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POROSITY PREDICTION OF HYDROCARBON RESERVOIRS FOR BASINS OF DIFFERENT CATEGORIES: A CASE STUDY FROM CHINA

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Abstract: Sandstone porosity is an important factor for hydrocarbon reservoirs. Based on the analysis of statistical porosity data from ten Chinese basins, three different trendlines has been found for basins of different categories. High average porosity reservoir is often developed in the Eastern Rift Basins, occasionally in the Western Superimposed Basins. The sandstone reservoir of Middle Craton Basins is always developed with low average porosity. However, the reservoir porosity decreased with increasing depth vertically with one or two anomalously high porosity belt only in the Eastern Rift Basins. According to these results, we should take basin category as a key factor to make porosity prediction in the hydrocarbon exploration.

Key words: Hydrocarbon reservoir; tectonic background; porosity prediction; basin category

1. INTRODUCTION

Sandstone is one of the important reservoirs for oil and gas exploration, thus, the porosity prediction of sandstones is the most effective method to reduce the exploration risk. The question is how to make the prediction for a new basin or new play without any drilling well information. On this idea, the statistical model of other basins will give more support for that kinds of exploration.

The overall goal of this article is to present, and if possible, quantify, the porosity evolution diversity associated with the basin types, based on the detailed investigation of porosity and tectonic evolution of those twelve sedimentary basins of China. Countless wells of hydrocarbon exploration and exploitation had been drilled in all twelve important sedimentary basins from the main land to the sea across the whole China (Sun et al., 2010). The success of commercial hydrocarbon exploration should partially attributed to a great number of sandstone reservoirs with good reservoir quality in those sedimentary basins (Fig. 1). In the last four decades, extensive geological and geochemical investigations have been carried out on these sandstone reservoirs porosity, leaving an abundant amount of data and competing interpretations.

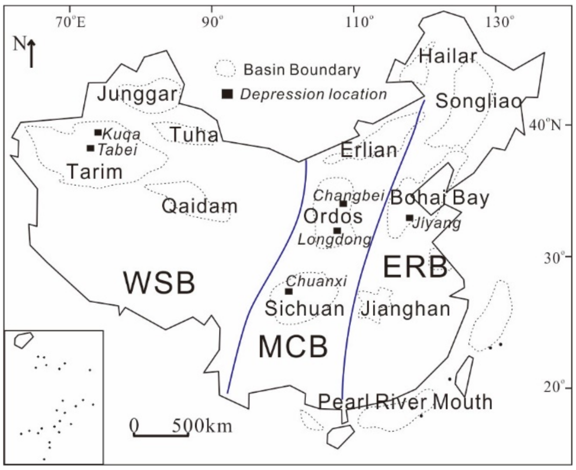

Figure 1. Regional map showing the location of some large Chinese basins, with the locations of their depressions (Liu, 1996). WSB: western superimposed basins, such as Tarim Basin and Junggar Basin, MCB: middle craton basins, such as Sichuan Basin and Ordos Basin, ERB: eastern rift basins, such as Bohai Bay Basin, Songliao Basin and Pearl River Mouth Basin.

The main objective is to determine whether there are systematic and statistical porosity models that relate to basin types of different tectonic background (Zhai et al., 2007). This study is based on two data sets: a compilation of all available tectonic evolution literatures for those basins, and a subset of thousands sandstone porosity measurements for those basins by us.

2. GEOLOGICAL BACKGROUND

Based on the latest plate tectonic theory, the origin of sedimentary basins in China, was strongly influenced by Tethyan, Palaeo-Asian and Pacific tectonic system. Those sedimentary basins were formed since the start of continental accretion and continental assembling, and developed in the stage of intercontinental orogenic deposition. The start were the three Chinese cratons, North China, Yangtze and Tarim cratons, which were the results of Paleo-Asian tectonic systems and generated earlier during the splitting and assembling of continents or plates since Sinian to Triassic (Liu, 1996). Three categories of sedimentary basins were formed during the evolution of those three cratons: Western Superimposed Basins, Middle Craton Basins and Eastern Rift Basins (Fig. 1).

2.1. Western Superimposed Basins

In the western China, Tethyan tectonic system and multi-stages tectonic events bring us the formation of many western superimposed basins knowed as WSB, which refers to different basin superimposing or overlying at the same geographical position with different stage and type, separated by unconformity surface (Pang et al., 2012). Tarim Basin is a typical one. Since the basement formation at 800 Ma, firstly, it was carbonated succession of Cambrian and Ordovician, and then the marine clastic succession of Silurian and Devonian (Liu, 1996). After the uplifting during to Carboniferous and Permian, a second carbonate success filled the Palaeozoic craton basin. Since Mesozoic to Cenozoic, it was not a craton basin anymore, but acting as a superimposed Triassic and Cenozoic foreland basin, which is mainly filled by continental clastic sedimentary as is presented in figure no. 2. Curve “a” (the blue curve) shows the evolution of the Silurian sandstones of Tazhong Depression in Tarim Basin, presenting subsidence with two uplift at 380 Ma and 150 Ma. And curve “c” (the pink curve) shows the evolution of the Cretaceous sandstone of Kuqa Depression in Tarim Basin, presenting the fastest subsidence in Cenozoic (Fig. 2).

2.2. Middle Craton Basins

Middle Craton Basins (MCB), such as Sichuan Basin and Ordos Basin are developed in the Yangtze craton and North China craton of middle China. Carbonated sequences deposited widely in those two cratons from the beginning to mid-Ordovician. Then, after a long time uplifting of the North China craton, a typical Mesozoic continental craton basin, Ordos basin, has developed since Middle Triassic (Liu et al., 2006) as is indicated in the cur”ve “b. Curve “b” (the green curve) shows the evolution of the Triassic sandstones of Chuanxi Depression in Sichuan Basin, presenting fast and deep subsidence in the first half stage and fast uplift in the second half stage since 100 Ma (Fig. 2). It is a large continental sag basin filled by clastic rocks of fluvial-delta deposit system. From Late Cretaceous, Ordos Basin has been reformed by different tectonic events, but its nature of craton basin was not changed. Dissimilar to Ordos basin, Sichuan basin was a stable carbonated platform during to the whole Palaeozoic. Due to a tafrogenesis at Late Palaeozoic and the basaltic eruption of Omei Mountain, from Permian to Mesozoic, there developed two types deposition, carbonated platform and fluvial-delta deposits (Li & He, 2014; Liu et al., 2011; Zhang et al., 2011).

2.3. Eastern Rift Basins

Finally, to the eastern China, a series of eastern rift basins (ERB) were formed from Mesozoic to Cenozoic, including Songliao Basin and Bohai Bay Basin, which are controlled by the Tethyan and Pacific tectonic systems. Above the Paleozoic basement, as a result of multi-stages tectonic rift events, those ERB are filled up with clastic sequences during their continuous subsidence (Hou et al., 2001; Li et al., 2010), which is the distinguishing feature between the ERB and other sedimentary basins (Fig. 2). Curve “d” (the red curve) shows the evolution of the youngest Eocene sandstones of Jiyang Depression in Bohai Bay Basin, presenting the fast subsidence, without any uplift. The deepest burial depth of ERB is very smaller than that of WSB and MCB at geological history.

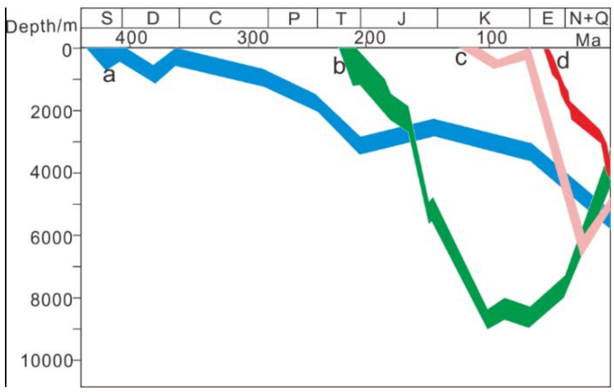

Figure 2. Burial curves of different sandstone reservoirs.

Table 1. Reservoir quality data from different sedimentary basins of China. The depth is the deepest burial depth of nowadays. The porosity is the average value of the strata.

BASIN LOCATION	BASIN TYPES	PERIOD FORMATION	SEDIMENTARY FACIES LITHOLOGY	DEPTH m	POROSITY %
Tarim, Kuqa	WSB	Paleogene Kumugeliemu	Alluvial-Fan delta Lithic sandstone	5200	14
Bohai Bay, Jiyang	ERB	Paleogene Shahejie	Alluvial-Fan delta Lithic sandstone	3500	15
Tarim, Kuqa	WSB	Cretaceous Bashijiqike	Alluvial-Fan delta Lithic sandstone	6000-8000	0.68-11.3
Tarim, Tabei	WSB	Triassic	Fluvial-Delta Lithic sandstone	4200	10~30
Sichuan, Chuanxi	MCB	Triassic Xujiahe	Delta Lithic sandstone	2000	2~5
Ordos, Lodong	MCB	Triassic Yanchang	Flvial-Delta Lithic sandstone	<1000	10
Ordos, Changbei	MCB	Permian Shanxi	Shore Quartz sandstone	2800	5~8
Tarim, Tabei	WSB	Devonian Donghetang	Shore Quartz sandstone	6000	20

3. RESERVOIR POROSITY MODELS

Reservoir porosity is different in those mentioned basins. First, the average value of typical sandstone reservoir of each basin is different (Table 1). The highest porosity is belonged to WSB and the lowest porosity is from MCB, although its depth shallower than that of WSB. Second, the reservoir porosity evolution with depth is also not the same in those three types of basin.

3.1. Reservoir Porosity of ERB

The Paleogene clastic reservoirs in Bohai Bay basin is the typical sandstone reservoir of ERB. The depositional environments of this reservoir has been interpreted to be a complex system of nearshore subaqueous fan, delta and turbidite. So the sandstones are fine-grained to medium-grained, poorly sorted, arkoses, lithic arkoses and litharenite.

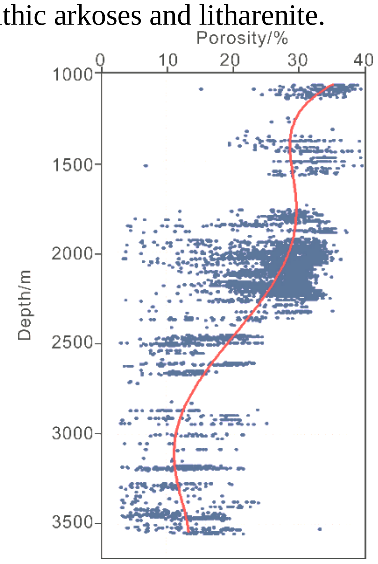

Figure 3. Plot showing the sandstone porosity varying with depth of Eocene in Jiyang Depression of Bohai Bay Basin.

As we could find the reservoir porosity value of Jiyang Depression, one typical large depression in Bohai Bay Basin, is decreasing with the increasing burial depth from the upper strata (Fig.3). However, there are always many samples between 2000-2400 meteres displaying anomalously high porosity relative to the decreasing trend, in different sags of Jiyang Depression. Meanwhile, at the depth deeper than 3000m, there are also many samples with anomalously high porosity. Thus the average porosity/depth trend, which was denoted by the dashed line, was a polynomial curve with at least two anomalously high values. The depths of anomalously high porosity were various in different sags, and it was deeper in the east and the south of the depression.

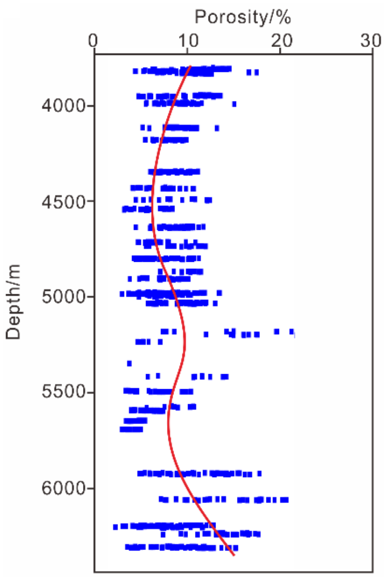

Figure 4. Plot showing the sandstone porosity varying with depth of Silurian in Tazhong Depression of Tarim Basin.

3.2. Reservoir Porosity of WSB

The situation of the reservoir porosity in the WSB is a little more different and complicated than that of ERB. In the WSB, the reservoir porosity varies in different strata. For example, Donghetang Formation from Devonian has high porosity, while the low porosity present in younger strata such as Bashijiqike Formation of Cretaceous (Table 1). Although the reservoir of WSB is buried much deeper than the depth of 3000-4000m of ERB, the porosity of WSB is not smaller than that of ERB. The present depth of Donghetang Formation is 6000m with porosity of 20%, the Bashijiqike Formation, 6000-8000m with porosity less than 10% (Table 1). And the same as ERB, there is also an enhancement of the porosity in the deep depth of ERB (Fig. 4), and the anomalously high porosity belt is at the 6000 meters.

3.3. Reservoir Porosity of MCB

It is very obviously that the lowest porosity of sandstone reservoirs is in the MCB (Table 1). Whether to Shanxi Formation of the Permian or Yanchang Formation of Triassic, both of their porosity is very small at Ordos Basin. It is the same as Xujiahe Formation of Triassic in Sichuan Basin, which is also a kind of reservoir with low porosity (Table 1 and Fig. 5). Different from ERB, the porosity is always lower than 10% without any increasing. For MCB, the fitting curve with burial depth is a downward straight line. Although the burial depth is not very large, but the average value of porosity is always very small from the top to the bottom, and does not present any change (Fig. 5).

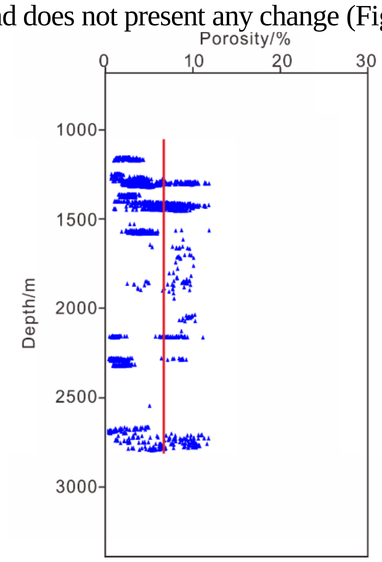

Figure 5. Plot showing the Triassic sandstone porosity varying with depth in Chuanxi Depression of Sichuan Basin.

4. DISCUSSION

Average porosity and porosity models of sandstones are different within basins of ERB, WSB and MCB. High average porosity reservoir is often developed in ERB, occasionally in WSB. Our question is what is the controlling factors for this porosity trend in each kind of basin and, our answer is the we believe that tectonic background may be the most important one.

4.1. The porosity differences between three categories basins

Average value of porosity decreases from 40% at 1000 meter to 15% at 3500 meter in ERB. However, the fitting curve is not a straight line with deep slop, but with two increasing phases at about 2000 meter and 3500 meters. The increasing porosity is not a common trend with increasing depth, so there must be some reason to enhance porosity (Fig. 3). The porosity increasing from 15% at 3500 meters to 20% below 5000 meters in WSB (Fig. 4), and this is not a coincidence while the Eocene sandstone porosity of Jiyang Depression is also 15% at about 3500m (Fig. 3). But it is hard to make a fitting curve for these porosity data. By comparing the reservoir porosity data from those basins, both average value and variation with depth (Table 1, Fig. 3, Fig. 4 and Fig. 5), the difference is very obviously. First, generally for three kinds of basins in China, high average porosity sandstone reservoir is often developed in the ERB, occasionally in WSB. The sandstone reservoir of MCB is always developed with low average porosity. Second, some other backgrounds of reservoir should be took for consideration. To the sandstone reservoir of the same sedimentary facies, the porosity of quartz sandstones from Donghetang Formation of Tarim Basin is much higher than that from Shanxi Formation of Ordos Basin (Table 1), however, the Donghetang Formation of Devonian is much deeper and older than the Shanxi Formation of Permian. Then to the lithic sandstones of the same period and sedimentary facies, there is still different porosity between WSB (Paleogene and Cretaceous reservoir of Kuqa Depression) and ERB (Paleogene reservoir of Dongying Depression). This general situation could also be found in other strata, such as Triassic of Lunan, Xujiahe Formation of Chuanxi and Yanchang Formation of Longdong. Indeed, there were more examples similar to that situation across Chinese sedimentary basins.

Finally, according to the detailed correlation, we can find that the reservoir porosity decreased with increasing depth vertically with one or two anomalously high porosity belt in the ERB. This can be found in Jiyang, Liaohe and Huanghua of the ERB, and in those basins secondary porosity developed in the similar depth (Zheng & Wu, 1996; Zhong et al., 2003). On the contrast, to the MCB and WSB, there is no obvious relationship between porosity and burial depth. For the MCB, Permian and Triassic reservoir in Ordos Basin, and Triassic reservoir of Sichuan Basin, are all shallow buried and low porosity without any increasing and decreasing (Li et al., 2005; Hu & Li, 2007; Liu et al., 2002; Zhu, 1982; Luo et al., 2001). And in the WSB, there is good sandstone reservoir of Silurian, Devonian and Triassic, deep buried but high porosity (Gu et al., 1998; Jia & Gu, 2002; Zhong et al., 2000; Zhong et al., 2003; Zhong et al., 2007; Zhu et al., 2002; Zhu et al., 2007). The question is what caused the porosity difference between those three types' basins.

4.2. The reason for the porosity differences

Based on the porosity differences we talked previously, we will discuss the relationship of the porosity evolution and the tectonic background. This issue will be unfold by three cases.

For example, to the differences between Cretaceous reservoir of Kuqa Depression in WSB, and Paleogene reservoir of Dongying Depression in ERB, the only difference for the reservoir evolution is the tectonic subsidence of each basin (the curves "c" and "d" in Fig. 2). The fast and deep subsidence for Cretaceous sandstones of WSB is the only differences from Paleogene reservoir of ERB, which may also be the only reason for its porosity decreasing. Behind the fast and deep subsidence, the foreland tectonic background is the root of this issue.

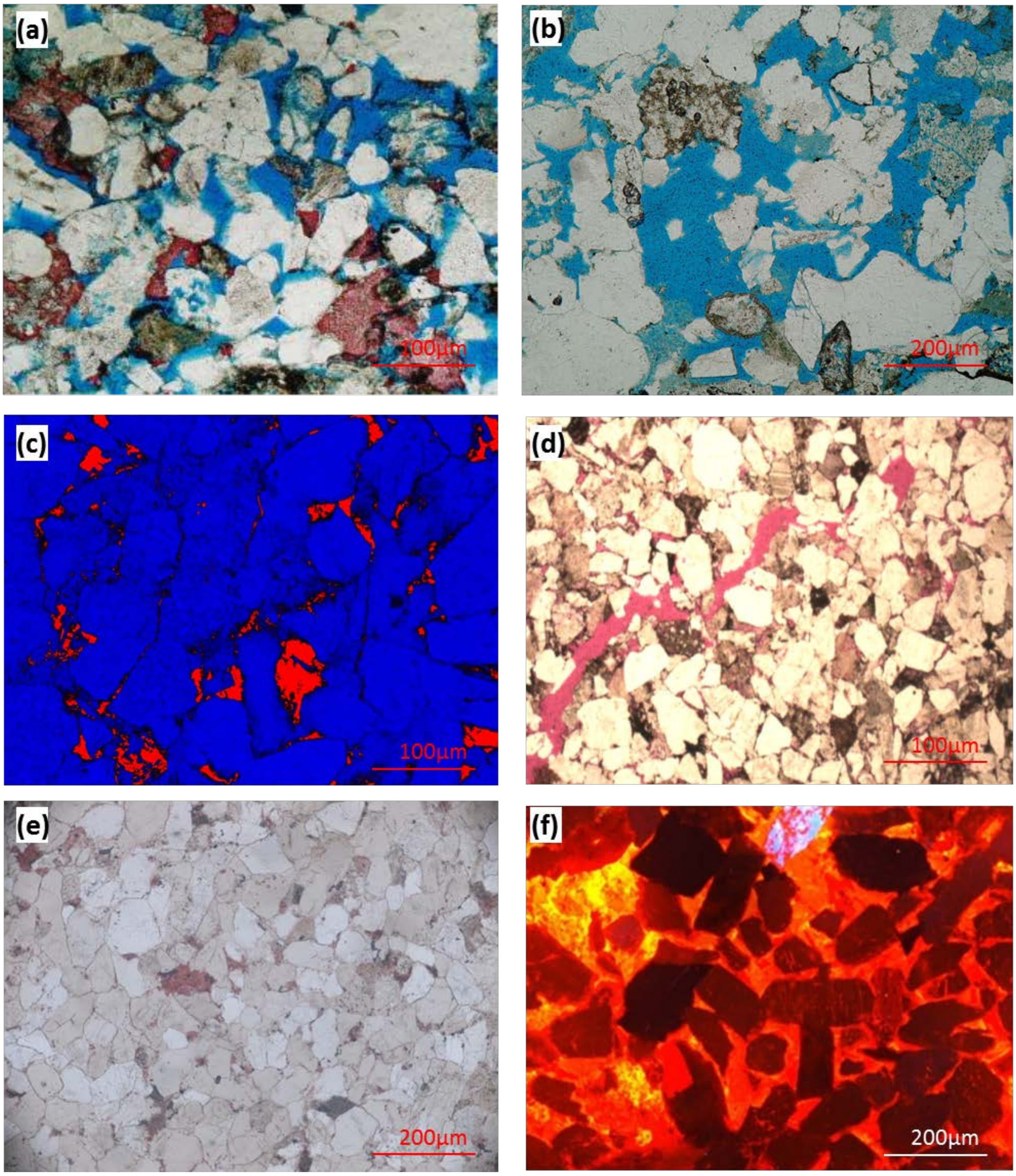

Figure 6. Photos of micro pores and some diagenesis features in different basins.

To the ERB with regular changed porosity, how the anomalously high porosity belt formed? We should remind types and origin of those pores: secondary pores (Fig. 6). The sedimentary facies and lithology of the samples are same, but the pores and porosity are different. (Fig. 6a) Many intergranular pores (the blue) and calcite cement (the red), the grains are not very close to each other, microscope image, Y3-7-7 well, 3199.6m, Jiyang Depression, ERB. (Fig. 6b) Large dissolution intergranular pores and some grain dissolution, this sample presents the secondary pores are the reason of high porosity, microscope image, Y3-7-7 well, 3200.5m, Jiyang Depression, ERB. (Fig. 6c) Only some small intergranular pores (the red), none inner granular pores, the clastic grains are close to each other by great compaction during the fast and deep subsidence, laser scanning confocal microscope image, KS802 well, 7326.95m, Kuqa Depression, WSB. (Fig. 6d) Little intergranular pores are developed in the samples, which is caused by heavy compaction, microscope image, KS207 well, 6798m, Kuqa Depression, WSB. (Fig. 6e) Intense compaction leads to the low porosity and none dissolution, microscope image, YB204 well, 4551.31m, Sichuan Basin, MCB. (Fig. 6f) Long term subsidence leads to the early calcite cementation (the dark orange), which reduce the fluid flowing and dissolution. The result is also low porosity, cathode luminescence image, YL6 well, 4461.9m, Sichuan Basin, MCB. It is characterized by a significant number of secondary pores in this kind of basins. According to the thin slices, all the secondary pores are mainly generated by dissolution, both of feldspar grains and calcite cements (Zhu et al., 2007; Cai et al., 2002; Sun et al., 2010). The emplacement of hydrocarbons, and chlorite coats has also made some contributions. But the most important one is the dissolution, which is most directly caused by the organic acid generated from the source rocks. The more close to the center of source rocks, the reservoir is much easier to be dissolved. Then what controls the depth of anomalous porosity belt in ERB? The answer is also the tectonic background. The sedimentary facies, burial depth and thickness of source rocks can be limited by the subsidence of rifting activities (Zhong et al., 2003). Meanwhile, there is always a depth, maybe 1500m, to be the shallowest threshold to the generation of organic acid and the secondary pores. This number is just coincided to the depth of the mature of the source rocks, which can be calculated using the temperatures and pressures data. The geothermal grade, the temperatures and the pressures are all controlled by the rifting activates of ERB (TTI index or another). So, the rifting tectonic background is the reason for the regular changed porosity of those sandstone reservoirs.

The third case is the unchanged porosity of MCB (Fig. 5). Whether it is the Shanxi Formation of Permian or the Yanchang Formation and Xujiahe Formaion of Triassic, low porosity is their same feature. Compared with WSB, the reason for the low porosity is also related to the long and deep burial process. The intense compaction and early cementation decrease the reservoir porosity significantly, and the result is that reducing of the fluid flow and the reducing of the dissolution, which should be the only process to increase the porosity. Unfortunately, we cannot see any intense dissolution in the samples of MCB (Fig. 6). The intense compaction and early cementation are the direct results of the long term subsidence, which is controlled by the cratonic background.

4.3. The implication for reservoir quality prediction

Porosity is one of the major controls on reservoir quality. So, the reservoir quality prediction has to find the controlling factors of porosity. It is believed that the porosity evolution of sandstones are complex, being controlled by numerous known factors, such as rock compositions, depositional environments, burial depth, basin flows and tectonic activities. However, based on the porosity variation of those different types' basins, we believe that the tectonic background of sedimentary basins should be the specific and main controlling factor.

According to current research, textbook and document, for quite a long period, sandstone reservoir quality, which is especially important in hydrocarbon exploration, was thought to be controlled by complex interplay of factors including carbon dioxide and organic acids dissolution (Surdam et al., 1989; Surdam et al., 1993; Schmidt and McDonald, 1979; Schmoker & Guautier, 1988), burial time (Saigal et al., 1992), abnormal overpressure (Bjørkum et al., 1998), clay mineral dehydration (Crossey et al., 1986), thermal convective geofluid (Wood & Hewett, 1984), regional and local tectonic (Shou et al., 2003; Sun et al., 2018), and sequence stratigraphic surface (Morad et al., 2000). Those factors could be generalized finally to two aspects: depositional conditions and diagenesis. The former controlled the initial property, while the later controlled property changes during the burial process of reservoirs. However, what lies behind the deposition and diagenesis? The depositional conditions is closely related with provenance and sources, basin size, slope and geomorphology, and other parameters. But these parameters are all decided by tectonic activates of basin. And main parameters of the diagenesis are temperature, pressure, fluids and rock grains, obviously, which are all controlled by types and intensity of tectonic activities. So, the root factor controlling reservoir porosity evolution is the tectonic background of basins.

5. CONCLUSION

There are many sedimentary basins of three categories in China, which are Eastern Rift Basins lying in the eastern area, Superimposed Basins lying in the western area and craton basins in the middle area. The tectonic background and evolution of each type basin is different from each other.

Average porosity and porosity models of sandstones are also varying within basins of ERB, WSB and MCB. High average porosity reservoir is often developed in ERB, occasionally in WSB. The sandstone reservoir of MCB is always developed with low average porosity. The reservoir porosity decreased with increasing depth vertically with one or two anomalously high porosity belt only in the ERB. The tectonic background of sedimentary basins should be the specific and main controlling factor for the differences of the porosity evolution. Thus, it is very important to take basin category as a key factors for oil and gas exploration in a new basin.

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