

四川盆地剑阁地区须家河组致密砾岩储层 裂缝特征及对天然气产能的影响

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摘要:天然裂缝是致密砾岩储层重要的储集空间和主要的渗流通道,影响致密天然气的成藏、富集及单井产能。利用地表相似露头、岩心、薄片、测井和生产资料,在研究四川盆地剑阁地区须家河组致密砾岩储层天然裂缝类型和发育特征的基础上,分析并阐明了天然裂缝对天然气产能的影响。四川盆地剑阁地区须家河组致密砾岩储层发育穿砾缝、砾内缝和砾缘缝,从地质成因上,穿砾缝为构造裂缝,砾内缝包括构造、构造-成岩和母岩裂缝,砾缘缝为构造-成岩裂缝。其中穿砾缝的面密度、孔隙度和渗透率最大,其次为砾内缝,砾缘缝相对较小,穿砾缝对致密砾岩储层贡献更大,更有利于天然气富集高产。裂缝发育程度与产气量呈正相关,裂缝密度越大,产气量越高。在近东西(EW)向至NWW-SEE向现今地应力作用下,不同方向裂缝对天然气产能的贡献存在差异,其中近EW向裂缝地下开度相对较大,连通性好,对天然气产能贡献最大;其次为近NS和NW-SE向裂缝,NE-SW向裂缝对天然气产能的贡献较小。

关键词:产能;天然裂缝;致密砾岩储层;须家河组;剑阁地区;四川盆地

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Fracture characteristics and their influence on natural gas production: A case study of the tight conglomerate reservoir in the Upper Triassic Xujiahe Formation in Jian'ge area, Sichuan Basin

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Abstract: Natural fractures are important storage space and main seepage channels in tight conglomerate reservoirs, which function to influence the accumulation, enrichment and single-well productivity of tight gas. An integration of analogous outcrop, core, thin section, well log and production data, is applied to the study on the types and characteristics of natural fractures in the tight conglomerate reservoir of the Upper Triassic Xujiahe Formation in Jian'ge area, Sichuan Basin, and then the influence analysis of natural fractures on tight gas productivity. Trans-gravel, intra-gravel and gravel-edge fractures are developed in the tight conglomerate reservoirs. In terms of geological origin, trans-gravel fractures are tectonic fractures; intra-gravel fractures include tectonic, tectonic-diagenetic and parent-rock fractures; and gravel-edge fractures are tectonic-diagenetic fractures. Among others, trans-gravel fractures are the largest in areal density, porosity and permeability, followed by intra-gravel fractures and gravel-edge ones. Thus, the trans-gravel fractures are more contributive to the formation of the tight conglomerate reservoirs, and the most conducive to natural gas enrichment with

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high yield. The degree of fracture development is positively correlated with gas production; the greater the fracture density is, the greater the tight gas productivity could be. Under the present-day in-situ stress trending towards the nearly east-west (EW) to NWW-SEE direction, the contributions made by fractures of diverse directions are differential on the tight gas productivity. The nearly EW-trending fractures feature bigger apertures and good connectivity, being the most favorable area for tight gas production, followed by nearly NS- and NW-SE-trending fractures, and then the NE-SW-trending ones.

Key words: productivity, natural fracture, tight conglomerate reservoir, Xujiahe Formation, Jian'ge area, Sichuan Basin

随着能源需求日益增长,常规油气资源逐渐递减,砂砾岩储层等油气资源逐渐成为油气勘探的新领域。中国砂砾岩储层分布广泛,如新疆准噶尔盆地、克拉玛依油田、渤海湾盆地、二连盆地、大庆油田徐家围子断陷及四川盆地北部等地均有分布^[1-2]。通常砂砾岩储层致密、非均质强、分布复杂,裂缝发育^[1-3]。裂缝是致密砾岩储层重要的储集空间和渗流通道,影响着致密砾岩储层的油气成藏、富集和高产^[4-5]。弄清致密砾岩储层天然裂缝的发育特征及对产能的贡献,可以为致密砾岩储层油气的探勘开发提供地质依据。

前人对致密砾岩储层的沉积特征、储层特征、主控因素、致密化成因、有利储层成因及高产控制因素进行了研究^[6-12],一些学者对致密砾岩储层裂缝的分布特征、控制因素、预测方法及其贡献也开展了一些研究工作^[3-5,13-14],相对而言,对致密砾岩储层的裂缝研究较少。目前,对四川盆地剑阁地区研究主要集中在古隆

起的基本特征、成因及演化及致密砂岩储层的层序演化、沉积与储层特征^[15-30],而对须家河组致密砾岩储层尚未开展系统的裂缝研究。本文综合利用地表相似露头、岩心、薄片、测井和生产动态等资料,在对四川盆地剑阁地区须家河组致密砾岩储层天然裂缝发育特征研究的基础上,探讨了天然裂缝对天然气产能的影响,可以为该地区致密砾岩储层天然气的有效勘探开发提供地质依据,同时为致密砾岩储层天然裂缝研究提供一个实例。

1 地质概况

剑阁地区位于四川盆地川西地区北部,北临米仓山台缘隆起带,西接龙门山推覆断褶构造带,位于秦岭造山带与上扬子陆块北缘接合部的米仓山台缘隆起断褶构造带前缘和川北平缓构造带^[15-17](图1)。

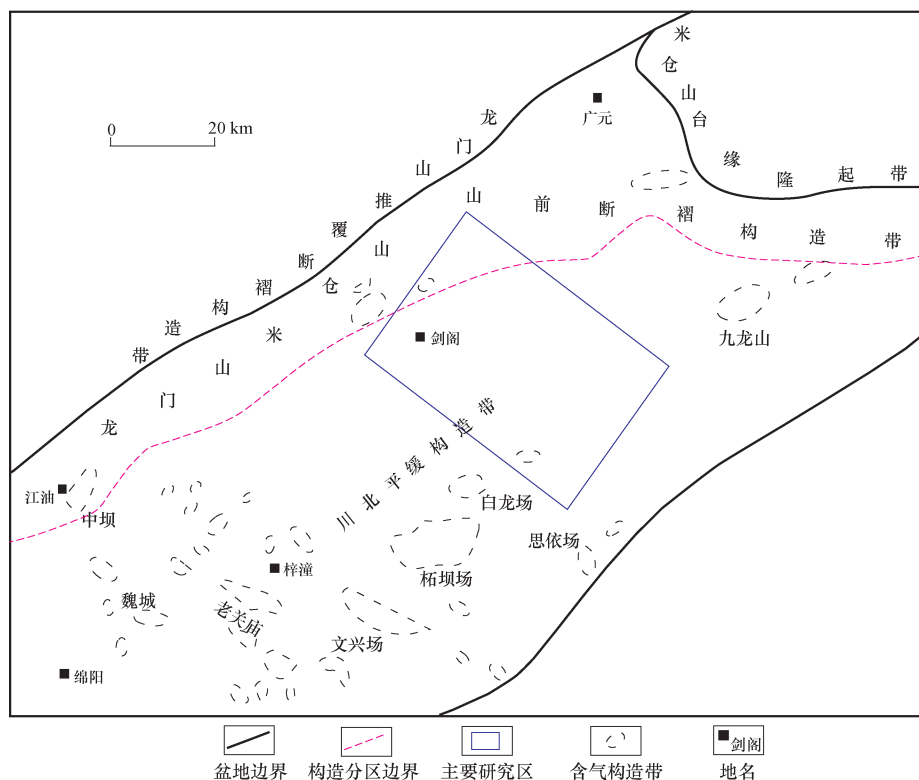


图1 四川盆地剑阁地区区域构造位置

Fig. 1 The map of regional tectonic location of Jiang'e area, Sichuan Basin

川西北地区须家河组三段(须三段)沉积时期在龙门山前发育冲积扇,剑阁地区主要为扇三角洲-湖泊的沉积环境,主要发育扇三角洲前缘亚相和滨浅湖亚相^[19,21]。根据地表露头、地震、钻井和测井资料,上三叠统须家河组自下而上分为须一段至须五段,共 5 段,因后期抬升剥蚀作用强烈,剑阁地区大部分地区发育须一至须四段,缺少须五段^[21]。其中须一段主要为黑色页岩、泥岩与灰色细砂岩夹泥质粉砂岩及薄层煤层;须二段为一套巨厚的浅灰色块状中、细粒砂岩夹薄-中厚层状页岩及煤线组成;须三段厚度稳定,以薄-中厚层状岩屑砂岩,砾岩与泥页岩不等厚互层;须四段顶部为灰云屑砂岩和黑色页岩互层,中上部灰云屑砂岩夹页岩,下部夹黑色页岩与细粒灰云屑砂岩互层夹褐灰色砾岩,底部为大套砾岩夹薄层石英砂岩;须五段主要为黑色页岩和泥岩夹泥质粉砂岩、细砂岩和薄层煤层^[21-22]。近期,在剑阁地区须二段、须三段和须四段测试均获得工业气流,显示良好的勘探开发前景^[17,21]。

剑阁地区须家河组砾岩储层主要分布在须三段和须四段中。根据岩心和测井资料,须家河组单层砾岩厚度一般较小,砂地比大约为 40%,以泥岩层为主夹薄层砾岩。根据样品物性分析结果,致密砾岩储层孔隙度主要分布在 1%~3%,最高可达 8%,渗透率主峰值分布在 $0.001 \times 10^{-3} \mu\text{m}^2 \sim 0.01 \times 10^{-3} \mu\text{m}^2$,属于低孔低致密储层。

更新世以来的构造应力场即现今应力场可用震源机制解、井径崩塌法、诱导裂缝、水力压裂及声发射等方法来测得^[23-28]。根据成像测井资料反映的诱导裂缝方位,剑阁地区须家河组现今应力场最大主应力为 NWW-SEE 至近 EW 方向,优势方向为 280°(图 2)。剑阁地区现今地应力方向主要受龙门山构造活动的影响,米仓山构造活动对其影响较小^[29]。

2 砾岩储层裂缝类型与发育特征

通过地表相似露头、岩心、薄片和成像测井资料分析,四川盆地剑阁地区须家河组致密砾岩储层中发育的裂缝根据裂缝与砾岩颗粒之间的关系,可分为穿砾缝、砾缘缝和砾内缝(表 1;图 3);根据裂缝的地质成因,可分为在构造应力场作用形成的构造裂缝、在构造应力场作用下成岩过程中形成的构造-成岩裂缝以及在早期母岩中形成的母岩裂缝^[4]。

穿砾缝切穿砾石颗粒,缝面平直,延伸较长,可达数十米,具有方向性明显、分布规则的特征,在地质成

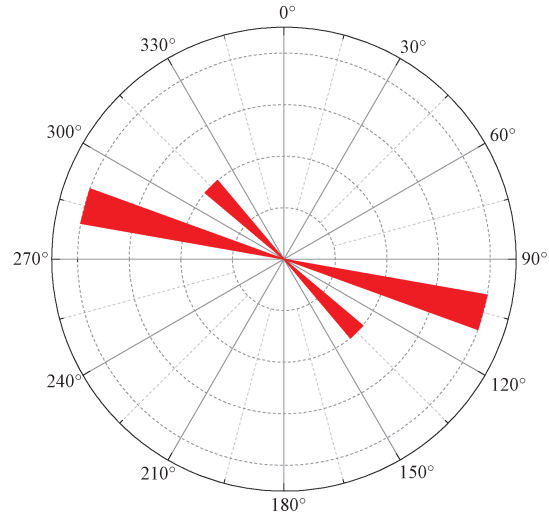


图 2 剑阁地区现今最大水平主应力方向玫瑰花图
Fig. 2 The rose diagram showing the present-day maximum horizontal principal stress direction in Jian'ge area

表 1 剑阁地区须家河组致密砾岩储层裂缝分类
Table 1 Fracture types of the tight conglomerate reservoirs in the Xujiache Formation in Jian'ge area

砾岩裂缝类型	地质成因	发育特征
穿砾缝	构造裂缝	切穿砾石颗粒,缝面平直,延伸较长
砾缘缝	构造-成岩裂缝	顺着砾石颗粒边缘分布,其形态与砾石颗粒形态有关
	构造裂缝	与穿砾缝近平行,缝面平直
	构造-成岩裂缝	垂直于砾石接触面,延伸较短
砾内缝	母岩裂缝	发育在砾石颗粒内部,无规则,被石英等矿物全充填

因上为构造裂缝(表 1)。根据地表相似露头 and 成像测井资料,剑阁地区须家河组致密砾岩储层主要发育近 EW 向、近 NS 向、NW-SE 向和 NE-SW 向 4 组穿砾缝(图 4),以高角度和低角度为主。通过对研究区微观薄片观察和统计分析,大部分穿砾缝没有被充填,少数穿砾缝被沥青、方解石、炭质和泥质等充填;在数量上,穿砾缝较发育,占砾岩裂缝总数的 39%(图 5a);穿砾缝面密度为 90 m/m^2 ,反映穿砾缝较发育(图 5b);薄片上穿砾缝延长长度一般为数厘米,穿砾缝开度一般小于 $50 \mu\text{m}$,主要分布在 $20 \sim 30 \mu\text{m}$;根据 Monte Carlo 方法^[30-32],穿砾缝孔隙度主要分布在 1.0%~3.0%,平均为 1.43%(图 5c),穿砾缝渗透率一般小于 $1 \times 10^{-3} \mu\text{m}^3$,部分穿砾缝渗透率达数十毫达西。

砾缘缝一般沿着砾石颗粒边缘分布,其形态与砾石颗粒形态有关,是强烈的机械压实、压溶作用、溶蚀

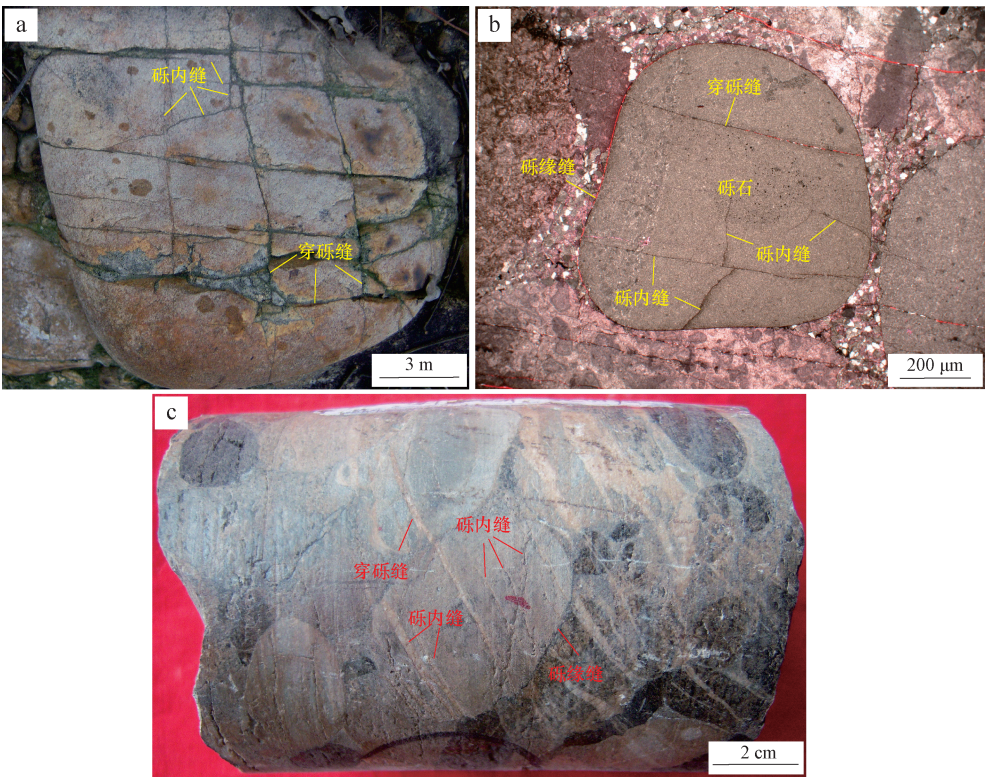


图 3 剑阁地区须家河组致密砾岩储层裂缝照片

Fig. 3 Pictures of fractures in the tight conglomerate reservoirs in the Xujiache Formation in Jian'ge area
a. 地表露头砾岩裂缝,须家河组; b. 薄片砾岩裂缝,JM103 井,埋深 4 455.7 m,红色为树胶;
c. 岩心砾岩裂缝,JM104 井,埋深 4 232.05 ~4 232.15 m,箭头指示裂缝

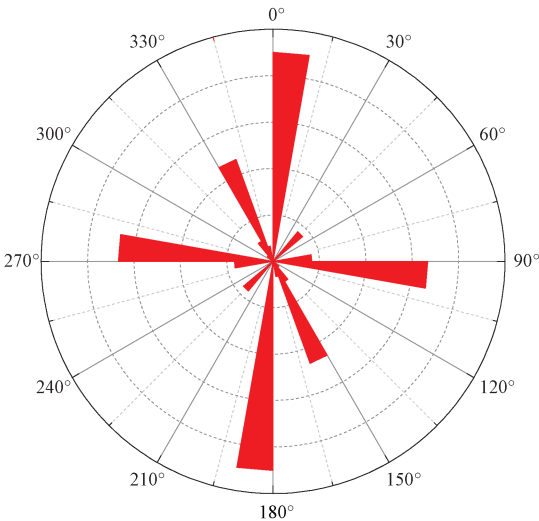


图 4 剑阁地区须家河组致密砾岩储层裂缝走向玫瑰花图
Fig. 4 The rose diagram showing the strike of the tight conglomerate reservoir fractures in the Xujiache Formation in Jian'ge area

作用和后期构造挤压作用共同作用的结果,在地质成因上为构造-成岩裂缝(表 1)。通过对剑阁地区须家河组致密砾岩储层的微观薄片观察和统计分析,大部分砾缘缝没有被充填,少数被方解石、沥青、

炭质和泥质等充填;在数量上,砾缘缝数量最少,占砾岩裂缝总数的 4%(图 5a);砾缘缝面密度小于 10 m/m^2 ,反映砾缘缝相对不发育(图 5b);砾缘缝开度一般小于 $10\text{ }\mu\text{m}$;根据 Monte Carlo 方法^[30-32],砾缘缝孔隙度一般小于 0.1%(图 5c),其渗透率一般小于 $0.1\times 10^{-3}\text{ }\mu\text{m}^3$ 。

砾内缝是指裂缝在砾石颗粒内部发育,终止在砾石颗粒内部或砾石边缘,延伸较短。不同形态的砾内缝其地质成因亦存在差异,其中与穿砾缝平行的砾内缝,缝面平直,具有明显的方向性,表现为与穿砾缝同期形成的裂缝,为构造作用形成的裂缝,在地质成因上为构造裂缝(表 1;图 3c);其次,部分砾内缝垂直于砾石接触面,延伸较短,没有明显的方向性,为构造和成岩作用共同作用形成的裂缝,在地质成因上为构造-成岩裂缝(图 3b);此外,少数砾内缝无规则分布在砾石颗粒内部,无明显的规律,且被石英完全充填,这类裂缝形成时期早于构造裂缝和构造-成岩裂缝,为早期母岩中形成的裂缝,在地质成因上为母岩裂缝^[4]。通过对剑阁地区须家河组砾岩储层的微观薄片观察和统计分析,大部分砾内缝没有被充填,少数砾内缝被沥青、石英、方解石、炭质和泥质等充填;在数量上,砾内

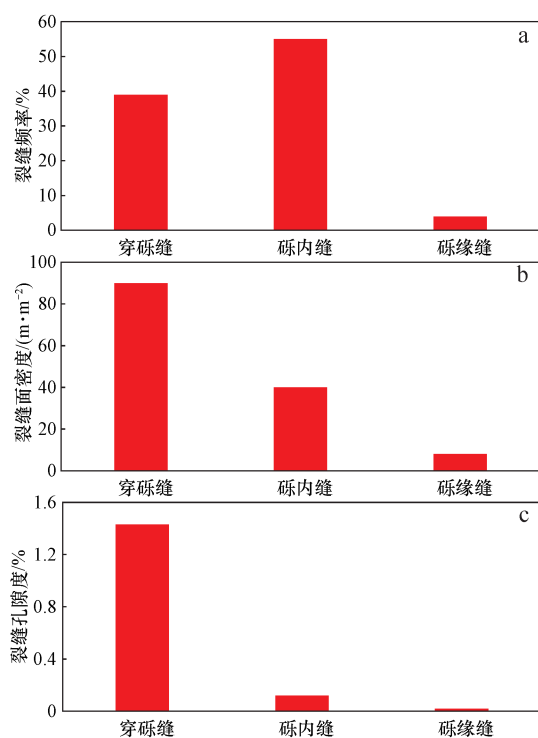


图5 剑阁地区须家河组致密砾岩储层微观裂缝频率、面密度和孔隙度分布 ($n=111$)

Fig.5 The frequency, areal density and porosity distribution of microfractures of the tight conglomerate reservoirs in the Xujiahe Formation in Jian'ge area ($n=111$)
a. 裂缝频率分布直方图; b. 裂缝面密度分布直方图;
c. 裂缝孔隙度分布直方图

缝的数量最多,占砾岩裂缝总数的55%(图5a);砾内缝面密度为40 m/m²,反映砾内缝较发育(图5b);薄片上,砾内缝延伸长度一般为数微米至数百微米;砾内缝开度一般小于10 μm;根据 Monte Carlo 方法^[30-32],砾内缝孔隙度主要分布在0.08%~0.2%,平均为0.12%(图5c),其渗透率一般小于 $0.1 \times 10^{-3} \mu\text{m}^3$ 。

3 裂缝对天然气产能的影响

生产动态资料显示,剑阁地区须家河组致密砾岩储层单井产能差异较大。通过分析剑阁地区须家河组致密砾岩储层主要测试产气段的电成像测井资料和岩心裂缝资料,在主要的产气层段天然裂缝普遍发育,且裂缝有效性好,少数裂缝被充填;而气测显示差的井段,通常裂缝发育程度差。如JM1井须三段储层中A段,测井显示储层物性好,录井显示日产气 $9.0 \times 10^4 \text{ m}^3$,电成像测井显示A段裂缝发育,且裂缝未被矿物充填,为有效裂缝;而B段测井显示储层物性差,录井显示无气测异常,成像测井显示B段裂缝不发育(图6)。这表明有效

裂缝对致密砾岩储层的天然气产能起重要的控制作用。

不同类型天然裂缝的发育特征存在较大差异,对致密砾岩储层的贡献也不相同。砾缘缝数量最少,规模和开度较小,其面密度和孔隙度小于穿砾缝和砾内缝,其渗透率远低于穿砾缝;虽然砾内缝数量比穿砾缝数量多,但是由于砾内缝规模和开度较小,而穿砾缝的规模和开度较大,砾内缝的面密度和孔隙度明显比穿砾缝低,砾内缝的渗透率较穿砾缝低。与致密砾岩储层基质孔隙度和渗透率相比,穿砾缝、砾内缝和砾缘缝增加了致密砾岩储层的储集空间,提高了致密砾岩储层的渗透性,尤其是穿砾缝极大提高了致密砾岩储层的渗透性,同时高角度和低角度穿砾缝交织构成了渗流网络。这说明穿砾缝是致密砾岩储层的有效渗流通道和重要的储集空间,砾内缝和砾缘缝沟通了基质孔隙,提高了致密砾岩储层的连通性,是致密砾岩储层重要的储集空间。相对砾内缝和砾缘缝而言,穿砾缝对致密砾岩储层渗流的贡献更大,更有利于致密天然气的富集高产。

天然裂缝发育程度直接影响天然气产量,裂缝发育程度越高,产气量越高;反之,裂缝发育程度越低,相应的产气量越低。当裂缝发育程度相近时,裂缝开度和裂缝发育方位的不同,天然气产能亦存在差异。如JM1井和LG61井产气层段裂缝密度分别为1.1条/m和1.0条/m,裂缝发育程度相似,而产气量存在较大差异,其中JM1井的产气量为 $9 \times 10^4 \text{ m}^3/\text{d}$,LG61井的产气量为 $4.9 \times 10^4 \text{ m}^3/\text{d}$ 。分析发现JM1井产气层段主要发育近EW向裂缝,其次为NW-SE向裂缝,平均裂缝开度为62 μm,而LG61井产气层段主要发育近EW向和NS向裂缝,其次为NW-SE向裂缝,平均裂缝开度为55 μm(图7)。

JM101井和JM104井产气层段裂缝密度分别为1.3条/m和1.2条/m,裂缝发育程度相似,而产气量存在较大差异,其中JM101井的产气量为 $21.27 \times 10^4 \text{ m}^3/\text{d}$,JM104井的产气量为 $3.39 \times 10^4 \text{ m}^3/\text{d}$ 。分析发现JM101井产气层段主要发育近EW和NS向裂缝,平均裂缝开度为73 μm,JM104井产气层段发育四组裂缝,其中以近EW向为主,其次为NW-SE向、NS向和NE-SW向裂缝,平均裂缝开度为70 μm。这说明当裂缝发育程度相似,裂缝开度和裂缝发育的方位存在差异,其对天然气产能的贡献存在差异。通过统计分析发现,剑阁地区须家河组主要产气层裂缝开度与产气量呈正相关,裂缝开度越大,产气量越高。为了进一步综合反映裂缝发育程度和开度对天然气产量的贡献,本文将裂缝开度和裂缝密度的乘积定义为裂缝有

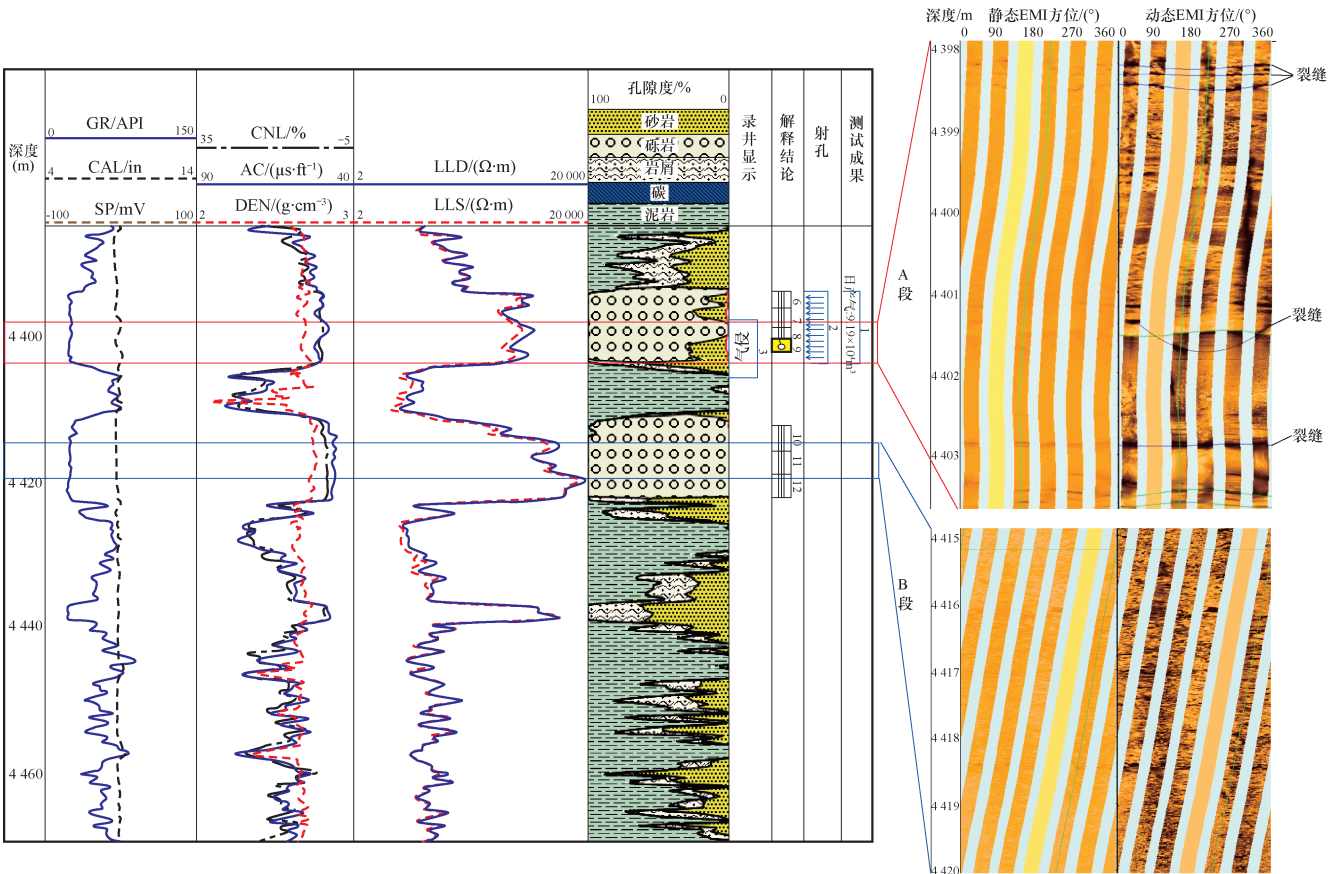


图 6 剑阁地区 JM1 井须三段产气情况与裂缝发育情况对比

Fig. 6 The comparison of gas production and fracture development in the 3rd member of Xujiache Formation in Well JM1 in Jian'ge area
A 段裂缝发育,物性较好,日产气 $9.0316 \times 10^4 \text{ m}^3$; B 段裂缝不发育,无气测异常

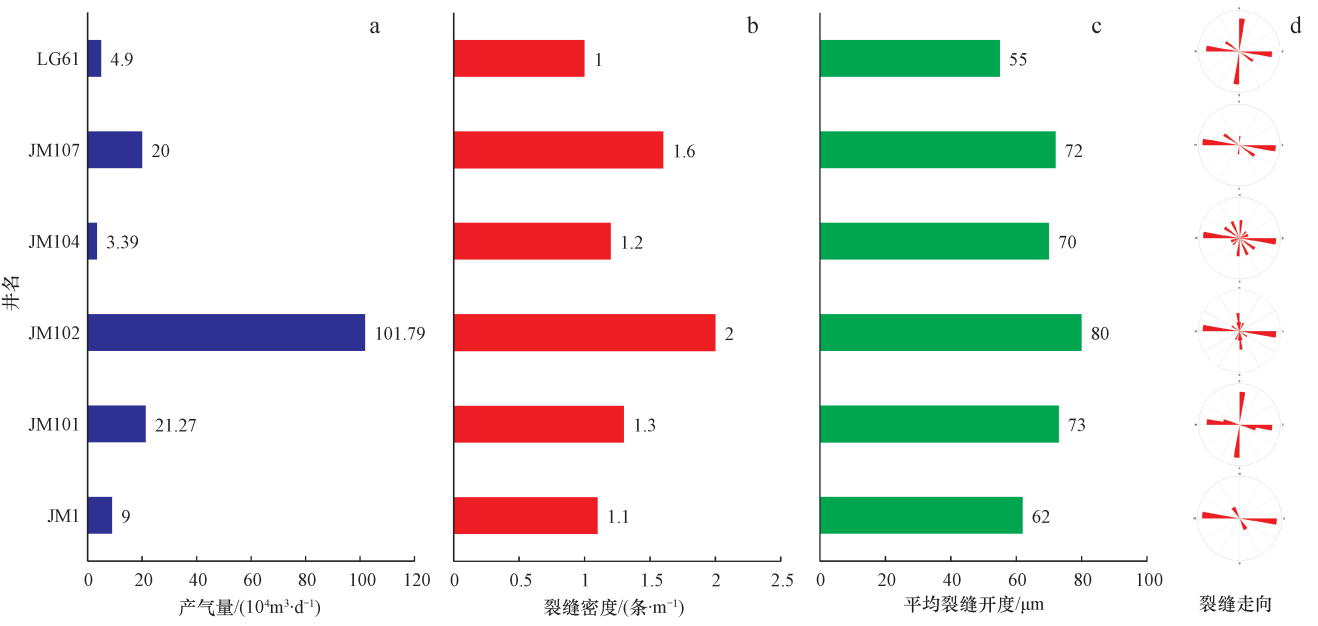


图 7 剑阁地区各井须三段主要产气层产气量与裂缝特征

Fig. 7 The gas production and fracture characteristics of the major gas pay zones in the 3rd member of Xujiache Formation in Jian'ge area
a. 不同井产气量分布; b. 不同井裂缝密度分布; c. 不同井平均裂缝开度分布; d. 不同井裂缝走向分布

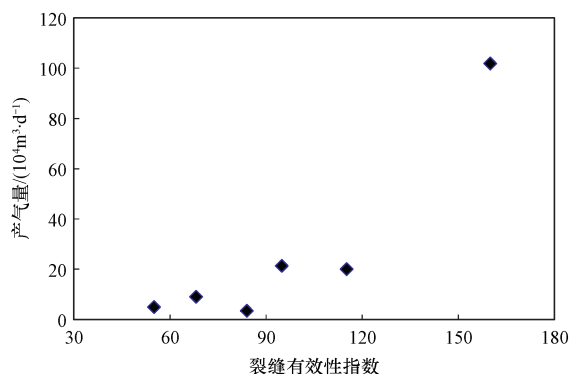


图8 剑阁地区须三段主要产气层裂缝有效性指数与产气量关系

Fig.8 The relationship between the fracture effectiveness index and the gas production of the major gas pay zones in the 3rd member of Xujiahe Formation in Jian'ge area

效性指数。通过统计表明,剑阁地区须家河组主要目的层的天然气产量与裂缝有效性指数之间呈较好的指数关系,裂缝有效性指数越大,产气量越高(图8)。

JM107井产气层段裂缝密度为1.6条/m,稍大于JM101井产气层段裂缝密度(1.3条/m),但JM107井的产气量($20 \times 10^4 \text{ m}^3/\text{d}$)略低于JM101井的产气量($21.27 \times 10^4 \text{ m}^3/\text{d}$),分析发现JM107井主要发育近EW向裂缝,其次为NW-SE向和近NS向裂缝,平均裂缝开度为72 μm ,而JM101井主要发育近EW向裂缝和NS向裂缝,平均裂缝开度为73 μm (图7)。这说明虽然裂缝的平均开度相近,但由于发育裂缝的方位存在差异,而不同方向裂缝的有效性存在差异,其对天然气产能的贡献存在差异。这是由于在现今地应力作用下,当化学成岩作用较弱时,不同方向裂缝的有效性存在差异^[31,33-35]。受现今应力场(优势方位为280°,图2)的影响,近EW向裂缝地下开度大,连通性好,有效性好,为主渗流方位,其次为NW-SE向和近NS向裂缝,而NE-SW向裂缝有效性较差,对渗流的影响较小。

通过统计剑阁地区须家河组致密砾岩储层主要产气层段裂缝方位的分布情况,其中以近EW向裂缝为主,占裂缝总数的50%;其次为NS向和NW-SE向裂缝,分别占裂缝总数的29%和18%;NE-SW向裂缝相对较少,占裂缝总数的3%。通过上述分析表明,研究区致密砾岩储层近EW向裂缝有效性最好,发育程度最高,对天然气产能的贡献最大,其次为NS向和NW-SE向裂缝,NE-SW向裂缝有效性较差,发育程度较差,对产能的贡献相对较小。研究区JM102井产气层段裂缝较发育,主要发育近EW向裂缝,其次为近NS向裂缝,NW-SE向和NE-SW向裂缝相对不发

育,平均裂缝开度较大为80 μm ,该井为高产井,产气量达 $101.79 \times 10^4 \text{ m}^3/\text{d}$ (图7)。

4 结论

1) 四川盆地剑阁地区须家河组致密砾岩储层裂缝可以分为穿砾缝、砾内缝和砾缘缝。主要发育近EW向、近NS向、NW-SE向和NE-SW向4组裂缝。

2) 不同类型裂缝对储层及天然气产能的贡献存在差异。穿砾缝是致密砾岩储层的有效渗流通道和重要的储集空间,砾内缝和砾缘缝是致密砾岩储层重要的储集空间;较砾内缝和砾缘缝,穿砾缝对致密砾岩储层的贡献更大,更有利于致密天然气的富集高产。

3) 裂缝发育程度、裂缝开度及主渗流裂缝方位控制了致密砾岩储层的天然气产能。裂缝发育程度和裂缝开度与产气量均呈正相关,裂缝密度和裂缝开度越大,产气量越高;在现今地应力作用下,近EW向裂缝地下开度大,连通性好,有效性好,为主渗流方位,发育程度最高,对天然气产能的贡献最大,其次为NW-SE向和近NS向裂缝,NE-SW向裂缝有效性较差,发育程度较差,对产能的贡献相对较小。

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