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多级构型界面下致密砂岩储层构造裂缝发育特征

——以川西坳陷须家河组二段为例

李莉妃,任启强,杨田,蔡来星,李政,崔蓉

成都理工大学 沉积地质研究院,成都 610059

摘要:裂缝对四川盆地川西坳陷须家河组二段致密砂岩储层天然气的高产稳产至关重要,不同沉积环境下形成的砂体构型界面控制了储层裂缝的发育。通过野外露头勘测、岩心观测、测井识别和岩相精细刻画等方法,提出了川西坳陷须家河组二段砂体构型界面划分方案,识别划分了研究区的 2~4 级砂体构型界面,厘清了不同级别构型界面约束下裂缝发育的特征及其油气地质意义。不同级别构型界面控制着储层裂缝的产状、开启程度、发育程度和储渗能力;2 级、3 级界面的有效控制范围分别为 0~0.35 m 和 0~3 m,4 级界面控制范围较大(0~11 m)。不同构型界面控制下裂缝发育特征存在差异,其中 2 级界面下裂缝欠发育,4 级界面下裂缝一般发育,3 级界面下裂缝最发育,主要为低角度斜缝;裂缝走向主要为 NNE—SSW、SEE—NW 和 SSE—NNW,开度较大(>0.04 mm)和倾角较大的裂缝较多。多级界面控制下裂缝发育段的岩心孔渗呈明显的正相关,3 级界面下裂缝对储层物性的改善作用最强,对油气贡献度最高;4 级界面次之,2 级界面最弱。明确不同级别构型界面对裂缝发育的控制作用,有利于研究区致密砂岩储层气藏的有效开发。

关键词:裂缝发育特征;构型界面;储层构型划分;致密砂岩;川西坳陷;四川盆地

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Development characteristics of structural fractures in tight sandstone reservoirs under multi-level configuration interfaces: a case study of second member of Xujiahe Formation in Western Sichuan Depression

LI Lifei, REN Qiqiang, YANG Tian, CAI Laixing, LI Zheng, CUI Rong

Institute of Sedimentary Geology, Chengdu University of Technology, Chengdu, Sichuan 610059, China

Abstract: Fractures are crucial for the high and stable production of natural gas from the tight sandstone reservoirs in the second member of the Xujiahe Formation in the Western Sichuan Depression, Sichuan Basin. The development of these fractures is controlled by the configuration interfaces of sand bodies formed under different sedimentary environments. Through field outcrop surveys, core observations, logging identification, and detailed characterization of lithofacies, a classification scheme for sand body configuration interfaces was proposed for the second member of the Xujiahe Formation in the Western Sichuan Depression. These interfaces were identified and classified into second to fourth levels. The study clarified the characteristics and geological significance of fractures under different levels of configuration interfaces. These interfaces controlled the occurrence, opening degree, development degree, and storage-permeability capacities of reservoir fractures. The effective control ranges of the second and third level interfaces were 0-0.35 m and 0-3 m, respectively, while the fourth level interface had a larger control range (0-11 m). The development characteristics of fractures differed under different configuration interfaces. Specifically, fractures were underdeveloped at the second level interfaces; fairly developed at the fourth level;

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作者简介:李莉妃(1998—),女,硕士生,从事油气储层地质学和构造地质学研究。E-mail:lilifei91@163.com。

通信作者:任启强(1990—),男,博士,研究员,从事裂缝定量预测、含油气盆地构造解析、构造演化史等研究。E-mail:renqq2022@cdut.edu.cn。

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and most developed at the third level, primarily as low-angle dipping fractures. Fracture orientations were predominantly NNE-SSW, SEE-NWW, and SSE-NNW, with more fractures having larger openings (>0.04 mm) and larger dip angle. There was a clear positive correlation between core porosity and permeability in the fracture development under the control of the multi-level interfaces. Fractures at the third level interface had the strongest improvement effect on reservoir physical properties and made the highest contribution to oil and gas production, followed by the fourth level interface, with the second level interface being the least effective. Clarifying the control of different levels of configuration interfaces on fracture development is conducive to the effective development of tight sandstone gas reservoirs in the study area.

Key words: fracture development characteristics; configuration interface; reservoir configuration classification; tight sandstone; Western Sichuan Depression; Sichuan Basin

深层—超深层致密砂岩的油气保供和增储上产已成为全球油气勘探开发的重大需求。我国深层—超深层致密砂岩油气广泛分布在鄂尔多斯、四川、松辽、塔里木、准噶尔、吐哈以及渤海湾等盆地,总资源量大于 $21.85 \times 10^{12} \text{ m}^3$ ^[1-2]。川西坳陷上三叠统须家河组二段(须二段)是四川盆地陆相致密砂岩气勘探开发的重要目的层^[3-4],但因其埋藏深、岩性致密、低孔低渗、非均质性强,使得后期开发难度大^[4-5]。自晚三叠世起,在龙门山逆冲推覆构造与米仓山隆起的双重挤压应力作用下,川西坳陷须家河组地层历经了印支、燕山和喜马拉雅等多期构造运动的复合改造^[6-8],发育了类型多样、非均质性强的多期次裂缝。裂缝作为致密储层的有效储集空间和主要渗流通道,影响着致密储层高产稳产^[9-11]。前人研究了须二段裂缝的发育特征^[12-16]、形成期次^[13,17-19],探讨了岩性、层厚、断层、褶皱、构造应力等裂缝主控因素^[14,16,20-22],但川西坳陷须二段储层非均质性强,不同级次砂体构型界面控制着储层的非均质性^[23],也是影响储层裂缝发育的关键因素^[24-25]。ALLEN 于 1977 年首次提出储层构型的概念后,将构型界面分为了 3 级^[26]; MIALL 在此基础上于 1985 年首次完整地提出了河流相储层构型分析方法^[27]。目前被广泛应用的是 MIALL^[28-30] 的 3 级层序地层内的 9 级构型界面划分方案、吴胜和等^[31] 的岩性体构型和层序构型统一的沉积体 12 级构型界面划分方案和胡光义等^[32] 的海上油田河流相复合砂体构型 13 级划分方案。近年来有不少学者对不同储层进行了砂体构型界面的识别划分以及分析构型界面与剩余油分布的关系等研究^[33-36]。就目前而言,不同级次构型界面如何影响储层裂缝发育尚缺乏相关认识。本文利用露头调查、岩心观察、测井解释、岩相分析等手段,对川西坳陷须二段砂体构型界面进行识别与划分,并明确不同级次构型界面对储层裂缝

发育的控制作用,以期为川西坳陷须家河组致密砂岩裂缝预测、识别优质储层和高效勘探开发天然气提供参考。

1 区域地质概况

川西坳陷是晚三叠世以来在四川盆地西部陆相沉积形成的前陆拗陷,西临龙门山造山带,北东接昆仑—秦岭造山带,南至峨眉—乐山一带过渡到川滇南北向构造带,呈北东向延伸^[37],为构造活跃地带(图 1)^[13,38-39]。研究区遭受了印支、燕山和喜马拉雅多期构造运动,形成了北东向、北西向、近东西向、近南北向等主要构造^[40-41],产生了大量构造裂缝,油气资源丰富。上三叠统须家河组是一套以砂—泥互层为主、夹煤层的地层^[3],自上而下分为 6 段(须一段—须六段),须二段是主要的天然气储层和产层。须二段主要为大型湖相浅水三角洲前缘沉积,发育大套砂岩夹少量泥岩,以中—细粒岩屑砂岩、岩屑石英砂岩和长石岩屑砂岩为主^[42],埋藏深度大于 4 500 m,层厚 550~660 m,基质平均渗透率为 $0.6 \times 10^{-3} \mu\text{m}^2$ ^[3],平均孔隙度为 3.72%,属于典型的低孔、低渗—特低孔、低渗深层致密砂岩气储层^[42]。须家河组沉积期间,水系弥散,河道频繁改道、交叉和归并,多期河道叠置、侧接等,形成了非均质性较强的砂体复合体^[43];砂体内部叠置关系复杂,存在着不同级次的构型界面,控制着储层的非均质性和天然裂缝的发育。

2 多级砂体构型界面的识别划分

通过对研究区进行露头调查、岩心观察、测井解释及岩相分析等,参考 MIALL^[27-29]、吴胜和等^[31,44] 关于河流相储层构型界面的划分方法,提出了川西坳陷须二段沉积体构型界面的划分方案(图 2)。由于 1 级构型界面内的纹层组厚度较小和 5 级构型界面内的复合河道带范围太大,岩心与测

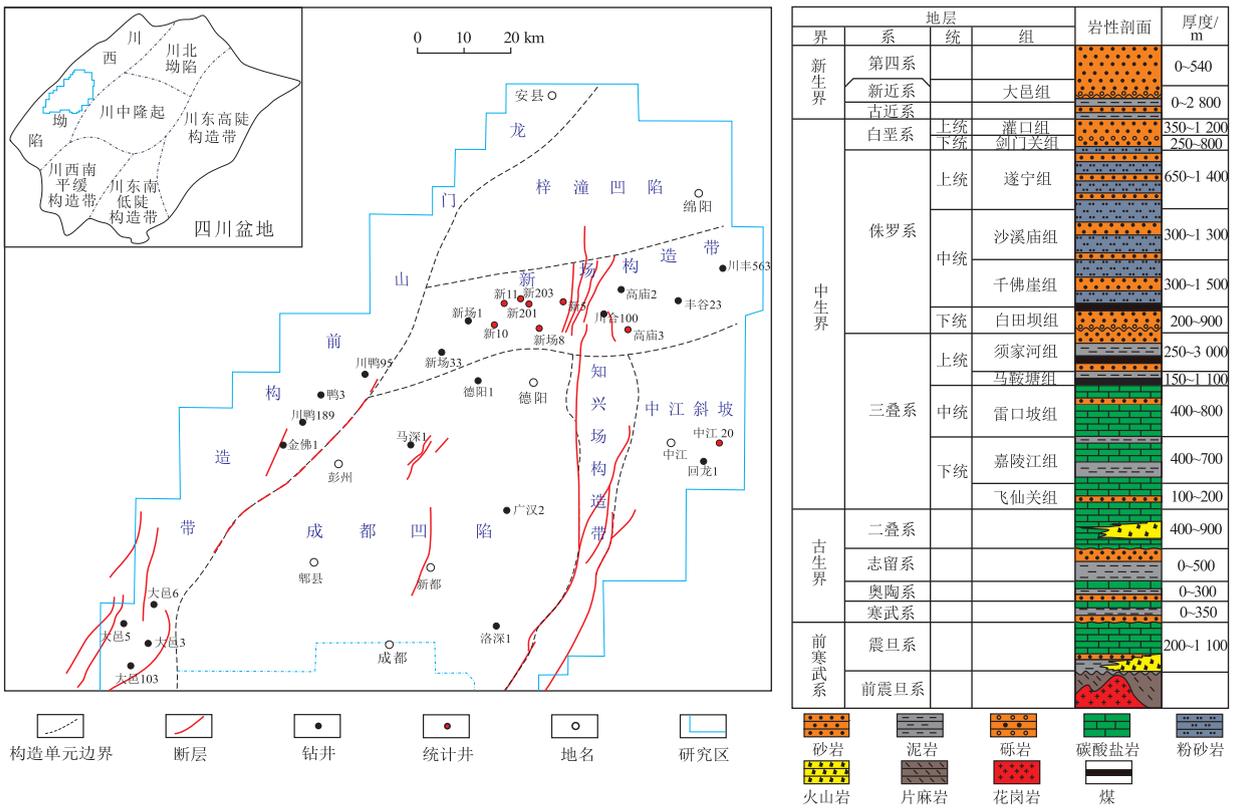


图 1 四川盆地西部坳陷地质背景(a)及地层综合柱状图(b)

图 1a 据吴小奇等^[38]和刘志远等^[39]修改;图 1b 据 ZHANG 等^[13]修改。

Fig.1 Geological background of Western Sichuan Depression, Sichuan Basin (a) and comprehensive stratigraphic column chart (b)

界面级别	沉积单元	成因分析	层次结构模式
1级	层系(纹层组)	单一岩相(纹层组构成的层系)	<p>①1级界面:交错层系界面 ②2级界面:交错层系组界面 ③3级界面:单一河道砂体内部泥质夹层</p>
2级	岩石相	单一岩相的叠加(层系叠加构成的层系组),不同层系组之间的界面,界面上岩相变化	
3级	岩相组合	由轻微侵蚀界面控制的连续沉积序列,在岩心上为泥质含量增加的界面,岩相组合不变	
4级	单一河道带	由大型侵蚀界面控制的连续沉积序列,底部可见滞留沉积,顶部泥岩或冲刷侵蚀边界,岩相组合变化	<p>③3级界面:单一河道砂体内部泥质夹层 ④4级界面:单砂体边界</p>
5级	复合河道带	垂向上由若干有序迁移并连续沉积的单期河道构造的复合河道,底部为冲刷面	<p>④4级界面:单砂体边界 ⑤5级界面:同期河道复合(叠置)砂体边界</p>

图 2 四川盆地西部坳陷须家河组二段砂体构型级次划分

据 MIALL^[27-29]和吴胜和^[44]修改。

Fig.2 Classification of sand body configuration levels in second member of Xujiahe Formation in Western Sichuan Depression, Sichuan Basin

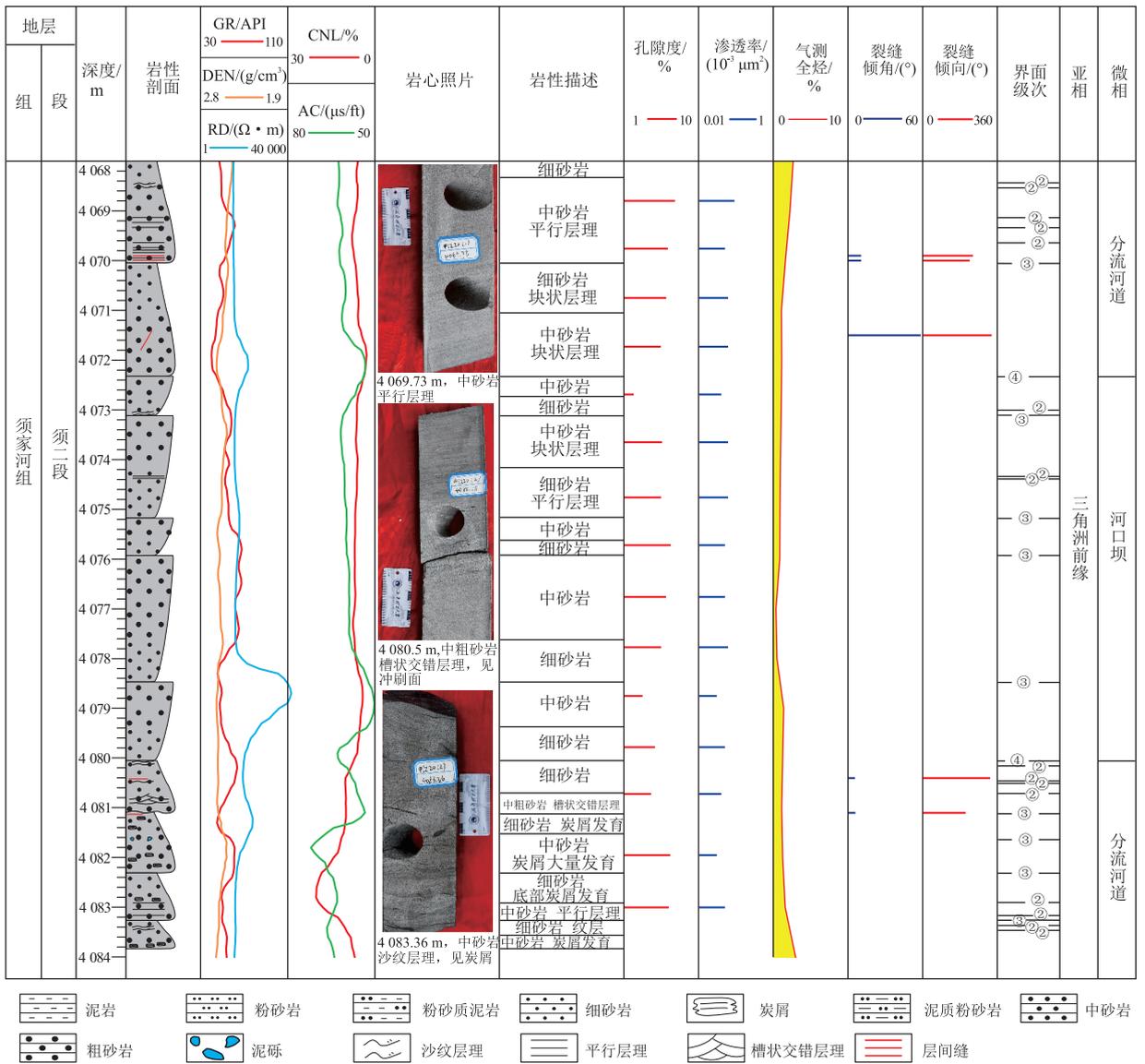


图 3 四川盆地西部坳陷中江 20 井须家河组二段构型界面划分

Fig.3 Classification of configuration interface in second member of Xujiahe Formation, well Zhongjiang 20, Western Sichuan Depression, Sichuan Basin

井无法有效识别,因此主要对 2 级、3 级和 4 级构型界面进行研究(图 3)。2 级构型界面为单一岩相的叠加界面,层系组与层系组之间的界面,底部无侵蚀,界面上下有岩相的变化,如平行层系组与交错层系组之间的界面;3 级构型界面为巨型底形内的侵蚀面,其倾角一般小于 15°,界面上通常泥质含量增加,见碎屑泥砾,界面上下岩相组合相似;4 级构型界面为巨型底形的界面,单期河道的界面,以滞留沉积与冲刷面识别,岩相组合变化,沉积微相变化的界面。

3 多级构型界面对裂缝发育的控制

根据上述构型分级方案,识别统计了川西坳陷新场 8 井、中江 20 井、高庙 3 井、新 5 井、新 10

井、新 11 井、新 201 井和新 203 井等 8 口井的 2 级、3 级、4 级构型界面所在深度;再以各级构型单元内的每条裂缝与最近的下个同级次构型界面的距离为标准,分别统计了这 8 口井的裂缝所在深度与各单井的 2 级、3 级和 4 级构型界面所在深度的距离(距构型界面距离),并分析了距构型界面距离与裂缝的关系,明确不同级次构型界面对裂缝发育的控制作用。

3.1 2 级构型界面与裂缝参数的关系

由距 2 级构型界面与裂缝参数交会关系(图 4)可知,2 级构型界面控制下裂缝分布的范围较小(0~0.35 m),在此范围内,距 2 级界面距离与裂缝倾角呈负相关关系。随着距离的增加,裂缝倾角逐渐减小。裂缝平均开度和密度的有效数据

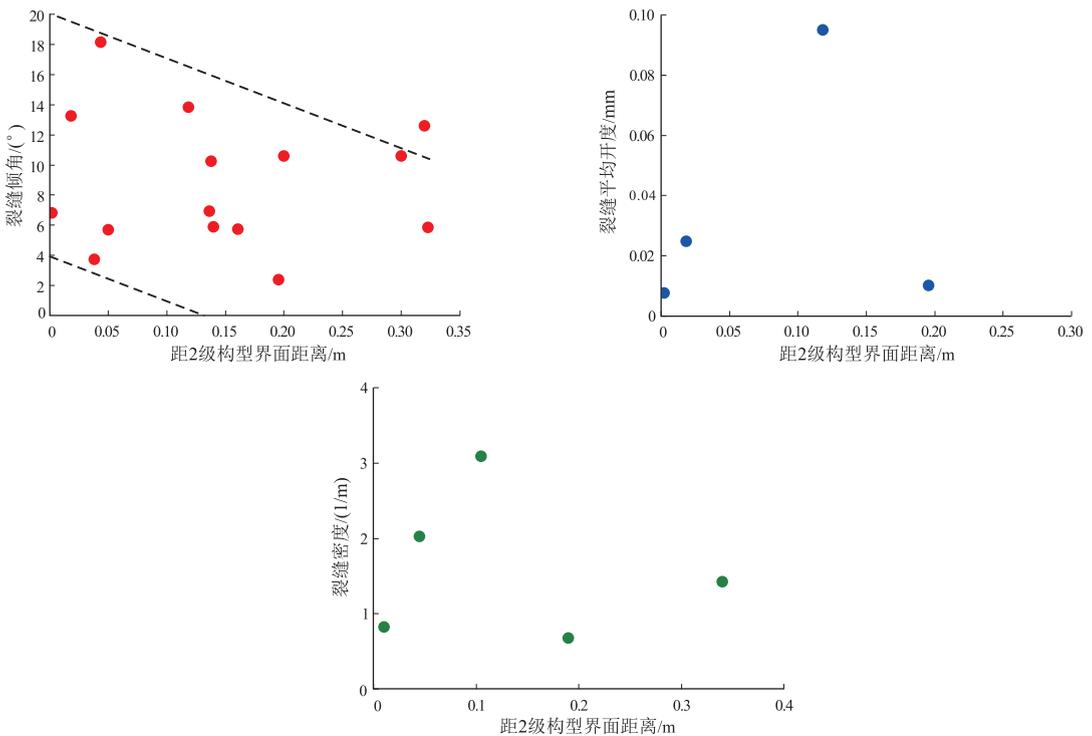


图4 四川盆地西部坳陷须家河组二段距2级构型界面距离与裂缝参数关系

Fig.4 Relationship between distance to second level configuration interface and fracture parameters in second member of Xujiahe Formation, Western Sichuan Depression, Sichuan Basin

量较少,与距2级界面距离在一定程度上呈正相关关系。随着距离的进一步增加,裂缝平均开度和发育密度一定程度增大。上述交会关系表明,2级构型界面对裂缝的控制作用相对有限,其有效控制范围为0~0.35 m,一定程度上影响裂缝产状和发育程度。

3.2 3级构型界面与裂缝参数的关系

由距3级构型界面与裂缝参数交会关系(图5)可知,3级构型界面控制下裂缝分布的范围较大(0~4.5 m),且距界面越近,裂缝越发育。在此范围内,距3级界面距离与裂缝倾角、密度呈负相关关系,与裂缝平均开度呈正相关关系。随着距离的增加,裂缝倾角、密度总体呈快速波动减小的趋势,裂缝平均开度呈增大的趋势。上述交会关系表明,3级构型界面对裂缝的产状、开启程度、发育程度和储渗能力有较明显的控制作用,影响着储层有效裂缝的形成和分布。其中,在距3级构型界面0~3 m,裂缝大量发育且裂缝倾角、平均开度、密度波动变化明显。因此,3级构型界面对裂缝的有效控制距离为0~3 m。

3.3 4级构型界面与裂缝参数的关系

由距4级构型界面与裂缝参数交会关系(图6)可知,4级构型界面控制下裂缝分布范围最广(0~11 m)。在此范围内,距4级界面距离与裂缝

密度呈正相关关系,与裂缝倾角呈负相关关系,与裂缝平均开度的关系较复杂。随着距离的增加,裂缝平均开度呈先快速增大再快速减小的趋势,密度相对缓慢增大,倾角快速减小。上述交会关系表明,4级构型界面对裂缝的控制范围较广,对裂缝的产状、开启程度、发育程度和储渗能力同样有明显的控制作用。

4 构型界面控制下裂缝发育特征

4.1 2级构型界面下裂缝发育特征

根据倾角大小,裂缝可以分为5种类型,即立缝(倾角为 $80^{\circ} \sim 90^{\circ}$)、高角度斜缝(倾角为 $60^{\circ} \sim 80^{\circ}$)、斜缝(倾角为 $30^{\circ} \sim 60^{\circ}$)、低角度斜缝(倾角为 $10^{\circ} \sim 30^{\circ}$)和平缝(倾角为 $0^{\circ} \sim 10^{\circ}$)^[45]。

在2级构型界面控制下,裂缝相对欠发育(图7),主要发育走向为SSE—NNW($160^{\circ} \sim 170^{\circ}$)向裂缝,其次是NNE—SSW($10^{\circ} \sim 20^{\circ}$)向裂缝。裂缝类型为平缝和低角度斜缝($10^{\circ} \sim 20^{\circ}$)。裂缝平均开度主要在0~0.02 mm,其次在0.02~0.04 mm和0.08~0.1 mm,其平均值为0.034 mm。总体上,2级构型界面控制下基本只发育少量倾角较小、开度较小的裂缝。

4.2 3级构型界面下裂缝发育特征

在3级构型界面控制下,裂缝最发育(图8),

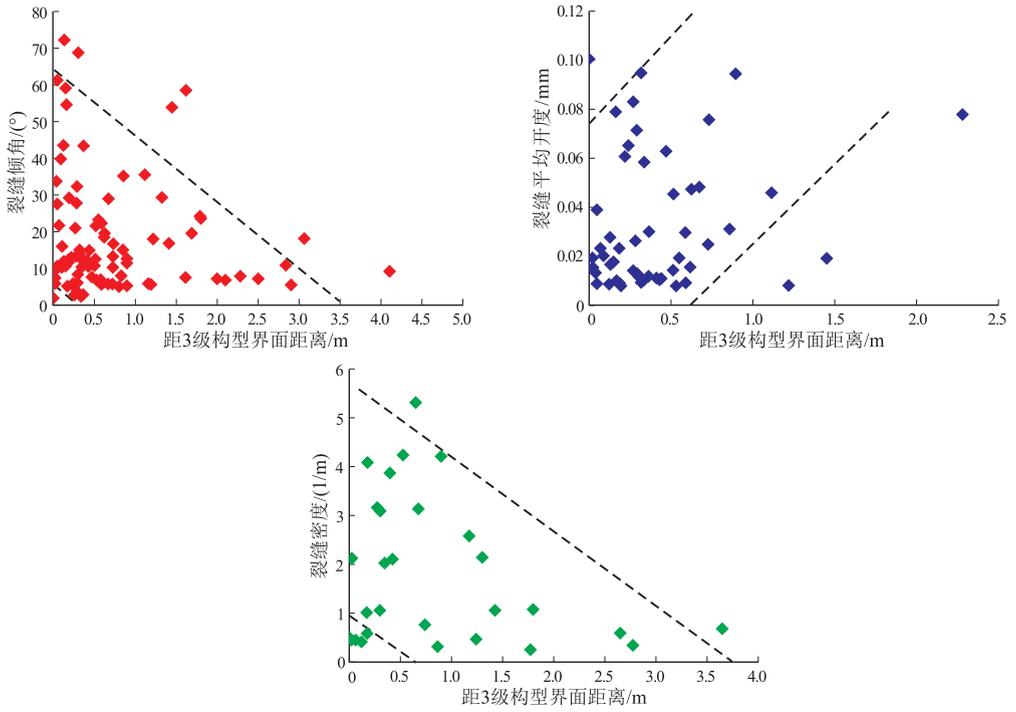


图 5 四川盆地西部坳陷须家河组二段距 3 级构型界面距离与裂缝参数关系

Fig.5 Relationship between distance to third level configuration interface and fracture parameters in second member of Xujiahe Formation, Western Sichuan Depression, Sichuan Basin

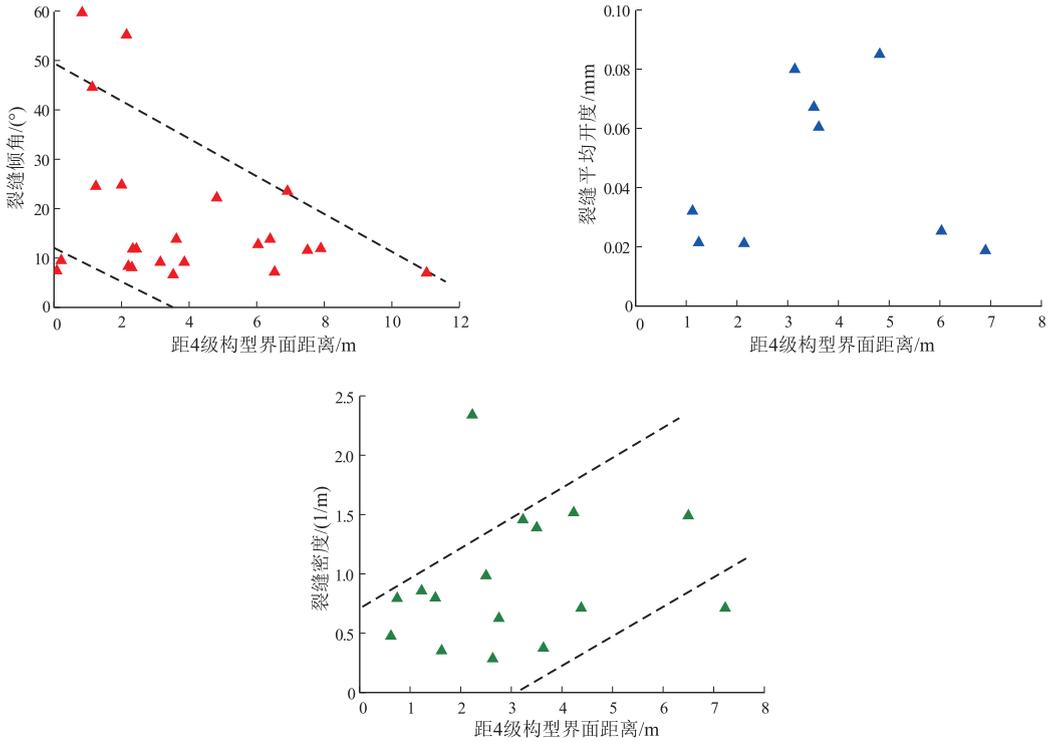


图 6 四川盆地西部坳陷须家河组二段距 4 级构型界面距离与裂缝参数关系

Fig.6 Relationship between distance to fourth level configuration interface and fracture parameters in second member of Xujiahe Formation, Western Sichuan Depression, Sichuan Basin

主要发育走向为 NNE—SSW ($0^{\circ} \sim 10^{\circ}$)、SEE—NWW ($100^{\circ} \sim 110^{\circ}$) 和 SSE—NNW ($160^{\circ} \sim 170^{\circ}$) 的裂缝。主要裂缝类型为低角度斜缝 ($10^{\circ} \sim 20^{\circ}$) 和

平缝,还发育少量角度较高的斜缝 ($50^{\circ} \sim 80^{\circ}$)。裂缝平均开度分布范围较广 ($0 \sim 0.1 \text{ mm}$),主要在 $0 \sim 0.02 \text{ mm}$,其次在 $0.02 \sim 0.04 \text{ mm}$ 及 $0.06 \sim 0.08 \text{ mm}$,

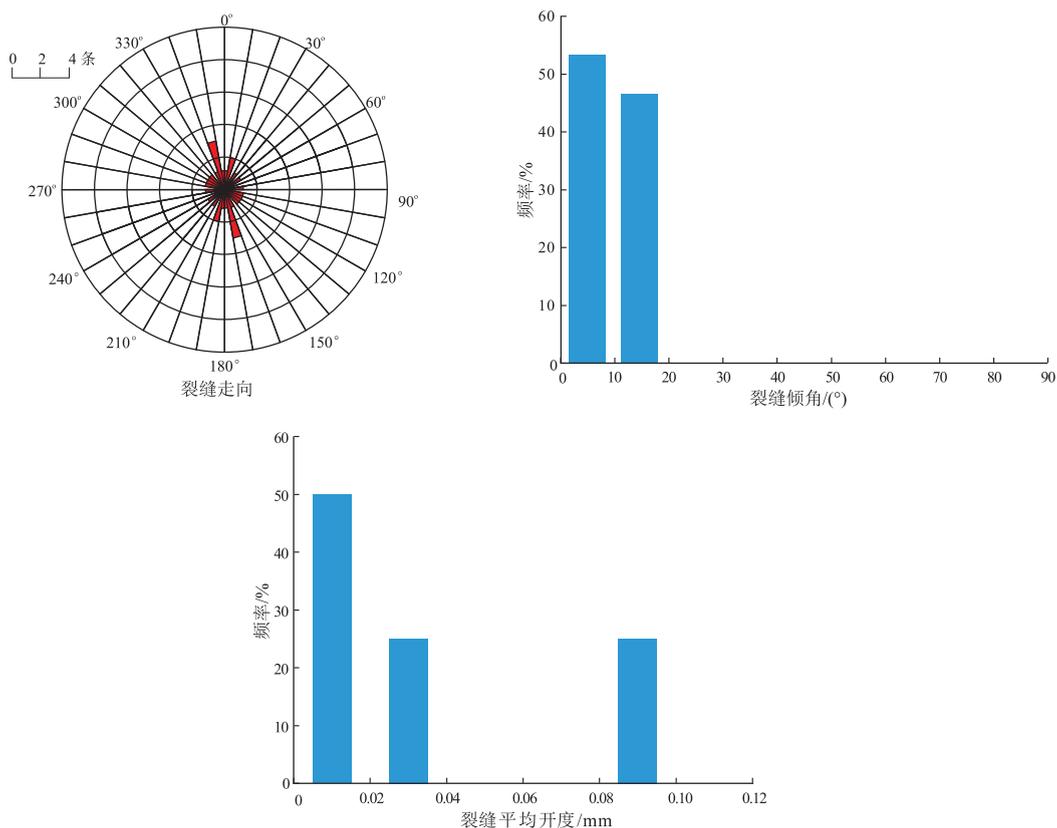


图7 四川盆地西部坳陷须家河组二段2级构型界面下裂缝发育特征

Fig.7 Characteristics of fracture development at second level configuration interface in second member of Xujiahe Formation, Western Sichuan Depression, Sichuan Basin

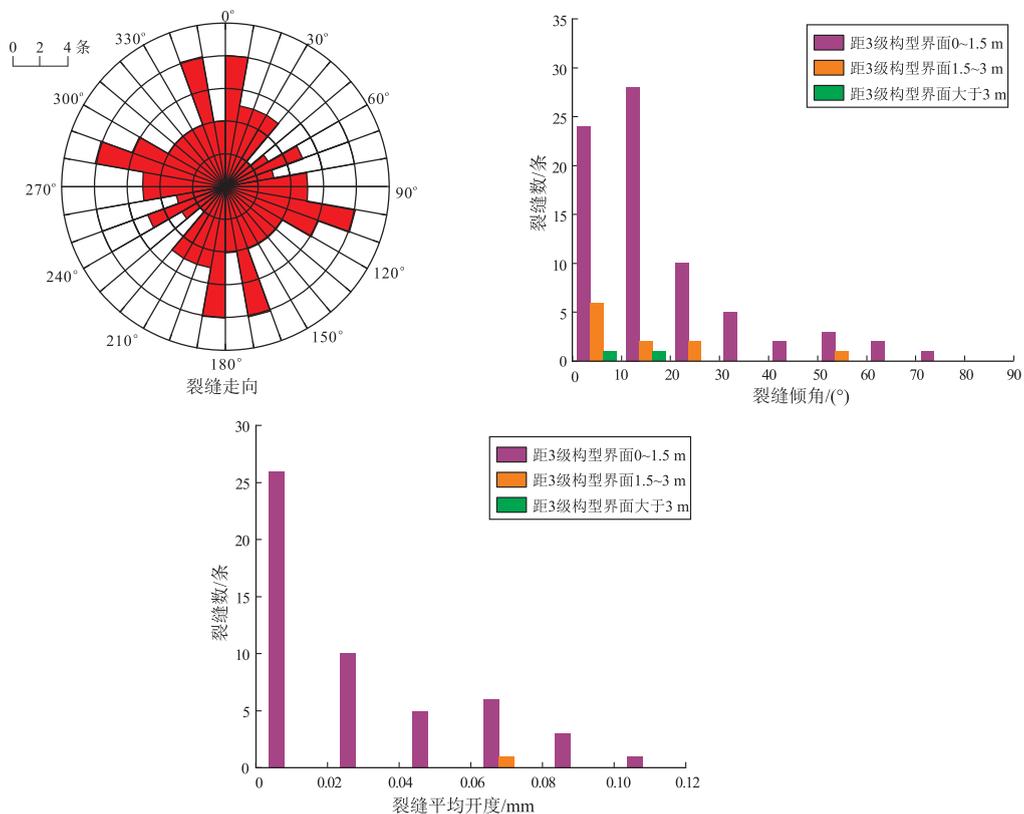


图8 四川盆地西部坳陷须家河组二段3级构型界面下裂缝发育特征

Fig.8 Characteristics of fracture development at third level configuration interface in second member of Xujiahe Formation, Western Sichuan Depression, Sichuan Basin

其平均值为 0.033 mm。距 3 级构型界面距离的不同,裂缝发育特征有较大差异,0~1.5 m 内裂缝最发育,而且发育的裂缝倾角类型多样,平均开度分布范围广。距离 3 级构型界面越远,发育的裂缝越少,裂缝倾角越小。总体上,3 级构型界面控制下裂缝发育程度高,且倾角较大、开度较大的裂缝较多。

4.3 4 级构型界面下裂缝发育特征

在 4 级构型界面控制下,裂缝一般发育(图 9),主要发育走向为 NNE—SSW($0^{\circ}\sim 10^{\circ}$)的裂缝。主要裂缝类型为平缝和低角度斜缝($10^{\circ}\sim 20^{\circ}$),也发育少量斜缝。裂缝平均开度分布范围也较广($0\sim 0.083$ mm),主要在 $0\sim 0.02$ mm,其次是 $0.06\sim 0.08$ mm,其平均值为 0.044 mm。距 4 级构型界面距离的不同,裂缝发育特征也存在着差异。随着距离的增加,裂缝发育程度呈先升高再降低的趋势,2~4 m 时裂缝最发育;距离越远,角度较高的裂缝越欠发育,但裂缝平均开度一定程度上增大。总体上,4 级构型界面控制下,多发育角度较低、开度较大的裂缝。

5 裂缝成因模式和油气地质意义

5.1 裂缝成因模式

不同级次的构型界面形成于不同的沉积环境^[46],对裂缝形成的控制作用也存在差异(图 10)。

2 级构型界面为不同层系组之间的界面,而层系是形成于相对稳定的水动力条件下,为相类似的纹层组成^[32],沉积物质差异性小,内部结构相对稳定,岩石力学性质差异小,且分布不连续和发育范围较小。因而在构造应力挤压作用下,一般只沿着 2 级构型界面产生少量的角度较低、开度较小的裂缝。

3 级构型界面为巨型底形内部的侵蚀面,增生体之间的界面,可见碎屑泥砾,是形成于不同水动力阶段的界面^[29]。因沉积水动力环境的不稳定,导致沉积物粒度频繁变化,形成了密集的粒度差异变化面,增大了岩石力学性质的差异^[22];而且砂体沉积厚度相对适中,所以在构造应力作用下容易发生应力集中,更有利于产生裂缝,也容易发育角度

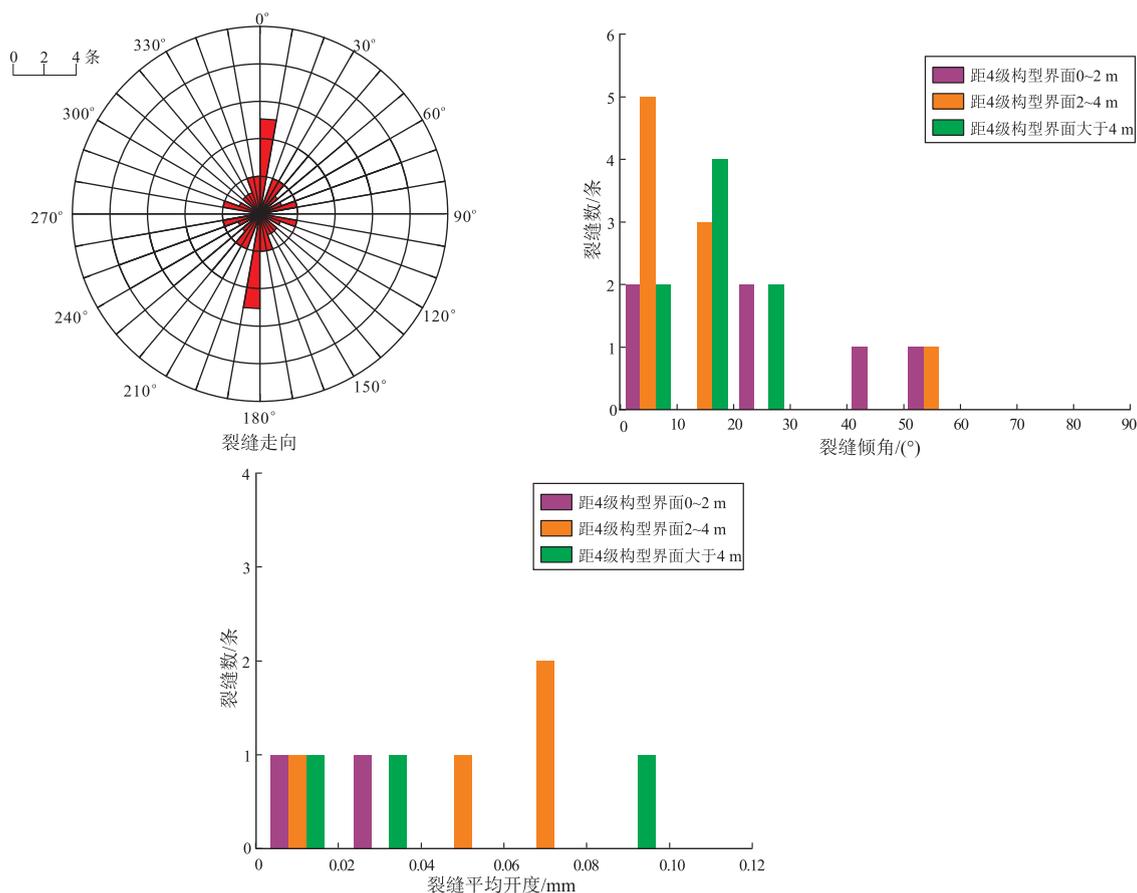


图 9 四川盆地西部坳陷须家河组二段 4 级构型界面下裂缝发育特征

Fig.9 Characteristics of fracture development at fourth level configuration interface in second member of Xujiahe Formation, Western Sichuan Depression, Sichuan Basin

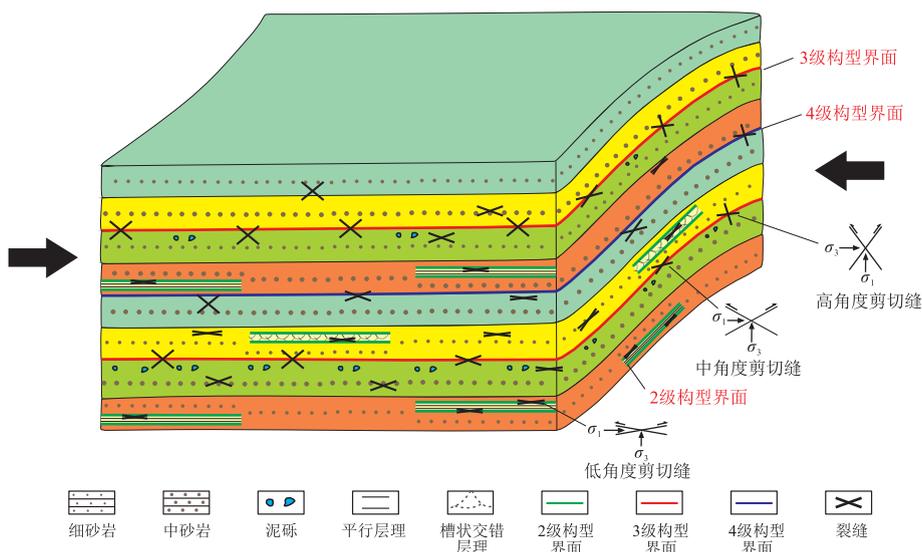


图 10 四川盆地西部坳陷须家河组二段多级构型界面下裂缝成因模式

Fig.10 Genesis patterns of fractures at multi-level configuration interfaces in second member of Xujiahe Formation, Western Sichuan Depression, Sichuan Basin

较高、开度较大的裂缝。相比较而言,3 级构型界面比 2 级、4 级构型界面更广泛发育,所以此界面下裂缝发育程度高。

4 级构型界面为沉积微相变化的界面,沉积水动力环境变化使得岩相组合发生变化^[28,44],岩石力学性质存在差异,但界面上下多发育大套砂体,砂体岩性韵律循序变化,且沉积厚度较大,因而裂缝发育程度有所降低,但发育范围较广。

5.2 裂缝油气地质意义

川西坳陷深层致密砂岩具有低孔、低渗的特

点,但天然裂缝的发育能有效改善储层的物性,为储层油气提供储集空间和渗流通道^[15,42]。通过分析不同级次构型界面下裂缝参数(裂缝倾角和平均开度)与裂缝发育段储层的物性参数(岩心孔隙度和渗透率)、油气参数(日产气和气测全烃)的交会关系(图 11),可明确不同级次构型界面控制下的裂缝对储层油气的贡献程度。

裂缝平均开度与岩心孔隙度、渗透率呈正相关关系(图 11a-b)。随着裂缝平均开度的增大,岩心孔隙度、渗透率总体也呈增加的趋势,尤其是裂缝

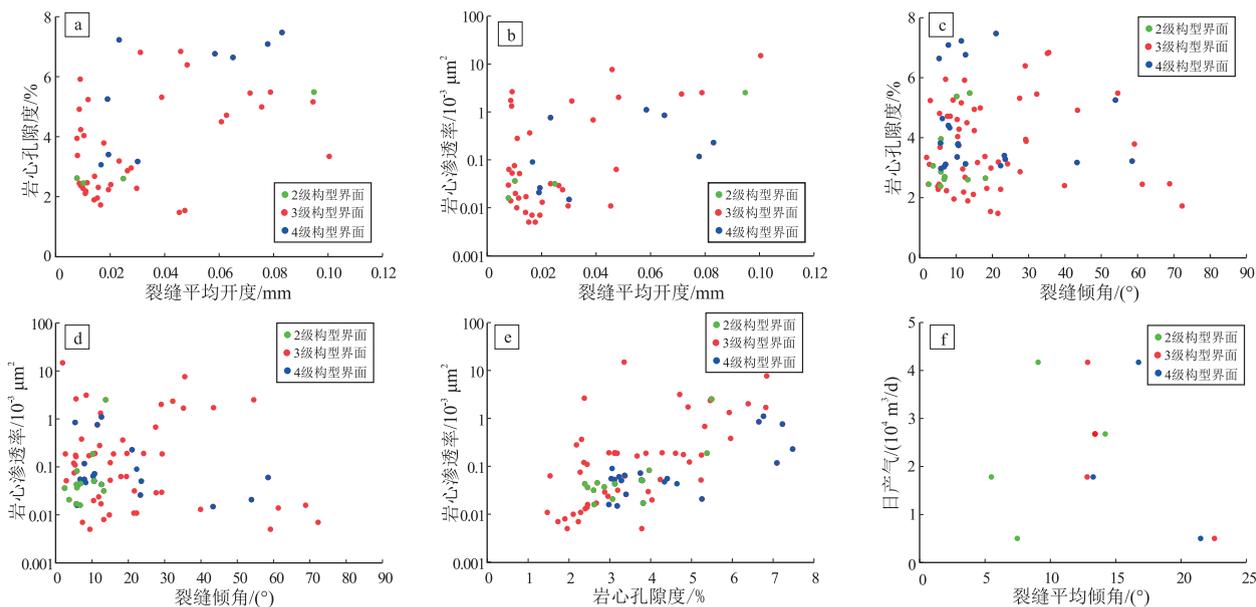


图 11 四川盆地西部坳陷须家河组二段多级构型界面下裂缝与储层物性、油气的相关性

Fig.11 Correlation between fractures, reservoir physical properties, and oil and gas at multi-level configuration interfaces in second member of Xujiahe Formation, Western Sichuan Depression, Sichuan Basin

平均开度在 0.05~0.1 mm 时,岩心孔渗明显增大(孔隙度基本大于 4%,渗透率大于 $0.1 \times 10^{-3} \mu\text{m}^2$)。表明裂缝开度越大,连通性更好和储渗空间越大,对储层物性的改善作用越明显。

裂缝倾角与岩心孔隙度、渗透率呈一定的负相关关系(图 11c-d)。随着裂缝倾角的增大,岩心孔渗一定程度上降低。裂缝倾角在 $0^\circ \sim 40^\circ$ 左右时,岩心孔渗总体较好,岩心孔隙度达到最高值 7.5%,渗透率最高值达 $14.86 \times 10^{-3} \mu\text{m}^2$ 。表明在多级构型界面控制下发育的平缝和低角度缝,角度虽然较低,但常呈密集的带状分布,横向连通性较好^[47],有利于沟通储层孔隙和增加储层渗透率,极大地改善储层的物性条件。总体上,岩心的孔隙度和渗透率呈良好的正相关关系,随着岩心孔隙度的增加,岩心渗透率也逐渐增加(图 11e)。

不同级次构型界面控制下裂缝对岩心孔渗的改善作用存在差异,4级构型界面控制下的裂缝对岩心孔隙度改善作用更明显,3级构型界面控制下的裂缝对岩心渗透率的增渗作用更明显(图 11e)。但就岩心孔渗关系而言,3级构型界面下的孔渗关系比4级界面的更好;2级构型界面控制下裂缝发育段的岩心孔渗基本较低,对储层物性改善作用比较有限。总体而言,3级构型界面下储层物性最好,4级次之,2级最差。主要是因为3级构型界面控制下的裂缝发育程度最高,且角度较高、开度较大的裂缝较多;4级构型界面控制下的裂缝一般发育,也发育一些角度较高、开度较大的裂缝;而2级构型界面控制下基本只发育少量角度低且开度小的裂缝。

裂缝倾角与日产气呈正相关关系(图 11f),随着裂缝倾角的增大,日产气也逐渐增加,表明裂缝改善储层的物性,对储层油气的储集和渗透具有重

要作用。

气测全烃是录井过程中唯一连续性测量的含油气参数,全烃数值越高,表明储层的油气丰度越高^[48]。全烃含量与裂缝倾角呈一定的正相关关系(图 12a),随着裂缝倾角的增大,全烃含量总体上呈增大的趋势。裂缝倾角在 $0^\circ \sim 30^\circ$ 时,全烃含量较高,其中 $0^\circ \sim 10^\circ$ 最高;裂缝倾角在 $40^\circ \sim 90^\circ$ 时,全烃含量基本在 1% 小幅度上下波动。在多级构型界面控制下发育的平缝和低角度缝,横向连通储层孔隙,增加储层水平渗透率,可有效改善储层物性,因此对储层油气的贡献度也高。主要为3级构型界面控制下发育的中高角度裂缝,与角度较低的裂缝相互交织,形成横向、纵向连通的裂缝网络,对储层油气储集和渗透也有很大的促进作用。

全烃含量与裂缝平均开度也呈一定的正相关关系(图 12b),随着裂缝平均开度增大,全烃含量总体上呈增大的趋势。主要是因为裂缝开度越大,孔隙度高且渗透率大,储层物性越好,有利于油气的储集和渗流。总体上,因3级构型界面下裂缝最为发育,且有发育较多的角度较高、开度较大的裂缝,对储层物性的改善作用最强,油气贡献度最高;4级界面次之,2级界面相对最弱。

6 结论

(1) 不同级次构型界面控制着储层裂缝的发育。随着距构型界面距离的增加,裂缝开度总体上呈波动增大的趋势,裂缝倾角总体呈大波动减小的趋势。2级界面对裂缝的有效控制范围为 0~0.35 m,3级界面对裂缝的有效控制距离范围为 0~3 m,4级界面对裂缝的控制范围较大,为 0~11 m。

(2) 不同级次构型界面控制下裂缝特征存在差异。2级界面下只发育少量平缝和低角度斜缝,

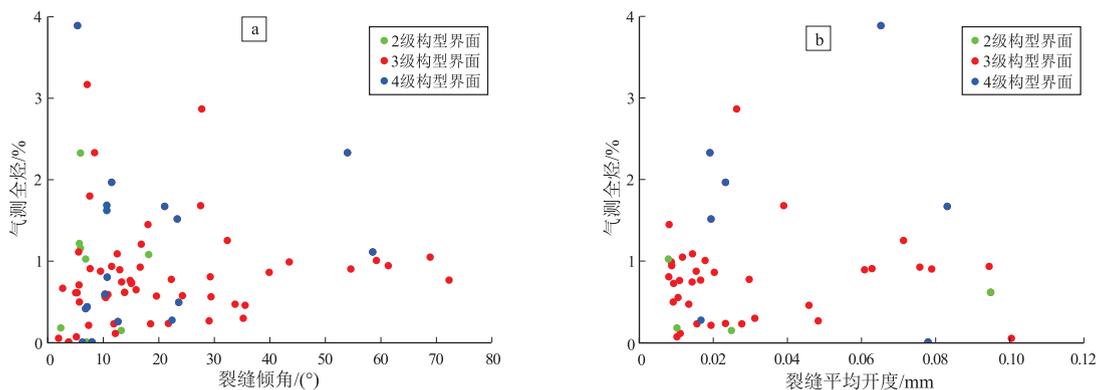


图 12 四川盆地西部坳陷须家河组二段气测全烃和裂缝参数的相关性

Fig. 12 Correlation between total hydrocarbons from gas logging and fracture parameters in second member of Xujiahe Formation, Western Sichuan Depression, Sichuan Basin

裂缝走向主要为 $160^{\circ} \sim 170^{\circ}$, 平均开度主要在 $0 \sim 0.02 \text{ mm}$; 3 级界面下裂缝发育程度高, 主要为低角度斜缝, 裂缝走向主要为 $0^{\circ} \sim 10^{\circ}$ 、 $100^{\circ} \sim 110^{\circ}$ 和 $160^{\circ} \sim 170^{\circ}$, 且平均开度较大 ($>0.04 \text{ mm}$) 的裂缝较多; 4 级界面下裂缝一般发育, 主要发育平缝, 裂缝走向主要为 $0^{\circ} \sim 10^{\circ}$, 平均开度主要在 $0 \sim 0.02 \text{ mm}$ 。

(3) 不同级次构型界面下发育的裂缝对储层物性的改善作用存在差异。4 级界面下裂缝对岩心孔隙度改善作用更明显, 而 3 级界面下裂缝对岩心渗透率的改善作用更明显。3 级界面下裂缝发育段的岩心孔渗关系最好, 4 级界面次之, 2 级界面最差。3 级界面下裂缝对储层孔渗改善作用最强, 油气贡献度最高; 4 级界面次之, 2 级界面最弱。

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

李莉妃负责论文撰写; 任启强负责论文构思和修改; 杨田和蔡来星负责提出构型界面划分方案; 李政和崔蓉参与数据收集。所有作者均阅读并同意最终稿件的提交。

LI Lifei was responsible for thesis writing. REN Qiqiang was responsible for the conception and modification of the paper. YANG Tian and CAI Laixing were responsible for proposing the architecture interface division scheme. LI Zheng and CUI Rong assisted in data collection. All authors have read the last version of the paper and consented to its submission.

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