

doi: 10.12029/gc20210321

高凤琳,王成锡,宋岩,姜振学,李卓,刘庆新,梁志凯,张欣欣. 2021. 松辽盆地长岭断陷沙河子组页岩有机显微组分孔隙演化规律研究[J]. 中国地质, 48(3): 948-958.

Gao Fenglin, Wang Chengxi, Song Yan, Jiang Zhenxue, Li Zhuo, Liu Qingxin, Liang Zhikai, Zhang Xinxin. 2021. Pore evolution of organic maceral in Shahezi Formation shale of Changling fault depression, Songliao Basin [J]. *Geology in China*, 48(3): 948-958(in Chinese with English abstract).

松辽盆地长岭断陷沙河子组页岩有机显微组分孔隙演化规律研究

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摘要:有机质孔隙是页岩储集空间的重要组成部分,具有强烈的非均质性,阻碍对页岩储层质量的正确认识和评价,其本质是受有机显微组分类型及其在生烃过程中孔隙演化的影响。本文采用场发射扫描电镜和荧光显微镜定位观察手段实现特定显微组分孔隙发育特征的表征,结合 Image J 图像处理技术,对不同演化阶段的显微组分进行定量化统计,总结不同有机显微组分的孔隙演化规律。研究表明:固体沥青孔隙度随着成熟度的升高呈现先增加后减小的趋势,在固体沥青反射率 SBR_o 介于 1.6%~2.0%时,固体沥青孔隙最为发育,而以 $SBR_o=2.0%$ 为界,固体沥青孔隙度开始减小。镜质体和惰质体的孔隙发育规律相似,随着成熟度增加,总体表现出先减小而后微弱增加的趋势。在生油窗阶段,镜质体和惰质体孔隙度最小,无机矿物和固体沥青的充填使胞腔孔隙损失达 90%以上,而进入高成熟阶段,固体沥青孔隙的发育使原始胞腔孔隙得到一定程度的恢复,成为镜质体和惰质体残余孔隙的主要贡献者,贡献率达 56.73%和 100%,可见固体沥青孔隙对页岩储层储集空间的重要性。综合沉积成岩作用和生烃作用,页岩储层在未成熟阶段和高成熟阶段晚期孔隙最为发育,前者有机质以原始胞腔孔隙为主,后者以固体量孔隙为主。明确有机显微组分孔隙演化规律为页岩有利储层预测和页岩气生产开发储层改造提供参考。

关键词:显微组分;孔隙演化;场发射扫描电镜;荧光显微镜;页岩储层;油气勘查工程;松辽盆地

中图分类号:TE135 文献标志码:A 文章编号:1000-3657(2021)03-0948-11

Pore evolution of organic maceral in Shahezi Formation shale of Changling fault depression, Songliao Basin

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收稿日期:2020-08-17;改回日期:2021-05-06

基金项目:中国地质调查局项目(DD20190405)和国家科技重大专项(2016ZX05034001-005)联合资助。

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Abstract: As an important part of shale reservoir space, organic pores possess strong heterogeneity, which hinders the correct understanding and evaluation of shale reservoir quality. The heterogeneity is essentially affected by organic macerals and their pore evolution during hydrocarbon generation process. Through located observation based on the field emission scanning electron microscopy and optical microscopy for pore development of the specific macerals, combined with Image J digital process technique, the pore evolution law of different organic macerals was summarized by quantitative statistics of macerals at different evolutionary stages. The results show that the porosity with solid bitumen is first increased and then decreased with the increase of maturity. The solid bitumen porosity is the highest when SBR_o ranges from 1.6% to 2.0%, while the porosity begins to decrease when SBR_o exceeds 2.0%. The pore development models of vitrinite and inertinite are similar. The both porosity decreases first and then increases slightly as maturity rise. In the oil window stage, the porosity of vitrinite and inertinite is the lowest, because the filling of inorganic minerals and solid bitumen in the primary cell lumen make the loss of pores more than 90%. In the high mature stage, pore development of solid bitumen makes the original cellular pore getting a certain degree of recovery, becoming the main contribution and accounting for 56.73% and 100% of residual pores of vitrinite and inertinite respectively. It can be seen that solid bitumen pores are of importance to the shale reservoir. Combined with sedimentary diagenesis and hydrocarbon generation, the pores of shale reservoir are the most developed in the immature stage and the late stage of high maturity. The former is dominated by primitive cell pores, while the latter is dominated by solid bitumen pores. Clarification of the pore evolution pattern of organic macerals can provide a significant reference for favorable shale reservoir prediction and reconstruction of shale gas development.

Keywords: organic maceral; pore evolution; FE-SEM; fluorescence microscope; shale reservoir; oil-gas exploration engineering; Songliao Basin

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Fund support: Funded by project of China Geological Survey(No.DD20190405), National Science and Technology Major Project (No.2016ZX05034001-005).

1 引言

随着非常规页岩油气勘探开发取得巨大成功,人们对页岩储层微观孔隙结构特征的认识也逐渐深入。有机质孔隙是页岩储层中一类重要的储集空间,不仅在一定程度上影响着页岩储层的连通性(Klaver et al., 2012, 2015; Wang et al., 2015; Wang et al., 2017; Gao et al., 2018a),更对页岩气的赋存具有重要影响(Maver et al., 2003; Chalmers et al., 2008, 2012; Ambrose et al., 2012),尤其是在地层饱水条件下,有机质孔隙可能成为甲烷吸附气的优势吸附位(Chalmers et al., 2008, 2012; Ross et al., 2009; Ambrose et al., 2012)。无论是孔隙发育程度还是孔隙分布,有机质孔隙都表现出十分强烈的非均质性特征(Curtis et al., 2012; Loucks et al., 2012; Reed et al., 2014; 马中良等, 2017; 王香增等, 2018;

Gao et al., 2018b; Guo et al., 2018),如同一视域下的两个相邻有机质,一个发育丰富的蜂窝状孔隙,一个孔隙不发育或只见零星不规则孔隙(Curtis et al., 2012; Gao et al., 2018b; Guo et al., 2018),同一片有机质其外围孔隙不发育,内部孔隙却呈海绵状十分丰富,并且具有良好的连通性(高凤琳等, 2019)。这些现象主要受控于构成有机质的显微组分差异及其在生烃过程中的演化(张慧等, 2015; 马中良等, 2017; 焦淑静等, 2018; 商斐等, 2020; 白静等, 2020)。

目前国内外关于页岩储层的研究主要有两类技术手段,一类是流体注入法,采用 CO_2 、 N_2 吸附实验,高压压汞等方法对孔径分布、孔体积及比表面积进行定量分析(胡海燕等, 2013; Gao et al., 2018a, b)。胡海燕等(2013)通过热模拟实验和气体吸附实验对美国俄克拉荷马州Woodford露头样品进行研究,得

出页岩储层孔隙的增加与有机质的热降解相关。但注入法难以对特定显微组分的孔隙发育情况进行刻画。另一类是直接观察法,通过场发射扫描电镜、微纳米CT、聚焦离子束扫描电镜等方法对页岩孔隙类型、孔隙形状及孔隙分布进行定性描述(Curtis et al., 2012; Loucks et al., 2012; 王飞宇等, 2013; 吴松涛等, 2015; 杨璠等, 2020)。王飞宇等(2013)通过对不同成熟阶段页岩样品进行扫描电镜图像分析发现,页岩有机质孔隙度并非随有机质成熟度升高而一直增加,而是当成熟度 $R_o > 2.0\%$ 以后,有机质孔隙度随着埋深增加而降低。吴松涛等(2015)通过温压模拟实验和纳米CT三维表征技术对鄂尔多斯盆地长7低熟页岩的孔隙发育随温度的变化进行定性观察,认为在 R_o 介于 $1.2\% \sim 1.7\%$ 时,有机质大量降解,蜂窝状有机质孔隙大量发育。薛莲花等(2015)对长7页岩采用相似的研究方法,同样得出页岩孔隙度的增加主要来自于有机质孔隙的贡献。

有机质孔隙对页岩储层的重要性及其受生烃过程的重要影响已被广泛证实,但通过扫描电镜观察难以有效刻画各显微组分的孔隙发育情况。目前,鲜有对不同有机显微组分的孔隙演化开展系统的研究,制约着人们对有机质孔隙非均质成因机理的揭示,也阻碍了对页岩储集空间的正确评价。荧光显微镜是鉴定有机显微组分的主要手段。因此,本文采用场发射扫描电镜和荧光显微镜相结合定位观察的方法,结合Image J图像处理软件,对不同显微组分在不同成熟阶段的有机质孔隙发育特征进行提取,通过有机面孔率这一参数表征有机孔隙的发育程度,综合沉积成岩作用和生烃演化过程,总结不同显微组分的有机质孔隙演化模式,揭示有机质孔隙发育非均质性成因机理。

2 样品和实验方法

2.1 实验样品

本文所用6个样品均来自松辽盆地长岭断陷东南部B2井、SL2井和S103井的沙河子组,该地层发育于湖盆快速裂陷时期,为一套深灰色—黑色页岩,采样深度位于2663.7~3942.1 m,样品的地球化学参数和矿物组成特征详见高凤琳等(2019)。

2.2 场发射扫描电镜观察

所采样品制备成大约 $1\text{ cm} \times 1\text{ cm} \times 1\text{ cm}$ 的规则

方块,并对观察面进行氩离子抛光,以清楚地观察页岩储层微观孔隙结构特征,观察面选择垂直于页岩层理面。观测仪器采用配备有二次电子和能量色散光谱仪的Zeiss SUPRA 55 Sapphire型号的场发射扫描电镜,其分辨率最高可达1 nm,在样品导电性较好的情况下,为了不影响对页岩孔隙发育状况的准确表征,一般对样品观察面不进行镀金或者镀碳。

2.3 光学显微镜观察

用于场发射扫描电镜的块样随后用来进行光学显微镜的观察,观察的目的有两个:一是进行位置标定,对扫描电镜中所观察到的同一片有机质进行显微组分的鉴定,实现对特定显微组分孔隙发育特征的刻画,位置标定的具体方法见高凤琳等(2021),显微组分的鉴定采用配有油浸目镜和蓝色荧光装置的显微镜进行,显微组分类型的划分依据程克明等(1989)的分类方案;二是对不同有机显微组分进行反射率测定,在Leica DM4500型显微镜上用CRAIC型分光光度计对各显微组分的反射率进行测定,测定之前,采用已知反射率标准对测量系统进行线性校准,每种显微组分至少进行30个点的测定。

2.4 图像处理方法

图像处理采用Image J软件进行,Image J是由美国国家卫生健康研究院所开发的一款基于Java语言的专业图像处理和分析软件,适用于TIFF、JPEG、BMP、PNG等多种格式的电子图像。在油气地质学领域中,Image J软件常用来分析沉积储层的孔缝结构系统。通过Image J软件分析,可实现对特定显微组分孔隙发育特征定量化表征。将分辨率高质量好的扫描电镜图像导入该软件之后,首先将图像转化为8bit的灰度图像,然后选取需要提取孔隙的有机质,由于有机质一般都是不规则形状的,利用图像编辑模块手动将有机质圈定出来并统计其面积大小,再利用阈值模块对有机质当中的孔隙进行分割,统计孔隙面积,孔隙面积与所在有机质面积大小相比得出有机孔隙面孔率。提取时,采用多人多次操作取其平均值的方式进行,以避免人为因素所造成的统计偏差。

3 有机显微组分孔隙演化

3.1 固体沥青孔隙演化特征

根据高凤琳等(2019)研究结果显示,尽管沙河

子组页岩整体经历了相似的热演化程度,但同一岩块中不同固体沥青的反射率值明显存在差异,这主要是因为固体沥青形成于不同的生烃演化阶段,多孔固体沥青多形成于高成熟阶段的后期,无孔固体沥青多在成熟阶段早期充注。因此,采用Image J软件统计有机孔隙面孔率,对不同反射率的固体沥青孔隙发育特征进行定量统计。结果显示,当固体沥青反射率 $SBR_o=0.89\%$ 时,固体沥青几乎不发育有机质孔隙,有机孔隙面孔率几乎为零(图1a~c);当 $SBR_o=1.49\%$ 时,有机孔隙面孔率为18.52%(图1d~f);当 $SBR_o=1.92\%$ 时,有机孔隙面孔率达到19.98%(图1g~i),进一步有所增加;当 $SBR_o=1.98\%$ 时,有机孔隙面孔率为4.62%(图1j~l)。可以看出,随着固体沥青反射率值升高,有机孔隙面孔率呈现先增大而后减小的趋势,固体沥青孔隙大量发育在 SBR_o 介于1.5%~1.9%。这与前人通过生烃模拟实验观察整个页岩孔隙发育特征所得结论相似(王飞宇等,2013;吴松涛等,2015),说明固体沥青对整个页岩的孔隙系统起着重要的作用。为了进一步验证这一变化趋势,本文同时对所有固体沥青测点的孔隙发育情况进行统计,计算出在不同 SBR_o 范围内多孔固体沥青占比情况(表1)。根据前人建立的 SBR_o 向 Ro 转化方程,转化前后的值仍十分接近(Mastalerz et al., 2018),因此仍采用 SBR_o 值对固体沥青的演化程度进行划分。在0.7%~1.2%范围时,无孔(少孔)固体沥青占该阶段固体沥青总数的85.71%,多孔固体沥青占比14.29%,前者是后者的近6倍,说明在成熟阶段固态沥青孔隙总体是不发育的,且固体沥青孔隙度较低;在1.2%~1.6%范围内,固体沥青孔隙仍然不发育,无孔固体沥青数量占比增至87.50%,这是因为处于成熟—高成熟阶段的有机质仍以干酪根裂解生成液态烃类占主导地位,该阶段的固体沥青很可能是液态烃类经过后期物理变化而形成的,孔隙欠发育。当 SBR_o 处于1.6%~2.0%范围时,多孔固体沥青占比增大,为81.82%,说明在高成熟阶段晚期,大多数固体沥青发育孔隙,固体沥青孔隙度增加,该阶段液态石油进一步裂解生气,形成多孔的固体沥青,也称之为焦沥青(Bernard et al., 2012; Mastalerz et al., 2018)。而当 $SBR_o>2.0\%$ 时,多孔固体沥青占比又有所减小,占比数降至30%,固体沥青孔隙度也相

应有所减小,无孔固体沥青占比增加。从以上两方面的统计结果均可以看出,固体沥青孔隙度随着成熟度的升高呈现先增加后减小的趋势。

3.2 镜质体和惰质体孔隙演化特征

对一个保存完好的镜质体或惰质体来说,在沉积初期,镜质体或惰质体的原始胞腔是中空的。随着沉积物不断的堆积,受压实作用和沉积物充填影响,镜质体和惰质体的原始胞腔会被压缩变形或被充填,使有机孔隙度减小。图2和图3为通过Image J图形处理软件分别对镜质体和惰质体胞腔面积,沉积物充填面积以及孔隙发育面积等的统计效果图,统计结果如表2所示。图2所示有机质均为惰质体,图2a~b惰质体的6个原始胞腔均被充填,图2c~d惰质体有一个胞腔被黄铁矿所充填,而另一个胞腔未被充填,图2e~f惰质体仅含有少量孔隙。假如这些胞腔均未被充填,则胞腔占整个有机质的面孔率可近似认为惰质体发育的原始孔隙度,图2b和图2d惰质体的原始胞腔面孔率分别近似为37.00%和42.11%。图3均为镜质体,相似的,图3b和图3d原始胞腔面孔率分别近似为38.45%和30.87%。随着沉积作用不断进行,成熟度不断升高,镜质体和惰质体的原始胞腔逐渐被无机矿物和固体沥青所充填,有的胞腔被全部充填,有的胞腔还残留有少量原始胞腔孔隙。图2f和图3f的残余面孔率分别为4.52%和0.28%。惰质体无机矿物充填面孔率为28.31%~31.58%,其所造成的孔隙损失率达74.99%~76.51%;镜质体无机矿物充填面孔率为16.99%~26.11%,其所造成的孔隙损失率为44.19%~94.29%。当进入生油窗,液态烃类大量生成,并充填在部分胞腔中,惰质体固体沥青充填面孔率为8.24%,造成的孔隙损失率为20.68%,镜质体固体沥青充填面孔率为21.46%,造成的孔隙损失率为49.55%,至此阶段,惰质体和镜质体由于无机矿物和固体沥青造成的孔隙损失率分别达97.19%和93.74%。当页岩进入高成熟阶段后期,液态烃开始裂解产生一定数量的微纳米级孔隙,使得原先被固体沥青占据的孔隙空间得到一定程度的恢复,经计算,惰质体和镜质体中的固体沥青孔隙面孔率分别为0.59%和2.41%,分别占残余面孔率的56.73%和100%,可见惰质体和镜质体中现存的孔隙主要由固体沥青所贡献,这进一步证明了固体沥青孔隙对页

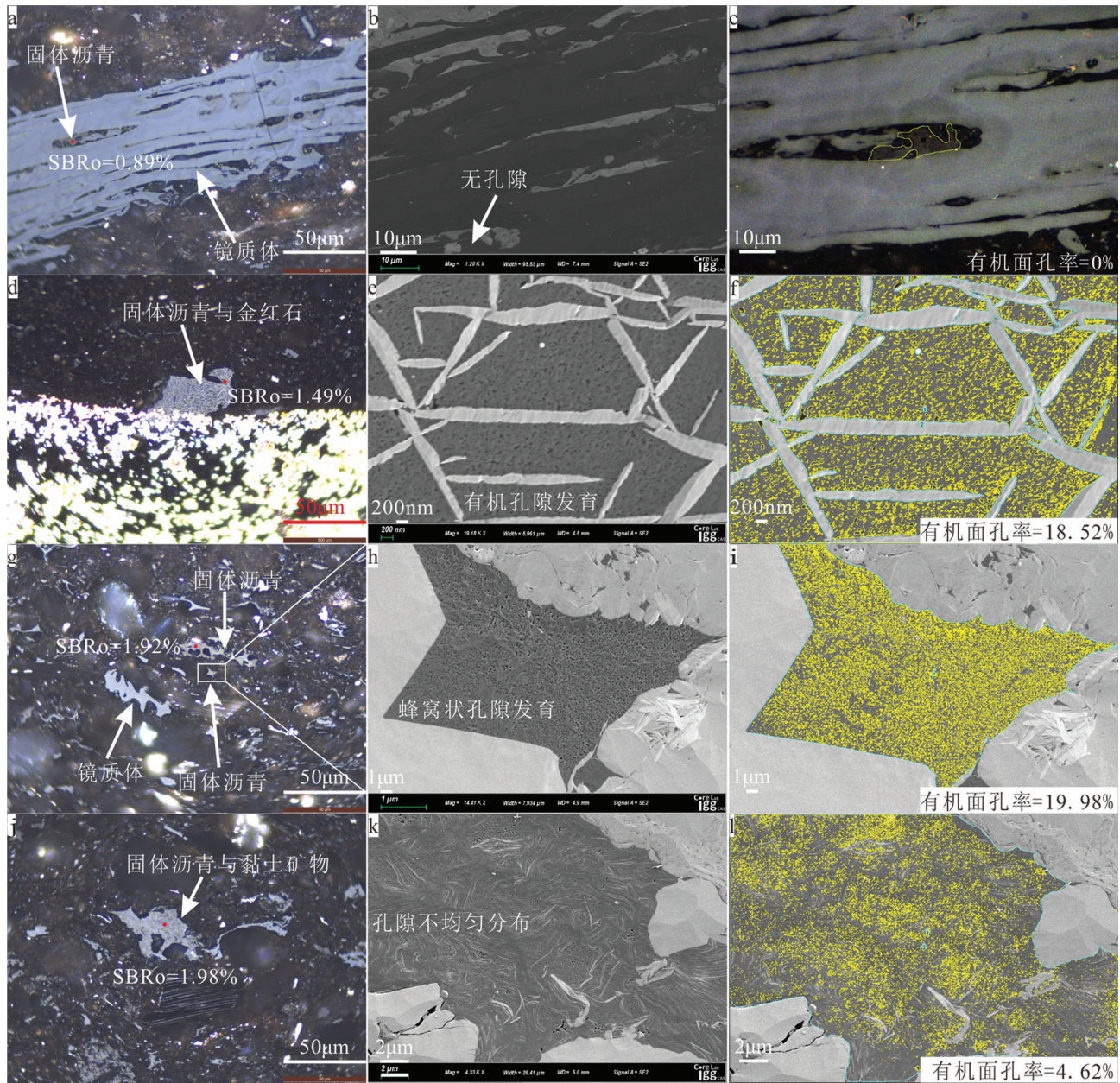


图1 不同成熟度固体沥青孔隙信息提取

a—结构镜质体,少量胞腔被固体沥青充填, $SBR_o=0.89\%$,S103-N05井2663.7 m,反射光;b—图a的SEM照片,充填固体沥青孔隙不发育;c—图a的局部放大,孔隙提取有机面孔率为0;d—固体沥青与金红石共生, $SBR_o=1.49\%$,B2-N10井3938.2 m,反射光;e—图d的SEM照片,固体沥青孔隙发育;f—图e的孔隙提取,有机面孔率18.52%;g—星状固体沥青, $SBR_o=1.92\%$,SL2-N06井3430.1 m,反射光;h—图g的SEM照片,蜂窝状孔隙发育;i—图h的孔隙提取,有机面孔率为19.98%;j—固体沥青与黏土矿物共生, $SBR_o=1.98\%$,B2-N04井3896.1 m,反射光;k—图h的SEM照片,蜂窝状孔隙不均匀分布;l—图k的孔隙提取,有机面孔率4.62%

Fig. 1 Pores information extraction of solid bitumen with different SBR_o

a—Telinite, a few cellular cavity filled by solid bitumen, $SBR_o=0.89\%$, S103-N05, 2663.7 m, reflected light; b—SEM image of a, solid bitumen filled in the cavity have no pores; c—Partial enlargement of a, organic porosity is 0; d—Solid bitumen coexists with rutile, $SBR_o=1.49\%$, B2-N10, 3938.2 m, reflected light; e—SEM image of d, porous solid bitumen; f—Pore extraction of e, organic porosity is 18.52%; g—Star shaped solid bitumen, $SBR_o=1.92\%$, SL2-N06, 3430.1 m, reflected light; h—SEM image of g, honeycomb pores; i—Pore extraction of h, organic porosity is 19.98%; j—Solid bitumen coexists with clay minerals, $SBR_o=1.98\%$, B2-N04, 3896.1 m, reflected light; k—SEM image of h, unevenly distributed honeycomb pores; l—Pore extraction of k, organic porosity is 4.62%

岩储层储集空间的重要性。惰质体和镜质体中最终均保留有一定的孔隙,惰质体的残余面孔率为1.04%~10.53%,镜质体的残余面孔率为0.28%~2.41%,通过以上分析,这些残余孔隙主要来自于固体沥青高温裂解生烃所产生的孔隙,其次来自于最终未被充填或受压实作用未完全收缩而保留的原始残余孔隙。

3.3 不同有机质显微组分的孔隙演化模式

通过上述观察和统计结果,综合热演化生烃和沉积成岩的一般规律,总结出不同有机显微组分和页岩储层的孔隙发育演化模式(图4)。由图4可以看出,固体沥青孔隙随着成熟度的增加,呈现出先增加后减小的趋势;镜质体和惰质体的孔隙发育规律相似,都随着成熟度的增加先迅速减小,而后又呈现微弱幅度的上升。

当 $Ro < 0.5\%$ 时,页岩处于未成熟阶段,该阶段页岩储层孔隙度最为发育,沉积物还未完全固结,碎屑颗粒之间的孔隙较大,镜质体和惰质体还保留有高等植物的原始细胞结构,细胞腔孔隙尚未被充填和破坏。但随着沉积作用的不断进行,受上覆地层压力的影响,页岩储层孔隙逐渐减小,该阶段压实作用是最主要的成岩作用类型,无机矿物粒间孔隙受压实作用的不断增强而逐渐减小,镜质体和惰质体原始细胞结构受压实作用的影响会发生不同程度的变形和收缩,使镜质体和惰质体相关原生孔隙减小,固体沥青在这个阶段还未产生,对页岩储层的影响不大。

当 $0.5\% < Ro < 1.2\%$ 时,页岩处于低熟到成熟阶段,该阶段压实作用持续进行,有机质干酪根大量生烃并且首先就近充填在干酪根内部及其附近的

孔隙当中,且生成的烃类主要为前油沥青和液态石油,镜质体和惰质体胞腔孔隙也被无机矿物和烃类最大程度充填,镜质体和惰质体孔隙降到最低,受压实作用和生烃作用影响,页岩储层孔隙度迅速减小,而随着有机质生烃作用的进行,有机酸大量产生,在同一阶段对长石、碳酸盐等矿物进行溶蚀,产生一定的溶蚀孔隙,有机酸的产生还大大刺激了蒙脱石向伊利石的转化,产生一定的孔隙,若溶蚀作用强烈,溶蚀孔隙较发育,则溶蚀作用增加的孔隙可与压实作用以及生烃作用造成的孔隙损失相抵,甚至有可能出现微弱的增加。

当 $1.2\% < Ro < 2.0\%$ 时,页岩进入高成熟阶段,该阶段压实作用与其他支撑作用已趋于平衡状态,对储层孔隙影响较弱,除部分干酪根继续进行降解生烃之外,大多数原先生成的液态烃类发生裂解生气,固体沥青开始产生大量的有机孔隙,固体沥青孔隙度迅速升高,原先占据镜质体和惰质体胞腔的固体沥青由于裂解生气也产生了孔隙,使胞腔空间得到一定程度的恢复,镜质体和惰质体孔隙有所增加,对整个页岩来说,由于烃类裂解生孔使得总孔隙也出现相应程度的增加。

当 $Ro > 2.0\%$ 时,重质油继续裂解,使得固体沥青发育更多的微纳米级孔隙,然而随着成熟度继续升高,有机质出现石墨化的现象,生烃潜力逐渐萎缩,生成的气体逸散导致微纳米孔隙一方面得不到气源的支撑而产生坍塌(吴松涛等,2015;Gao et al., 2018),孔隙度进而会出现逐渐减小的趋势。

由此可见,不论处于哪一个热演化阶段,页岩都存在有机质孔隙的发育,只是在不同演化阶段有机显微组分孔隙发育程度不同,各显微组分孔隙对有机质总孔隙贡献的量不同,这进一步补充了前人对有机质孔隙演化的认识。

4 对海相和陆相页岩孔隙结构差异性认识的启示

有机显微组分是构成有机质的基本物质单元,各显微组分孔隙在不同演化阶段的变化决定了有机质孔隙发育的整体情况以及对页岩储集空间的贡献程度,从而在一定程度上影响页岩油气勘探选区。海陆相页岩孔隙结构差异性明显,海相页岩的有机质孔隙贡献率(平均37.0%)高于陆相页岩

表1 无孔固体沥青和多孔固体沥青分布频率
Table 1 Frequency distribution of porous solid bituman and non-porous solid bituman at different maturation stages

SBRo 范围 /%	多孔固体	无孔固体	多孔固体	无孔固体
	沥青测点 /个	沥青测点 /个	沥青占比 /%	沥青占比 /%
0.7%~1.2%	1	6	14.29	85.71
1.2%~1.6%	2	14	12.50	87.50
1.6%~2.0%	9	2	81.82	18.18
> 2.0%	3	7	30	70
测点总数:44	15	29	34.09	65.91

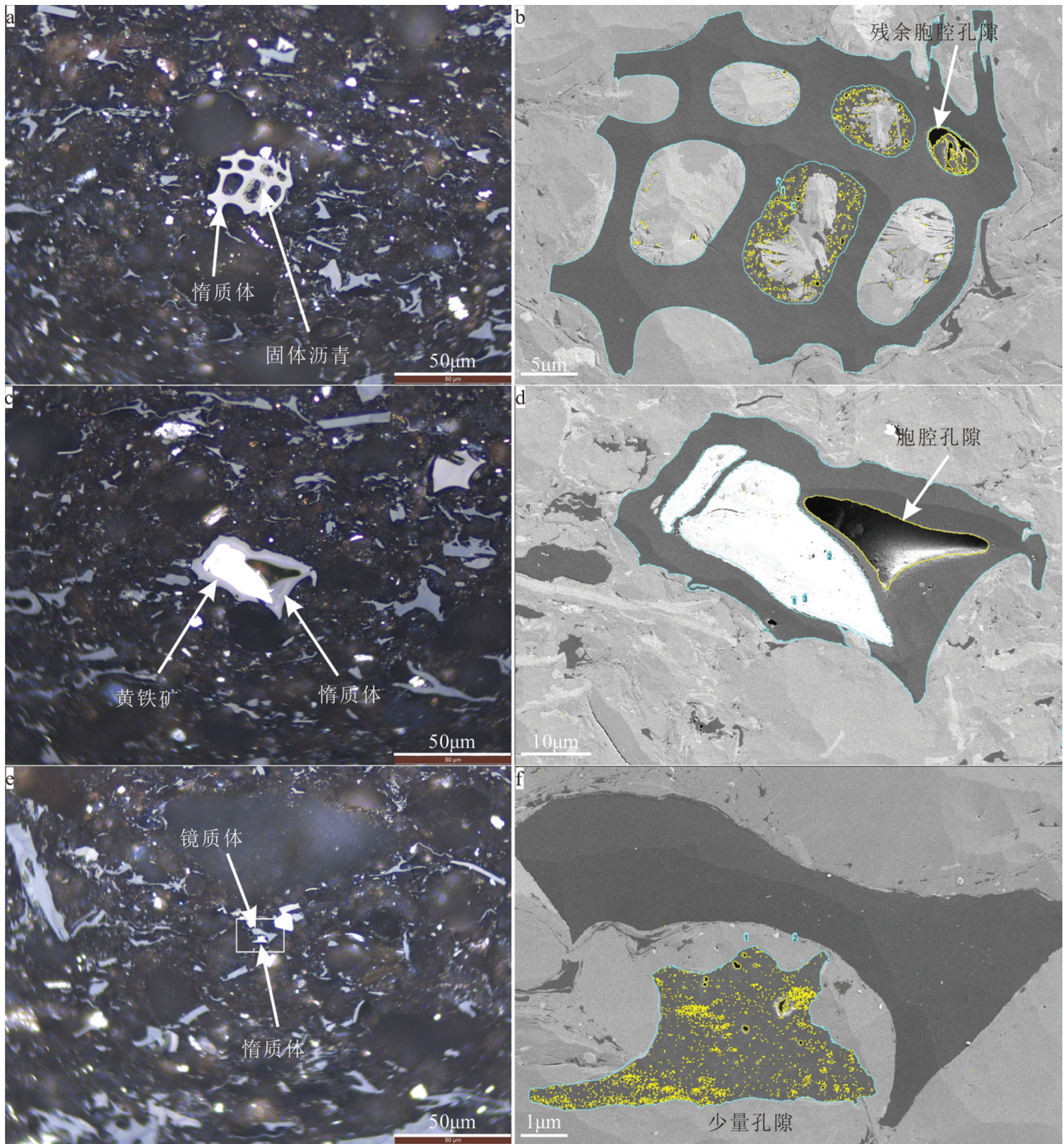


图2 惰质体孔隙信息提取

a—惰质体,具有胞腔结构,SL2-N06 井3430.1m,反射光;b—图a的SEM照片,胞腔被无机矿物和固体沥青充填,残余少量孔隙和固体沥青孔隙;c—惰质体,一胞腔被黄铁矿充填,一胞腔未被充填,SL2-N06井3430.1m,反射光;d—图c的SEM照片,残余胞腔孔隙发育;e—惰质体和镜质体相邻分布,SL2-N06井3430.1m,反射光;f—图e的SEM照片,惰质体含有少量孔隙

Fig.2 Pores information extraction of inertinite

a—Inertinite with cellular structure, SL2-N06, 3430.1m, reflected light; b—SEM image of a, some cells in the inertinite are not fully filled with nonporous solid bitumen and possess large residual spaces; c—Inertinite, one cavity is filled with pyrite and the other is filled with nothing, SL2-N06, 3430.1m, reflected light; d—SEM image of c, unfilled cavity well-preserved; e—Inertinite and vitrinite are adjacent to each other, SL2-N06, 3430.1m, reflected light; f—SEM image of e, inertinite contains a few pores

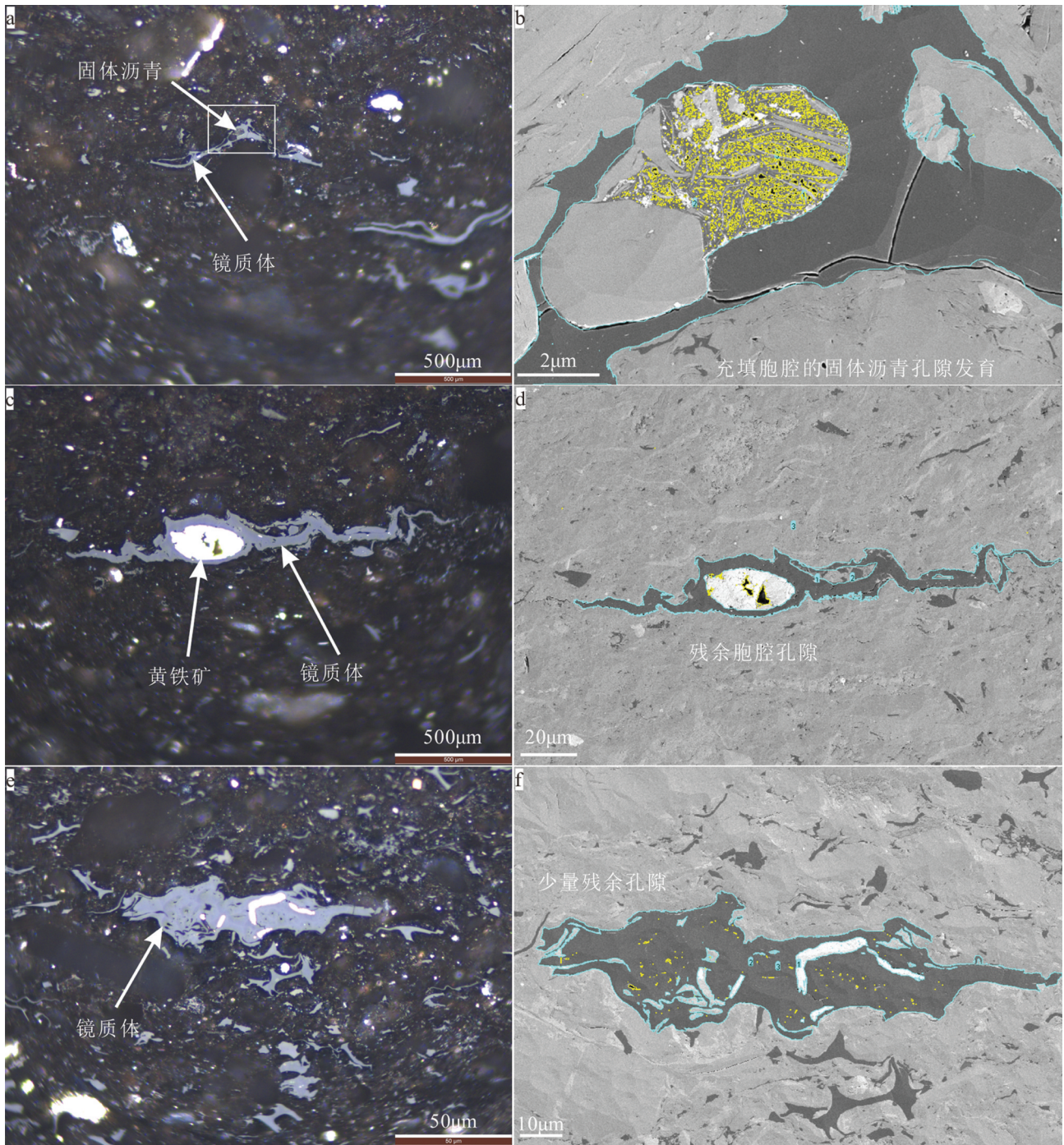


图3 镜质体孔隙信息提取

a—镜质体具有胞腔结构,B2-N10井3938.2 m,反射光;b—图a的SEM照片,胞腔被固体沥青和无机矿物充填,固体沥青孔隙发育;c—镜质体具有胞腔结构体,B2-N10井3938.2 m,反射光;d—图c的SEM照片,胞腔被黄铁矿不完全充填,残余少量原始胞腔孔隙;e—镜质体发生变形,B2-N10井3938.2 m,反射光;f—图e的SEM照片,残余少量有机质孔隙

Fig.3 Pores information extraction of vitrinite

a—Vitrinite with cellular structure, B2-N10, 3938.2 m, reflected light;b—SEM image of a, cell lumen is filled with porous solid bitumen and minerals;c—Vitrinite with cellular structure, B2-N10, 3938.2 m, reflected light;d—SEM image of c, cell lumen is unfully filled with pyrite and remain a few cell pores; e—Deformed vitrinite, B2-N10, 3938.2 m, reflected light; f—SEM image of e, a few residual organic pores

表2 镜质体和惰质体面孔率统计

Table 2 statistics of surface porosity in vitrinite and inertinite

图片	显微组分	胞腔面孔率/%	残余面孔率/%	无机矿物充填面孔/%	无机矿物充填损失率/%	固体沥青充填面孔率/%	固体沥青充填损失率/%	固体沥青增面孔率/%	固体沥青增孔率/%
图2a~b	惰质体	37.00	1.04	28.31	76.51	8.24	20.68	0.59	56.74
图2c~d	惰质体	42.11	10.53	31.58	74.99	/	/	/	/
图2e~f	惰质体	/	4.52	/	/	/	/	/	/
图3a~b	镜质体	38.45	2.41	16.99	44.19	21.46	49.55	2.41	100
图3c~d	镜质体	30.87	1.77	29.11	94.29	/	/	/	/
图3e~f	镜质体	/	0.28	/	/	/	/	/	/

(24.0%),而黏土矿物孔隙贡献率(53.0%)低于陆相页岩(67.0%)(宋岩等,2021)。海相和陆相页岩有机质孔隙贡献率差异的本质原因在于不同演化阶段显微组分孔隙组成的差异。海相页岩有机质以次生有机质、沥青质以及藻类体等腐泥组为主,平均占比达82.2%,且处于高过成熟阶段,结合显微组分孔隙演化规律可知,高过程成熟海相页岩腐泥型有机质生烃潜力大,有机质孔隙发育;而陆相页岩既有来自陆生高等植物,又有来自湖盆水生生物,以镜质体、惰质体为主的腐殖组为主,平均占比为62.3%,且多处于低熟—高熟早期阶段,要么有机质本身不发育孔隙,要么生油窗阶段被大量烃类充填,造成有机质孔隙发育程度整体较差。因此,不同于海相页岩选取有机质丰度高、有机质孔隙发育、脆性矿物含量高“又甜又脆”的有利储集区,陆相页岩油气有利层段应为无机矿物孔隙发育的纹层段。

5 结 论

(1)随着成熟度的增加,固体沥青孔隙逐渐发育,多孔固体沥青占比增加,在 SBR_o 介于1.6%~2.0%时,固体沥青孔隙最为发育;当成熟度增加到一定程度,以 $SBR_o=2.0%$ 为界,固体沥青孔隙度减小,多孔固体沥青占比减小,固体沥青孔隙度表现出随着成熟度的升高呈现先增加后减小的趋势。

(2)镜质体和惰质体孔隙发育规律相似,总体表现出先减小而后增加的趋势。至生油窗阶段,受压实作用、无机矿物和固体沥青充填影响,镜质体和惰质体原始胞腔孔隙损失率分别达97.19%和93.74%,孔隙度降至最低;高成熟阶段后期,充填其中的固体沥青裂解生孔,贡献了镜质体和惰质体残余孔隙的56.73%和100%,原始胞腔得到一定程度的恢复。

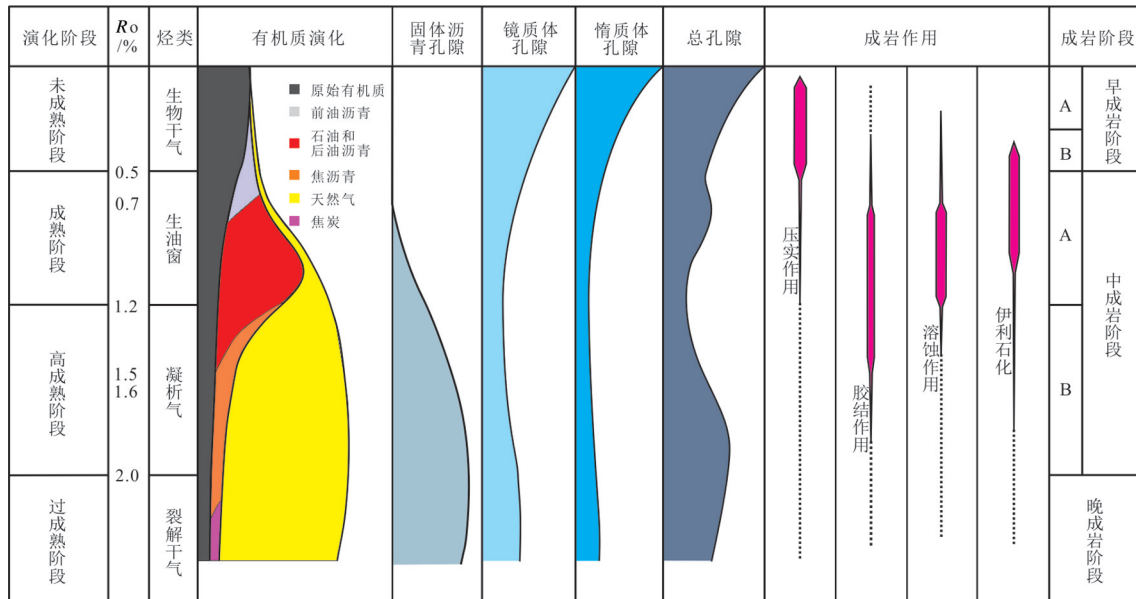


图4 不同有机质显微组分的孔隙演化模式
Fig.4 Pore evolution model of different organic macerlas

(3)综合沉积成岩作用和生烃作用,页岩储层在未成熟阶段孔隙最为发育,有机质孔隙以原始胞腔为主;在低成熟阶段页岩储层孔隙迅速减小;进入高成熟阶段,由于烃类裂解生孔使得页岩总孔隙度达到最大;过成熟阶段,生烃潜力逐渐萎缩,有机质孔隙得不到支撑使得整个页岩储层的孔隙整体减小。

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