引用格式：熊亮，魏力民，赵挺，等．断层及相关裂缝发育特征对页岩气保存的影响：以四川盆地东南部林滩场地区为例[J]. 油气藏评价与开发，2026，16(3)：509-519.

XIONG Liang, WEI Limin, ZHAO Ting, et al. Influence of development characteristics of faults and associated fractures on shale gas preservation: A case study of Lintanchang area, southeastern Sichuan Basin[J]. Petroleum Reservoir Evaluation and Development, 2026, 16(3): 509-519.

DOI: 10.13809/j.cnki.cn32-1825/te.2025518

断层及相关裂缝发育特征对页岩气保存的影响
——以四川盆地东南部林滩场地区为例

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摘要：四川盆地林滩场地区经历多期构造运动，断层与裂缝体系发育复杂。实钻结果显示：上奥陶统五峰组—下志留统龙马溪组具备良好的勘探与开发潜力，探明该层系断层及相关裂缝的发育规律对于后续勘探至关重要。研究将林滩场地区断层划分为A、B、C、D共4个级别，主要存在北东向、近东西向和近南北向3组走向。A级断层主要分布在背斜两翼，背斜倾没端断层发育较少。采用三维地震属性融合与FDI（裂缝发育指数）裂缝带刻画方法，对五峰组—龙马溪组断层相关裂缝进行了定量研究。结果表明：①断层相关裂缝发育带宽度与断距显著正相关，A级裂缝带宽度介于510～660 m（均值约600 m），B级裂缝带宽度介于160～280 m（均值约220 m），C级裂缝带宽度介于130～200 m（均值约168 m），D级裂缝带宽度介于115～170 m（均值约150 m）。断层上盘裂缝带普遍宽于下盘，断层交叉部位的裂缝最为发育。同级断层中，近东西向裂缝带最宽，近南北向次之，北东向最窄。②裂缝发育带与页岩气保存条件密切相关。裂缝带内井表现为较低的地层压力系数和产能，远离裂缝带的井具有较高压力系数和更大产量，二者呈显著正相关关系，说明断层相关裂缝对压力保持与气体逸散具有重要控制作用。研究揭示了林滩场地区五峰组—龙马溪组断层及相关裂缝的发育规律，可为区内页岩气选区优选和井位部署提供重要参考。

关键词：林滩场；五峰组—龙马溪组；页岩气；属性融合；断层相关裂缝；勘探选区

中图分类号：TE37　　**文献标识码：**A

Influence of development characteristics of faults and associated fractures on shale gas preservation: A case study of Lintanchang area, southeastern Sichuan Basin

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Abstract: The Lintanchang area of the Sichuan Basin has experienced multiple stages of tectonic movements, resulting in a complex fault and fracture system. Drilling results show that the Upper Ordovician Wufeng Formation-Lower Silurian Longmaxi Formation possesses favorable exploration and development potential. Clarifying the development patterns of faults and associated fractures in these strata is critical for subsequent exploration. In this study, faults in the Lintanchang area were classified into four levels (A, B, C, and D), with three dominant strike directions: NE-trending, near-EW-trending, and near-NS-trending. A-level faults were mainly distributed on the flanks of the anticline, whereas fewer faults developed at the plunging end of the anticline. Using three-dimensional seismic attribute fusion with the fracture development index (FDI), a quantitative study was performed on fault-related fractures in the Wufeng-Longmaxi Formation. The results showed that: (1) The width of fault-related fracture zones exhibited a significant positive correlation with fault displacement. The widths of A-level fracture zones ranged from 510 m to 660 m (average ～600 m), B-level from 160 m to 280 m (average ～220 m), C-level from 130 m to 200 m (average ～168 m), and D-level from 115 m to 170 m (average ～150 m), respectively. Fracture zones in the hanging wall were generally wider than those in the footwall, and fractures were most developed at fault intersections. Among faults of the same level, near-EW-trending faults exhibited the widest fracture zones, followed by near-NS-trending faults, whereas NE-trending faults showed the

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收稿日期：2026-01-05。

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基金项目：国家自然科学基金项目"三大盆地深层—超深层海相油气高效勘探开发基础研究"（U24B6001）。

narrowest zones. (2) Fault-related fracture zones were closely associated with shale gas preservation conditions. Wells located within fracture zones had lower formation pressure coefficients and productivity, whereas wells far from fracture zones exhibited higher pressure coefficients and greater gas production. A significant positive correlation was observed between these two, indicating that fault-related fractures played an important role in controlling pressure maintenance and limiting gas escape. This study reveals the development patterns of faults and associated fractures in the Wufeng-Longmaxi Formation of the Lintanchang area, providing important reference for shale gas sweet-spot selection and well placement in the region.

Keywords: Lintanchang; Wufeng-Longmaxi Formation; shale gas; attribute fusion; fault-related fractures; exploration area selection

四川盆地及其周缘地区页岩气资源丰富,约占中国页岩气总储量的三分之一。上奥陶统五峰组—下志留统龙马溪组是中国最具勘探和开发潜力的页岩层系[1-5]。近年来,四川盆地的涪陵、长宁、威远、威荣等区块已实现商业化页岩气开发[6-10]。为了响应中国油气增储上产的号召,进一步拓展油气勘探领域,亟须探索新的开发区域。当前,页岩气勘探开发逐渐从超压向常压、从盆内向盆缘发展,部分地区已取得常压页岩气藏的勘探突破[11-15]。

贵州林滩场地区位于四川盆地盆缘,具有良好的页岩气形成条件。已钻井实测的地层压力系数和单井最大产能表明,该区页岩气储层具备较好的勘探开发潜力[6]。X1井的单井最大产能可达$4.30\times10^4\ m^3/d$,而X2井最大产能为$17.19\times10^4\ m^3/d$,表明该区常压储层之间存在较大差异性。盆缘林滩场地区受多期构造运动影响,研究区内的差异变形明显,导致页岩气的保存条件差异较大,页岩气富集与高产需要具备良好的保存条件[16]。构造变形期次及强度、多尺度断层和裂缝的发育特征直接影响页岩的含气性[17]。涪陵、泸州等地区的勘探开发结果表明,不同构造部位的构造变形强度体现在断层分布和裂缝发育特征上,并控制着单井产量的差异[18-19]。断层相关裂缝的发育是影响页岩气保存的关键因素,断层相关裂缝密度随距断层距离增加而递减[20]。大断距断层相关裂缝对页岩气藏保存具有显著的破坏作用,而小断距断层相关裂缝虽对保存条件影响较弱,但其潜在的不利效应仍不可忽视[21]。断层相关裂缝对非常规油气的勘探和开发具有重要意义,利用FDI(裂缝发育指数)方法定量刻画断层相关裂缝发育带,在中国多个盆地中已取得良好应用效果[22-24]。

林滩场地区受多期构造运动的叠加影响,区内断层发育较为复杂,导致页岩气保存条件差异较大。目前,前人对林滩场地区的研究多集中在储层物性、岩石力学、压力演化等方面[1,6,25-26],但对断层相关裂缝的研究较为缺乏。研究在三维地震属性融合基础上,利用FDI方法,对研究区不同级次、不同方位和不同部位的断层相关裂缝进行精细刻画,以期为林滩场地区的勘探选区提供指导。

1　地质背景

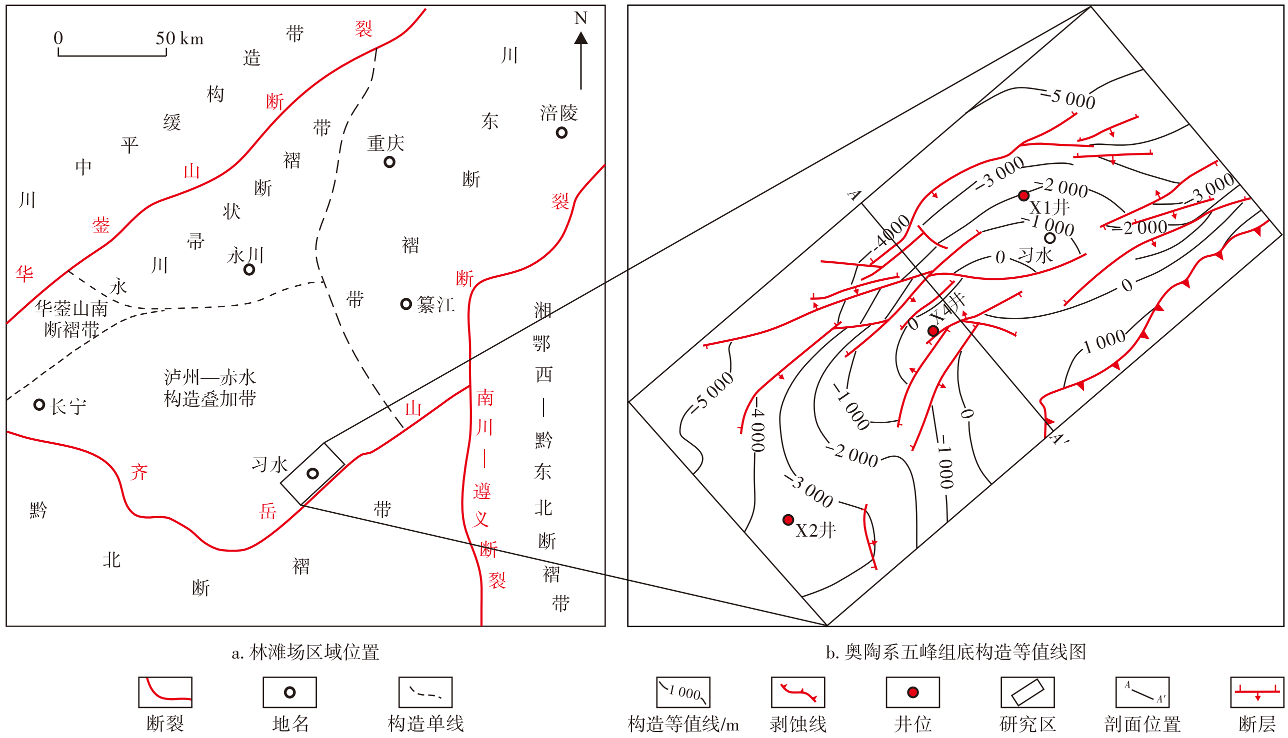
林滩场地区位于川东南隔挡式断褶带与黔北凹陷交汇处,行政区划隶属于四川省古蔺县及贵州省赤水市和习水县[27](图1a)。自晚中生代至新生代以来,研究区在多期构造运动作用下,经历了褶皱与隆升[28-29],由基底逆冲推覆作用形成长轴断背斜,呈北东—南西方向展布(图1b)。研究区主要发育北东向和南西向断层,且存在少量近南北向断层,北东向断层主导区域构造形态主要为基底逆冲断层。背斜两翼地层倾角较大,断层密集,冲起构造明显;而背斜南北倾没端地层倾角较低,断裂较少。区域构造变形受滑脱层控制明显,呈现出基底逆冲断层和双滑脱层的剖面结构[30](图1c)。受多期构造作用影响,研究区缺失泥盆纪、石炭纪、中—上三叠纪、下白垩纪及新生代地层,背斜核心区以二叠纪和三叠纪地层为主,两端则出露侏罗纪地层。研究的目标层为五峰组—龙马溪组海相页岩,沉积时处于深水陆棚相带,地层沉积厚度稳定,介于80～106 m。顶底板分别为上覆的石牛栏组灰岩和下伏的临湘组—宝塔组灰岩。多期复杂的构造变形产生了大量断层及相关裂缝,导致研究区保存条件存在显著差异。

2　断层相关裂缝带识别与表征方法

2.1　断层相关裂缝带识别方法

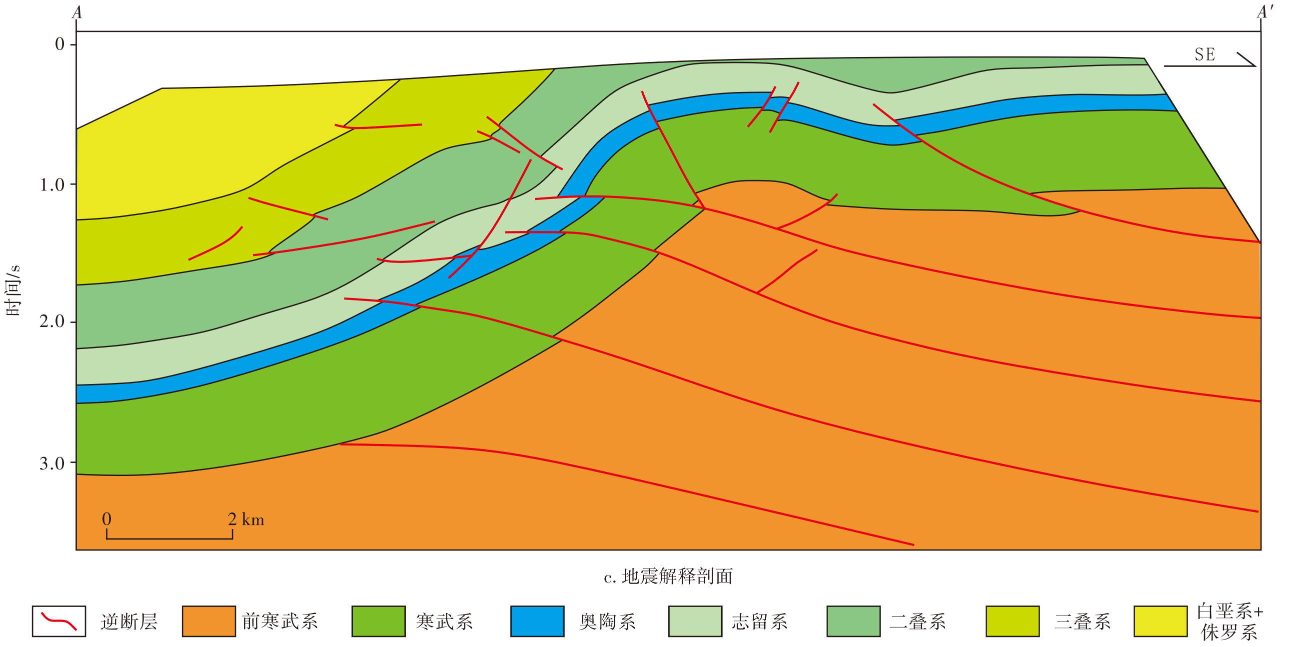
近年来,叠后地震属性分析技术已广泛应用于油气勘探与开发,叠后裂缝预测技术包括曲率、边缘检测、相干、最大似然、蚂蚁体等方法[31-34]。这些方法的原理不同导致裂缝识别的尺度和精度存在差异。现有研究多采用单一预测方法来反映裂缝发育情况,尽管取得了一定的预测效果,但往往忽略了各裂缝预测方法的不同侧重点,导致预测结果具有多解性[35-36]。针对五峰组—龙马溪组页岩储层中天然裂缝成因机制复杂和叠后地震属性侧重不同的特点,研究采用多属性融合方法进行裂缝预测。属性融合技术通过数学运算将多个属性组合,实现信息的综合可视化[37]。

受研究区复杂构造变形影响,位于林滩场背斜西北翼的大断裂发育区域以及高程突变区的地震信噪比较低,叠后地震属性易受地震噪声影响。传统的叠后裂缝预测方法通常依赖于构造平滑技术抑制噪声,然而,这种方法在降噪的同时可能会导致一些关键信息,特别是裂缝特征的丢失[38-39]。与传统的叠后裂缝预测方法相比,构造导向滤波技术能够在有效去噪的同时保留裂缝信



a. 林滩场区域位置

b. 奥陶系五峰组底构造等值线图



c. 地震解释剖面

图1　四川盆地林滩场区域地质特征(图1a、图1b据文献[22]修改)

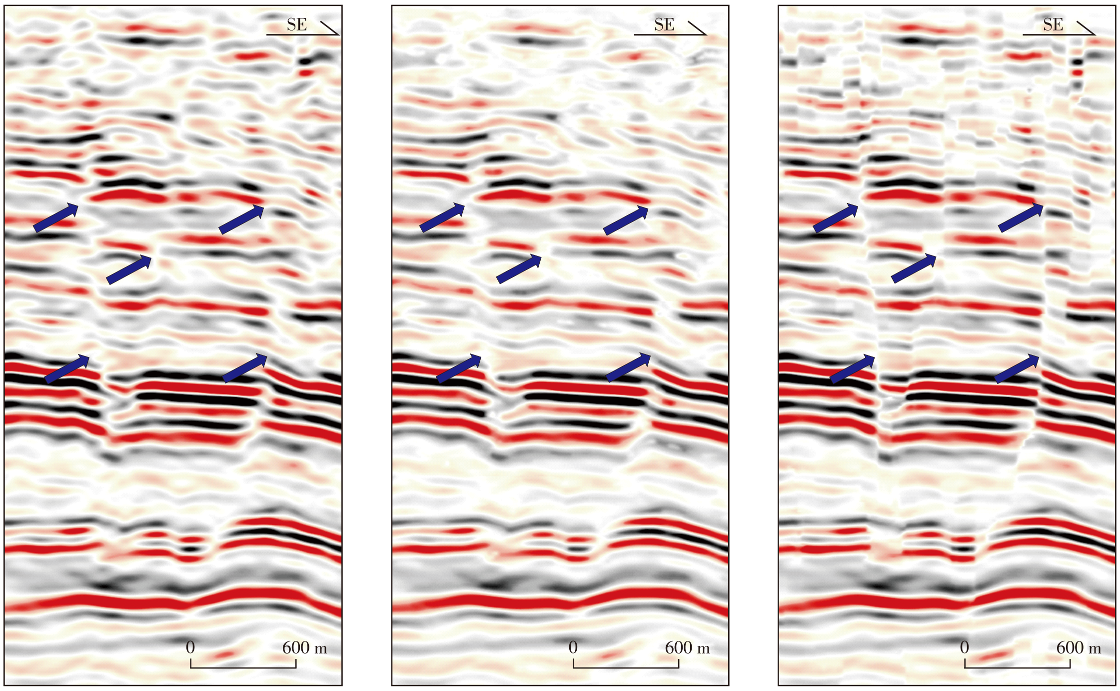
Fig. 1　Regional geological characteristics of Lintanchang area, Sichuan Basin (Figs. 1a and 1b modified from reference [22])

息[40]。因此,研究首先采用构造导向滤波方法提高地震信噪比。构造导向滤波的原理:在地层倾角属性和相干属性的双重约束下,沿着地震同相轴去除噪声,既能增强同相轴的连续性,又能提高断层和裂缝的清晰度[36]。滤波后的地震数据不仅降噪效果明显,还增强了裂缝信息(图2)。在此基础上,提取了多种裂缝敏感地震属性,包括方差体、本征相干、最大曲率、最大似然以及构造熵等。首先,将这些属性在目标层段范围内进行计算与提取;然后,将提取的各类地震属性与成像测井解释结果获得的单井裂缝密度数据进行统计分析;最后,采用皮尔逊相关系数方法定量评估属性与裂缝发育之间的相关性,从而确定各地震属性对裂缝的敏感程度。在相关性分析的基础上,筛选出与裂缝密度具有较高相关性的属性作为优选裂缝敏感属性。为了提高裂缝识别的可靠性与分辨率,对这些优选属性进行多属性融合。融合过程分为2个步骤:①属性归一化,对优选出的裂缝敏感属性进行归一化处理,使不同量纲和数值范围的属性在同一尺度上具有可比性;②权重调整与优化,通过多次迭代试算,对各属性赋予不同的权重系数,并与井上裂缝解释结果进行对比分析。不断调整权重组合,使融合结果在空间分

布特征及裂缝强度上与实际测井解释结果达到最佳一致性(图3a)。最终,确定最优权重方案并计算得到融合裂缝属性体,从而实现对研究区裂缝发育特征的综合表征(图3b)。

2.2　断层相关裂缝带宽度确定方法

断裂带内部结构包括断层核和裂缝带2个部分,且裂缝带呈现出距离断层核越远、规模越小的规律[41]。受主观因素的影响,野外观察或地震剖面观测难以定量刻画断层相关裂缝发育带的宽度。本研究采用FDI方法[24]对研究区不同级次、不同走向、不同构造部位的断层相关裂缝进行精细刻画。FDI方法的核心流程如下:首先基于属性融合地震体,选取包含目标点及其邻近地震道的时间窗口,计算目

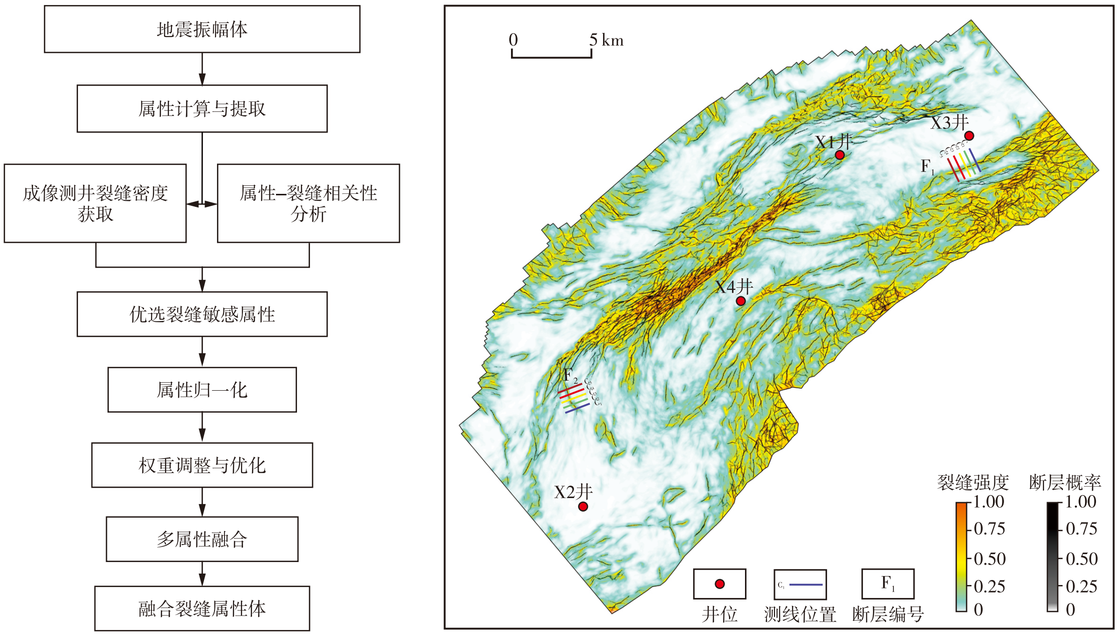


a. 原始地震剖面　b. 构造平滑后地震剖面　c. 构造导向滤波后地震剖面

注:图中箭头指向断点位置。

图2　四川盆地林滩场地区构造导向滤波处理前后地震剖面效果对比

Fig. 2　Comparison of seismic profile effects before and after structural-guided filtering processing in Lintanchang area, Sichuan Basin



a. 多属性融合流程示意图　b. 五峰组—龙马溪组融合属性沿层切片

图3　四川盆地林滩场地区地震多属性融合流程及成果示意图

Fig. 3　Schematic diagram of flowchart and results of seismic multi-attribute fusion in Lintanchang area, Sichuan Basin

标采样点与窗口内所有采样点均值之间的方差值，然后通过加权归一化处理获得采样点方差特征值。基础公式为：

$$D_{ij}=\frac{\sum_{i=1}^{n}\sum_{t=-T}^{T}\left(u_{ij}-u\right)^{2}}{\sum_{i=1}^{n}\sum_{t=-T}^{T}u_{ij}^{2}} \qquad (1)$$

式中：D_{ij}为FDI值大小；u_{ij}为j时第i地震道的融合地震属性值；u为计算视窗内所有样点的平均值；n为地震道数；t为样点距测线中心距离，单位m；T为半视窗长度，单位m。FDI值基于地震数据，且显著降低了主观因素的影响。FDI值越大，表明裂缝带发育程度越高，适用于定量刻画断层相关裂缝发育带的宽度。

针对林滩场地区不同级次、不同走向和构造部位的断层，布置了若干条地震测线（图4a）。围岩区域作为背景值，FDI值高于背景值的区域被定义为断层相关裂缝发育带（图4b、图4c、图4d）。

3　断层及其相关裂缝带发育规律

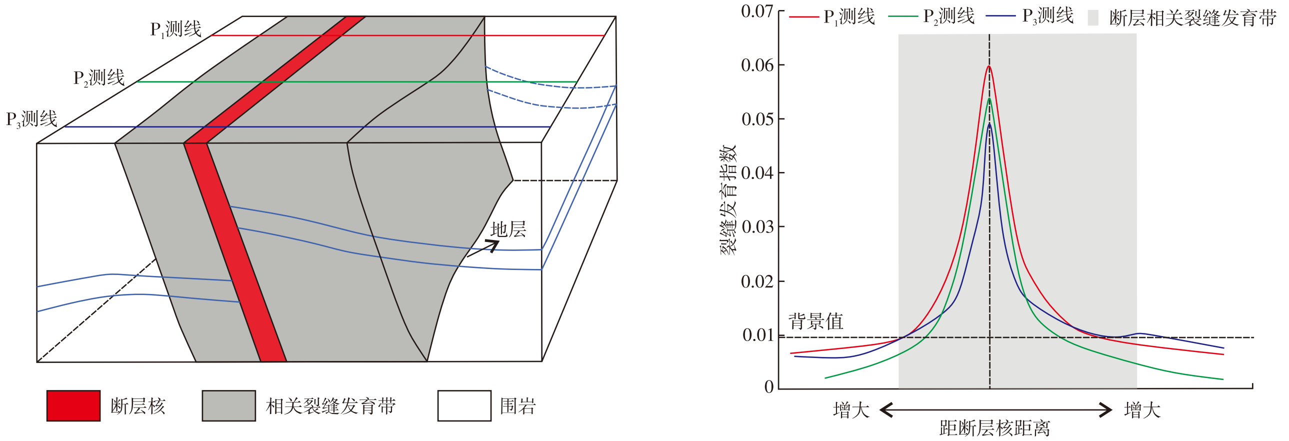
3.1　不同级次断层发育特征

林滩场地区受多期构造运动影响，断裂发育显著。根据是否切断盖层、顶底板和储层，结合断距与延伸长度，将研究区断层分为A、B、C、D四级（图5a）。A级断层为大规模断层，共发育5条，向上断穿区域盖层，向下断至五峰组以下地层，断距通常大于200 m；B级断层切穿储层顶底板但未穿透区域盖层，共发育14条，断距介于40～200 m；C级断层完全断开页岩气储层，但未切穿顶底板，共发育11条，断距小于40 m；D级断层未完全断开页岩气储层，共发育26条（图5b）。

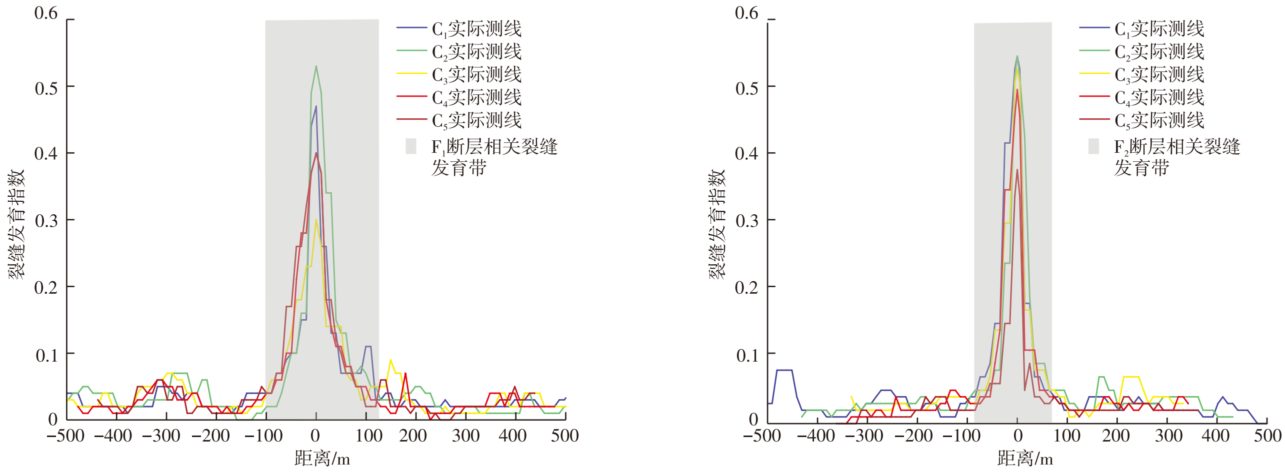
A级断层主要分布于背斜两翼，走向以北东向为主；B级断层数量较多，主要走向为北东向，部分为近南北向；C级断层以北东向为主，少量为近东西向或近南北向；D级断层以北东向为主，亦发育少量近东西向或近南北向断层（图5c）。总体而言，研究区主要发育北东向、近东西向及近南北向3组断层，A级断层主要集中在背斜两翼，背斜南北两端的断层相对较少，主要为C级断层和D级断层（图5b）。受控于断层和滑脱层，研究区发育深层基底卷入推覆与浅层多层滑脱褶皱的复合构造（图6）。

3.2　断层相关裂缝带发育特征

研究区内断层相关裂缝发育带的展布方向与断层的



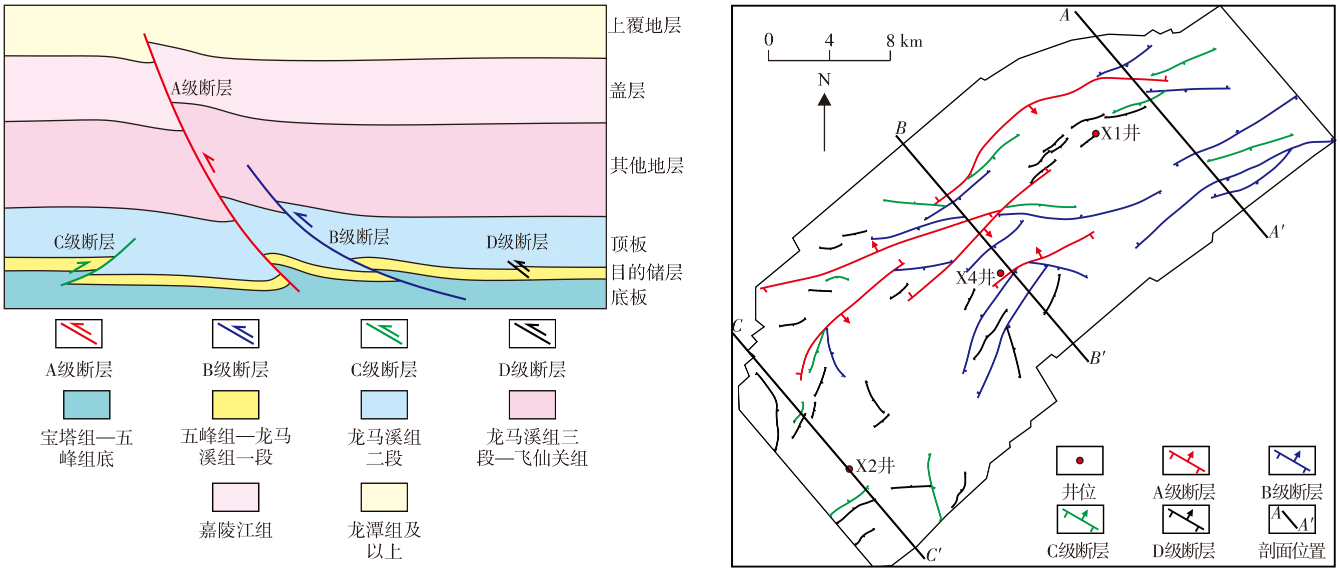
a. 断层相关裂缝发育带结构模式　　b. FDI响应示意图



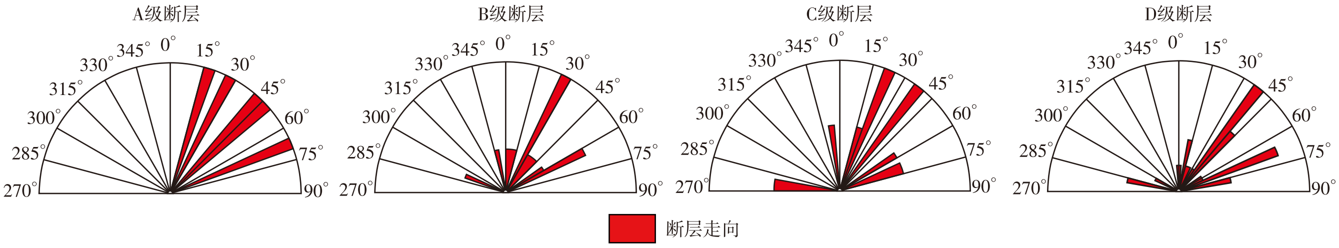
c. F_1断层FDI响应图　　d. F_2断层FDI响应图

图4　四川盆地林滩场地区断层相关裂缝结构模式及FDI响应图（测线位置见图3b）

Fig. 4　Fault-related fracture structural model and FDI response diagram in Lintanchang area, Sichuan Basin (profile location shown in Fig. 3b)



a. 断层分级示意图　　b. 断层纲要图



c. 不同级次断层走向玫瑰花图

图5　四川盆地林滩场地区断层发育情况

Fig. 5　Fault development in Lintanchang area, Sichuan Basin

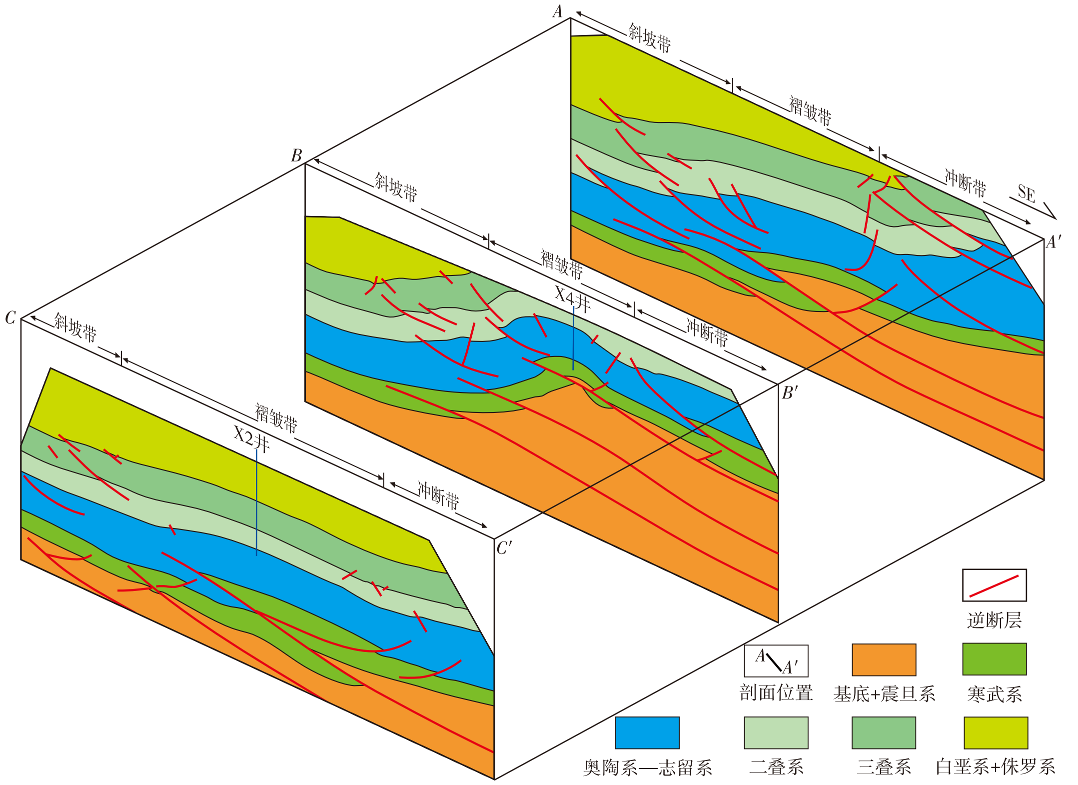
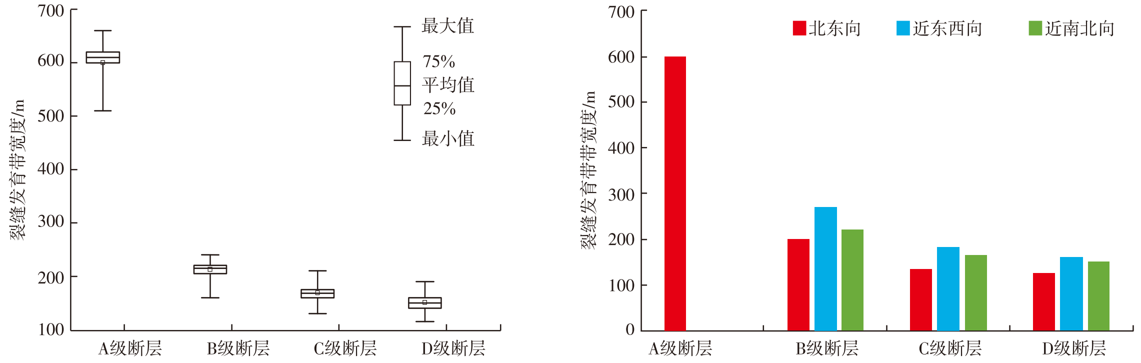


图6　四川盆地林滩场地区地震解释剖面栅状图（剖面位置见图5b）

Fig. 6　Grid diagram of seismic interpretation profiles in Lintanchang area, Sichuan Basin (profile locations shown in Fig. 5b)

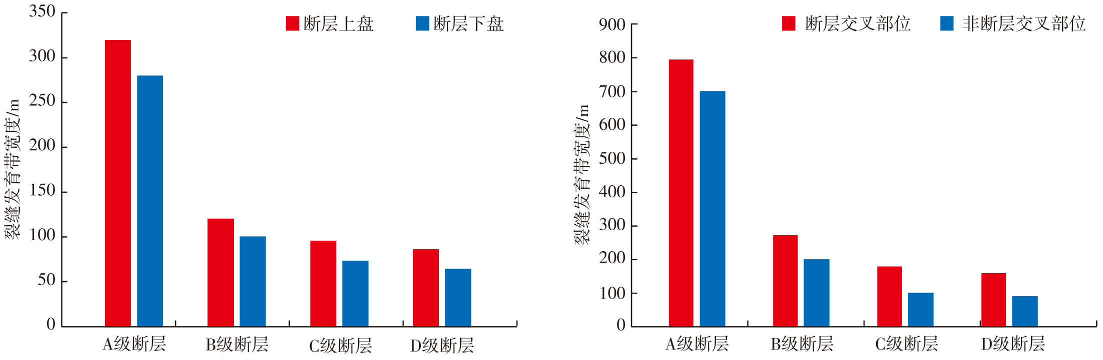
走向基本一致,整体呈北东—南西向。不同级次断层所控制的断层相关裂缝带宽度差异显著(图7)。具体而言,A级断层相关裂缝带宽度介于510~660 m,平均约600 m;B级断层相关裂缝带宽度介于160~280 m,平均约220 m;C级断层相关裂缝带宽度介于130~200 m,平均约168 m;D级断层相关裂缝带宽度介于115~170 m,平均约150 m(图7a)。总体上,随着断层级次的增高,构造变形程度加剧,其控制的裂缝发育带宽度也增大。断层相关裂缝发育带宽度与断距之间呈良好的正相关关系(图8)。

相同级次断层,走向不同也导致断层相关裂缝发育带宽度的差异。基于对同级、断距相近的不同走向断层的裂缝带宽度统计分析,结果表明:近东西向断层相关裂缝发育带宽度相对最宽,其次为近南北向断层,而北东向断层的宽度相对较小(图7b)。断层不同构造部位的裂缝发育带宽度也存在显著差异。研究结果表明:断层上盘的裂缝发育带宽度显著高于下盘(图7c),与前人研究结果一致[42-44],形成的差异可能与断层主动盘的位移有关。断层交叉部位的裂缝发育带宽度明显高于非断层交叉部位(图7d),这可能是由于断层交叉部位裂缝发育带的叠加效应。



a. 不同级次断层相关裂缝发育带宽度箱线图

b. 不同走向断层相关裂缝发育带宽度柱状图



c. 断层上、下盘裂缝发育带宽度柱状图

d. 不同构造部位断层相关裂缝发育带宽度柱状图

图7 四川盆地林滩场地区断层相关裂缝发育带特征

Fig. 7 Characteristics of fault-related fracture development zones in Lintanchang area, Sichuan Basin

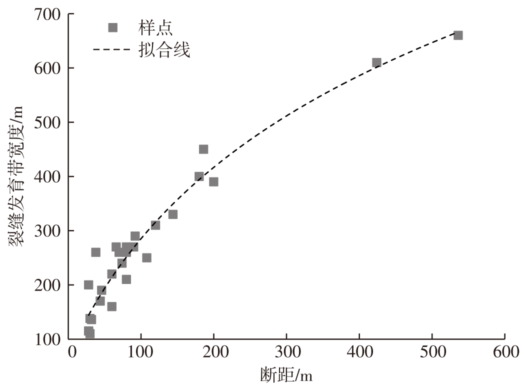


图8 四川盆地林滩场地区断层相关裂缝发育带宽度与断距交会图

Fig. 8 Cross plot of fault-related fracture development zone width and fault displacement in Lintanchang area, Sichuan Basin

4 断层相关裂缝带对页岩气保存的影响

盆缘复杂构造带相比盆内区域受到多期构造运动叠加的影响,表现出更强烈的构造变形及明显的抬升剥蚀特征。构造变形强度是影响页岩气保存的关键因素[45]。不同规模和走向的断层相关裂缝发育带对页岩气的保存具有显著的影响[46-48]。断层相关裂缝发育带通常会导致页岩气逸散,降低地层压力,从而使得页岩气的保存条件变差[49]。由于A级断层的断距较大,相关裂缝发育带较宽,其对页岩气藏保存条件的破坏作用更加显著。靠近A级断层的井产能普遍较差。

林滩场地区位于齐岳山断层附近，构造上位于基底逆冲构造带，具有较大的构造变形强度和较高的构造隆升幅度，断层多断穿五峰组—龙马溪组，且高角度裂缝较为发育。地层压力系数是评价页岩气保存条件的重要参数，广泛应用于页岩气保存状况的综合评估[50-51]。对研究区几口井的构造部位及地层压力系数进行分析，结果表明：X1井位于断层相关裂缝发育带内部，地层压力系数为1.03，保存条件相对较差；相比之下，X2井位于背斜南端，远离断层相关裂缝发育带，其地层压力系数为1.11，表现出较好的保存条件；而X3井位于背斜北端，远离断层发育带，地层压力系数为1.41，表明该井的保存条件较优（图9）。因此，靠近断层相关裂缝发育带的井通常地层压力系数较低，页岩气保存条件相对较差。地层压力系数与页岩气产量之间表现出良好的正相关性，即地层压力系数越高，页岩气产量越大（图9）。

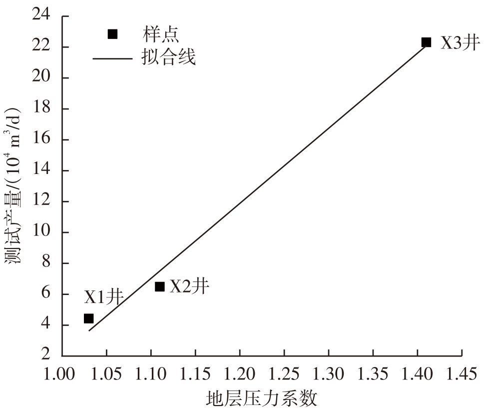


图9 四川盆地林滩场地区各井地层压力系数与测试产量关系

Fig. 9 Relationship between formation pressure coefficient and test production for each well in Lintanchang area, Sichuan Basin

本研究基于地震多属性融合与FDI技术，对研究区不同级次、不同走向及不同构造部位的断层相关裂缝发育带进行了精细刻画，明确了其宽度及空间分布特征，为后续井位优化部署提供了科学依据。

5 结论

1）四川盆地林滩场地区受多期构造运动叠加影响，构造变形特征复杂。依据是否切断储层、顶底板和盖层，结合断距与延伸长度特征将五峰组—龙马溪组内的断层划分为A、B、C、D共4级。断层优势走向主要表现为北东向、近东西向和近南北向3组。断层多分布于林滩场背斜的两翼，而在背斜南北2个倾没端断层发育程度明显较弱，仅见少量C级和D级断层。

2）研究区A级断层相关裂缝带宽度介于510～660 m，平均宽度为600 m；B级断层相关裂缝带宽度介于160～280 m，平均宽度为220 m；C级断层相关裂缝带宽度介于130～200 m，平均宽度为168 m；D级断层相关裂缝带宽度介于115～170 m，平均宽度为150 m。断层相关裂缝带宽度与断距呈明显正相关。断层上盘的裂缝带宽度普遍大于下盘，断层交叉部位的裂缝带宽度大于非断层交叉部位。同级断层中，近东西向裂缝带最宽，近南北向次之，东北向最窄。

3）井位处于断层相关裂缝发育带内部时，其页岩气保存条件显著受损，地层压力系数偏低，实测产能明显下降。地层压力系数与页岩气产量呈显著正相关关系，说明地层压力系数是影响产能的关键因素。因此，避开裂缝带、优选压力保持较好的位置是研究区井位部署的主要方向。

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（编辑　黄颖）