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# 扬子地区下寒武统与下志留统黑色页岩孔隙度与有机碳关系差异性及原因

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**摘要:**下寒武统牛蹄塘组与下志留统龙马溪组页岩是扬子地区发育的两套富有机质黑色页岩,由于其分布面积广、厚度大、有机质丰度高而成为页岩气勘探的重点层位。然而牛蹄塘组孔隙度表现出了与龙马溪组截然不同的规律,两套页岩的孔隙结构、有机碳含量、密度也存在显著差异。结合测井、埋深(上覆压力)、孔隙度、有机碳及成熟度测试数据进行了对比分析。结果显示,牛蹄塘组过高的有机碳含量和热演化程度严重影响了页岩的孔隙结构,使有机质碳化,有机质孔发生坍塌和充填;牛蹄塘组埋深大、上覆压力也大,导致无机孔被压实,因此其总孔隙度明显小于龙马溪组。

**关键词:**页岩;孔隙度;有机碳;成熟度;龙马溪组;牛蹄塘组;石油地质。

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## Relationship Differences and Causes between Porosity and Organic Carbon in Black Shales of the Lower Cambrian and the Lower Silurian in Yangtze Area

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**Abstract:** The black shales in lower Cambrian Niutitang and lower Silurian Longmaxi develop well in Yangtze area, which are the key horizons for shale gas exploration because of its wide distribution, large thickness, high organic matter abundance. The porosity of Niutitang Formation shows a distinct difference from Longmaxi Formation. There are also significant differences in the pore structure, organic carbon content and density of the two sets of shales. Based on the logging data, buried depth (overlying pressure), porosity, organic carbon and maturity test data, comparative analysis is conducted. Results show that pore structure has been affected by the high degree of thermal evolution and organic carbon of Niutitang Formation. Organic matter is carbonized, organic porosity is collapsed and filled. The depth of Niutitang Formation is deep and the overburden pressure is also large, causing the inorganic porosity to be compacted. These factors make the porosity of Niutitang Formation obviously less than Longmaxi Formation.

**Key words:** shale; porosity; organic carbon; maturity; Longmaxi Formation; Niutitang Formation; petroleum geology.

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## 0 引言

页岩气作为一种非常重要的非常规天然气已经受到了全世界广泛关注,而我国的页岩气勘探和开发也逐渐进入到了商业化发展阶段(聂海宽等,2009;董大忠等,2010;康玉柱,2010;张大伟,2010;叶泰然等,2011;何发岐和朱彤,2012)。结果显示中国南方地区发育的富有机质海相页岩具有非常好的页岩气成藏条件,其中下寒武统牛蹄塘组与下志留统龙马溪组,以其分布面积广、厚度大、有机质丰度高而成为页岩气勘探的重点层位(邹才能等,2011;董大忠等,2012)。孔隙度和有机碳含量是页岩气甜点区评价的关键参数,不同的孔隙度和有机碳含量将导致页岩产气量的巨大差异(Loucks *et al.*, 2009; Ambrose *et al.*, 2010; Passey *et al.*, 2010; Sondergeld *et al.*, 2010; Curtis *et al.*, 2012b; Milliken *et al.*, 2013; 范文斐等,2015; 吴松涛等,2015)。

通过对龙马溪组和牛蹄塘组的样品进行分析测试,笔者发现两个层系的孔隙结构、孔隙度与有机碳含量存在显著差异,其中龙马溪组的中孔和宏孔比牛蹄塘组发育,孔隙度也较大,分布在4%~6%;而牛蹄塘组主要以微孔为主,孔隙度较小,分布在1%~3%。龙马溪组有机碳含量普遍较低,分布在1.0%~2.5%;牛蹄塘组有机碳含量较高,为2.0%~5.0%,普遍大于龙马溪组。同时,通过对龙马溪组和牛蹄塘组孔隙度、有机碳、密度进行统计分析,笔者发现两个层系的孔隙度、密度与有机碳含量之间的关系也存在显著差异,即牛蹄塘组孔隙度在有机碳含量约为3.0%时会出现一个峰值,密度在此时会出现一个谷值,而龙马溪组却没有出现这种规律.Kitty *et al.*(2013)在研究北美 Marcellus 页岩时也发现了相似的现象,即有机碳含量在5.6%时,孔隙度也出现了一个峰值;Curtis *et al.*(2012b)通过对具有不同成熟度的 Woodford 页岩样品开展扫描电镜观察与孔隙度测试分析,发现其孔隙度在成熟度为3.6%时达到峰值,但随着成熟度继续增加,孔隙度反而减小。而 Kitty *et al.*(2013)和 Curtis *et al.*(2012b)未对这些异常现象进行详细地分析。下寒武统页岩作为我国分布最广泛的页岩,对这种异常现象进行详细分析可以更好地揭示其形成机理,同时给下寒武统页岩气富集机理的研究提供新的思路,也给其他地区页岩气的勘探和开发提供指导作用。

## 1 区域概况

扬子地区发育下寒武统牛蹄塘组和下志留统龙马溪组两套富有机质黑色页岩。牛蹄塘组页岩具有分布面积大的特点,主要形成以川南、湘西—渝东鄂西为两个发育中心,总体分布稳定,厚度大,一般为35~200 m,大部分地区厚度大于100 m。下部主要为黑色碳质页岩,发育水平层理;中部为浅灰色薄层(板状)钙质粉砂岩夹灰—深灰色钙质页岩,发育大量粉砂岩块状透镜体或页理薄层,发育水平层理;上部为灰绿色、黄灰色、灰色薄—中层细—粉砂岩夹深灰色钙质页岩,见灰岩扁球体,发育透镜状层理(郭念发等,2002;叶舟等,2006)。天马A井、天星A井和宣页A井都钻遇到较大厚度牛蹄塘组页岩,笔者在野外实测剖面过程中也观察到了出露良好的牛蹄塘组页岩,自西向东渭潭天城剖面、凤冈琊川剖面、昌桥剖面、杨树岭剖面牛蹄塘组页岩埋深变浅、厚度增大(图1)。下志留统龙马溪组页岩主要为灰黑、黑色页岩、硅质页岩、钙质页岩等,与下寒武统牛蹄塘组页岩相似,其也具有自上而下颜色逐渐加深、砂质钙质减少的变化特征。该套地层以产笔石为特征,可富集成黑色笔石页岩,局部可见放射虫、骨针等。龙马溪组页岩主要发育在滇黔隆起到江南—雪峰低隆起以北较深水的非补偿性缺氧环境中,主体呈NE向带状分布,厚度大,为连续稳定发育,主要形成川南宜宾—长宁—泸州和渝东鄂西石柱—彭水—利川—恩施两个黑色页岩发育中心(丁幼文等,1985;刘宝珺等,1990)。焦页A井、焦页B井和彭页A井均钻遇较大厚度的龙马溪组页岩,其中桐梓剖面、漆辽剖面、鹿角剖面和白果坪剖面都有良好的页岩出露,厚度较大,都在100 m左右(图1)。

下寒武统牛蹄塘组黑色页岩主要发育在大陆边缘的内陆盆地和斜坡区,总体西高南东低;在早寒武世早期,盆底地形极为平缓,水体相对较浅,水流不畅,形成停滞缺氧盆地,之后海平面快速上升并形成早古生代最大海侵作用,低等植物在滨岸带发育,滨浅海区域海生动物及水生低等植物也大量繁殖,为该期碳质泥岩、页岩及硅质岩的发育提供了充足的有机质组分。在快速海进和缓慢海退的沉积背景下,下寒武统页岩形成了被动大陆边缘大陆架模式(图2a)。下志留统龙马溪组黑色富有机质页岩受控于海湾深水陆棚沉积体系,在全球性海平面下降和海域萎缩的背景下,形成了川南、川东—鄂西和川北—川(渝)东北三个主要的滞留、低能、缺氧环境深水陆棚

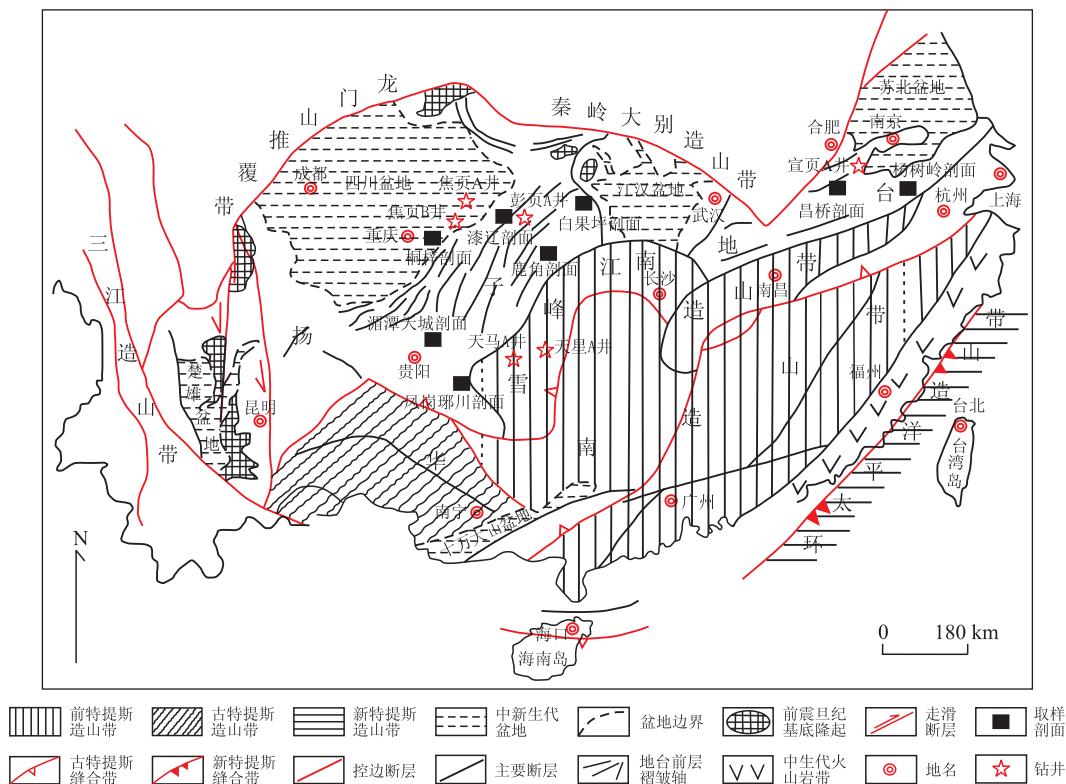


图1 扬子地区构造纲要图

Fig.1 Tectonic outline map of Yangtze area

据徐良伟等(2016)

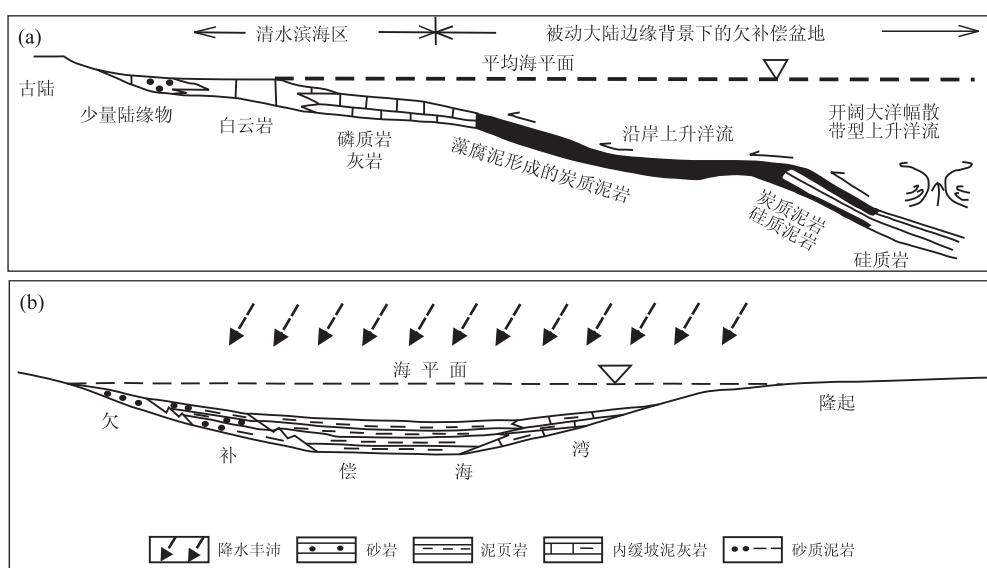


图2 下寒武统(a)与下志留统(b)的海相页岩沉积模式

Fig.2 Marine shale depositional pattern of the lower Cambrian(a) and the lower Silurian(b)

据林拓等(2015)

区,为半封闭海相模式(图2b);发育了一套深灰—黑色粉砂质页岩、富有机质(碳质)页岩、硅质页岩夹泥质粉砂岩、钙质页岩等,富含微粒黄铁矿和笔石,是川东南地区重要的烃源岩(吕宝凤,2005;蒲泊

伶,2008;张延山等,2008;郭旭升等,2014).前陆盆地发育阶段,浮游生物繁盛,为烃源岩发育提供了充足的物源.

## 2 牛蹄塘组、龙马溪组页岩 TOC 与孔隙度、密度的响应特征

笔者选取了宣页 A 井、天马 A 井、天星 A 井作为牛蹄塘组页岩的代表井,焦页 A 井、焦页 B 井、彭页 A 井作为龙马溪组的代表井,来对比分析其孔隙度与有机碳、密度与有机碳的响应关系。

### 2.1 孔隙度与 TOC 含量的响应特征

图 3 显示,当有机碳含量小于 3% 时,孔隙度会随有机碳含量的增加而变大,两者呈正相关关系,孔隙度在有机碳含量为 3.0% 时达到最大,而当有机碳含量继续增加,孔隙度却逐渐减小,两者又呈现出负相关关系;北美 Marcellus 页岩也表现出了相同的规律.Kitty *et al.*(2013)统计了 Marcellus 页岩孔隙度与有机碳含量的关系,发现孔隙度峰值出现在有机碳含量超过 5.6% (图 3a);同样,Curtis(2012a)在对 Woodford 页岩孔隙度进行研究的过程中发现孔隙度的峰值点出现在有机碳含量为 3.6% 时,而这些现象与我国牛蹄塘组页岩所表现出的规律一致。然而龙马溪组孔隙度随有机碳含量增加而持续变大

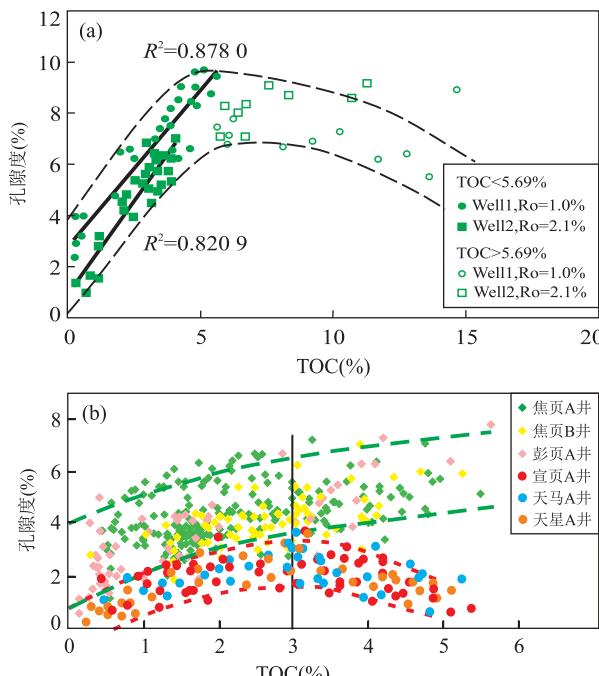


图 3 Marcellus 页岩(a)和龙马溪组、牛蹄塘组页岩(b)的有机碳含量与孔隙度关系

Fig.3 The relations of organic carbon content and porosity of Marcellus shale (a) and Longmaxi-Niutitang shales (b)

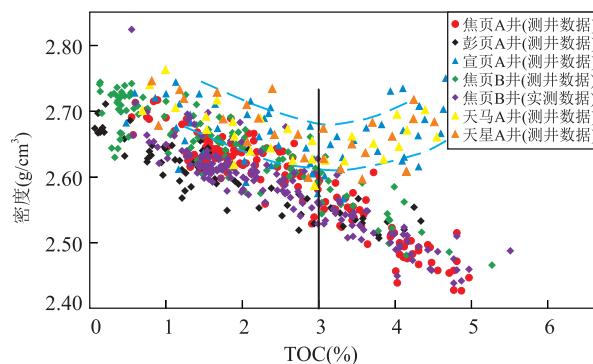


图 4 各井有机碳含量与密度交汇图

Fig.4 Intersection figure of organic carbon content and density of different wells

(图 3b),显然与牛蹄塘组、Marcellus 页岩、Woodford 页岩表现的现象不一致。

### 2.2 TOC 含量与密度的响应特征

密度作为重要的测井参数,与孔隙度也有非常好的响应关系,当孔隙度增大时页岩密度会降低,因此将密度与有机碳进行统计分析,可以从另一方面揭示孔隙度与有机碳的响应特征。笔者对龙马溪组与牛蹄塘组页岩样品进行分析测试,发现两个层系的有机碳含量与密度的响应特征也存在显著差异。图 4 显示,当有机碳含量小于 3.0% 时,宣页 A 井、天马 A 井、天星 A 井的密度随有机碳含量增加而减小,当有机碳含量为 3.0% 时达到最低,随着有机碳含量的继续增加,这些井的密度又显著增大,且有持续增大的趋势;而焦页 A 井、焦页 B 井、彭页 A 井的密度值随着有机碳含量的增加表现出持续下降的现象,两者呈较好的负相关关系。

依据以上分析的牛蹄塘组与龙马溪组页岩孔隙度和密度与 TOC 含量的响应特征,笔者归纳如下:(1)当 TOC 含量在小于 3.0% 的范围内逐渐增加时,下寒武统牛蹄塘组页岩的孔隙度逐渐增大、密度逐渐减小;当 TOC 含量在大于 3.0% 的范围内逐渐增大时,孔隙度逐渐减小、密度逐渐增大;(2)下志留统龙马溪组页岩随着 TOC 含量的增大,其孔隙度持续增加而密度持续减小。岩石物理学模型表明,随 TOC 含量的增大,龙马溪组页岩孔隙度增大、密度减小是一种正常的响应特征,而牛蹄塘组页岩孔隙度、密度表现出了一种异常的响应特征,而分析这种异常响应特征的形成机制有助于认识南方页岩气的赋存机理。

### 3 异常响应特征的形成机制

#### 3.1 页岩孔隙度演化的影响因素

地层孔隙度随着有效应力的增加而逐渐减小的趋势已被大家所熟知(Athy, 1930; 刘震, 1997; 张厚福和张万选, 1997; Bernard *et al.*, 2012; 张林晔等, 2015), Cander(2012)在预测 Eagle Ford 和 Woodford 页岩储层压力的时候,建立了有机孔隙度、无机孔隙度与埋藏深度的模板(图 5a);由于受到上覆地层的压实,无机孔隙度随埋藏深度的增加而持续降低,同时地层温度也不断升高,有机质开始逐渐成熟生成大量烃类,有机孔逐渐增加(吴胜和等, 1998; Jarvie *et al.*, 2007; Loucks *et al.*, 2009; Sisk *et al.*, 2010).页岩的总孔隙度受无机孔和有机孔联合控制,在不同深度段无机孔或有机孔所占比例不同(Selley, 1978; 赵澄林和朱筱敏, 2001).总体而言,埋藏深度对于页岩孔隙度的演化具有十分重要的影响作用(Allen and Allen, 1990; 刘震等, 2007).

成熟度与有机碳含量也是影响页岩孔隙度演化

的重要因素.Schmoker and Gautier(1988)研究了页岩孔隙度与成熟度之间的内在联系,发现两者是幂函数关系.根据 Tissot and Welte(1984)的干酪根热降解生烃模式,有机质在生烃过程中,伴随着成熟度的增加,有机质的孔隙结构会发生显著变化,微孔和中孔的数量将增多,但是当  $R_o$  超过 3.0% 之后,有机质孔隙开始减少,这可能与成熟度过高、导致有机质碳化有关(Cander, 2012; 郑伦举等, 2015).孔隙度与成熟度的关系表现为 3 个阶段:对于  $R_o < 3.0\%$  的样品,随着成熟度的增加,有机质孔隙度快速增加;对于  $3.0\% < R_o < 4.0\%$  的样品,随成熟度的进一步增加,有机质孔隙度明显降低;对于  $R_o > 4.0\%$  的样品,有机质孔隙度的降低速度减缓(图 5b).有机碳含量代表了页岩中有机质的多少,在有机碳含量较高的页岩中,有机质大量发育,当成熟度达到一定水平时,有机质中就会产生有机孔,且随着成熟度的增加,有机孔数量也会增加;同样,在成熟度相同的页岩中,有机碳含量越高的页岩中发育的有机孔也会越多(图 5c).

综上所述,埋深(上覆压力)、有机质热演化程度

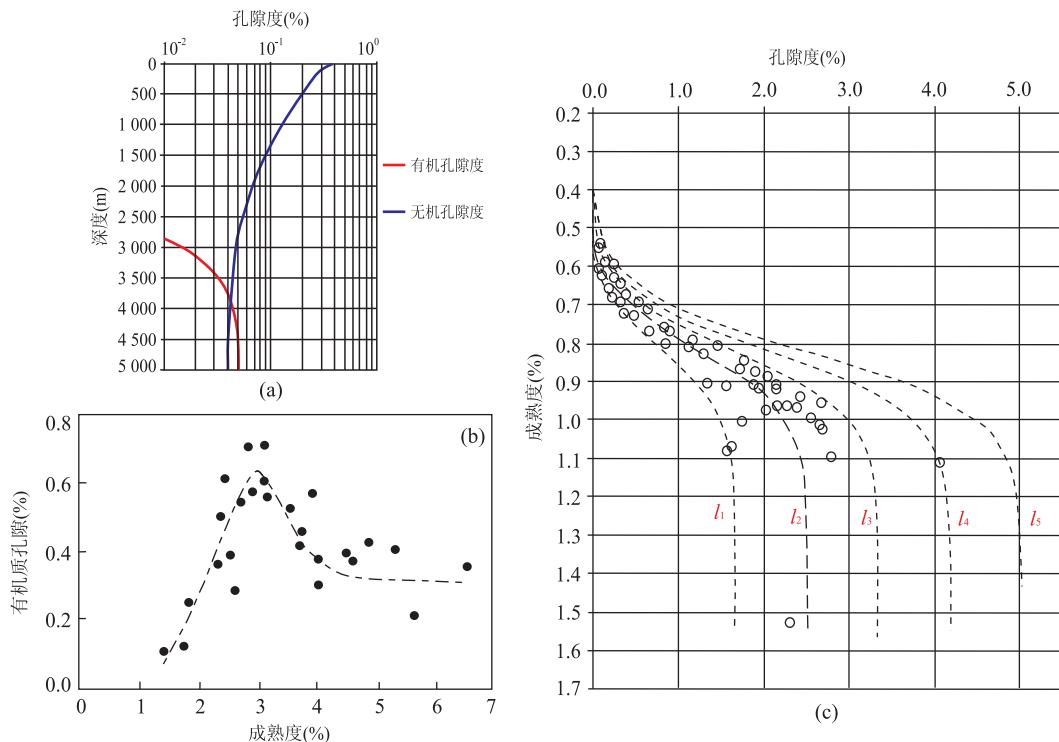


图 5 孔隙度、埋深与成熟度关系

Fig.5 The relations of porosity, depth and maturity

a.孔隙度与埋深关系;b.孔隙度与成熟度关系;c.在不同有机碳含量条件下孔隙度与成熟度关系,其中  $l_1$  的条件为有机碳含量为 2.0%、最大孔隙度为 1.68%,  $l_2$  的条件为有机碳含量为 3.0%、最大孔隙度为 2.50%,  $l_3$  的条件为有机碳含量为 4.0%、最大孔隙度为 3.35%,  $l_4$  的条件为有机碳含量为 5.0%、最大孔隙度为 4.20%,  $l_5$  的条件为有机碳含量为 6.0%、最大孔隙度为 5.00%

和有机碳含量对孔隙度的演化起控制作用。埋深会使无机孔减小,达到一定深度时有机孔会大量发育;有机碳含量能够决定页岩中有机质含量的多少,成熟度在一定范围时,有机质含量越多,存在的有机孔也越多;有机质热演化程度能够提高孔隙度( $R_o < 3.0\%$ ),当  $R_o > 3.0\%$  时,有机孔也会减小。

### 3.2 牛蹄塘组页岩孔隙度异常现象的形成机制

前已述及,牛蹄塘组在有机碳含量为 3.0% 时,孔隙度和密度都存在一个变化的临界点,致使孔隙度和密度在有机碳含量大于 3.0% 和小于 3.0% 时表现出截然不同的变化趋势;而龙马溪组的孔隙度、密度与有机碳含量呈单一正比或反比的正常变化规律。在烃源岩演化过程中,随着热演化程度的升高,有机质发生缩聚作用形成高分子腐殖酸类,进而演化为地质有机聚合物即干酪根,干酪根在随后的变化过程中产出挥发性不断增强、含氢量不断增加的碳氢化合物,最后形成甲烷气(Milner *et al.*, 2010; Slatt and O'Brien, 2011; 崔景伟等, 2013)。随着温度的不断增加,干酪根发生变化,其化学成分也发生变化,逐渐转变成氢含量较低的碳质残余物,并最终成为石墨,发生碳化。而下寒武统牛蹄塘组的这种异常响应特征产生的原因就是当有机碳含量超过 3.0% 以后,页岩由于成熟度的不断增加,有机质发生碳化,有机质孔隙出现坍塌和充填,致使总孔隙度减小、密度增大。

目前,国内外对烃源岩在热演化过程中的碳化现象研究较少,对干酪根在何种条件开始碳化(即碳化门限)的认识尚不清楚,并且缺乏判识有机质碳化的有效地球化学方法。但是烃源岩发生碳化以后可能导致测井曲线表现出低—超低电阻率的特征(程克明等, 1995; 阎存章等, 2009),因此笔者应用电阻率测井曲线对下寒武统牛蹄塘组有机质碳化现象做进一步研究,并结合高精度扫描电镜照片研究碳化作用对有机孔隙的影响。

牛蹄塘组与龙马溪组页岩主要由粘土矿物、脆性矿物和有机质组成,而这 3 类矿物的导电性差异极大。粘土矿物主要由伊利石、蒙脱石、伊蒙混层和绿泥石等具有附加导电性的物质组成,一般在电测曲线上表现出低阻特性。脆性矿物主要由石英、长石、黄铁矿等物质组成,孔隙极少,一般认为只有黄铁矿导电,但是岩心观察显示研究区黄铁矿含量普遍低于 10%,且主要呈点状、细条纹状分布,因此其对页岩导电性的贡献不大。有机质一般导电性不好,但是在热演化阶段发生碳化现象后就会表现出较强

的导电性。赵政璋等(2000)和阎存章等(2009)分别对北美地区页岩和渤海湾地区砂泥岩的低阻油气层的典型特征进行了研究,发现页岩电阻率一般随着泥质/粘土矿物的增加而降低,随着有机质丰度的增加而升高。渤海湾地区砂泥岩低阻油气层粘土矿物含量为 20%~65%,电阻率为 5~20 Ω·m,且随着粘土矿物含量增加而降低;川南龙马溪组页岩电阻率为 8~40 Ω·m,且随着有机质丰度增加而升高(王玉满等, 2012)。

牛蹄塘组页岩电阻率与有机碳含量呈非常好的负相关关系,但是与粘土矿物没有相关性(图 6)。2 600~2 688 m 井段,厚度为 88 m,粘土矿物含量为 25%~43%,TOC 含量为 1.4%~2.2%,有机质含量少,但是电阻率为 231~652 Ω·m,显然是粘土矿物的导电性在发挥主导作用;在 2 688~2 708 m 井段,粘土矿物含量变化不大(32%~46%),TOC 增加至 2.4%~3.1%,但是电阻率却下降至 76~187 Ω·m,页岩导电性下降,这表明有机质导电性开始显现;在 2 708~2 728 m 井段,粘土矿物含量稍有下降(19%~40%),TOC 含量继续增加至 2.9%~3.7%,而页岩电阻率快速下降至 0.2~6.5 Ω·m,表现出明显的低阻特征,这表明有机质开始主导页岩地层的导电性;在 2 728~2 748 m 井段,粘土矿物含量持续下降至 17%~38%,有机质含量持续增加至 3.4%~7.3%,页岩电阻率下降至 0.1~2.1 Ω·m,明显低于川南龙马溪组页岩,表现出超低电阻率特征,这进一步证明了有机质是影响牛蹄塘组页岩导电性的关键介质(图 6,表 1)。由此可知,下寒武统页岩有机质可能出现了明显的碳化现象,导致有机质具有比粘土矿物更强的导电性,当 TOC 超过 3% 后,富有机质页岩段出现低—超低阻特征,表明有机质碳化作用进一步加强,使有机孔出现坍塌和充填的机率大大增加。

基于 8 个剖面露头及 6 口钻井,笔者选取下寒武统 53 块样品和下志留统 47 块样品,统计并比较了牛蹄塘组和龙马溪组 TOC 含量的分布特征。图 7 显示龙马溪组有机碳含量大于 3.0% 的只有 11%,而牛蹄塘组页岩有机碳含量大于 4.0% 和范围在 3.0%~4.0% 的高达 43%,其 TOC 含量普遍高于龙马溪组。牛蹄塘组页岩热成熟度为 2.7%~6.2%,主体在 3.0%~3.5%,普遍高于 3.0%;龙马溪组页岩热成熟度为 1.9%~3.4%,主体在 2.5%~3.0%(图 8)。高有机碳含量、高成熟度的牛蹄塘组页岩生成大量的有机孔隙,在特定的上覆压力和热演化作用下,

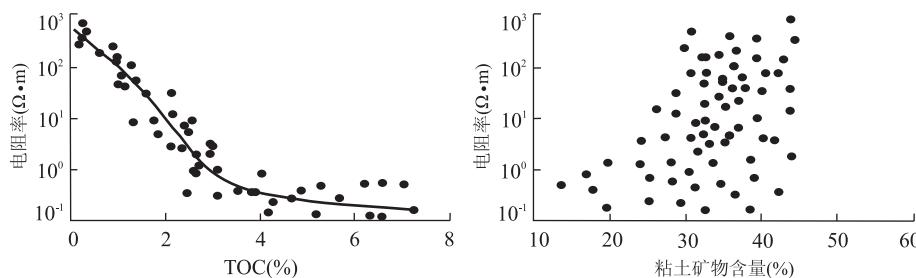


图 6 宣城地区牛蹄塘组页岩电阻率与有机碳含量、粘土矿物含量的关系

Fig.6 The relation between resistivity and organic carbon content (a), and the relation between resistivity and clay mineral content (b) of Niutitang shale in Xucheng area

表 1 宣页 A 井牛蹄塘组页岩岩矿与电阻率统计

Table 1 The statistics of resistivity and mineral contents of Niutitang shale in well XY A

页岩井段 (m)	厚度 (m)	样品数	TOC (%)	矿物含量(%)				电阻率 (Ω·m)	
				石英	斜长石	方解石	黄铁矿		
2 600~2 688	88	15	1.43~2.20	28~44	3.1~10.3	4.3~17.1	0.0~2.1	25~43	231.0~652.0
2 688~2 708	20	19	2.41~3.14	32~46	2.2~10.0	3.9~19.7	0.0~3.2	27~44	76.0~187.0
2 708~2 728	20	20	2.87~3.66	36~52	5.7~12.4	2.3~13.9	0.0~5.7	19~40	0.2~6.5
2 728~2 748	20	19	3.42~7.25	35~79	1.2~11.6	0.0~18.5	0.0~7.1	17~38	0.1~2.1

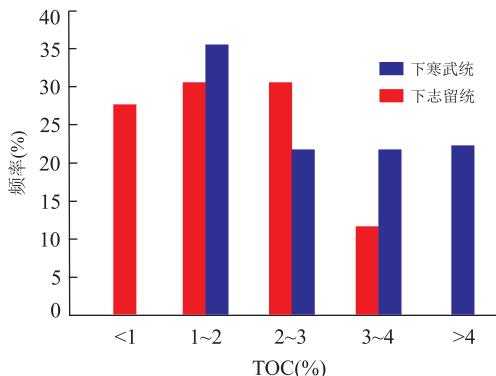


图 7 扬子地区下志留统和下寒武统页岩有机碳含量直方图

Fig.7 The histogram of organic carbon content in lower Cambrian and lower Silurian shales in Yangtze area

无孔被进一步压实,有机质发生碳化,有机孔发生坍塌和充填,致使总孔隙度有减小的趋势(Chalmers *et al.*, 2009; Nelson, 2009).这与 Tissot and Welte(1984)观察到的现象一致.前已述及,当  $R_o > 3.0\%$  时有机质孔隙开始减少,因此成熟度普遍高于 3.0% 的牛蹄塘组的孔隙度将比成熟度普遍低于 3.0% 的龙马溪组减小趋势更大.

美国 Marcellus 页岩、Woodford 页岩和牛蹄塘组页岩 TOC 与孔隙度的响应特征表明页岩孔隙度随着 TOC 的增加而增加,达到某个值后又逐渐减小的变化规律具有一定的普遍性(图 3).TOC 含量越高、有机质热演化程度越高,有机孔就越发育(Chalmers and Bustin, 2007, 2008; Curtis *et al.*,

2012a);随着热演化程度的不断增加,有机质出现碳化,导致有机孔坍塌和充填,则其孔隙度必然要减小,密度必然要增大,因此高有机碳含量和高成熟度的页岩是有机孔发生坍塌和充填的前提条件.

碳化不仅导致有机质导电性变强,还会对孔隙结构造成影响.牛蹄塘组页岩与龙马溪组页岩的孔隙结构统计结果显示,龙马溪组页岩微孔占到 28.24%,中孔和宏孔的比例分别为 37.31% 和 34.45%,微孔的比例明显小于中孔和宏孔;牛蹄塘组页岩微孔比例占到了 55.33%,而中孔和宏孔的比例为 30.76% 和 13.91%,微孔的比例明显大于中孔和宏孔的比例(图 9),表明牛蹄塘组页岩微孔发育而龙马溪组中一宏孔发育,原因可能是牛蹄塘组一部分宏孔和中孔发生坍塌和充填,形成了微孔的一部分(杨永飞等, 2016).邹才能等(2010)通过对威远地区牛蹄塘组( $R_o > 3.0\%$ )和龙马溪组( $R_o > 3.0\%$ )页岩样品开展高倍电镜(氩离子抛光处理后)观察,发现在相近尺度(比例尺刻度值为  $1 \mu\text{m}$ )的电镜照片中,牛蹄塘组有机孔隙发育程度较龙马溪组差(图 10),主要表现在:受有机质碳化影响,牛蹄塘组有机质孔隙出现明显的塌陷和充填现象,边界模糊不清或弧形,孔径变小,其中大量直径小于  $40 \text{ nm}$  的孔隙因完全充填而基本消失(图 10b<sub>2</sub>),进而导致有机质内微孔体积大幅度减少,测试面孔率为  $4.6\% \sim 10.6\%$ ;相反,龙马溪组页岩有机质孔隙不仅数量多,且形态轮廓清晰(多呈菱形或多边形),较少出现充填现象,测试面孔率为

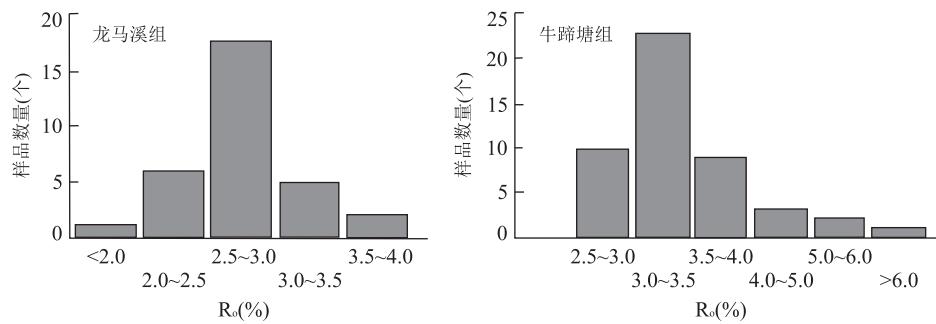
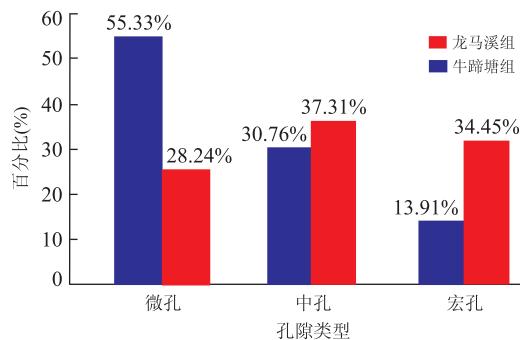
图 8 龙马溪组与牛蹄塘组页岩  $R_o$  直方图Fig.8 The histogram of  $R_o$  of the Longmaxi-Niutitang shales

图 9 牛蹄塘组与龙马溪组页岩不同孔径体积直方图

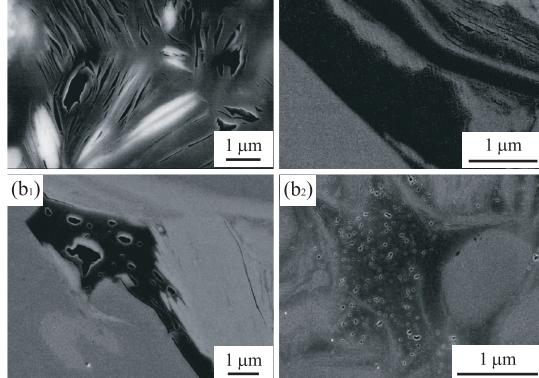
Fig.9 The histogram of different aperture size of the Niutitang-Longmaxi shales  
据杨潇等(2015)

图 10 威远地区龙马溪组(a)与牛蹄塘组(b)页岩有机质孔隙微观特征对比

Fig.10 Comparison of microscopic characteristics of organic porosity between Niutitang Formation and Longmaxi Formation in Weiyuan area  
据邹才能等(2010)和王道富等(2013)

a. $R_o > 3.0\%$ , 有机质孔隙形态轮廓清晰, 孔隙率为 11.9%~23.9%;  
b. $R_o > 3.0\%$ , 有基质孔隙部分出现坍塌且边界模糊, 孔隙率为 4.6%~10.6%;据邹才能等(2010)和王道富等(2013)

11.9%~23.9%(图 10a).

综上所述,牛蹄塘组页岩孔隙度出现异常变化

趋势的原因是其有机碳含量较高、热成熟度高,有机质发生碳化,当有机碳含量高于 3.0% 时,有机质碳化程度增加,有机质孔隙出现明显的坍塌和充填现象,致使牛蹄塘组页岩的总孔隙度减小、密度升高。

## 4 结论

(1)笔者对下寒武统牛蹄塘组与下志留统龙马溪组页岩的有机碳、孔隙度和密度进行统计分析,发现两套页岩存在显著差异,龙马溪组页岩孔隙度和密度随有机碳含量增加表现出持续增大和减小的现象;而牛蹄塘组页岩在有机碳含量为 3.0% 时,孔隙度出现一个峰值,密度出现一个谷值,表现出与龙马溪组截然不同的规律,这种现象与北美 Marcellus 页岩、Woodford 页岩一致。

(2)扬子地区测井、埋藏深度、孔隙度、有机碳及成熟度测试数据的详细分析表明,牛蹄塘组页岩有机碳含量较高,普遍高于 3.0%,有机质出现碳化现象,但当有机碳含量高于 3.0% 时,有机质碳化程度增加,有机质孔隙出现明显的坍塌和充填现象;同时,牛蹄塘组页岩的成熟度较高(普遍高于 3.0%),且埋深较大,上覆压力也大,致使其无机孔被压实减小,总孔隙度减小,从而详细解释了牛蹄塘组页岩与龙马溪组页岩有机碳、孔隙度表现出截然不同现象的原因。

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