary seal system, which employs a combination seal ring structure, can achieve 140 MPa, a high temperature of 150 °C and an ultrahigh pressure rotary seal at a rotational speed of 600 RPM.
5) A rock specimen push system, which incorporates an automatic spring docking structure. By means of a hydraulic and electrical automatic control system, a high level of automation is achieved in rock specimen docking.

3.2.2 Deep ICP environment non-contact test system

The deep in-situ condition-preserved non-contact testing system utilizes acoustic-electric-magnetic non-contact testing methods and techniques under high temperature and pressure. The original physical and mechanical parameters of the core are obtained via non-destructive testing, which is vital for understanding the deep in-situ rock mechanics and developing a new theory in this field that is suitable for deep underground engineering.

The system consists of an ICP test chamber and three independent non-contact acoustic-electric-magnetic test modules (Fig. 8). The deep in-situ condition-preserved environment (maximum working pressure and temperature of 140 MPa and 150 °C, respectively) is reconstructed by using the ICP chamber. The core specimen is placed transversely in the ICP chamber and a sensor is arranged along the circumferential direction of the specimen. Among them, the acoustic module uses one transmitter and multiple receivers to excite ultrasonic waves on the specimen (each sensor can be used both as a transmitting device and a receiving device) to obtain the full-field monitoring results of the core wave velocity and calculate the elastic modulus, density and other parameters of the core. The electrical module employs a symmetrical excitation-receiver mode to excite the artificial electric field, analyses the spatial distribution of the resistivity inside the core, and inverts the porosity and water content of the original core. The magnetic module utilizes an ungrounded loop to emit a pulsed magnetic field and tests the secondary induced eddy current field in the core during the interval of a pulsed magnetic field to detect the apparent resistivity distribution of the core (Xie et al., 2023).

Non-contact tests of the physical parameters of core specimens under different pressures, temperatures and media (water, membrane and casing) were carried out by using this system (Xie et al., 2021). From Fig. 9, the following results can be deduced:

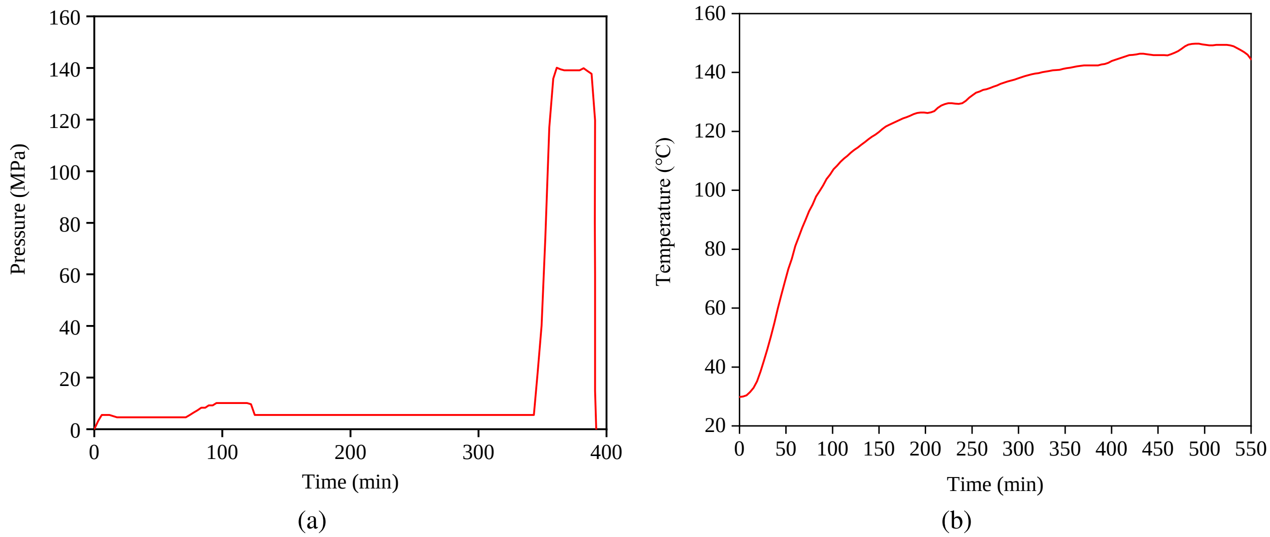


Fig. 6. (a) Pressure curves and (b) temperature curve.

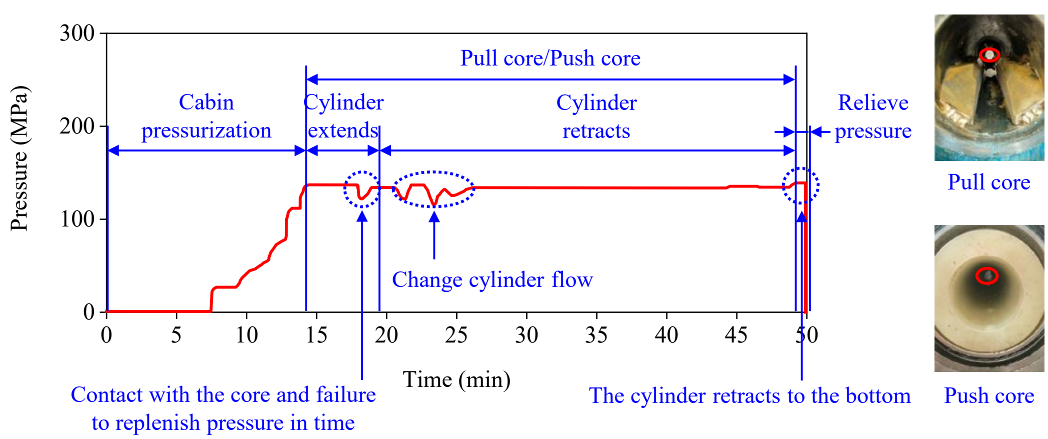


Fig. 7. Core transfer test and pressure curve during the test.

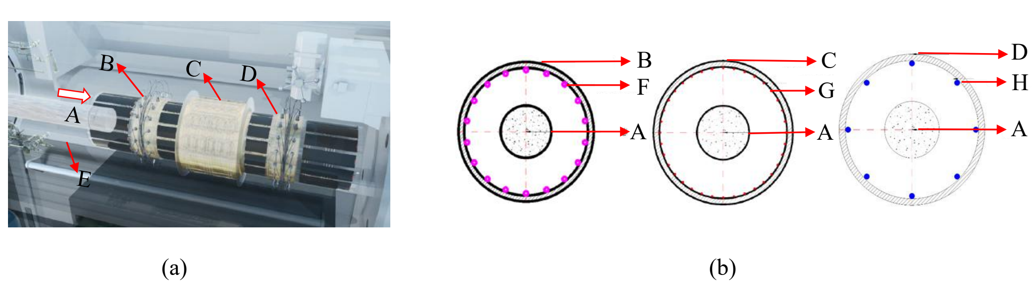
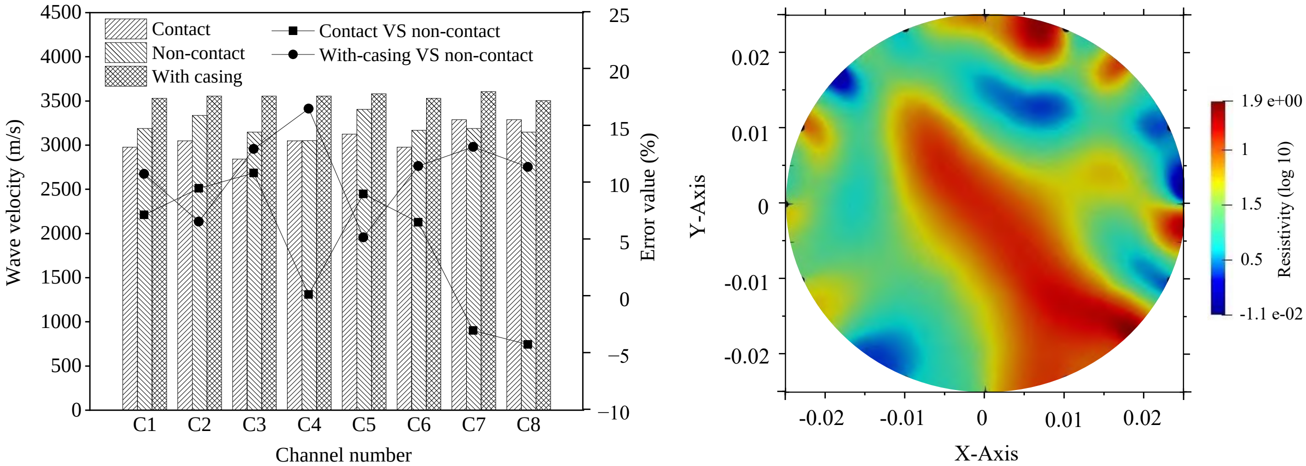
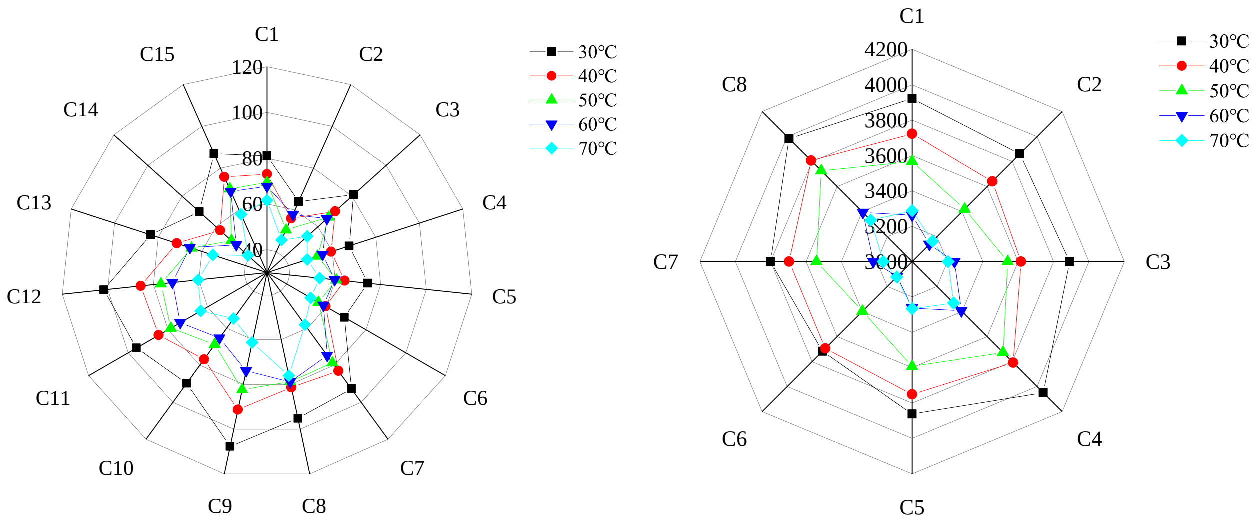


Fig. 8. Deep in-situ condition-preserved environment non-contact testing system: (a) Structural diagram, (b) sensor layout of different modules. A-Core sample, B-Test ring (sound), C-Test ring (electric), D-Test ring (magnetism), E-Non contact testing chamber, F-Sensor (sound), G-Sensor (electric) and H-Sensor (magnetism).



(a) (b)

Fig. 9. Acoustic-electric-magnetic non-contact test results of the core physical parameters: (a) Wave velocity (acoustic method) and (b) resistivity distribution (electrical method).



(a) (b)

Fig. 10. Influence of environmental conditions on the acoustic-electric-magnetic test results: (a) Temperature vs. wave velocity (m/s) and (b) temperature vs. resistivity (Ohm).

1) The error of the wave velocity results obtained by the non-contact acoustic method is small, basically within 10%; when the specimen with a casing can withstand high temperature and high pressure, the wave velocity test results increase and the error is small, close to 10%. As the temperature rises, the wave velocity decreases.
2) Using electrical testing, the resistivity distribution results of the specimen section are obtained via inversion and the internal cracks of the specimen are identified with high resolution and sensitivity. With increasing temperature, the resistivity decreases.

The above results demonstrate that a core specimen can obtain effective acoustic-electric-magnetic signals in the reconstructed in-situ environment. When the specimen is equipped with a casing, this changes the test results but the error is small and can be corrected. As shown in Fig. 10, with increasing temperature in an in-situ condition-preserved environment, the wave velocity and resistivity decrease (values in various channels, C1∼C8) with an approximately linear trend. Furthermore, inversion calculation models (Eqs. (1) to (6)) were developed for important parameters such as elastic modulus (E_d), quality factor (Q), resistivity (ρ), apparent resistivity ($\rho_\tau(t_i)$), porosity (φ), and water saturation (S_w) of the deep in-situ rock mass. These results were verified based on the results of the acoustic-electric-magnetic non-contact test, which were basically consistent with the real values:

$$E_d = \frac{(1+\mu)(1-2\mu)}{1-\mu}\rho_d v^2 \tag{1}$$

$$Q = \frac{\pi f}{\alpha v} \tag{2}$$

where E_d represents the elastic modulus, μ represents the Poisson's ratio, ρ_d means density, v denotes the longitudinal wave velocity in rock, Q denotes the rock quality factor, f represents the frequency of the signal, where all acoustic tests are taken at 500 kHz, and α is the attenuation coefficient:

$$\rho = \frac{2\pi\Delta U_{MN}}{I\left(\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}\right)} \tag{3}$$

$$\rho_\tau(t_i) = \frac{\mu_0 L^2}{4\pi t_i z^2} \tag{4}$$

where ρ represents the resistivity obtained by the electrical method, M and N are the receiving electrodes, A and B are the emission electrodes, AM, BM, AN, BN represent the distances between the electrodes, ΔU_{MN} denotes the potential difference between the receiving electrodes, I denotes the emission current value, $\rho_\tau(t_i)$ is the apparent resistivity obtained by the magnetic method, μ_0 represents the vacuum permeability, L stands for the equivalent side length of the transmitting loop, and z is a transient electric field parameter:

$$\frac{\rho_s}{\rho_w} = \frac{3-\phi}{2\phi} \tag{5}$$

$$R_t = \frac{abR_w}{\phi^m S_w^n} \tag{6}$$

where ρ_s represents the resistivity of rock, ρ_w represents the resistivity of pore water, φ denotes the porosity, R_w represents the formation water resistivity, R_t represents the resistivity of formation rock, S_w represents the formation water saturation, a denotes the lithology coefficient related to rock, b is a constant related to lithology, m denotes the cementation index, and n is the saturation index.

3.2.3 Deep ICP real-time loading and testing system

The loading and testing of deep in-situ condition-preserved coring specimens under deep in-situ environmental conditions is an important experimental foundation for studying the mechanical behaviour of deep rocks and further developing the deep rock mechanics theory. To overcome the shortcoming that deep in-situ condition-preserved coring specimens cannot be loaded into and tested in a common tester, a novel separable triaxial loading and testing structure was proposed (Xie et al., 2021; Xie et al., 2023). This structure is composed of a triaxial loading test chamber containing deep in-situ condition-preserved coring specimens and a triaxial tester simulating deep in-situ environmental conditions. Both of them were well designed and manufactured. The triaxial loading test chamber can be docked with the front specimen cutting preparation chamber, and then the deep in-situ condition-preserved coring specimen can be transferred from the preparation chamber into the test chamber under the deep in-situ environment conditions. After the specimen is pushed into the test chamber, a support rod is pushed into and seals the test chamber. This triaxial loading test chamber containing deep in-situ condition-preserved coring specimens can be moved into a triaxial tester for experimental studies under deep in-situ environmental conditions.

A triaxial loading test chamber was manufactured by cutting integral forging high-strength heat-resistant stainless steel 630. In addition, Che's combined seal set, which can work under high temperatures and high pressures, was chosen. The docking device of the support rod is an eight-petal snap ring, and the test chamber can safely bear 160 MPa of pressure.

The triaxial tester was manufactured as a four-column structure with high rigidity. The maximum loads along the vertical direction can reach 1,500 t. Several servo cylinders were adopted to control triaxial loading, which is controlled by a series of hydraulic sources and dispensers. The tester is equipped with a temperature and pressure control system that can simulate any deep in-situ environmental conditions.

4. Evaluation and prospective analysis

Building upon a deep in-situ condition-preserved coring and testing system, this research expands into the development of technology and methodology for accurate assessment and exploration in several critical areas, including deep coal and gas extraction, precision evaluation of deep oil and gas resources, exploration of subsea gas hydrates, and investigation and extraction of deep-sea sediments. The in-situ condition-preserved coring equipment and testing methods developed in this study demonstrate the good application prospects in these fields.

4.1 Field application outcomes

In the field of deep coal and gas extraction, this study proposes a novel in-situ low-disturbance pressure and gas-preserved coring tool. Industrial-scale experiments have been conducted in multiple coal mines located in Pingdingshan, Baoji, Jixi, and Jincheng, which demonstrate that this system enhances the accuracy of underground pressure and gas content measurements in potential construction zones within mines, providing preliminary validation for the development of the in-situ condition-preserved coring instrument. Fig. 11 compares the gas content measurements obtained using our method versus traditional methods, along with samples of the retrieved cores. The gas content and pressure of coal samples obtained using this tool were found to be approximately 31.4% greater than those measured by traditional methods. The maximum length of a single sample reached 500 mm, with a core retrieval success rate of 100%, and the maximum depth achieved exceeded 120 m.

For the precise evaluation of deep oil and gas resources, we developed a specialized deep in-situ petroleum pressure-preserving coring tool. In August 2023, this tool was successfully deployed in the Qianjiang well at a depth of 1,970 m within the Jianghan Basin in Hubei, where two rock cores measuring 1.95 and 1.36 m were obtained. The average solid core recovery rate was 86%, with a maintained pressure of 22 MPa. In addition, in the areas of subsea gas hydrate exploration and deep-sea sediment prospecting, specialized tools have been designed and manufactured for reservoir drilling and core retrieval based on drilling platforms and manned submersibles. The temperature- and pressure-preserving coring tool, designed for use on drilling platforms, incorporates thermoelectric cooling and enhanced heat conduction technologies

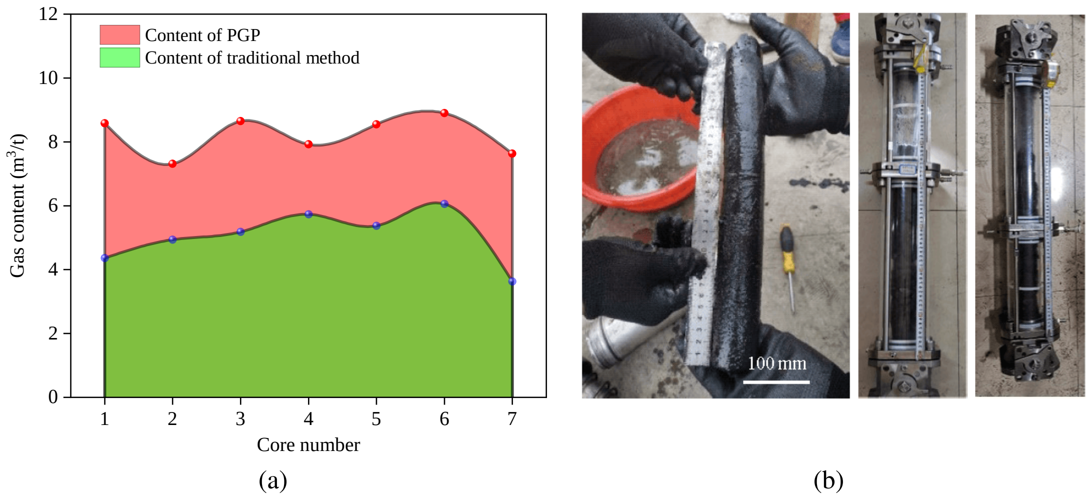


Fig. 11. Application of the proposed in-situ condition-preserved coring concept in deep coal and gas: (a) Comparison between the pressure and gas-preserved (PGP) and traditional method and (b) the obtained coal samples.

using autonomously developed passive insulation microbeads. This tool is capable of maintaining temperatures below 5 °C for over 90 minutes, filling a technological void in the in-situ temperature preservation of gas hydrate coring, and has a pressure maintenance capacity exceeding 70 MPa. Multiple coring trials in test wells achieved a success rate of 77.6% for in-situ temperature and pressure maintenance. In September 2022, a first-generation deep-sea sediment temperature and pressure preservation coring device, deployed using the 4,500 m rated manned submersible Shen Hai Yong Shi, retrieved in-situ condition-preserved sediment samples at a depth of 1,370 m in the South China Sea's Haima cold seep with a pressure of 13.8 MPa and a temperature of 6.51 °C. In September 2023, a second-generation device was deployed on the Fen Dou Zhe submersible in a 1,385 m depth zone of the same region, securing and maintaining solid deep-sea sediment and gas hydrate samples at an original pressure of 14.5 MPa and temperature of 3 °C.

4.2 Future application prospects

Rock coring is crucial for understanding subsurface geology and mineral resources, with drilling and data collection underpinning China's deep-Earth drilling and resource exploitation for national energy security. The in-situ condition-preserved coring and testing technology proposed in this paper enables the acquisition of authentic cores and the analysis of the physical and mechanical behaviours of rocks under deep in-situ conditions. These research outcomes have significant application prospects in geological exploration and deep energy prospecting. Furthermore, they can also support underground energy storage, deep-space utilization, military defence engineering, and deep disaster control, bolstering the development of emerging disciplines and significantly enhancing China's national energy security.

5. Conclusions

Focusing on the strategic needs of national energy security, this research creatively presents the fundamental principles and technical conception of deep in-situ condition-preserved coring and testing, and develops the first deep in-situ condition-preserved coring and testing analysis system equipment in the world. The main contributions of this work are as follows:

1) In-situ condition-preserved coring, core transfer, docking, and testing under the extreme environment of 140 MPa and 150 °C have been realized, which can improve in-situ deep rock mechanics research and fill the gaps in the principles, technology and equipment currently adopted for global deep in-situ rock mechanics research.
2) Based on the evaluation of the deep in-situ condition-preserved coring and testing analysis system, the coring and testing equipment for deep coal, petroleum, and deep sea resources have been independently developed. The results have been successfully applied to deep resource exploration and space development, such as deep mines, deep petroleum in the Jianghan Oilfield and hydrate-bearing sediments in the South China Sea.
3) This study provides not only research methods and technical support for deep sea sediments, NGH, deep coal, deep petroleum and other deep resources and space development but also the principle and technical platform for the establishment and development of new disciplines, such as deep environmental science, deep material science, deep agricultural science, deep medicine, deep microbiology, and other life sciences.

Acknowledgements

The authors are grateful for the financial support from the National Natural Science Foundation of China (No. 51827901) and the National Science Fund for Distinguished Young Scholars (No. 52225403).

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Conflict of interest

The authors declare no competing interest.

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