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临兴地区下二叠统太原组页岩气地质特征及勘探潜力

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摘 要:为揭示鄂尔多斯盆地东缘临兴地区太原组页岩气地质特征及勘探潜力,以富含有机质泥页岩为研究对象,基于野外钻孔和测井基础地质资料,查明了泥页岩累计厚度和单层最大厚度分布规律;针对泥页岩开展了有机地化、物性特征、X射线衍射和等温吸附等试验测试分析,对页岩气聚集成藏条件及勘探潜力进行了研究。结果表明:临兴地区太原组泥页岩分布稳定,累计厚度为10~50 m,平均为30 m,单层最大厚度为5~25 m。有机质丰度较高,TOC含量介于0.26%~12%,平均为3.81%,有机质类型以II、III型干酪根为主,最高热解峰温介于443~576 ℃,在紫金山岩体附近泥页岩热成熟度明显增大。泥页岩发育纳米级-微米级的孔裂隙,有机质孔多呈圆形、椭圆形和蜂窝状,碎屑矿物溶蚀孔等其它类型孔隙均有发育,矿物颗粒内部、碎屑颗粒边缘和有机质内部的微裂隙较为发育。石英、长石等脆性矿物含量占45%~65%,黏土矿物含量介于28%~62%,多为非膨胀类矿物。泥页岩含气量变化范围大,介于0.08~7.3 m³/t,平均为1.41 m³/t,含气量与TOC呈明显的正相关关系。综合考虑泥页岩厚度、有机质丰度、热演化程度等因素,临兴地区的中北部泥页岩厚度大、TOC含量高,矿物组合有利于储层改造,为页岩气勘探有利区。与四川盆地海相页岩气勘探区相比,临兴地区太原组泥页岩具有埋深浅、含气量偏低的特点,在油气资源勘探开发中宜注意与煤系地层的砂岩气和煤层气的联合勘探开发。

关键词:鄂尔多斯盆地;地质特征;页岩气;海陆过渡相;勘探潜力

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Shale gas geological characteristics and exploration potential of lower permian Taiyuan Formation in Linxing Area

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Abstract: In order to reveal the geological characteristics and exploration potential of shale gas in Taiyuan Formation in Linxing area, eastern Ordos Basin, taking organic-rich mud shale as the research object, the distribution rules of mud shale cumulative thickness and single layer maximum thickness were found out based on field drilling and logging geological data. The organic geochemistry, physical properties, X-ray diffraction and isothermal adsorption experiments were carried out for shales, and the accumulation conditions and exploration potential of shale gas were studied. The results show that the distribution of mud shale in Taiyuan Formation in Linxing area is stable, the cumulative thickness is 10-50 m, the average thickness is 30 m, and the maximum thickness of single layer is 5-25 m. The Organic matter abundance is high, TOC content is 0.26%-12%, with an average value of 3.81%. Organic matter type is mainly II and III kero-gen, and peak temperature of pyrolysis is between 443 ℃ and 576 ℃. The thermal maturity of shale near zijinshan rock mass increases ob-

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viously. The pores and fissures of nanoscale–micron scale are developed in shales. The pores of organic matter are mostly round, oval and honeycomb. Other types of pores such as the dissolution pores of clastic minerals are developed. The microcracks in mineral particles, the edge of clastic particles and the internal organic matter are relatively developed. The content of brittle minerals such as quartz and feldspar are 45%-65%, and the content of clay minerals is 28%-62%, which are mostly non-expansive minerals. The variation range of gas content in shale is large, ranging from $0.08 \text{ m}^3/\text{t}$ to $7.3 \text{ m}^3/\text{t}$, with an average value of $1.41 \text{ m}^3/\text{t}$. There is a significant positive correlation between gas content and TOC. Considering the factors such as shale thickness, organic matter abundance and thermal evolution degree, the central and northern shale in Linxing area has large thickness and high TOC content. The mineral assemblage is conducive to reservoir reconstruction and is a favorable area for shale gas exploration. Compared with marine shale gas exploration area in Sichuan Basin, Taiyuan Formation shale in Linxing area has the characteristics of shallow burial depth and low gas content. In the exploration and development of oil and gas resources, it is necessary to pay attention to the joint exploration and development of sandstone gas and coalbed methane in coal measure strata.

Key words: Ordos Basin; geological characteristics; shale gas; marine-continental transitional facies; exploration potential

0 引言

天然气作为一种清洁的能源,成为化石能源向新能源转换的“桥梁”,伴随着北美“页岩气革命”的成功,页岩气成为影响世界天然气能源供给格局的重要角色^[1-2]。据2015年油气资源动态评价,我国页岩气地质资源量为 $121.86 \times 10^{12} \text{ m}^3$,可采资源量为 $21.81 \times 10^{12} \text{ m}^3$ ^[3]。页岩气的勘探开发在美国的马塞勒斯、伊格尔福特、海因斯维尔、巴奈特和尤提卡等页岩气区带取得了一定成功^[4]。2020年美国页岩气产量 $7330 \times 10^8 \text{ m}^3$,中国页岩气产量为 $200 \times 10^8 \text{ m}^3$,阿根廷页岩气产量为 $103 \times 10^8 \text{ m}^3$ 。近年来,国内学者在总结国外页岩气勘探开发成功经验的基础上,对我国含油气盆地进行了页岩气的研究。四川盆地为我国页岩气勘探开发的前沿阵地,在涪陵焦石坝、威远、长宁、昭通、威荣等地区取得了页岩气的成功开发^[4-8]。鄂尔多斯盆地作为潜力盆地,已发现靖边、苏里格、乌审旗、榆林和大牛地等常规大气田,预示着鄂尔多斯盆地页岩气也可能具有巨大的勘探潜力^[9-10]。

鄂尔多斯盆地的临兴地区是国内致密砂岩气、页岩气、煤层气多气合采的热点地区,目前对致密砂岩气和煤层气做了大量研究,但针对页岩气的研究与认识不足^[11-12]。笔者对临兴地区下二叠统太原组泥页岩分布特征、有机地化特征、储层特性及含气性进行了研究,对页岩气勘探潜力区进行了评价。

1 地质背景

鄂尔多斯盆地是一个典型的克拉通盆地,具有丰富的煤、气、油资源^[13]。临兴地区位于山西省西部,构造位置为鄂尔多斯盆地东缘晋西挠褶带(图1)。研究区总体为一西倾的单斜构造,地层倾角小,构造具有幅度低、影响范围小的特点^[14]。受华北板块早

白垩世构造热事件的影响,临兴地区的东侧发育以碱性杂岩体为主的紫金山岩体,断裂较为发育。区内构造以岩浆岩穿刺构造为中心,由内向外划分为底辟构造隆起带、环形沟槽带、低幅背斜带3个次级构造单元。南部构造平缓,局部发育小断层,北部的断层受EW向挤压应力作用形成,断层呈NW向和NE向2组主体方向展布,发育规模较小^[15-16]。

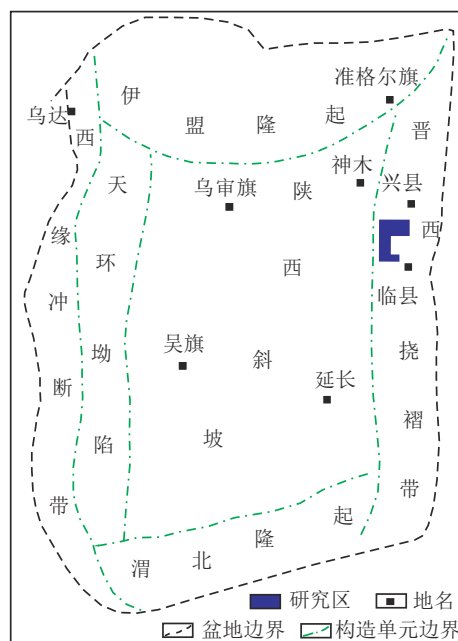


图1 研究区构造位置

Fig.1 Structural location of the study area

研究区地层自东向西逐渐变新,依次发育中奥陶统马家沟组、上石炭统本溪组、下二叠统太原组和山西组、中二叠统上石盒子组和下石盒子组、上二叠统石千峰组、下三叠统刘家沟组、中三叠统和尚沟组 and 纸坊组、上三叠统延长组和第四系地层。

2 泥页岩分布特征

临兴地区太原组沉积相类型为障壁海岸相沉积,

沉积亚相主要为障壁岛亚相、潮坪亚相和泻湖亚相,包括障壁砂坝、砂坪、混合坪、泥炭沼泽和潮汐水道等沉积微相。太原组厚度为33~76 m,主要由暗色泥岩、页岩、泥质粉砂岩与砂岩互层、灰岩及煤层组成^[16]。上部为灰黑色泥岩、碳质泥岩,夹煤层;下部为厚层浅灰色细砂岩、中砂岩,层内发育多层泥岩,

横向具有连续性,泥岩层间常伴有煤层(图2)。泥页岩厚度稳定,累计厚度为10~50 m,平均厚度约为30 m,在区块东部以及西北部厚度较大,主要介于30~50 m(图3)。泥页岩单层最大厚度为5~25 m,与累计厚度分布规律相似,在区块东部和西北部以及中部地区,均有厚度大于15 m的区域分布(图4)。

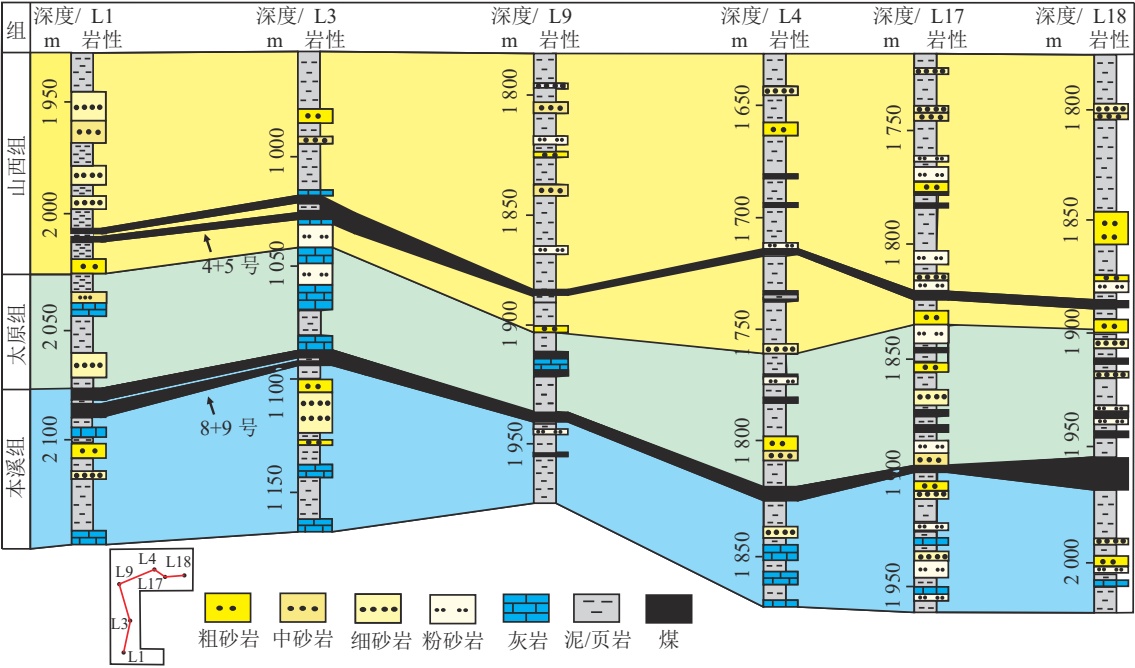


图2 临兴地区山西组-太原组-本溪组地层连井剖面

Fig.2 Stratigraphic connecting well profile of Shanxi Formation, Taiyuan Formation and Benxi Formation in Linxing Block

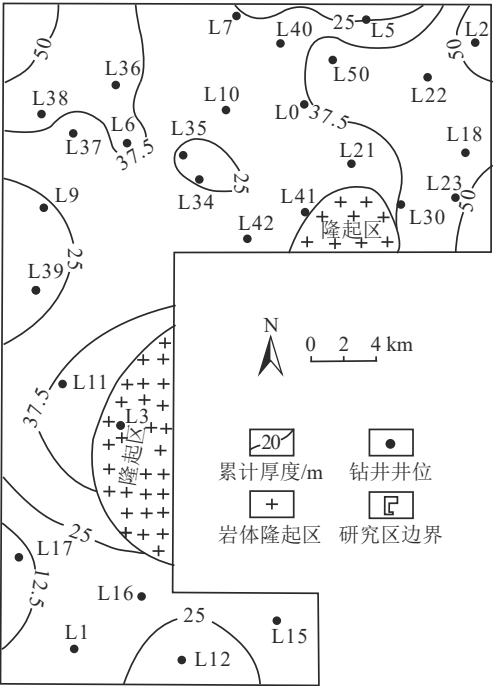


图3 太原组泥页岩累计厚度

Fig.3 Accumulated thickness of Taiyuan Formation shales

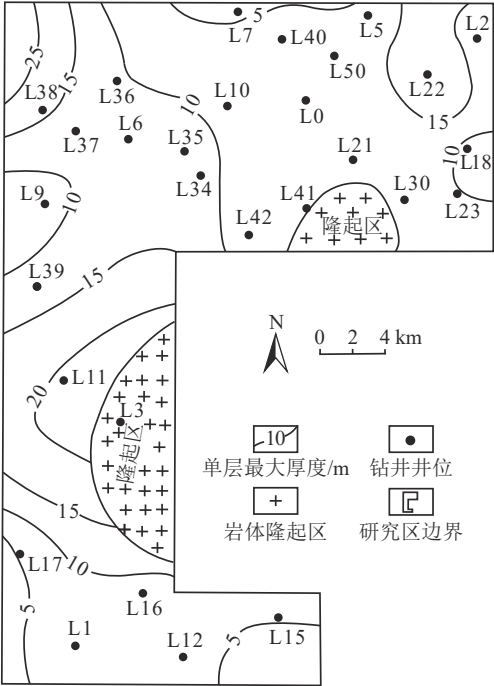


图4 太原组泥页岩单层最大厚度

Fig.4 Maximum thickness of single layer of Taiyuan Formation shales

3 有机地化特征

3.1 有机质丰度

烃源岩有机质丰度是油气生成的重要物质基础。经历了长期地质演化,烃源岩原始有机质丰度已经很难准确测得,只能通过其它指标与方法来间接反映,常用的指标如残余总有机碳(TOC)、氯仿沥青“A”、总烃含量(HC)、生烃潜量($S_1 + S_2$)等,其中总有机碳是评价页岩有机质丰度的主要指标^[17-18]。

对临兴地区的 17 口井 32 样次的太原组泥页岩样品进行有机质含量统计,测试的泥页岩主要为暗色泥岩,少部分为碳质泥岩,TOC 含量为 0.26%~12%,平均为 3.81%。(图 5)。从泥页岩 TOC 平面分布规律上来看,TOC 高值区主要分布在研究区的中北部,TOC 主要集中在 3%~6%,南部及东北部 TOC 含量较低(图 6)。

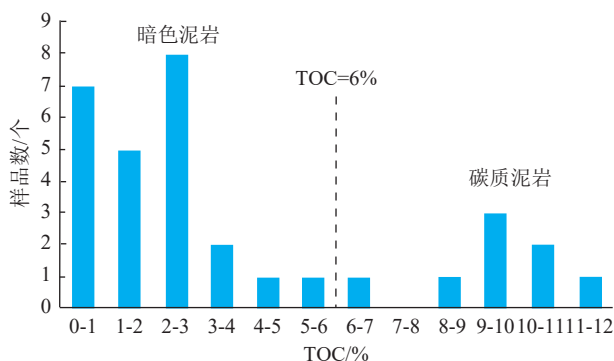


图 5 太原组泥页岩 TOC 分布直方图

Fig.5 Distribution histogram of TOC of Taiyuan Formation shales

3.2 有机质类型及成熟度

据泥页岩有机质干酪根类型来看,太原组泥页岩干酪根类型以 II、III 型干酪根为主,即有机质类型以混合型-腐植型为主,偏生气型(图 7)。热解试验结果表明,最高热解峰温 T_{max} 为 443~576 °C,平均为 477 °C,泥页岩进入生气窗。热成熟度自北向南随着埋深的增加而逐渐增高,中部地区紫金山岩浆岩体对成熟度的影响明显,如 L22 井泥岩 T_{max} 达到 526 °C,主要是由于紫金山岩浆热液的侵入导致局部烃源岩成熟度异常(图 8)。已有研究成果表明太原组烃源岩镜质体反射率主要集中在 0.96%~2%,受紫金山岩体的热接触作用影响区可增大至 3% 以上,有机质成熟度主要为成熟-高成熟,部分可达过成熟^[19]。

4 储层物性特征

4.1 孔裂隙特性

基质孔隙和裂缝是页岩气的主要储气空间,

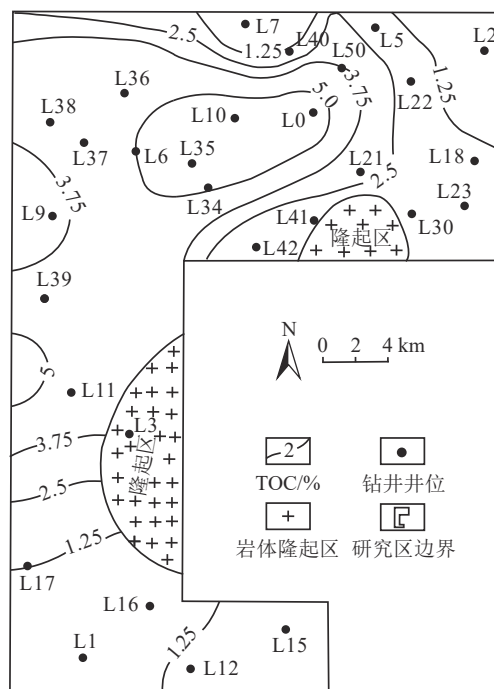


图 6 太原组泥页岩 TOC 平面分布

Fig.6 Distribution of TOC of Taiyuan Formation shales

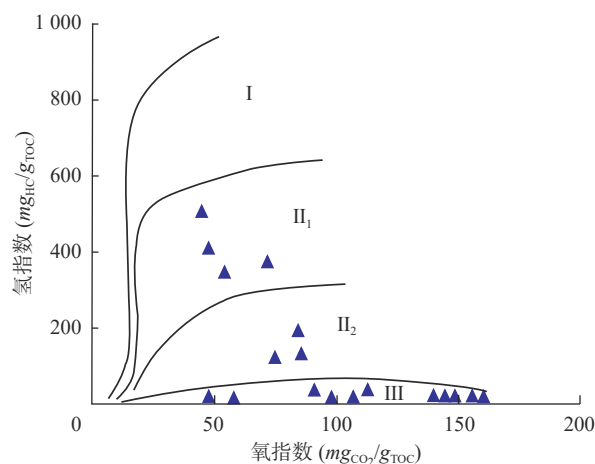


图 7 太原组泥页岩有机质类型图解

Fig.7 Diagram of the type of organic matter of Taiyuan Formation shales

基质孔隙为吸附气的赋存提供了吸附空间,裂缝使页岩的孔比表面积增加,不仅增大了储层的吸附能力,同时为游离气提供了赋存空间^[20]。泥页岩扫描电镜测试表明,孔隙包括有机质孔,多为圆形、椭圆形,呈蜂窝状分布(图 9a、图 9c),发育程度一般。碎屑矿物溶蚀孔相对发育(图 9a、图 9e),孔径范围较大,在纳米~微米级均有发育,主要为长石等矿物颗粒溶蚀后形成。裂隙相对发育,主要为微米级裂缝(图 9b、图 9d、图 9f)。泥岩样品

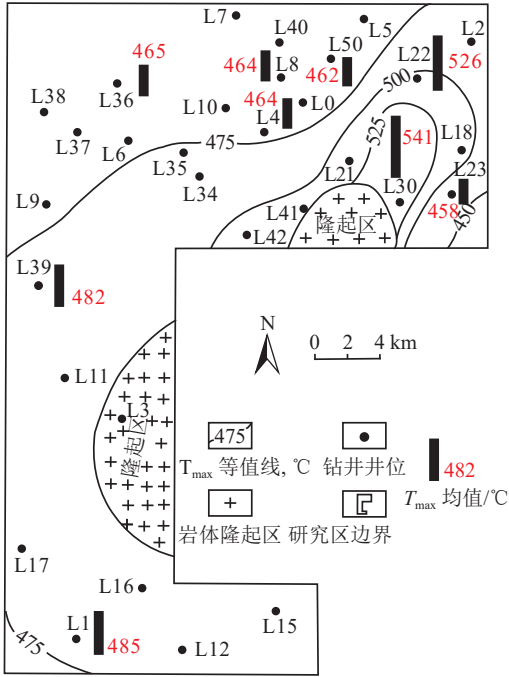


图 8 太原组泥页岩最高热解峰温分布

Fig.8 Distribution of peak temperature of pyrolysis in Taiyuan Formation shales

深度如下: a 样品深度 1 867.0 m, b 样品深度 1 866.7 m, c 样品深度 1 878.8 m, d 样品深度 1 893.6 m, e 样品深度 1 941.9 m, f 样品深度 1 941.2 m。与南方五峰组-龙马溪组、牛蹄塘组的海相页岩相比, 临兴地区太原组页岩有机质孔隙发育程度低, 孔径较大, 矿物颗粒内部、碎屑颗粒边缘和有机质内部的微裂隙较为发育。

4.2 脆 性

泥页岩的脆性直接影响储层的可压裂性, 泥页岩脆性主要受其矿物成分的影响。一般情况下, 随着泥页岩的黏土矿物含量增高, 其脆性变差, 硅质或钙质矿物含量高, 泥页岩的脆性好^[20-21]。

临兴地区太原组 12 个泥页岩全岩及矿物 X 射线衍射试验结果表明, 泥页岩的石英+长石+黄铁矿含量占 45%~65%, 黏土矿物含量介于 28%~62%, 平均为 43%(图 10)。泥页岩碳酸盐矿物少见, 石英、长石含量高于北美博西尔(Bossier)页岩, 低于北美巴奈特(Barnett)页岩, 黏土矿物含量低于鄂尔多斯盆地长 7 和长 9 页岩^[22-23]。虽然部分样品中黏土矿物较高, 但黏土矿物多为高岭石、伊利石和绿泥石等非膨胀性矿物, 蒙脱石类膨胀性黏土矿物含量相对较少。研究区泥页岩脆性中等-好, 利于储层压裂改造。

5 勘探潜力

5.1 储层含气性

1) 吸附能力。泥页岩的吸附能力对其含气性有着重要的影响, 等温吸附实验是评价页岩吸附能力的重要方法。表 1 为 4 个泥页岩样品信息和采用体积法等温吸附试验结果, 吸附压力为 0~20 MPa, 吸附温度为 55 ℃。结果表明: 在吸附平衡压力为 0~10 MPa, 随着吸附压力的增大, 吸附气量增大; 当吸附压力超过 10 MPa, 随着吸附压力的增大, 吸附量有减小的趋势(图 11)。暗色泥岩的吸附能力较

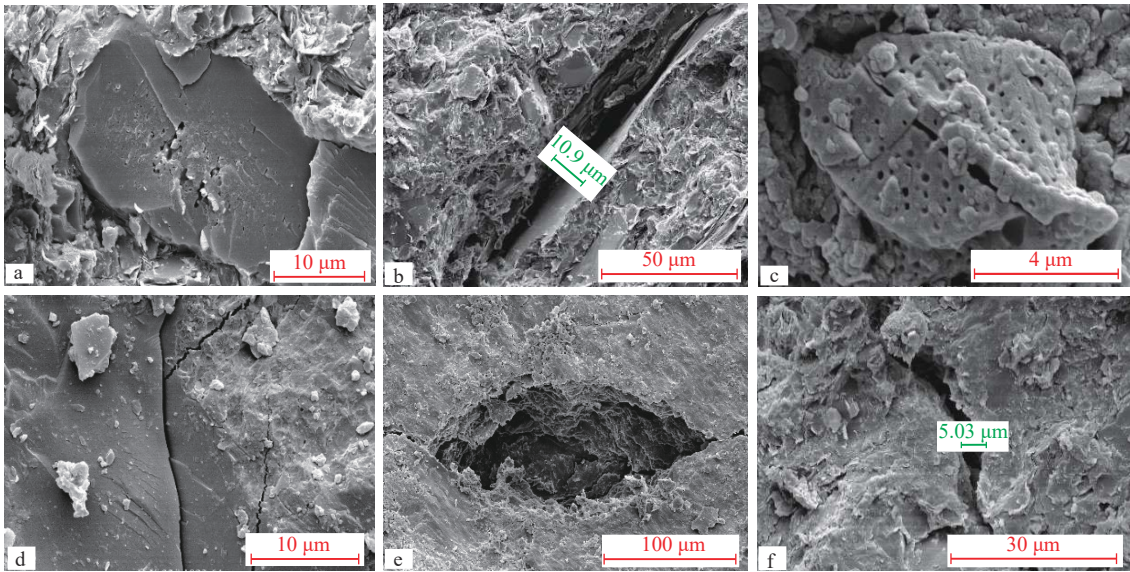


图 9 太原组泥页岩孔裂隙特征

Fig.9 Pore-fracture characteristics of Taiyuan Formation shales

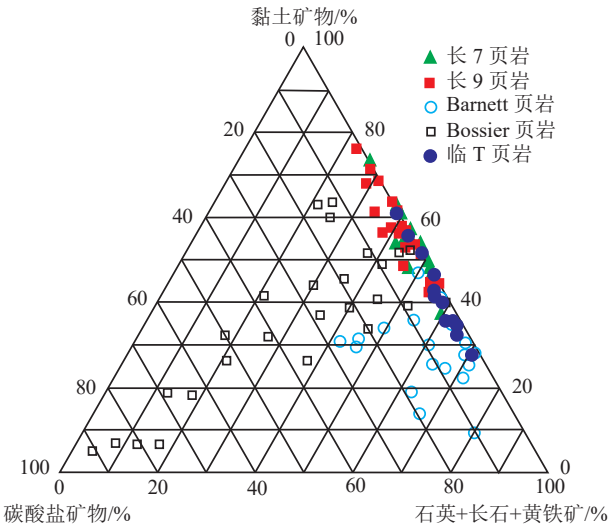


图 10 临兴地区太原组页岩与其它地区页岩矿物含量三角图^[23]

Fig.10 Triangular diagram of mineral content of Taiyuan Formation shales in Linxing Area and other areas^[23]

表 1 等温吸附试验泥页岩样品信息和朗格缪尔常数
Table 1 Information and Langmuir constants of shale samples for isothermal adsorption experiment

样品编号	深度/m	岩性	TOC/%	$V_L/(\text{m}^3 \cdot \text{t}^{-1})$	P_L/MPa
TN	1 871.18	碳质泥岩	6.3	3.92	1.95
TN1	1 870.20	碳质泥岩	6.0	3.81	1.88
N1	1 866.98	暗色泥岩	1.6	0.75	1.53
N2	1 864.10	暗色泥岩	1.4	0.82	1.61

低, 兰氏体积分别为 $0.75 \text{ m}^3/\text{t}$ 和 $0.82 \text{ m}^3/\text{t}$, 碳质泥岩的吸附能力较高, 兰氏体积分别为 $3.92 \text{ m}^3/\text{t}$ 和 $3.81 \text{ m}^3/\text{t}$ 。暗色泥岩较碳质泥岩的兰氏压力小, 但相差不大, 碳质泥岩发育区可能为页岩吸附气量的高值区。

2) 含气量。吸附气和游离气是页岩气主要的赋存形式, 两者含量一般呈此消彼长的关系^[24]。临兴地区太原组泥页岩含气量解吸测试结果表明: L50 井 5 个泥页岩样品含气量介于 $0.25 \sim 2.73 \text{ m}^3/\text{t}$, 平均为 $1.15 \text{ m}^3/\text{t}$; L37 井 5 个泥页岩含气量介于 $0.08 \sim 2.51 \text{ m}^3/\text{t}$, 平均为 $0.66 \text{ m}^3/\text{t}$ 。采用 USBM 直接法计算的损失气量占比约为 25%。页岩含气量和 TOC 含量相关性分析表明, 两者呈较好的正相关性, 即随着 TOC 含量变大含气量值增大(图 12)。

5.2 勘探潜力分析

页岩气藏的生、储、盖、运、聚、保等 6 大成藏要素都集中于同一泥页岩层中, 烃类气体在烃源岩

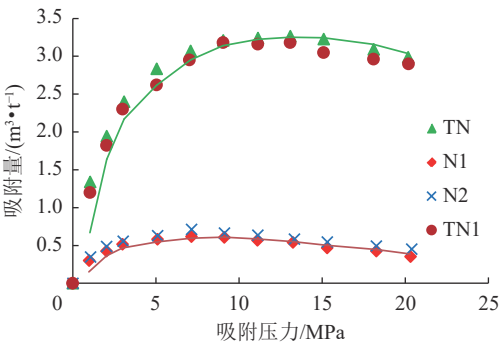


图 11 泥页岩空气干燥基等温吸附曲线
Fig.11 Isothermal adsorption curves of shales in air-dry basis

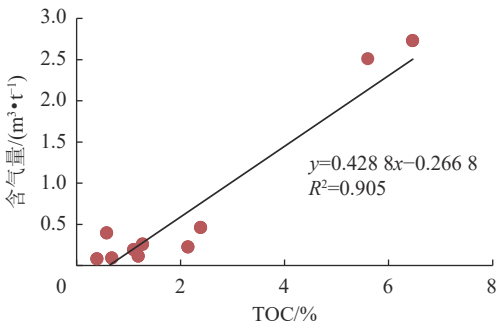


图 12 页岩含气量与 TOC 含量相关性
Fig.12 Correlation between gas content and TOC content of shales

中大量滞留聚集。一般认为有利生气的有机质成熟度为 $R_o < 0.4\%$ (生物成因气) 或 $R_o > 1.0\%$ (热成因气)^[25-26]。

与四川盆地海相页岩气资源相比, 临兴地区太原组页岩气具有埋深浅、TOC 含量高的特点, 泥页岩厚度和含气量均值一般, 但是在 TOC 含量较高的碳质泥岩发育区, 泥页岩层的含气量明显增高(表 2)。太原组泥页岩的埋深为 1 620~2 120 m, 累计厚度为 10~50 m, 有机质丰度较高, TOC 为 0.26%~12%, 平均为 3.81%, 热演化程度主要为成熟-高成熟度, 具有较强的生烃能力, 属于较为有利的生气泥页岩。室内试验分析表明, 泥页岩具有较强的吸附能力, 加之泥页岩地层的低渗透性, 富含有机质的泥页岩含气量较高, 具有较好的资源潜力。脆性矿物含量较高, 膨胀性黏土矿物含量较少, 泥页岩储层具有较好的可改造性。综合分析拟定 $\text{TOC} > 2.5\%$ 和泥页岩累计厚度大于 25 m 是页岩气勘探潜力较高的相对有利区, 有利区主要在区块的北部 L23~L38 井位连线区及围绕紫金山岩体有机质丰度较高区(图 13)。

表 2 我国典型页岩气盆地泥页岩发育特征

Table 2 Development characteristics of shales in typical shale gas basins in China

盆地/地区	地层/组	埋深/m	厚度/m	TOC/%	R_o /%	含气量/($\text{m}^3 \cdot \text{t}^{-1}$)	文献
四川/长宁	五峰组~龙马溪组	1 500~6 000	60~80	1.9~7.3(4.0)	2.3~2.8	3.1~7.8(5.3)	[4]
四川/涪陵	五峰组~龙马溪组	2 000~4 000	40~80	1.5~6.1(3.5)	2.2~3.1	1.3~6.3	[4]
四川/威远	五峰组~龙马溪组	1 300~3 700	30~40	1.1~6.3	2.1~2.8	1.9~4.8	[7]
四川/焦石坝	五峰组~龙马溪组	2 330.4	85	0.55~5.89(2.54)	2.2~3.13	0.44~5.19(1.97)	[8]
四川盆地	龙马溪组	—	—	2.0~5.0	2.1~3.6	1.70~8.4	[27]
	筇竹寺组	—	—	4.0~8.0	2.5~4.3	0.8~2.8	[27]
四川/川东南	龙马溪组	2 326~2 378	12~33	—	—	1.47~6.60	[28]
	五峰组	2 411.0	—	4.5	—	6.16~7.18	[28]
渝东北	牛蹄塘组	2 983.6	—	0.42~3.67(2.05)	2.31~2.78	2.16(解吸气)	[29]
鄂尔多斯盆地	山西组	3 451.6	—	0.32~3.72	—	0.18~0.62	[30]
	本溪组	2 543.6	—	0.24~4.71	—	0.45~0.74	[30]
鄂尔多斯/延长	山西组和本溪组	3 565~3 633	—	0.5~11.0	1.0~3.0	0.59~4.05(1.3)	[31]
鄂尔多斯/临兴	太原组	1 620~2 120	10~50(30)	0.26~12.0(3.81)	>0.96	0.08~2.73(1.41)	—

注：数据格式为最小值~最大值(平均值)。

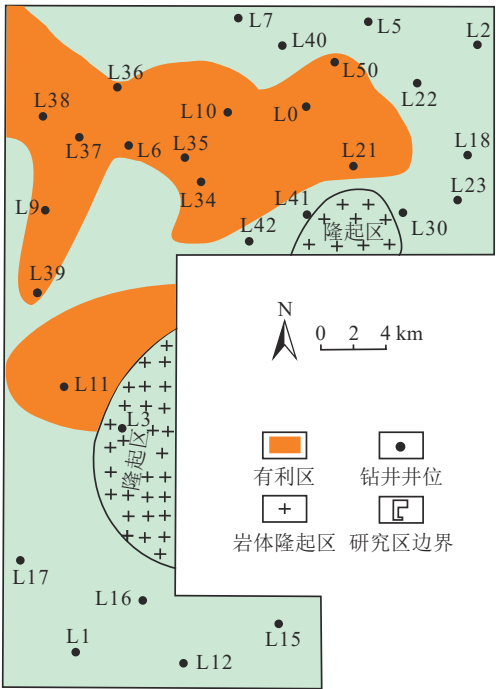


图 13 临兴地区太原组页岩气勘探潜力区评价

Fig.13 Evaluation of shale gas exploration potential area of Taiyuan Formation in Linxing area

6 结 论

1)临兴地区太原组泥页岩分布稳定,有机质丰度较高,TOC 含量介于 0.26%~12%,平均为 3.81%;有机质类型以 II、III 型干酪根为主;最高热解峰温 T_{max} 介于 443~576 $^{\circ}\text{C}$,平均为 477 $^{\circ}\text{C}$,进入生气窗,具备页岩气成藏的资源条件。

2)泥页岩发育纳米级~微米级的孔裂隙,石英、长石等脆性矿物含量占 45%~65%,黏土矿物含量介于 28%~62%,多为非膨胀类矿物,储层可改造性强。

3)泥页岩含气量变化范围大,介于 0.08~2.73 m^3/t ,平均为 1.41 m^3/t ;碳质泥岩有机质丰度高,含气量偏高,TOC 高值区为页岩气勘探有利区。

4)与我国其它页岩气勘探区相比,临兴地区太原组泥页岩具有埋深浅的特点,与海相页岩相比,含气量较低,与海陆过渡相及陆相相比,含气量较高,在今后油气勘探开发中宜注意与邻近砂岩气、煤层气的联合勘探开发。

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