Generation and accumulation of Quaternary shallow gas in eastern Qaidam Basin, NW China*

SU Aiguo (苏爱国)[1,2**], ZHAO Wenzhi (赵文智)[2], DANG Yuqi (党玉琪)[3], ZHANG Shuichang (张水昌)[2], LI Maowen (黎茂稳)[4], PANG Xiongqi (庞雄奇)[5], ZHOU Ruilian (周瑞年)[3], GUAN Ziqiang (管自强)[3], XU Ziyuan (徐子远)[3], ZHANG Daowei (张道伟)[3], TAN Yanhu (谭彦虎)[3], CHEN Jianfa (陈践发)[5], LI Sumei (李素梅)[5]

[1] *China University of Mining & Technology (Beijing), Beijing* 100083, *China*

[2] *PetroChina Research Institute of Petroleum Exploration and Development, Beijing* 100083, *China*

[3] *PetroChina Qinghai Oilfield Company, Denghuang* 736202, *China*

[4] *Geological Survey of Canada, Calgary, T2L 2A7, Canada*

[5] *China University of Petroleum (Beijing), Beijing* 102249, *China*

Abstract This study presents an overview on the geological setting and geochemical characteristics of Pleistocene shallow gas accumulations in eastern Qaidam Basin, NW China. Five largest gas accumulations discovered in this region have a combined enclosure area of about 87 km^2 and 7.9 trillion cubic feet (tcf) of proven plus controlled gas reserves. The dominance of methane (>99.9%) and the $\delta^{13}C$ and δD values of methane (−68.51‰ to −65.00‰ and −227.55‰ to −221.94‰, respectively) suggest that these gases are biogenic, derived from the degradation of sedimentary organic matter by methanogens under relatively low temperatures (<75℃). A sufficient supply and adequate preservation of organic matter in the Pleistocene sediments is made possible by the lake basin's high altitude (2600 − 3000 m), high water salinity (>15%) and strong stratification. The deposition and extensive lateral occurrence of shore and shallow lake sands/silts in beach sand sheets and small sand bars provided excellent reservoirs for the biogenic gas generated from adjacent rocks. Effective but dynamic gas seals were provided by such factors as intermittent vertical variations in the sediment lithologies, hydraulic trapping due to mudstone water saturation, the hydrocarbon gradient created as a result of gas generation from potential caprocks, and the presence of a regional caprock consisting of 400 − 800-m-thick mudstones and evaporites. It appears that the most favorable traps for large gas accumulations occur on structural slopes near the major gas kitchen, and the prolific gas pools are often those large gentle anticlines with little faulting complication.

Key words biogenic gas; generation; accumulation; Quaternary; Qaidam Basin

1 Introduction

Shallow (mostly biogenic) gas accounts for over 20% of the world's discovered gas reserves (Rice and Claypool, 1981; Claypool and Kaplan, 1974), and represents one of the unconventional energy sources that increasingly attract the attention of petroleum geologists. Numerous Cretaceous and Tertiary shallow gas accumulations have been documented throughout the world, and some accumulations such as those in Siberia, USA and Canada, are of very important economic value (Martini et al., 1998; Littke et al., 1999; Shurr and Ridgley, 2002). Over the past decade, a number of significant shallow gas accumulations have been discovered in China, such as the Qaidam, Songliao, Bohai Bay, Erlian, Jianghan, Subei and Baise basins (Qi Houfa et al., 1997), and the southeastern offshore areas (Xu Wang, 1997) including the Hangzhou Bay (Lin Chunming et al., 2004).

The only giant shallow gas accumulations in China are located in the Sanhu Region of eastern Qaidam Basin, NW China. Five largest gas accumulations discovered in this region have a combined enclosure area of about 87 km^2 and 7.9 trillion cubic feet (tcf) of proven plus controlled gas reserves. The largest gas accumulations include those in the Sebei-1, Sebei-2 and Tainan gas fields (Fig. 1). The gas payzones range from 65 to 1738 m in depth, with a single well daily production rate of 3.5 − 14 million cubic feet (mcf). These gases were generated and trapped in the Pleistocene sediments (Zhou Zhuhong et al., 1994; Gu Shusong, 1996; Qi Houfa et al., 1997; Guan Ziqiang et

ISSN 1000-9426

* This study was funded by the China 973 Key Foundation Research Development Project (Grant No. 2001CB209100), National Key Scientific Program (Grant No. 96-111-01-03) and the ESS Global Opportunities Program.

** Corresponding author, E-mail: aiguosu@yahoo.com

al., 2001; Dai Jingxing et al., 2003).

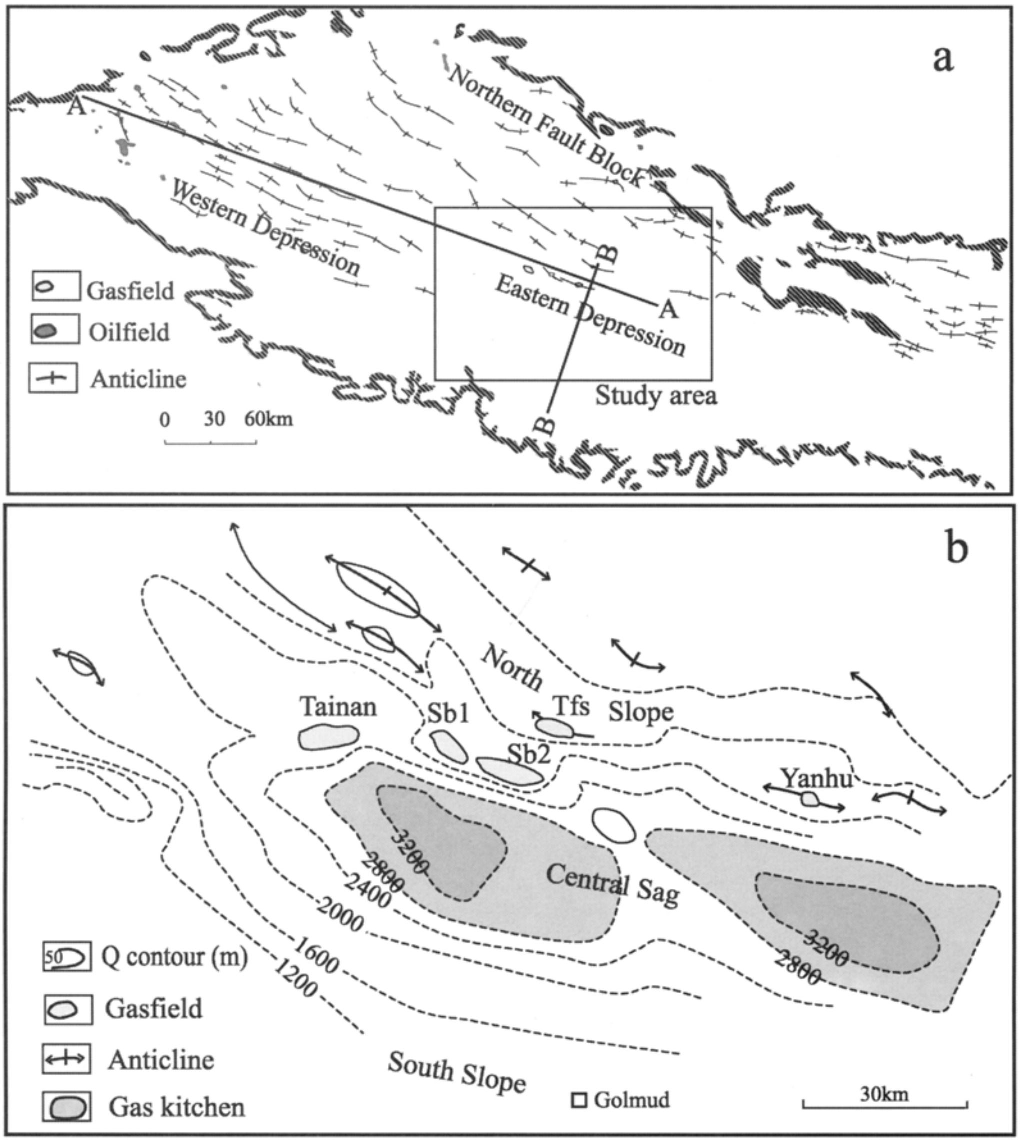

Fig. 1a. Map showing the oil and gas field locations and surface recognizable anticlinal structures in the Qaidam Basin, NW China; 1b. enlarged map of the study area showing the Quaternary sediment contour, together with the biogenic gas fields. Sb1 and Sb2. Sebei-1 and Sebei-2 fields; Tfs. Tuofengshan Field.

The origin of shallow biogenic gas is a topic involving many discussions (Wang Wanchun et al., 2005). It is generally believed that biogenic gas is the product of anaerobic degradation of sedimentary organic matter at low temperatures, and it is typically trapped in relatively shallow and immature sediments (Rice and Claypool, 1981). The suitable biogenic gas habitats include swamps, paddy fields, anoxic freshwater lakes, sublittoral-marine bays, glacial drifts, and marine sediments beneath the anaerobic sulfate-reducing zones (Vilks et al., 1974; Rashid and Vilks, 1977; Schoell, 1980, 1983, 1988; Whiticar, 1990; Albert et al., 1998; Okyar and Ediger, 1999; Lin Chunming et al., 2004). Such gases are different from routine ones (Liu Luofu et al., 2005), and typically rich in methane, but not associated with oil, and their origins can be constrained by carbon and hydrogen isotope data of methane (Stahl, 1974, 1977; James, 1983; Shoell, 1983; Sundberg and Bennett, 1983; Faber, 1987; Berner and Faber, 1988; Galimov, 1988; Whiticar, 1990; Floodgate and Judd, 1992; Jenden et al., 1993; Baylis et al., 1997; Kaplan et al., 1997).

This study on the Pleistocene gas accumulations in eastern Qaidam Basin aims to describe the general geological settings of shallow gas pools, with an emphasis on the salt lake sediments, discuss the conditions required for the formation of gas pools, and provide a synthesis on the geological controls of shallow gas distribution.

2 Geological setting

The Qaidam Basin is situated on northern Qinhai-Xizang (Tibet) Plateau (90° - 98°20′ E, 35°55′ - 39°10′N), with an area of 121000 km^2 and 2600 - 3600 m altitude above sea level. This intermontane basin is surrounded by Kunlun in the south, Qilian in the northeast, and Altun mountains in the northwest (with the altitudes ranging from 4000 - 4500 to over 5000 m, Fig. 1). It is filled with over 16000-m-thick Mesozoic-Cenozoic sediments on the top of the pre-Mesozoic basement consisting of metamorphic and igneous rocks. Structurally, the basin is divided into a Mesozoic fault block zone in the north and two Cenozoic depressions in the west and south (Fig. 1). The depocenters of the basin during the Jurassic were located within the Northern Fault Block Zone (NFBZ), with several Jurassic freshwater lacustrine and deltaic coal-bearing petroleum source rocks being developed. During the Tertiary, the depocentres shifted to the Western Depression (WD), with the sediments being characterized by saline lacustrine source rocks. The collision with the northeastward moving Indian plate during the Late Himalayan orogeny at the end of Tertiary resulted in differential uplift in the Qaidam Basin and the depocenters shifted further to the Eastern Depression (ED) during the deposition of the Pleistocene strata (Fig. 2A.

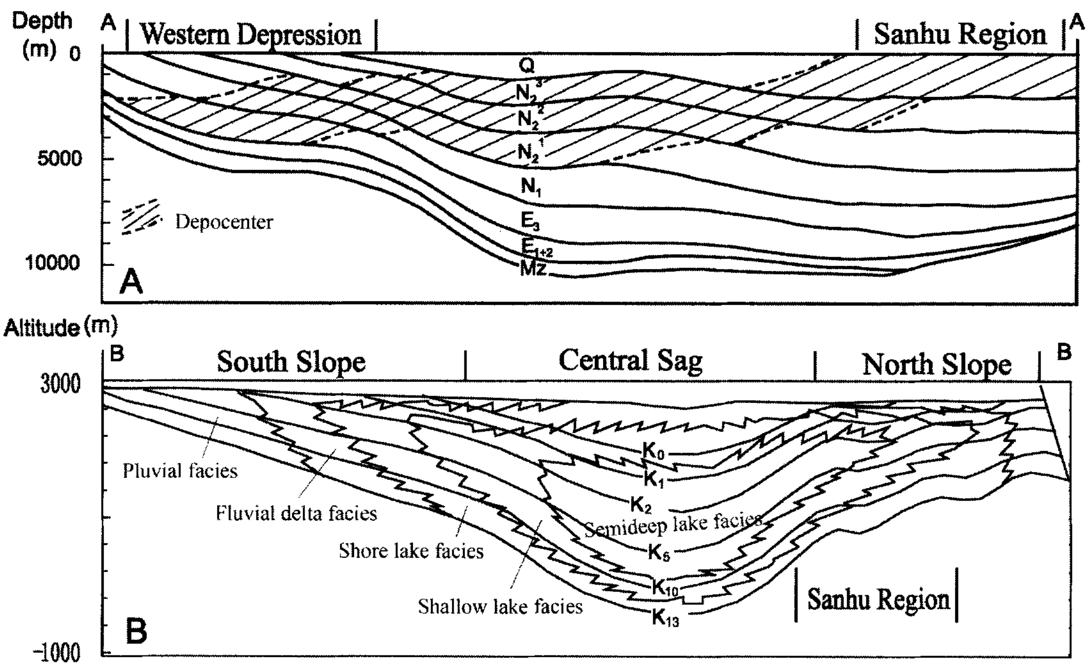

Fig. 2. Cross sections showing the shift in depocentres in the Qaidam Basin and the variation in Quaternary sedimentary facies in the Eastern Depression.

The Eastern Depression, with an area of approximately 37000 km^2, contains an inland sedimentary sequence dominated by lacustrine clastic rocks (Fig. 2B). Its depocentres during the Quaternary were located immediately south of the current biogenic accumulation zones. The Pleistocene sediments were deposited in brackish water—saline lakes that peaked at approximately 1.5 Ma (equivalent to the K_2 esistivity marker in Fig. 2B). The sediments generally have high Cl^- contents (0.5% - 2.5%), which increase upwards within each sedimentary cycle.

The Pleistocene sediments in the Eastern Depression are distinguishable from the underlying Pliocene Shizigou Formation by their poor compaction, high porosity (>30%), high water content (>30%), and little lithification (Kang Zhuling et al., 2000). Based on its lithology and wireline log characteristics, the Pleistocene stratigraphic column can be divided, from

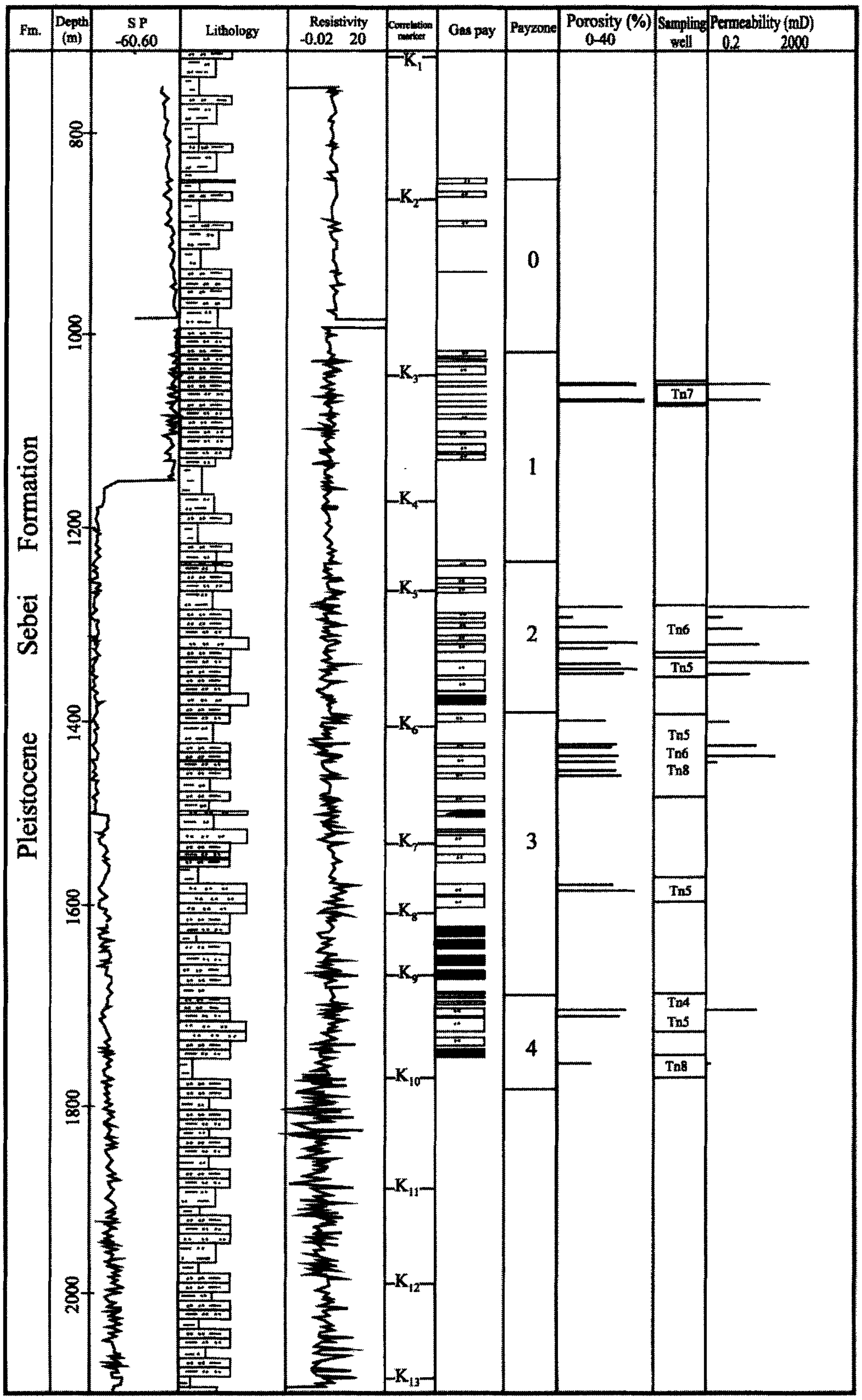

Fig. 3. Stratigraphic column of the Pleistocene Sebei Formation in the Tainan Gasfield area showing the positions of stratigraphic correlation markers, gas pays and payzone divisions.

the bottom to the top, four formations: Sebei (Q_1), Chaerhan (Q_2), Dabusen (Q_3) and Yanqiao (Q_4). The Sebei Formation is the main gas-bearing one in the study area, and it can be divided into three units (Fig. 3). The lower unit corresponds to the K_{10} – K_{13} marker in Fig. 2B, with a thickness of about 310 m. Its lithologies include shallow gray-brownish gray mud, sandy mud, silt, muddy silt interbeds, with dark gray carbonaceous mudstone layers above the K_{12} marker. This unit is coarsest among the Pleistocene sediments, with sands and silts accounting for over 100-m cumulative thickness (or 35% of the sedimentary column). The middle-upper units are equivalent to the K_1-K_{10} marker (Fig. 2B), with a cumulative thickness of 1450 m. Their lithologies are dominated by dark gray-gray muds, with some shallow gray silts and muddy silts, in over 10 upward coarse to finer gravel grading cycles. The middle-upper units are generally rich in muds (70% – 80%), and are considered the main source and reservoir units for biogenic gas in this basin. The regional seals for the gas accumulation are the overlying Chaerhan, Dabusun and Yanqiao formations. These formations have a total thickness of about 300 m, consisting of several evaporite sequences. The Yanqiao Formation is dominated by evaporites, whereas the Chaerhan and Dabusun formations contain mainly gray to shallow brownish muds.

3 Samples and methods

Used in this study are 55 gas samples, 320 mudstone samples and 240 sand/siltstone samples collected from the Pleistocene strata in the Sanhu Region of eastern Qaidam Basin. The 22 exploration and appraisal wells from which the samples were collected cover all of the discovered shallow gas accumulations in the study area. The gas samples, collected at their wellheads or separators, were analyzed routinely for chemical composition and for stable carbon, hydrogen and helium isotope composition of methane. Oil-associated gas samples from several oilfields in the western and northern parts of the Qaidam Basin were also collected and analyzed for geochemical comparison. In addition to routine paleomagnetic and paleotectonic analysis, the mudstone samples were analyzed using a Rock-Eval/TOC analyzer for their total organic carbon content (TOC). A portion of the mudstone samples were suspended in distilled and deionized water, and the Cl^- and total salt contents were determined by ion chromatography. The selected mudstone samples were extracted using dichloromethane for their soluble organic content, and the extracts were subjected to routine petroleum geochemical characterization by gas chromatography and gas chromatography-mass spectrometry.

All of the rock samples were also characterized routinely for their seal and reservoir properties (mineralogical composition, pore texture, porosity and permeability). Detailed bacteria counting was made on a number of recent mud samples from the bottom of the Qinghai Lake and mudstone samples from 15 exploration wells (0 – 2000 m in depth) using the Maximum Probable Number approach (Siebert and Hattingh, 1967). Several culture samples were used in subsequent laboratory incubation experiments to estimate the gas generation capacities and mechanisms. In order to evaluate the key geological controls on the occurrence of biogenic gas accumulations, regional sandstone and mudstone isopach maps were made based on seismic reflection data, calibrated using mud log and wireline log data from approximately 110 wells.

4 Results and discussion

4.1 Gas geochemistry and origin

Fifty-five shallow gas samples from the Sebei-1 and Sebei-2 gas fields were analyzed for both chemical composition and stable carbon isotope ratios of the methane. Hydrogen isotope data of the methane were also collected from a dozen of gas samples. The summarized results (Table 1) showed that the samples were dominated by methane (>99.9%), with minor C_{2+} hydrocarbons (<0.07%), N_2 and CO_2. Gas samples from the Yanhu gas field contain more N_2 and CO_2, as well as trace amounts of H_2S (Table 1). The $\delta^{13}C$ and δD values of methane in these gases range from −68.51‰ to −65.00‰ and −227.55‰ to −221.94‰, respectively. The δD values of methane are within the range of worldwide commercially produced gases from sedimentary basins (−310‰ to −130‰, Schoell, 1980; Jenden et al. 1993). The δD values of the Sebei gases are close to those of the oil-associated gases from the western part of the Qaidam Basin (−210.8‰ to −157.8‰), suggesting the common origin of methane from sedimentary organic matter (Fig. 4). This is supported by the lack of a remarkable depletion of deuterium in methane that is commonly associated with abiotic methanogenesis (e.g. up to −470‰ in Canadian Shield rocks, Sakata et al., 1997 and references therein). These results indicate a biogenic origin for the shallow gas, in contrast to those thermogenic gases derived from other parts of the Qaidam Basin. As reported in Su Aigauo et al. (2003), gases derived from the Jurassic coal-bearing strata in the Northern Fault Block Zone (e.g. the Nanbaxian, Lenghu and Mahai fields) contain 81% –

94% methane and 1% – 10% $N_2 + CO_2$, with $\delta^{13}C_1$ values in the range of –24‰ to –37‰. On the other hand, oil-associated gases in the Western Depression (Zhang Xiaobao et al., 2002) contain 78% – 95% methane and 2% – 4% $N_2 + CO_2$, with $\delta^{13}C_1$ values in the range of –42‰ to –29‰.

Table 1. Chemical and isotopic compositions of natural gases in the Qaidam Basin

Field	Well No.	Depth (m)	Composition (%)					$\delta^{13}C$ (‰)				Noble gas	
			N_2	CO_2	CH_4	C_2H_6	C_3H_8	$\delta^{13}C_1$	$\delta^{13}C_2$	$\delta^{13}C_3$	$\delta^{13}C_{CO_2}$	$^3He/^4He$	R/Ra
Tainan	Tn4	1717.8 – 1721.2			99.93	0.06	0.01	–68.54	–46.52	–32.58			
	Tn6	1599.0 – 1602.0	1.05	0.59	98.24	0.05	0.03	–68.25	–36.30	–23.95	–13.27	$(4.27 \pm 0.13) \times 10^{-7}$	0.30
Sebei-1	Ss13	1053.4 – 1056.8	0.68		99.24	0.06	0.02	–68.51					
	S4-15	1447.8 – 1456.4	0.007	0.40	98.23	0.97	0.22	–66.32	–44.80	–32.71			
	S22	780.4 – 797.4			99.94	0.059		–66.21	–43.79	–32.90			
	S24	1081.2 – 1084.8		0.03	99.97			–66.65	–43.76	–31.76			
	S27	1256.2 – 1265.2		0.03	99.93		0.04	–60.53					
	S79	1026.2 – 1031.2		0.005	99.20			–66.32	–43.63	–32.22			
Sebei-2	Sz3		2.05	0.11	97.84			–66.40					
	S21	1479.2 – 1482.0		0.44	99.21	0.25	0.06	–64.90	–37.66	–23.57	–20.04	$(1.21 \pm 0.11) \times 10^{-7}$	0.09
	Sx1	1132.2 – 1135.6	2.17	0.68	96.95	0.07	0.03	–67.03	–37.57		–21.51	$(4.19 \pm 0.65) \times 10^{-8}$	0.03
	S26	792 – 795						–66.7	–49.8	–23.3			

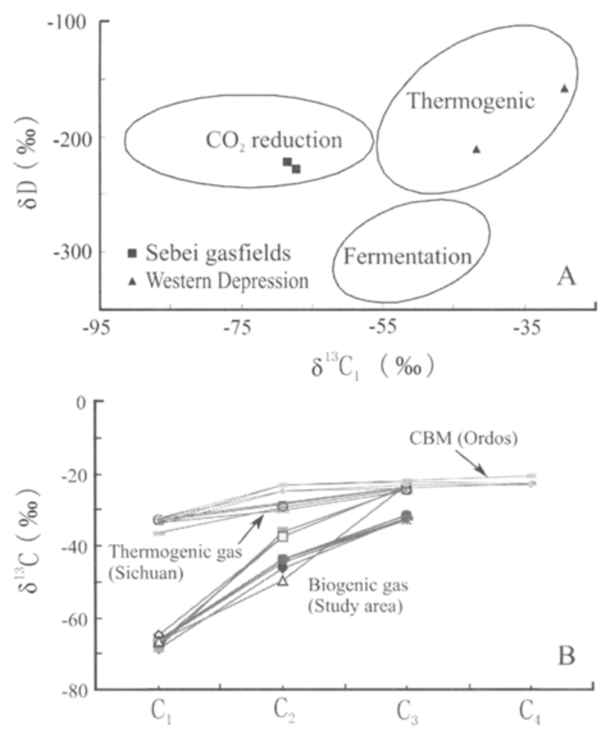

Fig. 4. Gas isotopic compositions as indicators for the biogenic origin of gases in the study area. Fields for thermogenesis, fermentation and CO_2 reduction were taken from Kaplan et al. (1997).

4.2 Hydrocarbon source and gas generation

The dark mud beds of the shallow to semi-deep lake facies in the Sebei Formation are possible sources for the shallow gas (Zhou Zhuhong et al., 1994; Dai Jingxing et al., 2003; Ding Anna et al., 2003). The dark mud beds are presently buried at up to 1500 m depth, with a cumulative thickness of up to 1400 m. These beds account for more than 70% of the sedimentary column, distributed over an area of up to 30000 km^2 (Fig. 1). According to sporopollen assemblages (Dang Yuqi et al., 2003), the lower unit of the Sebei Formation was formed in a shallow lake under relatively wet climatic conditions (1.5 – 1.7 Ma), whereas the middle-upper units contain more evaporates, indicating a cooler and drier climate after 1.5 Ma because of the high altitude.

The hydrocarbon source beds in the study area include organic-lean dark mudstones (with 0.15% – 0.46% TOC and 100 – 200 mg extract per kg rock, Dang Yuqi et al., 2003) and carbonaceous muds containing up to 19% TOC (with an average of 9.06%) and 6000 mg extract per kg rock. Data obtained from the Rock-Eval pyrolysis of the freeze-dried rock samples and elemental analyses of the demineralized rocks (Table 2) indicate dominantly type-III organic matter, and the relatively shallow burial and low vitrinite reflectance values suggest thermally immature sediments. Due to the large difference in paleoclimatic conditions as suggested by the sporopollen data (Gu Shusong, 1993; Dang Yuqi et al., 2003), the $\delta^{13}C$ values of isolated protokerogen samples from the upper-middle units of the Sebei Formation are considerably higher (> –24.5‰) than those from the lower unit (–27.35‰ to –25.79‰).

A sufficient supply and adequate preservation of organic matter is essential to the formation of biogenic gas accumulations (Oremland and Taylor, 1978). Because of the lake basin's high altitude (2600 – 3000 m), high water salinity (> 15%) and strong stratification, the oxidized zone of the lake sediments is narrow, leading to excellent preservation of organic matter in the Quaternary sediments under the Sanhu Region. In the study area, sulfate-reducing bacteria occurred from a few centimeters below the sediment-water interface to a maximum depth of 200 m. Anaerobic bacteria were commonly observed at the bottom of the water column and within the sulfate reduction zone. However, the most favorable conditions for methanogens to thrive appeared to be in the sediments with burial depth of 200 – 1750 m. Mud logging results from several exploration wells indicated that the maximum methane generation in the study area occurred at the depth of 500 – 1500 m, corresponding to a formation temperature of 27 – 55℃. Laboratory incubation experiments using the Quaternary sediment samples collected from the study area indicated that methanogens thrived mostly under 62℃, and virtually no methane was generated during experiments conducted above 75℃ (Deng Yu et al., 1996).

Table 2. Organic enrichment and kerogen composition of Quaternary sediments in the Sanhu Region of the Qaidam Basin

Well No.	Depth (m)	Lithology	H/C	O/C	S_2/S_3	HI	OI	$\delta^{13}C$ (‰)	Kerogen type	R_O(%)	TOC (%)
River mud	–	Dark mud	1.06	0.35	10.99	395	36	-25.0	II_1		0.42
Lake mud	–	Dark mud	0.96	0.29	2.07	169	81	-19.5	II_2	0.43	0.15
Tn1	114.5	Dark mud	0.49	0.20	0.5	48	97	-23.0	III_1	0.35	0.14
Tn1	315.1	Dark mud	0.61	0.19	0.24	18	76	-23.1	III_1	0.45	0.16
Tz2	205.0	Grey mudstone	0.66	0.23	6.67	38	6	-22.4	III_1		0.22
Tz2	300.0	Grey mudstone	5.22	2.29	0.24	22	90	-23.9	III_2		0.25
Tz2	350.0	Grey mudstone	0.59	0.25	0.30	22	75	-21.0	III_1		0.27
Sz6	400.0	Grey mudstone	3.90	1.52	0.31	60	192	-22.6	III_1		0.14
Sz6	520.0	Grey mudstone	0.95	0.16	0.31	46	149	-24.5	III_2		0.22
Sz6	717.0	Grey mudstone	0.78	0.30	0.92	55	60	-22.6	III_1	0.41	0.21
Sz6	973.0	Grey mudstone with carbonaceous band	1.06	0.25	2.22	151	68	-25.8	II_2	0.36	1.47
Sz6	1056	Grey mudstone with carbonaceous band	1.23	0.19	4.69	260	56	-27.2	II_2	0.25	9.48
Ss1	1206	Grey mudstone with carbonaceous band	1.13	0.27	2.40	178	74	-27.4	III_1	0.33	2.51
Ss1	1240	Carbonaceous mudstone with marlstone	0.75	0.19	1.22	67	55	-24.0	III_1	0.43	7.23
Ss1	1422	Grey mudstone with carbonaceous band	0.98	0.24	2.14	129	60	-26.2	III_1	0.27	2.32
Ss1	1537	Grey mudstone with carbonaceous band	0.93	0.27	1.07	69	64	-26.0	III_1	0.47	1.25

Biogenic methane formation usually occurs via one of the two routes, reduction of carbon dioxide and acetate fermentation, even though the latter has both effects: acetate can be converted to methane and carbon dioxide by methanogens, and the resultant fermentative carbon dioxide in turn provides carbon source for the methanogens to add hydrogen to form methane (Balch et al., 1979; Mah, 1981). As discussed earlier, methanogens are common in the Quaternary sediments of the study area. The stable carbon and hydrogen isotopes of the methane in the Sebei Gasfield are significantly different from those of thermogenic gases in the Western Depression of the Qaidam Basin and those from acetate fermentation (Fig. 4). The extremely low acetate concentrations in the potential gas source rocks (6 – 50 μg/g) are clearly favorable to a derivation from carbon dioxide reduction (Ding Anna et al., 2003).

Previous internal studies by PetroChina Qinghai Oilfield Company suggested that a minimum of 0.18% TOC and 30% dark mudstone within the Quaternary sediment column is needed for significant biogenic gas generation, whereas 0.35% TOC and 50% dark mudstone in the sedimentary column are necessary for favorable biogenic gas kitchens (Gu Shusong, 1993; Zhou Zhuhong et al., 1994). Although the specific merit of these criteria is debatable, this approach does not give us a practical tool for preliminary biogenic gas potential evaluation. Based on these criteria, the likely and favorable biogenic gas kitchen areas are estimated to be around 15000 and 4500 km^2, respectively (Fig. 5). Perhaps not surprisingly, all of the known biogenic gas fields occur within the most favorable gas kitchens, with the gas generation intensity greater than 3.5 billion cubic meters (BCM) per km^2.

4.3 Biogenic gas reservoirs

The Quaternary biogenic gas reservoirs in the Sanhu Region were deposited mainly near a shoreline-shallow lake setting, with the reservoir rocks being primarily beach sand sheets and small sand bars. The lithology is dominated by silty detritus, with siltstones and argillaceous siltstones accounting for over 90% of the reservoir volumes. Fine-grained sandstones and oolitic sandstones are seen occasionally. The proportions of quartz, feldspar and other detritus are usually in the ranges of 38% – 60%, 17% – 39% and 5% – 28%, respectively. The sheet-like beach sands extend extensively laterally with each gas field, and some show excellent correlation across several gas fields. The thickness of individual sand layers ranges from 1 – 3 m, with some sand bars up to 6 m. These sandy reservoirs generally show strong vertical heterogeneity but good lateral homogeneity, accounting for 16% – 28% of the total Quaternary sedimentary column.

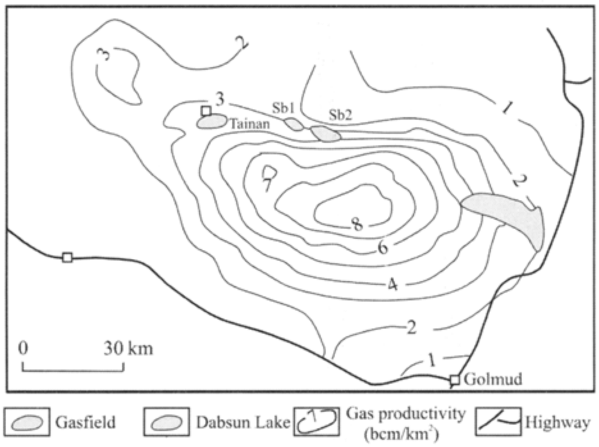

Fig. 5. Variations in gas productivity in the Sanhu Region of the Qaidam Basin showing the relative locations of gas fields and gas source kitchens.

Because all the Quaternary reservoirs in the study area are currently at the early stage of diagenesis, they possess excellent primary porosity (20% – 39%, mostly 22% – 36%). The permeability ranges from 10 to 2694 mD, with an average of 595 mD. The porosity generally decreases with increasing burial depth. The porosity and permeability vary with lithology (Fig. 6), which is more noticeable in deeper strata. As shown in Fig. 7, over 120 porous sand layers have been identified in the Sebei Formation within the Sebei-1 Gasfield Pliocene strata.

4.4 Caprocks and gas seal capacities

The Quaternary mudstones in the study area are characterized by poor consolidation and high porosity. It is highly remarkable that such rocks could form effective seals for such giant gas accumulations as observed in the Tainan, Sebei 1 and 2 gas fields. The following four factors are considered important in this regard.

4.4.1 Differential porosity texture

As mudstones are dominated by fine-grained clay minerals, they have much smaller pore throats and thus much higher breakthrough pressure than sandstones. Results obtained from the Qinghai Oilfield Company database indicated that the microporosities in the mudstones are mainly 16 – 160 nm in diameter, 2 – 3 orders of magnitude lower than those of sandstones. The difference in porosity texture between the different lithologies led to an increase in permeability from mudstone, through silty mudstone and argillaceous siltstone, to siltstone (Fig. 6). A difference of over three orders of magnitude in permeability between mudstone and siltstone would effectively stop or reduce the escape of gases in the underlying strata, forming the backbone of the Quaternary gas seals.

4.4.2 Hydraulic seal

The water saturation levels of the Quaternary mudstones are up to 80% – 99%, which is very important for sustaining the gas sealing capacity of the rock. When its pores are filled with water with high salinity, the gas permeability of a mudstone will be drastically reduced for three different reasons. Firstly, the increased elasticity reduces the probability of microfracture formation. Secondly, the swelling of hydrophilic clay minerals reduces the net porosity and pore throat dimension of the rock. Thirdly, the presence of water increases the rock capillary pressure and thus the seal breakthrough pressure. This is in contrast to the siltstones and sandstones that usually show much larger pore throats.

4.4.3 Hydrocarbon gradient seal

Dark mudstones serve as both source rocks and caprocks for the biogenic gas. As the methanogenesis in a dark mudstone proceeds, a gradient in methane concentration will be created, leading to diffusion of methane from high potential to low potential field. The diffusion of methane from this rock would to some extent stop or slow down the vertical flow of methane from the underlying rocks, thus forming a gas seal virtually by the hydrocarbon concentration gradient.

4.4.4 Regional caprocks

The interplay of the above three factors is vital for the formation of immediate gas seals with the biogenic source/reservoir beds. The presence of 400 – 800-m-thick mudstone, anhydrite and halite above the vertically stacked, multiple gas pays also provides excellent regional caprocks for the biogenic gas pays.

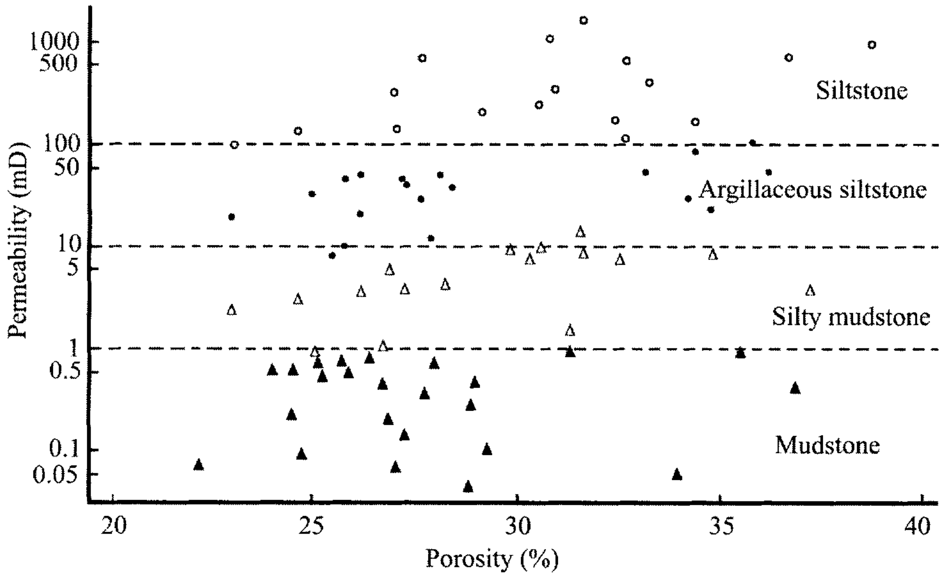

Fig. 6. Relationships between porosity and permeability as a function of reservoir lithology in the study area.

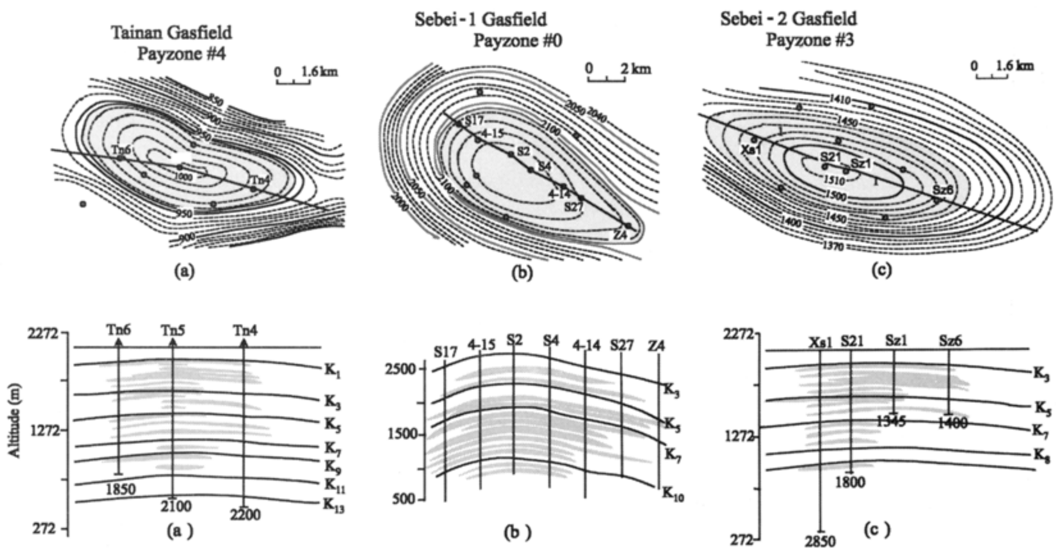

Fig. 7. Structural maps and cross sections of the three largest biogenic gas fields in the Qaidam Basin.

4.5 Biogenic gas traps

Figure 7 shows the structural enclosures and cross sections of the three major gas fields in the study area. A total of twelve structural traps have been identified so far in the Sanhu Region of the Qaidam Basin (Fig. 1), 11 of which are surface structures. All of them are Quaternary anticlines, occurring along the Northern Slope of the Eastern Depression. They are distributed in three rows, trending in an NW-SE direction. The amplitude of the anticlines decreases from north to south: the two anticlines in the northernmost position have large enclosure areas (600 and 370 km^2), big amplitude (450 and 370 m), and steep dipping (35° and 20°, respectively). The five anticlines in the middle row show large variations in enclosure area (596 – 96 km^2) and amplitude (200 – 18 m), with relatively gentle dipping (< 5°). The Sebei-1 and -2 structures are located on the third row of the structural belt, with extremely small dipping (< 1°30′). Their enclosure areas are 71 and 128 km^2, and amplitudes 60 and 17 m, respectively.

Surface erosion and fault intensity in the Quaternary sediments decreased from north to south. For the three rows of structures, drilling results indicated that the residual Quaternary sedimentary columns increased from 385 – 470 m in the north, 848 – 1156 m in the middle, and over 1600 m in the south. A number of highly angular normal faults perpendicular to the anticline axis were observed in the structures of the north and middle rows. However, only 2 small, near-surface, normal faults have been observed in the Sebei-2 anticline of the south row.

The above structural variations generally favor the better preservation of anticlinal structures, thus improving prospect for gas accumulation in the south row. Exploration results showed that little gas has been discovered from the structures in the north row; there have been found two small gas fields (Tuofengshan and Yanhu) and a gas-bearing anticline (Taijilaier) in the middle row, and two giant gas fields (Sebei-1 and -2) in the south row.

In addition, a giant gas field has also been discovered recently in the Tainan anticlinal structure. This structure is located within the Central Sag area of the Eastern Depression, adjacent to the Northern Slope (Fig. 1). It is a near E-W trending, syndepositional, short-dimension subtle anticlinal structure, with no traceable faults or surface erosion. The structure has extremely gentle dipping, 1°15′ – 1°35′ in the south and 1°35′ – 1°45′ in the north flank. Its enclosure area is 104 km^2, and amplitude 110 m.

Therefore, the most favorable traps for gas accumulation in the study area are located on the North Slope, near the depocenters and effective gas kitchens in the Central Sag area. These localities have experienced only mild tectonic activities, with relatively little faulting.

4.6 Biogenic gas accumulation models

All of the biogenic gas accumulations in the study area occurred in vertically stacked payzones, each with separate gas-water contact. As the Quaternary sediments were deposited in rhythmic bands, most of the thin mudstone and shale layers interbedded with sandy/silty beds can only act as dynamic barriers. Only those thick mudstones located near the top of each rhythmic cycle could be considered effective seals to prevent upward gas migration.

Detailed examination of the Tainan Gasfield by Dai Jingxing et al. (2003) indicated that the Tainan anticline was initiated at the Early Pleistocene (Late Himalayan orogeny) because of the compressing force from north and south directions (Fig. 8). During the deposition of the K_{11} marker, the amplitude of the Tainan anticline had reached a few meters. This was followed by a relatively calm period of structural development. After the deposition of the K_7 marker, the anticlinal development was accelerated, with the structural amplitude reaching approximately 30 m by the time of the K_3 deposition. During the Middle-Late Pleistocene to Holocene, the Qinghai-Xizang (Tibet) Plateau was strongly compressed by the subducting Indian Platform. The resultant Tainan anticlinal structure has an amplitude of 110 m for the K_9 marker. The structural evolution is similar at the Sebei-1 and Sebei-2 gas field locations, except that the structures were formed slightly earlier.

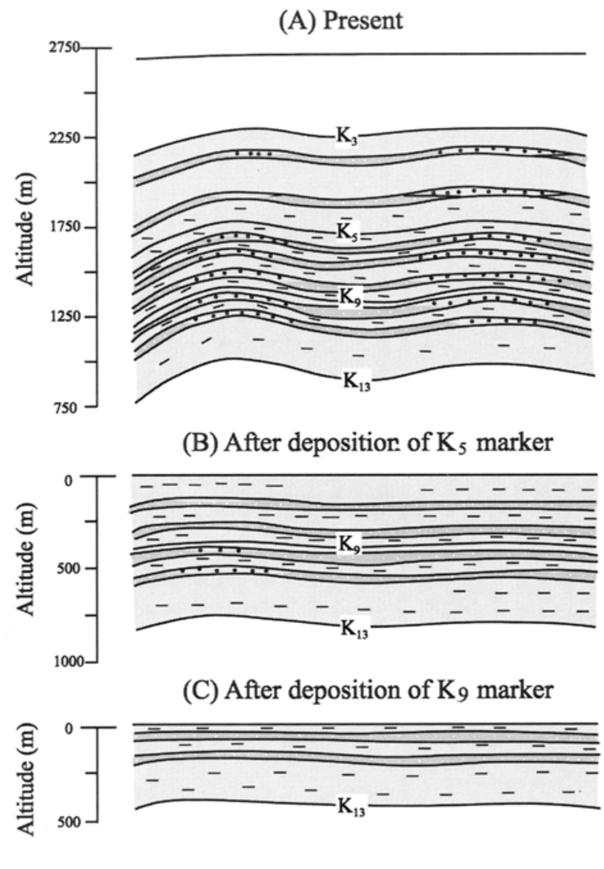

Fig. 8. Structural evolution of the Tainan anticline.

Figure 9 illustrates the expected sequence of events as biogenic gas migrated into a previously water wet structure. The migrating oil initially entered the coarse sand/silt layer immediately below the thick mudstone caprocks, and only a relatively small part of the accumulation was initially gas saturated. As more gas migrated into the structure, the increased buoyant pressure caused the gas to displace water and drove the gas-water contact down. When the gas-water contact went below the top of the underlying porous sand/silt layer, the gas began to accumulate in this new reservoir zone. Freshly generated gas, generated from one or both sides of the trap, was forced to advance into the structure and drove the gas-water contact of this new

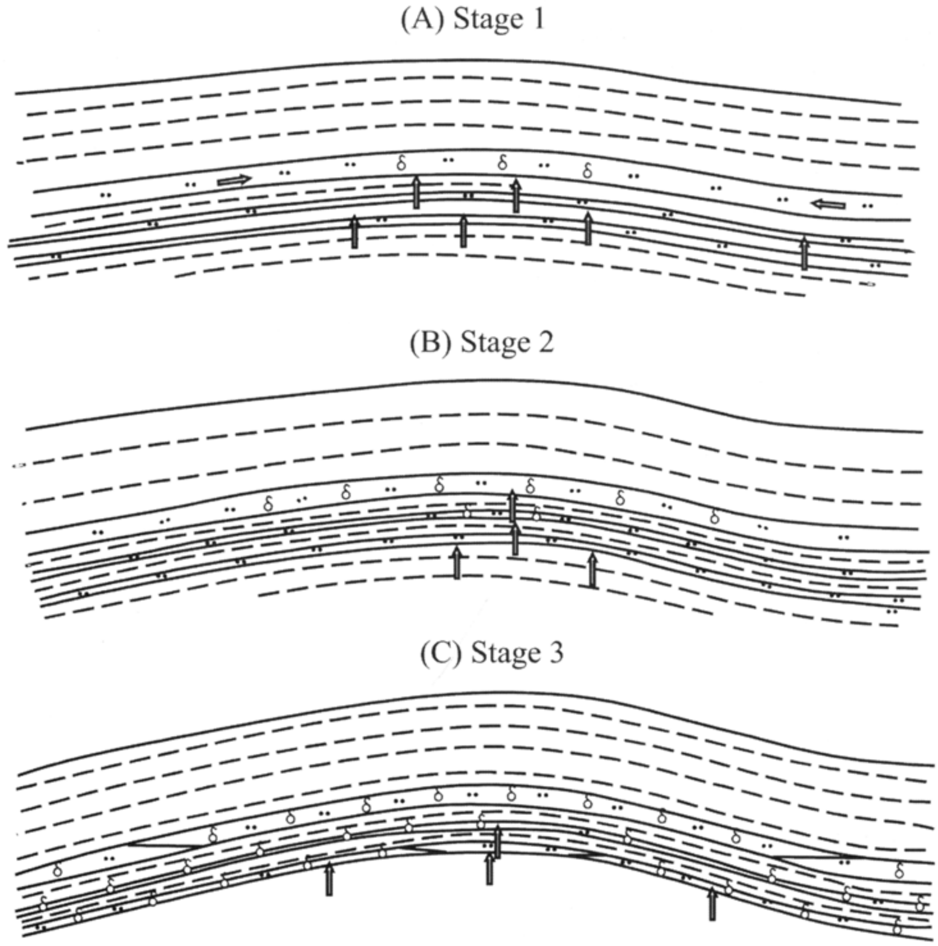

Fig. 9. Generalized biogenic gas accumulation model for the Sanhu Region of the Qaidam Basin.

reservoir zone further down. Eventually, multiple payzones with close vertical approximation would be formed for a single trap. These payzones can be considered as a single gas reservoir unit, ultimately controlled by the same thick mudstone caprocks. As more gas was accumulated in the trap, the gas column grew. When the buoyant pressure became greater than the critical breakthrough point of the mudstone seal, some of the pores in the seal open and gas leakage occurred. When gas leakage reduced the net gas buoyant pressure to or below the mudstone breakthrough point, the mudstone became a gas seal again and gas accumulation continued. Therefore, the formation of biogenic gas accumulations in the study area is the result of highly dynamic processes.

Testing results showed that almost 99% of the biogenic gas reserves occurred in the Lower-Middle Pleistocene strata (between K_2 to K_{10} marker). Key characteristics of the biogenic gas accumulations in the study area include (1) shallow burial depth (500 - 1500 m); (2) strong structural control on gas yields, with the gas yields decreasing drastically from the top to the flanks of the anticlinal structure; (3) the presence of many mudstone interbeds within the gas column, leading to multiple gas-water systems; (4) high free gas flow during testing (7 - 21, up to 50 mcf/d); and (5) increasing trap enclosure area and gas reserves with increasing reservoir depth for all of the major gas fields.

5 Conclusions

This study provided an overview on the geological setting and geochemical characteristics of the Pleistocene shallow gas accumulations in eastern Qaidam Basin, NW China. The dominance of methane (> 99.9%) and the $\delta^{13}C$ and δD values of methane (−68.51‰ to −65.00‰ and −227.55‰ to −221.94‰, respectively) in these gases suggested a biogenic origin associated with methanogenesis of sedimentary organic matter under relatively low temperatures (< 75℃). The formation of a large quantity of biogenic gas in the Pleistocene sediments of the study area is possible as the sufficient supply and adequate preservation of organic matter is ensured by the lake basin's high altitude (2600 - 3000 m), high water salinity (> 15%) and strong stratification. The deposition and extensive lateral occurrence of shoreline-lacustrine sands/silts in beach sand sheets and small sand bars provided excellent storage spaces for the biogenic gases generated from interbedded dark mudstones. Effective gas seals are largely related to the variation in porosity of different lithotypes, the hydraulic seal due to the high water saturation of the mudstones, the hydrocarbon gradient created because of the due role of dark mudstones as both gas source rock and caprock, and the presence of a regional caprock consisting of 400 - 800-m-thick mudstones and salts above the vertically stacked gas pays. The most favorable traps for large gas accumulation tend to occur on the structural slopes near the major gas kitchens, in large but gentle anticlines that have experienced only mild tectonic activities with relatively little faulting.

Acknowledgements The authors thank the Research Institute of Petroleum Exploration and Development (RIPED) and Qinghai Oilfield Company of PetroChina for providing samples and making much of their internal data accessible to this study.

References

Albert D. B., Martens C. S., and Alperin M. J. (1998) Biogeochemical processes controlling methane in gassy coastal sediments. Part 2. Groundwater flow control of acoustic turbidity in Eckernforde Bay sediments [J]. *Continental Shelf Research.* **18**, 1771 - 1793.

Balch W. E., Fox G. E., Magrum L. J., Woese C. R., and Wolfe R. S. (1979) Methanogens: Reevaluation of a unique biological group [J]. *Microbiology Review.* **43**, 260 - 296.

Baylis S. A., Cawley S. J., Clayton C. J., and Savell M. A. (1997) The origin of usual gas seeps from onshore Papua New Guinea [J]. *Marine Geology.* **137**, 109 - 120.

Berner U. and Faber E. (1988) Maturity related mixing model for methane, ethane and propane, based on carbon isotopes [J]. *Organic Geochemistry.* **13**, 67 - 72.

Claypool G. E. and Kaplan I. R. (1974) The origin and distribution of methane in marine sediments. In *Natural Gases in Marine Sediments* (ed. I. R. Kaplan) [M]. pp. 99 - 139. Plenum Press, New York.

Dai Jingxing, Chen Jianfa, Zhong Ningning, Pang Xiongqi, and Qin Shengfei (2003) *Giant Gas Fields in China and Their Sources* [M]. pp. 199. Science Press, Beijing (in Chinese).

Dang Yuqi, Hou Zesheng, Xu Ziyuan, Zhang Daowei, and Zhao Mingjun (2003) Biogenic gas accumulations in the Qaidam Basin [J]. *Xinjiang Petroleum Geology.* **24**, 374 - 378 (in Chinese with English abstract).

Deng Yu, Zhang Hui, Qian Yibai, Qi Houfa, Guan Deshi, and Zhang Xiang (1996) The classification and distribution of anaerobic microorganisms in the Quaternary sediments of the Qaidam Basin [J]. *Acta Sedimentologica Sinica.* **14**, 220 - 226 (in Chinese with English abstract).

Ding Anna, Wang Mingming, Li Bengliang, Zhang Daowei, Peng Xiuli, and Hui Rongyue (2003) Biogenic gas formation and its source characteristics [J]. *Natural Gas Geosciences.* **14**, 402 - 407 (in Chinese with English abstract).

Faber E. (1987) Zur Isotopengeochemie gasformiger Kohlenwasserstoffe [J]. *Erdol Kohle.* **103**, 210 - 218.

Flodgate G. D. and Judd A. G. (1992) The origin of shallow gas [J]. *Continental Shelf Research.* **12**, 1145 - 1156.

Galimov E. (1988) Source and mechanisms of formation of gaseous hydrocarbons in sedimentary rock [J]. *Chemical Geology.* **1**, 77 - 95.

Gu Shusong (1993) *Biogenic Gas Accumulations and Exploration Practice in the Qaidam Basin* [M]. Petroleum Industry Press, Beijing (in Chinese).

Gu Shusong (1996) Biogenic gas accumulation models in the Quaternary of the Qaidam Basin [J]. *Natural Gas Industry.* **16**, 6 - 9 (in Chinese with English abstract).

Guan Zhiqiang, Xu Ziyuan, Zhou Ruinian, and Jiang Guifeng (2001) Geological controls on the Quaternary biogenic gas accumulations in the Qaidam Basin [J]. *Natural Gas Industry.* **21**, 1 - 5.

James A. T. (1983) Correlation of natural gas by use of carbon isotopic distribution between hydrocarbon components [J]. *Bulletin of American Association of Petroleum Geologists.* **67**, 1176 - 1191.

Jenden P. D., Drazan D. J., and Kaplan I. R. (1993) Mixing of thermogenic natural gases in Northern Appalachian basin [J]. *Bulletin of American Association of Petroleum Geologists.* **77**, 980 - 998.

Kang Zhuling, Fu Chengde, Cui Shufeng, and Yang Xianyi (2000) *Largeand Medium Sized Gasfields in China* [M]. Petroleum Industry Press, Beijing (in Chinese).

Kaplan I. R., Galperin Y., Lu S. T., and Lee R. P. (1997) Forensic environmental geochemistry: Differentiation of fuel types, their sources and release times [J]. *Organic Geochemistry.* **27**, 289 - 317.

Lin Chunming, Gu Lianxing, Li Guangyue, Zhao Yanyan, and Jiang Weishan (2004) Geology and formation mechanism of late Quaternary shallow biogenic gas reservoirs in the Hangzhou Bay area, eastern China [J]. *Bulletin of American Association of Petroleum Geologists.* **88**, 613 - 625.

Littke R., Cramer B., Gerling P., Loptin N. V., Poelchau H. S., Schaefer R. G., and Welte D. H. (1999) Gas generation and accumulation in the West Siberian Basin [J]. *Bulletin of American Association of Petroleum Geologists.* **83**, 1642 - 1665.

Liu Luofu, Zhao Suping, Chen Lixin, and Huo Hong (2005) Distribution of major hydrocarbon source rocks in the major oil-gas-bearing basins in China [J]. *Chinese Journal of Geochemistry.* **24**, 17 - 29.

Mah R. A. (1981) The methanogenic bacteria, their ecology and physiology. In *Trends in the Biology of Fermentations for Fuels and Chemicals* (eds. A. Hollsender and R. Rabson) [M]. pp. 357 - 374. Plenum Press, New York.

Martini A. M., Walter L. M., Budai J. M., Ku C. W., Kaiser C. J., and Schoell M. (1998) Genetic and temporal relations between formation waters and biogenic methane: Upper Devonian Antrim Shale, Michigan Basin, USA [J]. *Geochimica et Cosmochimica Acta.* **62**, 1699 - 1720.

Okyar M. and Ediger V. (1999) Seismic evidence of shallow gas in the sediment on the shelf of Trabzon, southeastern Black Sea [J]. *Continental Shelf Research.* **19**, 575 - 587.

Oremland R. S. and Taylor B. F. (1978) Sulfate reduction and methanogenesis in marine sediments [J]. *Geochimica et Cosmochimica Acta.* **42**, 209 - 214.

Qi Houfa, Guan Deshi, Quan Yibai, and Zhang Xiang (1997) *Biogenic Gas Accumulations in China* [M]. Petroleum Industry Press, Beijing (in Chinese).

Rashid M. A. and Vilks G. (1977) Environmental controls of methane production in Holocene basin in eastern Canada [J]. *Organic Geochgemistry.* **1**, 123 - 135.

Rice D. D. and Claypool G. E. (1981) Generation, accumulation and resource potential of biogenic gas [J]. *Bulletin of American Associa-

tion of Petroleum Geologists. **65**, 5 – 25.

Sakata S., Sano Y., Maekawa T., and Igari S. I. (1997) Hydrogen and carbon isotope composition of methane as evidence for biogenic origin of natural gases from the Green Tuff Basin, Japan [J]. *Organic Geochemistry.* **26**, 399 – 407.

Schoell M. (1980) The hydrogen and carbon isotopic composition of methane from natural gases of various origins [J]. *Geochimica et Cosmochimica Acta.* **44**, 649 – 662.

Schoell M. (1983) Genetic characterization of natural gases [J]. *Bulletin of American Association of Petroleum Geologists.* **67**, 2225 – 2238.

Schoell M. (1988) Multiple origin of methane in the earth [J]. *Chemical Geology.* **1**, 1 – 10.

Shurr G. W. and Ridgley J. L. (2002) Unconventional shallow biogenic gas systems [J]. *Bulletin of American Association of Petroleum Geologists.* **86**, 1939 – 1970.

Siebert M. L. and Hattingh W. H. J. (1967) Estimation of methane-producing bacterial numbers by the most probable number (MPN) technique [J]. *Water Resources.* **1**, 13 – 19.

Stahl W. (1974) Carbon isotope fractionations in natural gases [J]. *Nature.* **251**, 134 – 135.

Stahl W. (1977) Carbon and nitrogen isotopes in hydrocarbon research and exploration [J]. *Chemical Geology.* **20**, 121 – 149.

Su Aiguo, Zhu Yangming, and Liang Digang (2003) Oil source and reservoir formation mechanisms of the Nanbaxian oil and gas field, Qaidam Basin [J]. *Geochimica.* **32**, 393 – 399 (in Chinese with English abstract).

Sundberg K. R. and Bennett C. R. (1983) Carbon isotope paleothermometry of natural gas. In *Advances in Organic Geochemistry* 1981 (eds. M. Bjorφy, P. Albrecht, and C. Cornford) [M] pp. 769 – 774. John Wiley & Sons, Chichester, England.

Vilks G. M., Rashid A., van der Linden J. M. (1974) Methane in recent sediments of the Labrador shelf [J]. *Canadian Journal of Earth Science.* **11**, 1427 – 1434.

Wang Wanchun, Liu Wenhui, Xu Yongchang, Shen Ping, Kang Yan, and Ren Junhu (2005) Genetic identification of natural gases from shallow reservoirs in some oil- and gas-bearing basins of China [J]. *Chinese Journal of Geochemistry.* **24**, 91 – 95.

Whiticar M. (1990) A geochemical perspective of natural gas and atmospheric methane [J]. *Organic Geochemistry.* **16**, 531 – 547.

Xu Wang (1997) Prospective regions for shallow gas accumulations in China [J]. *Natural Gas Industry.* **17**, 1 – 5 (in Chinese with English abstract).

Zhang Xiaobao, Hu Yong, Ma Liyuan, Peng Dehua, Meng Zhifang, Duan Yi, and Zhou Shixin (2002) Stable carbon isotopes, origin and occurrence of natural gases related Tertiary hypersaline sediments in the western Qaidam Basin [J]. *Science in China* (Series D). **32**, 598 – 608 (in Chinese with English abstract).

Zhou Zhuhong, Zhou Ruilian, and Guan Ziqiang (1994) Geochemical characteristics of the Quaternary gas source beds in the eastern Qaidam Basin [J]. *Petroleum Exploration & Development.* **21**, 30 – 36 (in Chinese with English abstract).