

Fine-grained rock fabric facies classification and its control on shale oil accumulation: a case study from the Paleogene Kong 2 Member, Bohai Bay Basin

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Abstract Lacustrine shale oil resources in China are abundant, with remarkable exploration breakthroughs being achieved. Compared to marine shale oil in North America, efficient exploration of lacustrine shale oil is more difficult; thus, selecting favorable layer and optimization zone for horizontal wells is more important. In this study, based on systematic coring of approximately 500 m fine-grained deposits of the Kong 2 Member, combining laboratory tests and log data, source rock geochemistry and reservoir physical properties, the favorable rock fabric facies for oil accumulation was analyzed and classified. First, the dominant lithologic facies, organic facies, and bed combination facies were determined based on mineral composition from logging, total organic content (TOC), and sedimentary structure. Secondly, 10 fabric facies were classified by combining these three facies, with 4 fabric facies were found to have high TOC content, high total hydrocarbon, and strong fluorescence features, indicating good shale oil enrichment. Thirdly, the distribution of the upon good fabric facies was identified to be located at the top of the Kong 2 Member, with evidences of seismic resistivity inversion, thermal maturity, structure depth, and strata thickness. And the favorable facies were found to be stably distributed lateral at the area of about 100 km². High oil flow has been detected at this layer within this area by several wells, including horizontal wells. The exploratory study of fabric facies classification and evaluation provides a new research idea for lacustrine shale oil exploration and effectively promotes breakthroughs in lacustrine shale oil exploration in Bohai Bay Basin.

Keywords fabric facies, fine grained deposits, lithologic facies, organic facies, Bohai Bay Basin

1 Introduction

Lacustrine shale in China is much more heterogeneous than North American marine shale and features tight reservoirs and deep burial; therefore, efficient lacustrine shale oil exploration is more difficult (Jarvie et al., 2007; Zhao et al., 2019). Optimizing the desert layer and favorable zones for horizontal wells is important for shale oil production (Macquaker and Adams, 2003; Slatt, 2007; Macquaker et al., 2010; Li et al., 2019a). Fine-grained shale facies has been studied systematically, which provides an important basis for selecting shale oil and gas favorable areas and wells deployment (Yang et al., 2012; Chen et al., 2016; Cui et al., 2019). And there are extensive studies focus on the characteristics and classification of lithofacies, as well as log response characteristics analysis in semi-deep to deep lacustrine shale strata (Jin et al., 2001; Geng, 2013; Li et al., 2019b). For example, Loucks and Ruppel (2007) classified the Barnett shale into three major lithofacies, i.e., layered siliceous shale, layered argillaceous limestone, and bioclastic packstone. Idived the deep lacustrine shale in the Dongying sag of the Bohai Bay Basin into 8 lithofacies, namely, black shale, calcium shale, calcareous shale, homogeneous blocky mudstone, graded lamina mudstone, heterogeneous massive argillite, deformed argillite, and mixed argillite. Zhang et al. (2014) classified the fine-grained sedimentary rocks in the semi-deep lacustrine facies of the Dongying sag into 9 facies and 14 subfacies, including laminated limestone, massive dolomite, leafy clay, siltstone, and lamellar mixed fine-grained rock. Wang et al. (2016) maintained that organic-

rich layered lithofacies have various types of reservoir space, high total organic carbon (TOC) content, good oiliness, and are the key target for lacustrine shale oil exploration. Lithofacies classification primarily depends on mineral composition, sedimentary structure, organic geochemical feature, biological combination, and rock color on the drilling cores analysis. However, few studies focus on the shale oil reservoirs physical properties, upon which the distribution of sweet spots can be classified (Gu et al., 2010; Fu et al., 2013; Wang et al., 2013).

Cangdong Sag is a sub-sag in the southern part of the Huanghua depression in the Bohai Bay Basin. The Kong 2 Member is deposited in the lake center, rich in mudstone and shale (REF). The Kong 2 Member is traditionally regarded as source rock — rather than a reservoir with no movable hydrocarbons — and, thus, a forbidden zone of oil and gas exploration. Through systematic analysis of cores from Well G108-8, the shale strata have been found to include various rock types and frequent interbeds (REF). Additionally, the source rock is of high quality with a considerable amount of retained hydrocarbons, and the reservoirs are well developed with dense fractures and pores, which universally contain oil at multiple intervals, thus laying the foundation for the development of large-scale oil reservoirs. To date, industrial oil flows have been successfully obtained at different intervals of several wells, such as KN9, Z1605, and G1608, with a maximum daily oil production of 47.1 t (Pu et al., 2015; Pu et al., 2016; Zhao et al., 2017; Zhao et al., 2018). However, shale oil is mostly distributed in a scattered manner, with low abundance and strong subtlety, making exploration more difficult. The evaluation and selection of sweet spots is the key to the efficient exploration and development of shale oil. Accordingly, this study attempted to provide theoretical understanding and technical support for shale oil exploration of the Kong 2 Member. For this purpose, fabric facies and their identification criteria were established, and favorable sweet spots of fabric facies were predicted on the basis of systematic coring and experimental analysis.

2 Geology setting

The Cangdong Sag (exploration area of 1760 km²) is a Cenozoic inter-lacustrine fault basin developed under the background of regional extension held between the Cangxian uplift, Xuhei uplift, and Kongdian uplift (Li et al., 2011; Ren et al., 2010). The Kongdian Formation consists of a set of “red-black-red” early Paleogene lithologic deposits; the Kong 2 Member, deposited during a lake flooding period, can be further divided into four oil groups: Ek2¹, Ek2², Ek2³, and Ek2⁴. According to the lithological combination and cycle changes, low stand, lacustrine-expansion, and high stand system tracts can be identified. The lower part of Ek2⁴ is comprised of coarse-grained sandstone sediments from a braided river delta in

the low stand period, and the upper part of Ek2¹ is comprised of silty shale with a sandstone interbed from the late high stand period. Ek2⁴ and Ek2¹ are separated by a 400-m thick layer of fine-grained shaly shale with semi-deep lacustrine carbonate interbeds that cover 430 km² (Fig. 1). Whole-rock X-ray diffraction analysis shows that the mineral composition of the fine-grained sedimentary rocks of the Kong 2 Member is complex (ref). The principal minerals are quartz, feldspar, calcite, dolomite, clay, and analcime. Thin section observation and correction by X-ray diffraction revealed that approximately 72% of the fine-grained sediments are primarily composed of shale and (calcarenic) dolomitic shale; (calcarenic) argillaceous dolomite and less-developed pure dolomite account for approximately 28%. Thus, dolomite accounts for nearly 1/3 of the core composition. Vertically, the development of dolomite varies at different intervals due to the frequent lacustrine level changes. Of the four oil groups, dolomites are mostly concentrated in layer Ek2²; dolomite and shale are concentrated in Ek2¹ and Ek2³ (Pu et al., 2015).

3 Materials and methods

500-m cores were taken systematically from Well G108-8; laboratory tests, log data from more than 100 wells, and lithology identification using log data were performed to determine the dominant lithologic facies, organic facies, and bed combination facies based on mineral composition from logging, TOC, and sedimentary structure. TOC and XRD experiments were performed by the State Key Laboratory of Oil and Gas Resources and Exploration.

Pyrolysis analysis was tested by a Vinci Technologies Rock-Eval 6 instrument following similar procedure by Lin et al. (2020) and Hood et al. (2020). The data acquired are S_1 (oven kept isothermally at 300°C) and S_2 (oven temperature increased to 550°C at intervals of 25°C/min) (Erik and Ay, 2020). The TOC values were measured as a percentage of carbon by weight (wt %) with the organic carbon analysis instrument is CS-600 organic carbon analyzer, following Chinese National Standards GB/T 19145–2003 (Li et al., 2019c; Akinyemi et al., 2020).

The analysis of the basic geochemistry and petrology characteristics of the sample uses the following instruments: the analysis standard is UB/T 19145-2003. For vitrinite reflectance (R_o) analysis, the detection instrument DM LPWITH MSP200 was used, following Chinese Industry Standard SY/t5124-1995, the test condition temperature was 23°C and the humidity was 65%.

XRD analysis and physical properties analysis, with the rest used for physical properties analysis. Identification, XRD and physical property analysis of thin sections were done by State Key Laboratory of China University of Petroleum (East China). The XRD analysis was performed on X'pert Pro MPD with CuK α ray, under laboratory

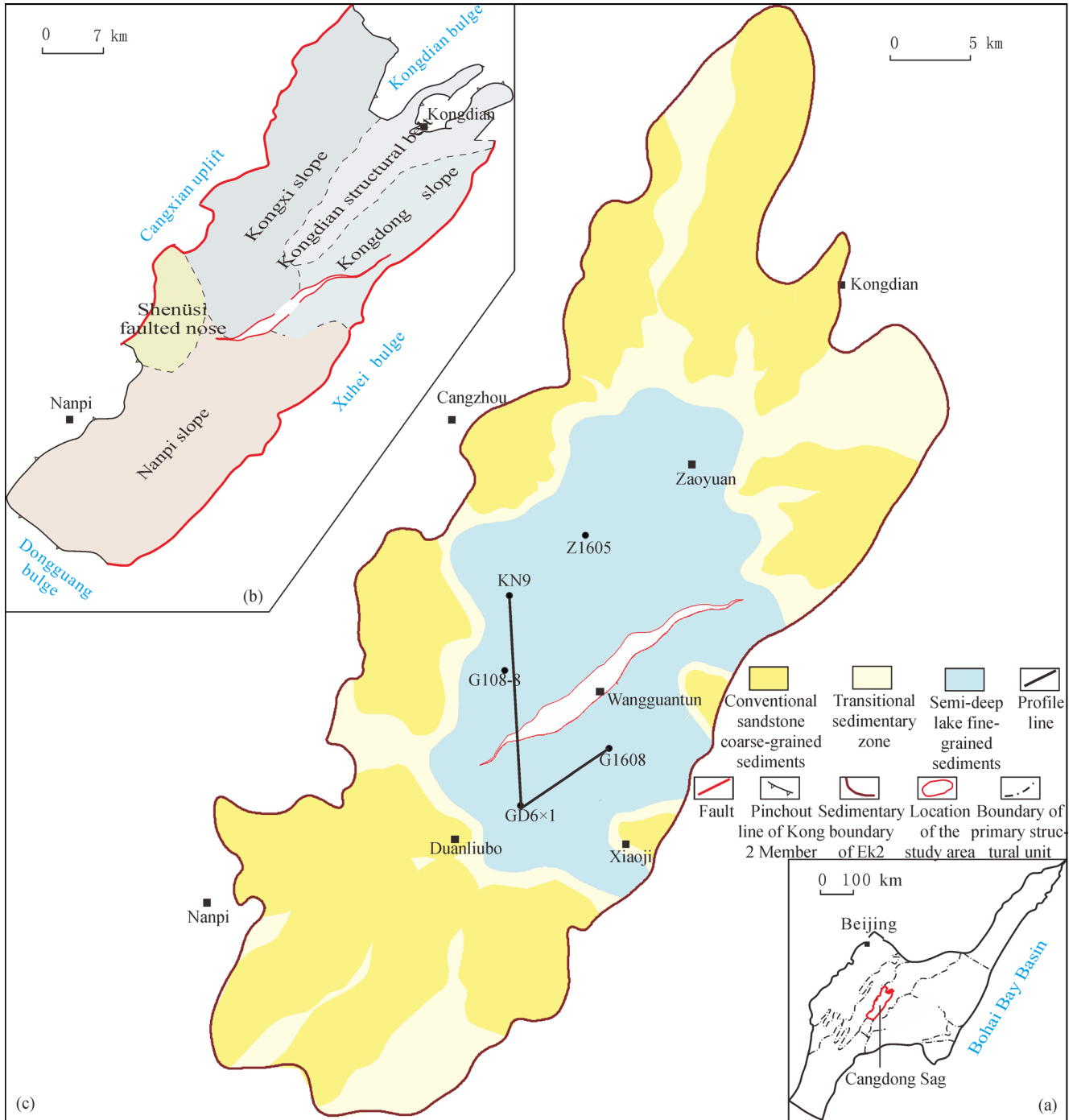
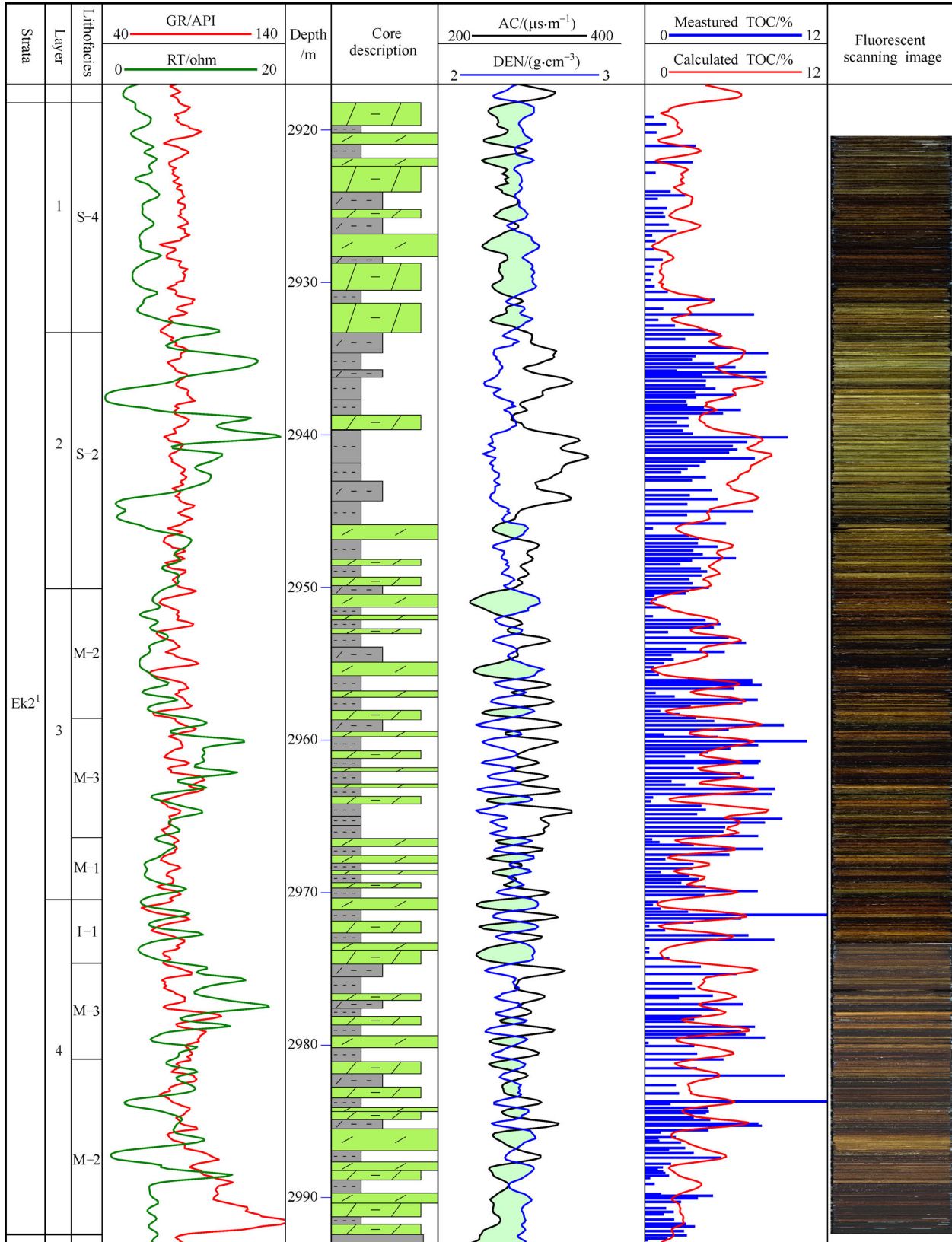


Fig. 1 Sedimentary system of Ek2¹ in the Cangdong Sag.

conditions of 40 kV, 40 mA, 20 (mineral diffraction angle) measuring range of 5°–60°, and 20 sampling step width of 0.016°. The porosity and permeability were measured by QKY-II gas porosimeter, STY-II gas permeability tester, with precision of 0.5% and $0.01 \times 10^3 \mu\text{m}^2$, under measuring pressures of 0.7 MPa and 1.0 MPa respectively.

Four basic criteria should be considered in the fabric facies classification of fine-grained sediments in lacustrine

faulted basins: 1) the degree of reflection of the mineral composition and dominant rock types of the fine-grained sedimentary rocks, 2) the ease of evaluating hydrocarbon-bearing properties, 3) the ability to reflect certain sedimentary environments, and 4) easy operability. A fabric facies naming and classification scheme was established with primary dominant lithology data and supplementary TOC and layer combination data (Figs. 2



Note: Fluorescent scanning image shows oil content in rocks
 Yellow, oily asphalt, the higher the brightness, the higher the content
 Black, carbonaceous asphalt

Shale Dolomitic shale Argillaceous dolomite Dolomite

Fig. 2 Major fabric facies types of Ek2¹ in Well G108-8.

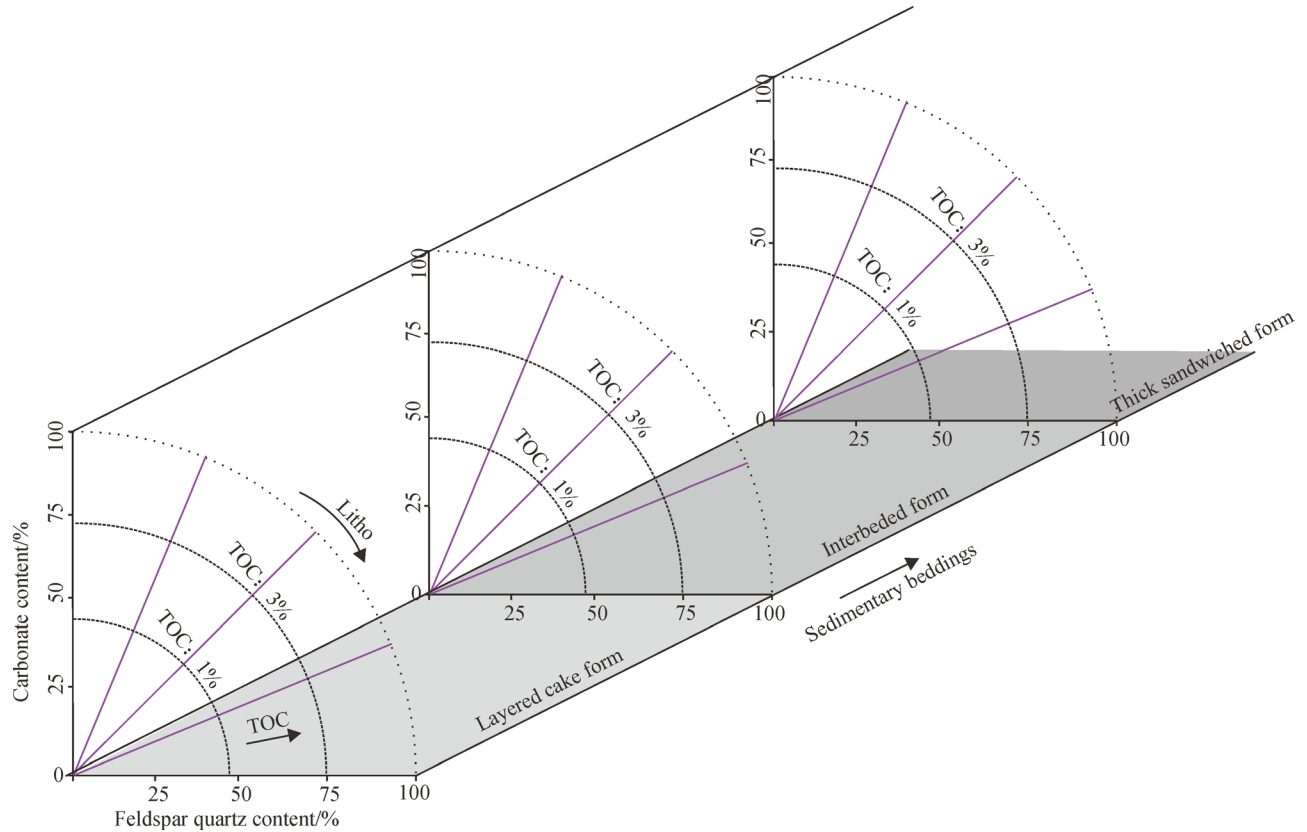


Fig. 3 Fabric facies division in Kong 2 Member of the Cangdong Sag.

and 3, Table 1).

The dominant lithologic facies, organic facies, and formation structure facies are the three major aspects of fabric facies division. Of these, the formation structure facies can be easily identified by the shape of the well log. Therefore, lithology identification and TOC calculation are the keys to the identification of dominant and organic facies.

Correlation analysis between mineral composition from X-ray diffraction and TOC from a log of Well G108-8 (Zhao et al., 2017) revealed that the acoustic time difference and bulk density were closely correlated with carbonate content and TOC. The amplitude difference between the acoustic time difference log and the compensation density log curve is defined as ΔL (Eq. (1), Fig. 2). As AC and DEN increase in the same direction, the AC value ranges from 200 to 400 $\mu\text{s}/\text{m}$, and the DEN value ranges from 2 to 3 g/cm^3 . If AC is located to the left of DEN, the value of ΔL is positive, and the intersection of the two curves is filled with green color. If AC is located to the right of DEN, ΔL is negative, and the intersection of the two curves is blank (Fig. 2). The study shows that green-filled sections often correspond to dolomite or argillaceous dolomite, whereas uncolored sections often denote dolomitic shale or shale. ΔL is correlated with the carbonate mineral Cca, felsic mineral Cc, and carbon TOC (Eqs. (2) and (3)).

$$\Delta L = \frac{\rho - 2}{3 - 2} - \frac{\Delta t - 200}{400 - 200}, \quad (1)$$

$$C_{ca} = 12.0\Delta L^2 + 47.57\Delta L + 37.28R^2 = 0.95, \quad (2)$$

$$C_c = -22.0\Delta L + 31.6R^2 = 0.67, \quad (3)$$

$$TOC = -8.52\Delta L + 2.79R^2 = 0.91. \quad (4)$$

4 Results

4.1 Source rock characteristics

The fine-grained sedimentary rocks of the Kong 2 Member generally reach the standards of good to excellent source rock. The organic carbon content ranges from 0.13%–12.92%, with an average value of 3.6%; hydrocarbon generation potential ($S_1 + S_2$) ranges from 0.1 to 73.0 mg/g, with an average of 18.9 mg/g; and chloroform asphalt “A” ranges from 0%–3.65%, with an average of 0.47%. The number of excellent samples ($TOC > 2\%$, $S_1 + S_2 > 5$ mg/g) account for 57.1%, and the number of non-source rock samples ($TOC < 0.5\%$, $S_1 + S_2 > 0.5$ mg/g) account for 8%. Vertically, source rocks of different sequences differ in quality. The source rock in the Ek2¹

Table 1 Fabric facies classification and naming scheme of shale in the Cangdong sag

No.	Lithologic facies		Organic facies		Layer combination		Fabric facies type			
	Rock type	Ratio of dolomite to gross/%	Organic facies	TOC/%	Sedimentary structure	Single layer thickness from log interpretation	Dominant fabric facies	Fabric facies	Sub-facies	Sub-type
1	Dolomite	> 75	High TOC	> 3	Thick sandwiched form	Thick layer (> 2 m)	Dolomite facies	For instance: High TOC dolomite	Layered cake	High TOC
2	Argillaceous dolomite	60–75					Argillaceous dolomite	dolomite facies		
3	Mixed rock of shale and dolomite	40–60	Moderate TOC	1–3	Interbed form	Medium layer (1–2 m)	Mixed rock of mudstone and dolomite	Up to 15 sub facies associations can be formed		
4	Dolomitic shale	25–40					Dolomitic mudstone			
5	shale	< 25	Low TOC	< 1	Layered cake form	Thin layer (< 1 m)	Mud-shale			

Note: Dolomite to gross ratio: thickness of argillaceous dolomite and pure dolomite to the thickness of the total formation (%)

high stand system tract and the Ek²³ lacustrine expansion system tract are of the highest quality — consisting of 70% excellent samples with high organic abundance. The source rock of Ek²² is the second highest, with excellent rock samples accounting for 52.9%. The source rock of the Ek²⁴ low stand system is relatively poor in quality, but good source rock samples still account for a certain proportion. The kerogen of the Kong 2 Member source rock is primarily type I and IIA, which account for 69% and 13%, respectively; the vitrinite reflectance *R*_o of the source rock is generally between 0.6 and 1.3, and the mature source rock areas are primarily located on the Nanpi slope and the lower part of the Kongxi and Kongdong slopes.

4.2 Physical property characteristics

The fine-grained sedimentary rocks of the Kong 2 Member are generally dense and compact, but the occurrence of intergranular pores, intercrystalline pores, and various micro-fractures render this tight shale formation effective reservoir rocks (Table 2). The mud shale contains bedding fractures, intergranular pores, and organic matter nanopores and has an average effective porosity of 3.3% and a permeability of 0.17 mD. Dolomitic shale contains intergranular pores, bedding fractures, and micro-cracks and has a porosity of 3.1% and permeability of 0.12 mD. Argillaceous dolomite contains inter-crystalline pores, bedding fractures, and micro-cracks and has an average effective porosity of 5.2% and permeability of 0.28 mD. Dolomite (the most important shale oil reservoir rock) contains intercrystalline pores and micro-cracks and has an average effective porosity of 7.5% (maximum 10.0%) and permeability of 0.56 mD.

4.3 Fabric facies classification

Considering the operability of favorable sweet spot prediction and the areal distribution of these fabric facies, the rocks were classified following the principle that shale, dolomitic mudstone, argillaceous dolomite, and dolomite can be identified and classified through thin section observation and logging. X-ray diffraction can distinguish up to 8 mineral components but is greatly affected by the heterogeneity of the lithology, and the accuracy of conventional logging data are not sufficient to quantitatively identify these minerals. Naked eye recognition and thin section observation have low accuracies but are less affected by lithological heterogeneity and match logging accuracy well.

As the stratum unit often has a certain thickness (15–30 m), the dominant fabric facies of a stratum unit was selected as the base fabric facies based on lithology identification. Five fabric facies were defined according to the proportion of the base fabric facies in each stratum unit, namely dolomite, argillaceous dolomite, dolomitic shale,

shale, and mixed shale and dolomite (Table 1). The source rock is the material basis of shale oil. The TOC of organic matter in the source rock determines the abundance of hydrocarbon generation materials and is easily and accurately determined by logging calculation. Therefore, combining source rock characteristics — especially TOC — into fabric facies classification benefits the analysis of hydrocarbon-bearing property. Accordingly, a certain fabric facies can be subdivided into subfacies with high, moderate, and low TOC. Under the logging scale, the formation structures with thin, medium, and thick layered cake interbeds reflect different sedimentary environments, according to which — combined with the dominant fabric facies and TOC — the subfacies can be further subdivided into subtypes, such as thin layered cake argillaceous dolomite with medium TOC.

5 Discussion


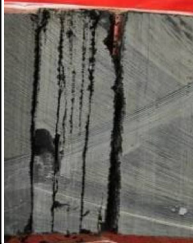
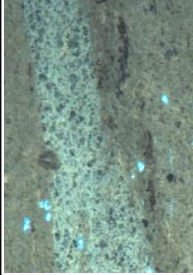
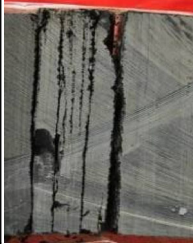

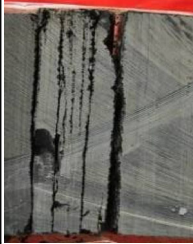
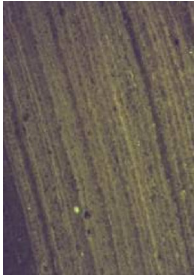
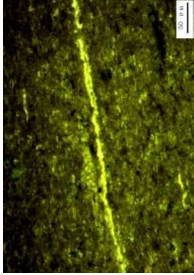
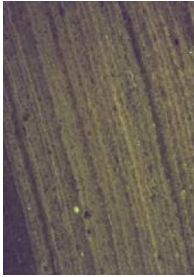

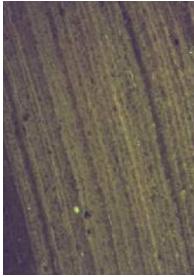







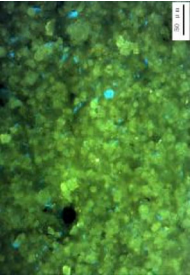

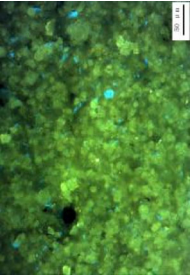

5.1 Features of primary fabric facies

Based on the analysis of 500-m cores taken systematically from Well G108-8 and lithology identification using log data at a study unit scale of 10 m, 10 types of primary fabric facies, such as thin layered cake argillaceous dolomite with medium-high TOC, thick interbedded dolomite with low organic matter, and thick mud-shale sandwich with high TOC, were identified (Fig. 4). The layers of shale fabric facies were affected by the sedimentary cycle, ancient climates, and water body conditions, and show differences (Table 3).

Taking the Ek²¹ high system tract of Well G108-8 as an example, 6 kinds of lithofacies were identified: S-2, S-4, M-1, M-2, M-3, and I-1 (Fig. 2). S-2 is thick shale with thin argillaceous dolomite interbeds and an average TOC of 4.5%; S-4 is thick (argillaceous) dolomite with thin mudstone interbeds with an average thickness of 0.7 m and average TOC of 1.0%; M-1 consists of laminated shale and dolomite with average layer thickness of 0.48 m and average TOC of 3.6% — of which shale accounts for up to 7.8% of TOC; M-2 also consists of frequent interbeds of shale and dolomite but has a higher average single-layer thickness of 0.75 m, dolomite to gross ratio of 65%, and average TOC of 3.1%. M-3 has an average thickness per layer of 0.65 m, a dolomite to gross ratio of 26%, and an average TOC of 5.5%. I-1 is comprised of interbedded medium-thick shale and dolomite, with an average thickness per layer of 0.9 m and average TOC of 2.6%.

The fine-grained deposits in the center of the lake basin are more strongly affected by seasonal lake level variations and less affected by source material supply, especially during high stand and late lake expansion periods; thus, the Ek²¹-1 and Ek²¹-2 lithofacies types show little lateral change (Fig. 5). Ek²¹-3 shows some lateral variation but is dominated by M-3 combination. Ek²¹-4 has a dolomite

Table 2 Fracture and pore system in fine grained sediments of Kong 2 Member in the Cangdong Sag

Lithology	Major fracture pore system			Porosity /%	Permeability /mD
	Microscopic photo	Macroscopic photo	Microscopic photo		
Shale	Bedding fracture			3.3	0.17
	Intergranular pore				
	Organic matter nano-pore				
Dolomitic Shale	Intergranular pore			3.1	0.12
	Bedding fracture				
	Micro fracture				
Argillaceous dolomite	Intercrystalline pore			5.2	0.28
	Bedding fracture				
	Micro fracture				
Dolomite	Intercrystalline pore			7.5	0.56
	Micro fracture				

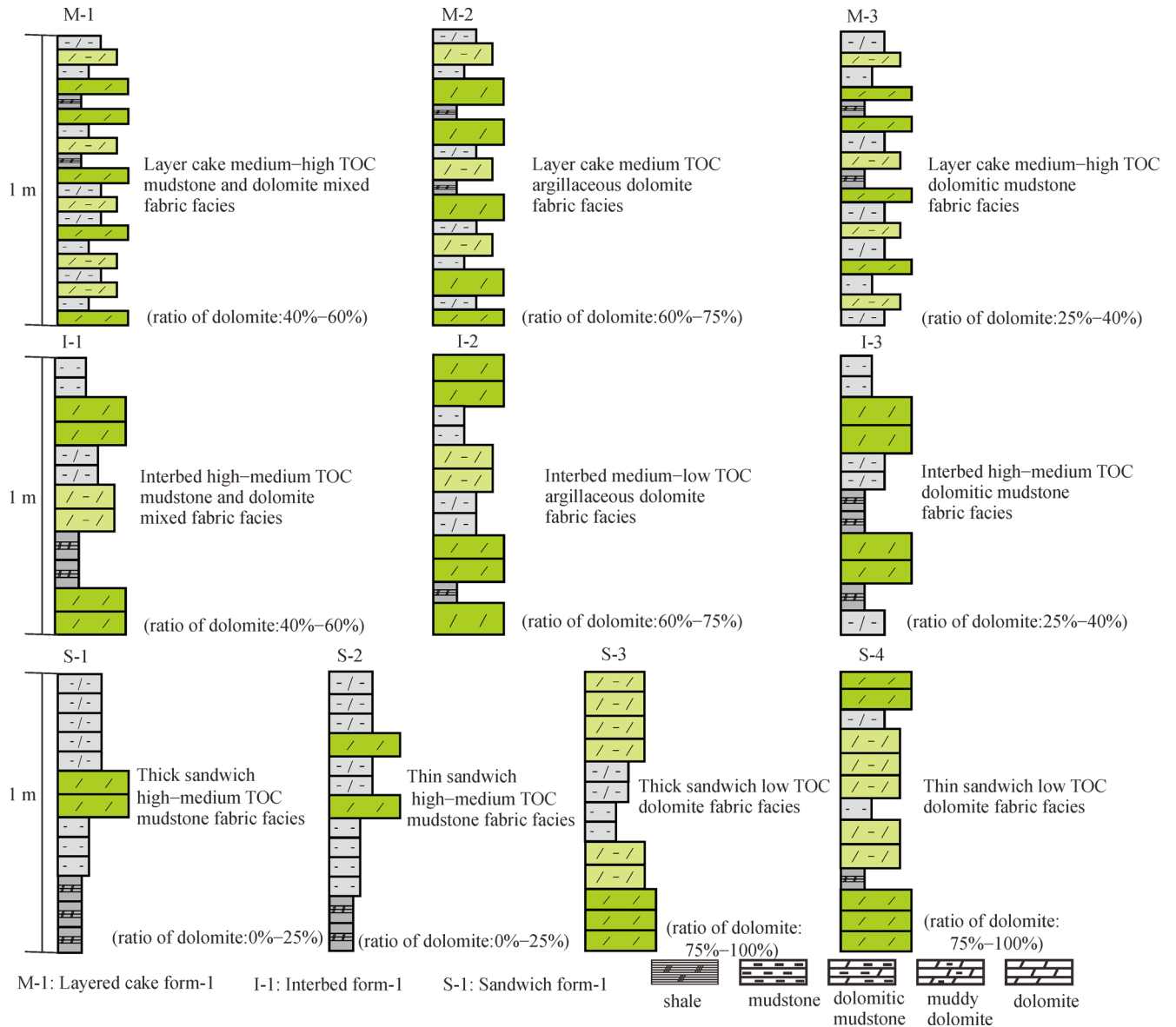


Fig. 4 Main types of fabric facies in Kong 2 Member of the Cangdong sag.

Table 3 Features of shale fabric facies of Kong 2 Member in the Cangdong sag

Types	M-1	M-2	M-3	I-1	I-2	I-3	S-1	S-2	S-3	S-4
Dolomite ratio /%	40–60	60–75	25–40	40–60	60–75	25–40	0–25	0–25	75–100	75–100
Average porosity/%	4.5	5.1	3.5	5.2	5.8	4.9	3.1	3.4	6.7	8.7
Fluorescence	Moderate	Low-moderate	Moderate	Moderate	Low-moderate	Moderate	Strong	Strong	Low	Low
$S_1/(mg \cdot g^{-1})$	3.6	2.1	4.1	2.5	1.1	3.3	5.7	6.3	0.7	0.5
Average TOC/%	4.3	2.8	3.6	2.7	1.9	3.1	4.8	5.0	1.0	0.8
Fabricfeature	Layered cake form			Interbed form			Thick sandwich form			
Log curve structure	Micro-serrate			Serrate			Box-like			

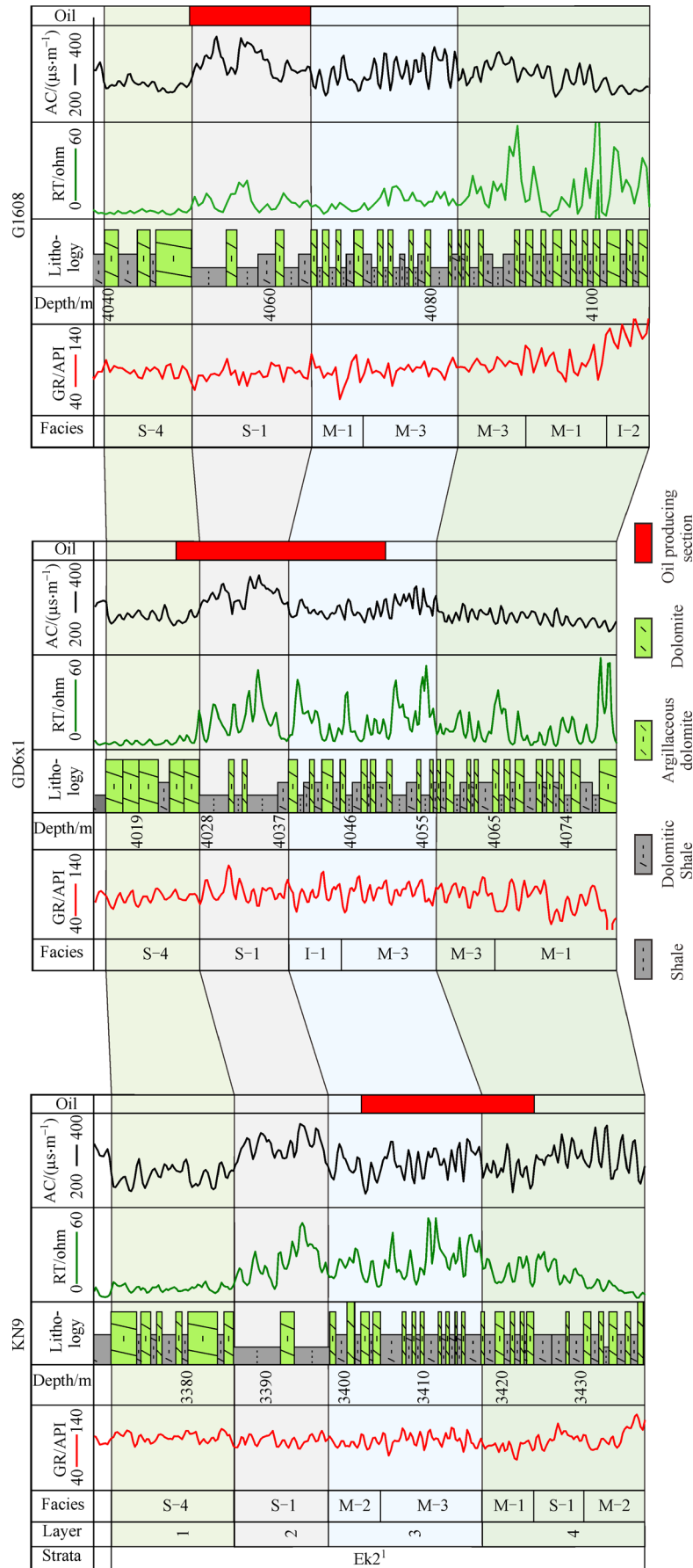


Fig. 5 Comparison of fabric facies of Ek2¹ in different parts based on log interpretation.

ratio of 38%–46% and belongs to M-1, which contains larger differences in detailed lithofacies on the plane. In Well KN9 (Fig. 5), argillaceous dolomite occurs at the two ends of the sublayer; in Well GD6x1, argillaceous dolomite is distributed evenly in this sublayer. In Well G1608, argillaceous dolomite is found in the lower part of the sublayer. Such variations are related to the lake basin microscopic landscape and to cyclic lake level variations.

5.2 Selection of favorable fabric facies

Researchers in China often comprehensively evaluate sweet spots based on several factors, such as lithology, physical properties, oiliness, source rock characteristics, brittleness, sensitivity, ground stress anisotropy, and economic efficiency (Jia et al., 2012; Zhao and Du, 2012; Yang et al., 2015; Li et al., 2020), and the values of the indexes differ for different classes of sweet spots. Nevertheless, areas with high TOC, high free hydrocarbon content, high brittleness, high porosity and permeability, and high fluid pressure are generally deemed the most favorable. In this work, favorable fabric facies types were selected according to oiliness (free hydrocarbon content and fluorescence show), layer combination features, and oil testing results; sweet spots on the plane were predicted based on the maturity and burial depth of structures.

5.2.1 Oiliness

Oiliness is closely related to TOC, the thermal evolution of organic matter, and free hydrocarbon content. Different burial depths in different areas produce large discrepancies in organic matter maturity, and the oiliness of different fabric facies are not comparable. Under similar maturity, fabric facies with higher TOC often contain more abundant free hydrocarbon and exhibit stronger fluorescence. Figure 6 shows that M-1, M-3, I-3, S-1, and S-2 generally

have TOC of over 3%, free hydrocarbon content of 3.3–6.3 mg/g, and medium–strong fluorescence. Among them, S-1 and S-2 have higher contents of free hydrocarbon and higher fluorescence (Fig. 2) but lower matrix porosity and brittle mineral content. From the characteristics determined from the log curves, S-1 and M-3 appear to have obviously higher resistivity and higher total hydrocarbon values from gas logging, whereas M-2, I-1, and I-2 have medium oiliness, and S-3 and S-4 have poor oiliness (Fig. 6).

5.2.2 Combination pattern

In the Kong 2 Member, fine-grained source rocks are of good quality, and the reservoirs include argillaceous dolomite, mud, and shale source rocks (Fig. 2). Therefore, the combination of different kinds of rocks is another key factor affecting shale oil enrichment. The layer cake combination consists of laminated thin source rock and reservoir beds, in which oil and gas can migrate to nearby reservoirs, creating good oiliness in the source rock and the reservoir. Figure 2 shows that M-1, M2, and M-3 have stronger fluorescence. Logging showed interbedded combination features consisting of medium thickness source rock and a single layer reservoir with a thickness of 1–2 m. Thicker combination layers allow oil and gas to fill the dolomite reservoirs less than 0.5 m from the source rock; consequently, the reservoirs have lower overall oiliness. Thickly sandwiched fabric facies include two kinds of combinations: medium-thin shale held between medium-thick dolomite layers and thin dolomite held between thick shale layers. The former has poorer oiliness; for example, in the S-4 fabric facies (Fig. 2), the shale and argillaceous dolomite have weaker fluorescence. Argillaceous dolomite has more reservoir space and higher brittleness, and faults connecting the source rock from above or below can lead to fairly good oiliness. The latter has higher retained hydrocarbon content that favors shale oil. For example, the

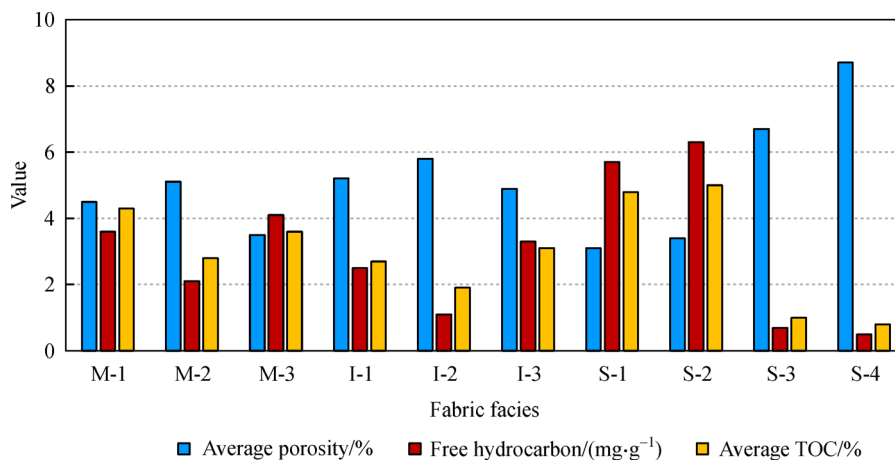


Fig. 6 The porosity, free hydrocarbon and TOC bar chart of different fabric facies.

S-2 fabric facies (Fig. 2) has strong fluorescence, and the argillaceous dolomite contained therein has good fluorescence.

5.2.3 Formation testing results

In recent years, shale oil exploration of Kong 2 Member in the Cangdong sag has made breakthroughs in several wells, among which Wells GD6x1, G1608, and KN9 have daily oil production of more than 20 t. Fractured primarily in M-3 and I-1, Well KN9 has a daily oil production of 29.6 t, with a 2 mm choke. Well GD6x1, with primarily fractured S-1, M-3 and I-1, has a daily oil production of 32.6 t, with a 3 mm choke. The tested section in Well G1608 (S-1) has an average TOC of 5.6% and S1 content of 3.7 mg/g. After fracturing, the well initially produced 47.1 t of oil daily, with a 3-mm choke and produced a total of 1540.7 t of oil at 10 MPa pressure over the 105-day testing period, which corresponds to an average daily production of 14.7 t. The success of formation testing indicates that the above fabric facies, especially S-1, have fairly high productivity, and are the most favorable sweet spots in Ek2¹ (Fig. 7).

The above-mentioned analysis shows that S-1, S-2, M-3, and M-1 are the most favorable fabric facies, M-2, I-1, and I-3 are the second most favorable fabric facies, and I-2, S-3, and S-4 are the least favorable fabric facies.

5.3 Prediction of fabric facies sweet spots on the plane

Here, we considered S-1 in Ek2¹ as an example (Fig. 8). On the basis of single well fabric facies identification, favorable sweet spots were preliminarily determined by

considering seismic resistivity from inversion, vitrinite reflection R_o , burial depth of structure, and formation thickness. In this manner, the most favorable sweet spots, including the Z1605, KN9, G108-8, GD6x1, and G1608 well blocks were selected. These sweet spots have a combined area of 100 km², burial depth of 3000–4000 m, R_o of 0.8%–1.2%, and general fabric facies thickness of over 15 m. The second most favorable sweet spots have burial depths of less than 3000 m, R_o between 0.5 and 0.8, thickness of 10–15 m, and cover an area of 90 km².

Two horizontal wells, GD1701H and GD1702H, were deployed in the most favorable area near G1608 and have a more than 1300-m horizontal interval length in Ek2¹ with fabric facies S1, M-1, and M-3. After volume fracturing using 75388 m³ (including 80% of slick water) of fracturing fluid and 2731 m³ of sand (including 30% of quartz sand), both wells had high daily oil production more than 20 t. Well GD1702H, for example, produced 4860 t of oil and 459500 m³ of gas 256 days after blow-off of and currently produces a stable 17.5 t/d (Fig. 9), proving that fabric facies evaluation could help explorers choose layers for horizontal wells.

6 Conclusions

1) The fine-grained deposits of the Kong 2 Member in the Cangdong sag develop 4 types of rocks, such as shaleshale, dolomitic shaleshale, argillaceous dolomite, and dolomite. Fine-grained deposits are good–excellent source rocks, with an average TOC of 3.6%, porosity of 4%–6%, permeability of 0.01 mDa, and a variety of pores and fractures, and lay the foundation for the enrichment and

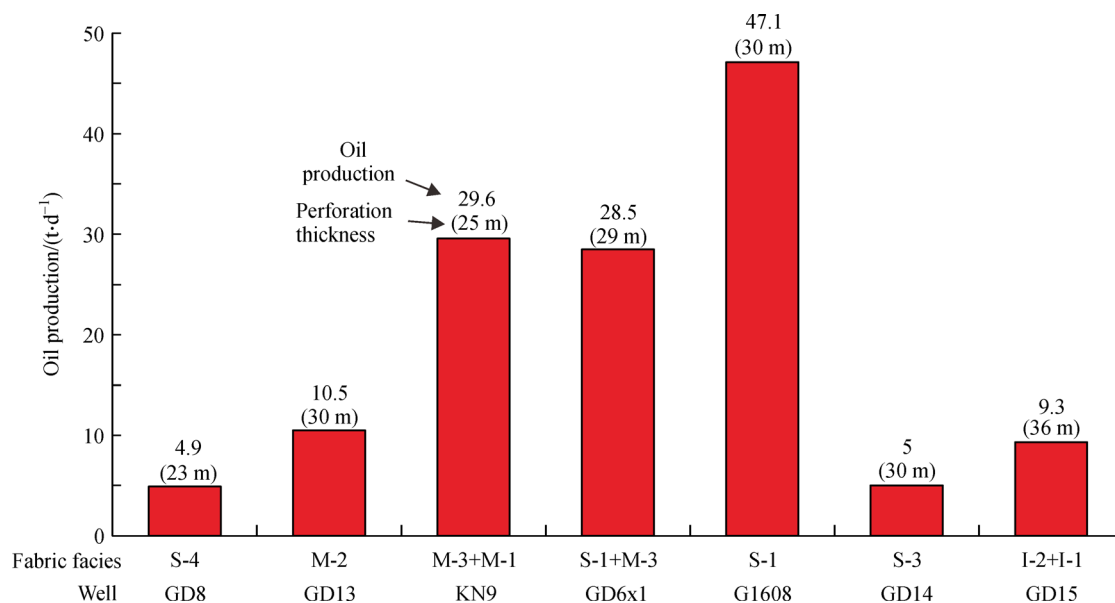


Fig. 7 Oil production of different fabric facies.

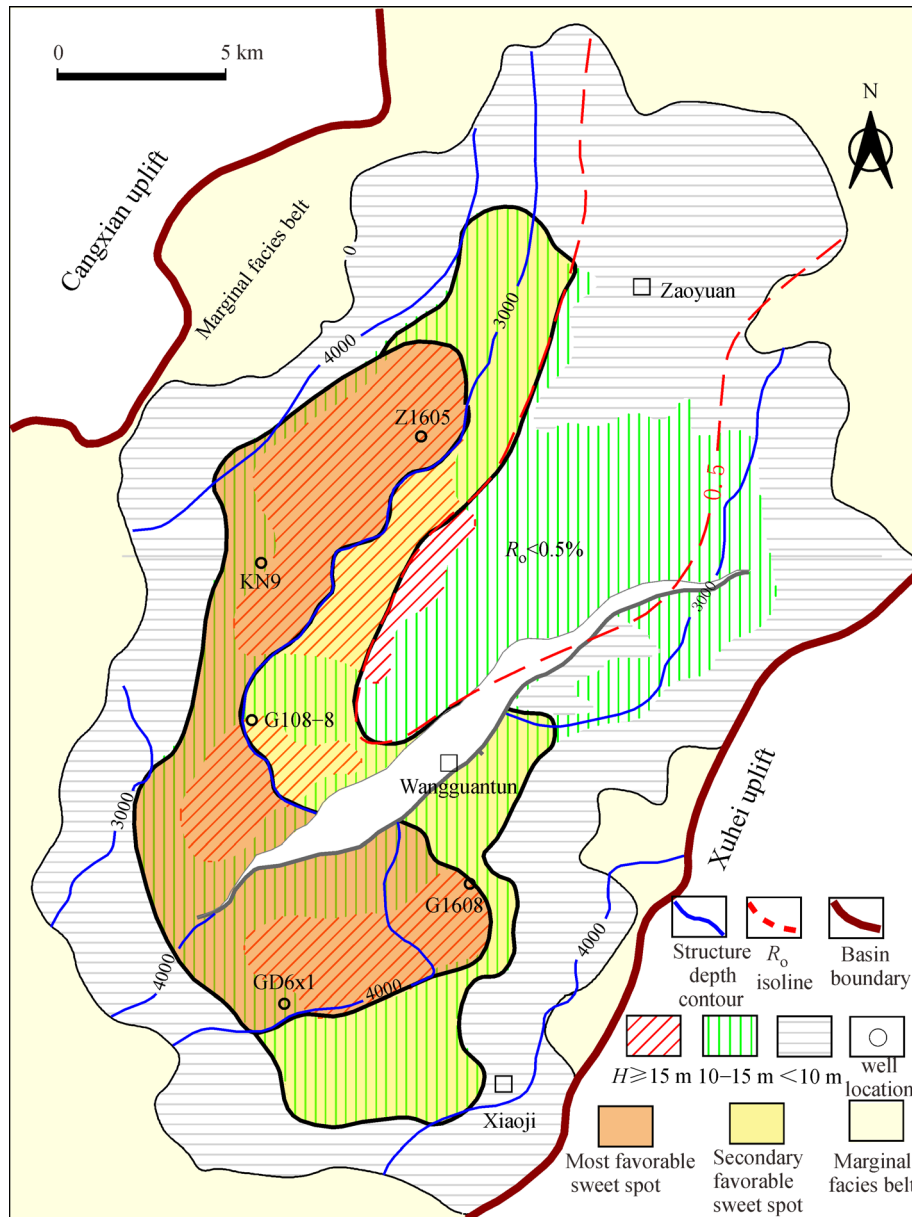


Fig. 8 Favorable sweet spots of S-1 fabric facies in Ek2¹ fine grained facies belt of the Cangdong sag.

accumulation of shale oil.

2) To clarify sweet layers and areas for shale oil exploration, a logging scale fine-grained fabric facies classification scheme based on dominant lithology, organic matter abundance, and sedimentary structure was established. The method of fabric facies classification and evaluation is widely applicable for lacustrine shale oil.

3) A total of 10 types of fabric facies were identified in the Kong 2 Member, of which S-1, S-2, M-3, and M-1

being favorable shale oil enrichment with a good superposition of high TOC, S_1 values, high resistivity, high total hydrocarbon, and strong fluorescence. M-2, I-1, and I-3 are the second most favorable fabric facies, whereas I-2, S-3, and S-4 are the least favorable fabric facies.

4) Comprehensively considering seismic resistivity, R_0 , structural burial depth, and formation thickness, the most favorable sweet spots of S-1 were predicted at approximately 100 km².

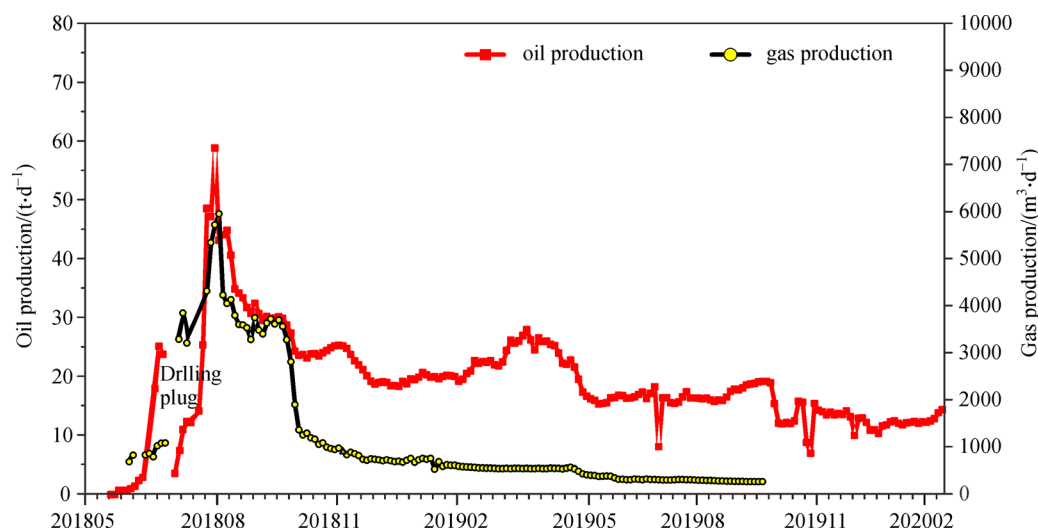


Fig. 9 Oil testing curve of GD1702H in Ek2¹.

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