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鄂尔多斯盆地长7段页岩油富集控制因素及勘探方向

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摘要 【目的】厘清鄂尔多斯盆地长7段不同类型页岩油富集主控因素及勘探潜力, 可明确下一步的勘探方向。【方法】综合利用有机地球化学、全岩X射线衍射、场发射扫描电镜与岩石热解实验, 对长7段泥页岩岩石学、地球化学特征和储集能力等页岩油形成条件与勘探潜力进行了综合研究。【结果】(1)长7₃亚段页岩有机质丰度高、成熟度最高、发育I型有机质, 生烃潜力最大。(2)长7段泥页岩主要发育无机孔缝, 其中微孔占比最大, 页岩储集能力优于泥岩。(3)长7段页岩油富集主要受优质烃源岩展布、岩性组合、裂缝、泥页岩可动性和可压裂性等五大要素控制。优质烃源岩展布控制页岩油分布范围; 岩性组合控制排烃效率和页岩油富集类型, 源储互层型排烃效率最高, 有利于夹层型页岩油富集, 厚源夹薄储型排烃效率最低, 有利于页岩油型页岩油富集; 裂缝对不同类型页岩油表现出两面性, 裂缝发育有利于砂岩夹层型页岩油富集, 而裂缝欠发育有利于纯页岩型页岩油滞留富集; 原油可动性和可压裂性控制页岩高产, 页岩原油可动性和脆性指数总体优于泥岩。【结论】姬塬地区长7₃亚段是纯页岩型页岩油的有利勘探目标, 正宁和陕北地区是长7₁和长7₂亚段砂岩夹层型页岩油的有利勘探目标, 陇东华池地区可考虑兼探砂岩夹层型和纯页岩型页岩油。

关键词 页岩油; 富集因素; 长7段; 鄂尔多斯盆地

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0 引言

陆相页岩油资源潜力巨大, 是保障国家能源安全的重要资源类型之一(赵文智等, 2023)。按照储集层“甜点”类型, 将其划分为夹层型、混积型和页岩型。其中鄂尔多斯盆地延长组7段(以下简称长7段)陆相页岩油主要发育夹层型和页岩型(焦方正等, 2020)。长7段沉积厚度约110 m, 以泥页岩为主, 夹多期薄层砂岩, 油气资源丰富, 是中国原油稳产的重要战略接替领域(赵文智等, 2020)。1970年长庆

油田庆6井在长7段页岩层系内直井压裂砂岩获得工业油流, 鄂尔多斯盆地长7页岩油的勘探开始步入探索阶段, 但受限于钻井和压裂工艺技术, 未获实质性勘探突破(孙龙德等, 2023); 2009年, 随着钻井和储层改造工艺的改进, 单井产能提升, 页岩油勘探进入快速突破阶段, 长7段水平井丹101井获得突破, 获气0.2 m³/d(赵喆等, 2024); 2011年, 在借鉴美国页岩油革命成功经验的基础上, 中国特色陆相页岩层系石油地质理论逐渐完善(邹才能等, 2020; 付锁堂等, 2021), 针对长7段油层组储层非均质性强、致密

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化程度高、地层压力系数低、裂缝发育和岩石脆性指数低等瓶颈问题,积极开展“水平井+体积压裂”攻关,形成“长水平井细分切割体积压裂技术”,实现了“千方砂、万方液、十万排量”的水平井体积压裂目标。2019年,在湖盆中部探明 10×10^8 t级国内最大页岩油田—庆城油田,并成功建成陇东百万吨页岩油生产基地,规模效益开发成果显著(付锁堂等,2020;付金华等,2022;何永宏等,2023;姚东升等,2024)。

我国陆相盆地沉积范围小、时空变化大,沉积过程受物源、气候和水动力等条件影响较大,导致陆相页岩层系普遍具有优质烃源岩空间展布差异大、储层非均质性强、烃源岩成熟度跨度大、岩性组合复杂多变的特点。强烈的沉积非均质性使得不同区域页岩油成藏地质条件和富集主控因素存在显著的差异性,单一的富集地质理论难以适用不同区域,导致勘探开发难度较大(邱振和邹才能,2020;郭旭升等,2023;邹才能等,2023)。长7段沉积时期,鄂尔多斯盆地经历了大规模的湖侵,沉积了一套广泛分布的富有机质泥页岩,为页岩油规模性富集奠定了物质基础(王广利等,2024;郑奎等,2024)。目前,长7段页岩油的研究主要集中于沉积相、生烃条件、有机质富集机理、储层孔隙结构以及生排烃特征研究等方面,页岩油区域化差异富集规律认识不清(范柏江等,2022;仓辉等,2023;刘翰林等,2023;吕奇奇等,2023;王梓毅等,2023;葛云锦等,2024)。长7段纵向上长 7_1 、长 7_2 、长 7_3 亚段沉积时期湖盆水体变化大,泥页岩分布差异大,同时湖盆发育辫状河三角洲、半深湖—深湖和重力流等多种类型沉积相,不同区块岩性组合类型差异大,不同类型页岩油有利勘探方向难以准确预测(付金华等,2021;邓秀芹等,2024)。此外,长7段发育油页岩和暗色泥岩两种类型的烃源岩,不同岩性页岩油地质特征存在明显差异(刘群等,2018;范柏江等,2020;Lu *et al.*, 2022)。为明确长7段页岩油地质特征以及富集主控因素,本文收集了油田姬塬、陕北、陇东三个地区长 7_1 、长 7_2 、长 7_3 亚段暗色泥岩和油页岩岩石热解、总有机碳(TOC)含量和显微组分等3类实验数据共计255样次,并采集上述三个地区各层段暗色泥岩样品10个和油页岩样品13个,开展全岩X射线衍射(XRD)、普通薄片鉴定、扫描电镜、 CO_2 吸附、 N_2 吸附和高压压汞等6类实验。综合对比不同亚段和不同岩性页岩油地质特征,剖析烃源岩、岩性组合、裂缝、可动性和可压裂性对页岩油富

集的控制作用,以期不同类型页岩油勘探部署提供有利勘探方向,为鄂尔多斯盆地和国内其他盆地页岩油勘探开发提供理论指导和借鉴意义。

1 地质背景

鄂尔多斯盆地位于我国西北部,构造上被划分为伊盟隆起、西缘冲断带、天环坳陷、晋西挠褶带、渭北隆起和伊陕斜坡等6个一级构造单元(图1a),总面积 37×10^4 km^2 ,是我国第二大沉积盆地(陈世加等,2019;罗力元等,2024;张春雨等,2024)。上三叠统延长组沉积时期,鄂尔多斯盆地为一大型陆相坳陷湖盆。该湖盆历经了形成、发展、全盛、消退乃至最后消亡,最终沉积了一套厚度约为1 200 m的陆源碎屑岩,上三叠统延长组成为鄂尔多斯盆地主要的生油和储油层系(肖正录等,2020;付金华等,2023a)。

研究区位于鄂尔多斯盆地西南地区,构造上隶属于伊陕斜坡。长7段沉积时期是湖盆发育的最鼎盛时期(唐玮玮等,2022),以暗色泥岩和油页岩为主要生油岩,浊积砂体和三角洲前缘砂体为主要储集岩(图1b)。长7段自下而上被划分为长 7_3 、长 7_2 和长 7_1 三个亚段(杨华等,2017)(图1c):长 7_3 亚段沉积时期为湖盆范围最大时期,重力流沉积发育较弱,以厚层油页岩和暗色泥岩为主;长 7_2 亚段沉积时期,湖盆开始萎缩,下部为中厚层泥页岩,上部发育重力流沉积,以浊积砂体为主;长 7_1 亚段沉积时期湖盆进一步萎缩,整体以重力流沉积为主,浊流砂体厚度与泥页岩厚度相当。

2 泥页岩矿物学和有机地球化学特征

2.1 矿物组成特征

XRD实验结果表明,石英和黏土矿物是长7段泥页岩中的主要矿物,碳酸盐类矿物含量较低。不同岩性的矿物组成存在明显差异,页岩的石英和黏土矿物含量较泥岩低,黄铁矿和斜长石含量较高。页岩中石英平均含量为35.57%,斜长石平均含量为12.55%,黄铁矿平均含量为15.84%,黏土矿物平均含量为31.73%;泥岩石英平均含量为45.79%,斜长石平均含量为8.28%,黄铁矿平均含量为4.34%,黏土矿物平均含量为40.05%(图2a)。

纵向上,不同亚段的泥页岩矿物组成也存在一定差异(图2b)。长 7_1 和长 7_2 亚段泥页岩石英平均含

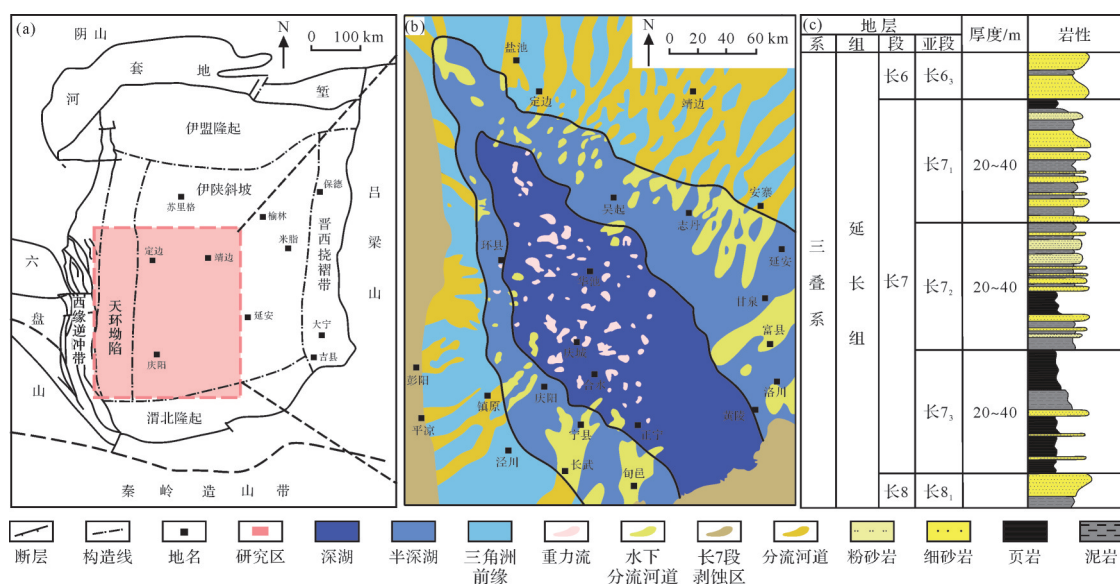


图1 鄂尔多斯盆地长7段沉积相图及地层柱状图(付金华等, 2021)

(a)研究区地理位置;(b)长₇亚段沉积相图;(c)长7段地层柱状图

Fig.1 Sedimentary facies map and stratigraphic histogram of the Chang 7 member in the Ordos Basin (Fu et al., 2021)

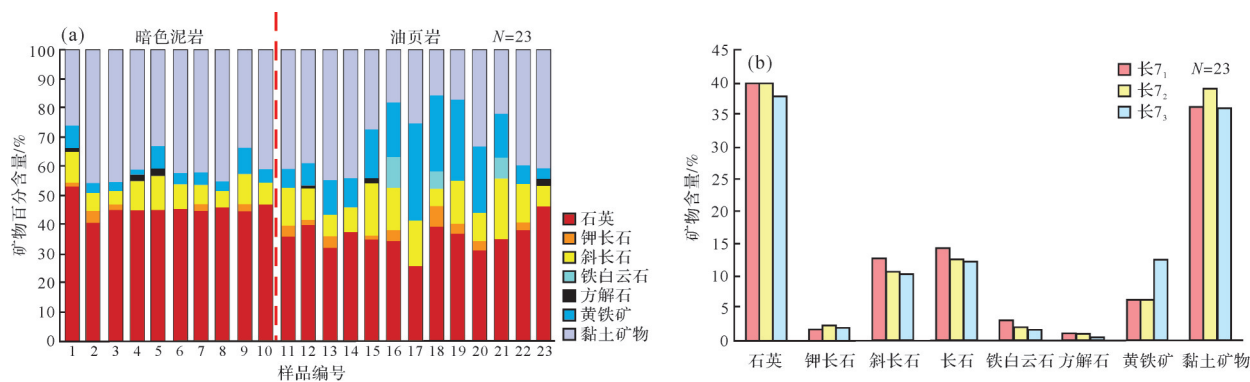
(a) geographical location of the study area; (b) sedimentary facies map of the Chang 7₃ sub-member; (c) stratigraphic histogram of the Chang 7 member

图2 鄂尔多斯盆地长7段泥页岩矿物组成特征

(a)长7段泥岩和页岩矿物组成差异;(b)长7段不同亚段矿物组成差异

Fig.2 Mineral composition characteristics of mudstone and shale in the Chang 7 member, Ordos Basin

(a) differences in mineral composition of mudstone and shale in the Chang 7 member; (b) the differences in mineral composition among different sub-members in the Chang 7 member

量为39.80%,长石平均含量为13.22%,黄铁矿平均含量为6.21%,黏土矿物平均含量为37.48%;长₇亚段泥页岩石英平均含量为37.95%,长石平均含量为12.06%,黄铁矿平均含量为12.29%,黏土矿物平均含量为35.88%。长₇亚段泥页岩硅铝质和黏土质矿物含量明显减少,黄铁矿含量增多。

2.2 有机质丰度

鄂尔多斯盆地长7段烃源岩有机质丰度相对较高,页岩和泥岩均达到好—最好烃源岩的标准,其中,页岩的有机质丰度明显高于泥岩(图3a)。页岩的TOC含量介于6.09%~33.68%,平均为14.18%,

S_1+S_2 介于15.72~116.17 mg/g,平均为46.39 mg/g。泥岩的TOC含量介于1.35%~10.60%,平均为4.55%, S_1+S_2 介于0.48~54.65 mg/g,平均为15.04 mg/g。纵向上,长₇亚段烃源岩有机质丰度最高,长₇亚段次之,长₇亚段最低(图3b)。长₇亚段TOC含量介于0.38%~22.30%,平均为3.49%, S_1+S_2 介于0.19~89.79 mg/g,平均为11.08 mg/g;长₇亚段TOC含量介于0.43%~21.04%,平均为5.36%, S_1+S_2 介于0.29~89.16 mg/g,平均为16.99 mg/g;长₇亚段TOC介于0.17%~33.68%,平均为8.68%, S_1+S_2 介于0.29~116.17 mg/g,平均为29.07 mg/g。

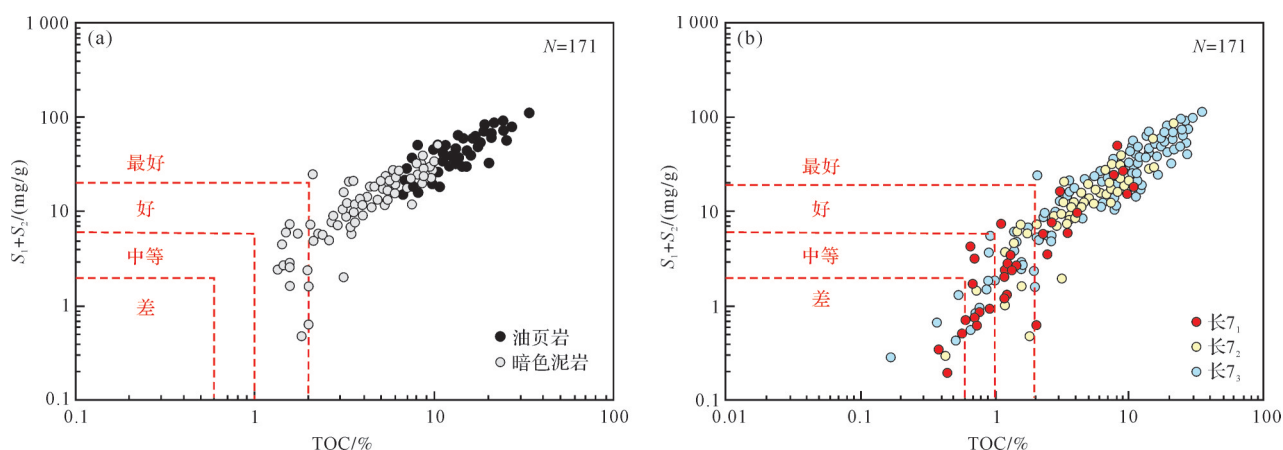


图3 鄂尔多斯盆地长7段泥页岩TOC—生烃潜量交会图
(a)长7段泥岩和页岩TOC—生烃潜量交会图;(b)长7段不同亚段TOC—生烃潜量交会图

Fig.3 Total organic carbon (TOC)-hydrocarbon generation potential intersection diagram for mudstone and shale in the Chang 7 member, Ordos Basin

(a) TOC-hydrocarbon generation potential intersection diagram for mudstone and shale in the Chang 7 member; (b) TOC-hydrocarbon generation potential intersection diagram for different sub-members in the Chang 7 member

2.3 有机质类型

有机质类型可以通过热解峰温($T_{\max}$)和氢指数(HI)交会图来判别(戴金星等,2007)。从整体来看,长7段烃源岩有机质类型好,以 $\text{II}_1 \sim \text{I}$ 型为主,少部分为 II_2 型。从岩性来看(图4a),页岩的有机质类型优于泥岩,页岩以 I 型和 II_1 型有机质为主,而泥岩以 II_1 型有机质为主,部分样品有机质类型呈 II_2 型。纵向上,长7₁亚段烃源岩的有机质类型相对较差,主要发育 II_2 型有机质,而长7₃亚段烃源岩的有机质类型最好,主要发育 I 型有机质(图4b)。

干酪根显微组分分析结果表明,页岩腐泥组分含量高于泥岩,再次印证长7段页岩有机质类型优于泥岩(图4c)。纵向上,长7₃亚段烃源岩有机质类型好于长7₁亚段和长7₂亚段。长7₁和长7₂亚段烃源岩镜质组含量较高,有机质类型偏差,以 II_2 型有机质为主,而长7₃泥页岩以腐泥组分为主,有机质类型主要为 I 型和 II_1 型(图4d)。

2.4 有机质成熟度

有机质成熟度是评价烃源岩生烃能力的重要指标,有机质必须达到一定热演化阶段才能生成油气,常用镜质体反射率(R_o)来表征(Hackley *et al.*, 2015)。统计陇东、陕北、姬塬等三个地区长7段不同亚段烃源岩样品的 R_o 值,并绘制分布密度特征图(图5)。结果显示,长7段烃源岩 R_o 主要介于0.7%~1.1%,平均为0.88%,表明长7段烃源岩已经达到成熟阶段,目前正处于生油高峰期。烃源岩成熟度主要与埋藏深

度有关,泥岩和页岩之间成熟度差异并不明显。纵向上,随着埋藏深度的增加,长7段烃源岩的成熟度也在增加,长7₃亚段烃源岩 R_o 略高于长7₂和长7₁亚段。长7₁亚段烃源岩 R_o 主要介于0.7%~1.0%,平均为0.81%;长7₂亚段烃源岩 R_o 主要介于0.8%~1.0%,平均为0.87%;长7₃亚段烃源岩 R_o 主要介于0.7%~1.1%,平均为0.93%。

3 泥页岩储集层特征

3.1 储集空间类型

从普通薄片镜下鉴定结果来看,鄂尔多斯盆地长7段页岩有机质含量较高,视域下多处被原油或沥青质和有机质覆盖,层状分布清晰可见,黑色有机质和基质矿物呈互层状分布(图6a,b)。长7段泥岩,有机质含量稍低,较页岩发育更多的碎屑颗粒(图6c,d),部分样品碎屑颗粒呈定向排列。

扫描电镜观察结果显示,长7段页岩有机质呈条带状分布,与黏土矿物等基质矿物表现为互层状,镜下可见大量的草莓状黄铁矿发育(图6e)。页岩中有孔孔欠发育,多发育层理缝、构造应力破裂缝和黄铁矿晶间孔等矿物基质孔缝(图6f~h)。反之,泥岩中有机质和黄铁矿含量大幅减少,有机质主要呈团块状分布(图6i),镜下可见有机孔、黏土矿物基质孔、黄铁矿晶间孔和构造应力破裂缝(图6j~l)。统计样品面孔率发现,长7段泥页岩主要发育无机孔缝(图7)。其中,长7段页岩面孔率为1.64%,以无机孔缝

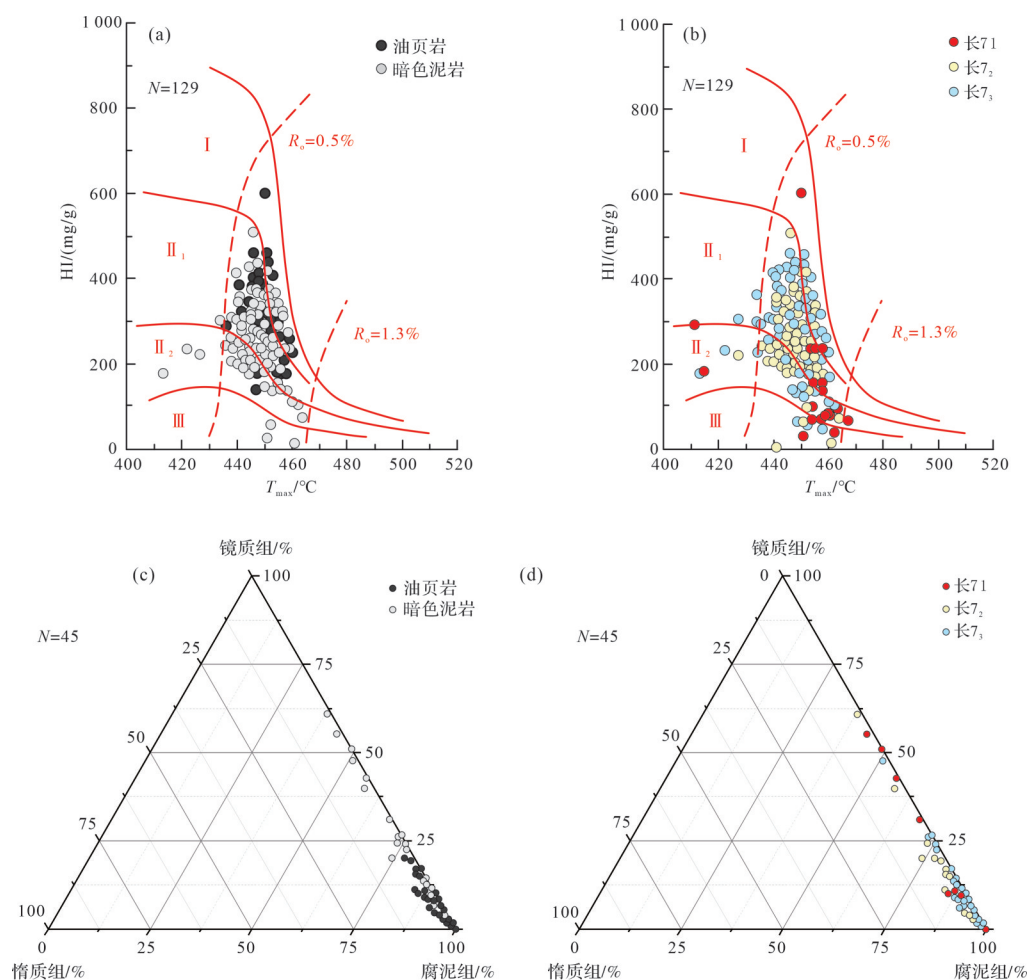


图4 鄂尔多斯盆地长7段泥页岩有机质类型判识图版

(a)长7段泥岩和页岩 $T_{\max}$ 与 HI 交会图; (b)长7段不同亚段 $T_{\max}$ 与 HI 交会图; (c)长7段泥岩和页岩干酪根显微组分三角图; (d)长7段不同亚段干酪根显微组分三角图

Fig.4 Organic matter type identification chart for mudstone and shale in the Chang 7 member, Ordos Basin

(a) $T_{\max}$ and HI (Hydrogen Index) intersection diagram for mudstone and shale in the Chang 7 member; (b) $T_{\max}$ and HI intersection diagram for different sub-members in the Chang 7 member; (c) maceral triangle diagram for mudstone and shale kerogen in the Chang 7 member; (d) triangular diagram of kerogen macerals for different sub-members in the Chang 7 member

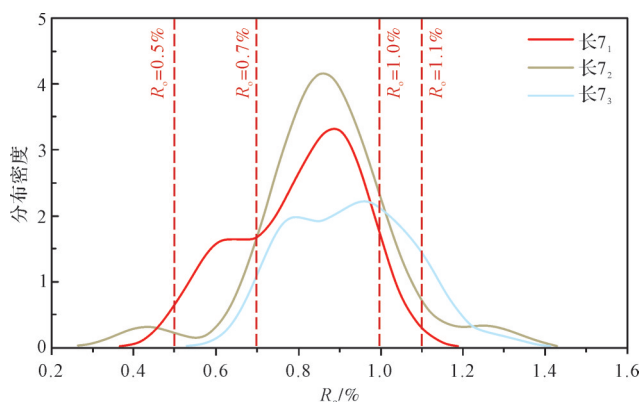


图5 鄂尔多斯盆地长7段泥页岩镜质体反射率分布密度图

Fig.5 Distribution density of vitrinite reflectance for mudstone and shale in the Chang 7 member, Ordos Basin

为主(面孔率为 1.08%),而有机孔缝面孔率仅占 0.56%;长7段泥岩面孔率为 1.47%,无机孔缝面孔率为 1.29%,而有机孔缝仅占 0.18%。因此,泥岩有机孔缝占比低于页岩。

3.2 孔隙结构定量表征

根据孔径大小,泥页岩孔隙可以进一步划分为微孔(<2 nm)、介孔(2~50 nm)和宏孔(>50 nm)(罗力元等,2025)。非常规储层微观表征技术方法较多(孙超和姚素平,2019;王濡岳等,2021),不同实验方法孔径测量范围可靠度存在差异。一般情况下,利用 CO₂ 吸附表征小于 1.5 nm 的微孔、N₂ 吸附表征 1.5~3.0 nm 和 3~50 nm 的孔径,高压压汞表征的宏孔(>50 nm)。基于多方法分段联合表征,最终可以得

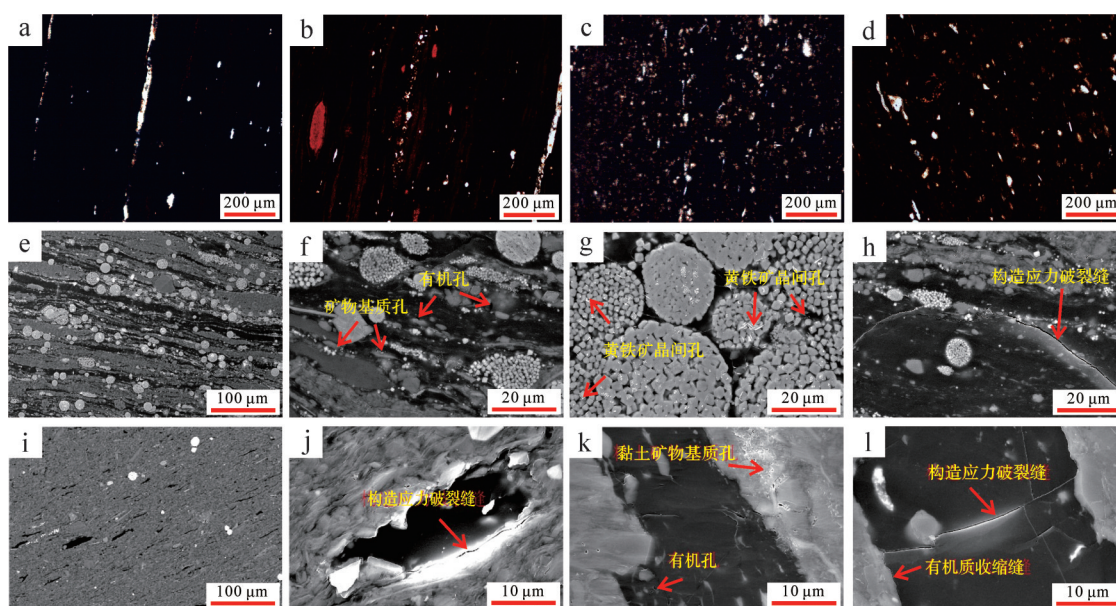


图6 鄂尔多斯盆地长7段泥页岩镜下形貌特征

(a)Z70井,长7段,页岩;(b)W336井,长7段,页岩;(c)Z233井,长7段,泥岩;(d)H261井,长7段,泥岩;(e)H269井,长7段,2 533.95 m,页岩镜下全貌图;(f)零星分布的有机质孔与矿物基质孔;(g)黄铁矿晶间孔;(h)构造应力破裂缝;(i)C96井,长7段,2 021.45 m,泥岩镜下全貌图;(j)有机质周围构造应力破裂缝;(k)零星分布的有机孔与矿物基质孔;(l)有机质内部构造应力破裂缝与边缘有机质收缩缝

Fig.6 Microscopic morphological characteristics for mudstone and shale in the Chang 7 member, Ordos Basin

(a) well Z70, Chang 7 member, shale; (b) well W336, Chang 7 member, shale; (c) well Z233, Chang 7 member, mudstone; (d) well H261, Chang 7 member, mudstone; (e) well H269, Chang 7 member, 2 533.95 m, a microscopic panoramic view of shale; (f) sporadic organic pores and mineral matrix pores; (g) pyrite intercrystalline pores; (h) structural stress-induced fractures; (i) well C96, Chang 7 member, 2 021.45 m, a microscopic panoramic view of mudstone; (j) structural stress fractures around organic matter; (k) sporadic organic pores and mineral matrix pores; (l) internal structural stress fractures of organic matter and marginal organic matter shrinkage fractures

到研究区泥页岩样品全尺度孔径分布曲线图(图8a, b)和全孔径比表面积分布特征图(图8c, d)。从分析结果来看,长7段泥页岩孔隙中微孔占比相对较多,且页岩比泥岩微孔更发育(图8e)。其中,页岩样品微孔占比为68.71%~77.83%,平均为73.45%,介孔占比为3.65%~8.91%,平均为5.66%,宏孔占比为17.30%~27.64%,平均为20.89%;而泥岩样品微孔占比为52.04%~60.82%,平均为57.22%,介孔占比为21.75%~39.69%,平均为29.94%,宏孔占比为8.27%~17.43%,平均为12.84%。从比表面积分析结果来看,微孔是长7段泥页岩比表面积的主要贡献者,介孔和宏孔对比表面积的贡献相对较小(图8f)。其中,页岩微孔比表面积占比为98.80%~99.43%,平均为99.20%,介孔比表面积占比为0.50%~1.14%,平均为0.74%,宏孔比表面积占比为0.06%~0.07%,平均为0.06%;而泥岩微孔比表面积占比为91.14%~96.27%,平均为94.29%,介孔比表面积占比为3.58%~8.82%,平均为5.63%,宏孔比表面积占比为0.04%~0.15%,平均为0.08%。

4 页岩油富集因素

4.1 优质烃源岩控制了页岩油分布范围

优质烃源岩的发育情况是决定页岩油能否大规模富集的物质基础,主要受有机质丰度、类型、成熟度和厚度控制(杨魏等,2024)。长7段泥页岩含油量(恢复后 S_1 (李进步等,2016))与有机质丰度(TOC)和氢指数(HI)呈正相关关系(图9)。因此,有机质类型越好、有机质丰度越高,泥页岩含油性更好。根据页岩含油性OSI评价标准,长7段泥页岩含油性整体属于中—高含油层,且页岩整体含油性高于泥岩。

烃源岩热演化程度控制了原油的产率及其产物性质,一般而言成熟度越高,原油和气体生成量越多,原油流动性越好(赵文智等,2023)。北美目前规模勘探开发的页岩油烃源岩主要处于中—高成熟阶段($R_o=1.0\%\sim 1.3\%$),其页岩储层原油含油量高、流动性好(蒋奇君等,2024)。长7段泥页岩 R_o 平均为0.88%,处于生油高峰期,不同岩性烃源岩成熟度差异较小,但纵向上长7₃亚段成熟度略高于长7₂和长7₁。

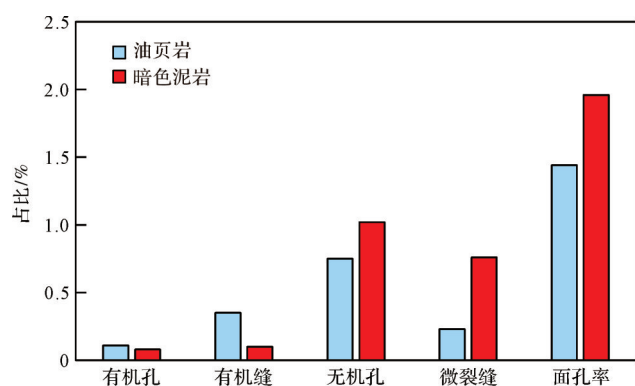


图7 鄂尔多斯盆地长7段泥页岩孔隙类型面孔率对比图

Fig.7 Comparison of surface porosity from the mudstone and shale pore types in the Chang 7 member, Ordos Basin

亚段。从平面上来看,长7段烃源岩成熟度呈现出由湖盆中心至湖盆边缘逐渐降低的趋势,湖盆中心姬塬和华池一带烃源岩成熟度 R_o 普遍高于1.0%(图10a)。

从烃源岩厚度展布特征来看,页岩主要分布在长7₃亚段,最大厚度超过20 m,主要分布在姬塬和华池一带;长7₂和长7₁亚段页岩发育较少,绝大多数地区页岩厚度低于10 m(图10b~d)。此外,泥岩比页岩的分布范围广,其中,姬塬地区泥岩沉积厚度最大,累计厚度可达60 m(图10e~g)。因此,姬塬和华池地区长7₃亚段页岩和泥岩发育,勘探潜力较大。

页岩油属于自生自储型油气资源,作为储集层,泥页岩的孔隙发育特征也将影响页岩油富集程度。根据长7段泥页岩含油性与孔径相关性分析发现,泥页岩总孔体积、微孔、介孔、宏孔均与含油性呈正相关,且与微孔和总孔体积相关性更强(图11)。前文研究表明,页岩总孔体积略高于泥岩,且微孔占比更大,而长7₃亚段页岩类型最好、丰度最高、成熟度最高,因此长7₃亚段发育的页岩是纯页岩型页岩油的最佳有利勘探层段。

4.2 岩性组合控制了页岩油富集规模

前人基于沉积相,将长7段页岩油划分为重力流型、三角洲前缘型、纹层型和页理型等4类,但该方案对纵源储配置关系指向不明确(边瑞康等,2022;付金华等,2023b)。因此,本文基于长7段泥页岩和砂岩的接触关系,将长7段划分为厚源厚储型、厚源夹薄储型以及源储互层型3种类型(图12a~c),其中厚源夹薄储型主要分布在湖盆中心姬塬一带,对应

纹层型和页理型,厚源厚储型主要分布在陇东地区,对应重力流型,而源储互层型主要分布在盆地边缘,对应三角洲前缘型(图12d)。

排烃效率是指烃源岩排烃量与生烃量的比值(刘立峰等,2010),反映了烃源岩排烃条件的好坏。从已有研究来看,三角洲前缘的源储互层型岩性组合中烃源岩排烃效率最高,砂岩含油性好(马艳丽等,2021)。为了进一步明确厚源厚储型和厚源夹薄储型岩性组合中烃源岩的排烃效率,选取发育2种岩性组合的典型井C96井和H269井,分别计算排烃效率(图13)。其中,C96井位于重力流发育区,为典型的厚源厚储型组合类型,计算长7₃亚段烃源岩排烃效率平均为68.25%(图13a)。湖盆中心的H269井为典型的厚源夹薄储型组合类型,计算长7₃亚段烃源岩排烃效率平均为50.65%(图13b),明显低于厚源厚储型。

综合上述分析,鄂尔多斯盆地长7段盆地边部三角洲前缘源储互层型岩性组合排烃效率最高,陇东重力流厚源厚储型岩性组合排烃效率居中,姬塬厚源夹薄储型岩性组合排烃效率最低。因此,针对长7段页岩油的勘探部署时,盆地边部三角洲前缘应以砂岩型页岩油为主要目标,而湖盆中心姬塬地区则应以纯页岩型页岩油为勘探目标,陇东重力流沉积地区可考虑兼探砂岩型和纯页岩型页岩油。

4.3 裂缝控制了页岩油富集程度

裂缝对页岩层系中原油富集的控制作用具有两面性。一方面,裂缝发育可以改善地层渗流条件,有利于页岩油向砂岩中富集;另一方面,对于泥页岩而言,尤其是高角度的构造缝,不利于原油的滞留,起到了破坏油藏的作用。在构造应力的作用下,正宁一带长7段普遍发育裂缝。岩心观察表明,该地区岩心高角度构造应力裂缝极其发育(图14),作为原油运移的优势通道,构造裂缝面含油性普遍较好。如Z40井,靠近裂缝周围的岩心含油性好,而远离裂缝的岩心含油性差。

根据裂缝发育的密度统计结果,认为合水—正宁一带为裂缝发育区。统计裂缝发育区和欠发育区的OSI指数($OSI=S_i/TOC$),其中,裂缝发育地区泥页岩的OSI值介于43.11~285.71 mg/g·TOC,平均为78.27 mg/g·TOC,裂缝欠发育地区的泥页岩的OSI值介于16.49~460.85 mg/g·TOC,平均为86.46 mg/g·TOC(图15a)。结果表明,裂缝欠发育地区的泥页岩含油

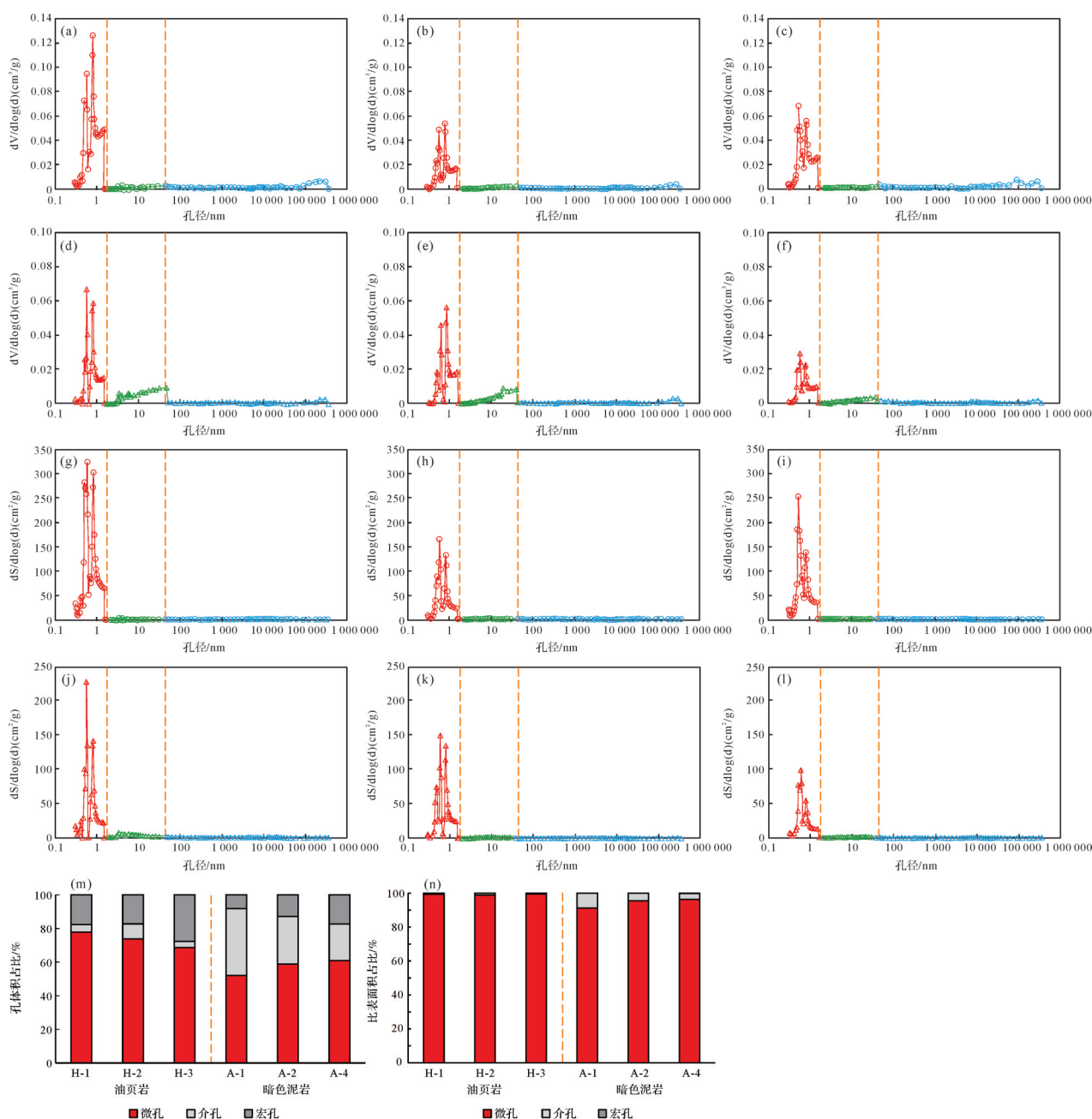


图8 鄂尔多斯盆地长7段泥页岩孔隙结构定量表征

孔体积分布特征:(a)H-1,TOC=20.5%,B522井,1 957.60 m,长 7_3 亚段,页岩;(b)H-2,TOC=8.25%,W336井,260.80 m,长 7_2 亚段,页岩;(c)H-3,TOC=21.4%,L254井,2 560.00 m,长 7_3 亚段,页岩;(d)A-1,TOC=9.69%,G135井,1 839.20 m,长 7_3 亚段,泥岩;(e)A-2,TOC=9.30%,A35井,2 451.65 m,长 7_3 亚段,泥岩;(f)A-4,TOC=8.22%,H261井,2 244.50 m,长 7_3 亚段,泥岩;比表面积分布特征:(g)H-1,TOC=20.5%,B522井,1 957.60 m,长 7_3 亚段,页岩;(h)H-2,TOC=8.25%,W336井,260.80 m,长 7_2 亚段,页岩;(i)H-3,TOC=21.4%,L254井,2 560.00 m,长 7_3 亚段,页岩;(j)A-1,TOC=9.69%,G135井,1 839.20 m,长 7_3 亚段,泥岩;(k)A-2,TOC=9.30%,A35井,2 451.65 m,长 7_3 亚段,泥岩;(l)A-4,TOC=8.22%,H261井,2 244.50 m,长 7_3 亚段,泥岩;(m)长7段泥页岩不同孔径孔隙体积占比;(n)长7段泥页岩不同孔径比表面积占比

Fig.8 Quantitative characterization of pore structure for mudstone and shale in the Chang 7 member, Ordos Basin

pore volume distribution characteristics: (a) H-1, TOC = 20.5%, well B522, 1 957.60 m, Chang 7_3 sub-member, shale; (b) H-2, TOC = 8.25%, well W336, 260.80 m, Chang 7_2 sub-member, shale; (c) H-3, TOC = 21.4%, well L254, 2 560.00 m, Chang 7_3 sub-member, shale; (d) A-1, TOC = 9.69%, well G135, 1 839.20 m, Chang 7_3 sub-member, mudstone; (e) A-2, TOC = 9.30%, well A35, 2 451.65 m, Chang 7_3 sub-member, mudstone; (f) A-4, TOC = 8.22%, well H261, 2 244.50 m, Chang 7_3 sub-member, mudstone; specific surface area distribution characteristics: (g) H-1, TOC = 20.5%, well B522, 1 957.60 m, Chang 7_3 sub-member, shale; (h) H-2, TOC = 8.25%, well W336, 260.80 m, Chang 7_2 sub-member, shale; (i) H-3, TOC = 21.4%, well L254, 2 560.00 m, Chang 7_3 sub-member, shale; (j) A-1, TOC = 9.69%, well G135, 1 839.20 m, Chang 7_3 sub-member, mudstone; (k) A-2, TOC = 9.30%, well A35, 2 451.65 m, Chang 7_3 sub-member, mudstone; (l) A-4, TOC = 8.22%, well H261, 2 244.50 m, Chang 7_3 sub-member, mudstone; (m) proportion of pore volume with different pore diameters for shale and mudstone in the Chang 7 member; (n) proportion of specific surface area with different pore diameters for shale and mudstone in the Chang 7 member

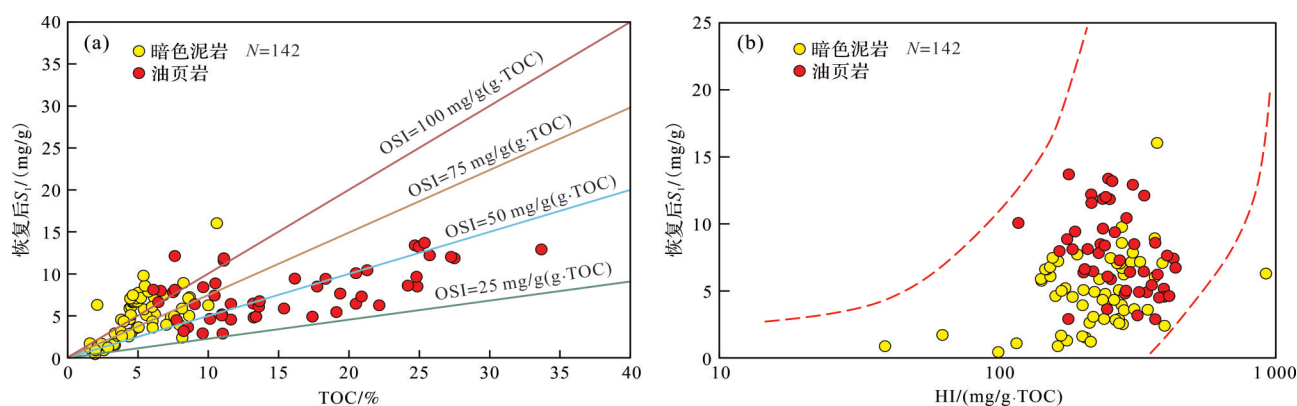


图9 长7段泥页岩含油量 S_1 与TOC和HI交会图(据李进步等, 2016修改)

(a)长7段泥页岩含油量 S_1 与TOC交会图;(b)长7段泥页岩含油量 S_1 与HI交会图

Fig.9 Intersection of oil content S_1 with TOC and HI for mudstone and shale in the Chang 7 member (modified from Li *et al.*, 2016)

(a) oil content S_1 and TOC for shale in the Chang 7 member; (b) oil content S_1 and HI for shale in the Chang 7 member

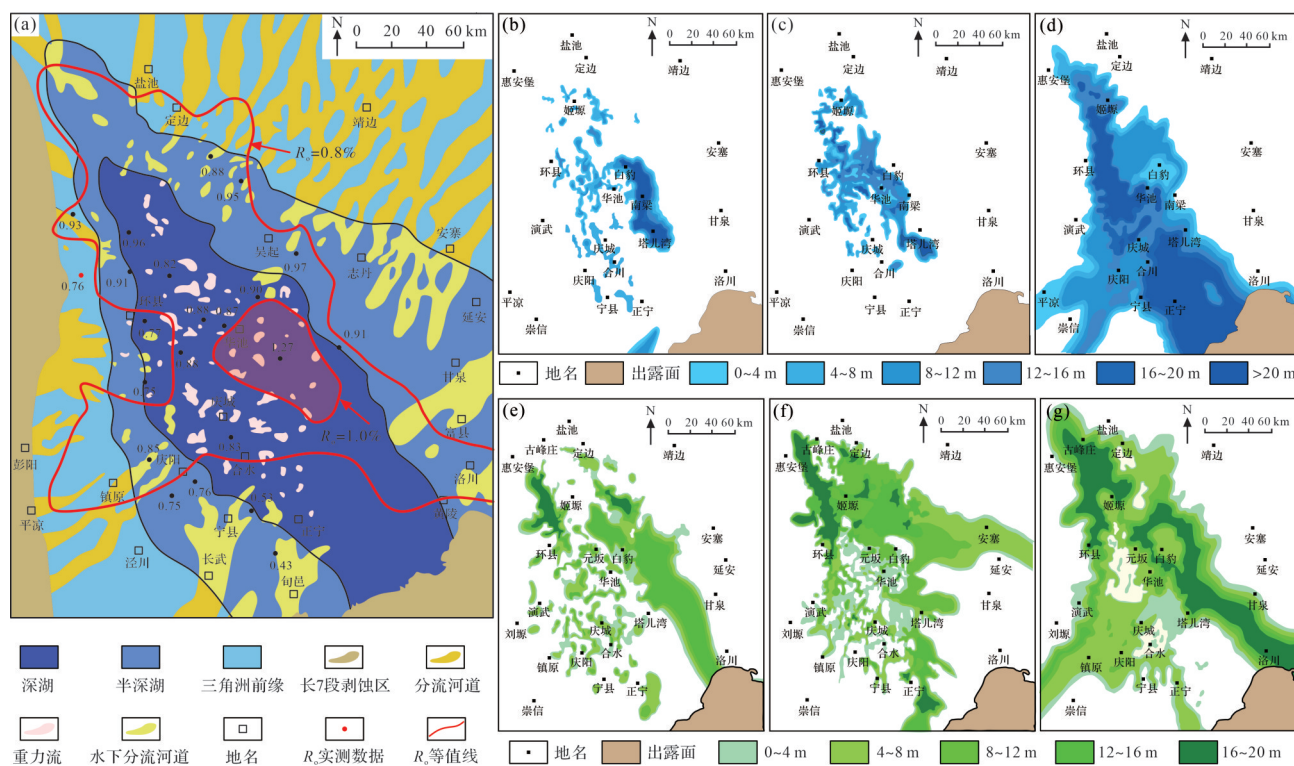


图10 长7段泥页岩成熟度 R_0 和厚度平面分布图(据付金华等, 2021修改)

(a)长7段烃源岩成熟度 R_0 平面分布图;(b)长7₁亚段页岩厚度展布;(c)长7₂亚段页岩厚度展布;(d)长7₃亚段页岩厚度展布;(e)长7₁亚段泥岩厚度展布;(f)长7₂亚段泥岩厚度展布;(g)长7₃亚段泥岩厚度展布

Fig.10 Planar distribution map of maturity (R_0) and thickness for mudstone and shale in the Chang 7 member (modified from Fu *et al.*, 2021)

(a) maturity R_0 plane distribution map for source rock of the Chang 7 member; (b) thickness distribution for shale in the Chang 7₁ sub-member; (c) shale thickness distribution for shale in the Chang 7₂ sub-member; (d) shale thickness distribution for shale in the Chang 7₃ sub-member; (e) thickness distribution of mudstone in Chang 7₁ sub-member; (f) Chang 7₂ thickness distribution of mudstone in the Chang 7₃ sub-member; (g) thickness distribution of mudstone in Chang 7₃ sub-member

性明显优于裂缝发育地区。从排烃效率计算结果来看,裂缝发育地区的泥页岩排烃效率介于37.24%~85.17%,平均为57.14%;而裂缝欠发育地区泥页岩排烃效率介于4.13%~87.49%,平均为49.27%,即裂缝

发育地区的泥页岩排烃效率高于裂缝欠发育区(图15b)。因此,从页岩油勘探角度来看,裂缝对于纯页岩型页岩油富集起到了消极作用,却促进了夹层型页岩油的富集。

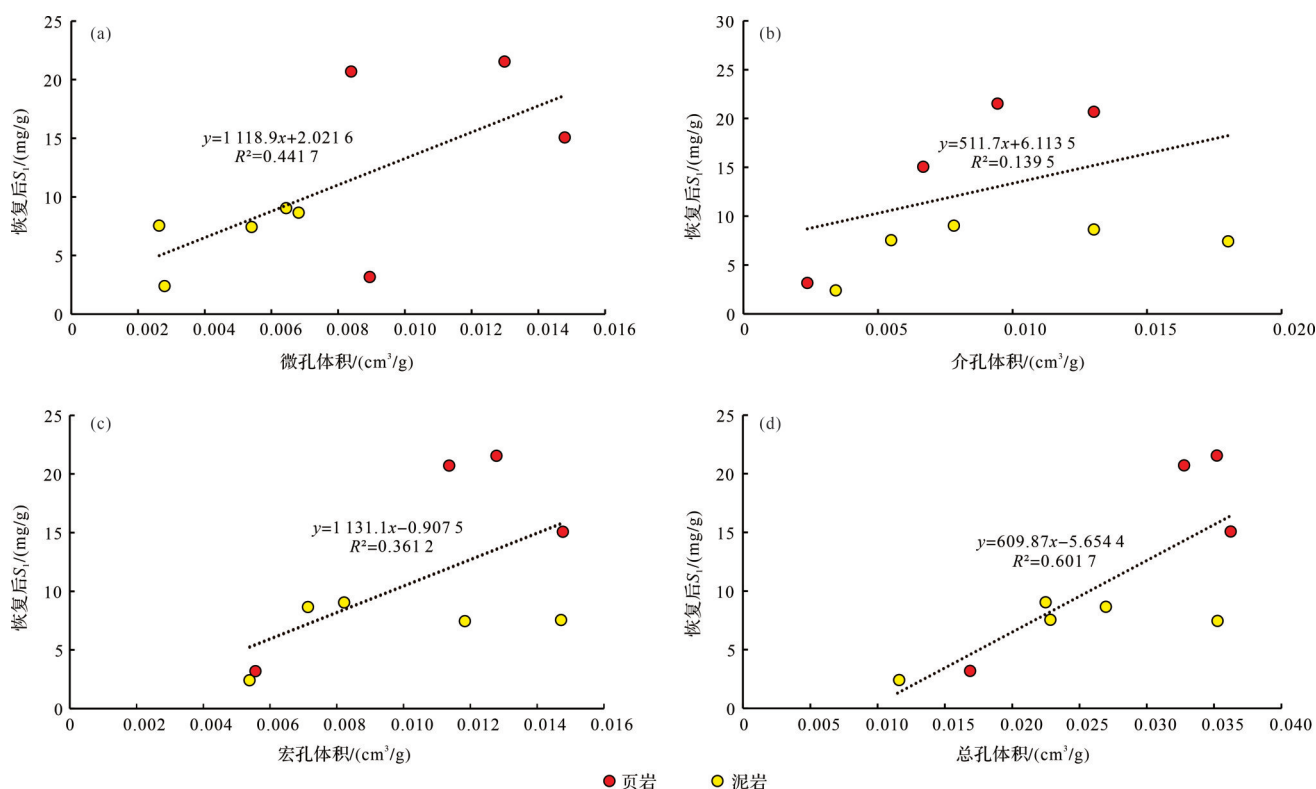


图 11 长7段泥页岩含油量 S_1 (据李进步等, 2016 修改) 与不同孔径孔体积相关性分析

Fig.11 Correlation analysis of oil content (S_1) (modified from Li *et al.*, 2016) and pore volume with different pore sizes for mudstone and shale in the Chang 7 member

4.4 原油可动性和工程可压裂性控制了页岩油高产

可动性和工程可压裂性是影响页岩油高产的重要因素(刘成林等, 2022)。从不同岩性页岩油可动性定量评价来看(图 16a), 页岩的原油可动油量平均为 1.81 mg/g, 泥岩的原油可动油量平均为 1.64 mg/g, 页岩的原油可动性要略好于泥岩。

页岩的可压裂性通常与脆性指数有关, 脆性指数越高, 页岩的可压裂性能就越好, 越有利于页岩油的开采(周立宏等, 2019)。脆性指数为脆性矿物占总矿物含量的百分比, 因此石英、长石及方解石等矿物含量越高, 脆性指数也就越高。目前常利用石英与总矿物的比值来计算脆性指数(Loucks and Ruppel, 2007), 研究发现长7段泥页岩除石英外, 其他脆性矿物如长石和黄铁矿等含量也较高, 因此本文将脆性指数定义为石英、长石、黄铁矿的总占比。结果显示, 鄂尔多斯盆地长7段泥页岩脆性指数分布介于 50.20%~72.78%, 平均为 60.71%; 从层段上看, 长7₃亚段泥页岩脆性指数最高, 平均脆性指数为 62.30%(图 16b); 从岩性来看, 页岩脆性指数高于泥岩, 页岩平均脆性指数 66.18%, 而泥岩平均脆性指数 59.35%(图 16c)。综上所述, 从原油可动性和

可压裂性来看, 鄂尔多斯盆地长7₃亚段页岩勘探潜力巨大。

5 页岩油有利勘探方向

长7段沉积时期, 鄂尔多斯盆地沉积了广泛分布的泥页岩, 其中页岩沉积面积达 4.3×10^4 km², 泥岩面积约 6.2×10^4 km², 优质烃源岩生烃总量达 $2\,000 \times 10^8$ t, 为长7段页岩油大规模成藏奠定了良好的物质基础(刘翰林等, 2023)。受湖盆沉积演化的影响, 不同亚段、不同区块长7段页岩油之间富集地质特征区域化差异明显, 制约了页岩油下一步有利勘探区带优选。综合前文不同岩性和不同亚段页岩油富集地质特征对比结果, 长7₃亚段页岩的有机质类型最好、有机质丰度最高、成熟度高、脆性指数高、储集能力强、可动性好, 是长7段纯页岩型页岩油的甜点发育层段。而长7₁亚段和长7₂亚段, 烃源岩厚度变薄, 砂体发育, 是砂岩夹层型页岩油勘探的有利层段。

从区带地质特征对比结果来看, 平面上划分了纯页岩型、重力流砂体夹层型、裂缝发育夹层型和

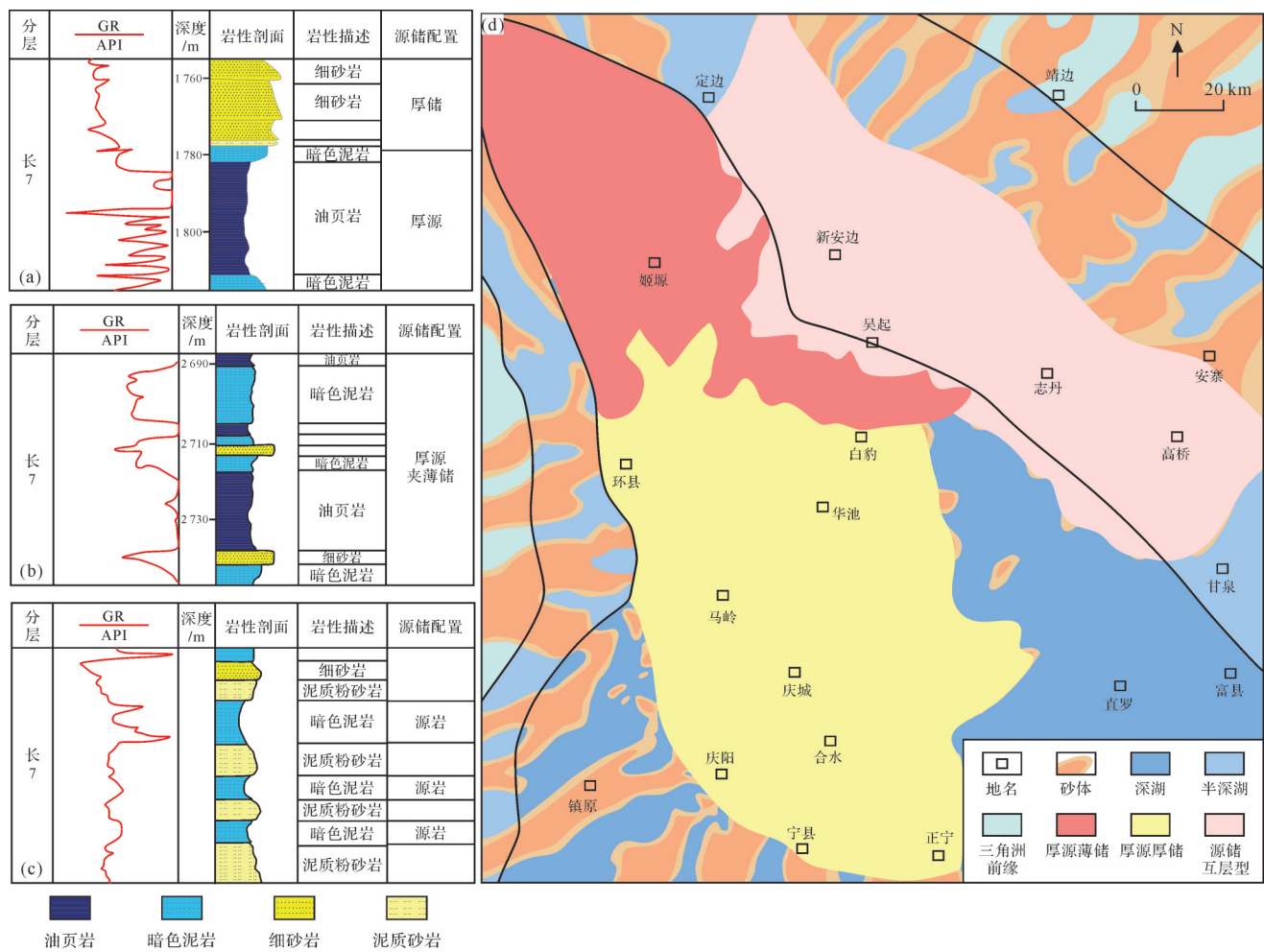


图 12 长 7 段页岩油岩性组合模式及其平面分布

(a) 厚源厚储岩性组合模式; (b) 厚源夹薄储岩性组合模式; (c) 源储互层型岩性组合模式; (d) 长 7 段页岩油岩性组合平面分布

Fig.12 Lithologic combination model and plane distribution of shale oil in the Chang 7 member

(a) thick source and thick reservoir lithology combination mode; (b) thick source with thin reservoir lithology combination mode; (c) source-reservoir interbedded lithology combination mode; (d) plane distribution of shale oil lithology combination in Chang 7 member

三角洲前缘互层型 4 类有利勘探区带(图 17)。湖盆中心姬塬一带,泥页岩厚度大,发育典型的厚源夹薄储型岩性组合类型,排烃效率低,有利于页岩油滞留富集,是纯页岩型页岩油的有利勘探目标。如姬塬地区的 G295 井,长₇₂亚段 2 650~2 668 m 井段泥页岩发育,其中页岩厚度 6.88 m,泥岩厚度 9.25 m,泥页岩层段试油获得 20.49 t/d,展示了纯页岩型页岩油的勘探潜力。陇东华池一带,长₇₃泥页岩发育,长₇₂和长₇₃重力流砂体发育,为典型的厚源厚储型岩性组合类型,排烃效率居中,长₇₁和长₇₂亚段重力流砂体夹层型页岩油以及长₇₃亚段纯页岩型页岩油勘探潜力巨大,如庆城油田。2019 年在陇东华池一带部署 CY1 和 CY2 两口风险探井,开展“水

平井+体积压裂”试验,试油均获百吨高产,进一步落实了该区块的勘探潜力(付金华等,2020)。陇东正宁地区,裂缝发育,有利于原油排烃运移至长₇₁和长₇₂砂体储集层,是裂缝发育砂体夹层型页岩油勘探的有利区带。2022 年,在合水以南裂缝发育区长₇₁亚段、长₇₂亚段砂体夹层型页岩油新增含油面积 406 km²,新增探明储量 1.1×10⁸ t(郭芪恒等,2023)。陕北地区,位于三角洲前缘,砂泥薄互层,发育源储互层型岩性组合类型,排烃效率高,前缘砂体是有利勘探区带,近两年来部署实施的 L31H、G62H 等系列水平井均获高产,陕北三角洲前缘互层型页岩油落实含油面积 1 200 km²,储量规模为 (3~5)×10⁸ t(付金华等,2023b)。

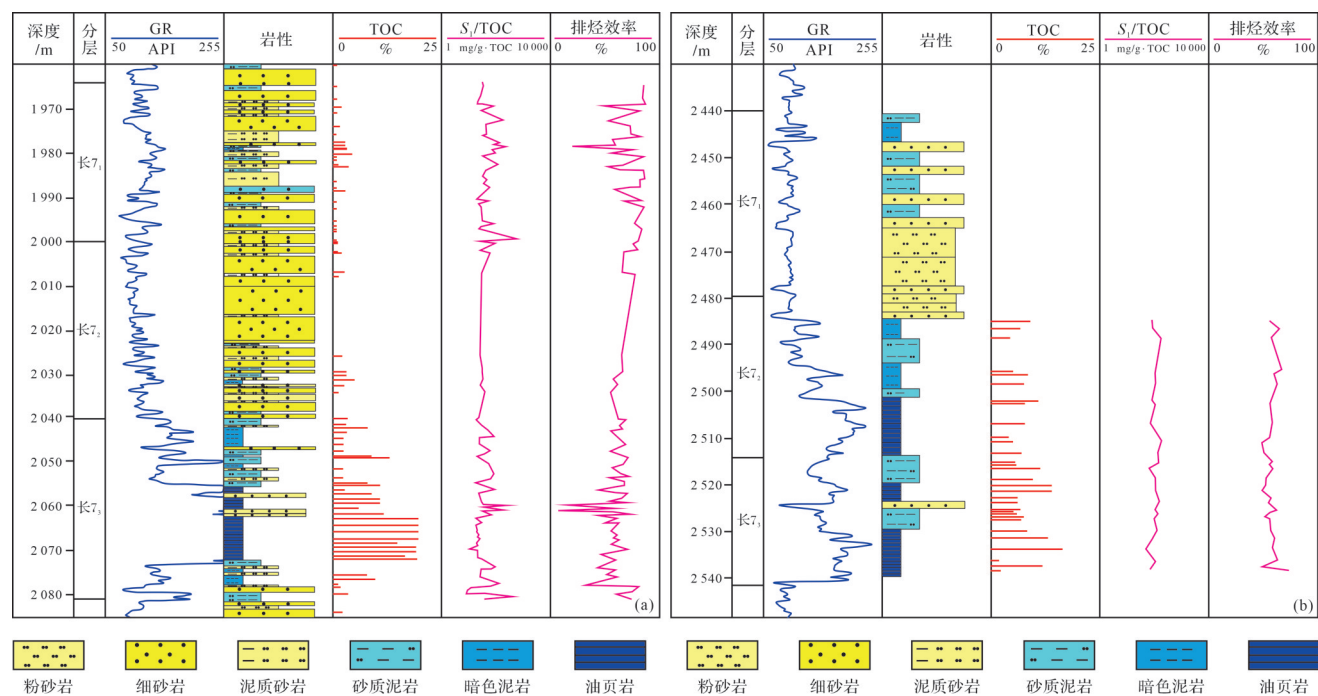


Fig.13 Comparative analysis of hydrocarbon expulsion efficiency under different lithology combinations

(a) hydrocarbon expulsion efficiency for thick source and reservoir in well C96; (b) hydrocarbon storage and expulsion efficiency for well H269 with thick source and thin reservoir



图 14 正宁地区长7段含裂缝岩心照片

(a)N33井,长7₁亚段,致密砂岩储层高角度构造缝;(b)N80井,长7₂亚段,致密砂岩裂缝充填原油;(c)N33井,长7₂亚段,粉砂质泥岩高角度裂缝面,被原油沾染,含油性明显;(d)Z40井,长7₂亚段,致密砂岩裂缝含油

Fig.14 Fractured core photos of the Chang 7 member in the Zhengning area

(a) well N33, Chang 7₁ sub-member, high angle structural fracture of tight sandstone reservoir; (b) well N80, Chang 7₂ sub-member, tight sandstone fracture-filled crude oil; (c) well N33, Chang 7₂ sub-member, silty mudstone high angle fracture surface, contaminated by crude oil, oiliness is obvious; (d) well Z40, Chang 7₂ sub-member, tight sandstone fracture oil

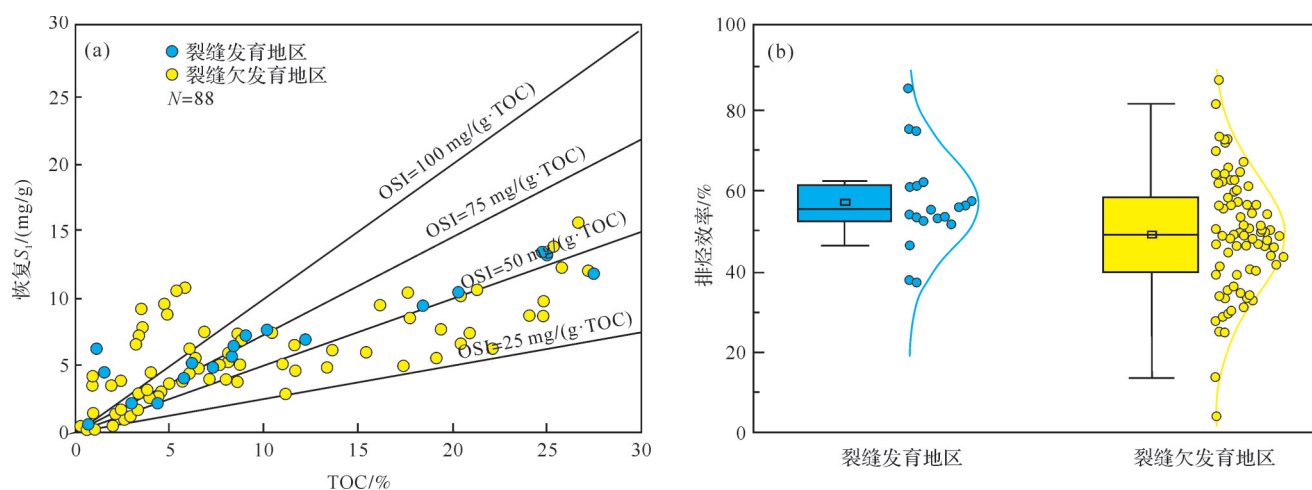


图 15 正宁地区泥页岩 S_1 -TOC 交会图和排烃效率对比图

(a) 长 7 段泥页岩 S_1 -TOC 交会图; (b) 长 7 段裂缝发育区与欠发育区泥页岩排烃效率对比

Fig.15 Intersection diagram of S_1 -TOC and comparison chart of hydrocarbon expulsion efficiency for shale and mudstone in the Zhengning area

(a) S_1 -TOC crossplot of shale and mudstone in the Chang 7 member; (b) comparison of hydrocarbon expulsion efficiency in shale and mudstone of the Chang 7 member: development fracture area vs. underdevelopment area

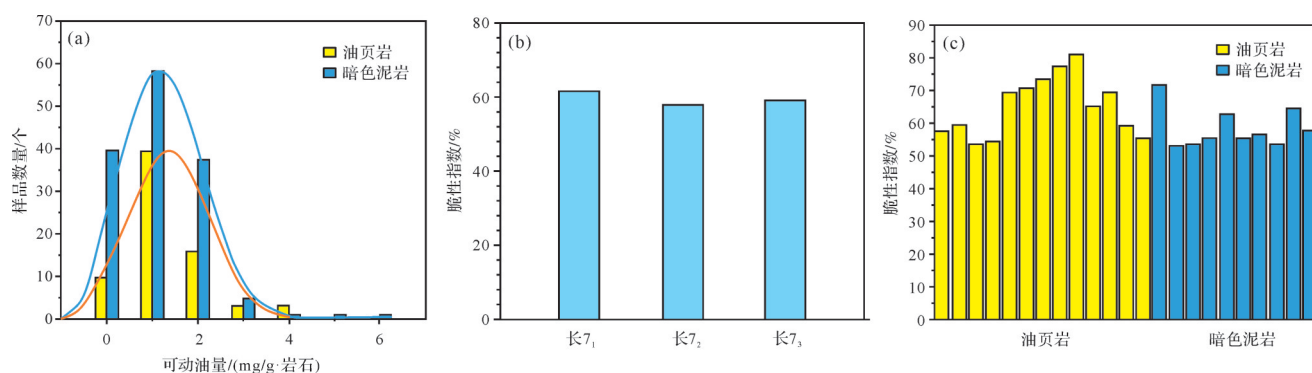


图 16 长 7 段页岩油可动性和压裂性对比分析

(a) 不同岩性可动性对比分析; (b) 不同亚段页岩脆性指数对比分析; (c) 不同岩性脆性指数对比分析

Fig.16 Comparative analysis of mobility and fracturing of shale oil in the Chang 7 member

(a) comparative analysis of different lithology mobilities; (b) comparative analysis of shale brittleness index in different sub-sections; (c) comparative analysis of brittleness index for different lithologies

6 结论

(1) 长 7 段泥页岩生烃能力与具体层段及岩性密切相关,其中长 7₃亚段烃源岩生烃能力最强,并且页岩生烃能力强于泥岩。储集空间以无机孔和微裂缝为主,页岩储集性能优于泥岩。

(2) 长 7 段页岩油富集主要受烃源岩、岩性组合、裂缝、可动性和可压裂性控制。优质烃源岩展布控制页岩油的分布;岩性组合决定排烃效率和页岩油类型;裂缝存在两面性,对纯页岩型页岩油藏起到破坏作用,但有利于夹层型页岩油富集;原油可动性

和页岩可压裂性控制了页岩油高产,原油可动性越强、脆性指数越高,页岩油越高产。

(3) 姬塬地区为纯页岩型页岩油的有利勘探区域;陇东华池地区长 7₃亚段为纯页岩型页岩油有利目标,长 7₁亚段和长 7₂亚段为重力流砂体夹层型页岩油有利目标;陇东正宁地区为裂缝发育夹层型页岩油的勘探有利目标;陕北地区为前缘砂体型页岩油的有利勘探目标。

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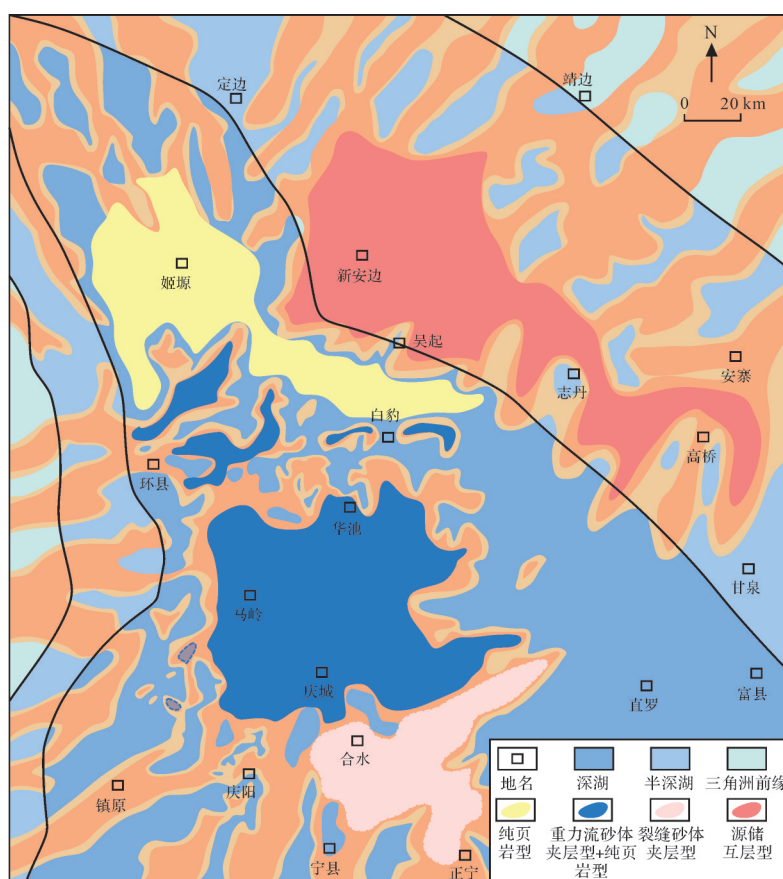


图 17 鄂尔多斯盆地不同类型页岩油有利勘探区带预测分布图

Fig.17 Prediction distribution map of favorable exploration zones for different types of shale oil in the Ordos Basin

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Main Controlling Factors and Exploration Direction of Shale Oil Enrichment in the Chang 7 Member of the Ordos Basin

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Abstract: [Objective] To identify the next exploration direction, the main controlling factors and exploration potential of different types of shale oil enrichment in the Chang 7 member of the Ordos Basin are discussed. [Methods] In this study, the formation conditions and exploration potential of shale oil such as petrology, geochemical characteristics and reservoir capacity of the Chang 7 member shale were comprehensively studied using organic geochemistry, whole rock X-ray diffraction (XRD), field emission scanning electron microscopy, and rock pyrolysis experiments. [Results] (1) The Chang 7₃ sub-member shale has high organic matter abundance, the best type, the highest maturity, and the greatest hydrocarbon generation potential. (2) The Chang 7 member shale is dominated by inorganic pores and fractures, with the largest proportion of micropores, and the shale reservoir capacity is stronger than that of mudstone. (3) The enrichment of shale oil in the Chang 7 member is controlled by five factors: high-quality source rock, lithologic combination, fracture, mobility, and fracability. The distribution of high-quality source rocks controls the distribution range of shale oil, the lithology combination controls the hydrocarbon expulsion efficiency and the enrichment type of shale oil. The hydrocarbon expulsion efficiency of the source-reservoir interbedded type is the highest, which is conducive to the enrichment of sand bodies; the hydrocarbon expulsion efficiency of the thick source-thin reservoir type is the lowest, which is conducive to the in-situ retention and enrichment of shale oil. The two-sidedness of fractures controls the enrichment degree of shale oil. The development of fractures is conducive to the enrichment of sandstone interlayer shale oil, and the underdevelopment of fractures is conducive to the retention and enrichment of pure shale-type shale oil. The mobility and fracability of crude oil control the high yield of shale, and the mobility and brittleness index of shale crude oil are better than those of mudstone. [Conclusions] The Chang 7₃ sub-member in the Jiyuan area is a favorable exploration block for pure shale-type shale oil. The Zhengning and northern Shaanxi areas are favorable exploration blocks for sandstone-intercalated shale oil in the Chang 7₁ and Chang 7₂ sub-members. The Huachi area in Longdong is a favorable area for the exploration of both sandstone-intercalated and pure shale-type shale oil.

Key words: shale oil; enrichment factors; Chang 7 member; Ordos Basin