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Origins and Differences in Condensate Gas Reservoirs between East and West of Tazhong Uplift in the Ordovician Tarim Basin, NW China

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ABSTRACT: The Ordovician of the Tazhong area in the Tarim Basin has suffered multi-cyclic hydrocarbon charging, making Tazhong a typical condensate gas district. In this paper, production and test data were gathered and a detailed comparison was conducted on the geology and the fluid distribution and characteristics between the eastern and western Tazhong area. Eastern and western regions exhibit significant differences in tectonic structure, fluid distribution, and physical-chemical properties of oil and gas. Compared with the eastern region, the western part has a greater development of discordogenic gas associated with strike-slip faults which, combined with the Tazhong No. 1 fault zone, control the fluid distribution. The eastern region is mainly controlled by the Tazhong No. 1 fault zone. Fluid have markedly homogeneous properties in the east, but are heterogeneous in the west. The origins of oil and gas are different between the east and the west. In the east, hydrocarbons are mainly from Ordovician source rocks and natural gas is mostly derived from kerogen pyrolysis. In the west, the hydrocarbons mainly originated from Cambrian source rocks, and the gas was mostly generated by crude oil cracking. In sum, the east region is dominated by primary condensate gas reservoirs, and the western region is dominated by secondary condensate gas reservoirs. Because of the different geological settings and fluid physical properties, differences in the condensate gas reservoirs in the eastern and the western Tazhong area have been analyzed, and appropriate formation mechanisms for condensate gas origins are established.
KEY WORDS: condensate gas reservoir, origin, Ordovician, carbonate, Tazhong area.

0 INTRODUCTION

Deep marine carbonates have become important targets for oil and gas exploration (Zhu et al., 2016; Zhu and Zhang, 2009; Zhu et al., 2005). There is potential for massive production of kerogen and crude oil cracking gas because of suitable subsurface temperatures and pressures within appropriate depth intervals that have resulted in anomalies in fluid phase and fluid activity. A gas–liquid phase transition occurs when temperature and pressure reach a certain level and a condensate gas phase develops in paleo-oil reservoirs because of gas invasion or interaction between natural gas and crude oil which causes pressure release and temperature change. Some experts call this process "phase fractionation" or "gas washing" (Losh et al., 2002; van Graas et al., 2000; Thompson, 1988, 1987). So condensate gas is a kind of gas generated by liquid hydrocarbons' inverse evaporation and the areas containing abundant condensate gas are named by condensate gas districts. A condensate gas reservoir is caused by physical and chemical changes that result from gas washing between later gas and earlier paleo-oil reservoirs, or by pressure and temperature changes in a natural gas reservoir. Significant amounts of condensate oil and high productive gas levels can arise during extraction of gas and oil as temperature and pressure change in the reservoir and at the surface, and they can have economic significance. Condensate gas reservoirs have been discovered all over the world, for example in the Gulf of Mexico (Roberts and Carney, 1997), Eugene Island Block 330 (Meulbroek et al., 1998), the San Juan Basin in New Mexico (Thompson, 1987, 1983), the coast of Taiwan (Dzou and Hughes, 1993), the Indonesian coast (Schoell et al., 1985), the Alaskan coast (Kvenvolden and Claypool, 1980), and in the North Sea (Larter and Mills, 1991). There are two types of condensate gas reservoirs: primary and secondary. A primary condensate gas reservoir formed by the injection of kerogen or crude oil cracking gas into the reservoir strata and remains stable before exploration. A secondary condensate gas reservoir refers to condensate oil made up of light oil derived from the injection of natural gas into an oil reservoir. This process causes a fluid phase change and continuous fluid migration and deposits of natural gas in other reservoirs after gas washing (Li, 1998). The two types of condensate

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gas reservoir can be distinguished by their fluid properties, such as light hydrocarbon characteristics, hydrocarbon maturity, physical properties of oil and gas, isotopic features, and whole oil chromatogram characteristics.

The central Tarim Basin has undergone multi-cycle superimposition and transformation (Jin, 2005), which has resulted in diverse types of hydrocarbon reservoirs and complex fluid properties. A group of large carbonate oil and gas fields have been proved consecutively in Lianglitage and Yingshan Formation of Ordovician in Tarim Basin (Lü et al., 2009). The Ordovician carbonate reservoirs in Tazhong area are usually buried at 5 000–6 500 m, covering a continuous distribution area of approximately 1.0×10^4 km^2, with 3P reserves up to 7×10^8 t. And they show the characteristics of large-area, low-abundance accumulation and large-span, quasi-layered distribution (Yang et al., 2007). Exploration at Tazhong has confirmed that it is a typical region of condensate gas reservoir. Its genetic mechanisms have yet to be established compbetely, but researchers agree on the importance of multi-phase oil and gas filling (Zhang et al., 2004; Huang et al., 2001; Meulbroek et al., 1998). Prospectors face issues such as whether there is a unique genetic mechanism producing condensate gas reservoirs in Tazhong, whether the means and extent of exploration and development of different regions require reconsideration, or how to explore potential deep oil and gas sources most effectively. Thus, establishing formation mechanisms for condensate gas reservoirs from different regions is a key step in resolving these problems and has great economic significance and practical value. Because of the different geological settings and fluid physical properties, differences in the condensate gas reservoirs in the eastern and the western Tazhong area have been analyzed, and appropriate formation mechanisms for condensate gas origins are established.

1 GEOLOGICAL SETTING

The Tarim Basin is the largest petroliferous basin in China with an area of about 56×10^4 km^2 (Li et al., 1996), and is a typical superimposed basin. The Tazhong area is located in the central uplift belt of the Tarim Basin, among a succession of paleo-highs running from NW to SE (Fig. 1). The central uplift joins the Bachu fault-block uplift to the west, connects with the Tadong minor uplift close to the Manjar depression in the north, and with the Tangguzibasi depression to the south. Major fracture systems developed in the area during the Ordovician: a NW-SE compressional Caledonian thrust fault system that parallels Tazhong No. 1 slope break belt, and an Early Hercynian NE-SW and N-S strike-slip fault system. The compressional thrust fault system presents a divergent shape in the west, and a convergence to the east, that mainly control Tazhong tectonic relief. The tectonic relief in the east is higher than the west. The west and east exhibit differences in the extent of strike-slip faulting which is stronger on the western than the eastern side. In the later stages, tectonic relief provided important channels for fluid migration and significantly influenced the intensity of gas cutting.

Tazhong wells have penetrated the following strata (in descending order): Neogene, Paleogene, Cretaceous, Triassic, Permian, Carboniferous, Devonian, Silurian, Ordovician, and Cambrian. Jurassic strata are absent in the whole district and Devonian strata in some regions. This study focuses on Ordovician reservoir rocks that consist of limestone with dense micrite cap rocks. Ordovician in the Tazhong area includes mainly Yingshan Formation and Lianglitage Formation. Yingshan Formation is mainly composed of beach bodies, few lime-mud mounds locally, and no organic reef, involving granular limestone, grain dolomite and crystalline dolomite, and also the transition of micrite, dolomite and limestone. Lianglitage Formation is mainly sandy bioclastic limestone, light gray sparry, bioclast and sand boundstone, organic skeleton rock, cryptomonas clotted limestone and micrite. Fracture porosity is absent in the matrices and porosity and permeability are low overall. Two unconformities are present, marked by weathering, ablation, and leaching after deposition of the lower Yingshan Formation and the Upper Lianglitage Formation. The two main reservoir types of Ordovician carbonates in the Tazhong area have secondary storage provided by unconformities and fractures enhanced by caves and karst cavities.

The Tazhong area has several hydrocarbon source rocks, mainly of Cambrian, Lower–Middle Ordovician, and Middle Ordovician Age (Zhang and Huang, 2005). Multiphase oil and gas fillings have led to the present extremely complex distribution of oil and gas reservoirs. Oil filling mainly occurred in the Late Caledonian and Late Hercynian, some oil reservoirs formed in the Late Caledonian have been destroyed by a later tectonic movement and there was some damage to reservoirs formed in the Late Hercynian. Gas filling primarily occurred during Late Himalayan movements that reconstructed pre-existing ancient reservoirs by different degrees of gas washing (Guo et al., 2016; Zhu et al., 2011a; Lü et al., 2009; Zhao et al., 2009; Han et al., 2007; Yang et al., 2007). Multi-cyclic tectonic movements, multiphase oil and gas filling, and several geological events have given rise to the complexity and particularity of reservoir distribution. The reservoirs of the Tazhong area mainly consist of gas condensate reservoirs without a large degree of infiltration of edge and basal groundwater. Normal oil/gas/water separation in local geological units causes complex fluid properties with only small volumes of oil or volatiles present (Zhang et al., 2011, 2007; Yang et al., 2010; Zhou et al., 2010).

We have divided the condensate gas reservoirs in the Tazhong area into two parts for discussion purposes, a western region and an eastern region with different geological settings and fluid properties. The fluid here includes both of the oil and the gas. Technically, the western region is defined by the Tazhong No. 1 fault to the north, the Tazhong No. 10 structural zone to the south, the NE-SW strike-slip fault passing TZ83 well to the east, and the eastern region is defined by the Tazhong No. 1 Fault to the north, the NE-SW strike-slip fault passing TZ83 well to the west, the south boundary of Tazhong No. 10 structural zone to the south. The western region has more strike-slip faults, and the eastern region more compressional thrust faults. Fluid properties are different between the east and the west parts (Fig. 1).

2 METHODS

We collected and analyzed samples collected from the whole Tazhong Oilfield, taking samples from Ordovician strata from 30 wells across the whole oilfield (Table 1). All samples

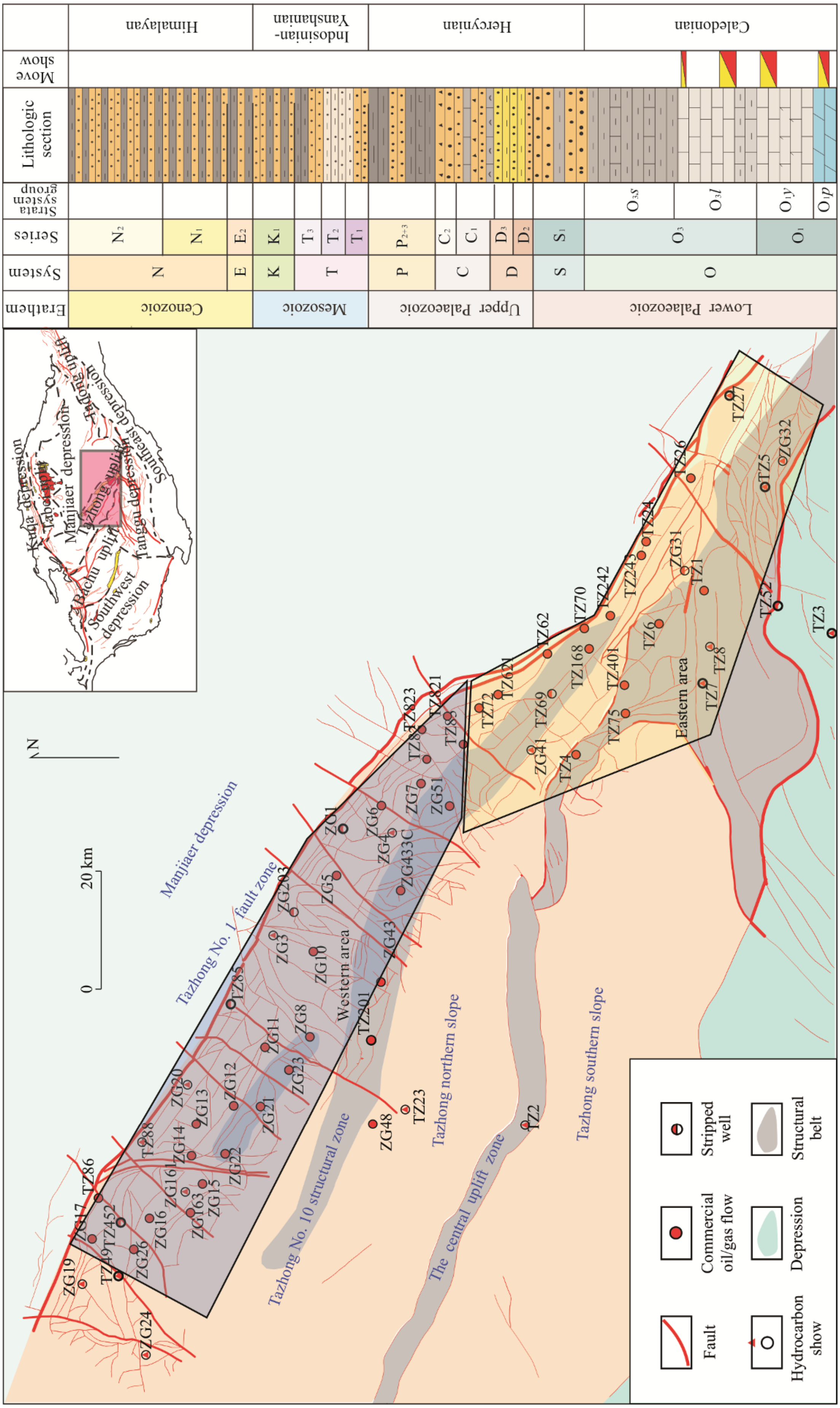

Figure 1. Location and general geological setting of the Tazhong area.

Table 1 Properties of petroleum in the Tazhong area

Zone	Well	System	Depth (m)	Salinity (mg/L)	Characteristics of natural gas						
					Aridity coefficient	CH_4 (%)	C_2H_6 (%)	C_3H_8 (%)	H_2S contents (mg/m³)	Oil intensity (g/cm^3)	Condensation point (°C)
Western	ZG19	O	6 438.5	122 891	0.661 4	29.10	5.89	4.20	19 500	0.805 8	-4
	ZG15	O	6 138.0	160 600	0.844 0	77.10	8.28	3.50	12 100	0.801 6	-14
	ZG163	O	6 240.0	85 210	0.835 1	75.88	8.95	3.10	8 332	0.789 8	-26
	ZG14-1	O	6 298.0	-	0.961 0	82.16	1.88	0.56	51 680	0.794 4	-14
	ZG101	O	6 222.0	76 916	-	-	-	-	-	0.812 9	-20
	ZG102	O	6 410.0	-	0.923 2	77.76	3.17	1.65	77 800	0.771 4	-12
	ZG103	O	6 233.46	95 600	0.899 2	85.16	5.94	1.48	4 500	0.772 7	-22
	ZG11	O	6 631.1	109 400	0.947 1	86.27	2.71	0.81	4 500	0.802 8	-2
	ZG111	O	6 250.0	-	0.904 5	86.33	4.43	1.81	3 800	0.783 9	-6
	ZG7	O	5 880.0	165 066	0.928 4	80.83	2.70	1.00	66 500	0.791 3	-4
	ZG48	O	5 531.54	150 000	0.937 0	84.23	2.66	1.36	12 100	0.777 7	-4
	ZG462	O	5 515.0	-	0.928 6	88.77	4.41	1.22	130	0.797 8	-2
	ZG43	O	5 334.1	11 330	0.911 6	84.04	4.63	1.57	38 900	0.805 2	-4
	ZG431	O	5 463.4	196 800	0.880 0	79.10	5.65	2.74	82 800	0.807 9	2
	ZG433C	O	6 221.71	199 100	0.829 5	68.70	6.45	4.22	8 208	0.814 4	-4
Eastern	TZ62	O	4 758.0	106 400	0.957 2	-	-	-	1 694	0.811 9	2
	TZ44	O	4 888.0	99 900	0.959 6	85.84	2.20	0.60	919	0.822 0	2
	TZ622	O	4 925.0	-	0.952 3	89.22	2.39	0.93	1 461	0.831 4	12
	TZ621	O	4 885.0	105 400	0.948 7	89.65	2.53	1.01	1 544	0.841 1	10
	TZ62-1	O	-	112 600	0.953 3	90.18	2.16	0.85	-	0.831 3	6
	TZ62-2	O	4 852.0	1 110	0.974 7	91.67	2.46	0.99	2 500	0.830 6	6
	TZ623	O	4 815.0	122 400	0.964 5	91.70	1.27	0.39	1 000	0.777 5	-30
	TZ161	O	4 306.0	81 687	0.970 1	93.00	-	-	-	0.850 3	-14
	TZ168	O	4 552.0	-	0.941 8	78.22	2.50	1.28	36	0.854 3	-18
	TZ169	O	4 283.0	117 000	-	-	-	-	-	0.873 5	2
	TZ24	O	4 465.0	-	0.954 9	81.00	2.43	0.93	43	0.822 4	18
	TZ242	O	4 546.56	106 600	0.944 3	88.76	2.69	1.08	324	0.819 1	-30
	TZ243	O	4 539.0	101 600	0.993 9	98.23	0.53	0.03	250	0.814 3	14
	TZ26	O	4 402.0	87 226	0.969 9	85.41	1.44	0.59	12	0.806 5	-23
	TZ75	O	4 015.0	-	0.827 6	-	-	-	-	0.914 7	<-30.0

Table 1 Continued

Characteristics of crude oil						Isotope and maturity parameters					
20R steranes			Isoheptane	Normal heptane	$\delta^{13}C_{oil}$ (‰)	$\delta^{13}C_{saturated\ group}$ (‰)	$\delta^{13}CH_4$ (‰)	$\delta^{13}C_2H_6$ (‰)	$\delta^{13}C_3H_8$ (‰)	Ts/(Ts + Tm)	C_{27}dia/C_{27reg}
C_{27} (%)	C_{28} (%)	C_{29} (%)									
32	30	38	5.00	30.99	-30.4	-30.4	-39.1	-32.5	-30.7	0.714 3	0.498 6
40	23	37	3.33	41.88	-31.5	-32.21	-	-	-	0.670 7	0.787 2
43	23	34	3.17	31.12	-31.4	-31.75	-51	-	-	0.660 2	0.820 6
41	27	32	3.41	38.55	-31.1	-31.3	-51.5	-	-	0.610 7	0.815 0
-	-	-	-	-	-	-	-53	-	-	-	-
36	33	31	-	-	-30.8	-	-54.4	-38.2	-32	0.554 3	1.108 0
39	27	34	3.52	28.62	-30.5	-30.8	-51.6	-	-	0.700 0	1.099 0
38	31	31	3.59	29.52	-30.5	-31.04	-47.1	-34.2	-31.4	0.769 6	1.256 5
-	-	-	-	-	-	-	-47.1	-34.2	-29.7	-	-
31	32	36	3.46	39.45	-30.7	-30.9	-33.8	-30.5	-41.8	0.679 9	1.519 2
40	31	29	-	-	-30.5	-30.5	-46.9	-	-	0.909 2	1.544 7
-	-	-	-	-	-30.6	-	-38.5	-	-	-	-
30	21	49	3.15	38.87	-30.7	-	-42.4	-36.7	-31.6	0.711 7	0.682 1
32	27	40	-	-	-31.6	-	-	-	-	0.598 6	0.480 6
43	26	31	2.75	39.57	-31.6	-31.8	-	-	-	0.681 5	0.782 4
36	32	32	3.57	34.25	-31.7	-	-38.7	-31.8	-30.1	0.403 9	0.293 3
26	35	39	-	-	-31.7	-31.7	-38.4	-31.5	-29.6	0.471 7	0.335 0
-	-	-	-	-	-31.1	-31.2	-38.6	-35.3	-32.2	-	-
-	-	-	3.04	35.28	-31.9	-32	-38.5	-33.8	-30.5	-	-
-	-	-	3.00	33.72	-	-	-38.3	-	-	-	-
34	32	34	3.30	32.43	-31.4	-31.6	-38.6	-	-	0.417 4	0.516 5
-	-	-	2.28	36.77	-	-	-38.7	-33.7	-31.5	-	-
-	-	-	-	-	-	-	-41.8	-33.4	-33.4	-	-
-	-	-	-	-	-31.3	-31.1	-38.5	-36.6	-34	0.414 2	0.501 4
34	21	45	-	-	-31.4	-31.3	-38.1	-	-	-	-
46	10	44	-	-	-31	-31.4	-38.3	-31.6	-34.9	0.515 2	0.607 3
-	-	-	-	-	-31.5	-31.9	-38.5	-29	-28.1	0.511 4	0.522 6
-	-	-	2.80	32.13	-	-	-37.1	-36.2	-32.6	-	-
45	9	46	2.31	31.64	-31.9	-32.4	-38.4	-36.8	-33.5	0.474 6	0.598 0
-	-	-	-	-	-32.5	-32.7	-	-	-	0.455 5	0.547 6

-. Undetermined

were analyzed by crude oil and gas physical property assay and natural gas C-isotope analysis; 25 of the samples were analyzed by crude oil biomarker assay. The experimental methods were as follows.

(1) Natural gas C-isotope analysis: The measuring instrument was a Thermo Delta V Advantage, and measurement was conducted by the CNPC Research Institute of Petroleum Exploration and Development Experiment Center with an accuracy of ±0.1‰.

(2) Gas chromatographic (GC) analysis: An HP7890A instrument equipped with an HPDB-5 silica column (model No. J&W 122-5-32, 30 m, 0.25 mm i.d., and film thickness of 0.25 μm) was used. The initial GC oven temperature was 40 °C and lasted for 2 min, and then programmed to 310 °C at a rate of 6 °C/min, with a final hold time of 30 min.

(3) Gas chromatography-mass spectrometry (GC–MS): A TRACE GC ULTRA/DSQII instrument was used, equipped with an HP-5MS silica column (60 m, 0.25 mm i.d., and film thickness of 0.25 μm). The initial GC oven temperature was 100 °C and lasted held for 5 min, and then programmed to 220 °C at a rate of 4 °C/min; it was then programmed to 320 °C at a rate of 2 °C/min and held isothermally for 20 min. The biomarker parameters were calculated by peak area of each component.

(4) Inclusion analysis: The selected host mineral was calcite with inclusions in healing cracks. Microscope observation showed that the inclusions were distributed in groups showing blue-white fluorescence arranged directionally with irregular, rectangular, and oval shapes. A multi-function microscope with ZEISS AXIOSKOP and LINKAM liquid nitrogen cooling and a heating plate was used (TMS 94). The results are shown in Table 1.

3 RESULTS AND DISCUSSION

3.1 Fluid Distribution Features

The Tazhong area is rich in oil and gas. Production performance data collected during exploration and exploitation shows that it mainly contains condensate gas reservoirs with gas/oil ratios (GOR) mostly over 1 000. Such an environment is a typical of condensate gas reservoirs. Analysis of GOR and drilling production capacity indicate that the characteristics of fluids in the east part display some similarities and some differences with those of the western part. The Tazhong No. 1 fault zone also influences oil/gas distribution in both eastern and the western fluids. A significant excess in production capacity on one side of the Tazhong No.1 fault zone resulted in oil/gas mainly being generated as condensate gas. There are other significant differences in distribution between eastern and western fluids. First, eastern oil/gas displays stronger control by the Tazhong No. 1 fault zone than western, and is confined to the Tazhong No. 1 fault zone. The western oil/gas is restricted by both the Tazhong No. 1 fault and the Tazhong No. 10 fault and has a wide southward spread. Second, a common phenomenon in the eastern oil/gas area is water gushing from wells; by contrast, water only springs out of wells in low-tectonic areas of western oil and gas adjacent to the eastern area. Therefore tectonic features have a stronger effect on the release of water from wells in the western part than in the eastern part. Third, condensate gas reservoirs in the eastern part have produced a smaller amount of oil but a larger amount of natural gas than in the western area (Fig. 2). Both eastern and western fluids display limited variation along the reservoir development zone from west to east; eastern and western fluids are arranged in a quasi-layered distribution adjacent to the unconformity and its weathering crust, and were not affected by tectonic relief. A normal separation between oil, gas, and water is observed in the partial fault block and the only fracture cave (Fig. 2).

3.2 Fluid Properties

3.2.1 Physical features

Various parameters were analyzed to illustrate differences in the physical features of the eastern and western fluids. Previous theories (Zhang and Huang, 2005; Zhang et al., 2004) and our own experience suggested that parameters representing the properties and origin of natural gas are dry coefficients and methane carbon isotopes, while those of crude oil are density and condensation points. The characteristics of formation water are shown by the dissolved mineral content (Chen, 2005).

Clear differences are evident in features of crude oil, natural gas, and formation water in the eastern and the western fluid in the Tazhong Area (Fig. 3). The density and condensation points of crude oil in the eastern area are higher than those in the western area. Density of crude oil in the eastern area is generally higher than 0.8 mg/cm^3 and the condensation point is above 0 °C; conversely, crude oil in the western area has a density lower than 0.8 mg/cm^3, with a condensation point below 0 °C. Differences in natural gas properties are of more significance than those of crude oil in volatile values and poor uniformity. Uniformity in the eastern part is strong with a dry coefficient which is greater than 0.95 and hydrogen sulfide content less than 5 g/m^3 in typical dry gas with low hydrogen sulfide. Western natural gas is distinctly non-homogeneous with dry coefficients that range from 0.8 to 0.95, mid-high to ultra-high hydrogen sulfide contents from 5 g/m^3 to more than 40 g/m^3 and coexistence of dry gas and wet gas. The $\delta^{13}CH_4$ of natural gas in the eastern part is relatively homogeneous with a proportion over -40‰ and an average of about -38.5‰. The $\delta^{13}CH_4$ in the western part is from -55‰ to -35‰, lower than that of the eastern part. Water salinity is homogeneous in the eastern part with dissolved solids of 100 g/L, and is more stable than in the western area. The western region has higher water salinity and is non-homogeneous, with a wider range of dissolved solids of 80 to 200 g/L than in the eastern part. Thus, the eastern fluid in the Tazhong area exhibits strong homogeneity, and the western fluid shows strong non-homogeneity. Value discrimination is also noted between them.

3.2.2 Biomarker and C-isotope characteristics

Biomarkers in crude oil and C-isotope values in natural gas are remarkably different between the eastern and western areas (Fig. 4). Biomarker values from the eastern area include Ts/(Ts+Tm) 0.35–0.52 and C_{27dia}/C_{27reg} is 0.25–0.6 with normal heptane 30–37 and isoheptane 2.0–3.6; western values are Ts/(Ts+Tm) 0.5–0.9, and C_{27dia}/C_{27reg} is 0.4–1.5 with normal heptane 25–40 and isoheptane 2.6–5.0. $\delta^{13}C_{oil}$ values in the eastern region are -32.5‰ to -31.0‰ with $\delta^{13}C_{saturated\ group}$ -32.75‰ to -31.25‰. $\delta^{13}C_{oil}$ values in the western region are -31.5‰ to -30‰, with $\delta^{13}C_{saturated\ group}$ -32.25‰ to -30.5‰. The values of

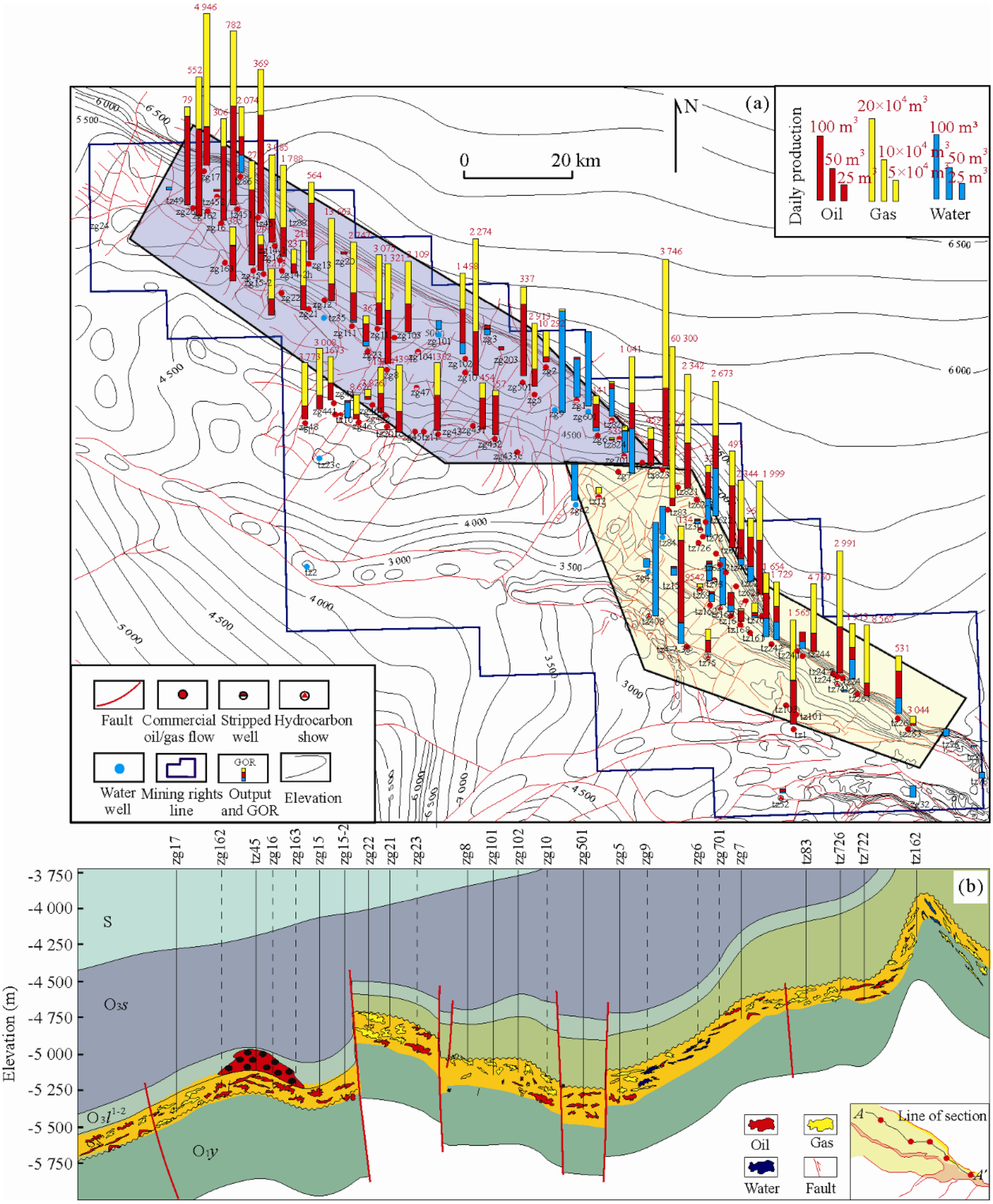

Figure 2. Regular fluid distribution in the Tazhong area in (a) map view and (b) cross-sectional view.

Ts/(Ts+Tm), normal heptane/isoheptane, and C_{27dia}/C_{27reg} are lower in western crude oil with higher values of $\delta^{13}C_{oil}$ and $\delta^{13}C_{saturated\ group}$. The C-isotope ratios of natural gas, $\delta^{13}C_1$ of the eastern part is higher than -40‰, mostly -40‰ to -35‰, whereas $\delta^{13}C_2$-$\delta^{13}C_1$ is mostly 0–10. By contrast, $\delta^{13}C_1$ of the western part is lower than -40‰, mostly -55‰ to -40‰, whereas $\delta^{13}C_2$-$\delta^{13}C_1$ is mostly 6–16. In conclusion, the C-isotope contents of natural gas in the eastern region of the Tazhong area are heavier than that in the west.

3.3 Fluid Inclusions

Fluid inclusion data (Figs. 5 and 6) indicates two phases of hydrocarbon inclusion in the condensate gas reservoirs of the Tazhong area. Hydrocarbon inclusions developed during the early stage of fracture-cavity filling by calcite in Phase I, indicating rapid calcite growth (nearly 90% of the early fracture–cavity fillings developed one-phase hydrocarbon inclusions). Dark brown liquid hydrocarbon inclusions show a uniform concentrated distribution pattern or are distributed in groups with a grayish brown color. Hydrocarbon inclusions developed during late stage fracture-cavity filling by calcsparite in Phase II, indicating rapid growth (nearly 10% of the late fracture-cavity fillings have two-phase hydrocarbon inclusions). Dark gray gas hydrocarbon inclusions developed along with micro-fractures in the late calcsparite fillings. Peak homogenization temperatures of these fluid inclusions were 90–100 and 120–130 °C and correspond to Late Hercynian and Late Himalayan periods according to the burial history (Fig. 5).

Statistical analysis of fluid inclusion photos from polarized microscope and UV fluorescence (Fig. 6) indicate that a large number of Late Hercynian liquid hydrocarbon inclusions and Late Himalayan gas hydrocarbon inclusions were widely distributed in both eastern and western gas oil reservoirs, and there was also a high proportion of gas inclusions. Bitumen was found only in eastern inclusions.

3.4 Origin of Oil and Gas and Sequence of Geological Events

3.4.1 Hydrocarbon filling phases

Previous studies (Yang et al., 2007; Zhang et al., 2004) show that the Tazhong area had undergone three main phases of oil/gas injection: a Late Caledonian injection, a Late Hercynian

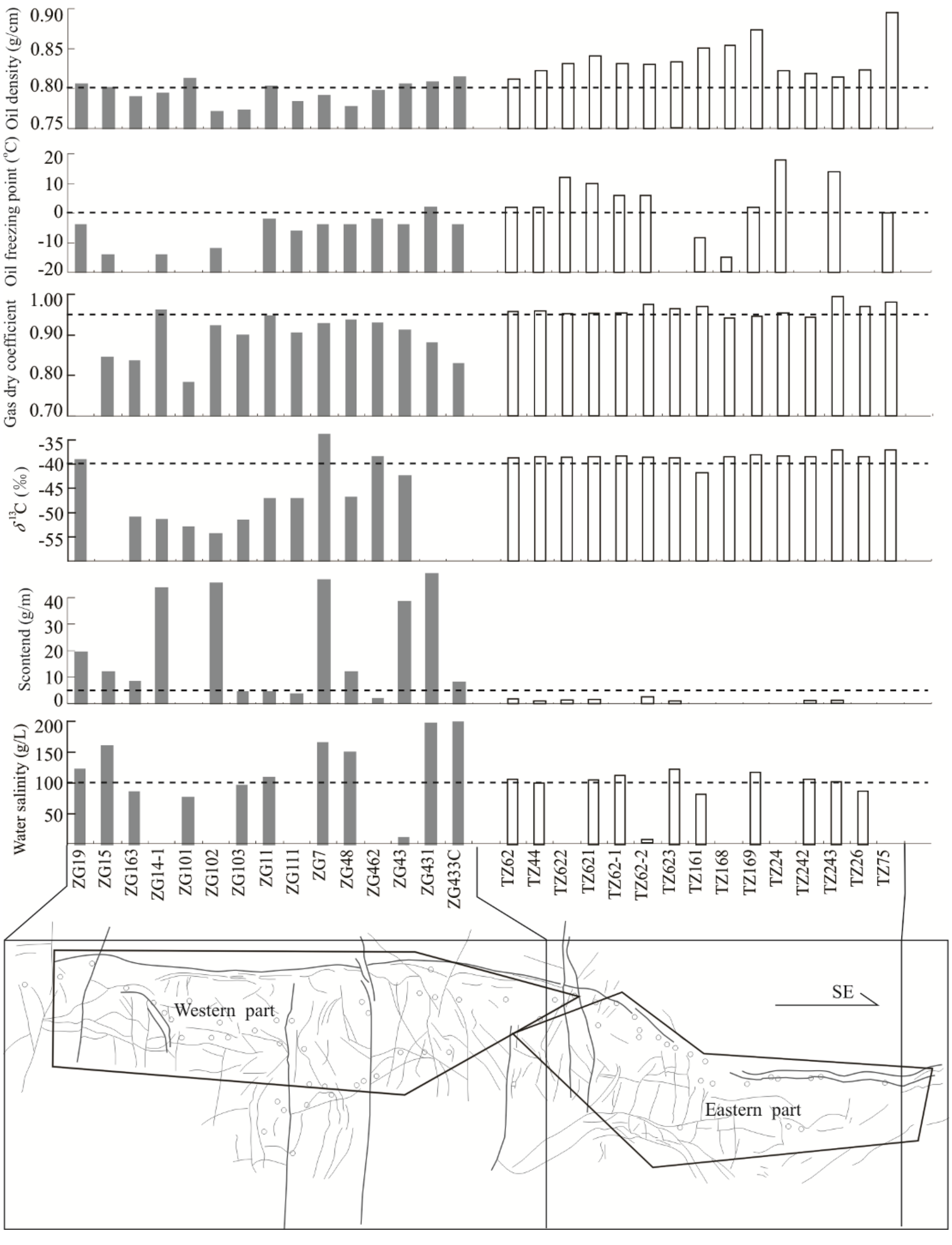

Figure 3. Comparison of fluid characteristics between the eastern and the western areas.

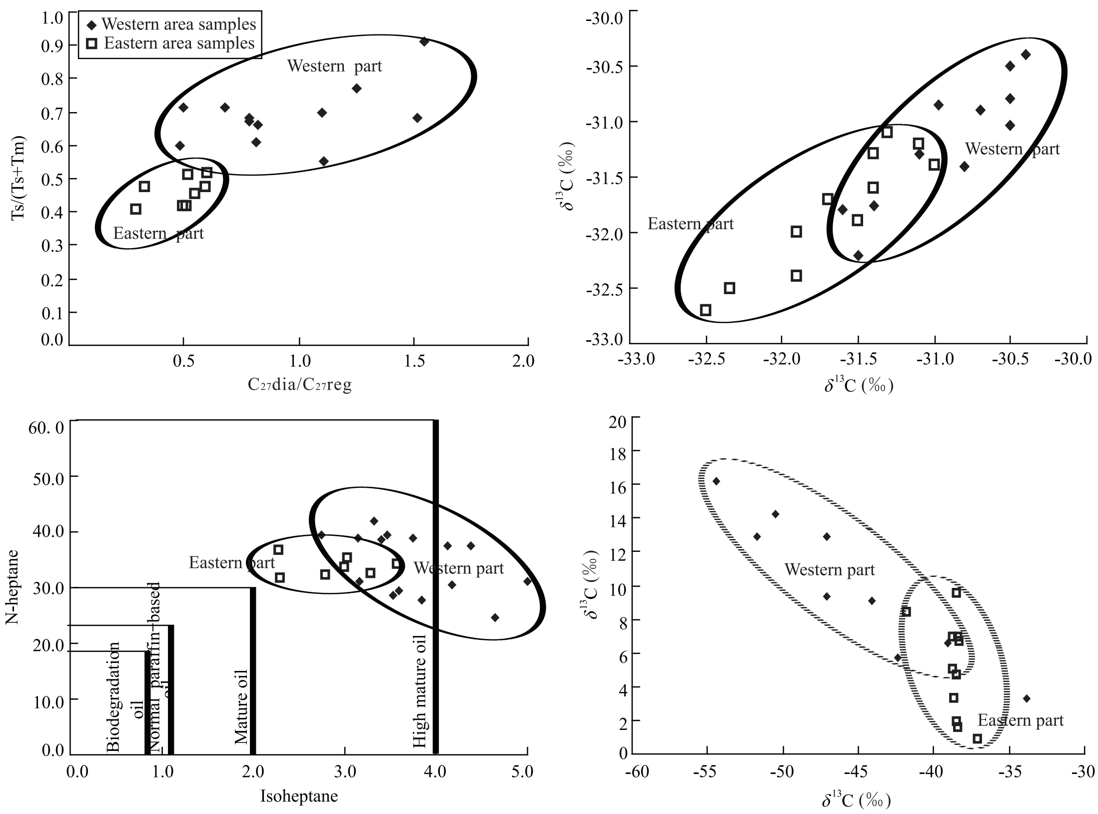

Figure 4. Comparison of hydrocarbon geochemical characteristics between the eastern and the western parts of the Tazhong area.

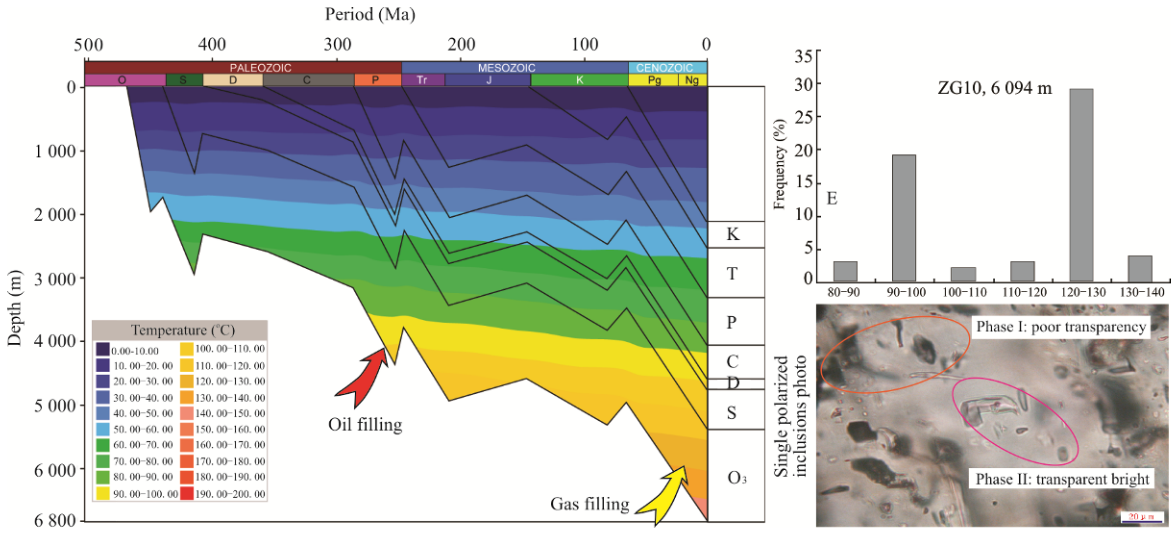

Figure 5. Burial-thermal history of the Tazhong area and characteristics of fluid inclusions.

crude oil injection, and a Late Himalayan natural gas injection (Zhu et al., 2011b). Uniform peak temperatures and timing of inclusion in fluid inclusions from the reservoirs indicate that almost all the present oil and gas were injected in the Late Hercynian and Late Himalayan; crude oil in the Late Hercynian and natural gas in the Late Himalayan. Asphalt is mainly contained in eastern fluid inclusions; and the lack of reservoirs in the eastern part proves that earlier oil reservoir and simple condensate gas reservoirs underwent later natural gas injection because of intensive damage to pre-existing oil reservoirs in the eastern part during the Late Hercynian to the Late Himalayan.

Thus the process of oil/gas injection in the Tazhong area involved three stages: (1) A first crude oil injection occurred in the Late Caledonian and was destroyed by subsequent tectonic movements. (2) A second crude oil injection occurred in the Late Hercynian but its reservoirs contained low volumes of oil and gas, especially in the eastern region. (3) A third large-scale gas injection occurred in the Tazhong area in the Late Himalayan, which forming the condensation gas reservoirs which have been preserved to this day.

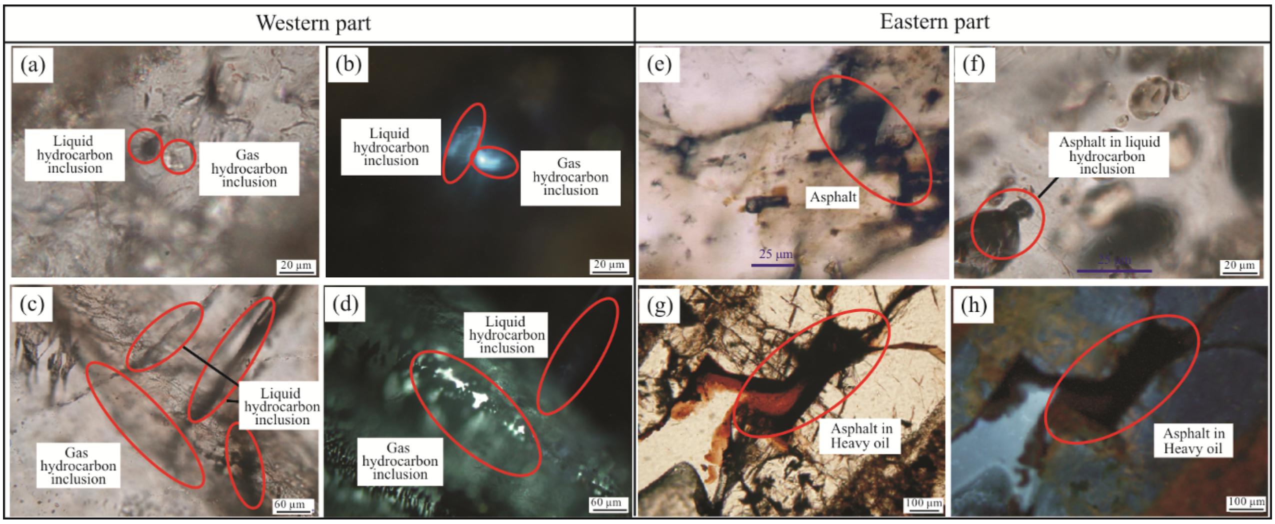

Figure 6. Micro-photographs of different types of fluid and gas inclusions. (a) (PPL) and (b) (UV fluorescence). inclusions distributed along micro-fractures in calcite, fluid inclusions grayish black, gas inclusions light gray to colorless in PPL; fluid inclusions gray and gas inclusions colorless to light blue under UV fluorescence; Well ZG22, O, 5 700 m; (c) (PPL) (d) (UV fluorescence). distributed along micro-fractures in calcite cement between limestone fragments, dark or blue fluorescent fluid inclusions, dark gray condensate gas inclusions fringed by blue fluorescence color; Well TZ11, O, 4 672.5 m; (e) (PPL): brown asphalt; Well TZ24, O, 4 600 m; (f) (PPL). dark thick oil containing asphalt; Well TZ263, O, 4 522 m; (g) (PPL) (h) (UV fluorescence). thick oil containing asphalt; Well TZ62, O, 4 711 m.

3.4.2 Fluid maturity

The distinct regionalization of chemical properties between the eastern and western Tazhong oil and gas fields demonstrate high maturity of natural gas in the eastern area and high maturity of gas condensate in the western area. Biomarker compounds, isotopic compositions, and normal heptane/isoheptane are important parameters for studying and predicting the properties of oil and gas. Previous studies have found that the parameters of biomarker compounds Ts/(Ts+Tm) and C_{27dia}/C_{27reg} are sensitive indices of maturity changes in crude oil (Peters and Moldowan, 1993) and also that high indices indicate a high degree of maturity. Ts/(Ts+Tm) and C_{27dia}/C_{27reg} at Tazhong indicate high maturity of gas condensate in the western region (Fig. 4). $\delta^{13}C_{oil}$ and $\delta^{13}C_{saturated\ group}$, also valid parameters for assessing crude oil maturity, show that the maturity of crude oil becomes less from west to east (Fig. 4). Thompson suggested that crude oil could be classified into four types depending upon the classification of normal heptane/isoheptane values of crude oil: biodegraded oil, paraffin oil, normal-maturity oil, and high-maturity oil (Thompson, 1983). We have analyzed data from the Tazhong area following Thompson's theory. In both eastern and western areas, gas condensate belongs to a high-maturity oil zone, and the eastern area has a lower maturity value than the western (Fig. 4). Methane and ethane isotopes as indexes of natural gas maturity, predict the geochemical differences in natural gas properties. The data indicated low maturity in the western Tazhong area (Fig. 4). The disparity between oil and natural gas maturity supports the late injection of gas into pre-existing oil reservoirs.

3.4.3 Differences in the oil/gas genesis in the eastern and western regions

Two different types of natural gas origins have been confirmed in the Tarim Basin: oil cracking gas and kerogen cracking gas, although neither exhibit differences from each other in natural gas composition and C-isotope ratios (Zhao et al., 2001). Previous research (Guo et al., 2011) concluded that the relationship of ($\delta^{13}C_2$-$\delta^{13}C_3$)-$\delta^{13}C_1$ and ($\delta^{13}C_2$-$\delta^{13}C_3$)-Ln(C_2/C_3) can distinguish oil cracking gas from kerogen cracking gas by conducting hydrocarbon-generating thermal simulation of synthetic oil and kerogen samples separately and then testing for pyrolysis gas compositions and C-isotope values. Zhang et al. (2004) also believed that the main sources of hydrocarbons can be roughly determined via triangular graphical plotting of the relative percentage of C_{27}-C_{28}-C_{29}20R steranes.

The origins of natural gas are different between the eastern and the western regions of the Tazhong area. Hydrocarbons in the eastern reservoirs derive mainly from Ordovician source rocks and gas mainly from kerogen pyrolysis. Hydrocarbons in the western condensate gas reservoirs derived mainly from Cambrian source rocks and gas mainly from oil cracking. We have found a partition between the eastern part and the western part by processing C-isotope and gas composition data in the Tazhong area using the ratios of ($\delta^{13}C_2$-$\delta^{13}C_3$)-$\delta^{13}C_1$, ($\delta^{13}C_2$-$\delta^{13}C_3$)-Ln(C_2/C_3), and ($\delta^{13}C_2$-$\delta^{13}C_3$)-(C_2/C_3) (Figs. 7a, 7b, 7c). Crude oil samples from the east show more kerogen pyrolysis gas characteristics, whereas those from the west show more characteristics of crude oil cracking gas. Methane C-isotope values from the east are overall heavier than the west, consistent with a previous view that "kerogen pyrolysis gas has heavier C-isotope values than crude oil cracking gas" (Tian et al., 2007). In addition, the discovery of 2-thio-adamantane in well TZ83 in the western part indicates that high temperature cracking of crude oil occurred; and the large difference in hydrogen sulfide content in gas between the east and the west indicates that crude oil cracking accompanied by strong TSR, led to high hydrogen sulfide content in the west part (Jiang et al., 2007). A triangular graph of proportions of C_{27}-C_{28}-C_{29}20R steranes (Fig. 7d) displays distinct fields for western and eastern samples indicating that western condensate gas reservoirs obtained

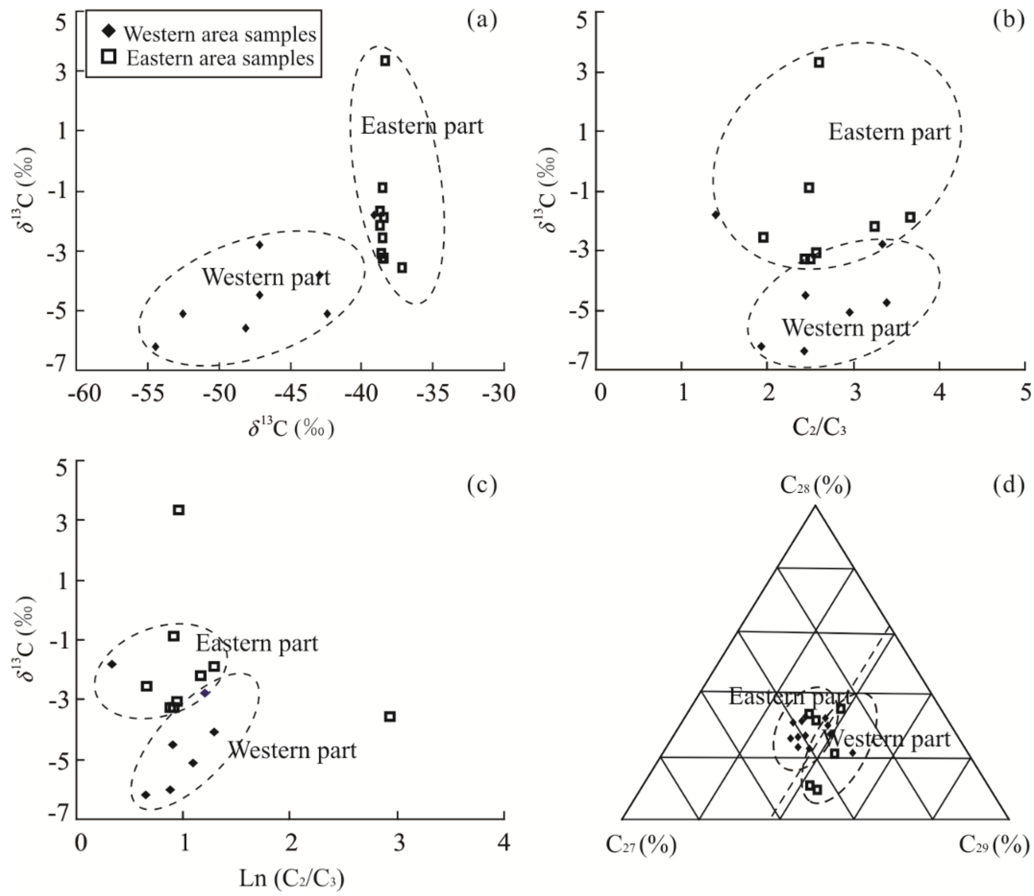

Figure 7. Differences of the hydrocarbon origin and source in the two parts of Tazhong area.

hydrocarbons mainly from Cambrian source rocks and eastern mainly from Ordovician source rocks.

Two different origins of condensate gas reservoirs were revealed in the east and the west Tazhong area. The eastern area obtained gas mainly from kerogen analysis because of the contribution of Ordovician source rocks; and the western gas is derived from oil cracking because of the Cambrian source rocks.

3.4.4 Two geological mechanisms that created condensate gas reservoirs

Table 2 lists similarities and differences in the geological setting of both the eastern and the western areas. The eastern area had undulating relief and a high terrain slope. There were few strike-slip faults but intensive compressive thrust faults and the transportation channel for lateral natural gas injection was along the Tazhong No. 1 fault zone. The tectonic relief of the western area was relatively flat. There are widespread strike-slip faults in the western area in addition to compressional thrust faults that cut downward to a Cambrian gypsolyte layer, and became transportation channels for lateral natural gas injection along with the Tazhong No. 1 fault zone. The predominant eastern oil gas was clearly dominated and shaped by the Tazhong No. 1 fault belt; the distribution of western crude oil was influenced by strike-slip faults, the Tazhong No. 1 fault zone, and the Tazhong No. 10 tectonic belt. The highly non-homogeneous western fluid shows large variation of ratios and compositions of natural gas and formation water; by contrast, the homogeneity of the eastern fluid is marked. The capacity and maturity of gas condensate in the eastern area are lower than those in the western area. The content of hydrogen sulfide of eastern gas is low while the western region exhibits high to extremely high hydrogen sulfide gas. The origin of the eastern nature gas was mainly controlled by kerogen cracking; the origin of the western natural gas was dominated by crude oil cracking.

Condensate gas reservoir formation mechanisms in the eastern and the western Tazhong areas were established considering factors such as geological environment, diversity of fluid distribution, properties, and origins (Fig. 8).

Western area: The first injection of crude oil occurred in the Late Caledonian when secondary porosity created reservoir space. Continuously powerful tectonic activity in the Early Hercynian period caused large NE-SW strike-slip faults and destroyed the Caledonian crude oil reservoirs, so there is negligible hydrocarbon capacity from the early injection. The second period of hydrocarbon charging occurred in the Late Hercynian when only a small part of a large crude oil charged reservoir had been damaged while most of its porosity had been preserved. Deep oil cracking gas recharged the underlying oil reservoir through gas invading along the channels of strike-slip faults in Late Himalayan times; natural gas then migrated upward to the ground surface, and settled as a secondary gas condensate reservoir through a fluid hybrid process. The gas condensate reservoir in the western area was formed by multiphase deep oil cracking gas washing into the ancient oil

Table 2 Geological events in the western and the eastern areas

		Western	Eastern
Geologic feature	Formations	Similar stratigraphic characteristics; the main oil- and gas-rich layers are Yingshan formation and Lianglitage formation of the Ordovician.	
	Tectonic relief	Terrain is significantly lower than the east, undulation is relatively low	Terrain is significantly higher than the west, undulation is relatively large
	Development of fracture	Strike-slip faults strongly developed	Compressed thrust fault strongly developed
	Fluid distribution	Fluid distribution controlled by Tazhong No. 1 fault zone, strike-slip faults, and Tazhong No. 10 fault zone	Fluid distribution significantly controlled by Tazhong No. 1 fault zone
Production characteristics	Oil production capacity	Lower oil and gas capacity than the east, higher condensate oil content	Higher gas content than the west
	Water breakthrough	A few wet wells, only in low-relief zone	Universal distribution
Fluid physical properties	Condensate oil	Density <0.8 mg/cm^3, freezing point <0 °C, higher maturity than the east	Density >0.8 mg/cm^3, freezing point >0°C, lower maturity than the west
	Natural gas	Extremely inhomogeneous, aridity coefficient between 0.80–0.95, medium to extremely high hydrogen sulfide content, coexistence of dry gas and wet gas	Extremely homogeneity, aridity coefficient general >0.95, free-low hydrogen sulfide content <5 g/m^3, coexistence of dry gas and wet gas, dry gas
	Formation water	Higher salinity between a wide range of 80–200 g/L than the east, strong inhomogeneity	Strong homogeneity, salinity around 100 g/L as a small range
Geochemical characteristics	Condensate oil	Data of Ts/(Ts+Tm)-C_{27}dia/C_{27}reg, $\delta^{13}C_{oil}$-$\delta^{13}C_{saturated\ group}$, normal/iso-heptane showed higher maturity	Data of Ts/(Ts+Tm)-C_{27}dia/C_{27}reg, $\delta^{13}C_{oil}$-$\delta^{13}C_{saturated\ group}$, normal/iso-heptane showed lower maturity than the west
	Natural gas	Lower$\delta^{13}CH_4$ value range between -55‰ to -35‰ than the east	Relatively homogeneous $\delta^{13}CH_4$ value, most >-40‰, average at -38.5‰
Oil and gas genesis	Condensate oil	All belong to high maturity oil	
	Natural gas	Coexistence of crude oil cracking gas and crude oil	Dominated by kerogen pyrolysis gas

reservoir, thereby generating wet natural gas. In addition, different transportation channels along strike-slip faults caused different amounts of gas injection and produced strong inhomogeneity of the western fluid.

Eastern area: Similar crude oil injection processes occurred in the eastern region as the western in the Late Caledonian and Late Hercynian. During the Hercynian to Himalayan, ancient oil reservoirs were extensively damaged by geological events near Tazhong No. 1 fault zone that few ancient oil reservoirs survived. The natural gas, mainly composed of deep kerogen cracking gas, directly charged the empty permeable reservoir and formed the primary condensate gas reservoir. As the primary condensate gas reservoir was formed by direct injection of kerogen cracking gas into the reservoir, the absence of strike-slip faults did not significantly influence deeper fluids in producing strong homogeneous natural gas.

4 CONCLUSIONS

(1) Tazhong area in the Tarim Basin in Ordovician has suffered multi-cyclic hydrocarbon charging, and made Tazhong a typical condensate gas district. Eastern and western regions exhibit significant differences in tectonic structure, fluid distribution, and physical-chemical properties of oil and gas.

(2) Compared with the eastern region, the west has a greater development of discordogenic gas associated with strike-slip faults which, combined with the Tazhong No. 1 fault zone, control the fluid distribution. The eastern region is mainly controlled by the Tazhong No. 1 fault zone. Fluid have markedly homogeneous properties in the east, but are heterogeneous in the west.

(3) The origins of oil and gas are different between the east and the west. In the east, hydrocarbons are mainly from Ordovician source rocks and natural gas is mostly derived from kerogen pyrolysis. In the west, the hydrocarbons mainly originated from Cambrian source rocks, and the gas was mostly generated by crude oil cracking. In sum, the east region is dominated by primary condensate gas reservoirs, and the western region is dominated by secondary condensate gas reservoirs.

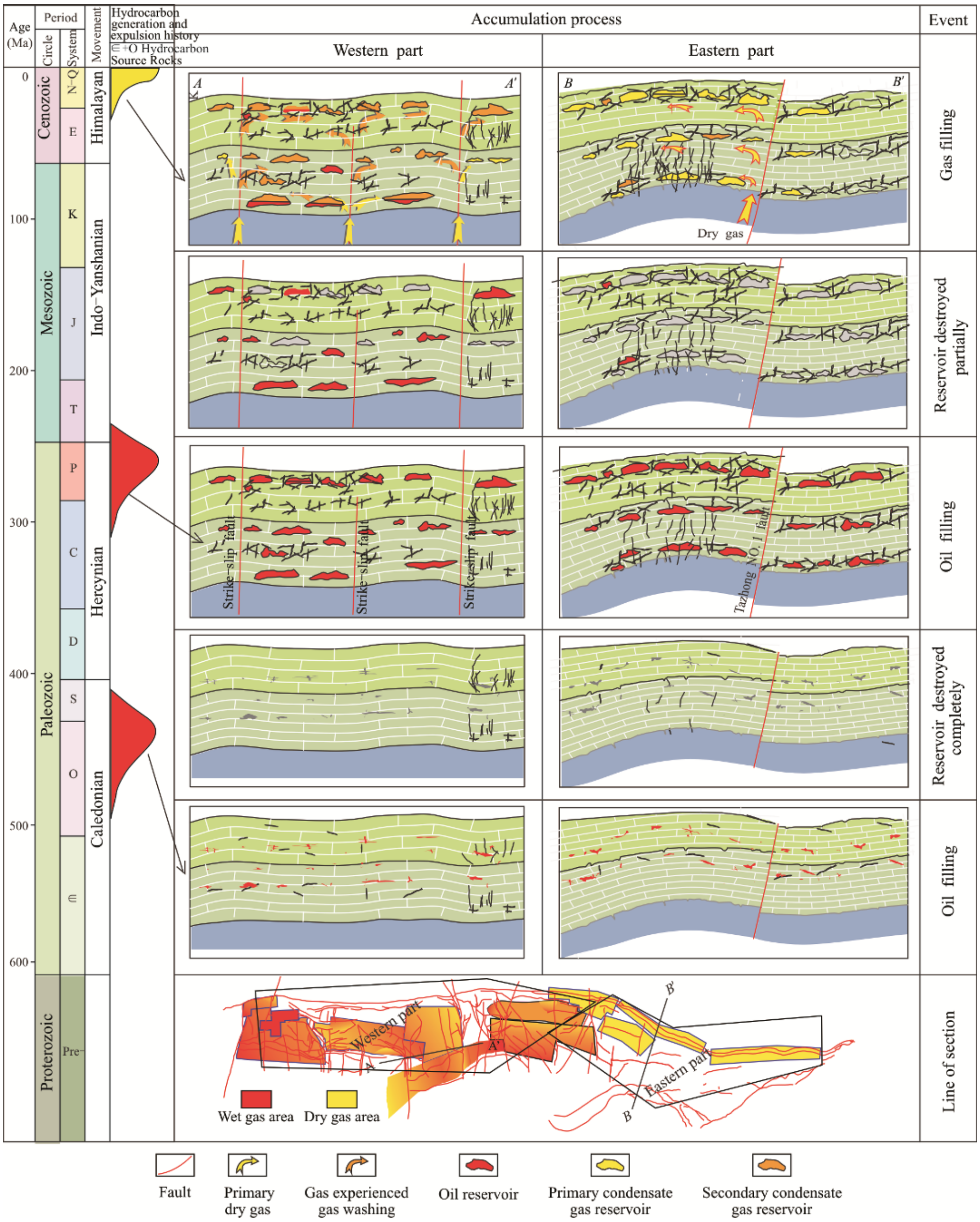

Figure 8. Condensate gas reservoir formation models of the western and the eastern regions of the Tazhong area.

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