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Research Article

Origins of natural gas and the main controlling factors of gas accumulation in the Middle Ordovician assemblages in Jingxi area, Ordos Basin☆

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Abstract

During the progressive exploration of the Jingbian Gas Field in the Ordos Basin, multiple gas-bearing regions have been discovered in the dolomite reservoirs in the Middle Ordovician assemblages of Lower Paleozoic in Jingxi area, but these gas-bearing regions and intervals are significantly different in terms of gas enrichment degrees. So far, however, the reasons for the difference have not been figured out. In this paper, the origin and source of natural gas in the Middle Ordovician assemblages in Jingxi area was investigated on the basis of geochemical data (e.g. natural gas composition and carbon isotope), and then the main factors controlling the gas accumulation were analyzed. It is shown that the natural gas in the Middle Ordovician assemblages in the Middle Ordovician assemblages in Jingxi area is similar to that in the Upper Ordovician assemblages and Upper Paleozoic reservoir in terms of genesis and sources, and they are mainly the Upper Paleozoic coaliferous gas with some oil-derived gas. Under the influence of hydrocarbon generation center of coal source rocks and the source–rock–reservoir contact relationship, the proportion of coaliferous gas increases areally from the north to the south and vertically from Ma_5^5 sub-member of the Lower Ordovician Majiagou Fm. It is concluded that the natural gas enrichment degree is controlled by the gas charging capacity at the hydrocarbon-supplying windows. Second, the vertical migration and distribution of natural gas is dominated by the differences of $Ma_5^5 - Ma_5^{10}$ transport pathways. And third, the lateral migration direction of natural gas and the range of gas accumulation are controlled by the superimposition relationship between structures and reservoirs.

Keywords: Ordos Basin; Jingxi area; Early Paleozoic; Middle Ordovician assemblages; Natural gas origin; Source rock–reservoir contact relationship; Charging capacity; Gas enrichment difference; Gas accumulation controlling factor

In the Ordos Basin, the gas-bearing area of the Lower Paleozoic Ordovician strata has been expanded continually with the progressive exploration of the Jingbian Gas Field. Of particular note is the discovery of multiple gas-bearing zones in dolomite reservoirs in Jingxi area, which together hold a nearly 1000×10^8 m^3 of natural gas reserves and thus have become an important successive domain for natural gas exploration [1,2]. Exploration practices show that in Jingxi area the Middle Ordovician assemblage gas is enriched in the Su 203 and Su 127 blocks rather than in the adjoining Tao 15, Zhao 44 and Zitan 1 blocks, and even within each block the gas–water relationship remains complex among different wells. Vertically, in the Lower Ordovician Majiagou Fm, the Ma_5^5 and Ma_5^6 sub-members are more gas-enriched than the Ma_5^7 to Ma_5^{10} sub-members. The reason for the difference in enrichment degree of natural gas is yet to be systematically studied, which adds to the difficulty in designing the next-step exploration of this area. Therefore, based on geochemical data

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(e.g., gas composition and carbon isotope) and in view of the difference in enrichment degree of the Middle Ordovician assemblage gas across Jingxi area, the authors provide a comparison of the Middle assemblage gas with the Upper assemblage gas and the Upper Paleozoic gas, analyze the gas origin and source, and determine the main controlling factors of gas accumulation, hoping to make a scientific explanation to the origin of natural gas and the difference in gas accumulation in this area and to provide reference information for the next-step oil & gas exploration in Jingxi area.

1. Overview of geology

Located in the westerner part of the North China platform, the Ordos Basin spans five provinces, i.e., Shaanxi, Gansu, Ningxia, Inner Mongolia and Shanxi. This rectangular-shaped structural basin covers a total area of 37×10^4 km^2. On a regional scale, the basin can be structurally divided into six first-order tectonic units, i.e., Yishan slope, Jinxi fold belt, Tianhuan depression, West Margin thrust belt, Yimeng uplift and Weibei uplift [3−5]. Jingxi area is situated in the western part of the Yishan slope belt, between the central paleo-uplift and the Jingbian Gas Field (Fig. 1). In the light of gas distribution feature, Jingxi area can be divided into several gas-bearing blocks, from the north to the south, i.e. Zhao 44, Tao 15, Su 203, Su 127 and Zitan 1.

Vertically, the Ordos Basin contains multiple gas-bearing layer series, of which the Ordovician Ma_5 member is deemed to be one of the most important. The Majiagou Fm that is present across the Ordos Basin was recently divided by prospectors into three gas-bearing assemblages [6,7]: the Upper assemblage, which comprises the Ma_5^1 to Ma_5^4 sub-members and mainly contains dissolved pore-type weathering crust reservoirs; the Middle assemblage, composed of the Ma_5^5 to Ma_5^{10} sub-members, mainly contains intercrystalline dissolved pore- and fracture-type dolostone reservoirs; and the Lower assemblage, consisting of the Ma_4 member and older strata, has the similar reservoir type with the Middle assemblage. Because of the impact of the Caledonian tectonic uplifting occurred at the end of Ordovician, Jingxi area was weathered and denuded in varying degrees from the east to the west, causing the Ordovician strata in this area to be topped with progressively older segments in the same direction [8]. As a result, in this area, the Ordovician strata are overlain directly by the Upper Paleozoic Carboniferous−Permian coal-bearing strata and layer series in contact with the Ordovician strata have a progressive east-to-west transition from the Upper assemblage to the Middle and Lower assemblages [9].

2. Origin of natural gas

2.1. Geochemical features of natural gas

2.1.1. Gas composition

According to statistics, the Middle Ordovician assemblage in Jingxi area has a total hydrocarbon content of gas that ranges from 92.52% to 99.11%, averaging 96.33%, and the hydrocarbon gas is CH_4-dominated, with low heavy hydrocarbon (C_2^+) content and methane dry coefficient that ranges from 0.933 to 0.999, averaging 0.978, exhibiting a typical feature of over-mature dry gas that contains extremely high methane content; and the content of CO_2 and N_2, which are non-hydrocarbon components, average 1.05% and 0.46%, respectively. Also in this basin, the Upper Ordovician assemblage has a total hydrocarbon content of gas that ranges from 82.05% to 98.80%, averaging 94.25%; and the Upper Paleozoic from 81.52% to 97.91%, averaging 92.70%. The hydrocarbon gas in them is high in methane and low in heavy hydrocarbon content, with an averaged methane dry coefficient of 0.961 and 0.956, respectively, exhibiting a typical feature of over-mature dry gas that contains extremely high methane content; and the CO_2 and N_2 content averages 2.24% and 3.21% in the Upper Ordovician assemblage, and 1.28% and 3.06% in the Upper Paleozoic, respectively. It can be seen that, in comparison with the Upper Ordovician assemblage and the Upper Paleozoic, the Middle Ordovician assemblage in Jingxi area contains natural gas with slightly higher methane content, lower content of heavy hydrocarbon and non-hydrocarbon components, and higher methane dry coefficient.

2.1.2. Gas carbon isotope

Gas carbon isotope varies with different gas-bearing assemblages (Fig. 2). In Jingxi area, the Middle Ordovician assemblage holds gas with relatively lighter gas carbon isotope: methane carbon isotope ranges from −32.16‰ to −39.26‰, averaging −33.52‰; ethane carbon isotope ranges from −23.78‰ to −39.42‰, averaging −31.06‰; and propane carbon isotope ranges from −19.72‰ to −34.2‰, averaging −27.03‰. Also in this basin, the Upper Ordovician assemblage contains gas with relatively heavier carbon isotope of methane, ethane and propane: methane carbon isotope ranges from −28.74‰ to −38.60‰, averaging −33.52‰; ethane carbon isotope ranges from −23.52‰ to −37.78‰, averaging −30.55‰; and propane carbon isotope ranges from −19.85‰ to −33.90‰, averaging −27.00‰. Gas carbon isotope becomes evidently heavier in the Upper Paleozoic than in the Ordovician strata: methane carbon isotope ranges from −21.02‰ to −38.83‰, averaging −32.86‰, ethane carbon isotope ranges from −19.07‰ to −36.17‰, averaging −25.74‰; and propane carbon isotope ranges from −18.15‰ to −35.50‰, averaging −26.00‰. It can be seen that, gas carbon isotopes from the Middle and Upper Ordovician assemblages and the Upper Paleozoic overlap with and differ from one another, representing the connection and difference in their origins. It has been widely accepted that the Upper Paleozoic gas is typical coaliferous gas [10,11]. The Ordovician gas exhibits a generally light carbon isotope, possibly due to the mixing of oil-derived gas in coaliferous gas. As for the Ordovician, the Middle assemblage gas was mixed in with more oil-derived gas than the Upper assemblage gas.

The Upper Paleozoic and Ordovician gas shows varying degrees of isotopic reversal (Fig. 3) from the perspective of change relationship of carbon isotopic sequence, but their

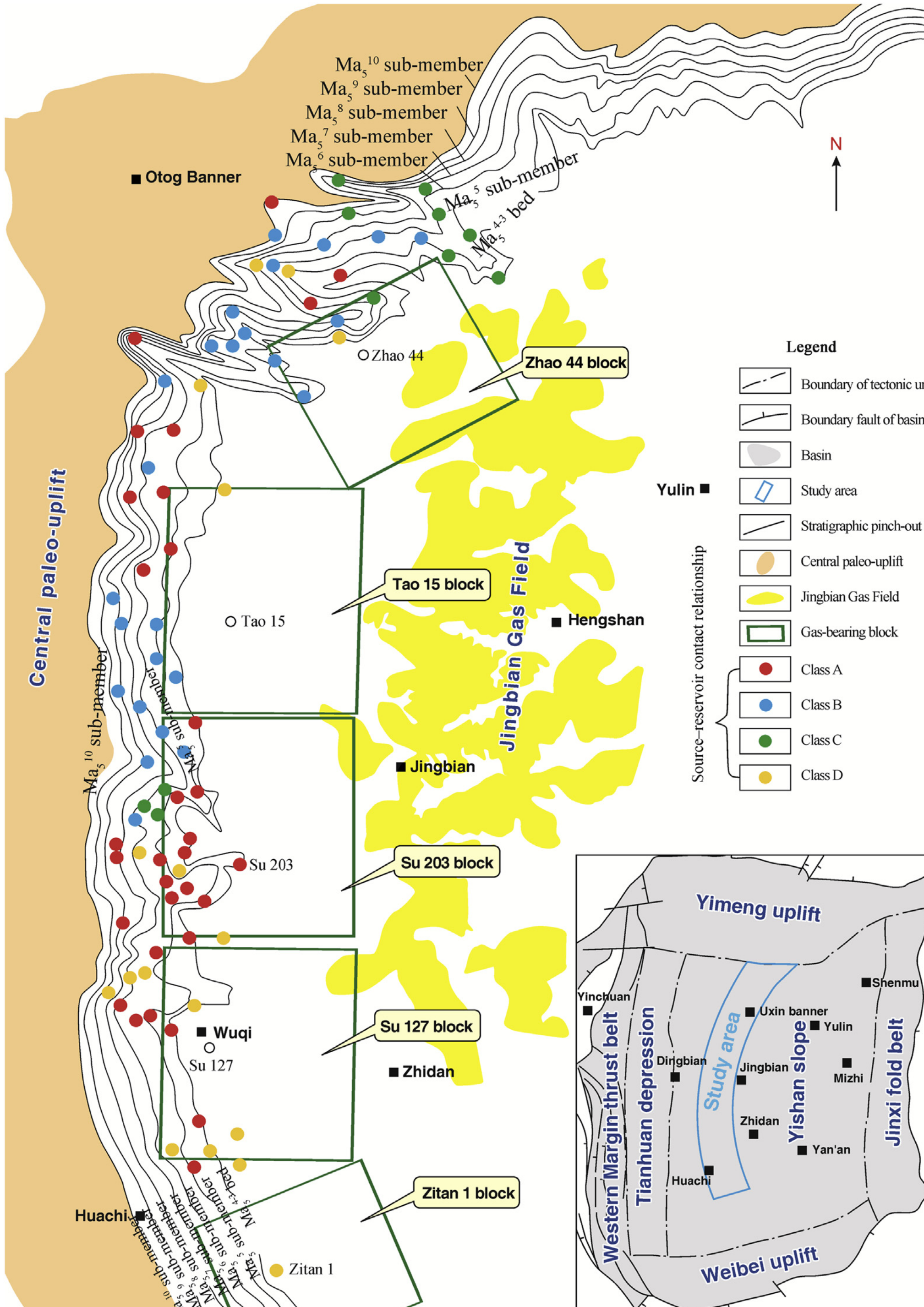

Fig. 1. Location of structures in Jingxi area and distribution of source–reservoir contact types at hydrocarbon-supplying window of the Middle assemblage.

reversal works in different ways. The Upper Paleozoic gas, which represents a typical coaliferous gas, primarily shows the $\delta^{13}C_2 > \delta^{13}C_3$ reversal, with exceptional $\delta^{13}C_1 > \delta^{13}C_2$ and $\delta^{13}C_1 > \delta^{13}C_3$ reversals or $\delta^{13}C_1 > \delta^{13}C_2 > \delta^{13}C_3$ reversal observed in few samples, which were previously interpreted to be the result of mixing of coaliferous gas that derived either from different sources or in different stages [10,11]. The Ordovician gas, particularly from the Middle and Upper assemblages, shows normal sequence of $\delta^{13}C_1 < \delta^{13}C_2 < \delta^{13}C_3$, with partially $\delta^{13}C_1 > \delta^{13}C_2$ reversal. Although the Ordovician gas shows a carbon isotopic reversal, it exhibits a distinctly different type from the Upper Paleozoic gas, reflecting their difference in origins. The $\delta^{13}C_1 > \delta^{13}C_2$ reversal that was less reported is possibly because the proportion of highly mature gas increases as source rock enters its late hydrocarbon-generating stage or coaliferous gas formed at

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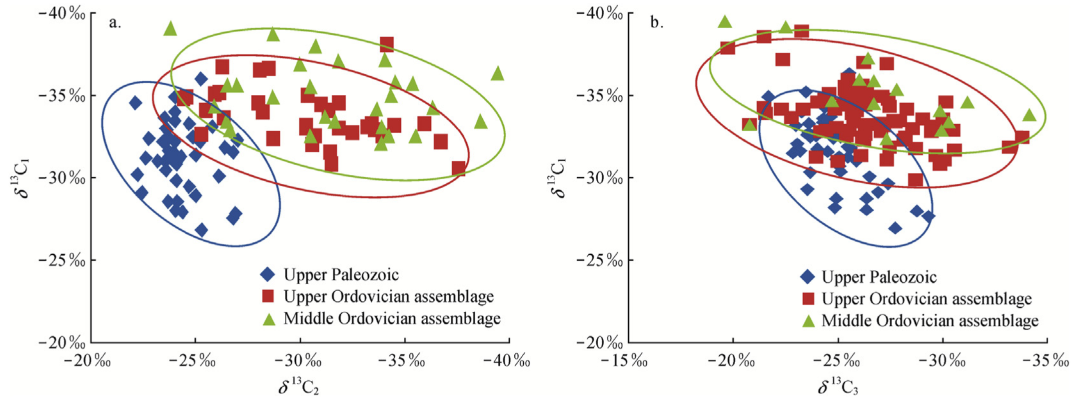

Fig. 2. Methane carbon isotope vs. ethane carbon isotope (Left) and methane carbon isotope vs. propane carbon isotope (Right).

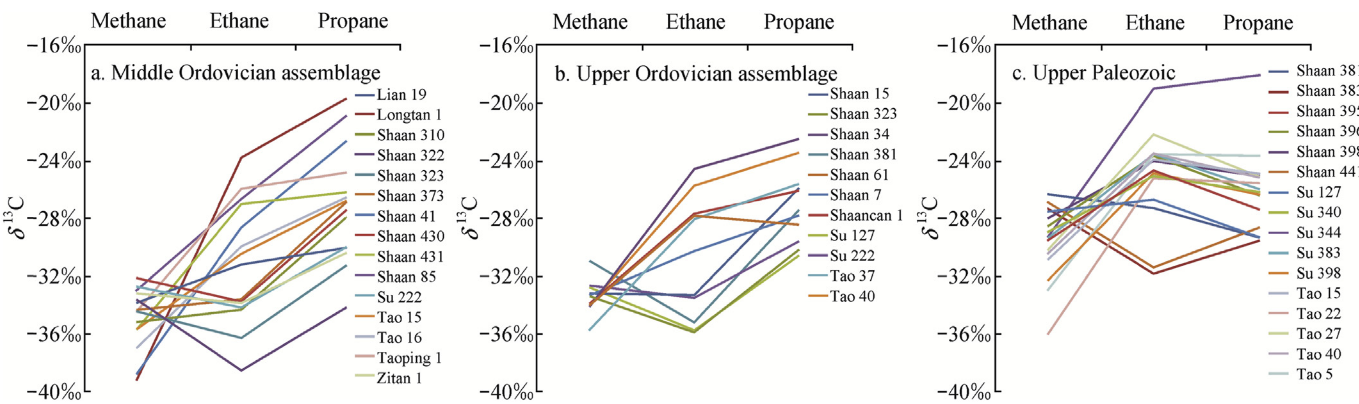

Fig. 3. Change of carbon isotopes of methane, ethane and propane.

highly mature to over-mature stage was mixed with oil-derived gas [11,12]. Since the Ordovician itself has a hydrocarbon-generating capacity and the Ordovician gas is somewhat different in composition from the Upper Paleozoic gas, it can be considered that the carbon isotopic reversal of the Ordovician gas is the result of mixing of highly mature to over-mature coaliferous gas in oil-derived gas. This further indicates that the Ordovician gas, particularly the Middle assemblage gas, is a mixture of coaliferous gas and oil-derived gas.

2.2. Difference between crude oil cracking gas and kerogen cracking gas

At present, gas hydrocarbon composition and carbon isotope remain the primary indexes for distinguishing between crude oil cracking gas and kerogen cracking gas. In China, $\ln(C_1/C_2)-\ln(C_2/C_3)$ and $\delta^{13}C_i-\delta^{13}C_j-\ln(C_i/C_j)$ relations proposed by Prinzhofer et al. are widely used [13,14]. The result of thermal simulation test of hydrocarbon generation indicates that, kerogen (particularly in muddy source rocks) can generate much more N_2 by cracking than crude oil [15]. As thermal maturity goes higher, the change of N_2 content in kerogen cracking gas is significantly higher than in crude oil cracking gas. Because of this, the relative relationship of N_2 content and $\ln(C_2/C_3)$ can be utilized to distinguish between crude oil cracking gas and kerogen cracking gas; that is, as $\ln(C_2/C_3)$ increases, crude oil cracking gas exhibits a much slower change in N_2 content than kerogen cracking gas. The relative relationships of $\ln(C_1/C_2)-\ln(C_2/C_3)$ and $\ln(C_2/C_3)-N_2$/total hydrocarbon in the Middle Ordovician assemblage gas in Jingxi area indicate that(Fig. 4), as $\ln(C_2/C_3)$ increases, both $\ln(C_1/C_2)$ and N_2 somewhat change, but that change is slower than in the Upper assemblage gas and the Upper Paleozoic gas, showing the feature of mixed kerogen cracking gas and crude oil cracking gas. In addition, the determination of the Ordovician ancient oil reservoir in the central Ordos Basin [16–19] has provided direct evidence to the existence of crude oil cracking gas in this area.

2.3. Calculation of source-mixed ratio of gas

Both the Upper Paleozoic gas and the Ordovician gas are composed mainly of methane. The methane carbon isotope shows relatively concentrated distribution, while the ethane and propane carbon isotopes are relatively scattered, indicating their frequent secondary variation. Therefore, the methane carbon isotope is used for calculating the source-

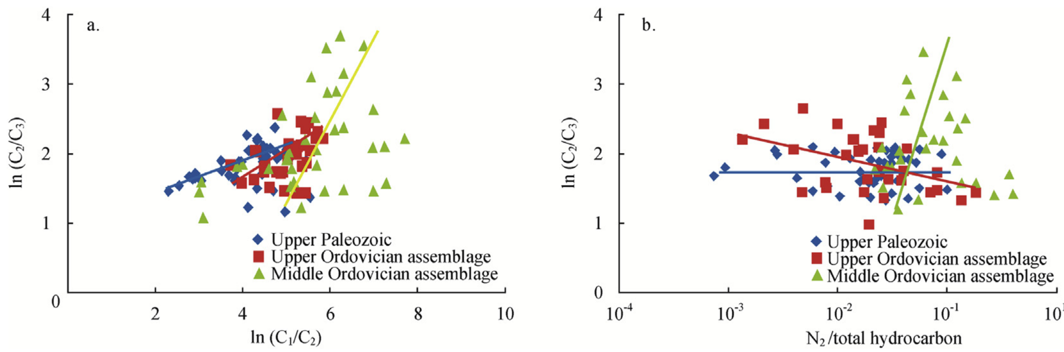

Fig. 4. Distinguishment between crude oil cracking gas and kerogen cracking gas.

mixed ratio of coaliferous gas and oil-derived gas in the Middle Ordovician assemblage in Jingxi area, with the following equation:

$$\delta^{13}C_1(\mathrm{AB}) = \frac{\delta^{13}C_1(\mathrm{A})\cdot n(\mathrm{A})\cdot X + \delta^{13}C_1(\mathrm{B})\cdot n(\mathrm{B})\cdot(1-X)}{n(\mathrm{A})\cdot X + n(\mathrm{B})\cdot(1-X)}$$

where, $\delta^{13}C_1(\mathrm{AB})$ is the methane carbon isotope of natural gas of the Middle Ordovician assemblage; $\delta^{13}C_1(\mathrm{A})$ is the methane carbon isotope of typical coaliferous gas of the Upper Paleozoic; $\delta^{13}C_1(\mathrm{B})$ is the methane carbon isotope of typical oil-derived gas of the Ordovician; $n(\mathrm{A})$ is the content of methane composition in typical coaliferous gas of the Upper Paleozoic; $n(\mathrm{B})$ is the content of methane composition in typical oil-derived gas of the Ordovician; X is the source-mixed ratio of coaliferous gas of the Upper Paleozoic; and $(1-X)$ is the source-mixed ratio of oil-derived gas of the Ordovician.

Selecting the values of two end members is critical to calculating the source-mixed ratio with this equation (Table 1). Averaged values of methane carbon isotope and methane composition content of the Upper Paleozoic gas are defined as values of end members for typical coaliferous gas, since the Upper Paleozoic gas is coaliferous in origin, i.e., $\delta^{13}C_1(\mathrm{A}) = -32.86‰$ and $n(\mathrm{A}) = 92.7\%$.

Averaged values of methane carbon isotope and methane composition content of natural gas generated by thermal simulation test of the Ordovician marine source rock [20], typical oil-derived gas defined by predecessors [20,21], and primary natural gas extracted from hydrocarbon inclusions associated with bitumen [22] are defined as values of end members for typical oil-derived gas of Ordovician, i.e., $\delta^{13}C_1(\mathrm{B}) = -40.33‰$ and $n(\mathrm{B}) = 97.4\%$.

Calculation results (Table 2) indicate that, in Jingxi area, the proportions of coaliferous gas and oil-derived gas in the Middle assemblage gas average 75.03% and 24.97%, respectively, with coaliferous gas being dominant. These proportions, however, may vary with blocks or formations. Macroscopically, the proportion of coaliferous gas increases from the Zhao 44 block in the north and the Zitan 1 block in the south, and within each block it increases from the deeper Ma_5^{10} sub-member to the shallower Ma_5^5 sub-member. In the Zhao 44 and Tao 15 blocks, the proportion of coaliferous gas reduces from 62.57% in the Ma_5^6 sub-member to 31.89% in the Ma_5^{10} sub-member (Zhao 44 block) and from 80.71% in the Ma_5^5 sub-member to 43.57% in the Ma_5^7 sub-member (Tao 15 block); and in the Su 203 and Su 127 blocks, this proportion reduces from 83.34% in the Ma_5^5 sub-member to 57.69% in the Ma_5^7 sub-member (Su 203 block) and from 85.47% in the Ma_5^5 sub-member to 57.95% in the Ma_5^7 sub-member (Su 127 block), but still higher than in the Ma_5^7 to Ma_5^{10} sub-members in the Zhao 44 and Tao 15 blocks; and in the Zitan 1 block, the Ma_5^5 and Ma_5^9 sub-members contain coaliferous-dominated gas, with the proportion of coaliferous gas reaching up to 95.8% and 91.33%, respectively. Although the Zitan 1 block has a great proportion of coaliferous gas, it actually holds less quantity of coaliferous gas than the Su 203 and Su 127 blocks, because the quantity of natural gas is limited. There are two reasons for the difference in proportion

Table 1
Composition and carbon isotopes of typical oil-derived gas of Ordovician in the Ordos Basin.

Sample	C_1	C_2^+	CO_2	N_2	$\delta^{13}C_1$	$\delta^{13}C_2$	Data source
Oil-derived gas of Ma_5^7 sub-member, Well Longtan 1	96.871%	2.397%	0.067%	0.665%	−39.26‰	−23.78‰	Yang Hua et al. [20]
Pyrolysis gas of the Ordovician carbonate rock (350 °C)					−39.26‰	−35.08‰	
Pyrolysis gas of the Ordovician carbonate rock (450 °C)					−45.26‰	−34.16‰	
Pyrolysis gas of the Ordovician carbonate rock (550 °C)					−42.62‰	−32.05‰	
Oil-derived gas of the Ordovician Wulike Fm, Well Yutan 1					−39.11‰	−27.26‰	Xiao Hui et al. [21]
Oil-derived gas of the Ordovician Kelimoli Fm, Well Yutan 1	96.240%	1.366%	0.913%	1.481%	−38.92‰	−27.17‰	
Oil-derived gas extracted from inclusions of Ma_5^7 sub-member, Well Longtan 1					−39.50‰	−35.50‰	Mi Jingkui et al. [22]
Natural gas extracted from inclusions of Ma_5 member, Well Yu 9	99.140%	0.860%					

Table 2
Calculation results of source-mixed ratio in the Middle Ordovician assemblage in Jingxi area.

Block	Horizon	Relative abundance of carbon isotope			Proportion of coaliferous gas
		$\delta^{13}C_1$	$\delta^{13}C_2$	$\delta^{13}C_3$	
Zhao 44	$Ma_5{}^6$ sub-member	−35.84‰ (1)	−35.33‰ (1)	/	62.57%
	$Ma_5{}^{10}$ sub-member	−38.20‰ (1)	−30.71‰ (1)	/	31.89%
Tao 15	$Ma_5{}^5$ sub-member	−34.41‰ (3)	−27.66‰ (3)	−24.16‰ (3)	80.71%
	$Ma_5{}^7$ sub-member	−37.31‰ (2)	−27.58‰ (2)	−22.62‰ (1)	43.57%
Su 203	$Ma_5{}^5$ sub-member	−34.20‰ (6)	−30.68‰ (4)	−26.51‰ (1)	83.34%
	$Ma_5{}^6$ sub-member	−36.22‰ (2)	−36.96‰ (2)	/	57.69%
Su 127	$Ma_5{}^5$ sub-member	−34.03‰ (8)	−33.92‰ (6)	−28.90‰ (6)	85.47%
	$Ma_5{}^6$ sub-member	−35.35‰ (2)	−26.95‰ (1)	−26.14‰ (1)	68.82%
	$Ma_5{}^7$ sub-member	−36.20‰ (2)	−31.35‰ (2)	/	57.95%
Zitan 1	$Ma_5{}^5$ sub-member	−33.20‰ (1)	−33.90‰ (1)	−33.40‰ (1)	95.80%
	$Ma_5{}^9$ sub-member	−33.56‰ (1)	−31.62‰ (1)	/	91.33%
Whole area		−34.86‰ (31)	−31.91‰ (26)	−27.55‰ (14)	75.03%

Note: Data in the parentheses are sample numbers.

of coaliferous gas. First, the hydrocarbon-generating intensity of the Upper Paleozoic coal-bearing source rocks in this area tends to increase progressively from the north to the south, and the southern part where a superior source condition for coaliferous gas is available has a higher proportion of coaliferous gas than the northern part. The unconformity on the top of the Ordovician strata that is in direct contact with the Upper Paleozoic is deemed to be the most favorable site for coaliferous gas to migrate and accumulate and, however, distances from the $Ma_5{}^{10}$ to $Ma_5{}^5$ sub-members to this unconformity decrease successively, resulting in a high proportion of coaliferous gas in the $Ma_5{}^5$ sub-member that has close proximity to the unconformity. It can be concluded that coaliferous gas remains the most primary source of natural gas for the $Ma_5{}^5$ and $Ma_5{}^6$ sub-members in the gas-rich Su 203 and Su 217 blocks.

3. Main controlling factors for gas accumulation

3.1. Natural gas enrichment degree is controlled by the gas charging capacity at the hydrocarbon-supplying window

The contact relationship of the Upper Paleozoic coal-bearing source rocks and the Middle Ordovician assemblage reservoirs has great significance to the migration and accumulation of natural gas, since the Middle Ordovician assemblage gas in Jingxi area is dominated by the Upper Paleozoic coaliferous gas. A structural inversion has enabled the transition in the tectonic framework from west-high & east-low to west-low & east-high [23,24], thereby being favorable for natural gas sourced from the Upper Paleozoic to migrate towards the Middle Ordovician assemblage. Of particular note is the erosion zone of the Middle Ordovician assemblage reservoir, which is overlain directly by the Upper Paleozoic and therefore can act as a favorable window for hydrocarbon supplying.

A statistics of lithology of the strata present at both sides of this window indicates that, the contact relationship of the Upper Paleozoic coal-bearing source rock and the Ordovician reservoir can be classified into four classes (Fig. 5): source rock/reservoir (Class A), source rock with sandstone interbed/reservoir (Class B), source rock/sandstone/reservoir (Class C), and source rock/buaxitic mudstone/reservoir (Class D). In the case of Class A, natural gas sourced from the Upper Paleozoic coal-bearing source rock tends to migrate into and then accumulate in the Middle assemblage reservoir; in the case of Class B, natural gas sourced from the Upper Paleozoic coal-bearing source rock would partially migrate into sandstone reservoirs present within the source rock and partially accumulate in the Middle assemblage reservoir; in the case of Class C, natural gas sourced from the coal-bearing source rock would firstly migrate into an underlying sandstone bed and then partially enter the Middle assemblage reservoir, causing the Middle assemblage reservoirs to receive only a limited quantity of gas; and in the case of Class D, natural gas sourced from the coal-bearing source rock is less likely to enter the Middle assemblage reservoir due to the presence of a bauxitic mudstone bed between the Upper Paleozoic coal-bearing source rock and the Middle assemblage reservoir, which is considered to be a good caprock with tight lithology, low porosity and low permeability, and for this reason, natural gas is less likely to migrate into the Middle Ordovician reservoirs.

The source–reservoir contact relationship can vary widely with the location of hydrocarbon-supplying window, as is illustrated by projecting the source–reservoir contact relationship obtained from a large number of wells on a planar map (Fig. 1). It is quite clear that, among these blocks, Su 203 and Su 120 have the best source–reservoir contact relationship, which is Class A-dominated but also has Class C and Class D; Tao 15 and Zhao 44 take the second place, with Class B being dominated and presence of Class A and Class D; and Zitan 1 is the worst, with Class D being dominated and limited Class A.

In addition to the source–reservoir contact relationship, hydrocarbon-generating intensity of the overlying source rock and porosity and permeability of the underlying reservoir are some other factors that exert a significant control on gas-charging at the hydrocarbon-generating window. In Jingxi area, the hydrocarbon-generating intensity of the Upper

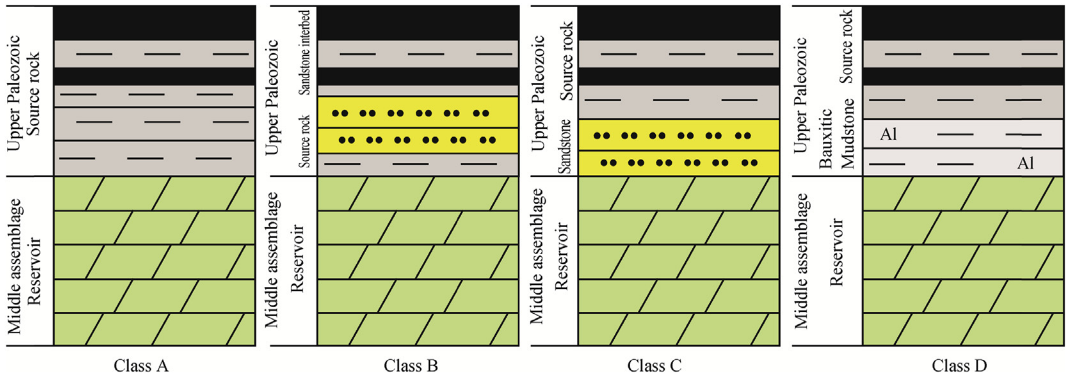

Fig. 5. Contact relationships between the Upper Paleozoic source rocks and the Middle Ordovician assemblage reservoirs in Jingxi area.

Paleozoic source rock tends to rise progressively from the north to the south. The Zhao 44 and Tao 15 blocks are within the intensity range of 18×10^8 to 26×10^8 m^3/km^2, and the Su 203, Su 120 and Zitan 1 blocks are within the intensity range of 26×10^8 to 30×10^8 m^3/km^2, implying that in this area the Upper Paleozoic source rock has a higher hydrocarbon-generating capacity in the southern part than in the northern part. The underlying reservoir situated at the hydrocarbon-supplying window has relatively a high porosity in the Zhao 44 (average 3.39%), Tao 15 (average 2.23%), Su 203 (2.16%) and Su 127 (2.27%) blocks. The permeability, however, varies greatly across these blocks. It averages 2.5153 mD in the Su 203 block, 0.7196 mD in the Zhao 44 block, 0.4802 mD in the Tao 15 block, and 0.4613 mD in the Su 207 block. The Zitan 1 block exhibits much lower porosity and permeability than others, which are 0.73% and 0.3116 mD that are unfavorable for oil & gas charging.

By studying the source—reservoir contact relationship, the hydrocarbon-generating intensity of source rocks, and physical properties of reservoirs across blocks, it is considered that the Su 203 block in the Middle Ordovician assemblage, with Class A-dominated source—reservoir contact, high hydrocarbon-generating intensity of overlying source rocks and good porosity and permeability of underlying reservoirs, is the most favorable site for the charging of the Upper Paleozoic gas; the Su 127 block, which has Class A-dominated source—reservoir contact, similar hydrocarbon-generating intensity of source rocks and porosity of reservoirs with the Su 203 block, but exhibits considerably lower permeability than the Su 203 block, takes the second place and allows for a strong charging of the Upper Paleozoic gas at the hydrocarbon-generating window; the Zhao 44 and Tao 15 blocks are ranked third with a moderate charging capacity of the Upper Paleozoic gas at the hydrocarbon-generating window, since they have Class B-dominated source—reservoir contact relation (although partially Class A reported), lower hydrocarbon-generating intensity than the Su 203 and Su 127 blocks, similar porosity and permeability of reservoirs with the Su 127 block; and the Zitan 1 block, although overlain by the source rock with a high hydrocarbon-generating capacity, has the worst charging capacity of the Upper Paleozoic gas at the hydrocarbon-generating window, because of its Class D-dominated source—reservoir contact and relatively poor porosity and permeability of reservoirs. Results of comparison of gas-charging capacity at the hydrocarbon-generating window across blocks in Jingxi area match perfectly with the present-day enrichment degree of the Middle assemblage gas, implying the significant control of gas-charging capacity at the hydrocarbon-generating window within the Middle Ordovician assemblage on the enrichment degree of natural gas.

3.2. Vertical migration and distribution of natural gas are dominated by the differences of $Ma_5^5 - Ma_5^{10}$ transport pathways

Diageneses, such as the pene-sedimentary dolomitization, supergene karstification and structural fracturing, have resulted in the formation of pore- & fracture-type reservoirs in the Middle Ordovician assemblage. The development degree of dissolved pores and structural fractures, however, varies greatly across sub-members, due to the differences in supergene karstification of $Ma_5^5 - Ma_5^{10}$ sub-members and structural fracturing degree of different types of rocks. Apart from the Zitan 1 block that holds fracture-type-dominated reservoirs in each sub-member, the proportion of pores in reservoirs decreases as the proportion of fractures increases progressively from the Ma_5^5 to the Ma_5^{10} sub-members. The Ma_5^5 and Ma_5^6 sub-members show the dominance of pore- & fracture-type reservoirs, while the Ma_5^7 to Ma_5^{10} sub-members hold the fracture-type-dominated reservoirs. Either the Upper Paleozoic coaliferous gas or the Ordovician oil-derived gas tends to migrate vertically upward and then accumulate in the Ma_5^5 and Ma_5^6 reservoirs where well-developed pores are available (Fig. 6).

Thus, natural gas tends to migrate towards the shallow zones via reservoir fractures within each sub-member and makes the Ma_5^5 and Ma_5^6 sub-members the primary gas-rich zone.

3.3. Lateral migration direction of natural gas and the range of gas accumulation are controlled by the superimposition relationship between structures and reservoirs

Structural configuration on the top of reservoirs exerts a significant control on the direction and the pathway of gas

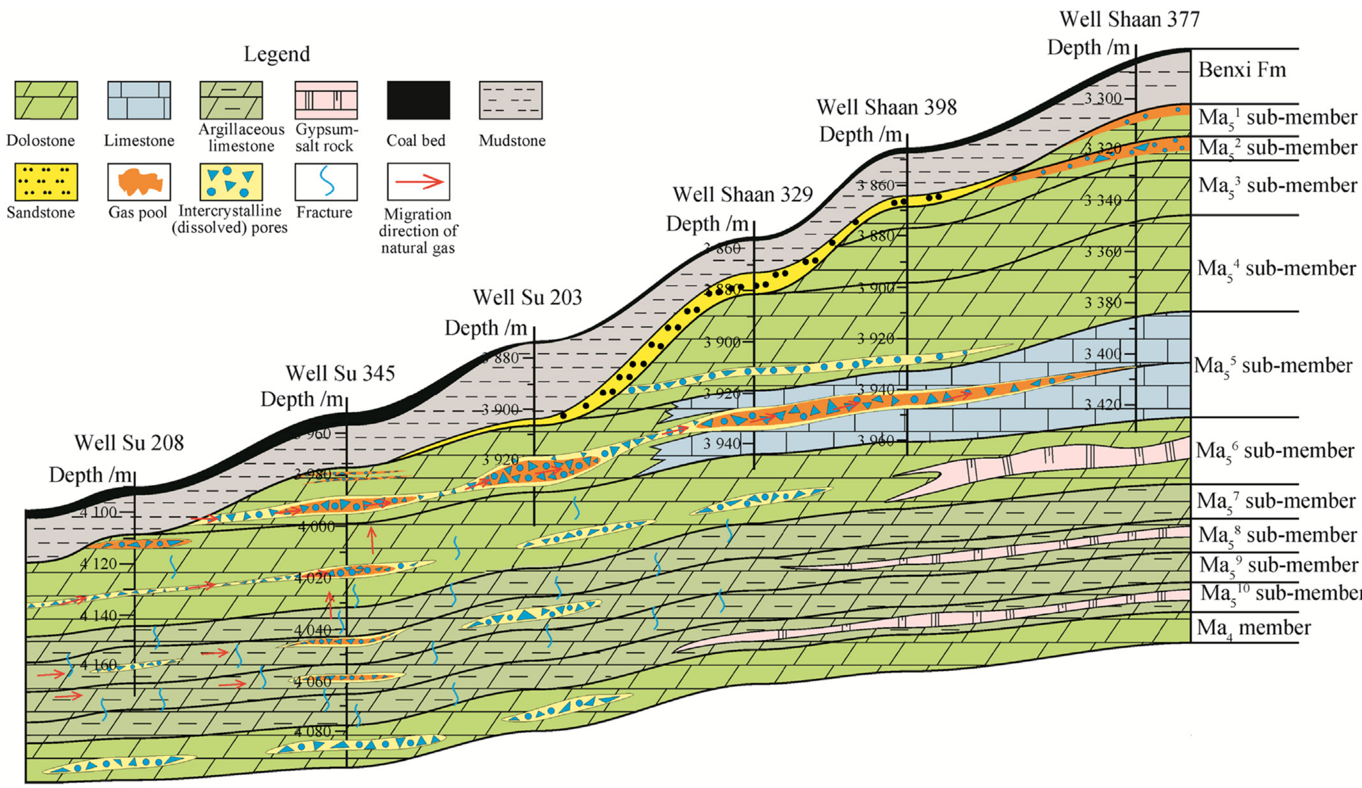

Fig. 6. Sketch map showing the transport pathways and migration direction of natural gas in the Middle Ordovician assemblage, Su 203 block.

migration. Natural gas is readily to migrate towards and then accumulate in structural highs (structural ridge) where reservoirs are available. The superimposition relationship between the structural configuration on the top of the Ma_5^5 sub-member and the thickness of dolostone reservoirs (Fig. 7) indicates that, this area is structurally high in north & east and low in south & west, and the coaliferous gas comes from the west hydrocarbon-supplying window and the oil-derived gas from the underlying strata, macroscopically, tend to migrate from west to east and south to north. Natural gas is distributed mainly in the development zone or the directional zone of structural ridges, because the structural ridges that control the lateral migration direction of gas are commonly present at sites where dolostone reservoirs were formed. Apart from the west hydrocarbon-supplying window that provides the area with coaliferous gas source, another significant gas-charging window is available in the middle section of dolostone reservoirs in the Su 203 block. This is an ideal place having a low structural amplitude and a good connectivity to adjoining reservoirs with a higher structural amplitude. Therefore, it is favorable for natural gas sourced from the Upper Paleozoic source rocks to charge the Ma_5^5 reservoirs and then migrate towards the structural highs or along the structural ridges. The majority of high-productivity wells drilled in the Su 203 blocks are distributed in the proximity of this window. Moreover, relative structural relief on the top of reservoirs also controls the gas–water distribution relationship in the Ma_5^5 sub-member. Due to the effect of gas–water differentiation, natural gas is distributed mainly in structural ridges or at positions with a higher structural amplitude, while water is distributed mainly along both sides of structural ridges or at positions with a lower structural amplitude.

4. Conclusions

(1) In comparison with the natural gas of the Upper Paleozoic and the Upper Ordovician assemblage in the Ordos Basin, gas of the Middle Ordovician assemblage in Jingxi area is mainly the coaliferous gas with some oil-derived gas. Under the influence of hydrocarbon generation center of coal-bearing source rocks and the source–reservoir contact relationship, the proportion of coaliferous gas increases areally from the north to the south and vertically from the Ma_5^{10} to Ma_5^5 sub-members. Of particular notes are the gas-rich Su 203 and Su 127 blocks, where the Ma_5^5 and Ma_5^6 sub-members hold coaliferous-dominated gas.

(2) The difference in the accumulation of natural gas in the Middle Ordovician assemblage in Jingxi area is controlled primarily by three factors. ① Natural gas enrichment degree is controlled by the gas charging capacity at hydrocarbon-generating windows. Charging of natural gas most likely occurs when the Middle assemblage reservoir having hydrocarbon generation centers with good porosity and permeability is overlain directly by the Upper Paleozoic source rocks having a high hydrocarbon-generating intensity. The differences of natural gas charging capacity of various blocks match

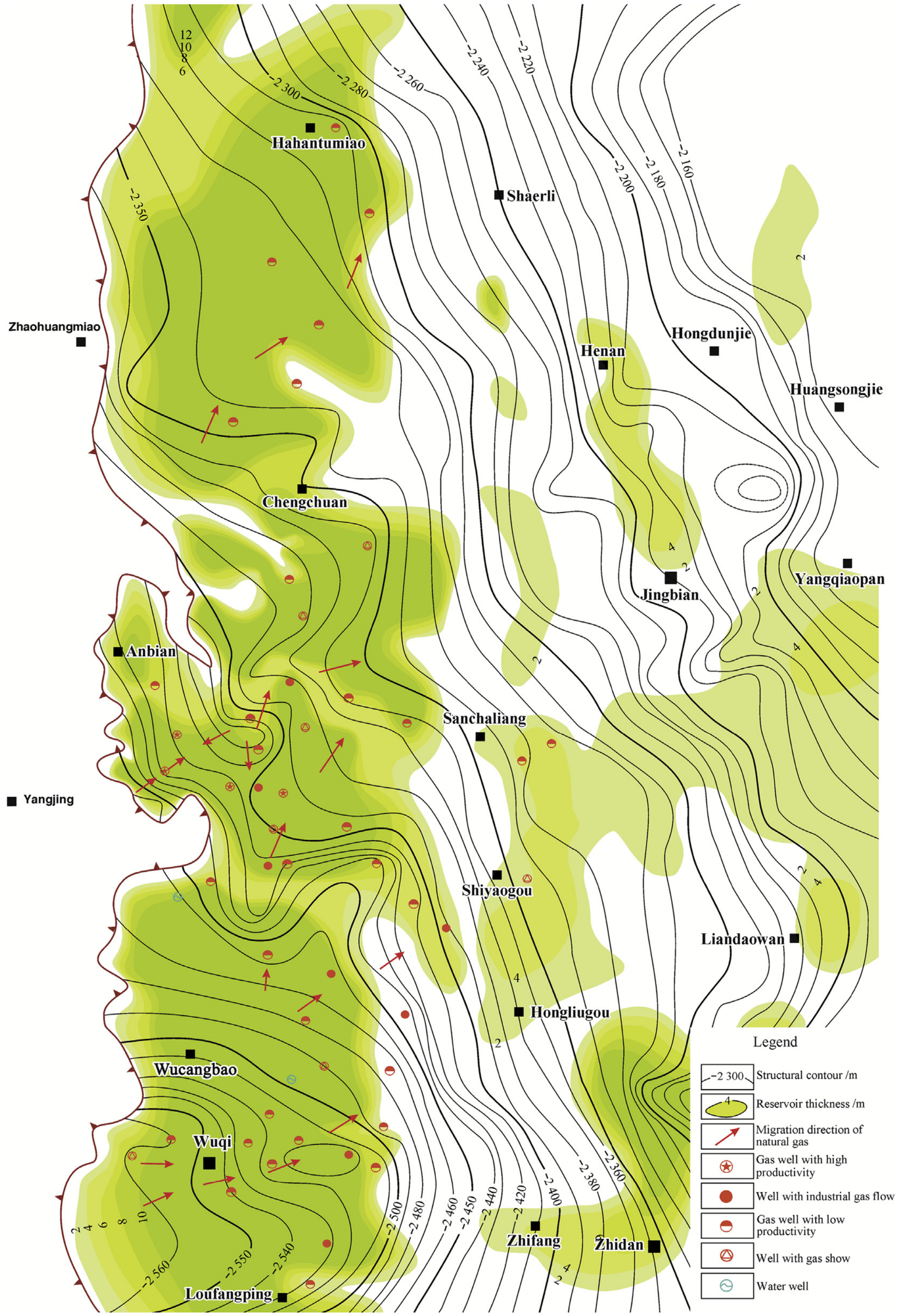

Fig. 7. Sketch map showing the top structures, reservoir thickness and natural gas migration direction of the Ma_5^5 sub-member across the Tao 15, Su 203 and Su 127 blocks.

well with the natural gas enrichment degree and proportion of coaliferous gas in natural gas. ② The vertical migration and distribution of natural gas are dominated by the differences of $Ma_5^5 - Ma_5^{10}$ transport pathways. For this reason, natural gas is mainly trapped in the $Ma_5^5 - Ma_5^6$ sub-members. ③ The lateral migration direction of natural gas and the range of gas accumulation are controlled by the superimposition relationship between structures and reservoirs, and the migration and accumulation of natural gas tend to occur along structural ridges where reservoirs are available.

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