A new method based on vitrinite reflectance gradient to determine paleotemperature gradient of a petroleum-bearing basin

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Abstract Based on the Arrhenius equation and Karweil method, a simulation calculation has been made on the thermal maturation of organic matter under a series of assuming paleotemperature gradients. Results show that there was a positive correlation of vitrinite reflectance gradient with paleotemperature gradient and vitrinite reflectance. According to this, a model has been established which presents the quantitative relationship between three parameters. This model can be directly applied to determining the paleotemperature gradient of a petroleum-bearing basin with the measured vitrinite reflectance.

Keywords: petroleum-bearing basin, paleotemperature gradient, vitrinite reflectance gradient, vitrinite reflectance.

THE evaluation of paleotemperature and paleotemperature gradient (ΔPT) of a petroleum-bearing basin is an important task for its exploration, but it has not been solved sucessfully[1,2]. Methods of common usage include simulation calculation of TTI and temperature measurement of fluid inclusions. However, both of them have obvious shortages. The calculation of TTI should be based on a pre-supposed PTG, and the results could be varied, especially for a basin where the burial history controlled by the sedimentation and tectonic movement is complicated[1]. Big problems for the temperature measurement of fluid inclusions are: (i) a great error usually occurs for the measurement of the temperature; (ii) the phases and geological time for the formation of the fluid inclusions can hardly be determined accurately; (iii) there is a minor amount of fluid inclusions in sedimentary rocks which can be used to measure the temperature. In recent years, apatite fission track analysis has also been applied to studying paleotemperature for a petroleum-bearing basin. However, this method has not been well established, and the results are affected by a series of factors including geological and man-made, and it is believed to be used as a supplementary method at this moment. Even for this, the above methods could reveal valuable information on paleotemparature for the exploration of a petroleum-bearing basin from different viewpoints. However, they are complicated and much time-consuming, and sometimes the error is too big to be used in exploration.

Organic petrologists observed many years ago that there was some relationship between vitrinite reflectance and the paleotemperature, but it is not easy to evaluate directly the relationship between them because there are many geological factors having a significant effect on vitrinite reflectance. Teichmuller (1979) discovered a positive correlation between VR_0 (vitrinite reflectance) and ΔVR_0 (vitrinite reflectance gradient)[4]. The quantitative relation has not been established up to now although a similar description was followed by others in literature.

In this study, the quantitative relationship between ΔVR_0 and ΔPT is investigated by using theories and methods of organic maturation such as Arrhenius equation and Karweil method. A new method based on ΔVR_0 to determine the paleotemperature of a petroleum-bearing basin is suggested.

1 Method

Researches have shown that organic maturation level depends mainly on temperature and length of time the organic matter retains that temperature, and that this process follows the chemical reaction of the first order and Arrhenius equation, i.e. the thermal maturation has an exponential relation with temperature and a linear relation with the duration of its influence. The correlation between them can be described by the following equation:

$$L_n \cdot n_0/n = A \cdot t \cdot e^{-E/RT},$$

where n_0 and n represent the reactive groups for initial stage of thermal maturation and the groups for a maturation level arriving at, respectively. n_0/n is an indicator of the thermal maturation level. A is the frequency factor; E, the activation energy; R, the universal gas constant; t, the duration of a temperature; T, the temperature.

This equation is a starting point for all calculations concerning the rate of maturation[5,6].

Based on the equation, Karweil took Ruhr coalfield as an example, made a calculation of the relationship between maturation level, temperature and the duration of that temperature, and established a well-known Karweil's diagram[5]. It was added and improved by Bostick[7], and this improved Karweil's diagram has been widely applied to petroleum exploration.

A current opinion, based on a number of examples, suggested that although the obvious shortage for Karweil's diagram was that it stressed the influence of the duration of temperature too much, it is very suitable for determining the paleotemperature with a high accuracy for a basin which is characterized by a continuous subsidence or a relative short duration of a temperature range (less than 100 Ma for which the thermal maturation should not arrive at an equilibrium). Thus in the present study, the simulation calculation was directly based on Karweil method, and the following steps are taken.

(i) The maturation level was calculated, starting from 50℃, by a series of assumed paleotemperature gradients of 20℃/km, 20℃/km, 30℃/km, 40℃/km, 50℃/km and 60℃/km, respectively.

(ii) A supposition was made that the basin was continuously subsiding, and the duration of a temperature range was less than 70 Ma, mainly 30 Ma.

(iii) In order to investigate the influence of the duration of the temperature on ΔVR_0, a simulation calculation for the above supposed paleotemperature gradients was made with the durations of 10, 30, 50 and 70 Ma, respectively.

(iv) The standard rules for vitrinite reflectance gradient and paleotemperature gradient were used, expressed as ΔVR_0/km and ΔPT/km, respectively.

2 Results and discussion

The simulation calculation results are presented in figs. 1 and 2. It can be seen that ΔVR_0 depends mainly on ΔRT and maturation level (VR_0), but the influence of the duration of the temperature depending on it is not obvious. The higher the maturation level and/or the higher the ΔPT, the greater the ΔVR_0. Thus, the effect of the duration of the temperature on ΔVR_0 could be neglected in normal geological conditions.

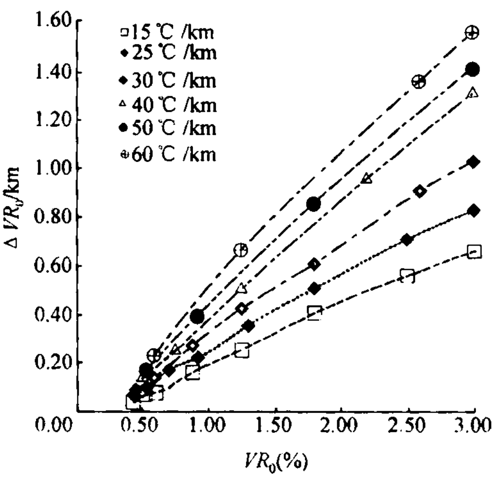

Fig. 1. Correlation of $\Delta VR_0 - VR_0$ for different paleotemperature gradients.

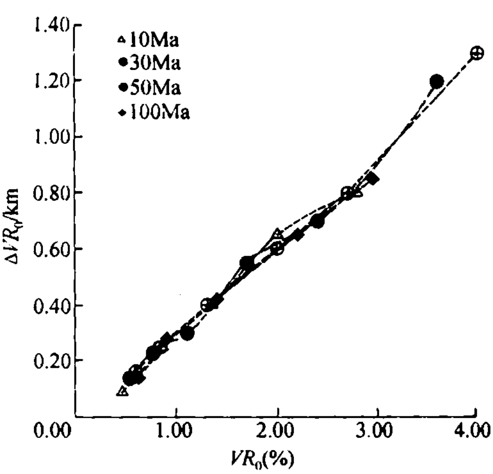

Fig. 2. Correlation of $\Delta RV_0 - VR_0$ for different durations of temperature.

According to the measuring vitrinite reflectance, a ΔVR_0 can be calculated by the following equation:

$$\Delta VR_0 = (R_{H2} - R_{H1})/(H2 - H1),$$

where $H2$ and $H1$ represent the depth of two measuring samples ($H2 > H1$); R_{H1} and R_{H2} represent the vitrinite reflectance of the two samples.

ΔPT can be deduced in fig. 1 by the correction of $\Delta VR_0 - VR_0$ of the measuring samples. For a reasonable explanation of the data of ΔPT, the following points should be mentioned.

(i) The calculation of a ΔVR_0 should be based on the reflectance data with a high reliability, and the depth range between $H2$ and $H1$ had better be kept at 1 000 m. Since ΔVR_0 could vary in a minor range with the sample points being selected for the calculation, a better way to minimize the error is to calculate ΔVR_0 by selecting the sample points alternatively when the available data are adequate.

(ii) The sedimentation and tectonic movement of a basin is an important factor to affect the correlation of $\Delta VR_0 - VR_0$. For the Mesozonic-Cenozonic young basin where its burial history was usually simple and could be considered as continuous subsiding, the correlation of $\Delta VR_0 - VR_0$ presents the paleotemperature gradient during the basin subsiding. For a subsiding-uplifting basin, since the thermal maturation took place mainly before the basin uplifting, the correlation of $\Delta VR_0 - VR_0$ presents the paleotemperature before the basin uplifting. For a basin with the movement of sudsiding-uplifting-sudsiding, two situations are included: one is that the thermal maturation occurred mainly during the first phase of subsidence, and the correlation of $\Delta VR_0 - VR_0$ presents the paleotemperature gradient before the basin uplifting; the other is that the thermal maturation occurred mainly during the second phase subsidence, and it presents the paleotemperature gradient after the basin uplifting.

(iii) Since the paleotemperature gradient of a basin would vary from age to age, any available method for the determination of paleotemperature gradient could not show its evolution directly. The correlation of $\Delta VR_0 - VR_0$ can be applied to revealing the paleotemperature gradient at the main evolution stages of the basin.

3 Examples

ΔVR_0 for a few typical basins, whose paleo-temperature and paleotemperature gradient were well studied, was calculated using the available vitrinite reflectance data. The results show that the paleotemperature gradients deduced by the correlation of $\Delta VR_0 - VR_0$ in fig. 1 were quite similar to those from other methods in literature (table 1). Moveover, the paleotemperature gradients of TZ-1 (Tazhong 1 borehole) and TZ-12 (Tazhong 12 borehole) in Tazhong uplift of Tarim Basin were studied by the method. The results in fig. 3 show that the paleotemperature gradient for TZ-1 is 25℃/1 000 m in the Cambrian-Ordovician, 50℃/1 000 m in the Carboniferous-Permian (the higher paleotemperature gradient would be caused by the volcano activities occurring in the Early Permian), and 20℃/1 000 m in the Mesozonic which is close to current geotemperature gradient. TZ-12 is located at the northern slope of the uplift, and the

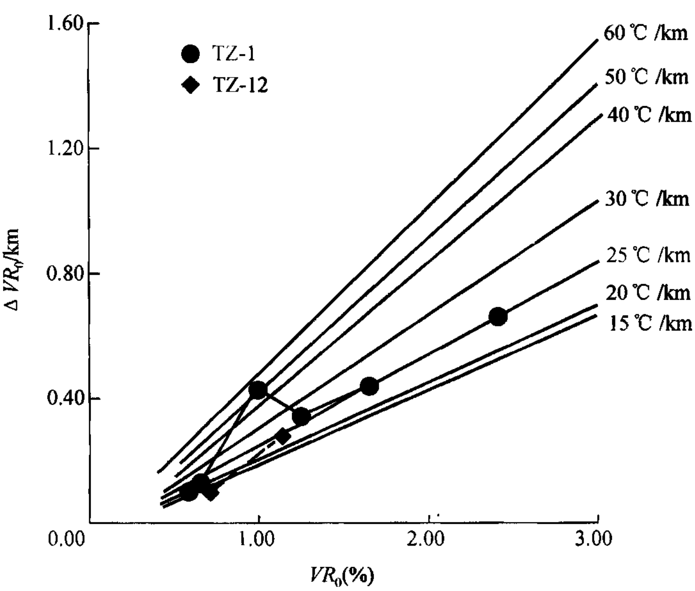

Fig. 3. Position of $\Delta VR_0 - VR_0$ in the model for TZ-1 and TZ-12 in Tazhong uplift of Tarim Basin.

paleotemperature gradient in the Cambrian-Ordovician was about 23℃/1 000 m. These results are quite similar to those determined by Jin[3] using other methods.

Table 1 Comparison of the paleotemperature gradients determined by ΔVR_0 method with other methods for some typical basins in the world

Basin	Borehole	Age of sample	Range of depth/m	ΔPT determined by other methods (℃/1 000 m)	Sample depth/m	Vitrinite R_0(%)	ΔVR_0 (%)/1 000 m	ΔPT determined by ΔVR_0 (℃/1 000)
Ruhr Coalfield	Munsterland 1	C	2 000—4 000	43.5	2 000	1.35		
					3 000	2.50	1.15	43.0
					4 000	4.00	1.50	43.0
Upper Rhine graben	Sandhausen 1	R	2 000—2 850	42.0	2 000	0.45		
					2 850	0.70	0.29	44.0
	Hatanhausen 1	R	1 500—2 250	67.0	1 500	0.65		
					2 250	1.25	0.62	52.0
Bohaiwan Basin	Dongpu depressin	E	3 045—3 849	54.0	3 040	0.80		
					3 367	1.00		
					3 528	1.10		
					3 849	1.30	0.62	52.0
	Jinzhong Raoyangning 3	E	4 267—5 240	28.0	4 263	0.89		
					4 692	1.05		
					5 240	1.24	0.36	28.0
Beise Basin	Bai 45	N	1 234—1 801	34—36	1 234	0.48		
					1 520	0.57		
					1 609	0.61		
					1 801	0.63	0.25	35

4 Conclusion

To use ΔVR_0 to determine paleotemperature gradient has two obvious advantages over the other methods. Firstly, it is only involved in one parameter of vitrinite reflectance, and the calculation of ΔVR_0 and ΔPT is quite simple. Secondly, the measurement of vitrinite reflectance is standardized internationally, and the high accuracy and repeatability of it compensates for the deficiencies of error of other methods. Thus this method has great potential to be used to determine paleotemperature gradients in the exploration of a petroleum-bearing basin, and is worth improving and popularizing.

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