A new method to reconstruct hydrocarbon-generating histories of source rocks in a petroleum-bearing basin——the method of geological and geochemical sections

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Abstract Via investigating typical Palaeozoic and Mesozoic petroleum-bearing basins in China by using thermal maturation theories of organic matter to improve the conventional Karweil's method, a new method to reconstruct hydrocarbon-generating histories of source rocks has been suggested. This method, combining geological background with geochemical information makes the calculated VRo closer to the measured one. Moreover, it enables us to make clear the hydrocarbon generation trend of source rocks during geological history. The method has the merits of simple calculation and objective presentation, especially suitable to basins whose sedimentation and tectonic movements are complicated.

Keywords: **petroleum-bearing basin, hydrocarbon-generating histories, organic maturation.**

In the study of petroleum-bearing basin, an important task is to reconstruct hydrocarbon-generating history of petroleum basins by means of simulation calculation methods, especially in the case of lapped -basins in which the sedimentation and tectonic movements were usually complicated. There are three methods to calculate organic maturity for a petroleum-bearing basin: Karweil's method[1], effective heating time by Hood and Bostick[2,3] and time-temperature index (TTI) by Loptain and Waples[4, 5]. All these methods have some shortages in practice. The latter two are suitable to basins in which the sedimentation and tectonic movement histories were simple, and could be regarded as a continuously developing depression, but a big error could be created when it was used to calculate maturity of basins in which the tectonic movements were complicated and there was a secondary hydrocarbon generation[6]. Although tectonic movements of a petroleum-bearing basin have less effect on Karweil' s method, the calculated maturity could be higher than the measured one in case the basins have a shallow burial, very old deposits or a very slow sinking rate during geological histories[6, 7]. Moreover, they neglect the effect of hydrocarbon-generating patterns of source rocks evaluated by organic geochemical data, which confined the use of data obtaned with these methods[6].

The key to reconstructing hydrocarbon-generating histories of source rocks is to take a simulation calculation of their maturity. When applying simulation calculation methods to petroleum exploration, it is more significant to reconstruct hydrocartbon-generating histories for those basins in which the source rocks were buried deep, with a high maturation level, or whose main stage of oil generation occurred in the past. These basins usually underwent a complicated sedimentation and tectonic evolution. Thus, under this condition, Karweil's method has advantages over other methods for the simulation calculation of maturity. In this paper, the recent organic maturation theories are used to improve Karweil's method and a new method for combining geological background with geochemical data to reconstruct hydrocarbon-generating histories is suggested.

1 Method

Much exploration work carried out recently has shown that the calculated maturity by means of Karweil's method in some cases was higher than the measured one because of the overstress of the influence of heating duration of a temperature (table 1). It has been realized that the organic maturation does not always develop continuously, but could go on in stages for a basin with a complicated sedimentation and tectonic history (table 1). Therefore, it is necessary to calibrate Karweil's method in order to present objectively thermal maturation pattern under geological conditions. The most direct way to evaluate a simulation calculation method is to test whether the calculated VRo for a source rock is equal to its measured VRo. This study, based on simulation calculation results on many petroleum-bearing basins and recent theories of thermal maturation, has improved the Karweil's method in the following aspects:

Table 1 Comparison of calculated VRo with the measured VRo by the conventional Karweil's method and the improved Karweil's method

Basin	Well	Depth of sample/m	Age	Measured VRo[3](%)	Conventional Karweil' s method		Improved Karweil's method	
					Maturation rule	VRo(%)	Maturation rule	VRo(%)
Tarim[a)]	TZ1	3 600	O_1	0.95	$Z=Z_1+Z_2+Z_3=0.237$ $Z_1(63^0C,14Ma)=0.012$ $Z_2(68^0C, 170Ma)=0.18$ $Z_3(88^0C, 25Ma)=0.045$	1.05	$Z=Z_1+Z_2+Z_3=0.187$ $Z_1(63^0C,14Ma)=0.012$ $Z_2(68^0C, 150Ma)=0.13$ $Z_3(88^0C,25Ma)=0.045$	0.95
	TZ1	5 310	O_1	1.65	$Z=Z_1+Z_2+Z_3=0.82$ $Z_1(84^0C,28Ma)=0.04$ $Z_2(96^0C,260Ma)=0.65$ $Z_3(121^0C, 25Ma)=0.13$	2.20	$Z=Z_1+Z_2+Z_3=0.45$ $Z_1(84^0C,28Ma)=0.04$ $Z_2(96^0C,100Ma)=0.28$ $Z_3(121^0C,25Ma)=0.13$	1.62
	TZ1	6 500	C	2.40	$Z=Z_1+Z_2+Z_3=1.95$ $Z_1(124^0C,50Ma)=0.25$ $Z_2(136^0C,300Ma)=1.40$ $Z_3(155^0C,25Ma)=0.30$	3.40	$Z=Z_1+Z_2=Z_3=1.04$ $Z_1(124^0C,50Ma)=0.25$ $Z_2(136^0C,75Ma)=0.50$ $Z_3(155^0C,25Ma)=0.03$	2.45
	TZ12	5 079	$O_{2\text{-}3}$	1.08	$Z=Z_1+Z_2+Z_3=0.42$ $Z_1(63^0C,14Ma)=0.01$ $Z_2(77^0C,260Ma)=0.30$ $Z_3(116^0C,25Ma)=0.12$	1.52	$Z=Z_1+Z_2+Z_3=0.26$ $Z_1(63^0C,14Ma)=0.01$ $Z_2(77^0C,100Ma)=0.13$ $Z_3(116^0C,25Ma)=0.12$	1.10
	MC1	3 138	T	0.71	$Z=Z_2+Z_3=0.118$ $Z_2(48^0C,165Ma)=0.015$ $Z_1(61^0C,25Ma)=0.018$	0.76	$Z=Z_2+Z_3=0.098$ $Z_2(48^0C,150Ma)=0.08$ $Z_3(61^0C,25Ma)=0.018$	0.72
	MC1	4 424	C	0.912	$Z=Z_1+Z_2+Z_3=0.20$ $Z_1(57^0C,40Ma)=0.01$ $Z_2(67^0C,165Ma)=0.13$ $Z_3(89^0C,25Ma)=0.05$	0.98	$Z=Z_1+Z_2+Z_3=0.17$ $Z_1(57^0C,40Ma)=0.01$ $Z_2(67^0C,150Ma)=0.10$ $Z_3(89^0C,25Ma)=0.05$	0.92
Tuha[b)]	AC1	3 298	P_2	0.78	$Z=Z_1+Z_2=0.19$ $Z_1(64^0C,200Ma)=0.15$ $Z_2(86^0C,25Ma)=0.04$	0.88	$Z=Z_1+Z_2=0.14$ $Z_1(64^0C,150Ma)=0.10$ $Z_2(86^0C,25Ma)=0.04$	0.80
	AC1	4 222	$C_{2\text{-}3}$	1.10	$Z=Z_1+Z_2=0.35$ $Z_1(81^0C, 205Ma)=0.26$ $Z_2(112,25Ma)=0.09$	1.35	$Z=Z_1+Z_2=0.23$ $Z_1(81^0C,100Ma)=0.14$ $Z_2(112^0C, 25Ma)=0.09$	1.10
	LN1	3 448	$C_{2\text{-}3}$	1.05	$Z=Z_1+Z_2+Z_3=0.30$ $Z_1(58^0C,35Ma)=0.02$ $Z_2(79^0C,128Ma)=0.15$ $Z_3(95^0C,67Ma)=0.13$	1.25	$Z=Z_1+Z_2+Z_3=0.26$ $Z_1(81^0C,100Ma)=0.02$ $Z_2(79^0C,100Ma)=0.11$ $Z_3(95^0C,67Ma)=0.13$	1.08
	TC2	4 710	J_{2x}	0.90	$Z(88^0C,137Ma)=0.24$	1.15	$Z(88^0C,100Ma)=0.19$	0.92

a) Xiao Xianming, Liu Dehan, 1998, The formation and evolution of the oil and gas pools in Tazhong area, Internal report of a state key project, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. b) Fu Jiamo, Xiao Xianming, 1998, Hydrocarbon-generating conditions and petroleum migration of Lukeqing structure belts in Tuhan Basin, Internal report of a contract project with the Exploration and Development Institute of Tuha Oil Field, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. The VRo of early Palaeozoic source rocks is from the measured reflectance of bitumen and marine vitrinite.

(1) Unreversal rule of maturity. When a source rock reached a maturation level, it could not be reduced by the uplifting and a reducing palaeotemperature during the late geological evolution.

(2) Thermal maturation equilibrium rule. The duration of heating has a positive effect on organic maturation, but when the organic maturation reactions arrive to an equilibrium at a temperature, the duration of heating will no longer have a significant effect on maturation.Only with increasing temperature, would the thermal maturation go on further. For instance, the lower Carboniferous coal in the Moscon Basin is still in the stage of liginite because it has never sinked to a depth corresponding to

temperature of higher than 25℃ since its deposition[4]. The conventional Karweil's method paid too much attention to the duration of heating to get a higher calculated maturity than measured one in many cases. According to the results of thermal simulation tests[8] and a number of typical examples of petroleum basins, it has been found that the equilibrium time is related to temperature, and the higher the temperature, the shorter the equilibrium time. The equilibrium time suggested in the study is: 150 Ma (<75℃); 100 Ma (75—100℃); 75 Ma (100—150℃) and 50 Ma (>150℃). The thermal maturaton equilibrium rule is an important improvement to the Karweil's method.

(3) Thermal maturation stage rule. It is necessary to subdivide maturation histories of source rocks into several stages on the basis of the burial and palaeotemperature history controlled by tectonic movements of a basin in applying Karweil's method to calculate maturity. The thermal maturation could be continuous or interrupted, but the late maturation could incorporate into the early maturation.

(4) Re-maturation rule of organic matter. For a basin with a tectonic movement by the manner of sinking-uplifting-sinking, the condition for rematuration of a source rock is usually that palaeotemperature during the secondary subsidence should be higher than during the earlier subsidence. However, for a basin in which source rocks have never arrived to a thermal maturation equilibrium during the first subsidence, a lower palaeotemperature would make the maturation restart[6].

Quite a few examples have shown that the VRo calculated with the improved Karweil's method is very close to the measured VRo (table 1).

Another aspect to be considered in reconstructing hydrocarbon-generating histories of a set of source rocks in a petroleum-bearing basin is its hydrocarbon-generating pattern. Much work has shown that different combinations of macerals in source rock could lead to a significant variation in their oil window. For instance, the oil birth line of type II kerogen, a wide occurrence of kerogen type in various origins of source rocks, varies from 0.40% to 0.65% of VRo, and its oil death line from 0.90% to 1.25% of VRo. Even in the normal palaeotemperature gradient field, this differential maturation will lead to a corresponding burial depth difference in the position of oil window in a geological section varying from 400 to 700 m. Lithology of source rocks is another important factor that influences the position of oil window. Because of the debt compaction of carbonate, it presents a lag of the hydrocarbon generation behind its associate argillaeous source rocks. This lag could be as high as 0.20%—0.30% of VRo[9].

To reconstruct the hydrocarbon-generating history of a source rock for a borehole in a petroleum-bearing basin, the following steps are suggested.

(1) Making a diagram to present the burial history of strata of the borehole according to the stratigraphic data.

(2) Making a geological section for a selecting geological age for simulation calculation of maturity and determining the points to be calculated, which are usually selected near the boundary between strata of different ages.

(3) Calculating the maturity for the selected points by using the improved Karweil's method, and making a diagram of VRo against depth.

(4) Determining the position of oil window for the target source rocks by using the analytical results of organic geochemstry. For a new area or the deep strata of the borehole for which there are not available data, the oil window could be deduced by relative analytical results of nearby boreholes, seismic stratigraphic data and the distribution pattern of sedimentary facies. Then, the hydrocarbon-generating model is applied to the above geological-geochemical section.

These four steps have completed the establishment of a hydrocarbon-generating section at the selected geological age for the borehole. In the same way, hydrocarbon-generating sections for the borehole at any other geological ages can be obtained. A collection of a group of these sections presents the hydrocarbon-generating history of source rocks at the borehole and it is useful to investigating their hydrocarbon-generating trend of the source rocks.

2 Examples

The Tazhong petroleum system in the Tarim basin includes two main source areas: the North Slope and the southern part of the Manjiaer Depression (fig. 1). Substantial data obtained by organic geochemical analysis have confirmed that the black grey argillacous limestone of middle and upper

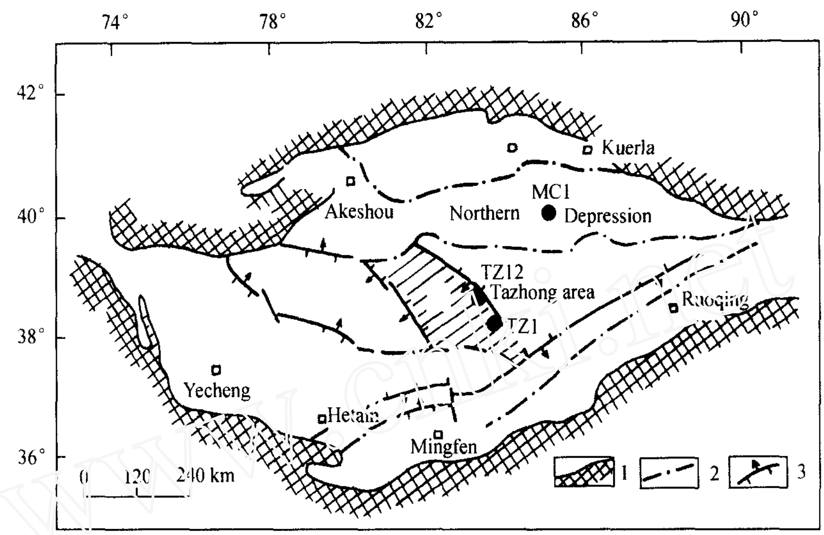

Fig. 1. A map showing the well position of the Tazhong area in Tarim Basin.

Ordovician age in the North Slope is a set of significant source rocks. There are no boreholes deep enough to intersect the Cambrian-Ordovician strata in the Manjiaer Depression, so no data are available for the strata. Based on seismic stratigraphic sections through this depression, some analytical data on the boreholes in the surrounding areas, and the distribution of sedimentary facies, it has been postulated that there could be a set of similar source rocks in the Cambrian-Ordovician strata in the Manjiaer Depression[10]. At present, there is no general idea on the hydrocarbon-generating history for the source rocks in the two source areas. In this paper, two typical boreholes TZ12 and MC1 were selected to investigate the hydrocarbon-generating histories of Cambrian and Ordovician strata by means of the method suggested by this paper.

Fig. 2(a) shows the burial history of the strata of the well TZ12. It is obvious that the thermal maturation of the Cambrian- Ordovician strata can be subdivided into three stages:

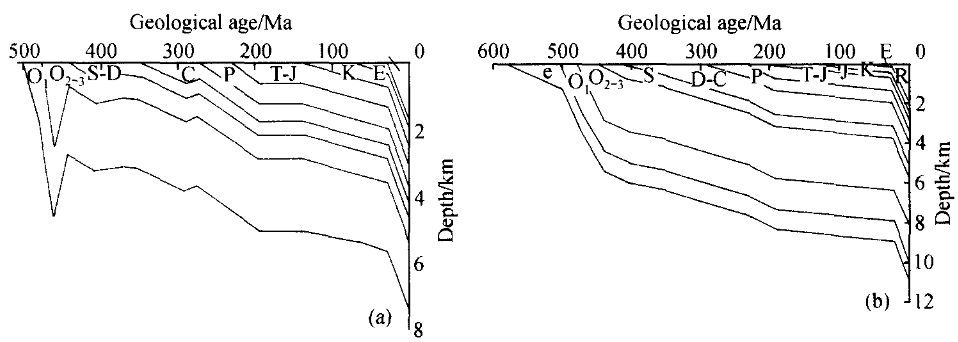

Fig. 2. The burial histories of the well TZ12 in the North Slope(a) and the well MC1 in the Manjiaer Depression (b).

Stage I. Ranging from Cambrian to middle and late Ordovician. The marine strata with a thickness of about 4 500 m deposition and the source rocks underwent an early maturation. The maturation reactions never reached an equilibrium because of the uplifting of this area during Caledonian movement.

Stage II. Ranging from Triassic to Early Tertiary. After the uplifting and erosion of the strata during the Caledonian and early Hercynian movements, this area rapidly subsided again, and a set of strata with a thickness of more than 2 000 m deposited. Although the palaeotemperature suffered by the Cambrian-Ordovician strata was not high during this period, the maturation could go on. This maturation was characterized by low temperature and long duration, with a slow maturation rate.

Stage III. Covering the whole late Tertiary. Nearly 2 500 m thick flurial and lake deposits were formed during this period and the Cambrian-Ordovician strata suffered from the highest temperature, having a significant increase in their maturity.

Fig. 2 (b) shows the burial history of the well MC1. This area could be regarded as a continuously developing depression . The thermal maturation of the Cambrian-Ordovician strata could be subdivided into three satges:

Stage I. Ranging from Cambrian to Siliurian; marine strata with a total thickness of 6 000 m developed in this area, which led to a rapid maturation of the source rocks.

Stage II. Ranging from Devonian to early Tertiary, with total sediment about 2 500 m and thermal maturation of the Cambrian-Ordovician strata increasing slowly during a long period.

Stage III. Occurring in the late Tertiary, with sediments about 2 300 m thick, and the maturity pushed on further.

According to the maceral analysis results of the Cambrian-Ordovician strata in the North Slope and the Tazhong area, the original source matter that forms hydrocarbon is mainly algae-amorphinite and biodegraded-amorphinite, with a type II kerogen. The source rocks are dominated by mudstone and argillacous limestone. This type of source rocks has an oil window ranging from 0.60% to 1.20% of VRo, and its oil generating peak occurs at about 1.0% of VRo. This hydrocarbon-generating pattern has been applied to the Cambrian-Ordovician source rocks in the Manjiaer Depression.

Both areas had a lower palaeotemperature gradients: 2.3℃/100 m during Cambrian-Ordovician and 2.0℃/100 m after Mesozoic[7, 11].

According to these data, the hydrocarbon-generating sections of the well TZ12 and MC1 at a few geological ages have been established by this method. The results shows that the main stage for oil generation of the Cambrian source rocks was from late Silurian to early Devonian, and from late Triassic to early Jurassic for the middle and upper ordovician source rocks in the Manjiaer Depression (fig. 3). However, the main stages of oil generation of the middle and upper Ordovician source rocks in the north slope occurred during late Tertiary (fig. 4). In consideration of reservoir-cap rock combinations, as well as the relationship in time and space for the formation of the trap structures, it was believed that petroleum generation from the Cambrian strata in the Manjiaer Depression could migrate into the early Silurian sandstone reservoir in the Tazhong area to form oil and gas pools, but the tectonic movements occurred during late Caledonian, and early Hercynian destroyed them . Only the petroleum formed from middle and late Ordovician strata in the two areas during late Triassic—early Jurassic and late Tertiary had a good conservation condition for oil and oil pools. This idea is coincident with the results of recent petroleum exploration carried out in the Tazhong area. The early Silurium bitumen sandstone occurring widely in the North Slope has been confirmed to be a residual palaeo-oil

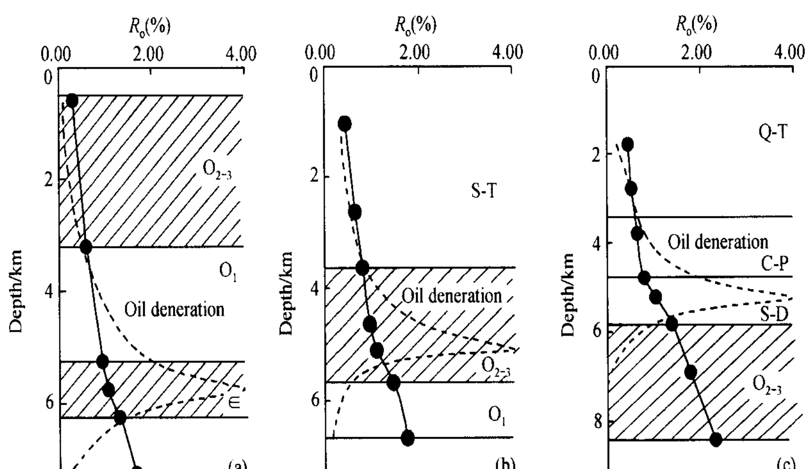

Fig. 3. Geological sections of hydrocarbon generation of the Cambrian-Ordovician source rocks in the Manjiaer Depression at a few geological ages. (a) After deposition of Silurian; (b) after deposition of Triassic; (c) after the deposition of Tertiary.

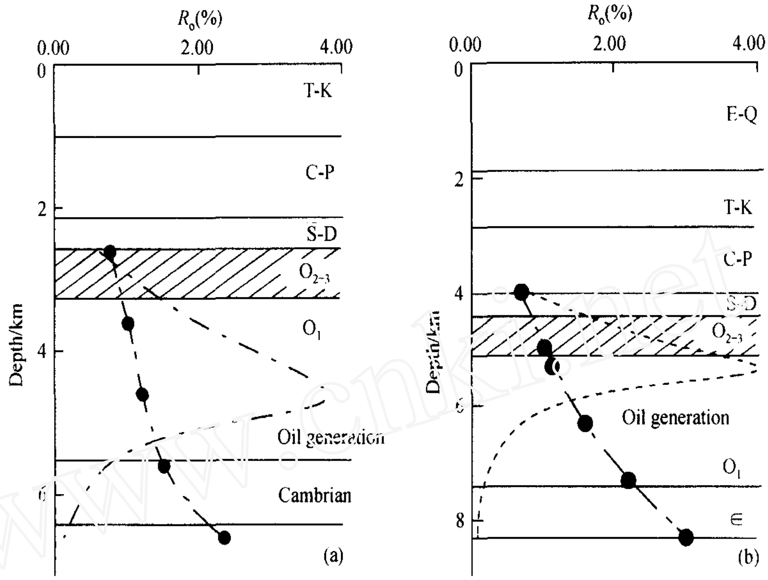

Fig. 4. Geological sections of hydrocarbon generation of the Ordovician source rocks in the North Slope at a few geological ages. (a) After the deposition of Cretacous; (b) after the deposition of Tertiary.

and gas pool which was destroyed during late Caledonian movement. The commercial oil and gas pools have been mainly formed from the middle and upper Ordovician source rocks in the North Slope during late Tertiary.

3 Conclusion

The reconstruction of the hydrocarbon-generating history for source rocks is an important tool to evaluate a petroleum-bearing basin. Since the method suggested in this paper has some obvious advantages over other methods in that it has simple calculation, objective results and a collection of geological and geochemical information, it has great potential for evaluating hydrocarbon generation and direct petroleum-exploration of lapped basins in China.

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