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An investigation of water-gas interface migration of the upper Paleozoic gas pool of the Ordos Basin using reservoir fluid inclusion information

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Abstract There is a particular characteristic in the formation of the Upper Paleozoic gas pool in the Ordos Basin that is its water-gas interface migrated regional during geological history. However, there has been lack of detailed research on this problem and also no similar report on other basins. In this paper, the formation time of the fluid inclusions formed in the water-gas transition zone of the gas pool was deduced using their trapping temperatures and combining of the burial with geothermal history of the basin. On the basis of this, the isochrone of water-gas interface migration for the gas pool was mapped. The result shows that the gas pool began to form around the Yanan Area at about 165Ma,and then developed and enlarged toward the north direction.The gas pool finally formed at about 129 Ma. Since the basin uplifted from the late Cretaceous and gas supply decreased,the water-gas interface of the gas pool migrated back to the present position.

Keywords: Ordos Basin, fluid inclusion, trapping temperature, watergas interface.

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Lots of geological and geochemical data obtained recently from the Ordos Basin have shown the following characteristics of the Upper Paleozoic gas pool[1—9]: (1) The source rock of the gas pool is the Carboniferous-Permian coal-bearing stratum and the reservoir rock is the Carboniferous-Permian tight sandstone with low porosity and low permeability; (2) the tectonic framework of the basin is a large asymmetric syncline, dipping steeply toward the south and west but gently toward the east and north; (3) the gas-bearing zone is distributed in the tectonic slope area of the basin. Toward up-dipping direction in the North and East areas, there is a water-gas transition zone, and then a water zone; and (4) the regional trap of the gas pool is a hydrodynamic regime, with water on the top of gas, showing a reverse water and gas relationship.

On the basis of these characteristics, some scholars have believed that the Upper Paleozoic gas pool of the Ordos Basin is a huge deep basin gas trap after comparing this gas pool with the deep basin gas trap of Alberta, Canada[1—5]. Although there is still a question of whether the gas pool is a deep basin gas trap, the characteristics for the formation of the gas pool are quite clear. For example, controlled by hand shaped reservoir sandstone bodies in the south-north direction, this gas pool consists of multi-small isolated gas pools, and these small gas pools all began to develop from the south area with a regional migration of their water-gas interface from the south to the north area[10,11].

On the basis of previous work, the authors would try to reconstruct the migration history of the water-gas interface during the gas pool formation. This study will not only provide important information to address the formation and evolvement of the gas pool, but also document approach for migration process.

1 Principle and method

There are lots of important information in fluid inclusions about the formation of oil and gas reservoir. As well known, a necessary condition for the formation of fluid inclusions is that there should be some water in rocks. Three different zones have existed during the formation of the Upper Paleozoic gas pool of the Ordos Basin[12], they are gas zone, water-gas transition zone and water zone. Since natural gases have a very low solubility in water and the gas migrate by diffusion[13,14], only aqueous inclusions and gas-bearing inclusions can form in the water zone. However, the situation in the water-gas transition zone is different from that in the water zone, all kinds of unmixed water and gas fluids occur widely, and different types of fluid inclusions with a variable vapor/liquid ratio can grow, including a type of boiling fluid inclusions. After a reservoir rock was fully filled with gases, there was no water in the rock pores and not any types of inclusions can form. Thus, the formation time of the fluid inclusions from the water-gas transition zone would record the time when gases injected into the reservoir rock and the isochrone of the inclusion formation would represent the evolution of the water-gas interface of the gas pool during geological history. Therefore, the migration of the water-gas interface in a gas pool could be deduced using fluid inclusion information in reservoir rocks.

A key problem to reconstruct the migration of the water-gas interface of a gas pool is to identify the fluid inclusions formed in the water and gas transition zone. A distinct characteristic of inclusions formed in water-gas transition zone is that gas inclusions coexisted with gas-bearing fluid inclusions and aqueous inclusions, the aqueous inclusions have a higher homogenization temperature (Th). In this paper, the aqueous inclusions coeval with gas inclusions were selected to measure Th (Fig. 1).

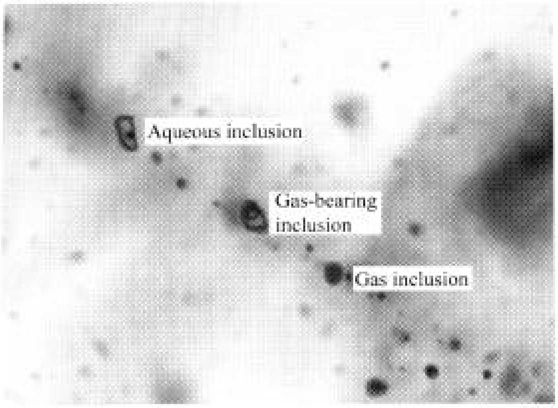

Fig. 1. Different types of fluid inclusions formed in the water and gas (Permian sandstone from well ZT-1, 1 depth of 2994 m).

The procedures to investigate the migration of the water-gas interface transition zone in a gas pool are in the following.

(1) Measurement of fluid inclusion homogenization temperature. The THMSG-600 micro-stage made by Linkcam Company was used. The increasing rate of temperature was controlled at 4—5℃/min. Aqueous inclusions should be distinguished from hydrocarbon-bearing inclusions before measuring their Th, since only the aqueous inclusion can represent its hosted rock temperature. With a cooling-heating stage, it is easy to distinguish an aqueous inclusion from a gas-bearing liquid inclusion. A gas-bearing liquid inclusion has a higher Th, usually above 170℃, and its melting temperature is below −100℃, but the Th of an aqueous inclusion is lower, in the range of 80—140℃, and its melting temperature is above −10℃.

(2) Calculation of fluid inclusion trapping temperature. Generally, only the trapping temperature (Tt) of an aqueous inclusion can represent its hosted rock temperature when the inclusion grown, and the Th of an aqueous inclusion is lower than its Tt. Only when water is saturated by gas in an inclusion, will the Th be equal to the Tt[15]. Under geological conditions, the water in aqueous inclusion is seldom saturated by gas. Thus, the Tt of inclusions should be obtained to present fluid temperatures when the inclusions formed. In this study, the Tt was calculated by combining isochores equations of a petroleum inclusion and its coeval aqueous inclusion using the Leica-Qwin and PVTsim software[16—18].

(3) Determination of formation depth of inclusions. The method was suggested by Xiao et al. (2002). In this study, the Tt of an inclusion was used instead of its Th .

(4) Formation time of inclusions. The formation time of an aqueous inclusion can be determined directly as presented in Fig. 2. There are two groups of aqueous inclusions in the sample from the well M5 (1890 m), with average Th of 112.5℃ and 93℃, respectively. The paleogeothermal temperature evolution curve of this sample can be drawn based on its burial history and paleogeothermal gradient (Ren, Z. L., 1994). The cross point between the horizontal line passing the Tt and the paleogeothermal temperature curve represents the trapped point of the inclusions, and the correspondent time in the *X*-axis is the formation time of the inclusions.

The real line and dashed line represent the two groups of inclusions formed before and after the basin uplifting, respectively.

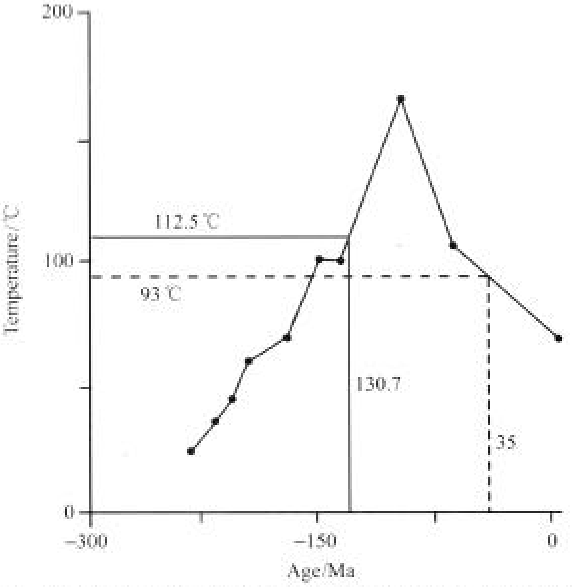

Fig. 2. Plot showing the determination of formation time of inclusions.

2 Geological distribution of samples

The studied samples are all tight sandstone, taken from the Shanxi Formation and Lower Shihezi Formation from the Ordos Basin. Table 1 presents the geological distribution of the samples, and Fig.3 shows the well locations from which the samples were taken.

3 Results and discussion

(i) Characteristics of fluid inclusions

There are abundant secondary fluid inclusions occurring in micro-fissures of the reservoir sandstone from the Ordos Basin. The inclusions are small size, and most of them are non-fluorescent. Fluorescence inclusions were only found in the samples from the wells located in the northeast area of the basin. The fluid inclusions can be subdivided into three types.

(1) Petroleum inclusion. This type of inclusions can be subdivided into three kinds: i) Liquid hydrocarbon inclusion: It is characterized by a small size, with Th of 80—115℃, and vapor/liquid ratios less than 20%. ii) Gas inclusion: This kind of inclusion has a

Table 1 Tt and Th data of fluid inclusions and their formation time

Well	Location	Depth/m	Age	Th/℃	Tt/℃	Formation depth/m	Formation time/Ma
M4	T-Z	2555—2560.5	P	103(93—118)	106.6	2617.1	131.9
M5	T-Z	1890	P	110(95—118)	112.5	2785.7	130.7
M8	T-Z	2104	P	107(98—120)	110	2714.3	129.2
D6	T-Z	2543.84	P	97(92—113)	114.5	2842.9	140.9
DT1	T-Z	2840.6	P	113.8(108, 117)	117.3	2922.9	142
ZT1	G-Z	2991.5—2994.7	P	114(94—123)	117.3	2922.9	142
SH5	G-Z	2860—2866.5	P	119(110—123)	122.5	3071.4	152.6
Sh231	G-Z	2905.9	P	113(112, 114)	116.5	2900	151.7
Z4	G-Z	3091—3101	P	118(103—135)	120.5	3014.3	149
S6	G-Z	3456.2—3460	P	118.5(121, 116)	122	3057.1	147.3
S1	G-Z	3655.1	P	123(121.3—125.7)	126.5	3185.7	162.7
S5	G-Z	3346—3370	P	117(108-126)	120.5	3014.3	147
S8	G-Z	3998—4072	P	121.1(108.7—128)	124.6	3131.4	147.1
Sh17	G-Z	2983.5	P	125(100—136)	128.5	3242.9	156.9
Y44-9	G-Z	2655—2660	P	127(124—132)	130.5	3300	161.5
G8-3	G-Z	3565—3600	P	124(110—127)	127.5	3214.3	163.1
G4-5	G-Z	3348—3398	P	118(115—127)	121.5	3042.9	149.2
Y7	G-Z	2889—2938	P	127(120—133)	130.5	3300	163.1
Y8	G-Z	2789	P	114(108—123)	117.5	2928.6	146.8
Y9	G-Z	2936.8	P	115.5(110—122)	119	2971.4	148.6
Sh219	G-Z	2875—2895	P	127.6(118—136)	131.1	3317.2	164.6
Sh233	G-Z	3189	P	117.3(116, 118.6)	120.8	3022.9	152.3
Sh101	G-Z	3115	P	127.5(120—136)	130.5	3300	168.3
Sh131	G-Z	3268.5	P	125.2(116—138)	128.7	3248.6	167.3
ZC8	G-Z	2095	P	114.4 (90—124.8)	117.9	2925.7	148.6
L2	G-Z	2401.5	P	123.4(117—129)	126.9	3197.1	159.3

T-Z, Water and gas transition zone; G-Z, gas zone. Tt is calibrated except for the wells M4 and M5 using the difference between the Th with Tt of inclusions from wells M4 and M5. The calibration formula: T=Th+ΔT. ΔT= 3.5℃.

larger size, with Th of 80—115℃, and vapor/liquid ratios of 63%—75%. iii) Three phases inclusions: This kind of inclusion consists of water, petroleum and gas phases. Under the transmitted light model, the boundary between the water phase and the petroleum phase is not clear, but under fluorescent light, the petroleum phase has blue fluorescence, and the water phase have no fluorescence. The Th for petroleum and gas phases is 85—120℃, and the Th of three phases is higher than 200℃.

(2) Aqueous inclusion. This type of inclusion has two kinds: i) Pure liquid phase inclusion: It has ellipse or irregular shape and variable size with only one phase, it is colorless and transparent under the transmitted light model; ii) aqueous inclusion: It is two-phase inclusion with vapor/liquid ratios of less than 20% and Th of 80—140℃. Most of the secondary inclusions belong to this kind.

(3) Gas inclusion. It includes two kinds: i) Pure gas inclusion: It is one phase and black color under the transmitted light model; ii) gas inclusion: It has two phases with vapor/liquid ratios of more than 50% and the size in the range of 10—20 μm.

(ii) Trapping temperature of inclusions. As mentioned above, the Th of an aqueous inclusion can represent its Tt only when the water in an inclusion was saturated by gas. It is obvious that the aqueous inclusions coexisted with pure-liquid inclusions and gas inclusions were not saturated by gas. Thus, the isochore of the aqueous inclusion is not a vertical line, but an incline. An accurate method to calculate the trapping pressure and temperature is to combine the isochore equations of both petroleum inclusions and its coeval aqueous inclusions. However, petroleum inclusions were only found in the samples from wells M4 and M5. The Tt of the inclusions in samples where no petroleum inclusions were found was calibrated using the difference between the Tt and the Th of the inclusion in the wells M4 and M5 samples. The results show that the Th of an inclusion is obviously lower than its Tt and the difference is 3—4℃, with an average of 3.5℃. The Th of inclusion in Table 1 is the calibrated temperatures.

Figure 3 is the isochrone map for the formation of the inclusions based on the studied samples. The Upper Paleozoic gas pool began to form in the Yanan Area before 165 Ma (Late Jurassic), and then extended toward the north direction, with a regional migration of water-gas

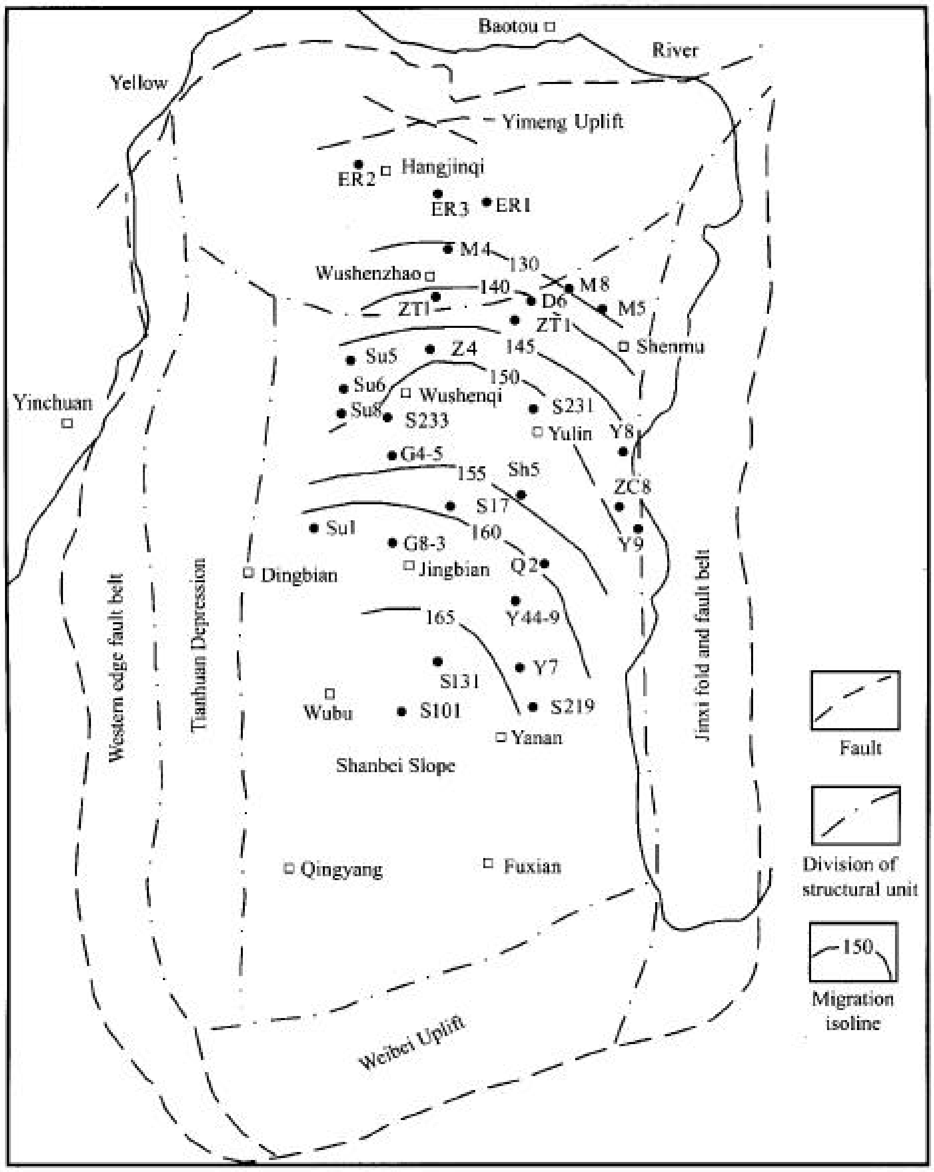

Fig. 3. A map showing the isochrone of water-gas interface migration.

interface from south to north. The gas pool finally formed before 129 Ma.

It should be noted that there were two groups of aqueous inclusions in the water-gas transition zone (samples from wells M4, M5 and D6). For example, the two groups of inclusions in the samples from well M5 have the Th of 82—93℃ and 95—118℃, and the vapor/liquid ratios of 6.12%—7.55% and 9.25%—12.55%, the minimum trapping pressures of 16.6 MPa and 23.2 MPa, respectively. The two groups of inclusions could be explained by the migration of the water-gas zone during geological history. During the early Cretaceous, the source rocks were matured into gas generation peak stage and generated a great deal of gases. The gas zone expended and the water-gas interface migrated from the south to the north direction. The water-gas interface passed through this area to form the inclusions with higher Th, and then this area became a gas zone. In the late Cretaceous, the basin began to uplift and about 1000—1600-m-thick strata were eroded. The gas supply from the source area decreased gradually, and gases from gas resource were not enough to maintain the equilibrium of the hydrodynamic trap. The water-gas interface moved back to present position to form the inclusions with lower Th and this area became into a water-gas zone again. The trapping temperature and pressure of this group of inclusions are consistent with the present strata temperature and pressure.

A conclusion can be made from the above discussion that the water-gas interface moved forward and back during geological history is the reason for the two groups of aqueous inclusions formation in the present water-gas zone. Some scholars have also discussed this phenomenon of the water-gas zone migration of the gas pool from the geologic background and had a similar view with this study[3].

4 Conclusion

The migration of the water-gas interface of a gas pool can be reconstructed using fluid inclusion information, with the combination of the geologic background of the basin. The results show that the Upper Paleozoic gas pool of the Ordos Basin began to form near the Yanan area at about 165 Ma, and then enlarged toward the northern area of the basin. The gas pool finally formed at about 129 Ma. The water-gas interface of the gas pool migrated back to the present position since the source rocks could not supply enough gas after the late Cretaceous.

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