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陆相页岩储层天然裂缝发育特征及主控因素
——以渤南洼陷沙河街组三段下亚段为例

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摘要：天然裂缝是济阳坳陷渤南洼陷陆相页岩储层重要的储集空间与渗流通道之一，天然裂缝的发育特征及成因机制直接制约着单井产能。利用地震解释、岩心与薄片观察、扫描电镜、全岩X射线衍射（XRD）等手段对渤南洼陷沙河街组三段下亚段（以下简称沙三下亚段）构造样式、天然裂缝发育特征、主控因素及有效裂缝对单井产能的影响进行研究。结果表明：沙三下亚段天然裂缝按照成因类型可划分为构造缝、成岩缝、生烃增压缝，构造缝根据地质成因分为剪切缝、张性缝、顺层滑脱缝；天然裂缝发育类型整体以直立剪切缝（75°～90°）为主，天然裂缝整体延伸长度不长（5～10 cm），张性缝的缝宽略宽（0.5～1.0 mm）；充填物主要为方解石、沥青，剪切缝无充填占比较高。天然裂缝形成主控因素包括距断层距离、构造组合样式、碳酸盐矿物含量、有机质含量及岩相组合类型，距离断层近、断层上盘、断块型构造组合样式导致天然裂缝较发育；碳酸盐矿物、有机质含量与天然裂缝发育程度呈正比关系，碳酸盐质页岩相、长英质页岩相天然裂缝较为发育。未—半充填高角度剪切缝、未—半充填张性缝是对页岩油产能贡献最大的有效裂缝，其次为未充填顺层滑脱缝。该研究有利于深化东部陆相页岩油天然裂缝形成机制的规律性认识，为渤南洼陷乃至整个济阳坳陷裂缝型页岩油的勘探开发实践提供重要依据。

关键词：渤南洼陷；沙三下亚段；陆相页岩；天然裂缝；主控因素
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Development characteristics and main controlling factors of natural fractures in continental shale reservoirs: A case study of lower submember of third member of Shahejie Formation in Bonan Subsag

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Abstract: Natural fractures are important reservoir spaces and seepage channels in continental shale reservoirs of the Bonan Subsag, Jiyang Depression. The development characteristics and genetic mechanisms of these fractures directly affect the productivity of single wells. Seismic interpretation, core and thin section observation, scanning electron microscopy, and X-ray diffraction (XRD) analysis were employed to investigate the structural styles, development characteristics of natural fractures, main controlling factors, and the influence of effective fractures on single-well productivity in the lower submember of the third member of the Shahejie Formation in the Bonan Subsag. The results showed that natural fractures in the lower submember of the third member of the Shahejie Formation were classified by genesis into tectonic fractures, diagenetic fractures, and hydrocarbon-generating overpressure fractures. Tectonic fractures were further subdivided based on geological origin into shear fractures, tensile fractures, and bedding-slip fractures. The dominant type of natural fractures was the vertical shear fractures (75°-90°). Overall, the fracture extension lengths were relatively short (5-10 cm), and tensile fractures exhibited slightly larger apertures (0.5-1.0 mm). The fracture fillings were mainly calcite and asphalt, with a high proportion of shear fractures remaining

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unfilled. The main controlling factors of natural fracture formation included distance from faults, structural combination style, carbonate mineral content, organic matter content, and lithofacies combination types. Natural fractures were more developed near faults, on the fault hanging wall, and in fault-block structural combination styles. Carbonate mineral and organic matter contents were positively correlated with the degree of natural fracture development. Natural fractures were relatively well developed in carbonate-rich shale facies and felsic shale facies. Unfilled and partially filled high-angle shear fractures and tensile fractures were the effective fracture types that contributed most to shale oil productivity, followed by unfilled bedding-slip fractures. This study helps deepen the understanding of the formation mechanisms of natural fractures in eastern continental shale oil, providing an important basis for the exploration and development of fractured shale oil reservoirs in the Bonan Subsag and the entire Jiyang Depression.

Keywords: Bonan Subsag; lower submember of third member of Shahejie Formation; continental shale; natural fracture; main controlling factors

页岩是具有低孔、低渗的致密性储层,页岩储层中开启的天然裂缝是有效的储集空间和渗流通道,极大影响了页岩油气的富集、保存、运移、成藏[1-4]。天然裂缝也是页岩油气后期开发压裂过程中重要的评价因素之一[5-11],存在大量天然裂缝或者经过水力压裂造缝后的页岩可以成为页岩油气的优质产层,进而影响页岩油气藏的开采效益。

目前,专家学者针对南方海相页岩储层、东部陆相页岩储层的天然裂缝均做了深入研究。裂缝发育特征主要包括裂缝类型、参数特征、充填物种类、赋存位置及与层理面的关系等[12-13]。裂缝发育的主控因素包括构造因素与非构造因素[14-18],构造因素主要包括断裂和褶皱,断裂规模及其活动强度控制天然裂缝的发育程度,褶皱对构造裂缝发育的影响主要体现在岩层曲率的变化上[5]。研究裂缝发育演化模式,与裂缝形成的地质力学机制匹配,从而分析页岩气保存条件的优劣以及页岩油气富集运移规律[19-21]。天然裂缝成因机理的研究也是构造应力关系、构造应力场模拟、工程地质建模等方法开展裂缝分布预测的前提[22-31]。基于裂缝参数与产能参数交会分析,可以明确不同类型裂缝对产能的贡献程度,天然裂缝对油气的产出具有重要作用,裂缝可作为基质型孔隙储集空间的有效补偿,与此同时裂缝也可以为基质中油的产出提供有利输导条件[32-33]。济阳坳陷裂缝型页岩油分为2种:一种为传统的泥页岩裂缝型,济阳坳陷早期发现的页岩油主要为该类油气藏,如沾化凹陷的罗42井在沙三段灰褐色油页岩中获得峰值日产油量为117 t的高产工业油流,自喷期累积产油量达到10 322 t;另一种为断裂系统发育的构造型页岩油,如东营凹陷南坡永54井,日产油量为46.5 t,生产668 d累积产油量为14 594 t。裂缝也是导致致密油藏储层压窜的重要因素,牛庄洼陷南部构造断裂带NY1-1HF井钻井过程中钻遇天然裂缝,发生了多次井涌井漏。因此,裂缝型页岩油具有初期产能高,后期产量递减快的特点。近年来天然裂缝分布规律不清,尤其是国内对于济阳坳陷页岩储层天然裂缝影响页岩油气富集、单井产能的原因仍不明确。

东部渤海湾盆地济阳坳陷古近系具有沉积相变快、沉积厚度大、成熟度低、地层年代新、构造演化复杂的特点[34-39],致使陆相断陷湖盆页岩天然裂缝发育特征与海相页岩天然裂缝存在较大差异;天然裂缝对于页岩气保存更多起到的是破坏作用,对于页岩油则增大其渗流作用。因此,以济阳坳陷渤南洼陷沙三下亚段页岩储层天然裂缝为研究对象,深入剖析陆相页岩天然裂缝的发育特征、主控因素及其对单井产能的影响,为渤南洼陷页岩油藏的有效勘探开发提供重要目标导向与实际意义。

1 区域地质概况

渤南洼陷是我国东部典型的页岩油聚集洼陷之一[40],自1964年开始勘探以来,已有多口钻井在沙三下亚段泥页岩层段获得高产工业油流,展现了渤南洼陷巨大的页岩油勘探潜力[41-44]。渤南洼陷是济阳坳陷沾化凹陷东北部的一个北断南超的二级构造单元,北邻埕东凸起,东接孤岛潜山带,南临三合村洼陷、陈家庄凸起,西为义和庄凸起,洼陷整体走向呈北东向,洼陷内发育多条东西向断裂,边界断层则呈现北东、北西向延伸的特点[35-46]。研究区共经历了泰山、加里东、海西和印支4次大规模构造活动,中、晚三叠世,研究区发育北西向断裂,整体处于水平挤压应力场中;晚侏罗世,研究区发育北东向具有走滑性质的断裂,整体处于左旋走滑应力场中;燕山—喜马拉雅期,发育大量近东西向断裂,整体处于右旋走滑应力场中[47-48]。古近系主要发育沙河街组、东营组两套地层,沙四段、沙三下亚段、沙一段(沙河街组一段)发育3套烃源岩(图1),其中沙三下亚段为主要生油层系,泥页岩厚度大,最厚处可达920 m,发育泥岩、灰质泥岩、灰质油泥岩、油页岩、油泥岩5种岩性,为深湖—半深湖相沉积[49]。

目前,在渤南、博兴、牛庄、民丰、利津5个富油洼陷初期单井产油量介于51.6~262.8 t/d,总产油量为972.63 t/d,平均单井产油量为32.42 t/d,累计产油量为30.71×10^4 t。大尺度裂缝和薄夹层复合型页岩油气是高产的页岩油气类型,如河54井距断裂1 km,日产油量为91.3 t,日产气量为4.68×10^4 m^3,投产后累计产油量为17 222 t,目前已在多地区见到此类页岩油气,如樊119井、樊120井、王76井、高7井、樊140井等[50-53]。

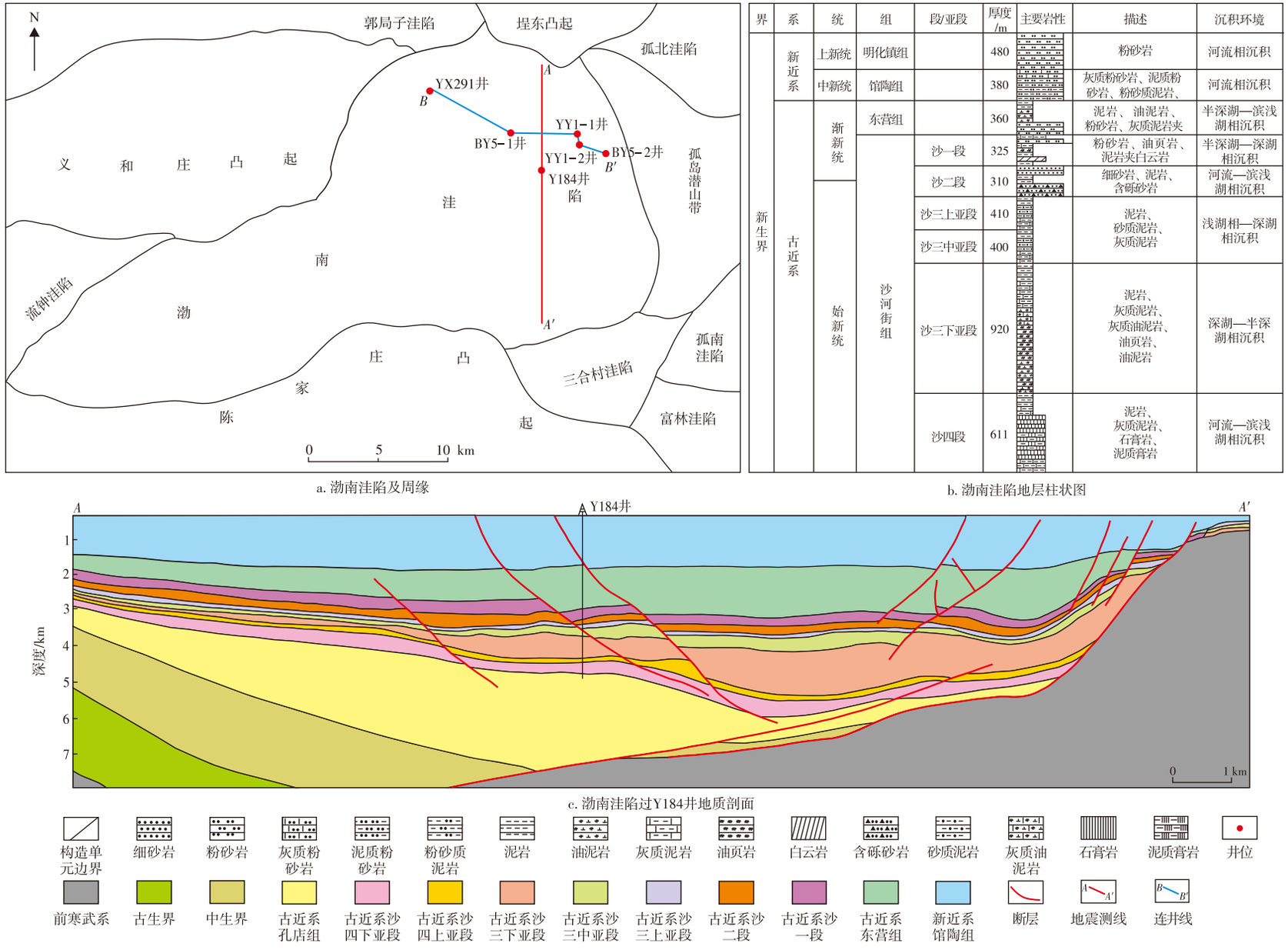


图1　渤南洼陷区域地质特征及地层柱状图

Fig. 1　Regional geological characteristics and stratigraphic column of Bonan Subsag

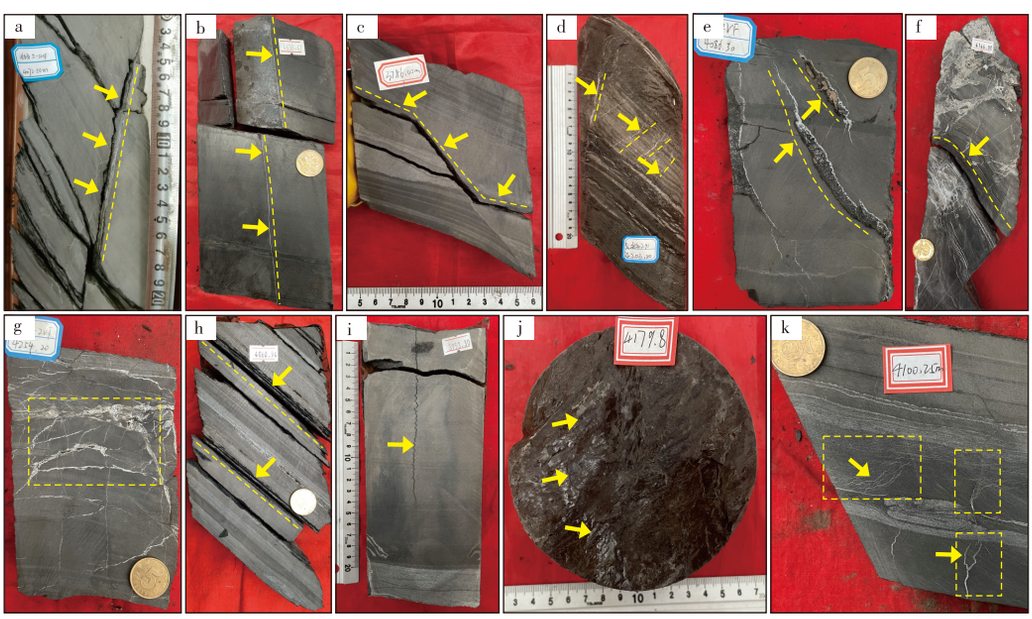
2　天然裂缝发育特征

2.1　天然裂缝宏观发育特征

2.1.1　天然裂缝类型

通过对渤南洼陷5口页岩油井（渤页5-1井、渤页5-2井、义斜291井、义页1-1井、义页1-2井）进行沙三下亚段岩心天然裂缝发育特征观察与描述，岩心总体埋深介于3～5 km，目的层最厚处可达600 m，裂缝倾角普遍大于70°，岩相变化快且天然裂缝类型复杂。5口井岩心累计长度共计2.5 km，合计共观察描述裂缝1 294条。

根据岩心、薄片、成像测井裂缝发育特点，结合其地质历史时期构造运动期次的影响[5]，按照成因类型划分为3类缝，分别为构造缝、成岩缝、生烃增压缝，其中构造缝根据力学成因分为剪切缝（图2a、图2b）、张性缝（图2d、图2e、图2g）、顺层滑脱缝（图2c、图2f、图2j），成岩缝分为层理缝（图2h）、压溶缝（图2i）、生烃增压缝（图2k）[54-57]。5口井整体以发育剪切缝为主，剪切缝占比60%；其次是顺层滑脱缝，占比30%；张性缝占比10%。按照裂缝倾角大小分为4种不同类型的裂缝，分别为水平缝（0°～<15°）、低角度缝（15°～<45°）、中—高角度缝（45°～<75°）、直立缝（75°～90°）。在5口页岩油井天然裂缝中，直立缝725条，占比55.0%；中—高角度缝152条，占比11.8%；低角度缝49条，占比3.7%；水平缝387条，占比29.5%。说明渤南洼陷天然裂缝发育类型整体以直立缝为主，其次为水平缝。



注：a. 剪切缝，无充填，渤页5-2井，4 072.50 m；b. 剪切缝，方解石充填，义页1-1井，4 638.47 m；c. 逆断层，发育顺层滑脱缝，渤页5-1井，3 786.00 m；d. 张性缝，发育在砂质条带中，方解石充填，义斜291井，4 203.20 m；e. 张性缝，方解石、沥青充填，义页1-2井，4 086.30 m；f. 韧性剪切带中的顺层滑脱缝，剪切带呈现压扭状态地层呈“S”形，发育镜面擦痕，渤页5-2井，4 146.80 m；g. 张性缝（网状），方解石充填，义页1-2井，4 254.20 m；h. 层理缝，发育镜面擦痕，渤页5-2井，4 060.94 m；i. 压溶缝，无充填，渤页5-1井，3 953.30 m；j 顺层滑脱缝，发育镜面擦痕，义斜291井，4 179.80 m；k. 生烃增压缝，方解石、沥青充填，渤页5-2井，4 100.25 m。

图2　渤南洼陷沙三下亚段不同类型天然裂缝岩心照片

Fig. 2　Core photos of different types of natural fractures in lower submember of third member of Shahejie Formation in Bonan Subsag

2.1.2　天然裂缝参数特征

根据裂缝延伸长度大小，将裂缝分为4种不同等级的裂缝：短缝介于0～<5 cm，中缝介于5～<10 cm，中—长缝介于10～15 cm，长缝大于15 cm。在5口页岩油井天然裂缝中，剪切缝短缝占比20.2%，中缝占比35.1%，中—长缝占比25.2%，长缝占比19.5%；张性缝短缝占比50.5%，中缝占比27.6%，中—长缝占比10.3%，长缝占比11.6%；顺层滑脱缝均为中缝。

根据裂缝宽度分布范围，将裂缝宽度分为<0.5 mm，0.5～1.0 mm，>1.0 mm。剪切缝缝宽小于0.5 mm占比83.6%，缝宽介于0.5～1.0 mm占比4.2%，缝宽大于1.0 mm占比12.2%；张性缝缝宽小于0.5 mm占比6.8%，缝宽介于0.5～1.0 mm占比78.2%，缝宽大于1.0 mm占比15.0%；顺层滑脱缝缝宽均小于0.5 mm。

剪切缝以发育中缝、缝宽小于0.5 mm为主，张性缝以发育短缝、缝宽介于0.5～1.0 mm为主，顺层滑脱缝在地下几乎处于紧闭状态，缝宽较小，说明陆相页岩天然裂缝与海相差别较大，天然裂缝整体延伸长度不长，张性缝的缝宽略宽（图3a、图3b）。

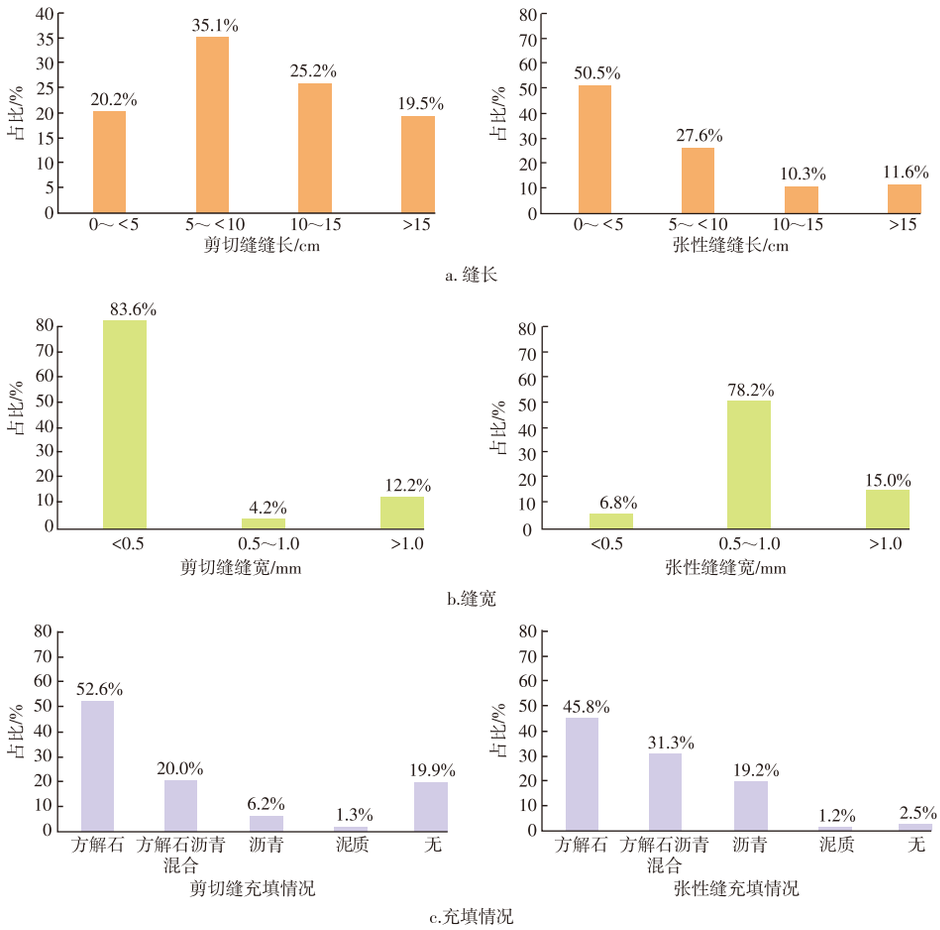


图3　渤南洼陷沙三下亚段剪切缝、张性缝的缝长、缝宽、充填情况

Fig. 3　Length, width, and filling of shear fractures and tensile fractures in lower submember of third member of Shahejie Formation in Bonan Subsag

义页1-2井成像测井产状特征显示，高导缝（剪切缝、张性缝）未被方解石、黄铁矿等矿物充填，在FMI图像上呈现为红色正弦曲线，走向以北西向、高角度为主；高阻缝（剪切缝、张性缝）缝内被方解石、黄铁矿等矿物充填，在FMI图像上呈现为亮黄色正弦曲线，走向以北西西至南东东向、高角度为主；层间缝（层理缝、顺层滑脱缝）无填充，在FMI图像上显示与地层产状近似平行的特征，走向以近北西向低角度为主（图4、图5）。

2.1.3　天然裂缝充填物种类

5口页岩油井天然裂缝充填物类型共有5种，分别为方解石充填、方解石沥青混合充填、沥青充填、泥质充填、无充填。剪切缝被方解石充填占比52.6%，方解石沥青混合充填占比20%，沥青充填占比6.2%，泥质充填占比1.3%，无充填占比19.9%；张性缝被方解石充填占比45.8%，方解石沥青混合充填占比31.3%，沥青充填占比19.2%，泥质充填占比1.2%，无充填占比2.5%；顺层滑脱缝均无充填（图3c）。剪切缝的无充填占比最大，说明有效性更好，对油气储集有利。

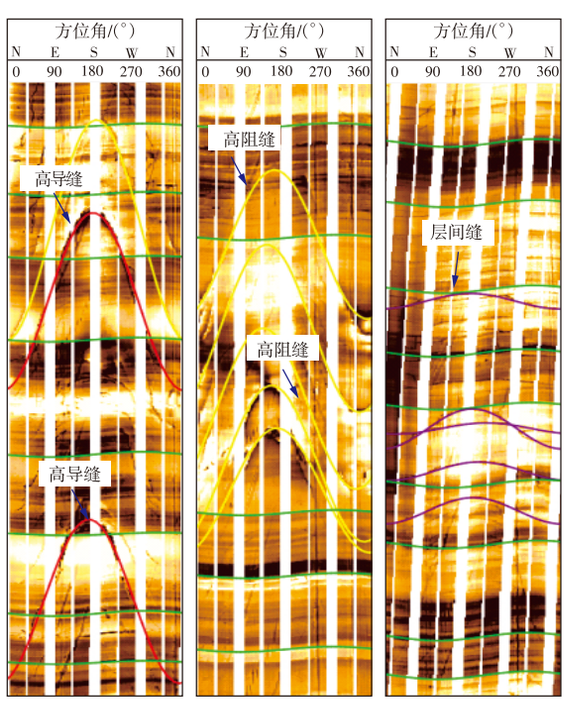


图4　渤南洼陷沙三下亚段义页1-2井FMI成像测井裂缝识别类型

Fig. 4　Fracture identification types of FMI imaging logging in well YY1-2 in lower submember of third member of Shahejie Formation in Bonan Subsag

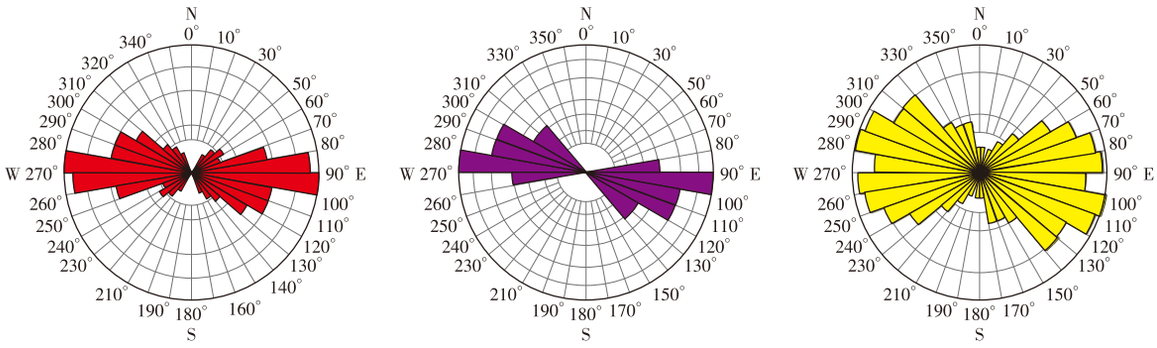


图5　渤南洼陷沙三下亚段义页1-2井成像测井天然裂缝走向统计

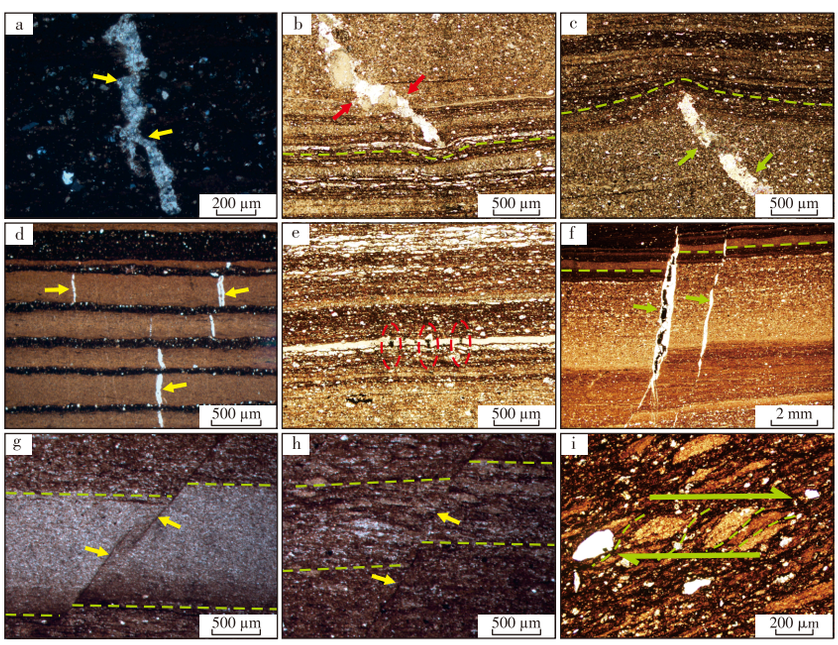
Fig. 5　Statistics of natural fracture trend from imaging logging in well YY1-2 of lower submember of third member of Shahejie Formation in Bonan Subsag

2.2　天然裂缝微观发育特征

根据天然裂缝镜下特征的差异，将其分为构造缝与成岩缝，成岩缝又分为层理缝、粒缘缝、粒内缝。基于普通薄片、荧光薄片、扫描电镜特征显示，构造缝在镜下多数以毫米级尺度呈现，成岩缝则以微米级尺度呈现。

2.2.1　构造缝

构造缝在镜下显示出剪切缝特征，与层面夹角介于45°～90°，以中—高角度剪切缝、直立剪切缝为主，延伸长度介于0.5～6.0 mm，平均值为3.25 mm，缝宽介于1～200 μm，平均值为100 μm，切穿脆性矿物、层理面，消失于软弱泥质纹层中（图6a—图6e），并形成微断层（图6g、图6h），裂缝内被细晶方解石、沥青和泥炭质充填，方解石充填早于沥青、次生硅质（图6f）；除剪切缝反映出的张扭性力学性质之外，根据矿物“多米诺”式定向排列也可以反映出研究区经历过走滑剪切应力作用（图6i）。



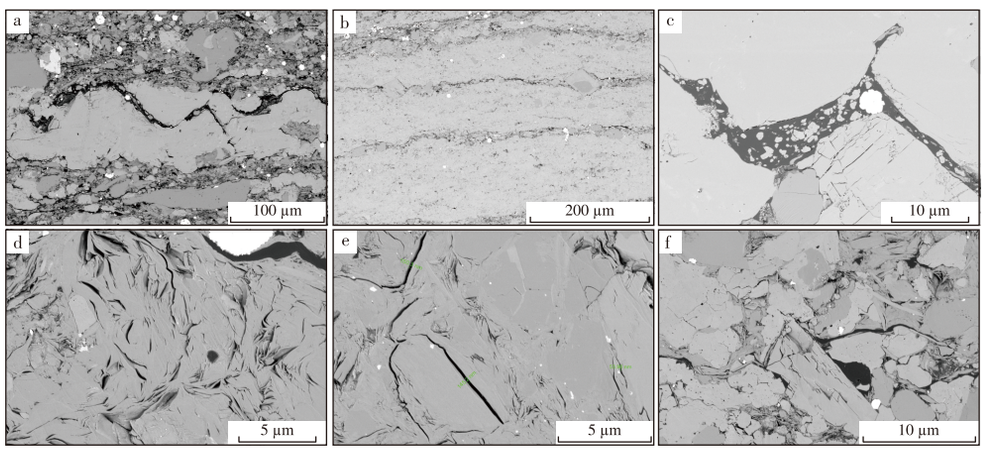
注：a. 直立剪切缝，灰质泥岩发育，方解石充填，义页1-1井，5 026.10 m，正交光；b. 中—高角度剪切缝，底部消失在泥岩软弱层中，灰质泥岩发育，方解石充填，义斜291井，4 203.20 m，单偏光；c. 中—高角度剪切缝，顶部消失在泥岩软弱层中，灰质泥岩发育，方解石充填，义斜291井，4 204.20 m，单偏光；d. 直立剪切缝，灰岩层发育，方解石充填，渤页5-1井，4 118.47 m，单偏光；e. 方解石条带中发育短小直立剪切缝，沥青充填，灰质泥岩发育，义斜291井，4 226.20 m，单偏光；f. 直立剪切缝，层位发生错断，灰质泥岩发育，方解石、沥青充填，义斜291井，4 263.30 m，单偏光；g. 正断层，砂泥岩层发育，渤页5-2井，4 045.89 m，单偏光；h. 正断层，灰质泥岩发育，渤页5-2井，4 047.00 m，单偏光；i. 方解石呈“多米诺”式定向排列，灰质泥岩发育，义页1-1井，5 009.10 m，单偏光。

图6　渤南洼陷沙三下亚段薄片天然裂缝发育特征

Fig. 6　Development characteristics of natural fractures in thin sections of lower submember of third member of Shahejie Formation in Bonan Subsag

2.2.2　成岩缝

基于氩离子抛光扫描电镜可以观察到大量纳米—微米级的成岩缝，其形成与重结晶、有机质沉淀、生排烃、体积收缩等因素密切相关。镜下显示层理缝缝长介于80～100 μm，缝宽介于10～20 μm，其延伸方向与矿物的定向排列方向一致（图7a、图7b）；粒缘缝缝长介于5～20 μm，缝宽介于0.5～5.0 μm，粒缘缝通常存在于矿物颗粒之间，缝内被有机质、亮晶方解石、自生石英充填（图7c—图7e）；粒内缝分布在矿物晶体之内，在长石和碳酸盐等矿物中较为常见，其形成主要受溶蚀作用的影响，有机质热演化过程中排出的大量有机酸是引起溶蚀作用的原因[58-60]（图7f）。



注：a. 重结晶形成层理缝，有机质充填，渤页5-1井，3 730.3 m；b. 层理缝，渤页5-1井，3 941.0 m；c. 粒缘缝充填沥青，渤页5-1井，3 804.0 m；d. 黏土矿物粒缘缝，渤页5-1井，4 056.0 m；e. 黏土矿物粒缘缝，渤页5-1井，4 057.9 m；f. 钠长石粒内缝，渤页5-1井，3 730.3 m。

图7　渤南洼陷沙三下亚段扫描电镜下天然裂缝发育特征

Fig. 7　Development characteristics of natural fractures under scanning electron microscopy in lower submember of third member of Shahejie Formation in Bonan Subsag

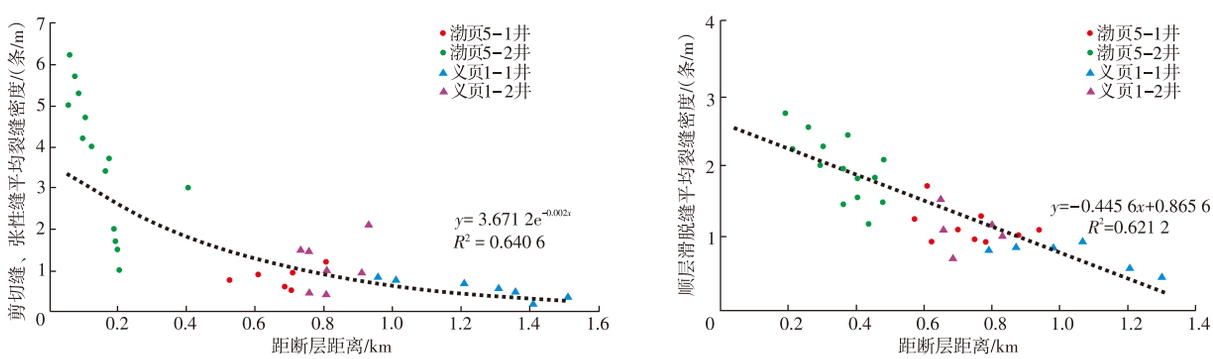
3　页岩裂缝发育主控因素

3.1　构造因素

3.1.1　断层对裂缝发育程度的控制

渤南洼陷整体发育北西、北东以及近东西向的断层，3个走向的断层叠加分布。4口试油井（义斜291井未试油，在此不再针对该井进行详细讨论）渤页5-1井、渤页5-2井、义页1-1井、义页1-2井天然裂缝发育程度受孤西断层、渤深4北断层的影响。孤西断层为渤南洼陷控洼断层，断层整体走向北西、倾向南西[48]，下部地层断至中生界，上部地层断至沙一段，在沙三段沉积期消亡；渤深4北断层整体走向近东西，倾向北东，为喜马拉雅期发育的断层，下部地层断至沙三段，上部地层断至平原组。

渤页5-2井、义页1-1井位于孤西断层上盘，渤页5-1井、义页1-2井位于渤深4北断层的上盘。通过对4口井沙三下亚段13砂组不同小层剪切缝、张性缝、顺层滑脱缝密度统计显示，不同小层的3种裂缝密度与距断层距离成反比关系。渤页5-2井沙三下亚段13砂组距离孤西断层小于500 m，3种裂缝发育程度最高；义页1-1井距离孤西断层大于等于800 m，3种裂缝发育程度相对较低（图8）。



a. 剪切缝、张性缝平均裂缝密度与距断层距离的线性关系　　b. 顺层滑脱缝平均裂缝密度与距断层距离的线性关系

图8　渤南洼陷4口井剪切缝、张性缝、顺层滑脱缝平均裂缝密度与距断层距离的线性关系

Fig. 8　Linear relationship between average fracture density of shear, tensile, and bedding-slip fractures and distance from faults in four wells in Bonan Subsag

通过对4口试油井成像测井天然裂缝密度进行统计，断层上盘平均天然裂缝密度大于下盘，说明断层上盘构造活动强度大，天然裂缝更发育（图9）。

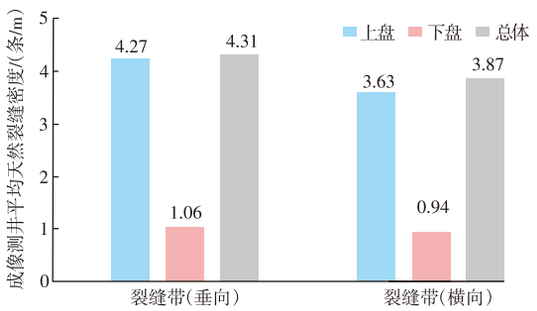


图9　渤南洼陷裂缝带平均天然裂缝密度与断层上、下盘的关系

Fig. 9　Relationship between average natural fracture density in fracture zones and fault hanging wall and footwall in Bonan Subsag

3.1.2　构造组合样式对裂缝发育程度的控制

构造应力的差异导致断层构造组合样式的不同，从而影响单井目的层段裂缝发育程度。渤页5-2井为断块型，目的层位于两条断层的相交处，为张扭应力作用下的强烈挤压变形区；义页1-2井为阶梯型，发育一系列正断层形成断阶构造，地层产状倾斜，构造变形相对强烈；渤页5-1井为地堑型，处于两条正断层之间平缓地层处，断层规模较小，构造变形较弱；义页1-1井为正断层上盘的单斜构造，距离断层较远，构造变形弱。构造组合样式变形强度为断块型>阶梯型>地堑型>单斜型，4口井天然裂缝密度大小依次为渤页5-2井>义页1-2井>渤页5-1井>义页1-1井，说明构造变形越强的组合样式，天然裂缝发育程度越高（图10）。

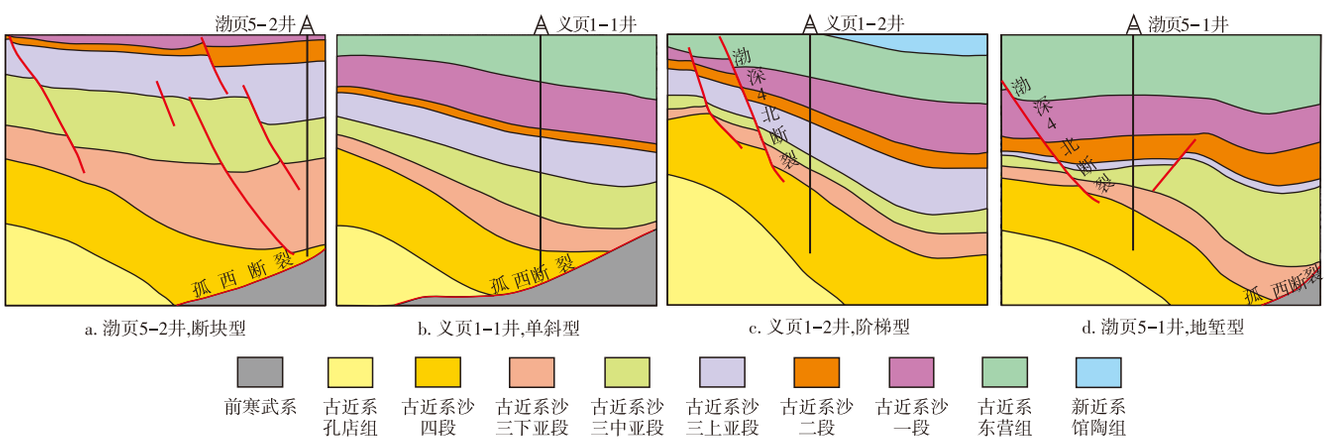


图10　渤南洼陷过4口井构造组合样式剖面

Fig. 10　Profiles of structural combination styles across four wells in Bonan Subsag

3.2　非构造因素

3.2.1　碳酸盐矿物成分与有机质含量

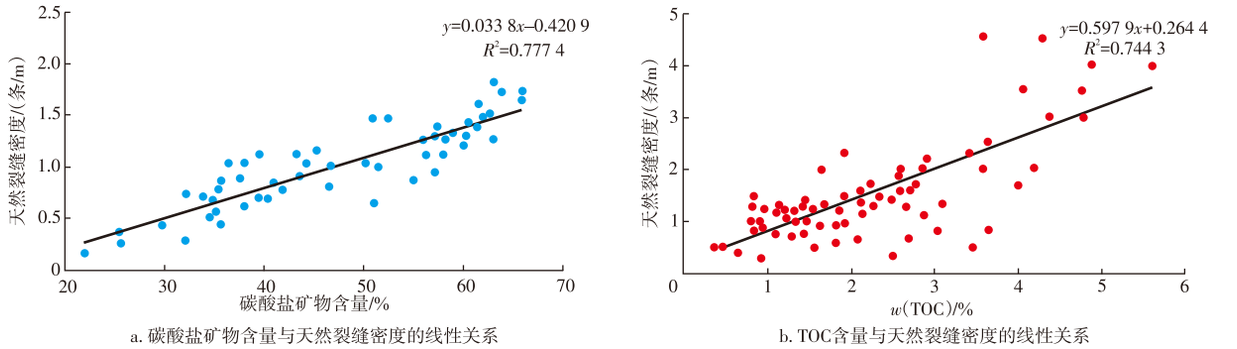
渤南洼陷深洼带沙三下亚段岩性主要为碳酸盐矿物、长英质矿物、黏土矿物3类，其中以碳酸盐矿物为主，碳酸盐矿物含量介于20%～70%，碳酸盐矿物包括方解石、白云石等，碳酸盐矿物含量越高，储层脆性越大，天然裂缝发育程度越高[5,14]。通过对研究区4口页岩油井天然裂缝密度进行统计显示，碳酸盐矿物含量与天然裂缝密度具有较好的正相关性（图11a），此外，在微—亮晶方解石发育的地方天然裂缝密度更大。

TOC（总有机碳）含量越高，有机质生烃能力越强，富有机质页岩在生烃过程会产生局部异常压力如欠压实作用、有机质生烃增压等，当局部异常压力大于岩石破裂压力时，页岩层则更易发生破裂[5]。统计数据显示TOC含量与天然裂缝密度也具有较好的正相关关系（图11b），说明TOC含量越高，天然裂缝越发育[52]。

3.2.2　陆相页岩岩相组合

天然裂缝发育程度与页岩岩相类型相关。根据渤南洼陷5口井矿物组分特征及中国石化胜利油田岩相分类方案，将渤南洼陷页岩岩相细分为7大类：富有机质纹层— 层状碳酸盐质页岩相（TOC含量大于2%，碳酸盐质大于50%）、含有机质纹层—层状碳酸盐质页岩相（TOC含量小于2%，碳酸盐质大于50%）、富有机质纹层—层状混合质页岩相（TOC含量大于2%，碳酸盐质、长英质、黏土质均小于50%）、含有机质纹层—层状混合质页岩相（TOC含量小于2%，碳酸盐质、长英质、黏土质均小于50%）、富有机质纹层—层状黏土质页岩相（TOC含量大于2%，黏土质大于50%）、富有机质纹层—层状长英质页岩相（TOC含量大于2%，长英质大于50%）、含有机质纹层—层状长英质页岩相（TOC含量小于2%，长英质大于50%）。

连井剖面对比图（图12）显示，剪切缝在4口井沙三下亚段13砂组均有发育，渤页5-2井、义页1-2井发育程



a. 碳酸盐矿物含量与天然裂缝密度的线性关系　　b. TOC含量与天然裂缝密度的线性关系

注：w(TOC)为TOC含量，%。

图11　渤南洼陷沙三下亚段碳酸盐矿物含量、TOC含量与天然裂缝密度的线性关系

Fig. 11　Linear relationship between carbonate mineral content, TOC content, and natural fracture density in lower submember of third member of Shahejie Formation in Bonan Subsag

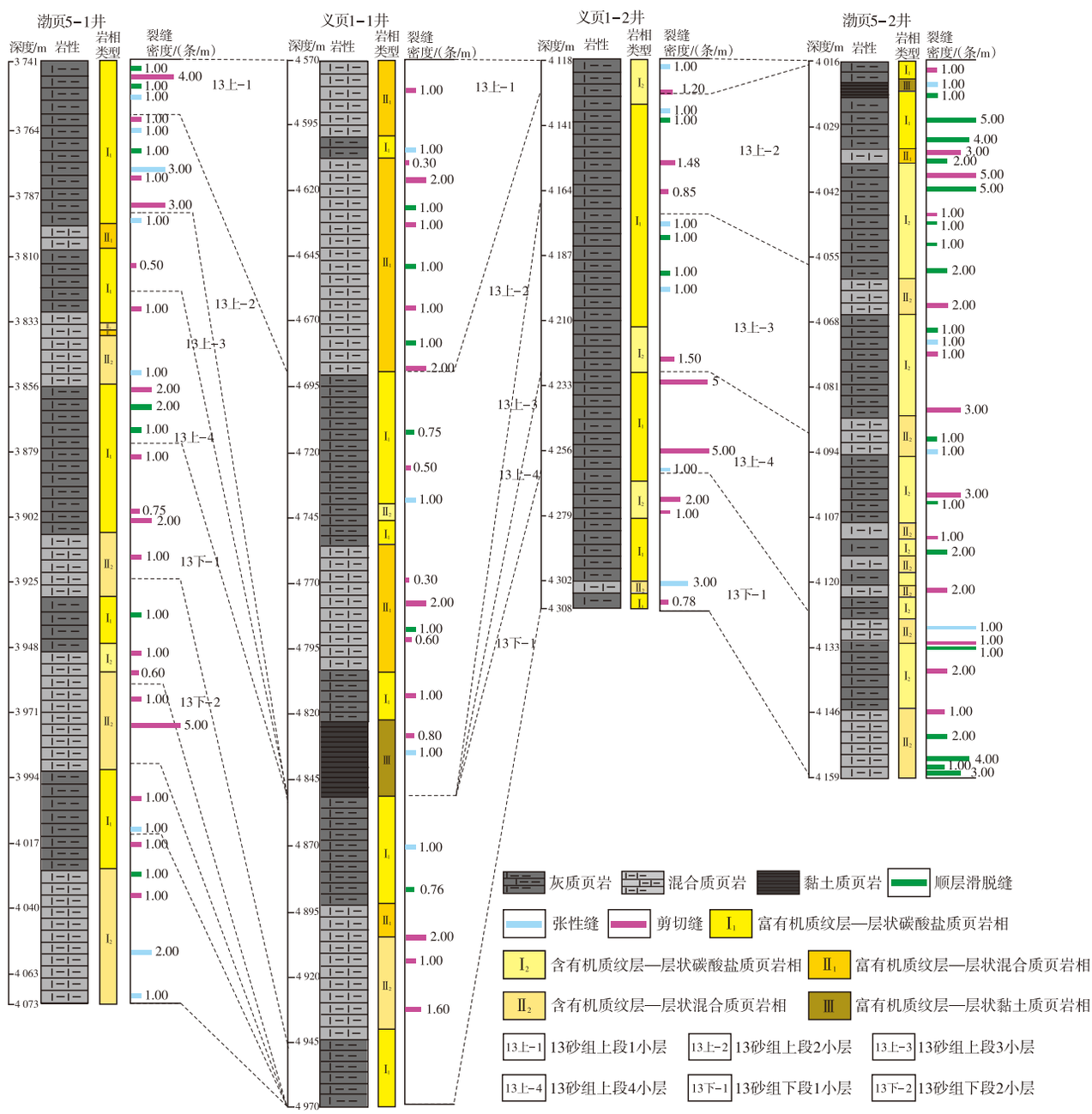


图12　渤页5-1井、义页1-2井、义页1-1井、渤页5-2井岩相与裂缝发育情况连井剖面对比

Fig. 12　Comparison of correlated well profiles of lithofacies and fracture development in wells BY5-1, YY1-2, YY1-1, and BY5-2

度明显，其中渤页5-2井发育较多的顺层滑脱缝，渤页 5-1 井、义页1-1井2口井天然裂缝密度相对较低。根据岩相类型与裂缝发育程度关系显示，富有机质纹层—层状碳酸盐质页岩相裂缝密度最大，其次为富有机质纹层—层状长英质页岩相、含有机质纹层—层状长英质页岩相，说明碳酸盐矿物方解石、长英质矿物石英等含量越高，脆性越大，裂缝易发育；在同等岩性组合条件下，有机质含量越高，裂缝越发育。

4 有效裂缝发育与产能的关系

渤南洼陷4口试油井均采用4 mm油嘴放喷，同一时间段内单井产能显示，渤页5-1井日产油量为52.1 t，累计产油量为9 990 t；渤页5-2井日产油量为35.7 t，累计产油量为12 460 t；义页1-2井日产油量为10 t，累计产油量为3 817 t；义页1-1井日产油量为7.2 t，累计产油量为4 429 t。4口井日产油量为渤页5-1井>渤页5-2井>义页1-2井>义页1-1井。

未—半充填天然裂缝即为有效裂缝，对页岩油产能产生贡献，渤页5-1井有效裂缝占比为32.2%，有效裂缝均为未—半充填高角度剪切缝、未—半充填张性缝，有利于增大储集空间以及页岩油渗流能力；渤页5-2井有效裂缝占比26.7%，80%以上的有效裂缝为无充填顺层滑脱缝，虽然顺层滑脱缝在地下处于紧闭状态，但仍有利于压裂改造；义页1-2井有效裂缝占比7.2%，剪切缝、张性缝几乎都被方解石、沥青充填，天然裂缝有效性较低；义页1-1井天然裂缝不发育，且天然裂缝几乎都是全充填，既不能增大储集空间，又不利于压裂改造。综上所述，未—半充填高角度剪切缝、未—半充填张性缝是对页岩油产能贡献最大的有效裂缝，其次为未充填顺层滑脱缝。

5 结论

1）渤南洼陷天然裂缝整体以发育直立剪切缝为主，其次为水平顺层滑脱缝；天然裂缝整体延伸长度不长，以短、中缝为主，剪切缝缝宽小于张性缝缝宽；天然裂缝走向整体以北西、北西西至南东东向为主；天然裂缝充填矿物以方解石为主，无充填占比最大，说明有效性更好。构造缝在镜下显示出剪切缝特征，与层面夹角介于45°～90°，以中—高角度剪切缝、直立缝剪切为主，反映出研究区经历过走滑剪切应力作用；基于氩离子抛光扫描电镜可以观察到大量纳米—微米级的非构造缝，主要分为粒缘缝、粒内缝、层理缝。

2）页岩天然裂缝发育主控因素分为构造与非构造因素。构造因素包括距断层距离与构造组合样式，距断层越近，构造组合样式为断块型，天然裂缝发育密度越大；非构造因素包括碳酸盐矿物含量、有机质含量及岩相组合类型，碳酸盐矿物、TOC含量与天然裂缝密度具有较好的正相关性，富有机质纹层—层状碳酸盐质页岩相裂缝密度最大。

3）未—半充填高角度剪切缝、未—半充填张性缝是对页岩油产能贡献最大的有效裂缝，其次为未充填顺层滑脱缝。

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