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Gas systems in the Kuche Depression of the Tarim Basin: Source rock distributions, generation kinetics and gas accumulation history

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Abstract

Six petroleum source beds have been developed in the Kuche Depression (also known as "Kuqa Depression") of the Tarim Basin, including three lacustrine source rocks (Middle and Upper Triassic Kelamayi and Huangshanjie formations, and Middle Jurassic Qiakemake Formation) and three coal measures (Upper Triassic Taliqike Formation, Lower Jurassic Yangxia Formation, and Middle Jurassic Kezilenuer Formation). While type I–II organic matter occurs in the Middle Jurassic Qiakemake Formation (J_2q), other source beds contain dominantly type III organic matter. Gas generation rates and stable carbon isotopic kinetics of methane generation from representative source rocks collected in the Kuche Depression were measured and calculated using an on-line dry and open pyrolysis system. Combined with hydrocarbon generation history modelling, the formation and evolution processes of the Jurassic–Triassic highly efficient gas kitchens were established. High sedimentation rate in the Neogene and the fast deposition of the Kuche Formation within the Pliocene (5 Ma) in particular have led to the rapid increase in Mesozoic source rock maturity, resulting in significant dry gas generation. The extremely high gas generation rates from source kitchens have apparently expedited the formation of highly efficient gas accumulations in the Kuche Depression. Because different Mesozoic source rocks occur in different structural belts, the presence of both lacustrine and coaly gas kitchens during the Cenozoic time can be identified in the Kuche Depression. As shown by the chemical and stable carbon isotope compositions of the discovered gases, the formation of the giant gas pools in the Kela 2, Dina 2, Yaha and Wucan 1 have involved very different geological processes due to the difference in their gas source kitchens.

1. Introduction

The amount of oil and gas generated from source kitchens that can be preserved in current reservoirs

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determines not only the reserves that are potentially available in a basin, but also the risk of various exploration scenarios. The earliest concept of "hydrocarbon kitchen" for characterizing the nature and distribution pattern of source rocks was proposed by Thomas et al. (1985). These authors systematically integrated the Upper Jurassic hydrocarbon kitchens, oil and gas migration pathways and directions in northern part of the Viking Graben of the North Sea. Their research dealt with the location and distribution of hydrocarbon kitchens, hydrocarbon (oil and gas) generation intensities from source kitchens, amount of hydrocarbons generated at different geological periods, and accumulated reserves in play zones. Demaison (1984) and Demaison and Huizinga (1991) suggested that identification and location of hydrocarbon kitchens were crucial to oil and gas exploration. As the characterization of hydrocarbon kitchens is fundamental in oil and gas system analysis, the following four facets have been incorporated into the standard routines of PetroChina's natural gas exploration programs: (1) organic facies of source rocks, including source rock location, organic richness, organic type, thickness and spatial distribution; (2) source rock maturity and thermal evolution history; (3) quantities of gas generated at different geological time, derived from source rock burial and thermal history, chemical kinetic calculation of hydrocarbon generation, gas kitchen extents at different geological time and gas generation intensities; and (4) gas emplacement time, derived from gas chemical and stable carbon isotopic compositions.

In the past decade, great breakthroughs have been made in the oil and gas exploration in the Kuche Depression of the Tarim Basin, NW China, with the discovery of a number of giant and medium-sized gas fields in the Kelasu – Yiqikelike and Qiulitake structural belts. The large proven gas reserves in the Kuche Depression were critical to the construction of over 4000 km of *trans*-China gas pipelines that transmit the natural gases in western China to industrial and populous eastern China (Jia et al., 2000, 2001). Understanding the factors controlling the development of oil and gas systems in the Kuche Depression will be helpful for reducing the exploration risk not only in future activities in the Kuche Depression, but also for other foreland basins with similar geological settings.

Several PetroChina in-house studies have examined the geochemical characteristics of Mesozoic source rocks in the Kuche Depression. It appears from these studies that the Triassic and Middle-Lower Jurassic strata contain significant source rock intervals, but detailed data of organic facies, source rock distribution, thermal maturity, hydrocarbon generation history, and relationships between source rock area and petroleum accumulation were scarce, due to relatively limited well coverage. Circumstantial evidence was presented earlier to show the importance of Middle-Lower Jurassic coal measures as gas source rocks in the Kuche Depression (Dai et al., 2000; Liang et al., 2003; Sun et al., 2001, 2004). In the context of the China 973 National Research and Development Program, every facet of the gas kitchens in the Kuche Depression has been re-examined in order to gain further insight into the geological controls involved in the formation of highly efficient gas accumulations. The objective of the present manuscript is to present a brief synthesis and overview on the current status of our knowledge on the natural gas systems in the Kuche Depression.

2. Geological background

The Kuche Depression is a Mesozoic foreland basin located in the northern part of the Tarim Basin, NW China. It has experienced three evolution phases: a foreland basin during the Late Permian to the Triassic, a continental depression during the Jurassic, and a rejuvenated foreland basin from the Cretaceous to Quaternary age (Jia et al., 2002). This depression consists of three sags, Yangxia, Baicheng and Wushi from east to west (Fig. 1).

During the Late Triassic to Middle Jurassic, the present Kuche Depression area was at the structural extensional stage (Jia et al., 1995), with a warm and humid climate. At the time, coal-bearing sediments were prevailing in the entire Central Asian region, with more than 1000 m of lacustrine and marginal lacustrine–swamp transitional sediments being deposited in the Kuche Depression. Three structural/depositional evolution cycles can be recognized from the stratigraphic column (Fig. 2). The first source rock depositional cycle comprises the Middle-Upper Triassic Kelamayi Formation (T_{2-3}-k_3), the Upper Triassic Huangshanjie T_3h) and Taliqike formations (T_3t). The structural style shifted from a deep, steep faulted boundary in the north and a shallow, gentle overlapping in the south to a structurally stable and topographically flat depression. Concurrently the depositional environments in the area shifted from a shallow–semi-deep–deep

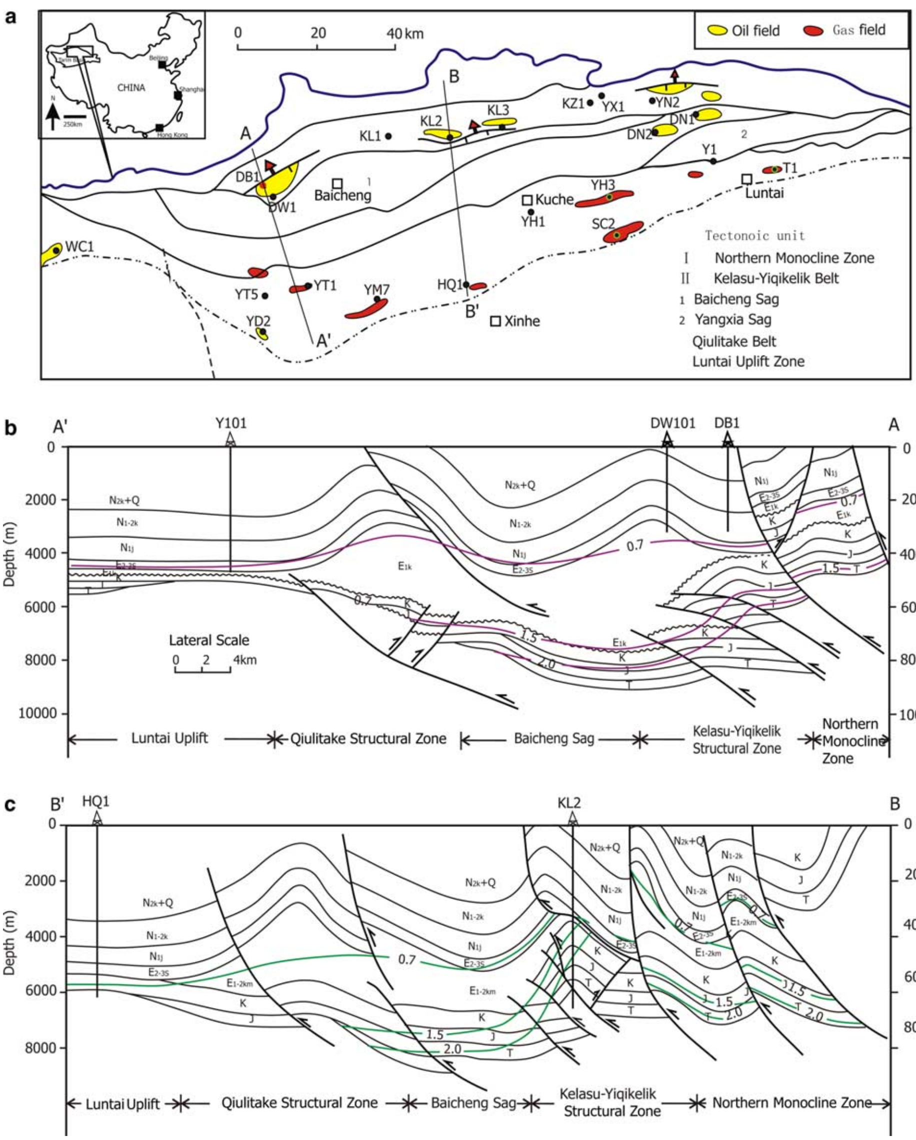

Fig. 1. Map showing the structural elements and oil and gas field distribution in the Kuche Depression of the Tarim Basin (a) and representative structural cross-sections (b and c).

lake to transitional swamp-lacustrine settings. The second source rock depositional cycle consists of the Jurassic Yangxia (J_1y) and Kezilenuer formations (J_2k). The structural/topographic evolution showed intensive to weak transitional features, while the sediments were deposited in alternate deltaic-swamp and lacustrine settings. As a result, the stratigraphic correlation marker band in the Yangxia Formation represents the peak lacustrine deposition. The Middle Jurassic Qiakemake Formation (J_2q) was formed in the third source rock depositional cycle. The structural style in the study area shifted from a rift to a depression and the climate changed from warm and humid to hot and dry. Thus, the source rocks are thin, with only of limited aerial extent.

The major petroleum source rocks in the Kuche Depression were developed in the Triassic and the Middle-Lower Jurassic strata. The lacustrine source rocks occur in the Middle-Upper Triassic Kelamayi Formation ($T_{2\text{–}3}k_3$), the Upper Triassic Huangshanjie Formation (T_3h), and Middle Jurassic Qiakemake Formation (J_2q). In contrast, coaly source rocks are distributed in the Upper Triassic

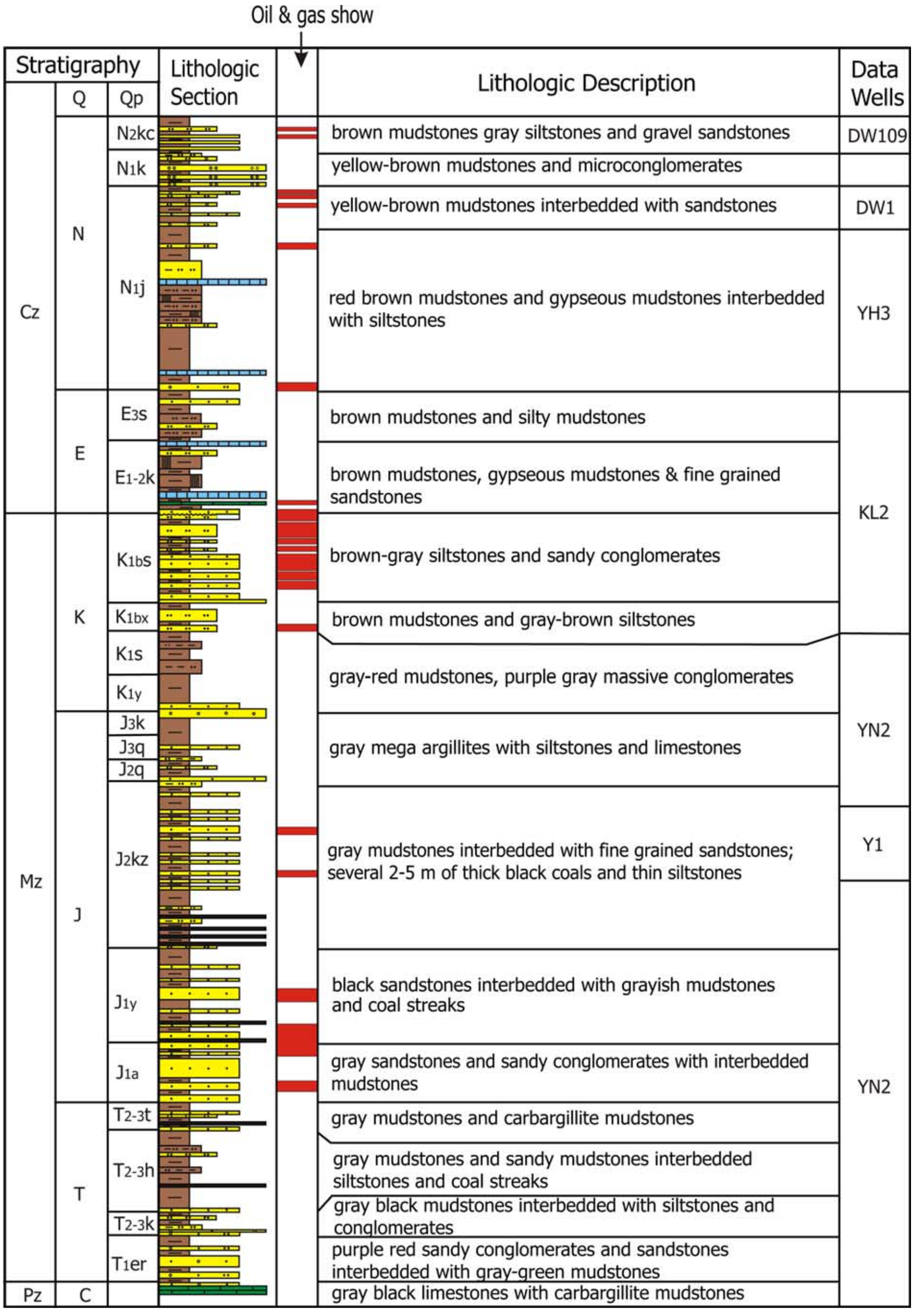

Fig. 2. Generalized stratigraphic column of the Kuche Depression.

Taliqike Formation (T_3t), Lower Jurassic Yangxia Formation (J_1y) and Middle Jurassic Kezilenuer Formation (J_2k, Fig. 2). Type I and II organic matter occurs only in the Middle Jurassic Qiakemake Formation (J_2q), while the other source rocks contain dominantly type III organic matter.

Regional uplift in the Kuche region began in the Late Cretaceous, with the Yiqikelike and Tugerming anticlines being initiated under the horizontal compressional stress. By the end of Paleogene, the northern Tarim Basin was uplifted to form the Tianshan Mountain belts due to the collision of the Indian and Qinghai–Tibet plates. A consequence was the rapid rising of the Tianshan Mountains and the accumulation of thick reddish continental sediments in the frontal depressions.

Since the Miocene, the neotectonic deformation has shifted from the north to south, leading to progressive thrust structures and various fault-related folds. The earliest structural deformation occurred in the Misibulake Anticline of the Jiesidelike anticlinal zone in northern Kuche, while Kelasu–Yiqikelike structural belt was formed slightly later. Structural activity was persistent during the deposition of the Miocene Kuche (N_2k) and Quaternary Xiyu formations (Q_1x). The Kalabahe, Kumugeliemu and Bashijiqike anticlines were formed earlier than the Kasangtuokai and Kelasu anticlines (Lu and Jia, 2003; Fig. 3).

Recent gas exploration in the Kuche depression has been very successful, with the discoveries of Kela 2 (KL2), Dabei 1 (DB1) and Yinan 2 (YN2) gas fields in the thrust zones, and Dina 2 (DN2) and Wucan 1 (WC1) gas fields along the depression margins, and Yudong 2 (YD2), Yangtake (YT), Yingmai 7 (YM7), Yaha (YH) and Tiergen gas fields in the frontal uplifts (Fig. 1). The gases occur in all of the Mesozoic–Cenozoic strata in the Kuche Depression, but the main payzones are located in the sandstone reservoirs of the Paleogene, Cretaceous and Lower Jurassic Ahe Formation, with the Tertiary evaporitic gypsum bearing mudstones acting as a regional seal. Commercial gas reserves occur largely in the Kelasu, Yiqikelike and Qiulitake structural belts and Luntai faulted uplift in northern Tarim Basin (frontal uplift zone) (Fig. 1(b) and (c)). The oil and gas fields form circles surrounding the Kuche Depression, with the deep gas pools in the inner circle (near source kitchens) and shallow condensate pools in the outer ring. As shown in Fig. 1(a), the outer circle includes the Heiyingshan, Yiqikelike, Tugeerming, Hongqi and Yingmaili structures dominated by oil accumulations; the middle circle includes the Luntai, Yaha, Yangtake and YD2 structures dominated by condensates, and the inner cycle consists of DB1, KL2 and YN2 dominated by gas accumulations.

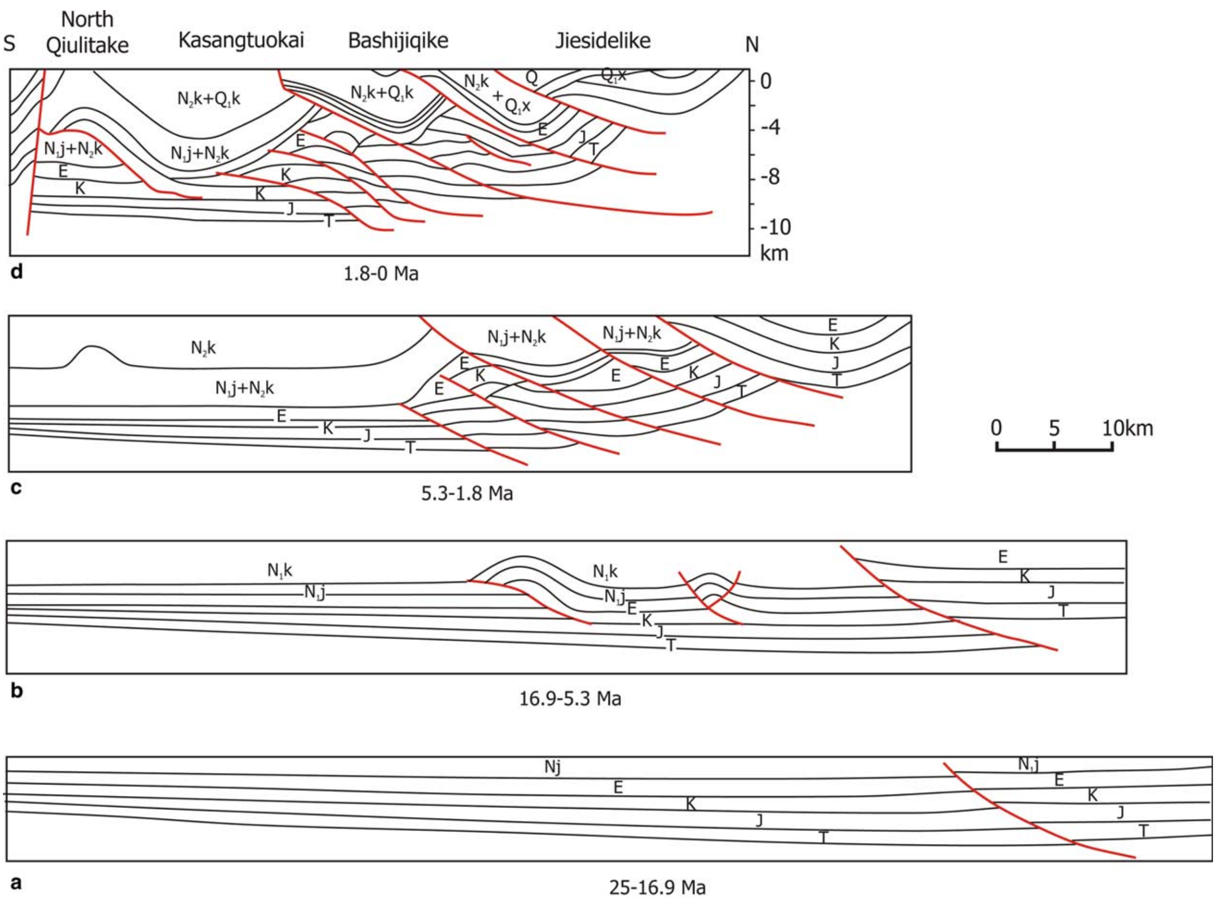

Fig. 3. Reconstructed structural cross-sections of the Kuche Depression at different geological times.

3. Methodologies

3.1. Source rock characterization

The total organic carbon contents of source rock samples (TOC) were measured using a Leco IR-112 elemental analyser, after the removal of carbonate mineral from rock samples with hydrochloric acid (HCl). The hydrocarbon generation potential of the samples was analysed using a Rock-Eval III instrument following the analytical and data interpretation scheme described by Espitalié et al. (1977) and Peters (1986).

3.2. Vitrinite reflectance measurement

Vitrinite reflectance was measured on polished whole rock section using a MPV-SP microscopic photometer. The ISO standard was applied for vitrinite reflectance measurement while using MPV-GEOR program that is compatible with Windows Process System.

3.3. Pyrolysis experiments simulating hydrocarbon generation rate and gas carbon isotopic kinetics

Several heating rates ranging from 0.1 to 5.0 °C/min were used to simulate hydrocarbon generation rate. An open pyrolysis system was used, following the methodologies described in Littke et al. (1995) and Krooss et al. (1995). Detailed experimental conditions and chemical kinetics parameter acquisition procedures were the same as those reported by Cramer et al. (1998, 2001). The studied source rock sample was collected from a coalmine in the Kuche Depression. The sample belongs to the Lower Jurassic Yangxia Formation, with a vitrinite reflectance of 0.70 %Ro and the stable carbon isotope value of the isolated kerogen sample from this rock is −22.7‰ versus PDB.

3.4. One-dimensional basin modeling

One dimensional hydrocarbon generation history modelling was performed using the Basin Mod-1D software, calibrated with detailed stratigraphic and paleo-geotemperature data. The LLNL model was selected for vitrinite reflectance chemical kinetics modelling (Burnham and Sweeney, 1989; Sweeney and Burnham, 1990). In this study, both exploration and pseudo wells were adopted. Data of exploration wells were provided by the Research Institute of Tarim Oilfield Company (1998) and Geological Research Centre of Petroleum Geophysical Research Institute (1999). Data of 220 pseudo wells were compiled during the course of this study, based on 12 N–S trending seismic cross-sections. Erosional thickness in the studied wells was estimated based on earlier work (internal RIPED reports). The present-day and paleo geothermal parameters were based on Wang et al. (1999, 2005). The present-day geothermal gradients in the study area decrease from 26–28 °C/km near the mountain front to 18–20 °C/km in the foreland depression areas.

4. Results and discussion

4.1. Source rock distribution and organic facies

The study of the source rock distribution and sedimentary organic facies was based on samples collected from nine outcrop sections, nine exploration wells, and seismic cross-sections. As shown by Rock-Eval pyrolysis data in Fig. 4, type I–II organic matter occurs only in the Middle Jurassic Qiakemake Formation (J_2q), while other potential source beds in the Kelamayi (T^3_{2-3k}) and Huangshanjie formations (T_3h) are dominated by type III organic matter (Liang et al., 2003).

The Kelamayi and Huangshanjie formations (T_3h), about 300–450 m in thickness, were deposited in lacustrine settings, with 0.5–3.5% TOC. As shown in Fig. 5(a), thick mudstones occur near the mountain front in the north, thinning southward. In the depocenters near the Kapushaliang and Kuche river profile, these units reach maximum thicknesses of 434 and 444 m, respectively. The thickness of source strata declined both southward and northward away from these two outcrop profiles, but the overall distribution pattern was thinning southward with a steep boundary in the north and gentle slope in the south (Fig. 5(a)).

The Taliqike Formation (T_3t) was deposited in a swamp to shallow lacustrine setting, with dominantly terrestrial organic matter. The thickness of source rocks in this formation is rather stable, approximately 55, 46, 72 and 44 m at the Kapushaliang River, Kelasu River, Kuche River sections and the Yinan 2 well location, respectively. The depocenters began in the western side of the Kuche Depression, with a source rock thickness of 160 and 210 m at the Takelaka and Xiaolantai River sections, respectively. According to seismic strati-

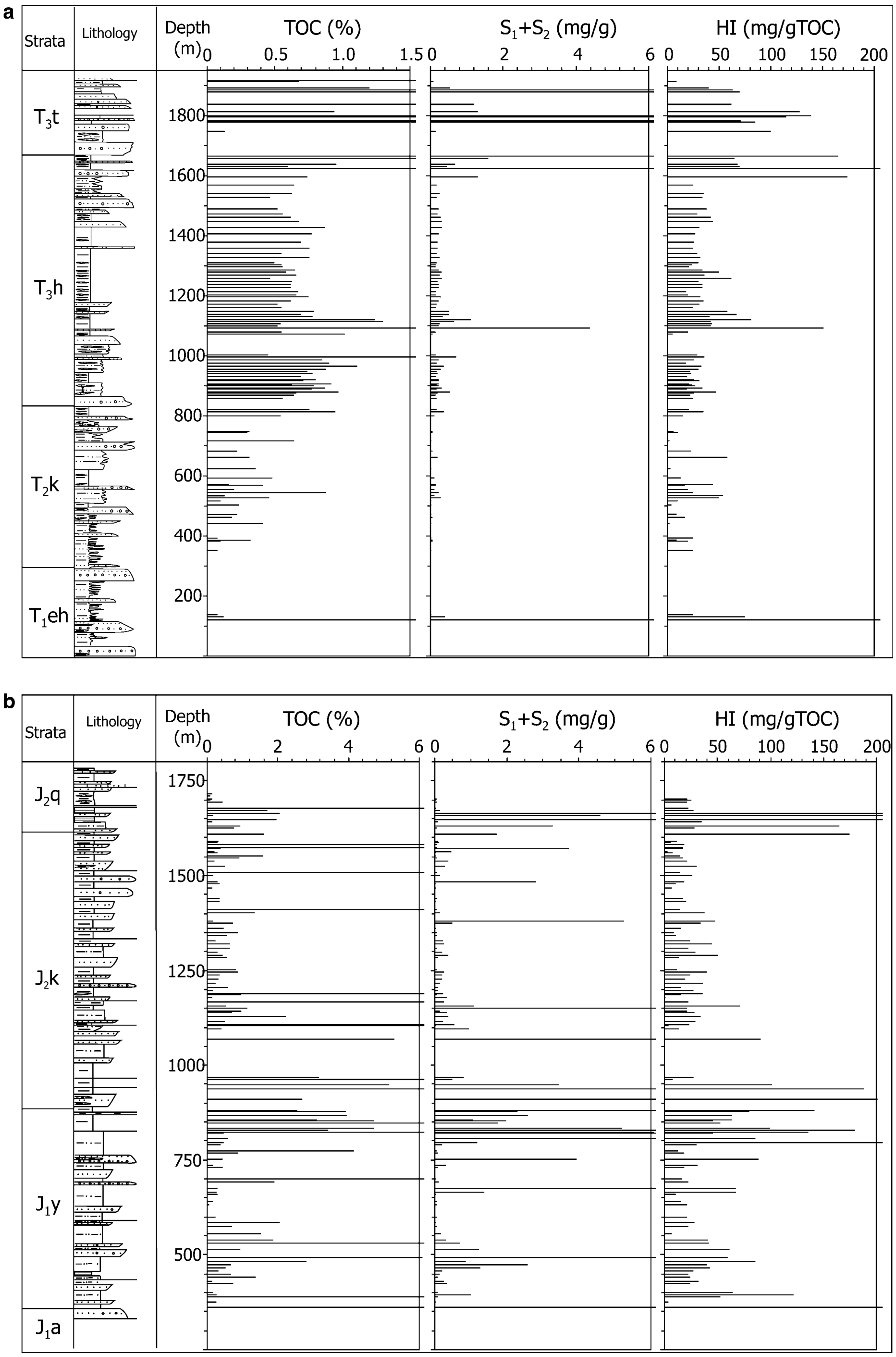

Fig. 4. Rock-Eval pyrolysis data of potential source rocks collected from the Kuche River section.

graphic data, the depocenters gradually shifted east toward the Dabei 1 well location and then Baicheng area. Relatively stable structural evolution and flat topography were possibly responsible for the stable distribution of source rocks in the Taliqike Formation of the Kuche Depression.

Source rocks in the Jurassic Yangxia (J_1y) and Kezilenuer formations (J_2k) consist of coals and

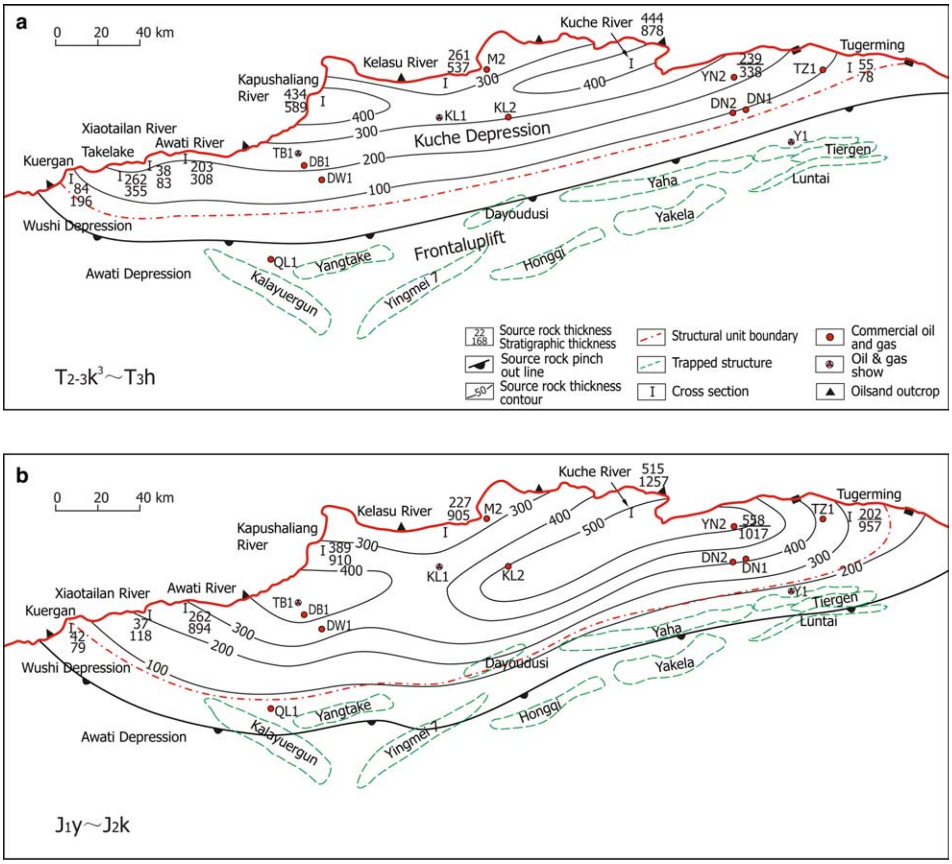

Fig. 5. Contour maps of the Middle-Upper Triassic (a) and Middle-Lower Jurassic strata (b) in the Kuche Depression (unit: m).

carbonaceous shales, deposited in delta plain, prodelta, fluvial plain, swamp to shallow lacustrine settings. These rocks, 200–560 m in thickness (Fig. 5(b)), contain dominantly type III organic matter. These rocks occur within two depocenters separated by an underwater uplift located in the Kelasu River area. The first depocenter is near the Kela 2 well – Kuche River – Yinan 2 well, with 515–558 m of the J_1y and J_2k sediments in the east. The other depocenter is close to the Kapushaliang River – Laohutai area in the west, with 400 m of J_1y and J_2k sediments.

The only source rocks that contain type I and II organic matter in the Kuche Depression are black shales and mudstones in the Middle Jurassic Qiakemake Formation (J_2q). These rocks, 50–150 m in thickness, were deposited in shallow to semi-deep lacustrine environment, occurring mainly in the mid-western part of the depression. The TOC contents range from 0.5% to 5.5%. The two depocenters were close to Awate River-Dabei 1 well–Kela 2 well areas, separated by an underwater uplift in the Kelasu River area. The J_2q source rock contours wedge out from the depocenters, with the maximum deposition of 155 m near the Awate River area.

Generally, the Kelamayi (T_{2-3k}), Huangshanjie (T_3h) and Qiakemake formations (J_2q) are dominated by lacustrine sediments. While the Taliqike Formation (T_3t), the Yangxia Formation (J_1y) and Kezilenuer Formation (J_2k) are coal measures. The coal beds are mainly developed in the Middle-Lower Jurassic Yangxia and Kezilenuer formations, about 50 m in the YN2 well location and thinning toward southwest. Compared with the adjacent Turpan Basin, the Mesozoic source rocks in the Kuche Depression contain thinner coal beds, with higher proportions of lacustrine sediments. Vertically, the TOC contents generally increase upward in the Triassic section, while high values are often observed in the Jurassic Yangxia and Kezilenuer formations. As most of these rocks contain dominantly type III organic matter (Table 1), they are generally gas-prone, with the exception of some oil-prone rocks in the upper part of the Middle

Table 1
Thickness and hydrocarbon source potential of the Mesozoic source rocks in the Kuche Depression

Strata	Thickness (m)	TOC (%)	S1 + S2 (mg/g)	Hydrogen index (mg/g)	T_{max} (°C)	Extract (mg/g rock)	Extractable HCs (mg/g rock)
Qiakemake (J_2q)	0–155	1.54 (44)[a]	3.09	109	449	1.151 (10)	0.420
Kezilenuer (J_2k)	32–320	2.15 (195)	2.67	82	447	0.401 (22)	0.172
Yangxia (J_1y)	37–238	2.58 (171)	3.20	90	462	0.550 (23)	0.221
Taliqike (T_3t)	6–210	2.35 (67)	1.57	47	484	0.148 (4)	0.063
Huangshanjie (T_3h)	38–444	1.03 (246)	0.58	29	510	0.149 (21)	0.045

[a] Number in the bracket shows the number of samples measured.

Jurassic Qiakemake Formation. Laterally, both the Triassic and Jurassic source rocks become thicker westwards. Although no significant variation in the TOC content of the Qiakemake Formation source rocks was observed from the Kuche River to Awate River area, hydrocarbon generation potential decreases dramatically westward as the maturity level of the rocks increases.

4.2. Thermal maturation as a function of time

Because of the presence of reverse faults and salt beds in the Kuche Depression, a special one-dimensional model was developed to calculate the effects of fault activities and salt flow events on burial and hydrocarbon generation histories. Serious inconsistency would arise between calculated maturity value and geological evolution history without considering these factors in modelling (Brewer, 1981; Edman and Surdam, 1984; Deming and Chapman, 1989). In the Kuche Depression, the variability of formation thickness caused by thrust faults or salt flow occurred mainly in the recent 5 Ma (Tang et al., 2004). Measured vitrinite reflectance, homogenization temperatures of saline water fluid inclusion and apatite fission track data were used to calibrate the LLNL kinetic model and parameters (Platte River Associates Inc., 2001).

The total thickness of the Mesozoic sediments deposited over 180 Ma in the Kuche Depression is less than 3200 m (with a maximum thickness of 3700 m before compaction). The average depositional rate in the Mesozoic was only around 0.02 mm/year. The brief uplift during the Late Cretaceous eroded the top of the Upper Cretaceous strata. The 'revival' of the orogenic belts of the Tianshan Mountains and the rapid subsidence of the rejuvenated Kuche foreland basin during the Neogene-Quaternary led to 4700 m of red beds within about 23 Ma. These include 2500 m of Pliocene and younger sediments (0–5 Ma). Thus, the average depositional rate in the Neogene was 0.2 mm/year, and up to 0.5 mm/year in the Pliocene.

The measured vitrinite reflectance values of the Triassic and Jurassic rocks in the Kuche Depression ranges from 0.56 to 2.30 %Ro, decreasing from west to east and from north to south (Wang et al., 1999). These rocks in the Baicheng–Yangxia Sag are presently over-mature with respect to oil generation. In the thrust fronts where the Mesozoic source rocks were pushed upward from deep buried regime by reverse faults, high Ro values were observed for samples presently with shallow burial.

The current geothermal gradients in the Kuche Depression are much higher than those in the cratonic region of the Tarim Basin. These are 25–27 °C/km in the northern Kuche Depression (near the Kelasu structural belt, Fig. 1(a)), but decrease to around 18–20 °C/km in the southern part of the depression. The study of Wang et al. (2005) from the YN2 well indicates that paleo-geothermal gradients in the Kuche Depression decreased from around 32 °C/km in the Triassic to 25–26 °C/km in the Neogene-Quaternary.

Utilizing the measured drill-stem test and bottom hole temperature data from a number of exploration wells and over 230 pseudo wells along 13 seismic sections, we used the BasinMod-1D package to model the maturity variation of the Mesozoic source rocks at different localities of the Kuche Depression as a function of time. The results (Fig. 6(a)) show that the subsidence in the study area during the Mesozoic was generally slow but rapid since the Neogene. The Triassic and Jurassic source rocks in the Kuche Depression remained at relatively low maturity levels (<0.60–0.70 %Ro), but was rapidly buried to reach a level of 2.50 %Ro within a short time span. The Upper Triassic and Middle-Lower Jurassic source rocks reached their peak oil windows during the Miocene (23–12 Ma) and within the past 5 Ma, respectively.

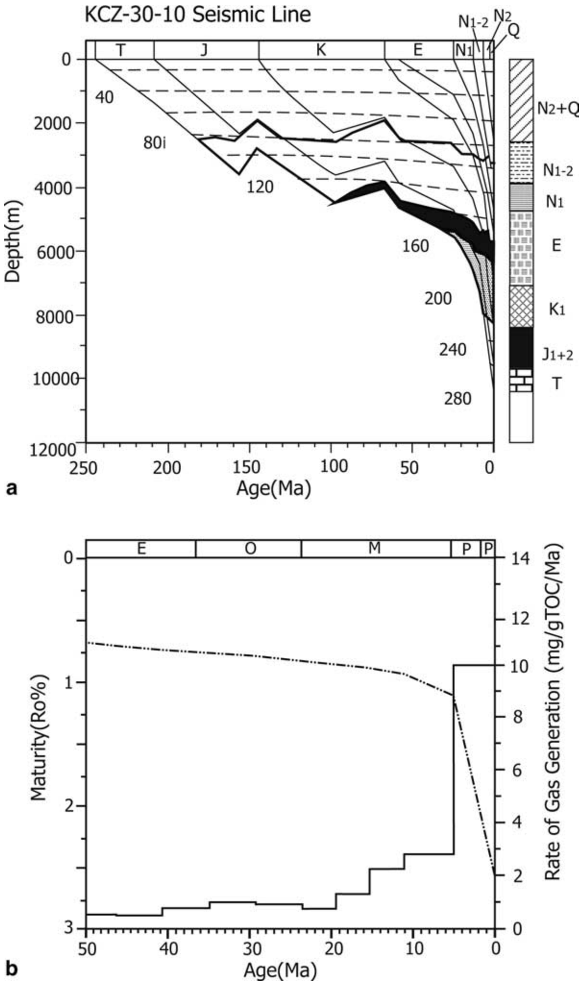

Fig. 6. One-dimensional model showing the burial history, thermal maturation and gas generation of the Triassic and Jurassic strata near the central Baicheng Sag in the Kuche Depression.

Particularly in the past 2.5 Ma, the Mesozoic source rocks in a large part of the Kuche Depression reached the dry gas generation stage, with a maturity of >2.0 %Ro. The recent rapid burial and thermal maturation in the past 5 Ma (Fig. 6(b)) is considered one of the most important factors for the formation of the giant Kela 2 gas field in the Kuche Depression.

As shown in Fig. 7(a), the present-day vitrinite reflectance values at the top of the Triassic source rocks in the Kuche Depression vary significantly laterally, generally >0.60 %Ro. Source rocks with relatively low maturity levels (<0.8 %Ro) occur in the northern monocline, southern gentle anticline and frontal uplift zones. In contrast, those with vitrinite reflectance >1.5 %Ro are distributed in the Baicheng and Yangxia sags, with the most mature source rocks occurring in the western Baicheng Sag. The maturity levels of the Jurassic source rocks decrease significantly from the hinterland to frontal uplift and the Tabei uplift. Highly to over-mature Jurassic–Triassic source rocks occur mainly in deeply buried hinterlands of the Yangxia and Baicheng sags, providing a source of dry gas to giant traps in the KL2 gas field.

At 5 Ma, similar lateral maturity distribution patterns can be observed for the top of the Triassic strata, except the maturity levels are much lower (Fig. 7(b)). The source rocks were thermally immature in the southern frontal uplift zone (0.4–0.5 %Ro), but were within oil-wet gas window in the Baicheng and Yangxia sags (1.0–1.4 %Ro). As the area with vitrinite reflectance above 1.0 %Ro was much smaller than that at the present-day, rapid subsidence of the foreland basin in the past 5 Ma appears to be the primary cause of significant gas generation.

At 12 Ma, the vitrinite reflectance values at the base of the Jurassic source rocks in the Baicheng and Yangxia sags, as well as the Yi–Ke structural belt, were around 0.7–1.1 %Ro (Fig. 7(c)). This suggests that the Jurassic–Triassic source rocks were mainly in the oil generation stage during this period.

At 23 Ma, source rocks with vitrinite reflectance greater than 0.7 %Ro at the top of Triassic occur only in the western Baicheng Sag and Ke–Yi structural belt (Fig. 7(d)). The maximum vitrinite reflectance value was below 0.9 %Ro, thus oil generation took place only in a small area of the Kuche Depression.

At 65 Ma, marginally mature source rocks (with 0.5–0.7 %Ro) were present only near the central depression zone and Ke–Yi structural belt, with limited liquid hydrocarbon generation.

Therefore, the Mesozoic source rocks in the Kuche Depression were in the conventional oil window at around 23–5 Ma, and reached peak oil generation at about 12 Ma. Extensive gas generation occurred even more recently.

4.3. Gas generation intensities of Mesozoic source rocks as a function of time

Gas generation intensities of the Triassic and Middle-Lower Jurassic source rocks in the Kuche Depression as a function of geological time were estimated using the gas yield rate, source rock thickness and TOC content.

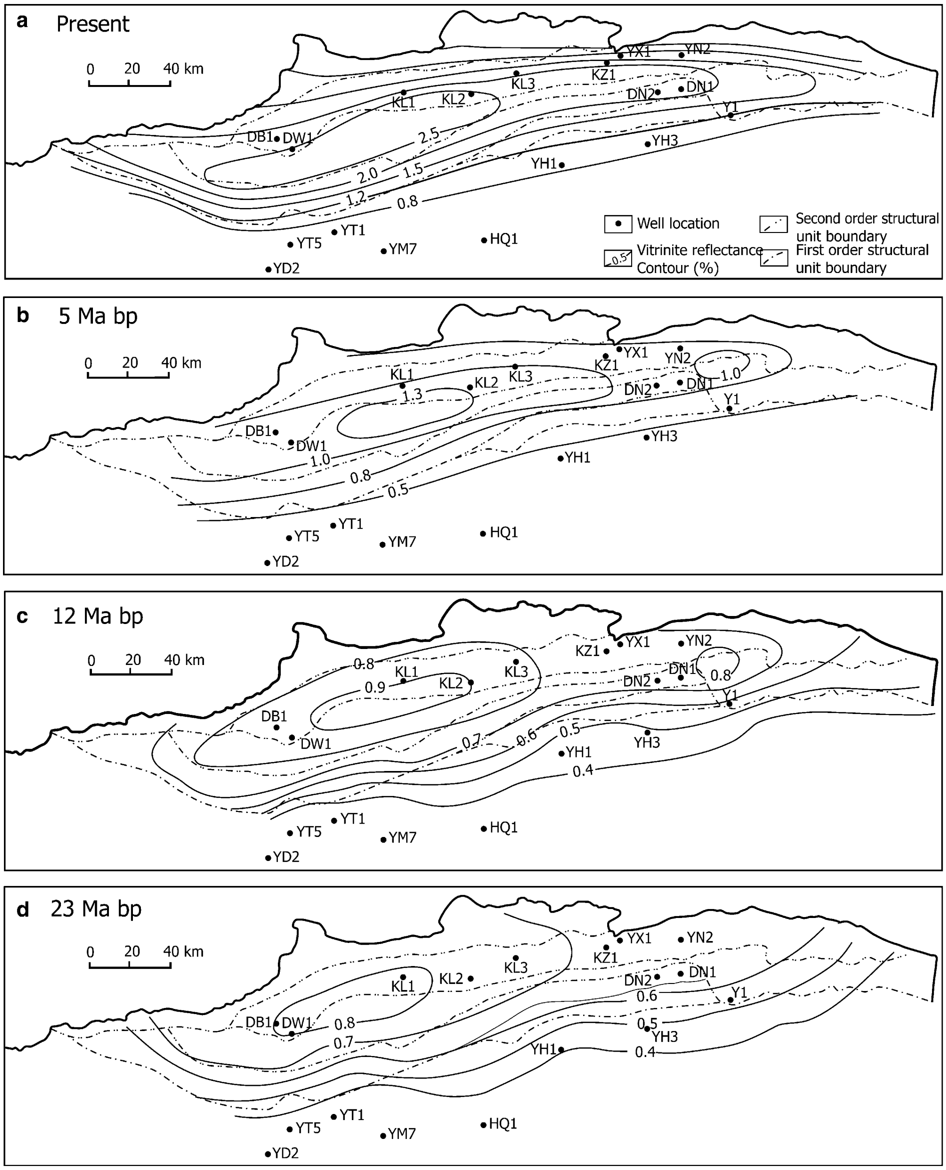

Fig. 7. Vitrinite reflectance contour maps (%Ro) at the top of the Triassic strata of the Kuche Depression at different geological times.

As shown in Fig. 8, the Triassic source rocks were marginally mature before 65 Ma, with vitrinite reflectance values generally below 0.6 %Ro. The gas generation intensities in the Kuche Depression were largely below 100×10^6 m^3/km^2. At around 65 Ma, when the Triassic source rocks in the Baicheng and Yangxia sags entered the conventional oil window (>0.6 %Ro), their average gas generation intensities reached about 50 million m^3/km^2, with the highest values of 150–320 million m^3/km^2 occurring near KL3 – KZ1 – YX1 well locations (Fig. 8(a)). The gas generation intensities were around 50–100 and less than 15 million m^3/km^2 in the western Baicheng Sag and frontal uplift zone, respectively. At 23 Ma, the vitrinite reflectance values of the Triassic source rocks went above 0.7 %Ro in the Baicheng and Yangxia sags and generally greater than 0.6 %Ro in other areas with the exception of frontal uplift zone. As a result, the gas generation intensities increased significantly, with a westward shift in gas generation centers (Fig. 8(b)). At this stage, the highest gas generation intensities in the Kuche Depression (over 1 billion m^3/km^2) occurred near the KL2 well location. At around 12 Ma, the gas

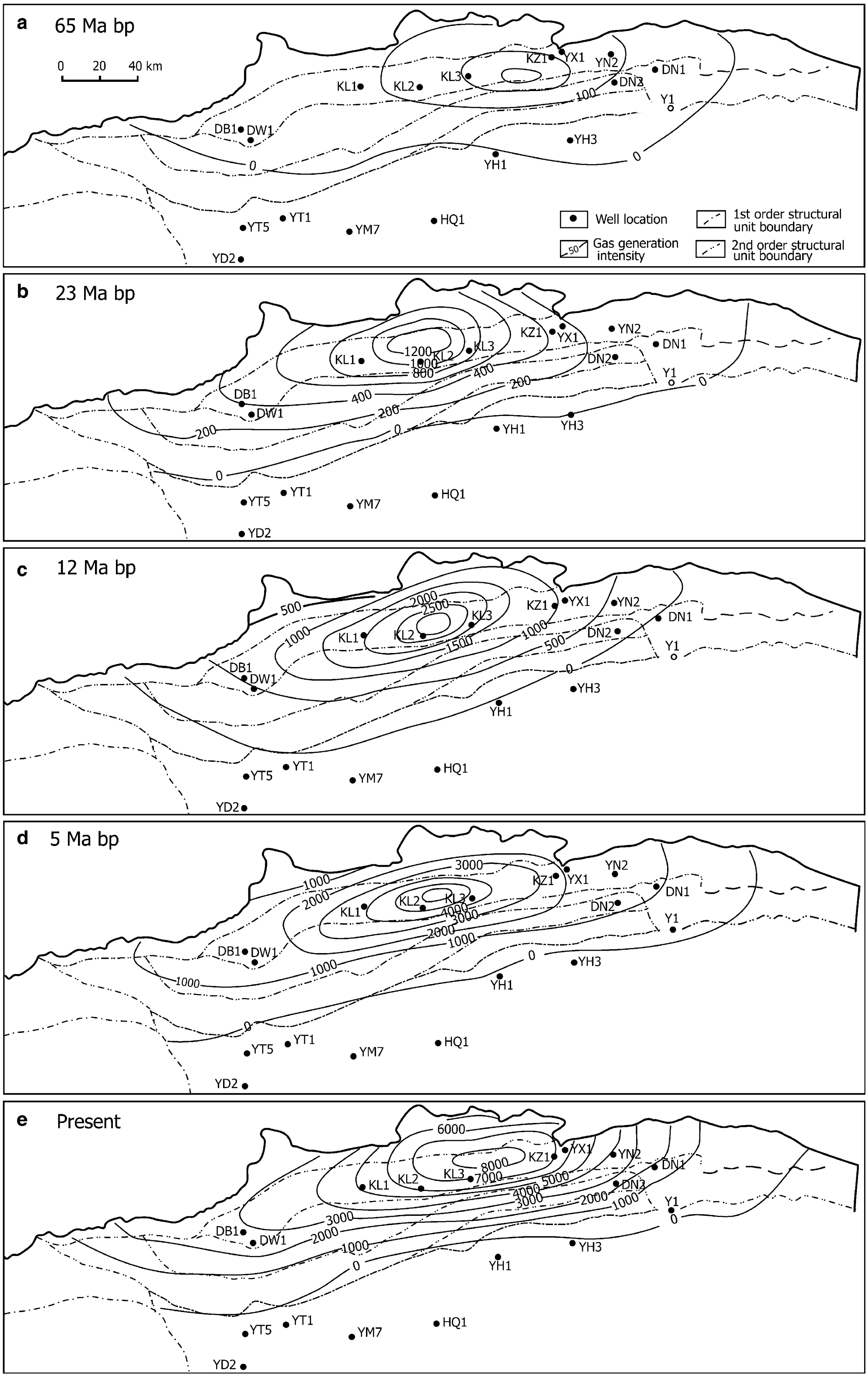

Fig. 8. Calculated gas generation intensities (unit: million m^3/km^2) of the Triassic source rocks in the Kuche Depression at different geological times.

generation intensities of the Triassic source rocks in the Baicheng and Yangxia sags increased drastically, with over 2 billion m^3/km^2 at the gas generation center near the KL2 well (Fig. 8(c)). At 5 Ma, the vitrinite reflectance values of the Triassic source rocks were generally above 1.0 %Ro, and the gas generation intensities in most of the Kuche Depression were greater than 1 billion m^3/km^2. At the gas generation center near the KL2 well, the gas generation intensities reached more than 4–7 billion m^3/km^2. In contrast, those in the northern monocline zone, southern Qiulitake structural belt and frontal uplift zone were generally below 1 billion m^3/km^2 (Fig. 8(d)). The gas generation intensities of the Triassic source rocks increased more rapidly in the past 5 Ma. The present-day gas generation intensities of the Triassic source rocks are over 2 billion m^3/km^2 in most part of the Kuche Depression, with even higher values in the hinterland region. The gas generation center moved eastward to the KL3 well location.

As shown in Fig. 9, the Middle-Lower Jurassic source rocks generally follow a similar thermal evolution pattern to the Triassic source rocks, with the exception of a slight shift in the localities of gas generation centers over time. At 65 Ma, these rocks in the deepest part of the depression entered the oil window, with gas generation intensities of 50–240 million m^3/km^2 (Fig. 9(a)). The most intense gas generation was observed near the KZ1–YN2 well locations and in the Baicheng Sag. At 23 Ma, a large part of the depression had reached low maturity stage, with the highest gas generation intensities of 600–930 and 200–330 million m^3/km^2 being observed near the centers of the Baicheng and Yangxia sags (Fig. 9(b)). At 12 Ma, the Jurassic source rocks were buried much deeper. Gas generation centers with intensities over 1 billion m^3/km^2 occurred in the KL2 well location, western Baicheng Sag and central Yangxia Sag (Fig. 9(c)). Due to the rapid sedimentation in the large part of the depression, the maturity levels of the Middle-Lower Jurassic source rocks at 5 Ma reached approximately 1.0 %Ro. As a result, the gas generation intensities exceeded 2 billion m^3/km^2 in the Yangxia and Baicheng sags, with extremely high values (4–5 billion m^3/km^2) in the gas kitchens near KL2 well and Yangxia Sag (Fig. 9(d)). Subsequent subsidence in the past 5 Ma led to further intensification of gas generation in the Kuche Depression (Fig. 9(e)).

A review of the regional petroleum geology indicates that the gas source kitchens in the Kuche Depression are characterized by: (1) excellent gas generative potentials of the Triassic–Jurassic source rocks; (2) rapid subsidence and thermal maturation of the gas source rocks to maturity levels of 1–2 %Ro within the past 5 Ma; and (3) perfect matching in the timing of peak gas generation and intensive structural deformation, providing ideal conditions for the formation of giant gas accumulations.

4.4. Control of gas kitchens on gas accumulation in the Kuche Depression

Comparison of Figs. 8(e), 9(e) and 1(a) indicates clearly that large gas accumulations are distributed either in an area with high gas generation intensity or within a short lateral distance (10–20 km). Empirical evidence led Dai et al. (2003) to propose two main criteria for finding giant gas fields from the Kuche Depression: (1) gas traps formed within or adjacent to gas source kitchens with a gas generation intensity of over 2 billion m^3/km^2 and (2) a relatively recent subsidence, thermal maturation and trap formation (i.e., in Neogene). The gas generation intensities of the Triassic and Jurassic source rocks are higher than 2 billion m^3/km^2 in most of the Kuche Depression, exceeding 4 billion m^3/km^2 in the hinterland area.

Earlier studies based on stable carbon isotopes of gaseous alkanes suggest that the primary gas source in the Kuche Depression was likely the Middle-Lower Jurassic coal measures (Dai et al., 2003). Based on molecular and isotopic evidence, however, it is very difficult to differentiate natural gases generated from the Triassic and Middle-Lower Jurassic source rocks, as both contain dominantly type III organic matter.

As shown in Table 2, the stable carbon isotope values of ethane in the natural gas samples collected from the Kuche Depression generally show little variation (with $\delta^{13}C_2 > -26‰$, Fig. 10(b)), while the stable carbon isotopes of methane in the gases change systematically laterally (Fig. 10(a)), i.e., from more negative $\delta^{13}C_1$ values (−33.5‰ to −39.3‰) in the frontal uplift zone to less negative values (−25.1‰ to −33.5‰) in the Kelasu and KL2 well region. Thus, different gas accumulation zones appear to have been charged with gases generated at various maturity stages from similar type III gas kitchens. This suggestion is supported by the lateral variation in the chemical compositions of the gases, where gases accumulated near the

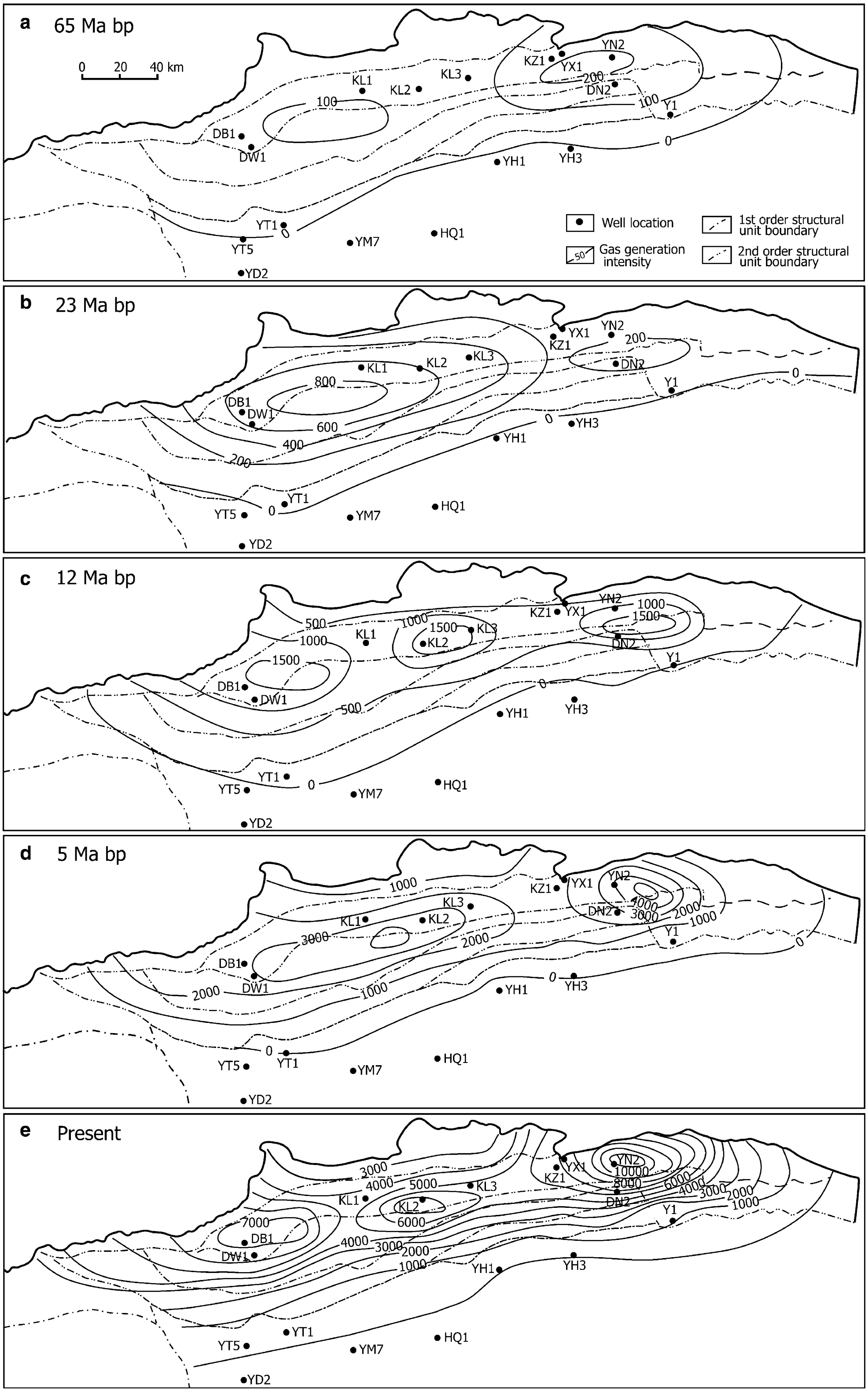

Fig. 9. Calculated gas generation intensities (unit: million m^3/km^2) of the Lower-Middle Jurassic source rocks in the Kuche Depression at different geological times.

Table 2
Characteristics of gas accumulations in the different structural regions of the Kuche Depression (1, thrusting zone; 2, depression and slope zone; 3, frontal uplift zone)

Region	Gas field	C_1 (%)	C_1/C_{1-5}	$\delta^{13}C_1$ (‰)	$\delta^{13}C_2$ (‰)	Source rocks	Maturity level (%Ro)	Charge time
1	KL2	93.5–98.3	0.99–1.0	−26.2 to −28.2	−16.6 to −19.4	Triassic	>1.3	Late
						Jurassic	>0.9	
1	DB1	92.2–96.2	0.95–0.97	−29.7 to −30.8	−21.4 to −21.5	Triassic	>1.0	Late
						Jurassic	>0.7	
1	YN2	88.0–94.4	0.90–0.95	−32.8 to −34.8	−22.4 to −24.6	Triassic	>0.8	Early
						Jurassic	>0.6	
2	DN2	87.0–89.4	0.89–0.91	−34.3	−20.9	Triassic	>0.8	Early
						Jurassic	>0.6	
2	WC1	82.0–83.2	0.84–0.85	−38	−28.05	Triassic	>0.6	Late
						Jurassic	>0.4	
3	YD2	82.3–83.5	0.87–0.88	−34.8	−22.4	Triassic	>0.6	Late
						Jurassic	>0.4	
3	YT	75.4–92.4	0.85–0.97	−36.2 to −38.9	−22.9 to −24.1	Triassic	>0.6	Late
						Jurassic	>0.4	
3	YM 7	77.8–91.5	0.78–0.98	−33.1 to −37.0	−21.3 to −23.2	Triassic	>0.6	Late
						Jurassic	>0.4	
3	YH	76.5–90.6	0.73–0.98	−34.1 to −37.5	−22.1 to −23.9	Triassic	>0.6	Late
						Jurassic	>0.4	
3	Tiergen	72.3–87.5	0.76–0.93	−35.2 to −39.0	−21.8 to −23.7	Triassic	>0.6	Late
						Jurassic	>0.4	
3	YM 4–10	Heavy oil				Triassic		Early oil, no gas

central depression are much drier than those in the frontal uplift region (Table 2).

The relationships between the gas kitchen thermal evolution and gas accumulation processes in the foreland thrusting zone and frontal uplift zone of the Kuche Depression can be described using the KL2 gas field and YH3 condensate field. As shown in Table 3, gases from the KL2 gas field contain relatively high proportions of methane, with rather high $\delta^{13}C_1$ and $\delta^{13}C_2$ values. Using the empirical $\delta^{13}C_1$-Ro relationship proposed by Dai et al. (1992), the equivalent vitrinite reflectance values for the source rocks of the KL2 gas field were estimated to be 2.90–3.85 %Ro, or 1.0–1.6 %Ro if the relationship proposed by Stahl (1977) was used. An intermediate range (1.0–2.8 %Ro) was also suggested (Zhao et al., 2002; Wang et al., 2004).

In order to provide some constraints on this maturity estimation, kinetic hydrocarbon generation and carbon isotopic modelling based on the temperature history of the respective source rock (Tang et al., 2000; Cramer et al., 2001) were used to infer the trapping history of the KL2 field. For this purpose, dry, open system pyrolysis experiments were conducted on a Lower Jurassic coal sample (J_1y) collected from the Kuche Depression. The coal is characterised by high TOC content (71.5%), low hydrogen index (30.7 mg HC/g TOC) and moderate vitrinite reflectance value (0.75 %Ro). Based on the $\delta^{13}C$ values of methane generated during pyrolysis experiments, isotope specific reaction kinetic sets for the generation of ^{12}C- and ^{13}C-methane were calculated, following the method developed by Cramer et al. (2001). For gas isotope modelling, the burial history of the KL2 gas field shown in Fig. 6 was used to reconstruct the temperature evolution of the Jurassic coal. To consider minimum and maximum scenarios, the temperature history at the top and base of the coal was used as input for the isotope model.

Fig. 11 displays the simulation results with the $\delta^{13}C_1$ values shown as a function of the degree of conversion (cumulative yield) of the initial methane potential of the coal. The dotted line displays the isotope evolution of instantaneously generated methane with a pronounced minimum in the $\delta^{13}C$ (−32.5‰) at about 5% cumulative methane yield. From this moment on, the $\delta^{13}C$ value of instantaneously generated methane from Jurassic coal increases continuously (Fig. 11). In addition, Fig. 11 shows two modelled $\delta^{13}C$ trends (solid lines) of methane accumulating since the beginning of the development of the anticlinal structure of the KL2 gas field about 5 Ma. Only gas generated during this recent time was available for being trapped in the reservoir. In fact, these modelled isotope trends coincide well with the measured isotope signatures of methane in the field today (Fig. 11) suggesting

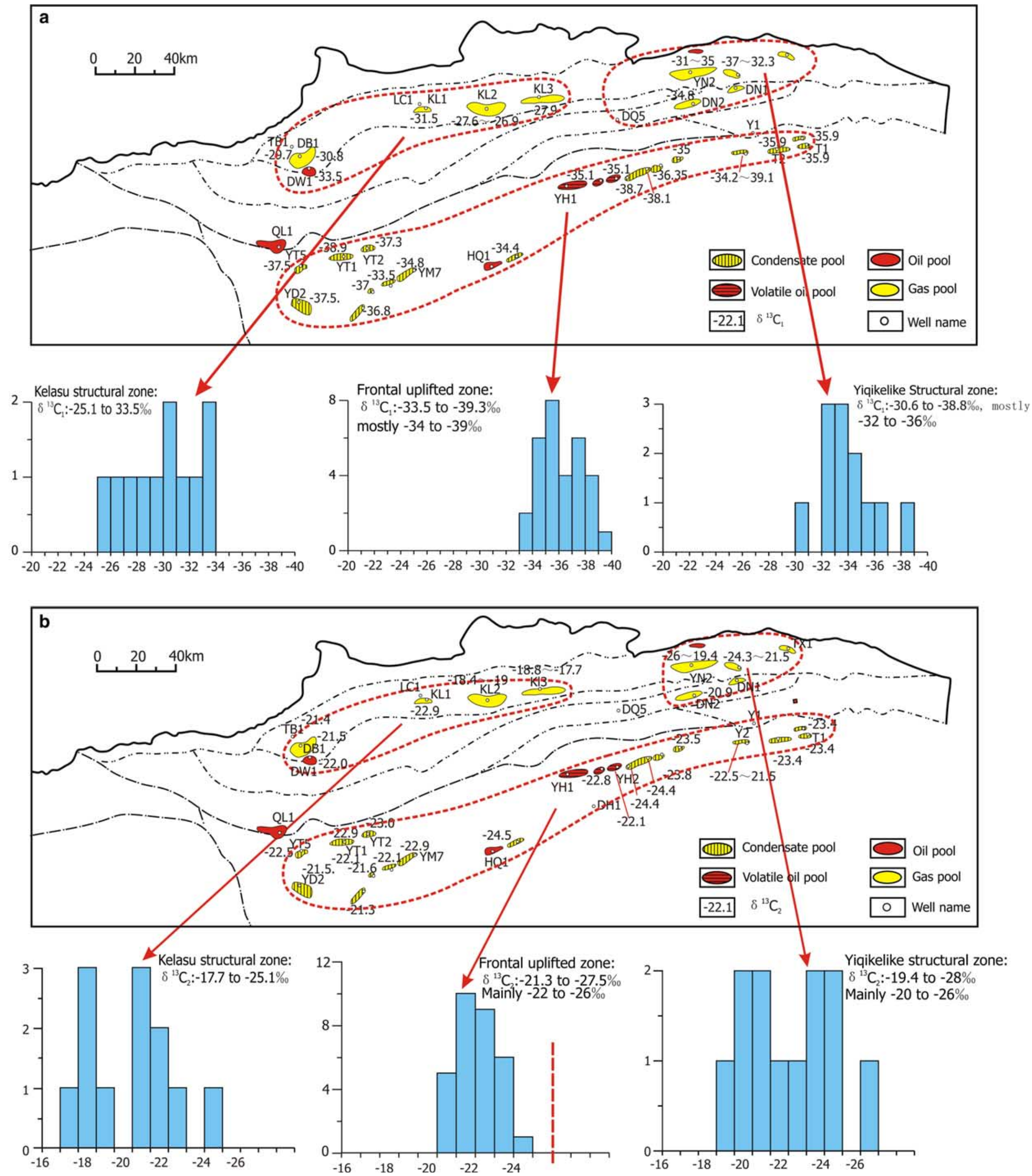

Fig. 10. Lateral variation in the stable carbon isotopes of gaseous alkanes in the discovered gases from the Kuche Depression.

that gas accumulation in the KL2 gas field mainly occurred in the last 5 Ma at maturities of the source rock ranging from 1.0 to 2.5 %Ro. Earlier accumulation prior to 5 Ma would have resulted in less negative stable carbon isotope values and a later onset would have resulted in isotopically lighter gases. This model of reservoir charging suggests that about 15–30% of the total methane potential of the source rock is trapped in the field today (Fig. 11). The high efficiency of gas accumulations in the KL2 gas field is thought to be associated with the rapid gas generation from the Triassic and Jurassic humic type

Table 3
Stable carbon isotopic compositions of the natural gases from the KL2 gas field

Well	Strata	Depth (m)	$\delta^{13}C_{CO_2}$ (‰)	$\delta^{13}C_1$ (‰)	$\delta^{13}C_2$ (‰)	$\delta^{13}C_3$ (‰)	$\delta^{13}C_4$ (‰)
KL201	K_1b	3936–3938	−15.83	−26.16	−18.09	−19.06	−22.14
KL201	K_2b	3630–3640	−19.78	−27.07	−18.48	−19.08	−20.31
KL201	K_2b	3770–3795	−22.57	−27.19	−17.87	−19.14	−20.55
KL201	K_2b	4016–4021	−18.58	−27.32	−19.00	−19.54	−20.90
KL202	E	1472–1481	−15.37	−28.24	−18.86	−19.15	−20.91

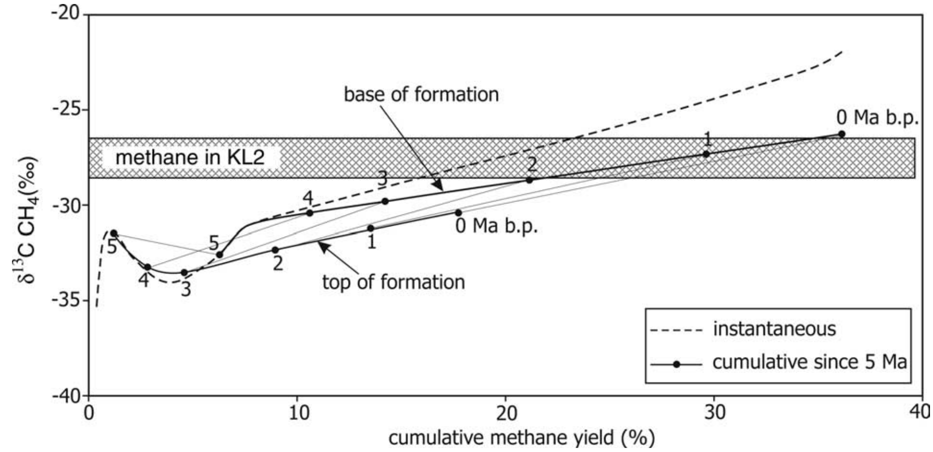

Fig. 11. Stable carbon isotopes of methane generated from the Lower Jurassic coal near the KL2 gas field location as a function of cumulative methane yield. Isotope trends were calculated with reaction kinetic models derived from dry, open system pyrolysis experiments. Trends are shown for instantaneously generated methane as well as for methane accumulating since 5 Ma at the base and top of the formation. Numbers at the cumulative lines indicate the time in Ma corresponding to the calculated $\delta^{13}C$ of methane in the reservoir.

source rocks and the presence of excellent salt beds as cap rocks on the top.

In contrast, gas carbon isotopic compositions and related isotopic chemical kinetic simulation results for the gas kitchens indicate that the YH3 condensate field was initially charged with gases generated at early to middle oil window (0.5–0.8 %Ro) from a lacustrine source rock at 12–6 Ma, with relatively light gas isotopes. In contrast, the late gas charge occurred most likely in the past 5 Ma, from a type III source rocks (Wang et al., 2005). Results of 1-D basin modelling (Fig. 7) indicate that these gases represent late charged humic gases from the adjacent gas kitchens, not those migrated long distance from the hinterland region.

Data in Table 2 illustrate the influence of the characteristics of gas source kitchens on the chemical and carbon isotopic compositions of natural gases accumulated in different structural units of the Kuche Depression. Due to the relatively low thermal maturity levels of Mesozoic source rocks in the eastern part of the Kuche Depression, gases in the YN2 gas field were likely to have been generated from a relatively mature Triassic source rock (>0.8 %Ro) and a slightly less mature Jurassic source rock (>0.6 %Ro). While no later charged, high maturity gases are recognized in the YN2 gas field, such gases appear to be common in the KL2 and DB1 gas fields.

5. Conclusions

This study demonstrates the presence of lacustrine and coaly source rocks in the Mesozoic strata of the Kuche Depression, Tarim Basin. The lacustrine source rocks occur in the Middle-Upper Triassic Kelamayi Formation, Upper Triassic Huangshanjie Formation and Middle Jurassic Qiakemake Formation; and the coaly source rocks are distributed in the Upper Triassic Taliqike Formation, Lower Jurassic Yangxia Formation, and Middle Jurassic Kezilenuer Formation. While the

Qiakemake Formation contains type I–II kerogen, organic matter in all other source rocks consists primarily of type III organic matter. Based on kinetic parameters derived from open system pyrolysis experiments and calibrated with measured geothermal data, the lateral variation in thermal maturity and gas generation yield at different geological time was modelled at a number of exploration well locations as well as 230 pseudo wells constructed along 13 seismic lines. The results show that Mesozoic source rocks in the Kuche Depression have experienced substantial burial and thermal maturation since the Neogene, and the extremely high gas generation rate in the past 5 Ma is critical for the formation of giant gas accumulations in the Kuche Depression. The chemical and stable carbon isotope compositions of the accumulated gases are such that clearly favours a scenario of lateral variation in the maturity levels of the Mesozoic type III source rocks. Thus, gases in the YH3 condensate field in the frontal uplift zone appear to represent gases generated within early to middle oil window (0.5–0.8 %Ro) with relatively low $\delta^{13}C_1$ values, whereas the isotopically heavy gases in the KL2 gas field in the Ke–Yi structural belt are most likely high maturity gases (1.0–2.5 %Ro) generated in the past 5 Ma.

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