Fractal Characterization of Multi-Scale Pore Structures in Marine-Continental Transitional Shale of the Upper Permian Longtan Formation, South Yellow Sea Basin

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Introduction

The global energy landscape has been reshaped by shale oil and gas . Unlike conventional resources, shale oil and gas are stored in nanoscale pores and require advanced reservoir stimulation technologies for economic extraction.

Continuous micro-nanoscale pore size distribution, diverse pore types, and poor connectivity—intergranular pores, intragranular pores, organic pores, and microfractures coexist, resulting in strong heterogeneity.

Fractal theory provides the answer: pore structures exhibit statistical self-similarity, and the fractal dimension D ($2 < D < 3$) increases with structural complexity. This approach has been widely applied in reservoir evaluation and permeability modeling.

Methods

For pores in three size ranges, different experiments and fractal models were used to calculate fractal dimensions of 11 shale samples:

- **Micropores** (r<2nm): CO_2 adsorption + V-S model
- **Mesopores** (2nm<r<50nm): N_2 adsorption + FHH model
- **Macropores** (r>50nm): Mercury intrusion porosimetry (MIP) + capillary bundle model

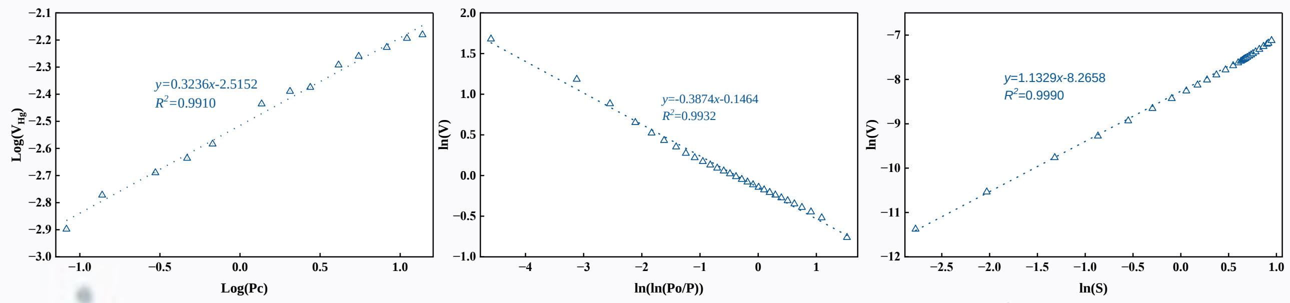

Fig.1 CO_2 adsorption, N_2 physisorption and MIP curves for G10

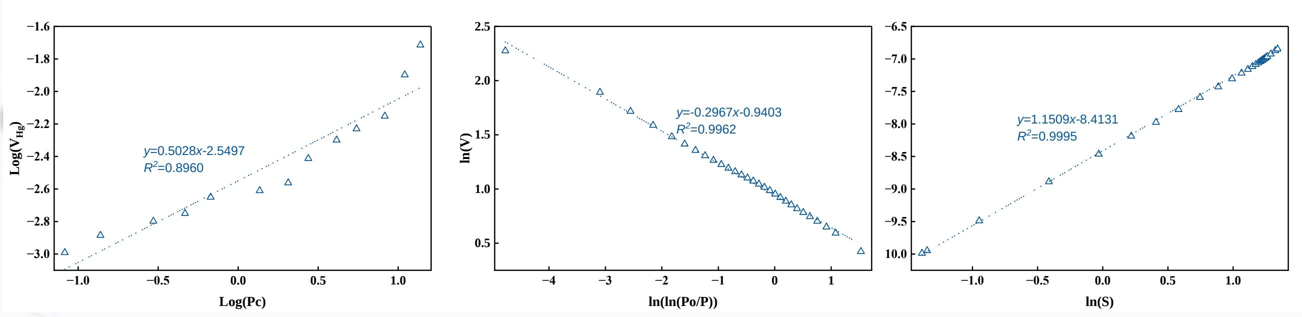

Fig.2 CO_2 adsorption, N_2 physisorption and MIP curves for G23

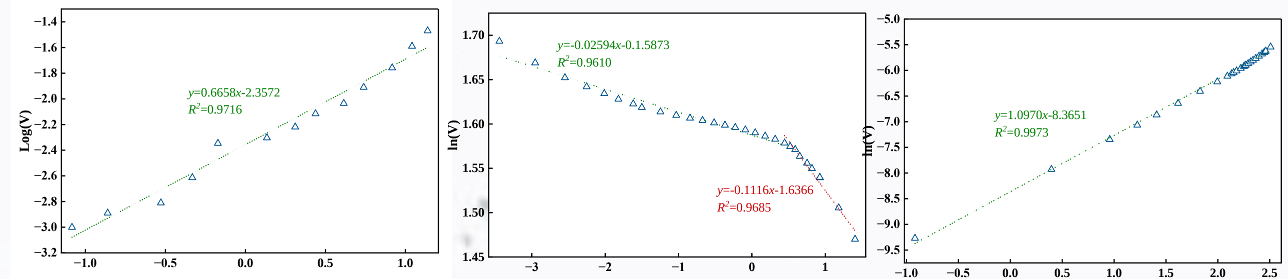

Fig.3 CO_2 adsorption, N_2 physisorption and MIP curves for G14

Method	Equation	Fractal dimension
MIC	$S_{Hg} = aPc^{-(2-D)} = \frac{V_{Hg}}{V_P}$	$D=K+2$
N_2 adsorption	$lnV = Kln[ln(P_0/P)] + C$	$D=K+3$
CO_2 adsorption	$ln(v) = \frac{3}{D} ln\, S + C$	$D=3/K$

Note1: K is the slope of the corresponding double-logarithmic fitting curve.

Note2: This study involves a total of 11 samples, among which three representative samples are selected for data presentation.

Results and discussion

In the N_2 adsorption isotherms, eight samples (e.g., G-10, G-23) exhibit continuous single-segment linearity in the mesopore range (Figs.1&2), whereas three samples (e.g., G-14) show distinct dual-segment fractal features (Fig.3), suggesting scale-dependent complexity of mesopore structures in some samples.

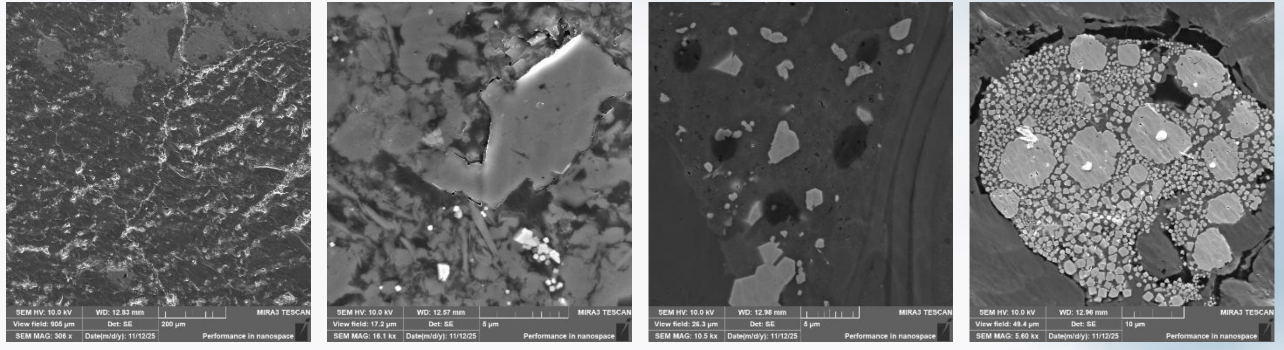

Fig.4 High-resolution SEM images of the Longtan Formation shale samples

SEM observation (Fig.4) confirms that the studied shale develops intergranular pores, intragranular pores, organic pores, and micro-fractures, indicating diverse pore types and strong heterogeneity.

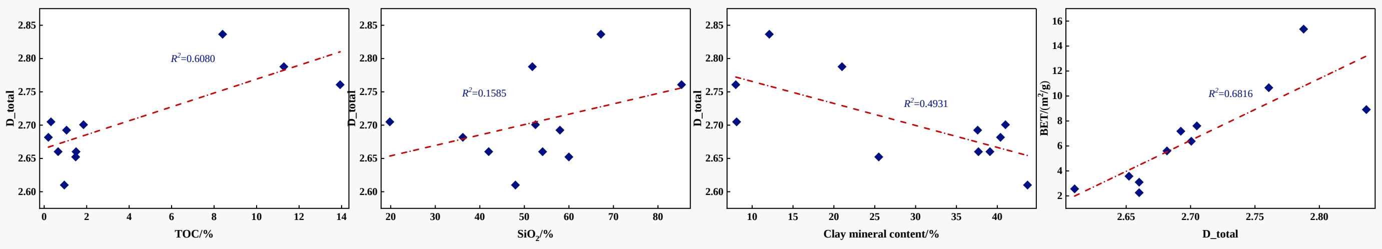

Fig.5 Cross-plots showing correlations of *D_total* with TOC content, BET specific surface area, quartz content, and clay mineral content.

After calculating fractal dimensions for all pore types, the **volume-weighted** total fractal dimension *D_total* was obtained. Correlation analysis (Fig. 5) reveals that:

- *D_total* is positively correlated with **TOC content** and **BET specific surface area**;
- *D_total* is also positively correlated with **quartz content**, but weakly correlated with **clay mineral content**.

Table 1. Fractal dimensions of all samples from CO_2 adsorption, N_2 adsorption, MIP and the calculated total fractal dimension *D_total*

	D_CO_2	D_N_2		D_MIP	D_total
G-10	2.648	2.61263		2.3236	2.6099
G-11	2.710	2.67067		2.4025	2.6601
G-15	2.740	2.65998		2.5500	2.660
G-16	2.582	2.70678		2.4359	2.6924
G-20	2.608	2.68358		2.7214	2.6816
G-21	2.607	2.64789		2.6628	2.6522
G-23	2.817	2.70329		2.5028	2.7049
G-26	2.608	2.70933		2.9163	2.7006
G-12	2.768	2.9548	2.8332	2.5448	2.8365
G-13	2.677	2.9328	2.8324	2.4826	2.7607
G-14	2.735	2.9740	2.8783	2.6658	2.7877

conclusion

- This approach overcomes the limitations of single-fractal models, enabling unified quantification of pore complexity from **micropores to macropores**.
- In the Upper Permian **Longtan** Formation shale of the South Yellow Sea Basin, **mesopores** dominate the pore network.
- High-TOC samples exhibit **dual-segment fractal features** in N_2 adsorption data, revealing the controlling role of organic matter on pore complexity.
- *D_total* shows strong positive correlations with TOC, quartz content, and BET specific surface area, indicating that **organic richness and brittle minerals synergistically** govern pore-system complexity.

reference

[1]Liu, K., & Ostadhassan, M. (2017). Multi-scale fractal analysis of pores in shale rocks. Journal of Applied Geophysics, 140, 1–10.

[2]Fan, Y., Liu, K., Yu, L., Liu, J., & Regenauer-Lieb, K. (2022). Assessment of multi-scale pore structures and pore connectivity domains of marine shales by fractal dimensions and correlation lengths. Fuel, 330, 125463.

[3]Wang, D., Hu, H., Wang, T., Tang, T., Li, W., Zhu, G., & Chen, X. (2024). Difference between of coal and shale pore structural characters based on gas adsorption experiment and multifractal analysis. Fuel, 371, 132044.

[4]Wang, F., & Zai, Y. (2021). Fractal and multifractal characteristics of shale nanopores. Results in Physics, 25, 104277.