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Calculating single layer production contribution of heavy oil commingled wells by analysis of aromatic parameters in whole-oil GC-MS

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Abstract: Traditional fluid production profile logging is not usually suitable for heavy-viscous crude oil wells. Biodegradation of heavy oil can lead to the loss of *n*-alkanes, and the use of chromatogram fingerprint techniques in studying the production contributions of single layers in heavy oil commingled wells has limitations. However, aromatic compounds are relatively well preserved. We took the heavy oil commingled wells of small layers NG55 and NG61 in the ninth area of the Gudong oil field as examples. Based on the principle of chromatography, the whole-oil GC-MS was used, and the aromatic parameters which have a strongly linear relationship with the ratio of mixed two end member oils were verified and selected in laboratory. Studies showed that the ratio of (1, 4, 6- + 2, 3, 6-trimethylnaphthalene) to 1, 2, 5-trimethylnaphthalene has a strongly linear relationship with the ratio of the mixed two end member oils (R^2=0.992). The oil contributions from single layers NG55 and NG61 in six commingled heavy oil wells were calculated using established charts and this relationship. The calculated results are consistent with the results of long period dynamic monitoring and logging interpretation in the study area and can provide a scientific basis for monitoring production performance and hierarchical management of reservoirs. The study provides a new geochemical method for calculation of the contributions of single layers in heavy oil commingled wells when conventional fluid production profile logging is not suitable.

Key words: Whole-oil GC-MS, aromatic parameters, commingled producing wells, single layer production, the ninth area of the Gudong oilfield

1 Introduction

In the development and production of many oil fields, multiple wells are combined to optimize production and reduce cost. Therefore, the produced oils can be from different oil reservoirs. To design and adjust development projects and to optimize reservoir management, it is important to know the contributions of each single layer to total oil production, to dynamically monitor changes in oil production over time, to monitor oil well production performance, to adopt a hierarchical reservoir management strategy, and to detect casing leakage and edge water incursion. For normal crude oil wells, the layered performance of oil fields can be tested and studied using production profile logging technology. Researchers from the U.S. Chevron Oil Company determined the fluid profiles using total hydrocarbon chromatographic fingerprint techniques to obtain the contribution ratio of single reservoirs (Kaufman et al, 1987; 1990; Hwang et al, 2000). This method successfully incorporates chromatographic techniques in active oil fields (Peters and Fowler, 2002; Jarvie et al, 2001; Karlsen and Larter, 1989; McCaffrey et al, 1996; England, 2007; Nicolle et al, 1997). High-pour-point heavy oil becomes stringy very abruptly and can gradually lose fluidity as temperature drops, which typically occurs after the oil enters the wellbore and flows to the surface. Then the wellbores can be blocked by the heavy oil. This hinders the instruments and cables which then cannot be moved into the wellbore (Zhu and Xu, 2007). Production profile logging technology is difficult to use. Because biodegraded heavy oil loses its *n*-alkanes, qualitative and quantitative analysis of its chromatography is difficult. Therefore, the use of standard chromatographic fingerprint techniques in the study of the contributions of single layers to the total productivity of heavy oil commingled wells has limitations (Lin et al, 2005; Xu and Chen, 2009; Zou et al, 2000).

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Usually, aromatic compounds are well preserved during the biodegradation of viscous crude oil. We took the commingled heavy oil wells of two single layers in the ninth area of the Gudong oil field as examples. The oils from the two single-layers were mixed with different proportions and measured in the laboratory, and then analyzed using whole-oil chromatography-mass spectrometry (whole-oil GC-MS). The geochemical method of calculating the single-layer productivity contribution in heavy oil commingled production wells was developed in this way.

2 Geological background

The Gudong oil field is located on the northern bank of the Yellow River estuary. The heavy oil block of the ninth area is located in the south of the Gudong oil field (see the inset in Fig. 1). The main oil-bearing series is the Neozoic Upper Guantao Formation of fluvial deposition. From top to bottom, the Upper Guantao Formation has been divided into 1+2, 3, 4, 5, and 6 sand groups respectively. At present, small layers NG55 and NG61 are the main oil-bearing series (NG61 stand for the first small sand layer of the sixth segment in the Neozoic Guantao Formation, and NG55 is in the same way). They are mud silt-fine sandstones of positive rhythm fluvial deposition. The reservoir rock is loosely cemented, with low-to-moderate permeability and the depth of reservoir is about 1,320-1,400 m. When the temperature is 50 °C, the viscosity of oil in the ground is about 1,153-4,660 MPa·s. It is a thin layer common heavy oil reservoir (Cheng et al, 2003). The top-bottom surface microstructure of the sand body shows a faulted nose structure and dips down from north to south (Fig. 1).

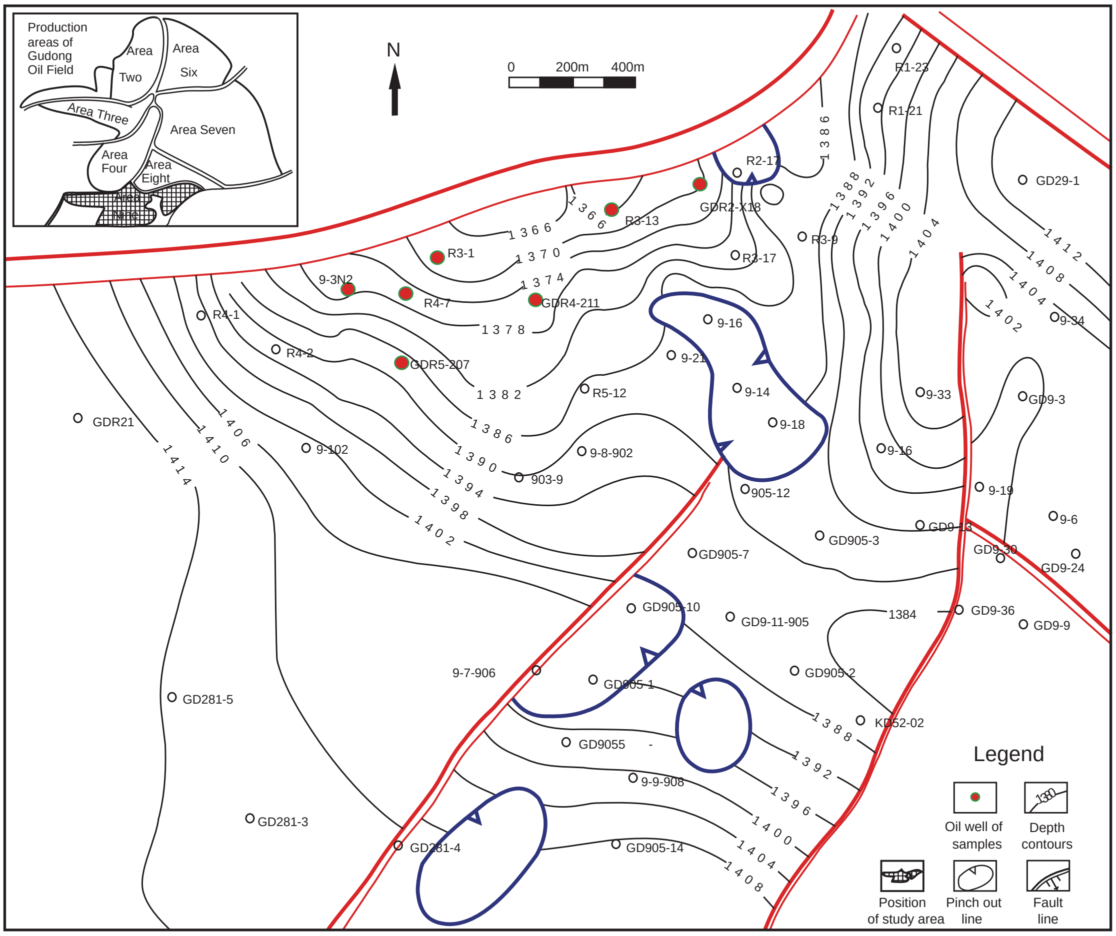

Fig. 1 Microstructure and well locations of the 6^1 group top of the upper Guantao Formation in the ninth area of the Gudong oil field

3 Samples and experimental method

An Agilent P6890 GC 5973MSD chromatography–mass spectrometry system, HP-5MS (30 m × 0.32 mm × 0.25 μm), constant current mode, and carrier gas flow rate of 1 mL/min were used at a helium temperature of 50 °C. The temperature was held constant for 1 min and then it was increased to 100 °C at the rate of 15 °C/min and then to 300 °C at the rate of 4 °C/min. This temperature was held constant for 18 min. Then a scan/selection ion analysis was performed using the EI ionization method and electron flow at 70 eV.

The crude oil samples were obtained from wellheads in the ninth area of the Gudong oil field at the same time (Fig. 1). The crude oils from GOGDR5-207 and GOGDR4-211 wells were NG61 and NG55 single-layer crude oil, respectively. Samples from other wells were multi-layer mixed crude oil that was produced from both layers NG61 and NG55. The total ion flow diagram of crude oil shows an obvious bulge and the loss of normal alkanes is serious. It shows that the oil has undergone considerable biodegradation (Fig. 2).

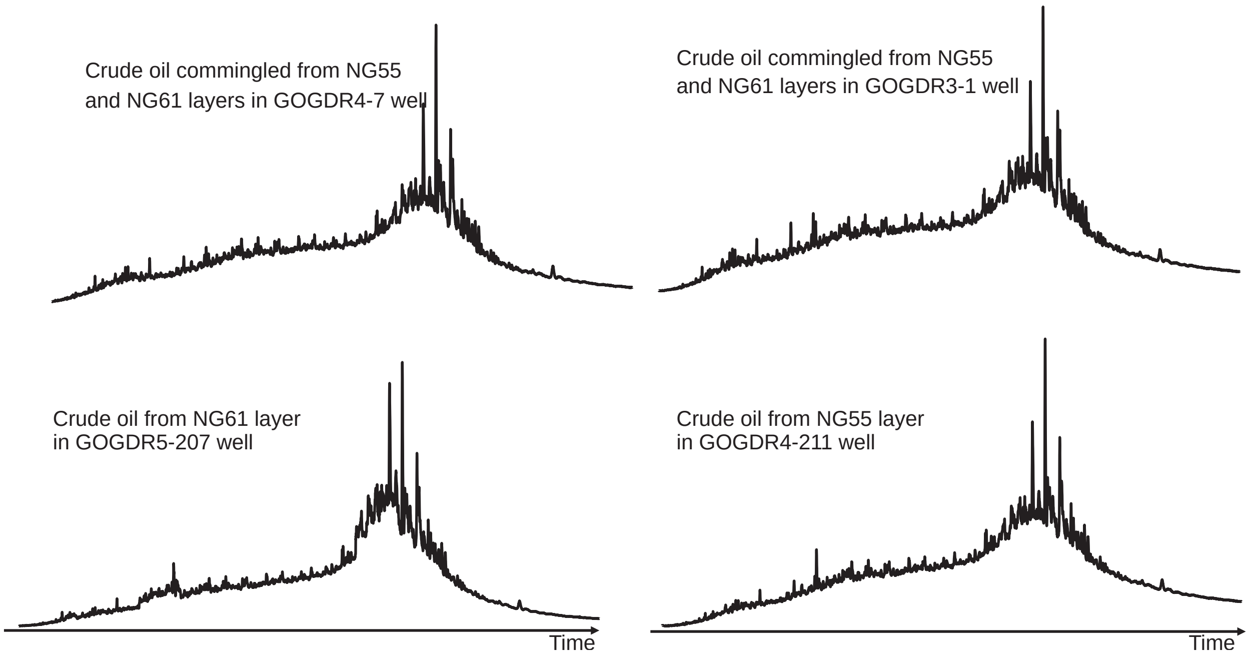

Fig. 2 Typical crude oil total ion flow diagram

The oil from the monolayers NG55 and NG61 from the GOGDR5-207 and GOGDR4-211 wells served as the crude oil end-members. Five mixed oil samples were prepared. They were weighed and mixed in different proportions (Table 1).

Table 1 Calculated ratio and weight of crude samples

Number		Ratio 1	Ratio 2	Ratio 3	Ratio 4	Ratio 5
Weight, mg	NG61 (GOGDR5-207 well)	3.7	6.2	8.9	11.4	27.5
	NG55 (GOGDR4-211 well)	15.7	12.4	7.7	6.4	5.4
The actual percentage value of NG61, %		19	33	54	64	84
The calculated percentage value of NG61, %		23	29	52	64	80
Absolute error, %		-4	4	2	0	4

4 Results and discussion

The concentration of a compound in crude oil determines the height and area of the chromatographic peak (the response signal) of the compound, i.e.:

$$H = c \times H_s \times M / m_s \tag{1}$$

The peak area ratio of two compounds a and b (or peak height ratio of two compounds a and b) is as follows:

$$H_a / H_b = c_a / c_b \tag{2}$$

In these two equations, H is the peak area of the chromatographic peak (or peak height), c is the concentration of the compound in the crude oil, H_s is the peak area of the standard sample, M is the quality of the crude oil, and m_s is the quality of the standard sample.

H_a and H_b are the areas of the peaks produced by compounds a and b in crude oil, c_a is the concentration of compound a in crude oil, and c_b is the concentration of compound b in crude oil.

According to this equation, the peak area ratio of the two compounds in crude oil is the same as the ratio of the two concentrations.

If the crude oil samples are mixed crude oil from two single-layers and the peak area ratio of compounds a and b in mixed oil is k_c, so the following equation can be determined:

$$k_c = \frac{H_a}{H_b} = \frac{c_a}{c_b} = \frac{c_{1a} \times p_1 + c_{2a} \times p_2}{c_{1b} \times p_1 + c_{2b} \times p_2} = \frac{(c_{1a} - c_{2a}) \times p_1 + c_{2a}}{(c_{1b} - c_{2b}) \times p_1 + c_{2b}} \tag{3}$$

In this equation, c_{1a}, c_{2a}, c_{1b}, and c_{2b} represent the concentrations of compounds a and b in crude oil from the two single-layers, and they are constant. P_1 is the proportion of crude oil from one single-layer. In this way, for mixed oils from two different reservoirs commingled in the same well, the peak area ratio of two compounds has a curved relationship with the contribution proportion of single layer oil. Fingerprint parameters are the ratio of concentrations (peak height or peak area) of the two compounds. This eliminates the influence of systematic error on the result to the greatest degree possible (Chang et al, 2000). Chromatography-mass spectrometry analysis is used to calculate the fingerprint parameters. The relationship between the aromatic compounds parameters analyzed by chromatography-mass spectrometry and the matching ratio in the laboratory has been discussed.

The m/z170 chromatogram of the NG61 layer oil from the GOGDR5-207 well and the m/z184 chromatogram of the NG55 layer oil from the GOGDR4-211 well show an obvious difference in the distribution of the isomers of tri-methylnaphthalene (TMN) (Fig. 3). The relative abundances of 1, 2, 4-TMN and 1, 2, 5-TMN of the crude oil from the NG55 layer of GOGDR5-207 well are higher than those of the crude oil from the NG61 layer of GOGDR4-211 well, and the relative abundances of 1, 4, 6-TMN and 2, 3, 6-TMN of the former are lower than those of the latter. When the mixture ratio changes, the TMN relative abundance of five oil samples changes accordingly between two end-member oils. Tetra-methylnaphthalenes (TEMN) also have such features. For example, the relative abundance of 1, 3, 5, 7-TEMN

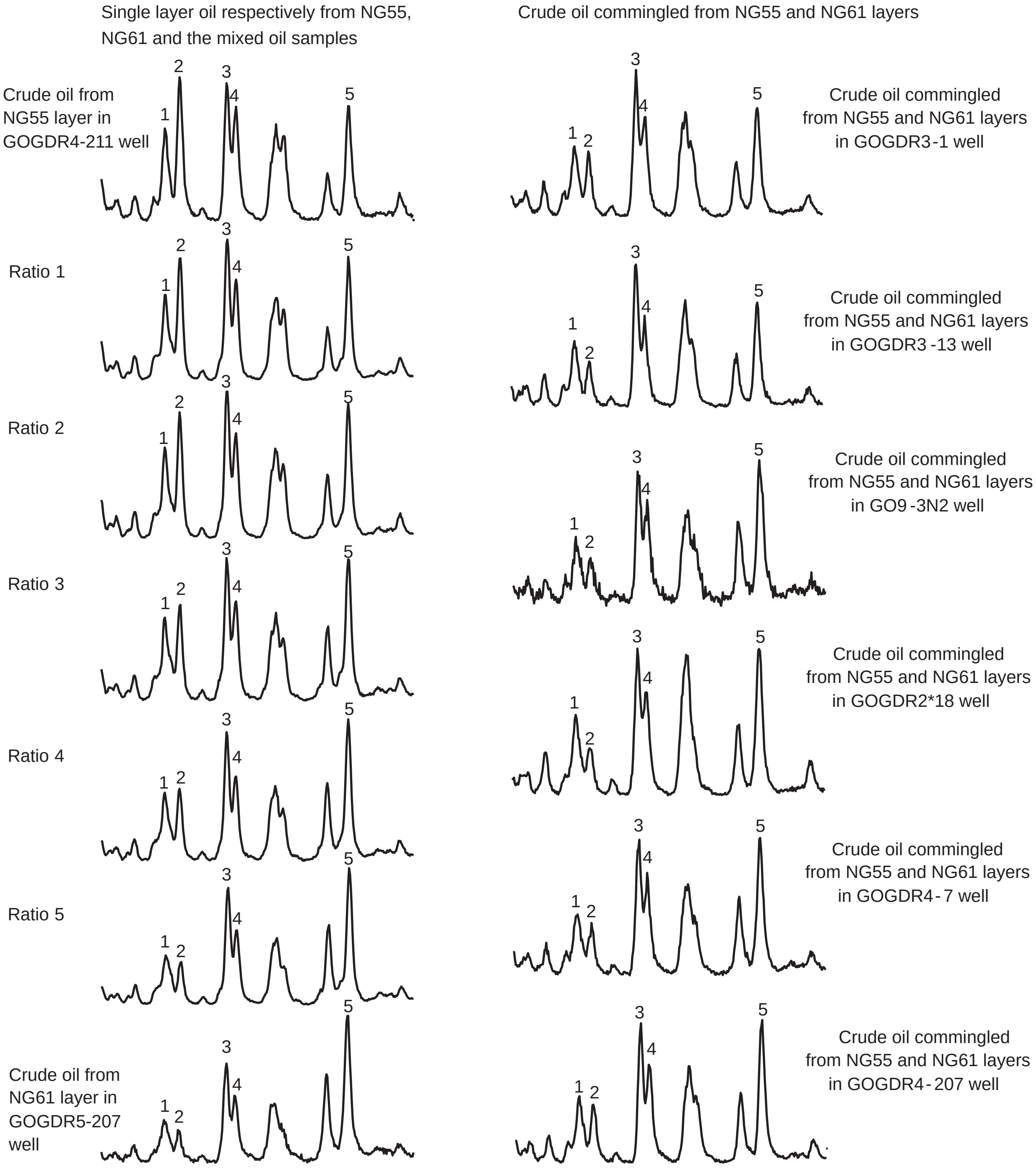

Fig. 3 m/z170 chromatograms of the crude oil from single layers, mixed oil samples, and crude oil from commingled wells. 1: 1, 3, 7-TMN; 2: 1, 3, 6-TMN; 3: 1, 4, 6-TMN; 4: 2, 3, 6-TMN; 5: 1, 2, 5-TMN of the oil from the NG55 layer is lower than that of the oil from the NG61 layer, and the relative abundances of 1, 3, 6, 7-TEMN, 1, 2, 3, 5-TEMN, and 1, 2, 5, 6-TEMN from the NG55 layer are higher than those of the oil from the NG61 layer. The relative abundance of TEMN in five mixed oil samples changes between the two end-member oils (Fig. 4).

We calculated the total area of the two peaks of 1, 4, 6-TMN and 2, 3, 6-TMN because the two peaks are not completely separated (Fig. 3). The correlation diagram of the ratio of peak area of (1, 4, 6-TMN + 2, 3, 6-TMN) to that of 1, 2, 5-TMN and the proportion of end oil in mixed oil shows that they have a very good linear correlation, with R^2 up to 0.992 (Fig. 5). This means that the relation curve between the ratio of peak area of (1, 4, 6-TMN + 2, 3, 6-TMN) to that of 1, 2, 5-TMN and the proportion of end oil in mixed oil is approximately a straight line. Kaufman calculated the relative contribution of each single-layer of commingled wells by identifying parameters of chromatographic fingerprint that have linear relations (Chen et al, 1999; Kaufman et al, 1990; Jin et al, 2003a; 2003b). Many parameters of multi-methyl naphthalene compounds have similarly linear relations with the mixed ratio in crude oil (Lin et al, 2005). The study shows that the correlations between aromatic parameters such as 1, 3, 7-TMN / 1, 2, 5-TMN and 1, 3, 5, 7-TEMN

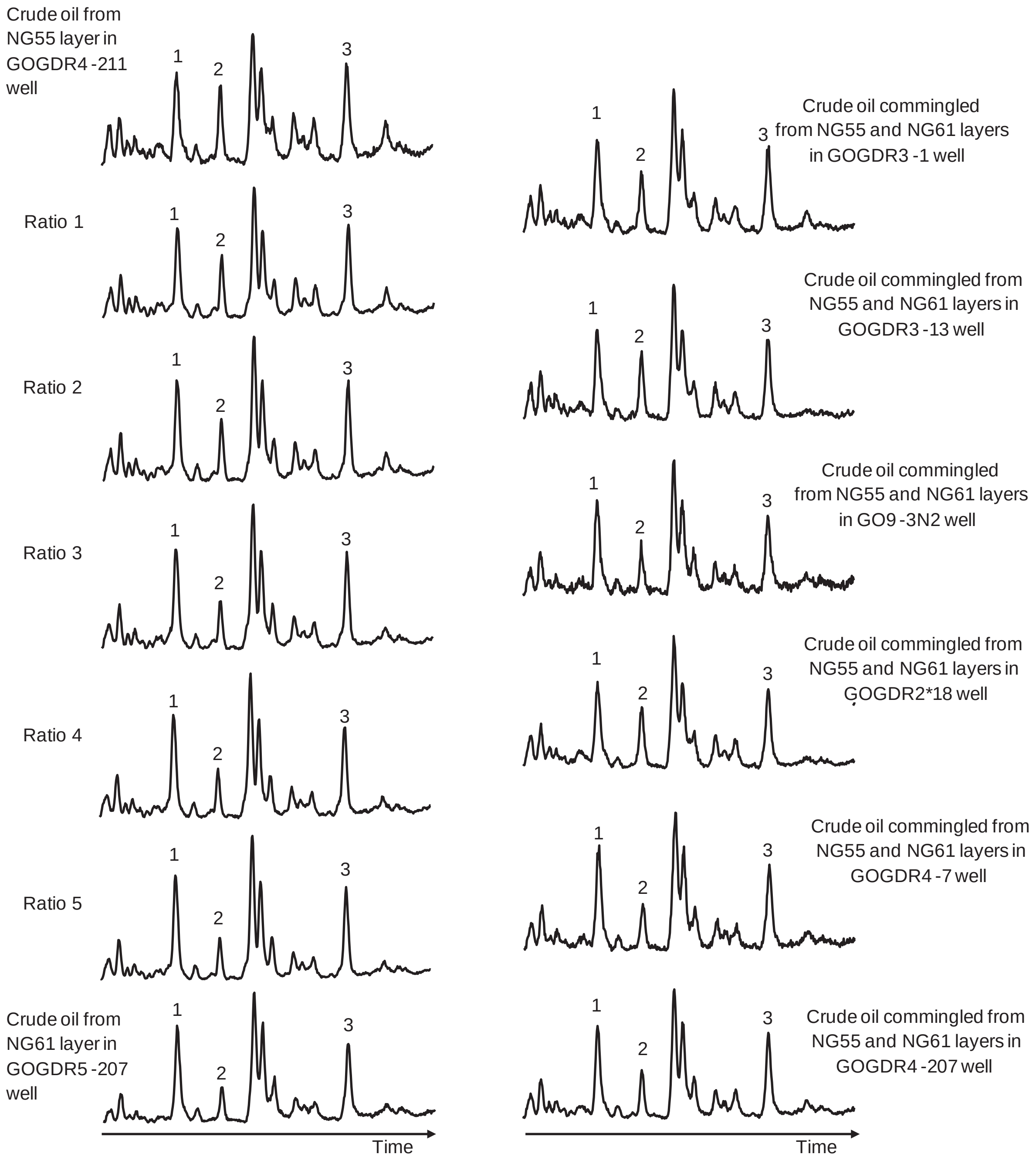

Fig. 4 m/z184 chromatogram of the crude oil from single layers, mixed oil samples, and crude oil from commingled wells. 1: 1, 3, 5, 7-TEMN; 2: 1, 3, 6, 7-TEMN; 3: 1, 2, 3, 5-TEMN and 1, 2, 5, 6-TEMN

/ 1, 3, 6, 7-TEMN and the mixed ratio in crude oil are not strongly linear and R^2 is 0.763 and 0.852 respectively (Fig. 5). Many other parameters did not have this linear correlations with the mixed ratio in the crude oil, such as 3-methyl-phenanthrene/2-methyl-phenanthrene. This is consistent with the results of the previous analysis, i.e., the ratio of the peak areas of two compounds and the contribution of single layer oil in mixtures of oil from two layers in commingled wells have a curved relationship.

According to the experiments in the laboratory and the above analysis, the parameter of (1, 4, 6-TMN+2, 3, 6-TMN)/1, 2, 5-TMN has the most linear correlation with the mixed ratio in crude oil and it can be used as a fingerprint parameter to calculate the contribution of oil from each layer in a commingled heavy oil reservoir in the ninth area of the Gudong oil field. This method is relatively simple and to the greatest degree possible eliminates the influence of calculation using absolute concentrations on the results.

Heavy oil samples from layers NG55 and NG61 in wells GO9-3N2, GOGDR2*18, GOGDR3-1, GOGDR3-13, GOGDR4-1, GOGDR4-7, and GOGDR4-207 in the ninth area of the Gudong oil field were analyzed under the same chromatography-mass spectrometry experimental conditions. The relative abundances of their TMN and TEMN isomers differed between two small layers of NG55 and NG61 (Fig. 3, Fig. 4). The ratios of (1, 4, 6-TMN + 2, 3, 6-TMN) / 1, 2, 5-TMN of oil from every commingled well were determined using the method established above, and the relative contributions of oil from the small layers of NG55 and NG61 were obtained (Table 2). The GOGDR3-1 and GOGDR3-13 wells are worthy to be paid attention to and the NG55 layer makes almost no contribution to production. Crude oil was mainly from the NG61 layer. The results suggest that development measures should be implemented for these two wells.

Conventional production profile logging technology cannot be used in heavy oil reservoirs because underground crude oil has a high density and high viscosity and the oil companies did not perform production profile testing on the reservoirs in the ninth area of the Gudong oil field. We took the single layer exploitation of NG61 from the GOGDR5-207 well, the single layer exploitation of NG55 from the GOGDR4-211 well, and commingled well exploitation of GOGDR3-1 and GOGDR4-7 as examples (Fig. 6). The reservoirs of these four wells provided contrast profiles and production information showed that oil from the GOGDR3-1 well was mostly from the NG61 layer. For the GOGDR4-7 well, the contribution coming from the NG55 layer increased, but the oil was still primarily from the NG61 layer. The reservoir connectivity, production dynamics and log interpretation results showed that the calculated contributions of crude oil from single-layers of NG55 and NG61 in commingled wells were consistent with the actual production.

The calculated results provide a sound scientific basis for monitoring well performance and hierarchical management of the reservoir.

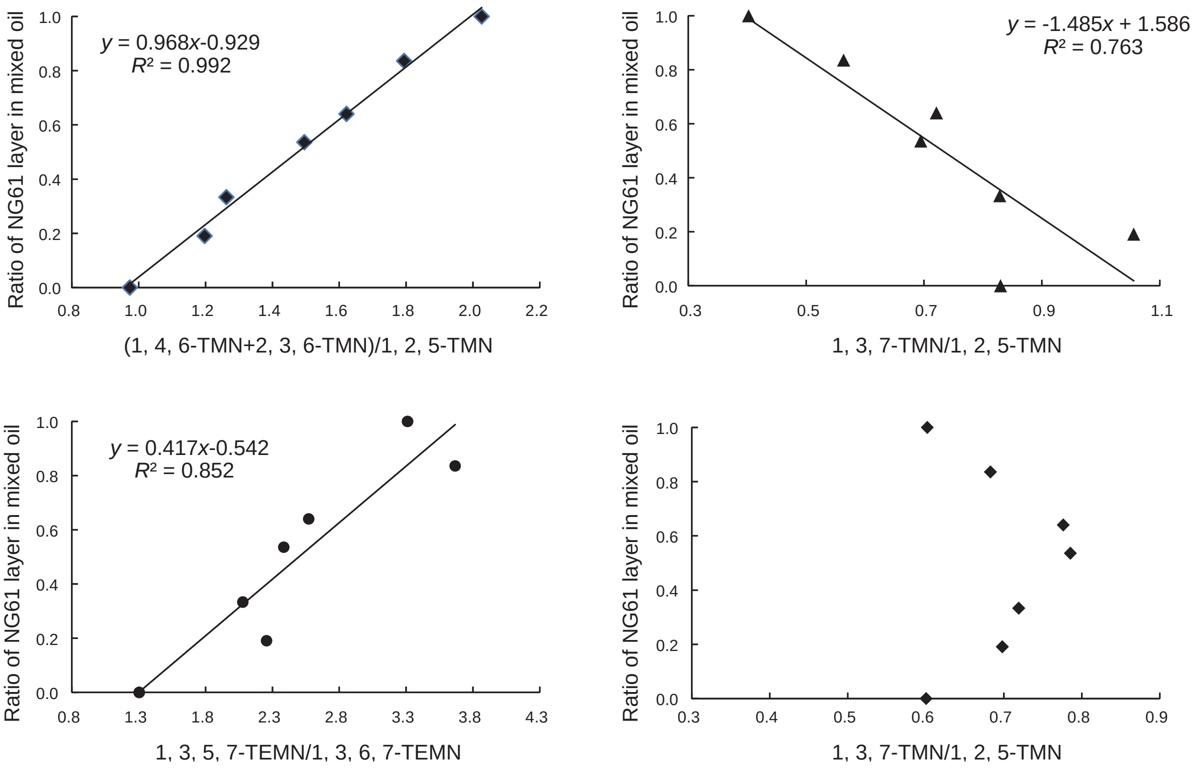

Fig. 5 Diagram about the relations between typical aromatic parameters and crude oil proportion from single layers

Table 2 Relative productivity contributions of oil from the NG55 and NG61 layers in commingled wells in the ninth area of the Gudong oil field

Number	Well number	Horizon	(1, 4, 6-TMN + 2, 3, 6-TMN) / 1, 2, 5-TMN	Contribution of NG55 layer, %	Contribution of NG61 layer, %
1	GOGDR5-207	NG61	0.97	0	100
2	GO9-3N2	NG55+61	1.43	54	46
3	GOGDR2*18	NG55+61	1.40	57	43
4	GOGDR3-1	NG55+61	1.96	3	97
5	GOGDR3-13	NG55+61	1.92	6	94
6	GOGDR4-7	NG5561	1.52	46	54
7	GOGDR4-207	NG55+61	1.50	48	52
8	GOGDR4-211	NG55	2.03	100	0

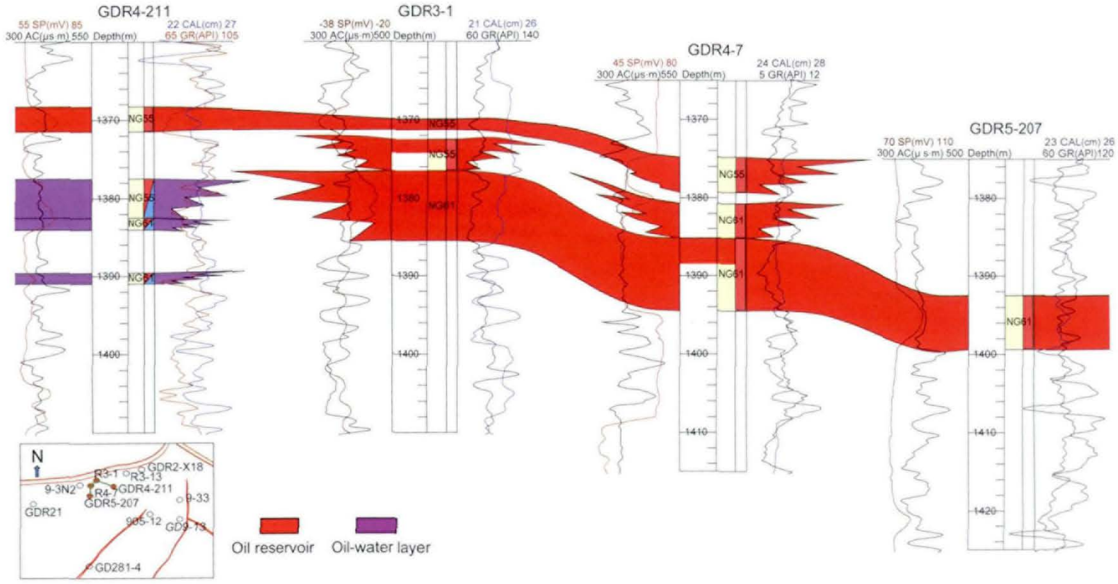

Fig. 6 Reservoir correlation profile of wells GOGDR5-207, GOGDR4-211, GOGDR3-1 and GOGDR4-7

5 Conclusions

Aromatic compounds are preserved relatively intact in biodegraded heavy oils. Two end member oils were mixed and analyzed by whole-oil chromatography-mass spectrometry in the laboratory, and the aromatic parameters which have a linear relation with the proportion of end-member oil in mixed oil were selected, so that the contributions of oil from single layers in commingled heavy oil wells can be obtained. Taking the commingled heavy oil wells in the ninth area of the Gudong oil field for example, the ratio of (1, 4, 6-TMN + 2, 3, 6-TMN) / 1, 2, 5-TMN has a strongly linear relationship with the mixed ratio of two end member oils, and R^2=0.992. The production contributions of oil from single layers of NG55 and NG61 in six commingled heavy oil wells were calculated by establishing a chart based on the relationship mentioned above. These calculation results were consistent with production monitoring and logging interpretation results. They also provide a good geochemical testing method for the calculation of the contributions of oil from two single-layers in commingled heavy oil wells when a conventional liquid production profile logging in heavy oil reservoirs cannot be implemented in the ninth area of the Gudong oil field.

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References

Chang X C, Zhang Z H and Wang T G. A study on the productivity contribution of single horizon in multiple horizons exploitation by reservoir geochemistry. Journal of Xi'an Petroleum Institute (Natural Science Edition). 2000. 15(4): 35-38 (in Chinese)

Chen S J, Lin F, Chen X F, et al. Calculating separate zone production allocation of commingled oil wells using oil chromatography fingerprints technique. Petroleum Exploration and Development. 1999. 26(6): 63, 64, 71 (in Chinese)

Cheng S X, Sun S D, Yang Q P, et al. Production conditions and development mode conversion in viscous oil block of region 9 of Gudong oilfield. Journal of Jianghan Petroleum Institute. 2003. 25(Supplement): 70-71 (in Chinese)

England W A. Reservoir geochemistry—a reservoir engineering perspective. Journal of Petroleum Science and Engineering. 2007. 58(3-4): 344-354

Hwang R J, Baskin D K and Teerman S C. Allocation of commingled pipeline oils to field production. Organic Geochemistry. 2000. 31(12): 1463-1474

Jarvie D M, Morelos A and Han Z W. Detection of pay zones and pay quality, Gulf of Mexico: application of geochemical techniques. Gulf Coast Association of Geological Societies Transactions. 2001. 51: 151-160

Jin X H, Zhu D, Lin R Z, et al. Partition experiment of GC fingerprint of crude oil. Experimental Petroleum Geology. 2003a. 25(1): 53-57 (in Chinese)

Jin X H, Zhu D, Lin R Z, et al. Mechanization of the heterogeneity of petroleum chromatographic fingerprint compounds and its stabilization. Geological Review. 2003b. 49(2): 217-221 (in Chinese)

Karlsen D A and Larter S. A rapid correlation method for petroleum population mapping within individual petroleum reservoirs: applications to petroleum reservoir description. In: Collinson J D. Correlation in Hydrocarbon Exploration. Norwegian Petroleum Society, Graham and Trotman. 1989. 77-85

Kaufman R L, Ahmed A S and Elsinger R J. Gas chromatography as a development and production tool for fingerprinting oils from individual reservoirs: applications in the Gulf of Mexico. In: GCSSEPM Foundation Ninth Annual Research Conference Proceedings. Mexico. 1990. 263-282

Kaufman R L, Ahmed A S and Hempkins W B. A new technique for the analysis of commingled oils and its application to production allocation calculations. In: Proceedings of the Sixteenth Annual Convention of Indonesian Petroleum Association, Indonesian. 1987. 2: 247-268

Lin Q, Sun F J, Liu S, et al. Calculation of single-zone productivity contribution in a commingled producing well by multi-methylnaphthalene parameters: a case of a heavy oil reservoir, QHD32-6 oilfield. China Offshore Oil and Gas. 2005. 17(5): 316-321 (in Chinese)

McCaffrey M A, Legarre H A and Johnson S J. Using biomarkers to improve heavy oil reservoir management: an example from the Cymric Field, Kern County, California. AAPG Bulletin. 1996. 80(6): 898-913

Nicolle G, Boibien C, Ten-Haven H L, et al. Geochemistry: a powerful tool for reservoir monitoring. In: Middle East Oil Show and Conference. Society of Petroleum Engineers. 1997: 395-401

Peters K E and Fowler M G. Applications of petroleum geochemistry to exploration and reservoir management. Organic Geochemistry. 2002. 33(1): 5-36

Xu Y H and Chen D. Calculating the productivity contribution of single zones in commingled producing wells using ultraviolet spectrum technique. Petroleum Geology and Recovery Efficiency. 2009. 16(3): 95-96 (in Chinese)

Zhu Y and Xu A F. Logging technology for production fluid profile of the viscous oil well in Tahe oilfield. Petroleum Instruments. 2007. 21(3): 55-57 (in Chinese)

Zou Y Z, Ma T and Mei B W. Ultraviolet spectrometry—a new technique for calculating oil production allocation of mingling recovery wells. Oil and Gas Geology. 2000. 21(2): 168-172 (in Chinese)

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