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高一过成熟陆相断陷盆地页岩与海相页岩储层特征对比

——以徐家围子断陷沙河子组和四川盆地龙马溪组为例

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摘要:我国陆相断陷盆地含气页岩发育广泛,以往主要作为气源岩研究,对其储集性及影响因素的研究较少,亟须开展相应研究来明确陆相断陷盆地页岩储层发育主控因素。选取松辽盆地徐家围子断陷沙河子组与四川盆地龙马溪组页岩,利用有机地化、全岩分析、扫描电镜、低温氮气吸附和核磁共振等实验,对比研究高一过成熟陆相断陷盆地和海相含气页岩储层特征差异并探讨主控因素。研究表明:沙河子组页岩形成环境多样,有机质类型以Ⅲ型(腐殖型)为主,黏土矿物含量高,胶结石英发育,黏土相关孔和石英粒间孔为主要孔隙类型,比表面积小但孔径大,储层发育受压实作用、黏土矿物转化和煤层发育的控制;龙马溪组页岩形成于陆棚环境,有机质类型以Ⅰ型(腐泥型)为主,有机质丰度高,生物成因石英含量高,有机孔和黏土相关孔为主要孔隙类型,有机质类型和成熟度主控孔隙发育。整体上,沙河子组页岩储层发育条件稍差于龙马溪组,但平原沼泽微相页岩紧邻煤层发育,自生胶结石英发育、伊蒙混层比例高,储层有机质丰度高、可压性好、孔体积和比表面积较大、孔隙发育较好,可作为潜在有利目标开展进一步评价研究。

关键词:页岩气;孔隙发育;储层差异;龙马溪组;沙河子组;陆相断陷盆地

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Comparison of reservoir characteristics between continental shale from faulted basin and marine shale under high-over mature stage: Taking Shahezi Formation in Xujiaweizi faulted basin and Longmaxi Formation in Sichuan Basin as an example

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Abstract: Gas bearing shale is widely developed in continental faulted basins in China. In the past, it was mainly studied as the gas source rock, and there was little research on its reservoir and influencing factors. It is urgent to carry out corresponding researches to clarify the main controlling factors of shale reservoir development in continental faulted basins. For the researches, the shale of Shahezi Formation in Xujiaweizi fault depression of Songliao Basin and Longmaxi Formation in Sichuan Basin are selected, and the difference of reservoir characteristics between high over mature continental fault depression basin and marine gas shale is compared and studied by the experiments such as organic geochemistry, whole rock analysis, scanning electron microscope, low-temperature nitrogen adsorption and nuclear magnetic resonance. The research shows that the shale formation environment of Shahezi Formation is diverse, the organic matter type is mainly type III, the clay mineral content is high, the cemented quartz is

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developed, the clay related pores and quartz intergranular pores are the main pore types, the specific surface area is small but the pore diameter is large, and the reservoir development is controlled by compaction, clay mineral transformation and coal seam development; Longmaxi Formation shale was formed in shelf environment. The type of organic matter is mainly type I, with high abundance of organic matter and high content of biogenic quartz. Organic pores and clay related pores are the main pore types, and the type and maturity of organic matter mainly control the development of pores. On the whole, the shale reservoir development conditions of Shahezi Formation are slightly worse than those of Longmaxi Formation, but the plain swamp microfacies shale is developed close to the coal seam, the authigenic cemented quartz is developed, the proportion of Yimeng mixed layer is high, the reservoir has high organic matter abundance, good compressibility, large pore volume and specific surface area and good porosity development, which can be used as a potential favorable target for further evaluation and research.

Keywords: shale gas; pore development; reservoir difference; Longmaxi Formation; Shahezi Formation; continental faulted basin

页岩气作为一类新兴的非常规油气资源,展现了巨大的资源潜力和开发价值^[1-2]。从沉积环境上,我国含气页岩类型可分为海相、海陆过渡相和陆相3种,其中,海相含气页岩主要分布在四川盆地,上奥陶统五峰组一下志留统龙马溪组已实现页岩气工业开发^[3];陆相含气页岩分布面积更广,主要在松辽盆地沙河子组、济阳拗陷沙河街组、鄂尔多斯盆地延长组和四川盆地自流井组^[4-6]等;海陆过渡相集中分布在扬子区龙潭组、华北地区山西组和准噶尔盆地滴水泉组等^[7-8]。整体上,陆相和海陆过渡相页岩气尚处于勘探初期,资源潜力及甜点富集条件需要进一步研究。

与含气海相页岩相比,陆相页岩形成环境多样,既能在拗陷盆地三角洲—湖相沉积背景发育(如鄂尔多斯延长组),也可在断陷盆地扇三角洲、辫状河三角洲—湖相背景发育(如松辽盆地沙河子组),并且成熟度(R_o)分布跨度大^[9](1.0%~3.0%),从成熟到高过成熟阶段均有发育。前人对陆相含气页岩储层特征、含气性、富集规律等方面开展了大量研究^[5-6],且与海相龙马溪组的差异进行了对比,认识到有机质类型及成熟度是导致海相和陆相页岩储层发育差异的重要控制因素^[10]。然而,上述研究或对比主要针对处于成熟—高成熟阶段($R_o < 2.0\%$)拗陷期湖相页岩,对断陷期沉积页岩研究较少,尤其是高一过成熟阶段,该类型页岩的沉积类型更为复杂,在扇三角洲平原沼泽微相、扇三角洲前缘亚相和浅湖—深湖亚相中均有发育,并且多作为气源岩研究,对其自身页岩气储层发育情况及含气性特征急需开展相关评价及对比研究。

因此,以徐家围子断陷沙河子组含气页岩为例,利用有机地化、全岩分析、扫描电镜、低温氮气

吸附和核磁共振等实验,分析高一过成熟阶段断陷盆地不同沉积环境陆相页岩的储层发育特征,并与典型海相龙马溪组页岩进行对比,揭示不同沉积环境页岩储层孔隙类型及发育主控因素,丰富页岩储层发育相关理论,同时明确沙河子组页岩气优质储层形成条件,为断陷盆地陆相页岩气勘探开发提供一定参考。

1 区域地质概况

陆相页岩选取松辽盆地徐家围子断陷沙河子组高一过成熟页岩(图1a),沙河子组埋深介于2 500~4 200 m,厚度介于300~600 m。该套地层以页岩(此处页岩包括泥岩和页岩,是泥页岩的统称)为主,混杂煤层、砂砾岩和砂岩等薄层(图1c)。在辫状河/扇三角洲—湖泊沉积背景下^[11],暗色泥岩以混合质页岩和黏土质页岩为主,分布在平原沼泽微相、前缘亚相和浅湖—深湖亚相中(图1c),由盆外到盆内,陆源碎屑输入减少,页岩厚度逐渐变大。沙河子组形成于盆地断陷期,经历了早期快速沉积^[12](图1e),在青山口组开始大量生气,部分滞留后形成页岩气藏,喜马拉雅期构造抬升幅度小,对沙河子组页岩气破坏程度弱;由于页岩和砂岩频繁互层,缺乏有效顶底板保存条件,含气页岩层压力系数偏低(小于1.4)。目前,对FS12井进行现场解析气测试,恢复后含气量变化范围介于1.51~3.12 cm³/g,均值为2.29 cm³/g,显示出较好的页岩气勘探前景,急需深入开展页岩储层发育特征及主控因素等相关研究。

海相页岩气甜点评价体系已较成熟,可为高一过成熟阶段断陷期陆相页岩气勘探提供一定借鉴。选择四川盆地彭水地区(包括桑拓坪向斜和武隆向

斜)龙马溪组页岩为例来开展对比(图1b),该套地层形成于深水和浅水陆棚环境(图1d)^[13],自下而上陆源碎屑输入增加,沉积速率增大,岩性从硅质页岩过渡为混合质页岩、粉砂质页岩和黏土质页岩。龙马溪组具备较好的顶底板条件^[14](图1f),但后期经历了燕山和喜马拉雅期两次强构造运动,页岩气发生散失,尤其是位于盆地边缘的彭水地区(现今埋深介于2 200~3 500 m),地层抬升幅度大、抬升时间早。在该区已钻探了多口常压页岩气井^[15],如LY1井,压力系数低(小于1.3),也呈现出较好的商业开发价值。

前人研究表明,构造运动对含气页岩孔隙结构会产生影响^[16]。一方面构造抬升、应力释放,产生大量微裂缝,改善储层物性,但不利于页岩气保存;另一方面构造抬升还会导致页岩气散失、压力系数降低,改变孔隙空间的受力状态,有机孔圆度变差,但对无机孔(受脆性矿物支撑)影响较弱。整体上,与沉积环境、成岩及成烃过程相比,构造运动对两个地区含气页岩基质孔隙结构的影响相对较弱。

2 实验方法及样品选择

考虑埋深和沉积相带,在沙河子组和龙马溪组优选页岩样品49块(表1)。其中,平原沼泽微相14块、前缘亚相11块、浅湖亚相8块、深水陆棚相11块和浅水陆棚相5块(表1)。开展全岩矿物衍射(XRD)、扫描电镜、核磁共振、低温氮气吸附和核磁共振等实验,以对比高一过成熟阶段断陷期陆相和海相含气页岩储层特征,揭示含气页岩储层发育控制因素。

核磁共振利用纽迈公司MicroMR23-060H-1型核磁共振分析仪开展,分别测得干燥状态(烘干12 h, 110 °C)和饱和油状态(正十二烷)下的核磁共振弛豫时间(T_2 谱);利用FEI Quanta 200F场发射扫描电镜进行观察,获取不同视域背散射(BSE)和二次电子(SEM)图像,观察石英等矿物形态及孔隙特征;低温氮气吸附在Micromeritics ASAP2460比表面积与孔隙率分析仪上开展,分别利用多分子层吸附模型(BET模型)和毛细管凝聚理论(BJH模型)得出比表面积、孔体积和孔径分布;利用布鲁克(Bruker)X射线衍射仪进行矿物组分分析,测得样品全岩矿物组成及黏土矿物相对含量。

3 页岩岩石学特征对比

3.1 有机地化特征

沙河子组页岩形成于断陷期陆相扇三角洲—湖相沉积环境,有机质多来自陆地动植物和少量湖相生物^[17],有机质类型以腐殖型(Ⅲ型)为主,局部为腐泥腐殖型(Ⅱ₂型),有机质丰度(TOC)整体偏低(表1),介于0.33%~5.33%,平均为1.61%,其中,平原沼泽微相页岩TOC值较高(均值约为1.9%),其次为前缘亚相(1.62%)和浅湖亚相(1.21%)。龙马溪组页岩形成于海相陆棚沉积环境,有机质主要来自海洋浮游生物和藻类^[18],类型以腐泥型(I型)—腐殖腐泥型(Ⅱ₁型)为主,龙马溪组页岩TOC较高,介于0.90%~6.46%,平均为3.32%,深水陆棚相(平均为4.39%)明显高于浅水陆棚相(平均为1.41%)。龙马溪组页岩 R_o 介于2.1%~3.31%^[19],平均值为2.53%;沙河子组页岩 R_o 介于1.6%~3.25%^[20](平均为2.24%),两者均处于高一过成熟阶段。

3.2 页岩矿物组成

矿物组成对页岩气储层评价至关重要^[21]。一方面,矿物颗粒间形成孔隙能为页岩气赋存提供空间,另一方面,脆性矿物含量也影响着储层压裂效果。沙河子组与龙马溪组矿物组成类似(表1),主要由石英、长石和黏土矿物组成,其次为碳酸盐矿物和黄铁矿,少见菱铁矿、铁白云石等。但在主要造岩矿物含量上,两者差异较大。

对于沙河子组页岩(表1),黏土矿物含量最多,介于31.3%~63.1%,平均为47.7%,其次为石英,介于23.6%~58.8%,平均为34.7%,而长石(平均为16.1%)和碳酸盐矿物(平均为1.04%)较少。不同沉积相带页岩石英含量差异较大,平原沼泽微相石英含量最高(均值为37.7%),其次为浅湖和前缘亚相(分别为32.9%和32.1%)。黏土矿物类型以伊蒙混层和伊利石为主(图2a),随埋深增加,伊蒙混层占比降低。平原沼泽微相页岩伊蒙混层比例最高(均值为26.2%),明显大于埋深相近的浅湖和前缘亚相,这主要与其紧邻煤层发育,易于形成酸性成岩环境^[22],抑制蒙脱石向伊利石的转换有关。

与断陷期陆相页岩相比,龙马溪组页岩表现出高石英、低黏土、黄铁矿发育的特征。石英含量介于

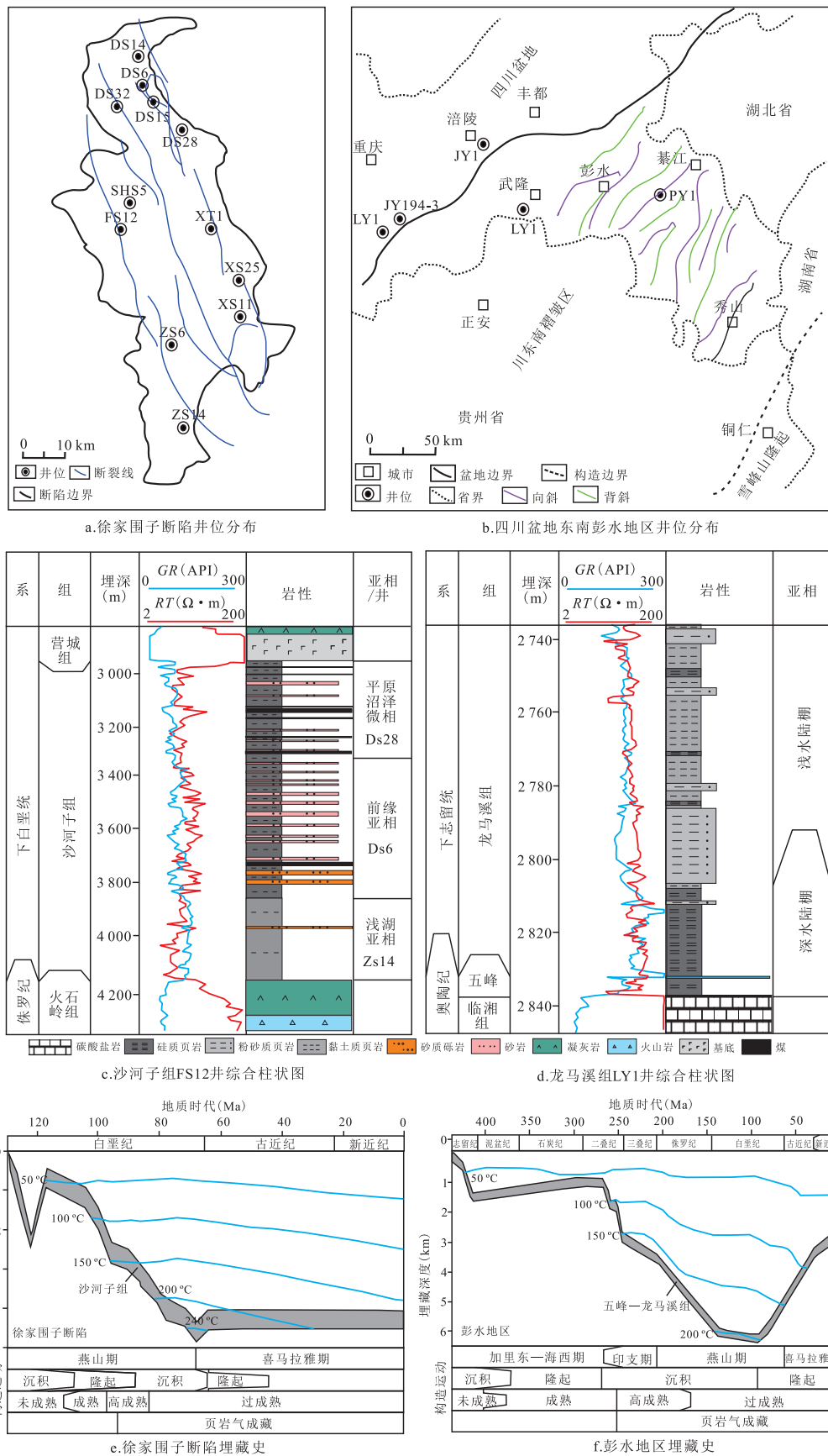


图1 龙马溪组及沙河子组构造位置、综合柱状图及埋藏史

Fig. 1 Regional structure, stratigraphic column and burial history of Longmaxi and Shahezi Formations

27.9%~79.1%,均值为51.3%,黏土矿物均值为29.1%,黄铁矿均值为3.4%,黄铁矿含量明显高于沙河子组。深水陆棚相石英含量(平均为52.9%)高于浅水陆棚(平均为47.7%),但长石含量相反,说明浅水陆棚相页岩受陆源输入影响更大^[23]。黏土类型以伊利石为主(图2b),相对含量均值为59%,其次为绿泥石(平均为22%)。

页岩储层中石英的发育与沉积环境及成岩作用密切相关。石英主要来源包括两大类,陆源输入和自生石英^[24],自生石英又有生物成因和胶结成因2种。自生石英的颗粒结晶度低,长度通常小于5 μm(图3),明显小于陆源石英颗粒(图3c)。沙河子组页岩石英与TOC相关性较弱(图4),表明生物成因石英不发育。沙河子组石英多为陆源输入^[25],但也发育自生

胶结石英,主要充填于粒间孔隙中或分布在有机质周围(图3a)。同时,自生石英多发育在平原沼泽页岩中,这可能与其邻近煤层有关^[26]。胶结石英颗粒对沙河子组页岩的孔隙保存和脆性也具有积极意义。龙马溪组页岩石英多为生物成因的自生石英^[27],石英含量与有机质丰度呈明显正相关(图4)。同时,生物成因石英与有机质共存(图3e),对龙马溪组页岩的抗压性和有机孔隙的保存起到积极作用。

4 页岩孔隙结构特征对比

4.1 孔隙类型

沙河子组页岩孔隙以无机孔为主,主要包括黏土相关孔、粒间孔和溶蚀孔^[28],有机孔少量发育

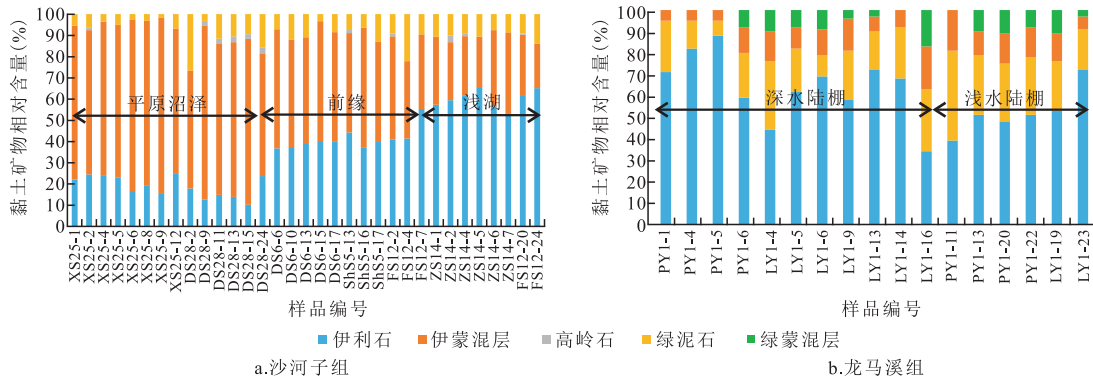
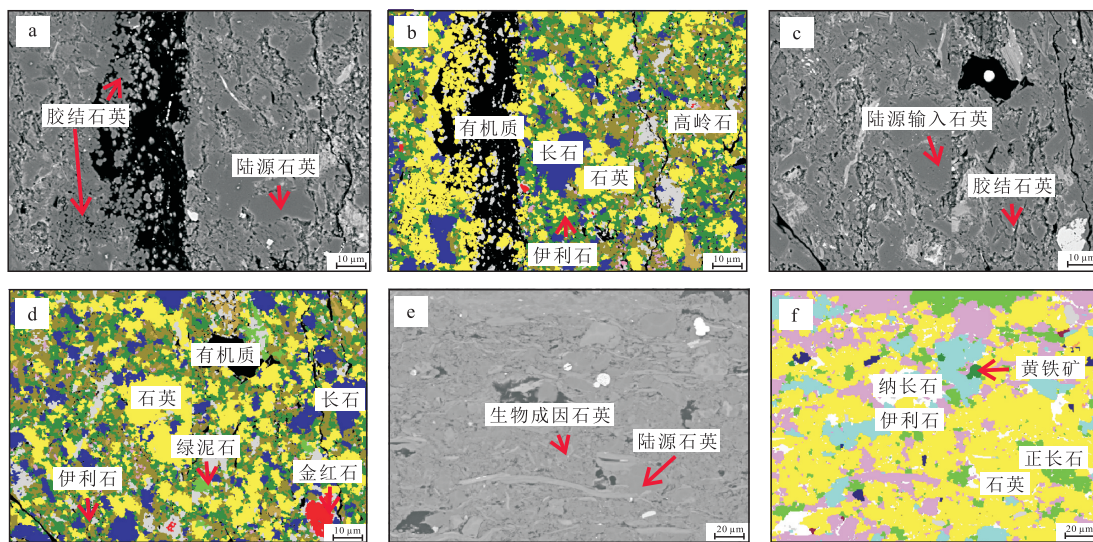


图2 沙河子组和龙马溪组页岩黏土矿物相对含量

Fig. 2 Relative content of clay minerals of Shahezi and Longmaxi shale



注:a.胶结成因石英,DS28-2样品,沙河子组;b.为a图对应矿物扫描;c.陆源输入石英,DS28-2样品,沙河子组;d.为c图对应矿物扫描;e.生物成因石英,JY194-3-1样品,龙马溪组;f.为e图对应矿物扫描。

图3 沙河子组与龙马溪组石英成因分析

Fig. 3 Analysis of quartz genesis of Shahezi and Longmaxi shales

(图5a—图5c)。其中,黏土相关孔最多,该类孔隙形态多样,从长条状到不规则圆形均有发育(图5a—图5c);长石溶蚀孔形态较为复杂,多被黏土矿物充填(图5c);粒间孔隙主要为石英颗粒边缘孔隙,发育于脆性矿物与塑性矿物接触部位(图5a、图5b);沙河子组页岩有机质内部孔隙不发育,仅仅在有机质边缘形成有机质收缩缝(图5a)。海相龙马溪组页岩主要发育有机质孔、粒间孔、晶间孔和黏土相关孔等(图5d—图5f)。其中,有机孔的数量明显占优,多呈密集的蜂窝状排列,孔隙连通性较好(图5d),为页岩气提供了丰富的储集空间;龙马溪组石英粒间孔、溶蚀孔和黄铁矿晶间孔隙也有一定的发育(图5e),大多被有机质充填(图5f)。

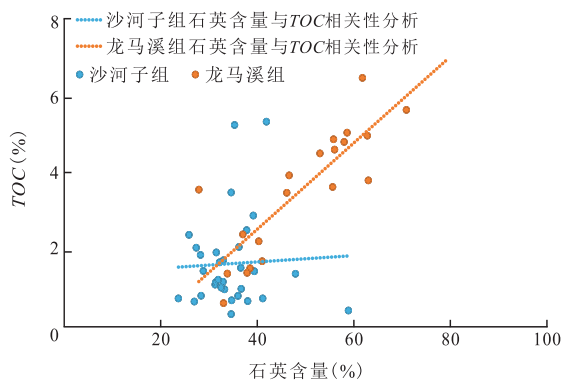


图4 沙河子组与龙马溪组石英与TOC相关性
Fig. 4 Relativity between quartz and TOC in Shahezi and Longmaxi Formations

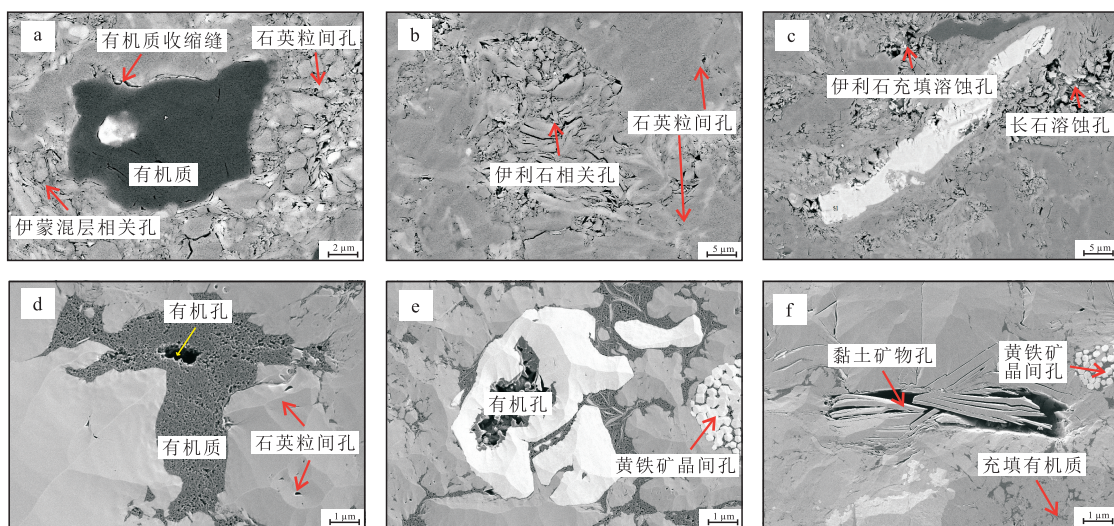
4.2 孔隙结构

页岩孔隙结构主要包括页岩储层的比表面积、孔体积及孔隙的大小分布,直接影响着页岩气的储集性能、吸附能力和渗流特征等方面。基于低温氮气吸附^[29]和核磁共振^[30]实验来表征页岩孔隙结构特征,并分析主控因素。

4.2.1 低温氮气吸附孔隙表征

按国际理论与应用化学联合会(IUPAC)分类方案^[31],沙河子组和龙马溪组页岩样品的氮气吸附等温曲线均属于IV型(图6),均发育滞后回环,形态主要对应H2型和H3型,分别指示页岩主要发育细颈广体的墨水瓶型孔隙和平行板状孔隙,这与页岩中发育有机孔和黏土相关孔密切相关^[29]。沙河子组页岩样品的最大吸附量分布范围介于4~12 cm³/g,明显低于龙马溪组页岩(图6)。

龙马溪组页岩孔径分布曲线呈多峰(图7),峰值分别位于1~2 nm、3 nm和8~10 nm附近;沙河子组页岩孔径分布为双峰,峰值位于2~3 nm和30~80 nm,表明沙河子组页岩储层大孔更发育。沙河子组页岩孔径分布范围介于6.71~17.4 nm,均值为10.9 nm;比表面积分布范围介于2.5~8.03 m²/g,平均为4.9 m²/g;孔体积分布范围介于0.007~0.02 cm³/g,平均为0.012 9 cm³/g(表1)。其中,平原沼泽微相页岩具有



注:a.石英粒间孔、伊蒙混层相关孔和有机质收缩缝,XS25-9样品,沙河子组;b.伊利石相关孔和石英粒间孔,DS28-2样品,沙河子组;c.长石溶蚀孔及伊利石充填溶蚀孔,ZS14-5样品,沙河子组;d.有机孔和石英粒间孔,LY1-4样品,龙马溪组;e.有机孔和黄铁矿晶间孔,LY1-4样品,龙马溪组;f.黏土矿物孔、黄铁矿晶间孔和充填有机质,PY1-6样品,龙马溪组。

图5 沙河子组与龙马溪组孔隙发育类型情况
Fig. 5 Pore development of Shahezi and Longmaxi Formation

表1 样品选样信息、矿物组成及孔隙特征参数
Table 1 Sample selection information, mineral composition and pore characteristics parameters

样品编号	深度(m)	沉积环境	石英 (%)	长石 (%)	碳酸盐岩 (%)	黄铁矿 (%)	黏土矿物 (%)	比表面积 (m ² /g)	孔体积 (cm ³ /g)	平均孔径 (nm)	有机质丰度 (%)
XS25-1	4 217.64	平原沼泽	47.91	5.27	0.88	0	45.94	3.353	0.010	12.0	1.37
XS25-2	4 218.54	平原沼泽	58.88	0	0.91	0	40.21	5.106	0.013	10.2	0.42
XS25-4	4 219.84	平原沼泽	34.67	16.15	0.69	0	48.49	2.752	0.010	13.8	0.69
XS25-5	4 269.37	平原沼泽	31.50	10.67	0	0	57.83	4.028	0.013	12.6	1.93
XS25-6	4 270.27	平原沼泽	32.93	7.70	0.68	0	58.69	4.746	0.016	13.1	1.17
XS25-8	4 271.87	平原沼泽	35.28	15.98	0.77	0	47.97	3.361	0.012	14.5	5.24
XS25-9	4 273.17	平原沼泽	26.95	8.94	0.62	0	63.17	3.840	0.017	17.4	0.66
XS25-12	4 274.87	平原沼泽	34.58	11.29	0	0	54.13	2.796	0.009	12.6	3.48
DS28-2	3 018.88	平原沼泽	41.13	15.96	1.52	0	41.39	6.464	0.020	12.1	0.74
DS28-9	3 021.58	平原沼泽	39.16	10.89	0	0	49.95	5.824	0.020	13.7	1.45
DS28-11	3 022.63	平原沼泽	39.39	14.02	0	0	46.59	5.832	0.019	12.9	1.44
DS28-13	3 023.58	平原沼泽	36.56	19.03	0	0	44.41	6.260	0.020	12.6	1.53
DS28-15	3 024.78	平原沼泽	28.35	17.95	0.33	0	53.37	5.611	0.018	12.7	0.81
DS28-24	3 060.69	平原沼泽	41.89	8.01	1.72	0	48.38	7.301	0.019	10.4	5.33
DS6-6	3 543.04	前缘	39.16	9.20	0	0.50	51.14	7.225	0.017	9.5	2.89
DS6-10	3 839.26	前缘	36.22	21.29	1.16	0.63	40.70	2.849	0.008	11.1	2.07
DS6-13	3 840.36	前缘	33.21	20.07	0	0	46.72	5.704	0.012	8.5	0.97
DS6-15	3 841.56	前缘	25.86	15.18	0	0	58.96	8.030	0.016	8.2	2.39
DS6-17	3 842.46	前缘	34.59	19.29	1.25	0	44.87	7.193	0.015	8.2	0.33
ShS5-13	3 879.65	前缘	28.24	30.52	0.76	0	40.48	4.010	0.009	8.8	1.87
ShS5-16	3 880.15	前缘	31.27	20.07	0	0	48.66	4.756	0.012	9.9	1.09
ShS5-17	3 882.75	前缘	37.79	24.78	3.17	0	34.26	3.068	0.008	10.0	2.51
FS12-2	3 885.28	前缘	23.66	33.80	4.69	0	37.85	4.561	0.012	10.9	0.74
FS12-4	3 886.98	前缘	36.66	28.56	0	0	34.78	4.187	0.011	10.7	0.98
FS12-7	3 888.88	前缘	27.37	27.40	0	0	45.23	2.734	0.008	11.9	2.05
ZS14-1	4 028.85	浅湖	32.53	5.46	5.90	0	56.11	5.626	0.011	7.9	1.02
ZS14-2	4 030.10	浅湖	31.38	5.45	5.23	0	57.94	6.834	0.013	7.8	1.16
ZS14-4	4 031.30	浅湖	32.97	25.10	1.08	0.53	40.32	2.832	0.009	13.1	1.73
ZS14-5	4 032.40	浅湖	32.18	7.83	9.52	0.56	49.91	7.298	0.012	6.7	1.67
ZS14-6	4 033.50	浅湖	28.81	5.48	3.34	0.25	62.12	6.361	0.012	7.3	1.45
ZS14-7	4 035.00	浅湖	31.91	9.97	1.96	0	56.16	6.816	0.012	7.0	1.22
FS12-20	4 095.48	浅湖	36.01	26.53	0	0	37.46	2.743	0.009	12.9	0.80
FS12-24	4 103.94	浅湖	38.01	30.67	0	0	31.32	2.558	0.008	11.8	0.67
PY1-1	2 157.78	深水陆棚	40.30	12.60	3.70	0.70	42.70	18.193	0.008	3.6	2.22
PY1-4	2 155.68	深水陆棚	27.90	5.60	3.00	5.70	57.80	8.433	0.003	4.3	3.56
PY1-5	2 152.89	深水陆棚	46.10	9.80	10.30	4.70	29.10	17.888	0.010	3.8	3.48
PY1-6	2 151.20	深水陆棚	55.60	7.10	9.30	4.70	23.30	18.270	0.010	3.9	3.63
PY1-11	2 138.83	浅水陆棚	38.50	19.60	7.50	2.80	31.60	11.320	0.006	4.6	1.52
PY1-13	2 134.77	浅水陆棚	79.10	2.80	1.90	0.90	15.30	8.868	0.005	4.5	1.88
PY1-20	2 114.85	浅水陆棚	37.90	20.30	10.90	2.00	28.90	8.522	0.007	5.2	1.40
PY1-22	2 106.35	浅水陆棚	49.60	12.90	3.90	1.50	32.10	9.848	0.006	4.3	0.90
LY1-4	2 832.33	深水陆棚	70.90	4.40	5.40	3.60	15.70	25.074	0.023	4.6	5.63
LY1-5	2 830.93	深水陆棚	61.80	7.50	4.90	4.00	21.80	29.425	0.020	3.8	6.46
LY1-6	2 828.68	深水陆棚	55.80	8.70	8.00	4.40	23.10	24.564	0.015	4.1	4.87
LY1-9	2 824.42	深水陆棚	58.60	6.50	8.70	4.40	21.80	24.558	0.015	3.9	5.04
LY1-13	2 819.13	深水陆棚	56.00	7.70	9.90	4.00	22.40	21.290	0.012	4.0	4.60
LY1-14	2 817.70	深水陆棚	62.80	6.30	7.10	3.20	20.60	24.152	0.015	4.1	4.96
LY1-16	2 811.65	深水陆棚	46.60	12.80	5.80	4.70	30.10	21.671	0.013	3.9	3.93
LY1-19	2 794.40	浅水陆棚	33.80	7.20	6.40	3.80	48.80	12.172	0.007	4.4	1.38

较大的孔体积、比表面积、平均孔径(表1),浅湖和前缘亚相次之;孔隙以介孔(2~50 nm)为主(大于70%),其次为宏孔(大于50 nm),微孔(小于2 nm)占比最低(小于5%),尤其是平原沼泽微相,宏孔占比更多,微孔占比更少(图7)。与沙河子组相比,龙马溪组页岩具有相似的孔体积,但平均孔径明显偏小、比表面积偏大(表1),平均孔径均值为4.19 nm,比表面积均值达17.3 m²/g;孔隙以介孔和微孔为主,宏孔比例低(小于5%)。

4.2.2 核磁共振孔隙表征

核磁共振弛豫时间(T_2 谱)也能反映孔隙结构信息,借助于其他实验(比如低温氮气吸附)标定,能更全面揭示页岩储层不同尺度空间分布^[32],低温氮气吸附主要表征小于100 nm孔隙,而 T_2 谱的表征范围更宽(0.1~1 000 nm)。通过对比发现,低温氮气吸附孔径分布与页岩饱和油 T_2 谱的分布形态基本一

致,峰值重叠(图8),说明两者均能揭示页岩主要孔隙空间,利用低温氮气吸附标定 T_2 谱,可进一步刻画大于100 nm孔径的分布。

整体上海相、陆相页岩样品 T_2 谱分布范围介于0.01~1 000 ms,呈双峰态(图9a),主峰靠左,多小于5 ms,次峰多大于10 ms,表明页岩以较小孔为主,也局部发育较大孔或微裂缝。龙马溪组页岩样品 T_2 谱的差异较大,深水陆棚主峰位置(大于1 ms)明显大于浅水陆棚,指示两者的孔隙类型有较大差异;而沙河子组不同沉积环境页岩储层 T_2 谱范围变化小,平原沼泽微相页岩主峰稍大,说明孔隙类型差异小。

标定后孔径分布与 T_2 谱有所不同(图9b),这与页岩中绿泥石、黄铁矿等铁磁性矿物含量不同导致弛豫率差异有关^[33]。沙河子组页岩孔径分布范围宽,横跨几纳米至几个微米,主峰多位于10~200 nm。其中,平原沼泽微相(浅)主峰最大(90 nm左右),其次为平原沼泽微相(深)和前缘亚相,浅湖亚相孔径

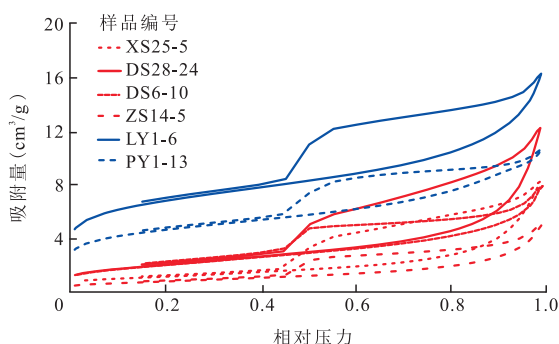


图6 沙河子组和龙马溪组低温氮气吸附—脱附曲线
Fig. 6 Low-temperature nitrogen adsorption-desorption curves of Shahezi and Longmaxi formations

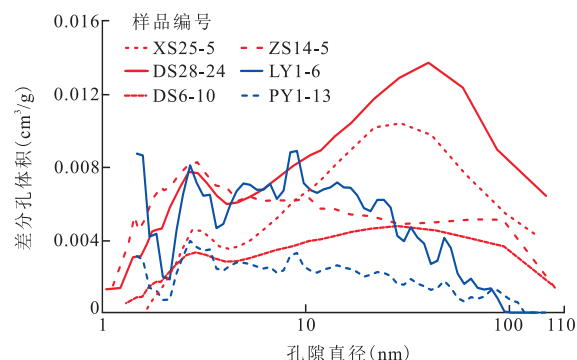
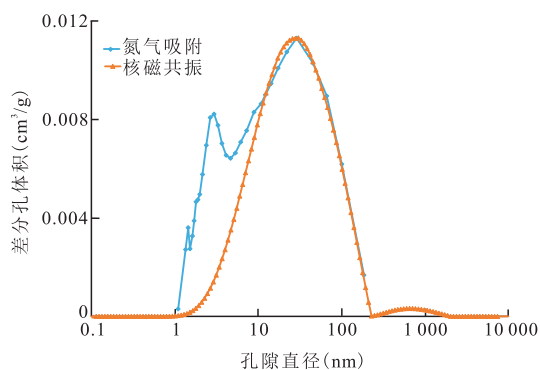
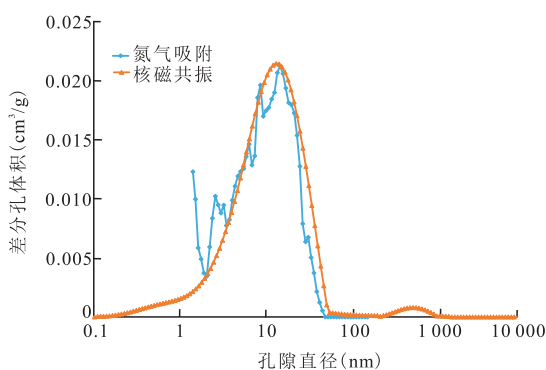


图7 沙河子组和龙马溪组页岩BJH孔径分布
Fig. 7 BJH pore size distribution of shale of Shahezi and Longmaxi Formations



a.沙河子组DS6-6样品, 标定系数: 7



b.龙马溪组LY1-4样品, 标定系数: 6

图8 沙河子组和龙马溪组低温氮气吸附和 T_2 谱对比

Fig. 8 Comparison of pore size distribution calculated by low-temperature nitrogen adsorption and saturated oil T_2 spectra for Shahezi and Longmaxi shales

最小,主峰位于10 nm附近。而龙马溪组页岩孔径分布明显小于沙河子组,主峰多小于10 nm,浅水陆棚和深水陆棚页岩的差异较小。

4.3 不同沉积相页岩孔隙发育特征

为揭示不同类型孔隙对储集空间的贡献,深化不同沉积环境页岩储层成因机制的认识,基于物质平衡方法^[34]开展了孔隙发育类型定量评价。对于相同沉积环境的页岩,有机质类型及矿物组成相近,经历了相似的成岩演化作用(成熟度相近),单位质量有机质或矿物贡献的孔体积或比表面积可假定为一个定值,因此,可根据多块样品优化求解单位质量矿物的贡献量,实现样品中不同类型孔隙贡献的定量计算。研究共细分平原沼泽微相(深)、平原沼泽微相(浅)、前缘亚相、浅湖亚相、深水陆棚和浅水陆棚亚相6类页岩,结合扫描电镜观察划分出有机质、石英、长石、伊利石、伊蒙混层和绿泥石6种主要组分,分别对应有机质孔、石英粒间孔、溶蚀孔、黏土相关孔等。

图10展示了沙河子组和龙马溪组不同沉积环境

下不同类型孔隙对比表面积和孔体积的贡献。整体上,沙河子组页岩孔体积主要由石英粒间孔、溶蚀孔、黏土相关孔贡献,比表面积主要由黏土相关孔贡献,有机孔对两者的贡献均较少,比例小于10%。从孔体积贡献来看,不同沉积环境页岩发育的孔隙类型差异较大,在平原沼泽微相中,石英粒间孔对孔体积贡献最大,其次为黏土相关孔和长石溶蚀孔,随埋深增加,长石溶蚀孔比例降低、黏土相关孔比例增多;对于浅湖亚相页岩,黏土相关孔起主要贡献,石英粒间孔和溶蚀孔的比例低于30%;前缘亚相与浅湖类似,以黏土相关孔为主,主要是伊蒙混层孔。对于龙马溪组页岩,有机质孔对孔体积的贡献比例超过50%,尤其是深水陆棚相页岩(大于70%),有机质孔对比表面积的贡献更大,比例超过80%,这与有机质孔大量发育有关。

5 优质储层发育控制因素

结合孔隙类型贡献定量评价,分析高一过成熟

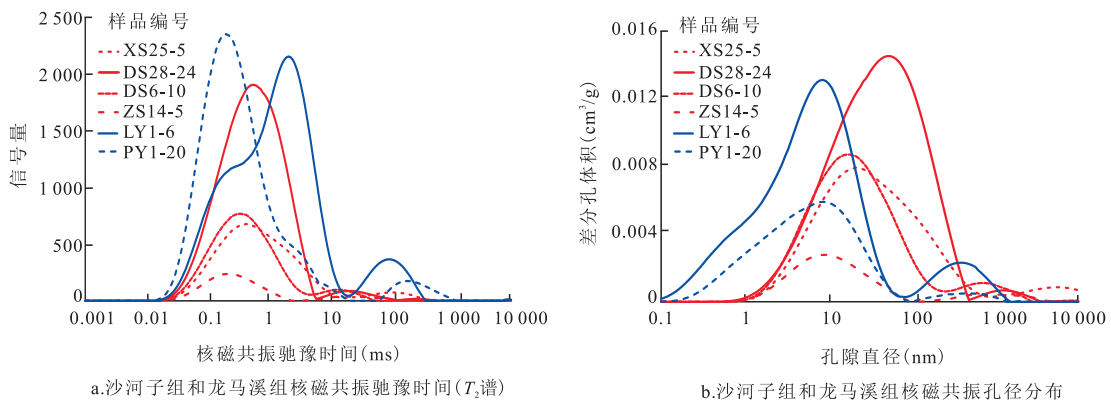


图9 沙河子组和龙马溪组页岩 T_2 谱及标定孔径分布

Fig. 9 T_2 spectra and calibrated pore size distribution of shales in Shahezi and Longmaxi Formation

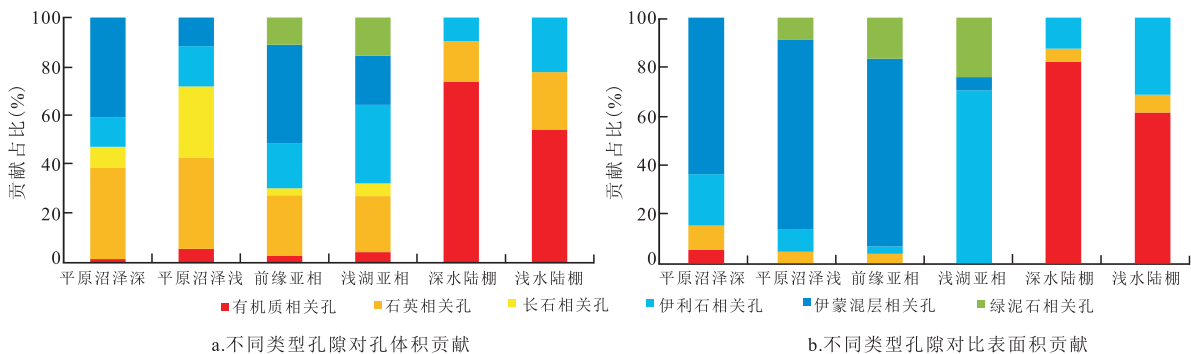


图10 沙河子组和龙马溪组页岩不同类型孔隙对孔体积和比表面积的贡献

Fig. 10 Contribution of different types of pores to pore volume and specific surface area in shales of Shahezi and Longmaxi Formation

阶段海相和断陷期陆相含气页岩储层控制因素,明确海、陆相页岩优质储层的发育条件。龙马溪组页岩孔隙发育受控于有机质富集程度和成熟度两大指标,处于适当成熟度的富有机质页岩有利于优质储层的发育。龙马溪组页岩形成于陆棚沉积环境,利于有机质富集和保存,I型干酪根先生油,后裂解生气,同时产生大量蜂窝状有机孔,提供丰富的储集空间,生物成因石英与有机质伴生发育,有效增加地层骨架的抗压性^[35]。但当成熟度过高时($R_o > 3.6\%$),干酪根会发生石墨化^[36],有机孔减小、孔隙度降低;当成熟度过低时,有机孔不发育。综合分析,龙马溪组的有利储层为深水陆棚相页岩储层,其适宜的成熟度、高有机质含量、高脆性矿物为优质储层的发育提供了有利条件。

对于沙河子组页岩储层,有机质的影响微弱,主要由压实作用、黏土矿物转化和煤层发育共同控制优质储层的发育。有机质对储层发育影响较小,主要因为沙河子组页岩Ⅲ型干酪根发育,难以形成大量蜂窝状有机孔^[21,37],对孔体积及比表面积贡献低,难以为有机质富集提供储集空间(图10)。压实作用对沙河子组页岩储层孔隙发育影响明显,随埋深增大,孔体积和比表面积呈现明显降低趋势(图11a、图11b),而平均孔径则呈先降低后增大的趋势(图11c)。孔体积和比表面积随埋深降低,一方面与沙河子组页岩脆性矿物含量低、黏土含量高,岩石抗压能力弱有关;另一方面与沙河子组页岩与砂岩频繁互层,顶底板条件差,缺乏超压对孔隙的保护有关^[12,38]。黏土矿物转化会导致孔隙减小^[39],随埋深增加,黏土矿物转化程度增加,伊蒙混层向伊利石转化

增多,伊利石含量增多,造成页岩平均孔径降低(图12)。而与煤层共生对页岩储层发育起积极作用^[22,26],一方面与煤层共生,有利于胶结石英的发育,增加脆性矿物含量,增强孔隙的抗压性;另一方面,煤层在成岩作用中呈酸性环境,能有效抑制黏土矿物中伊利石的转化,增大页岩的平均孔径。沙河子组平原沼泽微相就紧邻煤层发育,黏土矿物转化程度较弱,伊利石含量低,造成其在较大的埋深下仍有较大的平均孔径(图11c)。综合分析,沙河子组平原沼泽微相页岩储层紧邻煤层发育,有机质丰度及石英含量高,黏土矿物中伊蒙混层含量多,保证了良好的有机质富集、脆性和孔隙发育条件,可作为潜在优质储层开展下一步含气性及综合甜点评价研究。

6 结论

通过沙河子组与龙马溪组页岩在矿物组成、孔隙发育特征和孔隙发育主控因素等方面的对比,揭示了高一过成熟阶段陆相断陷盆地页岩与海相页岩气储层差异及发育主控因素,认识到:

1) 断陷盆地陆相页岩可形成于平原沼泽微相、前缘亚相和浅湖—深湖相沉积环境之中,有机质类型以Ⅲ型干酪根为主,黏土含量高,自生石英多为胶结成因,可压性稍差。海相页岩形成于陆棚沉积环境中,以I型干酪根为主,有机质丰度高,自生石英多为生物成因,与有机质呈共生关系,具有较高可压性。

2) 海、陆相页岩储层孔隙类型及发育主控因素不同。沙河子组页岩储层孔隙类型以黏土相关孔、

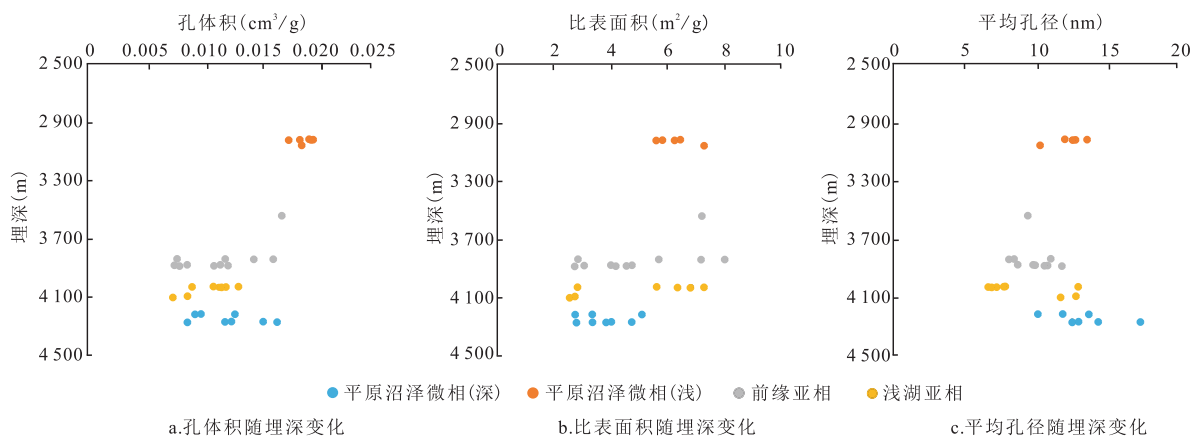


图11 沙河子组不同沉积环境孔隙参数随埋深变化

Fig. 11 Variation of pore structure parameters with buried depth for Shahezi shales in different depositional environments

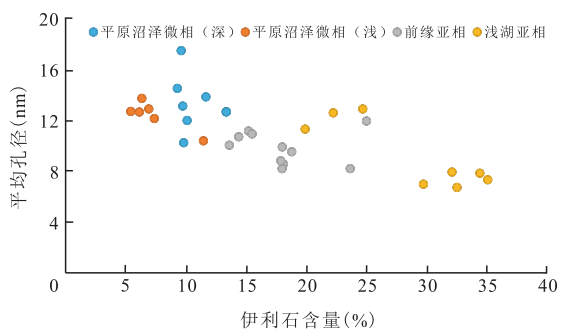


图12 沙河子组不同沉积环境页岩的伊利石与平均孔径关系

Fig. 12 Relation between illite and mean pore size of Shahezi shales in different depositional environments

石英粒间孔等无机孔隙为主,比表面积明显偏低,但孔径较大,孔隙发育受控于压实作用、黏土矿物转化和煤层发育;龙马溪组孔隙类型以有机孔为主,比表面积大、平均孔径小,孔隙发育与有机质丰度和成熟度有关。

3) 沙河子组平原沼泽微相较前缘和浅湖亚相页岩紧邻煤层发育,有机质丰度及自生胶结石英含量高,确保了有机质富集和储层的脆性,酸性成岩环境抑制伊利石转化,黏土矿物中伊蒙混层占比高,孔体积及孔径较大,孔隙发育较好。其中,平原沼泽微相埋深较小的页岩储层有机质丰度更高,脆性矿物更多,孔隙更为发育,勘探条件更优,可作为页岩气有利潜在目标开展进一步评价研究。

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