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Characteristics and formation of high quality reservoirs in sediment gravity flows of Gangzhong area, Huanghua depression

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Abstract: Reservoirs can be developed in the sediment gravity flows. However, high quality reservoirs are found widespread in sediment gravity flows of Gangzhong area, Huanghua depression, Bohai Bay Basin, East China. Characteristics and formation of these reservoirs are key problems to be solved. Through comprehensive analysis of thin section petrography, scanning electron microscopy and X-ray diffraction, two distinct rules were obtained. 1) These high quality reservoirs have apparent characteristics: lithology consists mainly of medium-fine grained sands; moderately-well sorted and rounded; intergranular pores dominating >70% of the entire pores, surface per unit pore volume reaches 15%; average porosity is 21% and average permeability is 55×10^{-3} μm^2. 2) Types of sedimentary microfacies and dissolution strongly control on the formation of high quality reservoirs. Main channels and sandy braided bars have the best reservoir properties. Because that sediments are mainly medium-fine grained sands in high-energy environments. The favorable primary porosity and permeability may promote calcite cementation and help to produce more secondary pores. Besides, at the depth of 2500−3200 m, basically matching threshold of oil generation, organic acid expelled when organic matter became mature, and H^+ released during clay mineral transformation. These both result in the dissolution of calcite cements and create large volume pores, then physical properties improve correspondingly. Moreover, deep hydrothermal fluid intrusion may also have impacts on the development of secondary pores.

Key words: Huanghua depression; sediment gravity flows; diagenesis; intergranular pores; hydrothermal fluid intrusion

1 Introduction

Reservoirs can be developed in the sediment gravity flows, though not widely. This is because sedimentary gravity flows mainly deposit mixture of shale, sand and conglomerate, influenced by gravity. Thus, the poor physical properties make it hard to develop high-quality reservoirs. Though former researchers did works, their studies were almost all focused on low porosity and low permeability reservoirs [1−6]. This changed greatly along with recent drillings in the second member of the Shahejie Formation in the Gangzhong area; relatively high-quality reservoirs were found through out a large area. Many researchers have studied sedimentary characteristics of this formation [7−10], whereas no consensus has been obtained. During the deposition of the member, strong tectonic movements occurred and abundant faults developed. As a consequence, the complicated fault system cut the large sedimentary body to fault blocks like checkerboard patterns. Because of such a complicated tectonic system, characteristics and formation of these reservoirs are still unclear. This work summarizes identification features and sedimentary microfacies of gravity flows in the Gangzhong area by integrating seismic and logging data and stratigraphic correlation. In addition, thin section petrography, scanning electron microscopy, X-ray diffraction and physical properties are used to help explain formation of these high-quality reservoirs.

2 Regional geology

Gangzhong area is situated in the center of Binhai fault belt, located on the Qikou sag of Huanghua depression, and Banqiao sub-sag, Qibei sub-sag in the south, Qikou sag in the east, Gangxi uplift in the west, the total area is about 100 km^2 (Fig. 1) [11]. Well-

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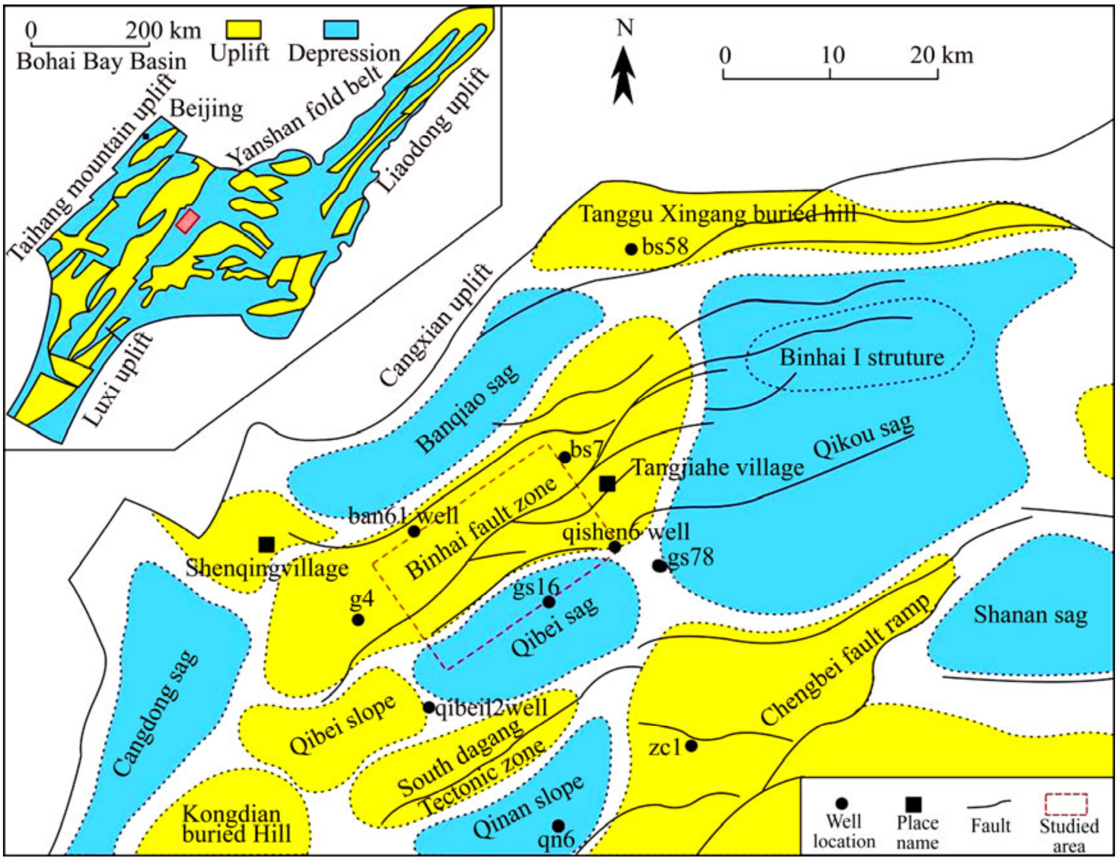

Fig. 1 Structural location of study area

developed fault system was found in the studied area, consisting of north-east faults and north-west faults. The largest Binhai fault has a longer than 800 m horizontal displacement, and extends farther than 30 km. Drilling strata includes Mesozoic, Paleogene, Neogene and Quanternary from bottom to top. During Paleogene, this area mainly deposited Shahejie formation and Dongying formation [12−13]. Shahejie formation contains three members. The thickness of the third member of Shahejie formation which presumably ranges from 100 to 600 m, consists of dark gray or taupe gray shale, gray sandstones, calcareous sandstones and pebbly sandstones. Local unconformities exist in sand layers. The second member of Shahejie formation, which is characterized by consisting of black shale with gray sandstone interlayers, about 170−300 m thick, and can be subdivided into Bin II, Bin III, and Bin IV oil groups. The first member of Shahejie formation contains three sections. The upper part is about 100−300 m thick and made up of gray shale with a few sand interlayer; the middle part is about 100−200 m thick, and lithology is marked by dark gray or taupe gray shale with thin oil shale and argillaceous siltstone interlayers. The lower part is about 100−450 m thick and consists of interbeds of gray or dark gray shale and light gray sands in different thicknesses.

3 Characteristics of gravity flow channels

The widespread gravity flow channels in Gangzhong area are one of the main sedimentary facies during Es2. Lithology is predominately composed of gray-black pure shale, gray and fine sand interlayer. In sand layers, there develop massive slump deformation structures (Figs. 2(a) and (b)), water-escape structures (Fig. 2(c)), small-scale subset of graded beddings and Bouma sequence et al (Fig. 2(d)). The shale-sand contact is mainly sharp (Fig. 2(e)). Shale contents in sands vary greatly, ranging from argillaceous sandstone of high shale content to massive medium-fine sands with low mud content. Sandstones appear in lenticular shape in cross sections and like ribbon or stripe on planes. Based on deposit pattern, sediment gravity flows can be subdivided into four sedimentary microfacies: main channels, sandy braided bars, distributary channels, channel margins and extremity of channels. Their identification features are as follows (Table 1).

The bulk of gravity glow channels are composed of main channels and sandy braided bars, in which massive sandstone overlapped with each other. Their spontaneous

Fig. 2 Lithology and tectonic characteristics of sediment gravity flows in Gangzhong area: (a) Slump deformation structure, well z11-70, 2673.53 m, Es2; (b) Deformation structure, well z11-70, 2633.14 m, Es2; (c) Water escape structure, well gs56, 3190.31 m, Es2; (d) Slump deformation structure, well z11-70, 2673.53 m, Es2; (e) Sharp contact between well gs56, 3194.6 m, Es2; (f) Light gray medium sand, well z11-70, 2667.79 m, Es2

Table 1 Characteristics of gravity flow channels

Sedimentary facy	Microfacy	Lithology pattern	Bedding	Log character
Gravity flow channels	Main channels, sandy braided bars	Matrix-supported conglomerate, massive sandstones	Massive or cross-bedding, deformation structures are common	In box or saw-tooth shape, high deviation from shale line
	Channel margins, distributary channel	Siltstones, some shale	Small-scale cross-beddings	In dentation or finger shape, low deviation from shale line
	Extremity of channels	Dark gray shale	Horizontal beddings	Low resistivity and high Gamma ray

potential curve and resistivity curve are like bell or box. The main channels are limited by channel margins, which formed by gravity flow overflowing the channel and the lithology is dominated by interbedding of fine sandstone, siltstone and shale. They are characterized on well logs by straight sp curve and zigzag resistivity curve (Fig. 3). Extremities of channels which are the terminate deposits of gravity flow channels, are mainly overly on the slope where channel forwards or areas where channels flow to the open lake. These terminal channels are in a fan shape on the plane, and the lithology and log curve of which are similar with those of channel margins, except that they are of lower extent. Thus, it is hard to distinguish them from lacustrine mudstones.

It is concluded that the characteristics of horizontal distribution of gravity flow channels in Gangzhong area are as follows: 1) Isopach maps of sandstones show ribbon-stripes shape; 2) The sedimentary facies are dominated by main channels and sandy braided bars; 3) Channel forwards right along fault trough formed by Binhai faults; 4) Channels flow to the southwest, which are on the down thrown side of Gangdong fault (Fig. 4).

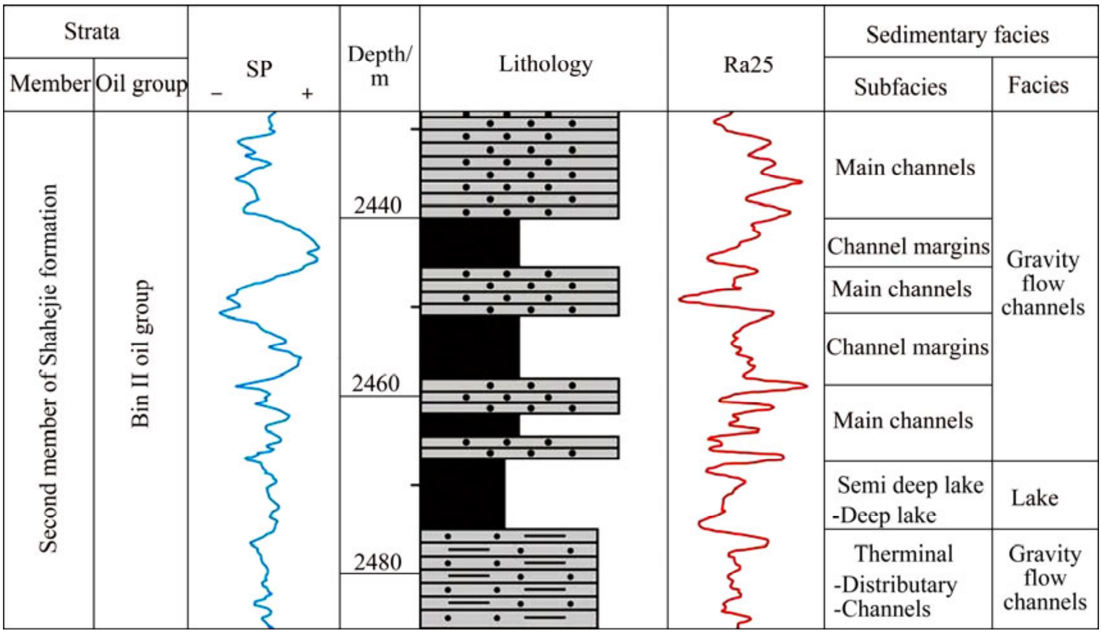

Fig. 3 Well logs for Gang 368, showing sediment gravity flow characteristics

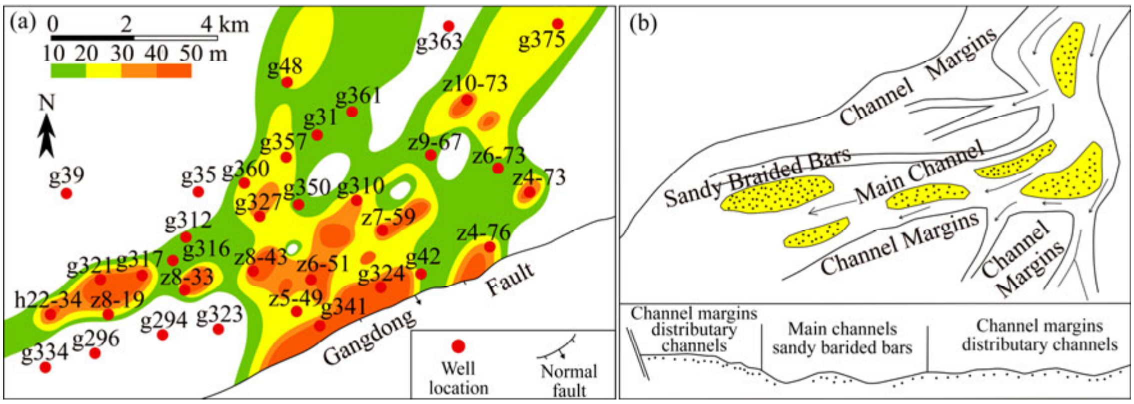

Fig. 4 Depositional models for gravity flow channels of Es2, Gangzhong area: (a) Isopach of Bin IV sands, second member of Shahejie formation, Gangzhong area; (b) Depositional model of sedimentary gravity flows, second member of Shahejie formation

4 Reservoir characteristics

4.1 Petrography analysis

Lithology of gravity flow channels in Gangzhong area is characterized by arkosic arenite (Fig. 5(a)), quartz arenite (Fig. 5(b)) and lithic arkosic arenite (Fig. 5(c)). Clastic particles consist mostly of feldspar, quartz secondary, and lithic fragments the least. Feldspar contains plagioclase, orthoclase and microcline, and about 50% of these are plagioclase. Some plagioclase surface is still fresh, without weathering or eroding, while most have occurred sericitization. Kaolinization occurred in orthoclase and resulted in dusty surface. Usually microcline has fresh surface and develops twin lattice. Quartz mainly derived from igneous rock, about 60%−80% of the total. Undulatory extinction and inclusions are common, including tourmaline and zircon. Acid igneous rock fragments occupying 50%−75% of lithic fragments which were discovered around.

Apart from sandstones, clay minerals are common in this area, which mainly include kaolinite (Figs. 6(a) and (c)), illite (Fig. 6(b)), illite-smectite (Fig. 6(d)) and smectite, and their distributions are closely related with depth. Above the depth of 2500 m, kaolinites grow and consist 2%−15% of sands. As the depth increases, authigenic kaolinites become less, and almost can not be found bellow the depth of 3200 m, however, illite content increases with the depth increasing. Often the chlorite content is lower than 10%. Shallower than 2800 m, smectite appears sporadically; deeper than 2800 m, it may disappear gradually. Mixed layer illite-smectite displays alveolar or blanket aggregates through scanning electron microscope, addicting to the particle surface or among particles.

4.2 Reservoir physical properties

Physical properties in this area make high quality

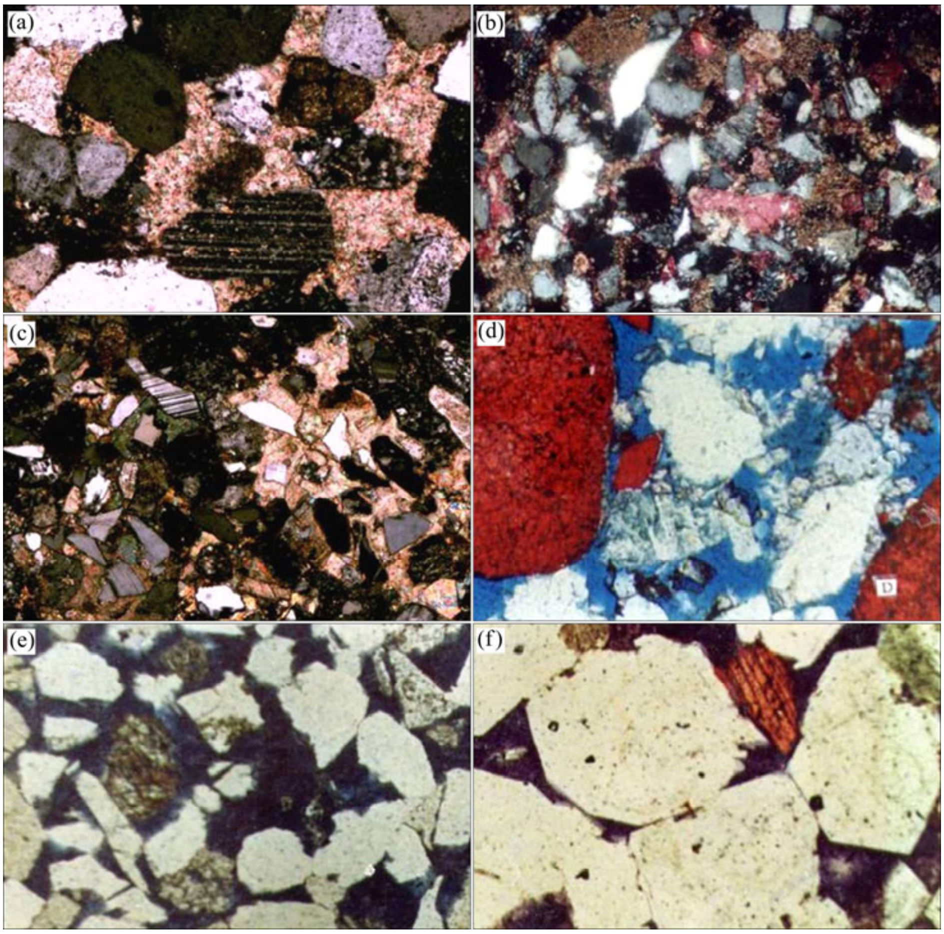

Fig. 5 Sands and major pore types in Gangzhong area: (a) Arkosic arenite, calcite cemtnation, well gs56, 3193.28 m, Es2, orthogonal polarized light, (×10); (b) Quartz arenite, well z8-39, 2348.5 m, Es2, orthogonal polarized light, (×4); (c) Lithic areninte, well gs52, 2559.3 m, Es2, orthogonal polarized light, (×4); (d) Secondary intergranular pores, well z7-59, 2789.22 m, Es2, orthogonal polarized light, (×10); (e) Secondary intergranular pores, well g68, 2518.2 m, Es2, orthogonal polarized light, (×4); (f) Dissolution pores on quartz surface, well z8-55, 2841.7 m, Es2, orthogonal polarized light, (×10)

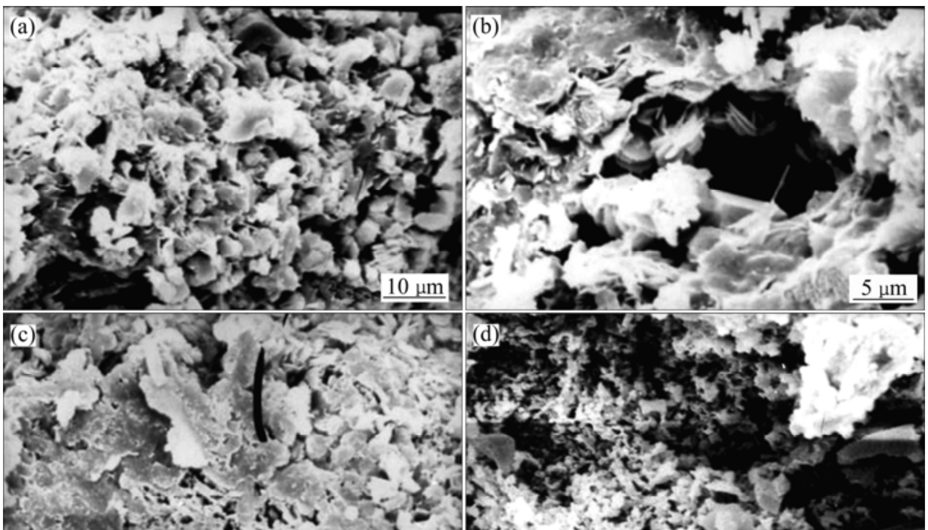

Fig. 6 Clay minerals in Gangzhong area: (a) Authigenic illite and Kaolinite, well g352, 2488 m, Es2; (b) Sheet-like illite in micro-pores well g352, 2528.75 m, Es2; (c) Dissolution pores and sheet-like Kaolinite, well g28, 2693.3 m, Es2; (d) Relics of calcite, fragmentary illite-smectite mixed-layer, well gs57, 2952.29 m, Es2

reservoirs. The average porosity is 21%, and mean permeability is 55×10^{-3} μm^2. Inter-grain pores make more than 70% of the total pores (Figs. 5(d)−(f)), and others are pores in grains and primary intergranular pores, only few large pores and fractures. Major types of throat which connecting pores in this area are 10−20 μm lamellar throat or less than 10 μm contracted throat. The larger throat, the higher permeability.

4.3 Diagenesis characteristics

According to a through analysis of casting thin sections, scanning electronic microscopy, Cathode Luminescence and X-ray diffraction, it is concluded that sand reservoir of gravity flow channels have undergone destructive compaction, cementation and constructive dissolution.

4.3.1 Compaction

Compaction reduced primary porosity, but the effect was limited. According to scan observation and quantitative classification of the compaction (Table 2) [14], it is referred that the sandstone of study area went through moderate compaction with point contact and linear contact mostly, the concavo-convex and sutured grain contacts are rare. Gangzhong area is situated in the center of Binhai fault system, after the deposition of second member of Shahejie formation, tectonic movements enhanced and sediments were rapidly buried. As the depth increases, cementation intensifies and compaction's impact on reducing primary porosity pronounced weakens. At the depth of 2200 m, attenuation gradient of porosity reduces to 1%.

Table 2 Quantitative classification of compaction [12]

Compaction	Burial depth/m	Percentage of contact type/%		
		Point contact	Linear contact	Concavo-convex contact
Weak compaction (I)	<1000	>75	<25	0
Moderate-weak compaction (II)	1000−2300	50−75	25−50	0
Moderate compaction (III)	2300−3000	25−50	50−75	Almost 0
Moderate-strong compaction (IV)	3000−5000	Almost 0	>75	<25
Strong compaction (V)	>5000	0	25−50	50−75

4.3.2 Cementation

Cementation which mainly occurs at the depths ranging from 2200 to 2500 m in this area also has significant impact on reducing the primary porosity. Calcite cementation can be divided into two periods: early cementation and late cementation. The early calcite cementation obviously controlled by burial depth [15−18] is the main type in Gangzhong area, and is characterized by occurring above the depth of 2600 m, filling in pores, 0.1−0.15 μm particles, showing dark orange or dark tangerine in the cathodoluminescence images (Fig. 7). Late calcite cementation is different from early calcite cementation in that these calcites fill in spaces between grains. They often replace other minerals and cause ferrocalcite and ankerite symbioses [19−21], and rarely appear in the form of joined crystal. Due to the SiO_2 originateing from dissolution of unstable feldspar and clay minerals transformation, quartz overgrowths are common, about 3% of the overall. The overgrowth rim broadens with the increasing depth.

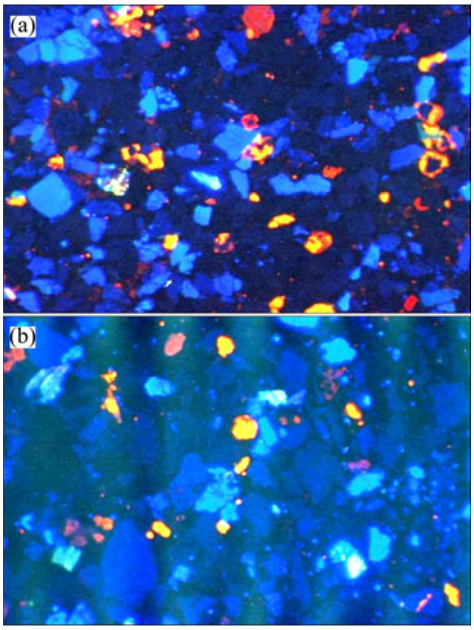

Fig. 7 Calcite cements in sandstones (Cathodoluminescene photo): (a) Orange calcite, replace feldspar and lithic fragments, well gz8-39, 2348.5 m, Es2, (×4); (b) Orange calcite, replace feldspar, well gz7-59, 2779 m, Es2, (×4)

4.3.3 Dissolution

Dissolution, as the major constructive diagenesis in Gangzhong area, controls the formation and distribution of secondary pores. Micritic calcites precipitated earlier are dissolved later into calcite debris filling in intergranular pores. The calcites precipitated in the late period are dissolved less extensively, resulting embay-shaped margin. At the depth of 2600 m, dissolution makes particles migrate all around, and few quartz overgrowth rims and filling between grains are left. As a result, physical properties improve. At the same time, as for feldspathic quartz sandstone of low maturity, feldspar dissolves under eluviation, creating intercrystalline pores and intracrystalline pores, enlarging intergraular pores, and therefore greatly improves reservoir porosity.

5 Factors controlling high quality reservoirs

5.1 Lithology and sedimentary microfacies

Reservoir physical properties of second member of Shahejie formation in study area are closely related with sedimentary microfacies and their distribution. The permeability increases rapidly with the reducing shale content in sands (Fig. 8(a)), and the permeability shows linear growth as the grain size increases (Fig. 8(b)). In the gravity flow channels, main channels and sandy braided bars have the best reservoir properties. Compared with other microfacies, they have relatively low shale content and larger grain size, they are well sorted and well rounded, which result in good primary porosity and permeability. These pores provide space for calcite cements and therefore prepare easy-to-dissolve materials for dissolution. In this case, more secondary pores are produced. From channels to channel margins, from main channels to distributary channels, the shale contents increase, the sand grain size reduces, causing low porosity and permeability. Extremities of channels have the poorest physical properties (Fig. 9).

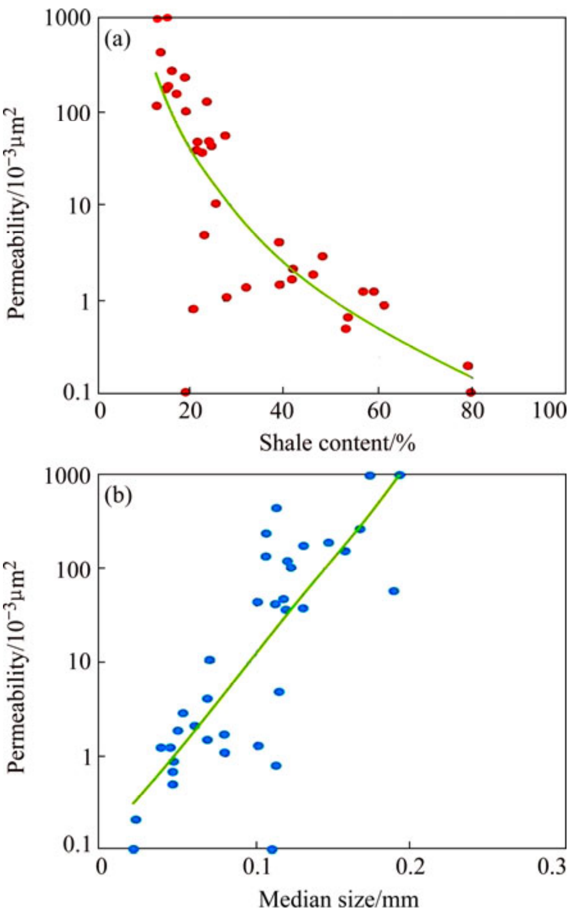

Fig. 8 Permeability versus shale content and permeability versus median size: (a) Relationship between shale content and permeability; (b) Relationship between median size and permeability

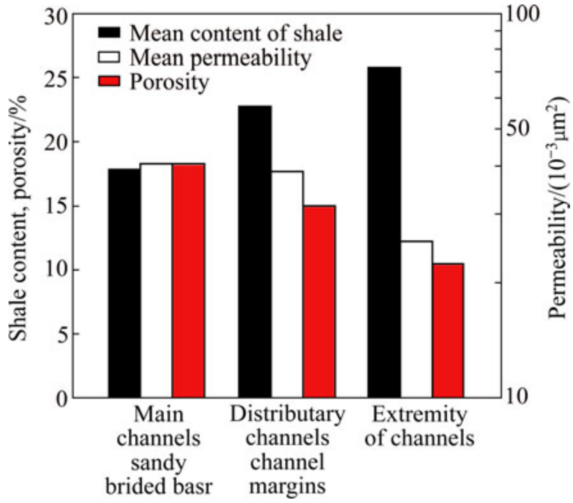

Fig. 9 Various sedimentary microfacies in physical properties

5.2 Diagenesis influence

Dissolution is the decisive factor of improving reservoir physical properties. On the one hand, cementation tends to reduce the primary porosity, but on the other hand, it may improve physical properties as a result of providing more dissolved materials and space for the later dissolution. Take high H^+ concentration accelerating dissolution for example. As the burial depth reached 2500−3200 m, basically matching the threshold depth of oil generation, organic matter becomes mature and then releases organic acid, increasing H^+ concentration. Besides, we can see from converted ratio of illite-kaolinite mixture (Fig. 10) [14] that the content of kaolinite reduces from 70% to 35% at the depth of 2500 m, resulting in more H^+ which tends to enhance

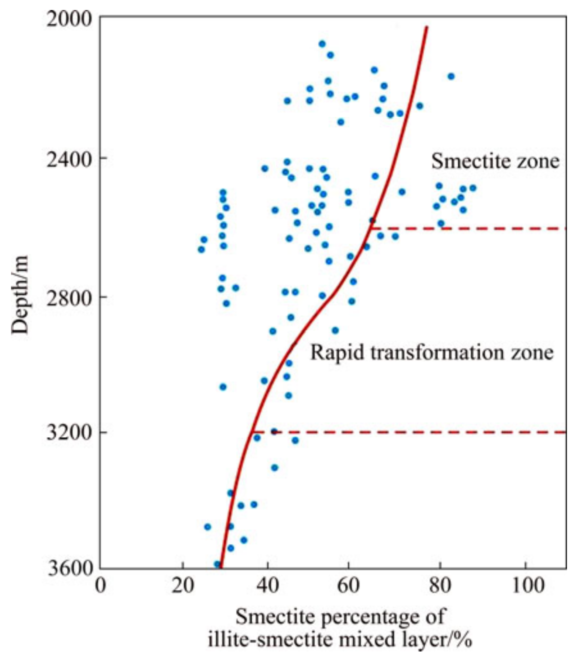

Fig. 10 Percentage of smectitie to illite-smectite mixed layer varies with depths

dissolution and produce lots of secondary pores, reaching 60% of the total.

5.3 Deep hydrothermal fluid intrusion

Deep magma intrusion may have impact on the development of secondary pores. According to the study on fluid inclusions, homogenization temperature increases from the center of depression to structural crest. This change shows that reservoir exchanges fluid with aqueous solution expelled from shale frequently. Besides, oil-source correlations data shows that oil in second member of Shahejie reservoir not only comes from the second member but also originates from the third member. Therefore, it is possible that the hydrothermal fluid intrusion enhances development of secondary pores.

6 Conclusions

1) Sediment gravity flows in Gangzhong area are different from others in that relatively good reservoirs found here. The reservoirs have distinctive characteristics: medium-fine sands; well-sorted and well-rounded; solution pores occupy about 70% of the total; average porosity and permeability are 21% and 55×10^{-3} μm^2.

2) Reservoir physical properties are closely related with types and distribution of sedimentary microfacies. The main channels and sandy braided bars of reservoir are better than channel margins and extremity of channels for the following reasons: reservoir's lithology mainly consists of medium-fine sands, with high primary porosity and permeability; reservoir has favorable conditions for calcite cementation and development of secondary pores.

3) Dissolution is the decisive factor to improve reservoir physical properties. Both the organic acid expelled when organic matter becomes mature and H^+ formed during clay materials transformation increase H^+ concentration in aqueous solution. These result in the dissolution of calcite cements and form large volume of secondary dissolution pores.

References

[1] LUNDEGARD P D. Sandstone porosity loss—A "big picture" view of the importance of compaction [J]. Journal of Sedimentary Petrology, 1992, 62(2): 250−260.

[2] BLOCH S, LANDER R H, BONNELL L M. Anomalously high porosity and permeability in deeply buried sandstone reservoirs: Origin and predictability [J]. AAPG Bulletin, 2002, 86(2): 301−328.

[3] PAXTON S T, SZABO J O, AJDUKIEWICZ J M, KLIMENTIDISET R E. Construction of an intergranular volume compaction curve for evaluating and predicting compaction and porosity loss in rigid-grain sandstone reservoirs [J]. AAPG Bulletin, 2002, 86(12): 2047−2067.

[4] ANA R S, CARLOS L L, MARIA P M, JOSE A, LAIA A, LGNACIO A, ALFONSO M. Slumping and a sandbar deposit at the Cretaceous-Tertiary boundary in the EI Tecolote section(northeastern Mexico): An impact-induced sediment gravity flow [J]. Geology, 2001, 29(3): 231−234.

[5] DONALD R L. Sediment gravity flows: II. Depositional models with special reference to the deposits of high-density turbidity currents [J]. Journal of Sedimentary Petrology, 1982, 52(1): 279−297.

[6] MICHAEL R S, STEPHEN M H. Sedimentology, stratigraphic architecture, and ichnology of gravity-flow deposits partially ponded in a growth-fault-controlled slope minibasin, tres pasos formation(cretaceous), southern chile [J]. Journal of Sedimentary Research, 2005, 75(3): 440−453.

[7] LI Hui-jun, CHEN Wen-yan, ZHANG Wen-cai, CHEN Hong-wen. An approach to the diagenesis of clastic rocks under abnormal high temperature and pressure-Taking the Lower Tertiary deep formation in Banqiao sag as an example [J]. Petroleum Exploration and Development, 2001, 28(6): 28−31.

[8] ZOU Hai-feng, GAO Fu-hong, XU Xue-chun, LIU Li. Geochemistry study on the forming mechanism of the cement of dagang exploration area [J]. Journal of Jilin University: Earth Science Edition, 2002, 32(1): 34−38.

[9] YOU Jun, ZHENG Jun-mao. Factors of affecting the reservoir physical properties of deep strata in the Huanghua Depression [J]. Geoscience, 1999, 13(3): 350−354.

[10] CUI Yong, ZHAO Cheng-lin. Secondray porosity generation and the relationship associated with overpressure leakage [J]. Journal of Chengdu University Technology, 2002, 29(1): 49−52.

[11] ZHOU Li-hong, LU Yi, XIAO Dun-qing, ZHANG Zhi-pan, CHEN Xian-bao, WANG Hui, HU Shi-ying. Basinal texture structure of Qikou sag in Bohai bay basin and its evolution [J]. Natural Gas Geoscience, 2011, 22(3): 373−382.

[12] WANG Zhan, MENG Qing-kuan, XIE Jian-min, WANG Xiang. Huanghua depression geological tectonic evolution and hydrocarbon distribution [M]. Beijing: Science Press, 1999: 10−25.

[13] DAI Jun-sheng, LU Ke-zheng, QI Jia-fu, CHEN Shu-ping. Structure style evolution in paleogene Bohai Bay basin [J]. Acta Pet Rolei Sinica, 1998, 19(4): 16−20.

[14] JIN Zhen-kui, LIU Chun-hui. Quantitative study on reservoir diagenesis in Northern Dagang Structural Belt, Huanghua Depression [J]. Petroleum Exploration and Development, 2008, 35(5): 581−587.

[15] FU Qiang. Diagenesis effect on reservoir pores-taking the rong-37 block of the lower tertiary, Liaohe basin as an example [J]. Acta Sedmentologica Sinica, 1998, 16(3): 92−96.

[16] JEFFREY J D. Rapidity of freshwater calcite cementation-implications for carbonate diagenesis and sequence stratigraphy [J]. Sedimentary Geology, 1996, 107: 1−10.

[17] KENNETH J T, KENNETH R W, STEVEN G G. Burial diagenesis of middle Ordovician carbonate buildups (Alabama, USA): Documentation of the dominance of shallow burial conditions [J]. Sedimentary Geology, 1997, 114: 223−236.

[18] CHENG Xiao-lin. Influence of the diagenesis of clay minerals on reservoirs and productivity: A case study on the fu-3 reservoirs of taixin oilfield, the north jiangsu basin, 2003, 25(2): 164−168.

[19] MENG Yuan-lin, WANG Zhi-guo, YANG Jun-sheng, YANG Jun-sheng, YING Feng-xiang, LIU Yun-hua, LUO Xian-ying, BI Yan-bin, WANG Jia-liang. Comprehensive process-oriented simulation of diagenesis and its application [J]. Petroleum Geology & Experiment, 2003, 25(2): 211−215. (in Chinese)

[20] LIU Bao-jun. Some problems on the study of sedimentary diagenesis [J]. Acta Sedimentologica Sinica, 2009, 27(5): 787−791.

[21] ZHANG Jie, QIU Nan-sheng, WANG Xi, WANG Xin, DUAN Jian-kang. Thermal evolution and reservoiring history in Qikou sag, Huanghua depression [J]. Oil & Gas Geology, 2005, 26(4): 506−510.

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