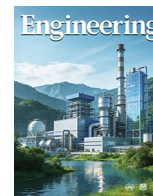




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Engineering Achievements

The 10 000-m SDTK #1 Well-Drilling Project

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The deep and ultra-deep strata represent a crucial strategic succession domain for oil and gas in China. Approximately 39% of China's remaining oil resources and 57% of its remaining natural gas resources are distributed within these strata. It is estimated that the ultra-deep (8 000–12 000 m) formations in the Ordovician to Sinian systems of the Tarim Basin hold approximately 1.017 billion tonnes of oil and 1.9 trillion m³ of natural gas [1]. Scientific exploration for oil and gas in these deep-earth layers currently presents dual challenges: the scientific quest to discover resources at even greater depths and the need to surpass the current limits of engineering technologies. Since the 1970s, the Soviet Union and its successor states, the United States, and Germany have completed more than 20 ultra-deep and super-deep wells that approach or exceed 10 000 m (Table 1). However, these wells are mainly scientific-exploration and extended-reach wells [2,3]. The SG-3 well on the Kola Peninsula in Russia (drilled during the Soviet Era) remains the world's deepest well. Drilling commenced in 1970 and was completed in 1992, with the well reaching a depth of 12 262 m [4]. This accomplishment signified the entry of human drilling into the 10 000-m realm. However, during the drilling process, the project encountered 27 incidents of drill string breakage due to fatigue, steel quality issues, and thread wear. Moreover, sidetracking drilling was carried out three times. The endeavor spanned 23 years, with the upper 9884 m section taking 10 years and the lower 2379 m section taking 13 years to complete [5]. These results illustrate that each meter drilled deeper into the Earth's crust presents a significant challenge.

The favorable exploration zones for the ultra-deep Sinian layers in the Tarim Basin are primarily distributed around paleo-uplifts, platform marginal belts, and deep structural transition zones. These areas are regarded as key exploration targets due to their superior reservoir-development conditions, favorable hydrocarbon source supply, and advantageous trap preservation environments. Currently identified major favorable zones include the Lunnan–Fuman platform marginal belt, the deep structural belt on the northern slope of the Central Tarim Uplift, and the deep zones of the southern margin of the Bachu Uplift and the Maigaiti Slope. Among these, the Lunnan–Fuman platform marginal belt is the current main focus and the most practical area for exploration. As a landmark project for deep-earth scientific exploration, the Shenditaka (SDTK) #1 Well was precisely deployed within the

Lunnan–Fuman platform marginal belt of the Tarim Basin, for the purpose of exploring oil and gas resources at depths of up to 10 000 m.

Drilling of the well started on 30 May 2023, and the final depth of 10 910 m was reached on 5 January 2025, after a total construction period of 586 days. Remarkably, drilling from the surface to 10 000 m took only 279 days, setting a global land record for the fastest drilling to such a depth. However, the final 910 m from 10 000 m to the total depth took over 300 days, underscoring the immense challenges posed by each additional meter beyond the 10 000 m threshold. The final stratum of located in through the Cambrian Yurtus Formation, and 12 sets of strata were encountered. The drilled strata basically matched with those anticipated in the design planning, and the depth error was less than 1%. The project successfully retrieved invaluable core samples from depths exceeding 10 000 m, including rock specimens dating back 540 million years, whose rarity and scientific value are comparable to those of lunar soil. Within the Cambrian strata, specifically between 10 851 m and 10 910 m, high-quality hydrocarbon source rocks were uncovered, marking a groundbreaking global discovery of oil and gas resources below 10 000 m on land. This achievement not only fills a critical gap in the understanding of ultra-deep geological theories but also provides a solid foundation for the strategic exploration and discovery of deep-earth oil and gas resources.

1. Project overview

The deeper the drilling, the greater the challenges. Deep-earth drilling projects encounter a multitude of extreme well conditions due to their absolute depth, including ultra-high temperature, pressure, and stress. The SDTK #1 Well was designed with a target depth of 11 100 m, with the aim of exploring the ultra-deep trillion-cubic-meter natural gas zone in the Lunman–Gucheng area and thereby aiding China in establishing a strategic replacement domain for oil and gas resources at 10 000 m depths. However, due to the severe complexity of the geological conditions and the immense difficulty of drilling, the project presented four extreme well conditions—extreme depth, ultra-high temperature, ultra-high pressure, and high sulfur content—making it a world-class engineering challenge with a level of comprehensive difficulty rarely seen globally. To ensure the high-quality completion of

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Table 1
Statistical table of typical ultra-deep wells around the world.

No.	Well name	Depth (m)	Completion date	Region/country	Well type
1	Banden 1	9 195 (vertical depth)	1972	USA	Vertical well
2	Betha Rogers 1	9 583 (vertical depth)	1974	USA	Vertical well
3	Kola SG-3	12 262 (vertical depth)	1993	Soviet Union	Vertical well
4	KTB	9 101 (vertical depth)	1994	Germany	Vertical well
5	Kaskida	10 059 (vertical depth)	2006	USA	Vertical well
6	Tiber	10 685 (vertical depth)	2009	USA	Vertical well
7	Tashen 5	9 017 (vertical depth)	2021	China	Vertical well
8	Pengshen 6	9 026 (vertical depth)	2023	China	Vertical well
9	BD-04A	12 289 (total depth)	2008	Russia	Extended reach well
10	Sakhalin O-05RD	15 000 (total depth)	2017	Russia	Extended reach well
11	UZ-688	15 240 (total depth)	2022	UAE	Extended reach well

China's first 10 000 m-deep well-drilling project, numerous problems and challenges had to be addressed [6–8]; of these, the main issues were as follows:

- (1) The drilling would encounter a variety of formation pressure systems, making the well structure design difficult;
- (2) The ultra-deep and ultra-long well section would result in low power-transmission efficiency, making it difficult to efficiently break rock and speed up drilling;
- (3) Extreme temperatures and pressures at a depth of 10 000 m would pose challenges to well-construction equipment, tools, instruments, and working fluids;
- (4) Well control would present high risks in a 10 000 m-deep well, with outstanding difficulties in maintaining wellbore safety monitoring systems and emergency response.

Focusing on the technical challenges listed above, we undertook research and development on key core technologies, including the optimization of wellbore structures for 10 000 m-deep wells, super-hard and abrasive-resistant materials and high-efficiency drilling bits, high-temperature- and high-pressure-resistant drilling measurement and control, extra-deep coring, and working fluids for the wellbore. In this endeavor, we were able to achieve important advances and stage-by-stage results. These efforts led to the establishment of five major engineering records: ① the world's deepest liner cementing; ② the world's deepest wireline imaging logging; ③ the fastest onshore drilling to surpass 10 000 m globally; ④ the deepest vertical well drilling in Asia; and ⑤ the deepest onshore coring in Asia. These accomplishments signify that China has essentially mastered the technology for 10 000 m deep-earth drilling, successfully completing Asia's first and the world's second onshore vertical well with a depth exceeding 10 000 m. This achievement marks another major advancement in the field of deep exploration following China's significant progress in deep-space and deep-sea exploration.

This paper introduces the achievements made in the drilling project of the SDTK #1 Well in terms of integrated geological engineering design technology, drilling and completion process technology, key technology and equipment, drilling fluid technology, and digital information technology.

2. Technical engineering achievements at a depth of 10 000 m underground

2.1. Integrated geological engineering design technology

In the field of deep-earth exploration, the integration of geological and engineering design technologies is the key to achieving efficient and safe drilling. In particular, the design of the wellbore structure is crucial to the success of scientific deep-earth drilling. Through the synergistic innovation of geology and engineering and the integration of multidisciplinary technologies and methods, comprehensive and accurate technical support was provided for

the engineering design of a 10 000 m-deep well under complex geological conditions. When combined with the key technology and equipment used in onshore seismic exploration, this innovation and integration made it possible to carry out a multi-dimensional geological information analysis. The lithological profile of the SDTK #1 Well is shown in Fig. 1.

Secondly, through refined seismic data processing and interpretation, precise predictions of formation depth information were achieved, with an accuracy rate of 99.46%. By applying geological modeling and inversion techniques, quantitative predictions of the thickness and spatial distribution of special complex formations were realized. Concurrently, comprehensive predictions of the lithology, thickness, temperature, pressure, and fluid properties across all formation series were completed, enabling the accurate identification of complex geological structures such as faults, fractures, and cavities. Based on these results, well locations were scientifically optimized. The actual drilling successfully avoided complex geological bodies such as Carboniferous salt layers and Ordovician fractures, as illustrated in Fig. 2.

Furthermore, to enable geo-engineering risk identification, the well structure casing levels were further optimized with the help of the engineering equipment and technical capabilities. In regional drilling operations, a layer of technical casing is generally used to seal the Permian strata and the strata above it to avoid the risks of fluid loss and collapse in the Permian–Silurian strata. Through the comprehensive application of technologies such as stabilization of the long open-hole wellbore, monitoring and control of the equivalent circulating density (ECD) in the annulus, complete cementing of large-diameter long open holes, and safe running-in of overweight casing, it was possible to drill the fluid-loss- and collapse-prone strata of the Permian, Carboniferous, and Silurian systems together, saving one layer of casing and reserving design space for the risk control of deep strata.

To deal with issues caused by the abnormal pressure in the Ordovician and Cambrian systems, we applied pressure-controlled drilling and spillage coexistence control technology to meet safe drilling requirements in hydrocarbon-active formations. In this way, we realized the combined drilling of subdivisions M1 and M2 in the Ordovician Tierেকেawati–YingShan Formation, as well as the combined drilling of subdivisions M3 and M4 in the Ying-Shan Formation, which included the upper part of the Cambrian Formation in the lower part of the formation. The designed well structure level was optimized from seven sections to five sections, and the actual drilled well structure conformed to the design requirements, as shown in Figs. 3 and 4. This five-section wellbore structure avoided the problems of poor wall stability in an oversized borehole, the low strength of an oversized casing, and the difficulty cleaning an oversized borehole, significantly improving the implementability of the design.

Finally, the innovative drill-on-drill analysis technology used in the implementation of the project provided scientific guidance for

Formations		Depth	Lithology	Core	Petrographic description	Hydrocarbon source rock	Reservoir-seal assemblage	Predicted oil and gas formations
System	Group							
Cambrian	Awatag				Mainly paste rock, paste dolomite, mudstone, paste-bearing dolomite			
	Shaylik	10 000			Mainly granular autochthonous dolomite, grey dolomite, mud-bearing dolomite, interbedded pasty dolomite bands, fine-crystalline dolomite			
	Gosongar	10 200			The upper lithology is mainly granular dolomite, and the lower lithology is mainly grey dolomite-bearing rock, grey dolomite, and mud-bearing dolomite			
		10 400						
	Shorbulak	10 600			Mainly muddy greywacke, mud crystal greywacke, mudstone			
	Yurtus	10 800			The base is black mudstone and the top lithology is marl-bearing interbedded mudstone			
Aurora	Qigbulak	11 000			Mainly grey dolomite			

Fig. 1. The lithological profile of the SDKT #1 Well.

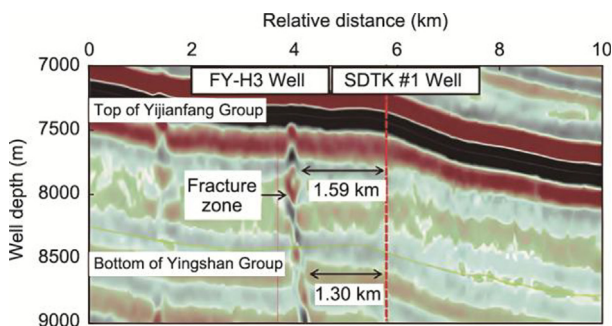


Fig. 2. Seismic profile of the Ordovician-Yijianfang Formation and Ordovician Tierekawati-YingShan Formation, subdivisions M1 and M2.

engineering measures and decision-making. It led to the construction of a seismic/outcrop/thin-section three-in-one figurative stratigraphic model that clarified the characteristics of the lithological combination and brought the stratigraphic characteristics hidden underground into plain view. Additionally, using various logging methods such as elemental analysis and rock thin-section

identification, comprehensive analyses were conducted on parameters such as cuttings, cavings, and downhole vibrations from abnormal well sections. This enabled the formulation of precise response measures, effectively preventing the escalation of engineering complications.

2.2. Drilling and completion process technology for 10 000-m-deep wells

2.2.1. Rock-breaking and speed-increasing tools for hard-to-drill formations

The high hardness and strong abrasiveness of the formations 10 000 m underground make conventional drill bits and auxiliary rate-of-penetration (ROP)-enhancement tools inefficient and prone to failure. These issues are key factors limiting drilling efficiency. Through targeted technological breakthroughs, a comprehensive technical system for rock-breaking and ROP enhancement in difficult-to-drill formations was developed. This system encompasses multiple critical components, including drill bits, drilling tools, and auxiliary equipment, all working synergistically to significantly improve drilling efficiency under challenging geological conditions.

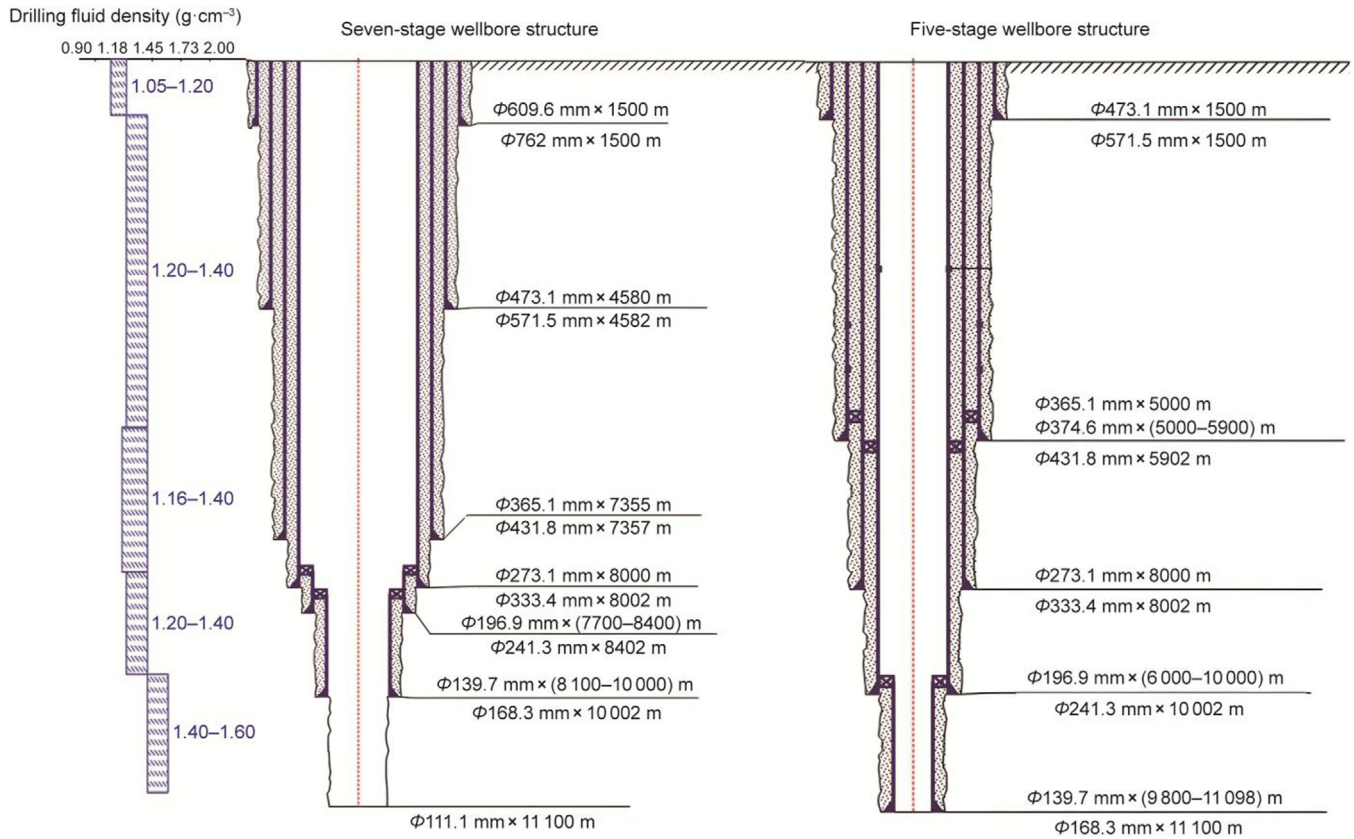


Fig. 3. Results of the wellbore structure design planning for the SDTK #1 Well. Φ : diameter.

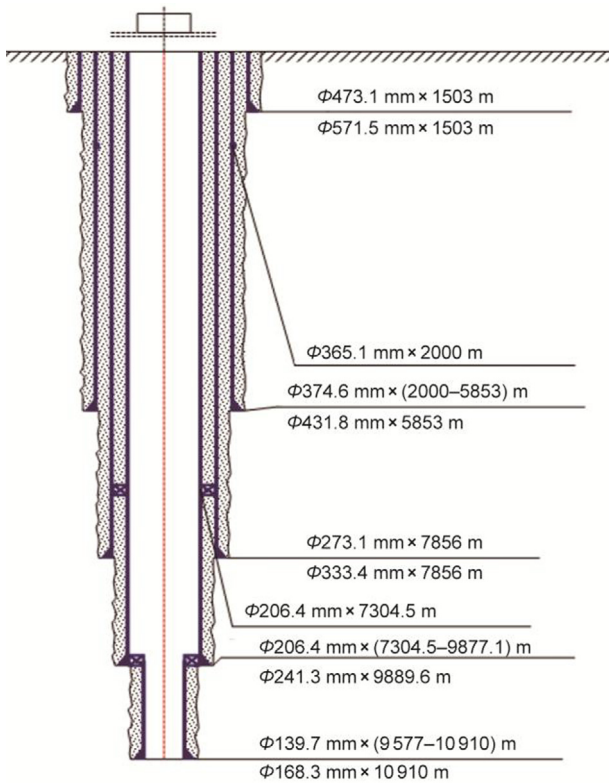


Fig. 4. Actual drilled wellbore structure of the SDTK #1 Well.

Among these advancements, accurate drill-ability evaluation identifies the direction for ROP enhancement. A rock-cuttings-based digital twin simulation method was established, continuous rock mechanical strength profiles and parameter profiles were set up, and it was clarified that the rocks of limestone and dolomite strata under ultra-high-temperature and high-pressure conditions in an extra-deep stratum are still hard and brittle. By integrating models for formation impact resistance and abrasiveness indices, a precise quantitative evaluation of the formation drillability indicators was achieved. This, in turn, offered accurate guidance for drill bit design.

Highly efficient rock-breaking drill bits are the metaphorical golden key to unlocking extremely hard rock at depths of 10 000 m. The rock-breaking efficiency of the drill bit directly affects the drilling efficiency. In the face of extremely hard deep-earth formations, it is necessary to design rock-breaking drilling bits that are super-hard, highly abrasion-resistant, and highly impact-resistant.

Three kinds of super-hard material formulation systems—namely, impact-resistant, wear-resistant, and balanced systems—were constructed, enabling four types of non-planar tooth diamond composite pieces to be successfully developed [9], as shown in Fig. 5.

Scientifically setting drilling parameters allows the full potential of drill bits and ROP enhancement tools to be harnessed. The key lies in establishing a parameter control chart based on drill string safety and a big-data analysis model for formation drillability, drilling parameters, and ROP sensitivity. This enables the optimization and adjustment of operational parameters, as illustrated in Fig. 6. Thanks to the innovations and advances described above,

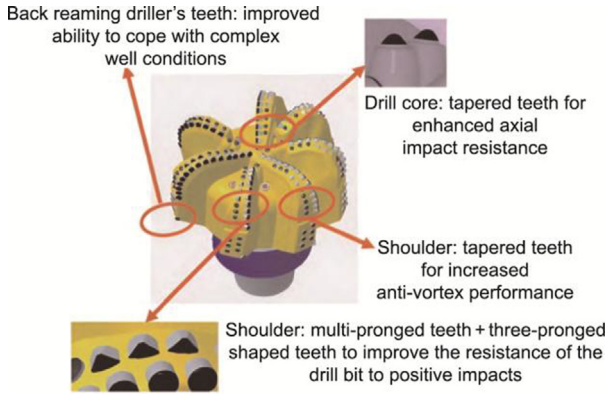


Fig. 5. An innovative hybrid tooth-arranged polycrystalline diamond compact (PDC) bit and its hybrid tooth-arrangement design.

it took only 279 days to break through 10 000 m in the SDTK # Well, with a daily drilling progress of 30–40 m in formations less than 10 000 m and an average ROP of 1.52 m·h⁻¹ for a drill bit with diameter 165.625 mm.

2.2.2. Drilling tool safety control technology

In the realm of ultra-deep well-drilling operations, the drill string serves as a metaphorical conveyor belt for the transmission of mechanical and hydraulic energy. The safety of the drilling tools is directly related to the success or failure of the entire drilling project, making its importance self-evident. Taking the Kola-3 well as an example, the well suffered 27 instances of drilling tool failures during the drilling process—lessons that provide valuable references for the subsequent drilling of extra-deep wells. In order to effectively ensure the safety of drilling tools, the kinetic theory of extra-deep drilling strings was systematically researched, and a series of application technologies—such as extra-deep trajectory control, drilling tool design, and safety control for drilling tools—were formed.

The motion state of 10 000-m drilling tools is extremely complicated, and these new insights into the dynamics of drilling strings guided the safe design and application of drilling strings for

10 000-m wells. An innovative dynamic model for ultra-deep well drilling strings with high flexibility and strong nonlinearity was established. By simulating the complex state of the downhole motion of the drilling string, it was found that an irregular borehole, bit collapse and instability, and poor trajectory of a borehole are the main causes of violent vibration of the drilling strings, while stick-slip and vortexing are the main forms of vibration. These findings identified the direction that should be taken to control harmful vibration and the effective transfer of surface energy, as shown in Fig. 7. Based on this theoretical understanding, a dynamic risk-assessment methodology for drill strings was developed, which takes into account the effects of drill string vibrations and alternating stresses. Complementing this methodology, a dynamic fatigue failure analysis technology for ultra-deep and ultra-long drill strings was also introduced. This method and technology provide strong technical support for the safe use and management of drilling tools onsite at 10 000 m-deep wells; they also help staff to prejudge possible problems with drilling tools in advance and take corresponding preventive measures.

During the fifth spud of the SDTK #1 Well, a dual-stabilizer pendulum bottom hole assembly (BHA) was employed for well-inclination control. The well inclination showed an increasing trend in the Wusonggeer Formation, in which high-angle fractures and vugs have developed. However, upon entering the tight formation, the inclination subsequently decreased. The measured well-trajectory variation exhibited four distinct stages: gentle, increasing, stable, and decreasing. These stages closely corresponded to the fracture-pore dolomite section, fractured-vuggy limestone section, and tight limestone section, respectively. Analysis indicated that the development of high-angle fractures and vugs was the primary cause of the increased well inclination, while trajectory variations led to persistent torque fluctuations when drilling below a depth of 10 786 m.

Therefore, straightening the borehole is the key to reducing the risk of tool failure. In order to ensure the quality of the wellbore in the SDTK #1 Well, a domestic temperature-resistant 175 °C vertical drilling system was upgraded for the shallow stratum above 9000 m, and a multi-factor coupled drilling-string dynamics model of the bit-rock-tubing string wellbore was established for depths below 9000 m. The maximum well deviation within 10 000 m

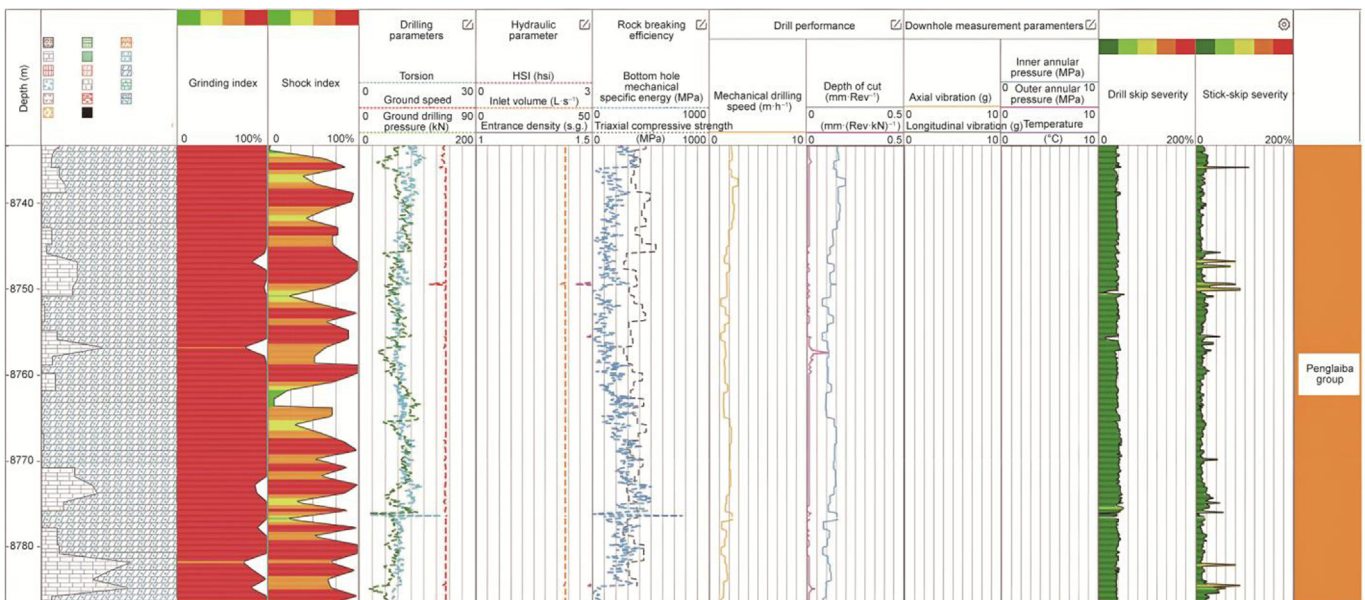


Fig. 6. Formation drillability, drilling parameters, and machine speed sensitivity in the big-data analysis model.

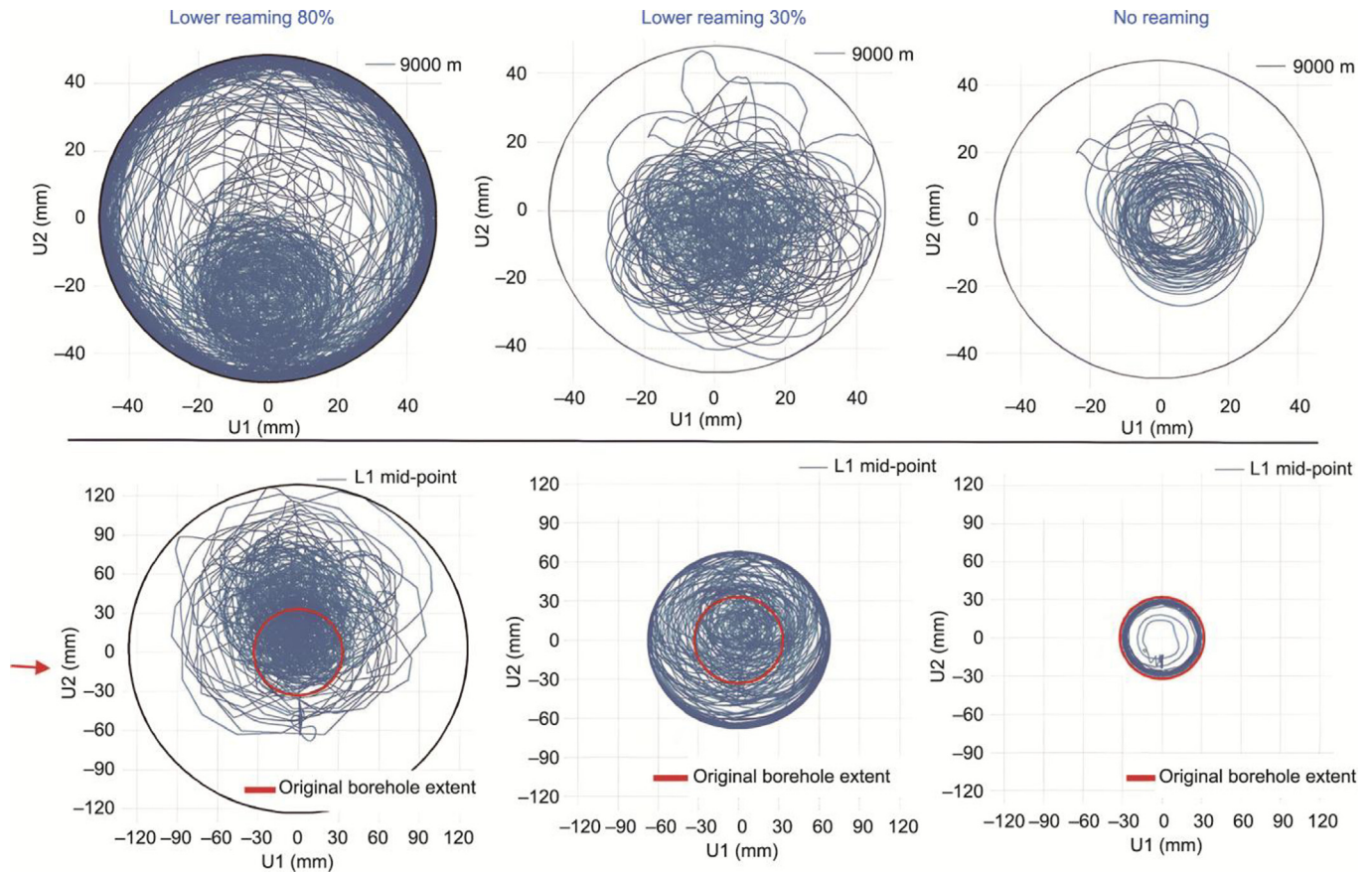


Fig. 7. The influence of well-bore enlargement on the dynamic characteristics of the drill-string in a 10 000-m-deep well.

was 4.26° , which effectively controlled the tortuosity of the borehole and reduced complex movement of the drill string caused by drastic trajectory changes. By the time the Kola-3 well was drilled to a depth of 4470 m, the well deviation had already reached 7.5° ; by the time the drilling reached 12 066 m, the deviation had increased to 23° [10]. In contrast, the wellbore quality control of the SDTK #1 Well was exceptionally well managed.

At a depth of approximately 10 000 m, drill string fracture accidents occurred twice in the SDTK #1 Well. Analysis indicated that the drill pipe failure was caused by fatigue under high-stress and overload conditions, leading to a serious incident. Thus, it was urgently necessary to improve the safe service capability of the drilling tools. Research and field measurement showed that the vibrations of the drilling strings of an extra-deep well are extremely complex and violent, so the drilling tools of the SDTK #1 Well were upgraded accordingly [11]. An innovative concept of overall strength enhancement for the entire drill string and all its components was proposed, leading to material upgrades for the BHA. A balanced tensile margin method was also innovatively established to guide the structural and strength design of the drill string, ensuring a tensile margin exceeding 100 t for each section. In addition, the entire drill string was upgraded with double-shoulder threaded connections, increasing the torsional resistance by 26.5%, as illustrated in Fig. 8. After these improvements were made, no further drill string failures occurred.

2.2.3. Technology for simulating the drill string dynamics

When challenging the drilling limit of a 10 000 m-deep well, two issues emerged: ① It was difficult to obtain information about the movement state of the drilling string in the whole well of a 10 000 m-deep well; and ② it was difficult to meet the engineering

requirements of the traditional method used for the stress analysis of tubular strings. To address these issues, a tubular string dynamics software called WellPulse was independently developed. This software constructs a three-dimensional (3D) well-trajectory model based on inclination and azimuth data, accounts for interactions between the drill string and the wellbore wall, simulates the drilling process of the drill string in the actual wellbore, and performs a dynamic strength verification of the BHA. It accurately identifies risk points, providing crucial references for onsite operations, as illustrated in Fig. 9. By conducting a simultaneous simulation analysis of the casing running process and predicting potential sticking points, the software completed multiple sets of dynamic simulations, ensuring the safety of the cementing operations. The software achieved independent control over the drill string dynamics analysis, offering not only vital support for the optimized design of the BHA but also significant assurance of the safety of drill strings in a 10 000 m-deep well.

2.2.4. Core sampling technology for 10 000 m-deep wells

Coring is the most important means of obtaining geological information at extreme depths around 10 000 m. However, core sampling presents significant challenges due to the extremely high temperatures, high pressures, and other complex working conditions in such a deep well, making it exceptionally difficult to achieve successful and high-quality coring. Through the innovative design of an all-metal sealed suspension structure, the overall temperature resistance of the coring tool was significantly increased from 180 to over 240°C , successfully resulting in a high-strength coring tool capable of withstanding temperatures up to 240°C . The adoption of a clearance-adjustable rotary assembly design effectively eliminated the erosive impact of the drilling fluid on

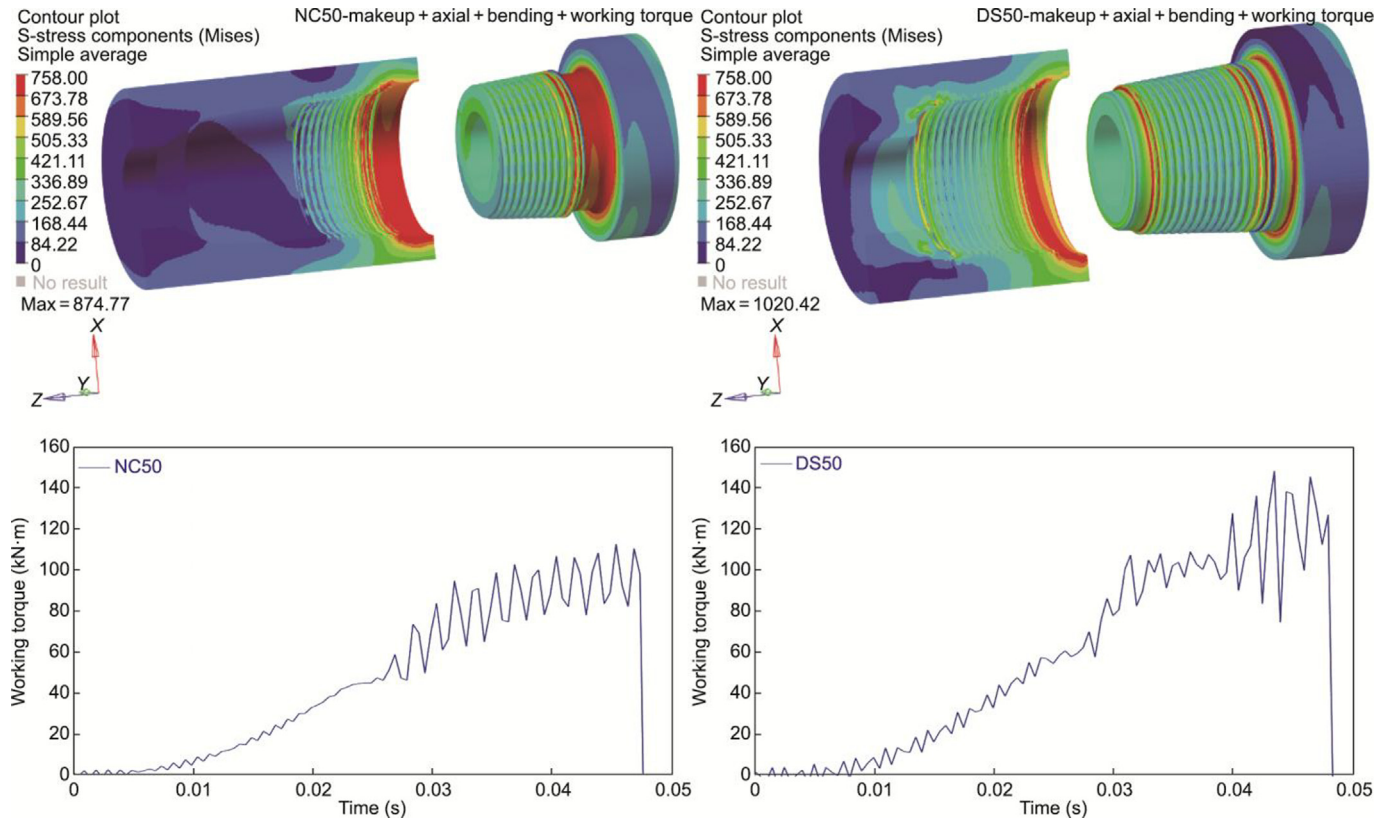


Fig. 8. A DS50 high-stress zone occurs at both ends of the threaded teeth; the yield zone is smaller than NC50.

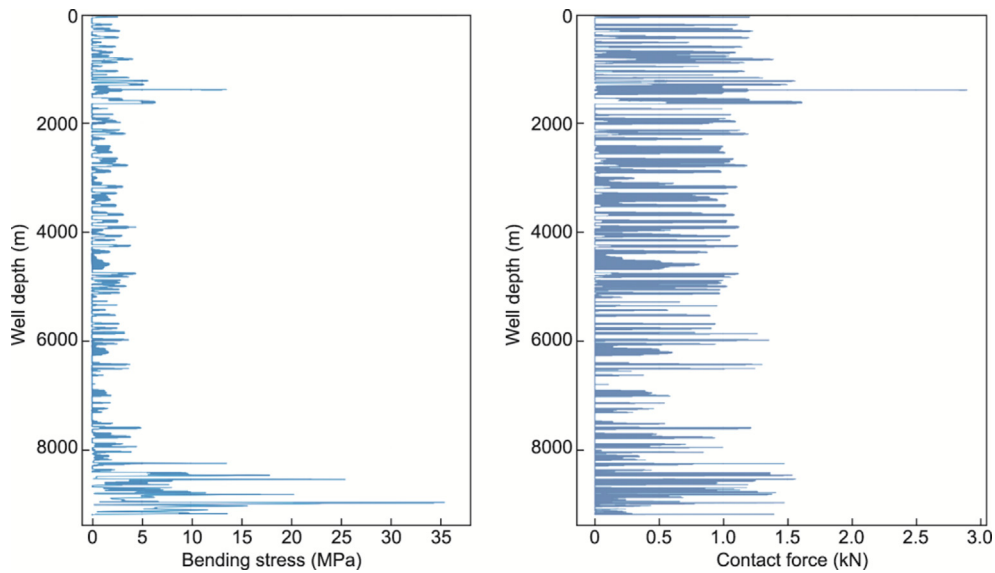


Fig. 9. Bending stress and contact force distribution of the drilling strings in the SDTK #1 Well, with peaks at high-risk locations.

the pressure channels, increasing the tool's erosion resistance by 20%. By optimizing the overall deep hole boring process and the surface treatment of the inner barrel, the smoothness, coaxiality and straightness of the inner barrel were significantly improved, reducing the core entry resistance by 50%.

Moreover, high-efficiency rock-breaking coring drill bits suitable for 10 000 m-ultra-deep well-coring operations were developed, as shown in Fig. 10; these included high-wear-resistant diamond cor-

ing bits for fractured formations and composite rock-breaking coring bits for strong plastic formations, to meet the coring needs of different geological formations. Field application showed that this series of tools and bits performed well in the coring operation of the SDTK #1 Well, making it possible to successfully obtain cores of the formation deeper than 10 000 m. A total of three tubes were completed during the coring operation, with a cumulative footage of 13.66 m and a length of 12.64 m of core obtained.



Fig. 10. Coring tool and drill bits.

2.3. Key equipment for 10 000 m-deep wells

Automated and intelligent equipment systems are playing an increasingly critical role in the field of oil and gas drilling. In fact, it can be said that the 10 000 m automated drilling rig and its supporting equipment are the concentrated manifestation of the strength of intelligent equipment [12,13]. The domestically produced 12 000 m automated drilling rig shown in Fig. 11 is known as the “Hercules of 10 000 m drilling” because of its strong working ability. With a maximum hook load of 9000 kN, this rig is capable of full-process automation. It is equipped with an advanced programmable logic control (PLC) system able to perform real-time data collection, processing, and analysis, providing intelligent monitoring and decision-making support for the drilling operation and greatly increasing the accuracy and efficiency of the operation. Its supporting equipment is equally outstanding. The 70 MPa high-pressure drilling pump has a stable high-pressure mud flow, which provides strong hydraulic support for deep drilling. Meanwhile, the 900t top drive device achieves fast and precise drilling tool connection and disassembly, which further improves the operation efficiency. The successful application of these pieces of equipment in a 10 000 m-deep well verified the stability and reliability of the intelligent equipment.

The fine-pressure controlled drilling and completion equipment represents another highlight of the intelligent equipment system. This equipment was designed to meet the precise monitoring and control requirements for “kick” (influx) during complex

deep-earth drilling and completion operations. It boasts a pressure rating of 35 MPa, with a pressure control accuracy of ± 0.1 MPa. It also offers a maximum wellhead backpressure control capacity of 14 MPa, a pressure response time of less than 1 s, and a kick/loss monitoring accuracy of ± 0.1 m³, all of which surpass advanced international standards. Through the dual-target regulation of the pressure and flow rate, the equipment achieves precise control of the annular pressure profile in the wellbore, effectively addressing the global challenges of simultaneous loss and kick and the loss-kick transition in the narrow density window. This equipment has been widely applied in complex oil and gas drilling and completion operations in regions such as Tarim, Sichuan, and Chongqing, as well as by the China National Offshore Oil Corporation (CNOOC), significantly reducing downhole complications such as kick, loss, collapse, and sticking. Its use ensures both safety and efficiency improvements throughout the drilling and completion process.

During the fifth spud of the SDTK #1 Well, a high-temperature-resistant drilling fluid system with a density of 1.06 g·cm⁻³ was used. Due to simultaneous leakage and storage in the open hole section (a leakage pressure equivalent of 1.10 at 10 289–10 383 m and a formation pressure equivalent of 1.11 at 10 315 m), the wellbore pressure profile was controlled in conjunction with the managed pressure drilling method. When drilling, the casing pressure was controlled to 0–0.5 MPa; when stopping the pump, the casing pressure was controlled to 4.2–4.5 MPa. When pulling out, the heavy slurry cap was calculated and executed according to an additional 5 MPa and an annular heavy slurry cap liquid level height of 200–500 m. After the SDTK #1 Well reached a depth of 10 777 m, the outlet continued to ignite during circulation, with a flame height of 1–2 m. During tripping after circulation, the flame heights ranged from 5 to 8 m. Through the above measures, the bottomhole pressure in each drilling process was effectively controlled, avoiding leakage and overflow.

To meet the high demands of drilling fluid treatment for the SDTK #1 Well, China’s first warehouse-style automatic dosing device for drilling fluid additives was developed. The solid dosing speed is flexible and adjustable within 0–3 m³·h⁻¹, and the liquid dosing speed covers 0.3–8 m³·h⁻¹ to meet different operational requirements, with a dosing control precision of more than 99% and a material clearance rate also surpassing 99%. During the operation of the third spud of the SDTK #1 Well, this device operated stably and reliably, withstanding the impact of severe sandstorms, rainstorms, high temperatures, and other harsh conditions. It successfully completed the enclosed one-button automatic dosing of four solid additives and two liquid additives, significantly improving the automation and health, safety, and environmental (HSE) standards of the on-site drilling fluid treatment.

2.4. Drilling fluid technology for a 10 000 m-deep well

Drilling fluid, often referred to as the “blood” of drilling, plays a critical role in 10 000 m-deep well exploration. Its functions



Fig. 11. The 12 000 m drilling rig for the SDTK #1 Well.

include carrying cuttings, balancing formation pressure, cooling the drill bit, maintaining wellbore stability, and protecting the oil and gas reservoirs. Drilling fluid technology for 10 000 m-deep wells is complex and highly challenging; it must ensure that the drilling fluid maintains a stable performance under extreme conditions such as ultra-high temperature, ultra-high pressure, and complex formations, so as to ensure the safety and efficiency of the drilling operations [14].

A polymer water-based drilling fluid system resistant to temperatures up to 240 °C was constructed with an ultra-high-temperature hyperbranched strong adsorption filter-loss reducer, an ultra-high-temperature-resistant micro-crosslinked heterocyclic polymer filter-loss reducer, and an ultra-high-temperature high-efficiency sealing agent as the core treating agents [15]. The drilling fluid system is good at resisting high temperatures and exhibits good stability under long-term aging and high mineralization contamination. Moreover, the filtration loss at high temperature and high pressure (HTHP) is only 9.8 mL, as shown in Table 2 and Fig. 12, with stable viscosity and gel strength maintained under HTHP conditions. The drilling fluid technology was upgraded by leaps and bounds, and is now at the international leading level, strongly supporting the SDTK #1 Well to advance to 10 000 m and beyond.

Novel core additives were developed, such as ultra-high-temperature-resistant emulsifiers and rheology modifiers, leading to the formulation of a high-temperature, high-density oil-based drilling fluid system. This system maintains stable rheological properties even after prolonged exposure to 220 °C for 72 h (Table 3). In the sidetrack drilling section, the drilling fluid system was switched to a 220 °C diesel-based drilling fluid, applied between the depths of 9416 and 9889 m, where the bottomhole temperature reached 191 °C. This ensured the successful completion of the fourth spud sidetrack section.

The new temperature- and pressure-responsive lost-circulation-control technology achieves fast and efficient leakage plugging to ensure downhole safety for leakage fractured/collapsed formations, weak formations, and other malignant leakage formations. The developed series of temperature- and pressure-responsive lost-circulation materials are suitable for formation temperatures of 50–200 °C. In addition, the forward/reverse bear-

ing pressure of the seam plate was more than 20 MPa, bringing the advantages of easy construction and long-lasting and stable bearing pressure, as shown in Fig. 13. When the complete loss of the oil-based drilling fluid occurred at a depth of 9889.63 m, conventional bridging methods failed to restore circulation. However, a single application of the temperature- and pressure-responsive material successfully resolved the issue, increasing the formation's pressure-bearing capacity by 13 MPa. In another instance at 10 388 m, a "beaded" vuggy formation was encountered, leading to continuous severe losses. All conventional lost-circulation-control methods proved ineffective. Yet, by employing the temperature- and pressure-responsive materials along with managed pressure injection techniques, a single sealing operation succeeded, increasing the formation's pressure-bearing capacity by 10.5 MPa. This effectively resolved the challenge of severe lost circulation in a deep carbonate formation with "beaded" fractures and vugs below 10 000 m.

2.5. Intelligent support and decision-making technology for drilling

By integrating artificial intelligence, an Engineering Operations Intelligent Support Center (EISC) was established with core functionalities such as big-data alerting, real-time operational condition recognition, and online well-control management. During the whole operation process, it carried out comprehensive and in-depth analyses of key performance indicators, while monitoring for potential accidents and complexities in real time. Precise well-control management and efficient remote technical support were provided. The front operation site and the back support team worked closely together to form an integrated working mode that dynamically tracked the progress of the operation, providing timely risk warnings, continuously optimizing the construction plan, and appropriately dealing with all kinds of complex situations. The company successfully developed auxiliary decision-making software for leakage prediction and early warning and for leakage prevention and plugging of ultra-deep and super-deep wells. Practical applications have demonstrated that the prediction accuracy of the software is as high as over 90%, and its fracture width diagnosis accuracy is over 85%; thus, the software provides reliable well leakage risk warning information

Table 2
Rheological filtration properties of the superheat and salt resistant water-based drilling fluid system.

Test condition	AV (mPa·s)	PV (mPa·s)	YP (Pa)	Gel 10"/10' (Pa·Pa ⁻¹)	API FL (mL)	HTHP FL (mL)
Pre-aging	53	47	6	4/6	0.2	—
240 °C for 16 h	47	42	5	3/4	2.2	9.8
240 °C for 48 h	52	46	6	3/5	3.2	12.4
240 °C for 72 h	49	44	5	2/4	3.2	14.8
240 °C for 96 h	47	43	4	2/4	3.6	16.2
240 °C for 120 h	42	38	4	2/4	3.6	18.6

AV: apparent viscosity; PV: plastic viscosity; YP: yield point; Gel 10"/10': gel strength at 10 s and 10 min; API: American Petroleum Institute; FL: API filtration loss.



Fig. 12. The high-temperature and high-pressure filter cake (thin, dense, and tough, with a thickness of about 2 mm) of the superheat and salt resistant water-based drilling fluid system.

Table 3
Properties of the high-temperature-resistant, high-density, oil-based drilling fluid system.

Conditions	AV (mPa·s)	PV (mPa·s)	YP (Pa)	Gel 10 ⁴ /10 ¹ (Pa·Pa ⁻¹)	ES (V)	HTHP FL (mL)
Before aging	41	31	10	12/10	1228	—
220 °C for 16 h	42	33	9	10/9	2000	5.0
220 °C for 48 h	47	36	11	12/10	2000	6.8
220 °C for 72 h	51.5	40	11.5	15/13	2000	7.6

ES: electrostatic stability.

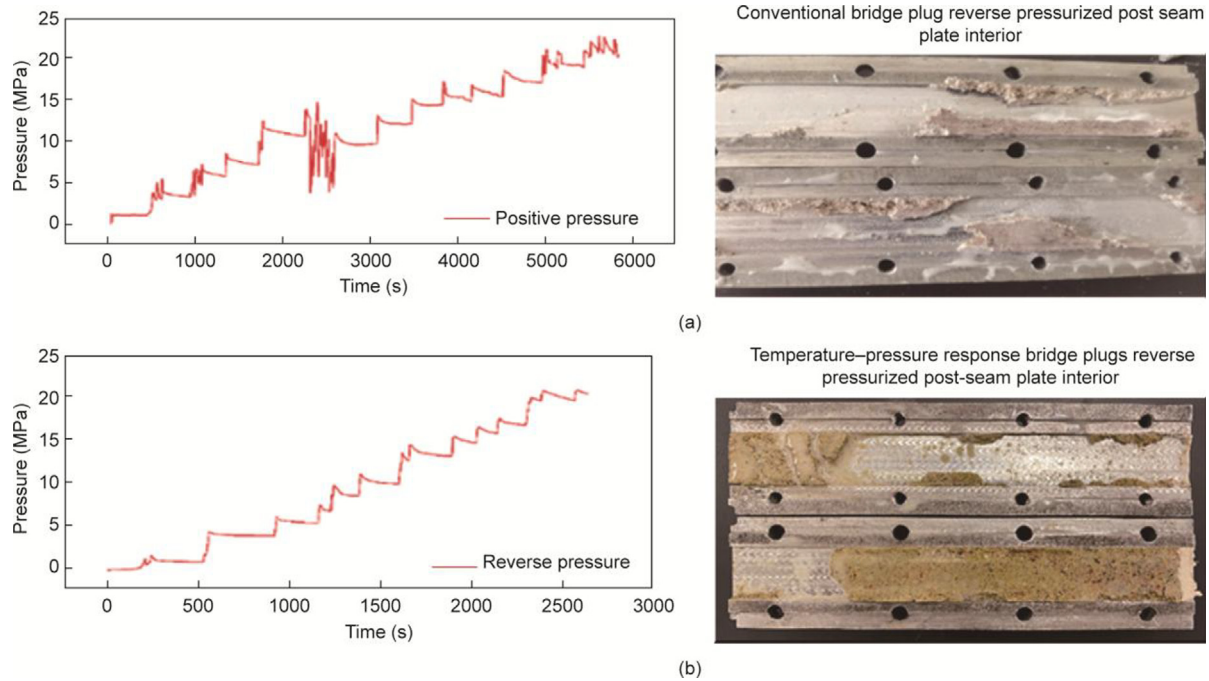


Fig. 13. Pressure-loaded plugging curve of a 1 mm seam plate of the temperature-and pressure-responsive plugging material type 3 and the state of the sealing layer of the seam plate.

and a scientific decision-making basis for the operation of 10 000 m-deep wells.

3. Conclusions and outlook

The 10 000 m drilling of the SDK #1 Well represents a monumental achievement for China in the realm of deep exploration, following the Chang'e lunar mission and the Jiaolong deep-sea expedition. Aiming at the challenges of ultra-heavy loads, ultra-long open-hole sections, highly abrasive rock formations, multiple pressure systems, and various complex lithologies, China independently developed the world's first 12 000 m automated drilling rig, high-efficiency rock-breaking diamond drill bits, 168.3 mm high-strength drill pipes, 240 °C temperature-resistant high-strength coring tools, and 220 °C temperature-resistant water-based drilling fluids, along with other achievements, driving forward the iterative upgrading of core equipment and tools. Key materials for deep-earth drilling were also iteratively upgraded. The SDK #1 Well has set a series of drilling records, including the shortest time globally to reach a depth of 10 000 m on land, the deepest global vertical well logging, the deepest vertical well drilling in Asia, the first retrieval of 10 000-m core samples in Asia, the heaviest casing run domestically in China, and the deepest cementing depth in China.

The deep earth is rich in oil and gas resources; thus, as exploration and development continue to advance, they are bound to accelerate into the field of 10 000 m deep earth. As the third lar-

gest onshore oil and gas field in China, the Tarim Oilfield accounts for 83.2% of the nation's petroleum and 63.9% of its natural gas resources exceeding depths of 6000 m, showcasing vast prospects for exploration and development. By implementing the technologies developed for the SDK #1 Well, which break through the barriers of oil and gas exploration, China will significantly accelerate the world's first achievement of ultra-deep oil and gas resource exploration and development. This will pave the way for a deep-earth oil and gas industrial cluster, laying the foundation for future international oil and gas exploration and development. In the context of underground oil and gas exploration and development, the issue of how to achieve the safe and efficient drilling and completion of wells in ultra-deep and super-deep formations has become an important research context in the field of energy at home and abroad. In order to accelerate progress into the deep earth and drive the global oil and gas industry toward greater depths, it is essential to build on the achievements of the Take-1 well drilling project by identifying new challenges and exploring innovative technologies. Through continuous scientific research and field practice, the industry can meet increasingly demanding engineering requirements and expand the frontiers of energy exploration.

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