A Method for Prediction of the Planar Distribution of Liquid Hydrocarbons in Shale Gas: A Case Study in Duvernay Shale in the West Canadian Sedimentary Basin

Houqin Zhu [*], Yuzhong Xing and Xiangwen Kong

Research Institute of Petroleum Exploration and Development, PetroChina, Beijing.
Email: zhuhouqin@petrochina.com.cn

Keywords: Liquid hydrocarbon, pyrolysis experiment, hydrogen index, planar distribution, Duvernay Shale, West Canadian Sedimentary Basin (WCSB)

Abstract: The pyrolysis experiment data and production data are applied to predict the planar distribution of liquid hydrocarbons in shale gas. On the basis of the variation of pyrolysis experiment parameters of samples before and after extraction, the quantitative relations of $\triangle S2$ with Ro, $\triangle S2/S2$ with Ro, $\triangle HI$ with Ro and $\triangle HI$ with $HI_{unextracted}$ are established and $HI_{unextracted}$ is corrected. Combined with the production data, the quantitative relation of HI with CGR is established. The planar distribution diagram of HI values is plotted, and based on the division standard for different grade of liquid hydrocarbons, the planar distribution of different grade of liquid hydrocarbons is predicted quantitatively. The results indicate that, (1) the pyrolysis comparison experiments before and after extraction indicate that $\triangle S2$, $\triangle S2/S2$ and $\triangle HI$ have a good correlation with Ro, $\triangle HI$ also has good correlation with $HI_{unextracted}$, and these quantitative relations can be used to correct $HI_{unextracted}$. (2) The corrected HI has a very good correlation with CGR, and the planar distribution of all grades of liquid hydrocarbons can be predicted according to HI. (3) The dry gas is distributed mainly in the structural deformation belt and Leduc ring reef belt. The northeast region of the study area is mainly a rich oil region. Gas condensate, rich gas condensate and very rich gas condensate are distributed in NW-SE banded shape from Simonette to Willesden Green.

1 INTRODUCTION

According to the practices in the North America, quantitative evaluation on planar distribution of liquid hydrocarbons and enhancement of well fluid deliverability are effective ways to improve the economic profit of shale gas exploration and development, in addition to technical progress. As is known, prior to shale gas exploration and development, shale was always considered as the source rock for conventional reservoir. Thus there are plenty of geochemical and logging data. Typically, the pyrolysis data can be acquired easily, fast and accurately with low cost. With the pyrolysis data, together with production performance data, the planar distribution of liquid hydrocarbons can be predicted quantitatively. Then, in combination with the shale facies research and the existing drilling/completion technologies, cost reduction and

benefit improvement can be achieved in shale gas exploration and development.

Rokosh et al. (2012) divided the Duvernay shale in the WCSB into four regions, i.e. Gas Maturity, Liquid Maturity, Oil Maturity and Immature, according to the kerogen thermal genetic theory and the Ro data (Rokosh et al., 2012). However, the thermal maturity can simply be used to qualitatively judge whether there is a potential of liquid hydrocarbon in the region, while the shale oil and gas operators and investors care more about whether the shale is dominated by liquid hydrocarbon or gas and how much liquid hydrocarbons are endowed. The liquid hydrocarbon refers to condensate oil herein.

The main purpose of this paper is, with the Duvernay shale in WCSB as an example, to establish the relations of HI vs. CGR, based on the pyrolysis and production performance data, and use these relations to predict the planar distribution of

liquid hydrocarbons. On the basis of this, a set of quantitative evaluation method is proposed quantitative evaluation on liquid hydrocarbons in shale.

2 GEOLOGIC SETTING

The West Canadian Sedimentary Basin (hereinafter abbreviated to WCSB) is a typical wedge-shaped foreland basin and covers an area of $170 \times 10^4 km^2$. WCSB is located between the Canadian Shield and Cordillera fold mountain system. The Rocky Mountain piedmont thickness is larger than 6000m in Albert and British Columbia (Jarvie et al., 2010; Shannon et al., 1989). WCSB can also be divided into two parts such as Albert Basin and Williston Basin. The study area is located in the central west of Albert and the slope belt of WCSB, where the strata are gentle and their burial depth is 1400~5500m. The study area is located in the central west of Albert and the slope belt of WCSB, with gentle formations buried at 1400~5500m (Figure 1).
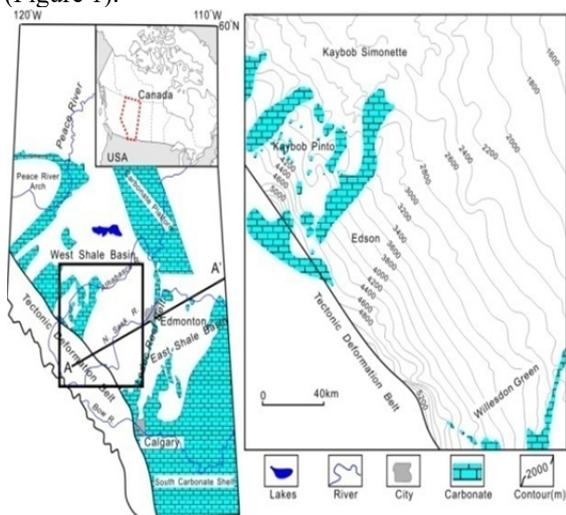

Figure 1: Regional location map of the study area (modified as per reference Jarvie et al., 2010 (Jarvie et al., 2010).

Duvernay shale is a set of dark brown or black organic-rich shale deposited in the maximum transgression period of Upper Devonian Woodbend Group. The shale and Leduc reefs deposited simultaneously. Large scale transgression occurred in the sedimentary period of Woodbend Group, apron reefs were mainly developed near the Peace River structural belt, the lithology inside the basin was deepwater limestone and shale, and Leduc reefs were characterized by patch reefs, and appeared mainly in the shallow water area on the carbonate platform and the west margin of the basin. At the end of the sedimentary period of Woodbend Group, the approximate 325km long NE-trending Rimbey-Meadowbrook reef belt across Edmonton Region divided Albert Basin into east and west shale basins (Mossop and Shetsen, 1994).

The WCSB has evolved in three stages, i.e. stable craton platform from pre-Cambrian to Middle Jurassic, foreland from Middle Jurassic to Eocene, and intra-craton basin from Eocene to the present.

3 DATA AVAILABLE AND METHODS

3.1 Data Available

For this study, pyrolysis data of 40 wells (including Beaton data in 2010) (Beaton et al., 2010) were acquired, including 3 wells with data both before and after extraction (whole core pyrolysis experiment for 2 wells, and cutting pyrolysis experiment for 1 well), and 37 wells with data before extraction, and production data of 67 wells were acquired. Among these wells, 32 wells have both pyrolysis data and CGR data.

3.2 Methods

According to the geochemical theory, with the pyrolysis, together with the production performance data, the planar distribution of hydrocarbons at different grades in the Duvernay shale is quantitatively predicted. Based on the variation of pyrolysis experiment parameters of samples before and after extraction, the quantitative relations of $\triangle S2$ with Ro, $\triangle S2/S2$ with Ro, $\triangle HI$ with Ro and $\triangle HI$ with $HI_{unextracted}$ are established, and then $HI_{unextracted}$ is corrected. Combined with the production data, the quantitative relation between HI and CGR is defined, and the HI division standard for liquid hydrocarbons at different grades is clarified. According to the division standard and the planar distribution map of HI, the planar distribution of liquid hydrocarbons at different grades is predicted quantitatively ($\triangle S2 = S_{2unextracted} - S_{2extracted}$, $\triangle HI = HI_{unextracted} - HI_{extracted}$).

4 RESULTS AND DISCUSSIONS

4.1 HI Correction

Espitalie et al. (1977) firstly proposed a rock pyrolysis method for obtaining S1 and S2 which respectively denote the amount of free or adsorbed hydrocarbons in source rocks and the amount of hydrocarbons generated from kerogen pyrolysis so as to reflect the hydrocarbon generation capacity of mature source rocks (Espitalie et al., 1980). S1 is corresponding with the hydrocarbons volatilized during heating to ≤300°C in a Rock-Eval experiment, and they are basically C7-33 hydrocarbons; S2 is corresponding with the hydrocarbon yields from pyrolysis during heating to >300°C in the Rock-Eval experiment. Delvaux et al. (1990) made some modifications on the definition and normalized the experiment results of the amount S1 of free or adsorbed hydrocarbons and the amount S2 of hydrocarbons generated from kerogen pyrolysis (Delvaux et al., 1990). Dan Jarvie (1987), Lafargue E. et al. (1998), Behar F. et al. (2001) (Dan, 1984; Lafargu et al., 1998; Behar et al., 2001) believed that S2 was hydrocarbons released during the pyrolysis of kerogen between 300 and 550 or 600 degrees C with a linear temperature gradient usually between 25 and 30 degrees C per minute. Wang Anqiao et al. (1987) found that the value of S2 after chloroform extraction was less than that before chloroform extraction through the comparison of a direct pyrolysis experiment on a source rock sample with a pyrolysis experiment on it after chloroform extraction (Wang and Zheng, 1987). This indicates that there are some liquid hydrocarbons in S2; due to the adsorption and swelling action of organic matters and too high boiling point of part liquid hydrocarbons (boiling point of n-C18 302°C), these liquid hydrocarbons cannot be evaporated out at<300°C in a Rock-Eval experiment. Delvaux et al. (1990) also obtained the same conclusion from their studies. According to the conclusion, part macromolecular substances belonging to free hydrocarbons S1 such as asphaltene and colloid in crude oil have similar pyrolysis hydrocarbon temperature during heating in a conventional sample pyrolysis experiment, so that the experiment value of free hydrocarbons S1 is relatively low while that of pyrolysis hydrocarbons S2 is relatively high. The determination of S2 is complicated by the retention of some of the generated hydrocarbons by the rock matrix, and thus HI (hydrogen index=S2/TOC×100)

will not give the true ratio of pyrolyzable hydrocarbons to organic carbon unless appropriate correction is made (Langford et al., 1990). The best treatment method is to resample and conduct a post-extraction pyrolysis experiment, but this will waste a lot of original pyrolysis data. In this paper, the regularity of all analytical data has been discussed on the basis of the analysis of core pyrolysis experiment data on two wells, and relevant formulas have been fitted to correct HI.

The comparative experiments on the full cores of two wells before and after extraction show a large difference, the S2 difference ($\triangle$S2) is 0.75~3.52mg HC/g Rock and the HI difference ($\triangle$HI) is 20.54~82.97mg HC/g TOC. $\triangle$S2, $\triangle$S2/S2 and $\triangle$HI show power decrease with Ro with correlation coefficient of 0.9, 0.9 and 0.93 respectively (Figure 2a~2c), i.e. the larger Ro is, the smaller $\triangle$S2, $\triangle$S2/S2 and $\triangle$HI are. $\triangle$HI increases exponentially with $HI_{unextracted}$ (Figure 2d) with a correlation coefficient of 0.98, the larger $HI_{unextracted}$ is, the larger $\triangle$HI is. According to the above-mentioned correlations, it is feasible that HI can be corrected by fitting relation.

Based on the formula HI=S2/TOC×100(mg HC/g TOC) and the above analysis, multiple methods can be used to correct HI.

4.1.1 To Calculate HI by Correcting S2

According to the above analysis, $S2=S_{unextraced}-\triangle S2$, where $\triangle$S2 can be calculated from the regression formula of $\triangle$S2 with Ro, i.e. $Ro = 1.4844 \times \triangle S2^{0.248}$.

In addition, S2 can also be calculated from $\triangle$S2/S2. Let $\triangle S2/S2 = K_{S2recovery\ coefficient}$, and then $S2 = S2_{unextracted} - K_{S2recovery\ coefficient} \times S2_{unextracted} = S2_{unextracted} \times (1 - K_{S2recovery\ coefficient})$, where $K_{S2recovery\ coefficient}$ can be calculated according to the regression formula of Ro with $\triangle$S2/S2, i.e. $Ro = 0.9632 \times K_{S2recovery\ coefficient}^{0.413}$. Substitute the corrected S2 into the HI calculation formula to calculate HI.

4.1.2 Direct HI Correction

Calculate $\triangle$HI according to the regression formula of $\triangle$HI with HI, i.e. $\triangle HI = 4.05 \times HI_{unextracted}^{0.304}$, $HI_{correction} = HI_{unextracted} - \triangle HI$.

4.2 Relation of HI with CGR

According to the viewpoints of Tissort et al. (1977), the higher the thermal evolution degree, the smaller the residual kerogen amount and the lower the content of hydrocarbons S2 generated from pyrolysis (Tissot and Welte, 1984). Therefore, the ratio of S2/TOC can reflect the fact that the higher the maturity, the smaller the value, the worse the residual hydrocarbon generation capacity and the lower the hydrocarbon generation amount. The oil and gas produced from shale are the residual hydrocarbons generated from thermal evolution of organic matters in shale and not migrated, and the amount of the residual hydrocarbons is affected by conversion and hydrocarbon generation of organic matters. The smaller the hydrocarbon generation capacity of the residual organic matter is, the more the shale oil and gas reserves may be. The HI of kerogen which has experienced thermal evolution to some extent is just used to calibrate the level of liquid-rich hydrocarbons in shale based on the characteristic of shale oil and gas such as self-generating and self-preserving so as to finally achieve the purpose of quantitative research. Therefore, the relation of HI with CGR can be established using the method of combining the HI of kerogen with the shale oil and gas production of a single well. The relation of HI with CGR of Duvernay shale is established according to the collected CGR and the corrected HI (Figure 3). As shown in the figure 3, CGR has a linear relation with HI, their correlation coefficient is up to 0.91, showing a very good correlation.

4.3 Prediction of Planar Distribution of Liquid-Rich Hydrocarbons

The shale oil/gas in the study area is mainly condensate oil, thus the grading of liquid-rich condensate can forecast the highly economic liquid-rich region. Due to difficult recovery, complicated operation modes and high E&D cost, the conventional liquid hydrocarbon grading is no longer suitable for the expensive shale oil/gas

exploration evaluation. The liquid hydrocarbon grading in this paper is defined with consideration to the economic profit in field practices. Specifically, the fluids produced from a well are divided into five grades according to CGR, i.e. dry gas, gas condensate, rich gas condensate, very rich gas condensate and rich oil. The quantitative relation between HI and CGR is used to confirm the threshold value of kerogen HI for the five grades of liquid hydrocarbons (Table 1).

The planar distribution of liquid hydrocarbons at all grades can be plotted on the basis of the planar map of HI, and according to the liquid hydrocarbon CGR division standard, or plotted directly with the planar map of HI and according to the liquid hydrocarbon HI division standard. The latter method is adopted in this study, because the correlation between the parameters and HI is good but not 100%, which will cause large error after multiple calculations.
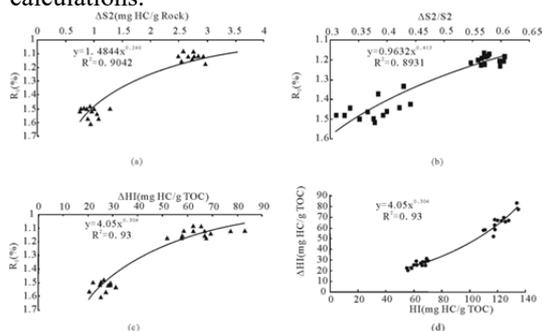

Figure 2: Relation chart of pyrolysis experiment parameters.((a) Relation of $\triangle S_2$ with Ro; (b) Relation of $\triangle S_2/S_2$ with Ro; (c) Relation of $\triangle HI$ with Ro; (d) Relation of $\triangle HI$ with HI)
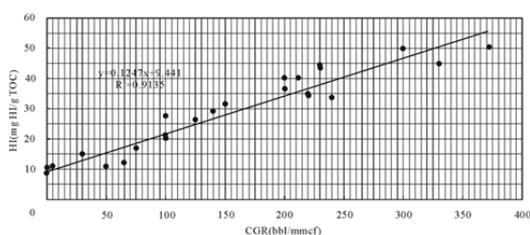

Figure 3: Relation chart of CGR with HI.

Table 1: Division standard for grades of liquid hydrocarbons in Duvernay shale.

Parameter	Grade of liquid-rich hydrocarbons				
	Dry gas	Gas condensate	Rich gas condensate	Very rich gas condensate	Rich oil
CGR(bbl/MMcf)[*]	<5	5~65	65~140	140~250	>250
HI(mg/g)	<10	10~18	18~27	27~40	>40

* From Duvernay reserves and Resources Report (2016)

The kerogen HI increases from the deformed belt in the southwest to the northeast (Figure 4). Pinto along the Leduc ring reef belt is in the CH4 generation stage due to relatively high thermal evolution degree, and the corresponding HI in the area is low, generally less than 10 mg HC/g TOC. Controlled by the deformed belt, Edson and local areas in South-eastern Willesden Green show high thermal evolution degree, thus the residual kerogen pyrolysis hydrocarbon is less in the shale. In Simonette and mostly Willesden Green, the organic matters are in the condensate gas-wet gas generation stage, showing the largest rate of conversion from kerogen to hydrocarbon.
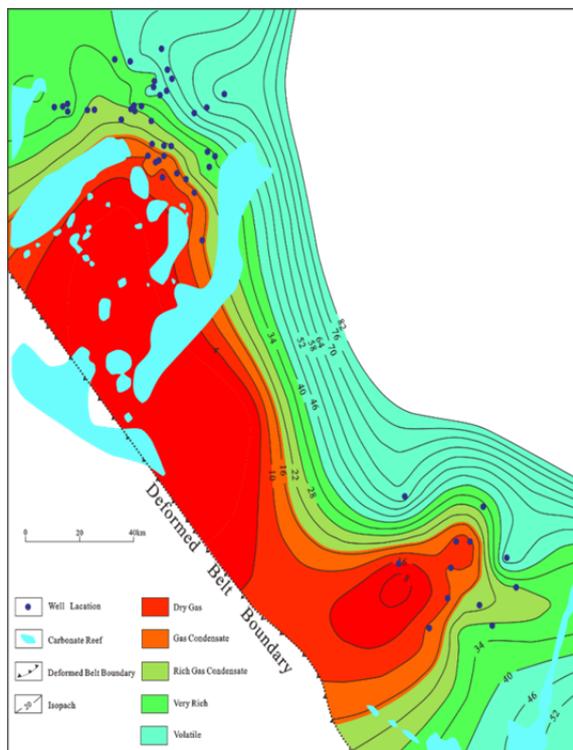

Figure 4: Planar distribution of HI values and all levels of liquid hydrocarbons.

All five grades of liquid hydrocarbons are observed in the study area, and they distribute distinctively in zones from the deformed belt to the northeast of the study area (Figure 4). In the region close to the deformed belt and the Leduc ring reef belt, dry gas is dominant. In the region within the oil generation threshold in the northeast, rich oil is dominant. The condensate oil, rich condensate oil and very rich condensate oil distribute as bands in NW-SE from Simonette to Willesden Green. The

dry gas region can serve as the reserve area, which can be developed in case of allowable economic and technical conditions. The rich oil region where liquid oil is dominant is not an ideal target due to proximal high clay mineral content, difficult drilling, high recovery cost and low recovery rate. The rich condensate oil and extra-rich condensate oil regions are the primary targets in the near future. The prediction results basically match the actual production performance of active wells.

5 CONCLUSIONS

Based on the geochemical theory, together with the pyrolysis data and well production data, the prediction of the planar distribution of liquid-rich hydrocarbons in Duvernay Shale is conducted. Some conclusions are made as follows.

According to the pyrolysis comparison experiments before and after extraction, $\triangle S2$, $\triangle S2/S2$ and $\triangle HI$ have a good correlation with Ro, $\triangle HI$ also has good correlation with $HI_{unextracted}$, and these quantitative relations can be used to correct $HI_{unextracted}$.

The corrected HI has a very good correlation with CGR. The quantitative division standard for liquid hydrocarbons has been established according to production data, and the planar distribution of all levels of liquid hydrocarbons can be predicted according to HI.

The dry gas region is distributed mainly in the tectonic deformation belt and Leduc ring reef belt. The northeast region of the study area is mainly a rich oil region. Gas condensate, rich gas condensate and very rich gas condensate are distributed in NW-SE banded shape from Simonette to Willesden Green.

ACKNOWLEDGMENT

REFERENCES

Beaton A P, Pawlowicz JG and Anderson S D A 2010-07 Organic Petrography of the Montney Formation in Alberta. Shale Gas Data Release. *ERCB/AGS Open File Report*

Behar F, Beaumont V And Penteado H L De B 2001 Roch-Eval 6 technology: Performances and development.*Oil&Gas science and technology* **56(2)** 111-134

Dan Jarvie 1984 Application of the Rock-EVAL III oil show analyzer to the study of gaseous hydrocarbons in an Oklahoma gas well. Presented at the 187th American Chemical Society National Meeting, Geochemistry Division. St. Louis, Mo

Delvaux D, Martin H and Leplat P 1990 Comparative rock-eval pyrolysis as an improved tool for sedimentary organic matter analysis. *Orangic Geochemistry* **16(4-6)** 1221-12294

Espitalie J, Madec M and Tissot B 1980 Role of mineral matrix in kerogen pyrolysis: influence on petroleum generation and migration. AAPG **64** 59-66

Jarvie D M, Philp R P and Jarvie B M 2010 Geochenical assessment of Unconventional Shale resource plays, *North America Special Issue on Shale Resource Plays due out 2nd quater*

Lafargue E, Marquits F and Pillot D 1998 Rock-eval 6 applications in hydrocarbon exploration, production, and soil contamination studies. *Revue de l'institut français du pétrole* **53(4)** 421-437

Langford F F and Blanc M M 1990 Interpreting rock-eval pyrolysis data using graphs of pyrolizable hydrocarbons Vs. total organic carbon. AAPG **74(6)** 799-804

Mossop G and Shetsen I 1994 Atlas of theWestern Canada Sedimentary Basin (Calgary: Canadian Society of Petroleum Geologists and the Alberta Research Council) chapter **3-12** pp 22-202

Rokosh C D, Lyster S, Anderson S D A 2012-06 Summary of Alberta's Shale- and Siltstone-Hosted Hydrocarbons, *ERCB/AGS Open File Report*

Shannon P M and Naylor D 1989 Petroleum Basin Studies(London) 41-57

Tissot B and Welte D H 1984 Petroleum formation and occurrence, Springen, Berlin Heideberg New York 131-160

Wang anqiao and Zheng Baoming 1987 Calibration of analytic parameters for pyrolytic chromatography (in Chinese with English Abstract). *Experiment Petroleum Geology* **9(4)** 342-350.

Yao T, Walter B A and William D M 2013 The Eagle ford shale play, South Texas: Regional variations in fluid types, hydrocarbon production and reservoir properties. **IPTC16808** 1-12