

原油物性演化规律新发现及其对页岩油勘探的启示

高岗^{1,2)}, 刘诗局^{1,2)}, 靳军³⁾, 张紫恒^{1,2)}, 柳广弟^{1,2)}, 向宝力³⁾, 黄志龙^{1,2)}, 康积伦⁴⁾, 刚文哲^{1,2)}

1) 中国石油大学(北京)地球科学学院, 北京, 102249;

2) 油气资源与探测国家重点实验室(中国石油大学(北京)), 北京, 102249;

3) 中国石油新疆油田分公司, 实验检测研究院, 新疆克拉玛依, 834000;

4) 中国石油吐哈油田分公司勘探开发研究院, 新疆哈密, 839009

内容提要:针对烃源岩生成的原油物性随热演化如何变化的问题, 本文基于对准噶尔盆地玛湖凹陷下二叠统风城组和吉木萨尔凹陷中二叠统芦草沟组下段源储紧邻自生自储页岩油物性、地化特征、成藏特征及原油物性与烃源岩热演化关系的分析, 综合烃源岩生烃热模拟实验结果与国内外相关文献资料, 首次确认了咸化湖相烃源岩生成的原油物性与烃源岩热演化程度之间的变化规律。认为页岩油源岩生成的原油密度和黏度具有随热演化程度增强先增加而后降低的规律, 其中生油高峰附近生成的原油非烃相对含量、密度和黏度最高。该认识不仅是对已有的石油地质学中原油物性随热演化规律认识的进一步厘定和修正, 而且对页岩油甜点段、甜点区的选择以及页岩油原位转化等都有极为重要和现实的指导作用。

关键词:原油物性; 页岩油气; 咸化湖相; 风城组; 芦草沟组; 准噶尔盆地

原油密度和黏度作为一种重要的原油物理性质已成为衡量原油质量的重要指标, 其值的高低对于原油运移、聚集和开发均有极为重要的影响, 尤其在页岩油和致密油开发过程中与原油产量有密切关系(王绪龙等, 2008; 柳广弟, 2018; 赵文智等, 2020a, 2020b)。有关原油物性的影响因素, 许多学者都进行过研究(Tissot and Welte, 1978; 胡见义等, 1989; Peters and Moldowan, 1993)。已有的研究表明烃源岩母质特征、地层层析作用、生物降解、水洗、氧化、轻烃散失、温度等都对原油的物性有影响(赵文智等, 1999; Gao Gang et al., 2020)。一般认为, 层析作用、温度升高主要导致原油密度、黏度等降低(Tissot and Welte, 1978; 柳广弟, 2018); 水洗、氧化、生物降解、轻烃散失等主要导致原油密度、黏度增加(Connan, 1984; Huang Haiping et al., 2003; Aitken et al., 2004); 原油密度和黏度随烃源岩的热演化程度增加而降低(Connan, 1984; 李素梅,

2008; 柳广弟, 2018; 李二庭等, 2020)。这些认识在实践中已被广泛认可。然而, 笔者在研究准噶尔盆地西北缘玛湖凹陷下二叠统风城组和东部吉木萨尔凹陷中二叠统芦草沟组下段咸化湖相页岩油时, 首次发现源储紧邻型页岩油的密度和黏度随埋深即热演化程度的升高有一定规律, 但并不像普遍认为的随深度增加而降低, 这显然与已有的认识不符。本文将基于准噶尔盆地上述两个层段的页岩油物性、分子地球化学特征、油源对比和生烃热模拟实验相结合的方法, 同时充分参考国内外相关文献, 探讨烃源岩热演化过程对原油密度、黏度的影响。该研究成果应该是对传统石油地质学中经典认识的重新厘定, 有助于对其他含油气盆地原油密度、黏度的分布特征进行更为客观的认识, 具有重要的理论和应用价值, 对页岩油勘探和开发以及页岩油原位转化也将会有重要的指导作用。

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作者简介: 高岗, 男, 1966 年生。博士, 教授, 从事油气地质与勘探的科研与教学工作。E-mail: gaogang2819@sina.com。

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Gao Gang, Liu Shiju, Jin Jun, Zhang Ziheng, Liu Guangdi, Xiang Baoli, Huang Zhilong, Kang Jilun, Gang Wenzhe. 2023. A new discovery of physical property evolution of crude oil and insights into shale oil exploration. Acta Geologica Sinica, 97(5): 1561~1575.

1 地质特征

准噶尔盆地位于中国新疆北部,面积约 $13 \times 10^4 \text{ km}^2$ (图 1a、c)。盆内发育了从石炭纪到第四纪等不同地质时代的地层,从石炭系到古近系均不同程度地发育有烃源岩(陈建平等,2016;支东明等,2019a;杨帆等,2019;何文军等,2019;龚德瑜等,2021;Liu Shiju et al.,2021,2022b;唐勇等,2022)。其中的二叠系烃源岩主要分布在下二叠统风城组(P_1f)和中二叠统芦草沟组(P_2l),这两套烃源岩也是该盆地的主力烃源岩(Liu Shiju et al.,2022a)。露头 and 井下钻遇的风城组主要分布在盆地西北部玛湖凹陷周缘(图 1b),是我国陆上优质的咸水湖相烃源岩之一。风城组形成于扇三角洲-湖泊沉积体系(许琳等,2019;王学勇等,2022)。岩石沉积颗粒由火山碎屑、陆源碎屑、深部热液和内沉积碳酸盐等多元混合而成,具有典型的混合沉积特点(支东明等,2019a;唐勇等,2022)。风城组烃源岩主要形成于干旱气候背景下的咸水湖相沉积环境,不仅通过深大

断裂、不整合、砂体等输导层为源外石炭系—新近系储集层提供了大量油气,而且在风城组内部还形成了大量自生自储的不同类型的油气资源(支东明等,2019b;许琳等,2019)。研究发现该烃源岩残余有机质丰度并不很高,但是在高盐度背景下沉积的有机母质生烃潜力非常大(唐勇等,2022)。源岩层系内部发育有泥质白云岩和凝灰岩储层,其与泥质岩成纹层状或层状互层,具备源储紧邻和源储一体的页岩油成藏条件(许琳等,2019;支东明等,2021)。随着页岩油勘探的进行,发现风城组内部具有页岩油勘探和开发的潜力(支东明等,2019b,2021;宋永等,2022)。本次研究主要采集风城组烃源岩层系内部源储紧邻的近源自生自储的原油和烃源岩样品进行原油物性与烃源岩特征分析,不考虑风城组源外长距离运移聚集的油藏原油。

露头 and 井下钻遇的芦草沟组烃源岩主要分布在盆地东部的吉木萨尔凹陷(图 1d)、石树沟凹陷、石钱滩凹陷及盆地南缘等部位。其中的吉木萨尔凹陷芦草沟组是我国第一个页岩油勘探和开发示范区

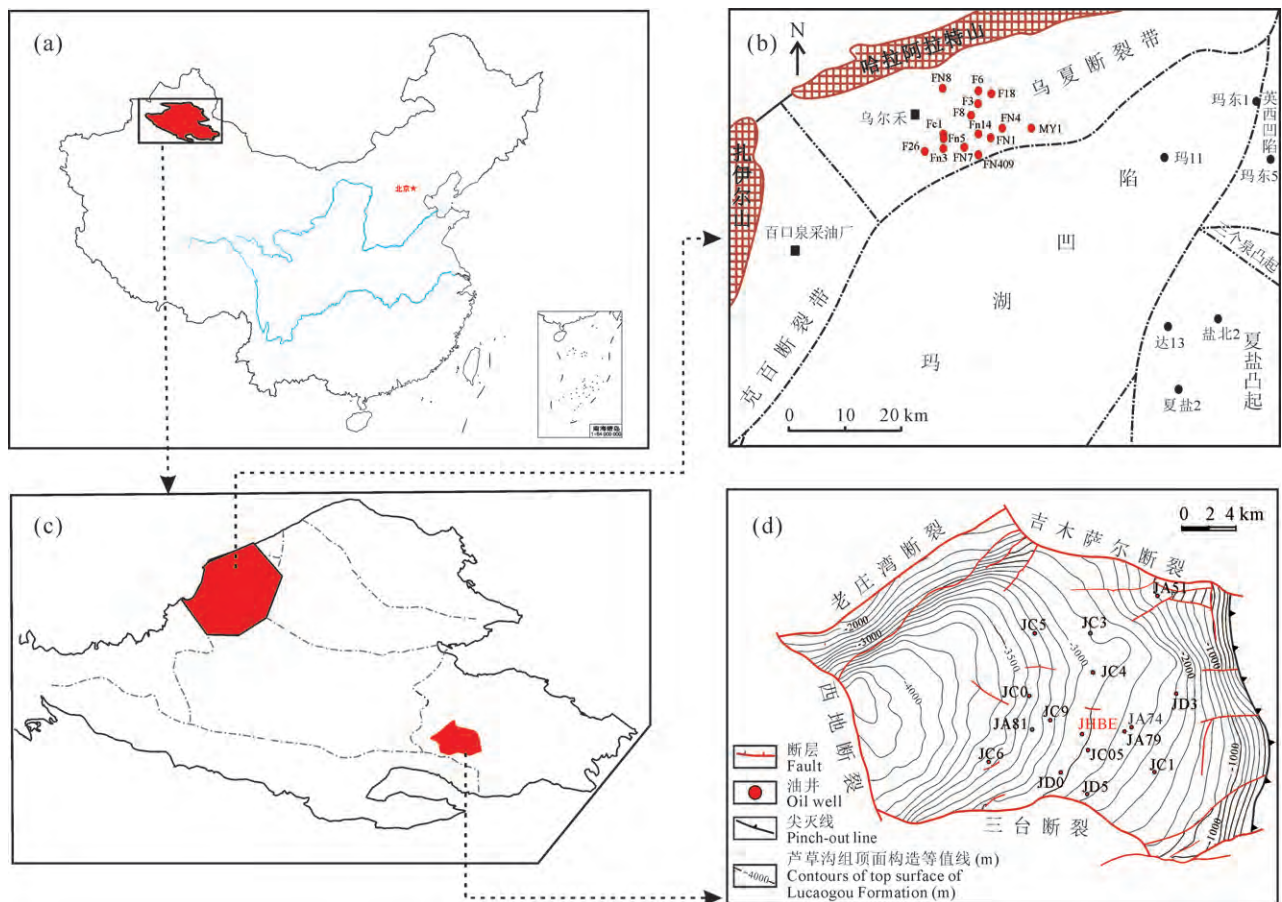


图 1 准噶尔盆地玛湖和吉木萨尔凹陷构造位置与井位分布图

Fig. 1 The structural position and borehole location of the Mahu and Jimusar sags in Junggar basin

(王小军等,2019),芦草沟组烃源岩也主要形成于干旱—半干旱气候背景下的咸水湖相沉积环境(康积伦等,2022),具有明显的咸水混合沉积特点(匡立春等,2012;高岗等,2016)。有机地化分析表明芦草沟组有机质丰度要明显高于风城组,但它们具有相近的生烃潜力(Liu Shiju et al.,2022a)。根据芦草沟组岩性及其组合变化特征,将其划分为上(P_2l_2)、下(P_2l_1)两个甜点段,其油气各自形成独立的含油气系统(Cao Zhe et al.,2016a,2016b;高岗等,2017)。上甜点发育单层厚度较大的砂体,并且分布范围广,所以,其原油具有较明显的二次运移特征(Liu Shiju et al.,2022b),而下甜点单砂体厚度总体比上段要薄,平面非均质性强,油气侧向运移作用微弱,表现为典型的近源自生自储特征(高岗等,2017;Liu Shiju et al.,2022b)。故本次在吉木萨尔凹陷主要针对芦草沟组下甜点段采集原油与烃源岩样品进行原油物性与烃源岩特征分析。

2 样品与实验

风城组的原油与烃源岩样品主要采集于玛湖凹陷风城组烃源岩中心所在的风城地区,该区风城组源、储紧密互层,以自生自储特征为主;吉木萨尔凹陷芦草沟组原油与烃源岩样品主要采集于芦草沟组下甜点段,也同样具有近源自生自储特征。对采集的烃源岩进行可溶有机质抽提,对抽提的可溶有机质和原油样品进行族组成分离和定量。采用安捷伦7890-5975c气相色谱(GC)-质谱(MS)联用仪对烃源岩可溶有机质和原油的饱和烃组分进行气相色谱-质谱(GC-MS)分析。氦气(纯度99.999%)作为载气;注射口温度为300℃;传输线温度为300℃;HP-5MS弹性石英毛细柱(30 m×0.25 mm×0.25 μm);GC烘箱程序设置为50℃保温1 min,20℃/min升温至120℃,以4℃/min升至250℃,再以3℃/min升至310℃保持30 min;载气流速为1 mL/min。质谱仪在1047 V电压下工作。

对含典型生烃母质的烃源岩进行生烃热模拟实验,以观察热演化过程中产物特征与生标物分子组成的演化特征。热模拟实验采用高温高压密闭容器加水热模拟法,实验时间为24 h。实验样品粉碎成块样,大小约为2 mm×2 mm×1 mm,用量为30 g,加水量25 mL。实验温度依次为300℃、335℃和370℃。实验产物主要有液态和气态两种,其中在样品表面、高压釜壁和管道收集的液态产物视为排出油,样品粉碎后有机质溶剂抽提得到的产物为残

余油。

收集于新疆油田公司的风城组和芦草沟组下段的部分烃源岩 TOC、热解(Rock-Eval)分析数据以及原油密度、黏度等以及部分参考文献的数据也用于该论文的研究中。

3 原油物性与地球化学特征

3.1 原油物性特征

对原油物性数据的整理和分析发现,风城组原油物性数值分布范围明显较宽,密度主要在0.8263~0.9313 g/cm³之间,属于轻质油—中质油范畴,主要为中质油;黏度介于3.76~1357.44 mPa·s之间,属于高黏油—稠油范畴;芦草沟组物性数值分布范围相对较窄,密度主要分布在0.8861~0.9308 g/cm³之间,全部属于中质油;黏度在25.64~988.08 mPa·s之间,主要属于稠油,少量为高黏油(表1,图2)。两个层段的原油密度和黏度之间均存在极好的指数相关关系,并且相关趋势吻合(图2)。两个层位的原油密度、黏度与胶质+沥青质含量均具有好的正相关性(图3),表明了原油密度和黏度主要与极性杂原子化合物含量有关(Tissot and Welte,1978;李素梅,2008)。上述原油密度、黏度及其与族组分含量的分布特征表明,这两个形成于咸水湖相的不同烃源岩层系的原油物性与组成均有较大的变化范围,并且其密度和黏度值总体明显较高。

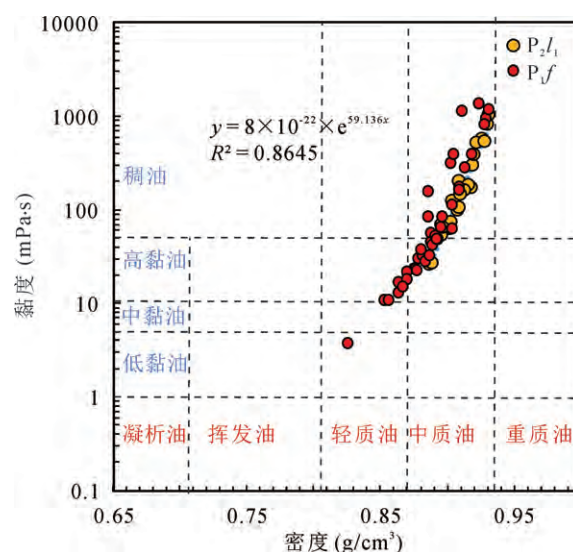


图2 准噶尔盆地风城组和芦草沟组下段原油密度与黏度关系图

Fig. 2 The relationship of density vs. viscosity of crude oil from the Fengcheng Formation and the lower Lucaogou Formation in Junggar basin

表 1 准噶尔盆地玛湖凹陷风城组和吉木萨尔凹陷芦草沟组下段试油、原油物性与族组成数据表

Table 1 Data of oil testing, physical properties and group composition of crude oil in the lower Lucaogou Formation of

Jimusaer sag and Fengcheng Formation of Mahu sag in Junggar basin

井号	层位	射孔井段 (m)	试油厚 度(m)	日产油 量(t/d)	日产气量 ($\times 10^4 \text{ m}^3$)	产能指数 (t/(m $\cdot$ d))	原油物性		饱和烃 (%)	芳香烃 (%)	非烃 (%)	沥青质 (%)	非烃+ 沥青质 (%)
							密度 (g/cm 3)	黏度 (mPa $\cdot$ s)					
F18	P ₁ f	2894.5~2925.0	15.5	0.372		0.02	0.8642	17.04					
F21	P ₁ f	3368~3385	17	9.21		0.54	0.8885	45.12	65	14	16	6	22
F26	P ₁ f	3261~3285	24	0.494		0.02	0.8699	21.52					
F26	P ₁ f	3297~3321	24	0.939		0.04	0.8534	10.91					
F3	P ₁ f	2983~3018	16	1.31		0.08	0.8752	23.56					
F501	P ₁ f	3298~3311	13	0.53		0.04	0.8877	56.10					
F501	P ₁ f	3400~3420	20	28.35	0.16	1.42	0.8930	49.64					
F6	P ₁ f	3260.5~3267.5	7				0.8811	38.20					
F8	P ₁ f	3025.8~3033.8	8				0.8788	30.59					
F8	P ₁ f	3052.8~3064.8	12	10.68	0.101	0.89	0.8817	32.29					
F8	P ₁ f	3222.8~3234.8	12				0.8764	23.83					
FC011	P ₁ f	3788~3800	12	0.41		0.03	0.8967	83.35	52	14	27	7	34
FC011	P ₁ f	3852~3864	12	28.35	0.631	2.36	0.8911	51.78	55	19	25	2	26
FC012	P ₁ f	3934~3947	13				0.9241	1357.44					
FC012	P ₁ f	4190~4228	18.5				0.9313	1164.21					
FC1	P ₁ f	3960~3976	16	8.96	0.073	0.56	0.8861	157.27	78	8	12	2	14
FC1	P ₁ f	4193.97~4272.18	78.21	38.7	3.32	0.49	0.8263	3.76	85	7	6	1	7
FC1	P ₁ f	4307~4319	12	12.4	0.237	1.03	0.8565	10.71	72	10	7	11	18
FC001	P ₁ f	3220~3260	16	0.66		0.04	0.9250	937.61	53	15	28	4	33
FN1	P ₁ f	4180.62~4212.79	32.17	0.09		0.00	0.9109	1141.54					
FN1	P ₁ f	4444~4456	12	0.636		0.05	0.9188	387.25					
FN14	P ₁ f	4316~4356	12	1.91		0.16	0.8867	33.06	56	23	17	5	22
FN14	P ₁ f	4391~4458	30	10.14	0.077	0.34	0.9038	64.04	56	14	17	12	30
FN3	P ₁ f	3906~3926	14	0.27		0.02	0.9033	319.21					
FN3	P ₁ f	3951~3963	12	0.181		0.02	0.9045	388.52					
FN4	P ₁ f	4254~4268	14	2.03		0.15	0.9278	829.00	60	16	17	7	24
FN4	P ₁ f	4388~4402	14	1.25		0.09	0.9041	113.25	61	14	16	8	24
FN4	P ₁ f	4568~4618	23	10.55	0.109	0.46	0.8894	41.65	67	15	12	6	18
FN4	P ₁ f	4635~4648	13	2.34		0.18	0.8889	41.69	70	16	10	4	14
FN409	P ₁ f	4374.0~4436.5	18.5	0.42		0.02	0.9086	164.08					
FN409	P ₁ f	4475~4522	20	10.04		0.50	0.9137	280.02					
FN5	P ₁ f	4418~4446	28	49.31	0.353	1.76	0.8703	18.09	78	12	8	2	10
FN7	P ₁ f	4296~4334	24	10.96		0.46	0.8858	85.09	63	13	14	11	24
FN7	P ₁ f	4835~4895	19				0.8670	15.35					
FN8	P ₁ f	4256~4286	14				0.9090	173.36	54	15	24	6	31
MY1	P ₁ f	4579~4852	26	20.78		0.80	0.8972	48.94	60	20	14	6	20
MY1	P ₁ f	4877~4937	22	16.03		0.73	0.8784	22.80	75	13	9	4	13
JA51	P ₂ l ₁	2224~2254	25	3.79		0.15	0.9032	119					
JC1	P ₂ l ₁	2875~2945	23	0.71		0.03	0.9256	551.8	47.77	21.34	28.66	2.23	30.89
JC3	P ₂ l ₁	3664~3717	17	5.51		0.32	0.9092	197.97	55.98	18.24	21.07	4.72	25.78
JA74	P ₂ l ₁	3255~3314	19	7.76		0.41	0.9222	510.35	48.11	17.30	30.82	3.77	34.59
JA81	P ₂ l ₁	4079~4091	9	10.2		1.13	0.9020	61.66					
JC6	P ₂ l ₁	4209~4255	17	13.88		0.82	0.8959	67					
JC05	P ₂ l ₁	3565~3588	13.5	5.76		0.43	0.9190	286.87	55.22	18.10	22.70	3.99	26.68
JC8	P ₂ l ₁	2784~2794	10	0.94		0.09	0.8983	69.33	57.15	17.94	22.19	2.73	24.92
JC9	P ₂ l ₁	3982~3987	5	5.82		1.16	0.9081	97.28	59.94	14.51	14.20	11.36	25.56
JD0	P ₂ l ₁	3579~3626	19	5.22		0.27	0.9278	525.29	46.14	23.96	26.01	3.89	29.90
JD2	P ₂ l ₁	3498~3502	4	3.11		0.78	0.9174	167.06					
JD3	P ₂ l ₁	2944~2954	7			0.00	0.9160	180.5					
JD5	P ₂ l ₁	3279~3283	4	1.14		0.29	0.9308	988.08	33.33	27.54	32.75	6.38	39.13

续表 1

井号	层位	射孔井段 (m)	试油厚 度(m)	日产油 量(t/d)	日产气量 ($\times 10^4 \text{ m}^3$)	产能指数 (t/(m·d))	原油物性		饱和烃 (%)	芳香烃 (%)	非烃 (%)	沥青质 (%)	非烃+ 沥青质 (%)
							密度 (g/cm ³)	黏度 (mPa·s)					
JHBE	P ₂ l ₁	3703~3709	6	5.12		0.85	0.9091	101.39					
	P ₂ l ₁	3683~3700	14.5	6.37		0.44	0.9029	71.22					
JH24	P ₂ l ₁	3623.5~3641.0	11.5	5.6		0.49	0.9127	154.8	52.25	19.22	23.12	5.40	28.53
JH33	P ₂ l ₁	3414~3427	13	5.76		0.44	0.9302	800					
JH35	P ₂ l ₁	3621.0~3633.5	10	0.16		0.02	0.9194	376.8					
	P ₂ l ₁	3590~3612	15	5.42		0.36	0.9097	143.7	53.69	24.59	20.49	1.23	21.72
	P ₂ l ₁	3567~3572	5	0.58		0.12	0.9194	376.8	50.35	17.38	23.05	9.22	32.27
JH40	P ₂ l ₁	3992.5~4021.5	19.5	10.42		0.53	0.8970	21.16					
	P ₂ l ₁	4037~4058	13.5	11.21		0.83	0.8952	51.06	64.08	16.15	17.16	2.52	19.68
JH45	P ₂ l ₁	3855~3887	21.5	5.4		0.25	0.9030	99.72					
	P ₂ l ₁	3909.5~3925.5	13.5	5.61		0.42	0.8968	63.14	54.25	17.99	22.39	5.37	27.76
JH47	P ₂ l ₁	4061~4064	3	10.88		3.63	0.8867	25.64	67.38	14.18	14.18	4.26	18.44
JH55	P ₂ l ₁	4040~4064	21	10.37		0.49	0.8887	26.49					
	P ₂ l ₁	4073~4085	9.5	2.31		0.24	0.8774	16.91					
	P ₂ l ₁	4008~4030	19	10.28		0.54	0.9058	76.03					

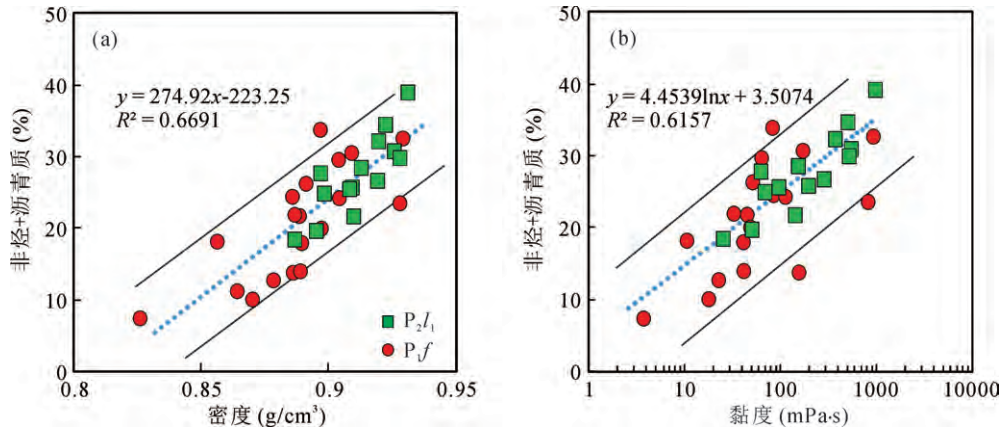


图 3 准噶尔盆地风城组和芦草沟组下段原油密度(a)-黏度(b)与非烃含量关系图

Fig. 3 Relationship of density (a) and viscosity (b) vs. non-hydrocarbon content of the crude oil from the Fengcheng Formation and the lower Lucaogou Formation in Junggar basin

3.2 原油分子地球化学特征

生标物分子组成能够较好地反映原油生烃母质的形成环境条件与母质来源差异(Seifert and Moldowan,1981;Peters et al.,2005)。风城组和芦草沟组下段原油在生物标志化合物组成上有许多相似之处,具体表现在等离子流图(TIC)中,均富含β-胡萝卜烷,且随成熟度增加,β-胡萝卜烷均呈现降低的趋势,同时植烷优势明显(图 4)。这均反映了风城组和芦草沟组沉积水体的盐度较高(Hall and Douglas,1981;Shanmugam,1985)。风城组原油的甾烷类化合物含量明显较高,而芦草沟组则具有明显高的藿烷含量,这说明了风城组原油真核生物的贡献较高,细菌贡献不明显,而芦草沟组细菌贡献相对较多(Peters et al.,2005;Summons et al.,2006)。

在 $m/z=191$ 质谱图(图 4)中,风城组三环萜烷中的 C_{23} 含量明显高于 C_{20} 和 C_{21} ,而芦草沟组 C_{23} 三环萜烷优势不明显,证实了风城组沉积盐度要高于芦草沟组下段(Waples and Machihara,1991)。另外,风城组原油的三环萜烷相对含量明显要高于芦草沟组,这主要与藻类来源有关,如塔斯马尼亚藻(绿藻门)就是三环萜烷的主要生源,而有的研究者对风城组生源研究中也发现了其烃源岩富含绿藻门(杜氏藻)(Cao Jian et al.,2021)。 C_{30} 重排藿烷含量在两个层段的原油中均很低,指示了风城组和芦草沟组都沉积于缺黏土的沉积环境中(Seifert and Moldowan,1981),这与盐度较高的特征是极为吻合的。风城组的伽马蜡烷含量明显很高,芦草沟组的伽马蜡烷含量中等,这指示了风城组的水体分层性更显著,盐度更高,而芦草沟组下段的

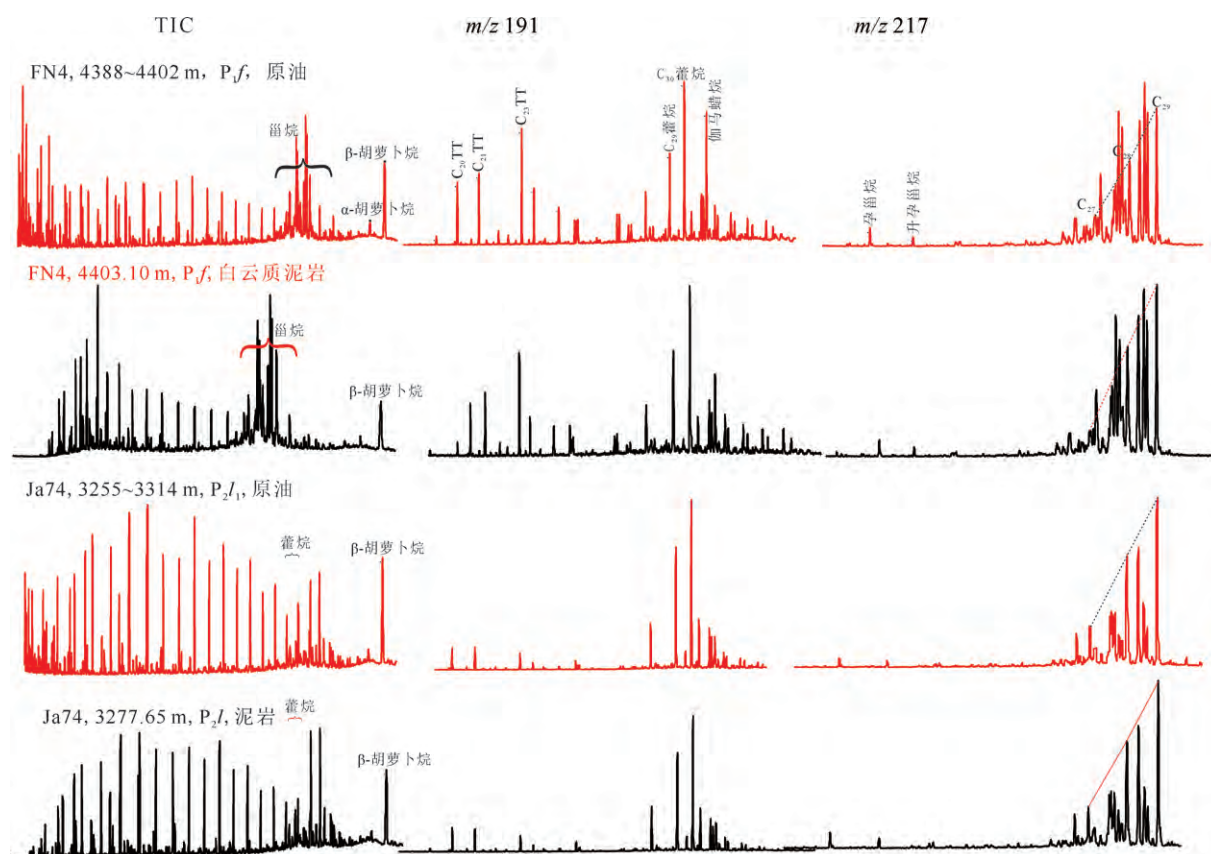


图5 准噶尔盆地风城组与芦草沟组下段原油与邻近烃源岩饱和烃 GC-MS 谱图对比

Fig. 5 GC-MS characteristics of saturated fractions of typical crude oil and source rock from the Fengcheng Formation and lower Lucaogou Formation in Junggar basin

其来源已没有争议(高岗等,2017;Gao Gang et al., 2018;Liu Shiju et al., 2022a, 2022b),其原油生标物组成特征都与邻近的烃源岩具有相似性(图5)。根据试油资料发现,风城组油藏原油可以划分为两类:含气油藏原油(试油结果中含气)和纯油藏原油(试油结果中只含油)。其中含气油藏并没有分布在风城组最深部位,而是在不同深度均存在,这在一定程度上暗示了这部分原油经历了一定的纵向运移作用。从原油和源岩甾烷异构化参数随深度变化图(图6)可以发现,风城组中纯油藏原油的甾烷异构化参数与邻近的源岩吻合得很好(图5;图6a、b),说明纯油藏原油与邻近源岩的成熟度一致,表明风城组纯油藏原油来源于邻近的源岩(图5),直接指示了纯油藏原油具有源储紧邻、近源运移的特点。含气油藏的原油甾烷成熟度参数 $\beta/(\alpha + \beta)$ C_{29} 甾烷和 $\alpha\alpha 20S/(20S + 20R)$ C_{29} 甾烷则要明显高于邻近源岩(图6a、b),反映了其原油经历了一定的垂向运移作用,来自更深部的、成熟度更高的烃源岩。芦草沟组下段原油均为纯油藏原油,其原油甾烷异构化参数 $\beta/(\alpha + \beta)$ C_{29} 甾烷和 $\alpha\alpha 20S/(20S +$

20R) C_{29} 甾烷与邻近源岩的变化完全吻合(图5;图6c、d),这也直接表明了芦草沟组下段原油也具有近源运移、自生自储的成藏特点。

此外,原油发生运移作用往往也会引起原油轻、重分子分异作用,从而分子含量比值发生变化(Tissot and Welte, 1978; Leythaeuser, 1988; Peters and Moldowan, 1993; Liu Shiju et al., 2020)。 $n-C_{21}/n-C_{22+}$ 比值和 $(C_{20} + C_{21} + C_{23} TT)/(C_{29} \text{ 藿烷} + C_{30} \text{ 藿烷} + \text{伽马蜡烷})$ 比值等常用来反映正构烷烃和萜烷类化合物的轻重比。根据风城组原油和源岩轻重比参数与深度关系图(图7)可知,风城组纯油藏中原油的轻重比参数与邻近的源岩一致,说明近源运移发生的运移分馏现象不明显,而含气油藏的轻重比要明显高于邻近源岩,说明了含气油藏的原油经历了运移作用,且随着运移方向(深度降低),运移分馏效应更加明显(图7)。

5 原油物性与热演化关系

图8展示了风城组和芦草沟组下段原油物性和烃源岩热演化参数[$HCI = 100 \times S_1/TOC$; $S_1/(S_1 + S_2)$]

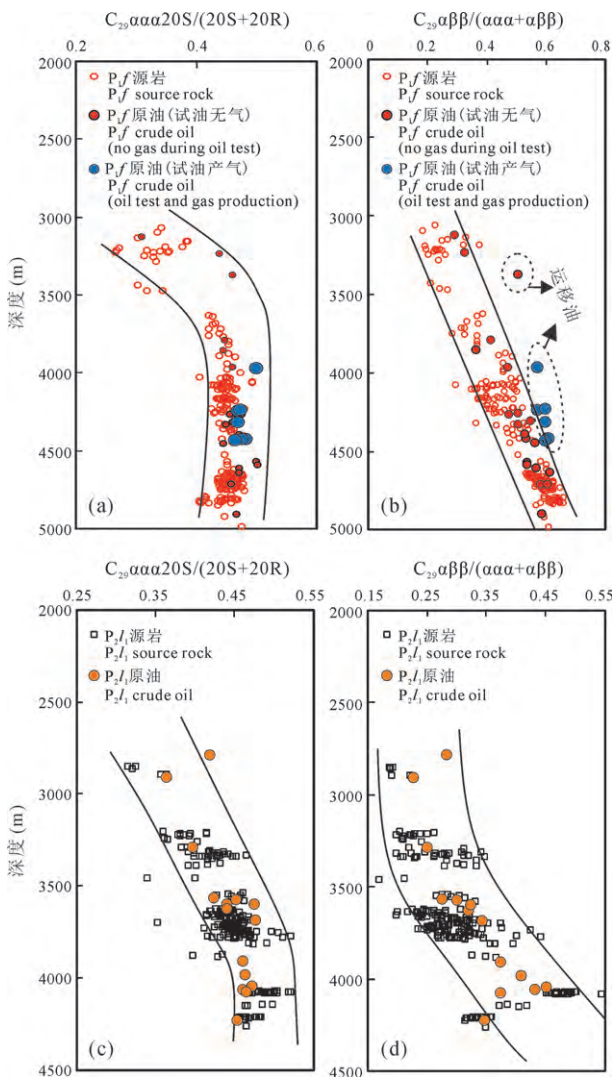


图6 准噶尔盆地风城组和芦草沟组下段原油与烃源岩规则甾烷 C_{29} 成熟度参数与深度关系图

Fig. 6 The relationship diagram of C_{29} regular sterane maturity parameters vs. depth of crude oil and source rocks from the Fengcheng Formation and the Lucaogou Formation in Junggar basin

随深度的变化,可见风城组和芦草沟组下段烃源岩的生油高峰深度分别大致在 4000 m 和 3300 m 左右,推测其生油高峰深度之下深部位一些较高值数据点应该受到了残留烃和运移作用的影响(图 8a、b、e、f)。仔细观察可以发现,风城组含气油藏和纯油藏原油的原油密度、黏度均呈现随深度增加先增大后降低的趋势,原油密度和黏度高值与烃源岩生油高峰有极好的对应关系,但在生油高峰深度附近及生油高峰深度之下,含气油藏的原油密度、黏度总体低于相近深度的纯油藏原油,而在生油高峰深度之上,两类油藏原油的密度和黏度接近(图 8c、d)。如前所述,含气油藏原油母质成熟度高于纯油藏原油

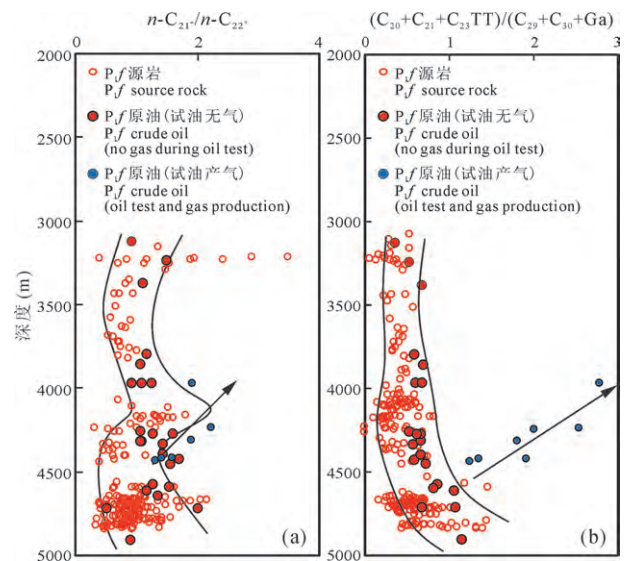


图7 准噶尔盆地风城组原油与源岩 $n-C_{21}-/n-C_{22}+$ 比值和 $(C_{20}+C_{21}+C_{23} TT)/(C_{29}$ 藿烷 + C_{30} 藿烷 + 伽马蜡烷) 比值与深度关系图(TT 代表三环萜烷)

Fig. 7 Relationship diagram of the $n-C_{21}-/n-C_{22}+$ ratio and the $(C_{20}+C_{21}+C_{23} TT)/(C_{29}$ hopane + C_{30} hopane + Gammacerane) ratio vs. depth of the Fengcheng Formation crude oil and source rock samples in Junggar basin (TT represents tricyclic terpanes)

母质成熟度,所以含气油藏原油应该来自更深部的风城组烃源岩,具有垂向运移过程,然后聚集成藏,其烃源岩深度更大,成熟度更高,因而含气更多,纯油藏原油就近运移聚集,含气少或不含气。在生油高峰深度之下,因保存条件好,来自深部原油中保存了较多的天然气,到了浅部保存条件变差,天然气散失,含气油藏与纯油藏原油组成接近,因而密度和黏度接近。相比于风城组,芦草沟组下段主要为纯油藏,其原油密度和黏度随深度增加也同样呈现先增加后降低的规律,密度和黏度最高值也对应于生油高峰(图 8g、h)。油源对比结果也表明了风城组和芦草沟组下段的纯油藏原油均来源于其邻近的烃源岩,因源储紧邻而近源初次运移产生的运移分馏效应不明显。这反映了生油窗范围内原油密度、黏度的变化与烃源岩热演化之间的对应关系应该具有一定普遍性,即随烃源岩热成熟度的增加,原油密度、黏度先增加后降低,原油密度、黏度最高值对应于烃源岩生油高峰。

烃源岩的生烃热模拟实验结果也佐证了上述认识。选取芦草沟组下段典型源岩(研究区常见的烃源岩岩性样品)样品进行了密闭容器加水热模拟生烃实验。实验样品的基础信息见表 2。热模拟实验

结果表明了烃源岩生油能力强,且排烃效率较高(图 9a)。液态烃产物的族组成特征表明,无论是排出油还是残余油,都在 335℃ (大量生油阶段)时非烃和沥青质含量最高(图 9b)。更为明显的特征是随着模

拟温度的增加,原油的颜色由浅变深再变浅(图 9b),而颜色深表明了非烃和胶质含量高,对应密度和黏度也高,也就直接佐证了烃源岩生成的原油密度、黏度在生油高峰时最高,生油高峰之前和之后均较低。

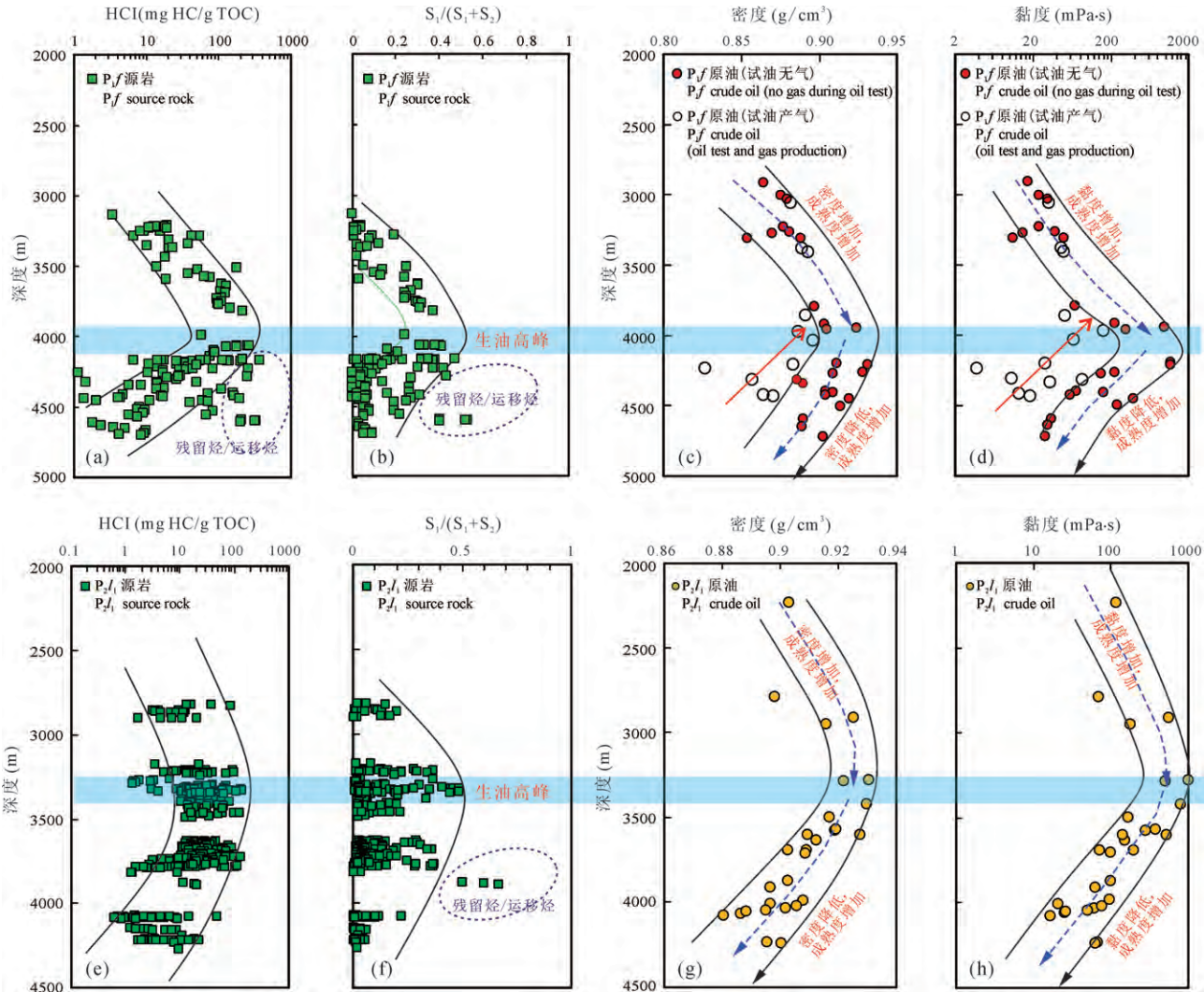


图 8 准噶尔盆地风城组和芦草沟组下段烃源岩 HCl (a,e), $S_1/(S_1+S_2)$ (b,f),原油密度(c,g)和黏度(d,h)深度关系图
Fig. 8 The relationship of the HCl (a, e), $S_1/(S_1+S_2)$ ratio (b, f), density (c, g) and viscosity (d, h) vs. depth of crude oil samples from the lower Lucaogou Formation and the Fengcheng Formation in Junggar basin

表 2 准噶尔盆地芦草沟组下段烃源岩热模拟实验样品的基础地球化学数据表

Table 2 Basic geochemical data of thermal simulation samples from the lower Lucaogou Formation in Junggar basin

井号	深度 (m)	TOC (%)	T_{max} (℃)	S_1 (mg HC/g rock)	S_2 (mg HC/g rock)	HI (mg HC/g TOC)	HCl (mg HC/g TOC)	EOM (%)	EOM/ TOC	R_o (%)
JHBE	3627.7	11.3	444	2.98	82.09	726	3.6	0.81	7.12	0.79

注:EOM 为可溶有机质。

前人有关烃源岩的生烃模拟实验也进行了较多的工作,这些实验数据也有力地支撑了上述认识。从 Hou Lianhua et al. (2020)对博格达山前芦草沟组露头的低成熟烃源岩样品的热模拟实验结果来看,随着成熟度增加,总液态产物中的胶质与沥青质相对含量先增加后降低,饱和烃相对含量变化相反

(图 10)。由于原油密度和黏度与非烃含量的良好线性相关性(图 3),这种族组分相对含量的变化特征自然反映了总液态产物密度和黏度随成熟度增加先升高后降低的特征。应该指出的是由于芳香烃相对含量较低且变化幅度较小,所以,其对密度和黏度的变化规律没有明显影响(图 10)。

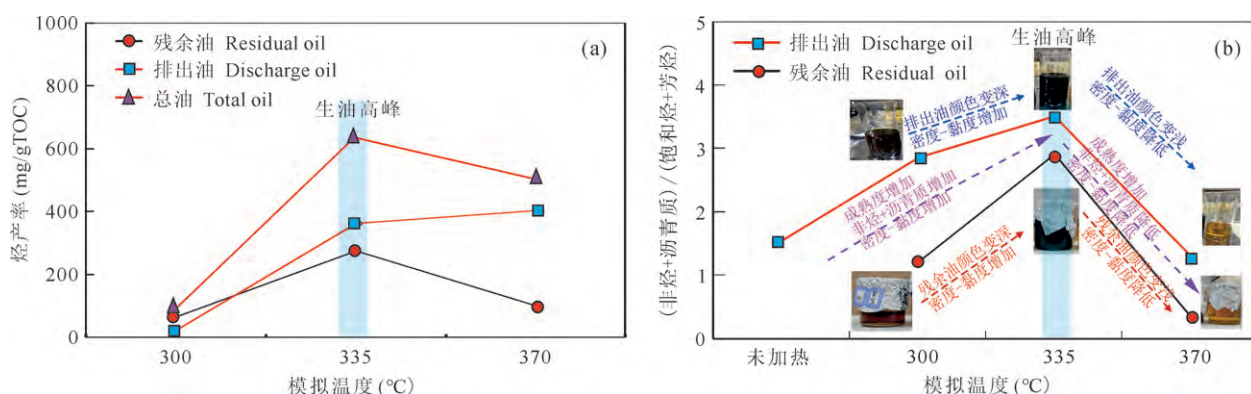


图9 准噶尔盆地芦草沟组下段烃源岩液态产物产率(a)和排出油与残余油族组成参数-产物颜色特征(b)与模拟温度关系图
Fig. 9 Relationship between gas and liquid product yield of organic carbon per unit mass and simulated temperature of source rock (a); relationship between (Polar+Asph)/(Sat+Arom) and simulated temperature of the oil discharged from the simulated product and the remaining oil, and color characteristics of simulated products (b) in the lower member of Lucaogou Formation, Jimusaer sag, Junggar basin

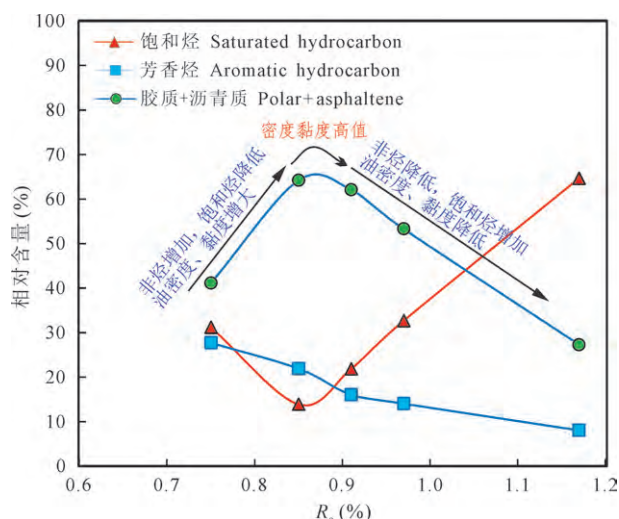


图10 准噶尔盆地芦草沟组烃源岩热模拟实验总液态产物族组分相对含量与热演化程度关系图(数据来源于 Hou Lianhua et al., 2020)

Fig. 10 Relationship between fraction contents of total simulated liquid product and vitrinite reflection from thermal simulation experiment of source rocks of the Lucaogou Formation in Junggar basin (data from Hou Lianhua et al., 2020)

澳大利亚塔斯马尼亚下二叠统富含有机质油页岩有机质主要为相对单一的塔斯马尼亚藻组成,成熟度较低。林静文等(2022)对该油页岩进行的生烃热模拟实验分析结果(图 11)显示,无论是热解油还是残留油,均表现为胶质+沥青质相对含量随模拟温度升高先增加后降低,芳香烃与饱和烃相对含量先降低后增加。可见同样显示了非烃含量变化有高值存在,该高值自然也对应于最高的原油密度和黏度,其高值对应的模拟温度为 340°C,而该温度对应

的热解油、热解沥青与总液态产物产率也最高。这也证实了本文上述认识的正确性。此外,其他许多学者的生烃热模拟实验结果也都能验证上述认识,在此不一一赘述。

除烃源岩热模拟实验外,大量的自然演化剖面中烃源岩可溶有机质的族组分含量的变化特征也具有上述规律。北非喀麦隆杜阿拉盆地的石炭系烃源岩可溶有机质中烃类与杂原子化合物含量与深度的变化被大量文献(Hunt, 1979;柳广弟, 2018)引用,一般主要以此说明烃源岩可溶有机质以及族组分含量随热演化的变化特点,未有研究者据此变化特征认识到烃源岩生成的原油密度和黏度的变化规律。仔细观察可以发现,烃与非烃产率均随深度(热演化程度)增加先增加,达到最高值后又同时降低,但非烃与烃产率的差异最大部位对应于产量最高值(图 12),这即说明了产率高峰即生油高峰时非烃相对含量是最高的。根据前面的分析可见,产率高峰对应的原油密度和黏度也应是最高。

由上述分析可见,无论是热模拟实验结果,还是自然演化剖面,都说明了烃源岩热演化过程中,液态产物非烃组成含量具有随热演化程度增加先增大后降低的特征。这说明该特征具有普遍性,由此来看,不同烃源岩生成的原油密度和黏度随热演化程度增大先增加后降低的规律也是普遍的。

6 原油物性变化对页岩油勘探的启示

页岩油作为目前重要的非常规油气勘探和开发领域,其烃源岩热演化特征与产能等都与原油物性有极为密切的关系。风城组和芦草沟组下段咸化湖

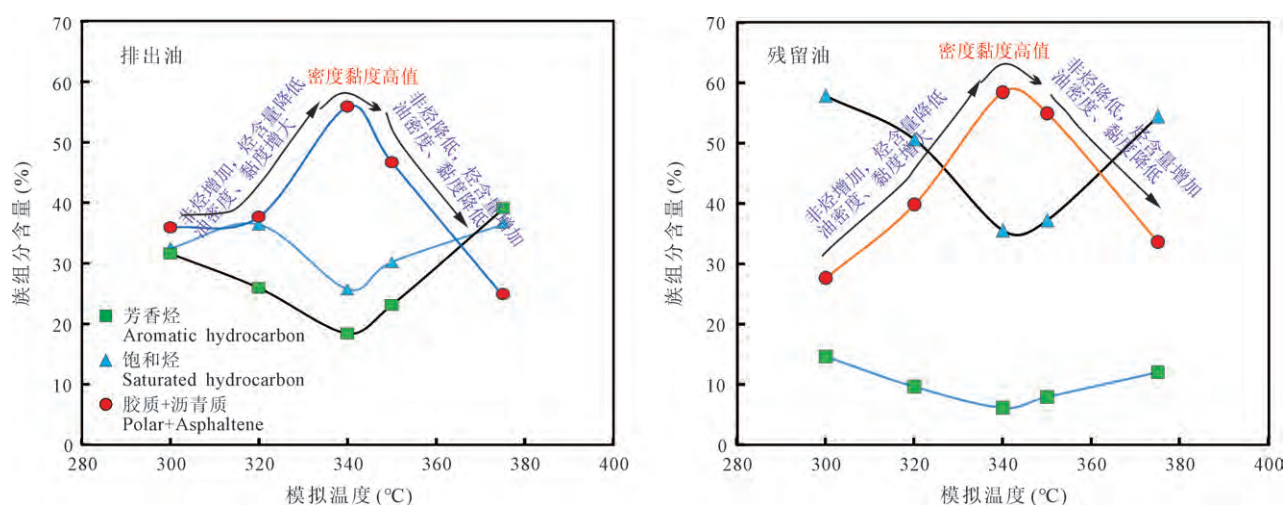


图 11 澳大利亚塔斯马尼亚下二叠统富含有机质油页岩热模拟液态产物族组分相对含量与热演化程度关系图(数据来源于林文静等,2022)

Fig. 11 Relationship between relative content and thermal evolution of components of thermosimulated liquid product families in organic-rich oil shale in the Lower Permian of Tasmania, Australia (data from Lin Wenjing et al., 2022)

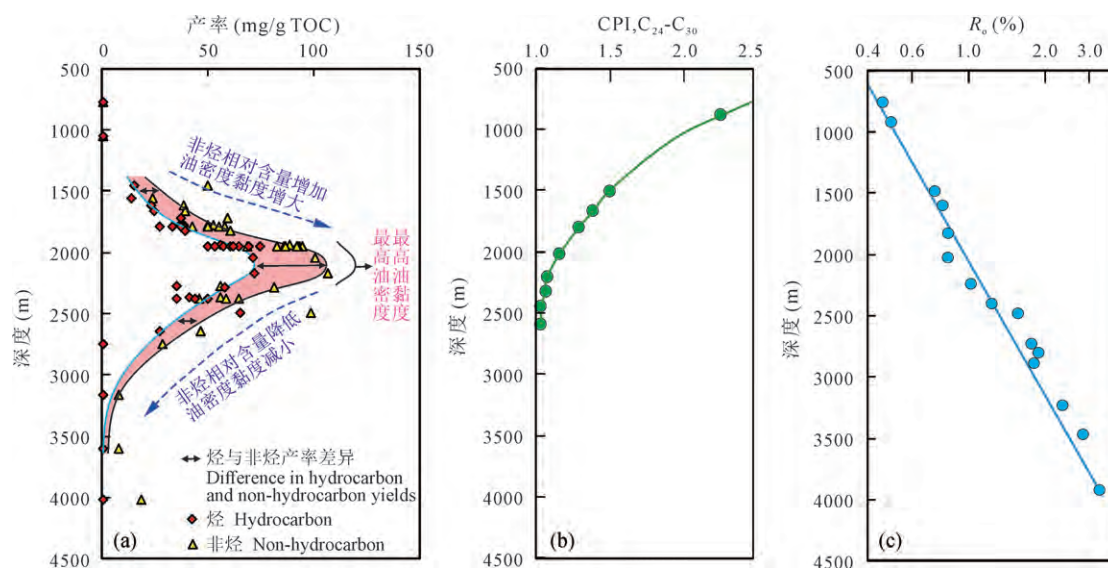


图 12 喀麦隆杜阿拉盆地上白垩统劳格巴巴组烃源岩可溶有机质转化率(a)、CPI (b)和 R_o (c)-深度关系图(据 Hunt, 1979)

Fig. 12 Relationship between soluble organic matter conversion rate (a), CPI (b) and R_o (c)-depth of source rocks of the Upper Cretaceous Laogebaba Formation in the Douala basin, Cameroon (after Hunt, 1979)

相源储紧邻型页岩油的富集程度与烃源岩热演化密切相关。一般认为,随着源岩成熟度的增加,生排烃量增加,邻近烃源岩的储层原油越富集。但从图 13 可见,原油日产能(t/d)和产能指数(t/(m·d))随深度增加先降低后升高。最为显著的特征是在烃源岩生油高峰深度段,原油的日产量、产能指数最低,开发效益显示最差(图 13),这应主要与该深度邻近烃源岩生油高峰生成的原油密度、黏度大有关。

上述研究区原油物性与热演化的关系可以给源储紧密互层型的页岩油勘探和开发、页岩油原位转

化等以重要启示,推测其他地区的页岩油层系原油物性演化也应具有类似特征。生油高峰之前虽然烃源岩产油相对较少,但其原油密度较低,储集层物性相对要好,这在一定程度上弥补了生烃量的不足,只要合理地选择有效储集层发育段以及优质源储品质耦合发育段也可以找到页岩油甜点段。生油高峰阶段并不是最有利的层段,该阶段虽然烃源岩生成的原油多,但密度和黏度明显较高,此时可以发育有甜点段,但应充分考虑原油密度和黏度较高给开发带来的影响。生油高峰之后的更高演化阶段,烃源岩

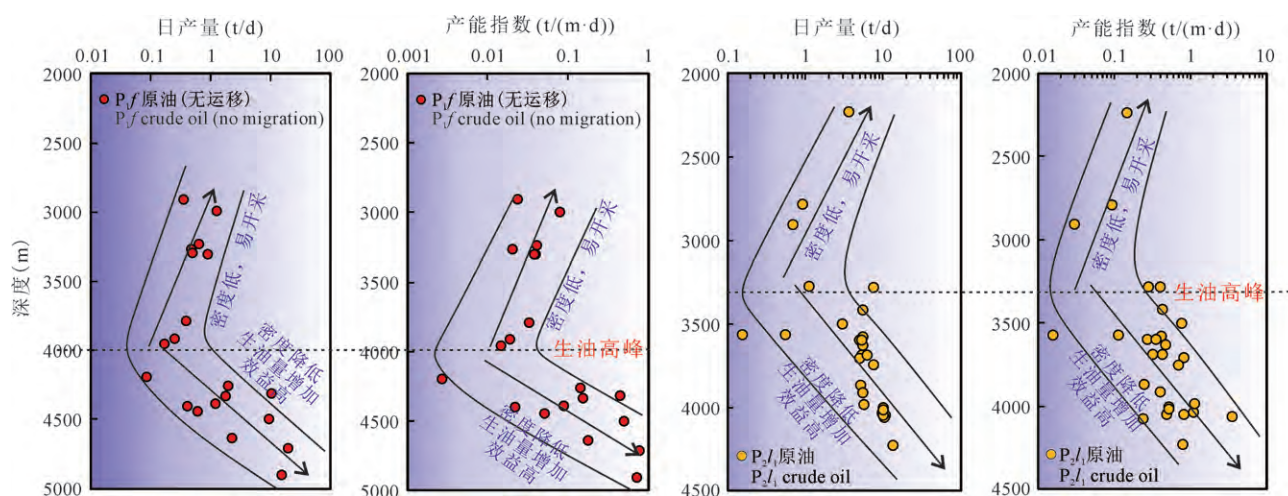


图 13 准噶尔盆地风城组和芦草沟组下段试油成果与深度关系图

Fig. 13 The depth trend of the oil test results of the Fengcheng Formation and the lower Lucaogou Formation in Junggar basin

有较高的生油量,并且有部分天然气的生成,原油密度和黏度较低,这有利于页岩油的开发,但此时在选取甜点段与有利区时应重点考虑储集层的厚度、规模与物性特征。

页岩油地下原位转化自 20 世纪 80 年代以来国内外许多石油公司就开始研究和发展的页岩油原位开采技术(汪友平等,2013),作为目前一种重要的人工转化地下富有机质页岩石油进行工业利用的手段已成为实现页岩油规模开发利用的最优选项之一(赵文智等,2018)。根据本文前述原油物性与热演化关系的认识,在地下人工转化液态石油时,究竟将烃源岩生油转化到何种演化程度是应该要考虑的基本问题。针对不同母质的油源岩应先通过自然演化剖面或热模拟实验等方法明确其生油高峰,进而确定生成的原油密度、黏度与热演化程度的关系,综合烃源岩残余烃转化潜力与热演化关系确定最佳的加热温度,以最大限度地转化液态石油,同时又尽量节省加热所消耗的能源成本。

7 结论

(1)风城组中含气油藏原油成熟度远高于邻近源岩成熟度,揭示其原油具有由深部烃源岩生成通过断裂调整、输导层运移的过程,不属于近源运聚特征。风城组与芦草沟组下段纯油藏页岩油均具有源储紧密互层就近自生自储特征,其页岩油就在油源岩附近,油源关系明确,其原油密度和黏度随烃源岩热演化程度增强先增后降,且最大值出现于生油高峰附近的特征是烃源岩生成的原油特征变化规律的

客观反映。

(2)页岩油甜点段与甜点区的选择应充分考虑原油密度、黏度随热演化变化的规律。生油高峰之前烃源岩的生油量相对少,但其原油密度、黏度较低,储集层物性相对较好,弥补了生油量的不足,利于页岩油的富集;生油高峰附近烃源岩虽大量生油,但原油密度与黏度高,实际开采难度增大;生油高峰深度之下生成的油量大,还伴有天然气生成,原油密度与黏度降低,更利于页岩油气富集,砂体发育是关键。

(3)页岩油源岩原位转化时应保证源岩热演化程度超过生油高峰,从而保证原油密度和黏度降低而利于开采,具体的最高演化程度应综合考虑烃源岩母质类型、热演化程度以及残余生烃潜力与热演化程度之间的关系。

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A new discovery of physical property evolution of crude oil and insights into shale oil exploration

GAO Gang^{*1, 2)}, LIU Shiju^{1, 2)}, JIN Jun³⁾, ZHANG Ziheng^{1, 2)}, LIU Guangdi^{1, 2)},
XIANG Baoli³⁾, HUANG Zhilong^{1, 2)}, KANG Jilun⁴⁾, GANG Wenzhe^{1, 2)}

1) College of Geosciences, China University of Petroleum, Beijing 102249, China;

2) State Key Laboratory of Petroleum Resource and Prospecting, China University of Petroleum, Beijing 102249, China;

3) Experimental Testing Institute, Xinjiang Oil Field Company, Karamay, Xinjiang 834000, China;

4) Exploration and Development Institute, Tuha Oil Field Company, Hami, Xinjiang 839009, China

* Corresponding author: gaogang2819@sina.com

Abstract

The Fengcheng Formation in Mahu sag and the Lower Lucaogou Formation in which crude oil is accumulated in the oil layers of closely interbedded source and reservoir combination with self-generated and self-contained model, are considered as case studies to discover the transformation law of crude oil physical properties with thermal evolution degree of source rock. The transition law of crude oil physical properties with increased thermal evolution degree is determined based on (i) the analysis of physical properties, organic geochemistry and enrichment characteristics of crude oil; (ii) the relationship between physical properties of crude oil and thermal evolution degree of source rock; and (iii) comprehensively considering thermal simulation experiment results of source rock and domestic and foreign relevant literature materials. The density and viscosity of crude oil from a source rock has the characteristic of first increasing and then decreasing with increasing thermal maturity, with the highest value at the oil peak depth. This understanding is not only a further clarification and revision of the existing understanding of the evolution law of crude oil physical properties with thermal evolution in petroleum geology, but also a very important and realistic guidance for the selection of sweet layer and sweet spot of shale oil and the in-situ transformation of shale oil.

Key words: physical properties of crude oil; shale oil and gas; saline lacustrine facies; Fengcheng Formation; Lucaogou Formation; Junggar basin