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Facies-controlled volcanic reservoirs of northern Songliao Basin, NE China

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Abstract: Volcanic rocks of the late Mesozoic are very important reservoirs for the commercial natural gases including hydrocarbon, carbon dioxide and rare gases in the northern Songliao Basin. The reservoir volcanic rocks include rhyolite, andesite, trachyte, basalt and tuff. Facies of the volcanic rocks can be classified into 5 categories and 15 special types. Porosity and permeability of the volcanic reservoirs are facies-controlled. Commercial reservoirs were commonly found among the following volcanic subfacies: volcanic neck (I_1), underground-explosive breccia (I_3), pyroclastic-bearing lava flow (II_3), upper effusive (III_3) and inner extrusive ones (IV_1). The best volcanic reservoirs are generally evolved in the interbedded explosive and effusive volcanics. Rhyolites show in general better reservoir features than other types of rocks do.

Key words: Songliao Basin; Cretaceous; volcanic facies; natural gas reservoir

1 Geological background

Songliao Basin developed on the Mongolia-North China block. Its basement is mainly composed of the Late Paleozoic metamorphosed marine sediments (slates, phyllites). Paleozoic carbonates, andesites and granites as well as Precambrian gneisses and schists contribute minor part of the basement (Wang *et al.*, 1993). The Mesozoic volcanic rocks in Songliao Basin are upper Jurassic and lower Cretaceous (Wang *et al.*, 2006). The volcanogenic successions are 1 300 ~2 800 m in thickness revealed by drilling and comprise the main body of the lower part of basin filling (Wang *et al.*, 1996). They are overlain by middle and upper Cretaceous sedimentary sequence (Albian to Maastrichtian) of up to 6 000 m thick (Gao, 1995) Songliao Basin is surrounded by faults and mountain ranges.

The Songliao Basin is the most important oil and gas bearing basin in China concerning annual production of crude oil. The largest oil field in China, Daqing oil field, was found in this basin in 1959. Basin fillings can be markedly separated into two different cycles. The upper cycle is composed of normal sedimentary sequences of late Early Cretaceous and Late Cretaceous which can be up to 5 000 m thick (Gao, 1997). The volcanogenic successions are major component of the lower cycle which can be up to 4 000 m in thickness (Chi *et al.*, 2000). The two basin forming cycles may belong to two different tectonic regimes. The former was under the influence of the Pacific plate subduction, the latter was controlled by the Okhotsk collision belt (Wang *et al.*, 2000, 2001, 2002a, 2002b; Meng *et al.*, 2005; Cheng *et al.*, 2003). We will focus on the volcanogenic successions in this study.

The reservoir volcanic rocks of Songliao Basin

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were developed in the lower basin filling cycle consisting of upper Jurassic Huoshiling Formation and lower Cretaceous Yingcheng Formation (Yang *et al.*, 2003). The Huoshiling Form. is composed mainly of andesite and the Yingcheng Form. predominantly of rhyolite. Pyroclastic rocks and sedimentary rocks are often intercalated or interbeded with those volcanic rocks. Based on the cuttings/core sections and outcrop descriptions of the volcanic rocks around and within Songliao Basin, we know that these volcanic rocks are widely distributed, covering an area of over 260 000 km^2. In recent ten years, most of the natural gases were found in the volcanic rocks and those gases contained in the volcanics may have quite different origins (Dia *et al.*, 1993, 1996, 2003; Guo *et al.*, 1997).

2 Petrology and facies of reservoir volcanic rocks

Since volcanic reservoir was first discovered by chance during the drilling of well SS2 in 1994, over 80 exploration wells designed for the volcanic reservoirs and gas traps were drilled until now (Fig. 1). The revealed volcanics are composed of predominantly lower Cretaceous and with minor upper Jurassic. The lower Cretaceous volcanic rocks include rhyolite, perlite, dacite, andesite, basaltic trachyandesite and tephrite. Those from the upper Jurassic are rhyolite, andesite, trachyte, trachyandesite and basaltic trachyandesite. The Cretaceous rhyolite, perlite and dacite have porphyritic or aphyric textures and are phenocryst-poor (less than 5%) rocks with phenocryst assemblage of quartz, feldspars, biotite, hornblende, magnetite and ilmenite. In contrast, the Jurassic rhyolite contains more phenocryst (up to 30%). Other types of volcanics both the Cretaceous and the Jurassic are typically composed of porphyritic texture. These rocks are also phenocryst-poor but with complexity of phenocryst assemblage commonly including quartz, feldspars (sanidine, anorthoclase and plagioclase), biotite, hornblende, magnetite, ilmenite and pyroxene. Cumulophyric intergrowth is common amongst the phenocrysts.

Volcanic facies indicate assemblage of the features that can reflect forming process and genesis of the lava. Five facies and 15 subfacies can be recognized in the volcanic rocks of Songliao Basin (Wang

Fig. 1 Typical volcanic reservoir rocks of Songliao Basin, breccia rhyolite with deformed fluidal structure and vesicle

et al., 2003a, 2003b). Most of them can be as reservoirs containing natural gases of methane and/or CO_2. The volcanic facies are as followings: I- volcanic vent assemblage include volcanic neck subfacies (I_1), subvolcanic subfacies (I_2) and underground-explosive breccia subfacies (I_3); II- explosive facies are composed of air-fall subfacies (II_1), base surge deposits (II_2) and pyroclastic flow deposits (II_3); III- effusive facies consist of lower subfacies (III_1), middle subfacies (III_2) and upper subfacies (III_3); IV- extrusive facies include inner subfacies (IV_1), middle subfacies (IV_2) and outer subfacies (IV_3); V- volcanogenitic sedimentary facies include epiclastic-bearing sedimentary subfacies (V_1), retransported volcanic sediments (V_2) and coal-bearing volcanic sediments (V_3).

3 Relationship amongst lithology, facies, porosity and permeability of the volcanic reservoirs

Although all kind of volcanic rocks and facies can be the reservoirs in the basin, the frequency practically discovered and capacity for gas storage are quite different from rocks to rocks due to their particular genetic pore space evolution. For the facies of 5 categories and 15 special types of the volcanic rocks only a few of them can be frequently found as effective reservoirs containing commercial natural gases It has been proved by exploration in recent 10 years that porosity and permeability of the volcanic reservoirs are facies-controlled. High productive reservoirs were commonly found among the following volcanic subfacies: volcanic neck (I_1), underground-explosive breccia (I_3), pyroclastic-bearing lava flow (II_3), upper effusive (III_3) and inner extrusive ones (IV_1). The best volcanic reservoirs are generally developed in the interbedded explosive and effusive volcanics. Rhyolites show in general better reservoir features than other type of rocks do (Table 1; Figs. 2, 3 and 4).

Table 1 Relationship among lithology, lithofacies and daily production of methane

Buried depth /m	Effective thickness /m	Lithology	Lithofacies*		Output grade*
			Facies	Sub-facies	
2860~2869	3.5	Rhyolite with deformed structrue	IV	IV_3	D
2970~2972	2	Rhyolite with vesicle and fluidal structure	III	III_3	A~B
2942~2949	6.9	Rhyolitic breccia lava	IV	IV_3	B
3002~3013	2.1	Cryptocrystalline rhyolite	III	III_2, III_1	C
2890~2898	8	Interbedded rhyolite and tuff	III and II	III_2 and II_3	A
2955~2965	10	Vesicle rhyolite	III	III_3	A
2868~2876	8	Vesicle rhyolite	III	III_3	A
2909~2917	8	Vesicle rhyolite	III	III_3	B

Note: ①Output grade indicates daily natural gas productions per well, A > 10×10^4 m^3, B = 10×10^4 m^3 − $5\times10^4 m^3$, C = 5×10^4 m^3 − 1×10^4 m^3, D < 1×10^4 m^3. ②symbols of volcanic facies the same as described in context.

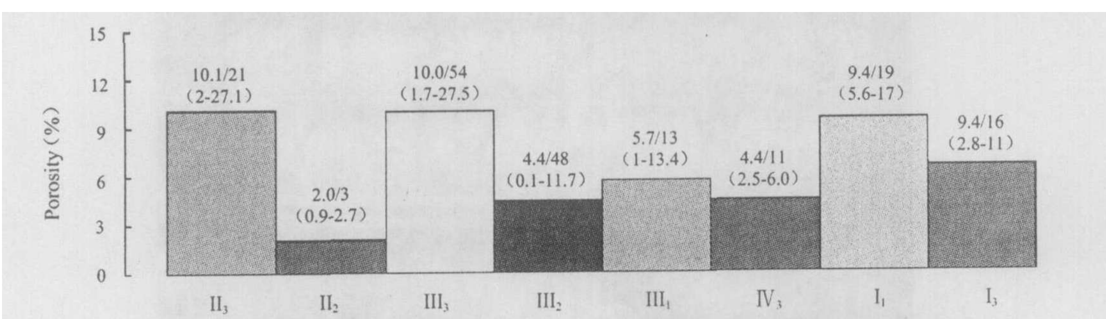

Fig. 2 Diagram showing subfacies-controlled porosity of volcanic reservoir

(values of 10.1/21 (2-27.1) indicate mean, sample number and range of the porosity; the same symbols of volcanic facies as described in context)

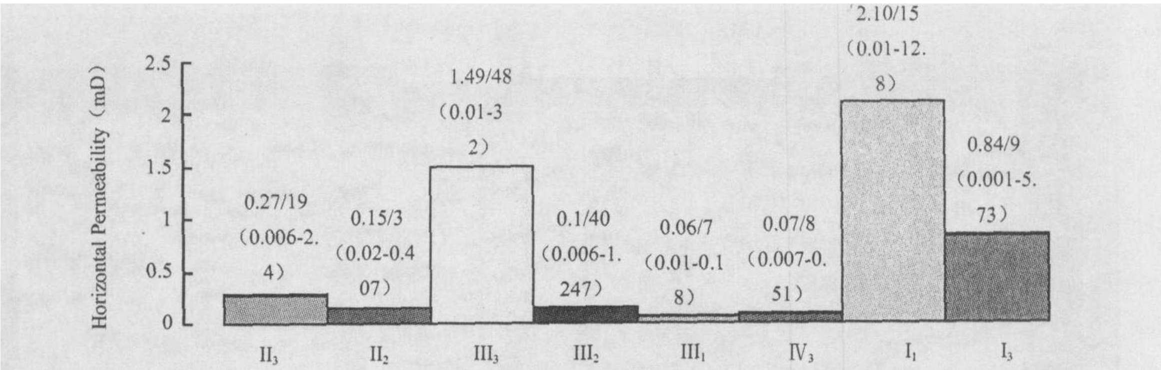

Fig. 3 Subfacies-controlled horizontal permeability (cf. Fig.4 for explanation)

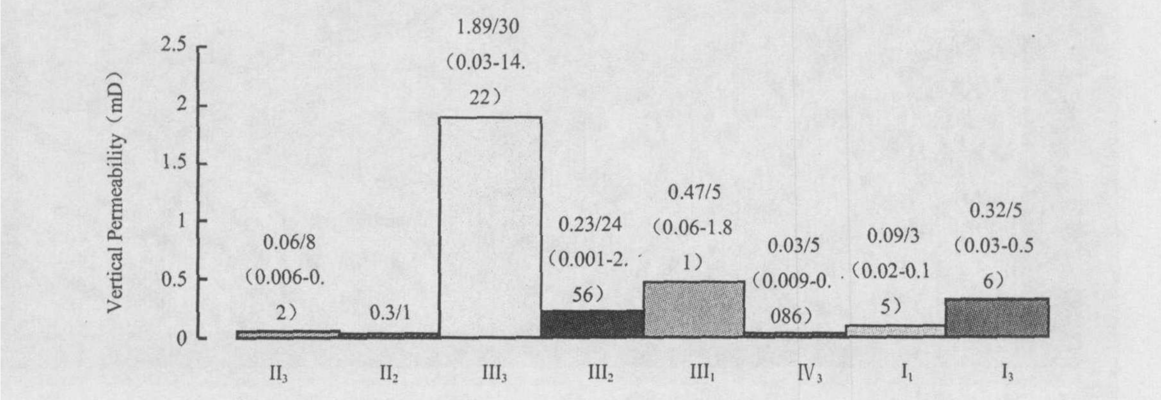

Fig. 4 Diagram showing subfacies–controlled vertical permeability of the volcanic reservoir

(values of 0.06/8 (0.006-0.2) indicate mean, sample number and range of the permeability; the same symbols of volcanic facies as described in context)

The effusive volcanic rocks (III), especially the upper subfacies (III_3), are rich in both primary vesicles and fault cracks as a result they often make good reservoirs. Circular primary cracks are generally well developed in the IV_1 pillow lavas resulted from rapid cooling and in turn they result in large-scale unconsolidated body within volcanic dome that is one of the best reservoirs. The loose units, regularly covered and preserved by an overlying hard lava shell, are always good reservoirs with a scale of ca. 200 m in amplitude and 2 000 m in diameter. But the subfacies of IV_1 is difficult to be recognized in the basin. Porosity and permeability of volcanic rocks will normally not decrease with buried depth because most of them are hard enough to withstand the incoming overlying load. In this case the reservoir features are not influenced by burying. But if the diagenesis is compaction dominant, like in the cases of pyroclastics and tuffs with facies V and subfacies of II_1 and II_2, their pore space will reduce with increasingly buried depth.

4 Conclusion and discussion

Controlling factor on pore space features of the volcanic rocks is subfacies of the related volcanic rocks. However, effective volcanic reservoirs can contain natural gases, water or nothing in the studied area, owing to the varying local conditions of fluids. The controlling factors for the formation of gas pool there include source rocks, reservoirs, structural features and

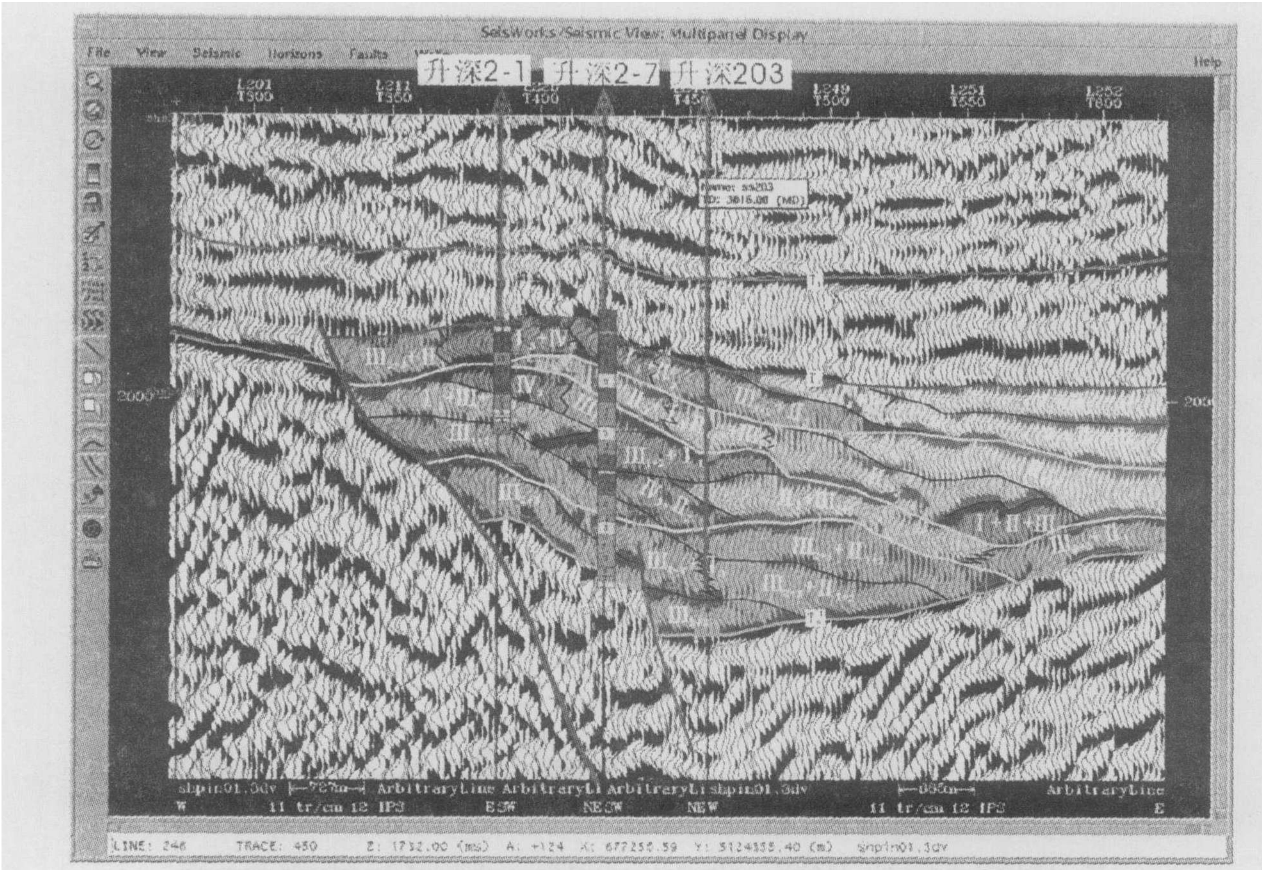

Fig. 5 Inter-well correlation and lateral facies change of volcanic reservoirs

cap rocks and the assemblage of sealing system (Liu *et al.*, 2003). The source rocks are (coal-bearing) black shale of Delouku Form. and Shahezi Form. (Wang *et al.*, 1996). Anticlines formed in early stage of basin formation are favorable structures for gas pool. Regional caps are the pelites of Quantou and Delouku Formations (Wang *et al.*, 1993). NW-SE direction uplifts in the depression are favorable for the formation of commercial gas pools. The association of dome-fault-volcanic reservoir-regional seal is the best condition for the high productive gas pools.

Morphology highs of buried volcano relief and/or structural highs resulted from tectonic movement are favorable situations for natural gas accumulation under the condition of suitable volcanic facies. In the case of Fig. 5, wells SS2-1 and SS2-7 are highly productive and commercial wells, while well of SS203 has only some gas shows very possibly because of its tectonic low.

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