

# 川西坳陷新场地区须二段断缝体 地震预测与地质发育模式

邵绪鹏,刘振峰,刘忠群,季玉新  
(中国石化石油勘探开发研究院,北京 100083)

**摘要:**川西坳陷新场地区须二段致密砂岩气资源潜力巨大,但断缝体展布范围的精细刻画成为制约勘探开发的技术难点。在地震、岩心、成像测井等资料基础上,利用地震属性技术,对新场地区须二段断缝体进行了地震预测,并总结了断缝体地质发育模式。研究结果表明,新场地区须二段西部地区断层欠发育,以背斜为主,整体上呈NE/NNE走向,东部地区三级、四级断层发育,主要呈NE向、近EW向与近SN向。已发现裂缝受研究区三级、四级断层控制,走向以近EW向为主,以平缝( $<10^\circ$ )和低角度缝( $10^\circ\sim30^\circ$ )为主,在须二段上亚段 $T_3x^{2-2}$ 砂组和中亚段 $T_3x^{2-4}$ 砂组最为发育。新场地区须二段裂缝可以分为断层相关和褶皱相关裂缝2类成因,针对断层相关裂缝,最大似然属性能够更客观地刻画断层滑动面,混沌(构造熵)属性能够刻画断层破碎带和诱导裂缝带;针对褶皱相关裂缝,曲度属性能够刻画褶皱相关裂缝发育区。新场地区须二段断缝体可以进一步划分为断缝体、断褶缝体和褶缝体3种类型,其中,以断缝体、断褶缝体普遍发育,主要分布于东部地区断层附近,在局部地区发育褶缝体,通常分布范围较小。

**关键词:**断缝体;地震预测;地质发育模式;新场地区;川西坳陷

中图分类号:TE121.1

文献标识码:A

## Seismic prediction and geological development mode of fault-fracture bodies in 2<sup>nd</sup> Member of Xujiahe Formation in Xinchang area of western Sichuan Depression

SHAO Xupeng, LIU Zhenfeng, LIU Zhongqun, JI Yuxin

(Petroleum Exploration & Production Research Institute, SINOPEC, Beijing City, 100083, China)

**Abstract:** The tight sandstone gas resources of the 2<sup>nd</sup> Member of Xujiahe Formation in Xinchang area of the western Sichuan Depression have great potential, but the fine description of the range of fault-fracture bodies is a technical difficulty that restricts exploration and development. On the basis of seismic, core, and imaging logging data as well as seismic attribute technology, seismic predictions were made for the fault-fracture bodies in the 2<sup>nd</sup> Member of Xujiahe Formation in Xinchang area, and the geological development modes of fault-fracture bodies were summarized. The results show that the faults in this member are undeveloped and are mainly anticlines, with an overall NE/NNE trend, and the third- and fourth-order faults are developed in the east, mainly in NE, near EW, and near SN trends. The fractures found in this member are controlled by the third- and fourth-order faults. With an EW trend, the fractures are dominated by flat fractures ( $<10^\circ$ ) and low-angle fractures ( $10^\circ\sim30^\circ$ ) and are most widely developed in the upper sub-member sand group  $T_3x^{2-2}$  and the middle sub-member sand group  $T_3x^{2-4}$ . The fractures can be divided into fault-related and fold-related fractures: For fault-related fractures, the seismic attribute of thin likelihood can objectively describe the fault slip surface, and the seismic attribute of chaos can depict the fault fractured zone and induced fracture zone; for fold-related fractures, the seismic attribute of curviness can describe the development area of fold-related fractures. Furthermore, the fault-fracture bodies in the 2<sup>nd</sup> Mem-

收稿日期:2021-05-11。

作者简介:邵绪鹏(1986—),男,山东青岛人,博士,从事构造地质学、地震地质综合研究。E-mail: sxpenggeo@163.com。

基金项目:国家科技重大专项“中西部重点碎屑岩层系油气富集规律与勘探方向”(2016ZX05002-006),中国石化科研项目“复杂裂缝系统地质模式波场特征与识别描述”(P20056-3)和“川西梓潼凹陷天然气成藏条件与勘探潜力评价”(P21042-7)。

ber of Xujiahe Formation can be classified into fault-fracture bodies, fault-fold-fracture bodies, and fold-fracture bodies, among which the fault-fracture and fault-fold-fracture bodies are the most widespread and are mainly distributed near the faults in the east, while fold-fracture bodies are developed locally, usually with a small distribution range.

**Key words:** fault-fracture body; seismic prediction; geological development mode; Xinchang area; western Sichuan Depression

致密砂岩气是一种重要的非常规油气资源类型,随着压裂改造技术的进步和应用,在中国多个盆地中获得了勘探突破,并逐渐成为中国非常规天然气增储上产的重要增长点和最为现实的资源类型<sup>[1-4]</sup>。勘探实践证明,裂缝在优质致密砂岩储层中普遍发育<sup>[5-8]</sup>,对致密砂岩气的运聚成藏具有重要作用<sup>[6,9-12]</sup>,是影响致密砂岩储层含气性的关键因素<sup>[13]</sup>。四川盆地川西坳陷是中国最早发现致密砂岩气的地区<sup>[1-2]</sup>,已发现的致密砂岩气藏具有超深、超高压、超致密及超晚期构造特征<sup>[14-15]</sup>。虽然近些年川西坳陷新场地区须家河组二段(简称须二段)致密砂岩气勘探成果丰硕,提交探明储量超千亿方,但整体动用率低,始终无法实现有效开发动用<sup>[16-17]</sup>。造成以上局面的重要原因之一,即裂缝发育范围能否准确刻画<sup>[16]</sup>。

断缝体的概念最早由王威等提出,指由断层、褶皱构造所伴生的裂缝与基质孔隙共同组成的具有立体网状孔缝特征的地质体<sup>[18]</sup>。其后,断缝体概念在多个地区被推广和应用,并取得了良好的勘探开发成效<sup>[19-20]</sup>。新场地区是川西坳陷重点的致密砂岩气产区,该区断缝体的分布特征、发育规律尚不明确,是制约勘探开发深化的关键问题。笔者利用地震、岩心、成像测井等资料,在分析断层、裂缝发育特征的基础上,利用地震属性对断缝体进行预测描述,并提出了断缝体地质发育模式,旨在从理论上深化断缝体的内涵,从生产实践上为该区域勘探开发的深化提供有益借鉴。

## 1 区域地质概况

川西坳陷位于四川盆地西部,是晚三叠世以来形成的前陆坳陷,大致呈NE向展布<sup>[21]</sup>。以安县、都江堰为界,川西坳陷分为南、中、北三段<sup>[22]</sup>。川西坳陷中段具有“三隆两凹一坡”的构造格局,依次为龙门山前构造带、新场构造带、知新场构造带、梓潼凹陷、成都凹陷和中江斜坡<sup>[16,23]</sup>(图1)。川西坳陷中段在空间上受秦岭造山带、青藏高原东缘构造带及扬子地块自身的构造作用;在时间上,自晚三叠世以来经历印支、燕山及喜马拉雅3大构造运动<sup>[21-22]</sup>。

在周缘造山带不同方向、不同期次构造挤压作用下,川西坳陷中段形成NE向、近EW向及近SN向3组构造,地表构造形迹和地腹构造呈现良好的对应关系<sup>[21]</sup>(图1)。新场构造带作为川西坳陷重要的正向构造单元,自晚三叠世以来经历了多期次构造作用的叠加,整体呈NEE向<sup>[16]</sup>。

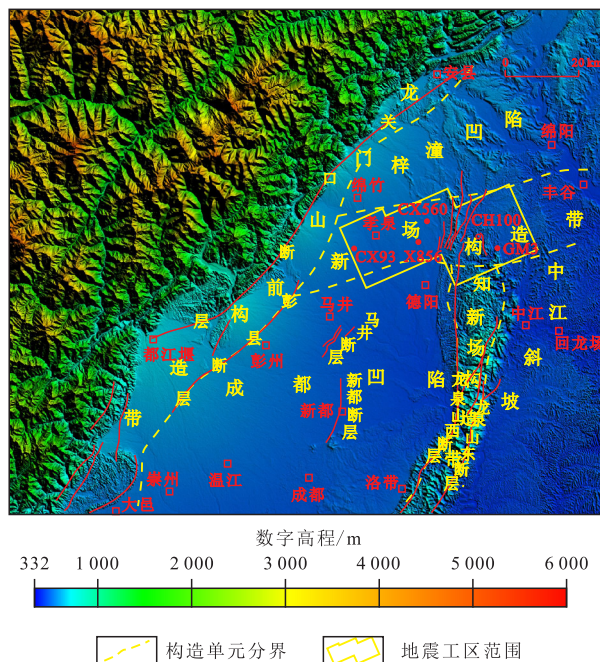


图1 川西坳陷新场地区构造位置与数字高程  
(数据来源于中国科学院计算机网络  
信息中心地理空间数据云平台)

Fig.1 Tectonic location and digital elevation of Xinchang area in western Sichuan Depression (The data is provided by Geospatial Data Cloud developed by Computer Network Information Center of Chinese Academy of Sciences)

川西坳陷须家河组自下而上分为须一段(相当于马鞍塘与小塘子组)至须五段,其中须一段、须三段、须五段以泥岩发育为主,须二段、须四段以砂岩发育为主<sup>[16,24]</sup>。川西坳陷已发现的须家河组气藏主力层位为须二段,主要分布在新场构造带<sup>[16]</sup>。新场地区须二段地层厚度呈现西厚东薄的特征,岩性以厚层中粗砂岩夹中薄层泥岩为主,主要沉积相类型为辫状河三角洲前缘水下分流河道<sup>[17,25]</sup>。新场地区须二段可以细分为3个亚段、10个砂组,自下而上依次为下亚段( $T_3x^{2-7}$ — $T_3x^{2-10}$ 砂组)、中亚段( $T_3x^{2-4}$ —

$T_3x^{2-6}$ 砂组)、上亚段( $T_3x^{2-1}$ — $T_3x^{2-3}$ 砂组)<sup>[17,25]</sup>。目前已发现的气藏主力产层和优质甜点发育砂组主要为 $T_3x^{2-2}$ 和 $T_3x^{2-4}$ 砂组。

## 2 构造与裂缝发育特征

新场地区须二段断裂发育,主要发育NE向、近EW向与近SN向断层(图2)。其中,控制新场构造带三级构造单元的断层以近EW向为主,为三级断层(南部近SN向断层为控制知新场构造带的三级断层);控制局部构造的断层以近SN向为主,为四级断层(图2)。新场地区须二段发育多个背斜(断背斜),整体上呈NE/NNE走向,西部地区断层欠发育,以背斜为主;东部地区断层发育,受断层改造,呈现断背斜构造形态(图2)。川西坳陷须二段NE向构造开始发育于印支期,继承于燕山期,强化于喜马拉雅期,在川西坳陷内部普遍发育;近EW向构造主要形成于燕山期;近SN向构造主要形成于喜马拉雅

期<sup>[21]</sup>。因此,新场地区须二段呈近EW向的三级断层主要形成于燕山期,为早期断层,经历后期构造造成岩等作用的改造,多被次生矿物充填,有效性差;而呈近SN向的四级断层主要形成于喜马拉雅期,为晚期断层,断层附近裂缝发育,常呈开启状态,有效性好。新场地区须二段裂缝发育,岩心和成像测井证实,裂缝发育区与断层和褶皱关系密切。须二段发育的裂缝以平缝( $<10^\circ$ )和低角度缝( $10^\circ\sim30^\circ$ )为主,局部地区可见高角度缝(图3)。裂缝的走向以近EW向为主,裂缝在各个砂组的分布差异明显,其中,以 $T_3x^{2-2}$ 和 $T_3x^{2-4}$ 砂组裂缝最为发育(图2)。

## 3 断缝体地震预测

### 3.1 断层相关裂缝的预测

新场地区须二段已发现的裂缝普遍沿断层发育,因此,在断层内部结构研究的基础上,进行断层相关裂缝的预测是断缝体地震预测的重要方面。

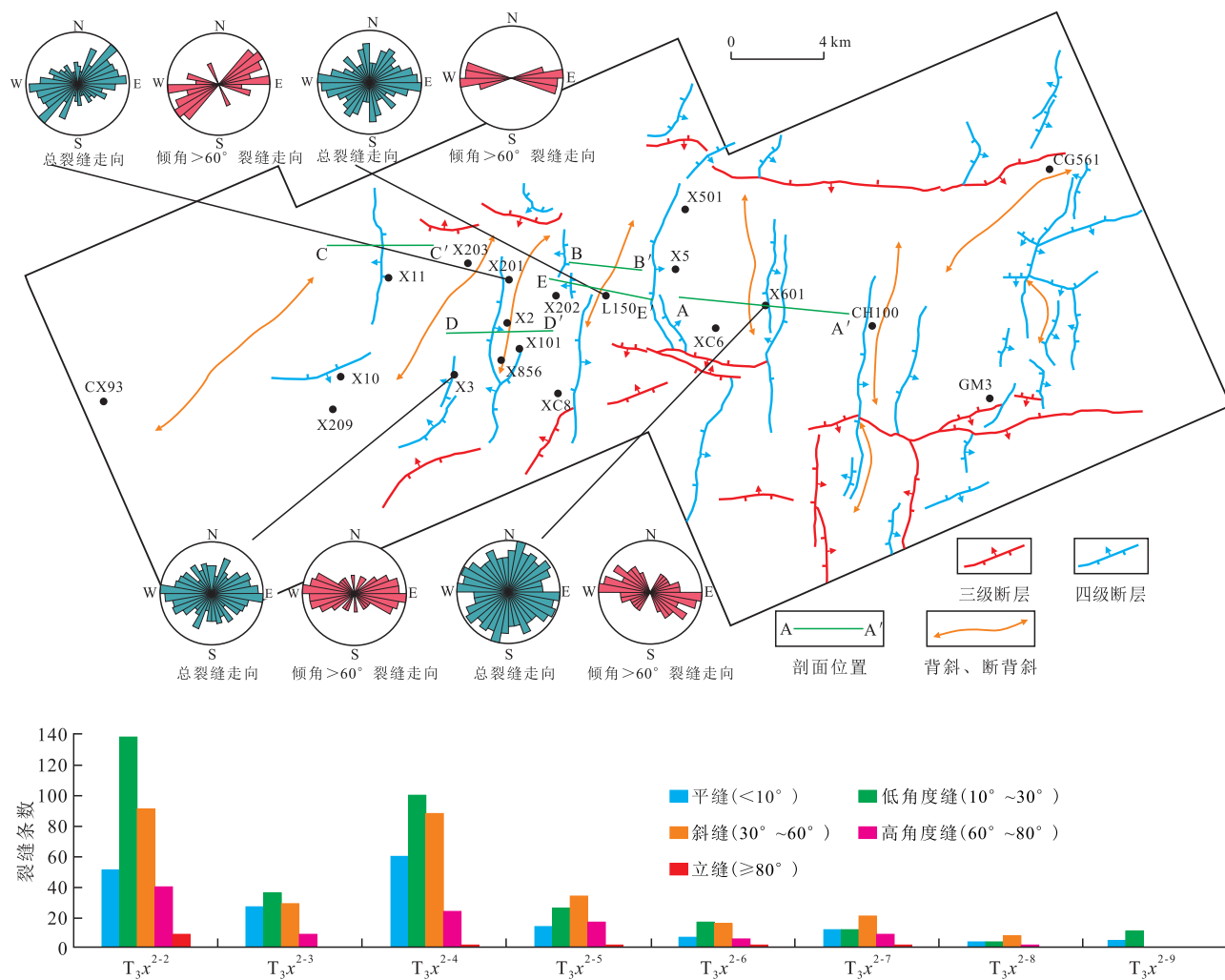
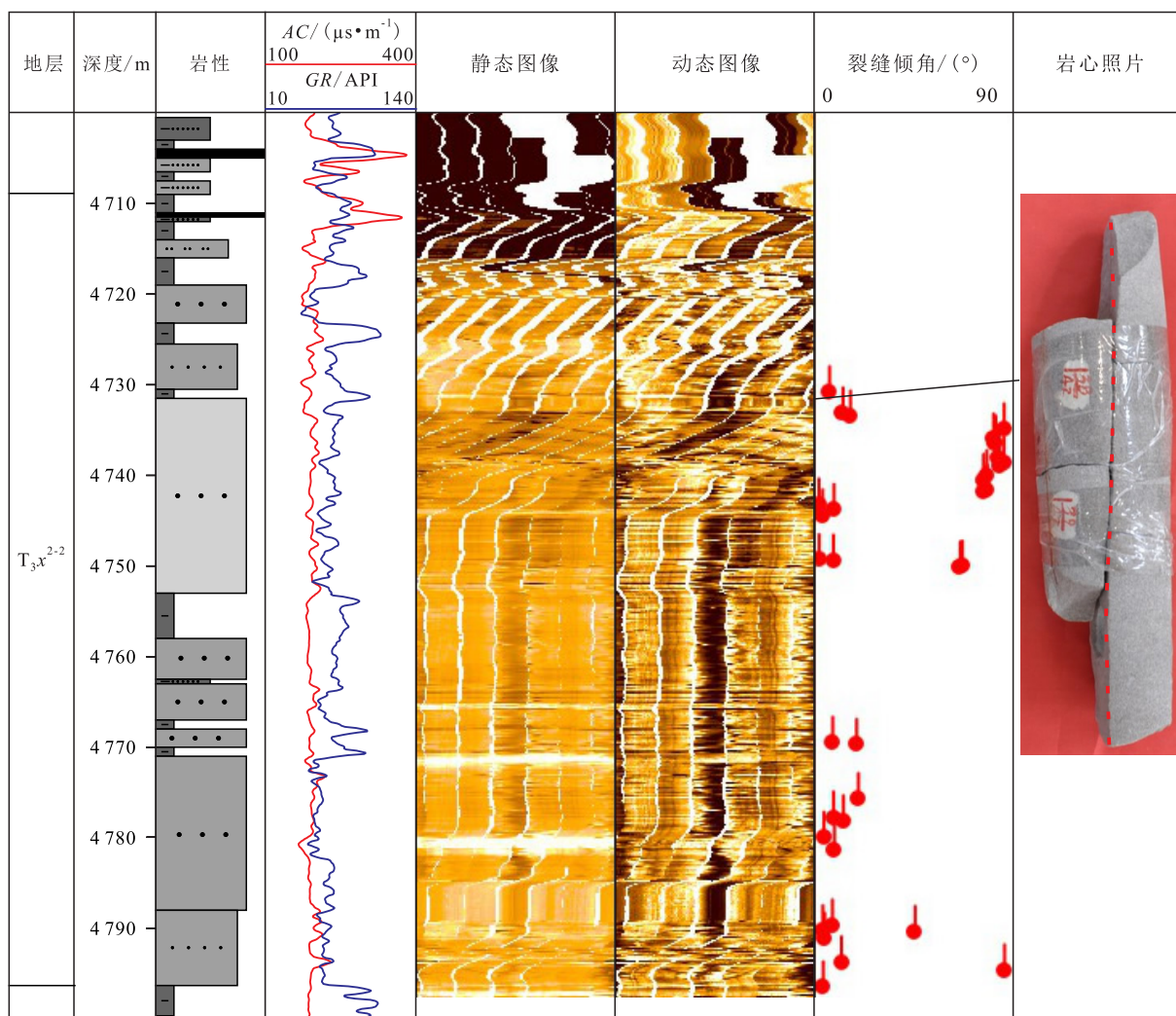


图2 新场地区须二段构造简图与裂缝分布

Fig.2 Schematic structure map and fracture distribution of 2<sup>nd</sup> Member of Xujiache Formation in Xinchang area



图3 L150井须家河组T<sub>3</sub>x<sup>2-2</sup>砂组电成像测井Fig.3 Electrical imaging logging of sand group T<sub>3</sub>x<sup>2-2</sup> in 2<sup>nd</sup> Member of Xujiache Formation, Well L150

断层实际上是具有复杂构造的三维地质体,具有“二元”结构,即断层中心部位的滑动破碎带和两侧的诱导裂缝带<sup>[26-30]</sup>。其中,滑动破碎带构造变形最为强烈,由断层滑动面、伴生裂缝和断层岩组成;诱导裂缝带以发育大量低级别裂缝为主要特征,通常与断层滑动面平行或呈锐角相交<sup>[26-28]</sup>。滑动破碎带的规模与断距相关,断距较小的断层,滑动破碎带规模小,仅由一条断层滑动面调节变形;断距较大的断层,滑动破碎带的规模也大,相应存在多条次级断层滑动面共同调节变形<sup>[28]</sup>。

新场地区须二段大部分断层的断距较小,存在诸多微小断裂,仅在地震剖面上很难区分断层的各个内部结构。笔者以断层的“二元”结构为指导,将人工解释的断层、岩心及成像测井揭示的裂缝发育带与最大似然属性(Thin Likelihood)、基于梯度结构张量的混沌(构造熵)属性所对应的属性值进行对比统计,分析认为最大似然属性能够反映断层滑动

面,混沌(构造熵)属性能够反映滑动破碎带和诱导裂缝带。由人工解释断层和成像测井解释裂缝结果刻度,得到断层各个内部结构的值域范围。反映断层滑动面的最大似然属性的值域范围为0.15~1,反映滑动破碎带的混沌(构造熵)属性的值域范围为0.18~1,反映诱导裂缝带的混沌(构造熵)属性的值域范围为0.05~0.18,值域范围之外的地震属性可视为背景值或噪音影响。借助最大似然属性的参考,使得断层的解释更加客观,在最大似然属性和混沌(构造熵)属性叠合剖面上,可以较好地分辨出滑动破碎带和诱导裂缝带,可以将诱导裂缝带及滑动破碎带范围作为断层相关裂缝发育区(图4)。T<sub>3</sub>x<sup>2-2</sup>砂组断层相关裂缝发育区主要受研究区三级、四级断层控制,沿断层走向分布,东部地区较西部地区裂缝发育(图5)。T<sub>3</sub>x<sup>2-4</sup>砂组裂缝发育区与T<sub>3</sub>x<sup>2-2</sup>砂组相比,虽然大致范围类似,但裂缝发育区更琐碎,这与该砂组断层规模相关,整体上围绕断

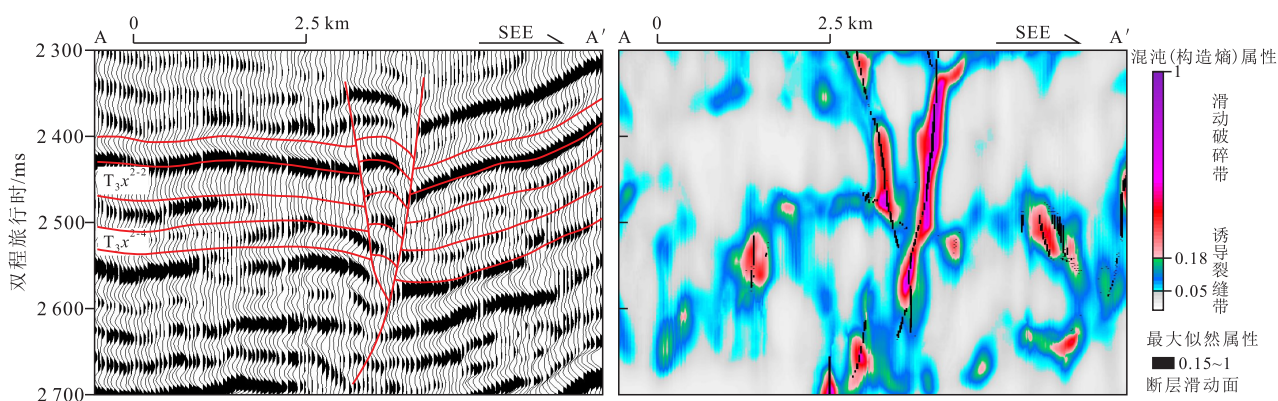
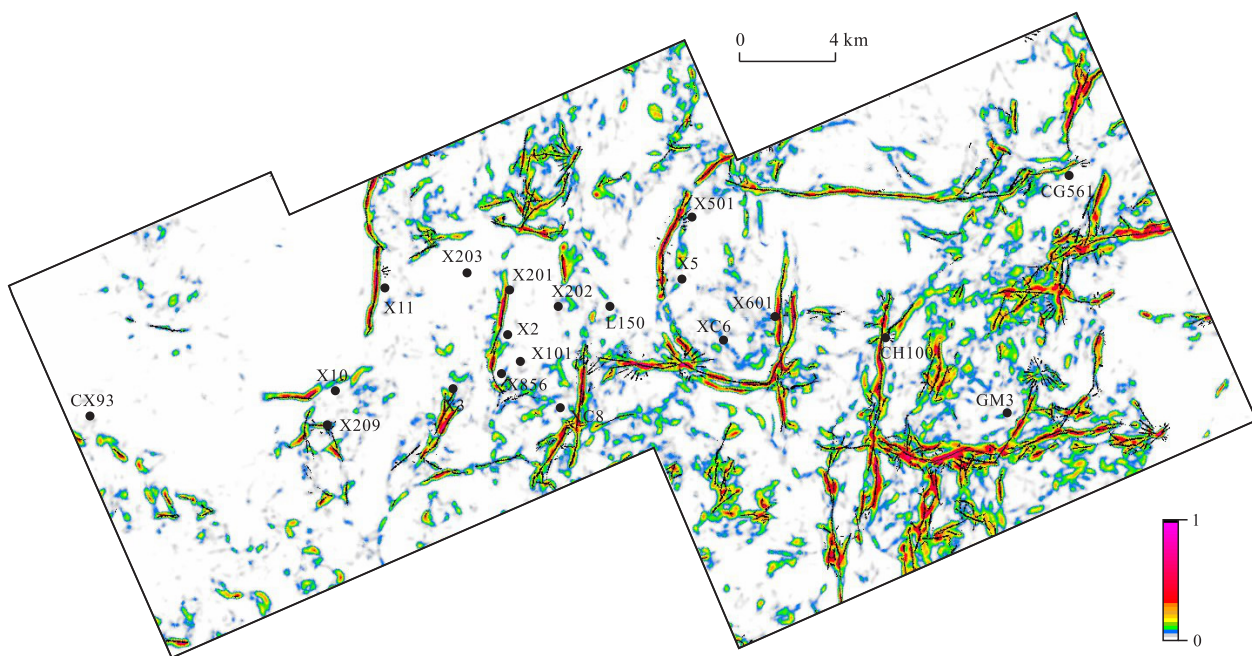


图4 新场地区须二段断层内部结构(AA'剖面位置见图2)

Fig.4 Internal structure of faults in 2<sup>nd</sup> Member of Xujiahe Formation in Xinchang area(See Fig.2 for location of AA' profile)图5 新场地区  $T_3x^{2-2}$  砂组断层相关裂缝发育区Fig.5 Fault-related fracture zone of sand group  $T_3x^{2-2}$  in Xinchang area

裂带发育(图6)。

### 3.2 褶皱相关裂缝的预测

新场地区须二段局部地区发育背斜(断背斜),存在与背斜构造伴生的裂缝带。关于褶皱相关裂缝的预测,曲率类地震属性已取得一定的应用效果<sup>[31-33]</sup>。在脆性岩层只发生脆性构造变形的前提下,纵弯褶皱中和面以上岩层受拉张应力作用而产生张裂缝,中和面以下岩层受挤压应力作用而产生剪裂缝。通常,岩层经受的挤压应力越大,岩层构造变形越大,地层越弯曲,对应的曲率越大,中和面以上岩层的张裂缝越发育<sup>[32-33]</sup>。曲率类地震属性就是利用曲率值来间接反映中和面以上岩层张裂缝发育程度的。曲率类地震属性虽然种类多样,但都是基于极大曲率、极小曲率的运算<sup>[33]</sup>。在地震剖面

揭示的褶皱发育区的基础上,对比多种曲率类地震属性与混沌(构造熵)属性的差异,发现地震剖面揭示的背斜(断背斜)的枢纽部位,在混沌(构造熵)属性剖面上为中低值区,而在曲度属性剖面上为高值区,且高值区的形态与理论上中和面以上岩层的张裂缝发育区形态相似(图7)。由此,可以认为曲度属性能够更稳定地反映研究区发育的褶皱相关裂缝,是混沌(构造熵)属性对裂缝预测的补充。

根据  $T_3x^{2-2}$  砂组曲度均方根振幅属性叠合最大似然属性,曲度均方根振幅属性的高值区整体上呈团块状,沿背斜(断背斜)枢纽展布,与断层相隔一定距离(图8),而断层相关裂缝地震属性的高值区通常位于断层中心(图5),这是新场地区背斜转折端通常位于断层上盘,与逆断层存在一定距离导



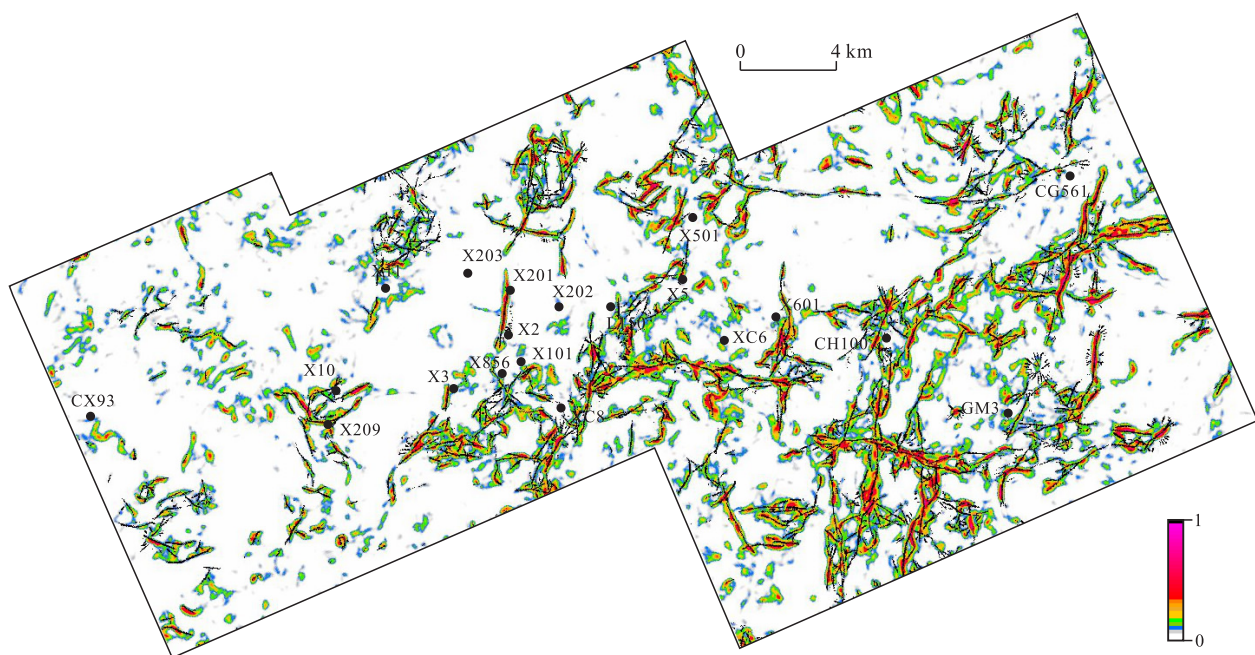
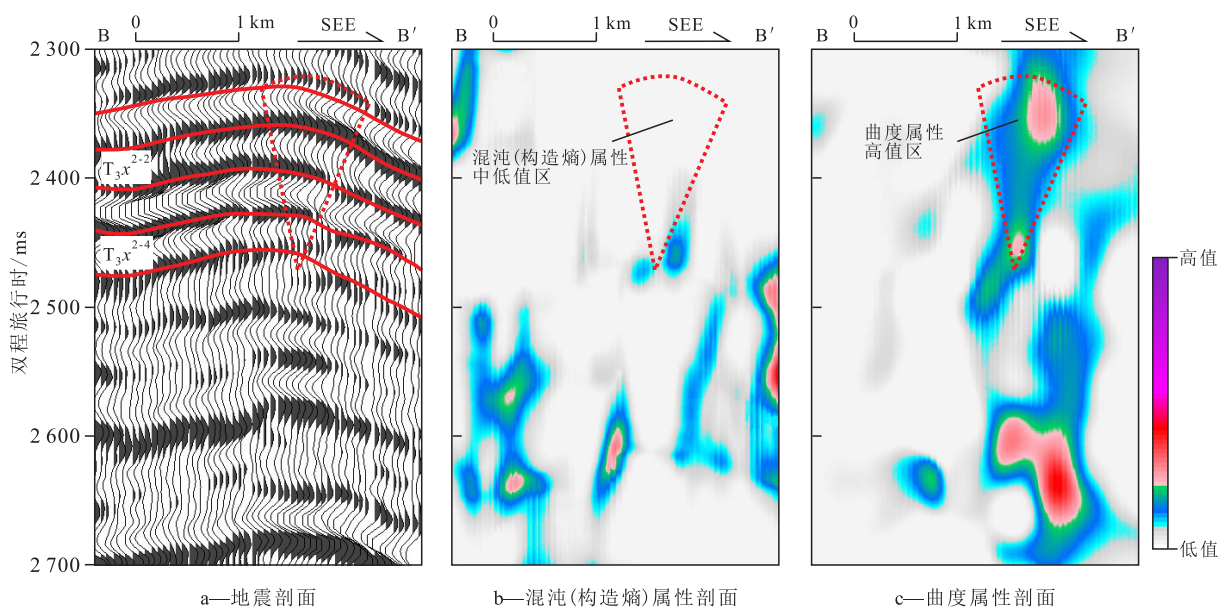
图6 新场地区  $T_3x^{2-4}$  砂组断层相关裂缝发育区Fig.6 Fault-related fracture zone of sand group  $T_3x^{2-4}$  in Xinchang area

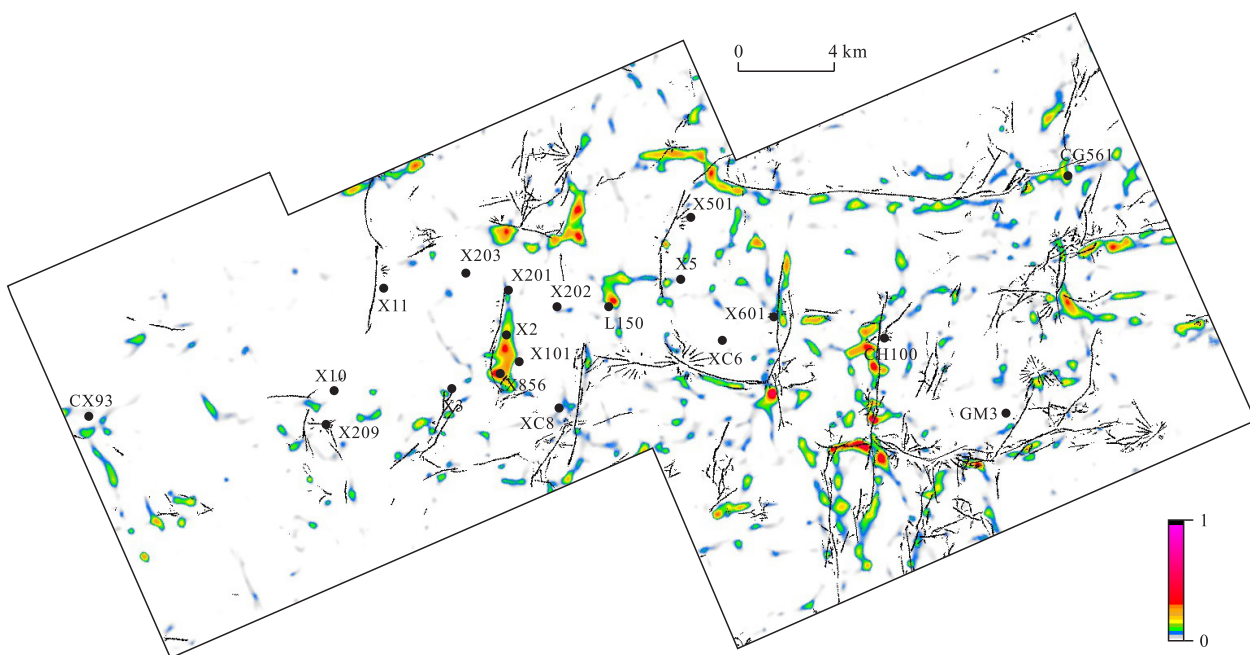
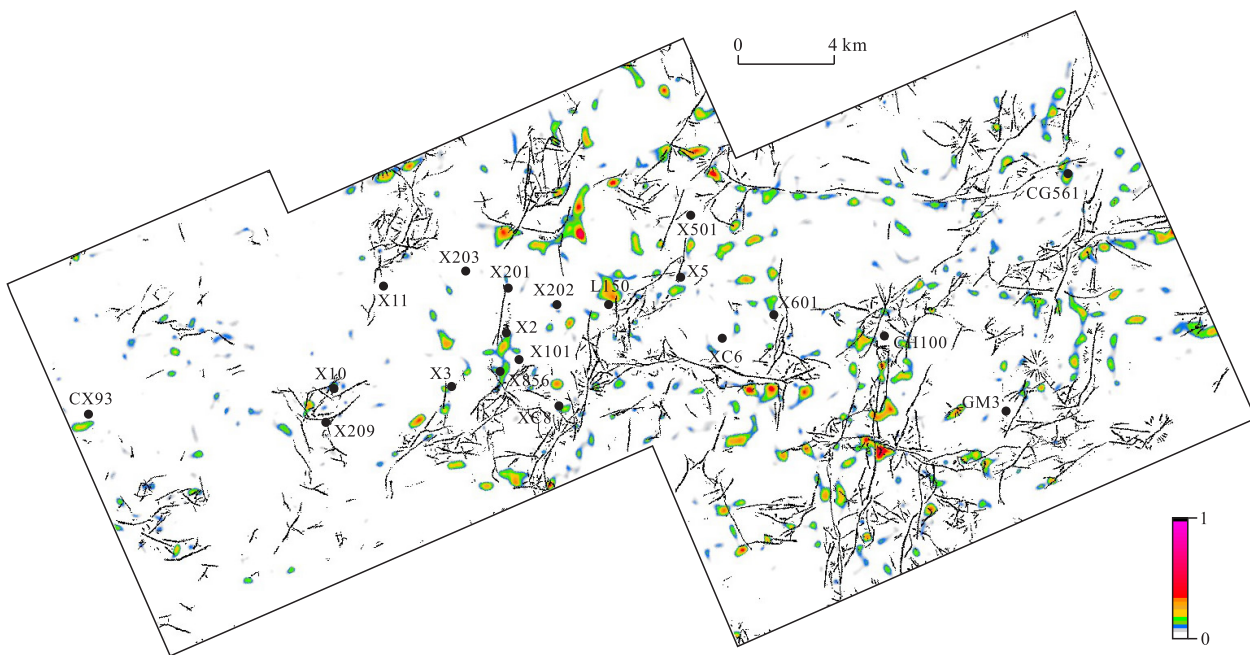
图7 新场地区须二段褶皱相关裂缝发育区混沌(构造熵)属性与曲度属性的响应差异(BB'剖面位置见图2)

Fig.7 Response difference between chaos(structural entropy)and curvature attributes in fold-related fracture zone in 2<sup>nd</sup> Member of Xujiache Formation in Xinchang area(See Fig.2 for location of BB' profile)

致。 $T_3x^{2-2}$ 砂组曲度高值区大多数为与逆断层关联的断背斜枢纽的响应,如X601井附近。少数地区,如L150井附近,在断层相关裂缝地震属性平面上为低值区(图5),而在褶皱相关裂缝地震属性平面上则呈高值异常(图8),这是L150井附近背斜导致的裂缝的响应,说明了曲度属性是对断层相关裂缝预测的有效补充。 $T_3x^{2-4}$ 砂组曲度均方根振幅属性高值区较 $T_3x^{2-2}$ 砂组分布分散,高值区大多围绕断层展

布,与断层间隔一定距离(图9),这是 $T_3x^{2-4}$ 砂组规模小、繁多杂乱的断层影响的断背斜导致。

对比图5与图8、图6与图9可知,曲度属性可以有效地补充混沌(构造熵)属性反映的裂缝发育区。因此,鉴于裂缝的成因机制和来源的差异性,为了更全面地预测裂缝发育区,应该针对不同成因的裂缝,采用不同的地震属性来刻画裂缝优势发育区。通过实际预测效果的验证对比,可见利用混沌(构

图8 新场地区 $T_3x^{2-2}$ 砂组褶皱相关裂缝发育区Fig.8 Fold-related fracture zone of sand group  $T_3x^{2-2}$  in Xinchang area图9 新场地区 $T_3x^{2-4}$ 砂组褶皱相关裂缝发育区Fig.9 Fold-related fracture zone of sand group  $T_3x^{2-4}$  in Xinchang area

造熵)属性来预测断层相关裂缝发育区,用曲度属性来预测褶皱相关裂缝发育区是具有适用性的。

#### 4 断缝体类型与地质发育模式

现阶段关于断缝体的研究<sup>[18-20]</sup>更多地强调和关注断层对裂缝发育区的控制作用,实际上褶皱对裂缝发育区也起到了重要的控制作用。新场地区须

二段裂缝发育,总结其成因机制,可以分为断层相关裂缝和褶皱相关裂缝。研究发现,新场地区须二段断缝体可以分为断缝体、断褶缝体和褶缝体3种类型。断缝体中裂缝的发育主要受断层控制,即根据断层的“二元”结构,在滑动破碎带和诱导裂缝带范围内广泛发育裂缝。在混沌(构造熵)属性叠合曲度属性剖面上,可以发现属性的高值区以断层滑动面为中心,呈现明显的圈层结构,在断距最大、构



造变形最强的部位,属性值越高(图10a)。断褶体中裂缝的发育受断层和褶皱共同控制,在地震剖面上呈断背斜构造,在地震属性剖面上,既有断层相关裂缝,也有褶皱相关裂缝。断层相关裂缝发育区类似于断缝体,以断层滑动面为中心,受断层控制;褶皱相关裂缝发育区则受控于断背斜的形态,在地层褶皱变形强的部位,属性值呈高异常(图10b)。褶皱体则主要受褶皱控制,在褶皱变形越强的部位,曲度属性值越高,裂缝发育的可能性越大(图10c)。

新场地区须二段断缝体以断缝体、断褶缝体为

主,褶皱体在局部地区发育,褶皱体可以作为裂缝预测中断缝体、断褶缝体的有效补充。新场地区须二段断缝体受喜马拉雅期至今近EW向区域构造应力场影响明显,造成了区内近SN向断层普遍发育<sup>[21]</sup>。围绕近SN向断层常发育断背斜,在局部地区也发育近SN或NE向背斜构造。在近SN向断层的滑动破碎带和诱导裂缝带、断层上盘发育的断背斜以及局部地区的背斜构造枢纽部位,通常为裂缝发育区,受近EW向区域构造应力场影响,这些裂缝走向呈近EW向(图11)。

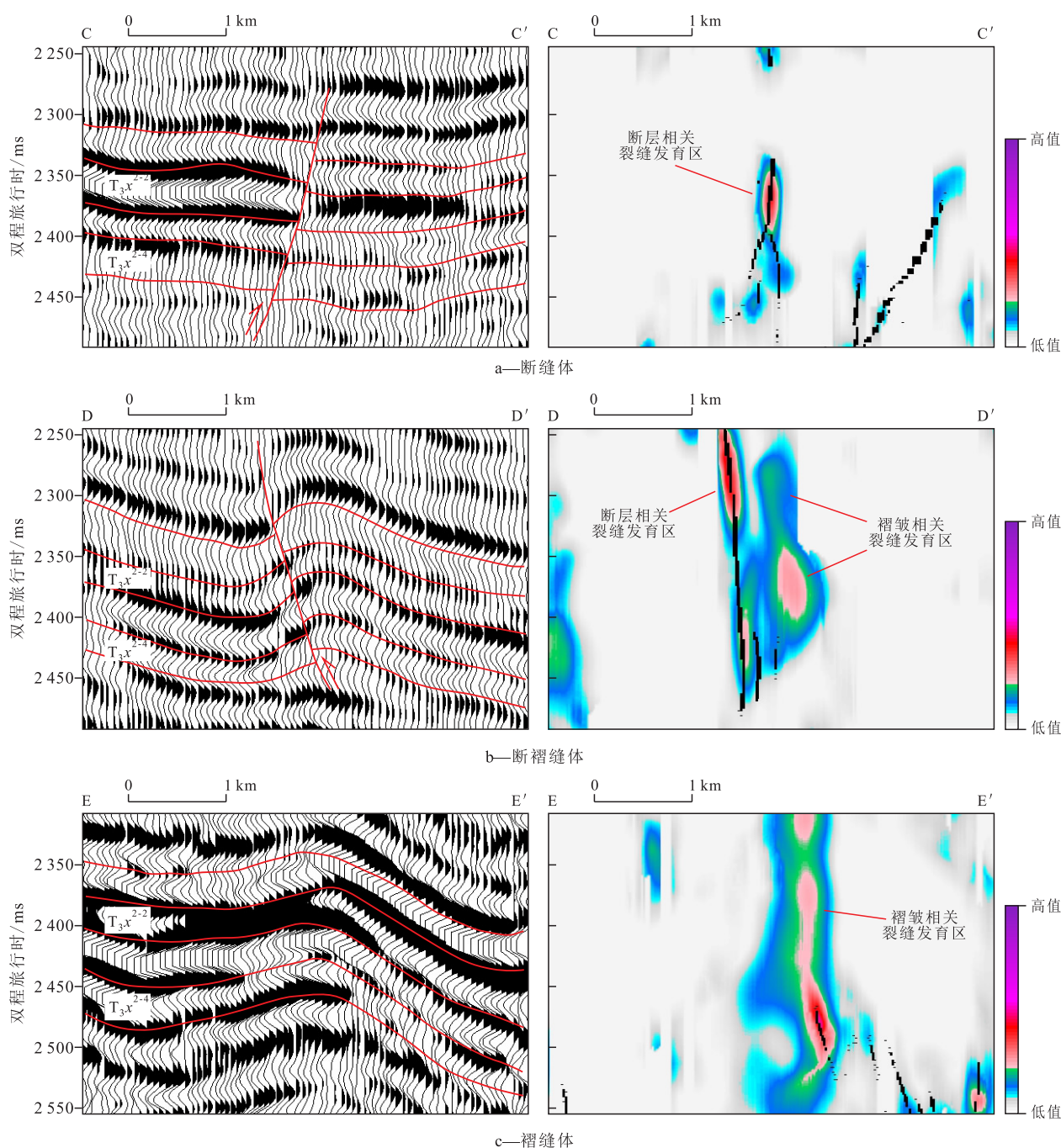


图10 新场地区须二段断缝体类型(剖面位置见图2)

Fig.10 Types of fault-fracture bodies in 2<sup>nd</sup> Member of Xujiahe Formation in Xinchang area (See Fig.2 for locations of profiles)



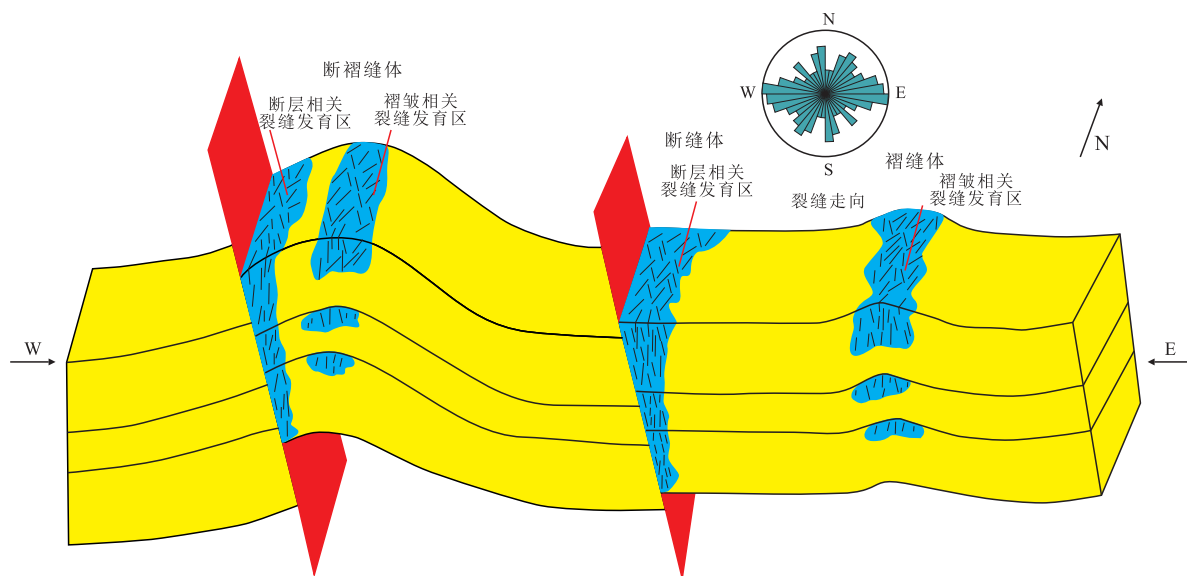


图11 新场地区须二段断缝体地质发育模式

Fig.11 Geological development modes of fault-fracture bodies in 2<sup>nd</sup> Member of Xujiache Formation in Xinchang area

## 5 结论

新场地区须二段已发现裂缝受研究区三级、四级断层控制,走向以近EW向为主,以平缝( $<10^\circ$ )和低角度缝( $10^\circ\sim30^\circ$ )为主,在上亚段 $T_3x^{2-2}$ 和中亚段 $T_3x^{2-4}$ 砂组最为发育。

人工构造解释借鉴最大似然属性能够更客观地刻画断层滑动面,混沌(构造熵)属性能够刻画断层破碎带和诱导裂缝带,曲度属性能够刻画褶皱相关裂缝发育区,实际应用效果也证实利用最大似然、混沌(构造熵)、曲度属性能够有效进行新场地区须二段断缝体的地震预测。

新场地区须二段断缝体可以细分为断缝体、褶皱体和断褶皱体3种地质发育模式,其中,断缝体、断褶皱体在全区普遍发育,局部地区发育褶皱体,褶皱体可以作为研究区断缝体地质发育模式的有效补充。

### 参考文献

- [1] 李建忠,郭彬程,郑民,等.中国致密砂岩气主要类型,地质特征与资源潜力[J].天然气地球科学,2012,23(4):607-615.  
LI Jianzhong, GUO Bincheng, ZHENG Min, et al. Main types, geological features and resource potential of tight sandstone gas in China[J]. Natural Gas Geoscience, 2012, 23(4): 607-615.
- [2] 邹才能,张国生,杨智,等.非常规油气概念、特征、潜力及技术——兼论非常规油气地质学[J].石油勘探与开发,2013,40(4):385-399,454.  
ZOU Caineng, ZHANG Guosheng, YANG Zhi, et al. Geological

concepts, characteristics, resource potential and key techniques of unconventional hydrocarbon; On unconventional petroleum geology[J]. Petroleum Exploration and Development, 2013, 40(4): 385-399, 454.

- [3] 魏国齐,张福东,李君,等.中国致密砂岩气成藏理论进展[J].天然气地球科学,2016,27(2):199-210.  
WEI Guoqi, ZHANG Fudong, LI Jun, et al. New progress of tight sand gas accumulation theory and favorable exploration zones in China[J]. Natural Gas Geoscience, 2016, 27(2): 199-210.
- [4] YANG P, ZHANG L K, LIU K Y, et al. Diagenetic history and reservoir evolution of tight sandstones in the second member of the Upper Triassic Xujiache Formation, western Sichuan Basin, China[J]. Journal of Petroleum Science and Engineering, 2021, 201: 108451.
- [5] 白斌,邹才能,朱如凯,等.川西南部须二段致密砂岩储层构造裂缝特征及其形成期次[J].地质学报,2012,86(11):1841-1846.  
BAI Bin, ZOU Caineng, ZHU Rukai, et al. Characteristics and formation stage-times of structural fractures in tight sandstone reservoir of the 2nd member of Xujiache Formation in Southernwestern Sichuan Basin[J]. Acta Geologica Sinica, 2012, 86(11): 1841-1846.
- [6] 王鹏威,陈筱,庞雄奇,等.构造裂缝对致密砂岩气成藏过程的控制作用[J].天然气地球科学,2014,25(2):185-191.  
WANG Pengwei, CHEN Xiao, PANG Xiongqi, et al. The controlling of structure fractures on the accumulation of tight sand gas reservoirs[J]. Natural Gas Geoscience, 2014, 25(2): 185-191.
- [7] 赵向原,曾联波,祖克威,等.致密储层脆性特征及对天然裂缝的控制作用——以鄂尔多斯盆地陇东地区长7致密储层为例[J].石油与天然气地质,2016,37(1):62-71.  
ZHAO Xiangyuan, ZENG Lianbo, ZU Kewei, et al. Brittleness characteristics and its control on natural fractures in tight reservoirs: A case study from Chang7 tight reservoir in Longdong area

- of the Ordos Basin[J]. Oil & Gas Geology, 2016, 37(1): 62–71.
- [8] XIE R C, ZHOU W, XIANG M L, et al. Development mode of reverse fault-associated fractures in deep tight sandstones: A case study in Xinchang Gas Field, Sichuan Basin, China[J]. Geological Journal, 2021, 56(1): 1–15.
- [9] AMEEN M S, MACPHERSON K, AL-MARHOON M I, et al. Diverse fracture properties and their impact on performance in conventional and tight-gas reservoirs, Saudi Arabia: The Unayzah, South Haradh case study[J]. AAPG Bulletin, 2012, 96(3): 459–492.
- [10] ZENG L B, HUI S, TANG X M, et al. Fractured tight sandstone oil and gas reservoirs: A new play type in the Dongpu depression, Bohai Bay Basin, China[J]. AAPG Bulletin, 2013, 97(3): 363–377.
- [11] XIAO L, LI J R, MAO Z Q, et al. A method to evaluate pore structures of fractured tight sandstone reservoirs using borehole electrical image logging[J]. AAPG Bulletin, 2020, 103(1): 205–226.
- [12] ZHANG Y Z, ZENG L B, LYU W Y, et al. Natural fractures in tight gas sandstones: a case study of the Upper Triassic Xujiahe Formation in Xinchang gas field, Western Sichuan Basin, China[J]. Geological Magazine, 2021, 158(9): 1–18.
- [13] 丁文龙, 尹帅, 王兴华, 等. 致密砂岩气储层裂缝评价方法与表征[J]. 地学前缘, 2015, 22(4): 173–187.
- DING Wenlong, YIN Shuai, WANG Xinghua, et al. Assessment method and characterization of tight sandstone gas reservoir fractures[J]. Earth Science Frontiers, 2015, 22(4): 173–187.
- [14] 张虹, 沈忠民. 超致密裂缝性储层地震预测方法研究——以川西新场气田须二气藏勘探为例[J]. 成都理工大学学报: 自然科学版, 2008, 35(2): 149–157.
- ZHANG Hong, SHEN Zhongmin. Study on seismic prediction methods for super tight fractured reservoirs—An example from the exploration of Member2 of Xujiahe Formation reservoir in Xinchang gas field, Sichuan Basin, China[J]. Journal of Chengdu University of Technology: Science & Technology Edition, 2008, 35(2): 149–157.
- [15] 蔡希源. 深层致密砂岩气藏天然气富集规律与勘探关键技术——以四川盆地川西坳陷须家河组天然气勘探为例[J]. 石油与天然气地质, 2010, 31(6): 707–714.
- CAI Xiyuan. Gas accumulation patterns and key exploration techniques of deep gas reservoirs in tight sandstone: an example from gas exploration in the Xujiahe Formation of the western Sichuan Depression, the Sichuan Basin[J]. Oil & Gas Geology, 2010, 31(6): 707–714.
- [16] 刘忠群, 徐士林, 刘君龙, 等. 四川盆地川西坳陷深层致密砂岩气藏富集规律[J]. 天然气工业, 2020, 40(2): 31–40.
- LIU Zhongqun, XU Shilin, LIU Junlong, et al. Enrichment laws of deep tight sandstone gas reservoirs in the Western Sichuan Depression, Sichuan Basin[J]. Natural Gas Industry, 2020, 40(2): 31–40.
- [17] 刘君龙, 刘忠群, 肖开华, 等. 四川盆地新场地区三叠系须家河组二段致密砂岩有利岩石相表征及油气地质意义[J]. 石油勘探与开发, 2020, 47(6): 111–121.
- LIU Junlong, LIU Zhongqun, XIAO Kaihua, et al. Characterization of favorable lithofacies in tight sandstone reservoirs and its significance for gas exploration and exploitation: A case study of the 2<sup>nd</sup> Member of Triassic Xujiahe Formation in the Xinchang area, Sichuan Basin[J]. Petroleum Exploration and Development, 2020, 47(6): 111–121.
- [18] 王威, 凡睿. 四川盆地北部须家河组“断缝体”气藏特征及勘探意义[J]. 成都理工大学学报: 自然科学版, 2019, 46(5): 541–548.
- WANG Wei, FAN Rui. Characteristics of Xujiahe Formation fault-fracture reservoirs in the northern Sichuan Basin and its exploration significance[J]. Journal of Chengdu University of Technology: Science & Technology Edition, 2019, 46(5): 541–548.
- [19] 蒋有录, 李明阳, 王良军, 等. 川东北通南巴地区断裂对致密砂岩天然气成藏及富集的控制作用[J]. 中国石油大学学报: 自然科学版, 2020, 44(5): 19–31.
- JIANG Youlu, LI Mingyang, WANG Liangjun, et al. Controlling effect of faults on tight sandstone natural gas accumulation and enrichment in Tongnanba Area, Northeast Sichuan[J]. Journal of China University of Petroleum: Edition of Natural Science, 2020, 44(5): 19–31.
- [20] 何发岐, 梁承春, 陆骋, 等. 鄂尔多斯盆地南缘过渡带致密-低渗油藏断缝体的识别与描述[J]. 石油与天然气地质, 2020, 41(4): 710–718.
- HE Faqi, LIANG Chengchun, LU Cheng, et al. Identification and description of fault-fracture bodies in tight and low permeability reservoirs in transitional zone at the south margin of Ordos Basin[J]. Oil & Gas Geology, 2020, 41(4): 710–718.
- [21] 李智武, 刘树根, 陈洪德, 等. 川西坳陷复合-联合构造及其对油气的控制[J]. 石油勘探与开发, 2011, 38(5): 538–551.
- LI Zhiwu, LIU Shugen, CHEN Hongde, et al. Structural superimposition and conjunction and its effects on hydrocarbon accumulation in the Western Sichuan Depression[J]. Petroleum Exploration and Development, 2011, 38(5): 538–551.
- [22] 刘殊, 任兴国, 姚声贤, 等. 四川盆地上三叠统须家河组气藏分布与构造体系的关系[J]. 天然气工业, 2018, 38(11): 1–14.
- LIU Shu, REN Xingguo, YAO Shengxian, et al. Relationship between gas reservoir distribution and structural system of Upper Triassic Xujiahe Fm in the Sichuan Basin[J]. Natural Gas Industry, 2018, 38(11): 1–14.
- [23] 叶素娟, 李嵘, 杨克明, 等. 川西坳陷叠覆型致密砂岩气区储层特征及定量预测评价[J]. 石油学报, 2015, 36(12): 1484–1494.
- YE Sujuan, LI Rong, YANG Keming, et al. Characteristics and quantitative prediction of tight sand gas reservoirs in superimposed tight sandstone gas-bearing area, western Sichuan depression[J]. Acta Petrolei Sinica, 2015, 36(12): 1484–1494.
- [24] 王志康, 林良彪, 余瑜, 等. 川西新场地区须家河组第二段优质储层主控因素[J]. 成都理工大学学报: 自然科学版, 2020, 47(6): 661–672.
- WANG Zhikang, LIN Liangbiao, YU Yu, et al. The main controlling factors of high quality reservoir in the second member of Xujiahe Formation in Xinchang area, Western Sichuan, China[J]. Journal of Chengdu University of Technology: Science & Technology Edition, 2020, 47(6): 661–672.



- [25] 王兴龙,刘磊,林良彪,等.川西坳陷新场地区须二段沉积微相与砂体展布[J].成都理工大学学报:自然科学版,2021,48(1):23-34.  
WANG Xinglong, LIU Lei, LIN Liangbiao, et al. Sedimentary micro-facies and distribution of sand bodies in the 2<sup>nd</sup> member of Xujiahe Formation, Xinchang area, western Sichuan Depression, China [J]. Journal of Chengdu University of Technology: Science & Technology Edition, 2021, 48(1): 23-34.
- [26] 付晓飞,方德庆,吕延防,等.从断裂带内部结构出发评价断层垂向封闭性的方法[J].地球科学:中国地质大学学报,2005,30(3):328-336.  
FU Xiaofei, FANG Deqing, LÜ Yanfang, et al. Method of evaluating vertical sealing of faults in terms of the internal structure of fault zones [J]. Earth Science: Journal of China University of Geosciences, 2005, 30(3): 328-336.
- [27] 陈伟,吴智平,侯峰,等.断裂带内部结构特征及其与油气运聚关系[J].石油学报,2010,31(5):774-780.  
CHEN Wei, WU Zhiping, HOU Feng, et al. Internal structures of fault zones and their relationship with hydrocarbon migration and accumulation [J]. Acta Petrolei Sinica, 2010, 31(5): 774-780.
- [28] 闫成龙,王海学,付晓飞,等.碎屑岩地层中逆断层内部结构演化模式及封闭性[J].天然气地球科学,2018,29(4):529-537.  
YAN Chenglong, WANG Haixue, FU Xiaofei, et al. The evolution model and sealing of reverse fault in clastic strata [J]. Natural Gas Geoscience, 2018, 29(4): 529-537.
- [29] 苏圣民,蒋有录.含油气盆地断裂带结构特征及其与油气运聚关系[J].中国石油大学学报:自然科学版,2021,45(4):32-41.  
SU Shengmin, JIANG Youlu. Fault zone structures and its relationship with hydrocarbon migration and accumulation in petroliferous basin [J]. Journal of China University of Petroleum: Edition of Natural Science, 2021, 45(4): 32-41.
- [30] 范婕,蒋有录,张奎华,等.断裂带结构的识别方法及其控藏作用[J].地质论评,2021,67(增刊1):89-90.  
FAN Jie, JIANG Youlu, ZHANG Kuihua, et al. The method of distinguishing fault zone structure and its control of reservoir [J]. Geological Review, 2021, 67(Supplement 1): 89-90.
- [31] 陈志刚,马文杰,赵宏忠,等.利用曲率类属性预测储层裂缝的流程及应用实例[J].物探与化探,2020,44(5):1 201-1 207.  
CHEN Zhigang, MA Wenjie, ZHAO Hongzhong, et al. A technical workflow of fracture prediction with curvature-related attributes and its applications [J]. Geophysical and Geochemical Exploration, 2020, 44(5): 1 201-1 207.
- [32] 王雷,陈海清,陈国文,等.应用曲率属性预测裂缝发育带及其产状[J].石油地球物理勘探,2010,45(6):885-889.  
WANG Lei, CHEN Haiqing, CHEN Guowen, et al. Application of curvature attributes in predicting fracture-developed zone and its orientation [J]. Oil Geophysical Prospecting, 2010, 45(6): 885-889.
- [33] 王世星.高精度地震曲率体计算技术与应用[J].石油地球物理勘探,2012,47(6):965-972.  
WANG Shixing. High-precision calculation of seismic volumetric curvature attributes and its applications [J]. Oil Geophysical Prospecting, 2012, 47(6): 965-972.

编辑 经雅丽