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海陆过渡相页岩储层研究现状与展望

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摘要:中国广泛分布石炭系—二叠系海陆过渡相富有机质页岩,开发利用其中赋存的页岩气对于缓解巨大的能源和环境压力具有重要意义。从沉积环境、地球化学、矿物学、岩石物理学等方面概述了不同区域、不同层位代表性海陆过渡相页岩的关键属性,并与典型海相和陆相页岩进行了对比和总结。结果表明,对于过渡相富有机质页岩,三角洲体系中的沼泽相及障壁-潟湖体系中的潟湖和沼泽相具备更优越的页岩气成藏条件。过渡相页岩与煤层、砂岩层频繁互层,岩相垂向上变化极其复杂,意味着其具有高度的非均质性。同时,TOC 含量垂向变化较大,高低值交互出现,平均 TOC 含量总体高于海相和陆相页岩,表明其巨大的页岩气勘探开发潜力。海陆过渡相页岩有机质类型以Ⅲ型为主,Ⅱ型为辅,腐殖质显微组分约占 70%,热演化程度普遍处于成熟—高成熟阶段,少数达到过成熟,总体介于陆相和海相页岩之间。过渡相页岩粘土含量较高,给压裂开发带来了较大的挑战。储集空间以粒间孔和粒内孔为主,有机质中可能普遍存在大量的不可见有机孔,但受有机质类型及成熟度的影响,它们理论上不是过渡相页岩的主要孔隙类型。高的粘土含量可能导致海陆过渡相页岩最低的孔隙度及较低的渗透率。海陆过渡相页岩的甲烷吸附能力分布范围较大,存在甲烷吸附能力较强的页岩,可能是受煤层的影响。目前,海陆过渡相页岩气储层的研究已经取得了很多重要的研究成果,但资源评价方法的不完善、“甜点”识别与预测技术不成熟、优势成藏环境研究不深入及“多气共采”可行性不确定,仍然是当前过渡相页岩气勘探开发面临的主要问题。

关键词:页岩气;海陆过渡相;资源潜力;孔隙结构;研究现状
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Abstract: The Carboniferous-Permian transitional organic-rich shales are widely distributed in China, and the development of shale gas in them is of great significance to alleviate the huge energy and environmental pressure.The key properties of representative transitional shales in different regions and layers are summarized from the aspects of sedimentary environments, geochemistry, mineralogy, and petrophysics, and compared with typical marine and continental shales.The results show that for the transitional shales, the swamp facies in the delta system and the lagoon and swamp facies in the barrier-lagoon system have superior conditions for shale gas accumulation. The transitional shales are frequently interbedded with coal and sandstone layers, and the vertical change of lithofacies is extremely complex, implying that they are highly heterogeneous.At the same time, the vertical variation of TOC content is large, and the average TOC content is generally higher than that of marine and continental shales, which means that it has great potential for shale gas exploration and development.The organic matter type of marine-continental transitional shales are mainly Type III, supplemented by

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Type II, humic maceral accounts for about 70%. The degree of thermal evolution is generally in the stage of maturity to high maturity, with a few reaching over-maturity, and generally between continental and marine shales. The high clay mineral content of transitional shales poses a great challenge to fracturing development. The reservoir space is dominated by intergranular pores and intragranular pores, and a large number of invisible organic matter pores prevalent in organic matter, but they are not theoretically the dominant pore type in transitional shales due to the type and maturity of the organic matter. High clay content may result in the lowest porosity and low permeability of marine-continental transitional shales. The methane adsorption capacity of transition shales are distributed in a wide range, and there are shales with strong methane adsorption capacity, which may be influenced by coal seams. At present, many important research results have been achieved in the study of marine-continental transitional shale gas reservoirs. However, the imperfection of resource evaluation methods, the immaturity of "sweet spot" recognition and prediction technology, the lack of in-depth study on favorable reservoir formation environment, and the uncertainty of the feasibility of the co-mining of various unconventional natural gas resources are the main problems in the exploration and development of transitional shale gas.

Key words: shale gas; marine-continent transitional; tesource potential; pore structure; research status

页岩气现在已成为油气勘探的热点,中国也已大力投入到页岩气的勘探开发中[1-2]。多旋回的构造演化使海相、过渡相及陆相富有机质页岩在中国均有发育。近年来,中国在海相及陆相页岩气的勘探中均获得了较大进展,而针对海陆过渡相页岩的研究仍然较欠缺[3]。

石炭纪—二叠纪是海相向陆相转变的关键时期,该时期海陆过渡相富有机质页岩在中国广泛沉积,主要分布在中西部的塔里木、鄂尔多斯、沁水等盆地,以及南方下扬子、滇黔贵等地区[4-5]。研究认为海陆过渡相页岩气成藏规模较小,单独开发的经济价值不高,但其通常与煤层、致密砂岩层等互层,有机质丰富,成熟度适中,累积厚度较大,资源前景较好[5-6],且与煤层气有诸多相似的特征及共性开采手段,理论上可实现"多气共采"的效果。由此看来,海陆过渡相页岩气具备良好的资源潜力和经济效益,如若成功开采,不仅可以提高页岩气产量,而且对于缓解中国巨大的能源和环境压力意义重大。

近年,针对海陆过渡相页岩的研究已陆续开展,对于其基本的地质属性及资源潜力也有了初步的认识[7-10],然而仍然缺乏全面、详细的总结,与典型海相和陆相页岩的对比研究薄弱。对此,笔者跨越不同层位、不同区域,从沉积环境、地球化学、矿物学、岩石物理学等方面概述了具代表性的海陆过渡相页岩的关键属性,并与典型海相和陆相页岩进行了对比和总结,以期为认识海陆过渡相页岩基本属性及下一步的勘探开发提供参考。

1 沉积环境

众所周知,沉积环境对有机质的聚集和保存、矿物组成、孔隙发育等有重要的控制作用。尽管目前针对海陆过渡相页岩气藏特征已有大量的研究成果[2, 5, 8, 11],但沉积环境对过渡相页岩储层的控制作用仍不清晰。因此,明确优势沉积环境,对于过渡相页岩气资源潜力评价及"甜点"预测至关重要。过渡相富有机质页岩通常沉积于受海洋和河流共同控制的浅水环境(缺氧-氧化环境及混合有机质来源),这与海相页岩有很大不同[4]。常见的沉积环境包括滨岸平原、三角洲、障壁滨岸等[5-6, 12],但并不是每一种沉积环境都有利于富有机质页岩的发育。长期以来,对富有机质页岩的成因机制一直存在较大争议[13-14],尤其对于具有复杂沉积环境的海陆过渡相页岩争议更大。海陆过渡相页岩有机质来源复杂,古气候控制着源区的植被丰度、岩石风化程度、径流量等,由于过渡相环境复杂的水动力条件,异地的Ⅲ型干酪根(高等植物有机质)通常经河流搬运后与Ⅱ型干酪根混合[6],这些碎屑流可以提供丰富的陆源有机质,但对有机质浓度也有一定的稀释作用[15]。河流的输入量及间歇性的海水侵入,决定了过渡相环境的水介质条件,进而影响了其中的生物组合及保存条件。底层水较低的含氧量可以为有机质提供了良好的保存条件,适宜的沉积速率也有利于有机质的积累[4]。半受限、低水动力的浅海盆地(潟湖)和缓坡滨海平原(潮坪),以及沼泽等环境有利于植物和微生物的生长发育,可以产生丰富的有机质,较低的含氧量有利于有机质的保存,因而它们是有机质聚集的理想场所[4, 12]。然而,大量研究表明,对于过渡相富有机质页岩,保存条件可能并不是决定性的控制因素[6]。三角洲沉积带距物源较近,温暖湿润的气候促进了陆地植物的生

长,提供了充足的有机质来源[15],在三角洲平原(沼泽)中,河流携带陆源碎屑以较高的速率注入盆地,也可使其成为良好的有机质聚集场所[4]。

不同沉积环境下石英的成因不同,自生石英(生物硅)可以提高页岩的脆性,而陆源石英则对脆性影响很小[11]。大量研究证实,页岩中石英与 TOC 含量正相关,表明其为生物成因,反之为碎屑成因[16]。Liang 等[6]指出,潮坪和障壁岛体系下页岩中石英与 TOC 含量的相关性很差,推测其石英多为陆源石英,而前三角洲和三角洲前缘环境下的页岩中石英多为生物成因。过渡相页岩中石英的复杂成因可能是频繁的海侵和海退引起的沉积环境的变化所致[11]。黄铁矿不仅是一种重要的脆性矿物,对有机质生烃也有一定的催化作用,有利于孔隙网络的发育[17]。此外,压裂液与页岩矿物间的相互作用也可使黄铁矿溶解,从而产生更多的孔隙空间[18]。众所周知,还原环境更有利于黄铁矿的形成和保存[19],研究发现潮坪和障壁岛体系中页岩常见黄铁矿,而三角洲体系中的页岩黄铁矿较稀少[6],说明潮坪和障壁岛体系具有更有利于黄铁矿发育的还原环境。因此,从黄铁矿保存条件的角度看,潮坪和障壁岛体系可以更大程度地改善页岩储层质量。

沉积环境对页岩孔隙网络也有重要影响[6-7]。翟正等[20]比较了中美两国典型的页岩沉积环境,指出还原微咸水的沉积环境更易于形成非均质性强的沉积物,有利于页岩纹层的发育。潮坪-障壁岛具有比三角洲体系更还原的沉积环境,页岩层状结构较发育,有利于页岩气的保存[6]。同时,不同沉积环境下的水动力强度也是决定微孔隙特征的关键变量[6-7]。具体来说,在弱水动力环境下,水动力强度越高,峰孔体积和总孔体积越小;而在强水动力环境下则相反,当水动力达到一定强度时,峰孔体积和总孔体积迅速减小[6-7]。与三角洲前缘和三角洲平原相比,潮坪和前三角洲具有更弱、更稳定的水动力环境[7],且更容易形成层状结构,因而更有利于孔隙网络的发育[6]。

通过上述分析,发现三角洲体系中的沼泽相,以及障壁-潟湖体系中的潟湖和沼泽相具备更优越的页岩气成藏条件[6, 12]。三角洲形成于海洋和陆地的交界处[21],沼泽是三角洲平原的一个低洼区域,常被周期性淹没于水下,处于还原环境中;岩性以炭质泥岩和煤为主,发育块状构造和水平层理,温暖潮湿的气候和丰富的植被导致富有机质页岩常与煤层互层[22](图 1-A)。潟湖是一个被海岸及障壁岛围限的浅水盆地,与广海呈半隔绝状态,属安静低能环境,沉积物以细粒为主,水平层理发育;厌氧菌在下部繁殖常形成还原环境[23],有利于有机质的保存(图 1-B),而沼泽广泛分布于潮上带,水动力相对较弱,沉积粒度较细,丰富的植物使有机质来源充足,高、低水位的频繁变化导致泥岩与煤互层(图 1-B)。总的来说,在上述沉积环境中页岩通常与煤层相邻,普遍发育的炭质泥岩生烃能力较强,煤层气向邻近页岩的补给可以提高页岩含气量[12];上部煤层又可作为烃浓度封闭的“盖层”,这种理想的“生储盖”组合不仅有利于页岩气的储集和保存,同时对于实现煤层气、页岩气等的“多气共

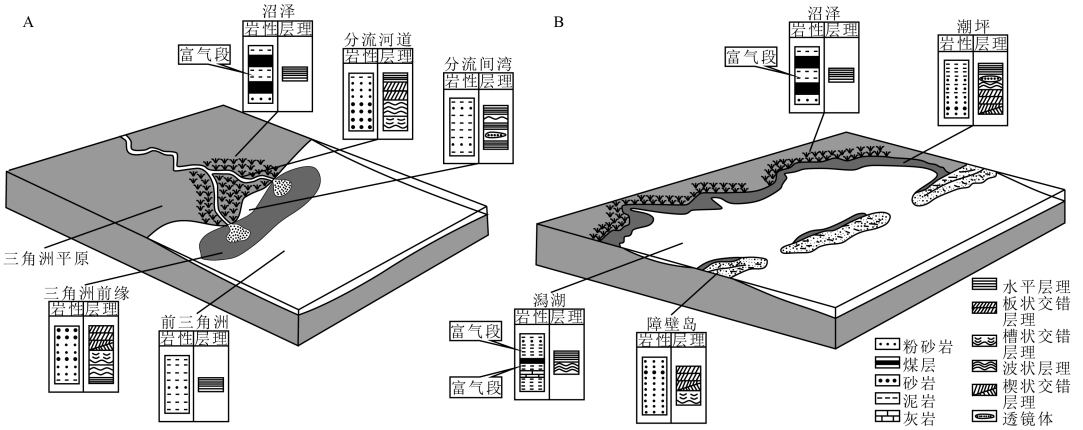


图 1　海陆过渡相页岩气富集特征(据参考文献[12,21]修改)

Fig. 1　Characteristics of shale gas enrichment in marine-continental transitional environment

A—三角洲;B—障壁型海岸

采”也具有现实意义。

2 储层特征

2.1 地球化学特征

有机质丰度、类型及成熟度是页岩储层的关键属性[24]。过渡相页岩 TOC 垂向上极不稳定,高低值交互出现,有一定旋回性(图 2),这在海相页岩中很少观察到[5]。造成这种现象的原因可能是沉积环境的控制,过渡相泥页岩与煤层、砂岩层频繁互层,导致岩相垂向上变化极其复杂。目前,页岩气商业开采的 TOC 下限一般为 2%,也有学者建议将高成熟页岩的下限降至 1%[27]。海陆过渡相页岩平均 TOC 含量总体上高于其他 2 种类型的页岩(图 3),尤其是龙潭组和大隆组页岩,平均 TOC 含量分别为 4.88% 和 7.61%(表 1)。因此,尽管海陆过渡相页岩具有单层厚度薄、非均质性强的特点,但其 TOC 含量高、累积厚度大、分布广,意味着页岩气勘探开发潜力巨大[44]。

沉积环境一定程度上决定了有机质的类型,而干酪根的组成特征又可以从侧面反映沉积环境[49]。海相页岩以Ⅰ型干酪根为主,腐泥组平均在 80% 以上,这主要是由于深海—半深海环境中沉积的大量浮游生物和微生物造成的[50]。而沉积于半深湖—深湖相的陆相页岩,干酪根以Ⅰ型及Ⅱ型为主,腐泥组平均占 67%。由于高等植物的大量输入,过渡相页岩的干酪根类型主要为Ⅲ型及Ⅱ型(表 1),腐

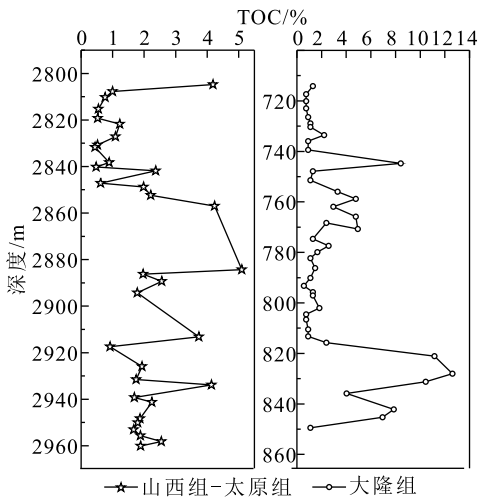


图 2 海陆过渡相页岩 TOC 含量垂向变化特征

(数据据参考文献[25-26])

Fig. 2 Vertical variation characteristics of TOC content in marine-continental transitional shales

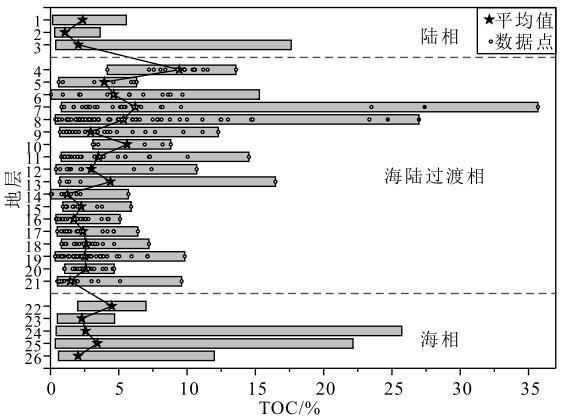


图 3 海陆过渡相与陆相及海相页岩 TOC 含量对比图

(数据据参考文献[3,5,27-32])

Fig. 3 Comparison of TOC content between transitional, continental and marine shales

1—鄂尔多斯盆地延长组;2—四川盆地自流井组;3—四川盆地须家河组;4—鄂西大隆组;5—湘中大隆组;6—下扬子大隆组;7—四川龙潭组;8—贵州龙潭组;9—鄂西龙潭组;10—湘中龙潭组;11—下扬子龙潭组;12—湘中测水组;13—沁水盆地下石盒子组;14—南华北盆地下石盒子组;15—沁水盆地山西组;16—南华北盆地山西组;17—鄂尔多斯盆地山西组;18—沁水盆地太原组;19—南华北盆地太原组;20—鄂尔多斯盆地太原组;21—鄂尔多斯盆地本溪组;22—美国 Barnett 页岩;23—美国 Ohio 页岩;24—中国南方五峰—龙马溪组;25—中国南方筇竹寺组;26—中国南方陡山沱组

殖质显微组分约占 70%(图 4),以生气为主。

复杂的构造热演化使中国产气页岩热演化程度普遍偏高[55],如中国南方下寒武统海相富有机质页岩 R_o 多数在 3% 左右。通过不同层位、不同类型页岩热演化程度的对比,发现从陆相到过渡相再到海相页岩,热演化程度有逐渐升高的趋势,其中海陆过渡相页岩普遍处于成熟—高熟阶段,少数达到过成熟(图 5)。有观点认为,R_o 在 1.1%~3.5% 之间的烃源岩具有相对较强的生气能力[56],Gai 等[57]通过对干酪根的热解实验,发现在 R_o>1.22% 后可以不断产生干气。过渡相页岩有机质主要为Ⅲ型和Ⅱ型,已进入生气窗,有较大的生气潜力。

2.2 矿物组成特征

沉积环境控制页岩的矿物组成,进而影响页岩的孔隙特征和吸附能力,同时对页岩气开发也至关重要[5,24]。与龙马溪组和 Barnett 海相页岩及延长组陆相页岩对比,陆相页岩粘土含量介于海相和过渡相页岩之间,过渡相页岩粘土矿物含量最高(图 6)。由于粘土矿物具有更大的比表面积[62],因此,

表 1　海陆过渡相页岩基本属性参数

Table 1　Basic property parameters of marine-continental transitional shales

地区	层位	TOC/%	R_o/%	干酪根类型	石英+长石/%	粘土矿物/%	碳酸盐岩/%	孔隙度/%	渗透率/10^{-3}mD	数据来源
四川盆地	龙潭组	0.80~35.70 6.22	2.01~2.40 2.22	Ⅱ、Ⅲ	8.3~47.7 22.9	32.5~89.2 60.1	1.0~42.1 17.0	0.6~16.5 5.4	/	[1,33]
贵州	龙潭组	0.35~26.99 5.35	0.86~2.90 2.05	Ⅲ	1.08~68.6 29.5	31.4~97.0 63.4	0~34.4 7.1	0.2~11.1 2.5	/	[2,5,8,12]
鄂西	大隆组	4.15~13.58 9.44	3.00~3.68 3.27	Ⅱ、Ⅲ	32.0~76.0 52.2	4.0~33.0 12.3	14.0~64.0 35.6	0.7~2.8 1.3	0.8~462.1 48.0	[34]
	龙潭组	0.68~12.28 2.95	1.54~2.66 2.05	Ⅱ、Ⅲ	56.4	7.8	36.3	2.18~3.18 2.54	2.3~5.8 3.5	[26]
湘中、湘东南	大隆组	0.60~6.30 3.94	1.20~1.80 1.52	Ⅱ、Ⅲ	39.1~89.1 61.6	10.1~42.1 21.5	0~35.2 16.9	0.2~4.2 1.8	3~7 4.5	[9]
	龙潭组	3.10~8.80 5.62	1.40~1.80 1.53	Ⅱ、Ⅲ	50.8~70.3 58.9	25.1~46.6 35.8	0~13.1 5.4	1.4~9.2 6.1	3.4~25 10.5	[9]
	测水组	0.40~10.70 2.97	1.60~2.40 1.93	Ⅱ、Ⅲ	19.3~63.7 50.6	27.7~69.1 43.6	0~53.0 5.7	2.3~8.6 5.9	3.4~64 20.8	[9]
下扬子	大隆组	0.03~15.30 4.63	0.85~2.73 1.42	Ⅱ、Ⅲ	48.9~83.4 64.9	11.3~42.7 26.4	50.8~70.3 58.9	0.5~5.1 3.1	330~1900 618	[11,35-36]
	龙潭组	0.79~14.53 3.51	0.46~2.51 1.87	Ⅱ、Ⅲ	35.8~56.0 44.1	36.5~62.2 54.0	0~7.5 1.9	0.1~4.2 1.8	1.6~2800 757	
沁水盆地	下石盒子组	0.67~16.48 4.38	1.69~2.28 2.01	Ⅱ2	40.0~43.0 41.5	/	57.0~60.0 58.5	3.5~3.6 3.51	6.1~7.9 7.0	[37]
	山西组	0.91~5.91 2.26	1.51~2.45 2.02	Ⅱ2	33.0~66.8 44.4	17.6~65.9 48.6	1.1~15.6 7.0	0.7~3.6 1.6	3.1~129 28.7	[37-38]
	太原组	0.80~7.21 2.63	1.72~2.92 2.09	Ⅱ2	27.2~62.9 41.1	17.6~62.2 47.1	0.6~43.4 11.9	0.7~3.8 1.4	2.8~19.4 8.6	[37-39]
南华北盆地	下石盒子组	0.01~5.70 1.25	1.09~1.60 1.43	Ⅱ、Ⅲ	/	57~60 58.5	0		/	[40]
	山西组	0.40~5.10 1.71	3.09~3.59 3.41	Ⅱ、Ⅲ	24.0~63.0 43.8	37.0~76.0 55.2	0~9.5 1.0	0.8~9.9 4.2	/	[25,41-44]
	太原组	0.34~9.84 2.51	3.12~4.2 3.54	Ⅱ、Ⅲ	20.0~68.0 43.5	19.2~66.6 47.7	0~59.0 8.8			
鄂尔多斯盆地	山西组	0.49~6.39 2.39	0.87~3.20 2.15	Ⅱ、Ⅲ	10.0~60.0 43.9	40.0~90.0 53.9	0~7.0 2.2	0.3~5.0 3.5	/	[12,45-47]
	太原组	1.04~4.66 2.59	1.26~3.32 2.02	Ⅱ、Ⅲ	26.0~47.0 36.0	52.0~71.0 60.1	0~10.0 3.9	1.1~5.8 3.1	3.1~12.6 6.1	
	本溪组	0.50~9.60 1.44	0.71~3.34 2.00	Ⅱ、Ⅲ	2.0~82.0 31.7	18.0~98.0 61.2	0.1~51.5 10.6	1.5~3.4 2.7	/	[48]

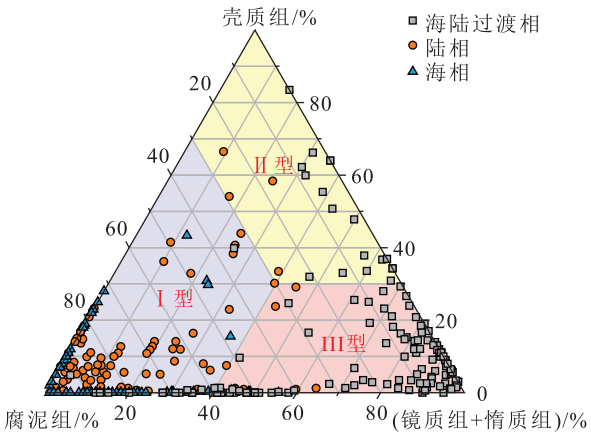


图 4 干酪根显微组分组成[6, 25, 30, 33, 34, 40, 44, 51-54]

Fig. 4 Ternary diagram of kerogen maceral composition

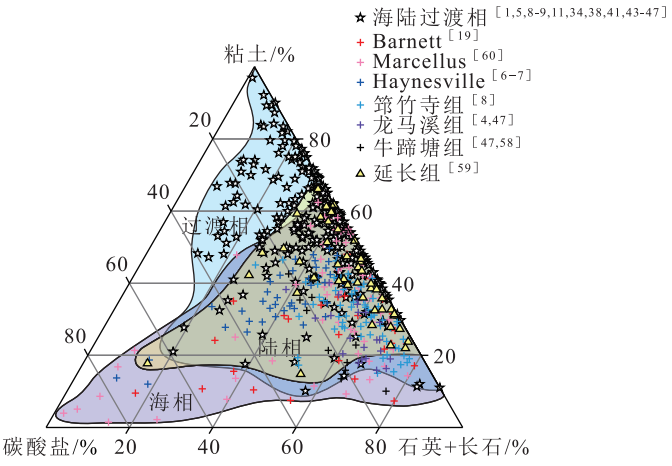


图 6 矿物组成三角图

Fig. 6 The ternary diagrammineral composition of transitional, marine and continental shales

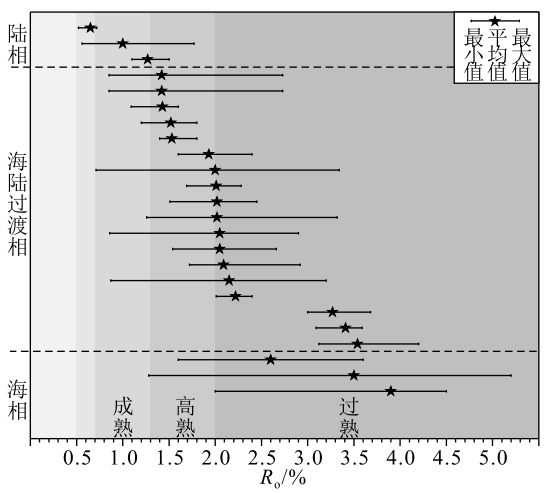


图 5 典型海陆过渡相与海相及陆相页岩有机质成熟度对比图(数据据参考文献[3,5,30,32])

Fig. 5 Comparison of organic matter maturity between typical transitional and marine and continental shales

它们的含量往往与气体吸附能力呈正相关,一定程度上有利于吸附气的保存[23]。然而,通常情况下富粘土的页岩具有较高的延性,很难进行压裂改造,对于开发极不利。

2.3 孔隙发育特征

前文述及,不同沉积环境下页岩有机质类型及矿物组成有很大差异,这必然会影响到有机质的生烃行为,以及页岩的抗压实能力等,并进一步控制页岩的孔隙结构。Loucks 等[63]将页岩储集空间划分为矿物基质孔、有机孔及微裂缝。虽然这些类型的孔隙在过渡相页岩中均有发育[1, 2, 4-5, 46](表 2),但不同类型的孔隙,尤其是有机孔的发育情况与陆相及海相页岩存在较大差异。

2.3.1 矿物基质孔

①粒间孔:过渡相页岩粒间孔较发育,主要存在于碎屑或自生颗粒之间,多呈三角形、多边形、狭缝状或不规则状,大小从几十纳米到几微米不等(图版Ⅰ-A)。粒间孔通常具有较强的抗压实能力,可以在压实和成岩作用中保存下来[63, 65],但随埋深的增加,孔径和数量都会显著降低,并逐渐向三角形孔转变[63],但它们仍保持着良好的连通性,有利于气体的吸附和迁移[63, 65];②粒内孔:粒内孔在海

表 2 海陆过渡相页岩可见孔隙分类

Table 2 Classification of visible pores in marine-continental transitional shale

类型	孔径	形状特征	成因机制
粒间孔	4 nm~3 μm	三角形、多边形、狭缝状和不规则形	矿物颗粒间不完全胶结
粒内孔	3 nm~2 μm	椭圆形、曲线形和不规则形	矿物成岩转化
晶间孔	3~900 nm	矩形、三角形和多边形	晶体生长过程中松散堆积及收缩作用
溶蚀孔	7 nm~3.5 μm	椭圆形、不规则形	溶蚀作用
有机孔	3~1000 nm	圆形、椭圆形、扇形和半月形	有机质成熟生烃
微裂缝	30 nm~10 μm	曲折形、拉长形	沉积、成岩及微观应力作用

陆过渡相页岩中也较为发育(图版Ⅰ-A),常见于方解石、白云石和粘土矿物中,通常呈椭圆形、细长形和不规则形[63, 65],大小不一,一般当长度足够小时(小于 5 μm)被归为粒内孔,当长度大于或等于 5 μm 时则被归为微裂缝[65]。较老的页岩尽管常受到腐蚀性流体的改善,但由于机械压实及胶结作用,粒内孔往往不丰富[63];且很可能是孤立的,因此对页岩孔隙连通性的贡献有限[64]。③晶间孔:晶间孔发育于石英、长石、黄铁矿等骨架颗粒接触处(图版Ⅰ-C),常呈矩形、三角形和多边形,孔径多介于 3~900 nm 之间,通常由晶体的松散堆积及不稳定的或多晶聚集体的成岩收缩形成[63, 65]。④溶蚀孔:溶蚀孔通常是由方解石、长石等不稳定矿物被有机酸溶蚀而成的一种次生孔隙。过渡相页岩溶蚀孔不如海相页岩发育,其形状多为椭圆形和不规则状,边缘光滑,孔径多在 7 nm~3.5 μm 之间(图版Ⅰ-D),易受压实作用的影响[58]。

2.3.2　微裂缝

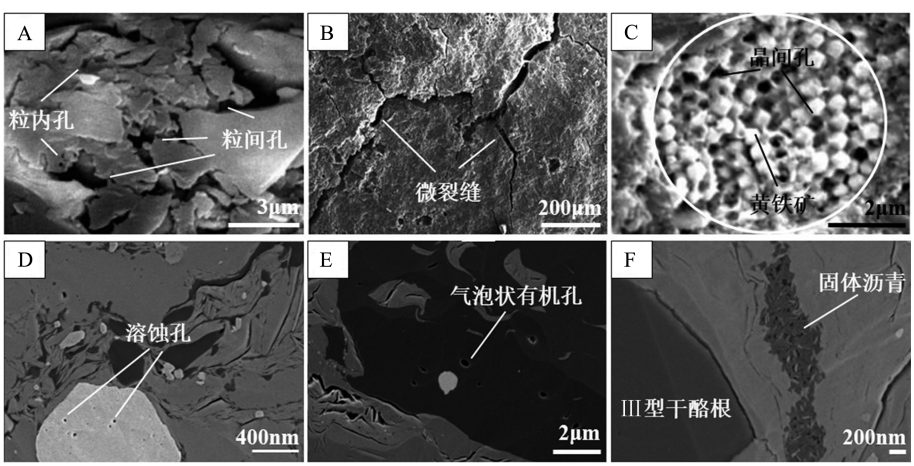
页岩中微裂缝常见于矿物颗粒之间或矿物颗粒与有机质之间,通常是由于粘土矿物或有机质的体积收缩及有机质内部不均匀的受力造成的[6]。作为页岩气系统中重要的储集空间和运移路径,微裂缝与孔隙网络和诱导裂缝之间存在重要联系[66]。海陆过渡相页岩中发育纳米级宽、微米到纳米级长的微裂缝,多呈拉长状(图版Ⅰ-B)。

2.3.3　有机孔

有机孔通常是有机质生烃过程中产生的孔隙[63],常呈圆状、气泡状、蜂窝状及不规则状[1],边缘光滑,边界清晰,尺寸从几十纳米到数百纳米不等[63]。有机孔是页岩重要的孔隙类型,它们在三维空间上相互连通,为页岩气提供了储集空间和运移路径[67]。Loucks 等[63] 认为,当 R_o 大于 0.6% 时,有机孔开始大量发育。海陆过渡相页岩 R_o 均大于 1.0%(图 5),足以发育有机孔。然而,以往在利用扫描电镜研究页岩孔隙时,发现过渡相页岩粒内孔、粒间孔和微裂缝发育良好[5],有机孔较稀少,仅在个别有机质中偶见(图版Ⅰ-E)[5, 47]。值得注意的是,与高过成熟海相页岩中发现的海绵状有机孔不同,发育在Ⅲ型干酪根内的有机孔常呈气泡状[68-69](图版Ⅰ-E),这可能是由于有机质不同的生烃行为引起的。另外,成熟度也可能是造成这种现象的因素之一,比如,有研究认为气泡状有机孔多在生油窗观察到,而海绵状有机孔多与凝析油有关[28]。

据报道,与Ⅰ型和Ⅱ型干酪根相比,Ⅲ型干酪根生烃速率较慢,在成熟过程中体积损失量较小[69],如 Pan 等[11] 认为,下扬子区二叠系海陆过渡相页岩有机碳含量低于 12% 时,每克有机质对孔隙度的贡献率仅为 0.29%,明显低于成熟度相近的海相页岩。Loucks 等[70] 发现,延长组页岩中的Ⅲ型干酪根,即使在放大近 20 万倍(分辨率为 5 nm)的情况下也无法观察到有机孔,这主要是由于Ⅲ型干酪根较低的生烃潜力造成的。然而,Liu 等[71] 认为,Ⅲ型干酪根同样具有较高的生烃潜力,其中有机孔的缺乏是由于陆源木质组分在由陆地向海洋迁移的过程中被氧化造成的。但是,有学者进一步研究发现,在近源沉积的过渡相页岩中,Ⅲ型干酪根中

图版Ⅰ　Plate Ⅰ



A~F.海陆过渡相页岩孔隙发育特征[1-2, 5, 33, 64];A.粒间孔及粒内孔;B.微裂缝;C.黄铁矿晶间孔;D.溶蚀孔;E.气泡状有机孔;F.固体沥青有机孔

的有机孔仍然很少见[2]。同时,另一项研究也发现原地沉积的煤也很少形成有机孔[72]。因此,生烃潜力并不是控制Ⅲ型干酪根有机孔是否发育的最主要因素。固体沥青中的次生孔隙是由液体沥青(或原油)产生的,热降解过程中有机质的演化可以解释有机孔不发育的原因。Ⅲ型干酪根是具有大分子交联结构的固体有机质,它们的热降解是"去官能化"的过程[73],在此过程中,如果其大分子结构未被解聚,则很难形成有机孔[2]。实际上,在过渡相页岩中存在少量与成岩矿物混合的无定形有机成分,它们与前人定义的固体沥青特征一致[68],应该是Ⅲ型干酪根在热演化过程中释放出的固体沥青,已有报道称在煤中同样存在固体沥青[74];在这些固体沥青中只可见少量有机孔(图版Ⅰ-F),并不像高过成熟海相页岩固体沥青中那样发育[68],这可能与固体沥青的来源及化学性质有关。

实际上,受扫描电镜分辨率的限制,过渡相页岩中也可能普遍存在大量的不可见有机孔,如Yang等[2]对分离出的Ⅲ型干酪根进行N_2和CO_2联合吸附,证实了有机微孔的存在(分布在0.34~0.36 nm)之间。Inan等[75]同样指出扫描电镜中的可见有机孔仅是其中的一小部分。Xi等[76]认为,有机孔仍是海陆过渡相页岩的主要孔隙类型。然而,由于当前显微技术分辨率的限制,有机质是否在较小尺度上是多孔的仍然不确定[42]。但过渡相页岩中有机孔的发现,为进一步认识中国页岩气的生成和赋存状态提供了新的思路[2]。

总的来讲,不同沉积环境的页岩其优势孔隙类型不同,海陆过渡相页岩粘土含量较高,发育大量的无机孔,且压实作用相对较弱,大量的无机孔得以保存[77],虽然有机质中可能存在大量的不可见有机孔,但受有机质类型、成熟度等多方面的影响,它们理论上仍然不是过渡相页岩的主要孔隙类型,因此,其孔隙类型应以粒间孔和粒内孔为主,有机孔为辅(图7)。

2.4 孔隙度与渗透率

孔隙度和渗透率是表征储集和渗流能力的重要参数。页岩作为一种细粒沉积物,孔隙度通常较低,且具有极低的渗透率。统计发现海陆过渡相页岩孔隙度介于0.2%~14%之间,平均为2.95%,主体分布在0.5%~4%之间,略高于海相页岩(0.34%~8.11%,平均3.28%),略低于陆相页岩(0.16%~8.73%,平均3.23%)(表1;图8)。三者渗透率的分布区间差异显著,海陆过渡相页岩渗透率主体分布在0.002~0.01 mD,而海相页岩渗透率主体分布在0.000001~0.0003 mD之间,陆相页岩主体分布在0.001~0.5 mD之间。因此,地质上最年轻的陆相页岩孔隙度最高,而海相页岩的渗透率最低,说明海相页岩相比湖相和过渡相页岩致密,这是由于海相页岩在地质历史上埋藏较深、成岩作用复杂所致。过渡页岩的孔隙度最低,渗透率也非常低,可能与其高的粘土含量有关。研究表明,粘土矿物更易受压实的影响,而脆性矿物具有较强的抗压实能力[77]。因此,与具有更多脆性矿物的海相和陆相页岩相比,具有高粘土含量的过渡相页岩应具有较低的孔渗。然而,有学者认为,页岩孔隙度与某些粘土矿物含量具有正相关性,与石英含量的相关性不明显。具体来说,高岭石和绿泥石有助于改善页岩孔隙度,可能是由于当长石被有机酸溶解产生高岭石时,孔隙度会随之增加[80],绿泥石的有序排列也会增加页岩储层的抗压能力和孔隙度[81]。而伊利石抑制孔隙网络的发育,主要是因为蒙脱石在晚成岩阶段转化为伊利石,以及新生成的伊利石会堵塞孔隙降低孔隙度[6]。另一方面,孔渗还受到孔隙结构的控制[82],而这种控制作用可能掩盖了粘土含量的控制作用。

2.5 甲烷吸附能力

页岩气中吸附气占比可达20%~85%[24, 27],甲烷吸附能力的评估有利于正确认识页岩气富集程度及预测资源潜力。甲烷吸附能力受内部因素(有机质含量、矿物组成和孔隙结构)及外部因素(如压力、温度和湿度)的共同影响[24, 83]。不同沉积环境下页岩的矿物组成、有机质含量及类型有很大差异,暗示它们对甲烷的吸附能力不同。比如,研究表明,TOC含量与甲烷吸附量呈正相关[24, 84],这是因为有机质在生烃过程中会产生大量纳米级孔隙,为甲烷气体提供吸附场所[84]。有机质类型对甲烷吸附能力的影响在于陆源有机质比水生有机质的甲烷吸附能力更高[85]。在无机矿物中,粘土矿物对甲烷吸附能力的影响最大,因为它们可以产生大量的微孔,可以吸附甲烷分子[24],其他矿物,如石英、长石、碳酸盐矿物对甲烷吸附能力影响不大。此外,大量研究表明,微孔(小于2 nm)具有较大的比表面积[86],因此,它们比中孔(2~50 nm)和大孔

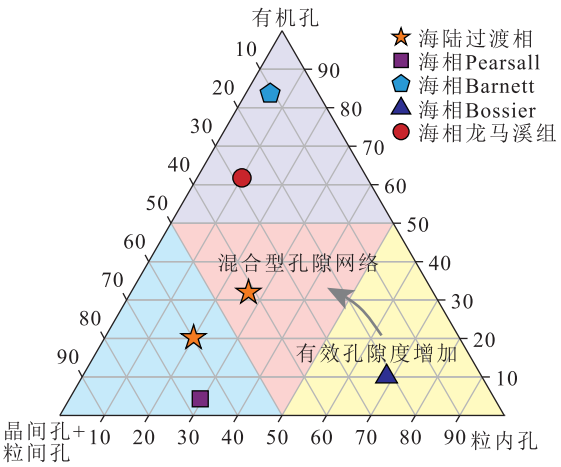


图 7　不同类型页岩孔隙结构示意图(据参考文献[1,63]修改)

Fig. 7　Schematic diagram of pore structure of different types of shale

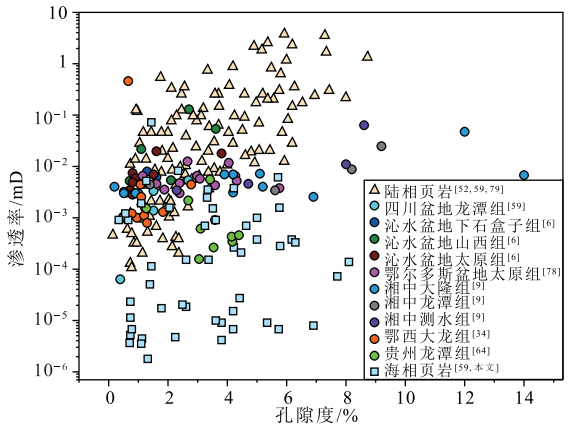


图 8　海陆过渡相与陆相及海相页岩孔渗对比图

Fig. 8　Comparison of porosity and permeability between transitional, continental and marine shales

(大于 50 nm)具有更高的吸附潜力。

笔者搜集了 3 种环境下典型页岩的甲烷吸附资料以供对比,为消除有机质丰度、温度、湿度等影响,使对比结果更可靠,本次搜集的数据全部为在相同温度条件下(30℃)、TOC 含量在 2%~5%范围内的干燥页岩样品的甲烷吸附数据。对比结果表明,陆相页岩的甲烷吸附能力总体较低,而过渡相页岩的甲烷吸附能力分布范围较大,存在甲烷吸附能力较强的页岩,这可能是受到煤层及粘土矿物含量的影响(图 9)。海相页岩的甲烷吸附能力总体较高,原因主要有 2 个:①海相页岩通常富含石英和长石矿物,而过渡页岩和陆相页岩相对富含粘土矿物(图 6)。由于粘土矿物的含水量一般高于石英和长石,必然导致过渡页岩的甲烷吸附能力下降。②海相页岩的有机孔比过渡相和陆相页岩发育,可以提供大量的甲烷吸附位。然而,较强的压实和热成熟作用,也可能会导致孔隙度和吸附能力降低[87],如滇东下寒武统筇竹寺组及上扬子地区鲁家坪组海相页岩,它们的甲烷吸附能力偏低。

3　研究展望

海陆过渡相页岩气资源前景广阔,但与海相及

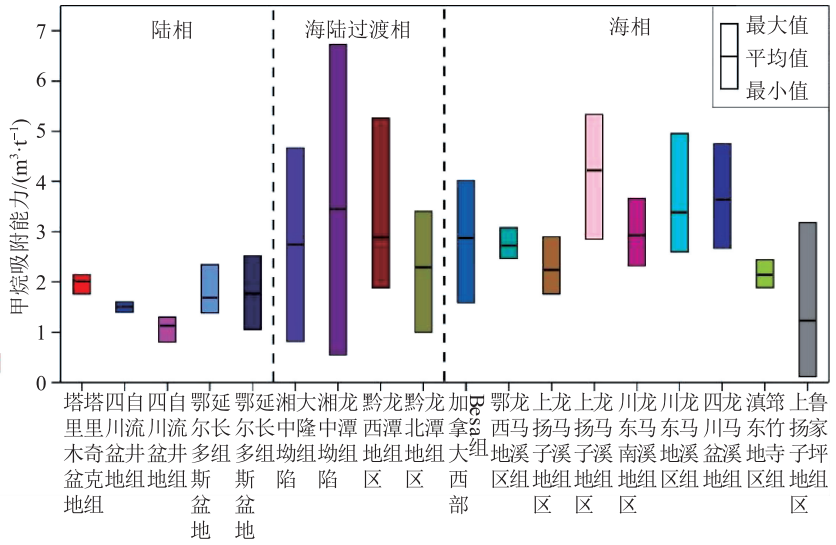


图 9　过渡相页岩与陆相及海相页岩甲烷吸附能力对比(数据据参考文献[2,8,24,44,83,87-96])

Fig. 9　Comparison of methane adsorption capacities of transitional, continental and marine shales

陆相页岩相比有其特殊性,如岩相变化快,单层厚度薄、TOC含量高但波动大、粘土含量高、有机孔不发育等。研究过程中存在一些问题制约了过渡相页岩气的发展,因而需要针对性地制定勘探开发策略。

(1)建立过渡相页岩气资源评价和调查标准体系。过渡相页岩气试采井少、试采时间短,基于井控的动态评价暂无法实现[48]。同时,过渡相页岩岩相变化快,与煤层、致密砂岩层等互层,因此海相页岩这种连续段的评价标准无法适用,导致过渡相页岩气资源潜力评价的方法、参数与标准仍然不完善。针对过渡相页岩地质特征的资源评价和调查标准体系亟待建立。

(2)完善过渡相页岩气"甜点"识别与预测技术。过渡相页岩岩相变化快、单层厚度薄、与煤层及砂岩层等互层的特点,使关键评价参数,如有机碳含量、厚度、含气性等获取不规范[48]。加之过渡相页岩气赋存机理及富集模式的研究还较薄弱,对储集空间的构成与演化及物性等的研究仍然不够深入,都使"甜点"的识别与预测面临困难,需集中力量开展技术攻关。

(3)加强过渡相页岩气优势成藏环境的研究。过渡相富有机质页岩在滨岸平原、三角洲及障壁滨岸等环境中皆有分布,但并不是每一种沉积环境都有利于页岩气大规模聚集。过渡相沉积环境对页岩有机质富集、矿物组成、孔隙特征等的控制作用仍缺乏了解。深入的研究和对比不同环境下页岩储层特征,对于明确优势沉积环境,指导过渡相页岩气勘探方向至关重要。

(4)明确"多气共采"的可行性及方案措施。"多气共采"可使过渡相页岩气的资源潜力最大化,且其具有理论上的可行性。但在共同开采中,压裂开发产生的裂隙会沟通不同类型的气藏,为防止层间干扰,多种气藏能量体系的一致性,是实现共采的首要条件[97]。而目前共探共采体系的划分及共同开发的方案措施,尚无可参考的理论方法与实际经验。因此,"多气共采"的可行性如何仍然不明确。对比分析"多气"之间的共性与差异,合理地划分共探共采系统,将有利于探索综合勘探开发技术。

参考文献

[1] Zhang J, Li X, Zhang G, et al. Microstructural investigation of different nanopore types in marine-continental transitional shales: Examples from the Longtan formation in Southern Sichuan Basin, south China[J]. Marine and Petroleum Geology, 2019, 110: 912-927.

[2] Yang C, Xiong Y, Zhang J, et al. Comprehensive Understanding of OM-Hosted Pores in Transitional Shale: A Case Study of Permian Longtan Shale in South China Based on Organic Petrographic Analysis, Gas Adsorption, and X-ray Diffraction Measurements[J]. Energy & Fuels, 2019, 33(9): 8055-8064.

[3] Cao Q, Zhou W, Deng H, et al. Classification and controlling factors of organic pores in continental shale gas reservoirs based on laboratory experimental results[J]. Journal of Natural Gas Science and Engineering, 2015, 27: 1381-1388.

[4] Liu S, Wu C, Li T, et al. Multiple geochemical proxies controlling the organic matter accumulation of the marine-continental transitional shale: A case study of the Upper Permian Longtan Formation, western Guizhou, China[J]. Journal of Natural Gas Science and Engineering, 2018, 56: 152-165.

[5] Luo W, Hou M, Liu X, et al. Geological and geochemical characteristics of marine-continental transitional shale from the Upper Permian Longtan formation, Northwestern Guizhou, China[J]. Marine and Petroleum Geology, 2018, 89: 58-67.

[6] Liang J, Huang W, Wang H, et al. Organic geochemical and petrophysical characteristics of transitional coal-measure shale gas reservoirs and their relationships with sedimentary environments: A case study from the Carboniferous-Permian Qinshui Basin, China[J]. Journal of Petroleum Science and Engineering, 2020, 184: 106510.

[7] Yu K, Shao C, Ju Y, et al. The genesis and controlling factors of micropore volume in transitional coal-bearing shale reservoirs under different sedimentary environments[J]. Marine and Petroleum Geology, 2019, 102: 426-438.

[8] He Q, Dong T, He S, et al. Methane adsorption capacity of marine-continental transitional facies shales: The case study of the Upper Permian Longtan Formation, northern Guizhou Province, Southwest China[J]. Journal of Petroleum Science and Engineering, 2019, 183: 106406.

[9] Xiao Z, Tan J, Ju Y, et al. Natural gas potential of Carboniferous and Permian transitional shales in central Hunan, South China[J]. Journal of Natural Gas Science and Engineering, 2018, 55: 520-533.

[10] 李琪琪,徐尚,陈科,等.下扬子地区上二叠统页岩气成藏条件分析[J].中国地质,2022,49(2):383-397.

[11] Pan L, Xiao X, Tian H, et al. A preliminary study on the characterization and controlling factors of porosity and pore structure of the Permian shales in Lower Yangtze region, Eastern China[J]. International Journal of Coal Geology, 2015, 146: 68-78.

[12] Wang F, Guo S. Upper Paleozoic Transitional Shale Gas Enrichment Factors: A Case Study of Typical Areas in China[J]. Minerals, 2020, 10(2): 194.

[13] Berner R A, Raiswell R. Burial of organic carbon and pyrite sulfur in sediments over Phanerozoic time: a new theory[J]. Geochimica et Cosmochimica Acta, 1983, 47(5): 855-862.

[14] Demaison G J, Moore G T. Anoxic environments and oil source bed genesis[J]. AAPG Bulletin, 1980, 64(8): 1179-1209.

[15] Yan D, Wang H, Fu Q, et al. Geochemical characteristics in the Longmaxi Formation (Early Silurian) of South China: Implications for organic matter accumulation [J]. Marine and Petroleum Geology, 2015, 65: 290-301.

[16] Bustin R M, Bustin A, Ross D, et al. Shale gas opportunities and challenges[J]. Search and Discovery Articles, 2009, 40382: 20-23.

[17] Slatt R M, O'brien N R. Pore types in the Barnett and Woodford gas shales: Contribution to understanding gas storage and migration pathways in fine-grained rocks [J]. AAPG Bulletin, 2011, 95(12): 2017-2030.

[18] Harrison A L, Jew A D, Dustin M K, et al. Element release and reaction-induced porosity alteration during shale-hydraulic fracturing fluid interactions[J]. Applied Geochemistry, 2017, 82: 47-62.

[19] Loucks R G, Ruppel S C. Mississippian Barnett Shale: Lithofacies and depositional setting of a deep-water shale-gas succession in the Fort Worth Basin, Texas[J]. AAPG Bulletin, 2007, 91(4): 579-601.

[20] 翟正, 王学军, 李政, 等. 页岩沉积环境对其油气潜力的影响: 以中国和北美对比研究为例[J]. 高校地质学报, 2016, 22(4): 690-697.

[21] Nichols G. Sedimentology and stratigraphy [M]. John Wiley & Sons, 2009.

[22] Jasper K, Hartkopf-Fröder C, Flajs G, et al. Evolution of Pennsylvanian (Late Carboniferous) peat swamps of the Ruhr Basin, Germany: comparison of palynological, coal petrographical and organic geochemical data[J]. International Journal of Coal Geology, 2010, 83(4): 346-365.

[23] Mclaughlin M R, Brooks J P, Adeli A. Characterization of selected nutrients and bacteria from anaerobic swine manure lagoons on sow, nursery, and finisher farms in the Mid-South USA [J]. Journal of Environmental Quality, 2009, 38(6): 2422-2430.

[24] Ross D J, Bustin R M. The importance of shale composition and pore structure upon gas storage potential of shale gas reservoirs[J]. Marine and Petroleum Geology, 2009, 26(6): 916-927.

[25] Dang W, Zhang J, Tang X, et al. Shale gas potential of Lower Permian marine-continental transitional black shales in the Southern North China Basin, central China: Characterization of organic geochemistry[J]. Journal of Natural Gas Science and Engineering, 2016, 28: 639-650.

[26] 孟凡洋, 陈科, 包书景, 等. 鄂西巴东地区(巴页 1 井)发现海陆过渡相页岩气[J]. 中国地质, 2017, 44(2): 403-404.

[27] Curtis J B. Fractured shale-gas systems [J]. AAPG Bulletin, 2002, 86(11): 1921-1938.

[28] Bowker K A. Barnett shale gas production, Fort Worth Basin: Issues and discussion[J]. AAPG Bulletin, 2007, 91(4): 523-533.

[29] 叶军, 曾华盛. 川西须家河组泥页岩气成藏条件与勘探潜力[J]. 天然气工业, 2008, 28(12): 18-25.

[30] Tang X, Zhang J, Wang X, et al. Shale characteristics in the southeastern Ordos Basin, China: Implications for hydrocarbon accumulation conditions and the potential of continental shales [J]. International Journal of Coal Geology, 2014, 128: 32-46.

[31] 郭旭升, 胡东风, 李宇平, 等. 海相和湖相页岩气富集机理分析与思考: 以四川盆地龙马溪组和自流井组大安寨段为例[J]. 地学前缘, 2016, 23(2): 18-28.

[32] 董大忠, 王玉满, 黄旭楠, 等. 中国页岩气地质特征, 资源评价方法及关键参数[J]. 天然气地球科学, 2016, 27(9): 1583-1601.

[33] Zhang J, Li X, Zhang X, et al. Geochemical and geological characterization of marine-continental transitional shales from Longtan Formation in Yangtze area, South China [J]. Marine and Petroleum Geology, 2018, 96: 1-15.

[34] 仇秀梅, 刘亚东, 董学林. 鄂西建始地区大隆组页岩有机地球化学特征[J], 2019.

[35] 韩京, 陈波, 赵幸滨, 等. 下扬子地区二叠系页岩有机质孔隙发育特征及其影响因素[J]. 天然气工业, 2017, 37(10): 17-26.

[36] 曹涛涛, 宋之光, 罗厚勇, 等. 下扬子地区二叠系海陆过渡相页岩孔隙体系特征[J]. 天然气地球科学, 2016, 27(7): 1332-1345.

[37] Fu J, Guo S, Gao Q, et al. Reservoir characteristics and enrichment conditions of shale gas in the Carboniferous-Permian coal-bearing formations of Qinshui Basin[J]. Earth Science Frontiers, 2016, 23(2): 167-175.

[38] Yan G, Wei C, Song Y, et al. Pore characteristics of organic-rich shale in the Carboniferous-Permian coal-bearing strata in Qinshui Basin[J]. Energy Exploration & Exploitation, 2017, 35(5): 645-662.

[39] Liu Y, Zhu Y. Comparison of pore characteristics in the coal and shale reservoirs of Taiyuan Formation, Qinshui Basin, China[J]. International Journal of Coal Science & Technology, 2016, 3(3): 330-338.

[40] 邢舟, 曹高社, 毕景豪, 等. 南华北盆地禹州地区 ZK0606 钻孔上古生界煤系烃源岩评价[J]. 天然气地球科学, 2018, 29(04): 518-528.

[41] Tang S, Zhang J, Elsworth D, et al. Lithofacies and pore characterization of the Lower Permian Shanxi and Taiyuan shales in the southern North China Basin [J]. Journal of Natural Gas Science and Engineering, 2016, 36: 644-661.

[42] Chen Q, Zhang J, Tang X, et al. Pore structure characterization of the Lower Permian marine-continental transitional black shale in the Southern North China Basin, Central China [J]. Energy & Fuels, 2016, 30(12): 10092-10105.

[43] Liu Y, Tang X, Zhang J, et al. Geochemical characteristics of the extremely high thermal maturity transitional shale gas in the Southern North China Basin (SNCB) and its differences with marine shale gas[J]. International Journal of Coal Geology, 2018, 194: 33-44.

[44] Li Q, Pang X, Tang L, et al. Occurrence features and gas content analysis of marine and continental shales: A comparative study of Longmaxi Formation and Yanchang Formation[J]. Journal of Natural Gas Science and Engineering, 2018, 56: 504-522.

[45] Li G, Qin Y, Wu M, et al. The pore structure of the transitional shale in the Taiyuan formation, Linxing area, Ordos Basin [J]. Journal of Petroleum Science and Engineering, 2019, 181: 106183.

[46] Xiong F, Wang X, Amooie M A, et al. The shale gas sorption capacity of transitional shales in the Ordos Basin, NW China [J]. Fuel, 2017, 208: 236-246.

[47] Yang C, Zhang J, Wang X, et al. Nanoscale pore structure and fractal

characteristics of a marine-continental transitional shale: A case study from the lower Permian Shanxi Shale in the southeastern Ordos Basin, China[J]. Marine and Petroleum Geology, 2017, 88: 54-68.

[48] 郭少斌,付娟娟,高丹,等.中国海陆交互相页岩气研究现状与展望[J].石油实验地质,2015,37(5):535-540.

[49] Miceli Romero A, Philp R P. Organic geochemistry of the Woodford Shale, southeastern Oklahoma: How variable can shales be? [J]. AAPG Bulletin, 2012, 96(3): 493-517.

[50] Sun M, Yu B, Hu Q, et al. Nanoscale pore characteristics of the Lower Cambrian Niutitang Formation Shale: A case study from Well Yuke # 1 in the Southeast of Chongqing, China[J]. International Journal of Coal Geology, 2016, 154/155: 16-29.

[51] He J, Ding W, Zhang J, et al. Logging identification and characteristic analysis of marine-continental transitional organic-rich shale in the Carboniferous-Permian strata, Bohai Bay Basin [J]. Marine and Petroleum Geology, 2016, 70: 273-293.

[52] Liu G, Huang Z, Chen F, et al. Reservoir characterization of Chang 7 member shale: A case study of lacustrine shale in the Yanchang Formation, Ordos Basin, China[J]. Journal of Natural Gas Science and Engineering, 2016, 34: 458-471.

[53] Liu S, Ma W, Jansa L, et al. Characteristics of the shale gas reservoir rocks in the Lower Silurian Longmaxi Formation, East Sichuan basin, China[J]. Energy Exploration & exploitation, 2013, 31(2): 187-219.

[54] Xi Z, Tang S, Wang J. The reservoir characterization and shale gas potential of the Niutitang formation: Case study of the SY well in northwest Hunan Province, South China [J]. Journal of Petroleum Science and Engineering, 2018, 171: 687-703.

[55] 王社教,王兰生,黄金亮,等.上扬子区志留系页岩气成藏条件[J].天然气工业,2009,29(5):45-50.

[56] Andrews I J. The Carboniferous Bowland Shale gas study: geology and resource estimation[M]. London, UK, British Geological Survey for Department of Energy and Climate Change, 2013.

[57] Gai H, Tian H, Xiao X. Late gas generation potential for different types of shale source rocks: Implications from pyrolysis experiments [J]. International Journal of Coal Geology, 2018, 193: 16-29.

[58] Chen Q, Zhang J, Tang X, et al. Relationship between pore type and pore size of marine shale: An example from the Sinian-Cambrian formation, upper Yangtze region, South China [J]. International Journal of Coal Geology, 2016, 158: 13-28.

[59] Jiang S, Xu Z, Feng Y, et al. Geologic characteristics of hydrocarbon-bearing marine, transitional and lacustrine shales in China[J]. Journal of Asian Earth Sciences, 2016, 115: 404-418.

[60] Wang G, Carr T R. Organic-rich Marcellus Shale lithofacies modeling and distribution pattern analysis in the Appalachian BasinOrganic-Rich Shale Lithofacies Modeling, Appalachian Basin [J]. AAPG Bulletin, 2013, 97(12): 2173-2205.

[61] Hammes U, Hamlin H S, Ewing T E. Geologic analysis of the Upper Jurassic Haynesville Shale in east Texas and west Louisiana[J]. AAPG Bulletin, 2011, 95(10): 1643-1666.

[62] Passey Q R, Bohacs K, Esch W L, et al. From oil-prone source rock to gas-producing shale reservoir-geologic and petrophysical characterization of unconventional shale gas reservoirs [C]// International OIL and Gas Conference and Exhibition in China, 2010.

[63] 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.

[64] Ma X, Guo S, Shi D, et al. Investigation of pore structure and fractal characteristics of marine-continental transitional shales from Longtan Formation using MICP, gas adsorption, and NMR (Guizhou, China) [J]. Marine and Petroleum Geology, 2019, 107: 555-571.

[65] Loucks R G, Reed R M, Ruppel S C, et al. Morphology, genesis, and distribution of nanometer-scale pores in siliceous mudstones of the Mississippian Barnett Shale [J]. Journal of Sedimentary Research, 2009, 79(12): 848-861.

[66] Liang C, Jiang Z, Zhang C, et al. The shale characteristics and shale gas exploration prospects of the Lower Silurian Longmaxi shale, Sichuan Basin, South China [J]. Journal of Natural Gas Science and Engineering, 2014, 21: 636-648.

[67] Curtis M E, Cardott B J, Sondergeld C H, et al. Development of organic porosity in the Woodford Shale with increasing thermal maturity[J]. International Journal of Coal Geology, 2012, 103: 26-31.

[68] Ko L T, Loucks R G, Zhang T, et al. Pore and pore network evolution of Upper Cretaceous Boquillas (Eagle Ford-equivalent) mudrocks: Results from gold tube pyrolysis experiments [J]. AAPG Bulletin, 2016, 100(11): 1693-1722.

[69] Milliken K L, Rudnicki M, Awwiller D N, et al. Organic matter-hosted pore system, Marcellus formation (Devonian), Pennsylvania[J]. AAPG Bulletin, 2013, 97(2): 177-200.

[70] Loucks R G, Ruppel S C, Wang X, et al. Pore types, pore-network analysis, and pore quantification of the lacustrine shale-hydrocarbon system in the Late Triassic Yanchang Formation in the southeastern Ordos Basin, China[J]. Interpretation, 2017, 5(2): SF63-SF79.

[71] Liu B, Schieber J, Mastalerz M. Combined SEM and reflected light petrography of organic matter in the New Albany Shale (Devonian-Mississippian) in the Illinois Basin: A perspective on organic pore development with thermal maturation [J]. International Journal of Coal Geology, 2017, 184: 57-72.

[72] Cardott B J, Curtis M E. Identification and nanoporosity of macerals in coal by scanning electron microscopy[J]. International Journal of Coal Geology, 2018, 190: 205-217.

[73] Ungerer P. State of the art of research in kinetic modelling of oil formation and expulsion[J]. Organic Geochemistry, 1990, 16(1/3): 1-25.

[74] Mastalerz M, Glikson M. In-situ analysis of solid bitumen in coal: examples from the Bowen Basin and the Illinois Basin [J]. International Journal of Coal Geology, 2000, 42(2/3): 207-220.

[75] Inan S, Al Badairy H, nan T, et al. Formation and occurrence of organic matter-hosted porosity in shales[J]. International Journal of Coal Geology, 2018, 199: 39-51.

[76] Xi Z, Tang S, Zhang S, et al. Pore structure characteristics of marine-

continental transitional shale: A case study in the Qinshui Basin, China[J]. Energy & Fuels, 2017, 31(8): 7854-7866.

[77] Jiang S, Tang X, Cai D, et al. Comparison of marine, transitional, and lacustrine shales: A case study from the Sichuan Basin in China[J]. Journal of Petroleum Science and Engineering, 2017, 150: 334-347.

[78] Li K, Chen G, Li W, et al. Characterization of marine-terrigenous transitional Taiyuan formation shale reservoirs in Hedong coal field, China[J]. Advances in Geo-Energy Research, 2018, 2(1): 72-85.

[79] 魏祥峰, 黄静, 李宇平, 等. 元坝地区大安寨段陆相页岩气富集高产主控因素[J]. 中国地质, 2014, 41(3): 970-981.

[80] Heydari E, Wade W J. Massive recrystallization of low-Mg calcite at high temperatures in hydrocarbon source rocks: Implications for organic acids as factors in diagenesis[J]. AAPG Bulletin, 2002, 86(7): 1285-1303.

[81] Wilson M, Wilson L, Patey I. The influence of individual clay minerals on formation damage of reservoir sandstones: a critical review with some new insights[J]. Clay Minerals, 2014, 49(2): 147-164.

[82] Wang Q, Wang T, Liu W, et al. Relationships among composition, porosity and permeability of Longmaxi Shale reservoir in the Weiyuan Block, Sichuan Basin, China[J]. Marine and Petroleum Geology, 2019, 102: 33-47.

[83] Yang R, He S, Hu Q, et al. Pore characterization and methane sorption capacity of over-mature organic-rich Wufeng and Longmaxi shales in the southeast Sichuan Basin, China[J]. Marine and Petroleum Geology, 2016, 77: 247-261.

[84] Zhang T, Ellis G S, Ruppel S C, et al. Effect of organic-matter type and thermal maturity on methane adsorption in shale-gas systems[J]. Organic Geochemistry, 2012, 47: 120-131.

[85] Chalmers G R, Bustin R M. Lower Cretaceous gas shales in northeastern British Columbia, Part I: geological controls on methane sorption capacity[J]. Bulletin of Canadian Petroleum Geology, 2008, 56(1): 1-21.

[86] Yang F, Ning Z, Zhang R, et al. Investigations on the methane sorption capacity of marine shales from Sichuan Basin, China[J]. International Journal of Coal Geology, 2015, 146: 104-117.

[87] Li A, Ding W, Zhou X, et al. Investigation of the methane adsorption characteristics of marine shale: a case study of Lower Cambrian Qiongzhusi Shale in eastern Yunnan Province, South China[J]. Energy & Fuels, 2017, 31(3): 2625-2635.

[88] Hu H, Hao F, Guo X, et al. Investigation of methane sorption of overmature Wufeng-Longmaxi shale in the Jiaoshiba area, Eastern Sichuan Basin, China[J]. Marine and Petroleum Geology, 2018, 91: 251-261.

[89] 郭彤楼, 李宇平, 魏志红. 四川盆地元坝地区自流井组页岩气成藏条件[J]. 天然气地球科学, 2011, 22(1): 1-7.

[90] 寇雨, 周文, 赵毅楠, 等. 鄂尔多斯盆地长 7 油层组页岩吸附特征与类型及吸附气量影响因素[J]. 岩性油气藏, 2016, 28(6): 52.

[91] 顾志翔, 彭勇民, 何幼斌, 等. 湘中坳陷二叠系海陆过渡相页岩气地质条件[J]. 中国地质, 2015, 42(1): 288-299.

[92] 陈康, 张金川, 唐玄, 等. 湘鄂西地区下志留统龙马溪组页岩吸附能力主控因素[J]. 石油与天然气地质, 2016, 37(1): 23-29.

[93] Wang Y, Zhu Y, Liu S, et al. Pore characterization and its impact on methane adsorption capacity for organic-rich marine shales[J]. Fuel, 2016, 181: 227-237.

[94] Li P, Jiang Z, Zheng M, et al. Estimation of shale gas adsorption capacity of the Longmaxi Formation in the Upper Yangtze Platform, China[J]. Journal of Natural Gas Science and Engineering, 2016, 34: 1034-1043.

[95] Ma Y, Zhong N, Li D, et al. Organic matter/clay mineral intergranular pores in the Lower Cambrian Lujiaping Shale in the north-eastern part of the upper Yangtze area, China: A possible microscopic mechanism for gas preservation[J]. International Journal of Coal Geology, 2015, 137: 38-54.

[96] Guo S, Lü X, Song X, et al. Methane adsorption characteristics and influence factors of Mesozoic shales in the Kuqa Depression, Tarim Basin, China[J]. Journal of Petroleum Science and Engineering, 2017, 157: 187-195.

[97] 苏育飞. 山西省海陆过渡相煤系"三气"共探共采展望[J]. 中国煤层气, 2016, 13(6): 5.