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苏北盆地高邮凹陷阜宁组二段页岩油储层特征及影响因素

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摘要：苏北盆地高邮凹陷古近系阜宁组二段（以下简称阜二段）是页岩油勘探的重点层系之一，页岩储层特征是影响油气储集、渗流和运移的重要因素，为研究其储层特征，利用岩心观察、X衍射矿物分析、N_2吸附、扫描电镜、核磁共振等方法，开展不同岩相"四性"研究，刻画储层特征，分析其影响因素。结果表明：研究区发育8种（①型—⑧型）主要岩相类型和长英质纹层、黏土质纹层、碳酸盐质纹层及混合质纹层4种纹层类型，中碳纹层状长英质-黏土质混合质页岩型、中碳纹层状长英质-碳酸盐质混合质页岩型以及中碳纹层状碳酸盐岩型为优势岩相类型，主要发育在Ⅲ亚段中下部、Ⅳ亚段以及Ⅴ亚段中下部，储集空间包括孔隙和裂缝，孔隙以粒间（缘）孔为主，裂缝以构造剪切缝、张剪缝和非构造层理缝为主。页岩储层受矿物组分、纹层发育程度和裂缝有效性影响，碳酸盐岩矿物粒间孔相对较小，长英质和黏土质矿物含量越高，孔隙越发育，中大孔占比越大，页岩矿物组分越单一，孔隙连通性越好。纹层状页岩孔渗、含油性及可动性优于其他构造类型页岩。未被充填的大型构造剪切缝、层理缝、顺层方解石脉和层内张剪缝为有效储集空间，压裂后可沟通孔隙，形成复杂孔-缝系统。研究成果为苏北盆地高邮凹陷阜二段页岩油储层评价和"甜点"优选提供支撑。

关键词：苏北盆地；高邮凹陷；阜宁组二段；页岩油；储集空间；影响因素
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Reservoir characteristics and influencing factors of shale oil in second member of Funing Formation, Gaoyou Sag, Subei Basin

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Abstract: The second member of the Paleogene Funing Formation in the Gaoyou Sag, Subei Basin, is one of the key strata for shale oil exploration. Shale reservoir characteristics are important factors influencing oil and gas accumulation, seepage, and migration. To investigate the reservoir characteristics, methods including core observation, X-ray diffraction mineral analysis, N_2 adsorption, scanning electron microscopy, and nuclear magnetic resonance were utilized to study the "four properties" (oil-bearing potential, storage capacity, mobility, and fracturability) of different lithofacies, characterize the reservoir features, and analyze their influencing factors. The results indicated that eight main lithofacies types (Type 1 to Type 8) and four lamination types (felsic lamination, argillaceous lamination, carbonate lamination, and mixed lamination) developed in the study area. The dominant lithofacies were medium-carbon laminated felsic-argillaceous mixed shale, medium-carbon laminated felsic-carbonate mixed shale, and medium-carbon laminated carbonate rock, which were mainly developed in the middle-lower part

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of sub-member III, sub-member IV, and the middle-lower parts of sub-member V. The storage spaces included pores and fractures. The pores were mainly intergranular (interparticle) pores, while the fractures were mainly tectonic shear fractures, tension-shear fractures, and non-tectonic bedding fractures. The shale reservoirs were influenced by mineral composition, lamination development, and fracture effectiveness. Specifically, intergranular pores in carbonate minerals were relatively small. Higher contents of felsic and argillaceous minerals led to more developed pores and a larger proportion of meso- and macropores. Furthermore, the more uniform the mineral composition of the shale, the better the pore connectivity. Laminated shale exhibited better porosity and permeability, oil-bearing potential, and mobility than other structural types of shale. Unfilled large tectonic shear fractures, bedding fractures, bedding calcite veins, and intralaminar tension-shear fractures constituted effective storage spaces. After fracturing, these could connect pores, forming a complex pore-fracture system. These findings provide support for the evaluation and "sweet spot" selection of shale oil reservoirs in the second member of the Funing Formation, Gaoyou Sag, Subei Basin.

Keywords: Subei Basin; Gaoyou Sag; second member of Funing Formation; shale oil; storage space; influencing factors

中国页岩油资源丰富，是推动中国原油增产稳产的重要接替领域[1-7]，其中，陆相页岩油是一个全新领域，目前，已在鄂尔多斯盆地、松辽盆地、渤海湾盆地、准噶尔盆地、柴达木盆地、苏北盆地等不同页岩层系取得了重要勘探实践进展[8-14]。2021年以来，中国石化江苏油田分公司在苏北盆地高邮凹陷阜宁组二段优选镜质组反射率（R_o）中等成熟度地区，R_o值介于0.8%～0.9%，针对阜宁组二段率先部署实施HY1HF井、H2CHF井，试获工业油流分别为29.7、50.5 t/d[15]，随后在高邮凹陷中—高成熟度（R_o>0.9%）地区部署导眼井HY7井，钻遇完整阜宁组二段地层，优选靶窗部署水平井HY7HF井压裂后峰值日产油气量为62.7 t，是苏北盆地高邮凹陷阜宁组二段页岩油新区、新层系勘探的重大突破（图1）[16-18]。

国内外学者对于岩相划分方案并不统一，但陆相页岩非均质性强，泥页岩岩相研究是页岩油气勘探开发评价的基础[19-21]，需考虑沉积环境、沉积构造、矿物组分、有机碳、古生物等多种因素[22]，因此，岩相划分方案对后续优质储层评价具有指导意义[23]。储层评价是页岩油勘探开发的核心问题[24]，包括有机质成熟度、有机质丰度、有机质类型、含油气性、矿物组分、储集特征、脆性指数等诸多方面[25-28]。诸多学者对页岩油储集性进行了分析，认为微纳米级孔缝系统是页岩油富集的主要空间，其系统表征与精细刻画更是实现页岩油有效评价的前提，对剖析油气赋存状态和富集机理至关重要[29-32]。

部分学者针对苏北盆地高邮凹陷阜宁组二段开展了沉积环境、页岩类型、成藏条件、富集主控因素等方面的研究[33-39]，但对于以岩相为基础的“四性”参数评价以及精细刻画不同岩相储集空间的研究相对较少。研究以苏北盆地高邮凹陷阜宁组二段HY7井为依托，利用岩心观察、薄片鉴定、N_2吸附、核磁共振等方法，明确了研究区重点层段页岩岩相类型，并针对不同岩相开展“四性”参数分析，剖析储集空间特征，分析其影响因素，以期为阜宁组二段“甜点”优选提供支撑[40-44]。

1 区域地质概况

苏北盆地位于苏北—南黄海盆地陆上部分，是晚白垩世在扬子地台古生界褶皱基底上发育起来的陆相中、新生代盆地，以建湖隆起为界，南北分为东台坳陷与盐阜坳陷2个一级构造单元。高邮凹陷位于东台坳陷中部，北东向长形分布，呈现“南断北超”的箕状断陷格局（图1）[33,43-44]。受到盆地沉积体系和构造演化的控制，盆内自下而上发育泰州组二段、阜宁组二段和阜宁组四段3套半深湖—深湖相暗色泥页岩，其中，阜宁组二段地层厚度介于230～450 m，页岩品质好，是页岩油勘探的主力层系之一[32]。

苏北盆地高邮凹陷阜宁组二段整体处于半干旱—干旱、半咸水—咸水的半深湖—深湖还原环境[32-35]。自下而上可划分为5个亚段（Ⅴ亚段—Ⅰ亚段），其中，Ⅳ亚段和Ⅴ亚段长英质矿物和白云石含量逐渐减少，黏土矿物含量增加，纹层、层状结构发育逐渐减少，块状结构增多，有机质类型由腐殖型向腐泥型逐渐转变，有机碳含量逐渐升高，S_1（游离烃）含量变化不大，OSI（含油饱和度指数）逐渐降低（图2），因此，Ⅳ亚段和Ⅴ亚段是高邮凹陷阜宁组二段页岩油的主力勘探层系[45]。

2 实验样品和方法

利用HY7井72块典型样品开展实验测试，分析项目包括：热解采用Rock-Eval7岩石热解评价系统测试；X-衍射全岩采用布鲁克（Bruker）衍射仪定量分析；He孔隙度与脉冲渗透率采用PorePDP-20测试仪测试，垂直纹层取约2.5 cm×8.0 cm柱体样品，一分为二，一半用于测试孔隙度和渗透率大小；薄片鉴定采用CPV-900C型偏光显微镜完成，采用He孔隙度柱端面样品制样；低温N_2吸附采用Micromeritics ASAP 2460型比表面积分析测试仪完成，选用端面4～5 g粉末状样品（40～60目）测试，利用吸附-脱附迟滞环形态判断孔隙类型，测试孔径范围2～100 nm的孔径分布特征和孔体积；扫描电镜采用FEI

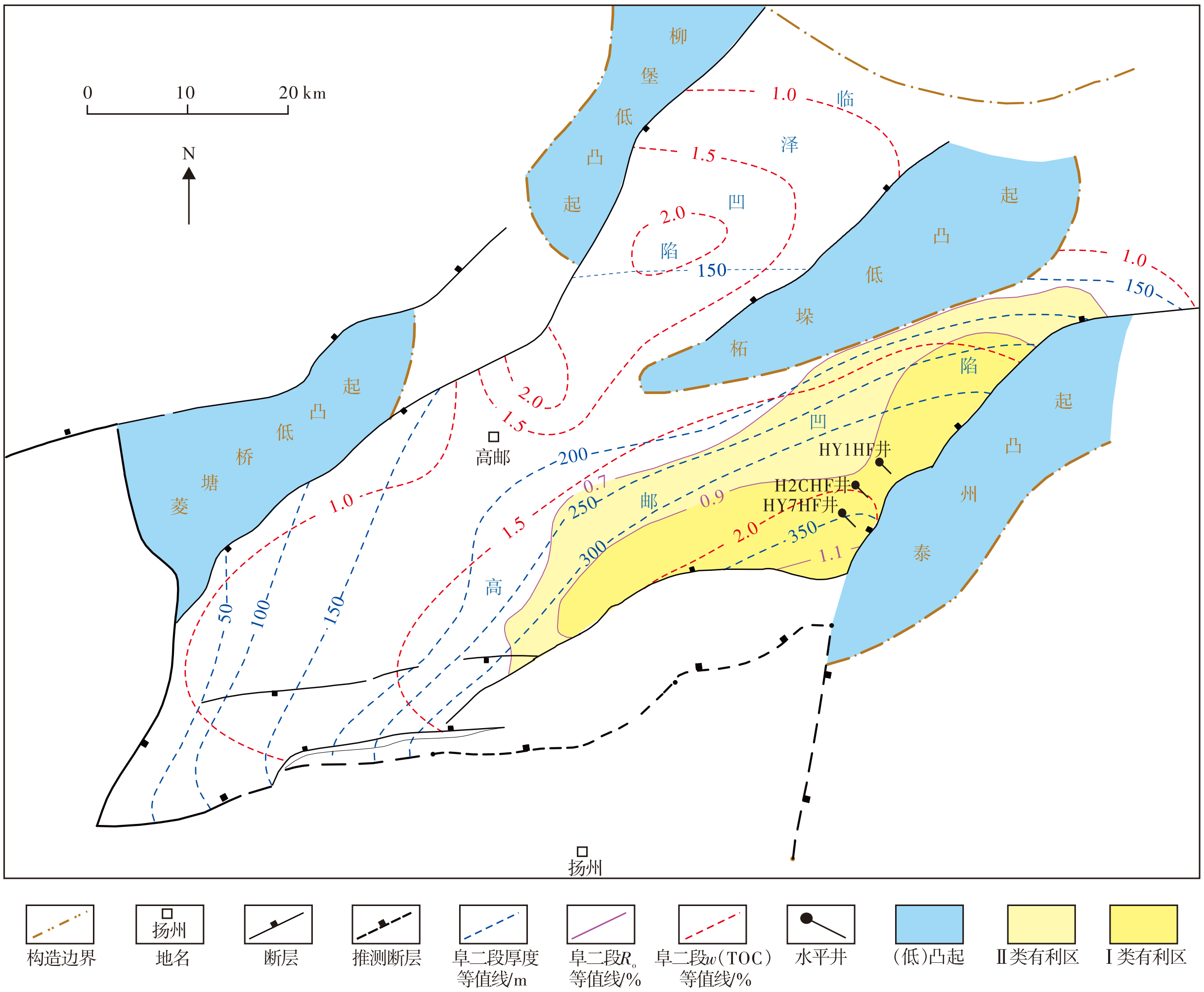


图1 苏北盆地高邮凹陷阜宁组二段页岩油井分布(据文献[14]修改)

Fig. 1 Distribution of shale oil wells in member 2 of Funing Formation, Gaoyou Sag, Subei Basin(modified from reference[14])

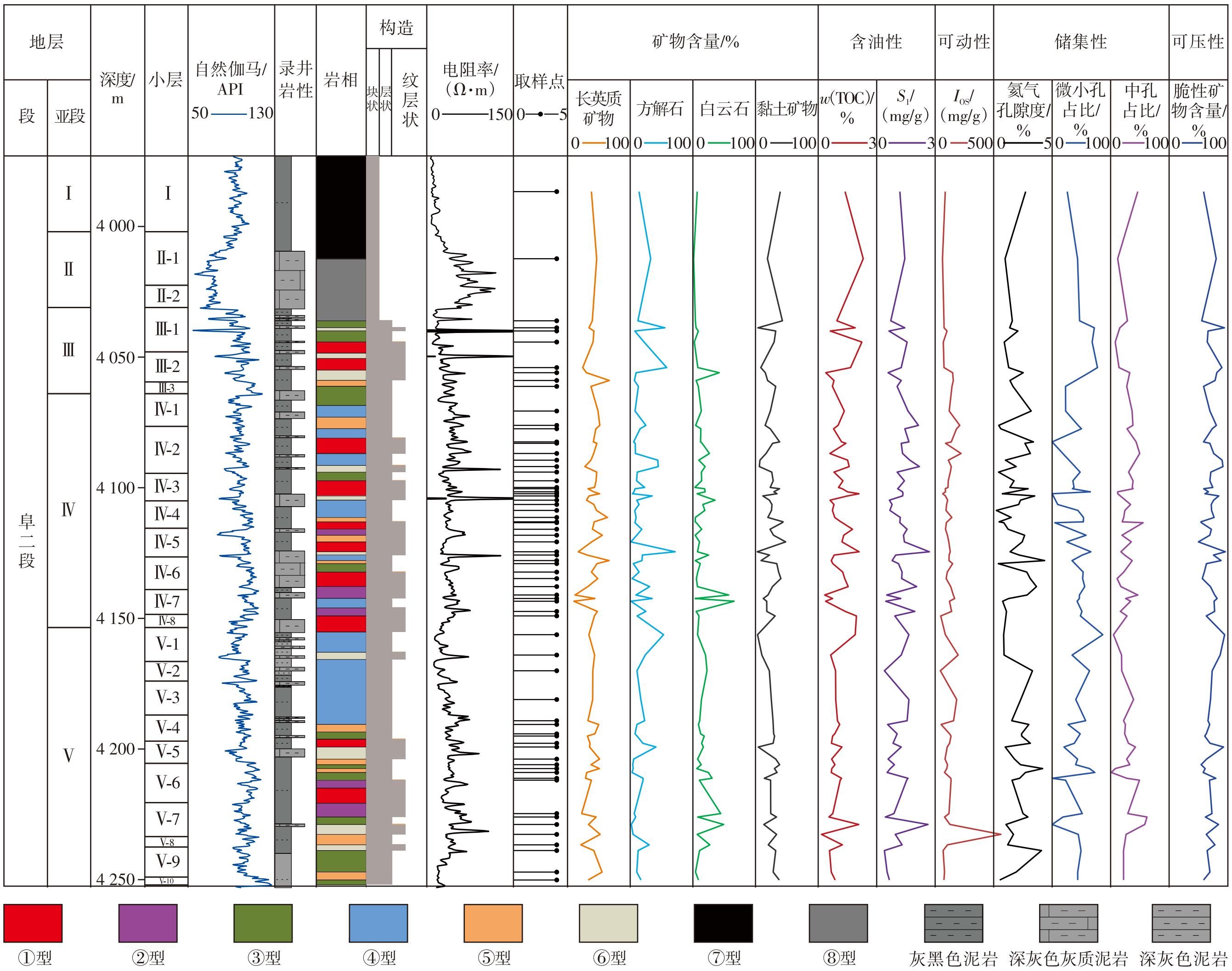
Quanta 200F场发射电镜,先将端面样品氩离子抛光后,观察孔隙类型[46],再大面积拼接后使用Image软件进行阈值划分,分析孔径大小介于100~1 000 nm的样品进行孔径分布特征和孔体积分析;核磁共振T_2(弛豫时间)谱测试采用MesoMR-060H-I型核磁共振分析与成像仪完成,利用剩余一半柱样,测试洗油干燥和饱和油两个状态一维核磁T_2谱,采用去基底反演方案获取饱和油T_2谱,可表征孔径范围广。分析结果表明:核磁共振可有效表征纳米—微米级全尺度孔径分布,但其T_2谱表示弛豫时间需转化为孔径[47],N_2吸附表征微小孔孔径分布可标定核磁共振P1峰,扫描电镜刻度中孔孔径分布可标定核磁共振P2峰,利用“分段联合”方法标定后可获得页岩全尺度孔隙结构特征[31,48-50]。

3 阜宁组二段页岩储层特征

3.1 岩相划分方案及特征

国内外学者对于岩相划分方案并不统一,对苏北盆地高邮凹陷阜宁组二段岩性岩相划分方案开展了研究[29,41-42],研究主要考虑“有机碳含量+沉积构造+岩性”的划分方案,页岩的有机碳含量低碳、中碳和高碳是以总有机碳(TOC)含量1.0%和2.0%为边界值确定,沉积构造类型块状、层状、纹层状以单层厚度1 cm和5 cm为边界值确定,岩性按照碳酸盐矿物、长英质矿物和黏土矿物三端元矿物含量不同划分(图3)[15,43]。

页岩储集特征的差异包括构造特征、纹层类型、孔隙类型和孔隙结构等多方面的不同,研究采用岩心观察、薄片鉴定等多手段储层测试方法(图4),具体分析不同岩相储集空间特征,开展储层评价。从生含油性、储集性、可动性及可压性等方面,对8种岩相逐一评价,结果为:中碳纹层状长英质-黏土质混合质页岩(①型)、中碳纹层状长英质-碳酸盐质混合质页岩(②型)、中碳纹层状碳酸盐岩(⑥型)3种岩相“四性”特征较好,属有利岩相类型;低碳纹层状/层状长英质-黏土质混合质页岩(③型)、低碳纹层状/层状长英质-碳酸盐质混合质页岩(④型)孔隙度、渗透率以及脆性矿物含量高,其储集性和可压性均较好,但有机碳含量较低,可动性相对较差;中/低碳纹层



注:w(TOC)为总有机碳含量,%;S_1为游离烃含量,单位mg/g;I_{os}为含油饱和度指数,单位mg/g。

图2 苏北盆地高邮凹陷HY7井阜宁组二段综合柱状图

Fig. 2 Comprehensive stratigraphic column of second member of Funing Formation in well HY7, Gaoyou Sag, Subei Basin

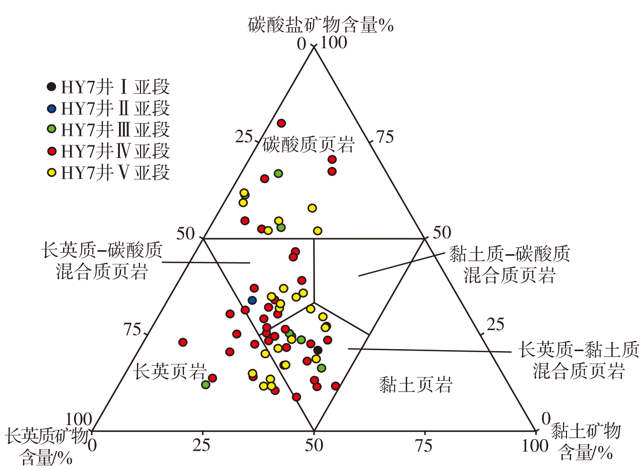


图3 苏北盆地高邮凹陷HY7井阜宁组二段页岩矿物组分三角图

Fig. 3 Triangular diagram of shale mineral composition in second member of Funing Formation in well HY7, Gaoyou Sag, Subei Basin

状/层状长英页岩(⑤型),主要由长英质组成,渗透率较差,总有机碳和游离烃含量偏低,生含油性较差;中碳块状长英质-黏土质混合质页岩(⑦型),有机碳含量较高,块状构造致使其孔隙度和渗透率均低,且黏土矿物含量高,储集性和可压性较差;高碳块状长英质-碳酸盐质混合质页岩(⑧型)与⑦型页岩储集性、生含油性特征相似,可压性较好,但可动性最差(表1)。

研究区HY7井阜宁组二段可划分为4种岩性、8种主要岩相类型,不同亚段主要岩相类型存在差异,统计各类岩相在不同亚段占比显示:Ⅴ亚段主要为②型、③型、④型、⑥型;Ⅳ亚段主要为①型、②型、④型、⑤型;Ⅲ亚段主要为①型、③型、⑥型;Ⅱ亚段为⑧型;Ⅰ亚段为⑦型。

3.2 不同岩相孔隙特征

3.2.1 中碳纹层状长英质-黏土质混合质页岩(①型)

①型页岩大多由亮色长英质纹层和暗色黏土质纹层互层组成,长英质纹层厚薄不等,介于10~100 μm,部分长英质纹层厚度可达1 mm,纹层边缘不平直,存在差异

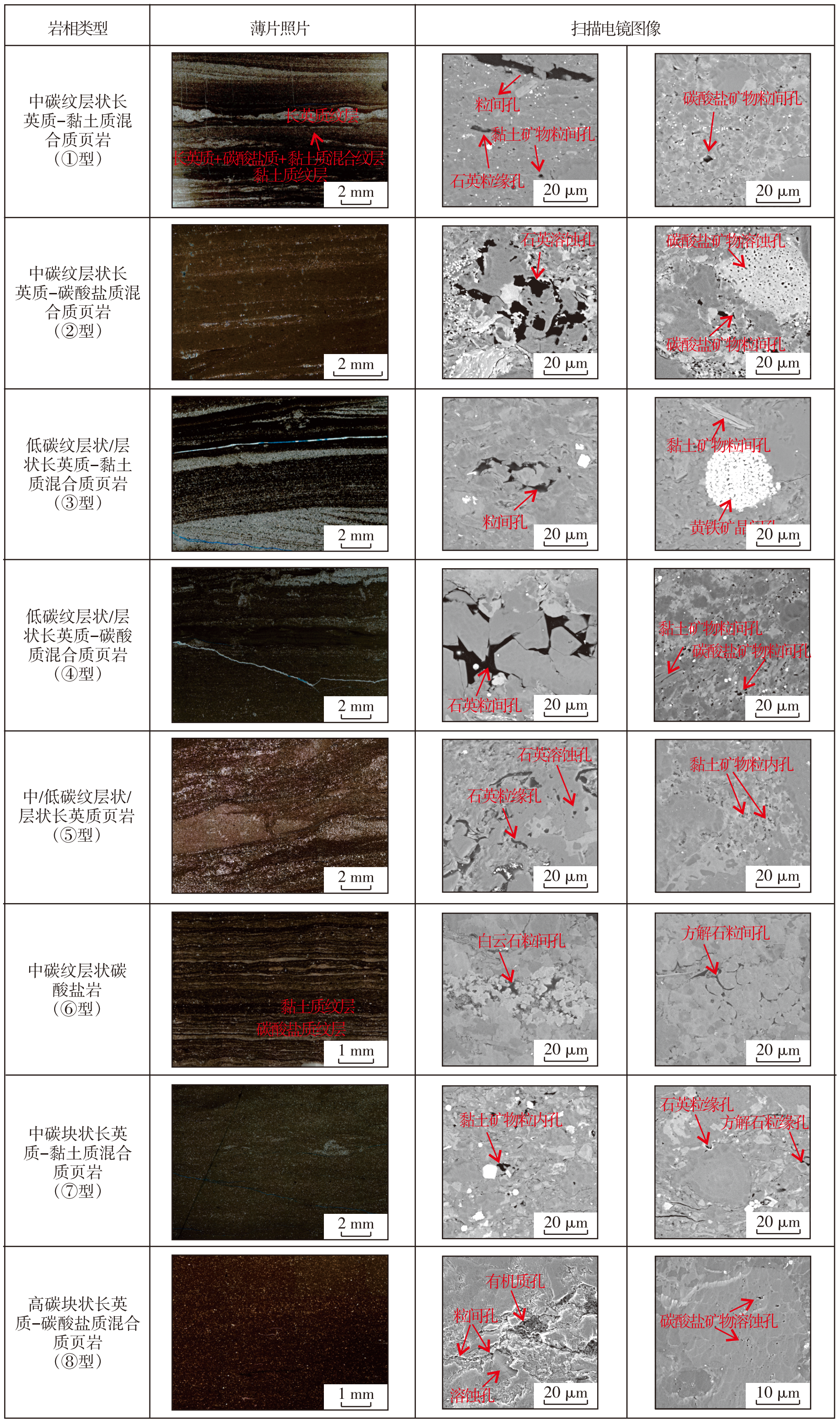


图4　苏北盆地高邮凹陷HY7井阜宁组二段各岩相薄片和扫描电镜图像

Fig. 4　Thin section and scanning electron microscopy images of different lithofacies in second member of Funing Formation in well HY7, Gaoyou Sag, Subei Basin

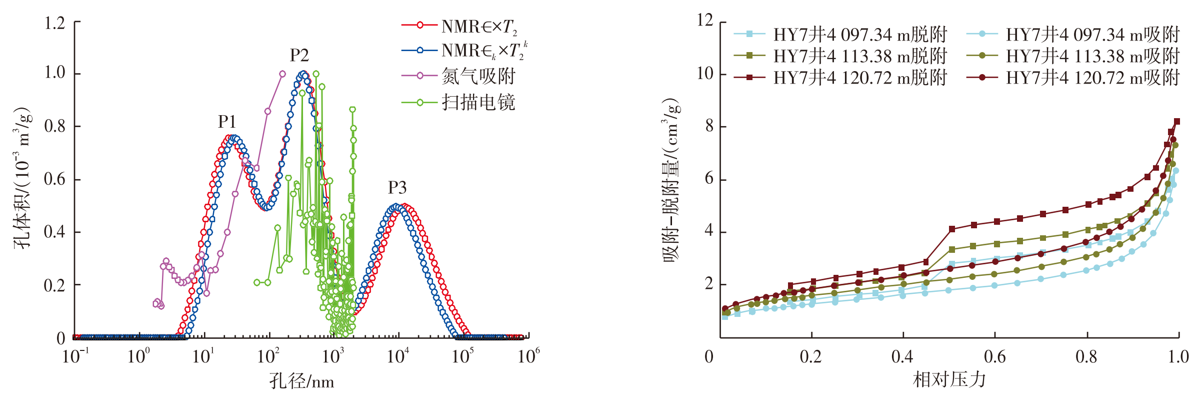
压实形成的揉皱状构造，长英质纹层占比介于40%～50%。孔隙以粒间孔、石英粒缘孔以及黏土矿物粒内孔等无机孔为主[46]，碳酸盐矿物含量相对较高时，可见孔径相对较小的碳酸盐矿物粒间孔，部分孔隙含油，局部偶见内部孔隙不发育的有机质。N_2吸附迟滞环类型以H2-H3型为主，发育宽平行板-墨水瓶过渡型孔隙，连通性一般。全尺度孔隙结构三峰特征明显，第二个峰（P2峰）和第三个峰（P3峰）发育较为明显，尤其P2峰更发育，孔径介于0～100 nm的微小孔占35%，大于100 nm的中大孔占65%（图5）。

表1　苏北盆地高邮凹陷HY7井阜宁组二段不同岩相参数对比

Table 1　Comparison of parameters of different lithofacies in second member of Funing Formation in well HY7, Gaoyou Sag, Subei Basin

主要岩相类型	含油性			可动性	储集性		可压性
	ω(TOC)/%	含油饱和度/%	S_1/(mg/g)	I_{OS}/(mg/g)	He孔隙度/%	渗透率/10^{-3} μm^2	脆性矿物含量/%
中碳纹层状长英质-黏土质混合质页岩(①型)	1.47	44.25	1.50	112	1.91	1.90	60.89
中碳纹层状长英质-碳酸盐质混合质页岩(②型)	1.13	41.77	1.38	126	2.05	1.22	73.69
低碳纹层状/层状长英质-黏土质混合质页岩(③型)	0.75	34.74	0.81	85	1.89	3.57	61.32
低碳纹层状/层状长英质-碳酸盐质混合质页岩(④型)	0.74	44.09	0.96	90	1.84	2.94	74.92
中/低碳纹层状/层状长英页岩(⑤型)	0.83	37.21	0.98	118	2.42	0.43	72.59
中碳纹层状碳酸盐岩(⑥型)	1.53	35.58	1.64	110	1.61	1.13	88.44
中碳块状长英质-黏土质混合质页岩(⑦型)	1.51	-	1.19	86	1.10	0.03	59.00
高碳块状长英质-碳酸盐质混合质页岩(⑧型)	2.31	-	1.44	62	0.98	0.01	80.50

注：ω(TOC)为总有机碳含量，%；S_1为游离烃含量，单位mg/g；I_{OS}为含油饱和度指数，单位mg/g。



a. 页岩孔隙分布　　b. 页岩N_2吸附-脱附

注：NMR∊×T_2为核磁共振线性拟合曲线；NMR∊$_k$×T_2^k为核磁共振幂指数拟合曲线。

图5　①型页岩孔隙分布和形态

Fig.5　Type ① shale pore distribution and morphology

3.2.2　中碳纹层状长英质-碳酸盐质混合质页岩(②型)

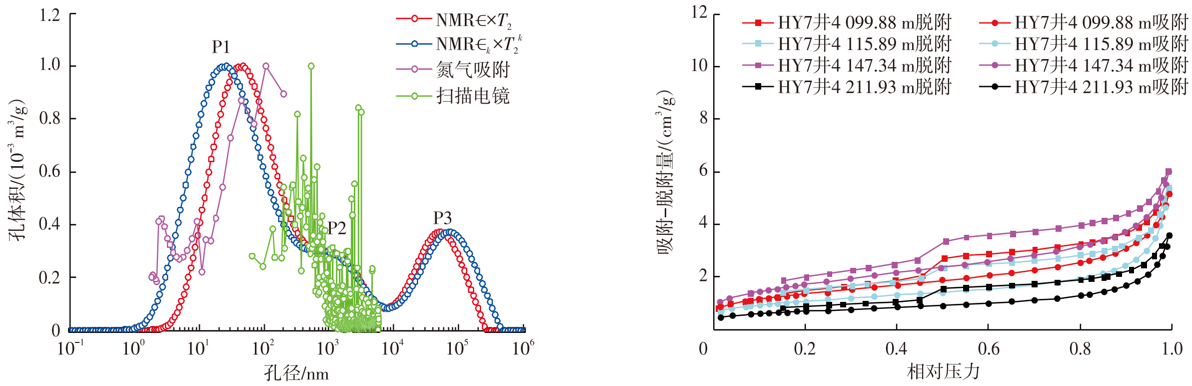
②型页岩除长英质纹层和黏土质纹层互层外，发育部分由长英质、碳酸盐质和黏土质组成的混积纹层，纹层较平直，单层厚度薄，纹层厚度介于50～150 μm，长英质纹层占比介于20%～30%。混积纹层中发育碳酸盐矿物与石英粒间孔、碳酸盐矿物粒缘孔以及石英溶蚀孔，孔内含油，主要发育H2-H3型孔隙，少量发育宽平行板H3型孔隙，连通性中等，孔隙结构以双峰特征为主，主要表现在第一个峰(P1峰)和P3峰发育相对明显，微小孔占55%，中大孔占45%(图6)。

3.2.3　低碳纹层状/层状长英质-黏土质混合质页岩(③型)

③型页岩与①型页岩纹层类型相似，均以长英质纹层和黏土质纹层互层为主，但③型纹层或层厚度不等，微米级、厘米级纹层均发育，部分纹层连续性较弱，亮色纹层与暗色纹层交界处，孔隙最为发育，以粒间孔、黏土矿物粒内孔、石英长石粒缘孔以及碳酸盐矿物晶间孔为主，局部发育黄铁矿晶间孔，微裂缝可切穿多个矿物颗粒。孔隙类型以H2-H3过渡型孔隙为主，孔隙结构三峰特征明显，P1和P2峰过渡自然，界限不明显，或与微小孔和中孔连通性较好有关，同①型页岩相似，中大孔亦发育占比60%(图7)。

3.2.4　低碳纹层状/层状长英质-碳酸盐质混合质页岩(④型)

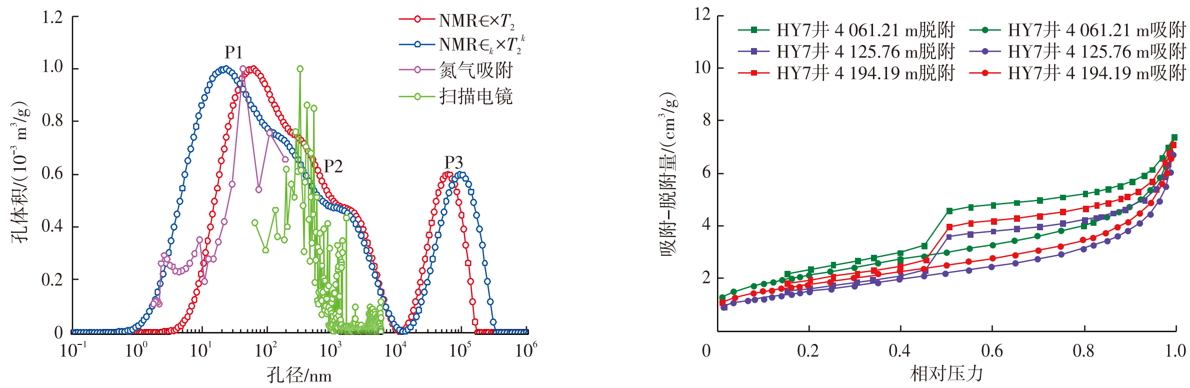
④型页岩与②型页岩岩相纹层类型相似，以长英质、黏土质纹层为主，发育部分长英质、黏土质、碳酸盐质混积纹层，纹层厚度不等，混积纹层厚度达4 mm，呈现出多类型、不等厚纹层互层沉积的特点。厚层长英质纹层内孔隙不发育，石英颗粒间被黏土矿物充填，偶见石英粒间孔，明暗混积的细粒纹层内孔隙发育，以黏土矿物粒内孔、粒缘孔为主，局部发育微裂缝。H2-H3型和H3型孔隙均发育，孔隙结构三峰特征明显，从P1到P3峰值逐渐降低，微小孔更为发育，占比达52%，中大孔占比48%(图8)。



a. 页岩孔隙分布　　b. 页岩N_2吸附-脱附

图6　②型页岩孔隙分布和形态

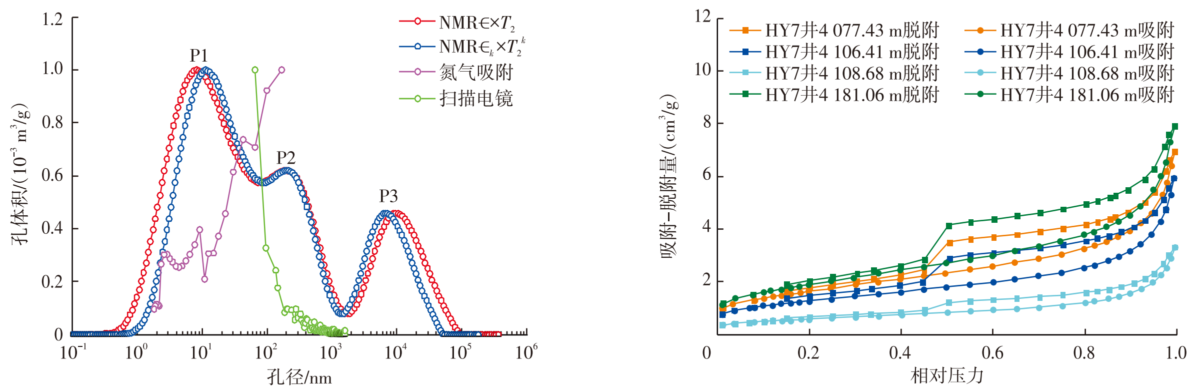
Fig.6　Type ② shale pore distribution and morphology



a. 页岩孔隙分布　　b. 页岩N_2吸附-脱附

图7　③型页岩孔隙分布和形态

Fig.7　Type ③ shale pore distribution and morphology



a. 页岩孔隙分布　　b. 页岩N_2吸附-脱附

图8　④型页岩孔隙分布和形态

Fig.8　Type ④ shale pore distribution and morphology

3.2.5　中/低碳纹层状/层状长英页岩(⑤型)

⑤型页岩纹层呈不等厚发育,多为长英质纹层和黏土质纹层互层,总有机碳含量较低的长英页岩长英质纹层厚度大,黏土质纹层占比少于20%,纹层连续性较差。页岩内发育含油石英粒缘孔和石英溶蚀孔,黏土矿物粒内孔在暗色黏土质纹层内发育,局部见有机质团块。H2-H3型和H3型孔隙均发育,孔隙连通性较好。孔隙结构三峰特征明显,与③型页岩相似,P1和P2峰界限不明显,中大孔占比较高达65%(图9)。

3.2.6　中碳纹层状碳酸盐岩(⑥型)

⑥型页岩纹层极为发育且连续性好,以碳酸盐质纹层和黏土质纹层互层为主,碳酸盐质纹层占比达50%以上,厚度多小于200 μm,层内发育方解石粒缘孔、白云石晶间孔等纳米级碳酸盐孔隙,纹层内零星发育微米级较

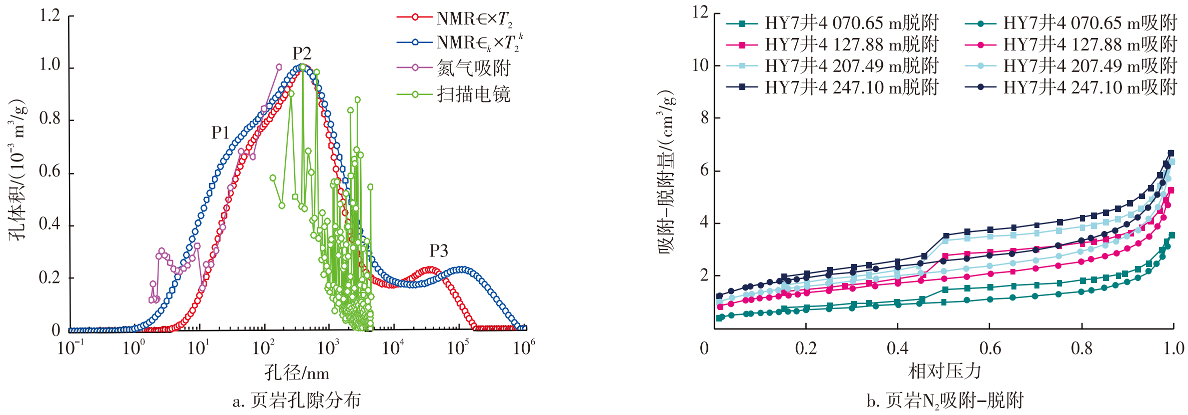


图9 ⑤型页岩孔隙分布和形态

Fig.9 Type ⑤ shale pore distribution and morphology

大石英粒间孔,局部见有机质和微裂缝。孔隙类型以H3型为主,连通性好。孔隙结构呈双峰,表现为P1、P3峰发育、P2峰不发育的特点,微小孔占比最高达72%(图10)。

3.2.7 中碳块状长英质-黏土质混合质页岩(⑦型)

⑦型页岩主要为块状构造,可见有机质团块,黏土矿物粒内孔、石英粒缘孔以及碳酸盐矿物晶间孔等无机孔发育,以H2-H3型孔隙为主,P3峰最为发育,占比74%,尽管该岩相呈块状,但是主要发育在Ⅰ亚段,埋深较下部①型和③型页岩相浅,加之长英质矿物含量较高,导致中大孔最为发育(图11)。

3.2.8 高碳块状长英质-碳酸盐质混合质页岩(⑧型)

⑧型页岩与⑦型页岩构造特征相似,矿物颗粒分

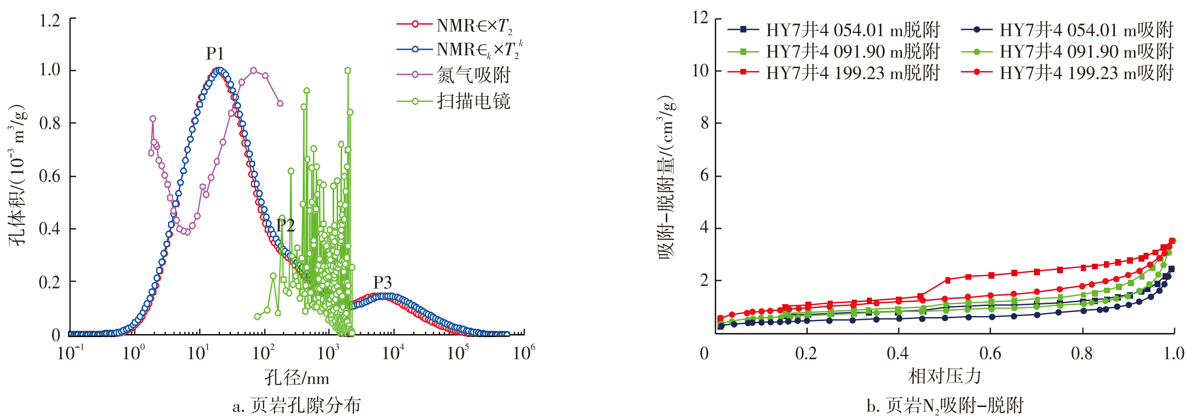


图10 ⑥型页岩孔隙分布和形态

Fig.10 Type ⑥ shale pore distribution and morphology

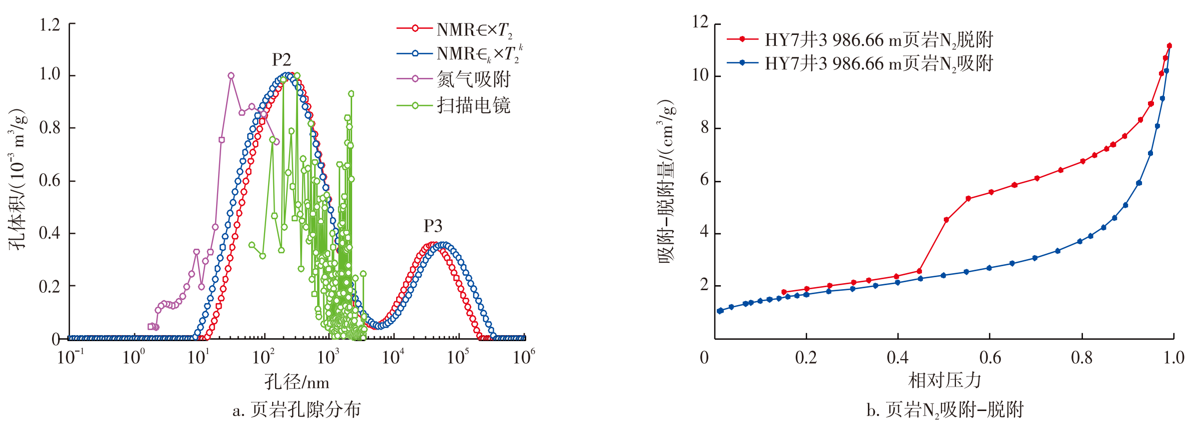
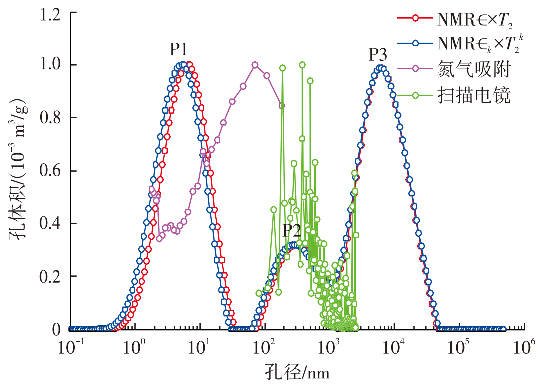


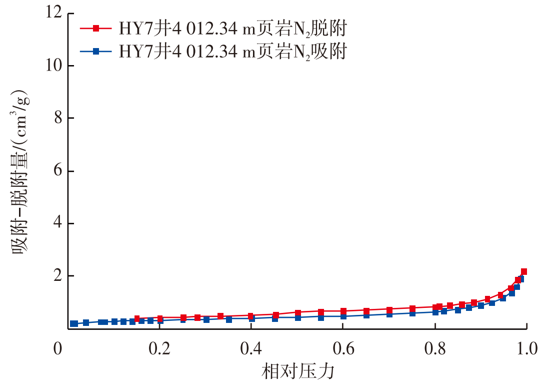
图11 ⑦型页岩孔隙分布和形态

Fig.11 Type ⑦ shale pore distribution and morphology

布均匀,尽管碳酸盐矿物含量相对较高,但碳酸盐矿物粒间孔不发育,主要发育黏土矿物粒内孔和石英粒缘孔,孔径相对较大,以H3型孔隙为主,孔隙连通性好,孔隙结构呈明显三峰分布,P1峰和P3峰发育,P2峰相对较弱,微小孔占比44%,中大孔占比56%(图12)。



a. 页岩孔隙分布



b. 页岩N_2吸附-脱附

图12　⑧型页岩孔隙分布和形态

Fig.12　Type ⑧ shale pore distribution and morphology

3.3　裂缝发育特征

裂缝是油气储集的主要空间之一,也是油气重要的输导通道[51]。HY7井阜宁组二段发育构造缝和非构造缝两大类裂缝[52-53]。构造缝是由于地质活动过程中,构造应力超过岩石破裂强度而形成,典型构造裂缝包括大型剪切缝(图13a)、树枝状张性缝(图13b)、张性缝(图13c)、白云石条带内张剪缝(图13d)、长英质纹层内张剪缝(图13e、图13f)、小断层(图13g)和滑脱缝(图13h)等。剪切缝和张剪缝是在区域构造应力作用下,页岩发生韧性剪切破裂形成,剪切缝多为高角度缝,缝面平直、延伸远,且缝面含油未被充填;张剪缝延伸距离较短,多垂直层面发育,受层控明显,形成于长英质条带或白云石条带内,部分被方解石充填,部分充填后被溶蚀形成储集空间;张性缝是岩石受到强于自身抗张强度形成的裂缝,往往多条不规则裂缝成树枝状、簇状或平行状出现,缝内多填充方解石脉,偶见方解石脉被溶蚀,可提供储集空间,此外,还发育小断层和滑脱缝等。非构造裂缝主要是层间裂缝,主要有层理缝(图13i)、层理缝面含油(图13j),不同纹层矿物成分不同,其接触面是岩石的薄弱面,岩石由地下处于高压环境,纹层间易出现层理缝,且由于生烃过程产生有机酸溶蚀碳酸盐岩矿物后,层理缝的存在为生长提供了生长空间,形成顺层方解石脉(图13k)和顺层方解石脉内溶蚀缝洞(图13l),微观尺度可见局部发育晶间缝或粒缘缝(图13m)。

4　储层影响因素

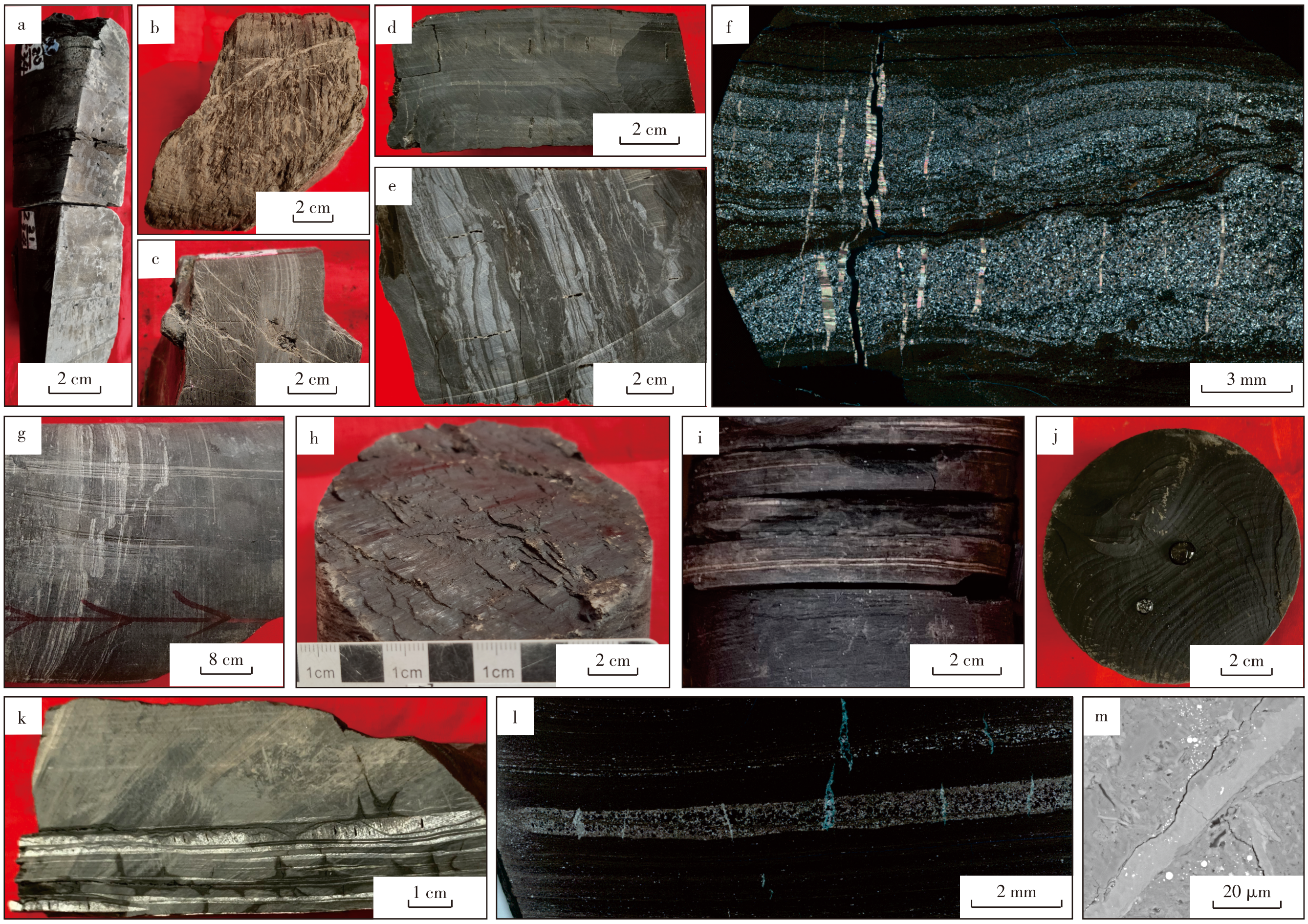
4.1　矿物组分

HY7井阜宁组二段页岩黏土矿物和长英质矿物呈一定的正相关性,碳酸盐矿物与黏土矿物呈较好的负相关性。长英质-黏土质混合质页岩和长英页岩以机械沉积作用为主[42,54],平均碳酸盐矿物含量低,分别为20.6%和16.4%,平均孔隙度相对较高,分别为2.0%和2.3%。气候处于转变期时化学沉积和机械沉积作用相对平衡,发育长英质-碳酸盐质混合质页岩,碳酸盐矿物含量为37.3%,孔隙度为1.84%;当化学沉积作用占主导时,发育碳酸盐岩,碳酸盐矿物含量为58.7%,孔隙度仅1.70%。长英质和黏土质矿物含量越高,孔隙越发育,孔隙度越高,碳酸盐矿物含量越高则反之(图14a)。

不同岩相均发育与长英质和黏土矿物相关的粒缘孔、粒间孔和溶蚀孔,当碳酸盐矿物含量较高时,发育一定的方解石或白云石粒间孔。矿物组分含量与孔隙结构也存在相关性,石英、长石等碎屑颗粒易发育粒间孔和粒缘孔,孔径达微米级孔,黏土矿物内部也可形成微米级狭长的粒内孔,碳酸盐矿物除发育少量溶蚀孔外,主要发育粒缘孔且孔径较小。统计结果表明:碳酸盐矿物和黏土矿物与微小孔占比具有一定的正相关性,与中大孔占比呈现负相关,长英质矿物与微小孔占比呈负相关性,与中大孔占比呈正相关,碳酸盐岩以H3型孔隙为主,连通性最好,其次是长英页岩,H2-H3和H3型孔隙均发育,长英质矿物或碳酸盐矿物单一组分越高,孔隙连通性越好(图14)。

4.2　纹层发育情况

沉积构造影响页岩孔隙度和渗透率,纹层状和层状页岩孔隙度相差不大,平均He孔隙度均接近1.9%,块状构造对页岩孔隙度影响较大,平均孔隙度为1.04%,沉积构造对渗透率影响较大,纹层状页岩渗透



注：a为大型剪切缝，HY7井3 974.2 m；b为树枝状张性缝，HY7井3 987.3 m；c为张性缝，HY7井4 047.54 m；d为白云石条带内张剪缝，HY7井4 146.47 m；e为长英质纹层内张剪缝，HY7井4 040.0 m；f为长英质纹层内张剪缝，HY7井4 142.39 m；g为小断层，HY7井4 149.32 m；h为滑脱缝，HY7井4 021.25 m；i为层理缝，HY7井4 124.0 m；j为层理缝面含油，HY7井4 107.34 m；k为顺层方解石脉，HY7井4 023.68 m；l为顺层方解石脉内溶蚀缝洞，HY7井4 230.19 m；m为粒缘缝，HY7井4 036.1 m。

图13　苏北盆地高邮凹陷HY7井阜宁组二段岩心裂缝特征

Fig. 13　Fracture characteristics of cores from second member of Funing Formation in well HY7, Gaoyou Sag, Subei Basin

率最高，平均渗透率2.25×10^{-3} μm^2，块状页岩平均渗透率仅0.02×10^{-3} μm^2，渗透率可高112倍（图14b）。沉积构造对孔隙结构影响不大，构造不同但岩性相同的页岩平均中大孔占比介于58%～60%（图14c），但结合矿物组分的影响，若纹层中长英质矿物含量越高，中大孔占比应当越大。

纹层发育程度影响页岩含油性、可动性，①型、②型、⑥型页岩总有机碳含量中等，S_1相对较高，⑥型页岩S_1最高达1.64 mg/g，含油饱和度指数同样处于高值，均大于110 mg/g，这类岩相纹层发育且类型多样，孔隙内含油明显，含油性和可动性均较好；③型、④型页岩纹层相对不发育，多为层状页岩平均S_1和OSI均较低，含油性和可动性较差；⑤型页岩长英质纹层发育，TOC含量仅0.74%，尽管OSI相对较高，但是S_1较低，含油性较差；⑦型、⑧型页岩平均TOC、S_1含量高，但为块状结构，OSI最低为62.5 mg/g，可动性最差。

4.3　裂缝有效性

HY7井阜宁组二段有效裂缝主要包括：未被充填的大型构造剪切缝是储集性效性较好的裂缝，在阜宁组二段各层段均有发育，缝面多含油，但由于平面上存在较强的构造运动，对保存存在不利影响；纹层间的层理缝在地下处于开启状态，取至地表常压环境后，压力释放，可能会闭合，纹层的发育程度应当可以反映层理缝的发育情况。HY7井发育4种类型的纹层，不同纹层之间可形成层理缝，岩心观察纹层缝面含油明显（图13j），是页岩油最主要的储集空间之一。一方面，由于其晶体垂直沉积界面的生长方式，不仅可以顺层沟通油气，也可以与垂直或近垂直裂缝沟通，提供垂向运移通道；另一方面，方解石脉再次被溶蚀后，可以形成更多的储集空间，与上覆和下伏泥岩相比，白云石或砂质条带脆性矿物含量高，层内易发育由压实作用形成的高角度小型张剪缝，此类裂缝为层控裂且缝内基本含油。无机孔为页岩油提供大量储

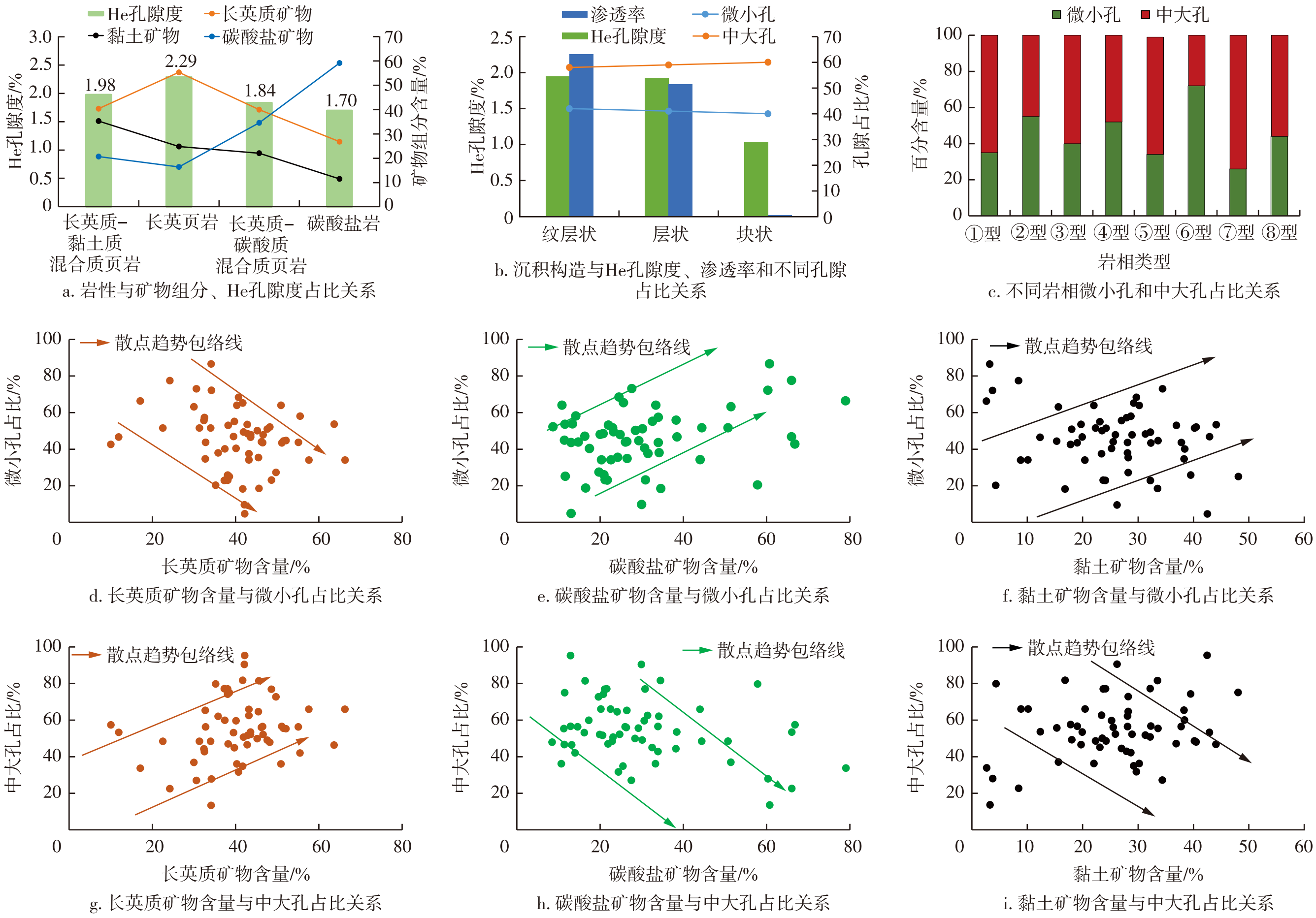


图14　苏北盆地高邮凹陷HY7井阜宁组二段页岩矿物组分、沉积构造与储层孔隙特征关系

Fig. 14　Relationship between shale mineral composition, sedimentary structures, and reservoir pore characteristics in second member of Funing Formation in well HY7, Gaoyou Sag, Subei Basin

集空间，但有效裂缝不仅是页岩油优质的储集空间，还提供了渗流通道，能够有效沟通孔、缝，压裂后易形成复杂的孔-缝系统，极大地改善了页岩储渗性能。

5　结论

1)苏北盆地高邮凹陷阜宁组二段纵向发育8种主要岩相类型和4种纹层类型，①型、②型以及⑥型页岩"四性"评价有利，属优势岩相类型，主要发育在Ⅲ亚段中下部、Ⅳ亚段以及Ⅴ亚段中下部。

2)储集空间包括孔隙和裂缝，①型页岩储集空间以石英粒间孔和黏土矿物粒内孔为主，③型页岩发育石英、碳酸盐矿物粒间孔以及黏土矿物粒内孔，⑥型页岩以碳酸盐矿物粒间孔为主。构造裂缝包括剪切缝、张性缝、张剪缝、小断层和滑脱缝，非构造裂缝包括层理缝、顺层方解石脉和微观晶间缝或粒缘缝。

3)储层受矿物组分、纹层发育程度和裂缝有效性影响，长英质、黏土质矿物含量越高，孔隙越发育，且长英质矿物含量越高，中大孔占比越大；纹层状页岩孔隙度和渗透率高于其他构造类型页岩；未被充填的大型构造剪切缝、层理缝、顺层方解石脉和层内张剪缝为有效储集空间。

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