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川东南林滩场地区五峰组—龙马溪组页岩气藏压力演化及其地质意义

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摘要:川东南林滩场地区的上奥陶统五峰组—下志留统龙马溪组具备较好的勘探开发条件,查明该层系古流体压力演化对揭示页岩气成藏及逸散过程具有重要意义。以林滩场地区五峰组—龙马溪组页岩构造裂缝和流体超压裂缝脉体为研究对象,综合阴极发光观察、包裹体显微测温、激光拉曼分析及盆地模拟等技术手段查明该地区的古流体压力演化过程及其控制作用。研究表明:(1)林滩场地区经历了常压、微超压—常压、超压、泄压 4 个阶段,其中超压主要来源于生烃作用,泄压主要由页岩气逸散导致,且使气藏泄压 54%。(2)五峰组—龙马溪组黑色页岩层系底部的裂缝存在两期脉体充填。第一期形成于沉降埋深阶段,时间在 131~118 Ma,形成温度介于 178~205 ℃,甲烷包裹体捕获压力为 105.6~119.8 MPa;第二期形成于构造抬升阶段,时间在 25~18 Ma,形成温度介于 150~175 ℃,甲烷包裹体具有相对较低的盐度,其捕获压力介于 80.8~92.1 MPa,较低的压力系数(1.37~1.49)指示气藏已发生大量逸散。(3)晚期构造运动,特别是喜马拉雅晚期的快速抬升是造成气藏逸散和泄压的根本原因。有机孔的圆度减弱、孔径减小表明储层物性变差。由于气藏形成和保存时间长,林滩场地区五峰组—龙马溪组页岩仍具备较好的勘探潜力。该研究有助于深化林滩场常压页岩气藏富集规律的认识,可为该地区页岩气勘探有利区的优选提供一定的理论支撑。

关键词:压力演化;流体包裹体;五峰组—龙马溪组;林滩场地区;川东南

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Pressure evolution of shale gas reservoirs in Wufeng-Longmaxi formations, Lintanchang area, southeast Sichuan Basin and its geological significance

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Abstract: The Upper Ordovician Wufeng Formation-Lower Silurian Longmaxi Formation in Lintanchang area of the southeastern Sichuan Basin has good exploration and development conditions, and clarifying the paleo-fluid pressure evolution is of great significance for revealing the process of shale gas accumulation and fugitive emission. Taking the shale tectonic fractures and fluid overpressure fracture veins of the Wufeng-Longmaxi formations in Lintanchang area as the research object, the paleo-fluid pressure evolution process in this area and its controlling impact were

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investigated using cathodoluminescence, inclusion temperature measurement, laser Raman analysis, and basin simulation. The study shows that: (1) Lintanchang area has experienced four stages: normal pressure, mild overpressure to normal pressure, overpressure, and pressure relief. Overpressure is mainly due to hydrocarbon generation. Pressure relief is mainly caused by shale gas fugitive emission. The gas reservoir pressure relief reaches 54% of the initial pressure during the pressure relief stage. (2) There are two stages of vein filling in the fractures at the bottom of the black shale in the Wufeng-Longmaxi formations. The first stage is formed in the sedimentation and burial stage at 131-118 Ma, the temperature is 178-205 ℃, and the trapping pressure of methane inclusions is 105.6-119.8 MPa. The second stage is formed in the tectonic uplift stage at 25-18 Ma, the temperature is 150-175 ℃, the methane inclusions have relatively low salinity and its trapping pressure is 80.8-92.1 MPa. The low pressure coefficient (1.37-1.49) indicates that mass fugitive emission has occurred. (3) The late tectonic movement, especially the rapid uplift in the late Himalayan period, is the root cause of the fugitive emission and pressure relief of the gas reservoirs. The decrease of the roundness and pore size of the organic pores indicates the deterioration of reservoir physical properties. However, due to the long formation and preservation time of the gas reservoirs, the shale in the Wufeng-Longmaxi formations in Lintanchang area still has good exploration potential. This study is helpful to deepen the understanding of the accumulation mechanism of the normal-pressure shale gas reservoirs in Lintanchang area and can provide theoretical guidance for optimal selection of favorable shale gas exploration areas.

Key words: pressure evolution; fluid inclusion; Wufeng-Longmaxi formations; Lintanchang area; southeast Sichuan Basin

四川盆地页岩气资源丰富,盆内及其周缘页岩气资源评价与勘探开发工作取得了显著成果[1-6]。其中,上奥陶统五峰组—下志留统龙马溪组是中国最具勘探潜力的页岩气层位。近年来,涪陵、威远、长宁—昭通、富顺—永川等区块取得商业开发,意味着该层系实现了页岩气的规模效益开发[7-8]。目前,四川盆地页岩气勘探开发逐渐从盆内拓展到盆缘(外),气藏压力由高压向常压发展[9]。盆缘林滩场地区页岩气形成条件较好,2017 年实钻 LY1 井的单井最大产能达 $4.3×10^4\ m^3/d$,2019 年实钻 LY3 井获最大日产气 $17.19×10^4\ m^3$,均表明该区具有良好的勘探前景。

从盆内到盆缘,页岩气保存条件差异明显。超压被认为是页岩气长期有效保存的直接证据,是控制五峰组—龙马溪组页岩气富集与高产的关键因素[10-12]。研究表明,流体的超压和保存也可作为构造平静期的微观指标[13]。川东南页岩气藏超压的主要原因是保存了深埋藏时由液态烃裂解生气形成的中高超压[12,14],且高超压流体可能超过静岩压力并诱导水力裂缝的形成[13],晚期强烈的构造抬升和剥蚀作用是造成压力散失的主要原因[14-15]。因此,恢复地层古压力场的演化有助于揭示页岩气成藏和逸散过程,对于页岩气勘探有利区预测具有重要意义[16-19]。充填于裂缝内的脉体所捕获的流体包裹体记录了含油气流体活动的古温压信息,并可作为盆地构造研究的微尺度指示物[12-13]。实际上,结合包裹体和埋藏热演化史确定流体活动时间被广泛用于古压力恢复、油气成藏和流体活动期次研究[15,20-21]。

尽管相关研究表明林滩场气藏具备十分可观的勘探开发前景,甚至可能优于同类常压页岩气藏(如彭水、丁山)[9,22-23]。丁山、彭水地区相关研究已取得较多进展,而与之相邻的林滩场气藏缺乏研究且该区块的勘探开发进展缓慢。因此,本文以林滩场地区五峰组—龙马溪组页岩构造裂缝和流体超压裂缝脉体为研究对象,结合包裹体显微测温和激光拉曼分析确定含甲烷流体活动的古温压信息,开展盆地模拟恢复该区钻井压力演化过程并探讨其影响因素及泄压机理。研究结果有望为林滩场地区常压页岩气的高效勘探开发提供理论依据。

1 地质背景

川东南主体位于齐岳山断裂带与华蓥山断裂带之间,其西北以华蓥山断裂为界并与川中平缓褶皱带相邻,向东至川东高陡褶皱带,东南以鄂湘黔断褶带为界(图 1)。川东南位于特提斯—喜马拉雅构造域和环太平洋构造域的过渡带[24],经历了古生代到新生代多个构造阶段,其中自晚中、新生代以来受多期构造运动叠加,发生多期褶皱、隆升构造运动,形成了复合联合构造格架,整个构造格

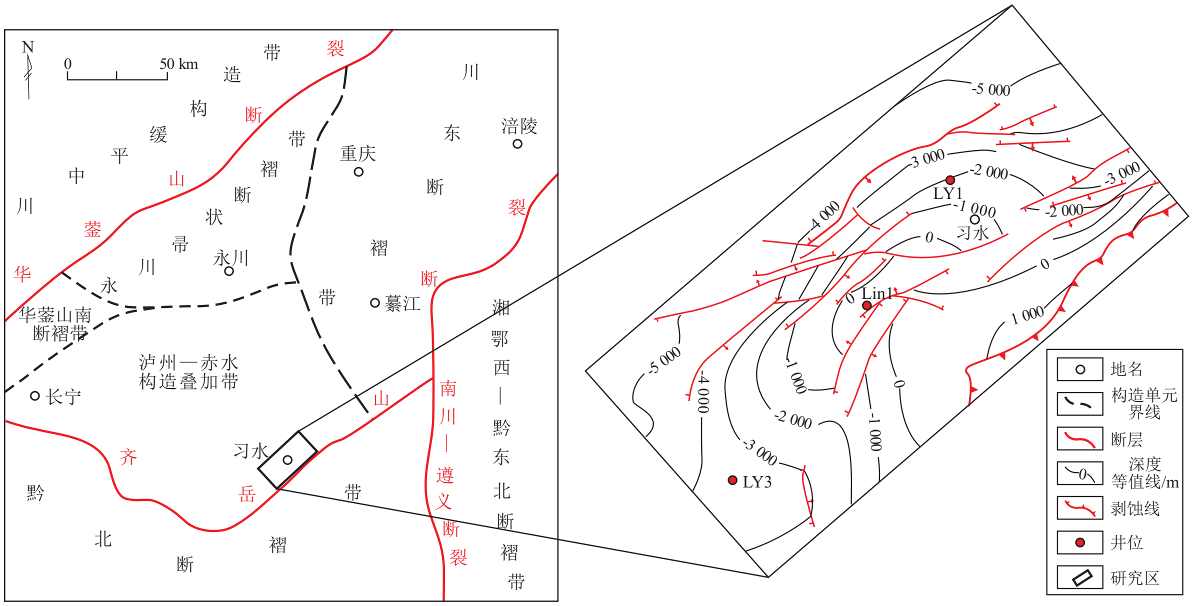

图 1　川东南林滩场区域位置及下奥陶统龙马溪组底界埋深

Fig.1　Regional location of Lintanchang area in the southeastern Sichuan Basin and the burial depth of the bottom boundary of the Lower Ordovician Longmaxi Formation

架定型于喜马拉雅晚期[25-26]。川东南在多期构造运动影响下,形成了现今盆缘的山前带构造、盆内的隔档式褶皱等[27]。

林滩场地区处于泸州—赤水构造叠加带,位于盆缘的齐岳山构造带前缘,为基底逆断层叠瓦逆冲推覆而形成的断背斜。林滩场背斜为一整体呈 NE 向展布的长轴断背斜,东南与桑木场构造之间以断洼相隔。背斜两翼发育逆断层,组合成冲起构造,两翼地层相对较陡。背斜南、北两个倾没端地层相对平缓。平面上自北西向南东可分为斜坡带、褶皱带和冲断剥蚀带。低温年代学资料揭示自中生代以来林滩场地区经历了 3 次热演化事件[28]:埋深增温阶段(~80 Ma)、缓慢抬升冷却阶段(80~20 Ma)、快速隆升剥蚀阶段(20 Ma 至今)。

研究区目的层为五峰组—龙马溪组龙一段的黑色富有机质海相页岩,为深水陆棚相沉积,地层厚度稳定,分布在 80~106 m 之间。岩性以黑色碳质笔石页岩为主,夹少量砂质泥岩及粉砂岩,层理发育,含较多黄铁矿星点、团块及结核,含丰富的笔石化石。LY1 和 LY3 井①—⑨小层平均 TOC 分别为 2.68%和 2.67%,属于中—高含量。此外 LY1 和 LY3 井①—④号层实测含气量均值在 4 m³/t 左右,显示出良好的含气性。

2　样品信息及实验方法

对 LY3 井五峰组—龙马溪组岩心(①—⑧小层)进行观察,累计长75m,其中①小层的层间滑移缝相对发育,实验样品来自①小层的水平裂缝中充填的方解石脉体(图 2)。

普通光学观察采用LeicaDM4500P显微镜。流体

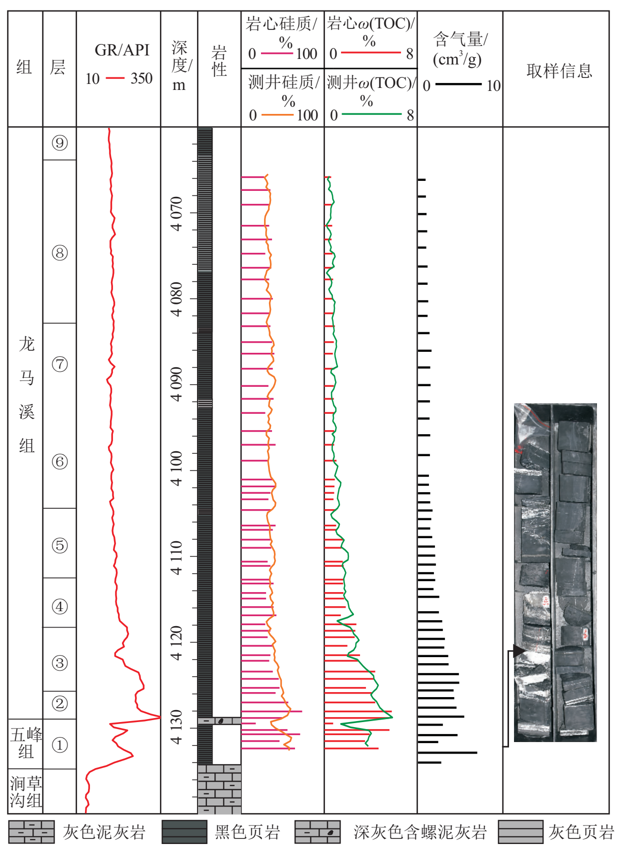

图 2　川东南林滩场地区 LY3 井单井柱状图及取样信息

Fig.2　Histogram and sampling information of well LY3 in Lintanchang area, southeastern Sichuan Basin

包裹体测温使用 THMSG600 冷热台和冷热控制系统,均一温度测定误差±1 ℃。测温过程中,冷热台的温度变化速率控制在 0.1~5 ℃/min,观察并记录包裹体完全均一时的温度。采用 CL8200—MK5 型阴极发光仪分析成岩期次,样品测试条件为:真空度 3 Pa、束电压 11 kV、束电流 250 μA。拉曼光谱分析在 LabRAMHR800 高分辨率拉曼光谱仪上完成,采用 Nd:YAG 激光器,激发波长为 532.06 nm,功率控制在 20 mW,单次光谱采集时间为 20~120 s,利用氖灯特征谱线对所测甲烷包裹体的拉曼散射峰位进行校正。采用 NanoFab ORION 显微镜对研磨和氩离子抛光后的样品进行显微观察,以分析有机孔特征;实验温度为 24 ℃,相对湿度为 35%。采用 Helios 650 型双束电镜进行岩心的 3D 扫描成像,建立孔隙三维网络模型。超压机制识别图版则基于测井声波速度值和密度值分析绘制。

3 实验结果

3.1 裂缝脉体特征

LY3 井五峰组—龙马溪组黑色页岩层系中主要发育层间滑移缝、高角度剪切缝以及层理缝,层间滑移缝是主要裂缝类型。由于靠近断裂核,水平层间断层作用导致页岩整体滑脱,缝内被方解石所充填,部分充填的方解石脉体形状不规则,呈断续的网状,可见构造角砾,脉体宽度最厚可达 4 cm(图 3a-c)。五峰组以上裂缝发育程度降低,龙一段发育的层理缝部分被黄铁矿充填,可见黄铁矿与方解石共同充填于层间滑移缝中,指示其处于深水还原环境;缝面具有明显的擦痕和阶步(图 3d)。而高角度的剪切缝穿层性强,部分末端见菱形对接,脉体形状平直,宽度介于 1~2 mm(图 3e)。此外,在龙一段底部发育的流体超压缝被纤维状方解石脉体充填,脉体沿水平展布(图 3f)。

裂缝脉体的光学及阴极发光特征显示脉体矿物主要为方解石,其次为石英(图 4)。脉体大部分区域被粗晶方解石颗粒充填,方解石多呈自形—半自形粒状,粒径可达 1 cm,具有角砾状构造特征,正交偏光下双晶纹明显。方解石充填分两期,粗晶方解石脉发中等强度橘黄色光,第二期方解石脉发暗橘黄色光。脉体中的石英在单偏光下无色,正交偏光下为十字消光且无阴极发光。少量的黏土矿物在阴极发光下发靛蓝色光,而有机质不发光。

3.2 流体包裹体特征

包裹体记录了古流体作用压力、温度、盐度等信息[29-30]。LY3 井五峰组—龙马溪组页岩裂缝中充填的方解石和石英脉体中包裹体种类丰富,其大小不一,表现出明显的非均质性,主要发育气相包裹体及盐水包裹体。单相盐水包裹体中无气泡(图 5a),属于亚稳态液相包裹体且无法对其进行均一温度测定,一般指示较低的捕获温度[31-32]。均一温度是确定包裹体类型和密度的重要参数[21,33]。分析结果显示,脉体中的气—液两相盐水包裹体均一温度分布范围较广,介于 165~208 ℃,平均为 186 ℃,其形成温度可划分为两期(图 6a)。含甲烷的气—液两相包裹体和纯气相甲烷包裹体共生,表明甲烷包裹体捕获于甲烷过饱和的不混溶流体[13,34]。在这种情况下,气—液两相盐水包裹体的均一温度值通常可代表包裹体的捕获温度。采用 BODNAR 提出的盐度—冻结温度关系计算包裹体盐度[35]。测试结果显示盐度分布介于 4.17%~11.59%(wt% NaCl equiv,下同),平均为 7.52%。包裹体均一温度和盐度投点图显示存在两期流体活动,一期为低温低盐度流体,捕获温度为 165~178 ℃,对应的盐度范围为 4.17%~8.67%,气—液两相盐水包裹体呈长方形、正方形或不规则多边形等形态,成群或成条带状分布,长轴介于

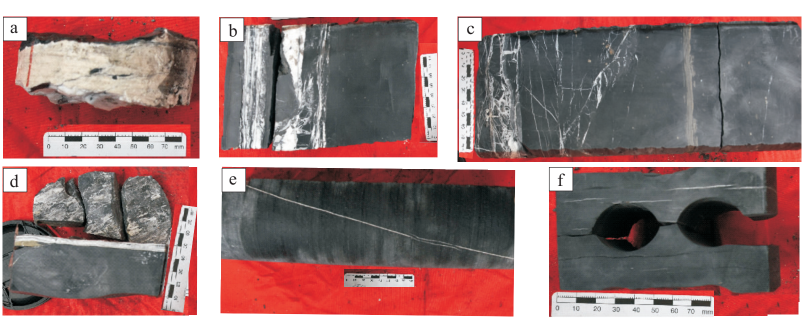

图 3 川东南林滩场地区 LY3 井页岩岩心裂缝脉体特征

a.水平层理缝充填块状方解石,五峰组,4 133.9 m;b.水平层理缝充填的方解石呈网状,五峰组,4 134.1 m;c.网状裂缝,岩心具揉皱破碎现象,龙马溪组一段,4 133.5 m;d.层间滑移缝充填方解石和黄铁矿,龙马溪组一段,4 074.7 m;e.高角度剪切缝充填方解石,龙马溪组一段,4 170.0 m;f.水平流体超压缝充填方解石,龙马溪组一段,4 129.8 m。

Fig.3 Characteristics of fracture veins of shale cores of well LY3 in Lintanchang area, southeastern Sichuan Basin

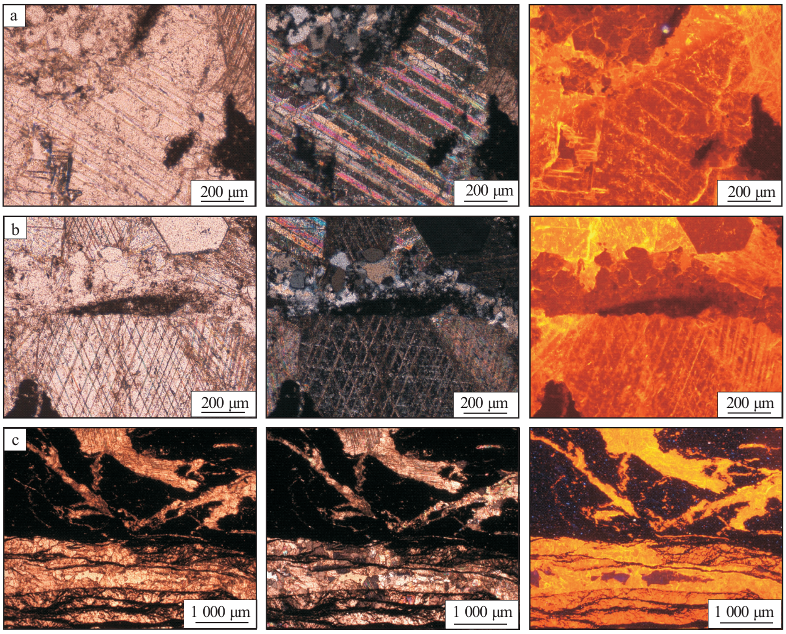

图 4　川东南林滩场地区 LY3 井五峰组页岩脉体光学及阴极发光特征
a-c.埋深分别为 4 134.0、4 134.1、4 133.9 m;从左至右依次为单偏光、正交偏光、阴极发光;第一期方解石发橘红色光,另一期为暗橘黄色。
Fig.4　Optical and cathodoluminescence characteristics of shale fracture veins in the Wufeng Formation of well LY3 in Lintanchang area, southeastern Sichuan Basin

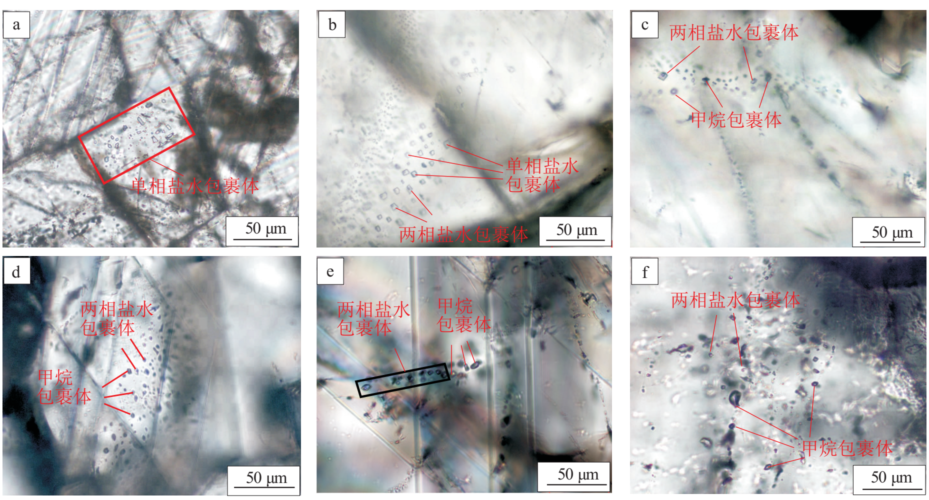

图 5　川东南林滩场地区 LY3 井页岩裂缝脉体中流体包裹体的岩相学特征
Fig.5　Petrographic features of fluid inclusions in shale fracture veins of well LY3 in Lintanchang area, southeastern Sichuan Basin

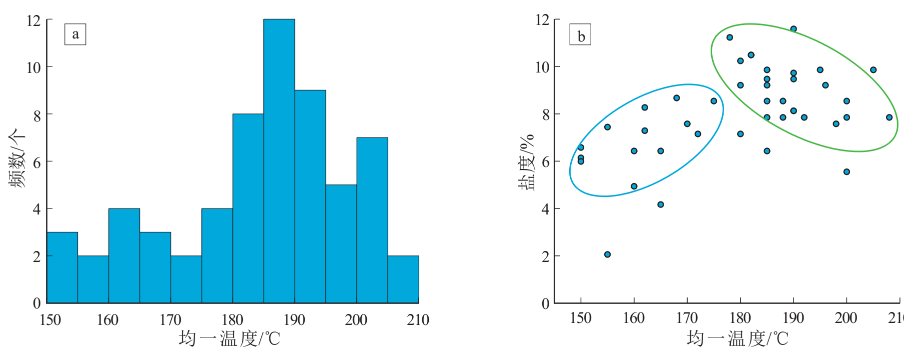

图 6　川东南林滩场地区 LY3 井流体包裹体均一温度和盐度测试结果
Fig.6　Test results of homogenization temperature and salinity of fluid inclusions of well LY3 in Lintanchang area, southeastern Sichuan Basin

5~15 μm,气相体积分数为 5%~15%,共生的甲烷包裹体则以纺锤状、次圆状为主,孤立分布,长轴介于 2~6 μm;另一期为高温高盐度流体,捕获温度为 185~208 ℃,其主峰介于 195~205 ℃,盐度范围为 7.58%~11.59%(图 6b),两相盐水包裹体透明度不及前者,形态以椭圆状,次圆状、不规则的长条状为主,呈带状分布,长轴介于 3~10 μm,气相体积分数为 6%~10%。伴生的甲烷包裹体形态以椭圆状、不规则多边形为主,呈带状分布,个体较大,长轴介于 5~20 μm。石英脉中的纯甲烷气相包裹体的均一温度分布介于-97.5~-95.4 ℃,明显低于纯甲烷体系临界温度(-82.6 ℃),因而属于高密度甲烷包裹体[36]。

3.3 甲烷包裹体捕获压力

流体包裹体拉曼光谱谱峰形态和强度被用来定性、定量分析包裹体成分。选取方解石脉中形态完整且轮廓清晰的气液两相盐水包裹体和共生的纯气相包裹体进行拉曼光谱测试。在两种包裹体中均检测到明显的甲烷 C-H 对称伸缩振动峰(ν_1)(图 7)。实测的 $\nu_1(CH_4)$峰位见表 1。$\nu_1(CH_4)$峰位用于计算甲烷压力或密度。本文纯甲烷单相包裹体的密度介于 0.245~0.283 g/cm^3(表 1)。

利用流体包裹体分析数据重建沉积盆地地层压力演化过程是研究古油气藏压力场的重要手段。以共生气液两相包裹体的均一温度为捕获温度,在确定纯甲烷包裹体的密度的基础上,依据 DUAN 等[37]建立的纯甲烷体系的状态方程,将纯甲烷包裹体密度沿等容线外推到捕获温度即可获得捕获压力。结果显示,甲烷过饱和流体的作用压力介于 80.8~119.8 MPa(表 1)。

3.4 有机孔孔隙结构特征

五峰组—龙马溪组底部有机孔发育,形态以扁平椭圆状、线状或不规则角状为主,少部分椭圆状或线状有机孔长轴介于 1~2 μm(图 8)。有机孔之间的相互结合增加了孔径,同时也增加了孔隙结构的复杂性。此外,部分孔隙的连接处呈闭合状态,显示遭受了压实影响(图 8b,c)。聚焦离子束扫描电镜分析结果显示 LY3 井五峰组—龙马溪组底部孔隙度介于 1.06%~2.87%,有机质内孔隙度介于 3.72%~9.01%,孔隙度连通率为 43.7%~74.9%(表 2),有机孔孔径主要分布于 10~30 nm(图 9)。

4 讨论

4.1 包裹体捕获时间

裂缝脉体形成与封闭时期及其古温压是分析气藏压力演化的重要参数,包裹体捕获温度被广泛

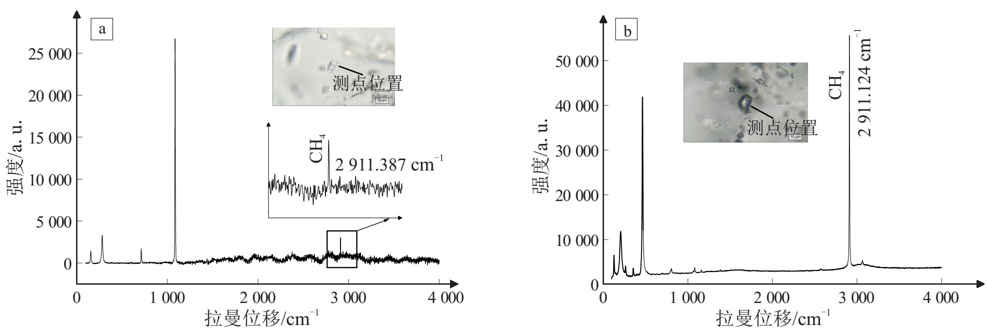

图 7 川东南林滩场地区 LY3 井方解石脉体中典型包裹体拉曼光谱图

Fig.7 Raman spectrogram of typical inclusions in calcite veins of well LY3 in Lintanchang area, southeastern Sichuan Basin

表 1 川东南林滩场地区甲烷包裹体捕获压力计算结果

Table 1 Calculation results of trapping pressure of methane inclusions in Lintanchang area, southeastern Sichuan Basin

样品编号	测点数	ν_1/cm^{-1}	ρ/(g/cm^3)	同期盐水包裹体均一温度/℃		捕获压力/MPa
				范围	平均	
BG1	5	2 911.871~2 911.062	0.268~0.276	183~208	198	107.4~116.1
BG2	3	2 910.926~2 910.984	0.271~0.274	184~203	196	109.8~112.5
BG3	4	2 910.743~2 911.045	0.266~0.269	182~205	193	106.7~109.1
BG4	4	2 911.281~2 911.602	0.267~0.282	180~194	196	110.7~119.8
BG5	3	2 911.278~2 912.516	0.244~0.256	150~184	163	80.7~88.7
BG6	3	2 911.203~2 911.381	0.251~0.259	165~179	165	85.8~92.4
BG7	4	2 911.267~2 911.418	0.249~0.256	155~177	163	83.0~88.2

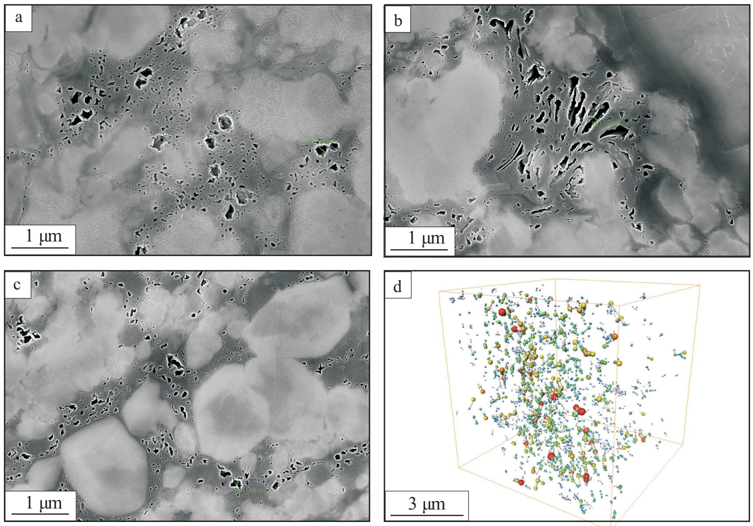

图 8　川东南林滩场地区 LY3 井五峰组—龙马溪组一段页岩有机孔形态扫描电镜照片

a.不规则角状、椭圆状的有机孔,4 132.34 m;b.狭缝状、扁平椭圆状有机孔,4 130.7 m;
c.不规则角状有机孔,部分孔隙相互结合,连通性变差,4 125.91 m;d.孔隙网络提取结果,4 130.7 m。

Fig.8　FE-SEM observations of shale organic pore morphology in the Wufeng Formation - the 1st member of Longmaxi Formation of well LY3 in Lintanchang area, southeastern Sichuan Basin

表 2　川东南林滩场地区 LY3 井聚焦离子束扫描电镜提取的孔隙参数

Table 2　Pore parameters extracted by FIB-SEM observations of well LY3 in Lintanchang area, southeastern Sichuan Basin

深度/m	有机质/%	孔隙度/%	有机质内孔隙度/%	连通孔隙度/%	孔隙连通率/%
4 132.34	65.3	1.06	3.72	2.09	56.2
4 130.70	41.8	2.87	4.76	2.08	43.7
4 125.91	53.4	1.43	7.05	5.28	74.9

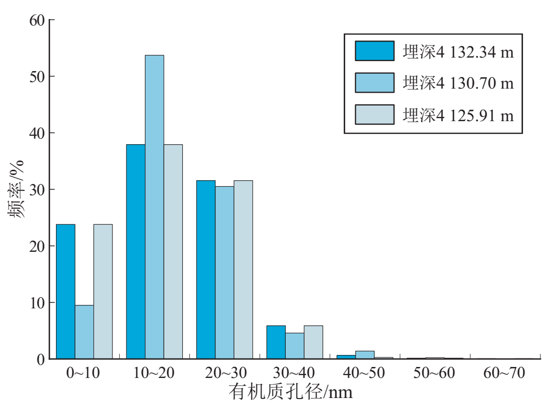

图 9　川东南林滩场地区 LY3 井有机质孔径分布

Fig.9　Organic pore size distribution histogram of well LY3 in Lintanchang area, southeastern Sichuan Basin

用于确定油气运移、成藏的时间和深度[38]。本文通过 BasinMod 模拟恢复了 LY3 井埋藏史、热演化史及生烃史。模拟结果显示,五峰组—龙马溪组在早三叠世 R_o 达到 0.5%~0.7%时开始生烃,进入初始生烃阶段;晚三叠世 R_o 达到 0.7%~1.3%,进入液态生烃高峰期;晚侏罗世 R_o 达到 1.3%~2.0%,进入高成熟阶段,生成大量湿气及油裂解气;侏罗纪末期 R_o 大于 2.0%,进入过成熟阶段,为干气生成期;研究区在晚白垩世发生抬升剥蚀,埋深增温及生烃作用停止(图 10)。通过埋藏史、热演化史与包裹体均一温度分布的匹配可大致确定包裹体捕获时间及深度。然而,在埋藏史图中,同一地层温度可能对应不同流体作用时间。因此,仅依据均一温度的约束难以获得准确的流体捕获时间。林滩场包裹体中的碳氢化合物仅有甲烷,表明高压的含甲烷流体包裹体被捕获时原油已裂解完成[13],这种高压流体很难在强烈的挤压条件下保存[13,39]。因此,脉体中捕获的第一期包裹体应在最大埋深前被捕获,其均一温度介于 178~205 ℃,对应时间为 131~118 Ma;第二期盐水包裹体均一温度为 150~175 ℃,捕获压力明显下降,因而最可能形成于晚白垩世以来的强烈挤压抬升期,对应时间为 25~18 Ma(图 10)。高压流体导致页岩的拉伸破裂和垂直扩张形成初期的水力裂缝[13,40],脉体形成过程中捕获了高温压的含甲烷流体。第二

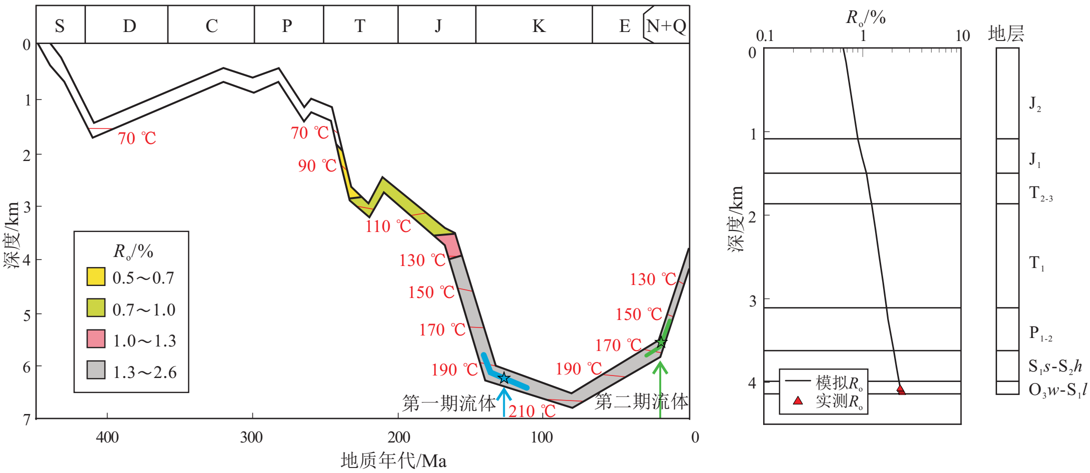

图 10 川东南林滩场地区 LY3 井五峰组—龙马溪组埋藏热演化史

Fig.10 Burial and thermal evolution histories of Wufeng-Longmaxi formations of well LY3 in Lintanchang area, southeastern Sichuan Basin

期包裹体具较低的盐度特征,同时产自同一脉体中的包裹体的均一温度具有分区性,表明后期的挤压抬升又使被封闭的裂缝再次开启并接受后续的流体充注,因而捕获了较低温压的含甲烷流体。

4.2 页岩气藏超压成因及压力演化

地层超压成因一般分为不均衡压实和流体体积膨胀[41]。不均衡压实作用是指地层中孔隙流体未能及时排出或排出受阻,孔隙内部流体聚集超压,要求极为严格的保存环境[42]。流体膨胀机制包括黏土矿物脱水、生烃过程及原油裂解等。目前超压页岩中的声波和密度交会图常被用来区分不同超压机制[14,43-44]。由不均衡压实产生的超压,其密度、声波速度及孔隙度与正常压实曲线基本一致。由流体膨胀产生的超压会使声波速度变低(流体压力垂向上的地层有效应力),但密度变化却很小(图 11a)。LY3 井五峰组①小层及龙一段②小层部分数据处于不均衡压实区域,同时部分数据声波速度变低且密度变化较小。龙一段③、④、⑤小层的数据分布也符合流体膨胀机制的趋势(图 11b)。林滩场地区抬升前处于稳定的埋深增温阶段,具备良好的封闭条件。现今五峰组—龙马溪组页岩气赋存空间以有机孔为主,不均衡压实作用对孔隙流体压力影响较小[14]。因此,本文推测 LY3 井五峰组—龙马溪组的超压与不均衡压实以及生烃作用相关,其中生烃超压起主导作用。

依据包裹体捕获时间和压力对 LY3 井压力演化史进行约束(图 12a)。结果表明 LY3 井压力演化存在 4 个阶段。第一阶段,受晚加里东期—海西期抬升剥蚀影响,并未形成不均衡压实导致的超压;第二阶段,印支早期—燕山中期,此时处于生油阶段,同时地层快速埋深,当剩余油指数(烃源岩

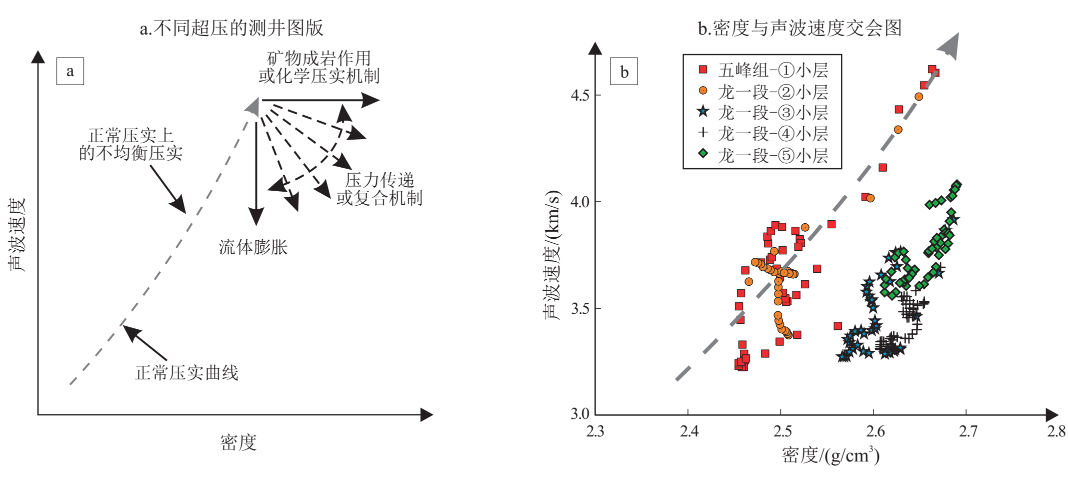

图 11 川东南林滩场地区 LY3 井密度与声波速度交会图

Fig.11 Crossplots of density and sound velocity of well LY3 in Lintanchang area, southeastern Sichuan Basin

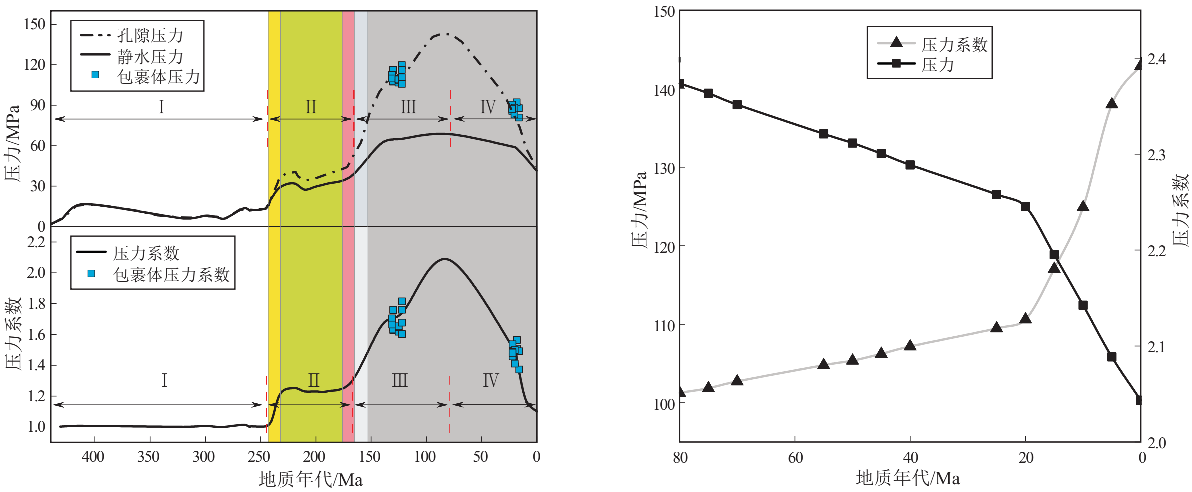

图 12　川东南林滩场地区 LY3 井压力演化

Fig.12　Pressure evolution process of well LY3 in Lintanchang area, southeastern Sichuan Basin

孔隙中剩余油与总油的比值)小于 0.75 时,烃源岩并不能产生超压,并且生油阶段通常只能形成微弱的超压[45-47],因此,我们推测这一阶段主要受生油以及不均衡压实影响地层形成微超压;第三阶段,燕山晚期—喜马拉雅早期处于高成熟到过成熟阶段,干酪根裂解生气和原油裂解导致流体膨胀是超压的主要形成期;第四阶段,喜马拉雅中—晚期,受构造挤压抬升影响,地层温度下降和开启性裂缝的形成导致页岩气逸散,降低了地层压力。假设页岩气未发生逸散(~80 Ma),计算得到的初始压力及压力系数分别为 140.67 MPa 和 2.05,对应的纯甲烷流体的密度为 0.287 g/cm^3。若忽略孔隙回弹影响[14,19],基于纯甲烷体系状态方程计算地层压力可用于揭示页岩气逸散对地层压力的影响规律(图 10b)。结果表明,尽管地层温度下降会导致孔隙流体压力下降,但地层压力系数因上覆负载降低反而增加,计算得到现今理想地层压力达 100.31 MPa,地层压力系数为 2.39。而实际受页岩气逸散导致泄压 54.21 MPa,损失压力 54%,致使现今地层压力为常压(压力系数为 1.1)。

通过压力演化分析认为,晚期构造运动特别是喜马拉雅晚期的快速抬升是造成林滩场地区气藏逸散和泄压的根本原因。五峰组—龙马溪组底部的层间滑移裂缝是页岩气逸散的直接通道,充填的脉体中捕获的包裹体记录了这一过程。在快速抬升作用下(抬升剥蚀速率为 85 m/Ma),早期已封闭的裂缝再次开启引发页岩气顺层逸散,甲烷包裹体捕获压力介于 80.78~92.09 MPa,对应压力系数介于 1.37~1.49,属于弱超压。这一期纯气相甲烷包裹体数量较第一期少也指示页岩气已发生大量逸散。对比 DY1、DY3、PY1 等常压井,LY3 井最大日产气量高达 17.19×10^4 m^3。分析其原因:一方面,研究区构造抬升时间晚,延长了气藏的形成和保存时间;另一方面,裂缝主要集中形成于五峰组—龙一段底部(①小层),上部小层(②—③小层)受滑脱构造带影响小,且高角度穿层剪切缝和层间滑移缝发育规模低,有利于页岩气的保存。

五峰组—龙马溪组页岩以有机孔隙为主,盆内超压地区的有机孔表现为高圆度,孔径大且有机孔形态具备较好的均一性[1]。盆内 JY1 井其孔隙度在 3.35%~4.86%,有机质内孔隙度介于 11.04%~15.43%,连通孔隙占比介于 69.13%~94.94%[48-49]。对比而言,JY1 井的孔隙参数是 LY3 井的 1~2 倍(表 2)。超压对压实的缓解利于有机孔形态与页岩物性的保持[1],晚期的强泄压导致研究区孔隙压力难以抵消上覆岩层影响,使已形成的孔隙圆度变差,孔径变小,连通性降低(图 8),储层质量变差。

5　结论

(1)林滩场地区五峰组—龙马溪组黑色页岩层系底部裂缝中的脉体可分为两期:第一期形成于沉降埋深阶段,对应时间介于 131~118 Ma,形成温度介于 178~205 ℃;第二期形成于构造抬升阶段,对应时间介于 25~18 Ma,形成温度介于 150~175 ℃,且捕获的两相盐水包裹体盐度较低。

(2)林滩场地区超压主要来源于生烃作用。LY3 井压力演化存在 4 个阶段:第一阶段(加里东期—海西期)为常压;第二阶段(印支早期—燕山中期)为微超压—常压,由生油和不均衡压实形

成;第三阶段(燕山晚期—喜马拉雅早期)主要由生气或油裂解气形成高超压气藏,地层压力系数最高达 2.05;第四阶段(喜马拉雅中—晚期)为泄压阶段,主要由页岩气逸散导致泄压 54%。

(3)喜马拉雅晚期的快速抬升是造成林滩场地区气藏逸散和泄压的根本原因。含甲烷包裹体分析结果显示,泄压后气藏压力介于 80.78~92.09 MPa,压力系数介于 1.37~1.49。晚期构造挤压使已形成的裂缝再次开启,同形成的滑脱构造带共同引发页岩气的大量逸散,但气藏较长的形成和保存时间使得林滩场地区仍然具备较好的勘探潜力。

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利益冲突声明/Conflict of Interests

所有作者声明不存在利益冲突。

All authors disclose no relevant conflict of interests.

作者贡献/Authors' Contributions

唐建明参与研究设计和论文审核;何建华参与论文写作和修改;魏力民和邓虎成参与实验设计;李勇、李瑞雪和赵爽完成实验操作。所有作者均阅读并同意最终稿件的提交。

The study was designed and examined by TANG Jianming. The manuscript was drafted and revised by HE Jianhua. The experiments were designed by WEI Liming and DENG Hucheng. The experimental operation was completed by LI Yong, LI Ruixue and ZHAO Shuang. All the authors have read the last version of paper and consented for submission.

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