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# 下扬子地区上二叠统页岩气成藏条件分析

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**提要:【研究目的】**下扬子地区上二叠统广泛发育龙潭组–大隆组暗色页岩,是中国页岩气调查的重点层位。目前该区勘探程度低,导致对该区页岩气成藏条件认识不清。**【研究方法】**通过龙潭组和大隆组页岩地球化学特征、储集性能,以及保存条件等方面的研究,对该区页岩气资源潜力进行了评价,对有利区进行了优选。**【研究结果】**龙潭组和大隆组有机质丰度高,TOC含量普遍大于2.0%,热演化程度适中(介于1.3%~2.5%),储集空间以墨水瓶和狭缝状中孔为主,脆性矿物含量普遍高于50%,具有较好的生烃物质基础和可压裂性。龙潭组页岩累计厚度较大,具有良好的自封闭能力,保存条件总体优于大隆组。二者均发育多种类型的裂缝,是页岩气逸散的主要通道,此外,后期岩浆活动较为频繁,对于页岩气有很强的破坏作用,保存条件是页岩气富集的关键。**【结论】**下扬子地区上二叠统页岩气选区评价应以沉积环境、生烃能力、储集性能等为基础,以页岩气保存条件为关键,采取"强中找弱"的原则进行,最终在下扬子地区大隆组和龙潭组分别划分了5个有利区。

**关 键 词:**页岩气;海陆过渡相;富集条件;上二叠统;下扬子地区;油气勘查工程

**创 新 点:**下扬子地区上二叠统页岩具备页岩气富集的物质基础;保存条件是下扬子地区上二叠统页岩气能否富集的关键。

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# Analysis of shale gas accumulation conditions of the Upper Permian in the Lower Yangtze Region

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**Abstract**: This paper is the result of oil and gas exploration engineering.

**[Objective]**The dark shale of the Longtan−Dalong Formation is widely developed in the Upper Permian of the Lower Yangtze region, which is the key formation for shale gas exploration in China. At present, the degree of exploration in this area is low, resulting in unclear understanding of shale gas accumulation conditions. **[Methods]**The geochemical characteristics, reservoir properties, and preservation conditions of the Longtan Formation and Dalong Formation shales were studied to evaluate shale gas exploration potential and optimize favorable exploration areas. **[Results]**The organic matter abundance of the Longtan Formation and Dalong Formation is high, TOC content is generally greater than 2.0%, the thermal evolution degree is moderate (between 1.3% and 2.5%), the reservoir space is mainly ink bottle and slit−like mesopores, the brittle mineral content is generally higher than 50%, with good hydrocarbon generation material basis and fracturability. The Longtan Formation shale is thick, with good self−sealing ability, and the preservation conditions are generally better than those of the Dalong Formation. Both of them develop various types of fractures, which are the main channels for shale gas escape. In addition, the late magmatic activity is frequent, which has a strong destructive effect on shale gas, and the preservation conditions are the key to shale gas enrichment. **[Conclusions]**The evaluation of the Upper Permian shale gas in the Lower Yangtze area should be based on sedimentary environment, hydrocarbon generation capacity, and reservoir conditions, taking the shale gas preservation conditions as the key and adopting the principle of finding weak areas in the context of strong tectonic activity. Finally, five favorable areas were divided in the Dalong Formation and Longtan Formation in the Lower Yangtze area.

**Key words:** shale gas; marine−continental transitional shale; enrichment condition; Upper Permian; Lower Yangtze region; oil and gas exploration engineering

**Highlights:** The Upper Permian shales in the Lower Yangtze region have the material basis for shale gas enrichment; The preservation conditions are the key to shale gas enrichment in the Upper Permian in the Lower Yangtze region.

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## 1　引　言

中国页岩气资源储量丰富,其勘探开发具有重要的能源战略意义(贾承造等, 2012)。中国沉积盆地在多旋回的构造演化过程中,发育海相、海陆过渡相及陆相3类富有机质泥页岩层系(邹才能, 2010;贾承造等, 2012;田巍等, 2019)。目前,中国在海相及陆相页岩气勘探中均取得了长足的进步(贾承造等, 2012;郭旭升, 2014;Zou et al., 2019),而海陆过渡相页岩的相关研究工作则仍然较为薄弱(孟凡洋等, 2017;宋腾等, 2017;Luo et al., 2018;石刚等, 2018;Du et al., 2019)。海陆过渡相页岩气成藏规模较小,但其通常与煤层、致密砂岩层交互频繁,且与煤层气有诸多相似的特征及共性开采手段。因此,可以采取“多气”兼探共采的思路,开展页岩气地质勘查,优选有利区,评价资源潜力。由此看来,海陆过渡相页岩气具备良好的资源前景。

目前中国页岩气勘探主要集中在上扬子的四川盆地及围区( Zou et al., 2019;Liang et al., 2020;苟启洋等, 2020;陈少伟等, 2021),相比之下,对下扬子区页岩气形成地质条件关注较少,针对上二叠统海陆过渡相泥页岩的研究则更少。前人研究认为下扬子二叠系具有良好的勘探前景(陈洁等, 2013;吴浩等, 2013;宋腾, 2019),但页岩气成藏条件与富集机理仍需进一步研究。中国地质调查局在下扬子皖南地区部署实施了JY1井,在上二叠统见良好页岩气显示,含气性较高主要为龙潭组煤系地层(高者达9.33 $m^3/t$),泥页岩含气量平均仅为0.65 $m^3/t$。该

井作为下扬子地区矿权空白区第一口获得海陆过渡相页岩气重要发现的钻井,对揭示该区富有机质泥页岩地质条件、明确页岩含气性、评价页岩气资源潜力等都具有重要意义。基于JY1井及GD1井的实测地质资料,结合前人研究成果,对龙潭组和大隆组页岩气成藏地质条件进行分析,并对有利区进行预测,旨在为该区页岩气勘探提供依据。

## 2 区域地质背景

下扬子区位于扬子地块东北缘,其西北部以郯庐断裂、嘉山—响水断裂带为界,西南部以赣江大断裂为界,南部及东南部以江绍断裂为界向南黄海延伸,总体呈南西窄、北东宽的"V"字型地带。其构造演化经历了晚震旦世至三叠纪末期的稳定大陆板块边缘阶段和印支运动之后西太平洋大陆板块边缘阶段,根据喜山期构造运动特征将下扬子陆上地区分为苏皖构造带和江南隆起两个大的构造单元(陈平等, 2013;吴浩等, 2013)。研究区位于下扬子苏皖南地区,横跨皖南—苏南坳陷,面积约为12000 km$^2$(图1)。该区二叠系海陆过渡相富有机质泥页岩主要发育于孤峰组($P_2g$)、龙潭组($P_3l$)和大隆组($P_3d$),其中龙潭组主要发育灰黑色泥岩、炭质泥岩和灰色细砂岩、泥质粉砂岩互层,夹煤层;大隆组主要发育炭质泥岩、硅质泥岩、黑色泥岩(潘继平等, 2011;黄保家等, 2013)。

## 3 页岩基本特征

### 3.1 有机地球化学特征

有机质的丰度、类型以及成熟度是控制页岩气成藏的重要因素(Bowker, 2007)。为了更客观的认识下扬子区上二叠统泥页岩的生烃物质基础,笔者对近几年前人的采样数据进行了综合分析(表1)。结果显示,龙潭组和大隆组泥页岩平均TOC普遍大于2%,平均分别为3.43%和4.36%。高产且经济效益好的页岩气储层TOC含量多数大于2%(邹才能, 2010),因此,二者都具有很好的物质条件。大隆组页岩TOC平均值普遍高于龙潭组,不同地区间差异不大(图2)。美国页岩气开采层位有机质类型以Ⅰ型及Ⅱ型为主,如福特沃斯盆地Barnett页岩有机质主要为Ⅱ型。同时也有少数层位为Ⅲ型,如圣胡安盆地白垩系Lewis页岩(David et al., 2004;Montgomery et al., 2005),扬子地区上二叠统页岩与Lewis页岩

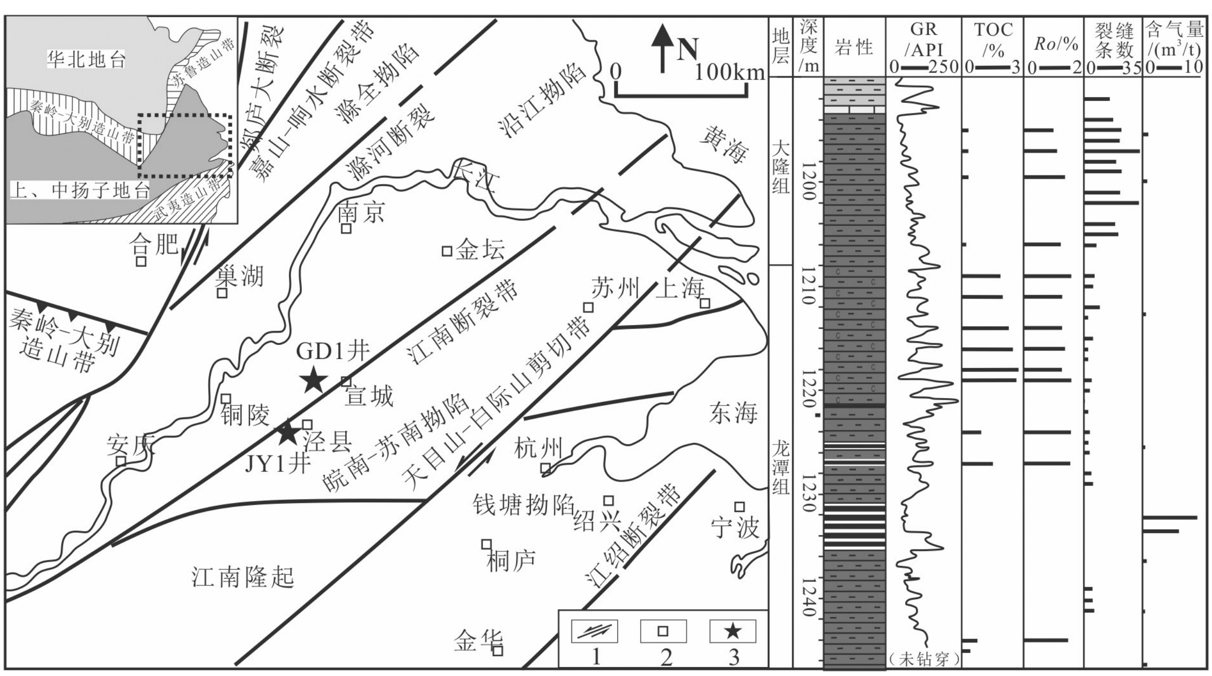


图1 研究区位置及JY1井地层综合柱状图(区域位置图据黄保家等, 2015修改)
1—走滑断裂; 2—城市; 3—井位
Fig.1 Location of the study area and stratigraphic column of well JY1(location map after Huang Baojia et al., 2015)
1−Strike−slip fault; 2−City; 3−Well

**表1 下扬子地区上二叠统页岩有机地球化学特征**

**Table 1 Organic characteristics of the Upper Permian shales in the Lower Yangtze region**

| 地区 | 采样点 | 层位 | 页岩厚度/m | TOC/% | 有机质类型 | *Ro*/% | 数据来源 |
|---|---|---|---|---|---|---|---|
| 苏南 | | $P_3l$ | | 6.13(19)/(2.46~14.88) | | 2.00~3.00 | 吴浩等, 2013 |
| | 黄桥 | $P_3d$ | 10~60 | 7.27(3)/(6.19~8.06) | Ⅱ$_2$ | 1.21(4)/(0.97~1.56) | 葛海霞等, 2015<br>Ge et al., 2016 |
| | | $P_3l$ | 80~200 | 2.49(55)/(0.66~5.82) | Ⅱ$_2$ | 1.09(5)/(0.98~1.24) | |
| | 句容 | $P_3d$ | | 2.91(10)/(2.84~4.86) | Ⅱ$_2$ | 1.41(4)/(1.27~1.86) | |
| | | $P_3l$ | | 1.95(27)/(0.12~3.87) | Ⅱ$_2$、Ⅲ | 1.34(2)/(1.2~1.48) | |
| | | $P_3l$ | | 6.13(19)/(2.46~14.88) | | | 宋腾等, 2019 |
| | | $P_3l$ | 100~200 | 2.26(161)/(0.12~15.83) | | | 陈洁等, 2013 |
| | | $P_3d$ | | 1.86(124)/(0.42~16.01) | Ⅱ$_2$、Ⅲ | 1.12/(0.85~1.96) | 刘敬维, 2018 |
| | | $P_3l$ | | 2.21(18)/(0.39~7.35) | Ⅱ$_2$ | 1.42/(1.22~2.08) | |
| | | $P_3l$ | 32~248.5 | 4.75(19)/(0.23~14.82) | Ⅱ$_2$、Ⅲ | 0.77~1.30 | 刘小平等, 2011 |
| | | $P_3l$ | 100~300 | 1.75(254)/(0.05~15.83) | Ⅱ$_2$、Ⅲ | 1.41(69)/(0.46~2.61) | 章亚等, 2013 |
| 皖南 | JY1井 | $P_3l$ | > 39.25 | 1.56(13)/( 0.37~2.90) | Ⅱ$_2$、Ⅲ | 1.52(13)/(1.27~1.71) | 本文 |
| | | $P_3d$ | 18.44 | 0.21 (4)/(0.20~0.22) | Ⅱ$_2$、Ⅲ | 1.62(4)/(1.22~1.67) | |
| | GD1井 | $P_3d$ | 70 | 2.76(32)/(0.47~6.39) | Ⅱ$_2$、Ⅲ | | |
| | | $P_3d$ | 30~60 | 3.11(13)/(0.70~9.83) | Ⅱ~Ⅲ | 1.22~3.00 | 黄保家等, 2013 |
| | | $P_3l$ | 30~60 | 1.86(40) /(0.50~7.75) | | | |
| | 芜湖 | $P_3l$ | | 4.98(35)/(2.29~12.93) | | 1.30~2.00 | 吴浩等, 2013 |
| | | $P_3d$ | | 7.76(4)/(1.19~12.80) | | 2.34 | 潘磊等, 2013 |
| | | $P_3l$ | | 3.77(2)/(2.59~4.94) | | | Panet al., 2015 |
| | CC1井 | $P_3d$ | | 4.65(7)/(0.86~8.19) | Ⅱ~Ⅲ | 2.34 | 曹涛涛等, 2015;<br>2016 |
| | | $P_3l$ | | 2.95(3)/(1.03~5.46) | | | |
| | HC1井 | $P_3l$ | | 5.39(6)/(1.04~15.3) | Ⅲ | | |
| | HY1井 | $P_3d$ | | 5.47(7)/(2.1~8.6) | | 1.87(7)/(1.68~1.98) | 韩京等, 2017 |
| | 马家山剖面 | $P_3d$ | | 9.54 (10)/(5.51~13.90) | Ⅱ$_2$、Ⅲ | 1.47~1.48 | 陈平等, 2013 |
| | 昌桥剖面 | $P_3d$ | | 5.70(5)/(2.05~11.20) | Ⅲ | > 2.00 | |
| | 泾县 | $P_3l$ | | 1.67(9)/(0.37~2.90) | | | 宋腾等, 2019 |
| | 牛山剖面 | $P_3d$ | | 2.06(219)/(0.04~10.90) | Ⅱ$_2$、Ⅲ | 3.17(29)/(2.36~4.26) | 廖志伟等, 2016<br>Liao et al., 2019 |
| | 蔡村剖面 | $P_3d$ | | 3.00(26)/(0.18~11.12) | Ⅱ$_2$、Ⅲ | 1.56(3)/(1.48~1.65) | |
| | 昌桥剖面 | $P_3d$ | | 1.67(77)/(0.03~9.17) | Ⅱ$_2$、Ⅲ | 2.53 (5)/(2.30~2.77) | |
| | 昌桥剖面 | $P_3l$ | | 4.11(10)/(0.52~8.17) | Ⅱ$_2$、Ⅲ | 2.20/(1.96~2.68) | |
| | 平顶山剖面 | $P_3l$ | | 2.09(4)/(0.54~3.83) | | | 宋修艳, 2012 |
| | CY1井 | $P_3l$ | | 0.93(74)/(0.11~4.84) | Ⅱ$_2$、Ⅲ | 0.98/(0.80~1.36) | |
| 浙西北 | | $P_3l$ | | 3.30(17)/(1.52~6.69) | | 0.90~1.30 | 吴浩等, 2013 |

注:2.21(18)/(0.39~7.35)=平均值(样品数)/(最大值−最小值);空白处代表数据缺失;$P_3d$—大隆组;$P_3l$—龙潭组。

沉积环境较为相似(周东升等, 2012),二者具有很好的可比性。研究区上二叠统页岩有机质类型以Ⅱ$_2$型及Ⅲ型为主,平均镜质体反射率多介于1.3%~2.5%,与Lewis页岩(*Ro*多分布在1.6%~1.9%(Curtis, 2002))的热演化程度较为接近,总体都处于高—过成熟演化阶段。

### 3.2 矿物组成特征

页岩中石英等脆性矿物含量对水力压裂具有重要影响,从而在一定程度上影响着页岩气的产能(黄保家等, 2015)。北美Barnett页岩石英含量为35%~50%,Lewis页岩石英含量为22%~52%,黏土矿物含量通常小于50%(Curtis et al., 2012)。根据实测及搜集到的数据(陈平等, 2013;潘磊等, 2013;Pan et al., 2015;曹涛涛等, 2015, 2016),下扬子区龙潭组—大隆组页岩主要矿物组成为石英、长石、黄铁矿和黏土矿物,黏土矿物以伊利石和绿泥石为主,碳酸盐岩含量较低。其中,龙潭组页岩石英含量为22.0%~57.9%,平均36.2%,碳酸盐岩平均含量

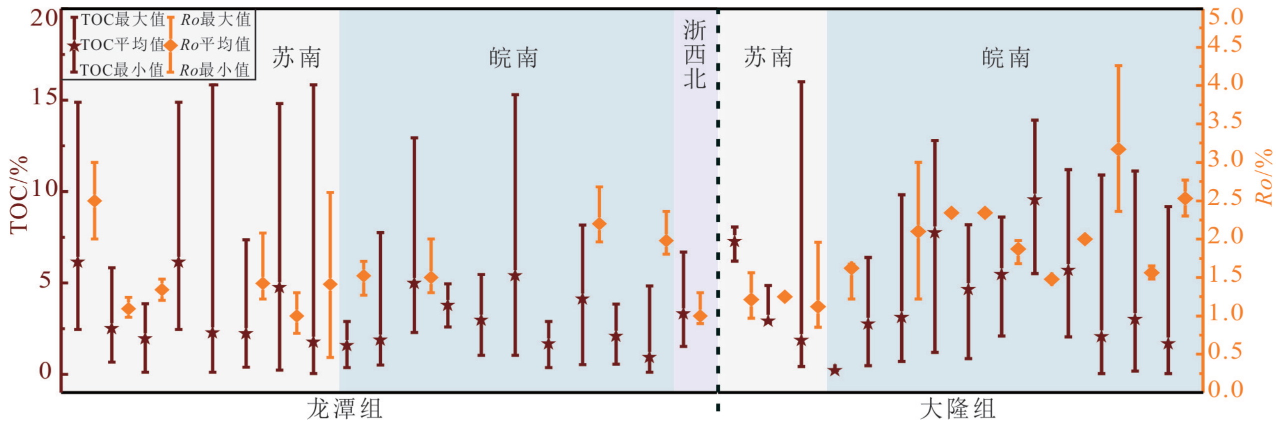


图2 下扬子区上二叠统页岩TOC与*R*o统计图

Fig.2 Statistical diagrams of TOC and *R*o of the Upper Permian shales in the Lower Yangtze area

9.1%,黏土矿物平均含量46.2%;大隆组页岩石英含量较高,介于8.8%~81.0%,平均53.3%,碳酸盐岩和黏土矿物平均含量较低,分别为5.2%、28.2%(图3)。大隆组脆性矿物(石英+长石+黄铁矿)含量普遍高于龙潭组,平均为66.7%,对后期压裂改造比较有利。

### 3.3 储层特征

页岩气储层具低孔、特低渗致密的物性特征(曹涛涛等, 2015)。由于采用的测试技术手段和测试条件不同,因此,与北美典型页岩物性没有可对比性。对实测以及搜集到的资料进行分析(宋修艳,2012;Pan et al., 2015;曹涛涛等, 2015;韩京等,2017;刘敬维, 2018),结果表明:龙潭组页岩储层孔隙度分布在0.12%~4.20%,平均1.80%,渗透率为(0.0016~2.8)×$10^{-3}$ μm$^2$,平均0.757×$10^{-3}$ μm$^2$;大隆组孔隙度介于0.52%~5.02%,平均3.02%,渗透率为(0.33~1.9)×$10^{-3}$ μm$^2$,平均0.618×$10^{-3}$ μm$^2$。二者渗透率差别不大,但大隆组页岩孔隙度明显高于龙潭组。

根据IUPAC的孔隙分类标准,页岩的纳米孔隙分为大孔(孔径＞50 nm)、介孔或中孔(孔径2~50 nm)、微孔(孔径＜2 nm)。扫描电镜观察发现,上二叠统页岩可见有机孔,但相较于海相页岩并不发育,另外,发育有机质收缩缝和黏土矿物层间孔(图4)。利用低温$N_2$吸附脱附法对上二叠统页岩储层的微观孔隙进行了研究,JY1井页岩样品测试结果显示龙潭组页岩氮气吸附量总体低于大隆组,吸附等温线在形态上稍有差别,但均呈反“S”型(图5),与IUPAC定义的Ⅳ型等温线相似(Rouquerol et al., 1994)。为分析孔隙形态特征,IUPAC将吸附回线分为了4类(Sing, 1985),各样品等温线图在中等相对压力处,解吸曲线比吸附曲线陡峭,在接近饱和蒸汽压时,吸附曲线陡直上升,兼具H2及H3型滞回环特征,即墨水瓶形以及狭缝状孔隙特征;另外,各样品吸附曲线在高相对压力区域没有表现出吸附限制,表明存在一定的大孔或微裂缝;图5c中吸附与脱附分支在低相对压力区域未闭合,说明孔尺寸不均匀。

根据实测以及搜集到的资料(潘磊等, 2013;Pan et al., 2015;曹涛涛等, 2015),龙潭组页岩平均孔径

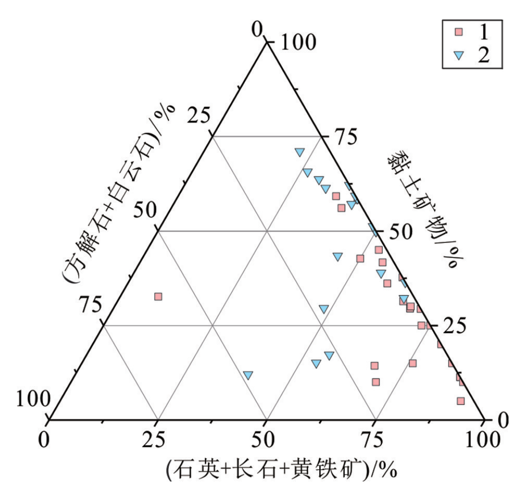


图3 下扬子区上二叠统页岩储层矿物组成三角图

1—大隆组; 2—龙潭组

Fig.3 Ternary diagram of mineral composition of the Upper Permian shales in the Lower Yangtze region

1−Dalong Formation; 2−Longtan Formation

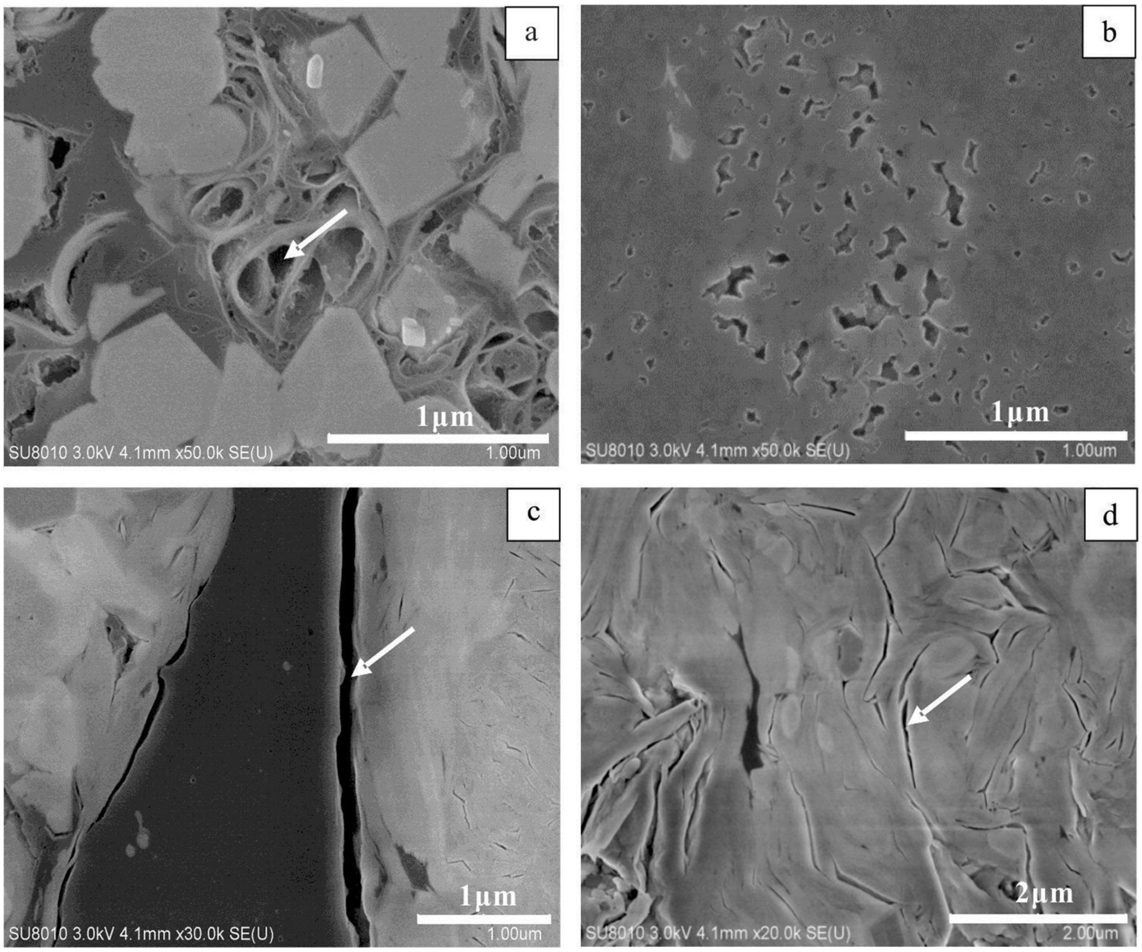


图4 下扬子区上二叠统页岩储层孔隙扫描电镜照片

a—GD1井，$P_3d$，977.5 m，圆形-椭圆形有机孔；b—GD1井，$P_3d$，983.4 m，凹坑状、不规则状有机孔；c—GD1井，$P_3l$，1034.3 m，有机质收缩缝；d—GD1井，$P_3l$，1042.5 m，黏土矿物层间孔

Fig.4 Scanning electron microscope photos of pores in the Upper Permian shale reservoirs in the Lower Yangtze area

a-GD1, $P_3d$, 977.5 m, Round-oval organic matter pores; b-GD1, $P_3d$, 983.4 m, Pit-shaped, irregular organic matter pores; c-GD1, $P_3l$, 1034.3 m, Organic matter shrinkage joints; d-GD1, $P_3l$, 1042.5 m, Clay mineral interlayer pores

介于9.6~15.6 nm；大隆组页岩平均孔径介于7.25~22.1 nm，平均孔径都在中孔范围内，有利于吸附气的储存，同时存在一定的大孔(图5)。龙潭组页岩比表面积介于1.11~13.78 $m^2/g$，平均8.47 $m^2/g$；孔体积介于0.0031~0.0173 mL/g，平均0.0094 mL/g。大隆组的比表面积及孔体积相对较大，比表面积介于3.12~32.82 $m^2/g$，平均15.65 $m^2/g$；孔体积介于0.0066~0.039 mL/g，平均0.0206 mL/g。与Berea砂岩相比(Donaldson et al., 1975)，龙潭组和大隆组页岩比表面积较大，能为吸附气的赋存提供有利条件。另外，龙潭组和大隆组页岩的孔体积普遍要比煤层高一个数量级(杨峰等, 2013)，较大的孔隙更有利于气体储集与渗流。

## 4 讨 论

### 4.1 页岩沉积环境

前人研究认为龙潭组和大隆组多形成于海湾潟湖以及三角洲平原沼泽，原始有机质丰富，但由于沉积水体中溶解氧含量较高，有机质遭氧化破坏严重(周东升等, 2012；陈洁等, 2013；叶加仁等, 2020)。另外，过高的陆源输入，也会导致有机质被稀释。利用常微量元素对JY1井和GD1井上二叠统页岩沉积环境进行判断(Boström, 1983；梅水泉, 1988； Jewell and Stallard, 1991； Wignall and Twitchett, 1996；Tribovillard et al., 2006)，发现JY1井龙潭组和大隆组页岩Al/(Al+Fe+Mn)值介于0.36~

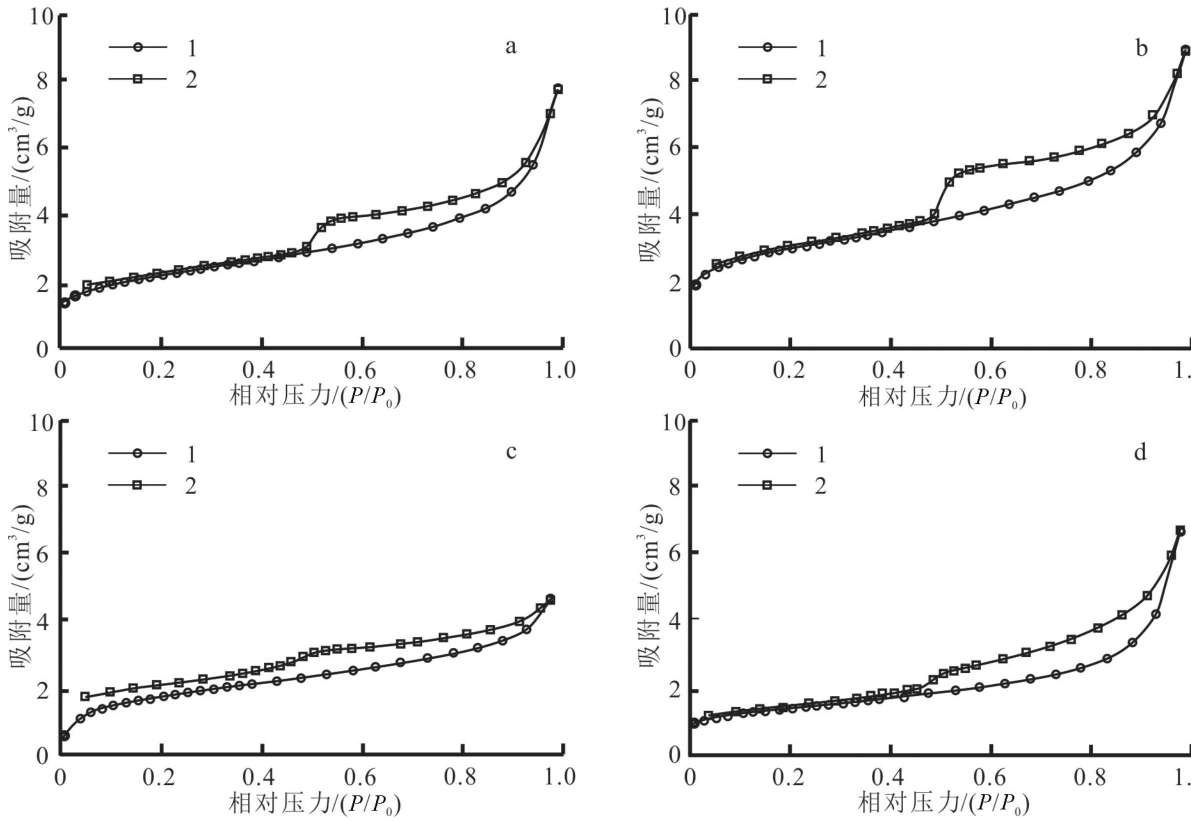


图5 上二叠统页岩等温吸附/脱附曲线

a−JY1, $P_3d$, 1198.2 m; b−JY1, $P_3d$, 1120.6 m; c−JY1, $P_3l$, 1214.8m; d−JY1, $P_3l$, 1230.0 m

1—吸附曲线; 2—脱附曲线

Fig.5 Adsorption/desorption isotherms of the Upper Permian shales.

1−Adsorption curve; 2−Desorption curve

0.75,平均0.55,表明有一定的陆源输入。在剔除陆源带入部分后计算的V/(V+Ni)值介于0.61~0.83,平均0.73,显示为弱氧化−还原环境(Wignall and Twitchett, 1996);U/Th值介于0.16~0.44,平均0.31,显示为强氧化环境(Boström, 1983);$\delta$U值介于0.65~1.14,平均0.93,显示为弱氧化环境(Wignall and Twitchett, 1996;李琪琪等, 2021);Cu/Zn值介于0.26~0.60,平均值为0.36,显示为弱还原−氧化环境(梅水泉, 1988)。以上现象揭示了JY1井龙潭组—大隆组沉积时期,水体中氧含量明显增高,处于氧化和还原交替的沉积环境。JY1井的实测资料显示,大隆组页岩TOC含量极低,实测值甚至均未达到生烃下限,平均仅为0.21%(4个样品),龙潭组TOC分布在0.37%~2.90%,平均1.56%(13个样品),相较于其他地区含量较低。而GD1井上二叠统页岩$\delta$U介于0.98~1.72,平均1.29;V/(V+Ni)值在0.66~0.89,均值为0.79;V/Ni比值介于1.95~8.25,平均为4.33(32个样品),指示页岩沉积时期水体处于还原状态,平均TOC为2.76%(32个样品)。

陈平等(2013)对巢湖马家山剖面及泾县昌桥剖面样品测试后表明,大隆组沉积时期水体为贫氧−厌氧环境,TOC较高,平均分别为9.54%和5.70%;Liao et al.(2019)对牛山、蔡村、昌桥剖面以及徽页1井大隆组样品进行实测分析后认为,下扬子沉积时水体总体处于中等—强滞留的厌氧环境,平均TOC含量为2.91%。这种差异反映了TOC与沉积环境密切相关,偏氧化的沉积水体是JY1井页岩TOC含量较其他地区低的重要原因。海陆过渡相相变较快,页岩非均质性较强,因此,沉积环境及沉积微相对海陆过渡相页岩有机质富集程度的控制尤为明显。

### 4.2 孔隙类型及影响因素

页岩孔隙可以分为无机孔和有机质孔(Ross and Bustin, 2009;Loucks et al., 2012)。多数学者研究认为海陆过渡相有机孔不发育(Loucks et al.,

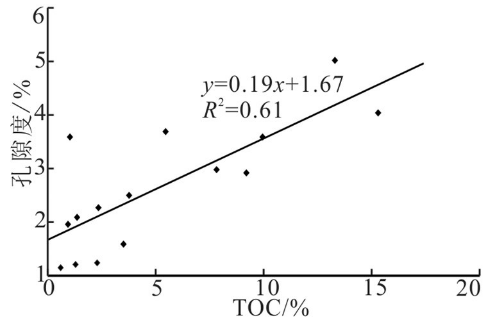


图6 下扬子地区上二叠统页岩TOC含量与孔隙度的关系
(部分绘图数据自Pan et al., 2015;曹涛涛等, 2015)
Fig.6 Relationship between TOC content and porosity of the Upper Permian shales in the Lower Yangtze area (some drawing data from Pan et al., 2015; Cao Taotao et al., 2015)

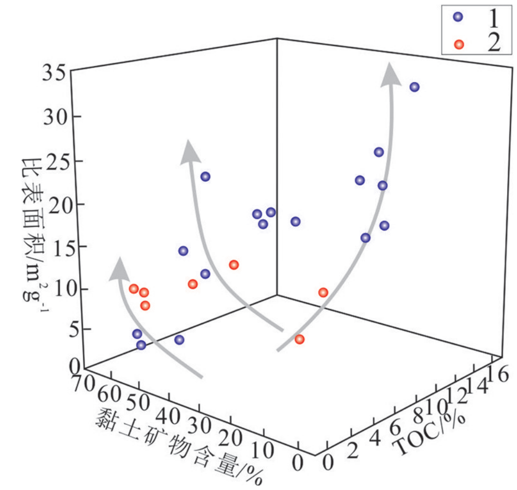


图7 下扬子地区上二叠统页岩BET比表面积与TOC及黏土矿物含量的关系
1—大隆组; 2—龙潭组
Fig. 7 Relationship between BET surface area and TOC content and clay mineral content of the Upper Permian shales in the Lower Yangtze area
1−Dalong Formation; 2−Longtan Formation

2012;Luo et al., 2018),而Yang et al. (2019)在对黔西北龙潭组海陆过渡相页岩孔隙进行研究后发现,有机孔是普遍存在的,且对比表面和孔容有很大的贡献。İnan et al. (2018)同样注意到了这种现象,并指出扫描电镜中的可见有机孔仅仅是其中的一小部分,因此,若仅仅基于扫描电镜的观察,则页岩的储集能力往往会被低估。下扬子地区上二叠统页岩有机质热演化程度适中,TOC与孔隙度存在较好的正相关性(图6),表明有机质孔对页岩孔隙度具有一定的贡献,同时,氮气等温吸附回线具有有机孔的特征也印证了这一认识(图5)。龙潭组页岩TOC较大隆组低,其孔隙度也相对较低。

研究表明,较高的比表面积有利于页岩气吸附,比表面积主要受TOC与黏土矿物含量的影响(Ambrose et al., 2010)。对于研究区上二叠统页岩来说,当黏土矿物含量在一定范围内(低于40%)时,比表面积较为显著的受控于TOC(图7);当TOC在一定区间变化时,黏土矿物对比表面积有积极影响,但并不显著,可能与黏土矿物主要为伊利石和绿泥石有关(Ji et al., 2012)。因此,TOC是该区上二叠统页岩比表面积的主控因素,有机孔对于龙潭组和大隆组页岩储集能力有很大的贡献。

### 4.3 可压裂性

可压裂性是页岩气勘探评价的重要指标。页岩中的石英除陆源供给外,自生成因也是重要来源,且自生微晶石英对提升脆性最为有效(Thyberg and Jahren, 2011),生源石英(生物硅)与TOC含量通常具有良好的正相关性。龙潭组和大隆组页岩TOC与脆性矿物含量较强的正相关性(图8),表明页岩中石英主要为自生成因,研究区二叠系富有机质页岩具有良好的可压裂性。

### 4.4 保存条件

薄层页岩气藏通常受控于顶底板条件,而厚层页岩气藏则具有自封闭的特点。下扬子地区龙潭组页岩累计厚度多在100 m以上,理论上具自封闭能力,但自中生代尤其是印支运动后,下扬子区构造活动剧烈(潘继平等, 2011),受印支—燕山运动的改造,龙潭组页岩的连续性遭受破坏,封闭性可能受到影响,但在保存较完整的地区仍具备良好的封闭条件;大隆组页岩厚度相对较薄,在JY1井仅18.4 m,自封闭能力较弱,上覆殷坑组发育一套厚约50 m的区域性膏岩层(宋修艳,2012),对大隆组页岩气的保存具有直接作用。

研究区各钻井不同层位的矿化度与水型存在很大差异(宋腾, 2019),反映本区水化学环境遭受过改造,且地表温泉活动多,大气水下渗深度多大于800 m(Du et al., 2019),断层的发育可能导致了深部与地表沟通。JY1井龙潭组和大隆组页岩裂缝发育(图9),其中龙潭组以剪切缝和网状缝等构造缝为主,裂缝密度约5条/m;大隆组非构造缝发育程度高,主要为层理缝,偶见高角度剪切缝,裂缝密度约

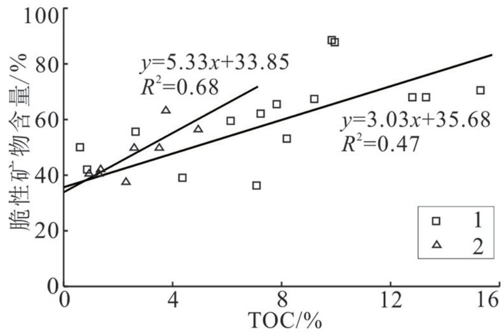


图8 下扬子地区上二叠统页岩脆性矿物含量与TOC含量关系图
1—大隆组; 2—龙潭组
Fig. 8 Relationship between brittle mineral content and TOC content of the Upper Permian shales in the Lower Yangtze area
1−Dalong Formation; 2−Longtan Formation

20条/m。断裂和裂缝导致页岩封闭系统遭到破坏，是页岩气散失的主要通道。

JY1井龙潭组和大隆组解析气$CH_4$占比17.05%，非烃气体$N_2$和$CO_2$占比分别为65.05%和17.87%。天然气中$N_2$主要为有机成因、大气和深部来源，$CO_2$主要有有机和无机成因两大来源(Krooss et al., 1995；Littke et al., 1995；Kotarba and Rice, 2001；Krooss et al., 2005)，对于$N_2$来说，当有机质进入过成熟阶段(*R*o>2.0%)时，有机质才会全面裂解产生$N_2$，但JY1井实测*R*o值平均1.67%，未达过成熟阶段，且有机质在最大脱氮阶段生成的$N_2$也仅占总生气量的2%(Krooss et al., 1995；Littke et al., 1995；Krooss et al., 2005)，即有机成因$N_2$的组分一般较低。此外，大气中$N_2$通常只占天然气$N_2$含量的5%~10%(朱岳年, 1994)，因此，大气源的$N_2$不是JY1井解析气中$N_2$的主要来源。研究表明下扬子区加里东期、燕山期以及喜山期都有很频繁的火山活动，其中又属燕山期岩浆的侵入范围最大(Ge and Zhang, 2016;Du et al., 2019)，而页岩的沉积时间远早于燕山期岩浆的侵入时间，因此，在岩浆的侵入过程中，会向页岩层传递相当大的热量，页岩气会受到岩浆的烘烤作用发生裂解。加之中、新生代伴随的多期次强烈构造运动(潘继平等, 2011;Du et al., 2019)，都会导致幔源气的上涌。由此推测，JY1井龙潭组和大隆组解析气中$N_2$应以幔源为主。对于$CO_2$来说，一方面上地幔岩浆中富含$CO_2$气体，随着岩浆上升，压力减小，岩浆中的$CO_2$逸出，另一方面碳酸盐岩以及有机质受到岩浆的烘烤作用也会分解产生$CO_2$(朱岳年, 1994)。

因此，研究区页岩气一方面通过广泛发育的裂缝逸散，另一方面构造运动与岩浆活动加快了页岩气散失(图10)。在双重破坏作用下，页岩气保存条件较差，含气性总体较差。下扬子地区二叠系页岩物质条件(页岩厚度、有机质丰度、生气能力、储集条件)较好，应加强页岩气保存条件研究，为页岩气勘探有利目标优选提供依据 (Zhang et al., 2020)。

### 4.5 页岩气有利区评价

目前针对海陆过渡相的选区评价相对较少，可借鉴的标准也较少，因此，参考中国南方地区海相页岩气选区评价标准(王世谦等, 2013;邱小松等, 2014)，同时充分考虑到下扬子区页岩气地质条件以及海陆过渡相有机质类型、单层厚度薄、互层频繁等特殊性，在关注断裂对研究区页岩气保存条件影响的基础上，进一步考虑了温泉和岩浆活动对保存的影响。鉴于目前仅有少量文献报道了下扬子地区二叠系页岩孔隙度数据(陈平等, 2013；Pan et al.,

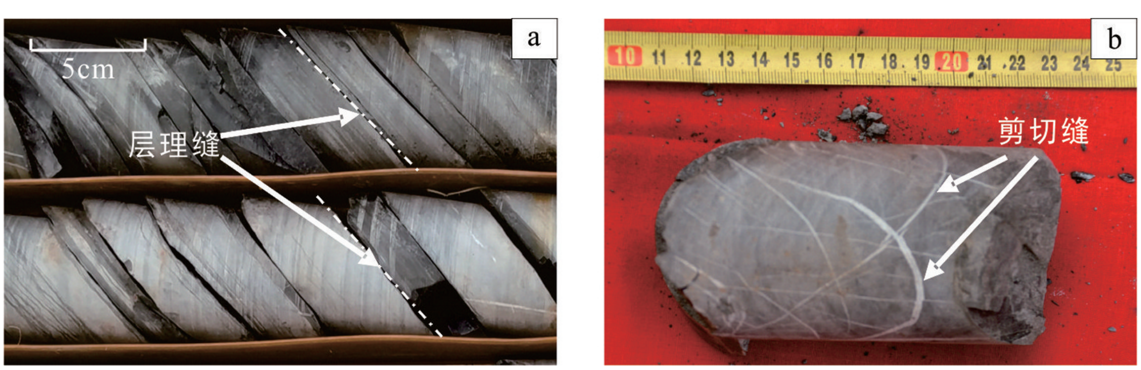


图9 JY1井岩心照片(a—大隆组；b—龙潭组)
Fig.9 The core photos of well JY1(a−Dalong Formation; b−Longtan Formation)

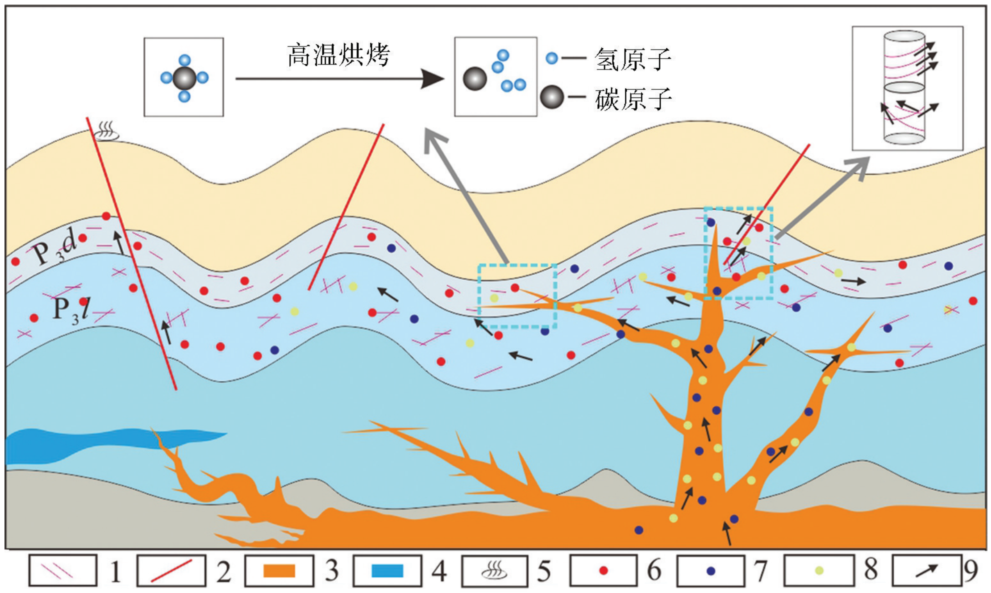


图10 岩浆及裂缝对页岩气的破坏模式示意图

1—裂缝; 2—断裂; 3—岩浆; 4—地下水; 5—温泉; 6—烃类气体; 7—二氧化碳; 8—氧气; 9—运移方向

Fig. 10 Schematic diagram of failure mode of magma and fracture to shale gas

1−Fracture; 2−Fault; 3−Magma; 4−Groundwater; 5−Hot spring; 6−Hydrocarbon gases; 7−Carbon dioxide; 8−Oxygen; 9−Migration direction

2015；曹涛涛等, 2015；黄保家等, 2015)，且测试手段不同，无法进行对比，加之本次实测的数据也较少，同时下扬子地区二叠系页岩整体孔隙度较低，渗透率也极低，因此，本次有利区优选未考虑孔渗条件。最终选取了5个参数(厚度、TOC、*Ro*、埋深、与断裂及温泉和活动区的距离，如此既可以考虑到生烃条件，又可以兼顾到保存条件)制定了下扬子海陆过渡相页岩气有利区优选指标(表2)，采用综合信息叠加法，开展了页岩气有利区的优选和评价。在大隆组和龙潭组分别预测了5个有利区(图11)，之后再利用5个参数对不同有利区页岩层进行半定量

**表2 下扬子区上二叠统页岩气选区评价标准**

**Table 2 Evaluation criteria for the Upper Permian shale gas in the Lower Yangtze region**

| 评价参数 | | 低风险区 | 中风险区 | 高风险区 |
|---|---|---|---|---|
| 发育条件 | 面积/km$^2$ | ＞100 | 50~100 | ＜50 |
| | 厚度/m | ＞50 | 30~50 | ＜30 |
| | 埋深/m | 1000~3000 | 3000~5000 | 大于5000或＜1000 |
| 生烃条件 | TOC/% | ＞2 | 1~2 | ＜1 |
| | *Ro*/% | 1~3.5 | 3.5~4 | ＜1或＞3.5 |
| 保存条件 | 距断裂、温泉及岩浆活动区距离/km | ＞10 | 5~10 | ＜5 |

的图解，并进行对比做进一步的优选和排序，在对比过程中注重一些重要参数，如厚度、TOC等的短板效应。对比结果表明，大隆组③号有利区各参数评价均好，耦合面积最大，其次为④号有利区，再次为②号和⑤号，二者耦合面积相当，但⑤号有利区TOC含量比②号低得多，短板效应明显，最后为①号有利区。因此，大隆组有利区排序为③>④>②>⑤>①；对于龙潭组来说，④号有利区耦合面积最大，其次为①号，再次为②号，之后为⑤号和③号，因此，龙潭组有利区排序为④>①>②>⑤>③。

## 5 结　论

(1)龙潭组和大隆组页岩有机质丰度高，热演化程度适中，具备形成页岩气的良好物质基础。但海陆过渡相页岩非均质性较强，有利区优选更应注重沉积环境的分析。

(2)研究区上二叠统页岩以墨水瓶形及狭缝状中孔为主，比表面积较大。孔隙度与TOC具有良好的正相关性，且比表面积显著受控于TOC含量。因此，有机质孔为龙潭组和大隆组页岩储层提供了储集空间，有利于游离气和吸附气的赋存。

(3)研究区上二叠统页岩脆性矿物含量普遍高于50%，TOC含量与脆性矿物含量具有良好的正相

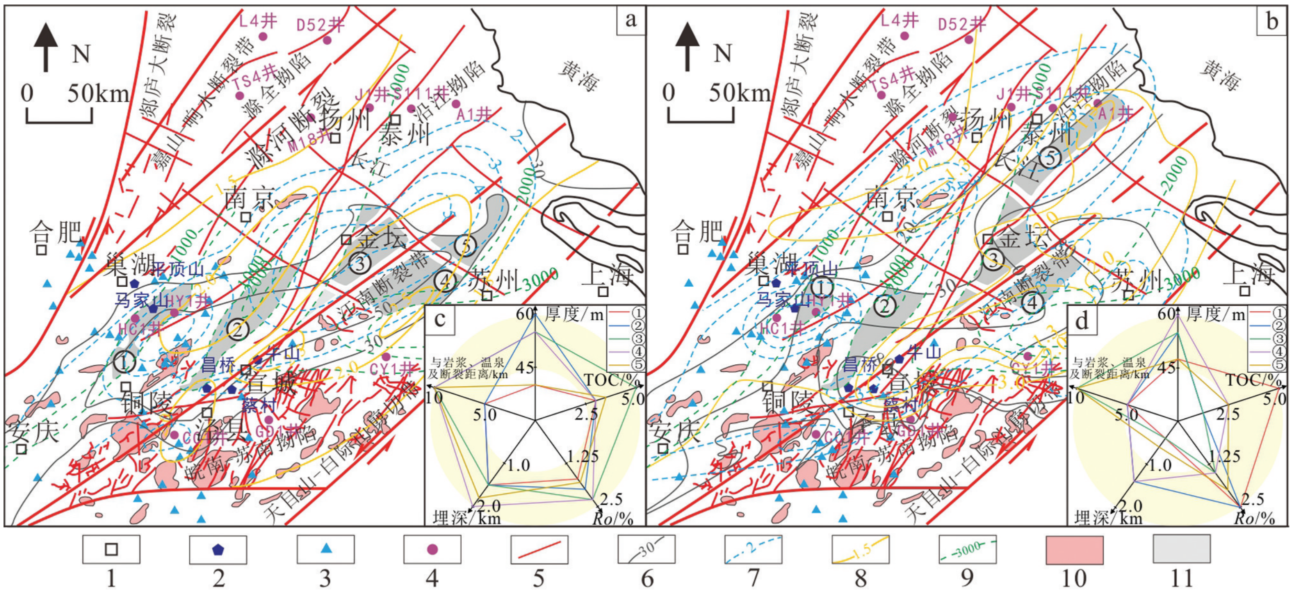


图11 下扬子区上二叠统页岩气选区评价参数指标(a—大隆组有利区预测;b—龙潭组有利区预测; c—大隆组有利区优选; d—龙潭组有利区优选)

岩浆岩分布据孙涛,2006;断裂分布据金之钧等, 2013; Du et al., 2019;温泉分布据Du et al., 2019;大隆组页岩分布据张敏强等, 2013;龙潭组页岩分布据宋腾, 2019;大隆组和龙潭组TOC分布据表1数据绘制;大隆组*Ro*分布据江苏油田,2010;龙潭组*Ro*据吴浩等, 2013,以及表1中数据修改;埋深线据吴浩等, 2013.1—城市; 2—野外剖面; 3—温泉; 4—井位; 5—断裂; 6—厚度; 7—TOC; 8—Ro; 9—埋深; 10—岩浆岩; 11—有利区

Fig.11 Evaluation parameter of favorable area of the Upper Permian shale gas in the Lower Yangtze region (a−Prediction of favorable area of the Dalong Formation; b−Prediction of favorable area of the Longtan Formation; c−Optimization of favorable area of the Dalong Formation; d−Optimization of favorable area of the Longtan Formation)

Distribution of magmatic rocks after Sun Tao, 2006; Fracture distribution, after Jin Zhijun et al., 2013; Du Xuebin et al., 2019; Hot spring distribution, after Du Xuebinet al., 2019; Distribution of the Dalong Formation shale, after Zhang Minqiang et al., 2013; Distribution of the Longtan Formation shale, after Song Teng, 2019; The TOC distribution of the Dalong Formation and Longtan Formation is plotted according to the data in Table 1;*Ro* distribution of the Dalong Formation, after Jiangsu Oilfield, 2010; *Ro* distribution of the Longtan Formation, after Wu Hao et al.,2013, and the data in Table 1.1−City; 2−Outcrop profile; 3−Hot spring; 4−Well; 5−Fault; 6−Thickness; 7−TOC; 8−*Ro*; 9−Buried depth; 10−Magmatic rock; 11−Favorable area

关性,石英以自生成因为主,研究区二叠系页岩具有良好的可压裂性。

(4)龙潭组页岩厚度较大,具有良好的自封闭能力,保存条件总体优于大隆组。二者均发育多种类型的裂缝,是页岩气逸散的主要通道,后期的岩浆活动对页岩气也有较强的破坏作用,保存条件是该区域二叠系页岩气富集与选区评价的关键。

(5)根据下扬子地区二叠系页岩气地质条件,选取了富有机质页岩厚度、TOC、*Ro*、埋深和保存条件为选区评价参数,评价优选了龙潭组和大隆组页岩气有利区。

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