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## 基于埋深变化的川南龙马溪组页岩孔隙特征及控制因素分析

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**摘要:**【研究目的】中国浅层-中深层页岩气勘探开发技术已经趋于成熟,深层页岩成为下一步勘探开发的重点,探明不同埋深条件下页岩的孔隙特征及其控制因素利于推动深层页岩的评优选区工作。【研究方法】本文基于核磁共振、场发射扫描电镜和X-射线衍射等实验分析手段,对比性评价了川南地区不同深度的龙马溪组页岩孔隙度、孔隙结构参数特征并进行影响因素分析。【研究结果】随着埋深的增加,总孔隙度呈现下降的趋势;3000 m以浅、3000~3500 m和3500 m以深页岩孔隙度主体分别为4%~8%、3%~7%和3%~6%。不同埋深龙马溪组页岩孔隙类型与大小分布无显著差异,各深度段页岩均发育大量纳米级有机质孔隙、矿物粒间孔、粒内溶孔和微裂缝。【结论】高U/Th比和低Ti含量下形成的丰富有机质是深层页岩孔隙发育的关键因素;高硅质矿物含量和高地层压力系数对页岩储层孔隙起到了保护作用,减缓了上覆地层的压实作用,但埋深过大仍会导致页岩孔隙减少、孔隙度降低。

**关键词:**四川盆地;页岩气;龙马溪组;孔隙度;孔隙特征;压力系数;深度;油气勘查工程

**创新点:**基于大量数据讨论了不同深度下孔隙度的变化规律,多角度探讨了页岩孔隙特征的控制因素。

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## Analysis of shale pore characteristics and controlling factors based on variation of buried depth in the Longmaxi Formation, Southern Sichuan Basin

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

**[Objective]** With the maturity of exploration and development technology in shallow and medium-deep shale, deep shale has become a focus of next exploration and development in China. Clarifying the pore characteristics of shale under different burial depths and its controlling factors is conducive to promoting the selection and evaluation of deep shale gas. **[Methods]** Methods such as nuclear magnetic resonance, field emission scanning electron microscopy and X-ray diffraction were used to comparatively evaluate the porosity and pore structure of Longmaxi-Formation in southern Sichuan Basin, and its influencing factors were also discussed. **[Results]** With the increase of burial depth, the total porosity shows a downward trend, and the main porosity of shale below 3000 m, between 3000–3500 m and deeper than 3500 m are 4%–8%, 3%–7% and 3%–6%, respectively. There is no significant difference in pore types and size distribution of the Longmaxi Formation shale at different depths, and a large number of nano-scale organic pores, mineral intergranular pores, intragranular dissolved pores and micro-fractures are developed at different depth. **[Conclusions]** A large amount of organic matter formed at high U/Th ratio and low Ti content is the key factor for the development of deep shale pores. High siliceous mineral content and high formation pressure coefficient could protect pores of shale reservoirs and slow down compaction of its overlying strata. However, excessive burial depth would also lead to a reduction of shale pores and porosity.

**Key words:** Sichuan Basin; shale gas; Longmaxi Formation; porosity; pore characteristics; pressure coefficient; depth; oil and gas exploration engineering

**Highlights:** Based on a large amount of data, the variation rules of porosity at different depths is discussed. Controlling factors of shale pore characteristics are discussed from multiple perspectives.

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## 1 引言

中国页岩气勘探开发已有十余年的发展,实现了巨大的突破,现已建成重庆涪陵、四川长宁、威远和云南昭通等国家级页岩气开发区(董大忠等, 2012; 刘若冰, 2015; 邹才能等, 2016; Zhai et al., 2018)。目前主要开采的是中浅层—中深层页岩气(500~3500 m),而资源量更大的深层页岩气(3500~4500 m)资源尚未得到有效开发(董大忠等, 2016),仅四川盆地南部(后简称川南)深层页岩气的可工作面积与资源量是中浅层—中深层的7倍以上(龙胜祥等, 2016; 马新华等, 2018; 赵文智等, 2020),深层页岩气的突破是页岩气“增产”与“上储”的关键(王世谦, 2017),也是实现“碳中和”目标的重要举措(马欢等, 2021)。页岩气藏属非常规气藏,良好的地层物性条件是获得工业性气流的关键(郭秀英等, 2015; 廖东良等, 2019)。四川盆地及周边地区

五峰组—龙马溪组深层页岩地面静态测试孔隙度主体为5%~6%,在覆压条件下30 MPa时,孔隙度下降约15%(何冶亮等, 2020);其中川南深层富有机质页岩具有良好的保存条件,异常高压条件使得孔隙得以保存,孔隙度平均值一般在5%左右(龙胜祥等, 2018);不同井孔隙类型相同,均以有机孔为主体,常见粒缘缝和微层理缝等(刘伟新等, 2020; Lu et al., 2020);有机质丰度与石英含量是影响深层龙马溪组页岩孔隙发育的关键因素,决定了孔隙体积(张梦琪等, 2019)。

随着埋深的增加,页岩气储层孔隙与孔隙类型特征,以及有机质是否闭合是亟需解决的问题。利用核磁共振、场发射扫描电镜、XRD分析等手段,对比性评价川南长宁、泸州和威远区块页岩气主产层——龙一<sub>1</sub>亚段页岩不同深度孔隙度、孔隙结构等参数特征,进一步明确页岩孔隙随埋深的变化关系以及各种因素对孔隙的影响,以期对深层页岩气的勘

探开发提供一定依据。

## 2 地质背景

四川盆地构造上属于扬子台地的西部,在晚奥陶世—早志留世分别沉积了五峰组和龙马溪组海相页岩地层(郑和荣等,2013;聂海宽等,2017)。早志留世在“三隆夹一坳”的构造格局下,因冰川消融、海平面快速升高,在半闭塞盆地内形成大面积缺氧的深水陆棚环境,沉积了龙马溪组富含笔石的黑色页岩,且整体上有水体逐渐变浅的变化趋势(郭英海等,2004;牟传龙等,2011;王同等,2015)。五峰组—龙马溪组页岩岩相主要为硅质页岩和混合质页岩,厚度变化较大,在盆内南部、东北部以及北部厚度介于300~600 m(王玉满等,2015);受乐山—龙女寺隆起、黔中古陆和湘鄂西水下高地的影响,川南泸州地区富有机质页岩沉积最厚,达到50 m(马新华等,2018)。

此次研究的龙一<sub>1</sub>亚段位于龙马溪组底部,由下至上进一步细分为4个小层,即龙一<sub>1</sub><sup>1-4</sup>小层,地层代号S<sub>1</sub>l<sub>1</sub><sup>1-4</sup>(郑和荣等,2013;赵圣贤等,2016)。长宁、泸州及威远三个工区从南至北依次展布,长宁区块有N201、N203、N208等井,龙马溪组页岩埋深主要在2000~3500 m;泸州区块有Yang101、Lai101等井,埋

深主要在3500~4500 m,属深层范围;威远区块有Wei206、Zhen101井,埋深介于3500~4000 m(图1)。

## 3 样品及实验方法

实验样品选取于川南长宁、泸州与威远三个工区不同深度的钻井取心,主要特征为黑色页岩,笔石与层理发育。实验前先将样品进行加工,部分样品加工成标准的圆柱状,直径25 mm,长30~50 mm,部分实验用碎样。气测法孔隙度采用美国CoreLab公司制造的CMS-300型非常规孔渗仪进行测定,选用高纯度氦气作为工作介质,测得结果为氦气孔隙度(简称孔隙度)。核磁共振实验(NMR)采用苏州纽迈公司生产的低场核磁共振仪,实验场强为0.5 T,主频率为23 MHz;实验室内温度为常温,磁体温度为恒定的32℃;页岩样品核磁共振T<sub>2</sub>谱的等待时间设置为10000 ms,实验测量的回波间隔设定为0.1 ms,回波个数为5000。页岩样品新鲜面置于Leica EM Ace 200型镀膜仪器下进行表面镀金膜后,再置于Quanta 650型场发射扫描电镜仪下对镀膜面进行直接观察可得到样品微观特征照片。X-射线衍射实验采用BRUKER D8 ADVANCE型衍射仪,应用K值法标定页岩矿物组分;使用CS230HC型碳硫分析仪对页岩样品进行TOC分析。

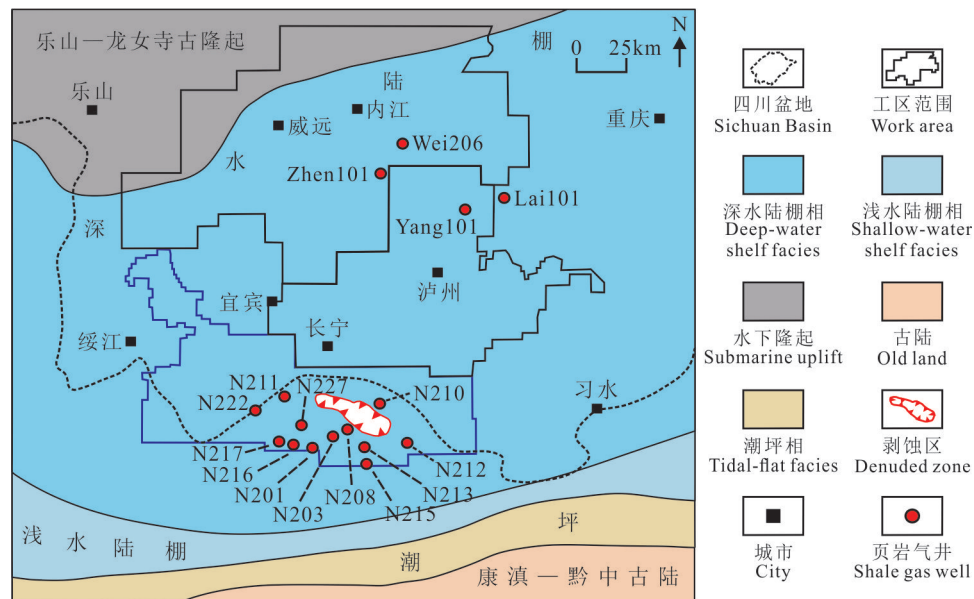


图1 川南地区沉积特征与井位分布图(修改自马新华等,2018)

Fig.1 Sedimentary characteristics and well location in Southern Sichuan Basin (modified from Ma Xinhua et al., 2018)

## 4 埋深对页岩气储层孔隙度的影响

常规储层因成岩作用、地层压实作用等因素,往往存在有效的物性下限,有效物性下限与深度存在一定的函数关系(王健等,2011;周立明,2016;张鹏飞等,2016);而页岩作为非常规储层,孔隙主要以纳米级孔隙为主,孔隙度随埋深变化规律并不清楚。为探究孔隙度与埋深规律,同时排除TOC差异过大导致的影响,选用不同埋深龙一<sub>1</sub>亚段页岩氮气孔隙度进行统计分析。

### 4.1 典型井埋深与孔隙度的关系

选取2500 m、3500 m与4000 m三个埋深级别的典型井(N201、Zhen101与Lai101)进行对比分析(图2)。对于单井而言,不论是浅埋藏还是深埋藏,孔隙度纵向上随深度变化不明显,与TOC含量呈正相关性,换言之页岩气储层中TOC含量是控制储层发育的关键参数。对比三口井发现,N201井埋深最浅,孔隙度最高,主体为4%~8%(图2 a);Zhen101井孔隙度主体在4%左右,纵向变化幅度较小(图2 b);Lai101井(图2 c)埋深最大,孔隙度主体在3%~5%,最高不超过6%。分布频率图能更清晰地反映处于

三个深度级别的典型井孔隙度差异特征,N201井呈现“三峰”特征,孔隙度值分布范围广,最大在10%以上,主峰为6%~7%;Zhen101与Lai101井孔隙度分布为“单峰”形态,孔隙度值以3%~5%为主(图3)。

### 4.2 孔隙度与埋深相关性分析

统计研究区共计17口井龙一<sub>1</sub><sup>3</sup>小层富有机质页岩共440个样品孔隙度值与埋深散点图。整体上,随着埋深大幅度增加,孔隙度呈现降低的趋势, $R^2$ 为0.1765;孔隙度主要分布范围从4%~8%降低到3%~6%,3500 m以深页岩孔隙度虽仍有较大值,但属于个例(图4)。从三个深度段页岩孔隙度分布频率图来看,埋深小于3000 m时,从2%到≥10%均有分布,孔隙度值分布区间较广,主体在3%~8%区间内;埋深3000~3500 m,整体上孔隙度值呈现减少趋势,主体在3%~7%,无7%以上值;埋深大于3500 m,孔隙度值进一步降低,主峰为3%~4%,孔隙度主体在3%~6%(图5)。

## 5 不同埋深页岩气储层孔径分布特征

定量表征页岩孔径具有多种方法,其中低场核磁共振技术具有无损、快速且制作简单的优点,且

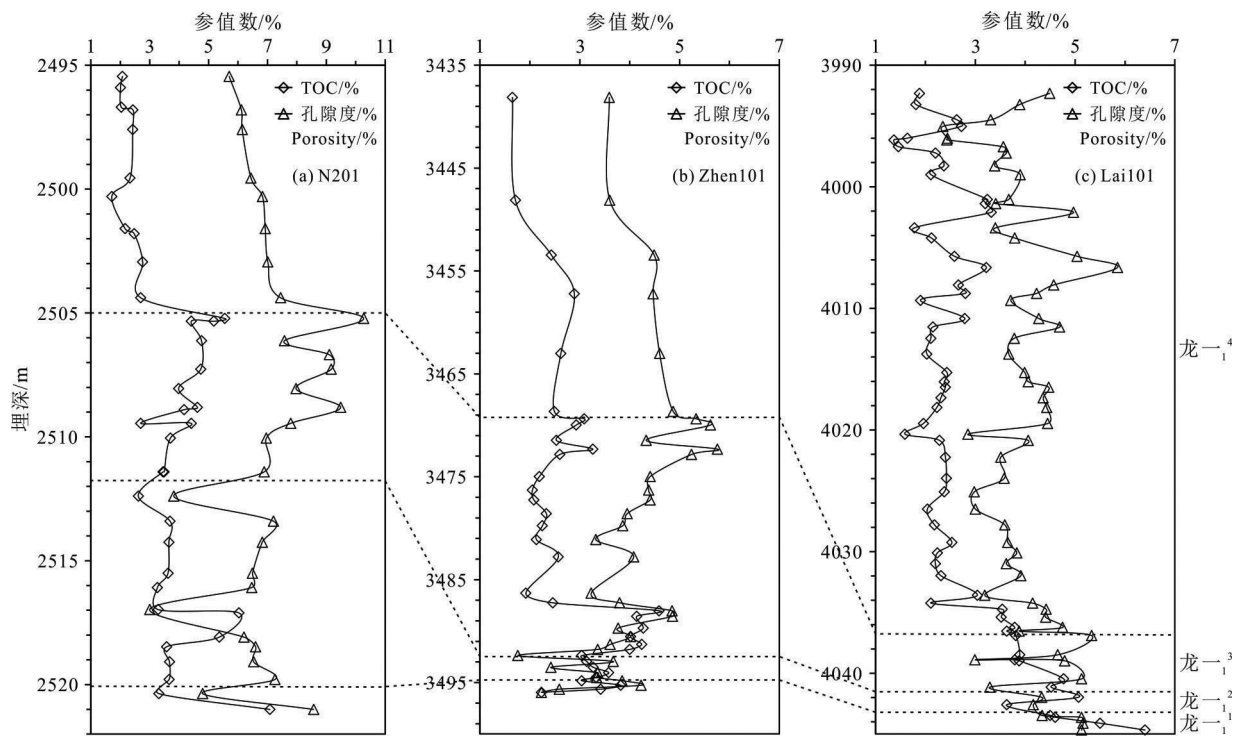


图2 典型井龙马溪组页岩TOC和孔隙度对比图

Fig.2 TOC and porosity of Longmaxi Formation from typical wells



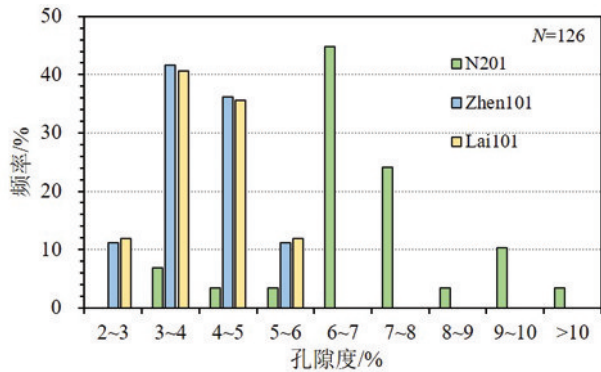


图3 典型井龙马溪组页岩孔隙度分布频率  
Fig.3 Shale porosity distribution of Longmaxi Formation from typical wells

能够反映纳米-微米级的孔径特征,近年来有较多学者通过该方法研究了页岩储层的物性和孔隙结构特征,取得了相应的成果(龚小平等,2016; Liu et al.,2018;李志清等,2018;Liu et al.,2019; Ma et al.,2020)。饱和流体的页岩样横向弛豫时间( $T_2$ )与孔径为一一对应关系,常利用转换公式和转换系数,将 $T_2$ 时间谱转换成对应的孔径分布图,龙马溪组页岩转换系数 $C$ 取为23 nm/ms。研究发现,页岩孔隙分布主要有具有“双峰”特征,部分呈“三峰”特征,主要孔径分布在1~1000 nm,与前人结论相符(张烈辉等,2015;龚小平等,2016)。长宁区块具有相近TOC含量( $TOC > 4\%$ )、不同埋深的页岩样品孔径分布特征具有相似性,大孔径部分无显著差异(图6a);威远区块同一小层、不同埋深的样品之间孔径分布曲线相接近,未出现埋深较浅者大孔径部分显著优于深埋样品的规律(图6b)。从分布频率柱状图来看,同为龙一<sup>1</sup>小层的5个样品孔隙体积均主要由100 nm以下孔隙提供,相同孔径范围内孔隙体积占比相近,大于100 nm的孔隙体积比例均较少(图6c)。通过场发射扫描电镜观察发现,深埋页岩样品有机质孔隙、粒间孔与粒内溶孔等与浅埋样均有发育,两者在孔隙类型方面无差异(图7)。

## 6 影响页岩气储层孔隙发育的其他因素

### 6.1 有机质含量对页岩气储层孔隙度的影响

有机质是有机质孔隙发育的载体,有机质孔隙是页岩气储层主要的孔隙类型,因而有机质的发育对页

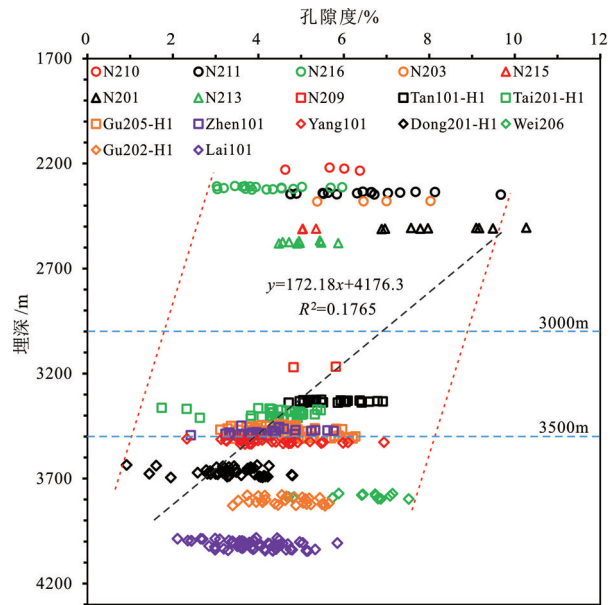


图4 川南龙马溪组富有机质页岩孔隙度与埋深关系图  
Fig.4 Relationship between porosity and depth of organic-rich shale from Longmaxi Formation in Southern Sichuan Basin

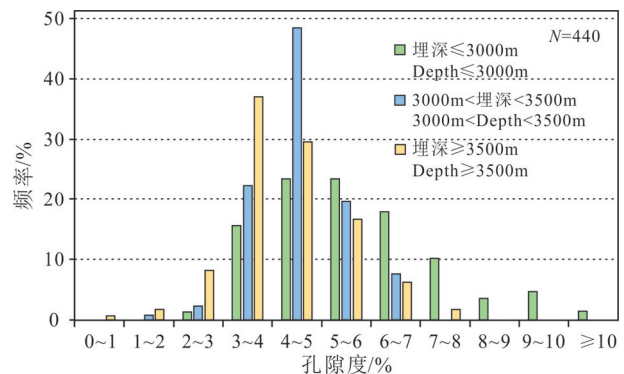


图5 龙马溪组富有机质页岩孔隙度分布图  
Fig.5 Porosity distribution of organic-rich shale from Longmaxi Formation in Southern Sichuan Basin

岩孔隙的发育具有重要的影响作用(张梦琪等,2019;刘伟新等,2020)。从两个埋藏深度段TOC与孔隙度相关性图来看,龙一<sup>1</sup>与龙一<sup>3</sup>小层相关性最好;龙一<sup>2</sup>与龙一<sup>4</sup>小层相关性相对较差(图8)。3000 m以深孔隙度与TOC的关联性在龙一<sup>2-3</sup>小层要好于3000 m以浅部分;在龙一<sup>1</sup>反而低于3000 m以浅部分,此时龙一<sup>1</sup>整体有机质含量很高,基本在3%以上,部分达到5%~7%(图9 a)。分析认为,当有机质含量较低时( $TOC \leq 5\%$ ),高有机质含量对孔隙度的增加有建设性作用,而当有机质过高( $TOC > 5\%$ )时,

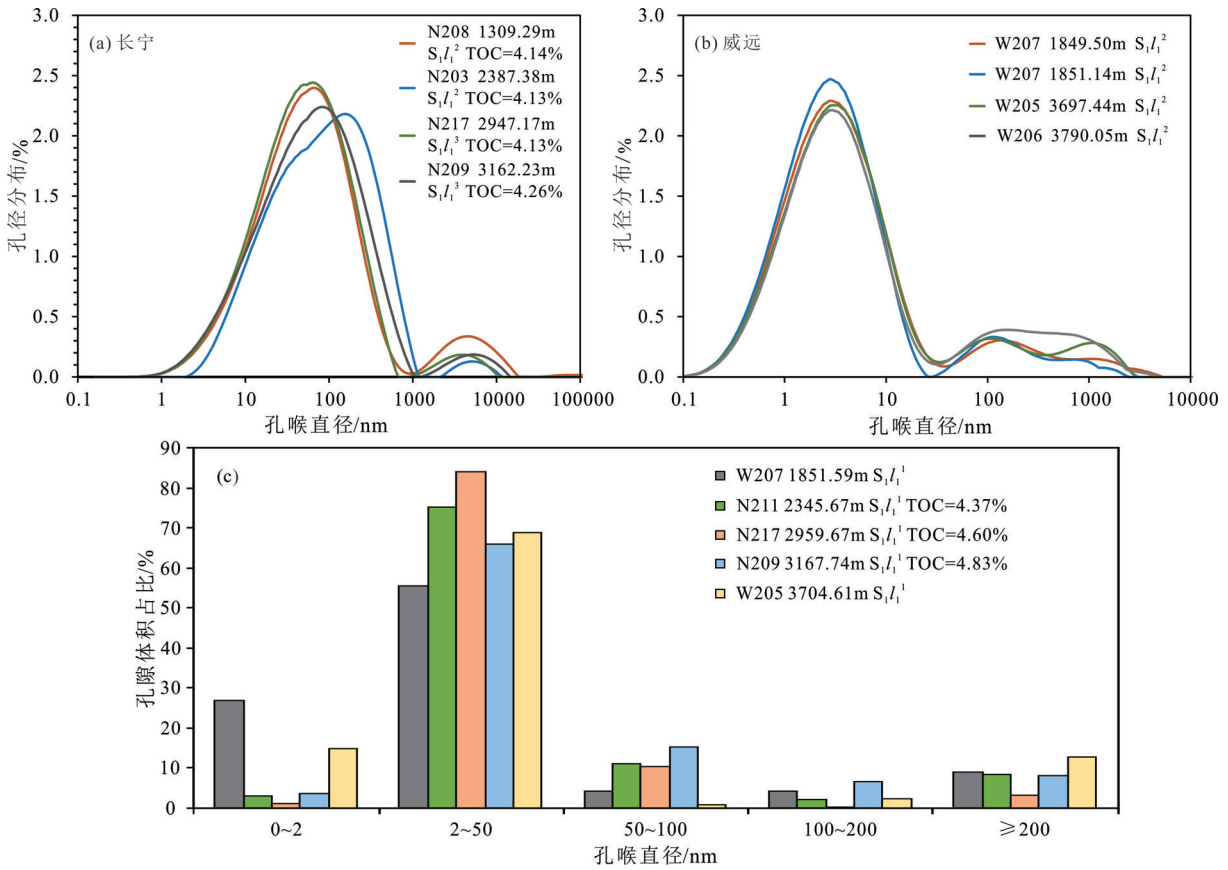


图6 不同埋深龙马溪组页岩孔径分布

Fig.6 Shale pores diameter distribution of Longmaxi Formation at different depth

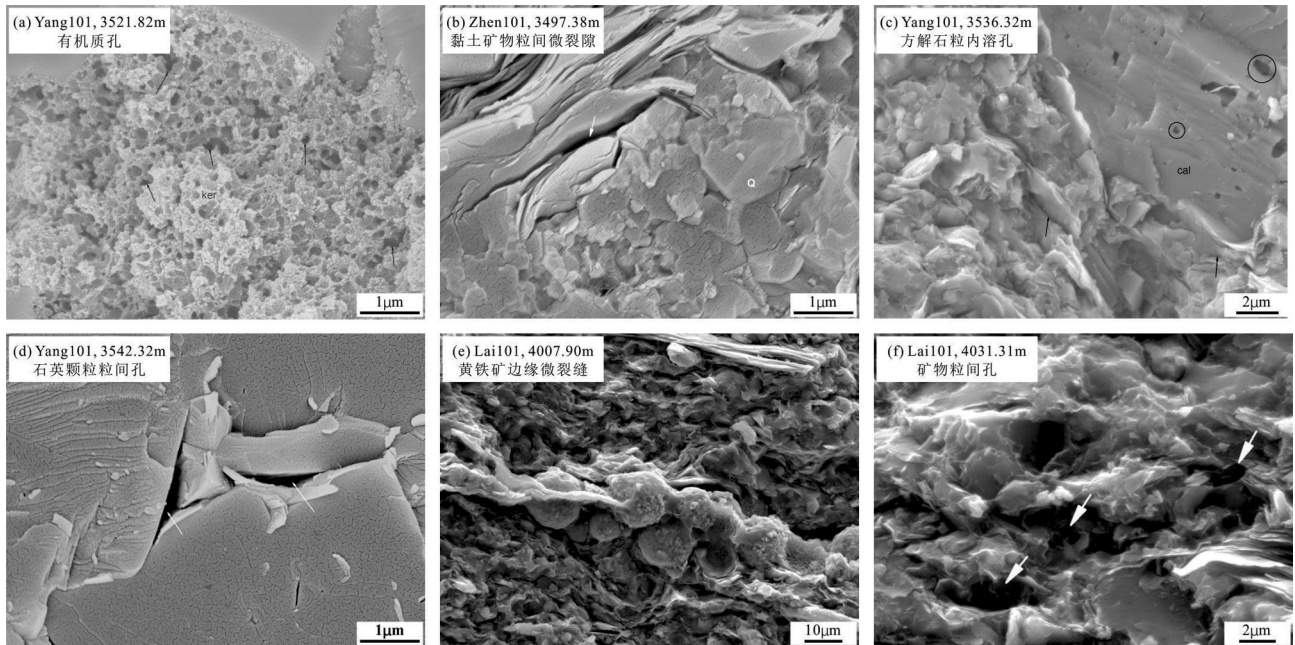


图7 深埋条件下龙马溪组页岩孔隙扫描电镜照片

Fig.7 SEM images of shale pores from Longmaxi Formation under deep burial conditions

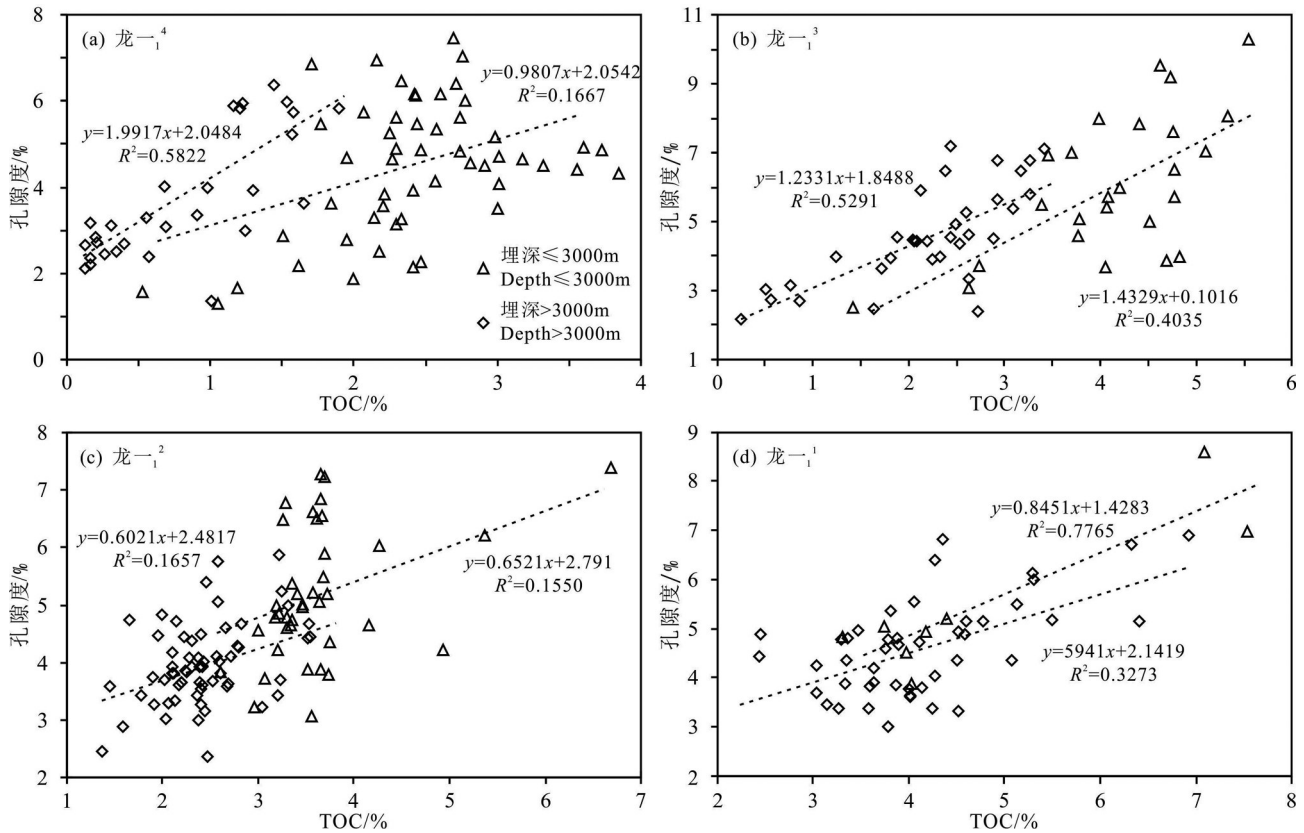


图8 不同深度龙马溪组页岩TOC与与孔隙度关系图

Fig.8 Relationship between TOC and porosity of Longmaxi Formation with different depth

高有机质含量降低了页岩骨架支撑能力,孔隙遭受上覆地层的压实作用更为强烈。

TOC含量受到诸多因素的控制,U/Th是表征沉积时期氧化还原条件的重要参数;Ti或TiO<sub>2</sub>含量指示陆源物质输入情况,含量越高陆源输入量越大,沉积受到陆源物质的影响就越大(江增光,2018;竺成林,2019)。N213井TOC与U/Th变化存在一致性,与Ti元素含量变化趋势则相反,高TOC含量出现在埋深2570~2585 m、高U/Th、低Ti的环境中;孔隙度的发育与TOC、U/Th变化趋势一致,与Ti元素含量相反(图9b)。由此表明高U/Th、低Ti是孔隙发育的物质基础。

## 6.2 脆性矿物对页岩气储层孔隙的影响

脆性矿物,尤其是硅质矿物,因其硬度大、抗压实作用较强,能够对深埋的页岩孔隙具有一定支撑保护作用(龙胜祥等,2018;张梦琪等,2019;徐中华等,2020),因此不同矿物组成、不同岩相页岩样品之间孔隙度将存在差异。统计分析3500 m以深样品矿物组成、岩相特征、孔隙度,以研究脆性矿物对

页岩气储层孔隙的影响作用。硅质矿物(石英+长石)含量与孔隙度具有一定正相关关系,整体上随着含量增高,孔隙度有增高趋势(图10a);总黏土矿物含量与孔隙度则具有相反的趋势,黏土含量越高,整体上孔隙度相对较低(图10b)。依据矿物组成三端元法可将研究区页岩划分为多种岩相,其中主要岩相为硅质页岩和混合质页岩,混合质页岩含钙质硅质混合页岩、黏土质硅质混合页岩和黏土质钙质混合页岩三种岩相(王玉满等,2016)。从不同岩相对应孔隙度分布柱状图可明显看出硅质页岩对应孔隙度主峰值高于高黏土质的页岩对应孔隙度,分别为4%~5%、3%~4%(图10c)。微观上看,在富石英的区域,不仅存在大量矿物粒间孔,同时这些孔隙还受到脆性矿物形成的刚性“骨架”的保护,从而得到保存(图7e)。

## 6.3 压力系数对页岩气储层孔隙的影响

压力系数是表征地下流体能量大小以及封闭程度的一个综合参数指标(刘洪林等,2013),按照压力系数大小分为>1.2、1.0~1.2和<1.0的A、B、C三



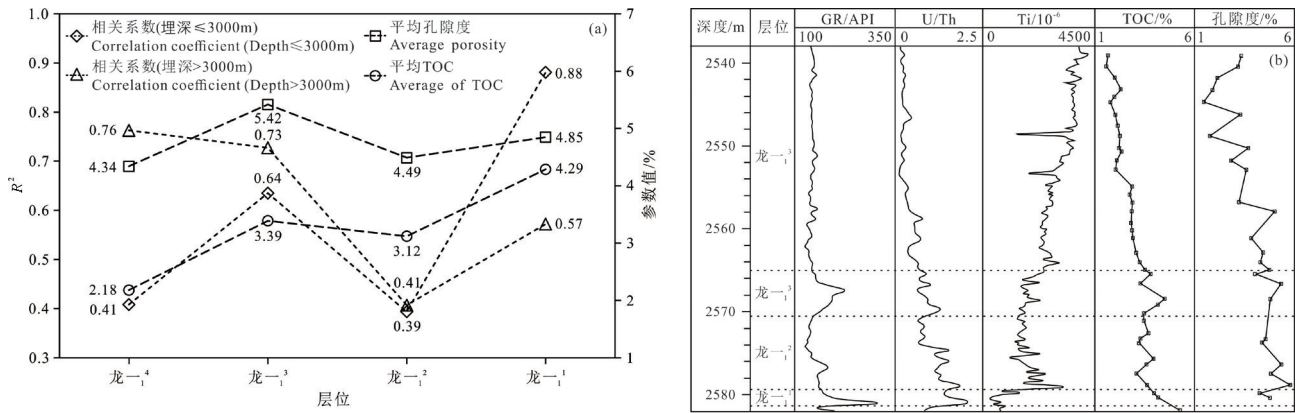


图9 不同小层页岩TOC和孔隙度的关联性及其与沉积环境关系

Fig.9 Correlation between TOC and porosity and the relationship between TOC and sedimentary environment of different unit shale

类,分别对应三类储层(陈斐然等,2020)。川南和渝东南地区龙马溪组页岩地层超压的存在,减缓了地层压实作用和成岩作用对页岩孔隙的影响,孔隙从而得到了“保护”(杨洪志等,2019;马新华等,2020;高玉巧等,2020)。利用已有数据及文献资料

对不同埋深页岩储层压力系数与孔隙度大小进行统计整理(表1),不同地区不同深度页岩TOC含量均较高,主体在3%~4%,地层埋深、压力系数及孔隙度差异较大。压力系数与埋深具有良好的正相关关系, $R^2$ 为0.7398,表明压力系数随地层深度增大而

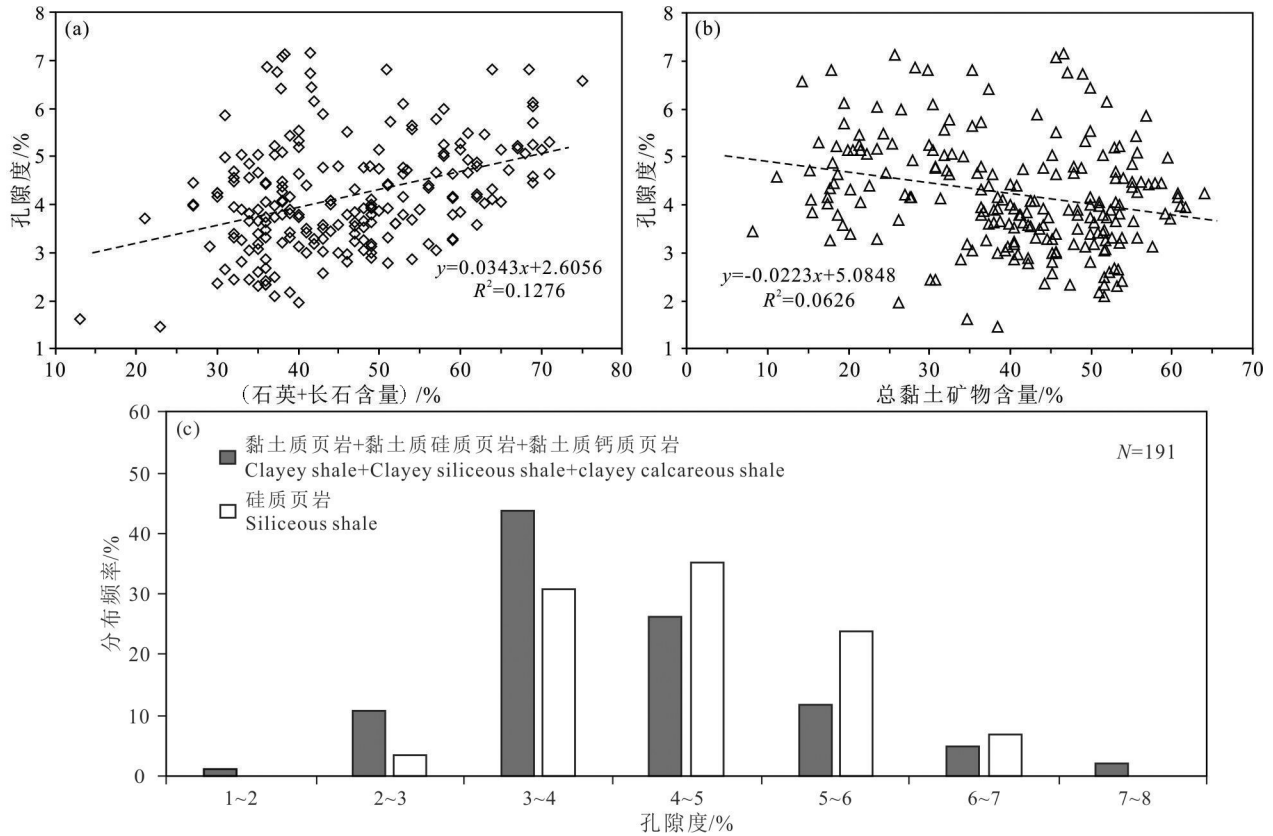


图10 3500 m以深页岩矿物含量与孔隙度相关性(a,b)及不同岩相页岩孔隙度分布频率图(c)

Fig.10 Below 3500 m, the correlation between mineral content and porosity (a,b) and Porosity distribution frequency of different facies in shale(c)



表1 不同埋深下压力系数与孔隙度统计表

Table1 Statistical table of pressure coefficient and porosity at different depths

井号/气田	埋深/m	地质年代	TOC/%	孔隙度/%	压力系数	备注	井号/气田	埋深/m	地质年代	TOC/%	孔隙度/%	压力系数	备注
Lu202	4308		-	6.00	2.24		N201	2510		4.15	7.09	2.03	
Yang01	3530		3.40	4.33	2.25	据杨洪志等, 2019	N203	2385		4.04	5.19	1.35	
Gu202-H1	3851	志留纪	3.44	4.61	2.10		N208	1311		3.45	5.22	0.96	
Gu205-H2	3480		3.45	4.65	2.19		N209	3115		4.23	5.32	1.29	
威荣	3550~3880		1.00~4.00	5.60~6.60/6.10	1.96~2.06/2.01		N210	2225		4.08	5.32	1.00	
Fayetteville	330~2300	石炭纪	4.00~9.80	2.00~8.00/5.00	0.98	据焦方正, 2019	N211	2327	志留纪	4.82	6.44	1.30	
Barnett	1980~2591		石炭纪	4.00~5.00	4.00~5.00/4.50		0.97~1.00/0.99	N213	3115		3.73	5.04	1.51
Ti201-H1	3450			3.46	4.43		1.94	N215	2746		3.60	5.14	1.80
Zhen101	3470		2.92	4.15	2.20	N216	2353		3.59	4.08	1.12		
Tan101-H1	3330		3.46	5.80	2.08	N217	3046		3.21	4.11	1.74		
Dong201-H1	3680		3.18	3.35	2.14	N227	3414		3.82	5.51	2.08		
Lai101	4016		2.92	4.07	2.08								

注:“/”前为数值范围,后为中间值,以作为该组数据平均情况。

增高(图 11 a)。不同深度段孔隙度与压力系数具有不同相关性,3000 m 以浅部分,孔隙度随压力系数增加而增大,两者具有较好的正相关性,  $R^2$  为 0.3984

(图 11b)。3000~3500 m 及 3500 m 以深部分,孔隙度与压力系数无明显相关性(图 11 c、d),整体上压力系数在 1.2~2.4,孔隙度为 4%~6%。

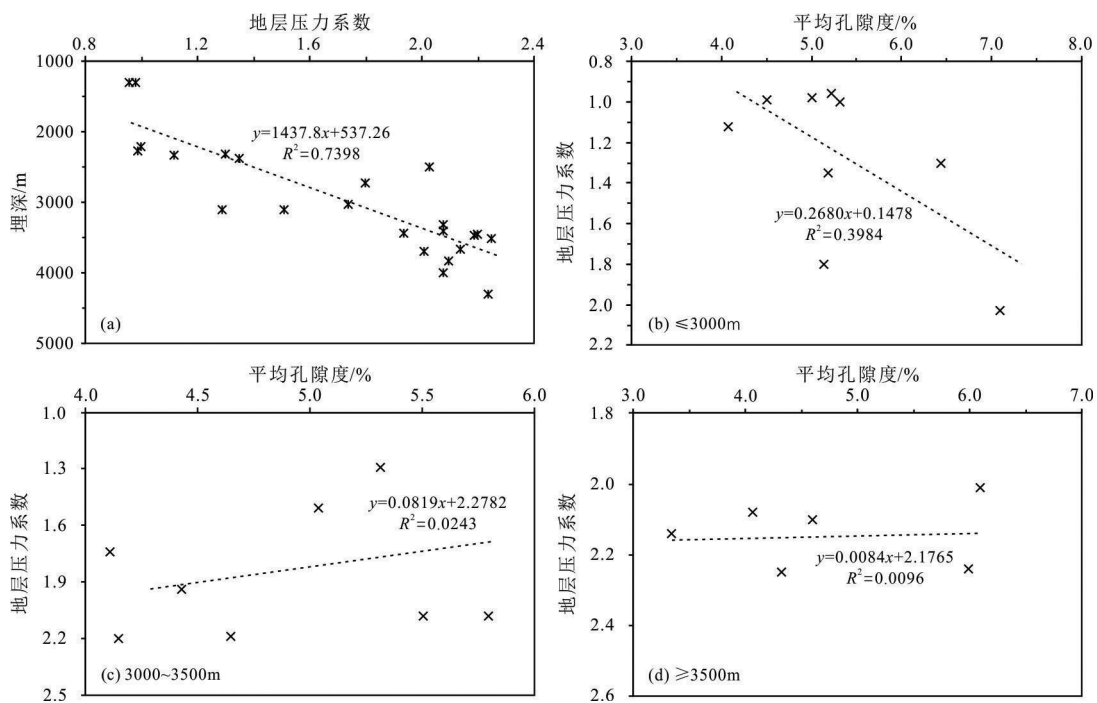


图 11 压力系数与埋深关系(a)、不同深度段孔隙度与压力系数相关性(b, c, d)

Fig.11 Relation between pressure coefficient and buried depth(a), correlation between porosity and pressure coefficient at different depths(b, c, d)

分析认为,埋深较浅( $\leq 3000$  m)时,压力系数对孔隙的影响作用更为明显,在此范围内,压力系数的增高,孔隙受到高压的保护作用逐渐增强,孔隙度因此呈现增大的趋势;当压力系数随着埋深进一步增大而增大(3000~3500 m及 $\geq 3500$  m),压力系数普遍较高,但同时上覆地层压力作用也极为强烈,此时孔隙度受到高压系数的“保护”作用相对有限,因此压力系数与孔隙度相关性不明显。

深埋条件下一般具备高地层压力系数特征(图11a),不同地层压力系数对应孔喉特征与不同埋深下孔喉特征具有一致性(图6),孔喉分布呈现“双峰”或“三峰”特征,孔径主体均在100 nm以下,不同压力系数下页岩孔喉分布差异并不显著。

## 7 结 论

(1)川南地区不同埋深页岩气井龙一<sub>1</sub>亚段孔隙度存在差异。2500 m、3500 m及4000 m三个深度级别的典型井龙一<sub>1</sub>亚段孔隙度纵向上随埋深变化不明显,与TOC呈正相关性。三口典型井对比发现埋深最浅井孔隙度最高,埋深最大孔隙度最低。17口井孔隙度数据统计显示孔隙度随埋深大幅度增加,呈现逐渐降低的趋势,孔隙度主要分布区间从4%~8%降低到3%~6%。

(2)页岩孔喉分布呈“双峰”和“三峰”形态,以“双峰”为主,主要孔径分布在1~1000 nm。埋深不影响页岩孔隙类型的发育,不同深度页岩有相同的孔隙类型;埋深对孔隙体积比例无显著影响,不同埋深页岩孔隙体积均以100 nm以下孔隙为主,大孔隙体积仅占少部分。

(3)TOC是控制页岩孔隙发育的关键因素,适中的有机质含量利于孔隙发育,TOC过高会导致页岩骨架支撑能力降低,上覆地层压实作用增强。高脆性矿物和高压系数的存在,使得页岩抵抗压实作用的能力增强,在深埋条件下页岩孔隙仍然得到了较好的保存;但当地层埋深达到一定程度时,脆性矿物和压力系数对孔隙的“保护”作用降低,页岩孔隙度仍会降低。

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