

川西北地区中泥盆统腐泥型烃源岩晚期生气特征实验研究

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摘要:中国南方古生界烃源岩的原始干酪根类型以腐泥型-偏腐泥型(I-II型)为主,目前主体处于过成熟阶段(镜质体反射率 $R_o > 2.0\%$),准确评价I-II型干酪根在生-排油之后的生气潜力(或晚期生气)及生气特征对中国南方古生界深层-超深层天然气勘探至关重要。鉴于此,以川西北地区中泥盆统观雾山组样品($R_o \approx 1.1\%$)为例,通过黄金管生烃模拟实验,结合已有文献资料,探讨了I-II型干酪根在高-过成熟阶段的生气潜力及气体地球化学特征。结果表明,研究样品残留油含量(按单位有机碳质量计算,以下同)为140 mg/g,现今生气潜力为220 mL/g,显示仍具有较好的生气潜力。其中,干酪根裂解气的贡献至少为140 mL/g,残留油裂解气最多为80 mL/g,表明腐泥型烃源岩在排油效率较高时,其晚期生气以干酪根裂解气为主。同时,排油之后的腐泥型烃源岩晚期生成的天然气干燥系数较高,随着甲烷产率的增加甲烷碳同位素快速变重,在成熟度达到 $R_o \approx 3.5\%$ 时,其甲烷碳同位素值与母质干酪根碳同位素值接近(碳同位素分馏程度约为0.5‰)。上述结果可为中国南方古生界深层-超深层天然气的资源潜力评价和天然气来源识别等研究提供有益的科学依据。

关键词:干酪根裂解气;甲烷碳同位素;腐泥型烃源岩;晚期生气;深层天然气;中泥盆统;川西北地区

中图分类号:TE122.1

文献标识码:A

Experimental study on late gas generation characteristics of the Middle Devonian sapropelic source rocks of in Northwestern Sichuan Basin

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Abstract: The Paleozoic source rocks in southern China contain mainly Type I - II kerogen and are currently over-mature with vitrinite reflectance (R_o) greater than 2.0%. Accurate evaluation of the gas generation potential of Type I - II kerogen after oil generation and expulsion and geochemical characteristics of over-mature gases are of great significance to natural gas exploration of deep and ultra-deep Paleozoic gas pools in southern China. In view of this, the mature Devonian source rock samples ($R_o \approx 1.1\%$) collected from the Guanwushan Formation in Northwestern Sichuan Basin are applied for gold tube pyrolysis experiments, and the gas generation potential of Type I - II kerogen at the high-to-over mature stage and the geochemical characteristics of over-mature gas generated are investigated in combination with existing documents. The results show that the residual oil content of the studied samples is 140 mg/gTOC and has a gas generation potential of 220 mL/gTOC at present, indicating high gas-generation potential. Furthermore, the amount of gas from kerogen cracking is at least 140 mL/gTOC and that of gas from residual oil cracking is at best 80 mL/gTOC, indicating that kerogen-cracking gas is the main source of late gas generated from the sapropelic source rocks under high oil expulsion efficiency. Meanwhile, the geochemical characteristics of the late gases generated from the sapropelic source rocks are obviously affected by oil expulsion efficiency. For example, the dryness coefficient of the gases is high, and the methane carbon isotope grows heavier rapidly with increasing methane yield. At $R_o \approx 3.50\%$, the carbon isotope of methane is close to that of the original kerogen (with a mere carbon isotopic fractionation difference of 0.5‰). The

收稿日期:2022-06-06;修订日期:2022-11-19。

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基金项目:中国科学院A类战略性先导科技专项(XDA14010104);国家自然科学基金杰出青年科学基金项目(41925014)。

results obtained above will be of scientific basis to the evaluation of natural gas exploration potential and the identification of natural gas sources in the deep and ultra-deep Paleozoic reservoirs in southern China.

Key words: gas from kerogen cracking, methane carbon isotope, sapropelic source rock, late gas generation, deep natural gas, Middle Devonian, Northwestern Sichuan Basin

引用格式:田辉,吴子瑾,盖海峰,等. 川西北地区中泥盆统腐泥型烃源岩晚期生气特征实验研究[J]. 石油与天然气地质, 2023, 44(1): 46-54. DOI: 10. 11743/ogg20230104.

TIAN Hui, WU Zijin, GAI Haifeng, et al. Experimental study on late gas generation characteristics of the Middle Devonian sapropelic source rocks of in Northwestern Sichuan Basin[J]. Oil & Gas Geology, 2023, 44(1): 46-54. DOI: 10. 11743/ogg20230104.

油气勘探实践表明,充足的生气潜力是形成常规和非常规天然气藏的先决条件之一^[1-3]。烃源岩的生气潜力与其总有机碳含量(TOC)、有机质类型及热成熟度密切相关^[4]。早期研究认为,腐泥型-偏腐泥型烃源岩(I-II型干酪根)主要以生油为主,干酪根直接裂解生成的气态烃数量有限^[5]。因此,早期发现的大型和超大型气田往往为煤型气或为原油裂解气^[6-9]。近十余年来,随着页岩油气的兴起,石油地质学家认识到腐泥型烃源岩,尤其是富有机质泥页岩的排油效率并不都是很高,有相当数量的液态烃可被滞留在页岩地层内^[10-14]。在进一步的热演化过程中,这些滞留烃或残留油可裂解生气,成为常规和非常规天然气的重要气源^[13, 15-18]。

随着勘探进程的不断推进,油气勘探开发逐渐转向深层-超深层。腐泥型烃源岩生油高峰后(通常镜质体反射率 R_o 为1.1%~1.3%,已经发生排油作用)的生气潜力,即晚期生气潜力^[19],越来越受到重视。在高-过成熟阶段,干酪根与滞留油均可生成一定数量的气态烃^[20-24]。大量研究表明,单位质量滞留油的生气潜力明显高于干酪根裂解气,因此,滞留油的裂解生气对腐泥型烃源岩的晚期生气潜力具有重要的影响^[25-30]。同时,滞留油与干酪根的生气机理及过程有所不同,原油裂解气主要来源于 C_{6+} 和 C_{2-5} 脂肪链的C—C键断裂,而干酪根裂解气主要来源于干酪根大分子的脱甲基作用,仅极少量来自于 C_{2-5} 脂肪链的C—C键断裂^[25, 31-33]。因此,滞留油的数量对天然气地球化学特征也有一定的影响^[3, 13, 15, 27-29, 34]。前人研究还发现,滞留油与干酪根在热演化过程中存在相互作用,也会影响烃源岩的生气特征及主生气阶段^[27, 35-38]。上述研究结果为进一步系统研究深层-超深层天然气形成机理提供了重要参考。

中国南方古生界烃源岩的原始干酪根类型以I-II型为主,主体处于过成熟阶段^[39-40],显示具有较好的

天然气生成潜力。川西北地区是四川盆地天然气勘探重要区域之一^[40-41]。其中,位于川西北地区双鱼石构造的双探3井在中泥盆统观雾山组白云岩储层获得了日产 $11.6 \times 10^4 \text{ m}^3$ 的工业气流,展示了泥盆系具有良好的天然气勘探前景^[42-44]。但目前对上述泥盆系储层天然气的相关研究仍较薄弱,天然气的来源仍不清楚。前人研究指出,川西北地区泥盆系发育富有机质烃源岩,如中泥盆统观雾山组泥灰岩^[43-44],这些烃源岩可能是泥盆系储层天然气潜在的气源之一。但由于该地区构造复杂,泥盆系出露较少,川西北地区泥盆系烃源岩的厚度、展布、埋深等地质信息仍不是很清楚。因此,这套烃源岩的规模仍存在一定疑问,同时该套烃源岩的生烃潜力也缺乏详细研究,一定程度上制约了该地区天然气的勘探。整体上,川西北地区泥盆系烃源岩有机质类型以腐泥型为主^[39],目前主体处于过成熟阶段($R_o > 2.0\%$),具有大量生气的地质条件。对于过成熟腐泥型烃源岩而言,地质过程中其早期(如生油窗阶段)生成的部分液态烃及气态烃已经排出或逸散,只有在排油作用之后、更高热演化阶段生成的天然气,即晚期生气潜力,才代表深层-超深层烃源岩真正的资源潜力^[28, 45]。因此,利用低成熟样品建立的封闭体系下的生气模型由于未考虑排油过程的影响,可能会高估烃源岩的晚期生气潜力。本研究选取了川西北地区中泥盆统生油末期的观雾山组烃源岩($R_o \approx 1.1\%$,发生过地质条件下的排油作用),通过黄金管生烃模拟实验系统测定了观雾山组烃源岩的晚期生气潜力及生气特征,并且对比了川西北地区中泥盆统金宝石组低成熟泥岩($R_o = 0.6\%$)以及不同类型腐泥型/偏腐泥型烃源岩残余干酪根(指生油潜力殆尽且利用有机溶剂抽提完全去除滞留油的干酪根, $R_o = 1.2\%$)的生气特征,以期评价腐泥型-偏腐泥型烃源岩(I-II型干酪根)在过成熟度阶段的生气潜力及川西北地区深层-超深层天然气勘探提供相关依据。

1 研究样品与实验方法

1.1 研究样品

研究样品采自川西北广元朝天地区(图1a,b),采样层位是中泥盆统观雾山组(图1c),露头厚度20~30 m(图1d),岩性以深灰色泥晶生物灰岩为主,泥质含量高,并发育有泥质夹层(图1e)。

采集的6个观雾山组泥灰岩样品的TOC介于

1.90%~3.57%,平均值为2.56%。Rock-Eval热解结果显示,样品游离烃(S_1)含量为0.48~1.18 mg/g,裂解烃(S_2)含量为2.47~5.43 mg/g,最高热解峰温(T_{max})为450~453℃,氢指数(HI)为130~155 mg/g(表1)。对D₂G-5泥灰岩样品进行二氯甲烷抽提,得到其滞留油含量(按单位有机碳质量计算,下同)为140 mg/g(C_{14+} 重烃组分,不包含已损失的 C_{6-14} 轻烃)。有机岩石学分析表明,观雾山组泥灰岩(样品D₂G-5)显微组分以微粒体为主,含少量沥青,表明其原始有机质类型为腐泥型或偏腐泥型。该样品实测沥青反射率(BR_o)为

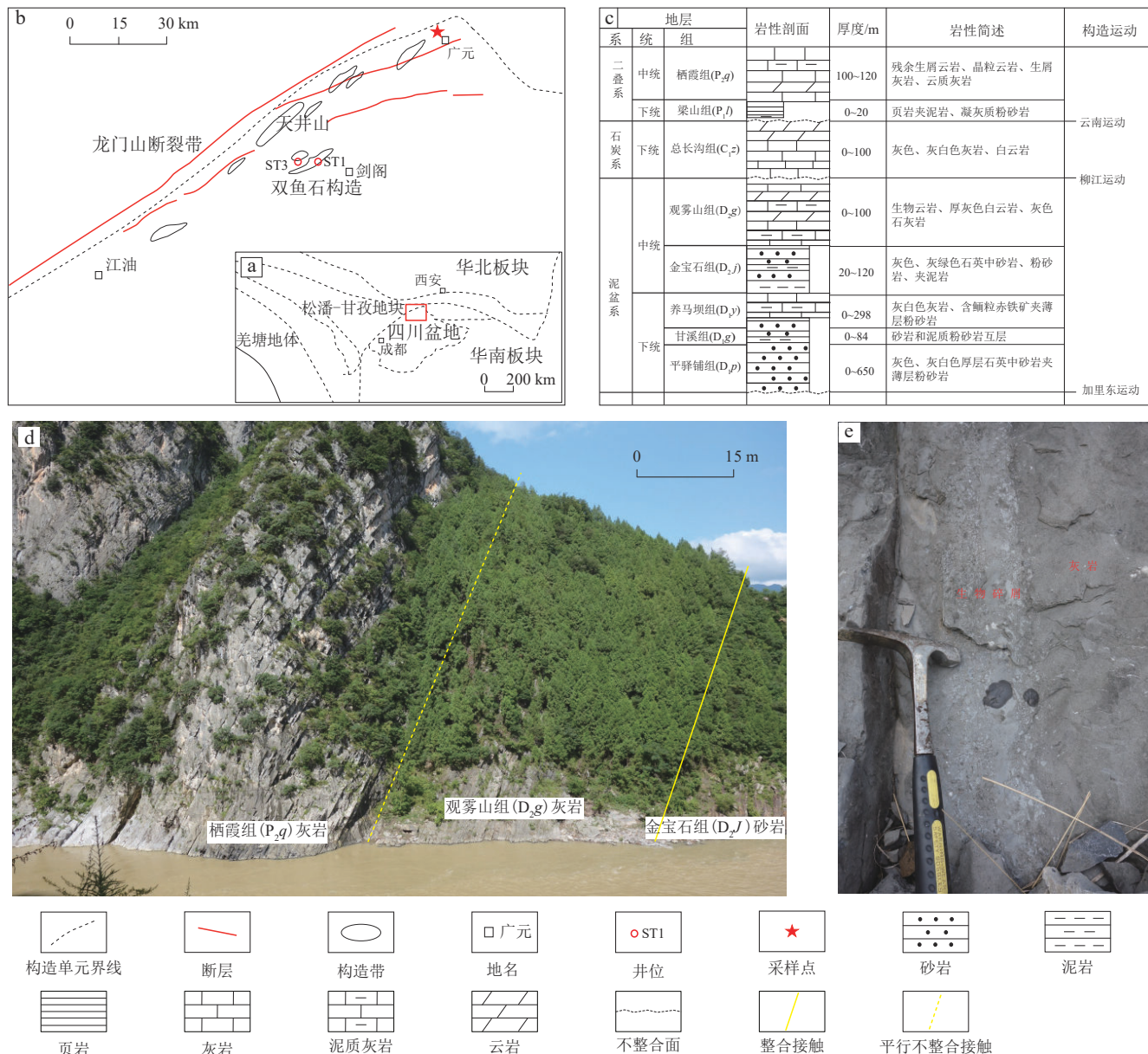


图1 川西北地区地质构造^[41]及样品层位信息

Fig. 1 Maps showing structural location and characteristics^[41] of the study area, stratigraphic columnar section, outcrop picture showing sampling horizon and photo showing the sample from the Middle Devonian Guanwushan Formation limestone in Northwestern Sichuan Basin

a. 构造位置;b. 构造特征;c. 上古生界岩性柱;d. 广元朝天地区野外剖面;e. 观雾山组泥灰岩样品照片

表 1 川西北地区中泥盆统观雾山组烃源岩基础地球化学参数

Table 1 Basic geochemical parameters of the Middle Devonian Guanwushan Formation source rocks in Northwestern Sichuan Basin

样品名称	TOC/%	$S_1/(mg \cdot g^{-1})$	$S_2/(mg \cdot g^{-1})$	$T_{max}/^{\circ}C$	$HI/(mg \cdot g^{-1})$	$\delta^{13}C/‰$
D ₂ G-1	2.75	0.72	4.19	450	152	-28.8
D ₂ G-2	2.67	0.78	4.15	453	155	-28.5
D ₂ G-3	3.57	1.09	5.43	450	152	-28.5
D ₂ G-4	1.90	0.48	2.47	453	130	-28.6
D ₂ G-5	2.20	1.10	3.17	451	144	-28.3
D ₂ G-6	2.27	1.18	3.33	450	147	-29.4
K-5	69.75	23.96	91.16	450	131	-28.3

0.93%, 根据 Schoenherr 等^[46]的转化公式 $E_qVR_o = (BR_o + 0.2443)/1.0495$, 该样品等效镜质体反射率(E_qVR_o)为 1.12%, 表明观雾山组烃源岩热成熟度已经处于生油窗晚期或末期。

本研究对样品 D₂G-5 进行干酪根制备(使用 HCl 和 HF 酸处理, 不经过有机溶剂抽提以尽可能保留其滞留油, 因此该干酪根样品实际为“含油”干酪根), 用于黄金管热模拟生烃研究。制备的干酪根样品 K-5 的 TOC 为 69.75%, HI 为 131 mg/g, $\delta^{13}C$ 值为 -28.3‰。与观雾山组泥灰岩对比的川西北龙门山断裂带金子山地区中泥盆统金宝石组泥岩样品, 实测 R_o 为 0.60%, HI 为 637 mg/g, 显微组分以孢子体为主, 镜质体含量低于 10%, 为典型的 II₁ 型干酪根^[48]。用于对比的残余干酪根是指生油窗末期、生油潜力殆尽且完全去除液态烃的干酪根, 其与由地质样品制备的观雾山组干酪根(含滞留油)最大区别是完全去除了液态烃, 可代表生气窗范围内单纯由干酪根裂解的生气潜力。具体而言, 残余干酪根的实测 R_o 为 1.22%, S_1 含量小于 1 mg/g, HI 为 17~39 mg/g^[28]。

1.2 生烃模拟实验

模拟实验装置采用中国科学院广州地球化学研究所有机地球化学国家重点实验室的黄金管高压釜体系, 实验原理和装置在前人的研究中已做过详细介绍^[25-26, 28, 47-48]。具体实验过程简介如下: 将样品在氩气的保护下装入黄金管中, 然后放入高压釜内。高压釜的温度和压力采用计算机程控技术, 温度误差在 $\pm 0.1^{\circ}C$, 外部压力为 50 MPa, 压力误差为 ± 2 MPa。样品先在 10 h 内从室温升至 240 $^{\circ}C$, 随后以 2 $^{\circ}C/h$ 升至 600 $^{\circ}C$, 自 384 $^{\circ}C$ 开始每 24 $^{\circ}C$ 设置一个温度点。在设定的温度点取出相应的高压釜和黄金管进行后续分析。

热模拟实验结束后, 将金管至于真空装置中进行气体收集, 然后采取外标法进行定量分析, 释放的气体进入安捷伦 7890 气相色谱分析仪, 色谱柱型号为

Poraplot Q (30 m $\times$ 0.25 mm $\times$ 0.25 μm), 载气为氮气, 升温程序设定为: 以 50 $^{\circ}C$ 的初始温度恒温 2 min, 之后以 4 $^{\circ}C/min$ 的升温速率加热到 180 $^{\circ}C$ 并保持恒温 15 min。气体碳同位素测定在 Delta Plus II XI 型气相色谱-碳同位素质谱联用仪上完成, 色谱柱型号为 Poraplot Q (30 m $\times$ 0.32 mm $\times$ 0.25 μm), 载气为氮气, 升温程序设定为: 初始温度为 50 $^{\circ}C$, 恒温 3 min, 之后以 15 $^{\circ}C/min$ 的升温速率加热到 190 $^{\circ}C$ 并保持恒温 7 min。实验结果采用 VPDB 标准进行换算, 误差控制在 ± 0.3 ‰ 以内。

2 结果与讨论

2.1 腐泥型烃源岩晚期生气潜力

观雾山组干酪根的黄金管生烃模拟数据见图 2 和表 2。整体上, 观雾山组干酪根的生气潜力明显低于金宝石组干酪根样品, 而高于腐泥型烃源岩完全排油之后残余干酪根的生气潜力(图 2)。热解过程中, 观雾山组干酪根甲烷和 C₂₋₅ 气体的最大产率分别为 219.6 mL/g 和 15.2 mL/g(图 2a, b), 明显低于金宝石组干酪根($R_o=0.60\%$)甲烷和 C₂₋₅ 气体的最大产率 398.8 mL/g 和 47.7 mL/g^[48], 但仍高于腐泥型烃源岩残余干酪根($R_o=1.22\%$)的甲烷和 C₂₋₅ 气体产率(138.9 mL/g 和 2.7 mL/g^[28])。

大量研究指出, 典型腐泥型烃源岩具有较高的液态烃生成潜力(通常在 500 mg/g 左右或更高)。在地质条件下, 这些优质烃源岩往往具有较高的排油效率(60%~90%)^[49-53], 大部分液态烃会排出烃源岩并在合适的条件下聚集成藏, 或在逸散过程中被次生作用氧化或生物降解。因此, 排出的液态烃对腐泥型烃源岩晚期生气并没有贡献, 只有滞留油及干酪根裂解生成的气态烃, 才能代表腐泥型烃源岩的晚期生气潜力。因此, 利用低成熟度腐泥型烃源岩开展封闭体系热模拟研究及生气潜力评价时, 所有生成的液态烃都将滞

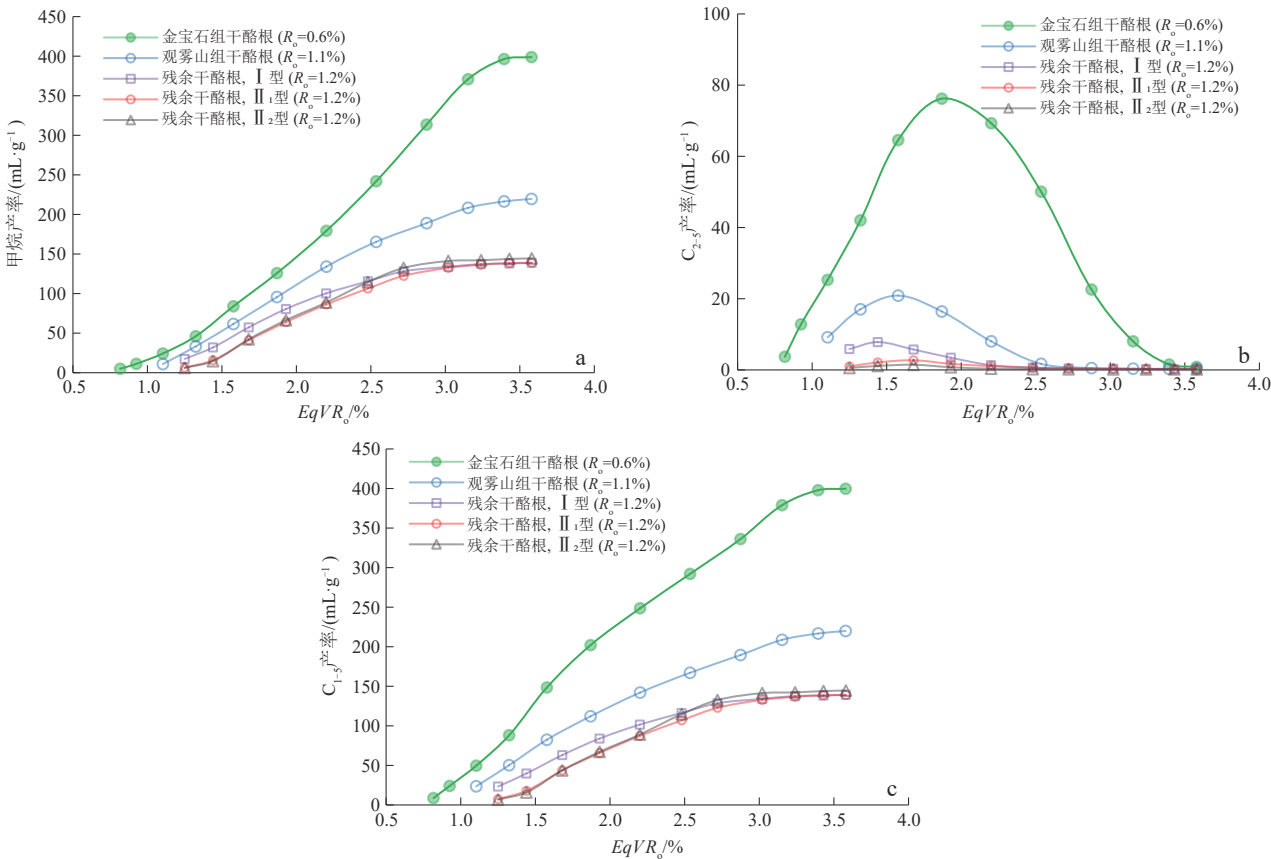


图2 川西北地区中泥盆统观雾山组干酪根($R_0=1.1\%$)晚期生气潜力特征

Fig. 2 Late gas generation potential of the Middle Devonian Guanwushan Formation kerogen ($R_0=1.1\%$) in Northwest Sichuan Basin
a. 甲烷生成特征;b. C_{2-5} 产率特征;c. 总气态烃 C_{1-5} 产率特征
(金宝石组干酪根生气数据引自文献[48],残余干酪根数据引自文献[28]。)

表2 川西北地区中泥盆统观雾山组干酪根黄金管生烃模拟气体产率及碳同位素组成

Table 2 Gas yield and methane carbon isotopic compositions in gold tube pyrolysis experiments of kerogen from the Middle Devonian Guanwushan Formation source rocks in Northwestern Sichuan Basin

模拟 温度/℃	$*EqVR_0/\%$	气体产率/(mL·g ⁻¹)									干燥系数/%	$\delta^{13}C_1/\%$
		CH ₄	C ₂ H ₆	C ₃ H ₈	iC ₄	nC ₄	iC ₅	nC ₅	C ₂₋₅	C ₁₋₅		
384	1.10	10.91	4.81	1.83	0.37	0.31	0.08	0.03	9.17	23.55	46.33	-44.4
408	1.32	33.19	11.54	4.07	0.54	0.64	0.15	0.09	17.03	50.22	66.09	-43.0
432	1.58	61.55	15.21	4.23	0.73	0.46	0.21	0.04	20.87	82.43	74.67	-40.2
456	1.87	95.65	13.98	1.85	0.42	0.12	0.04	—	16.41	112.06	85.36	-36.9
480	2.20	134.03	7.74	0.26	0.03	0.01	0.01	—	8.03	142.06	94.35	-34.6
504	2.54	165.37	1.66	0.05	—	—	—	—	1.71	167.07	98.98	-32.6
528	2.87	188.98	0.50	0.01	—	—	—	—	0.52	189.50	99.73	-31.7
552	3.15	208.35	0.34	0.01	—	—	—	—	0.35	208.70	99.83	-30.3
576	3.39	216.41	0.30	—	—	—	—	—	0.31	216.72	99.86	-29.4
600	3.58	219.60	0.29	—	—	—	—	—	0.29	219.90	99.86	-28.8

注：“*”表示数据引自文献[54]；“—”为低于检测限。

留在烃源岩中并在高-过成熟阶段裂解成气,进而会明显高估这类烃源岩的晚期生气潜力。

本研究中,观雾山组泥灰岩样品的成熟度 R_0 为1.12%,已经进入了生油窗晚期。该样品的残留油数量140 mg/g,明显低于金宝石组泥岩的生油量

(515.6 mg/g),表明大部分液态烃已经排出且排油效率较高。但即使在很高的排油效率条件(假设观雾山组原始生油潜力与金宝石组烃源岩相当,则排油效率大于70%)下,观雾山组成熟泥灰岩仍具有220 mL/g的生气潜力,表明腐泥型烃源岩在排油过程之后仍具

有较高的晚期生气潜力。另一方面,观雾山组泥灰岩样品的生气潜力明显低于金宝石组烃源岩样品的生气潜力(399.7 mL/g),这表明排油效率将大大降低腐泥型烃源岩的晚期生气潜力。

Gai等^[28]研究表明,不同类型的残余干酪根($R_o \approx 1.2\%$,不含液态烃)的生气潜力介于130~144 mL/g。这表明,在生油潜力消耗殆尽且完全去除液态烃/残留油时,不同类型残余干酪根的生气潜力差别不大,约为140 mL/g。而单位质量的滞留油裂解最多可产生约575 mL/g的甲烷^[28],明显高于残余干酪根。本研究中,考虑到干酪根制备过程中会损失少量滞留油,这使得滞留油数量会略低于140 mg/g,因而滞留油裂解气的数量要略低于80 mL/g这一估算值。因此,结合实验结果和地质样品情况可知,本研究中滞留油对观雾山组烃源岩晚期生气潜力的贡献最高可达80 mL/g,占总生气潜力的36%,而干酪根裂解气的贡献最低为64%。李剑等^[55]通过对比低成熟度腐泥型烃源岩在半开放体系和封闭体系条件下的生气特征指出,排油作用后,干酪根晚期裂解气量与滞留油裂解气量约分别占腐泥型烃源岩晚期生气潜力的60%和40%,本研究用地质样品获得的实验结果与这一结果非常接近。因此,在排油效率较高时,腐泥型烃源岩排油后的晚期生气以干酪根裂解为主。

2.2 腐泥型烃源岩晚期生气特征

本研究中,观雾山组干酪根 C_{2-5} 气体的最大产率仅为15.2 mL/g(表2)且在成熟度 $EqVR_o=1.6\%$ 之后快速下降,因此,观雾山组烃源岩晚期生气以甲烷为主。热解过程中,观雾山组干酪根生成的气体干燥系数明

显高于低成熟度的金宝石组干酪根,且更接近残余干酪根的趋势(图3),这与观雾山组烃源岩晚期生气主要以干酪根裂解气为主相一致。

碳同位素分析表明,观雾山组干酪根热解气体的甲烷碳同位素组成随着成熟度增加而逐渐变重,在 $R_o \approx 3.5\%$ 时,其甲烷碳同位素值达到 -28.8% ,非常接近干酪根的碳同位素值(-28.3%),而此时金宝石组干酪根生成甲烷的碳同位素值与干酪根的碳同位素值相差3.6‰(图4)。上述干酪根与甲烷碳同位素值的差异,同样反映了甲烷的来源及生成机制不同。成熟度高的烃源岩晚期生气以干酪根裂解气为主,因此其甲烷碳同位素组成非常接近干酪根的碳同位素组成。而低成熟腐泥型烃源岩具有较高的液态烃生成潜力,这些液态烃裂解生成的甲烷碳同位素较轻,因此甲烷的碳同位素值明显低于其母质干酪根的碳同位素值。

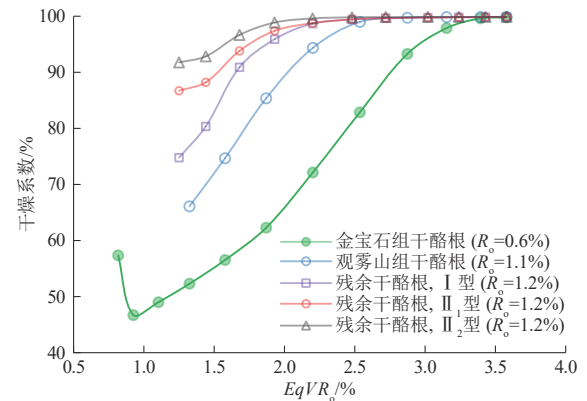


图3 川西北地区中泥盆统观雾山组干酪根晚期生气干燥系数
Fig. 3 Dryness coefficient curves of late gas generated from the Middle Devonian Guanwushan Formation kerogen in Northwestern Sichuan Basin (金宝石组干酪根数据引自文献[48],残余干酪根数据引自文献[28].)

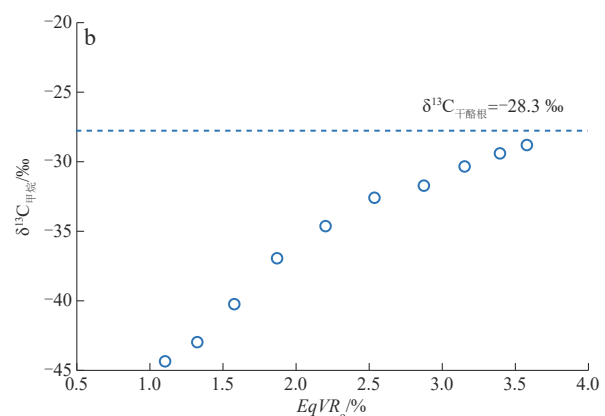
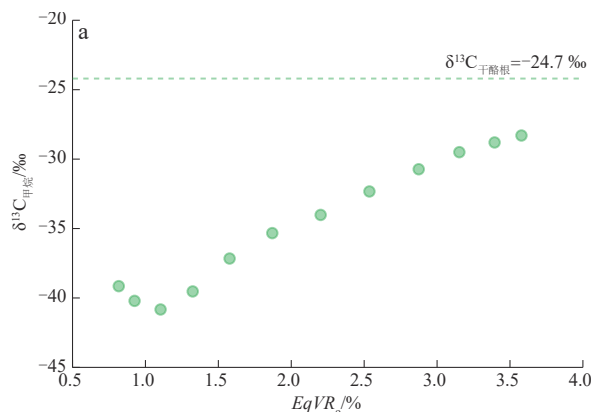


图4 川西北地区中泥盆统干酪根生成甲烷碳同位素分馏特征

Fig. 4 The fractionation characteristics of methane carbon isotope of the Middle Devonian kerogen generation in Northwestern Sichuan Basin

a. 金宝石组干酪根生成甲烷碳同位素分馏特征,数据引自文献[48];b. 观雾山组干酪根生成甲烷碳同位素分馏特征

(图中虚线为其干酪根碳同位素组成。)

生烃模拟过程中,甲烷产率与甲烷碳同位素的协变图通常反映了生烃过程中甲烷碳同位素的演化趋势。本研究中,观雾山组烃源岩晚期生气过程中,随着甲烷产率的增加,甲烷碳同位素值迅速变重,而低成熟金宝石组腐泥型烃源岩尽管具有更高甲烷产率,但其甲烷碳同位素值变重较缓慢(图5)。这表明,发生过排油作用的高成熟烃源岩晚期生气过程中,其甲烷碳同位素随热成熟度增加变化更快。已有的研究表明,干酪根裂解气主要来源于大分子结构缩聚过程中的脱甲基作用^[25, 31, 33],而 ^{13}C — ^{13}C 键的键能要高于 ^{13}C — ^{12}C 键和 ^{12}C — ^{12}C 键^[26],含 ^{13}C 键的甲基更多的是结合在大分子结构上。随着热演化程度的增加,干酪根分子进一步缩聚,更多的含 ^{13}C 键的甲基断裂形成甲烷,因此在干酪根裂解生成甲烷的过程中甲烷碳同位素快速变重。

上述结果表明,腐泥型烃源岩在热演化过程中,当生成的液态烃排出后,其晚期甲烷的生气潜力及碳同位素特征将发生明显改变。但是,即使排油效率较高时,腐泥型烃源岩在高-过成熟阶段仍具有一定的晚期生气潜力,有条件形成天然气藏。同时,排油之后的腐泥型烃源岩晚期生成的烃类气具有干燥系数高、甲烷碳同位素较重等特点。对于深层-超深层油型气天然气藏,当干燥系数不是很高且甲烷碳同位素较轻时,通常可认为其主要来自原油裂解气。但是,当天然气干燥系数很高且甲烷碳同位素较重时,则需考虑腐泥型烃源岩晚期裂解生气对气藏的贡献。成熟干酪根及残留油晚期裂解同样具有形成天然气藏的潜力,尤其是热演化程度很高的深层-超深层地层。

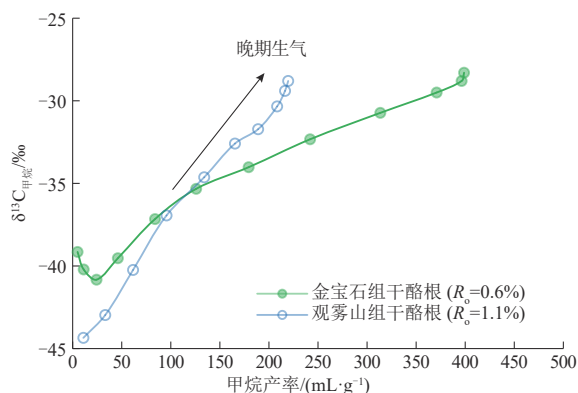


图5 川西北地区中泥盆统观雾山组干酪根晚期生气过程中甲烷碳同位素特征

Fig. 5 Methane carbon isotope features of the late gas generation in the Middle Devonian Guanwushan Formation kerogen in Northwestern Sichuan Basin
(金宝石组干酪根数据引自文献[48]。)

3 结论

1) 川西北地区中泥盆统观雾山组泥灰岩现今生气潜力为220 mL/g,其中干酪根裂解气至少为约140 mL/g左右,滞留油裂解气至多为80 mL/g左右,这表明当排油效率较高时,排油后的腐泥型烃源岩晚期生气($R_0=1.2\%$ 之后)以干酪根裂解气为主。

2) 观雾山组腐泥型烃源岩晚期生成的甲烷碳同位素随着成熟度的增加快速变重,当成熟度达到 $R_0 \approx 3.5\%$ 时,甲烷碳同位素值与观雾山组干酪根碳同位素值接近,碳同位素分馏程度仅为0.5‰,而在相同成熟度条件下,低成熟金宝石组腐泥型烃源岩生成的甲烷与干酪根碳同位素分馏程度可高达3.6‰。

3) 腐泥型烃源岩在过成熟阶段仍具有一定的生气潜力,对于干燥系数高、甲烷碳同位素较重的深层-超深层油型气天然气藏,需考虑腐泥型烃源岩晚期生气对气藏的贡献。

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