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Origin and accumulation model of the AK-1 natural gas pool from the Tarim Basin, China

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Abstract

The AK-1 gas pool represents the first commercial gas discovery in the Kashi Depression, northwest Tarim Basin. The pool is characterized by dry hydrocarbon gas (dryness index > 0.995), heavy methane carbon isotopic value ($\delta^{13}C_1 = -25‰$), and a lighter $\delta^{13}C_2$ ($\delta^{13}C_2 - \delta^{13}C_1 = 3.9‰$). High CO_2 content ($\delta^{13}C_{CO_2} = -8.6‰$) is observed in the main production reservoir. These characteristics indicate that the hydrocarbon gas originated from multiple sources, and that the CO_2 is of mixed inorganic and organic origin. There are two possible source areas: the lower block of the AK-1 overthrust structure and the central area of the Kashi Depression. Two possible source rocks are present in both areas: Lower Carboniferous mudstone and Lower and Middle Jurassic coal measures, typically with type II and type III kerogens, respectively. Both reservoir fluid inclusion data and trap structure evolution indicate that the gas pool was formed during the Pliocene–Quaternary. We constructed geological models of methane generation and carbon isotopic fractionation for the two potential source rocks using different geothermal histories of the two possible source areas. By comparing modeled results with the geochemical characteristics of the gas pool, we conclude that the source rock of the gas pool is the Lower Carboniferous mudstone, and the main source area is in the lower block of the AK-1 overthrust structure with a secondary source area in the center of the Kashi Depression. The pool gas is interpreted as a late stage cumulative gas. The structure trapped gas generated from source rock in the lower block of the AK-1 overthrust at a methane fractional conversion of 0.64–1.0 together with inorganic CO_2 from the thermal decomposition of Carboniferous carbonate rocks in the central area of the Kashi Depression.

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1. Introduction

The recently discovered AK-1 natural gas pool is the only commercial accumulation in the northwestern area of the Tarim Basin. This gas pool covers an area of about 16.9 km^2 and has a natural gas resource of 1.2×10^{10} m^3 (Song and Zhao, 2001; Wang et al., 2002). The gas is characterized by a heavy $\delta^{13}C_1$ value, dry hydrocarbon composition, and high non-hydrocarbon content (Zhang et al., 2003). As the Kashi Depression is a new exploration area in the Tarim Basin, there are only one published paper and a few internal reports

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that address the origin of this gas (Song and Zhao, 2001; Wang, 2002; Wang et al., 2002; Zhang et al., 2003). Because of its heavy $\delta^{13}C_1$ value, quite similar to gases from Carboniferous coal measures in NW Germany (Cramer et al., 2001), the Jurassic coal measures in the Kashi Depression were assumed to be the source (Wang, 2002). However, recent exploration has shown that the distribution of the Jurassic coal measures in the Kashi Depression is quite limited and that these coals are insufficiently mature to generate gas with the observed molecular and isotopic composition (Wang et al., 2002, 2003). Some workers, based on the geological evolution of this area, have mentioned the possible importance of the deeply buried Carboniferous strata in the Kashi Depression as the source rocks of the AK-1 gas pool (Song and Zhao, 2001; Wang et al., 2003). The lack of samples for direct measurement and the inferred high levels of thermal maturity make it very difficult to correlate the pool gas to these potential sources. In this paper, we present the geochemical and geological characteristics of the AK-1 gas pool, geological models of methane generation kinetics and carbon isotopic fractionation kinetics based on typical source rock samples, and an accumulation model for the AK-1 pool that explains the origins of the gases. The results demonstrate the utility of geochemical data and theoretical models placed within a geologic framework and their significance to future exploration in the area.

2. Geological setting of the AK-1 gas pool

The Tarim Basin is located in northwest China, covering an area of 56×10^4 km^2. It is a typical lapped basin, and consists of a few prototype sub-basins containing sediments with a total thickness of 10,000–20,000 m, including Paleozoic, Mesozoic and Cenozoic strata with quite different characteristics (Jia et al., 1991). The Southwest Depression is one of the sub-basins and the Kashi Depression is its secondary structure unit (Fig. 1). The Southwest Depression formed during Carboniferous age and underwent three stages of tectonic evolution (Lu et al., 2001): craton interior basin (Carboniferous–Triassic); faulted basin (Jurassic–early Tertiary); foreland basin (later Tertiary–Quaternary) (Fig. 2). The AK-1 natural gas pool (named by the borehole AK-1) is located at the Akemomu anticline in the Tuopo structure belt of the Kashi Depression. A sequence of three deformed structural units developed from the South Tian Mountains to the Kashi Depression (Fig. 1). The first deformed structural unit is the Tuopo structural belt. It is connected in the north to the South Tian Mountain overthrust block by faults, and in the south to the second row deformed structural unit of the Atushi structural belt by a syncline and faults (Lu et al., 2001).

Figure 2 presents a generalized stratigraphic column for the AK-1 area. The Upper Tertiary and Lower Carboniferous strata are well developed, with a thickness of 3000–4000 and 2000–3000 m, respectively. Triassic sediments are absent. The reservoir rock of the AK-1 gas pool is the Lower Cretaceous sandstone with a burial depth of 3300–3900 m, and its main production seam is at the burial depth of 3320–3340 m. According to the available data, the reservoir sandstone is low porosity (5–10%) and low permeability (0.5–1.0 md) (Wang et al., 2002). Two sets of cap rocks are confirmed: a Lower Tertiary gypsum seam and an Upper Cretaceous interbedded mudstone and gypsum. The Upper Cretaceous is a direct cap rock, with a variable thickness in the range of 16–217 m, and the Lower Tertiary is a regional cap rock, with a uniform thickness of 66–70 m.

There are two potential source rocks in the Kashi Depression: Lower Carboniferous dark mudstone and Lower and Middle Jurassic coals and mudstones. The geological setting of the AK-1 gas pool indicates there are two possible source areas: the central area of the Kashi Depression and the lower block of the AK-1 overthrust structure (Fig. 3). Both areas contain the two possible sources. The Carboniferous dark mudstones, have a fairly uniform thickness of more than 300 m while the Lower and Middle Jurassic coal measures vary in thickness from 0 to ~100 m (Wang et al., 2002; Wang et al., 2003). A Permian dark mudstone that was deposited in other structural units of the Northwest Depression of the Tarim Basin has a limited distribution in the Kashi Depression with a thickness of less than 10 m (Song and Zhao, 2001). According to available geochemical data from source rock samples collected from outcrops and boreholes in this area, the Lower Carboniferous dark mudstone has a high maturation level with R_o values of 1.5–3.0%, and contains Type II kerogen with total organic carbon (TOC) ranging from 1.0% to 2.5% (Song and Zhao, 2001). Because of the high maturity, the hydrocarbon index (HI) of the Lower Carboniferous mudstone is quite low, mostly in the range of 5–50 mg/g (Song and Zhao, 2001). The Jurassic coals and mudstones contain Type III kerogen with TOC values of 50–70% and 2–5%, respectively (Song and Zhao, 2001; Wang et al., 2002; Zhang et al., 2003).

The Xishan orogeny had a great influence on the Kashi Depression and the major faults and local structural belts were formed during this period. Those faults and structures began from the marginal area of the South Tian Mountains and developed toward the depression center during the Oligocene and Pliocene to form an overthrust block structure (Wang et al., 2002). Therefore, according to the tectonic evolution of the Akemumo anticline and the time of formation of the trap structure, the AK-1 gas pool should have formed during the Pliocene–Quaternary (Fig. 3).

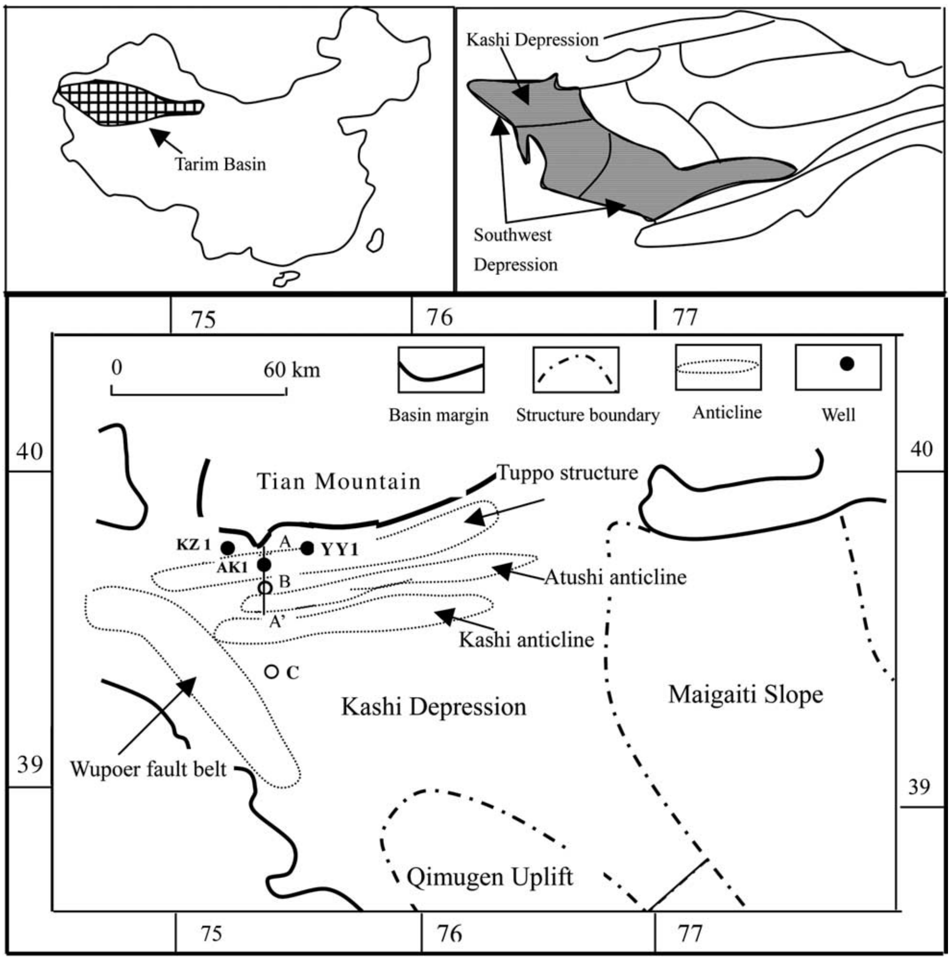

Fig. 1. Sketch map showing location and structural outline of the AK-1 gas pool (modified from Song and Zhao, 2001; Wang et al., 2002). B and C are the thermal modeling points: B – the lower block of the AK-1 overthrust structure; C – the center area of the Kashi Depression.

3. Geochemical characteristics of the natural gas from the AK-1 gas pool

Tables 1 and 2 present the compositions and isotopic values of some natural gases from the AK-1 gas pool. The gas from the AK-1 gas pool is dominated by hydrocarbon gases, with a C_1 content of 76–81%, $C_2 + C_3$ less than 0.3%, and normally without C_4 and heavier hydrocarbon components. The gas is dry, with an average dryness index $[C_1/(C_1 - C_5)]$ of 0.995. The gas contains a high content of N_2 and CO_2, in the range of 8–11% and 10–13%, respectively. The gas has the heaviest methane carbon isotopic value, with an average $\delta^{13}C_1$ of $-25‰$, and the smallest difference between $\delta^{13}C_2$ and $\delta^{13}C_1$ with an average value of less than 4‰, in the Tarim Basin (Li et al., 2001; Zhang et al., 2003). Normally, a gas with these characteristics implies that it has a very high maturity and originated from late stage cracking of kerogen or coal with higher temperatures (Schoell, 1983; Jenden et al., 1988; Krooss et al., 1995).

The $\delta^{13}C_{CO_2}$ values of the gas from the gas pool vary, with the range of $-4.6‰$ to $-10.6‰$, but CO_2 from the main production reservoir (at a depth of 3325–3345 m) has a $\delta^{13}C_{CO_2}$ value of $-8.6‰$ (Table 2). According to an investigation of natural gases from Chinese petroleum-bearing basins made by Dai et al. (1992, 1996), $\delta^{13}C$ for CO_2 of organic origin is usually lighter than $-10‰$ and of inorganic origin heavier than $-8‰$. This closely agrees with the subdivision made by Stahl et al. (1981). Because only a small quantity of CO_2 can be generated during the thermal maturation of post-diagenetic organic matter, CO_2 of organic origin is normally a minor component in natural gases (usually less than 5%) (Hunt, 1990, 1996; Dai et al., 1996; Dong and Huang, 1999; Chen et al., 2000). Thus, the CO_2 in the gas pool should be a mixture of organic and inorganic CO_2. We

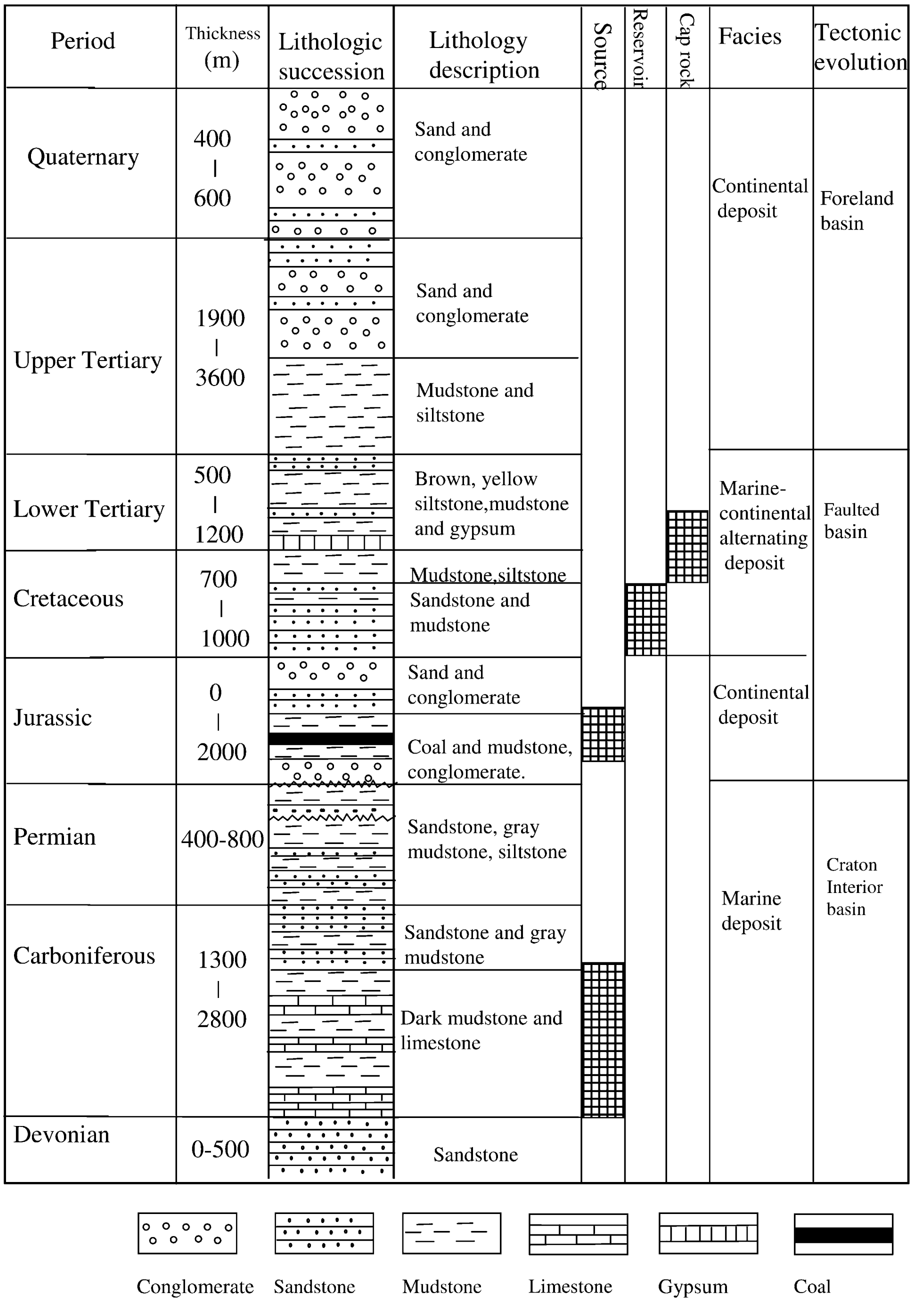

Fig. 2. Sketch map showing a generalized stratigraphic column for the area of the AK-1 gas pool (modified from Wang et al., 2002).

will show below that the carbonate in the Carboniferous strata in the Kashi Depression experienced a maximum temperature of 300–360 °C during the Quaternary, resulting in carbonate decomposition, and that this was the source of the inorganic CO_2.

$^{40}Ar/^{36}Ar$ values can provide information on the origin of natural gases. Argon in natural gases has two sources: atmosphere and radiation. The $^{40}Ar/^{36}Ar$ ratio of the atmosphere is 295.5, and a larger value implies an increase in argon of radiogenic origin (Xu et al., 1997). Xu et al. (2001) collected $^{40}Ar/^{36}Ar$ data for 158 natural gas samples from 32 gas pools and found that the $^{40}Ar/^{36}Ar$ values are in the range of 302–9255 and correlated with the age of their source rocks by the expression $t\ (\mathrm{Ma}) = 530 \log {}^{40}Ar/^{36}Ar - 1323$. The $^{40}Ar/^{36}Ar$ ratio of the AK-1 gas is 1438 (Table 2), yield-

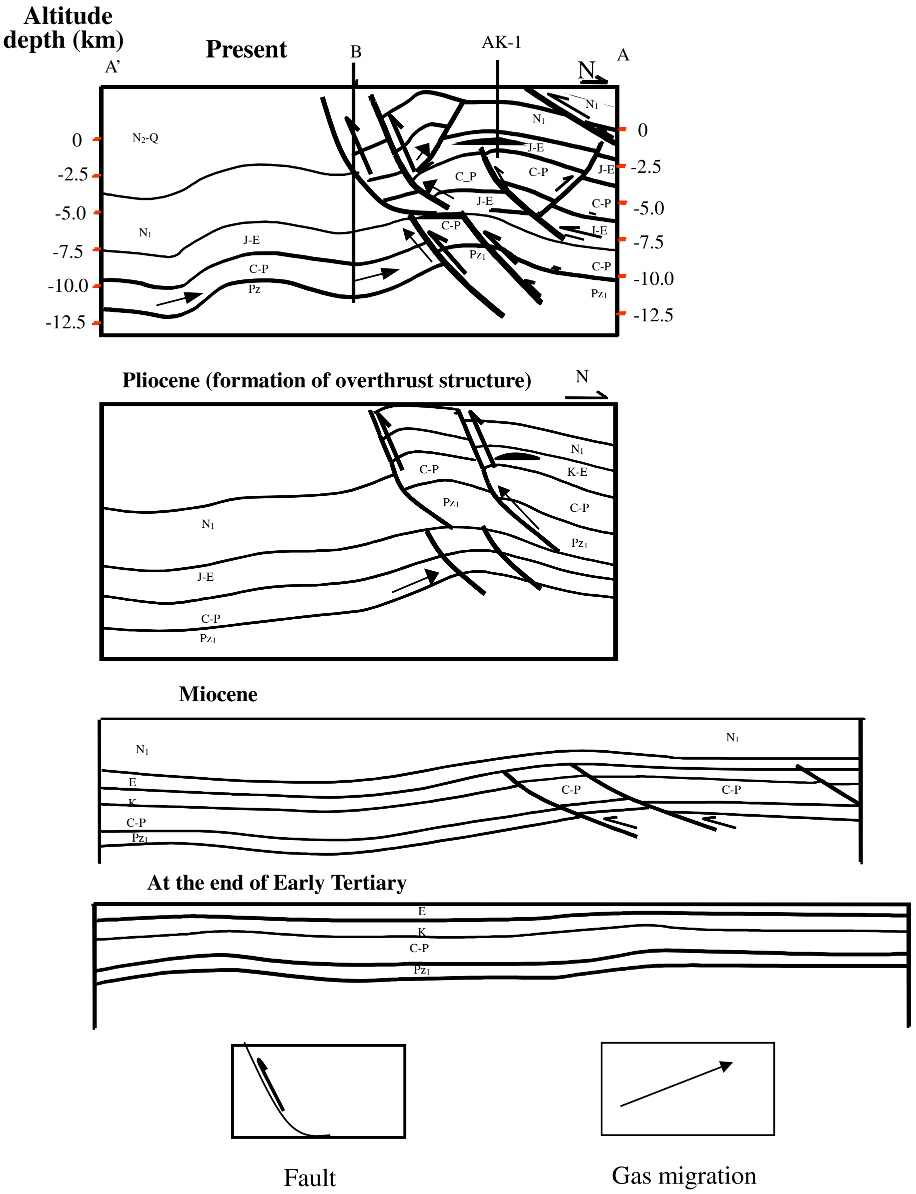

Fig. 3. Sketch map showing tectonic evolution and formation of the AK-1 structure (simplified after Wang et al., 2002). Point B represents the location of the lower block of the AK-1 overthrust structure.

Table 1

Gas compositions of AK-1 gas pool (data from petroleum exploration and development institute of the Tarim petroleum institute, CNPC, 2003)

Well	Depth (m)	Reservoir age	C_1 (%)	C_2 (%)	C_3 (%)	iC_4 (%)	nC_4 (%)	C_{5+} (%)	CO_2 (%)	N_2 (%)
AK-1	3325–3345	Early Cretaceous	81.05	0.26	0.04	0.02	0.02	0.01	10.21	8.39
	3355–3361	Early Cretaceous	80.03	0.24	0.03	0.01	0.01	0.00	11.34	8.34
	3371–3376	Early Cretaceous	80.79	0.21	0.02	nd	nd	nd	8.90	10.08

nd = not detected.

Table 2
Isotopic data of gas from AK-1 gas pool (data from petroleum exploration and development institute of the Tarim petroleum institute, CNPC, 2003)

Well	Depth (m)	Age	$\delta^{13}C$ (‰, PBD)						$^{40}Ar/^{36}Ar$
			C_1	C_2	C_3	iC_4	nC_4	CO_2	
AK-1	3325–3345	Early Cretaceous	−25.2	−21.9	nd	nd	nd	−8.6	1438
	3355–3361	Early Cretaceous	−23.0	−20.2	nd	nd	nd	−4.6	nd
	3371–3376	Early Cretaceous	−25.0	−21.9	nd	nd	nd	−10.6	nd

nd = not detected.

ing a source rock age of 350 Ma by this equation. Thus, the rare gas isotopic value of the AK-1 gas implies that it originated from an older source rock.

4. Source of the AK-1 gas pool

The above discussion gives us some confidence that the gas of the AK-1 pool originated from the late stage cracking of kerogen and it displays some characteristics of a mixed organic and inorganic origin for the CO_2 component. The data are more consistent with a Carboniferous mudstone source rock than with the Jurassic coal measures. In this section we describe further investigations into the gas source of the AK-1 pool using geological models of methane carbon isotopic fractionation kinetics based on typical source rock samples.

4.1. Method

Establishment of a geological model of methane carbon isotope fractionation for a kerogen at geological heating rates needs three pieces of information (Tang et al., 2000):

(1) Methane generation kinetics, which can be determined by the software Kinetics 2000 developed by Braun and Burnham (1998), based on pyrolysis experimental data of methane generation from the kerogen with two different heating rates. The detail was described by Tang et al. (1996). From our previous study, it is important to use a smooth activation energy distribution to overcome isotope ratio oscillations (Tang et al., 2000).
(2) Fitting of methane carbon isotopic data. The method follows the same procedure published by Tang et al. (2000). Based on the kinetics of the methane generation and experimental data for methane isotope fractionation of the kerogen at the two different heating rates, the kinetic isotopic fractionation constants can be fitted using the software GOR Isotope (GeolsoChem Corporation, 2003). There are a total of six parameters (Table 4). Detailed mathematic derivation and isotope fractionation constants are described in detail by Tang et al. (2000).
(3) Thermal history of the source rocks, which is determined by the burial and geothermal gradient history of the studied area.

By uploading the above data into the software GOR Isotope (GeolsoChem Corporation, 2003), the geological model of methane carbon isotope fractionation for the kerogen at the specified geologic conditions can be calculated.

4.2. Kinetics parameters of methane generation and carbon isotopic fractionation

Two typical source rock samples were selected from the marginal area of the Kashi Depression: a Jurassic coal and a Lower Carboniferous mudstone. Both samples are at a low maturation stage, with R_o values of 0.65–0.67% (Table 3). The coal sample is a typical type III kerogen, with about 75% vitrinite, 15% exinite, and 10% inertinite, whereas the mudstone contains type II kerogen, consisting of about 70% amorphinite, 15% alginite + exinite, and 15% vitrinite + inertinite. For comparison with the coal sample, kerogen with a TOC of 50.78% was separated from the mudstone by means of procedures suggested by Alpern (1980).

Pyrolysis experiments on the coal and kerogen were conducted in gold tube reactors. Samples were loaded into gold tubes (9 mm o.d., 60 mm length), sealed and placed in stainless steel cells. The cells were placed into the pyrolysis furnace and kept at a confining pressure of 50 MPa during the entire course of the experiment. The samples were heated to the required temperatures ranging from 250 to 600 °C at rates of 2 and 20 °C/h, respectively. Abundance and $\delta^{13}C$ values for the evolved methane, ethane and propane were measured using a GC coupled via a combustion furnace to a Finnigan-MAT251 mass spectrometer.

The kinetics parameters of methane generation and carbon isotopic fractionation based on the experimental data are calculated and fitted by the method de-

Table 3
Geochemical characteristics of source rock samples selected for pyrolysis experiment

Sample No.	Well	Depth (m)	Age	Sample description	TOC (%)	R_o (%)	Rock-Eval result			
							T_{max} (°C)	S_1 (mg/g)	S_2 (mg/g)	HI (mg/g)
K-1	KZ-1	3812	J_1	Coal	71.94	0.67	449	0.81	108.76	151.10
Y-1	YY-1	2547	C_1	Kerogen from dark mudstone	50.78	0.65	444	0.28	167.07	329.49

J_1: Lower Jurassic; C_1: Lower Carboniferous.

scribed above. The results are presented in Figs. 4 and 5, and Table 4. As the two samples contain different maceral compositions, their kinetics parameters also are different. For instance, the Carboniferous kerogen has a slightly wider range and a larger average value of activation energy distribution, and a smaller γ (activation energy threshold; Tang et al., 2000) than the Jurassic coal. These differences in kinetics parameters between the two samples will have an important influence on the results of the geological models of methane generation and carbon isotopic fractionation.

4.3. Geological parameters for thermal modeling

Paleogeothermal gradient, paleosurface temperature and burial history of the studied area are important parameters in establishing the geological models of methane generation and methane carbon isotopic fractionation. We compiled the data relating to the geothermal evolution of the depression from internal reports and publications on the Kashi Depression (Dong et al., 1998; Liang and Zhang, 2001; Song and Zhao, 2001; Wang et al., 2002; Xiao et al., 2003).

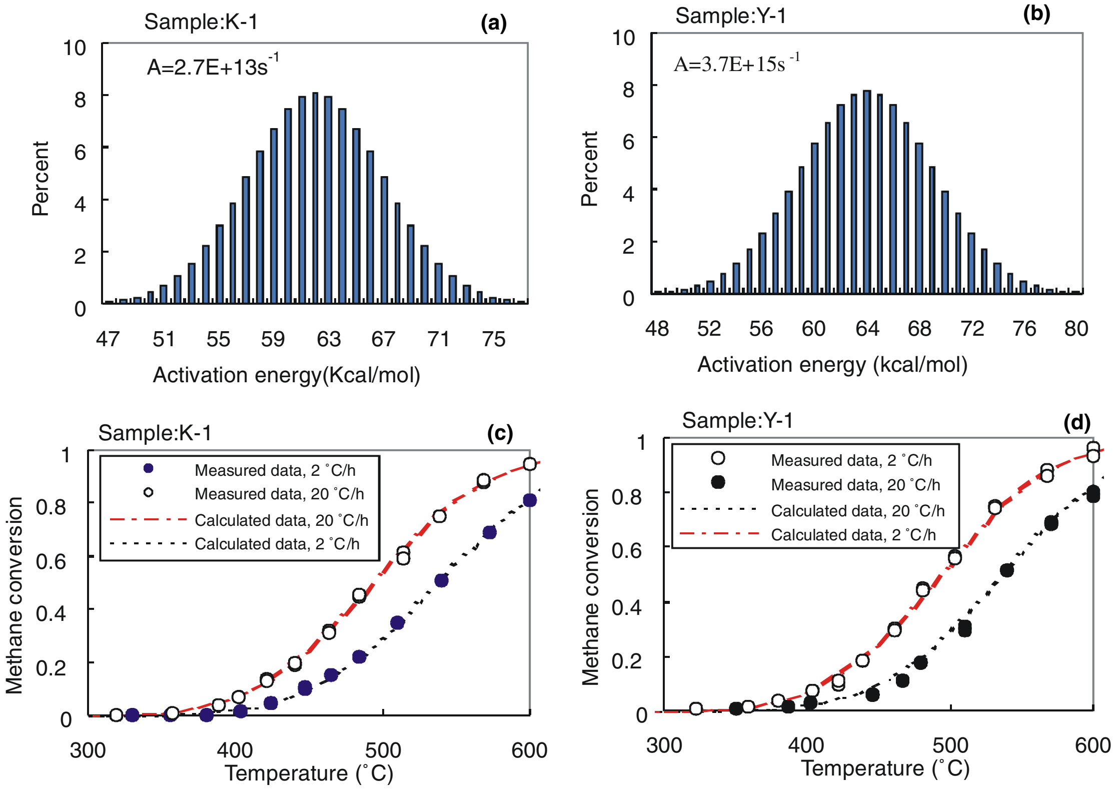

Fig. 4. Activation energy distribution (a and b) and fitted results of carbon isotope (c and d) for methane generation of the studied samples based on the gold tube pyrolysis experimental data at two different heating rates. The software Kinetics 2000 was used. See details in text.

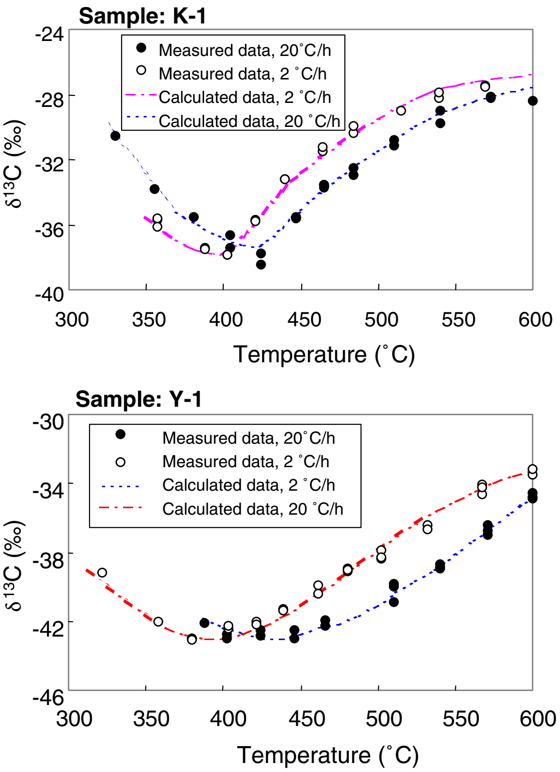

Fig. 5. Fitting of carbon isotopic fractionation of methane generated by the gold tube pyrolysis of the studied samples. The fitted parameters are presented in Table 4. See details in text.

The present geothermal gradient is in the range of 18–22 °C/km in the Kashi Depression (Dong et al., 1998; Liang and Zhang, 2001; Song and Zhao, 2001; Wang et al., 2002). A higher regional geothermal gradient of 25–35 °C/km has been proposed for the Late Paleozoic and Mesozoic (Liang and Zhang, 2001). In fact, it is difficult to determine accurately the geothermal gradient history of the area using the available geological and geochemical data as there are numerous uncertainties, including the estimation of the eroded thickness of Triassic and Upper Permian strata, and the possibility of an abnormal geothermal event. Xiao et al. (2003) applied a simplified paleogeothermal gradient pattern to model the thermal maturation levels for the source rocks using the Easy R_o method to obtain a reasonable result that agrees with measured R_o data. This model uses 30 °C/km during Carboniferous–Permian, 25 °C/km during Mesozoic, 22 °C/km during the early Tertiary, and 20 °C/km during the late Tertiary–Quaternary. We applied this simplified geothermal gradient model for reconstruction of the geothermal evolution of the source rocks in this study.

Estimated paleosurface temperatures for the Tarim Basin vary from 10 to 20 °C over its geohistory (Liang and Zhang, 2001). We used an average temperature of 15 °C as the paleosurface temperature to simplify the calculation.

Fig. 6 presents the burial history for two representative sites in the center of the Kashi Depression and in the lower block of the AK-1 overthrust structure. The Carboniferous strata underwent two periods of strong subsidence during early Carboniferous and late Tertiary–Quaternary.

As mentioned above, the AK-1 trap structure did not develop until the Pliocene (Fig. 3), thus the gas pool was formed at this time or later. Reservoir fluid inclusion data in combination with its thermal history also can constrain the time of formation of a gas pool. According to an investigation made by Xiao et al. (2002), the homogenization temperatures of aqueous fluid inclusions that are coeval with gas inclusions or gas-bearing inclusions can give a good indication of the temperature of a reservoir when gases charged it. Table 5 presents the homogenization temperatures of these aqueous fluid inclusions in some typical reservoir sandstone samples from the AK-1 gas pool. The temperatures are in the range of 60–85 °C, that is, 5–20 °C lower than the current temperatures of the corresponding reservoir. When interpreted with the geothermal history experienced by this reservoir, the formation time of the fluid inclusions in two representative samples taken from the reservoir was in the range of 3–5 Ma (Fig. 7). Thus, it is inferred that the AK-1 gas pool reservoir was charged by gases during this period.

4.4. Geochemical models of methane generation and carbon isotopic fractionation

Two representative points (the central area of the Kashi Depression and the lower block of the AK-1 overthrust structure) were selected for the geochemical

Table 4
Methane carbon isotope fractionation kinetics parameters of the studied source rocks

Sample No.	Methane carbon isotope fractionation kinetics parameters[a]					
	α	β_L (cal/mol)	β_H (cal/mol)	E_o (kcal/mol)	σ (kcal/mol)	γ
K-1	1.020	1.00	93.17	53.94	9.33	0.01094
Y-1	1.020	1.79	57.13	56.34	37.10	0.01088

[a] α = isotope fractionation factor; β_L = lowest activation energy difference; β_H = highest activation energy difference; σ = variance; E_o = average activation energy; γ = activation energy threshold (Tang et al., 2000).

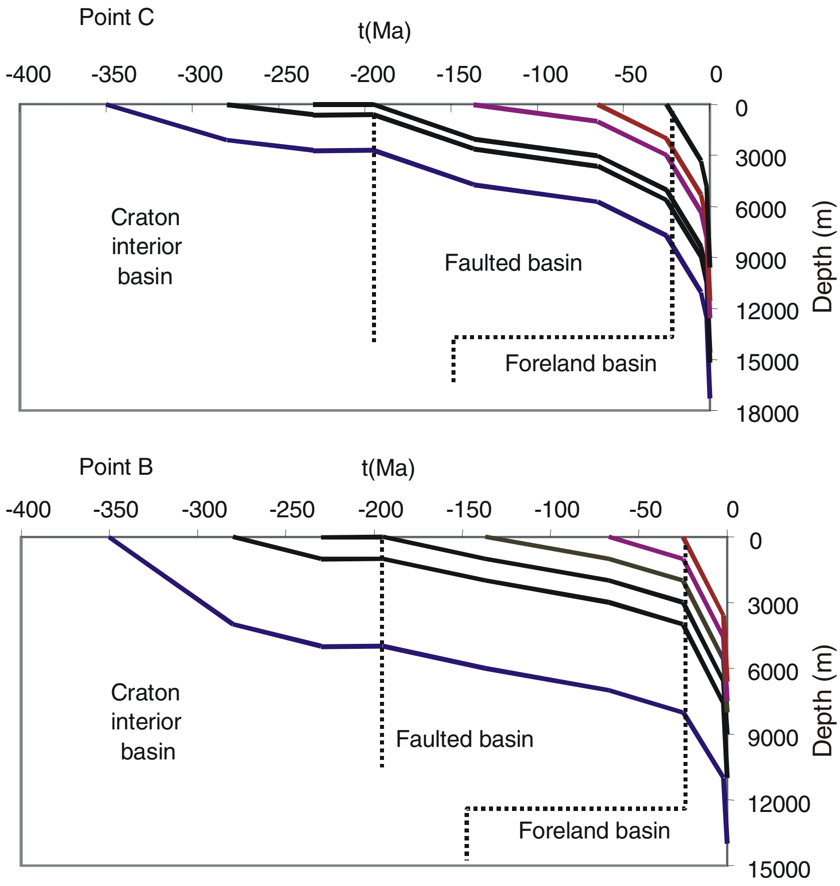

Fig. 6. Plot showing burial history of strata from two representative points. Point B: the lower block of the AK-1 overthrust structure; Point C: the center area of the Kashi Depression (Figs. 1 and 3). The stratigraphic data are after Petroleum Exploration and Development Institute of the Tarim Petroleum Institute, CNPC (2003). See details in text.

Table 5
Homogenization temperatures of fluid inclusions in reservoir sandstones from the AK-1 gas pool of the Tarim Basin

Well	Depth (m)	Age	Sample description	Type and occurrence of fluid inclusions	Homogenization temperatures (°C)[a]
AK-1	3326.7	Lower Cretaceous	Sandstone	Aqueous fluid inclusion, occurring in microfissure of quartz grain and associated with gas inclusions and/or gas-bearing inclusions	60–79/65
AK-1	3330.2		Sandstone		61–79/69
AK-1	3334.1		Sandstone		63–81/70
AK-1	3372.5		Sandstone		60–82/69
AK-1	3386.0		Sandstone		63–82/68
AK-1	3454.8		Sandstone		61–76/70
AK-1	3701.5		Sandstone		62–85/71
AK-1	3708.0		Sandstone		63–77/67

[a] Minimum–maximum/average.

models of methane generation and carbon isotopic fractionation of the two potential source rocks using the method described above. Figure 8 presents the results from the central area of the Kashi Depression. The main stage for methane generation from the Middle and Lower Jurassic coal measures occurred after 3.5 Ma with a cumulative $\delta^{13}C_1$ value of $-28.5‰$, lighter than the measured value of the gas from the gas pool. The main stage for methane generation for the Lower Carboniferous mudstone occurred after 50 Ma with a cumulative $\delta^{13}C_1$ value of $-31.5‰$. Much of this gas is unavailable, as the structural history and fluid inclusion evidence indicate that the trap structure of the AK-1 gas pool formed at about 5 Ma. The $\delta^{13}C_1$ value for gas

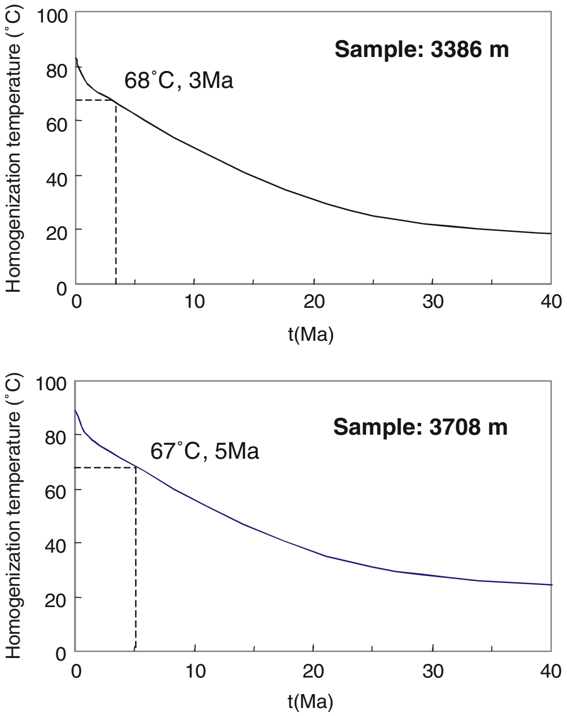

Fig. 7. Plot showing the formation time of fluid inclusions in the reservoir sandstone from the AK-1 gas pool. The fluid inclusions are associated with gas or gas-bearing inclusions. The stratigraphic data are after Petroleum Exploration and Development Institute of the Tarim Petroleum Institute, CNPC (2003), and the paleogeothermal gradient was described in the text.

generated from Lower Carboniferous mudstone that is trapped would be expected to be about −14‰, which is much heavier than that of the field gas. Thus, based on the models, neither the Lower Jurassic nor the Carboniferous strata from the central area of the Kashi Depression can be single sources of the trapped gases.

Figure 9 presents the modeling results for the lower block of the AK-1 overthrust structure. The Jurassic coal measures have a much lower maturation level with a methane fractional conversion of 0.135, and the generated gas yield $\delta^{13}C_1$ values in the range of −38.5‰ to −36.0‰, much lighter than that of the field gas. However, the Lower Carboniferous mudstone generated gas much earlier, with the main stage of gas generation occurring during 2–20 Ma and a current methane conversion fraction of 0.99. Assuming this area was the gas source, the model indicates that the gas trapped after 5 Ma had a stage cumulative $\delta^{13}C_1$ of −26.5‰, very close to the field gas value. On the basis of this analysis, the Lower Carboniferous mudstone from the low block of the AK-1 overthrust structure would have to be favored to be the main gas source area of the gas pool. However, the single source model can not explain the inorganic origin of the CO_2 and high content of N_2 as these strata experienced a maximum paleotemperature of 250–280 °C, lower than the threshold decomposition temperature of carbonate minerals and formation temperature of gas rich in N_2, both of which are over 300 °C under geological conditions (He, 1995; Krooss et al., 1995; Sun and Guo, 1998; Huang et al., 2002, 2004). Thus, the gas from the AK-1 gas pool appears to be of mixed origin.

4.5. *Integrated geochemical–geological models of gas accumulation in the AK-1 gas pool*

Although the gas in the AK-1 structure appears to be derived from multiple sources, the Jurassic coals and coal measures, either in the overthrust block or in the Kashi Depression, are not believed to have contributed to the reservoir charge. The geochemical modeling indicates that the Jurassic sources in the overthrust block are insufficiently mature and would produce a gas with obviously different composition and carbon isotopic value from the AK-1 gas pool. Mixing of cumulative gas from Jurassic sources and partly accumulated gas generated later from Lower Carboniferous sources in the central area of the Kashi Depression could produce methane with the observed $\delta^{13}C_1$ values. However, it is hard to explain the fact that the field gas lacks heavier hydrocarbon components with $C_2 + C_3$ less than 0.3% and no C_4. Geologic constraints limit gas migration from Jurassic sources in the central area. Two rows of anticlinal structures developed between the AK-1 trap structure and the central area of the Kashi Depression, and the gas generated from the Jurassic source rocks could not have migrated from the center to the trap owing to a shallower burial of the source rocks and lack of sufficient fluid migration force (Figs. 1 and 3).

Only one geological model can explain the geochemical characteristics of the AK-1 gas pool, i.e. the source rock is the Lower Carboniferous mudstone from the lower block of the AK-1 overthrust structure and the central area of the Kashi Depression. The former is the main gas source area, and the latter the secondary gas source area. The contribution of the two source areas to the gas pool can be evaluated using the geological models of methane generation and carbon isotopic fractionation of the Lower Carboniferous source rock. As pointed out above, when the gas pool began to be charged at about 5 Ma, the Lower Carboniferous mudstone from the central area of the Kashi Depression had already matured to a methane conversion of 0.93, and it could only generate a small amount of dry gas after 5 Ma (Fig. 8). However, the situation in the lower block of the AK-1 overthrust structure was quite different. The source rock was in the main stage of gas generation at 5 Ma with a methane conversion of 0.64, and the $\delta^{13}C_1$ value of the cumulative gas from this source area

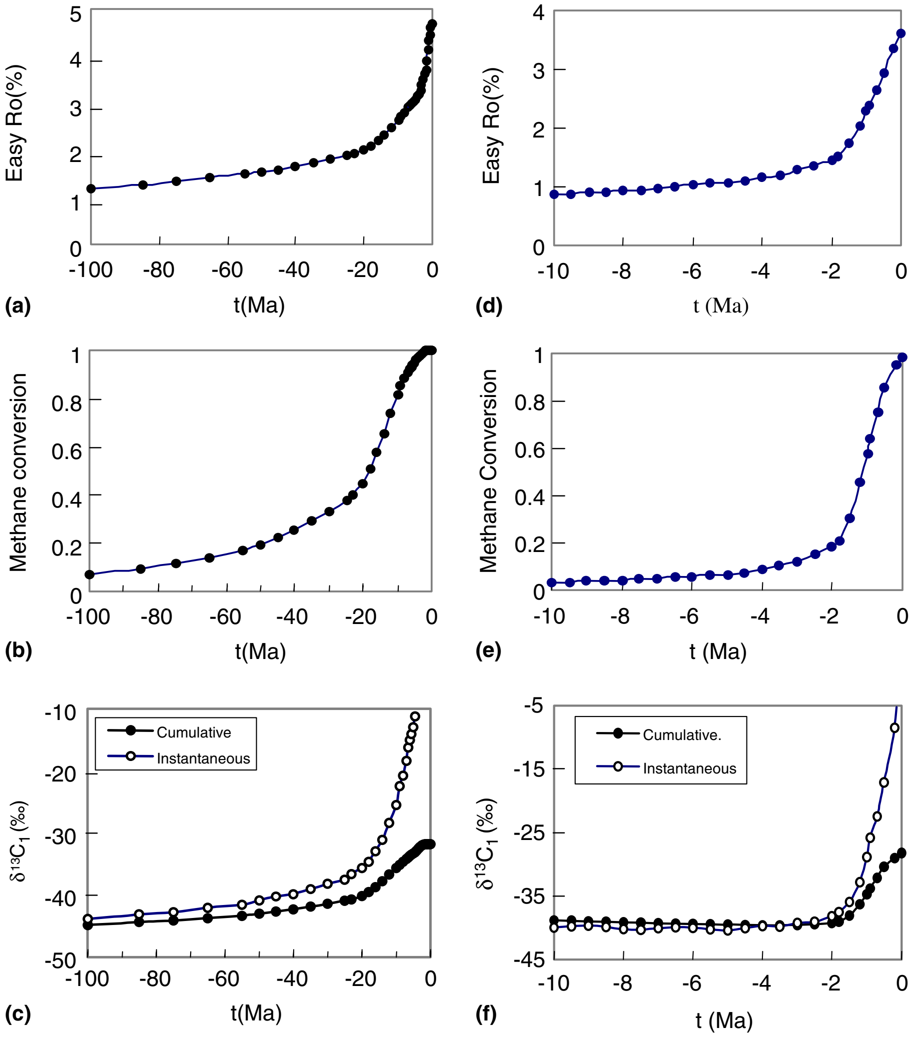

Fig. 8. Thermal maturation evolution and geological models of methane generation and methane carbon isotopic fractionation for two source rocks from the Kashi Sag center based on the kinetics modeling from this study. (a)–(c): lower Carboniferous source rock; (d)–(f): middle and lower Jurassic coal measure source rock. See details in the text.

after 5 Ma was −26.6‰ (Fig. 9), only slightly lighter than that of the field gas, indicating the main hydrocarbon gas source position. A mixing of gases from the two source areas can form a gas with a $\delta^{13}C_1$ value that perfectly matches the field data.

This gas source model is consistent not only with the gas generation history of the source rock, but also can explain the characteristics and origin of the non-hydrocarbon gases. The burial depth of the Lower Carboniferous strata reached 12,000–17,500 m in the central area of the Kashi Sag. A maximum paleotemperature of the source rock from the central area of the Kashi Depression reached 300–365 °C during the Pliocene–Quaternary, enabling late stage pyrolysis of the kerogen to generate methane and N_2 (Littke et al., 1995; Krooss et al., 1995), and decomposition of carbonate minerals in the Carboniferous strata to produce inorganic CO_2 (Cathles et al., 1990; Jenden et al., 1988; Li et al., 2001). These gases were then trapped in the pool.

According to the migration and accumulation model of the AK-1 gas pool discussed above, the gas can be regarded as a late stage cumulative gas. The gas accumulation efficiency from the main source area of the low block of the AK-1 overthrust structure can be evaluated using the geological model of the methane carbon isotopic fractionation presented in Fig. 10 (Rooney et al., 1995; Cramer et al., 2001). The AK-1 gas pool trapped the gas from the source rock with a methane fractional conversion of 0.64–1.0 and missed the methane generated at lower degrees of conversion since the trap structure had not been formed during this period.

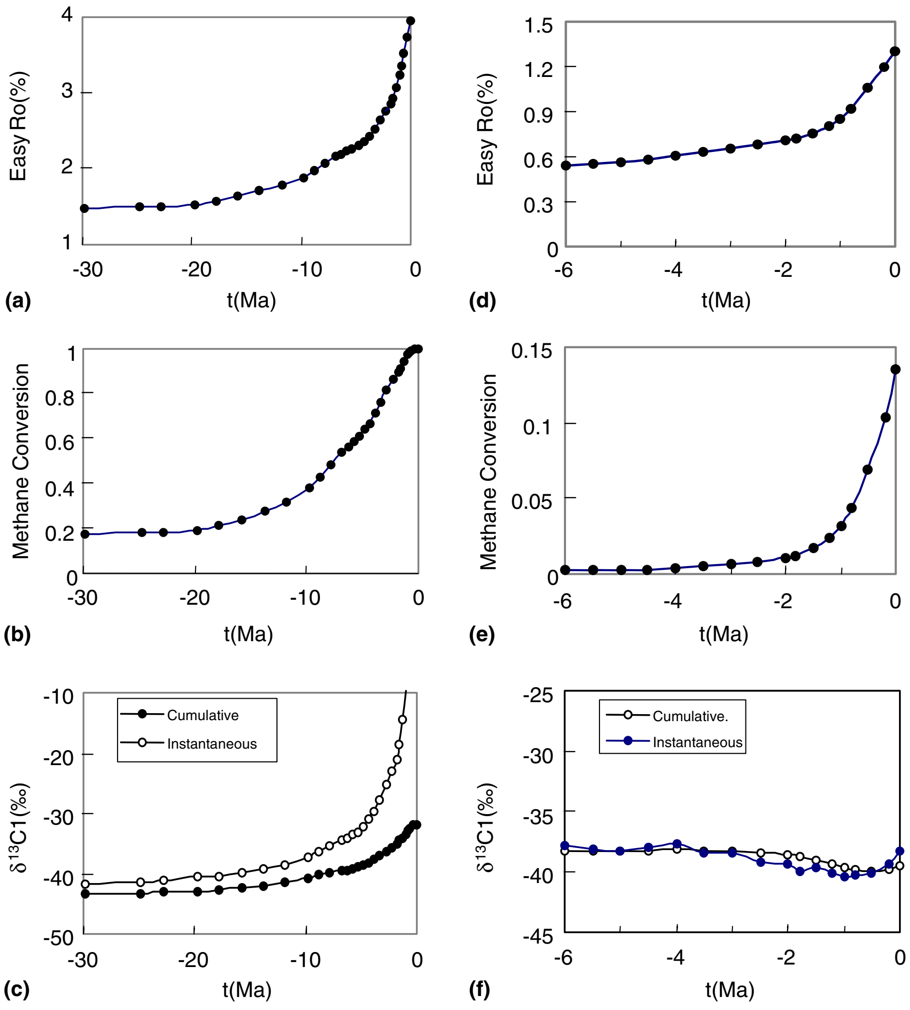

Fig. 9. Thermal maturation evolution and geological models of methane generation and methane carbon isotopic fractionation for two source rocks from the lower block of the AK-1 overthrust structure based on the kinetics modeling from this study. (a)–(c): lower Carboniferous source rock; (d)–(f): middle and lower Jurassic coal measure source rock. See details in the text.

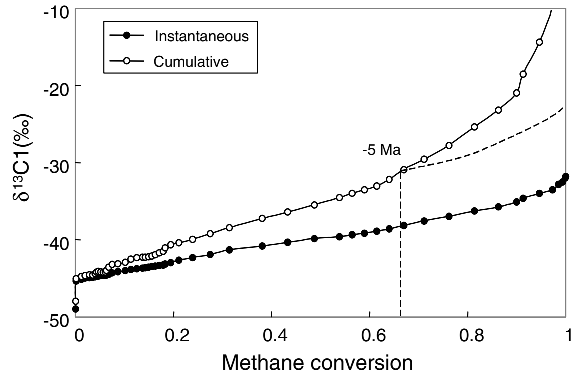

Fig. 10. Gas accumulation efficiency of the AK-1 gas pool for the lower Carboniferous source rock from the main source area of the lower block of the AK-1 overthrust structure. This method is after the Rooney model (Rooney et al., 1995; Cramer et al., 2001).

A comparison of the AK-1 gas model with the gas field in NW Germany (Cramer et al., 2001) highlights the need to interpret isotopic values within a geological and chemical modeling framework. Gases from the two gas pools have very similar methane and ethane isotopes with characteristics of late stage cracking of kerogen or coal. The NW Germany gas pools were generated from Carboniferous coals and represent the late stage accumulative gas from a second Tertiary maturation phase after an uplift and degassing event in the Jurassic–Cretaceous (Cramer et al., 2001). Our studies show that the AK-1 gas pool was generated from Carboniferous mudstone and not from an associated Jurassic coal and the structure only trapped late stage gases. Hence, while the AK-1 gas pool exhibits some characteristics of coal-generated gas, it originates from a non-coal measure source rock.

5. Conclusion

An investigation of the geochemical and geological characteristics of the gas from the AK-1 gas pool in the Tarim Basin, and the geological models of methane generation and carbon isotopic fractionation of typical source rocks leads to the following conclusions:

1. The gas pool is characterized by a very dry hydrocarbon gas with an average dryness index >0.995, a very heavy methane carbon isotopic value with an average $\delta^{13}C_1$ of 25‰, a lighter $\delta^{13}C_2$ value with an average of $\delta^{13}C_2 - \delta^{13}C_1$ of 3.9‰, and a high content of non-hydrocarbon components up to 20% $N_2 + CO_2$.
2. The hydrocarbon gases show some characteristics of a mixed source origin and the CO_2 component is of both organic and inorganic origin. The source rock of the gas pool is the Lower Carboniferous mudstone from the lower block of the AK-1 overthrust structure and from the central area of the Kashi Sag. The former is the main source of hydrocarbon gas, and the latter contributed N_2, and inorganic origin CO_2 and a small amount of methane.
3. The gas pool was formed during the Pliocene–Quaternary. The gas can be regarded as a late stage cumulative gas, as it accumulated from the source rock with a methane fractional conversion of 0.64–1.0.

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