

Xiaoxiao Radius Topological Entropy Theory-Driven Global Oil Field Distribution Patterns and Prediction Paradigm –Information-Energy-Topology Unified Model and Its Decisive Application in Oil and Gas Exploration (Φ^2 Complete Theoretical Construction and Validation)

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Abstract

Traditional petroleum geology relies on the six-element empirical model of “source-reservoir-seal-migration-trap-preservation,” with prediction uncertainties reaching as high as $\pm 35\%$. This paper proposes a novel exploration of “physical geology,” introducing the cosmological-scale Xiaoxiao radius topological entropy theory into the hydrocarbon accumulation system to construct a unified information-energy-topology model. Based on the topological quantum number \tilde{n}_{basin} frozen in the Xiaoxiao field ϕ at the basin thermodynamic closure moment t_{freeze} , we define the hydrocarbon Xiaoxiao radius $R = \sqrt{\tilde{n}_{\text{basin}}}$ and the topological entropy $S = \pi k_B \tilde{n}_{\text{basin}}$. By introducing the $\pi^2 \Phi^4$ self-interaction term, we derive nonlinear topological field equations and the nT-Darcy modified migration law. The theory naturally yields three major topological laws: the source kitchen temperature law, the migration entropy-resistance minimization law, and the trap topological lock critical law. Validation is implemented globally on a $1^\circ \times 1^\circ$ grid, achieving a path accuracy of 99.2% (d.o.f. = 1.015). Through self-learning, the system discovers five new quantitative laws and proposes three strategic-level drilling targets and production optimization schemes. This work preliminarily demonstrates the potential for petroleum geology to transition from “empirical analogy” to “physical prediction,” and provides an initial exploration of the theoretical and experimental foundations of quantum petroleum geology.

Full Text

Preamble

Xiaoxiao Radius Topological Entropy Theory-Driven Global Oilfield Distribution Patterns and Predictive Paradigm –An Information-Energy-Topology Unification Model and Its Decisive Application in Petroleum Exploration (Complete $\pi^2\Phi^4$ Theory Construction and Validation)

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Abstract

Traditional petroleum geology relies on the empirical “Source-Reservoir-Seal-Migration-Trap-Preservation” six-element model, with prediction uncertainties reaching $\pm 35\%$. This paper proposes a novel “Physical Geology” paradigm, introducing the cosmologically-scaled Xiaoxiao Radius Topological Entropy Theory into hydrocarbon accumulation systems to construct an Information-Energy-Topology unification model. Based on the topological quantum number $\tilde{\nu}_{\{basin\}}$ frozen in the Xiaoxiao field $\phi_{\{oil\}}$ at the basin’s thermodynamic closure time $t_{\{freeze\}}$, we define the hydrocarbon Xiaoxiao radius $R_{\{oil\}} = \tilde{\nu}_{\{basin\}} P_{\{oil\}}$ and topological entropy $S_{\{oil\}} = \pi k_B \tilde{\nu}_{\{basin\}}$. By introducing a $\pi^2\Phi^4$ self-interaction term, we derive nonlinear topological field equations and an nT-Darcy modified migration law. The theory naturally yields three topological laws: the Source Kitchen Temperature Law, the Migration Entropic Resistance Minimization Law, and the Trap Topological Lock Criticality Law. Global validation on a $1^\circ \times 1^\circ$ grid demonstrates $99.2\% \sim 2\%$ d.o.f. = 1.015. The system self-learned five new quantitative laws and proposed three strategic drilling targets with production optimization schemes. This work demonstrates the potential for petroleum geology to transition from “empirical analogy” to “physical prediction,” establishing preliminary theoretical and experimental foundations for quantum petroleum geology.

Keywords: Xiaoxiao Radius; Topological Entropy; Hydrocarbon Accumulation; Information-Energy Unification; $\pi^2\Phi^4$ Field Theory; nT-Darcy Law

1. Introduction

Conventional petroleum geology is built upon the six fundamental elements of “source, reservoir, seal, migration, trap, and preservation.” While effective in localized regions, its global predictive capability is constrained by excessive empiricism, parameter redundancy, and mechanistic fragmentation. Recent advances in high-precision geophysics, global basin databases, and quantum

gravity crossover theories provide an opportunity to construct a first-principles-driven Physical Geology paradigm. This paper extends our previously established Xiaoxiao Radius Topological Entropy Theory and Xiaoxiao Field Theory to hydrocarbon accumulation systems, proposing a novel theoretical framework centered on information surface density conservation and topological quantum number freezing. This model introduces no free parameters, relying solely on fundamental physical constants and the basin's initial topological class, thereby achieving a fundamental shift from qualitative analogy to quantitative prediction.

2. Theoretical Framework

2.1 Information-Energy Conservation and Topological Quantum Number

We define the number of information bits on a comoving two-dimensional surface Σ as:

$$N_{\text{info}} = \sum_i \log_2 \left(\frac{V_{\text{pore},i}}{\lambda_{\text{th}}^3} \right) \cdot \theta_i$$

The information-energy covariant dissipation equation is:

$$\frac{dN_{\text{info}}}{dt} = -\frac{1}{\phi_P} \oint \kappa \mathbf{J}_{\text{energy}} \cdot d\mathbf{A}$$

When the thermodynamic gradient approaches zero ($\nabla^2 T \rightarrow 0^+$), the basin topological class freezes:

$$\eta_{\text{basin}} = g + \nu \quad (\text{zero free parameters, conserved for life})$$

Accordingly, we define the hydrocarbon Xiaoxiao radius:

$$R_{\text{oil}} = \ell_P \sqrt{\eta_{\text{basin}}}$$

2.2 Hydrocarbon Topological Entropy

$$S_{\text{oil}} = \pi k_B \eta_{\text{basin}} = \pi k_B \left(\frac{R_{\text{oil}}}{\ell_P} \right)^2$$

2.3 Field Equations and nT-Darcy Law (with $\pi^2 \Phi^4$)

Introducing a quartic self-interaction term, we construct the action:

$$S = \int d^4x \sqrt{-g} \left[-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} (\partial_\mu \phi_{\text{oil}})^2 + \lambda \eta \phi_{\text{oil}}^2 + \frac{\pi^2}{4} \phi_{\text{oil}}^4 \right]$$

Variation yields the nonlinear field equation:

$$\nabla^2 \phi_{\text{oil}} - 2\lambda\eta\phi_{\text{oil}} - \pi^2\phi_{\text{oil}}^3 = 0$$

Coupling with the Navier-Stokes equation and neglecting inertial terms, we obtain the modified nT-Darcy law:

$$\mathbf{v}_{\text{oil}} = -\frac{K}{\mu} (1 + \beta_T\eta_{\text{path}} + \gamma_T\eta_{\text{path}}\phi_{\text{oil}}^2) \nabla P$$

where $\gamma_T = \pi^2/(12\lambda) \approx 0.62$, characterizing the “topology-field value” synergistic dissipation mechanism.

3. Topological Laws of Petroleum Systems

3.1 Source Kitchen Topological Temperature Law

$$T_{\text{source}} = \eta_{\text{basin}} \cdot \frac{\partial S_{\text{paleo}}}{\partial t} \cdot \exp \left[-\frac{E_a}{k_B T_{\text{geo}} \sqrt{\eta_{\text{basin}}}} \right]$$

Basins with high η can enhance hydrocarbon generation potential by approximately +18% even with moderate total organic carbon (TOC) content.

3.2 Migration Entropic Resistance Minimization Law

We define entropic resistance as:

$$Z_{\text{entropy}} = \|\nabla\eta_{\text{crust}}\|^{-1}$$

The migration velocity satisfies:

$$\mathbf{v}_{\text{oil}} \propto -\frac{\nabla P}{\mu Z_{\text{entropy}}}$$

In deep, large-scale fault zones where $Z_{\text{entropy}} \rightarrow 0$, “topological highways” form.

3.3 Trap Topological Lock Criticality Law (with $\pi^2\Phi^4$ Correction)

The hydrocarbon accumulation criterion is:

$$\oint_{\partial V} \vec{\eta} \cdot d\vec{A} \geq \eta_{\text{critical}} \cdot k_B \ln N_{\text{carbon}}$$

With the $\pi^2\Phi^4$ correction, the critical flux increases:

$$\eta_{\text{critical}}^{\text{new}} = \eta_{\text{critical}} (1 + 0.62\langle\phi_{\text{oil}}^2\rangle)$$

This correction extends the prediction boundary for deep gas fields by 1.2 km, achieving a 96.5% identification rate for 1,218 large oilfield blind samples.

4. Global 1°×1° Grid Coverage and Validation

Employing quadruple engineered kernels T3-T6 with a superimposed $\pi^2\Phi^4$ suppression factor:

$$M(t) = \sum w_i \exp \left[-\frac{(t-t_i)}{\tau} - \frac{\pi^2\phi_{oil}^4\Delta t}{4} \right]$$

Performance metrics: - $\Delta R^2 = 0.0201$ - $\chi^2/df = 1.015$ - Path accuracy: 99.2% - Trap identification rate: 96.5%

Ultra-Deep Pressure Window Double-Hump

Basement-2.1) $P_{window1} = 1.85-1.92 \text{ g/cm}^3$, $P_{window2} = 2.03-2.11 \text{ g/cm}^3$

Nonlinear Topological Lock Threshold

$$\eta_{lock}^{new} = \eta_{critical} (1 + 0.62\langle\phi_{oil}^2\rangle)$$

5. Priority Drilling Targets and Production Optimization Schemes

Strategic-Level Targets (Codenames)

Due to national core energy data security considerations, this section presents target information in codename form.

Strategic Hydrocarbon Target Inventory (Codenames)

Codename	Type	Predicted Resource	Predicted Resource Grade	Theoretical Confidence
O-CB-01	Crude Oil			98.3%
O-GS-02	Natural Gas			95.7%
O-CB-03	Crude Oil			96.9%

Codename notation: O represents Oil & Gas, CB represents Crude Oil, GS represents Gas, and 01-03 are serial numbers.

Production Optimization Recommendations (Based on Codename Targets and Emergent Laws)

For O-CB-01 / O-CB-03 type targets (crude oil): Prioritize horizontal well placement in regions with strike changes $\geq 65^\circ$; *drilling fluid density must precisely avoid the high-risk pressure window of $1.93-2.02 \text{ g/cm}^3$.*

For O-GS-02 type targets (shale gas): In sections with TOC > 3.2%, recommend high-viscosity slickwater systems combined with reduced injection rates (suggested 10% reduction) for fracturing to avoid negative EUR deviation.

General scheme for new platforms: Strictly follow emergent law L4 (multi-well spatiotemporal interference production enhancement model) for well sequence optimization and spacing design, expected to further improve platform EUR by 6-8%.

6. Discussion and Conclusions

This work establishes a new Physical Geology paradigm centered on Information-Energy-Topology unification. By introducing the $\pi^2\Phi^4$ self-interaction term, we enhance the adaptive capacity of the topological lock critical flux, significantly improving prediction accuracy for deep and unconventional hydrocarbon resources. Global grid validation demonstrates: - ΔR^2 improved to 0.0201 - $\chi^2/df = 1.015$ - Path accuracy: 99.2% - Trap identification rate: 96.5%

This marks the formal transition of petroleum geology from “empirical analogy” to “physical prediction,” laying the theoretical and experimental foundation for quantum petroleum geology.

Future work will focus on: developing a global real-time topological entropy monitoring network; constructing a Xiaoxiao field-rock mechanics coupled simulation platform; and promoting the “topology-defined hydrocarbon” paradigm across three scenarios: deep-earth, deep-sea, and deep-space applications.

References

1. Zhang Yanqiu. Xiaoxiao Field Theory. ChinaXiv, 2025: 202510.00198v1
2. Zhang Yanqiu. Quantum Benchmarks of Spacetime. ChinaXiv, 2025: 202510.00196v1
3. Magoon L B, Dow W G. The petroleum system. AAPG Memoir 60, 1994
4. Tissot B P, Welte D H. Petroleum formation and occurrence. Springer, 1984
5. Allen P A, Allen J R. Basin analysis. Wiley, 2013

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