

# 准噶尔盆地南缘下组合煤系烃源岩生烃模拟及 高探1井油气源研究

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**摘要:**随着准噶尔盆地勘探的不断深入, 准南下组合日益成为油气勘探的重点, 但目前针对下组合烃源岩生烃演化特征尚未进行系统性研究, 不同岩性煤系烃源岩生烃能力和生油气量如何等尚未进行系统性实验分析。最近获得高产的高泉背斜高探1井油气与哪种岩性煤系源岩关系最为密切等都值得进一步讨论。通过对侏罗系煤岩、碳质泥岩和泥岩进行密闭容器高压釜加水热模拟实验, 对3种岩性煤系烃源岩生烃特征及油气源对比进行了研究。碳质泥岩和泥岩具有较高的生油潜力, 碳质泥岩是侏罗系煤成油的主要贡献者, 且角闪体可能是碳质泥岩主要生油母质。煤岩在更高演化阶段较碳质泥岩和泥岩具有更高的生气潜力, 且主要为干酪根降解气。模拟气体随演化程度升高均不同程度出现碳同位素分馏效应, 即随成熟度增加气体稳定碳同位素先变轻后变重, 且 $\delta^{13}C_1$ 分馏效应较 $\delta^{13}C_2$ 明显。结合模拟实验进一步对高探1井油气源进行了分析, 认为高探1井下白垩统清水河组原油主要为侏罗系碳质泥岩生成的较高成熟度原油, 而3种岩性煤系烃源岩对天然气均有贡献。

**关键词:**热模拟实验; 油气源对比; 显微组分; 煤系烃源岩; 气体碳同位素; 侏罗系; 准噶尔盆地

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## Hydrocarbon generation simulation of coaly source rocks in the Lower combination on the southern margin of Junggar Basin and indications for oil and gas sources of well Gaotan 1

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**Abstract:** With the deepened exploration progress in the Junggar Basin, the lower assemblage has increasingly become the focus for oil and gas exploration. However, systematic research has not been achieved on the hydrocarbon generation characteristics of the lower assemblage source rocks, and systematic experimental analysis has not been carried out on the hydrocarbon generation potential and oil and gas generation capacity of coaly source rocks with different lithology. Oil and gas have highly yielded in the well of Gaotan 1 in the Gaoquan anticline, and which lithology of coaly source rocks have the closest relationship with it is worth for a further discussion. Sealed vessel autoclave hydrous simulation of Jurassic coaly rock, carbonaceous mudstone and mudstone was carried out in this study, results show that carbonaceous mudstone and mudstone have high oil generation potential. Carbonaceous mudstone is the main contributor of Jurassic coal formed oil, and cutinites may be the main oil source

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in carbonaceous mudstone. Coaly rock has higher gas generation potential than carbonaceous mudstone and mudstone in higher evolution stage, mainly generating kerogen cracking gas. The carbon isotopic fractionation of simulated gas appears in vary degrees with the increase of evolution, that is, with the increase of maturity, the stable carbon isotope of gas first becomes lighter and then becomes heavier, and the  $\delta^{13}\text{C}_1$  fractionation is more obvious than that of  $\delta^{13}\text{C}_2$ . Combined with simulation experiments, the oil and gas source of well Gaotan 1 was further analyzed. It was then concluded that the crude oil of Cretaceous Qingshuihe Formation in well Gaotan 1 is mainly high-mature crude oil generated by Jurassic carbonaceous mudstone, and the three lithologic coaly source rocks contributed to natural gas.

**Key words:** thermal simulation experiment; oil and gas source comparison; macerals; coal measure source rock; gas carbon isotope; Jurassic; Junggar Basin

准噶尔盆地南缘前陆冲断带油气苗分布广、类型多,大型构造带成排成带分布,潜在资源量巨大,一直被视为准噶尔盆地重要的油气勘探区<sup>[1-3]</sup>。其构造具有东西分段、南北分带的特点,纵向上可划分为上、中、下 3 套生储盖组合。长期以来,南缘勘探以中、上组合为主要对象,发现了多个油气田及含油气构造<sup>[4]</sup>。随着勘探不断深入,下组合成为了油气勘探的重点<sup>[5-6]</sup>。2019 年,部署在高泉东背斜上的风险探井——高探 1 井于白垩系清水河组获得了日产千立方米高产油气流,实现了南缘下组合油气勘探的首次突破,打开了南缘勘探新局面,开启了下组合大型油气富集区勘探新里程。关于高探 1 井油气来源,多数学者认为以侏罗系烃源岩贡献为主<sup>[7-8]</sup>,但以往研究认为,侏罗系虽然有丰度较高的烃源岩,但是主要是气源岩<sup>[9]</sup>。高探 1 井如此高产量油气显然与以往认识有所区别,因此仅依靠静态特征评价烃源岩显然不够,有必要对烃源岩生烃特征进行深入的研究。此外,针对南缘中—下侏罗统煤岩、碳质泥岩和泥岩生烃演化特征尚缺乏对比性研究<sup>[13]</sup>,而烃源岩热解生烃模拟实验作为认识不同母质类型油气形成机理、评价烃源岩生烃潜力并获取油气资源评价参数、研究各种因素对油气形成影响程度的重要手段之一,已经在油气地质勘探领域得到了广泛的应用<sup>[14]</sup>。因此,本文主要针对侏罗系主要生油层系不同岩性烃源岩进行密闭容器高压釜加水热模拟实验,明确不同演

化阶段生排烃特征、气油比、气体组分和同位素变化以及生烃演化规律等,建立主力烃源岩生烃模型,进而为下组合油气勘探提供理论依据。

## 1 实验样品与方法

为保证模拟序列的完整性,本次实验选择准噶尔盆地 NA 井侏罗系八道湾组煤岩、碳质泥岩和泥岩 3 种岩性低成熟烃源岩岩心样品(表 1), $R_o$  平均值分别为 0.639%, 0.527%, 0.605%, 煤岩和泥岩干酪根类型为 II<sub>2</sub> 型,碳质泥岩干酪根类型为 II<sub>2</sub>—III 型。前人研究认为,有机显微组分与热解参数判断有机质的类型有时会出现矛盾<sup>[15-16]</sup>,本次碳质泥岩样品有机显微组成中壳质组含量很高,且个体较大,因此,结合显微组分特征综合认为其有机质类型以 II<sub>2</sub> 型为主。本次采用密闭容器高压釜加水热模拟实验装置对 3 种岩性烃源岩分别进行生烃模拟实验。考虑到水的临界温度,为了尽量减小水对实验结果的影响,在 373 °C 之前加水 15~20 mL,在 373 °C 之后加水 8 mL 左右。煤岩模拟温度依次为 295, 315, 340, 350, 370, 450, 500 °C, 泥岩和碳质泥岩模拟温度依次为 315, 330, 340, 350, 370, 450, 500 °C, 每个温度点加热时间为 24 h,热模拟完成后,对热解气体进行组分、同位素分析,对模拟残渣进行抽提(残留油)、磨片,对残渣进行显微组分观察及镜质体反射率测定,对热解油和残留油进行分离并作饱和烃质分析。

表 1 准噶尔盆地南缘 NA 井侏罗系八道湾组烃源岩模拟样品地球化学特征

Table 1 Geochemical characteristics of source rock samples from Lower Jurassic Badaowan Formation, well NA, southern margin of Junggar Basin

样品编号	样品岩性	取样深度/m	$\omega(\text{TOC})/\%$	$T_{\text{max}}/\text{°C}$	$S_1/(\text{mg}\cdot\text{g}^{-1})$	$S_2/(\text{mg}\cdot\text{g}^{-1})$	$R_o/\%$	干酪根类型	有机显微组分	沉积环境
NA-1	煤岩	485.44	67.44	426	0.63	134.60	0.54%	II <sub>2</sub>	基质镜质体为主,少量孢子体	湖沼相
NA-2	碳质泥岩	484.32	31.88	425	1.39	54.17	0.52%	II <sub>2</sub>	角质体为主	湖沼相
NA-3	泥岩	483.07	3.14	437	2.59	6.86	0.53%	II <sub>2</sub>	孢子体为主,少量角质体	湖沼相

## 2 实验结果与讨论

### 2.1 热模拟产物特征

#### 2.1.1 排出油产率特征

热模拟实验表明,不同岩性煤系烃源岩热解排出油产率存在相似性(图 1a),即随温度升高先增加后减小,均在 340 °C 左右达到生油高峰,但其各自生油高峰产油率存在显著区别。泥岩具有最高排出油产率,最大排出油量约为 119.72 mg/g;碳质泥岩生油高峰最大排出油量约为 61.12 mg/g;煤岩最大排出油量约为 26.82 mg/g。总体而言,排出油产率有泥岩>碳质泥岩>煤岩的特征。但是由于碳质泥岩有机质丰度远高于泥岩,每吨烃源岩生油量远大于泥岩,因此,碳质泥岩可能是侏罗系煤成油的主要贡献者。

#### 2.1.2 气态烃组分特征

作为天然气藏的主力烃源岩,煤系源岩生气能力的研究显然具有重要的意义。实验结果显示,不同岩性煤系烃源岩样品模拟实验生成烃气产率变化趋势基本一致,即随着模拟温度的升高,烃类气体产率和甲烷产率不断增加(图 1b, c)。500 °C 时,泥岩、碳质泥岩和煤岩烃气产率分别约为 427.7, 219.3, 178.8 mL/g, 烃气产率大致呈泥岩>碳质泥岩>煤岩的特点。

但是通过对比不同岩性烃气增长率(图 1d)可以发现,泥岩在 350 °C 和 450 °C 出现两个烃类气体增长高峰。第一个高峰可能为干酪根开始降解生烃气时形成,第二个高峰可能为干酪根降解生气和

原油大量裂解生成烃类气体时共同形成,而碳质泥岩和煤岩还未出现烃类气体增长高峰,因此推测在更高成熟度时,碳质泥岩和煤岩生烃气量会持续增加并明显大于泥岩。此外泥岩具有较低温度生烃的特点,而碳质泥岩除了具有很强的生油潜力,在高温阶段和煤岩一样都具有很强的生气潜力,碳质泥岩和煤岩是侏罗系主要气源岩。

从重烃产率可以看出,在较高模拟温度时,泥岩和碳质泥岩重烃含量仍有增加趋势(图 1e),且气体中重烃百分含量仍较高(图 1f),而煤在较高模拟温度时生成的气体中重烃含量明显低,重烃百分比在 370 °C 时已经明显出现峰值。煤在较高演化阶段时,气体碳同位素较碳质泥岩和泥岩明显偏重。前人研究认为,原油裂解气的稳定碳同位素值和干燥系数总体上低于干酪根降解气<sup>[15]</sup>,因此,在较高模拟温度或更高成熟度时,碳质泥岩和泥岩可能以原油裂解气为主,少量干酪根降解气,而煤则主要为干酪根降解气。

#### 2.1.3 气态烃稳定碳同位素组成特征

尽管 3 种岩性的煤系烃源岩具有相似的沉积环境,但其稳定碳同位素特征却有明显差异。前人研究表明,无论是烃源岩、干酪根或是原油的热模拟实验,在相对低温阶段生成的烷烃气中, $\delta^{13}C_1$  值都具有先减小后增大的演化趋势<sup>[15]</sup>。

本次模拟实验 3 种岩性烃源岩甲烷碳同位素也出现了随着模拟温度升高整体呈先变轻后变重的特点(图 2a)。乙烷碳同位素虽变轻趋势不如甲烷碳同位素明显,但在高成熟阶段仍明显变重(图 2b)。

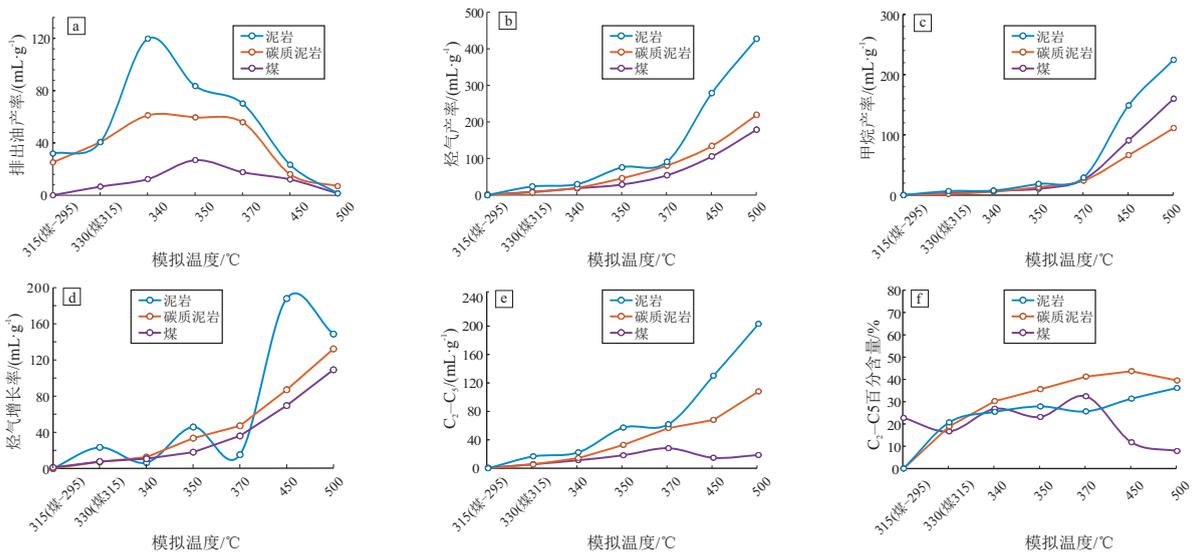
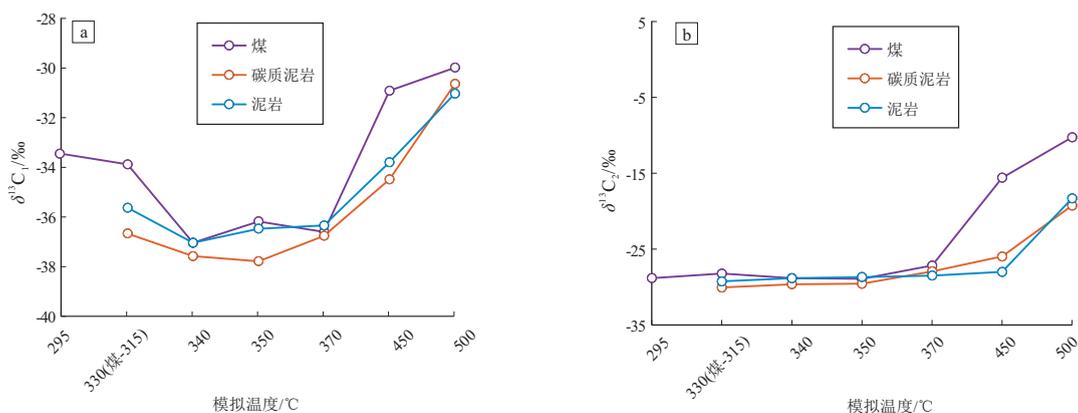


图 1 准噶尔盆地南缘侏罗系八道湾组煤系烃源岩模拟排出油、气态烃及各组分产率相关图

Fig.1 Simulated oil and gas emission and correlation diagram of each component yield of coal measure source rocks from Lower Jurassic Badaowan Formation, southern margin of Junggar Basin

图 2 准噶尔盆地南缘侏罗系八道湾组煤系烃源岩模拟  $\delta^{13}\text{C}_1$  和  $\delta^{13}\text{C}_2$  演变特征Fig.2  $\delta^{13}\text{C}_1$  and  $\delta^{13}\text{C}_2$  evolution of coal measure source rocks

from Lower Jurassic Badaowan Formation, southern margin of Junggar Basin

在生油高峰之前,原油伴生气碳同位素由重变轻,在生油高峰之后,原油碳同位素由轻变重,且随成熟度增加,变重趋势逐渐加快。

根据碳同位素分馏机理, $^{12}\text{C}-^{12}\text{C}$  键较  $^{13}\text{C}-^{13}\text{C}$  键键能小,干酪根中不稳定支链优先断裂。低温演化阶段,干酪根中不稳定支链优先断裂,导致原油伴生气中相对富集轻碳同位素;在高温演化阶段,天然气由于干酪根和原油裂解生成,天然气碳同位素逐渐变重。在过成熟阶段,天然气(以甲烷为主)主要由残余干酪根中少量低分子烷基侧链进一步脱落生成,而干酪根则进一步缩聚形成富碳的残余物质并最终石墨化<sup>[22]</sup>。天然气中碳同位素这种演变特征主要受控于油气生成演化阶段<sup>[24]</sup>。同时这种变化也暗示了我们在应用气体碳同位素进行气源对比时一定不能忽略成熟度的影响。

对比 3 种岩性烃源岩演化过程中碳同位素特征可以发现,不同模拟温度,煤和泥岩生成的甲烷碳同位素略重于碳质泥岩,但在 500 °C 时,呈现  $\delta^{13}\text{C}_1(\text{煤}) > \delta^{13}\text{C}_1(\text{碳质泥岩}) > \delta^{13}\text{C}_1(\text{泥岩})$ ; 不同模拟温度,煤生成乙烷碳同位素略重于碳质泥岩和泥岩,在 500 °C 时,呈现  $\delta^{13}\text{C}_2(\text{煤}) > \delta^{13}\text{C}_2(\text{泥岩}) > \delta^{13}\text{C}_2(\text{碳质泥岩})$ 。整体而言泥岩和碳质泥岩生成气体的碳同位素比较接近,而煤生成气体碳同位素整体偏重 3‰~5‰ 以上。

## 2.2 镜质体反射率校正

为了使热模拟实验结果更好应用于地质实际,需要对不同温度模拟产物  $R_o$  进行测定并校正,校正公式采用高岗等<sup>[24]</sup> 提出的经验公式:

$$R_{o\text{实}} = R_{os} + (R_o - R_{os})(1 - R_{os}) / (-R_{os})$$

式中: $R_{o\text{实}}$  为该样品实际镜质体反射率; $R_{os}$  为模拟样品初始镜质体反射率; $R_o$  为各模拟点残余样品的

镜质体反射率。

通过校正得到泥岩、碳质泥岩和煤岩生油气量与  $R_o$  关系图(图 3),进而更好地与实际演化剖面做对比。

根据模拟结果分别建立了侏罗系泥岩、碳质泥岩和煤岩生油气数学模型:

(1) 泥岩:

$$P_{oil} = 693.85R_o^2 - 864.28R_o + 307.94 \quad 0.782 \leq R_o \leq 1$$

$$P_{oil} = -403.43R_o^3 + 1\,848.7R_o^2 - 2\,901.8R_o + 1\,591.8 \quad 1 < R_o \leq 1.81$$

$$P_{gas} = 262.53R_o^3 - 717.22R_o^2 + 884.96R_o - 382.48 \quad 0.782 \leq R_o \leq 1.81$$

(2) 碳质泥岩:

$$P_{oil} = 95.52R_o^2 + 18.842R_o + 39.255 \quad 0.54 \leq R_o \leq 1$$

$$P_{oil} = 261.24R_o^3 - 1\,047.4R_o^2 + 1\,219.9R_o - 361.63 \quad 1 < R_o \leq 1.83$$

$$P_{gas} = 14.826R_o^3 + 69.097R_o^2 - 65.753R_o + 10.053 \quad 0.54 \leq R_o \leq 1.83$$

(3) 煤岩:

$$P_{oil} = 103.62R_o^2 - 96.366R_o + 32.384 \quad 0.74 \leq R_o \leq 1$$

$$P_{oil} = 80.638R_o^3 - 286.79R_o^2 + 268.96R_o - 23.15 \quad 1 < R_o \leq 1.85$$

$$P_{gas} = 173.56R_o^3 - 545.93R_o^2 + 647.79R_o - 253.2 \quad 0.74 \leq R_o \leq 1.85$$

式中: $P_{oil}$  为液态产物产率; $P_{gas}$  为燃气产率; $R_o$  为各模拟点残余样品的镜质体反射率校正值。

## 3 高探 1 井油气源分析

前已述及,高探 1 井下白垩统清水河组油气具有高油气比的特点,通过参数对比认为高探 1 井原油主要来自于侏罗系烃源岩(图 4)。对于常规油气藏而言,烃源岩只有生成并排出油气才对油气藏的形成有意义。本次模拟实验结果显示,侏罗系碳质泥岩具有很高的排出油产率,油气比相对泥岩和煤岩也要高一些。因此,本文主要根据碳质泥岩模拟生成的原油生物标记物、天然气碳同位素、热模拟过程中显微组分变化以及源储配置关系等方面

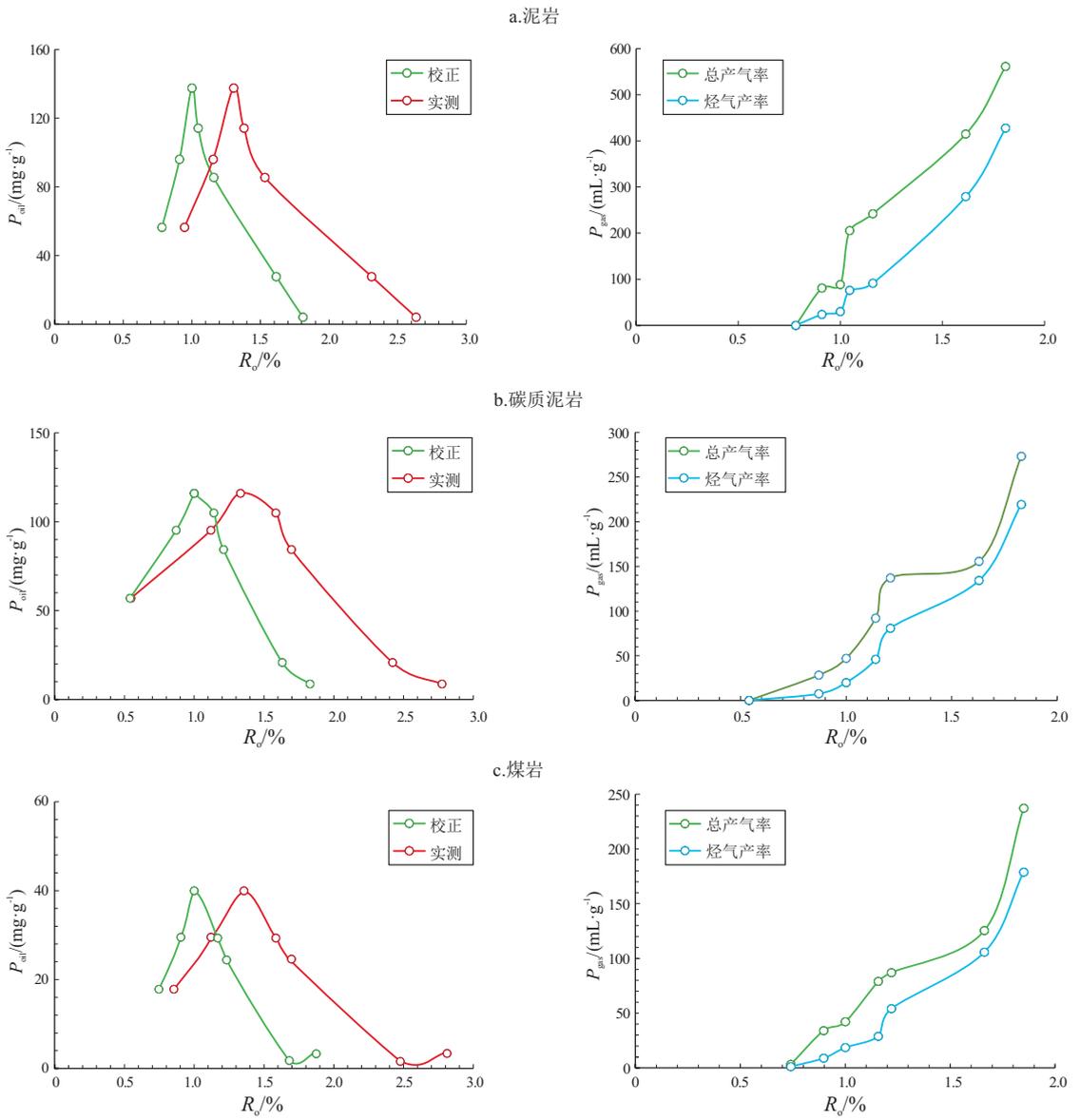


图3 准噶尔盆地南缘侏罗系八道湾组煤系烃源岩热模拟液态烃( $P_{oil}$ )、气态烃产率( $P_{gas}$ )与 $R_o$ 关系

Fig.3 Correlation between simulated oil and gas yields and  $R_o$  of coal measure source rocks in Lower Jurassic Badaowan Formation, southern margin of Junggar Basin

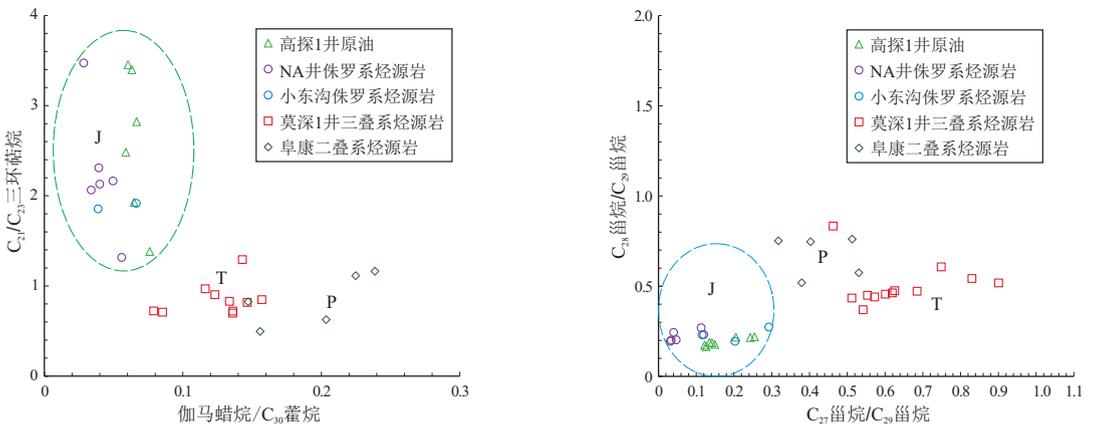


图4 准噶尔盆地南缘高探1井下白垩统清水河组原油与可能烃源岩对比

Fig.4 Correlation between possible source rocks and crude oil in Lower Cretaceous Qingshuihe Formation, well Gaotan 1, southern margin of Junggar Basin

对高探1井油气源进行研究。

### 3.1 生物标记物特征对比

高探1井清水河组原油正构烷烃呈前峰型(图5),成熟度较高,规则甾烷呈上升型,三环萜烷含量和伽马蜡烷含量很低,Pr/Ph值为3.16, $\beta$ -胡萝卜素丰度极低,指示形成于偏氧化的沉积环境。前人研究认为八道湾组未熟与成熟烃源岩相比,在规则甾烷相对组成上存在较大的差别<sup>[25]</sup>。对比高探1井原油与碳质泥岩模拟排出油生标物特点(图6)可以发现,高探1井原油与碳质泥岩340℃和500℃模拟排出油生标物吻合较差,同时高探1井原油成熟度较高。因此,高探1井原油应与模拟350~450℃排出油关系较为密切,对应 $R_o$ 约为1.14%~1.63%。通过相面法对比清水河组原油生标物质谱图(图5)和碳质泥岩热模拟排出油色质

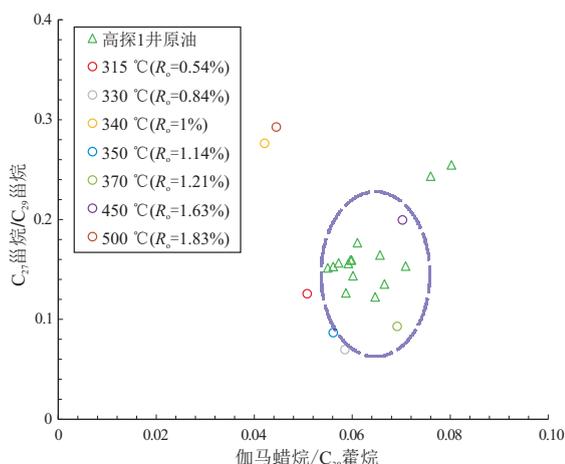


图6 准噶尔盆地南缘高探1井下白垩统清水河组原油与碳质泥岩模拟排出油生标物对比

Fig.6 Comparison of biomarkers between simulated discharged oil from carbonaceous mudstone and crude oil in Lower Cretaceous Qingshuihe Formation, well Gaotan 1, southern margin of Junggar Basin

图谱(图7)也可以发现,高探1井清水河组原油生标物色质峰形与模拟450℃(对应 $R_o$ 约为1.63%)时色质峰形最为相似。

### 3.2 烃源岩有机显微组分特征

对NA井碳质泥岩热模拟原样进行反射荧光观察可以发现,NA井碳质泥岩有机显微组分以角质体为主,且角质体个体较大,一般大于100  $\mu\text{m}$ (图8a)。前人研究认为壳质组是煤系烃源岩中最主要的液态物质来源<sup>[26]</sup>,可能是煤系烃源岩主要的生油母质<sup>[30-31]</sup>,而煤系烃源岩的生油潜力取决于壳质组或类脂组的数量<sup>[32-33]</sup>。因此,富角质体碳质泥岩具有较强的生油能力。进一步观察不同模拟阶段显微组分变化可以看出,在生油高峰之前(模拟温度小于340℃, $R_o < 1\%$ ),有机质颜色逐渐变深,但形态较为完整(图8b, c),在生油高峰(对应模拟温度介于340~350℃, $R_o$ 约为1%~

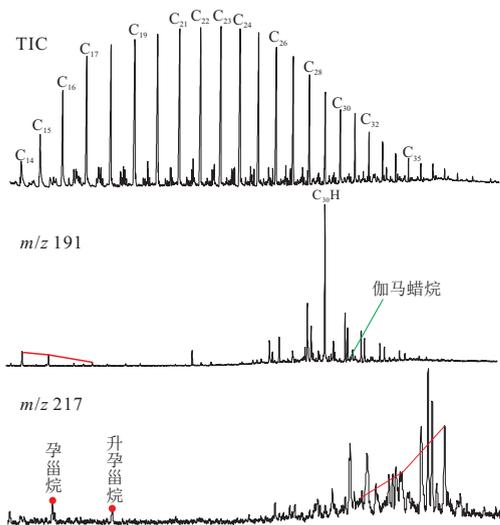


图5 准噶尔盆地南缘高探1井下白垩统清水河组原油生标物质谱图

Fig.5 Biomarker spectrum of crude oil in Lower Cretaceous Qingshuihe Formation, well Gaotan 1, southern margin of Junggar Basin

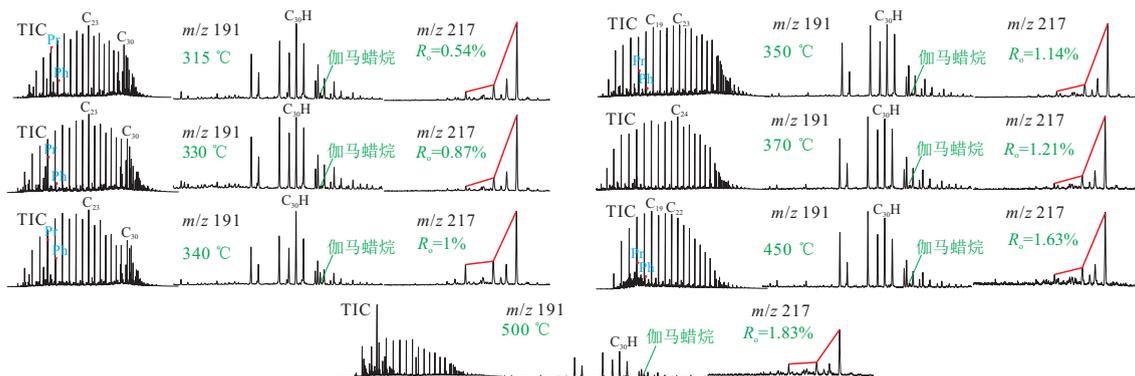


图7 准噶尔盆地南缘侏罗系八道湾组碳质泥岩热模拟排出油色谱—质谱图  
Fig.7 Chromatography and mass spectrometry of carbonaceous mudstone in Jurassic Badaowan Formation, southern margin of Junggar Basin

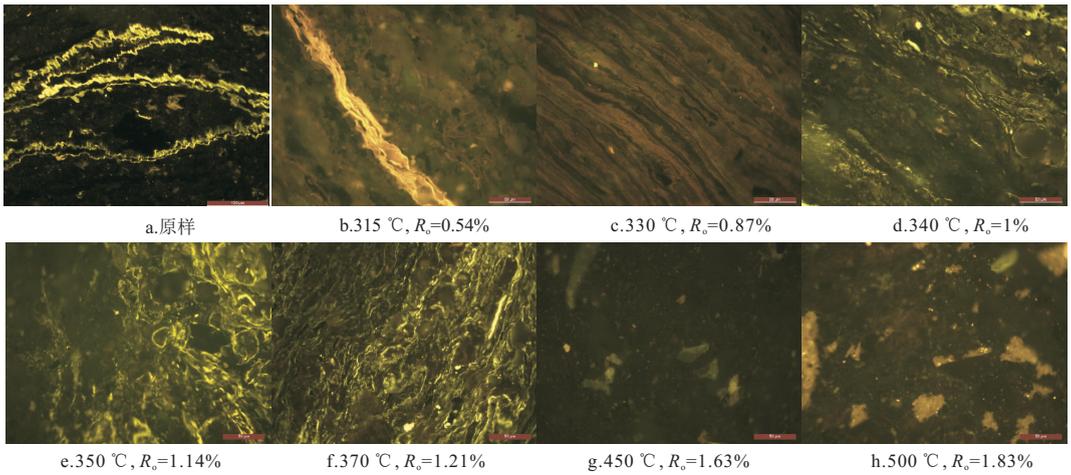


图8 准噶尔盆地南缘侏罗系八道湾组碳质泥岩热模拟有机显微组分演化

Fig.8 Thermal simulation of organic maceral evolution of carbonaceous mudstone in Jurassic Badaowan Formation, southern margin of Junggar Basin

1.14%)时,有机质迅速转化为烃类,镜下以沥青质体为主(图8d,e),当成熟度进一步增加(模拟温度大于350 °C,  $R_o > 1.14\%$ )时,沥青质体因大量排出或裂解生气而迅速减少(图8f-h)。因此,从侏罗系碳质泥岩生烃母质和生排烃角度考虑,高探1井原油与侏罗系碳质泥岩生成的较高成熟度原油 ( $R_o > 1.14\%$ )关系较为密切。此外,高探1井下伏侏罗系烃源岩已经达到成熟—高成熟阶段,具备生成较高成熟度原油的条件(图9)<sup>[34]</sup>。

### 3.3 天然气碳同位素特征

天然气碳同位素组成是研究天然气地球化学特征的重要参数<sup>[35]</sup>,天然气组分、碳同位素组成与母质的沉积环境、有机质类型及热演化程度密切相关,因此碳同位素组成常被用于判识天然气的成因类型与来源<sup>[36-42]</sup>。

高探1井5 768~5 775 m下白垩统清水河组天然气甲烷碳同位素较轻,主要分布在 $-40.9\text{‰} \sim -40.6\text{‰}$ ,乙烷和丙烷碳同位素偏重,分别分布在 $-29.14\text{‰} \sim -28.9\text{‰}$ 和 $-26.9\text{‰} \sim -26.5\text{‰}$ (表2),碳同位素组成呈正序分布(图10a),  $\delta^{13}\text{C}_1 / (\delta^{13}\text{C}_2 + \delta^{13}\text{C}_3)$ 值介于1~10(图10b),单从气体碳同位素来看,高探1井天然气似乎具有混合气特征。本文通过与风城组典型油型气、侏罗系典型煤型气以及吐哈盆地成熟度较低煤型气对比(图10b, c)<sup>[46-47]</sup>,认为高探1井天然气并不是典型I型、II<sub>1</sub>型干酪根生成的油型气与典型III型干酪根生成的煤型气混合构成的混合气<sup>[8]</sup>,而是侏罗系II型腐殖型干酪根生成的天然气,且成熟度较低,以原油伴生气为主,而甲烷碳同位素偏轻可能与同位素分馏效应有关。

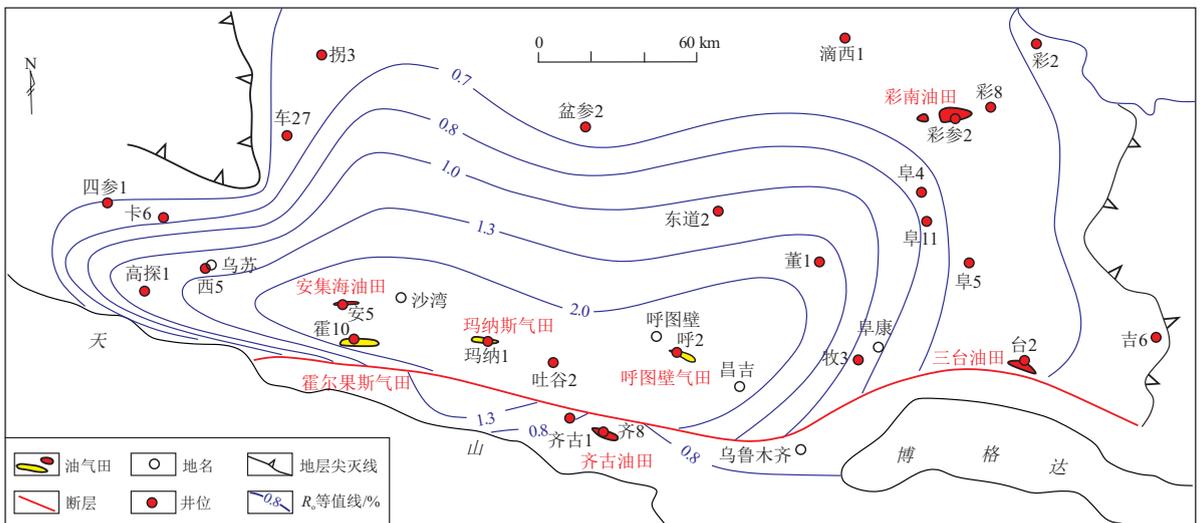


图9 准噶尔盆地南缘油气田分布及侏罗系煤系源岩成熟度<sup>[34]</sup>

Fig.9 Distribution of oil and gas fields and maturity of Jurassic coal measure source rocks on the southern margin of Junggar Basin

表 2 准噶尔盆地南缘高泉油气田高探 1 井下白垩统清水河组天然气组分与碳同位素统计

Table 2 Statistics of natural gas components and carbon isotopes of Lower Cretaceous Qingshuihe Formation in well Gaotan 1, Gaoquan Oil and Gas Field, southern margin of Junggar Basin

采样深度/m	C <sub>1</sub> /%	C <sub>2</sub> /%	C <sub>3</sub> /%	δ <sup>13</sup> C <sub>1</sub> /‰	δ <sup>13</sup> C <sub>2</sub> /‰	δ <sup>13</sup> C <sub>3</sub> /‰
5 768~5 775	76.50	13.32	5.94	-40.49	-29.14	-26.9
5 768~5 775	74.44	13.39	6.82	-40.35	-28.74	-26.54
5 768~5 775	58.93	10.78	5.34	-40.68	-28.92	-26.42
5 768~5 775	76.62	12.32	5.68	-40.72	-29.01	-26.53
5 768~5 775	78.34	12.60	5.45	-40.46	-28.91	-26.22

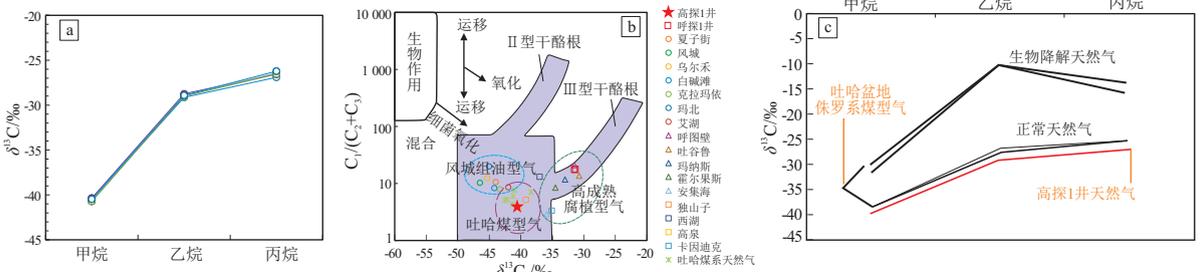


图 10 准噶尔盆地南缘高探 1 井天然气成因类型判别  
图 10b 的图版据文献[36,42-44]。

Fig.10 Identification of genetic type of natural gas in well Gaotan 1, southern margin of Junggar Basin

SCHOELL<sup>[37]</sup> 在研究俄罗斯地台和荷兰 Roliegendes 地区天然气运移时就认为运移可引起甲烷碳同位素分馏, 荷兰格罗宁根气田下方天然气的 δ<sup>13</sup>C<sub>1</sub> 为 -29.5‰ ~ -31.6‰, 运移前方天然气的 δ<sup>13</sup>C<sub>1</sub> 为 -36.6‰, 两者差值为 7.1‰。大量地质实例和实验也都证明运移可以造成天然气甲烷碳同位素分馏, 而且大多数学者认为运移可导致天然气甲烷碳同位素变轻<sup>[48]</sup>。因此, 如果剔除同位素分馏效应的影响, 高探 1 井下白垩统清水河组天然气则更具有侏罗系 II 型有机质生成的偏腐殖气的特点。

本次模拟实验碳质泥岩有机质类型为 II<sub>2</sub> 型, 结合碳质泥岩模拟气体碳同位素演化特征可以发现, 高探 1 井清水河组天然气乙烷碳同位素与侏罗系碳质泥岩成熟阶段之前乙烷碳同位素值较为接近, 这与乙烷碳同位素相对稳定, 运移分异效应影响较小有关(图 11b)。而甲烷碳同位素偏轻, 则主要受运移分异效应影响(图 11a)。

进一步结合源储配置关系(图 12), 下白垩统储层与侏罗系烃源岩具有良好的油气疏导条件。综合以上分析, 笔者认为高探 1 井清水河组油气源

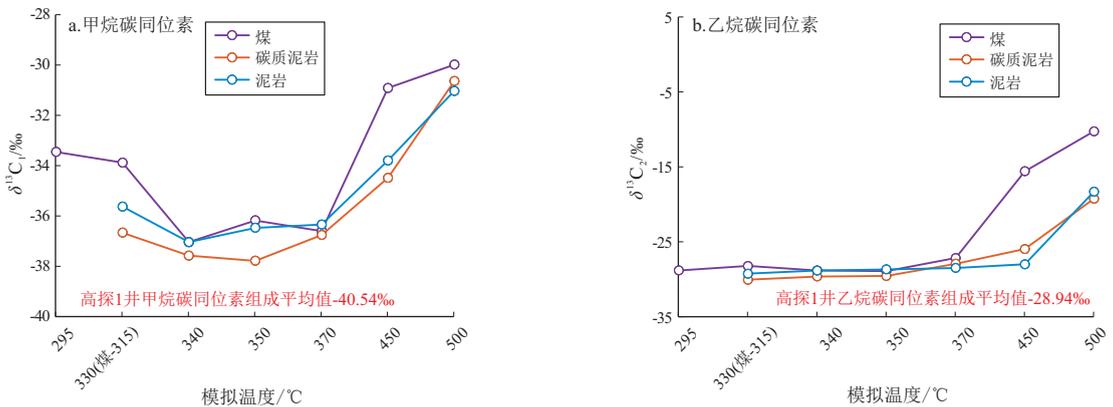


图 11 准噶尔盆地南缘高探 1 井甲烷碳同位素(a)、乙烷碳同位素(b)与模拟气碳同位素对比

Fig.11 Comparison of carbon isotope between methane (a), ethane (b) and simulated gas in well Gaotan 1, southern margin of Junggar Basin

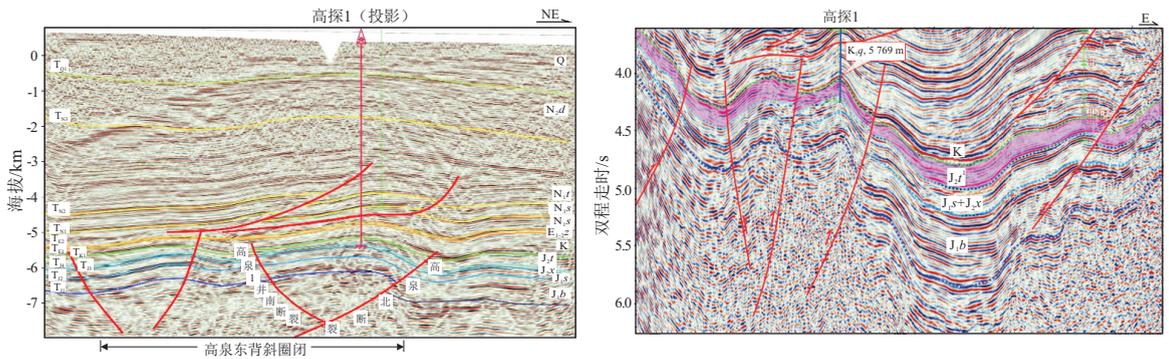


图12 准噶尔盆地南缘高探1井地震地质解释剖面

Fig.12 Seismic geological interpretation section of well Gaotan 1, southern margin of Junggar Basin

自侏罗系源岩,油气同源,其中原油与侏罗系碳质泥岩关系最为密切,而3种岩性煤系烃源岩对天然气均有贡献。

## 4 结论与认识

(1)对准噶尔盆地南缘侏罗系3种岩性煤系烃源岩生烃热模拟研究表明,不同岩性煤系烃源岩生烃演化规律大致相似,但其生油气能力差异较大。泥岩和碳质泥岩生油量较高,但碳质泥岩丰度远大于泥岩,因此碳质泥岩是侏罗系煤成油的主要贡献者,3种岩性烃源岩均可作为良好的气源岩。在较高演化程度时,碳质泥岩和泥岩以原油裂解气为主,煤岩则主要为干酪根降解气。

(2)3种岩性煤系烃源岩随模拟演化程度升高,由于气体碳同位素的分馏效应,甲烷碳同位素均呈明显的先变轻后变重的趋势,乙烷碳同位素也出现较明显的分馏现象,但不如甲烷碳同位素明显,在应用气体同位素时应考虑演化程度的影响。

(3)在较高模拟温度时,3种岩性甲烷碳同位素和乙烷碳同位素分别呈现 $\delta^{13}C_1(\text{煤}) > \delta^{13}C_1(\text{碳质泥岩}) > \delta^{13}C_1(\text{泥岩})$ 和 $\delta^{13}C_2(\text{煤}) > \delta^{13}C_2(\text{泥岩}) > \delta^{13}C_2(\text{碳质泥岩})$ 的特点。整体而言,泥岩和碳质泥岩生成气体同位素比较接近,而煤生成气体碳同位素整体偏重,幅度在3‰~5‰以上。

(4)主要受运移分异效应的影响,高探1井清水河组天然气甲烷碳同位素较轻。通过与模拟气体碳同位素和吐哈盆地典型侏罗系煤成气碳同位素对比,结合源储配置关系等分析认为,高探1井油气主要为侏罗系贡献,油气同源,其中原油与侏罗系碳质泥岩关系最为密切,主要为侏罗系碳质泥岩生成的较高成熟度原油,角质体是侏罗系碳质泥岩主要生油母质,而3种岩性煤系烃源岩对天然气均有贡献。

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