Determination of paleo-pressure for a natural gas pool formation based on PVT characteristics of fluid inclusions in reservoir rocks

——A case study of Upper-Paleozoic deep basin gas trap of the Ordos Basin

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Abstract It has been proved to be a difficult problem to determine directly trapping pressure of fluid inclusions. Recently, PVT simulation softwares have been applied to simulating the trapping pressure of petroleum inclusions in reservoir rocks, but the reported methods have many limitations in practice. In this paper, a method is suggested to calculating the trapping pressure and temperature of fluid inclusions by combining the isochore equations of a gas-bearing aqueous inclusion with its coeval petroleum inclusions. A case study was conducted by this method for fluid inclusions occurring in the Upper-Paleozoic Shanxi Formation reservoir sandstones from the Ordos Basin. The results show that the trapping pressure of these inclusions ranges from 21 to 32 MPa, which is 6—7 MPa higher than their minimum trapping pressure although the trapping temperature is only 2—3℃ higher than the homogenization temperature. The trapping pressure and temperature of the fluid inclusions decrease from southern area to northern area of the basin. The trapping pressure is obviously lower than the state water pressures when the inclusions formed. These data are consistent with the regional geological and geochemical conditions of the basin when the deep basin gas trap formed.

Keywords: Ordos Basin, fluid inclusion, PVTsim, trapping pressure.

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The determination of paleo-pressure and paleo-temperature for the formation of oil and gas pools is an important task to understand the formation mechanism of the oil and gas pools, and has great significance in petroleum exploration. The trapping pressure of fluid inclusions in a petroleum reservoir rock represents the paleo-pressure at which the petroleum formed. However, there are many difficulties in acquiring the trapping pressure of fluid inclusions in reservoir rocks. The conventional method is to use some charts and tables, and some empirical equations, which are based on aqueous inclusions or carbon dioxide inclusions to determine paleo-pressure. These methods have not been widely accepted since they have some limitations and different authors developed different empirical equations. In recent years, there have been some reports on the determination of trapping pressure of inclusions using PVTsim softwares. A typical work was done by Aplin et al.(2000) in the North Sea Oil Field[1]. They measured the liquid to vapor ratio of organic inclusions using Confocal Laser Scanning Microscopy(CLMS), and calculated the composition, physical property, saturated pressure and trapping pressure of petroleum inclusions in the reservoir rocks using PVT SIM software. In using the method, they thought that the intersection-point data of petroleum inclusion isoline and the vertical line which pass the point of the coeval aqueous inclusion homogenization temperature represent the trapping pressure and temperature of the petroleum inclusion. However, theoretically the isochore of an aqueous inclusion is not a vertical line in its PT diagram, but a bias. The slope of an aqueous inclusion isochore varies with its homogenization temperature and salinity. Additionally, the method by which Aplin et al. (1999, 2000) calculated the liquid to vapor ratio also has some shortages[2,3].

In this paper, the authors propose a method to calculate the trapping pressure and temperature of fluid inclusions by combining the isochore equations of both petroleum inclusions with their coeval aqueous inclusions.

1 Method

Natural gases could partly dissolve in water, but gas and water do not form a single-phase fluid in natural geological conditions. In a rock sample, fluid inclusions formed from the same fluid will have the same temperature and pressure, and it is also possible to form different types of fluid inclusions, mainly including petroleum inclusions, and aqueous fluid inclusions. Since an inclusion can be regarded as a closed system, its volume does not change unless it was broken or leaked. The phases of different inclusions will change along their isochors with temperature. When the temperature decreases (for instance, the petroleum inclusion A in fig. 1), the inner pressure of the inclusion decreases, and the phases of the inclusion will vary along the PT-TH isochore. In the point TH (homogenization temperature point), the dissolved gas begins to be separated from fluid to form a bubble in the inclusion. In two-phase area of the inclusion, its PT condition will change along TH-M isochore, up to room temperature (the M point). In fact, to measure the homogenization temperature of the petroleum inclusion is to try to find the minimum temperature (the TH point) at which the inclusion homogenizes into a single liquid phase from two phases along the M-TH isochore[1,4]. To find the trapping point (the PT point) of the petroleum inclusion is to look for the point where its temperature and pressure are equal to those of its coeval aqueous inclusions (such as the inclusion B in fig. 1) along the single phase isochore (TH-PT), i.e. the PT point in fig. 1 where its isochore will intersect the isochore of its coeval aqueous inclusion[2,5].

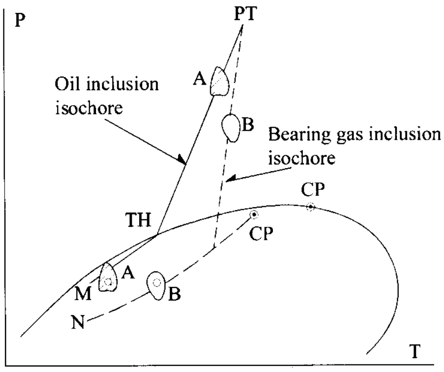

Fig. 1. The sketch of phrase change.

In order to get the trapping point of a petroleum inclusion or the isochore equations of a petroleum inclusion and their coeval aqueous inclusions, the following parameters should be achieved:

(i) homogenization temperatures of both petroleum inclusions and their coeval aqueous inclusions; (ii) liquid:vapor volume ratio of these inclusions; (iii) compositions of these inclusions.

The heating and cooling stages produced by U.S.G.S, FLUID INC were used to measure the homogenization temperature and ice melting point temperature. The heating rate is 2℃—4℃/min. The measuring error of the temperature is within 1℃.

A widely applied method to calculate the volumetric liquid to vapor ratio of a fluid inclusion is based on its area liquid to vapor ratio to represent its volumetric ratio[6]. Aplin et al. (1999) suggested a method by which a inclusion can be sliced into many layers using CLMS, and the areas of both the liquid phase and the vapor phase of a inclusion for different layers can be calculated by means of an image analysis software equipped with CLSM, and then the volumes of liquid phase and vapor phase can be achieved using volumetric equation of cylinder[11]. In our study, we have found that for a fluid inclusion without fluorescence, its liquid phase and vapor phase cannot be clearly distinguished. Thus, this method cannot be applied to calculating liquid to vapor ratio of this kind of inclusions. Moreover, for a fluorescence inclusion with a larger vapor phase, fluorescent liquid phase will illuminate some area of the bubble to get a less liquid to vapor ratio (fig. 2). Thus, the slice method to calculate an inclusion's volumetric liquid to vapor ratio is not very precise in some cases. Our method is that firstly, area liquid to vapor ratio of a inclusion was calculated by the image analysis software in CLSM, and then the inclusion is considered as spore to calculate its volumetric liquid to vapor ratio.

It is difficult to directly measure the compositions of a single petroleum inclusion. In this paper, we simulate an inclusion composition by PVTsim software after the method suggested by Aplin et al. (1999)[7]. Tables 1 and 2 present gas composition and petroleum composition used to simulate compositions of petroleum inclusions and gas-bearing inclusions. The method was reported in detail by Mi Jingkui et al. (2002)[7].

Table 1 A gas composition used for gas-bearing inclusion composition simulation

Composition	C1	C2	C3	iC4	nC4	iC5	nC5
Mole (%)	96.415	2.030	1.137	0.225	0.077	0.084	0.032

The data are the average composition of natural gas from Upper-Paleozoic strata in Ordos Basin.

After the inclusion composition was simulated, the isochore equation of a petroleum inclusion could be obtained by the following steps:

(1) Calculate its minimum trapping pressure (P_0) at the homogenization temperature. The saturated point (P_0, T_0) can be gotten. Remember the volume (V_0) of the inclusion at P_0 and T_0 conditions.

(2) Another PT point (P_1, T_1) should be obtained using the multi Flash programs of the PVT SIM, and a temperature T_1 slightly higher than its homogenization temperature. The correspondent P_1 can be achieved by

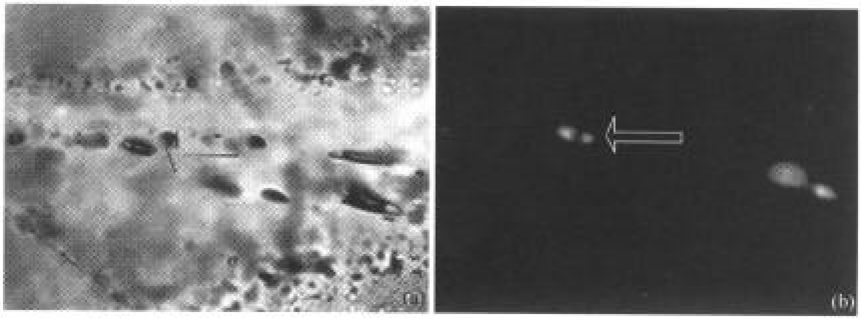

Fig. 2. Fluid inclusions (Meng Well 5, Shanxi Formation, 1890 m, sandstone reservoir). (a) Petroleum inclusions, transmission light, ×300, (b) petroleum inclusions, fluorescent light, ×300.

Table 2 A petroleum composition used for petroleum inclusion composition simulation

Composition	C_1	C_2	C_3	iC_4	nC_4	iC_5	nC_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}
Mole (%)	8.32	7.80	8.40	2.15	5.69	2.45	3.56	6.32	7.04	7.67	6.95	6.50	5.11	4.02
Composition	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}	C_{18}	C_{19}	C_{20}	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	
Mole (%)	3.40	3.11	2.74	2.01	1.64	1.19	1.11	0.84	0.64	0.53	0.40	0.30	0.21	

the condition of $V_1 = V_0$.

(3) Isochore equation can be obtained using the two-points (P_0, T_0 and P_1, T_1).

The isochore equation of an aqueous inclusion could be obtained with the same method. Thus, the trapping pressure and temperature can be obtained by combining the isochore equations of these two kinds of inclusions.

2 A case study

The reservoir sandstones of Upper-Paleozoic deep basin gas trap in the Ordos Basin are mainly quartz sandstones cemented by argillaceous. The overgrowth of quartz grains in the sandstones is not developed, but there are many secondary fluid inclusions in the micro-fissure. These fluid inclusions are mostly gas-bearing inclusions since the source rocks of the Carboniferous-Permian coal-measures[8—10] have higher maturity. These inclusions contain vapor phase and water. The vapor phase composition is believed to be mainly methane through exploded composition measurement of the inclusions and their ice melting point temperature measurement. Some petroleum inclusions associated with gas-bearing inclusions were found only in samples from a few wells in the northeast area of the basin. In this paper, the authors propose a method to deduce the trapping pressure and temperature of a gas-bearing inclusion without coeval petroleum inclusion. Firstly, we get the trapping pressure and temperature using the two kinds of inclusions occurring in the samples from the Wells M4 and M5. Secondly, we calculate the differences between trapping temperature and homogenization temperature, and between trapping pressure and the minimum trapping pressure of the gas-bearing inclusions from the two wells, respectively. Then, these differences can be used to calibrate trapping pressure and temperature of inclusions on the basis of the minimum trapping pressure and homogenization temperature of the gas-bearing inclusions occurring in other parts of the basin without petroleum inclusions.

The Upper Paleozoic sediments in the Ordos Basin are lake and river facies, and the thickness and distribution for a single sandstone body in the strata vary greatly. Much work has shown that the migration and accumulation of natural gases were controlled by the shape of sandbody. In this study, more than 20 reservoir sandstone samples from 18 boreholes were selected to measure the homogenization temperature and liquid to vapor ratio of fluid inclusions, and simulate and calculate their compositions and trapping pressure. The representative results are shown in figs. 3 and 4 and tables 3—5.

From the above data along with the strata state water pressure of the samples, the following recognitions can be gotten:

(1) From southern area to northern area of the basin, the content of the water in fluid inclusions increases from 80.915% to 89.951%, but the content of gas decreases from 19.09% to 10.049%. These are consistent with the practical geological conditions of

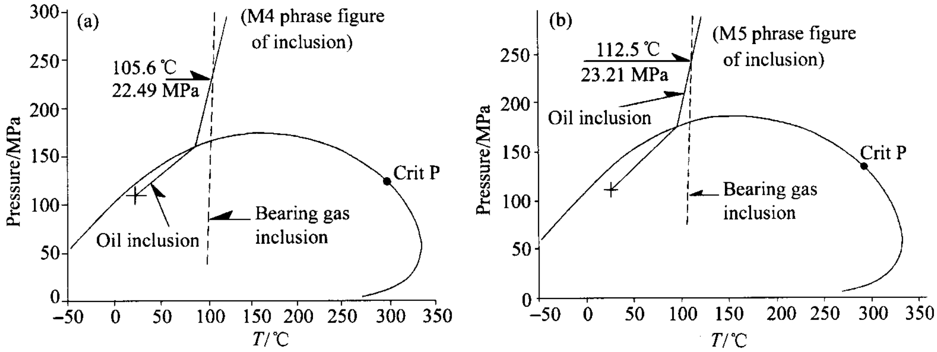

Fig. 3. Isochores of a petroleum inclusion and its covel gas-bearing inclusion. (a) Mang Well 4, Shanxi Formation, 2555—2560.5 m, (b) Meng Well 5, Shanxi Formation , 1903 m.

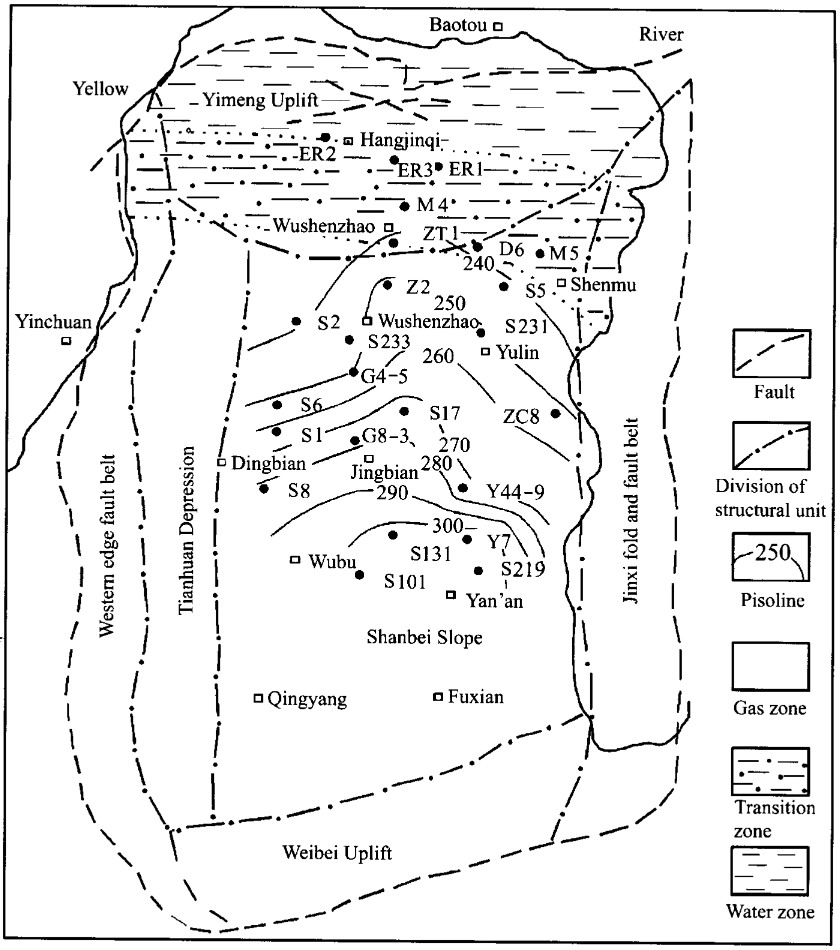

Fig. 4. A plot showing the trapping pressure of fluid inclusions.

Table 3 Compositions of gas- bearing inclusions gotten by PVTsim simulation

Well No	Age	Depth/m	Composition							
			H2O	C1	C2	C3	*i*C4	*n*C4	*i*C5	*n*C5
M5	P1	1890	84.699	14.699	0.313	0.176	0.035	0.012	0.013	0.053
M4	P1	2555/2560.5	85.951	13.496	0.287	0.162	0.032	0.011	0.012	0.049
ZT1	P1	2993	84.342	15.041	0.320	0.180	0.036	0.012	0.014	0.055
Z4	P1	3100	83.182	16.156	0.344	0.193	0.038	0.013	0.015	0.058
S17	P1	2983.5	80.915	18.334	0.390	0.219	0.043	0.015	0.017	0.066

Table 4 Compositions of petroleum inclusions gotten by PVTsim simulation

M5	composition	C_1	C_2	C_3	iC_4	nC_4	iC_5	nC_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
	mole (%)	46.089	5.316	5.274	1.322	3.272	1.433	2.176	3.595	4.005	4.363	3.954	3.698	2.907
	composition	C_{12}	C_{13}	C_1	C_{15}	C_{16}	C_{17-18}	C_{19-20}	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	
	mole (%)	2.287	1.934	1.769	1.559	1.143	1.610	1.109	0.364	0.302	0.228	0.171	0.119	
M4	composition	C_1	C_2	C_3	iC_4	nC_4	iC_5	nC_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
	mole (%)	43.633	5.477	5.477	1.376	3.428	1.499	2.266	3.772	4.202	4.578	4.148	3.880	3.050
	composition	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17-18}	C_{19-20}	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	
	mole (%)	2.399	2.029	1.856	1.635	1.200	1.689	1.164	0.382	0.316	0.239	0.179	0.125	

Table 5 Trapping pressure and temperature of fluid inclusions from the sandstones in the Ordos Basin

Well	Depth/m	Inclusion type	Number of Inclusion	T_H/℃	L/V ratio	P_{min} (MPa)	P_{Tr} ((MPa)	T_{Tr}/℃
M4	2555—2560.5	I	17	103 (93—118)	9.45 (8.6—10.53)	16.06	22.492	105.6
		II	1	88	12.22	15.984		
		I	3	83 (78—92)	6.83 (5.65—7.02)	9.8		
M5	1890	I	10	110 (95—118)	11 (9.52—12.55)	17.311	23.207	112.5
		II	4	96 (80—115)	14.57 (14.12—15.02)	17.409		
		I	3	86 (82—93)	7.21 (6.12—7.55)	12.6		
S2	3389.9	I	3	108 (102—118)	10.32 (9.32—11.4)	17.022	23.522	110.5
D6	2543.84	I	4	97 (92—113)	10.85 (9.86—12.15)	17.2	23.7	99.5
		I	2	87 (85,90)	6.76 (6.23,7.29)	12.834		
ZT1	2991.5—2994.7	I	15	110 (94—123)	11.21 (10.96—11.45)	17.719	24.219	112.5
		I	2	95 (88—108)	7.56 (7.33—8.87)	13.411		
SH5	2860—2866.5	I	3	116 (110—123)	12.3 (9.86—13.56)	17.9	24.4	118.5
SH231	2905.9	I	2	112 (111,113)	12.03 (11.98—12.1)	18.4	24.9	114.5
G4-5	2896.4—2901	I	5	125 (115—137)	13.54 (12.21—15.38)	18.695	25.195	127.5
Z4	3091—3101	I	13	118 (103—135)	12.78 (12.49—13.07)	18.871	25.371	120.5
S6	3456.2—3460	I	2	135 (135,135)	15.47 (15.30,15.64)	18.89	25.39	137.5
S1	3655.1	I	2	134 (130,138)	15.86 (15.27,16.48)	20.1	26.6	136.5
SH17	2983.5	I	10	126 (100—136)	15.32 (14.86—15.77)	21.032	27.532	128.5
Y44-9	2655—2660	I	3	128 (124—132)	14.88 (13.88—15.79)	21.231	27.731	130.5
G8-3	3565—3600	I	3	119 (110—127)	12.032 (10.59—13.38)	21.232	27.732	121.5
S8	3998—4072	I	6	98 (90.2—123)	11.01 (10.55—13.87)	22.026	28.526	100.5
Y7	2889—2938	I	4	128 (120—133)	17.35 (16.89—17.68)	23.9	30.4	130.5
SH219	2875—2895	I	4	120 (118—126)	15.87 (14.56—16)	24.5	31.1	122.5

The trapping pressure and temperature are calibrated except for the Wells M4 and M5 using the equation $P = P_{min}+\Delta P$ $T = T_{min}+\Delta T$; T_{min}, Homogenization temperature; P_{min}, minimum trapping temperature; $\Delta P = P_{tr}-P_{min}$ based on the inclusions from Wellls M4 and M5; $\Delta T = T_{tr}-T_H$ based on the inclusions from Wellls M4 and M5; Type I, Gas bearing inclusion, Type II, petroleum inclusion.

the basin, i.e. the sandstone reservoirs contain richer gases in the southern area where the reservoirs are gas-saturated, and toward north, there is water-gas transitional zone and then water-saturated zone[11].

(2) The trapping pressure and temperature of fluid inclusions also have a trend to decrease from the southern area to the northern area of the basin (fig. 4). The source rocks of the gas pool are Carboniferous-Permian coals and dark mudstones. According to the thermal history of the basin, these source rocks began to generate gases in the Late Triassic, and at the end of middle Jurassic two gas-generating centers around Yanan-Fuxian area and Wushenqi area developed. During the Early-Cretaceous, the basin subsided continuously and the source rocks matured to the gas-generating peak stage. Since the tectonic framework of the basin dipped gently toward south during this period, gases migrated from south to north to form the deep basin gas trap. Since the gas migration was affected by various resistances, thermal diffusing and thermal transfer, the temperature and pressure and the gas content would drop down gradually from south to north, which led to a decrease of the trapping temperature and pressure of fluid inclusion in reservoir sandstones.

(3) For gas -bearing inclusions with homogenization temperature in the range of 100℃—110℃, the trapping pressure of the inclusions is 6—7 MPa higher than its minimum trapping pressures, and the trapping temperature is 2℃—3℃ higher than its homogenization temperature.

(4) For the gas-bearing inclusions with homogenization temperature in the range of 100 to110℃, the trapping pressure obtained by Aplin et al.'s method is 0.9—10 MPa lower than the trapping pressure obtained by the present method. The reason is that the isochore of an aqueous inclusion is not a vertical line in the PVT diagram as Aplin et al. (2000) thought.

(5) The trapping pressure of fluid inclusions is

obviously lower than the state water pressures during the period of the inclusion formation (table 6). This characteristic is consistent with the inclusions negative abnormal pressure in the strata when the deep basin gas was trapped.

Table 6 A comparison between trapping pressure of fluid inclusions and state water pressure when the fluid inclusion formed by some representative samples

Well No	Depth/m	P_{tr1}(Mpa)	P_{tr2} (Mpa)	P_s((Mpa)
M4	2555—2560.5	23.207	22.326	29.5
M5	1890	22.492	21.531	25.5
ZT1	2991.5—2994.7	23.7—24.7*		32
Z4	3091—3101	24.8—25.8*		35
SH17	2983.5	27—28*		40

P_{tr1}, Trapping pressure after this method; P_{tr2}, trapping pressure after Aplin et al.'s method; P_s, state water pressure when fluid petroleum formed; *, calibrated trapping pressure.

3 Conclusions

The following conclusions can be obtained according to this investigation:

(1) A method was suggested to calculating the trapping pressure and temperature of inclusions by using the isochore equations of both petroleum inclusions and their coeval gas-bearing inclusions.

(2) A case study on fluid inclusions from the Upper-Paleozoic reservoir sandstone in the Ordos Basin was conducted after this method. The results show that the trapping pressure of the gas-bearing inclusions is 6—7 MPa higher than their minimum trapping pressures, the trapping temperature 2℃—3℃ higher than their homogenization temperature. The trapping pressure of fluid inclusion is obviously lower than the state water pressures when the inclusions formed. The trapping pressure and temperature decrease from the southern area to the northern area in the basin, which was controlled by the geological and geochemical conditions under which the deep basin gas trap formed.

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References

1. Liu Bin, Shen Kun. Thermodynamics of Fluid Inclusions (in Chinese). Beijing: Geological Publiishing House, 1999, 25—42.
2. Aplin, A. C., Macleod, G., Larter, S. R. et al., Combined use of Confocal Laser Microscopy and PVT simulation for estimating the composition and physical properties of petroleum in fluid inclusions, Marine and Petrolum Geology, 1999, 16: 97—109.
3. Aplin, A. C., Larter, S. R., Bigge, M. A. et al., PVTX history of the North sea's Judy oilfield, Journal of Geochemical Exploration, 2000, 60: 641—644.
4. Shepherd, T., Rankin, A. H., Alderdon D. H. M., A Practical Guide to Fluid Inclusion Studies, New York: Chapman & Hall, 1985, 63—77.
5. Roeder, E., Bodnar, R. J., Geologic pressure determinations from fluid inclusion studies, Ann. Rev. Earth Planet Sci., 1980, 8: 263—301.
6. Lu Huanzhang, Li Binglun, Inclusions Geochemistry (in Chinese), Beijing: Geological Publishing House, 1990, 6—16.
7. Mi Jingkui, Xiao Xianming, Liu Dehan, et al., Simulation for the minimum trapping pressure of fluid inclusions occurring in Upper-Paleozoic sandstone reservoir of the Ordos Basin using PVTsim, Geochemistry (in Chinese), 2002(4): 402—405.
8. Zhang Wenzheng, Li Jianfeng, Zan Chuanli, Study on the gas source rock of deep basin gas trap of Upper-Paleozoic reservoir in Ordos Basin, Low Permeability Gas Field (in Chinese), 1998, 13(2): 13—23.
9. Yang Junjie, Pei Xigu, Chinese Natural Gas Geology (Vol. 4): Ordos Basin (in Chinese), Beijing: Petroleum Industry Publishing Housing, 1998, 13(2): 13—23.
10. Qi Min, Deep basin gas trap and Ordos Basin, Low Permeability Gas Field (in Chinese), 1998, 3(2): 1—6.
11. Zhang Jinliang, Chang Xiangchun, Zhang Jingong, Study on the deep basin gas trap of Upper-Paleozoic reservoir in Ordos Basin, Petroleum Exploration and Development (in Chinese), 2000, 27(4): 30—36.