

页岩储层微观结构及其吸附非均质性研究评述

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摘要: 针对当前我国页岩气产能和产量还极为有限的现状,为正确评估页岩气储量,揭示页岩气赋存富集规律,系统阐述了制约和影响页岩气吸附性的储层微观结构及其吸附非均质性研究进展。分析认为,我国页岩气资源潜力和开发前景可观,但投入与产出尚不匹配,页岩气产量存在巨大的区域和井间差异性,规模开发仍面临困境。页岩气的吸附性是形成气藏的最关键因素,受到微观地质因素及其非均质性控制;产能和产量的局限性反映出对我国页岩储层微观结构及吸附非均质性本质规律认识不清。未来研究应注重页岩气赋存富集的地质过程,重点在页岩储层微观结构量化及其非均质性特征研究,储层微观非均质性与吸附非均质性的内在关系、页岩吸附机制,及其对页岩气富集规律影响的研究等方面,以期为页岩气富集区带勘查提供科学依据。

关键词: 页岩储层;微观结构;吸附机理;非均质性

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Study review on microstructure and adsorption heterogeneity of shale reservoir

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Abstract: At present, China shale gas production capacity and production rate are limited. In order to conductively and accurately estimate the shale gas reserves and to reveal the enrichment law of the shale gas deposition, the paper systematically stated the reservoir micro structure restricted and influenced to the shale adsorption and stated the study progress on the adsorption heterogeneity. The analysis held that the potential and development prospect of the shale resources in China would be considerable, but the input and output could not be matched yet, the shale gas production had a great difference between the regions and wells and the scale development would still have great difficulties. An adsorption would be the key to base form the shale gas reservoir and would be highly controlled by the micro geological factors and heterogeneity. The limitation of the production capacity and production rate could reflect that the micro structure and adsorption heterogeneity property law of the shale reservoir in China were not recognized. The future study should note the enrichment geological process of the shale gas deposition and the key study would be on the micro structure quantization and the heterogeneity features. The study on the internal relations between the micro heterogeneity and the adsorption heterogeneity and others were conducted in order to provide the scientific basis to the survey of the shale gas enrichment law.

Key words: shale gas reservoir; micro structure; adsorption mechanism; heterogeneity

0 引言

“中国页岩气研究现状与发展趋势^[1]”综述了中国页岩气研究现状,阐述了未来的研究走向和发

展需求,在启发和促进行业发展中起到了一定的引导作用。中国已经成为继美国和加拿大之后的第3个商业性页岩气开发国家^[2],中国的页岩气研究、勘探和开发现状均发生了很大变化。当前,国际石

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油与天然气价格整体低靡,国内经济新常态下能源需求也发生了显著变化,对页岩气行业的发展产生了一定的影响。

我国页岩气技术可采资源量为(25.08~31.6) $\times 10^{12} \text{ m}^3$,目前在勘探开发方面已取得令世界瞩目的业绩,但产能上的较大突破仅局限于南方下古生界海相、四川盆地侏罗系陆相、鄂尔多斯盆地三叠系陆相3个领域。尽管我国页岩气发展迅速,但投入与产出并不匹配,规模开发仍面临极大困境。2013年页岩气产量为 $1.93 \times 10^8 \text{ m}^3$,2014年约为 $13 \times 10^8 \text{ m}^3$,2015年产量逾 $40 \times 10^8 \text{ m}^3$ ^[3~4],未能实现 $65 \times 10^8 \text{ m}^3$ 的预期目标,页岩气发展前景受到质疑;除了涪陵、长宁、威远、昭通、延安等地,其他地区尚未取得较大规模的突破,产量也还极为局限,且存在巨大的区域和井间差异性,依然面临着一系列复杂的地质和技术问题。为减小勘探风险,确定经济可采性,页岩气富集规律和开发关键技术还亟需持续研究^[2~6]。

页岩气开采潜力最终取决于吸附性和渗透性2个关键要素,吸附性是形成气藏的最关键基础,高度受到微观地质因素及其非均质性控制。因此,笔者旨在梳理页岩气储层微观结构研究现状,阐述其对吸附非均质性影响的研究进展,指出未来一个时期在此领域的研究重点,以期为处于瓶颈期的我国页岩气勘探开发提供借鉴。

1 页岩储层微观结构及其吸附非均质性研究进展

1.1 页岩气赋存状态研究

赋存方式是页岩气成藏的核心。页岩气的赋存形式可能存在游离态、吸附态、溶解态等多种赋存形式^[7~8],以吸附态和游离态为主要存在方式^[9]。页岩气主要通过化学或物理作用吸附于有机质与黏土矿物颗粒表面或者存储于有机质内;游离于孔隙中,或有机质分解及其他成岩作用和构造运动所形成的裂缝中^[10~11]。吸附作用是页岩气聚集的基本方式之一,在很大程度上决定了页岩气的富集程度。吸附态页岩气含量所占总含气量的比值差异性较大^[12~15];美国5大页岩气藏吸附气含量介于20%~85%^[10]。蒲泊伶等^[16]认为吸附态是页岩气的主体赋存形式,所占比例可超40%^[17];但也有学者认为热成因页岩气中游离气量远高于吸附气量,只有生物成因页岩气的主体才是吸附气^[18];游离气一般

介于25%~30%^[6],溶解气量一般小于0.1%^[19],特别是处于过成熟阶段的页岩气溶解气含量更小^[18~20]。此外,秦勇提到乌克兰科学家用核磁共振氢谱和X射线衍射技术,在室温和低温条件煤样中发现在压力大于2 MPa条件下,甲烷能以固态晶体形式存在于煤基质中,并由此认为固溶态甲烷的存在使煤具有多级解吸动力学特征;页岩中是否可能存在这种晶态的甲烷以及它与“固溶态”甲烷的异同尚不可知,固溶态甲烷的含量在国内外亦鲜有报道^[21]。

不同地区不同页岩气藏,吸附气、游离气和溶解气等各种相态的总量及比例也不尽相同,取决于页岩分析时段^[11],并受到多种因素影响,包括温度、页岩成分、结构和地质条件^[3,19,22~24]。总体而言,页岩气赋存状态研究多集中在吸附态和游离态2种形式,吸附态页岩气是页岩气赋存中的主要组成部分,吸附作用是页岩气成藏的重要机理。

1.2 储层微观结构非均质性研究

有机质和黏土矿物是页岩的主要组成物质,也是页岩气的主要吸附载体。有机质中发现大量纳米级孔隙,是页岩气的主要储气空间;而页岩中平均含量约达58%的黏土矿物,存在由黏土晶层形成的层间微孔隙,增加了页岩比表面积,也为页岩气提供了吸附场所^[25~26]。页岩气吸附能力与有机质和黏土矿物自身吸附性或孔隙发育程度密切相关,Schettler等^[27]认为约50%的页岩气存储在泥盆纪页岩孔隙中。朱炎铭等^[28]认为古生物化可提供孔隙空间,可形成有机质孔隙网络体系,龙马溪组笔石体呈多层碳化薄膜保存,保留有一定的层间孔隙,笔石体内有一定孔隙空间,筇竹寺组藻类化石虽受矿化影响,但化石内部仍具有部分孔隙空间,是中国南方2套主要储层的孔隙组成部分。

页岩储层孔径较小,Barnett页岩典型孔喉小于100 nm^[29],10 nm左右的纳米孔隙含量丰富^[23]。页岩储层中黏土矿物具有较高的微孔隙体积和较大的比表面积,因而吸附性能较强^[22]。Ambrose等^[8]认为分散、细粒的多孔性有机质通常嵌入在无机基质之中,有机质中的微孔隙及其特征长度小于100 nm的毛细管组成了主要的气体孔隙体积,并推测页岩气原位天然气总量的一个重要部分似乎与有机质中相互联系的大纳米孔隙有关。5~50 nm孔隙尺寸取决于干酪根类型^[30],富有机质页岩中有机质平均孔径远小于无机质的平均孔径^[9],可见有机质与黏

土矿物孔隙尺度与类型存在显著的微观非均质性。

随检测手段不断进步,借助高分辨率场发射扫描电镜、原子力显微镜、聚焦离子束扫描电镜、CT 扫描和核磁共振等先进技术,发现大量存在于有机质与矿物颗粒间的微米-纳米级孔隙及微裂缝,是页岩气主要储集空间^[13, 36-41]。纳米级孔隙最先发现于有机质和富含黏土的泥岩中^[37]; Chalmers 等^[38]测得西加拿大盆地地下白垩统泥岩纳米级孔隙体积高达 $0.43 \sim 1.69 \text{ cm}^3/\text{hg}$ 。Reed 等^[37]报道 Barnett 页岩存在有机质纳米级孔隙,但直到 2009 年,Loucks 等^[31]采用离子抛光扫描电镜技术才对 Mississippian 盆地页岩有机质纳米孔隙及其网络进行了详细的图像表征和识别研究; Javadpour^[39]用原子力显微镜也观察到泥页岩中的纳米孔和纳米槽。在相同孔隙体积内,纳米孔的孔隙内表面积远大于微米孔,可为吸附气提供大量附着空间^[7]。

页岩有机质孔隙主要由微孔($< 2 \text{ nm}$)和中孔($2 \sim 50 \text{ nm}$)组成,平均孔径小于 5 nm ; 无机质一般由黏土矿物组成,孔径 $200 \sim 500 \text{ nm}$ ^[40-41]。但有机质中纳米级孔隙范围尚存较大争议,Loucks 等^[31]认为孔径范围为 $5 \sim 750 \text{ nm}$,平均为 100 nm ; Wang 等^[26]则认为范围为 $5 \sim 1000 \text{ nm}$ 。Sondergeld 等^[40]在高放大倍数 SEM 图像中发现孔隙直径达 $300 \sim 800 \text{ nm}$; 北美 Haynesville 盆地页岩主体孔径为 $2 \sim 20 \text{ nm}$,Frio 页岩孔隙半径主要在 $5 \sim 15 \text{ nm}$ 。邹才能等^[42]利用 FE-SEM 与纳米 CT 重构技术表明直径范围 $5 \sim 300 \text{ nm}$,主体 $80 \sim 200 \text{ nm}$ 。采用氮气吸附分析页岩孔隙结构,杨侃^[43]亦发现纳米尺度($< 50 \text{ nm}$)孔隙较为丰富; 陈尚斌等^[44]得到川南龙马溪组纳米级孔隙主孔位于 $2 \sim 40 \text{ nm}$,而武景淑等^[45]认为主要分布在 $2 \sim 5 \text{ nm}$; 郭为等^[46]得到昭通龙马溪组及五峰组页岩孔隙大小主要分布在 $4 \sim 6 \text{ nm}$; 杨峰等^[47]得到宁夏六盘山盆地白垩统乃家河组页岩平均孔径为 $3.6 \sim 4.3 \text{ nm}$ 。页岩储层中存在大量纳米级孔隙已得到证实,但纳米孔隙的主孔范围极具争议; 尽管有机质被认为具有大量的纳米级孔隙,但黏土矿物等无机质中同样存在丰富的纳米级孔隙,纳米级孔隙的物质来源与贡献情况尚无定论。

吸附载体的微观非均质性,不仅体现在主体孔径差异上,也反映在孔隙结构和类型方面。目前国际上对孔隙类型尚无统一分类,对页岩储层中细小孔隙的表征方法仍处于探索之中^[36]。Loucks 等^[31]认为 Barnett 泥页岩发育 3 类孔隙:矿物质及晶体之

间的粒间孔、矿物颗粒粒内孔及有机质孔;之后多位学者致力于识别和表征对页岩气生成、赋存和产能有重要影响的孔隙结构特征,并依据孔隙微观特征进行了描述分类^[10, 26, 32-34, 40, 42, 48-50]。

更多的分类则依据物质成因,诸如有机质孔、有机质生烃微裂隙、沥青孔、生物孔、絮凝孔、黏土矿物孔、黄铁矿晶间孔、粒间孔、粒内孔等,又分 3 类^[51-52]、4 类^[53-55]、5 大类^[56]、6 类^[57]、9 类^[58]; 还有其他学者也进行了相关分类^[19, 59-63]。但上述分类普遍存在分类依据相对单一的特点,于炳松^[36]提出了页岩储层孔隙的产状结构综合分类方案,朱炎铭等^[55]综合考虑了孔隙的定性观察和定量测定。

微观尺度下页岩矿物组分的分布与相对数量、孔隙及微裂隙的类型、分布、孔径、形态等均具有较显著的非均质性^[64]。陈尚斌等^[63]通过比较龙马溪组与筇竹寺组孔隙结构参数相对偏差和变异系数,认为筇竹寺组非均质性强,较小的中孔和过渡孔比例阻碍了页岩气运移和渗流。徐祖新^[65]利用 CT 扫描图像定量表征页岩矿物组分的非均质性,为水力压裂提供参考,并讨论矿物组分的含量与分形维数之间的关系。王欣等^[66]利用压汞数据计算孔隙分形维数,认为过渡孔、中孔和大孔的分形维数大,非均质性强。江凯禧等^[67]在分析连井剖面和单井泥岩层矿物特征后认为四川盆地筇竹寺组层内非均质性较强,横向地层总厚度、泥页岩单层厚度、泥页岩发育层数、夹层特征和顶底板岩性变化快,纵向上矿物成分和岩石脆性差异明显,黏土层间孔隙和有机质孔隙和基质微裂缝沟通情况微观非均质性显著。

可见,在吸附载体孔隙结构尺度、物质成因识别,以及基于单一依据的分类繁多,但未能系统地将孔隙结构的物质成因、量化指标与形貌特征相统一;针对吸附载体孔隙成因及多尺度空间定量表征与非均质性模型亟需研究。

1.3 页岩吸附非均质性影响因素研究进展

页岩的吸附能力直接决定吸附气量的大小,既受页岩物质组成、孔隙系统、成熟度与含水量等内部因素影响,又受温度、压力及埋深等外部因素的影响^[8, 11, 23, 68]。有机碳含量高、镜质组或者惰质组含量高、成熟度高,一般都会增加页岩的吸附能力^[69]。吸附量与载体有机碳含量(TOC)存在线性关系^[23, 68]。因此,TOC 是影响吸附非均质性的最主要因素。

比表面积和总孔体积等表征孔隙特征的参数与页岩吸附含气量具有显著的正相关关系^[59~70]。有机质因其多孔性而形成巨大的内表面积^[20],且其亲油性(较高的吸附热)有利于甲烷吸附^[71~72]。泥页岩中有机质含丰富的微孔,是吸附甲烷的主要空间,有机质含量越高,微孔隙越发育,微孔体积越大,比表面积越大,页岩对气体分子的吸附能力越强,吸附气含量越高^[23~38,68~69,73]。相同物质条件下,小于2 nm的孔隙具更大的内表面和强的吸附能力^[69]。有机质类型中,Ⅲ型干酪根比Ⅰ和Ⅱ型干酪根有更高的甲烷吸附量,与Ⅲ型干酪根的微孔体积更高有关^[38]。

矿物成分反映页岩沉积环境,通过影响有机碳含量而影响气体含量,其中微小孔隙影响吸附气含量,粒间孔隙及裂隙影响游离气含量^[74]。有机质纳米孔为储气的最重要空间,但也有学者认为吸附态甲烷主要赋存于伊利石表面,其次吸附于干酪根中^[27],因为黏土矿物具有层间和晶间微孔隙,增大了颗粒的比表面积,有利于甲烷分子的吸附。有学者认为在TOC含量低的情况下,吸附气的储存空间可以由伊利石弥补。大孔的发育与黏土矿物含量有关,黏土矿物含量增加,大孔的比表面积和孔体积都增大^[75]。黏土矿物含量是控制吸附能力的关键因素之一^[20~60]。吉利明等^[76]研究了常见黏土矿物微孔隙特征和甲烷吸附性,黏土矿物的孔隙多存在于层叠状结构之间、颗粒之间及颗粒内部板片的自然错断处,因结构差异,不同黏土矿物对甲烷吸附能力有所差异,蒙脱石最大,伊蒙混层次之;与表面积大小排序基本一致^[49~77];而宫美林等^[78]认为黏土矿物中伊蒙混层吸附能力强。此外,有机质向烃转化过程中黏土矿物起催化作用,黏土矿物的种类影响吸附态页岩气的分布;蒙皂石向伊利石转化过程中,页岩中产生微裂缝,为页岩气提供储集空间和运移通道,黏土矿物转化过程中层间水的析出为页岩气的运聚提供载体^[79]。黏土矿物气体吸附能力与矿物自身吸附性或内孔隙发育程度密切相关;但Bowker^[14]分析Barnett页岩基本控制因素时指出,萃取的黏土矿物的等温吸附结果表明,黏土矿物没有吸附甲烷。

泥页岩中伊利石多为成岩晚期产物,推断成岩和生烃作用会对泥页岩孔隙度有显著影响,因而成熟度与孔隙结构间也存在一定联系^[31~33,35,37~38,69,80]。随成熟度增高,微孔体积增加5

~200 nm的超细有机质孔隙增加,能提高页岩气赋存储集能力。比表面积与纳米孔隙的孔容随成熟度增加而增加^[81]。孔隙度较高的页岩产气能力通常更高;孔隙度与黏土矿物含量呈正相关^[82],孔隙度随硅铝酸盐丰度的增加而增大,与碳酸盐富集呈负相关,且孔隙度与岩石比表面积呈正比,与有机质和伊利石含量正相关^[22]。

甲烷和水分子共享相同吸附位,当同时存在于页岩中时会发生竞争吸附^[83];Ross等^[23]研究认为水分的存在极大地减少了气体的吸附量,使干燥条件下吸附量大于水平衡条件下的吸附量,因为水分占据了亲水的黏土矿物表面吸附位,使颗粒膨胀、堵塞孔喉,减小了孔隙度,降低了渗透率并限制了活性吸附位的可进入性;但并没有发现吸附量随水分增加而持续减小,可能其相关性被有机质和热成熟度影响所掩盖。

外部影响方面,Lu等^[68]对美国二叠系页岩吸附能力研究得到包含温度与压力2个参数的Bi-Langmuir模型;随压力升高,吸附气含量升高;不同温度下页岩吸附能力不同。Ross等^[22~23]指出储层温度对甲烷吸附能力具有很大影响,温度越高,甲烷吸附能力越小。对给定的页岩气藏,储层吸附物性不变,温度变化范围较小,气体吸附量是压力的函数;当孔隙压力下降时,吸附在基质颗粒表面的气体开始解吸^[84]。因吸附是放热过程,温度升高引起解吸,故吸附能力随温度的升高而降低^[85]。页岩埋深一般大于3 000 m,超压带泥页岩孔隙度相对较高^[18];用超高压压汞法分析压汞曲线发现Barnett页岩的孔隙吼道尺寸最低已达1.8 nm,且孔隙吼道的分选性差^[7~40],使其对吸附影响增加多变性。影响吸附非均质性的因素较多,其中最为关键的黏土矿物和有机质的吸附数据不多,特别是有机质孔隙与黏土矿物矿物颗粒表面间的关系仍不明确。

1.4 页岩气吸附运移机理研究进展

尽管微裂隙与粒间孔隙对页岩中烃类的运移最有利,但页岩吸附载体(有机质与黏土矿物)大量纳米级与微米级孔隙相连的纳米孔隙网络共同控制了页岩气赋存和运移;页岩中1~4 nm的孔隙比表面积占据总比表面积的30%,其吸附量却占到44%^[86];纳米级孔隙的大量存在使气体热力学状态复杂化^[8~87]。气体活动的体积大小依赖于孔隙大小,小于2 nm孔隙内,无足够运动空间;孔径达50 nm,分子与分子间、分子与孔隙壁间相互作用使气

体热力学状态改变 在孔隙中运动^[8]。Best 等^[88]认为能够为流体流动的通道可能在 3~12 nm; Hildenbrand 等^[89]则认为在 20 nm 左右,更细小孔径并不利于甲烷自由流动。利用 STXM 研究页岩微观结构和化学非均质性,发现纳米尺度孔隙会被有机质部分充填而形成孔径更小的次生孔隙,降低泥岩渗透性和储气能力。

页岩气在干酪根中的存储状态,干酪根、无机质与微裂缝分布和气体运移方式上存有争议^[90]。页岩气一般在大孔隙及微裂缝中的运移主要为黏滞性流动 服从达西流动 而在纳米基质孔隙中的运移主要为扩散运移^[31 91]。页岩气渗流机理研究难点在于涉及到多孔介质中流固耦合现象,包括黏滞流,气体的吸附与解吸附、纳米级孔隙中气体的渗流、及压裂后气体在多尺度储渗空间中的解吸、扩散和渗流耦合过程^[21 88]。页岩气藏流体运移,需综合考虑页岩气在孔隙中的黏性流动、Knudsen 扩散以及吸附气的表面扩散和因岩石变形引起的滑移^[92~95]。夏阳等^[96]认为各因素影响程度不同,吸附气的表面扩散与滑移对页岩气影响均在 0.1% 以下,可以忽略,黏性流动与 Knudsen 扩散主导页岩气的渗流,非平衡吸附速率对页岩气影响较大。常规分析方法主要考虑了甲烷与基质骨架的相互作用,忽略了孔隙和基质骨架在空间上非均质的影响;而储层非均质性将产生特殊的运移和动力效应,阻止甲烷从基质上解吸附^[97]。页岩水平渗透率和垂直渗透率的差异造成页岩气侧向渗流、扩散速率远比垂向上大,使得页岩气在遭受构造断裂作用,或是在距离龙马溪组泥页岩露头区位置,侧向渗流及扩散作用对页岩气的保存将产生不利的影响^[98]。由此综合考虑达西渗流、滑移扩散效应、井筒附近高速非达西效应等多重非线性效应,建立了页岩气储层多尺度统一流动模型^[99]。

吸附与运移机理也受到页岩吸附载体非均质性的控制,因此可以选择不同的吸附模型^[100]。当前仍有研究表明 Langmuir 模型描述页岩气等温吸附过程较为合适^[87],但也确实存在拟合误差较大问题^[101]。Gasparik 和 Chareonsuppanimit^[21 83]分别使用修正的朗格缪尔模型和 SLD 模型拟合了页岩吸附数据,得到了较好的拟合结果;聂海宽等^[102]也提出了校正建议;这些吸附模型较好地拟合了试验数据^[100~101]。但吸附模型与渗流模型是否可靠,必须通过吸附非均质性的系统认识,以及吸附的热力学

与动力学效应检验。

2 重点研究的问题与展望

围绕吸附性这一问题,前人从不同角度开展了大量研究工作,发现页岩储层中存在大量纳米级孔隙,是主要的储气空间之一;在储层评价中重视微观孔隙结构;认识到吸附态页岩气在赋存相态中具有重要作用,探讨了其在储层物质组成与孔隙结构等方面的影响;探索构建微-纳米孔隙中页岩气的渗流特征和渗流模型,为页岩气储量评估与产能甄别奠定基础。但目前产能和产量的局限性反映出对我国页岩储层微观非均质性及对吸附非均质性的本质规律认识还不清楚,而这恰是正确评估页岩气储量的关键,以及深入揭示页岩气富集规律的核心,因此,以下内容将是未来一个时期储层微观结构及其吸附非均质性领域的研究重点。

1) 页岩储层微观结构量化及其非均质性研究。

页岩主要由黏土矿物和有机质等成分组成,具多微孔性、低渗透率特点,非均质性显著,对页岩气赋存极有贡献的孔隙(特别是纳米级孔隙)的来源和性质尚无定论。储层不同矿物组成及纳米级孔隙的主要范围也存较大争议;所形成不同的孔隙类型、孔喉大小等孔隙结构特征各不相同;因此,为了合理评估和精细表征储层微观结构,必须开展以矿物成分和孔隙结构为核心的储层微观非均质性研究。

2) 储层微观非均质性与吸附非均质性的内在关系研究。

在吸附载体的显著非均质性上,现有研究未能很好地将孔隙形貌特征、量化特征及物质成因结合,在综合反映吸附非均质性影响因素上极为局限。在吸附载体孔隙方面,特别是占主导地位的纳米级孔隙,使自由空间体积增大,其中存储的气体可能具有复杂的热力学状态,成为建立页岩气赋存机理的瓶颈。优质的页岩储层需要具备大量容纳页岩气的孔隙和供页岩气流动的联通孔隙 2 个基本条件。为了建立页岩气赋存机理,必须开展微观非均质性与页岩气赋存状态内在规律的研究。

3) 页岩吸附机制及其对页岩气富集规律的影响研究。

根据吸附载体的类型与数量,从页岩气吸附赋存的分子动力学角度,建立非均质性吸附模型;以页岩储层演化为主线,通过储层的埋藏史、热史与生烃史及构造演化史研究,将生烃条件、赋存条件和保存特征研究与动态地质过程相结合,研究影响页岩气富集的地质因素及其内在耦合规律,揭示页岩

气富集规律，并建立可能的页岩气富集模式，为页岩气富集区带勘查提供科学依据。

3 结 论

1) 中国页岩气勘探开发实践表明，页岩气资源潜力和开发前景可观，但投入与产出尚不匹配，页岩气产量存在巨大的区域和井间差异性，发展极不均衡；因受宏观经济形势、复杂地质条件和赋存富集规律等因素制约，仍面临极大困境。

2) 页岩气开采潜力最终取决于吸附性和渗透性2个关键要素，前者是形成气藏的最关键基础，高度受到微观地质因素及其非均质性控制。目前产能和产量的局限性反映出对我国页岩储层微观结构及吸附非均质性的本质规律认识不清，是限制正确评估页岩气储量和深入揭示页岩气富集规律的瓶颈。

3) 页岩气赋存与富集规律深度研究，应注重地质过程，重点在页岩储层微观结构量化及其非均质性，储层微观非均质性与吸附非均质性的内在关系，页岩吸附机制及其对页岩气富集规律的影响研究等方面。

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