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Origin and accumulation of high-maturity oil and gas in deep parts of the Baxian Depression, Bohai Bay Basin, China

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Abstract: Great quantities of light oil and gas are produced from deep buried hill reservoirs at depths of 5,641 m to 6,027 m and 190 °C to 201 °C in the Niudong-1 Well, representing the deepest and hottest commercial hydrocarbons discovered in the Bohai Bay Basin in eastern China. This discovery suggests favorable exploration prospects for the deep parts of the basin. However, the discovery raises questions regarding the genesis and accumulation of hydrocarbons in deep reservoirs. Based on the geochemical features of the hydrocarbons and characteristics of the source rocks as well as thermal simulation experiments of hydrocarbon generation, we conclude that the oil and gas were generated from the highly mature Sha-4 Member (Es_4) source rocks instead of thermal cracking of crude oils in earlier accumulations. The source kitchen with abnormal pressures and karsted carbonate reservoirs control the formation of high-maturity hydrocarbon accumulations in the buried hills (i.e., Niudong-1) in conjunction with several structural–lithologic traps in the Es_4 reservoirs since the deposition of the upper Minghuazhen Formation. This means the oil and gas exploration potential in the deep parts of the Baxian Depression is probably high.

Key words: High mature oil and gas, origin, accumulation, deep part of Baxian Depression

1 Introduction

The Bohai Bay Basin contains the largest oil resources with the highest oil and gas production in China (Zhou et al, 2009). In the basin, the hydrocarbons are mainly distributed in middle and shallow reservoirs buried at depths of less than 3,200 m (Niu et al, 2002). The produced hydrocarbons are of low–middle maturity because the major source rocks are of low–middle maturity. The Bohai Bay Basin is a rift basin (Jin and McCabe, 1998) and the Baxian Depression in the basin is a typical semigraben (Fig. 1) filled with Eocene lacustrine sediments; the Kongdian, Shahejie, and Dongying Formations (Fig. 1). From the bottom to the top, the Shahejie Formation is divided into four members: Sha-4 (Es_4), Sha-3 (Es_3), Sha-2 (Es_2), and Sha-1 (Es_1). The major source rocks are in Es_3 and Es_4 as well as several reservoirs in the Baxian Depression. Near the source rocks in the Es_3 and Es_4 members are buried hills formed by Tertiary normal faults. The buried hills consist of Precambrian carbonates, which are good reservoir rocks with a large number of caves and fractures because of karstification before burial in the Eocene.

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Because of technical advances, significant hydrocarbon accumulations were discovered at depths greater than 4,000 m or even 5,000 m. In particular, highly productive hydrocarbon accumulations were found in buried hills at a depth of about 6,000 m in the Baxian Depression. In the Niudong-1 Well, the Precambrian buried hill reservoirs at depths of 5,671 m to 6,027 m record a daily flow of light oil of 642.9 m^3 and natural gas of 56×10^4 m^3, which indicates that there are abundant hydrocarbon resources in the deep reservoirs of the Bohai Bay Basin and these reservoirs are important exploration targets.

Compared with deep accumulations outside China (Pusey, 1973), the Niudong-1 Well is similar to them in terms of reservoir temperature and production rate. Presently, there is an ongoing debate regarding the genesis of deep hydrocarbons. Opinions include the genesis of crude oil from cracking of deeply buried ancient oil accumulations (Schenk et al, 1997; Tsuzuki et al, 1999), organic matter pyrolysis of deeply buried source rocks (Hunt, 1979; Mango, 1991; Price, 1993), crack and pyrolysis genesis (Quigley and Mackenzie, 1988; Domine et al, 1998), and inorganic genesis (Schoell, 1980). Hydrocarbon accumulation in deep reservoirs is quite complex and many controlling factors have been considered for different geological settings (Hunt, 1990; Al-Shaieb

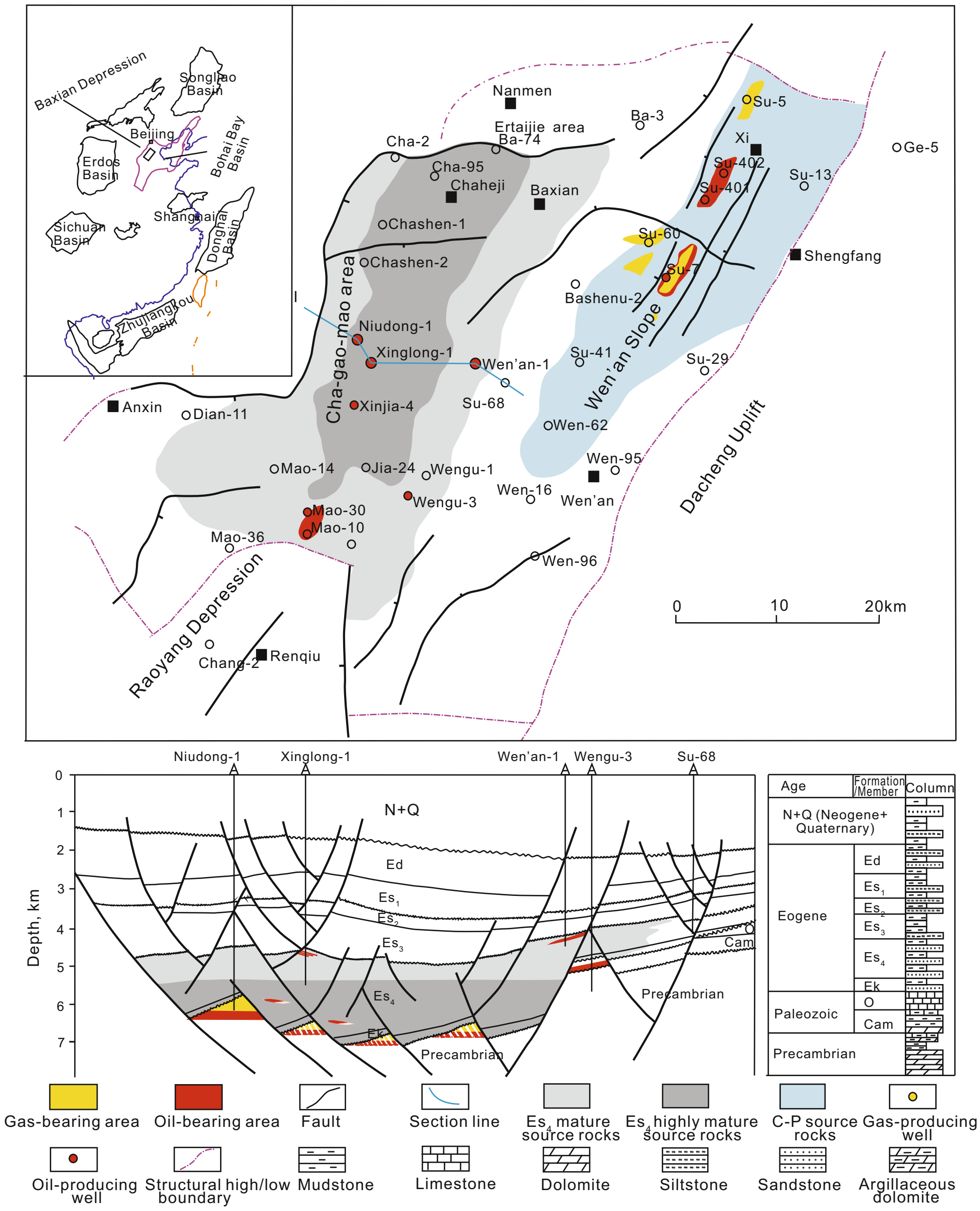

Fig. 1 A map showing the location of the Baxian Depression, the structural profile, and stratigraphic column as well as oil and gas distribution deep in the Baxian Depression

et al, 1994; Smith Jr and Davies, 2006). As a result, many hydrocarbon accumulation models have been proposed. In the Anadarko Basin in USA, for example, self-sourced gas accumulations were discovered at burial depths of 7,663 m to 8,083 m in Lower Ordovician carbonate rocks that are the deepest in the world with commercial-sized oil accumulations at 6,553 m (Davis and Northcutt, 1989).

In the deep zones of the Baxian Depression, below 4,000 m, the source rocks occur in stratigraphic intervals of the Es_3, Es_4, and the Kongdian Formation, whereas the reservoirs are present in the Precambrian buried hills and Shahejie Formation sandstones. Although the hydrocarbon accumulation conditions are favorable, the hydrocarbon genesis, crude oil cracking of earlier formed paleo-oil accumulations, or pyrolysis of highly mature deep source rocks is controversial. Furthermore, the effect of abnormal pressure, faulting, and reservoir-caprock assemblage in the deep zones on the hydrocarbon accumulation is unknown. Such basic geologic questions require investigation. Based on a regional hydrocarbon geologic survey, we analyzed the hydrocarbon genesis of the Niudong-1 Well by using thermal simulation experiments and then proposed deep hydrocarbon genesis and distribution patterns by investigating the essential elements and geological processes. We also point out future exploration targets. The results are enlightening for deep hydrocarbon exploration in the Bohai Bay Basin.

2 Hydrocarbon distribution and geochemical characteristics in deep zones

2.1 Hydrocarbon distribution characteristics

The Baxian Depression is similar to other depressions in the Bohai Bay Basin. In this depression, 60% of the oil and gas reserves discovered over several decades of exploration are mainly distributed in Tertiary reservoirs shallower than 3,000 m. Several hydrocarbon reservoirs were discovered in the Permo–Carboniferous at depths greater than 4,000 m in the Suqiao-Wen'an area in the northeastern Baxian Depression (Fig. 1), where the hydrocarbons were generated by Permo–Carboniferous coal measure source rocks (Su et al, 2003). Fig. 1 shows the areal distribution of the source rocks. When reburied to depths greater than 3,500 m in the Neogene, the source rocks generated for a second time hydrocarbons dominated by highly mature light oil and natural gas (Zhao et al, 2010a). These hydrocarbons could form accumulations separately or together with the hydrocarbons sourced from the Shahejie Formation (Zhao et al, 2010b). In the Suqiao-Wen'an area, therefore, the distribution of oil and gas in the Permo–Carboniferous is mainly controlled by the distribution of coal measure source rocks and their regeneration of hydrocarbons. There will be no further discussion on the genesis and accumulation of hydrocarbons derived from the Permo-Carboniferous source rocks in this paper.

In 2011, a high-yield hydrocarbon reservoir was discovered in the Precambrian Wumishan Formation buried hill at a depth of 6,000 m. To date, it is the deepest and hottest (201 °C) reservoir in the Bohai Bay Basin. In addition to this discovery, the Xinglong-1 and Wen'an-1 wells led to the discovery of lithologic reservoirs in the Es_4, and the Wengu-3 Well resulted in the discovery of intraburied hill reservoirs in the Cambrian Fujunshan Formation (Fig. 1). These findings indicate that zones deeper than 4,000 m in the Baxian Depression possess favorable hydrocarbon generation conditions and high exploration potential at high temperatures. However, there are still many questions regarding the source, genesis and accumulation, which hinder exploration.

2.2 Analysis of source rocks for deep hydrocarbons

Previous studies (Li et al, 2008) indicated that the deep hydrocarbons in the Baxian Depression were mainly derived from the Es_3 and Es_4. However, these two source rock intervals are different in terms of hydrocarbon generation capacity, properties, and distribution. Therefore, it is necessary to determine which one the deep hydrocarbons are from in order to make further exploration breakthroughs.

We looked at the correlation between the crude oil and the soluble organic material (SOM)–saturated hydrocarbon in the Shahejie Formation source rocks. The crude oil in the Niudong-1 Well has a closer relation to the Es_4 source rocks than to the Es_3 source rocks in terms of Pr/Ph, Pr/nC_{17}, and Ph/nC_{18}. The crude oil from the Wen'an-1 and Wengu-3 wells also correlates well with the Sha-4 Member source rocks (Table 1).

Based on the analytical results of sterane and terpane, the crude oil from the Niudong-1 Well has a close relation to the Es_4 source rocks rather than to the Es_3 source rocks in terms of C_{27}cholestane/C_{29}cholestane and C_{28}cholestane/C_{29}cholestane (Table 2). The C_{29}cholestane20S/20(S+R) and $C_{29}\beta\beta/\Sigma C_{29}$ value is 43.6% and 47.5%, respectively, close to the equilibrium value which shows the high maturity of the crude oil in the Niudong-1 Well. The correlation between the crude oil from the Wen'an-1 and Wengu-3 Wells and the Es_4 source rocks suggests that the deep oil in the Baxian Depression is mainly from the Es_4 source rocks (Li et al, 2006).

Gas production is higher in the deep zones, especially

Table 1 Parameter correlation of deep oil in the Baxian Depression vs. saturated hydrocarbons in the source rocks

Well	Interval, m	Horizon	Sample	Pr/Ph	Pr/nC_{17}	Ph/nC_{18}	Correlation with crude oil
Niudong-1	4270–4280	Es_3	Source rock	2.75	0.6	0.2	Poor
	5641–6027	Jxw	Crude oil	1.21	0.1	0.07	Correlated
	4915–4921	Es_4	Source rock	1.54	0.3	0.17	
Wen'an-1	4192–4224	Es_4	Crude oil	3.01	0.37	0.11	Correlated
	4425–4435	Es_4	Source rock	2.71	0.32	0.12	
Wengu-3	4470–4489	Cam_{1f}	Crude oil	2.06	0.08	0.04	Correlated
Xinglong-1	5380–5390	Es_4	Source rock	2.67	0.13	0.05	

Table 2 Correlation of crude oil in the Niudong buried hills vs. sterane and terpane in the source rocks

Well	Interval, m	Horizon	Sample	5α-C_{27}/5α-C_{29}	5α-C_{28}/5α-C_{29}	$C_{29}\alpha\alpha\alpha$20S/20(S+R), %	$C_{29}\beta\beta$/ΣC_{29}, %	Correlation with crude oil
Niudong-1	4210–4220	Es_3	Source	0.89	0.59	31.65	42.7	Poor
	5641.5–6027	Jxw	Oil	1.84	1.03	43.6	47.5	Correlated
	4915–4921	Es_4	Source	1.19	0.56	31.2	33.2	
Wen'an-1	4192–4224.2	Es_4	Oil	0.28	0.26	49.0	58.7	Correlated
	4425–4435	Es_4	Source	0.75	0.50	43.2	42.4	
Wengu-3	4470–4489	Cam_{1f}	Oil	1.09	0.72	45.4	43.1	Correlated
Xinglong-1	5380–5390	Es_4	Source	1.15	0.67	47.7	45.4	

in the Niudong-1 Well. In February and May of 2011, gas samples were collected from depths between 5,639 m and 6,027 m in the Niudong-1 Well, and chromatography and carbon isotope analyses were carried out. The dryness factor was 0.84–0.88 and the $\delta^{13}C$ of methane was about −38.7‰, reflecting the high maturity and poor kerogen type of the source rocks (Shen et al, 2011; Chen et al, 2012). When plotted on Dai's gas identification chart (Dai, 1992), both of them are in the range associated with condensate generated by type II_2 kerogen (Fig. 2). Thus, the oil pool in the Niudong reservoir is actually a condensate accumulation.

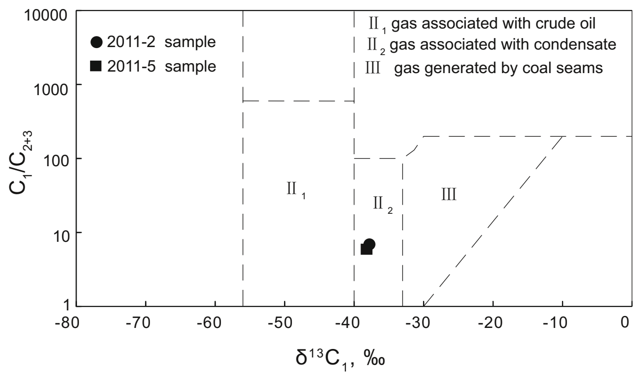

Fig. 2 Natural gas identification chart of the Niudong-1 Well

It is geologically important to determine the maturity of deep hydrocarbons, because it helps to understand hydrocarbon generation and accumulation. Biomarkers in light oils are not very reliable indicators of maturity; nonetheless, diamantane is a good maturity marker for the crude oil in the Niudong-1 Well.

Maturity can be better shown by the diamantane distribution in high-maturity crude oil (Fu and Li, 2001). A positive linear relation exists between the diamantane index I of source rock extracts with known maturities and the vitrinite reflectance in samples from the Tarim and Erdos basins (Chen et al, 1996; Huang et al, 1996; Li et al, 2010; Fig. 3). The diamantane index is defined as I = 1 − MA/(1 − MA + 2 − MA). Multiple diamantanes were detected in the crude oils of the Niudong-1 Well (Fig. 4, Table 3). When the calculated diamantane index I is plotted on Fig. 3, it is seen that the crude oil maturity of the Niudong-1 Well corresponds to a vitrinite reflectance of around 1.8%.

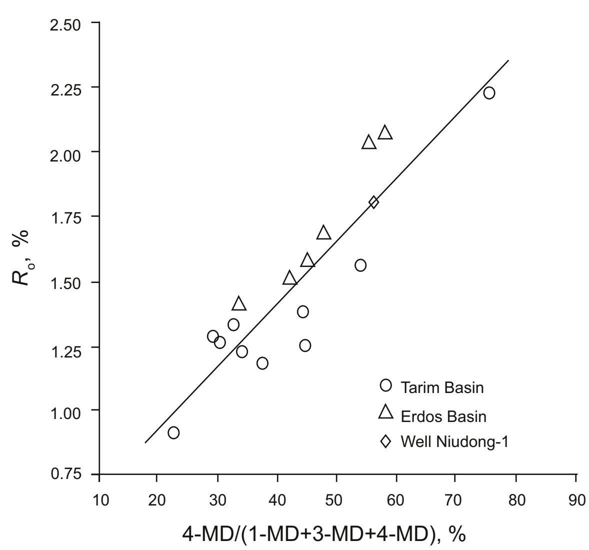

Fig. 3 Diamantane index I and II vs. $\%R_o$

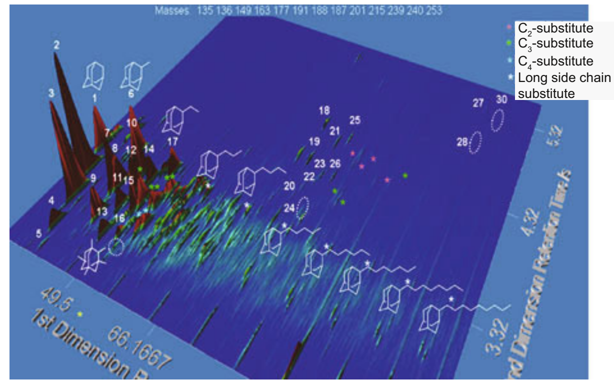

Fig. 4 Full 2D gas chromatograph and time-of-flight mass spectra of diamantane in crude oil from the Niudong-1 Well

Table 3 Identification of peak numbers in Fig. 4

Peak No.	Compound	Abbreviation
2	1-methyl diamantane	1-MA
6	2-methyl diamantane	2-MA
19	4-methyl bidiamantane	4-MD
21	1-methyl bidiamantane	1-MD
25	3-methyl bidiamantane	3-MD

Likewise, the determination of gas maturity is also geologically important. Gas chromatography of natural gas produced in the Niudong-1 Well was used to classify the maturity of the crude oil based on the calculated paraffin wax index and heptane value (Xu et al, 2008). The calculated paraffin index and heptane value fall in the R_o range of 1.8% to 2.1% (left plot in Fig. 5). The benzene/cyclohexane and toluene/methylcyclohexane values of natural gas rise with maturity and the values of the Niudong-1 Well are in the R_o range of 1.8% to 2.1% as well (right plot in Fig. 5), which indicates that the natural gas in the Niudong-1 Well is of high maturity. The R_o values in Fig. 5 were measured by using thermal simulations for the oil and source rock samples.

3 Genesis of deep hydrocarbons

3.1 Statement of the problem

It is necessary to study hydrocarbon genesis because the deep hydrocarbons in the Baxian Depression are mainly from Es_4 source rocks. The Es_4 source rocks began to generate low-maturity hydrocarbons at the end of the deposition of Es_1 (Sha-1 Member of the Eocene Shahejie Formation) (Fig. 6), when the buried hills were covered by the Es_4, and the traps in the Es_4 were filled with hydrocarbons forming hydrocarbon accumulations. During the deposition of the Minghuazhen Formation, most of the Es_4 source rocks were highly mature and the generated light oil and natural gas recharged the pre-

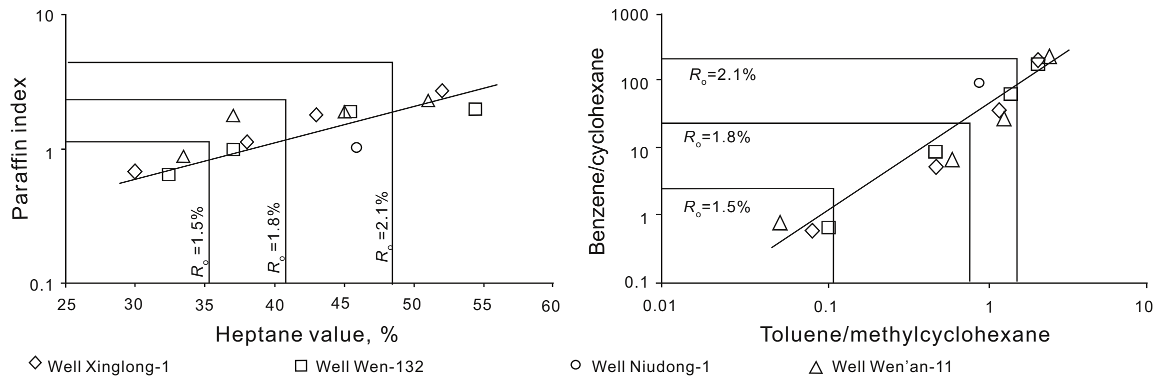

Fig. 5 Parameter scatter diagrams of high-gravity hydrocarbons

existing hydrocarbon reservoirs. Local geologists attribute the formation of the two kinds of hydrocarbon accumulations in the deep part of the Baxian Depression to the following processes (Zhang et al, 2007). First, the oil in the early-formed accumulations (i.e., "ancient oil reservoirs") cracked into light oil and natural gas because of high temperature (e.g., the reservoir temperature in the Niudong-1 Well was 201 °C) during deep burial in the Neogene. Second, the high-maturity Es_4 source rocks began to generate light oil and natural gas in the Neogene, which resulted in the accumulations. Hydrocarbons that are not generated in this manner need to be explored using different concepts. Prior to any exploration, it is necessary to first search for the "ancient oil reservoirs" and then to investigate the formation and preservation conditions of the cracked gas. As for the second kind of hydrocarbons, the only target is the trap with hydrocarbons derived from the Es_4 source rocks. Obviously, the resource potential of hydrocarbons from "ancient oil reservoirs" is limited. In contrast, the resource potential of the second kind of hydrocarbons is large, which calls for understanding of the genesis of deep hydrocarbons.

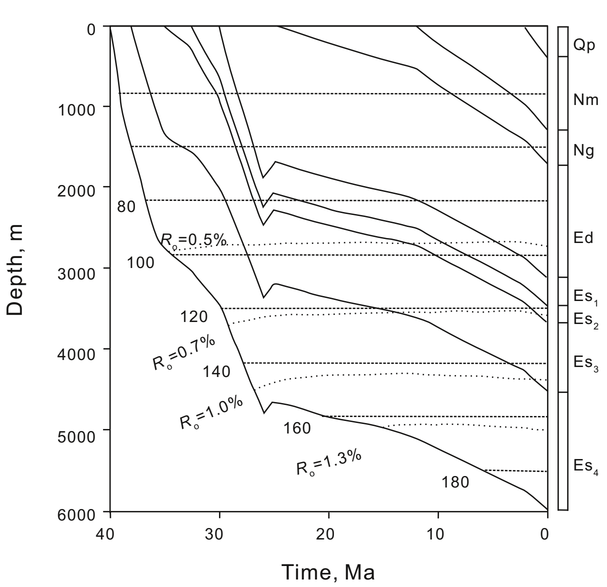

Fig. 6 Burial history of Es_4 source rocks in the Baxian Depression (the paleothermal gradient of 3 °C/100 m is from Zhao et al, 2010a)

3.2 Research methods and genesis of deep hydrocarbons

Low-maturity Es_4 source rocks and crude oil from the study area were sampled for high-pressure and high-temperature simulations (Fig. 7). The rock samples were crushed and sieved to 60 mesh, put into an autoclave (right side of Fig. 7), and heated from 250 °C to 300 °C, 350 °C, 400 °C, 450 °C, 500 °C, 550 °C, and 600 °C for 10 hours. These temperatures correspond to an R_o from 0.5% to 2.5%. We then analyzed the composition and properties of the degraded hydrocarbons and the high-maturity crude oil, and compared them with the hydrocarbons of the Niudong-1 Well to infer the genesis (pyrolysis or crack) conditions of the latter.

Table 4 lists the basic data of the collected samples. Crude oil is not produced from the Es_4 reservoir intervals but generated by Es_4 source rocks. The low-maturity source rocks are rich in organic matter (Table 4). Thermal simulation experiments were carried out in a closed autoclave at 450 °C, 500 °C, 550 °C, 600 °C, and 630 °C that correspond to R_o values of 1.3%, 1.5%, 1.8%, 2.1%, and 2.5%, respectively, to simulate the pyrolysis of source rocks and cracking of crude oil at the high-maturity stage. Then, the composition of the gaseous and liquid hydrocarbons from the simulation experiments was analyzed by gas chromatography and compared with the hydrocarbons from the Niudong-1 Well. The procedure details are documented in Wang et al (2009a).

3.3 Genesis of hydrocarbons in the Niudong-1 Well

We examined different compounds (Table 5) by looking at pairs of $\ln(CC_5/nC_6)$, $\ln(CC_5/nC_5)$, $(MCC_5+CC_6)/nC_6$, CC_6/nC_5, $(CC_5+MCC_5+CC_6)/(nC_5+nC_6)$, $(MCC_5+CC_6+MCC_6)/(nC_6+nC_7)$, methylbenzene/benzene, and $DMCC_5/CC_5$ (Fig. 8). The products of crude oil cracking and source rock pyrolysis possess different characteristics, which can be used to distinguish the products of crude oil cracking and source rock pyrolysis at high maturities.

Hydrocarbon data from the Lunnan and Mandong-Jingjisu areas in the Tarim Basin (Hu et al, 2005), and the Minfeng area in the Dongying Depression (Wang et al, 2008) are shown in Fig. 9 along with the data for the light hydrocarbons and natural gas of the Niudong-1 Well. The field and the

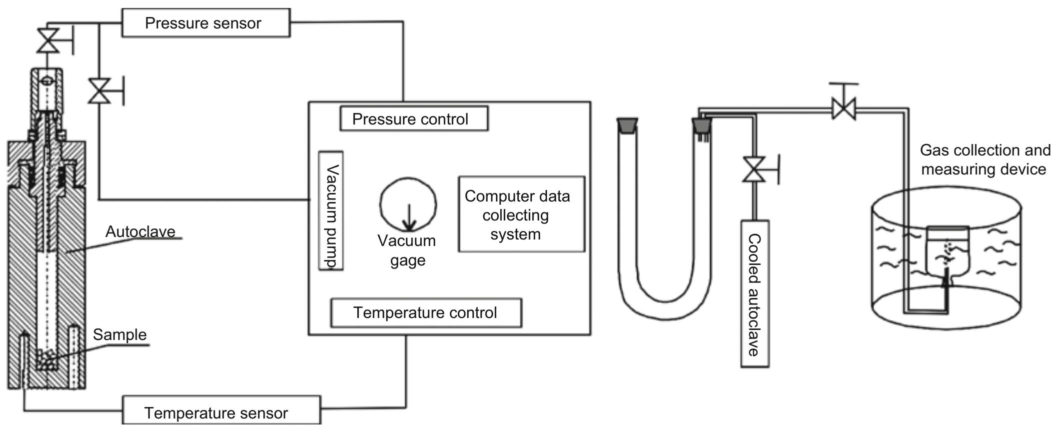

Fig. 7 High-pressure and high-temperature apparatus and experimental setup

Table 4 Basic sample data

Crude oil samples				Source rock samples			
Well	Horizon	Well depth, m	Density, g/cm^3	Well	Horizon	Depth, m	TOC, %
Dian-15	Es_3	3124–3133	0.858	Wen-132	Es_4	2874–2878	22.2
Dian-21-2	Es_1	2699–2672	0.850	Xinglong-1	Es_4	4287.3	4.62
Yan-50-1	Es_2	2571–2606	0.865	Wen'an-11	Es_4	3513–3513	1.89

Table 5 Abbreviations used in Fig. 8

Abbreviation	Compound name
CC_5	Cyclopentane
nC_5	Normal pentane
CC_6	Cyclohexane
nC_6	Normal hexane
nC_7	Normal heptane
MCC_6	Methylcyclohexane
MCC_5	Methylcyclopentane
$DMCC_5$	2-Methylcyclopentane

experimental data in Figs. 8 and 9 are in good agreement, which strengthens the validity of the simulation experiments and suggests that the hydrocarbons in the Niudong-1 Well were also generated by pyrolysis of Es_4 source rocks.

4 Deep hydrocarbon accumulation models and enrichment patterns

4.1 Factors controlling hydrocarbon accumulation

4.1.1 Hydrocarbon distribution controlled by the Es_4 source rocks

From Fig. 1, we can infer that mature to highly mature Es_4 source rocks with thickness of 200-300 m control the distribution of the hydrocarbon accumulations. The buried hills in the deep part of the trough are located in the high-maturity area of the Es_4 source rocks (i.e., Niudong buried hill), and hydrocarbons from the source rocks migrated into and accumulated in the buried hill traps. The Es_4 sand bodies at the edges of the trough are in the same area as the mature source rocks, which generated the oil in the accumulations (Wen'an-1 Well). In addition, the Es_4 high-maturity source rocks are rich in organic matter. In the Xinglong-1 Well, for example, the 617 m thick Es_4 source rocks have a TOC value between 0.7% and 13% with an average of 2.7%. The mature source rocks are relatively richer in organic matter. In the Wen'an-1 Well, for example, the TOC of the 46.4 m thick Es_4 source rocks is 0.47%-6.2% with an average of 1.1%. Deep oil accumulations such as Niudong-1, Wen'an-1, Xinglong-1, Xinjia-4, and Wengu-3 are distributed around source rocks rich in organic matter. Likewise, the deep part of the Wen'an slope and Cha-gao-mao area are on the periphery of source rocks rich in organic matter, which creates favorable locations for hydrocarbon accumulation. The buried hills and its internal structures in the deep parts of the troughs and inner slopes are located around deep high-maturity source rocks, which makes them good exploration targets.

4.1.2 Charging and accumulation of high-maturity hydrocarbons under abnormal pressure

The interval transit time of mudstones can reflect the variations in formation pressure. The formation pressure P is calculated by using the experimentally determined formula

$$P = 78.2 \times (A - 5.9386) + 1.33 \times H^2 \times 10^{-6} + H \times (0.01083 \times A - 0.04633) \qquad (1)$$

where H is the target depth (m), A is the ln(AC) at H, and AC is the interval transit time (μs/m) from acoustic well logging.

If reservoir pressure is equal to the pressure formed

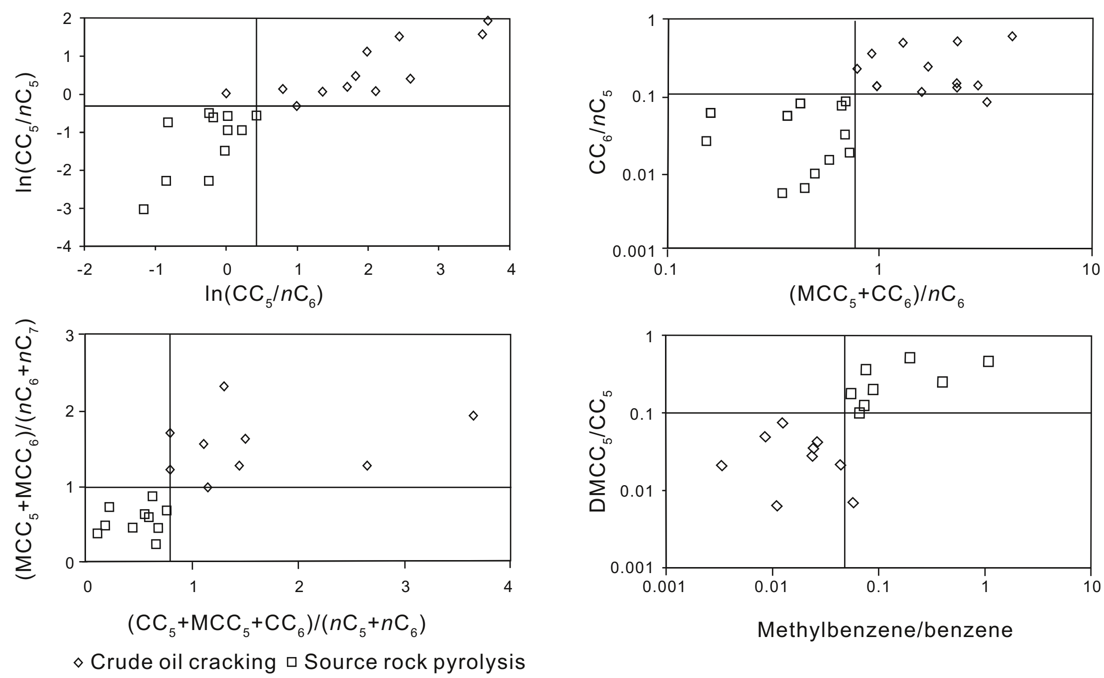

Fig. 8 Differences in light hydrocarbons from source rock pyrolysis and crude oil cracking

by water column at a given depth, the pressure is called hydrostatic pressure, then the ratio of measured pressure/hydrostatic pressure at any depth is called the pressure coefficient. When the pressure coefficient is over 1.2, we say there is abnormal pressure in the reservoir. There are two abnormal pressure zones in the Niudong-1 Well. One is between 4,000 m and 4,600 m in the Es_4 (left diagram in Fig. 10) with a maximum pressure coefficient of 1.28, and the other is at a depth of 5,000 m at the top of the buried hills with a pressure coefficient of 1.43. The abnormal pressure was the driving force behind the migration of the hydrocarbons from Es_4 into the buried hill traps. In the Xinglong-1 Well, there are three abnormal pressure zones at depths of 4,050 m, 4,900 m, and 5,550 m, with respective pressure coefficients of 1.27, 1.15, and 1.32 (right diagram in Fig. 10). According to Fig. 10, the pressures in source rocks below 5,500 m are very high, where the pressure index (real pressure/static pressure) calculated with Eq. (1) is greater than 1.3. Referring to the structural evolution history (Fig. 11), the highest pressure in the deep zones occurred in the Quaternary and increases at depths greater than 5,500 m because the depths of the studied area increased continuously, which may

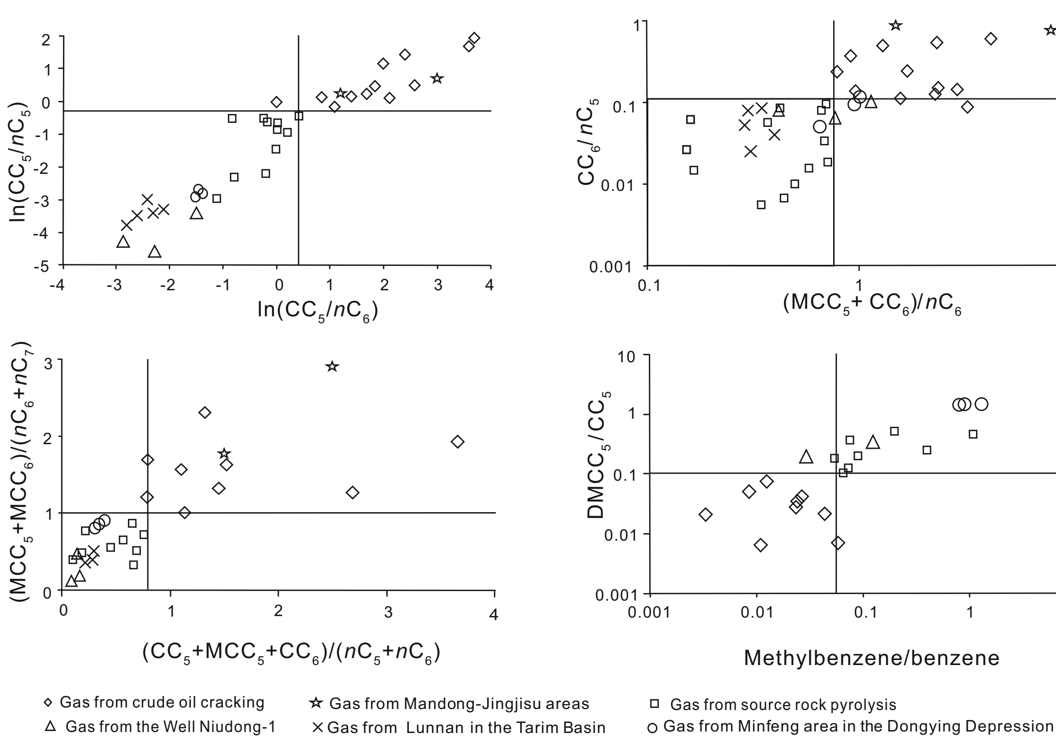

Fig. 9 Differentiation of gases from source rock pyrolysis and crude oil cracking

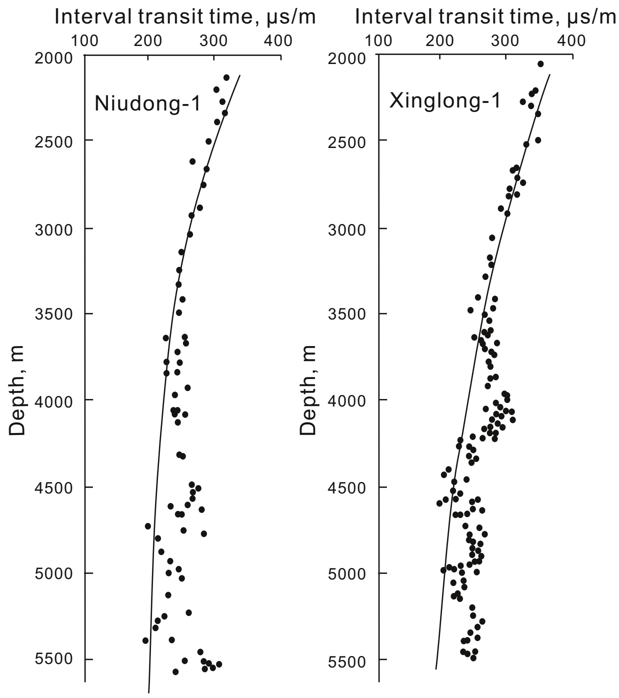

Fig. 10 Transit time vs. depth in the mudstones of the Niudong-1 and Xinglong-1 Wells

result in a large amount of natural gas and light oils generated from the Es_4 source rocks.

In light of this increasing trend, the pressure coefficient will reach 1.5 at 6,000 m in the Es_4 source rocks. In the Niudong-1 Well, however, the pressure coefficient of the oil reservoirs is less than 1.1. Thus, there must be a large pressure difference between the deep Niudong buried hill and the peripheral source rocks that facilitated the late-stage high-maturity hydrocarbons to directly fill the buried hill.

4.1.3 Hydrocarbon accumulation and reservoir pore space of the deep buried hills and Es_4 sand bodies

In the buried hills, the Wumishan Formation is about 1,500 m to 4,000 m thick and consists of restricted marine cryptalgal dolostone and siliceous stromatolites, which are porous and permeable to a certain extent. Within the formation, highly permeable reservoirs with secondary pores, cavities, and fractures formed after weathering and leaching, horizontal and along bedding karstification, and tectonic activity during the Yanshanian and Himalayan orogenies (Zhao et al, 2011). In the Niudong-1 Well, the Wumishan Formation is interpreted as type I and II reservoirs with a reservoir-to-strata ratio of 61.8%, effective porosity range of 2.2% to 19.5% and an average of 6.3%, and a permeability range of 0.01 mD to 2,489 mD. Image logging indicates that the reservoirs are of the pore–cavity–fracture-type. Obviously, the development of the Wumishan reservoirs was critical to hydrocarbon accumulation in the Niudong buried hill.

In the Cha-gao-mao area and the deep part of the Wen'an slope, the Es_4 delta front and turbidite sand bodies are the dominant reservoirs. Based on the petrophysical characteristics of the sandstones in key wells, the lower limits of the reservoir physical properties are determined with the distribution function (Wang et al, 2009b). The lower limit of porosity is 9.1% at 4,000 m to 4,500 m and 6.8% at 4,500 m to 5,500 m, and the corresponding lower limits of permeability are 0.82 mD and 0.82 mD in both depth ranges.

In the Cha-gao-mao area, the reservoirs at the upper part of the Es_4 have porosities of 2.6% to 18.6% (average 7.8%) and permeabilities of 0.01 mD to 28.99 mD (average 1.19 mD). The petrophysical properties of most sandstones are better than the accepted lower limits of reservoir rock; therefore, the conditions favor hydrocarbon accumulation. In the middle–lower part of Es_4, the sandstone average porosity and average permeability is 5.1% and 0.24 mD, respectively, which are lower than the lower limits and thus the conditions are relatively unfavorable for hydrocarbon accumulation.

In the deep part of the Wen'an slope, the Es_4 reservoirs have an average porosity of 8.9% and an average permeability of 1.8 mD, both higher than the lower limits, which make most of them potentially good reservoirs.

4.1.4 Proximal hydrocarbon accumulation under the combined effect of deep faulting and pressure

In the Baxian Depression, the deep buried hills mainly consist of faulted hills (Fig. 11) and are directly surrounded by Es_4 high-maturity source rocks. Therefore, the hydrocarbons generated by the Es_4 source rocks migrated under pressure into the buried hills through faults and then accumulated (Lü et al, 2007). Within the intraburied hills in the deep zones, the pore space is relatively well developed and the formation pressure coefficient is lower than 1.1. As a result, hydrocarbons derived from highly pressured source rocks could migrate and accumulate into the intraburied hill traps.

In the upper part of Es_4, sand bodies and faults make up the migration pathway network (Fig. 11), and hydrocarbons derived from highly pressured source rocks could migrate and accumulate in the sandstones through faults. In the lower part, the petrophysical characteristics of most sandstones are lower than the lower limits in the reservoirs; hence, the sand bodies could not act as effective migration pathways and the faults are the only migration pathways. In this manner, the hydrocarbons derived from the Es_4 source kitchen were driven by pressure into the sand bodies with petrophysical properties higher than the lower reservoir limits.

4.2 Deep hydrocarbon accumulation models

The timing of hydrocarbon entrapment is needed to understand the formation process and distribution patterns of the hydrocarbon accumulations (Burrus et al, 1985; Karlsen et al, 1993). The homogenization temperatures of hydrocarbon inclusions can be used to determine the timing of hydrocarbon entrapment in the deep, buried hill reservoirs (Shi et al, 1987; Zhu et al, 2012). We examined thin sections and measured the homogenization temperatures of hydrocarbon inclusions from drilling cuts collected from the Niudong-1 Well. The homogenization temperature range is from 120 °C to 160 °C (Fig. 12), indicating continuous hydrocarbon charging in the Niudong-1 buried hill. Regarding the burial history, we inferred that the hydrocarbon charging began at the end of the deposition of Es_1 and lasted until the end of the deposition of the Guantao Formation in the Niudong buried hill (Fig. 11).

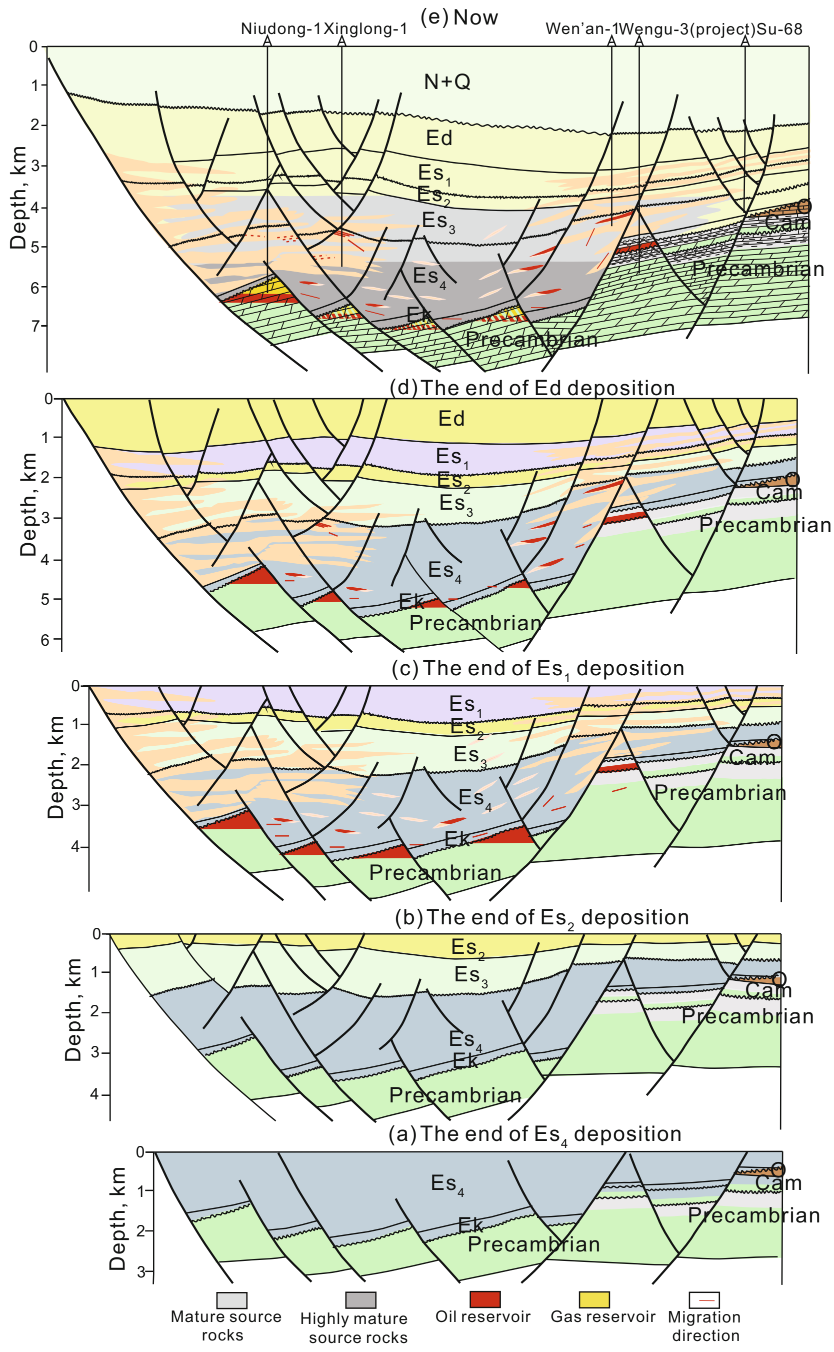

Fig. 11 Structural evolution and hydrocarbon accumulation models of the deep zones in the Baxian Depression

4.2.1 Early charging and accumulation

Based on the structural evolution of the Baxian Depression, the Niudong buried hill appears to have formed prior to the deposition of Es_3, and then Es_3 and Es_2 were deposited (Fig. 11(a), 11(b)). The Es_4 source rocks entered the oil window at the end of the deposition of Es_1, and the generated low-maturity hydrocarbons migrated up dip to the buried hill, thus formed the buried hill oil reservoirs that were charged at the early stage (Fig. 11(c)). They correspond to inclusion homogenization temperatures of 120 °C to 160 °C. Following the deposition of the Dongying Formation, the entire Baxian Depression was uplifted and experienced denudation, which caused part of the hydrocarbons within the buried hill trap to spill out of the oil reservoirs (Fig. 11(d)). At that time, oil generation by the Es_4 source rocks was slow without any abnormal pressure and, thus, low-maturity hydrocarbons migrated and mainly accumulated by buoyancy.

4.2.2 Characteristics of late hydrocarbon accumulation

Es_4 source rocks entered the high-maturity stage during the deposition of the upper Minghuazhen Formation, when the generated light oil and natural gas quickly charged the Niudong buried hill under abnormal pressure, accumulated in traps at high structural positions, and "squeezed" the low-maturity hydrocarbons that had accumulated earlier. In this manner, high-pressure hydrocarbon accumulations or condensate accumulations formed (Fig. 11(e)).

4.3 Exploration potential of deep zones

Es_4 source rocks are the major source of deep hydrocarbons. BASIMS basin modeling was used to evaluate the hydrocarbon generation potential of the source rocks. The generated amounts of oil and gas were estimated at 33.35×10^8 t and 3.66×10^{12} m^3, respectively. Based on the migration–accumulation coefficient of the third resource assessment conducted by the Huabei Oilfield Company (12% for oil and 4% for gas), the deep oil and gas resources were estimated at 4×10^8 t and $1,464\times10^8$ m^3. Clearly, deep hydrocarbon exploration is at the early stage, and great volumes of oil and gas are anticipated in the deep zones.

In the Baxian Depression, the buried hills of the Wumishan Formation (i.e., Niudong, east Xinglong-1, Cha-89) develop along the steep slopes, whereas the Paleozoic or Precambrian buried hills are along the gentle slope zones. These buried hills, together with the two-step buried hills in the north might be charged with hydrocarbons derived from Es_4 source rocks. In addition, hydrocarbon accumulation may occur in structural–lithologic traps in the Shahejie Formation and the underlying Kongdian Formation. Therefore, further exploration breakthroughs might be made by using seismic exploration in the deep zones.

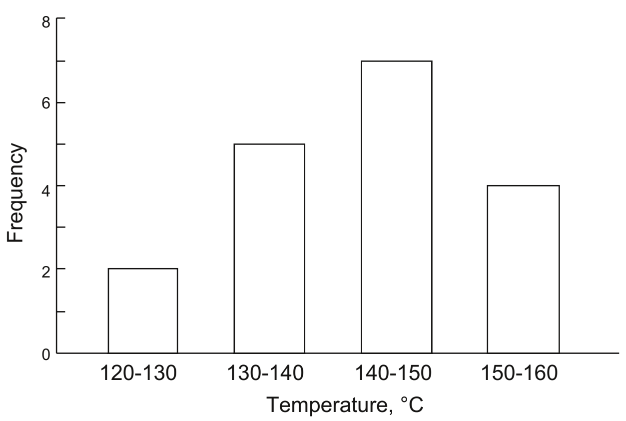

Fig. 12 Histogram of the homogenization temperatures of the hydrocarbon inclusions in samples from the Niudong-1 Well

5 Conclusions

1) In the Baxian Depression, the deep hydrocarbons were mainly generated by Es_4 high-maturity source rocks. These source rocks are thick and mainly contain type II organic matter. Their light oil and natural gas potential is significant, which increases the exploration potential of the deep zones.

2) Deep hydrocarbon accumulation is controlled by source kitchen, abnormal pressure, and reservoir pore space development. Favorable exploration pathways include the areas up dip of the Es_4 source kitchens, the buried hills with well-developed pore space, and various traps in the Shahejie Formation.

3) In the Baxian Depression, the buried hills (i.e., the Niudong-1 Well) have a long history of hydrocarbon charging and accumulation. The early-accumulated, low-maturity hydrocarbons were replaced by late-stage, high-maturity hydrocarbons after the end of the Minghuazhen Formation deposition. This hydrocarbon accumulation mechanism may be applicable to other structural or lithologic traps within the deep Shahejie Formation.

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