Into Earth's depths: China's 10-kilometer well refines the ultra-deep petroleum frontier

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HISTORICAL CONTEXT: FROM KOLA TO TARIM

The Soviet Kola Superdeep Borehole (SG-3; 12,262 m) demonstrated the feasibility of drilling into the lower continental crust, yielding critical geophysical and petrophysical calibration data, yet it intersected no active petroleum system. In contrast, SDTK-1, as the first borehole to exceed 10,000 m in a sedimentary basin, penetrates source rocks, reservoirs, and an active accumulation system. Previous wells in the Tarim Basin have systematically documented hydrocarbon preservation at ultra-depths, including commercially viable light oils recovered from > 8,200 m. The SDTK-1 contribution lies in extending this verified interval to ~10 km, capturing both high-resolution geochemical data and a complete wet-to-dry gas transition sequence.

By situating SDTK-1 within prior ultra-deep drilling and exploration, this study clarifies its incremental contribution: deeper verification of hydrocarbon preservation, high-resolution geochemical constraints, and systematic documentation of gas-phase evolution under extreme pressure-temperature conditions. Zhu et al. recently reported petroleum signals from an 11,156 m well in the Junggar Basin,[1] demonstrating that oil-related evidence can persist at depths beyond 10 km. SDTK-1 is complementary rather than duplicative. The Junggar case emphasizes ultra-deep oil signals in a different basin, whereas SDTK-1 constrains a methane-dominated Cambrian gas system in the Tarim Basin through integrated core, logging, geochemical, reservoir, and source-rock evidence. Together, these records indicate that ultra-deep hydrocarbon preservation is jointly controlled by basin thermal regime, tectonic evolution, pressure conditions, and the duration of high-temperature exposure. Because these controlling conditions vary among basins, the preserved hydrocarbon products may ultimately occur either as liquid crude oil or as methane-rich dry gas accumulations.

HYDROCARBON PHASE-TRANSITION AT ULTRA-DEPTH

SDTK-1 records a clear depth-dependent evolution of hydrocarbon phases. Within the Ordovician strata at 8.5–10 km, wet gas predominates, whereas depths exceeding 10 km in the Cambrian strata yield nearly pure methane, with dryness coefficients reaching 0.998–0.999. Detailed segmental analyses between 10,773 and 10,819 m reveal methane consistently exceeding 98%, ethane below 0.15%, propane under 0.01%, and negligible non-hydrocarbon components such as CO_2 and N_2.[2] These data illustrate a systematic progression from wet gas to ultra-deep methane, providing a precise characterization of the hydrocarbon phase sequence at extreme depths.

This vertical pattern is consistent with progressive thermal cracking, because methane-rich dry gas is a typical product of high-temperature evolution of oil and wet gas at overmature stages. The SDTK-1 data therefore most directly indicate advanced thermal maturation along the ultra-deep Ordovician–Cambrian interval. Additional processes may have modified this thermal-cracking pathway rather than replaced it. Exogenous hydrogen generated or mediated by water–rock interactions and deep fluid circulation could promote hydrogenation–cracking reactions and influence methane yield under overmature conditions.[3,4] Redox-buffering mineral assemblages, such as magnetite–hematite and fayalite–magnetite–quartz, have been proposed in experimental and theoretical studies as mechanisms that can regulate hydrogen fugacity and reaction pathways.[4] However, these specific assemblages have not yet been directly documented from SDTK-1 cores in the present dataset. Thus, the current evidence supports thermal cracking as the primary explanation for the methane-dominated gas, while fluid–rock interaction, redox buffering, and basin-scale migration remain plausible complementary controls that require further petrographic and mineralogical verification.

RESERVOIR AND SOURCE ROCK CONTINUITY

Cores from the Shayilike Formation reveal a complex and highly favorable reservoir architecture. Laminated algal dolomites display centimeter-scale vugs and interconnected fracture networks, some lined with pyrobitumen indicative of multiple prior oil charge events (Figure 1). Remarkably, porosities of approximately 4% are maintained across nearly 100 m at depths exceeding 10 km, highlighting the exceptional preservation of pore space under extreme overburden pressures. This continuity likely reflects a two-stage diagenetic history: an initial phase of meteoric dissolution during Cambrian sea-level lowstands created the primary porosity framework, followed by the preservation of pore networks due to dolomite's mechanical robustness and subsequent brittle reactivation, which enhanced fracture connectivity while maintaining structural integrity. Such characteristics suggest that these reservoirs can sustain fluid storage and migration pathways even at ultra-deep conditions, supporting hydrocarbon accumulations far below conventional exploration limits.

The Cambrian Yurtus Formation complements this reservoir potential by providing a highly effective ultra-deep source rock. Organic-rich shales within this formation exhibit total organic carbon (TOC) values of several percent or higher and were deposited in ferruginous, intermittently euxinic marine settings, conducive to the preservation of hydrogen-rich kerogen. SDTK-1 demonstrates that both the Shayilike reservoirs and Yurtus source rocks remain operationally effective at extreme depths, confirming their capacity for hydrocarbon generation and accumulation well beyond the traditional limits of the oil window. These findings not only validate the continuity of source–reservoir systems in ultra-deep settings but also extend the practical lower boundary for petroleum exploration, highlighting the potential for viable hydrocarbon exploitation in the deepest stratigraphic intervals of the basin.

ULTRA-DEEP HYDROCARBON GENERATION: INTEGRATING ORGANIC–INORGANIC MECHANISMS

Traditional models based on high-temperature oil cracking remain essential for interpreting ultra-deep methane-rich gas. In SDTK-1, the extremely high methane content, very low C_2+ hydrocarbons, and high dryness coefficients are most parsimoniously explained by advanced thermal maturation and progressive cracking of earlier oil or wet gas. This thermal pathway should therefore be regarded as the first-order control on the observed dry gas composition.

At the same time, thermal cracking alone may not fully capture the chemical boundary conditions of ultra-deep systems. Experimental and theoretical studies show that water–rock reactions, deep fluid circulation, hydrogen generation, and redox buffering can influence hydrocarbon transformation, hydrogen fugacity, and methane yield under high-temperature conditions.[3,4] These mechanisms provide a useful framework for interpreting possible organic–inorganic coupling in ultra-deep basins. However, in the present SDTK-1 dataset, direct petrographic evidence for specific redox-buffering mineral pairs, including magnetite–hematite or fayalite–magnetite–quartz assemblages, remains unavailable. Consequently, the relative contribution of organic–inorganic reactions cannot yet be quantitatively separated from conventional thermal cracking. The more conservative interpretation is that SDTK-1 records a methane-dominated gas system primarily generated by thermal cracking, with fluid–rock interaction and redox-controlled hydrogen processes acting as possible secondary modifiers to be tested by future mineralogical, isotopic, and fluid-inclusion studies.

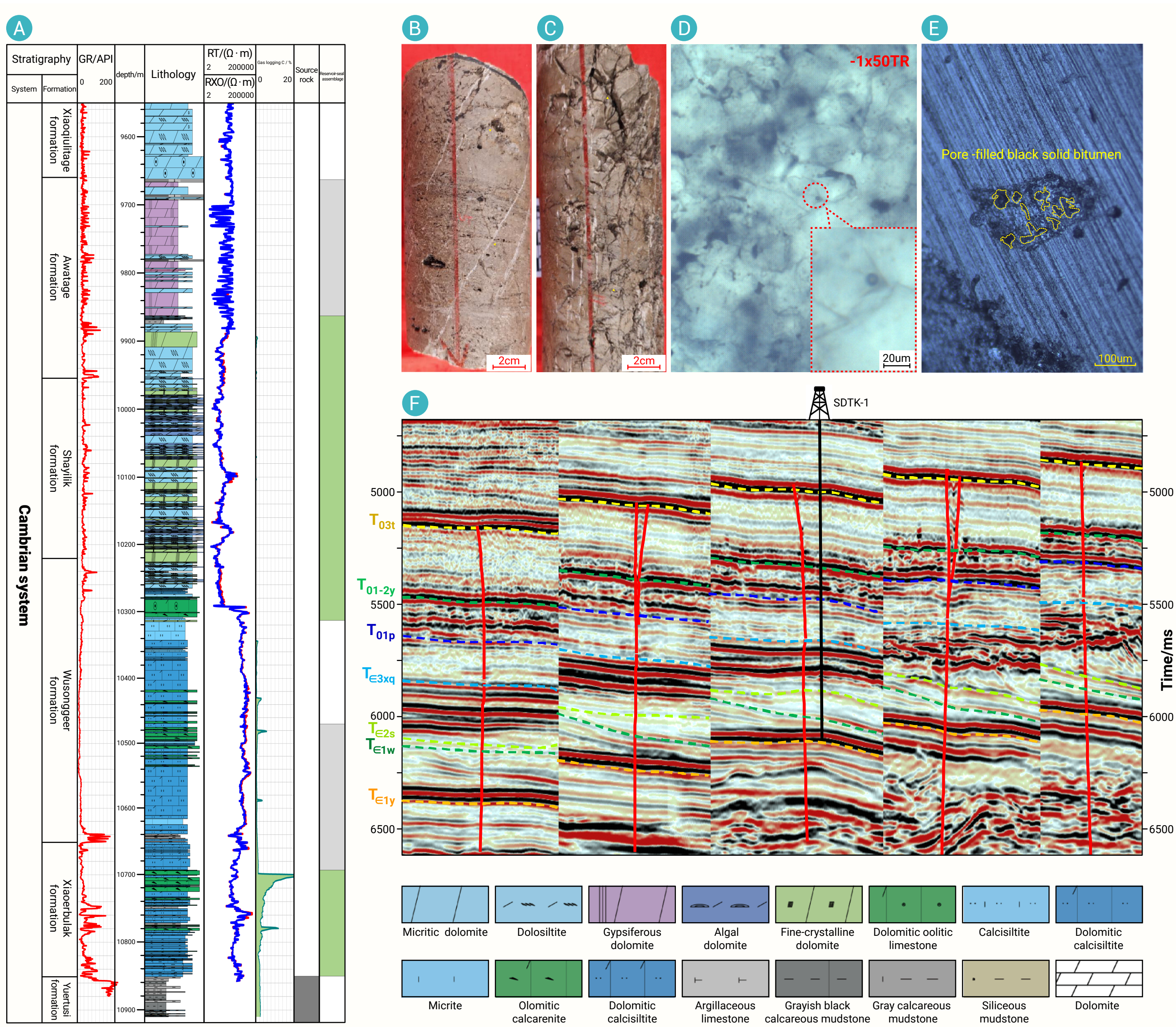

Figure 1. High-resolution seismic profile, representative ultra-deep cores, and hydrocarbon-related microscopic features from the SDTK-1 well (A) Stratigraphic and lithological column of the SDTK-1 well, showing the Cambrian succession penetrated by the well, modified after ref.[2]. (B) Core photograph from the Shayilike Formation at 10,043.02–10,043.19 m, showing dolomite with dissolution cavities up to 1.5 cm and bedding-parallel dissolution pores, modified after ref.[5]. (C) Core photograph from the Shayilike Formation at 10,045.56–10,045.75 m, showing fractured dolomite in which interconnected network fractures form breccia-like pore spaces, modified after ref.[5]. (D) Microscopic image of oil inclusions identified in >10-km dolomite at 10,041.5 m. (E) Microscopic image showing pore-filling black solid bitumen in ultra-deep dolomite, interpreted as residual products of hydrocarbon alteration. (F) High-resolution seismic profile crossing the SDTK-1 well, showing the deep Cambrian stratigraphic architecture and major seismic reflection horizons, modified after ref.[2].

STRESS, PERMEABILITY, AND GEOMECHANICS

Depth-calibrated measurements at SDTK-1 indicate minimum horizontal stresses (σ_{hmin}) of approximately 180–190 MPa and vertical stresses (σ_v) reaching up to ~260 MPa, demonstrating that brittle fracturing and episodic permeability persist even at depths approaching 11 km, contrary to expectations of fully ductile behavior. Fracture networks, whose orientations and connectivity vary relative to the maximum horizontal stress (SH_{max}), alternately facilitate or impede fluid flow, providing critical insights for modeling rock strength and geomechanical behavior. These observations refine constitutive models, define safe breakout and leak-off limits, and place robust constraints on the feasibility of CO_2 and H_2 storage under high-pressure, high-temperature (HP–HT) ultra-deep conditions.

LOGGING AND PETROPHYSICAL MILESTONES

At SDTK-1, 27 logging runs were conducted across five stages at depths exceeding 10.8 km; the reported logging temperature was ~207°C, distinct from the ~220°C bottom-hole condition cited for the final depth. These high-resolution datasets provide a reference atlas for lithostratigraphy, fracture networks, and petrophysical trends under extreme pressure–temperature conditions, enabling calibration of seismic velocities and geothermal gradients and supporting thermo-hydro-mechanical modeling of ultra-deep basins. They may also offer boundary-condition constraints for future assessments of subsurface storage and enhanced geothermal system (EGS) applications, although storage feasibility requires dedicated injection, sealing, and geochemical-reactivity studies.

IMPLICATIONS FOR ENERGY RESOURCES

SDTK-1 provides compelling evidence for ultra-deep petroleum systems extending beyond 10 km. Despite extreme depths, source rocks remain thermally mature while retaining hydrocarbon generative potential, reservoirs preserve significant porosity, and natural seals continue to function effectively. These observations support models of 10,000 m-scale petroleum systems and challenge conventional notions of the depth limits for hydrocarbon preservation. Similar ultra-deep plays identified in the Junggar Basin and other cratonic depressions indicate multiple prospective domains for systematic exploration, expanding the frontier of conventional and unconventional hydrocarbon targets.

The same conditions that preserve methane in ultra-deep reservoirs may also promote hydrogen generation through thermogenic pathways. Fracture-controlled permeability coupled with intact seals provides potential trapping mechanisms for H_2 accumulations. Stress measurements, permeability profiles, and fluid–rock interaction data from SDTK-1 enhance predictive models for hydrogen prospectivity, informing strategies for identifying viable ultra-deep H_2 reservoirs and ensuring long-term storage integrity.

Beyond hydrocarbons, SDTK-1 also provides boundary-condition information relevant to deep subsurface energy systems. The observed geothermal gradients and episodic fracture-controlled permeability may inform preliminary assessment of Enhanced Geothermal Systems (EGS) in ultra-deep sedimentary basins. Its stress, fracture, and petrophysical data may also provide indirect constraints for evaluating the mechanical and sealing conditions relevant to subsurface storage. However, because SDTK-1 was designed and interpreted primarily as an ultra-deep petroleum exploration well, the present dataset does not directly evaluate CO_2 injection, geochemical trapping, caprock reactivity, or long-term storage security. Therefore, implications for CO_2 storage should be regarded as exploratory and hypothesis-generating rather than as a direct risk assessment. Collectively, these findings highlight the broader energy relevance of ultra-deep wells while keeping the primary interpretation anchored in petroleum systems, deep methane preservation, and geothermal boundary conditions.

ULTRA-DEEP LABORATORY

SDTK-1 serves not only as an engineering milestone but also as a unique in situ ultra-deep laboratory. It enables direct integration of core, logging, and petrophysical datasets, allowing precise quantification of stress, fracture networks, and permeability behavior. The well provides a platform for advanced geochemical, geophysical, and isotopic investigations, offering high-fidelity constraints that improve modeling of ultra-deep resource systems and enhance understanding of subsurface processes under extreme pressure–temperature conditions.

Looking forward, SDTK-1 establishes a foundation for comprehensive research agendas targeting ultra-deep plays. Planned studies include detailed mapping of deep petroleum and gas accumulations, integration of noble gas and isotopic tracers to trace fluid sources and migration, and correlation of microstructural observations with geomechanical data. These efforts aim to optimize drilling, reservoir characterization, and hydrocarbon recovery strategies, positioning SDTK-1 as a benchmark for future ultra-deep exploration and energy resource development.

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AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.