

文章编号: 0253-2697(2025)09-1661-16 DOI:10.7623/syxb202509002

陆相页岩含油性研究现状与一种新的资源潜力分级评价方法

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摘要:页岩油目前已成为中国油气资源重要的接替类型,科学客观地开展页岩油资源分级评价可为油气勘探及商业开发提供技术支撑和参考依据。页岩油资源评价的关键是含油性的确定,目前常用的含油性评价方法众多,但由于陆相盆地地质条件差异巨大,评价结果具有不确定性。在对湖相页岩含油性评价的方法、模型进行系统梳理的基础上,讨论了各种含油性评价方法的优缺点,并基于现有研究成果,综合考虑含油量、可动性和地质参数间的动态耦合,提出了页岩油资源分级评价新模型。研究结果表明:①新模型以游离烃含量(S_1)、总有机碳(TOC)含量和 S_1 与TOC含量的比值作为分级参数,将资源分为富集资源、中等富集资源、低效资源和无效资源4级;②典型页岩盆地中的 S_1 随TOC含量变化的包络线呈“正态分布”特征,当TOC含量过低和过高时分别由烃源岩质量和储层物性控制着页岩油资源的富集程度;③在准噶尔盆地玛湖凹陷二叠系风城组和松辽盆地齐家—古龙凹陷白垩系青山口组,各自页岩油富集区的TOC含量上、下限分别为0.4%和2.2%以及1.5%和3.4%,页岩油有利区围绕生烃中心呈“环带状”分布。新模型的优势体现在:①考虑了烃源岩质量、储层物性以及二者在盆地尺度下的耦合关系对页岩油富集的影响;②能够从页岩含油性、可动性2个角度表征页岩油资源的富集程度。该模型的提出改变了含油量随TOC含量增大到一定值时保持恒定的认识误区,为科学评价页岩油资源量提供了依据。

关键词:陆相页岩;含油性;评价方法;资源评价;分级评价;富集资源

中图分类号:TE155 文献标识码:A

Research status on oil content of continental shale and a new grading assessment method of resource potential

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Abstract: Shale oil has become an important alternative resource for oil and gas in China. Scientifically objective grading assessment of shale oil resources can provide technical support and a reference basis for oil and gas exploration and commercial hydrocarbon development. The key to shale oil resource assessment is the determination of oil content. There are numerous commonly used methods for evaluating oil content; however, due to the significant differences in geological conditions of continental basins, the assessment results are subject to uncertainty. Based on a systematic review of the methods and models for evaluating oil content in lacustrine shale, the advantages and disadvantages of various oil content assessment methods are discussed. Furthermore, based on the existing research findings, the paper proposes a new shale oil resource grading assessment model, which comprehensively considers the dynamic coupling between oil content, mobility, and geological parameters. The research results show as follows. (1) The new model uses free hydrocarbon content (S_1), total organic carbon (TOC) content, and the ratio of S_1 to TOC content as grading parameters, dividing the resources into four categories, i.e., enriched resources, moderately enriched resources, low-efficiency resources, and ineffective resources. (2) The envelope curve of S_1 variation with TOC content in typical shale basins exhibits a normal distribution pattern. When TOC content is too low or too high, the enrichment degree of shale oil resources is controlled by the source rock quality and reservoir properties, respectively. (3) In the Permian Fencheng Formation of Mahu sag in Junggar Basin and the Cretaceous Qingshankou Formation of Qijia-Gulong sag in Songliao Basin, the upper and lower limits of TOC contents in their respective shale oil enrichment areas are 0.4% and 2.2%, and 1.5% and 3.4%, with the favorable shale oil areas distributed in a circumferential pattern around the hydrocarbon generation centers. The advantages of the new model lie in: (1) considering the influences of source rock quality, reservoir properties, and their coupling relationship at the basin scale on shale oil enrichment; (2) being able to characterize the degree of shale oil resource enrichment from two perspectives, i.e., shale oil content and mobility. The model corrects the misconception that oil content remains constant after TOC content reaches a certain value, providing a basis for scientifically evaluating shale oil resources.

Key words: continental shale; oil content; assessment method; resource assessment; grading assessment; enriched resource

基金项目:国家自然科学基金面上项目“全球 MECO 事件期的陆相咸化湖盆有机质富集机理及碳循环响应”(No. 42372147)资助。

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引用:姜福杰,张晨曦,陈迪,郑晓薇,张宇琦,李吉君,樊晓琦,郭婷玮,王晓昊,胡涛.陆相页岩含油性研究现状与一种新的资源潜力分级评价方法[J].石油学报,2025,46(9):1661-1676.

Cite :JIANG Fujie,ZHANG Chenxi,CHEN Di,ZHENG Xiaowei,ZHANG Yuqi,LI Jijun,FAN Xiaoqi,GUO Tingwei,WANG Xiaohao,HU Tao.Research status on oil content of continental shale and a new grading assessment method of resource potential [J].Acta Petrolei Sinica,2025,46(9):1661-1676.

作为化石燃料的重要部分,非常规资源受到越来越多的关注。美国率先大力勘探开发页岩油,其在 2022 年的页岩油产量占石油总产量的比例超过 60%,已成功完成能源从进口到出口的转变^[1]。中国陆相页岩油资源潜力巨大,主要盆地的页岩油地质资源总量达 $319 \times 10^8 \text{ t}$ ^[2-4],最新的资源评估结果显示全国页岩油可采资源量近 $35 \times 10^8 \text{ t}$ ^[5]。非常规油气资源的发现有效地延长了石油工业的生命,是实现中国石油资源增储上产接替与能源安全保障的重要领域^[6-7]。中国自 2010 年开始进军页岩油领域,并经过十余年的不断攻关,于近年实现了革命性突破^[8],在准噶尔盆地吉木萨尔凹陷、松辽盆地古龙凹陷和渤海湾盆地济阳坳陷等地区成功取得了勘探进展^[9-13]。2023 年,中国的页岩油产量突破 $400 \times 10^4 \text{ t}$,页岩油已成为中国油气能源的重要支柱^[3,8]。

与美国海相夹层型轻质页岩油相比^[14],由于陆相湖盆中的页岩对气候变化的响应敏感,其页岩油具有强非均质性、低—中等成熟、高黏度的特征,且生烃能力、储集能力、含油性与可动性在盆地纵、横向上的演化特征差异显著^[8,15-17]。对含油性的准确判断是评估页岩油的关键一步,直接影响到页岩油甜点区的优选和页岩油的高效开发。

含油性是甜点预测的基础和重要指标。为提升页岩油的勘探开发成效,众多地质学家围绕陆相页岩的含油性评价问题开展了积极探索,提出了多种含油性评价参数及标准^[1,14,18-24]。然而,由于获取这些参数的方法不尽相同,使得陆相页岩在含油性“甜点”评价关键参数界限的厘定方面仍存在争议。为此,笔者对已有的含油性评价方法进行归纳梳理,在现有研究的基础上,以准噶尔盆地玛湖凹陷为例,结合中国典型陆相湖盆的页岩资料,综合考虑含油性、可动性以及地质参数间的动态耦合,探讨陆相页岩含油性评价的关键参数界限,以期为科学评价页岩油的资源量提供指导,促进中国陆相页岩油资源的高效勘探和效益开发。

1 页岩含油性评价方法

目前的页岩含油性评价方法按照基本原理可以分为有机地球化学参数法、含油饱和度法、物质平衡法和荧光信号法 4 类^[14,23,25-30]。

1.1 有机地球化学参数法

1.1.1 游离烃含量和氯仿沥青“A”含量法

岩石中的游离烃含量(S_1)和氯仿沥青“A”含量常

被用于评价页岩油的富集程度。 S_1 是指 300 °C 下测得的岩石中的游离烃含量;氯仿沥青“A”是指用氯仿从页岩样品中抽提出来的可溶有机质^[31]。这 2 个参数的测试具有经济快捷、样品用量少、获取方便等优点。但 S_1 和氯仿沥青“A”含量并不等同于页岩的滞留烃量,因为轻烃逸散与重烃残留均会导致含油性被低估^[22]。

滞留烃中包含相当一部分低密度、低黏度和高流动性的轻烃(C_6-C_{13}),其在岩心存放、实验室粉碎过程中易蒸发散失,散失量受岩心放置的时长、有机质成熟度和类型等多因素影响^[24]。多数学者通过对比直接热解与放置不同时间后的热解结果,认为损失量与放置时间呈正相关。一些研究者依据化学动力学原理,模拟干酪根初次裂解与原油二次裂解,计算出不同镜质体反射率(R_o)的轻烃、重烃产率,建立了轻烃恢复系数图版^[32-33]。此外,针对重烃校正的问题,部分学者在传统热解法与抽提法的基础上提出了改进后的多温阶分段热解法^[30]和多溶剂逐级抽提法^[34],实现了页岩体系中滞留烃的精细定量表征。轻烃恢复与重烃校正有利于更加合理、准确地预测页岩油资源量和甜点发育情况。

1.1.2 自由烃差值法

自由烃差值法的关键参数 ΔS_1 表示页岩产烃量与滞留量之差,其中,产烃量通过干酪根热模拟实验获得^[23]。当 $\Delta S_1 < 0 \text{ mg/g}$ 时,页岩单元的储集性能更好,烃类从附近运移到目标页岩单元并滞留于其中,因此其属于开放型页岩单元,含油性一般较好;当 ΔS_1 约为 0 mg/g 时,页岩单元基本不发生排烃和外部烃的进入,属封闭型页岩单元,并可进一步根据生烃量的高低将其分为封闭型富烃单元和封闭型贫烃单元;当 $\Delta S_1 > 0 \text{ mg/g}$ 时,表明页岩系统以排烃为主,属于开放型页岩单元,含油性较差。该方法侧重于判断页岩中烃类的排出和运移情况,需结合滞留烃参数才能综合判断页岩油的富集程度。

1.1.3 含油饱和度指数法

Jarvie^[14] 通过统计美国页岩油潜力层中总有机碳(TOC)含量(C_{TOC})与 S_1 的关系,提出了含油饱和度指数(I_{os}):

$$I_{\text{os}} = S_1 / C_{\text{TOC}} \times 100 \quad (1)$$

当 $I_{\text{os}} > 100 \text{ mg/g}$ 时,页岩体系中存在较多游离烃,具备商业开发潜力。

含油饱和度指数法在美国海相页岩盆地^[35-36]以及

中国松辽盆地^[37]、准噶尔盆地^[38]、渤海湾盆地^[39]、四川盆地^[40]等湖相页岩盆地中均得到了较好的应用。然而,该方法有3方面的局限性:①湖相页岩非均质性强^[41-42],有机质丰度、类型、成熟度、矿物组成和孔隙空间特征等因素均会影响页岩油的可动性^[27,43-44],应用时需根据排烃门限等实际地质条件确定可动性阈值;②未考虑孔隙度和渗透率这2个参数,可能导致最终评价结果与实际产量存在偏差;③当S₁和TOC含量均较低时,也会出现高I_{os}的情况,造成对页岩油潜力的误判。

1.1.4 三分法

干酪根不仅是生成油气的主要物质,也是吸附油气的主要介质。卢双舫等^[18]发现S₁和氯仿沥青“A”含量随TOC含量的增加均呈现出“三段式”变化,据此提出了“三分法”,将页岩油资源分为富集资源、低效资源和无效资源3个级别。该方法考虑了石油的吸附作用,但对页岩油的可动性无法做出较为准确的判断。

1.1.5 四分法

在“三分法”的基础上加入参数S₁/C_{TOC},对页岩油资源进一步分类,即为“四分法”^[45-46]。综合S₁、S₁/C_{TOC},可将页岩油资源划分为富集资源、中等富集资源、低效资源和无效资源4类,但不同盆地的分级界限有所不同。该方法考虑了绝对含油量和相对含油量,减弱了湖相页岩非均质性的影响,节约了大量时间和成本,但需要足够的数据点支撑。

采用单一的可动油阈值来评价页岩油的含油性是不完善的。Wang等^[47]引入热成熟度参数,将岩石热解最高峰温度(T_{max})作为变量,构建了含油量评价三维模型。但这一方法仍存在一定不足,样品中重烃的存在使得测量的T_{max}偏小,成熟度偏低,因此需要通过前处理消除重烃的干扰。

1.1.6 含油量评价指数

Liu等^[48]提出了含油量评价指数(I_{oce})。该指数包含3个关键评价指标:C_L、C_g和S_{co}。利用灰度相关分析明确3项指标与页岩油产量间的关系权重,评价指标与相应权重的乘积之和即为I_{oce}:

$$I_{oce} = \omega_1 C_L + \omega_2 C_g + \omega_3 S_{co} \quad (2)$$

含油量评价指数法考虑了含气性对原油黏度的改善作用,并且可实现单井垂向连续评价。但存在两方面的局限:①轻烃损失导致岩心表面含油面积变化很大,且岩心描述含油面积较粗略,S_{co}指标的可靠性存疑;②需要大量的页岩油生产数据来确定权重,不适用于低勘探程度地区。

1.2 含油饱和度法

1.2.1 孔隙油饱和法

Su等^[49]综合考虑页岩储层物性和烃源岩的地球

化学特征,建立了孔隙中的油饱和指数(I_{pos}),其评价参数包括S₁、C_{TOC}以及孔隙度(ϕ)和渗透率(K):

$$I_{pos} = \frac{S_1}{C_{TOC} \times 100} \sqrt{\frac{\phi \times 100}{K}} \quad (3)$$

将I_{pos}=50定义为页岩油可动性下限,当I_{pos}>50时页岩油富集程度较高,反之则表示富集条件较差。该下限是经过统计分析得到的经验值,在不同盆地中应用时应灵活界定。此外,对于部分高孔低渗页岩,计算得到的高I_{pos}与实际较差的可动性相矛盾。

1.2.2 核磁共振法

油、水在二维核磁共振纵向弛豫时间(T₁)以及纵向弛豫时间与横向弛豫时间(T₂)的比值上存在差异。陈龙川等^[50]应用聚类分析方法来解释可动油、束缚油、束缚水等流体体积,确定了古龙页岩油的含油饱和度解释图版和计算模型:

$$S_o = \frac{V_{oil} + V_{bhc}}{V_{oil} + V_{bhc} + V_{irrw} + V_w} \quad (4)$$

核磁共振法可以从赋存相态的角度细致地评价页岩油含量及可动性,但需要保证密闭取心和液氮冷冻存储,操作复杂且成本高。

1.3 荧光信号法

激光共聚焦应用激光光源对含油页岩样品进行激发。根据原油的荧光特性,原油的成熟度越高、相对分子质量越小,会发生“蓝移”现象,即在荧光光谱中向左移动,反之则发生“红移”。据此原理进行多通道激光激发与信号接收,通过多重荧光信号的分离与重组成像,实现了原油在微米—纳米级孔隙中分布的三维数字成像及定量分析^[51]。该方法可以快速、精细刻画轻、重质油在孔隙中的分布^[52]以及识别微运移现象^[53-55],但荧光矿物的发育可能会导致含油量评价结果偏高。

1.4 物质平衡法

Cooles等^[56]提出基于岩石热解参数和质量守恒原理的物质平衡法。该方法使用未成熟样品中的S₁、热解烃量(S₂)和成熟样品的S₁、S₂计算生、排烃效率。在生烃强度一定的情况下,排烃效率直接影响了残留在页岩中的油气含量,排烃效率越高,页岩的含油性越差^[57]。然而,应用排烃效率评估页岩的含油性仍存在一定的局限性,例如,排烃效率的计算需要精确的氢指数和T_{max}数据,其本身的获取过程就可能存在误差,且实验模拟的生、排烃过程与实际地质条件存在差别。

2 页岩含油性的影响因素

中国主要的产页岩油盆地如渤海湾盆地、松辽盆地、准噶尔盆地、鄂尔多斯盆地等都是典型的陆相湖

盆,页岩油形成的地质条件复杂,含油性的影响因素众多。例如:渤海湾盆地济阳坳陷的页岩油可分为泥页岩型和夹层型,岩相、可动性以及微裂缝发育特征是泥页岩型页岩油富集的主要因素^[58-61];渤海湾盆地沧东凹陷页岩的含油性与烃源岩的热演化程度以及生烃能力相关^[62];渤海湾盆地东濮凹陷页岩的有机质丰度、孔隙比表面积与孔隙体积是影响页岩油可动性的主控因素^[63];三塘湖盆地马朗凹陷芦草沟组页岩油的富集主要受控于有机质丰度、储集条件以及油气运移阻力等条件^[64];在准噶尔盆地吉木萨尔凹陷芦草沟组和鄂尔多斯盆地延长组的页岩研究中发现,不同矿物组分通过影响润湿性和比表面积造成页岩吸附油与游离油比例的差异^[65-68]。此外,在沉积环境和热演化程度一定的情况下,保存条件也是陆相页岩油富集的关键影响因素。当油藏具有稳定分布的封闭致密顶、底板时,

页岩油气一般呈原位或近源顺层聚集,丰度较高;反之,页岩油会沿构造或层间裂缝、断裂运移散失^[69-71]。

2.1 生烃能力

页岩生烃能力评价指标包括有机质丰度、类型和成熟度等,其中,TOC 含量能够直接体现页岩生烃能力的强弱。在中国各类型陆相湖盆的研究中,众多学者使用 TOC 含量作为页岩生烃能力指标^[18,72-73]。笔者也选取 TOC 含量作为泥页岩生烃能力的典型指标进行研究。

中国淡水湖盆和咸水湖盆中的烃源岩质量和生烃特征存在差异,主要体现在:咸水湖盆烃源岩具有倾油有机母质占比高、生烃活化能低、生油窗长等特点,高有机质转化率导致咸水湖盆的 TOC 含量显著低于淡水湖盆^[74]。2 类湖盆中烃源岩的有机质丰度从盆地边缘至盆地中心总体呈增大趋势(图1),这是由于湖盆

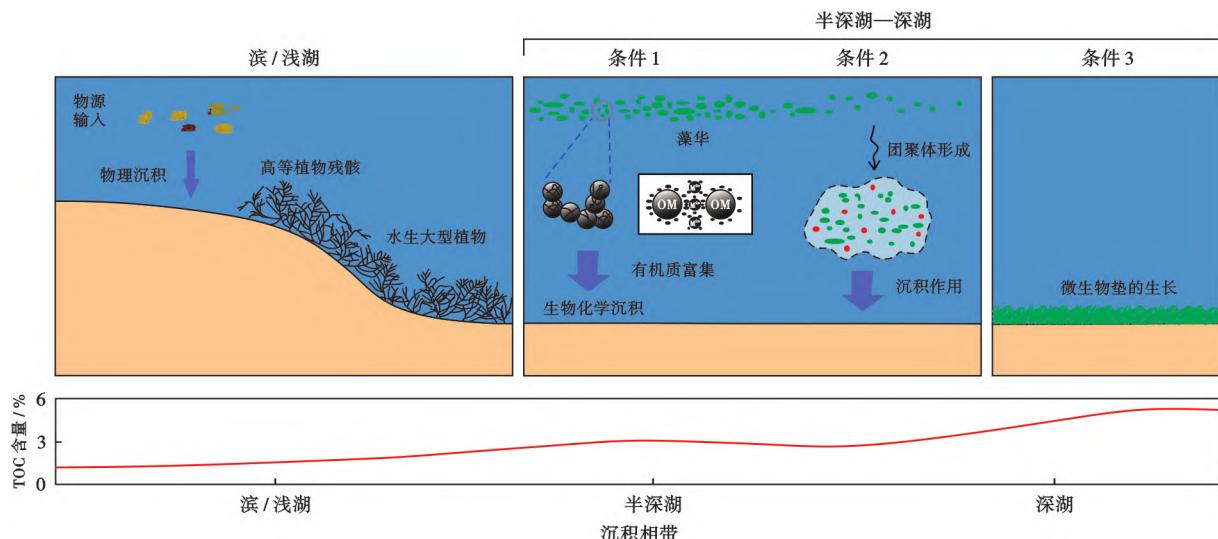


图 1 渤海湾盆地东营凹陷湖相烃源岩发育模式及有机质分布特征(据文献[75]修改)

Fig. 1 Development model of lacustrine source rocks and distribution of organic matters in Dongying depression, Bohai Bay Basin

中心静水区主要发育藻类、细菌,稳定的水体环境和强还原性使得大量优质生烃母质沉积并保存下来。因此,越靠近湖盆中心,沉积物的 TOC 含量往往越高,从而形成优质烃源岩;反之,在靠近盆地边缘区域,水体变浅,高等植物等腐殖型有机质数量增多,大量陆源碎屑的输入可导致沉积的有机质被稀释,同时水体含氧量的增加不利于有机质保存,从而导致在近岸区域,烃源岩的整体生烃能力较弱,TOC 含量较低^[75-76]。

然而,从渤海湾盆地和鄂尔多斯盆地的勘探生产来看^[77-78],有时在一些优质烃源岩发育段,页岩油产量并不理想,高有机质丰度页岩段的试油产量反而偏低(图 2)。这表明,页岩油资源的富集高产除了需要优质烃源岩供烃外,还有其他重要的影响因素。

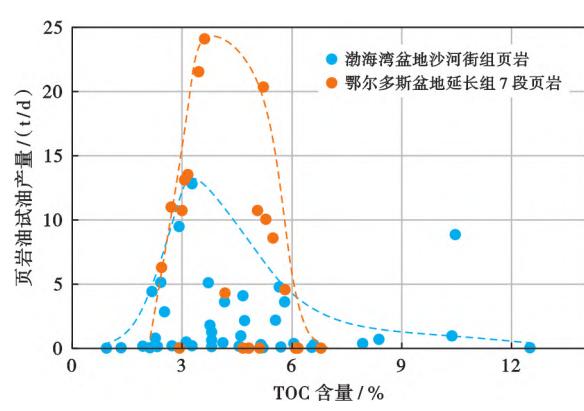


图 2 渤海湾盆地和鄂尔多斯盆地页岩层系试油产量与 TOC 含量的关系(数据据文献[77-78])

Fig. 2 Relationship between test oil production and TOC content of shale formations in Bohai Bay Basin and Ordos Basin

2.2 储集能力

储集能力包括储集空间类型和孔隙结构^[14,27,30,79-80]。国内外页岩油的储集空间分类依据多样,主要分类依据有2种:①按孔径大小;②基于矿物基质、结构和成因。孔隙通常被粗略分为矿物基质孔隙与有机质孔隙。矿物基质孔隙包括粒(晶)间和粒(晶)内孔^[81-82],按成因又可分原生孔隙和次生孔隙。此外,有学者将微观孔隙分为原生沉积型、成岩后生改造型和混合型3类,并进一步细分为古生物化石孔、有机质孔和原生一次生孔等多种亚类^[83-84]。

页岩储集空间的大小受多种因素共同作用。前人的研究发现,TOC含量、有机质类型、不同类型矿物含量和热演化程度等因素在不同程度上控制了页岩孔隙的发育^[85-86]。湖盆边缘通过底部运移粗颗粒碎屑物质,而粒径较小的沉积物则以悬浮的方式向离岸方向迁移,最终在湖盆中心形成细粒岩石沉积体系^[87-88]。沉积物粒度变细会导致储层中原生孔隙体积大幅减小,而黏土矿物占据孔隙和裂缝也会进一步缩减储集空间。肖佃师等^[86]对准噶尔盆地细粒沉积物岩石物理特征的研究结果表明,以粒径较大的砂质颗粒为主的岩石,其抗压保孔能力更强。有学者认为热演化程度是控制页岩孔隙发育的主要因素,并据此建立了描述干酪根中孔隙体积随热演化程度变化的动力学模型。曾秋楠等^[89]对鄂尔多斯盆地延长组页岩进行的

研究认为,在低成熟度($R_o < 1.0\%$)条件下,孔隙体积与TOC含量和 R_o 无明显关系,但受储层中的矿物类型及其含量影响较大;此外,在热演化过程中,有机质也可以形成一定的有效储集空间。

与孔隙体积相比,孔隙比表面积的演化趋势较为复杂。以渤海湾盆地东营凹陷为例,储层中的孔隙比表面积与孔径大小、黏土矿物含量和有机质孔的形成具有非常良好的相关关系,但在盆地斜坡带,孔隙比表面积呈现先降后增的趋势,其降低的原因可能是由于斜坡埋深较浅,有机质孔尚不发育,且此时伊/蒙混层发生脱水转化;随着埋深增大,当有机质达到生烃高峰后,有机质孔大量发育,孔隙比表面积呈现增加趋势。从总体趋势来看,孔隙体积与黏土矿物含量是影响孔隙比表面积的最主要因素,因此,在黏土矿物含量最高的湖盆中心,其孔隙比表面积远大于盆地边缘^[90]。

总体上看,从盆地边缘到沉积中心,受沉积物类型、压实程度与生烃作用多重影响,黏土矿物含量增加,矿物颗粒减小,孔隙体积和孔隙尺寸整体呈减小趋势,而孔隙比表面积则呈增加趋势^[61,91]。此外,根据多个典型页岩油盆地的勘探分析结果发现^[92-95],优质储层与含油性并非呈正相关,部分高孔优质储层的含油性反而较差(图3)。这表明,页岩的生烃能力与储存能力之间存在密切关联,二者共同制约着含油性。

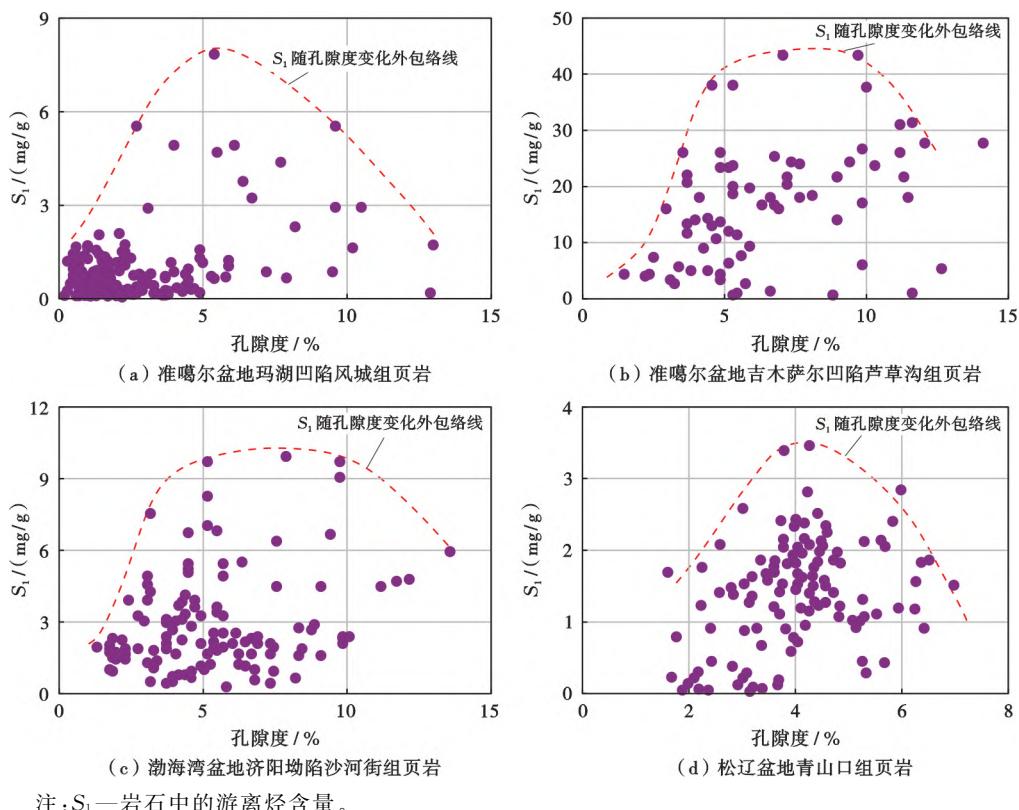


图3 准噶尔盆地、渤海湾盆地和松辽盆地页岩层系游离烃含量与孔隙度的关系(据文献[92-94]修改)

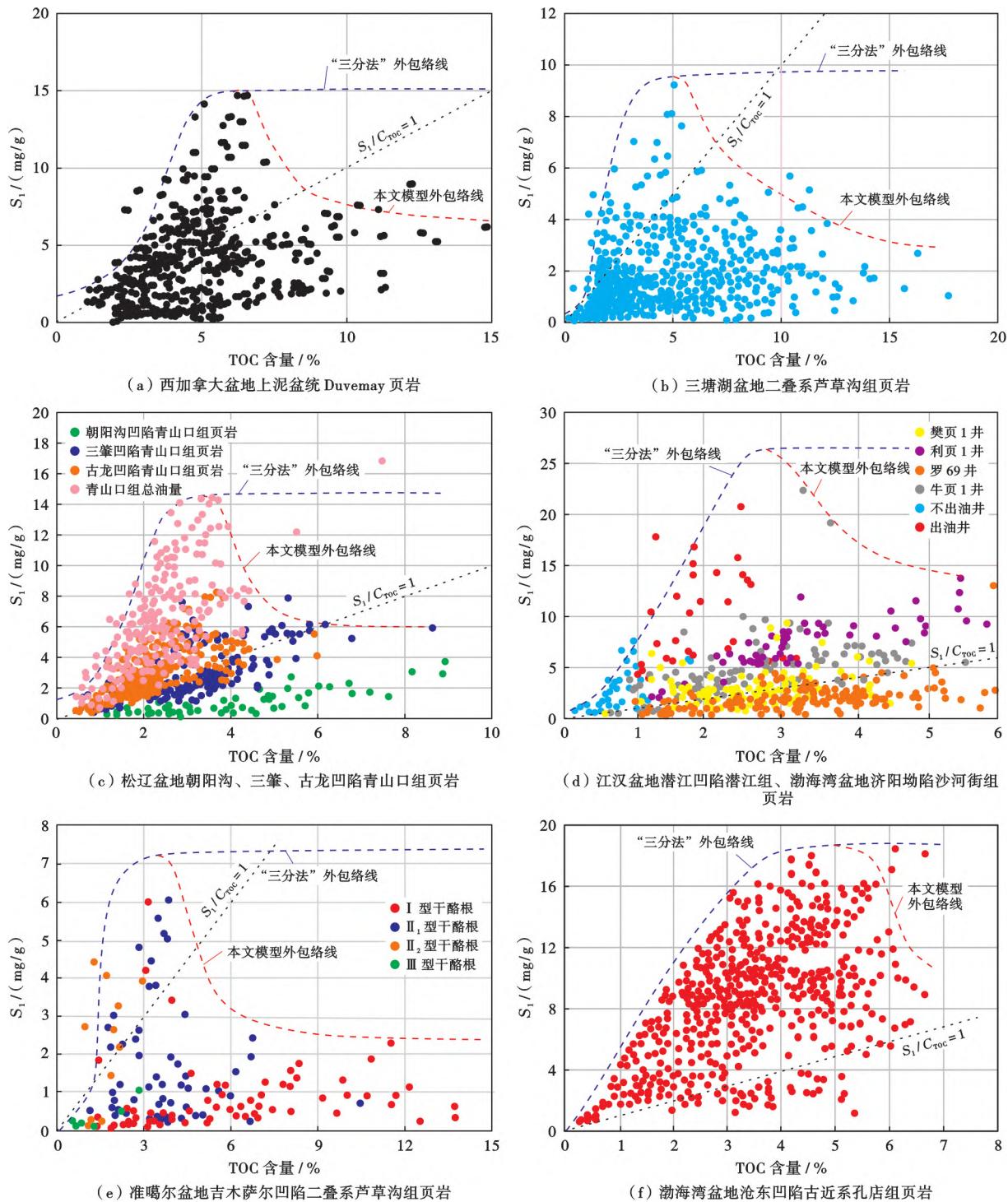
Fig. 3 Relationship between free hydrocarbon content and porosity of shale formations in Junggar Basin, Bohai Bay Basin and Songliao Basin

2.3 生烃能力与储集能力的耦合

页岩的生烃能力与储集能力共同影响着页岩的含油性。页岩中的有机质含量越高,类型越好,如果热演化程度处于生烃窗口,则其生烃能力越强,进而为页岩油的富集提供充足的油气源。如果页岩中的储集空间越大,其储集能力越强,能够容纳的页岩油气量也就越大。

在西加拿大盆地、三塘湖盆地、松辽盆地、江汉盆

地、准噶尔盆地和渤海湾盆地等多个典型页岩油盆地已发现,页岩中的 S_1 随 TOC 含量的变化呈现“正态分布”的特征^[10,38,96-99](图 4)。具体表现为:第 1 阶段, S_1 随 TOC 含量增大而增多,此阶段页岩沉积于盆地边缘,有足够的储集能力但生烃能力弱,含油性受生烃能力主导;第 2 阶段, S_1 随 TOC 含量增大显著减少,页岩沉积于盆地边缘—盆地中心的过渡区域,其生烃



注: S_1 —岩石中的游离烃含量; C_{TOC} —总有机碳含量;TOC—总有机碳。

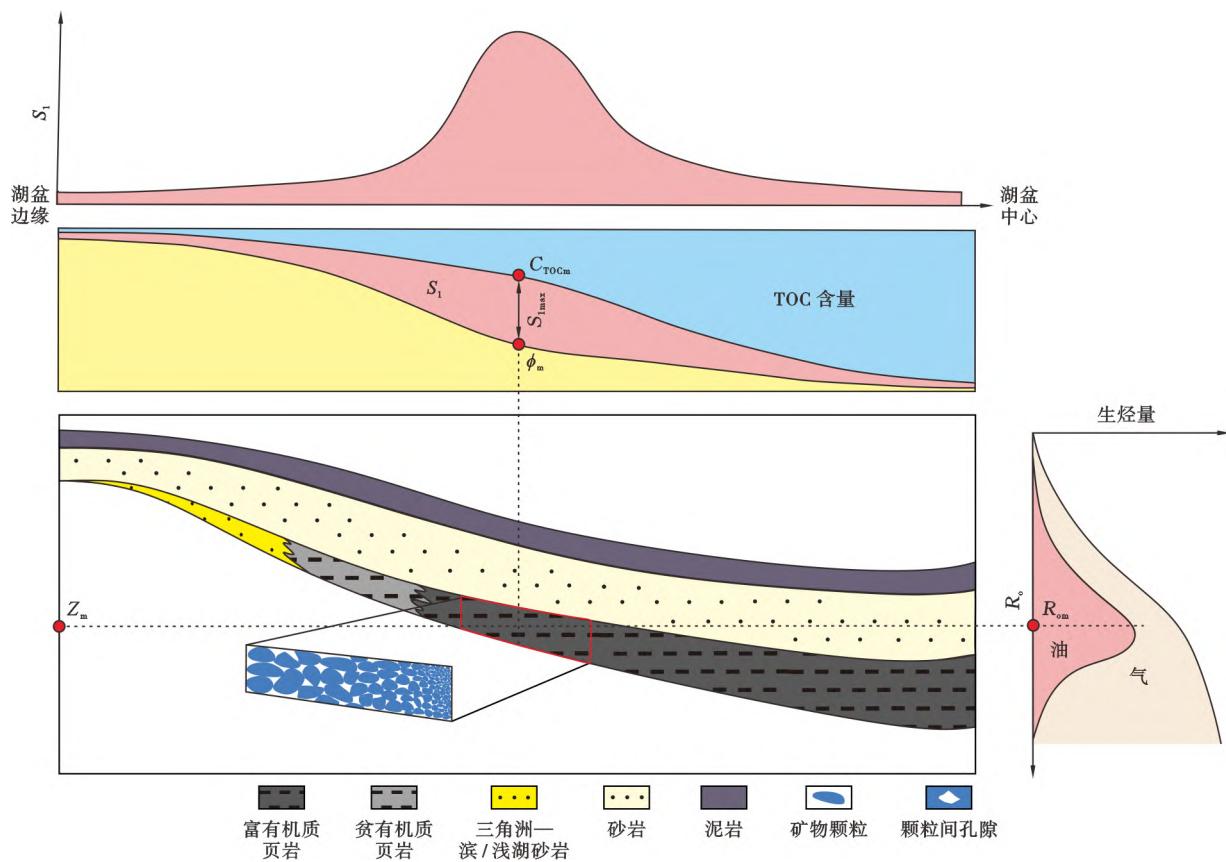
图 4 典型盆地页岩中游离烃含量和 TOC 含量的关系(据文献[10,38,96-99]修改)

Fig. 4 Relationship between free hydrocarbon content and TOC content of shale in typical basins

能力强但储集空间大幅缩减,生成的大量烃类无法有效储集,导致 S_i 降低,含油性受储集能力主导;第3阶段,当 TOC 含量达到较高值后, S_i 保持某一稳定低值,这是由于盆地中心的页岩在黏土矿物含量、颗粒粒径和压实作用共同影响下,无机质中的孔隙体积将被压缩至极限,而页岩的孔隙系统则以有机质孔为主导,滞留烃以吸附态存在于有机质孔中。

总之,从盆地边缘到盆地中心,伴随着沉积物粒度变细、压实作用增强、有机质保存条件改善、类型变好、

成熟度升高等多种地质因素变化,在页岩生烃能力增强的同时,其储集能力降低,含油性的主控因素由生烃能力过渡为储集能力。据此,提出页岩含油性影响因素模型(图5),认为在盆地边缘和盆地中心之间存在一个区域,该区域内沉积的页岩既具有一定的生烃能力,同时又保留了一定体积的孔隙空间,在生烃能力-储集能力的适当匹配下,含油性可达到最佳。在该区域至盆地边缘之间,生烃能力不足制约着页岩的含油性;而在该区域至盆地中心之间,储集能力变差制约着页岩的含油性。



注:TOC—总有机碳; C_{TOCm} — $S_{i\max}$ 对应的总有机碳含量; ϕ_m — $S_{i\max}$ 对应的孔隙度; R_o —镜质体反射率; R_{om} — $S_{i\max}$ 对应的镜质体反射率; Z_m — $S_{i\max}$ 对应的深度。

图5 含油性影响因素模型

Fig. 5 Model of influencing factors for oiliness

3 页岩油资源分级新图版及应用实例

3.1 页岩油资源分级新方法

基于上述分析,笔者利用 TOC 含量和 S_i 数据构建新的页岩油资源分级评价模型。采用 TOC 含量、 S_i 和 S_i/C_{TOC} 作为评价参数,构建过程分为 4 步:①绘制 S_i —TOC 含量关系散点图;②绘制 S_i —TOC 含量关系的外包络线;③界限值识别;④模型构建。数据点外包络线绘制结果显示, S_i 随 TOC 含量增大呈“缓慢增加—迅速增大—达到峰值—降低—稳定低值”的变

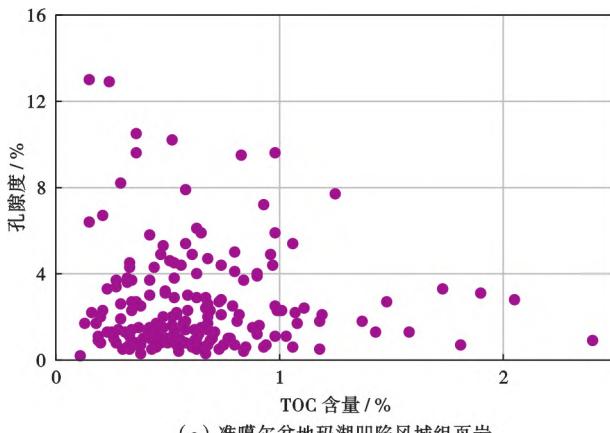
化规律,类似“正态分布”。

在 S_i 达到峰值以前,页岩油含量主要受有机质生烃能力控制,含油量的变化趋势与“三分法”中的描述一致:TOC 含量较低时,有机质生油能力差,生油量少且分散,页岩自身的储集空间无法充满;随着 TOC 含量进一步增加,有机质生油能力提高,页岩孔隙中富集页岩油。

当 S_i 达到峰值后,页岩油含量受储存能力控制。此时页岩中的油已充满自身容纳空间,多余生成的油从页岩中排出。前人的研究普遍认为,随着 TOC 含量的继续增大, S_i 会保持稳定高值,这一观点的前提

是页岩储集空间随 TOC 含量增大保持不变。然而,从盆地尺度来看,页岩 TOC 含量的增大往往伴随孔隙度的降低^[77,92](图 6),这就会导致页岩储集空间大

幅缩减,烃类被大量排出,因此滞留烃量持续降低。在最终保持稳定低值状态时,页岩孔隙以有机质孔为主,滞留烃主要以吸附态存在。



注:TOC—总有机碳。

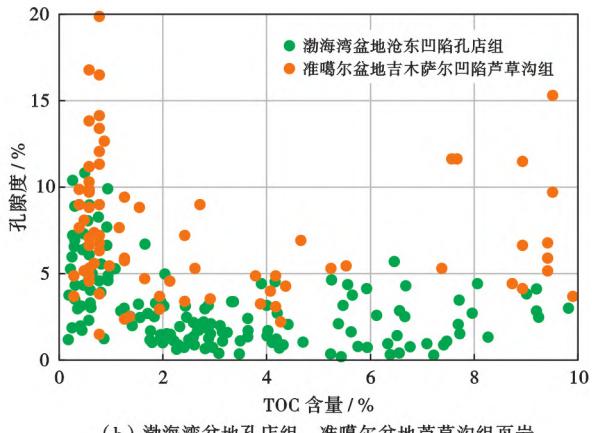


图 6 典型页岩盆地孔隙度与 TOC 含量的关系(据文献[77,92]修改)

Fig. 6 Relationship between porosity and TOC content of shale in typical basins

在 S_1 —TOC 含量关系的外包络线绘制完成后,在图 7 中加入 $S_1/C_{TOC} = 1$ 的数据线,该直线在上延方向与包络线存在一个交点 A,过此交点向纵坐标轴方向投影,投影线与包络线存在另一交点 B,与之对应,这 2 个交点在横轴上的投影分别为 C_{TOC}' 、 C_{TOC}'' (图 7),二者分别表示有利于页岩油富集的 TOC 含量的上限和下限。由图 7 可见:当 TOC 含量低于 C_{TOC}'' 或高于 C_{TOC}' 时,此类页岩油资源以现有技术无法得到经济有效开发,称为无效资源(图 7 中④);TOC 含量处于二者之间时,其中,高 S_1 区域的页岩油富集程度更高,属于富集资源(图 7 中①), $S_1/C_{TOC} < 1$ 的部分可动程度低,属于低效资源(图 7 中③),其余部分含油量居中,也具有一定的可动性,属于中等富集资源(图 7 中②)。

3.2 应用实例

准噶尔盆地和松辽盆地均已取得页岩油勘探突破。准噶尔盆地玛湖凹陷位于盆地西北缘,发育高碳酸盐含量的优质烃源岩层系——二叠系风城组,在咸化湖盆型页岩油勘探和盆地多类型油气藏有序共生研究等方面取得重要进展^[9],是咸化湖相页岩油的典型代表;松辽盆地齐家—古龙凹陷白垩系青山口组沉积于淡水—微咸水环境,其页岩油具有中等有机质丰度、较高成熟度、高滞留烃量等特征,是松辽盆地内页岩油资源潜力最大的层系^[100]。笔者对取自风城组和青山口组的岩心样品进行了大量的地球化学实验分析和物性测试, S_1 、TOC 含量和孔隙度分别采用 OGE-VI 型岩石热解仪、CS230HC 型碳硫分析仪和高压压汞实验测试完成。

笔者基于风城组和青山口组页岩的氯仿沥青“A”含量、 S_1 和 TOC 含量分别绘制了氯仿沥青“A”含量—TOC 含量关系图(图 8)和 S_1 —TOC 含量关系图(图 9),数据点的包络线均表现为先升高后降低的趋势。将资源分级评价模型分别应用于 2 个凹陷 [图 9(a)、图 9(b)],可得风城组页岩油富集区的 TOC 含量下限和上限分别为 0.4% 和 2.2%,青山口组页岩油富集区的 TOC 含量下限和上限分别为 1.5% 和 3.4%,可作为初步识别页岩油富集层段、富集区的标准。

风城组页岩油可分成 4 种资源类型[图 9(a)]:①富集资源,0.4% < C_{TOC} < 2.2% 且 $S_1 > 2.2 \text{ mg/g}$;②中等富集资源,0.4% < C_{TOC} < 2.2%, $S_1 < 2.2 \text{ mg/g}$ 且 $S_1/C_{TOC} > 1$;③低效资源,0.4% < C_{TOC} < 2.2% 且 $S_1/C_{TOC} < 1$;④无效资源, $C_{TOC} < 0.4\%$ 或 $C_{TOC} > 2.2\%$ 。

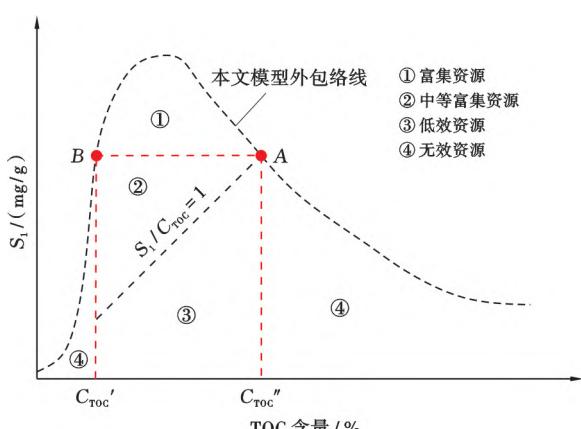


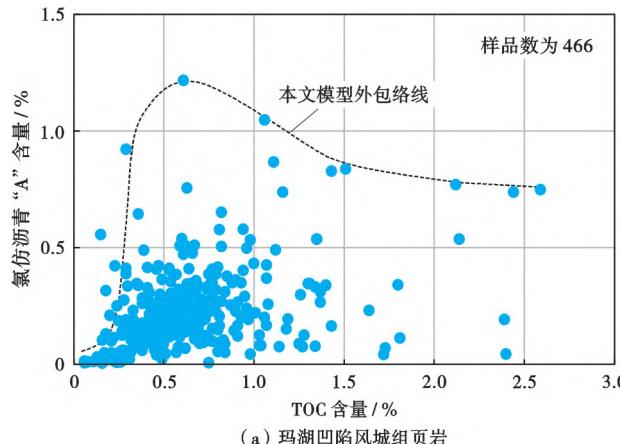
图 7 页岩油资源分级评价模型

Fig. 7 Grade assessment model of shale oil resources

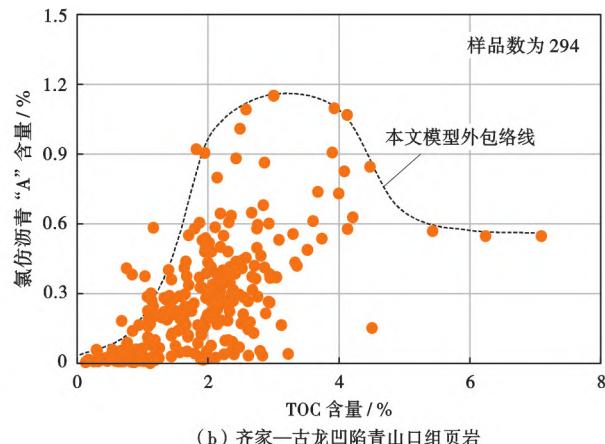
需要注意的是,受地质条件差异的影响,不同盆地间的TOC含量、 S_1 分级界限有所差别;为了提高分级界限的可靠性,数据集最好覆盖盆地边缘至盆地中心。

对比了“三分法”^[18]、“四分法”^[45]和笔者所述新模型在风城组的应用效果[图9(a)、图9(c)、图9(d)],新模型既考虑了页岩油含量、可动性,也考虑到储集空间

随TOC含量的动态演化。现有的研究普遍认为,越靠近生烃中心,页岩油越富集,大量老油区在对平面甜点和纵向甜点划分的过程中会将关注点放在高有机质丰度的地区,对页岩油富集区存在误判,遗漏了潜在的有利探区。笔者认为,烃源岩的TOC含量越高并不意味着页岩油就越富集,而是在某一适中区间内,当有



(a) 马湖凹陷风城组页岩

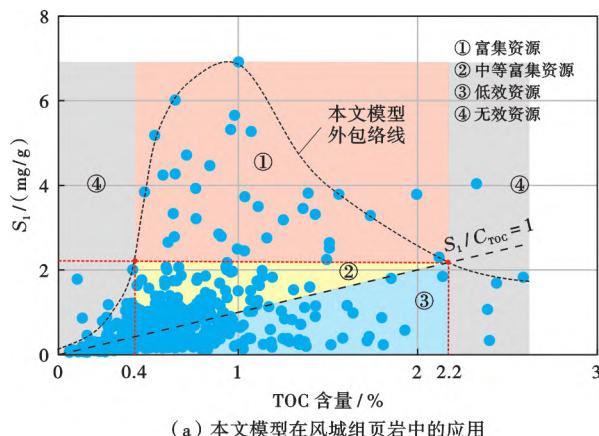


(b) 齐家—古龙凹陷青山口组页岩

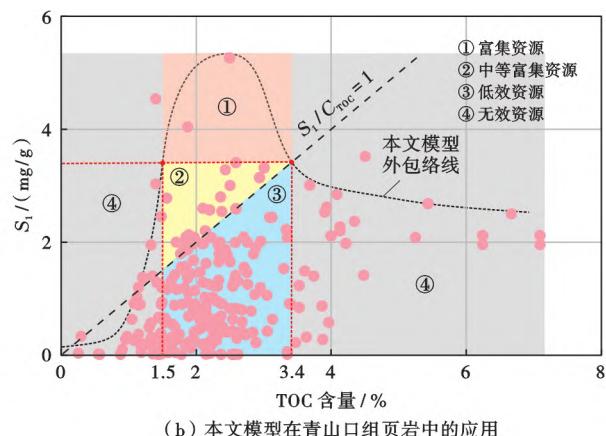
注:TOC—总有机碳。

图8 页岩氯仿沥青“A”与TOC含量的关系

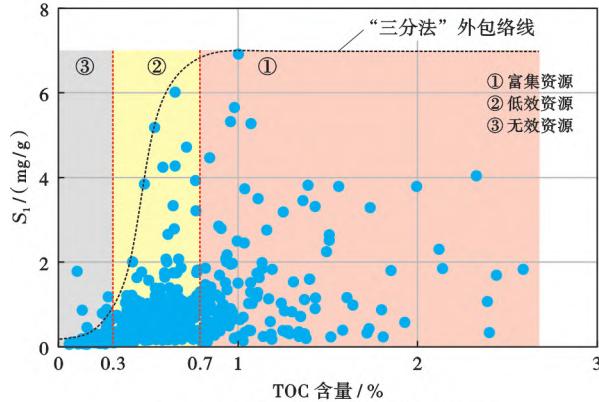
Fig. 8 Relationship between chloroform asphalt "A" and TOC content of shale



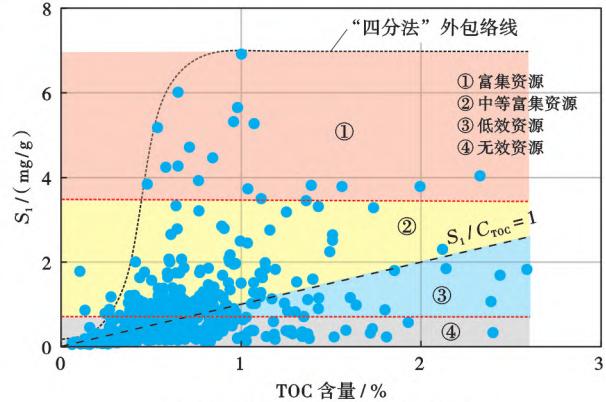
(a) 本文模型在风城组页岩中的应用



(b) 本文模型在青山口组页岩中的应用



(c) “三分法”在风城组页岩中的应用



(d) “四分法”在风城组页岩中的应用

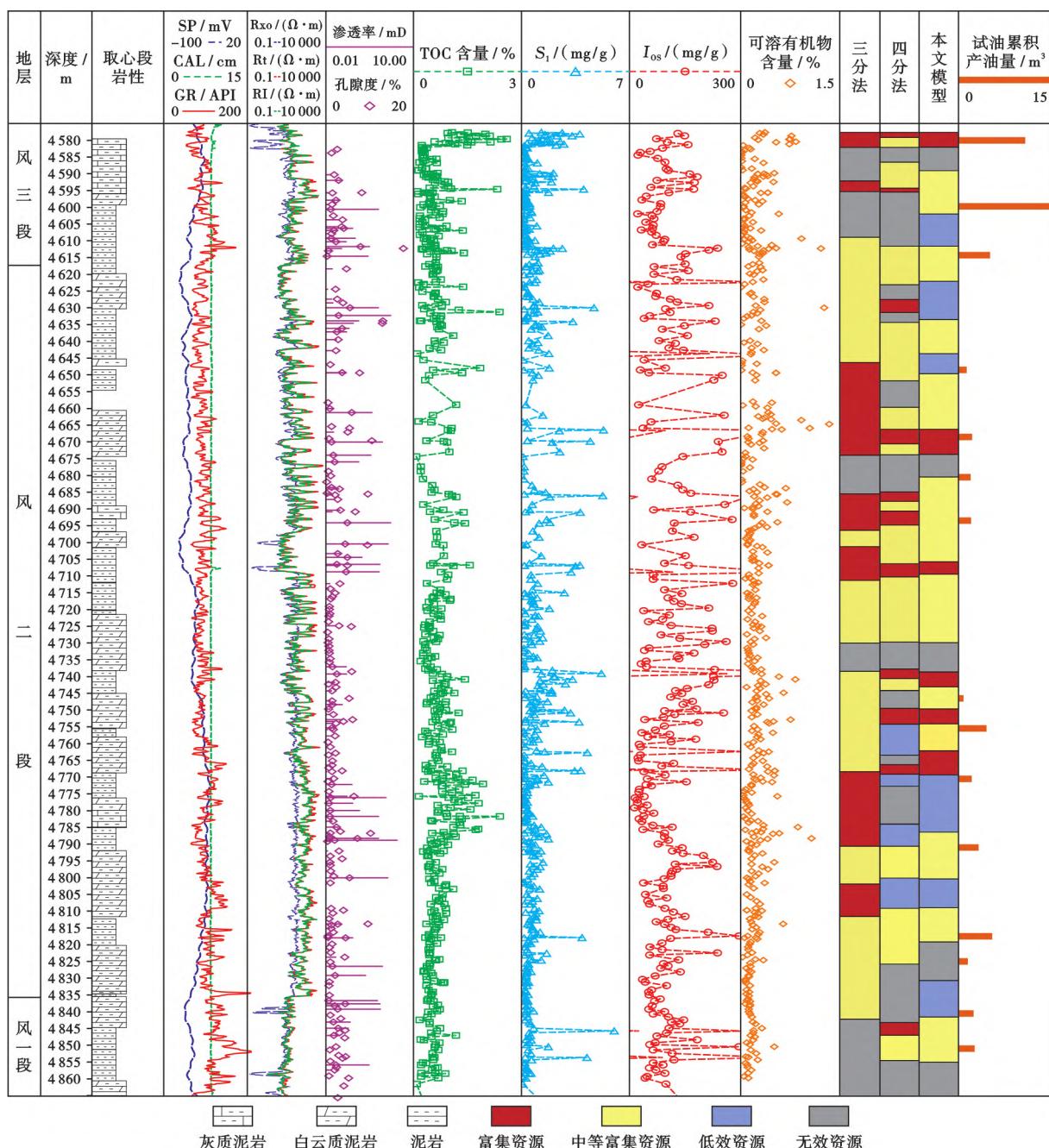
注:TOC—总有机碳。

图9 新模型在二叠系风城组、白垩系青山口组页岩中的应用以及与“三分法”、“四分法”应用结果的对比

Fig. 9 Application of new model in Permian Fengcheng Formation and Cretaceous Qingshankou Formation and its comparison with the triple-division model and the quarter-division model

机质丰度与储集空间达到平衡状态时,页岩油最为富集。在这种情况下,甜点围绕生烃中心呈“环带状”分布。当前,中国部分勘探程度较高的含油气盆地已积累了足够数量的地球化学实验分析数据,可以通过参考前述方法,重新建立资源分级模型,确定新的页岩油资源分级的 TOC 含量界限。由于中国不同页岩油盆地的源岩、储层等地质条件差异很大,因此,参考笔者新模型所做出的各级资源的 TOC 含量和 S_1 界限会有所不同。

在页岩油气资源的分级评价过程中,所采用的资源分级标准不同会导致在井剖面上不同级别的页岩厚度分布存在差异,从而影响了不同级别页岩油资源量的计算结果。例如,在 MY1 井单井剖面中分别采用“三分法”、“四分法”和笔者提出的新模型 3 种分级标准对甜点段进行划分,前两者均存在将低产油量段高估为富集资源段、遗漏高产油量段的问题,而在笔者提出的新模型中,试油高产段多分布于富集资源段和中等富集资源段,而低效资源段和无效资源段的试油产量较低(图 10),相比之下,



注:SP—自然电位;CAL—井径;GR—自然伽马;Rt—地层电阻率;R_{xo}—冲洗带电阻率;RI—感应电阻率;TOC—总有机碳。

图 10 准噶尔盆地玛湖凹陷 MY1 井风城组甜点分级评价结果与试产情况

Fig. 10 Grade assessment results and trial production situation of the Fengcheng Formation sweet pot at Well MY1 in Mahu sag, Junggar Basin

甜点分级评价结果的准确性得到加强。然而,产能的影响因素较多,如部分层段因风城组独特的碱湖沉积特征会对其生/排烃特征、储集物性和滞留烃量产生影响,构造裂缝的发育程度和压裂效果等也会对产能造成影响,匹配效果有待进一步提升。

整体上,笔者提出的新模型在典型淡水和咸水湖相页岩盆地中得到了较好的应用,可以为页岩油资源分级分类评价、资源量计算、页岩油富集层段及有利区的识别提供新思路。

4 结 论

(1) 页岩含油性评价方法按照原理可归纳为有机地球化学参数法、含油饱和度法、物质平衡法和荧光信号法,各方法的含油性评价有各自局限,其中,“三分法”和“四分法”是较为实用的页岩油资源分级评价方法。

(2) 多个典型页岩油盆地的滞留烃量与孔隙度、TOC含量关系的散点数据呈“正态分布”特征,据此可建立生烃能力与储集能力共同控制下的含油性影响因素模型。从盆地边缘至盆地中心,该模型显示页岩在生烃能力增强的同时储集能力降低,页岩含油性的主控因素由生烃能力过渡为储集能力。

(3) 新的页岩油资源分级评价模型以 TOC 含量、 S_1 和 S_1/C_{TOC} 为关键参数,将页岩油资源分为富集资源、中等富集资源、低效资源和无效资源 4 级并厘定了相应的评价标准。基于此标准,可确定各级别页岩的厚度与面积分布,从而合理评价各级页岩油资源量。页岩油勘探应多聚焦于围绕生烃中心呈“环带状”分布的生烃能力与储集能力相平衡的区域。新模型在准噶尔盆地玛湖凹陷和松辽盆地齐家—古龙凹陷得到了较好地应用,明确了 2 个凹陷页岩油富集区的 TOC 含量上、下限分别为 0.4% 和 2.2% 以及 1.5% 和 3.4%。

符号注释: S_1 —岩石中的游离烃含量, mg/g; C_{TOC} —总有机碳含量; I_{os} —含油饱和度指数, mg/g; T_{max} —岩石热解最高峰温度, °C; I_{oce} —含油量评价指数; C_L —归一化单位质量岩石中液态烃含量指数; C_g —归一化单位质量岩石中气态烃含量指数; S_{co} —归一化岩心描述含油面积指数; w_1 、 w_2 、 w_3 — C_L 、 C_g 和 S_{co} 的相对权重; I_{pos} —孔隙中的油饱和指数; ϕ —孔隙度; K —渗透率, mD; S_o —含油饱和度; V_{oil} —可动油体积占比; V_{bhc} —束缚油体积占比; V_{irrw} —毛细管束缚水体积占比; V_w —可动水体积占比; S_2 —岩石中的热解烃含量, mg/g; S_{1max} —最大游离烃含量, mg/g; C_{TOC}' 、 C_{TOC}'' —页岩油富集的 TOC 含量的下限和上限。

参 考 文 献

- [1] 孙龙德,刘合,朱如凯,等.中国页岩油革命值得关注的十个问题[J].石油学报,2023,44(12):2007-2019.
SUN Longde, LIU He, ZHU Rukai, et al. Ten noteworthy issues on shale oil revolution in China[J]. Acta Petrolei Sinica, 2023,44(12):2007-2019.
- [2] 张金川,林腊梅,李玉喜,等.页岩油分类与评价[J].地学前缘,2012,19(5):322-331.
ZHANG Jinchuan, LIN Lamei, LI Yuxi, et al. Classification and evaluation of shale oil[J]. Earth Science Frontiers, 2012,19(5): 322-331.
- [3] 王建,郭秋麟,赵晨蕾,等.中国主要盆地页岩油气资源潜力及发展前景[J].石油学报,2023,44(12):2033-2044.
WANG Jian, GUO Qiulin, ZHAO Chenlei, et al. Potentials and prospects of shale oil-gas resources in major basins of China [J]. Acta Petrolei Sinica, 2023,44(12):2033-2044.
- [4] 卢双舫,张亚念,李俊乾,等.纳米技术在非常规油气勘探开发中的应用[J].矿物岩石地球化学通报,2016,35(1):28-36.
LU Shuangfang, ZHANG Yanian, LI Junqian, et al. Nanotechnology and its application in the exploration and development of unconventional oil and gas[J]. Bulletin of Mineralogy, Petrology and Geochemistry, 2016,35(1):28-36.
- [5] 贾承造,王祖纲,姜林,等.中国页岩油勘探开发研究进展与科学技术问题[J].世界石油工业,2024,31(4):1-11.
JIA Chengzao, WANG Zugang, JIANG Lin, et al. Progress and key scientific and technological problems of shale oil exploration and development in China[J]. World Petroleum Industry, 2024, 31(4):1-11.
- [6] 金之钧,白振瑞,高波,等.中国迎来页岩油气革命了吗? [J].石油与天然气地质,2019,40(3):451-458.
JIN Zhijun, BAI Zhenrui, GAO Bo, et al. Has China ushered in the shale oil and gas revolution? [J], Oil & Gas Geology, 2019,40(3): 451-458.
- [7] 窦立荣,温志新,王建君,等.2021年世界油气勘探形势分析与思考[J].石油勘探与开发,2022,49(5):1033-1044.
DOU Lirong, WEN Zhixin, WANG Jianjun, et al. Analysis of the world oil and gas exploration situation in 2021[J]. Petroleum Exploration and Development, 2022,49(5):1033-1044.
- [8] 赵文智,朱如凯,张婧雅,等.中国陆相页岩油类型、勘探开发现状与发展趋势[J].中国石油勘探,2023,28(4):1-13.
ZHAO Wenzhi, ZHU Rukai, ZHANG Jingya, et al. Classification, exploration and development status and development trend of continental shale oil in China[J]. China Petroleum Exploration, 2023,28(4):1-13.
- [9] 支东明,唐勇,何文军,等.准噶尔盆地玛湖凹陷风城组常规-非常规油气有序共生与全油气系统成藏模式[J].石油勘探与开发,2021,48(1):38-51.
ZHI Dongming, TANG Yong, HE Wenjun, et al. Orderly coexistence and accumulation models of conventional and unconventional hydrocarbons in Lower Permian Fengcheng Formation, Mahu sag, Junggar Basin[J]. Petroleum Exploration and Development, 2021,48(1):38-51.

- [10] 赵贤正,周立宏,蒲秀刚,等.湖相页岩滞留烃形成条件与富集模式——以渤海湾盆地黄骅坳陷古近系为例[J].石油勘探与开发,2020,47(5):856-869.
ZHAO Xianzheng, ZHOU Lihong, PU Xiugang, et al. Formation conditions and enrichment model of retained petroleum in lacustrine shale:a case study of the Paleogene in Huanghua depression, Bohai Bay Basin, China[J]. Petroleum Exploration and Development, 2020, 47(5):856-869.
- [11] 焦方正,邹才能,杨智.陆相源内石油聚集地质理论认识及勘探开发实践[J].石油勘探与开发,2020,47(6):1067-1078.
JIAO Fangzheng, ZOU Caineng, YANG Zhi. Geological theory and exploration & development practice of hydrocarbon accumulation inside continental source kitchens[J]. Petroleum Exploration and Development, 2020, 47(6):1067-1078.
- [12] 焦方正.鄂尔多斯盆地页岩油缝网波及研究及其在体积开发中的应用[J].石油与天然气地质,2021,42(5):1181-1188.
JIAO Fangzheng. FSV estimation and its application to development of shale oil via volume fracturing in the Ordos Basin[J]. Oil & Gas Geology, 2021, 42(5):1181-1188.
- [13] 谢建勇,崔新疆,李文波,等.准噶尔盆地吉木萨尔凹陷页岩油效益开发探索与实践[J].中国石油勘探,2022,27(1):99-110.
XIE Jianyong, CUI Xinjiang, LI Wenbo, et al. Exploration and practice of benefit development of shale oil in Jimsar sag, Junggar Basin [J]. China Petroleum Exploration, 2022, 27(1):99-110.
- [14] JARVIE D M. Shale resource systems for oil and gas:part2:shale-oil resource systems[J]. AAPG Memoir, 2012, 97:89-119.
- [15] KATZ B J. Controls on distribution of lacustrine source rocks through time and space[M]// KATZ B J. Lacustrine basin exploration: case studies and modern analogs. Tulsa: AAPG, 1990, 61-76.
- [16] 聂海宽,张培先,边瑞康,等.中国陆相页岩油富集特征[J].地学前缘,2016,23(2):55-62.
NIE Haikuan, ZHANG Peixian, BIAN Ruikang, et al. Oil accumulation characteristics of China continental shale[J]. Earth Science Frontiers, 2016, 23(2):55-62.
- [17] 赵文智,朱如凯,胡素云,等.陆相富有机质页岩与泥岩的成藏差异及其在页岩油评价中的意义[J].石油勘探与开发,2020,47(6):1079-1089.
ZHAO Wenzhi, ZHU Rukai, HU Suyun, et al. Accumulation contribution differences between lacustrine organic-rich shales and mudstones and their significance in shale oil evaluation[J]. Petroleum Exploration and Development, 2020, 47(6):1079-1089.
- [18] 卢双舫,黄文彪,陈方文,等.页岩油气资源分级评价标准探讨[J].石油勘探与开发,2012,39(2):249-256.
LU Shuangfang, HUANG Wenbiao, CHEN Fangwen, et al. Classification and evaluation criteria of shale oil and gas resources: discussion and application[J]. Petroleum Exploration and Development, 2012, 39(2):249-256.
- [19] 邹才能,杨智,崔景伟,等.页岩油形成机制、地质特征及发展对策[J].石油勘探与开发,2013,40(1):14-26.
ZOU Caineng, YANG Zhi, CUI Jingwei, et al. Formation mechanism, geological characteristics and development strategy of nonmarine shale oil in China[J]. Petroleum Exploration and Development, 2013, 40(1):14-26.
- [20] 金之钧,梁新平,王小军,等.玛湖凹陷风城组页岩油富集机制与甜点段优选[J].新疆石油地质,2022,43(6):631-639.
JIN Zhijun, LIANG Xinping, WANG Xiaojun, et al. Shale oil enrichment mechanism and sweet spot selection of Fengcheng Formation in Mahu sag, Junggar Basin[J]. Xinjiang Petroleum Geology, 2022, 43(6):631-639.
- [21] 刘惠民,包友书,黎茂稳,等.页岩油富集可动性地球化学评价参数探讨——以威利斯顿盆地Bakken组和渤海湾盆地济阳坳陷古近系沙河街组页岩为例[J].石油与天然气地质,2024,45(3):622-636.
LIU Huimin, BAO Youshu, LI Maowen, et al. Geochemical parameters for evaluating shale oil enrichment and mobility;a case study of shales in the Bakken Formation, Williston Basin and the Shahejie Formation, Jiyang depression [J]. Oil & Gas Geology, 2024, 45(3):622-636.
- [22] 李进步,卢双舫,陈国辉,等.热解参数S₁的轻烃与重烃校正及其意义——以渤海湾盆地大民屯凹陷E₂s^{t(2)}段为例[J].石油与天然气地质,2016,37(4):538-545.
LI Jinbu, LU Shuangfang, CHEN Guohui, et al. Correction of light and heavy hydrocarbon loss for residual hydrocarbon S₁ and its significance to assessing resource potential of E₂s^{t(2)} Member in Damintun sag, Bohai Bay Basin[J]. Oil & Gas Geology, 2016, 37(4):538-545.
- [23] LI Shuifu, HU Shouzhi, XIE Xinong, et al. Assessment of shale oil potential using a new free hydrocarbon index[J]. International Journal of Coal Geology, 2016, 156:74-85.
- [24] 宋国奇,张林晔,卢双舫,等.页岩油资源评价技术方法及其应用[J].地学前缘,2013,20(4):221-228.
SONG Guoqi, ZHANG Linye, LU Shuangfang, et al. Resource evaluation method for shale oil and its application[J]. Earth Science Frontiers, 2013, 20(4):221-228.
- [25] GLASER K S, MILLER C K, JOHNSON G M, et al. Seeking the sweet spot: reservoir and completion quality in organic shales[J]. Oilfield Review, 2013, 25(4):16-29.
- [26] HEEGE J T, ZIJP M, NELSKAMP S, et al. Sweet spot identification in underexplored shales using multidisciplinary reservoir characterization and key performance indicators: example of the Posidonia Shale Formation in the Netherlands[J]. Journal of Natural Gas Science and Engineering, 2015, 27:558-577.
- [27] HU Tao, PANG Xiongqi, JIANG Fujie, et al. Movable oil content evaluation of lacustrine organic-rich shales: methods and a novel quantitative evaluation model[J]. Earth-Science Reviews, 2021, 214:103545.
- [28] PANG Xiongqi, LI Min, LI Boyuan, et al. Main controlling factors and movability evaluation of continental shale oil [J]. Earth-Science Reviews, 2023, 243:104472.
- [29] GONG Houjian, JIANG Zhenxue, GAO Zhiye, et al. Innovative standard for graded evaluation of oil enrichment of lacustrine shale:a case study of the lower third Member of the Shahejie Formation, Zhanhua sag, Eastern China[J]. Energy & Fuels, 2021, 35(21):17698-17710.
- [30] 蒋启贵,黎茂稳,钱门辉,等.不同赋存状态页岩油定量表征技

- 术与应用研究[J].石油实验地质,2016,38(6):842-849.
- [31] JIANG Qigui, LI Maowen, QIAN Menhui, et al. Quantitative characterization of shale oil in different occurrence states and its application[J]. Petroleum Geology & Experiment, 2016,38(6): 842-849.
- [32] PETERS K E. Guidelines for evaluating petroleum source rock using programmed pyrolysis[J]. AAPG Bulletin, 1986,70(3): 318-329.
- [33] 朱日房,张林晔,李钜源,等.页岩滞留液态烃的定量评价[J].石油学报,2015,36(1):13-18.
- ZHU Rifang, ZHANG Linye, LI Juyuan, et al. Quantitative evaluation of residual liquid hydrocarbons in shale[J]. Acta Petrolei Sinica,2015,36(1):13-18.
- [34] XUE Haitao, TIAN Shansi, LU Shuangfang, et al. Selection and verification of key parameters in the quantitative evaluation of shale oil:a case study at the Qingshankou Formation, northern Songliao Basin[J]. Bulletin of Mineralogy, Petrology and Geochemistry,2015,34(1):70-78.
- [35] 魏海涛,田善思,卢双舫,等.页岩油资源定量评价中关键参数的选取与校正——以松辽盆地北部青山口组为例[J].矿物岩石地球化学通报,2015,34(1):70-78.
- [36] QIAN Menhui, JIANG Qigui, LI Maowen, et al. Quantitative characterization of extractable organic matter in lacustrine shale with different occurrences[J]. Petroleum Geology & Experiment, 2017,39(2):278-286.
- [37] PIEDRAHITA J, AGUILERA R. Geochemical productivity index (I_{gp}): an innovative way to identify potential zones with moveable oil in shale reservoirs[J]. SPE Reservoir Evaluation & Engineering, 2019(4):1256-1264.
- [38] HAN Yuanjia , HORSFIELD B, LAREAU H, et al. Intraformational migration of petroleum:insights into the development of sweet spot in the Cretaceous Niobrara shale-oil system, Denver Basin[J]. Marine and Petroleum Geology,2019,107:301-309.
- [39] CAO Huaiyu, ZOU Yanrong, LEI Yan, et al. Shale oil assessment for the Songliao Basin, northeastern China, using oil generation-sorption method[J]. Energy & fuels,2017,31(5):4826-4842.
- [40] HU Tao, PANG Xiongqi, JIANG Shu, et al. Oil content evaluation of lacustrine organic-rich shale with strong heterogeneity: a case study of the Middle Permian Lucaogou Formation in Jimusaer sag, Junggar Basin, NW China[J]. Fuel,2018,221:196-205.
- [41] WANG Min, SHERWOOD N, LI Zhongsheng, et al. Shale oil occurring between salt intervals in the Dongpu depression, Bohai Bay Basin, China[J]. International Journal of Coal Geology, 2015,152:100-112.
- [42] 熊钰,郭美娟,王羚鸿,等.四川盆地侏罗系大安寨段页岩油特征及可动性评价[J].石油学报,2024,45(5):817-843.
- XIONG Yu, GUO Meijuan, WANG Linghong, et al. Characteristics and movability evaluation of shale oil in Jurassic Da'anzhai Member, Sichuan Basin[J]. Acta Petrolei Sinica,2024,45(5):817-843.
- [43] KATZ B, LIN Fang. Lacustrine basin unconventional resource plays: key differences [J]. Marine and Petroleum Geology, 2014,56:255-265.
- [44] ZOU Caineng, ZHU Rukai, CHEN Zhongqiang, et al. Organic-matter-rich shales of China[J]. Earth-Science Reviews, 2019, 189:51-78.
- [45] HUNT J M. Generation and migration of petroleum from abnormally pressured fluid compartments[J]. AAPG Bulletin, 1990,74(1):1-12.
- [46] MCAULIFFE C D. Chemical and physical constraints on petroleum migration with emphasis on hydrocarbon solubilities in water[J]. Physical and Chemical Constraints on Petroleum Migration,1978,8:1-39.
- [47] LI Wenhao, LU Shuangfang, XUE Haitao, et al. Oil content in argillaceous dolomite from the Jianghan Basin, China: application of new grading evaluation criteria to study shale oil potential[J]. Fuel,2015,143:424-429.
- [48] SU Siyuan, JIANG Zhenxue, NING Chuanxiang, et al. Study of the main controlling factors of shale oil enrichment in the Zhanhua sag[J]. Petroleum Science Bulletin,2017,2(2):187-198.
- [49] WANG Enze, LI Changrong, FENG Yue, et al. Novel method for determining the oil moveable threshold and an innovative model for evaluating the oil content in shales[J]. Energy,2022, 239:121848.
- [50] LIU Yazhou, ZENG Jianhui, YANG Guangqing ,et al. An innovative method for the characterization of oil content in lacustrine shale-oil systems: a case study from the Middle Permian Lucaogou Formation in the Jimusaer sag, Junggar Basin[J]. Marine and Petroleum Geology,2021,130:105112.
- [51] CHEN Longchuan, ZHANG Zhaoqian, ZHENG Jiandong, et al. Application of NMR logging in the evaluation of Gulong shale oil[J]. Well Logging Technology,2024,48(1):110-116.
- [52] 郑兆谦,郑建东,等.核磁共振测井在古龙页岩油评价中的应用[J].测井技术,2024,48(1):110-116.
- SHAO Hongmei, GAO Bo, HONG Shuxin, et al. Progress and application of the experimental technologies for the shale oil reservoirs:a case study on Gulong area in Songliao Basin[J]. Petroleum Geology & Oilfield Development in Daqing, 2020,39(3): 97-106.
- [53] 鲁峰,李照阳,杨召,等.激光扫描共聚焦显微分析技术表征页岩亚微米级孔隙中的含油性——以准噶尔盆地芦草沟组页岩为例[J].石油实验地质,2023,45(1):193-202.
- LU Feng, LI Zhaoyang, YANG Zhao, et al. Characterization of oil-bearing properties in sub-micron shale pores by laser scanning confocal microscopy technology: a case study of shale in Lucaogou Formation, Junggar Basin[J]. Petroleum Geology &

- Experiment, 2023, 45(1): 193-202.
- [53] 胡涛, 姜福杰, 庞雄奇, 等. 页岩油微运移识别、评价及其石油地质意义[J]. 石油勘探与开发, 2024, 51(1): 114-126.
HU Tao, JIANG Fujie, PANG Xiongqi, et al. Identification and evaluation of shale oil micro-migration and its petroleum geological significance [J]. Petroleum Exploration and Development, 2024, 51(1): 114-126.
- [54] GENTZIS T, CARVAJAL-ORTIZ H, XIE Z H, et al. An integrated geochemical, spectroscopic, and petrographic approach to examining the producibility of hydrocarbons from liquids-rich unconventional Formations[J]. Fuel, 2021, 298: 120357.
- [55] 孙先达, 索丽敏, 张民志, 等. 激光共聚焦扫描显微检测技术在大庆探区储层分析研究中的新进展[J]. 岩石学报, 2005, 21(5): 1479-1488.
SUN Xianda, SUO Limin, ZHANG Minzhi, et al. New progress of reservoir research by the technology of laser confocal scanning microscope analysis in the Daqing exploration area[J]. Acta Petrologica Sinica, 2005, 21(5): 1479-1488.
- [56] COOLES G P, MACKENZIE A S, QUIGLEY T M. Calculation of petroleum masses generated and expelled from source rocks [J]. Organic Geochemistry, 1986, 10(1/3): 235-245.
- [57] 冯家乐, 杨升宇, 胡钦红, 等. 沧东凹陷孔二段页岩生排烃效率及对含油性的影响[J]. 中国石油大学学报(自然科学版), 2024, 48(2): 45-56.
FENG Jiale, YANG Shengyu, HU Qinhong, et al. Hydrocarbon generation and expulsion efficiency and influence on oil bearing property of shale in the second Member of Paleogene Kongdian Formation in Cangdong sag[J]. Journal of China University of Petroleum (Edition of Natural Science), 2024, 48(2): 45-56.
- [58] 宁方兴. 济阳坳陷页岩油富集主控因素[J]. 石油学报, 2015, 36(8): 905-914.
NING Fangxing. The main control factors of shale oil enrichment in Jiyang depression[J]. Acta Petrolei Sinica, 2015, 36(8): 905-914.
- [59] 卢双舫, 薛海涛, 王民, 等. 页岩油评价中的若干关键问题及研究趋势[J]. 石油学报, 2016, 37(10): 1309-1322.
LU Shuangfang, XUE Haitao, WANG Min, et al. Several key issues and research trends in evaluation of shale oil[J]. Acta Petrolei Sinica, 2016, 37(10): 1309-1322.
- [60] 宋明水. 济阳坳陷页岩油勘探实践与现状[J]. 油气地质与采收率, 2019, 26(1): 1-12.
SONG Mingshui. Practice and current status of shale oil exploration in Jiyang depression[J]. Petroleum Geology and Recovery Efficiency, 2019, 26(1): 1-12.
- [61] 张林晔, 包友书, 李钜源, 等. 湖相页岩油可动性——以渤海湾盆地济阳坳陷东营凹陷为例[J]. 石油勘探与开发, 2014, 41(6): 641-649.
ZHANG Linye, BAO Youshu, LI Juyuan, et al. Movability of lacustrine shale oil: a case study of Dongying sag, Jiyang depression, Bohai Bay Basin[J]. Petroleum exploration and development, 2014, 41(6): 641-649.
- [62] 赵贤正, 周立宏, 蒲秀刚, 等. 断陷湖盆湖相页岩油形成有利条件及富集特征——以渤海湾盆地沧东凹陷孔店组二段为例[J]. 石油学报, 2019, 40(9): 1013-1029.
- ZHAO Xianzheng, ZHOU Lihong, PU Xiugang, et al. Favorable formation conditions and enrichment characteristics of lacustrine facies shale oil in faulted lake basin: a case study of Member 2 of Kongdian Formation in Cangdong sag, Bohai Bay Basin [J]. Acta Petrolei Sinica, 2019, 40(9): 1013-1029.
- [63] 胡涛, 庞雄奇, 姜福杰, 等. 陆相断陷咸化湖盆有机质差异富集因素探讨——以东濮凹陷古近系沙三段泥页岩为例[J]. 沉积学报, 2021, 39(1): 140-152.
HU Tao, PANG Xiongqi, JIANG Fujie, et al. Factors controlling differential enrichment of organic matter in saline lacustrine rift basin: a case study of third member Shahejie Fm in Dongpu depression[J]. Acta Sedimentologica Sinica, 2021, 39(1): 140-152.
- [64] 柳波, 吕延防, 赵荣, 等. 三塘湖盆地马朗凹陷芦草沟组泥页岩系统地层超压与页岩油富集机理[J]. 石油勘探与开发, 2012, 39(6): 699-705.
LIU Bo, LÜ Yanfang, ZHAO Rong, et al. Formation overpressure and shale oil enrichment in the shale system of Lucaogou Formation, Malang sag, Santanghu Basin, NW China[J]. Petroleum Exploration and Development, 2012, 39(6): 699-705.
- [65] 蔚克来, 张媛媛, 操应长, 等. 孔喉微观润湿性对页岩油赋存的控制作用——以准噶尔盆地吉木萨尔凹陷二叠系芦草沟组纹层状页岩为例[J]. 石油勘探与开发, 2023, 50(2): 297-308.
XI Kelai, ZHANG Yuanyuan, CAO Yingchang, et al. Control of micro-wettability of pore-throat on shale oil occurrence: a case study of laminated shale of Permian Lucaogou Formation in Jimusar sag, Junggar Basin, NW China[J]. Petroleum Exploration and Development, 2023, 50(2): 297-308.
- [66] 郑国伟, 高之业, 黄立良, 等. 准噶尔盆地玛湖凹陷二叠系风城组页岩储层润湿性及其主控因素[J]. 石油与天然气地质, 2022, 43(5): 1206-1220.
ZHENG Guowei, GAO Zhiye, HUANG Liliang, et al. Wettability of the Permian Fengcheng Formation shale in the Mahu sag, Junggar Basin, and its main control factors[J]. Oil & Gas Geology, 2022, 43(5): 1206-1220..
- [67] 金之钩, 朱如凯, 梁新平, 等. 当前陆相页岩油勘探开发值得关注的几个问题[J]. 石油勘探与开发, 2021, 48(6): 1276-1287.
JIN Zhijun, ZHU Rukai, LIANG Xinping, et al. Several issues worthy of attention in current lacustrine shale oil exploration and development[J]. Petroleum Exploration and Development, 2021, 48(6): 1276-1287.
- [68] 金旭, 李国欣, 孟思炜, 等. 陆相页岩油可动用性微观综合评价[J]. 石油勘探与开发, 2021, 48(1): 222-232.
JIN Xu, LI Guoxin, MENG Siwei, et al. Microscale comprehensive evaluation of continental shale oil recoverability[J]. Petroleum Exploration and Development, 2021, 48(1): 222-232.
- [69] 李吉君, 史颖琳, 章新文, 等. 页岩油富集可采主控因素分析: 以泌阳凹陷为例[J]. 地球科学, 2014, 39(7): 848-857.
LI Jijun, SHI Yinglin, ZHANG Xinwen, et al. Control factors of enrichment and producibility of shale oil: a case study of Biyang depression[J]. Earth Science, 2014, 39(7): 848-857.
- [70] 朱国文, 王小军, 张金友, 等. 松辽盆地陆相页岩油富集条件及勘探开发有利区[J]. 石油学报, 2023, 44(1): 110-124.
ZHU Guowen, WANG Xiaojun, ZHANG Jinyou, et al. Enrich-

- ment conditions and favorable zones for exploration and development of continental shale oil in Songliao Basin[J]. *Acta Petrolei Sinica*, 2023, 44(1): 110-124.
- [71] 赵文智, 卞从胜, 李永新, 等. 陆相页岩油可动烃富集因素与古龙页岩油勘探潜力评价[J]. 石油勘探与开发, 2023, 50(3): 455-467. ZHAO Wenzhi, BIAN Congsheng, LI Yongxin, et al. Enrichment factors of movable hydrocarbons in lacustrine shale oil and exploration potential of shale oil in Gulong sag, Songliao Basin, NE China[J]. *Petroleum Exploration and Development*, 2023, 50(3): 455-467.
- [72] 庞雄奇, 陈君青, 李素梅, 等. 塔里木盆地特大型海相油田原油来源——来自深部低 TOC 烃源岩的证据与相对贡献评价[J]. 石油学报, 2018, 39(1): 23-41. PANG Xiongqi, CHEN Junqing, LI Sumei, et al. Crude oil sources of giant marine oilfield in Tarim Basin: evidences and relative contribution evaluation of deep present-day low-TOC source rocks[J]. *Acta Petrolei Sinica*, 2018, 39(1): 23-41.
- [73] 陈建平, 魏军, 倪云燕, 等. 酒泉盆地西酒坳陷主力烃源岩分布及对油气勘探的启示[J]. 石油学报, 2018, 39(11): 1223-1240. CHEN Jianping, WEI Jun, NI Yunyan, et al. Determination of main source rocks in the Jiuxi depression of Jiuquan Basin and its implications for oil and gas exploration[J]. *Acta Petrolei Sinica*, 2018, 39(11): 1223-1240.
- [74] 赵文智, 卞从胜, 蒲秀刚, 等. 中国典型咸化湖盆页岩油富集与流动特征及在“甜点”评价中的意义[J]. 中国石油大学学报(自然科学版), 2023, 47(5): 25-37. ZHAO Wenzhi, BIAN Congsheng, PU Xiugang, et al. Enrichment and flow characteristics of shale oil in typical salinized lake basins in China and its significance for “sweet spot” evaluation [J]. *Journal of China University of Petroleum (Edition of Natural Science)*, 2023, 47(5): 25-37.
- [75] ZENG Xiang, CAI Jingong, WANG Xuejun, et al. Research on the sedimentary characteristics of organic matter in lacustrine mudrocks and their hydrocarbon generation potential based on palynofacies analysis: Eocene Shahejie Formation, Dongying sag [J]. *Frontiers in Earth Science*, 2022, 10: 936262.
- [76] XU Zhengjian, LIU Luofu, JIANG Shu, et al. Palaeoenvironment and organic matter of the Triassic Chang 9 lacustrine shales, Ordos Basin, China[J]. *Geological Journal*, 2020, 55(6): 4748-4771.
- [77] 宋国奇, 徐友兴, 李政, 等. 济阳坳陷古近系陆相页岩油产量的影响因素[J]. 石油与天然气地质, 2015, 36(3): 463-471. SONG Guoqi, XU Xingyou, LI Zheng, et al. Factors controlling oil production from Paleogene shale in Jiyang depression[J]. *Oil & Gas Geology*, 2015, 36(3): 463-471.
- [78] 孙龙德, 赵文智, 刘合, 等. 页岩油“甜点”概念及其应用讨论[J]. 石油学报, 2023, 44(1): 1-13. SUN Longde, ZHAO Wenzhi, LIU He, et al. Concept and application of “sweet spot” in shale oil[J]. *Acta Petrolei Sinica*, 2023, 44(1): 1-13.
- [79] CURTIS J B. Fractured shale-gas systems[J]. *AAPG Bulletin*, 2002, 86(11): 1921-1938.
- [80] 王民, 马睿, 李进步, 等. 济阳坳陷古近系沙河街组湖相页岩油赋存机理[J]. 石油勘探与开发, 2019, 46(4): 789-802. WANG Min, MA Rui, LI Jinbu, et al. Occurrence mechanism of lacustrine shale oil in the Paleogene Shahejie Formation of Jiyang depression, Bohai Bay Basin, China[J]. *Petroleum Exploration and Development*, 2019, 46(4): 789-802.
- [81] LOUCKS R G, REED R M, RUPPEL S C, et al. Spectrum of pore types and networks in mudrocks and a descriptive classification for matrix-related mudrock pores[J]. *AAPG Bulletin*, 2012, 96(6): 1071-1098.
- [82] 崔景伟, 邹才能, 朱如凯, 等. 页岩孔隙研究新进展[J]. 地球科学进展, 2012, 27(12): 1319-1325. CUI Jingwei, ZOU Caineng, Zhu Rukai, et al. New advances in shale porosity research[J]. *Advances in Earth Science*, 2012, 27(12): 1319-1325.
- [83] 郭旭升, 李宇平, 刘若冰, 等. 四川盆地焦石坝地区龙马溪组页岩微观孔隙结构特征及其控制因素[J]. 天然气工业, 2014, 34(6): 9-16. GUO Xusheng, LI Yiping, LIU Ruobing, et al. Characteristics and controlling factors of micro-pore structures of Longmaxi shale play in the Jiaoshiba area, Sichuan Basin[J]. *Natural Gas Industry*, 2014, 34(6): 9-16.
- [84] 朱筱敏, 王英国, 钟大康, 等. 济阳坳陷古近系储层孔隙类型与次生孔隙成因[J]. 地质学报, 2007, 81(2): 197-204. ZHU Xiaomin, WANG Yingguo, ZHONG Dakang, et al. Pore types and secondary pore evolution of Paleogene reservoir in the Jiyang sag[J]. *Acta Geologica Sinica*, 2007, 81(2): 197-204.
- [85] 刘毅. 渤海湾盆地济阳坳陷沙河街组页岩油储层特征研究[D]. 成都: 成都理工大学, 2018.
- [86] LIU Yi. Study on shale oil reservoir characteristics of Shahejie Formation in Jiyang depression, Bohai Bay Basin[D]. Chengdu: Chengdu University of Technology, 2018.
- [87] 肖佃师, 高阳, 彭寿昌, 等. 准噶尔盆地吉木萨尔凹陷混积岩孔喉系统分类及控制因素[J]. 石油勘探与开发, 2021, 48(04): 719-731. Xiao Dianshi, Gao Yang, Peng Shouchang, et al. Classification and control factors of pore-throat systems in hybrid sedimentary rocks of Jimusar sag, Junggar Basin, NW China[J]. *Petroleum Exploration and Development*, 2021, 48(4): 719-731.
- [88] 孙龙德, 朱如凯, 张天舒, 等. 陆相页岩沉积学研究进展与发展方向——以大庆古龙页岩为例[J]. 石油勘探与开发, 2024, 51(6): 1183-1198. SUN Longde, ZHU Rukai, ZHANG Tianshu, et al. Advances and trends of non-marine shale sedimentology: a case study from Gulong shale of Daqing oilfield, Songliao Basin, NE China [J]. *Petroleum Exploration and Development*, 2024, 51 (6): 1183-1198.
- [89] 朱如凯, 孙龙德, 张天舒, 等. 中国油气勘探开发中的沉积学研究新进展与发展方向[J]. 沉积学报, 2025, 43(1): 1-19. ZHU Rukai, SUN Longde, ZHANG Tianshu, et al. Advances and trends in sedimentological research in oil and gas exploration and development in China[J]. *Acta Sedimentologica Sinica*, 2025, 43(1): 1-19.
- [90] 曾秋楠, 周新桂, 于炳松, 等. 陆相页岩气储层评价标准探讨——

- 以延长组富有机质页岩为例[J]. 新疆地质, 2015, 33(3): 409-414.
- ZENG Qiunan, ZHOU Xingui, YU Bingsong, et al. Evaluation criteria of lake facies shale gas reservoir: a case study of the organic rich shale developed in Yanchang group, Ordos Basin[J]. Xinjiang Geology, 2015, 33(3): 409-414.
- [90] 李进步. 页岩油赋存机理及可动性研究——以济阳坳陷沙河街组为例[D]. 青岛: 中国石油大学(华东), 2020.
- LI Jinbu. Study on occurrence mechanism and mobility of shale oil: a case study of Shahejie Formation in Jiyang depression[D]. Qingdao: China University of Petroleum (East China), 2020.
- [91] 杨智峰, 唐勇, 郭旭光, 等. 准噶尔盆地玛湖凹陷二叠系风城组页岩油赋存特征与影响因素[J]. 石油实验地质, 2021, 43(5): 784-796.
- YANG Zhifeng, TANG Yong, GUO Xuguang, et al. Occurrence states and potential influencing factors of shale oil in the Permian Fengcheng Formation of Mahu sag, Junggar Basin[J]. Petroleum Geology & Experimental, 2021, 43(5): 784-796.
- [92] 支东明, 唐勇, 杨智峰, 等. 准噶尔盆地吉木萨尔凹陷陆相页岩油地质特征与聚集机理[J]. 石油与天然气地质, 2019, 40(3): 524-534.
- ZHI Dongming, TANG Yong, YANG Zhifeng, et al. Geological characteristics and accumulation mechanism of continental shale oil in Jimusaer sag, Junggar Basin[J]. Oil & Gas Geology, 2019, 40(3): 524-534.
- [93] 董美君. 松辽盆地南部青山口组一段页岩油甜点层段优选[D]. 青岛: 中国石油大学(华东), 2021.
- DONG Meijun. Optimization of shale oil sweet spots in the first member of Qingshankou Formation in the Southern Songliao Basin[D]. Qingdao: China University of Petroleum (East China), 2021.
- [94] 刘惠民, 李军亮, 刘鹏, 等. 济阳坳陷古近系页岩油富集条件与勘探战略方向[J]. 石油学报, 2022, 43(12): 1717-1729.
- LIU Huimin, LI Junliang, LIU Peng, et al. Enrichment conditions and strategic exploration direction of Paleogene shale oil in Jiyang depression[J]. Acta Petrolei Sinica, 2022, 43(12): 1717-1729.
- [95] 陈前. 典型含气页岩孔缝结构研究[D]. 北京: 中国地质大学(北京), 2017.
- CHEN Qian. Study on pore and fracture structure of typical gas shale[D]. Beijing: China University of Geosciences (Beijing), 2017.
- [96] 孙焕泉. 济阳坳陷页岩油勘探实践与认识[J]. 中国石油勘探, 2017, 22(4): 1-14.
- SUN Huanquan. Exploration practice and cognitions of shale oil in Jiyang depression[J]. China Petroleum Exploration, 2017, 22(4): 1-14.
- [97] 谌卓恒, 黎茂稳, 姜春庆, 等. 页岩油的资源潜力及流动性评价方法——以西加拿大盆地上泥盆统 Duvernay 页岩为例[J]. 石油与天然气地质, 2019, 40(3): 459-468.
- SHEN Zhuoheng, LI Maowen, JIANG Chunqing, et al. Shale oil resource potential and its mobility assessment: a case study of Upper Devonian Duvernay shale in Western Canada Sedimentary Basin[J]. Oil & Gas Geology, 2019, 40(3): 459-468.
- [98] 胡素云, 白斌, 陶士振, 等. 中国陆相中高成熟度页岩油非均质地质条件与差异富集特征[J]. 石油勘探与开发, 2022, 49(2): 224-237.
- HU Suyun, BAI Bin, TAO Shizhen, et al. Heterogeneous geological conditions and differential enrichment of medium and high maturity continental shale oil in China[J]. Petroleum Exploration and Development, 2022, 49(2): 257-271.
- [99] WANG Xiaomei, HE Kun, ZHANG Shuichang, et al. Vertical heterogeneity of Gulong shale oil governed by the OM precursors and oil accumulation: implications for shale oil exploration in the Songliao Basin, northeastern China[J]. Marine and Petroleum Geology, 2024, 163: 106803.
- [100] 孙龙德, 刘合, 何文渊, 等. 大庆古龙页岩油重大科学问题与研究路径探析[J]. 石油勘探与开发, 2021, 48(3): 453-463.
- SUN Longde, LIU He, HE Wenyuan, et al. An analysis of major scientific problems and research paths of Gulong shale oil in Daqing oilfield, NE China[J]. Petroleum Exploration and Development, 2021, 48(3): 453-463.

(收稿日期 2025-02-14 改回日期 2025-04-10 编辑 雷永良)