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Advances in TK1 ultra-deep drilling technology

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Overall Design Unit: PetroChina Tarim Oilfield Company
Construction Unit: CNPC Xibu Drilling Engineering Company Limited 120001 Team
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1 Project overview

The TK1 10,000-meter Deep-earth Scientific Exploration Project represents a significant milestone in the pursuit of exploring the Earth's deep layers. This crucial initiative aims at overcoming technological challenges and achieving a high level of self-reliance and advancement in deep-earth science and technology. This project exemplifies the implementation of national strategies to enhance core functions and capabilities. The TK1 well is China's first 10,000-meter scientific exploration well located in the hinterland of the Taklamakan Desert in Xinjiang, the "Sea of Death". Drilling commenced on May 30, 2023, with a design depth of 11,100m (Fig. 1). The primary objectives of this drilling are to reveal the mechanism of ultra-deep, high-temperature, and high-pressure oil and gas formation and enrichment, explore the distribution of ultra-deep oil and gas, examine the limits of scale exploration, and develop key technologies for the drilling, completion, oil testing, and transformation of 10,000-meter deep wells. The well site features steel pylons approximately 20 stories tall, standing steadily above the quicksand. Drill bits, drill pipes, casing, and other equipment, collectively weighing over 2,000 tons, will penetrate deep underground, serving as a "telescope" for exploring the deep part of the earth.

The geological and technical challenges of the TK1

well are of global significance. Thirteen formations are developed from top to bottom of the well, and no available geological data exists for reference in the depth of 10,000 meters. Predicting the petrographic properties, depth, temperature, pressure, and fluid characteristics is an exceptionally difficult task, as the well may encounter complicated situations such as special petrographic properties, difficulties in jamming the layer, high temperatures, high pressures, and other anomalies. The temperature of the TK1 well is over 200 °C, and the pressure is over 130 MPa. There is limited experience in drilling with water-based drilling fluids under such ultra-high temperature and pressure conditions. Tools and instruments, such as tooth wheel/mixed bit, screw, MWD, and drilling vibrator may have the risk of failure due to the extreme temperature and pressure.

In response to these unprecedented challenges, the research team is committed to technological innovation and has developed key construction technologies. These include integrated geo-engineering prediction technology, new-generation "two-wide and two-high" seismic equipment technology, drilling and completion engineering technology, logging acquisition, processing and interpretation technology, as well as oil testing and reservoir modification techniques. These groundbreaking advancements have not only established a "China Depth" in the "Sea of Death," but have also attracted global attention.

The Tarim Basin is recognized as a leading hydrocarbon basin in China, with its primary focus on ultra-deep exploration and abundant oil and gas resources. The proven reserves of ultra-deep oil and gas in the basin amount to 2.4 billion tons, and the annual production has exceeded 20 million tons, solidifying its position as China's largest ultra-deep oil and gas production base. TK1, China's first 10,000-meter ultra-deep well, has been specifically designed to explore the physical and chemical characteristics of rocks and fluids at such depths. This groundbreaking project has not only revealed the mechanisms of oil and gas accumulation and enrichment under high temperature and pressure conditions, but has also successfully tackled key technological challenges in ultra-deep drilling and completion. Additionally, it has identified

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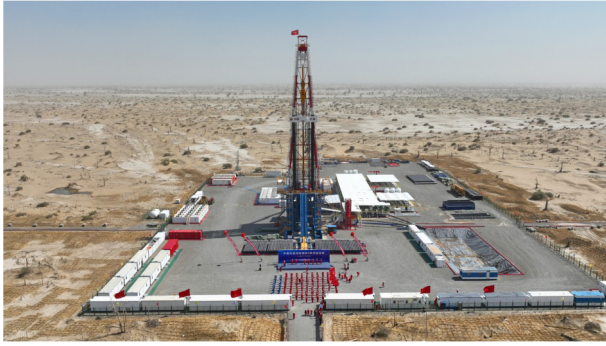


Fig. 1 TK1 Well construction site.

new strategic areas for ultra-deep oil and gas resources. The success of TK1 has significantly propelled China's ultra-deep exploration and development strategy, thereby enhancing technical support and core competitiveness.

2 Technological advances

2.1 Geological theory and technological progress

(1) Breakthroughs in ultra-deep geological theory

In addressing the major scientific problems in the field of deep-earth exploration, the TK1 well has acquired 10,000-meter-deep data to solve theoretical geological problems. These include hydrocarbon enrichment mechanisms in ultra-deep hydrocarbon source rocks, the formation and storage mechanisms of ultra-deep dolomite, hydrocarbon generation dynamics, the formation and storage mechanisms of oil and gas, and geomechanics. The data on lithology, electrical properties, radioactivity, electrical imaging, mechanical elasticity, gas anomalies, and vertical seismic profiling (VSP) were obtained through logging wells.

These measurements have revealed the depositional evolution process of the Lunan-Fuman platform margin belt in different periods, as well as the law of multi-phase three-dimensional complex reservoir formation. The 10,000-meter deep velocity field was acquired to address the controversial issue of the main hydrocarbon source rock in the Tarim Basin platform and the basic geological questions such as the lower limit of reservoir development and the lower limit of liquid hydrocarbon preservation. Furthermore, the storage state, phase, and production capacity of geological fluid under ultra-deep ultra-high-temperature and high-pressure conditions will be investigated, through the measurements of fluid, temperature, and pressure during drilling. Moreover, the basic characteristics of the ultra-deep geothermal temperature field and the changes in the geothermal temperature gradient will be revealed. The pressure of ultra-deep formation, the theoretical relationship between the mechanics of ultra-deep rock, and the mechanism of rock body rupture

and deformation will also be characterized.

Classical petroleum geological theory has addressed the theoretical questions of hydrocarbon formation from organic matter as well as the dynamic mechanism of oil and gas formation at low and medium temperatures ($< 160\text{ }^{\circ}\text{C}$). However, the 10,000-meter ultra-deep field in the deep parts of the basin is characterized by high temperature ($> 240\text{ }^{\circ}\text{C}$), high pressure ($> 100\text{ MPa}$), and active supercritical fluids. Its temperature-pressure field, fluid field, and geochemical environment differ significantly from those of the shallow parts of the basin. The mechanisms of hydrocarbon production, the formation and maintenance of large-scale effective reservoirs, and the law of formation and enrichment of hydrocarbons in the ultra-deep field of 10,000 meters remain poorly understood. Through the drilling of the TK1 well, the mechanism of hydrocarbon formation and resource distribution in the ultra-deep field will be elucidated, strengthening the theoretical foundation for evaluating the hydrocarbon exploration potential in the ultra-deep field of the Tarim Basin and in the Middle-Neoproterozoic stata.

(2) Breakthroughs in Ultra-deep geophysical techniques

In the field of seismic exploration technology, various integrated techniques will be developed to process and interpret seismic data from ultra-deep dolomites. These include ultra-deep multiple wave identification and suppression, ultra-deep resolution processing technology, ultra-deep petrophysical modeling technology, seismic reservoir prediction technology, and VSP acquisition and processing technology. In the domain of geophysical logging, novel technologies of ultra-deep logging acquisition, processing, and interpretation will be developed. These technologies include 13,000-meter ultra-long cable tensile and compression resistance technology, 15,000-meter large-capacity winch drum and power winch technology, 10,000-meter storage-type imaging logging technology, 10,000-meter ultra-deep and far-detecting acoustic measurement technology, 10,000-meter ultra-deep well dolomite reservoir parameter modeling and logging evaluation method, and cement acoustic impedance and reaction cementing quality evaluation technology under special mud conditions. In terms of geomechanics, the company has developed 10,000-meter ultra-deep geomechanical interpretation and evaluation techniques, including ultra-deep formation pore pressure evaluation techniques, geostress parameter analysis techniques, and 10,000-meter oil and gas reservoir rock body geomechanical modeling techniques.

2.2 Engineering and technological advances

(1) Independently developed China's first 12,000-meter automated drilling rig

To meet the drilling project requirements of the TK1 well, PetroChina independently developed the world's first 12,000-meter automated drilling rig. This rig is

equipped with a full set of tubular column automation system, push-support tubular column handling mode, dual driller integrated control system (Fig. 2), and one-button up and down drilling control. These features significantly enhance the safety standards while reducing the labor intensity of workers. With a maximum hook load of 900 tons for continuous lifting, it can easily lift the equivalent of two Airbus A380 airliners, effectively solving the problem of high loads caused by more than 1,200 sections of drill pipes connected to the top and bottom and other drilling tools.

(2) Integrated geological and engineering design for drilling and completion

During the program demonstration process of the TK1 well, complex situations including special lithology, unique fluids, and extreme temperature and pressure fields were accurately predicted. Necessary sealing points and risk points were scientifically determined through the analysis of seismic data, logging data, and information from neighboring wells (Fig. 3). With a clear understanding of the stratigraphy, high-performance drilling fluid technology was adopted to maintain the stability of the rock in the long bare hole section. Currently, the construction



Fig. 2 Dual driller integrated control system.

progress is smooth. For the first time in the region, the 22 1/2" borehole is drilled to 1,503 meters, the 17" borehole is designed to penetrate the Ordovician to 5,856 meters, and the 13 1/8" borehole has safely reached the Ordovician Yingshan Formation to 7,856 meters. The 9 1/2" borehole was successfully drilled to 10,006 meters, breaking the 10,000-meter mark and achieving a significant milestone.

(3) Development of safe running technology for over 600-ton heavy casing

The casing length of the TK1 well is 5,856 meters with a diameter of 365.12mm in the second section and 7,856 meters with a diameter of 273.05mm in the third section, both of which are the longest casings of their size in China. The challenge of lowering such long and heavy casings was significant. To overcome this challenge, 140 high steel-grade casings were developed to increase the strength of the casing. Physical tensile experiments on casings and hoops were conducted to determine their yield limits, ensuring the casings would not deform during the lowering process. The lowering process was supported by 750-ton slings, rings, and chucks. For the first time, lap counting meters and torque recorders were used to achieve intelligent control of casing upper buckling. The first and last connections of 580 pieces of second-section casing and 780 pieces of third-section casing were successfully sent to the bottom of the well. The floating weight of 625 tons for the 365.12 mm casing in the second section and 589 tons for the 273.05 mm casing in the third section were safely lowered into place without any casing deformation, setting the record of the deepest and heaviest casing of the same size in China (Fig. 4).

(4) Implementation of “one-trip drilling” technology, achieving over 800 meters per trip in the upper sections

The large-size drill bit used in the upper part of the TK1 well needed to penetrate deeper and harder formations, while the lower ultra-deep formations faced the

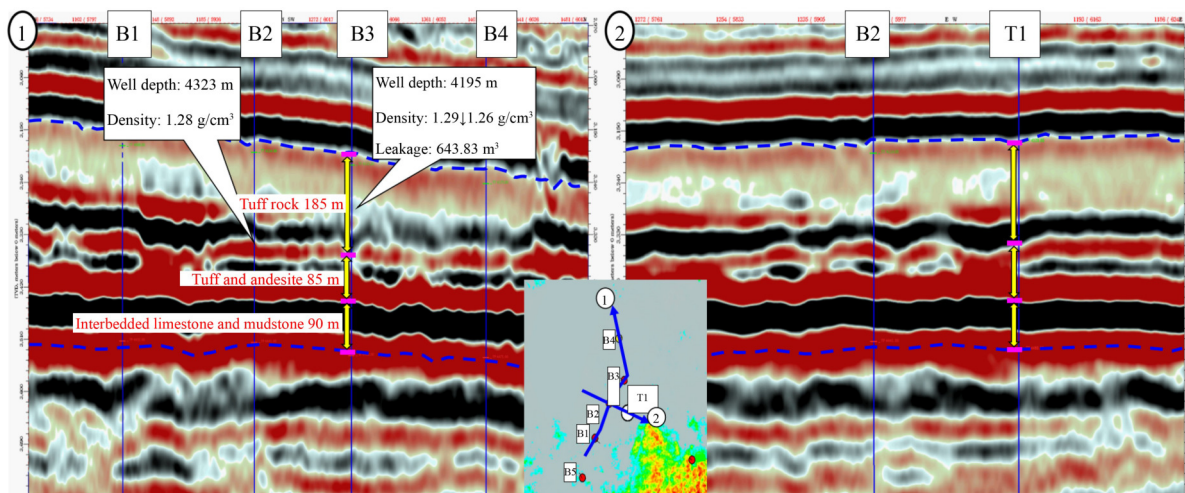


Fig. 3 Integrated geological and engineering analysis.

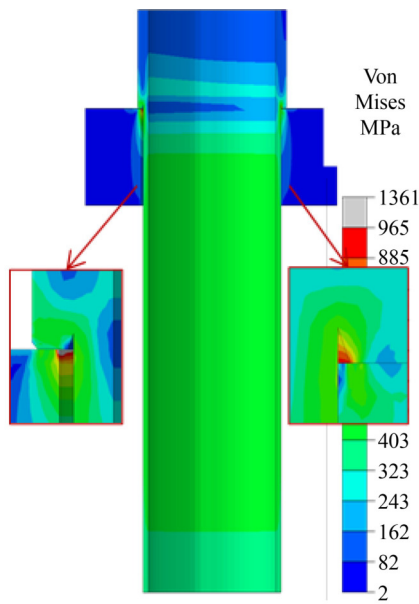


Fig. 4 Simulation of casing running process.

problem of poor drillability. During the construction process, formation drillability characteristics were quantitatively evaluated based on formation rock mechanics experiments and adjacent well logging data. Considering the indices of aggression, impact resistance, stability, and safety, a series of customized Polycrystalline Diamond Compact (PDC) bits were customized (Fig. 5). The system was optimized by pairing the footage target, drill bit, speed-up tool, and drilling parameters of each trip to achieve the maximum drilling speed. Individual drill bits were designed to suit the formation characteristics,



Fig. 5 Customized PDC bit design.

utilizing high-efficiency special-shaped tooth composite sheets to achieve high-efficiency rock breaking and improve the adaptability of the drill bit in multiple formations. The first three drill bits were domestically produced, completing a total of 9 trips and achieving a footage of 7,856 meters with an average drilling speed of 8.3 m/h. The average drilling speed in the fourth deep hard-to-drill formation reached 2.05 m/h, which is 47% higher than that of the adjacent wells in the same area.

(5) Comprehensive upgrade of drilling tools and study of drill string dynamics to ensure ultra-deep drilling

The SG-3 well in the Soviet Union, with a depth of 12,262 m, experienced 27 broken drilling tool accidents, highlighting the necessity of systematically upgrading the performance of drilling tools to ensure the safe drilling of 10,000 m extra-deep wells. For the TK1 well, significant upgrades were made with customized high-strength and high-toughness 5 7/8" V150 steel grade drill pipe, increasing the tensile strength increased from 440 t to 500 t. Additionally, the threads of the 7" collar were optimized for a double shoulder, enhancing the torsional strength by 40%. The kava tooth plate was also improved, reducing the depth of bite marks from 0.23 mm to 0.12 mm, thereby enhancing the safety of drilling tools. During the drilling process, a novel method was developed to monitor the impact torque of the bottom drilling tools. This innovation helped obtain the real distribution of the torque of the downhole drilling column, guiding the design of drilling tool threads and formulating specifications for the use and maintenance of the threads in ultra-deep wells.

After the well depth exceeded 9,000 m, the lateral vibration of the long drill string seriously exceeded the standard, with a maximum vibration value of 624.6 g. The drill bit exhibited the phenomenon of "ring cutting", and the drilling tools encountered multiple instances of low fatigue cracks within a short period of time, accompanied by abnormal downhole high-frequency vibrations. These problems posed challenges to the existing theories of drilling string dynamics. The mechanism of ultra-flexible and multi-deflection drilling columns in extra-deep wells is in research. A drilling column dynamics model with a super "length to slenderness ratio" is being built to optimize the drilling parameters and tool combinations, ensuring the dynamic stability of drilling tools downhole.

3 Conclusions

(1) The TK1 well is the first to obtain 10,000-meter ultra-deep geological data in the Tarim Basin. Through systematic experimental analysis and comprehensive geological research, major scientific questions regarding oil and gas geology in the 10,000-meter deep field will be addressed. This research will clarify the potential and scale of ultra-deep oil and gas resources, as well as the

associated resources, so as to enhance China's strategic resource security capabilities.

(2) With the well depth surpassing 10,000 meters on March 5, 2024, measures have been taken to optimize well location and trajectory to avoid complex formations as much as possible. Engineering and technical measures have been implemented to enable drilling through multiple

sets of formations simultaneously, preventing the force between the wellhead casing and the chuck, which could lead to the plastic deformation of the casing. The development and upgrade of 140-grade high-strength casing have successfully addressed the challenges associated with running and deforming ultra-deep casing, guaranteeing the successful drilling of this well.