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储层质量控制因素与优质储层测井预测 ——以福山凹陷流沙港组储层为例

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摘要 【目的】福山凹陷是北部湾盆地富油气凹陷之一, 流沙港组为主力产油层段, 储层控制因素不明且缺乏配套的预测技术, 制约了油气勘探开发的进程, 亟须揭示储层控制因素, 形成一套适用于研究区的测井预测方法。【方法】在分析储层岩石学、储集空间和物性特征的基础上, 以粒度、分选、接触方式等大量岩心分析实验为依据, 从沉积微相、成岩相和裂缝相“三元控储”角度揭示了储层质量控制因素, 并建立了相应的测井表征方法与识别标准。【结果】沉积微相、成岩相及裂缝相对于流沙港组储层质量均具有明显控制作用, 通过建立不同类型沉积微相、成岩相和裂缝相与储层质量参数之间的关系, 发现水下分流河道、河口坝高能水动力条件下对应压实强度低且溶蚀作用发育层段为优质储层发育段, 而裂缝的发育对储层质量具有明显改善作用。基于三相耦合(沉积微相+成岩相+裂缝相)并结合4项重要储层特征参数划分出四类储层。【结论】油气解释结论表明, 该方法可以有效评价和预测优质储层发育层段。该研究可为流沙港组增储上产提供理论指导, 为储集层的精细表征及优质储集体的预测和评价提供借鉴。

关键词 流沙港组; 沉积微相; 成岩相; 裂缝相; 控制因素; 优质储层预测

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0 引言

近年来我国油气勘探重心逐渐向低渗透油气藏转移^[1-3], 而储层是油气藏研究的重点内容^[4]。福山凹陷作为北部湾盆地富油气凹陷之一, 具有良好的勘探前景^[5]。流沙港组储层为该区最为重要的产层, 地质构造和油气聚集条件十分复杂^[6]。前人从沉积、成岩和构造等不同方面开展了储层特征研究, 明确了储层物性影响因素, 建立了适用于研究区的岩性、物性、含油性测井解释模型^[7-9]。但目前福山凹陷流沙港组储层的控制因素尚未明确^[10], 导致储层区域评价、预测及油气勘探开发受到限制。

碎屑岩储层受沉积、成岩和构造的共同控制^[11], 沉积、成岩控制了孔隙的形成与分布, 构造(裂缝)则

有利于进一步扩大储集空间^[12], 三者结合可有效评价储层物性^[13]。现今油气勘探理论认为油气藏都处于有利相带中, 是有利“相”耦合的结果^[14]。碎屑岩储层控制因素研究也逐渐从沉积环境、成岩作用的角度转向沉积、成岩和裂缝相的相控理论, 即“三元控储”^[15-16]。基于沉积微相、成岩相及裂缝相的“三元控储”机理可从内因和外因两方面反映储集性能^[17]。因此, 结合研究区储层沉积背景相变快, 成岩作用强以及裂缝发育的特点, 利用储层沉积微相、成岩相和裂缝相耦合的“三元控储”模式来阐明研究区储层质量主控因素十分必要。

通过分析岩心、薄片、扫描电镜、物性等资料, 从早期沉积、后期成岩改造和构造作用等方面出发, 对福山凹陷流沙港组储层沉积特征、成岩作用类型与

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强度及裂缝发育情况展开讨论,并从“相控论”的角度揭示沉积微相、成岩相及裂缝相三者耦合对储层的控制作用,以期为研究区有效识别和预测优质储层提供理论依据,提高优质储层测井识别符合率,进而推动该区域油气勘探开发和产能建设。

1 区域地质背景

福山凹陷为北部湾盆地东南部一个呈“北断南超”的箕状断陷湖盆,总面积为2 880 km²^[18]。南以海南隆起为界,西部和东部分别以徐闻隆起和云龙凸起为邻。其形态受临高、长流和定安三大断裂控制。福山凹陷为一个二级构造单元,构造演化经历了古近纪张裂(断陷)和新近纪裂后(拗陷)两个阶段^[19-20]。按构造和沉积特征,福山凹陷又可分为北部断阶带、中北断槽带、中部构造带和南部斜坡带等四个次一级构造单元(图1)^[21-22]。

福山凹陷从下至上发育白垩系、古近系(长流组、流沙港组和涠洲组)、新近系及第四系^[23]。本文研究目的层主要为古近系流沙港组,为一套滨浅湖相—半深湖相以及辫状河三角洲相沉积^[24]。流沙港组自下而上可进一步划分为流三段、流二段和流一段三个亚段,其中流一段和流三段为主要产油层,流二段为大套湖相暗色泥岩沉积,是福山凹陷主要烃源

岩层之一^[9]。

2 储层基本特征

2.1 储层岩石学特征

通过研究区普通薄片资料分析,福山凹陷流沙港组碎屑岩储层主要岩石类型为长石岩屑砂岩(46.90%)与岩屑砂岩(50.90%),成分成熟度(CMI)指数[Q/(F+R)]平均为1.43,成分成熟度较低。储层陆源碎屑物质主要为石英、岩屑及长石,石英平均含量为57.95%,岩屑平均含量为31.78%,长石平均含量为10.22%。其中岩屑以变质岩岩屑为主。通过对150个样品分析,发现流沙港组储层三个亚段沉积物颗粒间接接触方式以点一线和线接触为主,基本不发育颗粒间的凹凸接触(或缝合接触);颗粒磨圆度以次圆和次棱—次圆状为主,其中花场—白莲地区好于永安—朝阳地区(图2)。

2.2 储集空间特征

通过对研究区储层铸体薄片资料的观察和分析,福山凹陷流沙港组储层储集空间主要为原生粒间孔、粒内溶孔、粒间溶孔、黏土间微孔以及微裂缝(图3)。其中花场、白莲地区以粒间孔隙和粒内溶蚀孔隙为主,朝阳地区以粒间溶孔为主,孔隙连通性较差,永安地区则以粒内溶蚀孔隙为主。

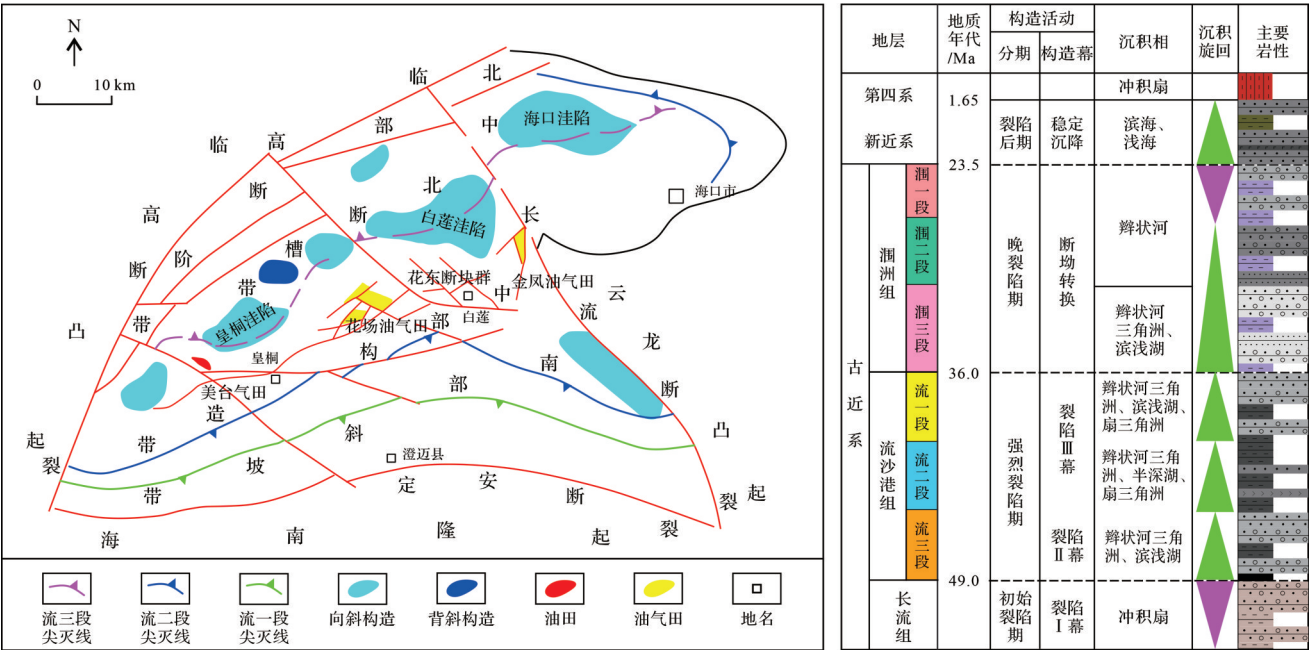


图1 北部湾盆地福山凹陷区域构造及综合柱状图(据文献[22]修改)
Fig.1 Regional structure and comprehensive stratigraphic column of the Fushan Sag, Beibuwan Basin (modified from reference [22])

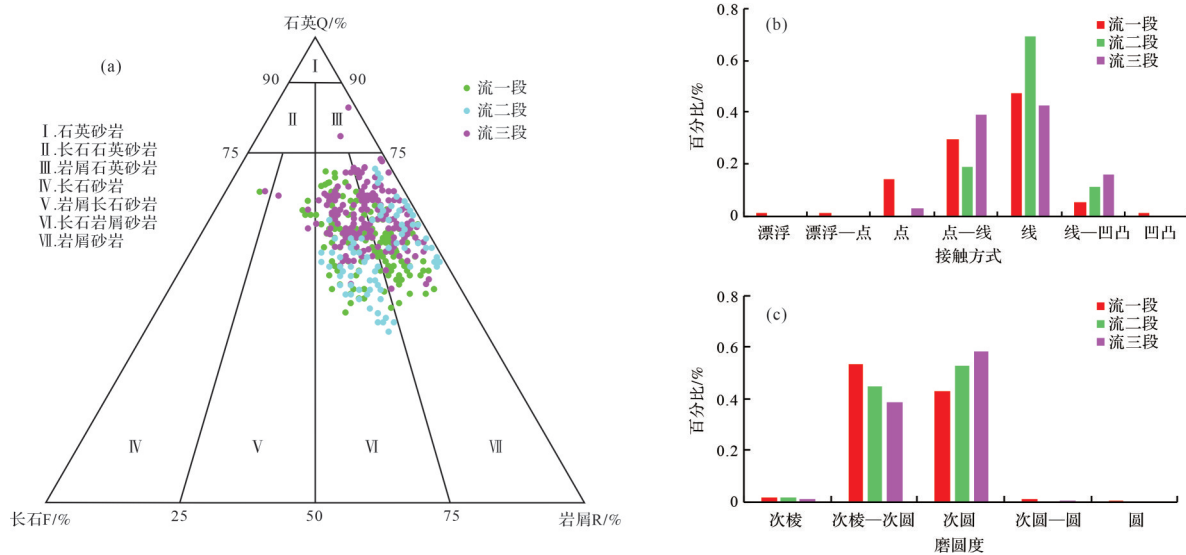


图2 福山凹陷流沙港组储层砂岩组分及碎屑颗粒结构特征

Fig.2 Characteristics of sandstone composition and clastic particle structure of Liushagang Formation reservoir in Fushan Sag

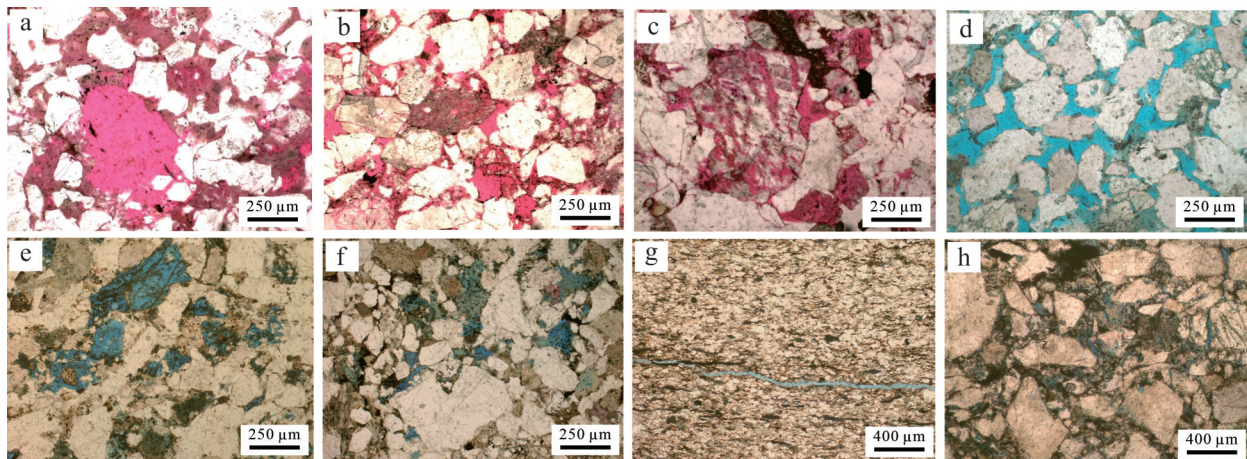


图3 福山凹陷流沙港组储层储集空间特征

(a)粒间微孔隙、粒内溶孔,花场地区,花7-1x井,3 460.96 m;(b)粒间原生孔、粒内溶孔,花场地区,花8井,2 651.35 m;(c)粒间溶孔、粒内溶孔,白莲地区,莲3x井,3 421.92 m;(d)粒间溶孔、少量粒内溶孔、微孔及铸膜孔,白莲地区,莲9-11x井,2 178.26 m;(e)粒内溶孔为主,粒间溶孔次之,部分粒内微孔隙,永安地区,永7井,3 888.54 m;(f)孔隙多为粒间溶孔,少量粒内溶孔,永安地区,永10x井,2 972.26 m;(g)偶见粒间、粒内溶孔,发育张开微裂缝,朝阳地区,朝3x井,2 604.40 m;(h)粒间、填隙物内溶孔,朝阳地区,朝6x井,2 798.90 m

Fig.3 Spatial characteristics of Liushagang Formation in Fushan Sag

2.3 储层物性特征

根据岩心实测数据资料统计分析,福山凹陷流沙港组渗透率与孔隙度整体呈正相关关系(图4),其中流二段相对拟合系数高。流三段、流二段和流一段平均孔隙度分别为11.4%、12.0%和13.2%;流三段、流二段和流一段平均渗透率分别为 $19.9 \times 10^{-3} \mu\text{m}^2$ 、 $45.5 \times 10^{-3} \mu\text{m}^2$ 和 $64.2 \times 10^{-3} \mu\text{m}^2$,三个亚段孔隙度主要介于5%~20%,而渗透率主要介于 $0.1 \times 10^{-3} \sim 100 \times 10^{-3} \mu\text{m}^2$ 。流三段部分层段由于黏土矿物充填作用,导致出现高孔低渗储层。

3 储层控制因素分析

有关储层控制因素的研究较多,普遍认为沉积和成岩是影响储层物性的关键因素^[25-26]。沉积相决定了储层砂体原始状态,控制储集空间展布,是形成优质储层的基础^[27-28]。成岩相是表征储层性质、类型和质量优劣的成因性标志,控制了孔隙结构,是研究储层品质好坏的关键^[29-33]。裂缝相是控制储层内流体流动的裂缝系统组合^[34],裂缝可改善储层渗流性能,控制油气分布^[35]。因此,结合研究区储层发育特

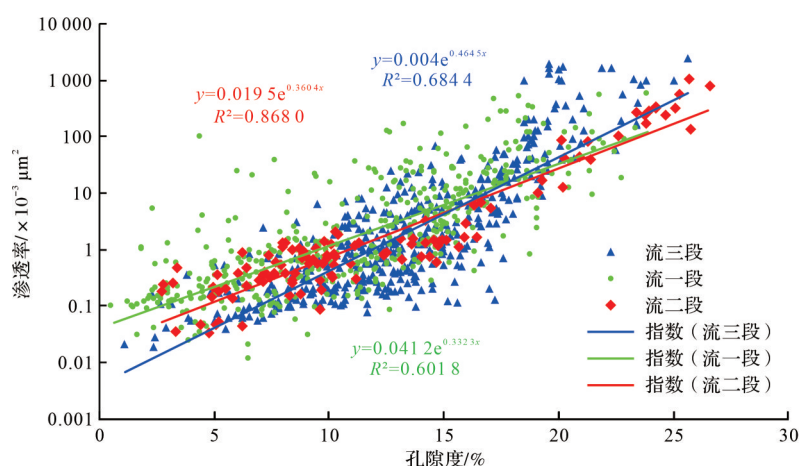


图4 福山凹陷流沙港组储层孔渗关系图

Fig.4 Reservoir porosity and permeability diagram for Liushagang Formation in Fushan Sag

征,本文将沉积微相、成岩相和裂缝相三者耦合预测研究区优质储层发育情况。

3.1 沉积微相对储层的控制

福山凹陷流沙港组发育湖泊—辫状河三角洲沉积体系,储层主要发育于流一段和流三段,为辫状河三角洲前缘亚相沉积,可进一步细化为水下分流河道、水下分流河道间、河口坝和远砂坝等沉积微相。

3.1.1 沉积微相测井响应特征

自然伽马(GR)测井利用地层天然伽马放射性强度能够很好地区分岩性,其曲线形态变化(测井相)能够反映地层岩性的纵向变化规律。声波时差(AC)测井通过测量地层的纵波时差,也可以很好地判断岩性、评价次生孔隙、欠压实或高压层识别。同样地,像自然电位(SP)、中感应电阻率(ILM)、深感应电阻率(ILD)等其他测井曲线也可以不同程度反映地层的沉积变化特征。研究区沉积微相在这些常规测井上就具有良好响应。因此可以应用GR、SP等测井曲线识别、划分沉积微相,建立沉积微相测井识别图版。

水下分流河道沉积是辫状河三角洲前缘亚相主要砂体,沉积物粒度较粗,岩性以浅灰色、灰色中砂岩与含砾砂岩为主,岩心上可见平行层理、斜层理、大、中型交错层理和冲刷面等沉积构造。概率累积曲线以“跳跃+悬浮”为主,呈斜率较高的两段式,反映水动力较强且沉积物分选好的沉积特征。GR曲线表现为明显箱形或钟形(图5)。

河口坝沉积主要岩性为灰色、灰白色细砂岩和含砾细砂岩,颗粒分选较好、成分成熟度高,具有明显上

粗下细的反粒序沉积特征,岩心上可见平行层理、波状层理和透镜状层理等沉积构造。概率累积曲线由“滚动+跳跃+悬浮”组成,呈三段式,包括分选较好(斜率较高)的滚动总体,分选中等的跳跃总体和分选较差的悬浮总体,反映其沉积于河口区中等能量的动荡水流环境。GR曲线具典型漏斗形特征(图6)。

远砂坝沉积在本区也较为发育,横向上分布范围广,但纵向上沉积砂体较薄,沉积物粒度也较细,岩性主要为灰色细砂岩和粉砂岩,岩心上可见平行层理、小型交错层理等沉积构造。概率累积曲线与水下分流河道沉积相似,以“跳跃+悬浮”为主,呈斜率较高的两段式。GR曲线具有中幅箱形和指形特征(图7)。

水下分流河道间岩性主要为浅灰色、灰黑色泥岩和泥质粉砂岩,岩心上可见水平层理和小型波状层理,反映较弱水动力条件,电性特征表现为高值或微齿化GR曲线(图8)。

3.1.2 沉积微相与基质物性的关系

建立研究区沉积微相与实测孔隙度、渗透率关系(图9),结果表明流沙港组储层不同沉积微相间物性差异较大,沉积微相与储层物性相关性良好,对储层质量控制明显。其中水下分流河道微相平均孔隙度为15.78%,平均渗透率为 $180.91 \times 10^{-3} \mu\text{m}^2$,物性最好;河口坝微相平均孔隙度为14.10%,平均渗透率为 $24.36 \times 10^{-3} \mu\text{m}^2$,物性较差;远砂坝微相平均孔隙度为11.09%,平均渗透率为 $5.15 \times 10^{-3} \mu\text{m}^2$,物性较差;水下分流河道间微相平均孔隙度为7.99%,平均渗透率为 $0.26 \times 10^{-3} \mu\text{m}^2$,物性最差。

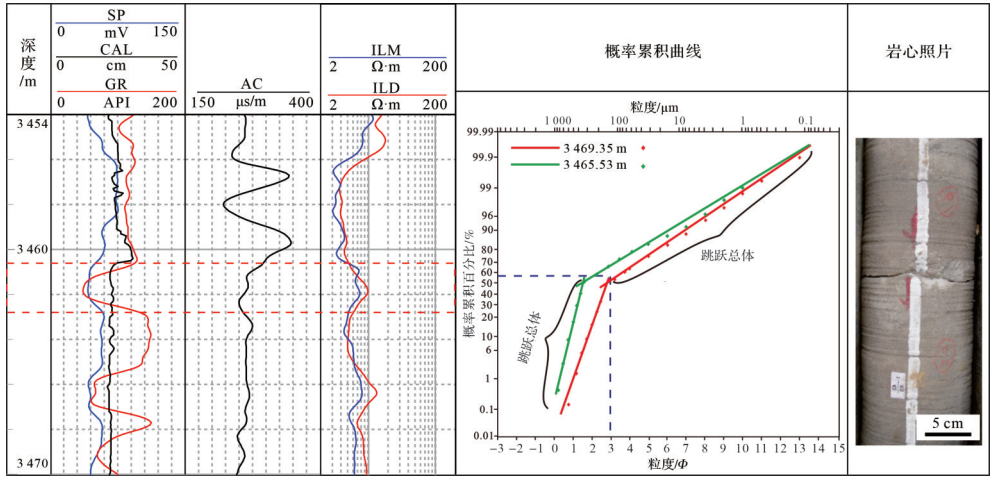


图5 福山凹陷流沙港组水下分流河道测井识别图版

Fig.5 Logging identification pattern of underwater distributary channel of Liushagang Formation in Fushan Sag

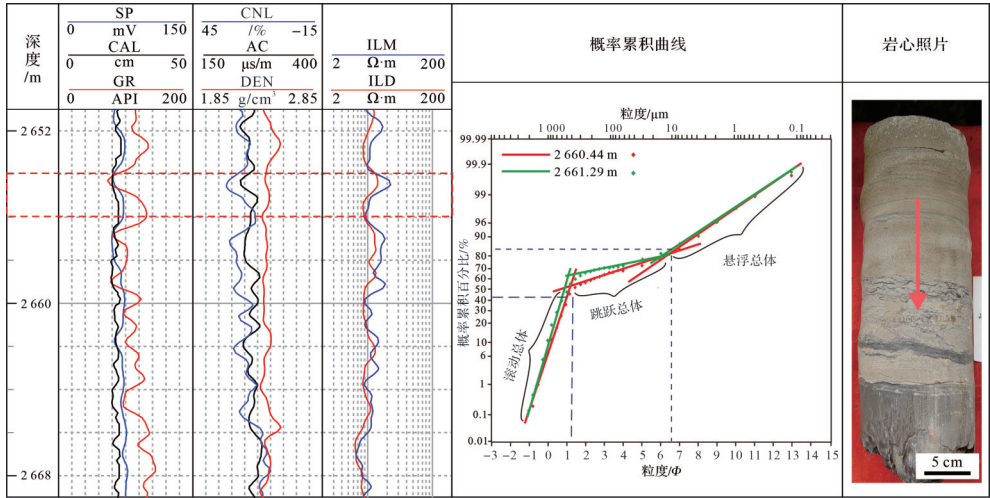


图6 福山凹陷流沙港组河口坝测井识别图版

Fig.6 Logging identification pattern of the mouth bar of Liushagang Formation in Fushan Sag

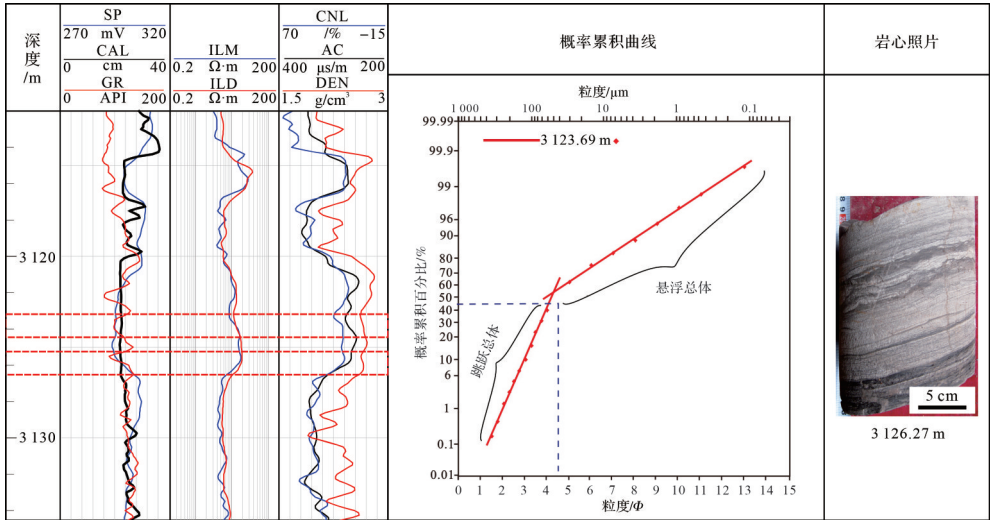


图7 福山凹陷流沙港组远砂坝测井识别图版

Fig.7 Logging identification pattern of far sand bar of Liushagang Formation in Fushan Sag

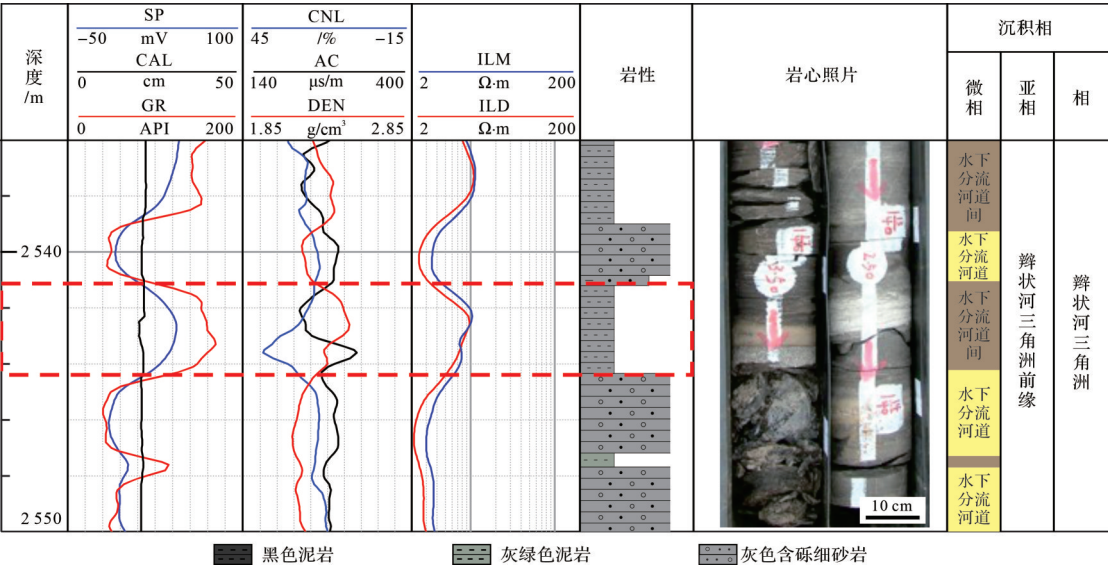


图8 福山凹陷流沙港组水下分流河道间测井识别图版

Fig.8 Logging identification pattern of underwater distributary channel of Liushagang Formation in Fushan Sag

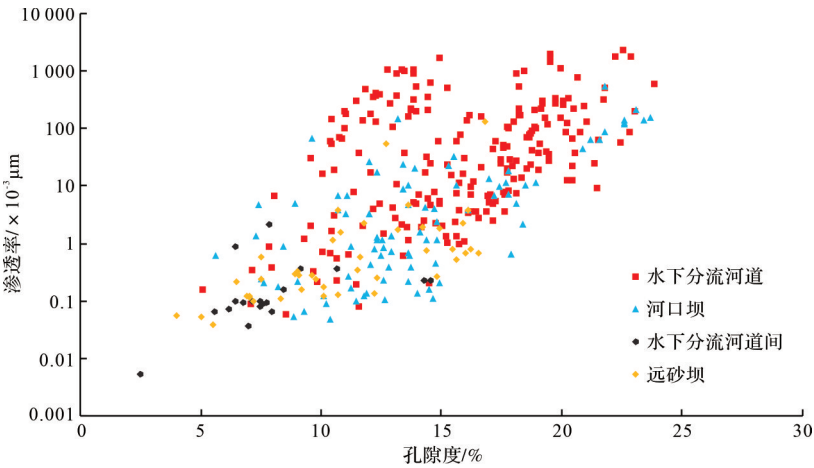


图9 福山凹陷流沙港组沉积微相与储层物性关系图

Fig.9 Sedimentary microfacies and reservoir physical relationship diagram for Liushagang Formation in Fushan Sag

3.2 成岩相对储层的控制

3.2.1 储层成岩作用类型

铸体薄片和扫描电镜观察表明,对研究区储层影响较大的成岩作用有压实、胶结和溶蚀作用。压实、胶结作用是导致研究区孔隙度下降的主要因素,而较强的溶蚀作用改善了储层孔隙结构,是研究区重要的建设性成岩作用^[36-37]。

流沙港组储层为近物源沉积,塑性颗粒含量较高,压实作用中等—强(图 10a,b)。胶结作用主要为黏土矿物、碳酸盐和硅质胶结,扫描电镜下可清晰识别出高岭石、伊利石等自生黏土矿物胶结(图 10c,d)。不稳定组分常被溶蚀产生大量次生孔隙,铸体

薄片下可见大量溶孔,多为粒间溶孔,可见铸模孔,扫描电镜下可观察到长石淋滤现象(图 10e,f),表明储层经历较强溶蚀作用。研究区常见交代作用有碳酸盐和黏土矿物交代碎屑颗粒,铸体薄片可见铁白云石、方解石交代颗粒现象(图 10g,h)。

3.2.2 成岩相划分与测井识别

成岩相的划分一般综合考虑成岩作用、成岩阶段、成岩环境、主要成岩事件和成岩演化序列等^[33,38-40]。在明确研究区储层成岩作用、成岩矿物组合特征、成岩阶段基础上,将福山凹陷流沙港组储集层划分为不稳定组分溶蚀相、黏土矿物充填相、碳酸盐胶结相和压实致密相等4类成岩相。

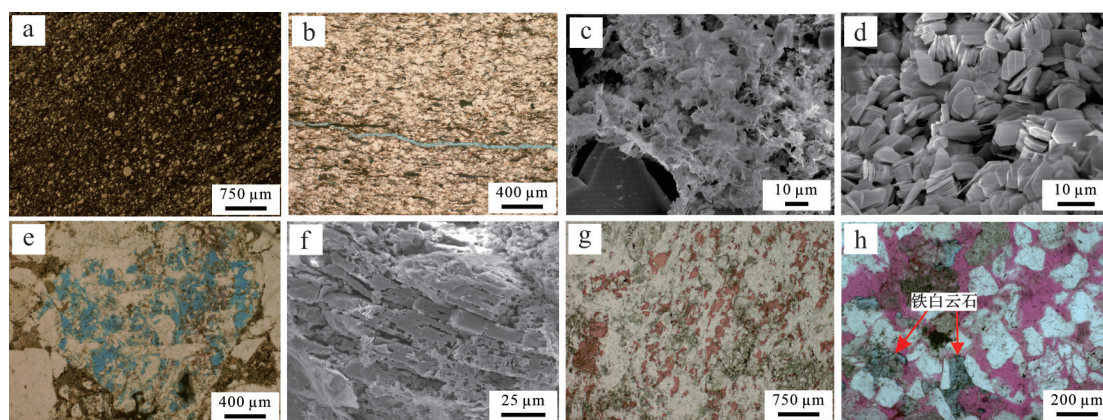


图10 福山凹陷流沙港组储层成岩作用镜下特征

(a)岩石内孔隙被充填压实,孔隙极不发育,花119A井3 113.14 m;(b)颗粒被压实致密,可见微裂缝,朝3x井2 604.40 m;(c)颗粒间充填的弯曲状伊利石,花3-5x井3 112.24 m;(d)颗粒间堆积的书页状自生高岭石,花3-5x井3 099.94 m;(e)粒内溶孔,永11x井2 549.96 m;(f)长石沿解理溶蚀形成次生孔隙,朝6x井2 414.02 m;(g)方解石、硬石膏强烈交代岩石,朝4x井4 215.00 m;(h)铁白云石交代颗粒,花9aX井2 462.12 m

Fig.10 Microscopic characteristics of diagenesis of Liushagang Formation in Fushan Sag

不稳定组分溶蚀相主要岩性为含砾砂岩、细砂岩,溶蚀作用强而胶结作用弱,溶蚀孔隙发育且未被次生矿物充填,长石、岩屑等不稳定组分部分或完全溶蚀形成残余孔隙和铸模孔,有效改善储层物性,为建设性成岩相。常规测井表现为相对的中低GR、中AC、中低DEN和中低CNL。黏土矿物充填相主要岩性为粉砂岩、细砂岩。高岭石、伊利石和伊—蒙混层等自生黏土矿物多以充填孔隙形式存在,堵塞孔隙喉道,降低孔隙连通性,为破坏性成岩相。常规测井表现为相对的中高GR、中AC和中DEN、中高CNL特征。碳酸盐胶结相主要岩性为细砂岩,碳酸盐以充填孔隙式或嵌晶式胶结粒间孔隙。常规测井呈相对中GR、低AC、中CNL和中高DEN的特征。压实致密相主要岩性为泥岩、粉砂岩,岩屑、杂基含量较高,孔隙极不发育。测井曲线上响应为相对的中到高值GR、中高AC、高DEN和CNL(图11)^[41]。

依据上述不同成岩相测井响应特征,并结合岩心、铸体薄片和扫描电镜等分析化验资料的分析,在单井上划分成岩相(图12),可以看出不同成岩相与测井油气综合解释结论匹配关系良好。不稳定组分溶蚀相沉积物砂质含量较高,往往对应于油层、差油层,压实致密相则泥质含量较高,对应为非储层,而黏土矿物充填相和碳酸盐胶结相介于二者之间。因此也验证了成岩相控制储层品质的优劣,不同成岩相所反映的储层特征差异明显,成岩相划分方案在本区具有良好适用性。

3.2.3 成岩相与基质物性的关系

统计分析福山凹陷花场地区流沙港组储层不同成岩相与孔隙度、渗透率关系(图13),结果显示不同成岩相下储层物性差异较大,孔—渗耦合关系良好,其中不稳定组分溶蚀相平均孔隙度为17.34%,平均渗透率为 $200.34 \times 10^{-3} \mu\text{m}^2$,储层物性最好;黏土矿物充填相平均孔隙度为9.48%,平均渗透率为 $1.91 \times 10^{-3} \mu\text{m}^2$,基质物性较差;碳酸盐胶结相平均孔隙度为11.71%,平均渗透率为 $1.24 \times 10^{-3} \mu\text{m}^2$,基质物性也较差;压实致密相平均孔隙度为7.24%,平均渗透率为 $0.17 \times 10^{-3} \mu\text{m}^2$,基质物性最差,属于非储层。因此,成岩相是优质储层发育的关键。

3.3 裂缝相对储层的控制

裂缝发育可有效连通其周围粒间孔隙、粒内溶孔和微孔隙,改善致密储层物性条件,提高储层渗透能力,成为有效的储集空间和运移通道,进而改善油气的运聚条件,有利于形成甜点^[42-43]。通过岩心和薄片观察可知流沙港组储层主要发育构造成因裂缝,按力学性质差异又可分为张裂缝和剪裂缝,按充填状态可分为张开缝、闭合缝和充填缝。本文则主要按照裂缝倾角将裂缝划分为近水平缝、低角度斜交缝、高角度斜交缝和网状缝四类,其中近水平缝与低角度斜交缝较为发育,而高角度斜交缝和网状缝发育较少,裂缝多呈张开状,有效性较好,少部分被方解石或泥质充填(图14)。

利用常规测井+成像测井+岩心来识别裂缝。网状裂缝在岩心上呈破碎状,常规测井上,GR、DEN、

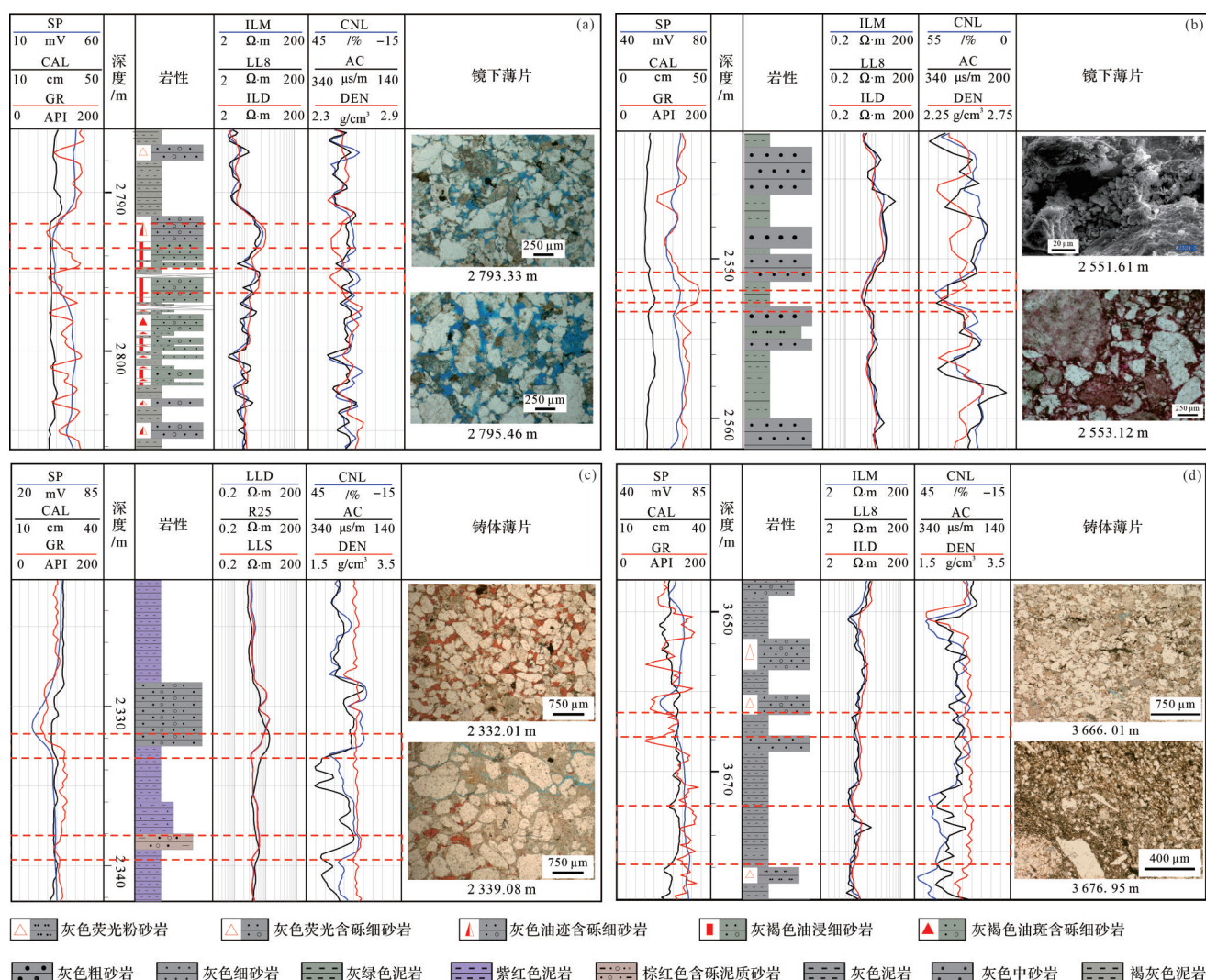


图 11 福山凹陷流沙港组不同成岩相测井响应特征

(a) 不稳定组分溶蚀相测井识别图版; (b) 黏土矿物充填相测井识别图版; (c) 碳酸盐胶结相测井识别图版; (d) 压实致密相测井识别图版

Fig.11 Logging response characteristics of different diagenetic facies of Liushagang Formation in Fushan Sag

LLD、LLS 值略有降低, AC 值增大; 通过岩心识别高角度斜交缝, 其在常规测井上具有 AC 略有增大, RILD 值大于 RILS, 呈正差异的特征, 成像测井图表现为高幅度的暗色正弦线状; 低角度斜交缝在常规测井上具有 GR 值略有减小, AC 值增大, RILD 值小于 RILS, 呈负差异的特征; 近水平缝特征与低角度缝特征较为相似, 常以层间缝的形式出现(图 15)。

裂缝对储层的控制主要体现在对产能的改善作用^[44]。通过人工拾取岩心裂缝, 并统计分析研究区部分井段裂缝密度与产能的关系, 发现除部分储层基质物性较好的井段, 其他井段裂缝密度和产能均具有良好相关性, 裂缝密度越大, 储集层具有更好的产液能力(图 16)。因此, 裂缝的发育能够改善储层储集和运移空间, 提高油气井的产液能力。

4 基于“三元控储”的优质储层预测

辫状河三角洲前缘水下分流河道、河口坝等水动力条件较强背景下形成的砂岩, 由于颗粒较粗, 分选、磨圆较好, 使得其抗压实能力强, 因此保留部分原生孔隙, 且在后期成岩改造作用中不稳定组分易遭到孔隙中流体溶蚀, 产生粒内溶蚀孔隙, 两者叠加将对储层物性起到改善作用, 有利于优质储层发育(图 17)。而水下分流河道间等水动力条件相对较弱背景下形成的粉砂岩和泥岩等, 由于抗压实能力弱, 在后期成岩改造中被压实致密(图 17)。此外, 部分颗粒粒度较粗但杂基含量较高的砂岩, 由于黏土矿物及碳酸盐胶结物的广泛发育, 也不利于优质储层的发育, 但当有一定规模裂缝发育时, 可

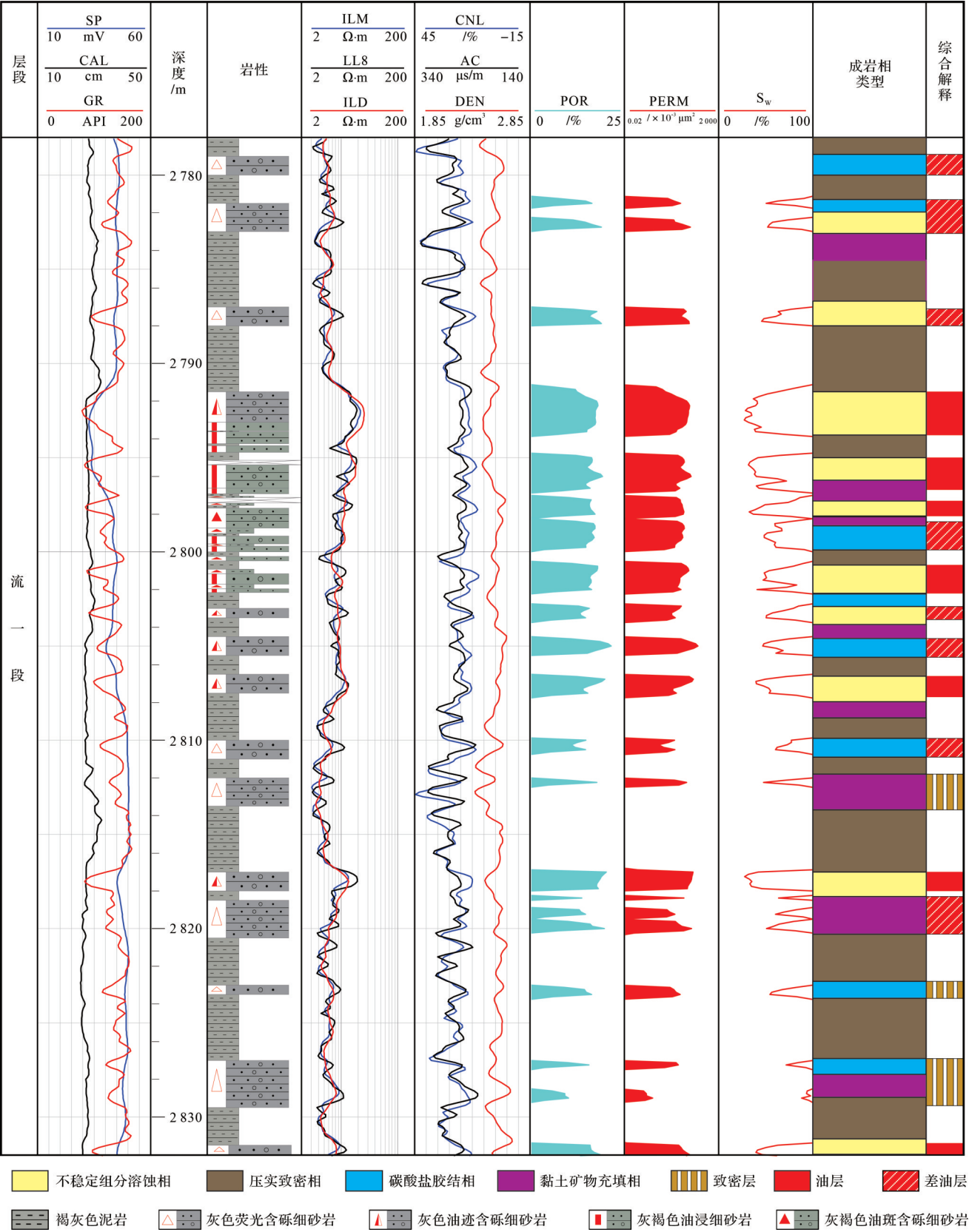


图 12 花 107-8x 井成岩相单井综合划分成果图

Fig.12 Comprehensive division of diagenetic facies in well Hua 107-8x

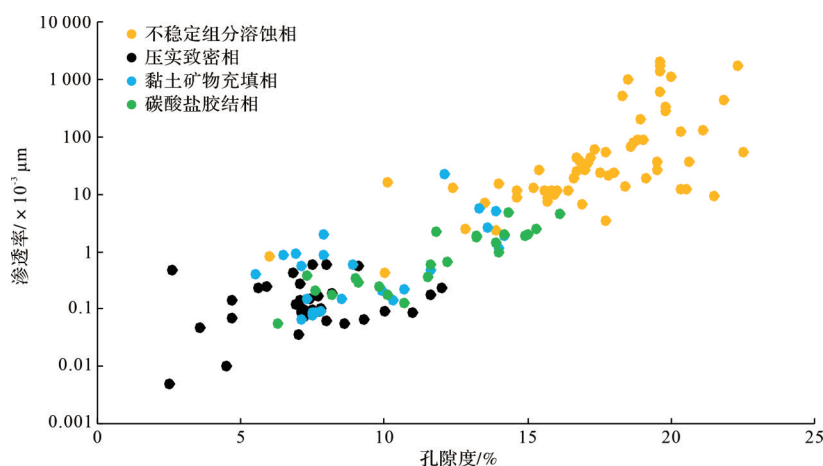


图13 福山凹陷花场地区流沙港组成岩相与物性关系图

Fig.13 Diagenetic facies and physical property relationship diagram for Liushagang Formation in Huachang area, Fushan Sag

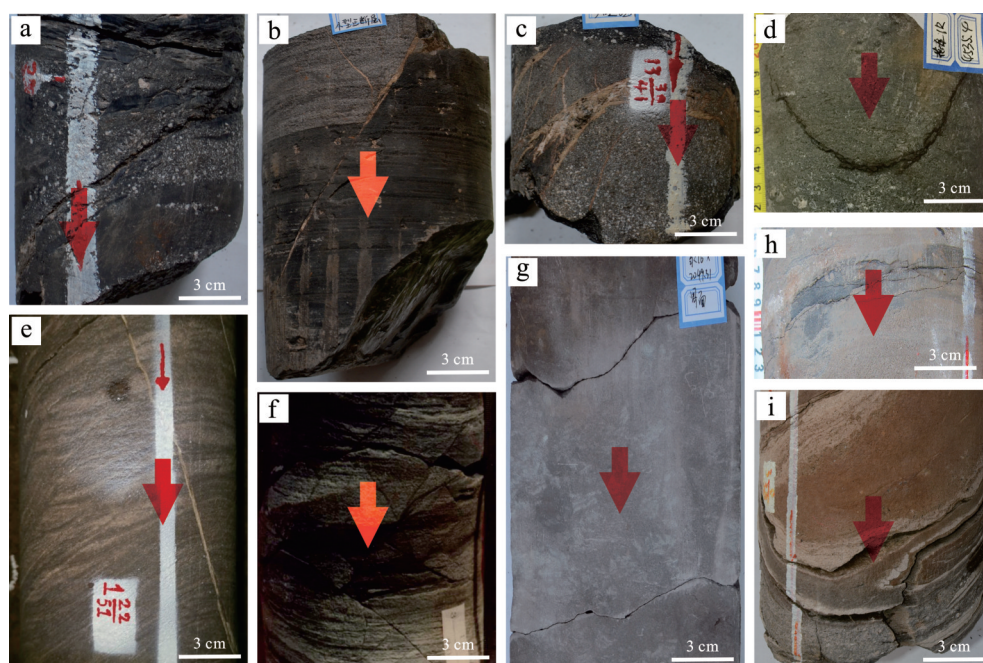


图14 福山凹陷流沙港组裂缝发育特征

(a)高角度斜交缝,永11x井,3 644.65 m;(b)小型正断层,永11x井,3 705.86 m;(c)方解石充填斜裂缝,永11x井,3 698.00 m;(d)高角度溶蚀裂缝,花东1R井,4 535.40 m;(e)高角度充填裂缝,朝23x井,2 562.73 m;(f)网状裂缝,福参1井,2 519.76 m;(g)低角度缝,永16x井,2 049.31 m;(h)多条近水平缝,朝6x井,2 541.00 m;(i)层间低角度缝,花13井,3 121.93 m

Fig.14 Fracture development in Liushagang Formation, Fushan Sag

连通孔隙改善储层渗流能力,形成有利储集层(图17)。

沉积是储层发育的基础,成岩作用是改造储层品质关键,裂缝对储层品质起调整作用^[45]。基于以上分析,将沉积微相、成岩相及裂缝相三者耦合并优选4类储层特征参数建立福山凹陷流沙港组储层质量分类标准(表1),综合评价储层优劣。可以看出,优质储层主要发育在水动力较强环境下的水下分流河道沉积微相,成岩相为溶蚀作用强而压实中等和胶

结作用较弱的不稳定组分溶蚀相,而裂缝相主要为受强烈构造作用产生的有效性较高的网状缝或高角度斜交缝。随着水动力条件减弱,压实作用和胶结作用的加强,以及裂缝角度与裂缝密度的降低,储层的物性也相对变差,储层品质下降^[46]。

基于沉积+成岩+裂缝的“三元控储”的综合评价方法,预测单井优质储层发育层段(图18)。可以看出,流沙港组优质储层受控于有利的沉积微相、成岩相及裂缝相,具有相对较好的储集空间、渗流能力和

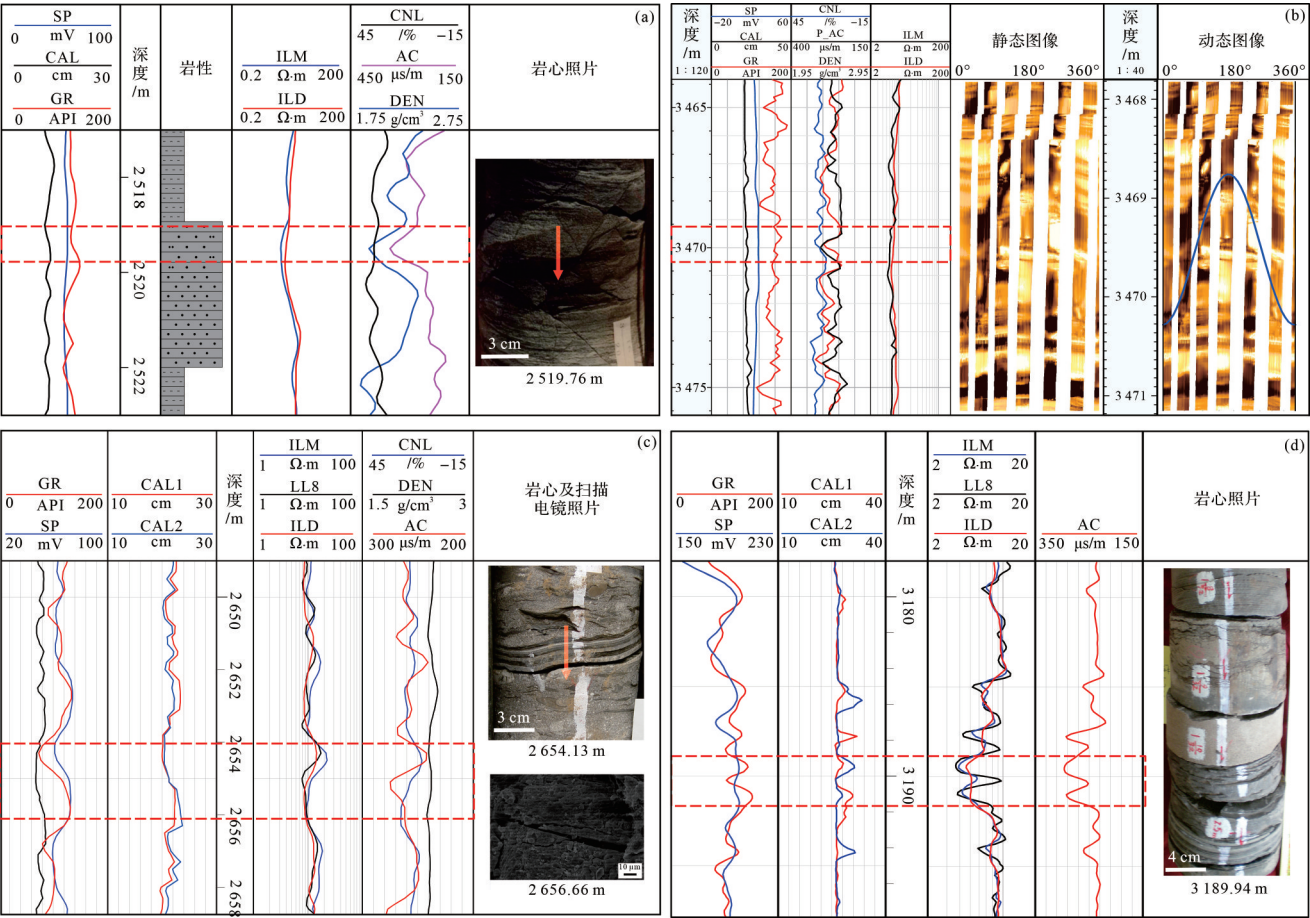


图 15 福山凹陷流沙港组裂缝测井识别图版

(a)网状缝测井识别图版;(b)高角度斜交缝测井识别图版;(c)低角度斜交缝测井识别图版;(d)近水平缝测井识别图版

Fig.15 Logging identification pattern of fractures in Liushagang Formation, Fushan Sag

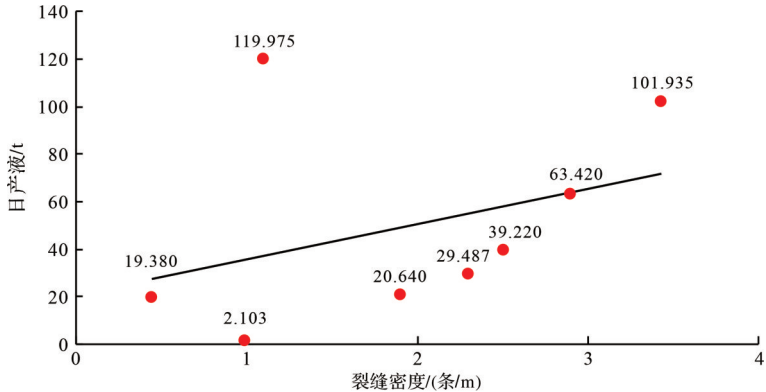


图 16 福山凹陷流沙港组储层裂缝密度与产能关系图

Fig.16 Fracture density vs. productivity for Liushagang Formation, Fushan Sag

含油气特征。基质物性较好且裂缝发育的层段,往往可以形成有利储层段。另外,对于储层基质物性良好、溶蚀孔隙大量发育的砂体储层,即使裂缝较不发育,但依然可以成为优质储集体,而一些裂缝较发育但处于不利沉积微相和成岩相的储集体常为非储层。以花 114x 井为例,将预测结果与测井综合解释

结论与试油结果进行对比,可以发现,该井目的层 I 类储层主要对应油层,日产量 59.16 t, II 类储层 14.36 t, III 类储层主要对应致密层, IV 类则为非储层,符合率较高,说明该分类方法具可行性。因此,可以运用“三元控储”机理来识别预测流沙港组优质储层在纵向上发育层段。

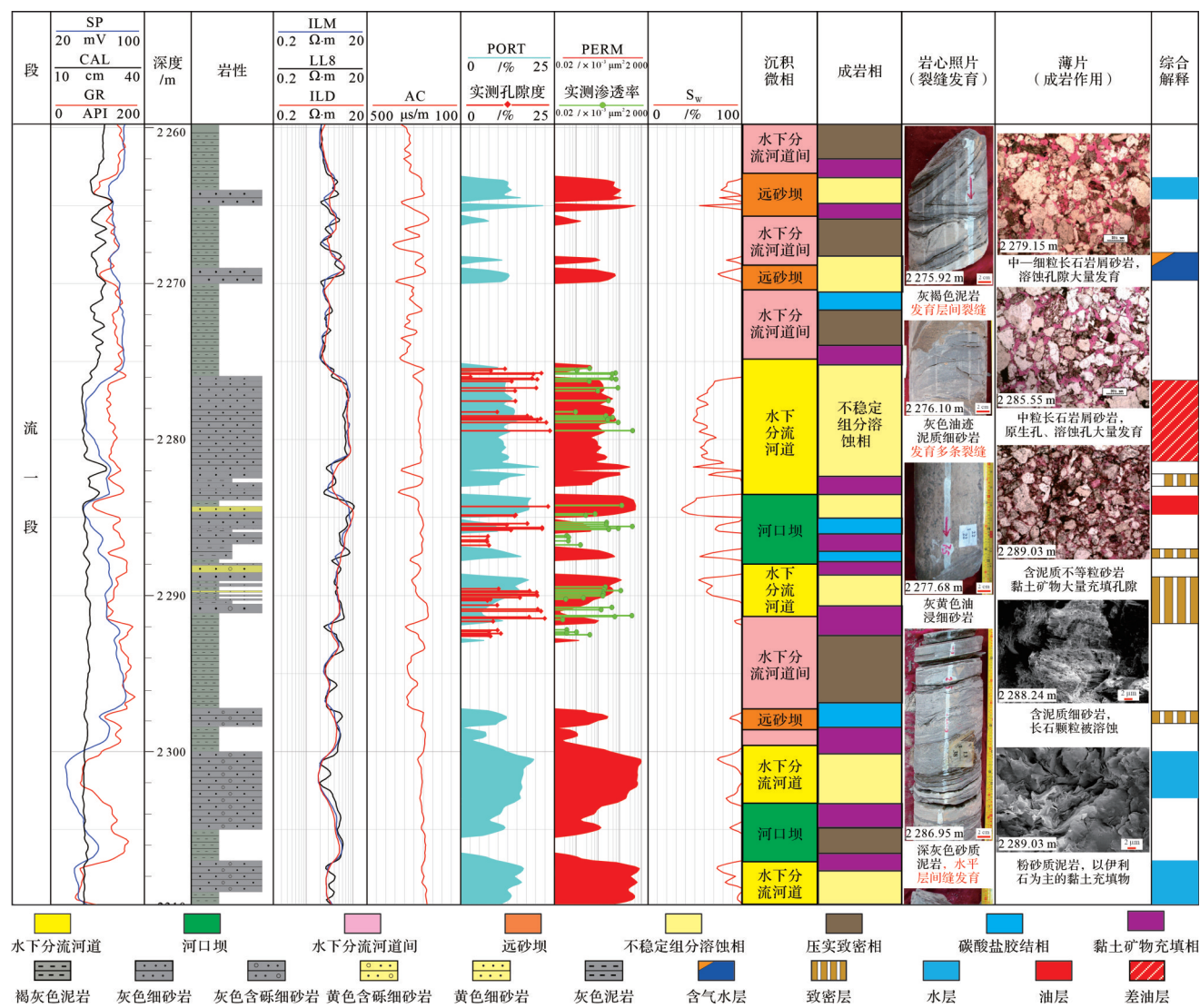


图 17 基于沉积微相、成岩相和裂缝相叠加的“三元控储”关系图

Fig.17 Diagram of “three-element controlling reservoir” based on sedimentary microfacies, diagenetic facies and fracture facies

表 1 福山凹陷流沙港组储层控制因素与储层综合分类标准

储层综合分类		I 类	Ⅱ类	Ⅲ类	Ⅳ类
储层控制因素	沉积微相	水下分流河道	水下分流河道、河口坝	河口坝、远砂坝	水下分流河道间、滨浅湖
	成岩相	不稳定组分溶蚀相	不稳定组分溶蚀相	碳酸盐胶结相、黏土矿物充填相	压实致密相
	裂缝相	网状缝、高角度斜交缝	低角度斜交缝、近水平缝	偶见裂缝	不发育裂缝
渗透率/×10 ⁻³ μm ²		>10	10~1	1.0~0.2	<0.2
孔隙度/%		>15	15~10	10~5	<5
岩性特征		中砂岩、含砾砂岩	细砂岩、含砾细砂岩	粉砂岩、泥质细砂岩	泥岩、泥质粉砂岩
薄片特征	分选	中、中—差	中—差	差、极差	极差
	接触方式	点、点—线	点—线、线	线、漂浮	线—凹凸、凹凸
	磨圆	次圆—圆	次圆、次棱—次圆	次棱—次圆	次棱
	孔隙类型	原生粒间孔、大量粒内溶孔	少量原生粒间孔、粒内溶孔	黏土矿物间微孔	少量粒内溶孔

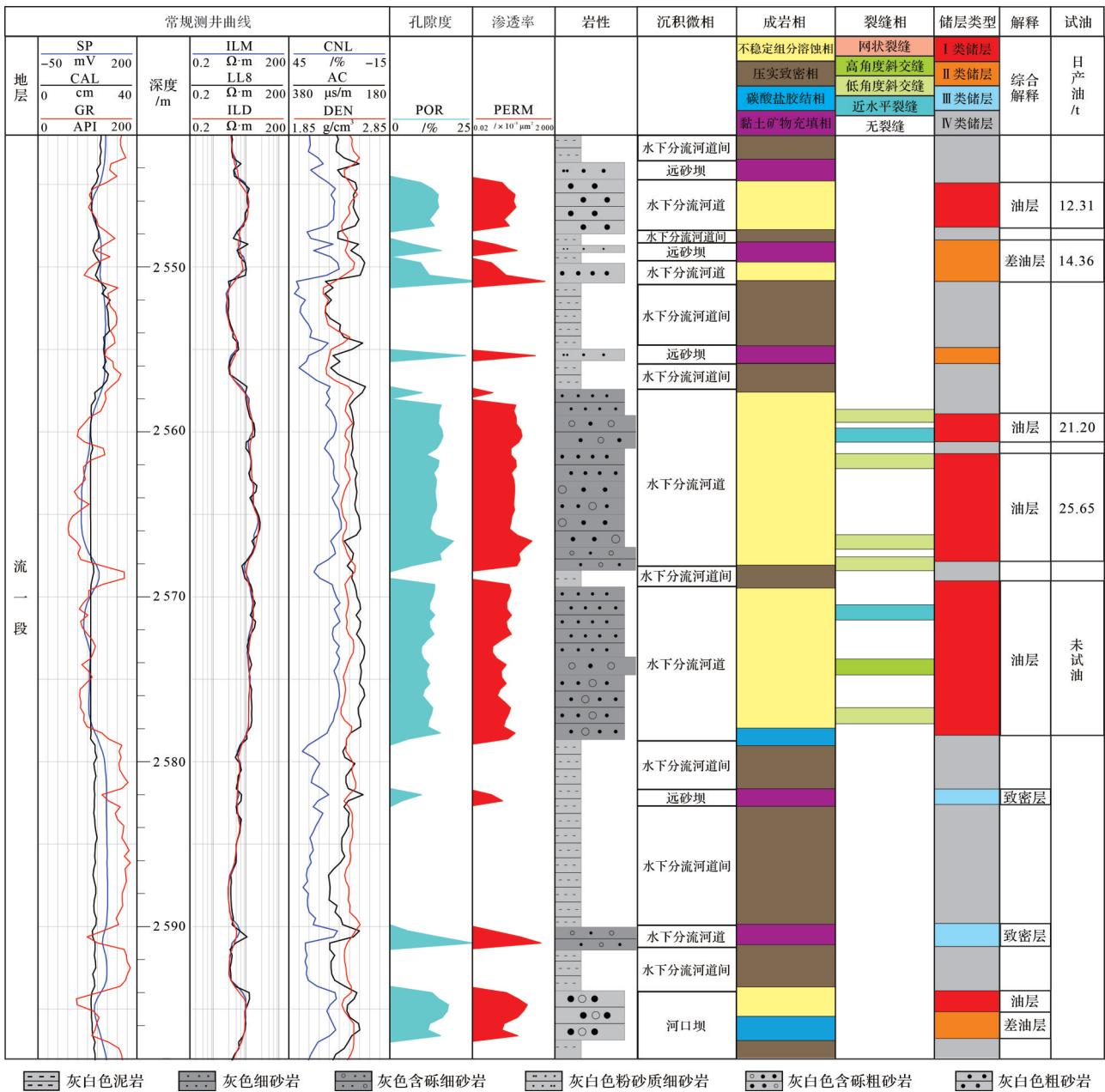


图 18 基于沉积—成岩—裂缝“三元控储”优质储层预测图

Fig.18 High-quality reservoir prediction based on “three-element controlling reservoir” of sedimentation, diagenesis and fracturing

5 结论

(1) 研究区储层岩石类型主要为长石岩屑砂岩和岩屑砂岩,成分成熟度较低,磨圆度以次棱一次圆和次圆状为主,主要发育水下分流河道、河口坝、水下河道间和远砂坝等沉积微相,不同沉积微相的储层质量差异明显,是储层品质的主要控制因素。其中水下分流河道平均孔隙度为 15.78%,平均渗透率为 $180.91 \times 10^{-3} \mu\text{m}^2$,物性最好。

(2) 压实作用、胶结作用和溶蚀作用为研究区主要成岩作用,其中压实、胶结作用中等一强,溶蚀作用较强。研究区发育不稳定组分溶蚀相、压实致密相、碳酸盐胶结相和黏土矿物充填相等 4 类成岩相,其中不稳定组分溶蚀相为本区有利成岩相类型。

(3) 研究区裂缝发育规模较小,主要发育的裂缝相为近水平缝和低角度斜交缝,裂缝多呈张开状,有效性较好,对压实致密层段的改造好于基质物性较好的储层段。

(4) 优质储层主要发育在水动力较强环境下的水下分流河道沉积微相,成岩相为溶蚀作用强而压实中等和胶结作用较弱的不稳定组分溶蚀相,而裂缝相主要为受强烈构造作用产生的有效性较高的网状缝或高角度斜交缝。随着水动力条件减弱,压实作用和胶结作用的加强,以及裂缝角度与裂缝密度的降低,储层的物性也相对变差,储层品质下降。

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Factors Controlling Reservoir Quality and Prediction of High-quality Reservoir Using Well Logs: A case study of the Liushagang Formation in the Fushan Sag, China

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Abstract: [Objective] The Liushagang Formation is one of the petroliferous reservoirs in the Fushan Sag, Beibuwan Basin. However, the factors controlling reservoir quality have been unclear and there is no matched prediction tech-

nology for reservoir quality, which restricts the oil and gas exploration and development process. Nearly 65 years of oil exploration and geological research has revealed multiple sets of oil-bearing target systems in the Weizhou and Liushagang Formations. Further clarification is urgently needed regarding their development and to determine the distribution of reservoirs in this area, in particular to define reservoir control factors and predict the most favorable direction for further oil and gas reservoir exploration, and also to form a set of logging prediction methods appropriate to the study area. **[Methods]** Large numbers of core analysis experiments (particle size, sorting, contact mode etc.) and the analysis of thin sections, scanning electron microscopy information, physical properties, petrology and other data were used to estimate reservoir space and the physical properties of the reservoir. Beginning with aspects of early sedimentation, late diagenetic transformation and tectonic action, the sedimentary characteristics, diagenetic types and strength and fracture development of the Liushagang Formation are discussed. The controlling factors of reservoir quality are unraveled from the perspective of “three-element reservoir controls”: sedimentary microfacies, diagenetic facies and fracture facies. Methods of logging characterization and identification standards are also established. Comprehensive histograms and fracture identification divisions of sedimentary microfacies and diagenetic facies logging are completed for a single well, and the comprehensive response characteristics and development criteria for high-quality reservoir logging are clarified. **[Results]** It was found that the sedimentary microfacies, diagenetic facies and fracture details are important factors in determining reservoir quality in the Liushagang Formation. The main sedimentary microfacies developed in the study area are underwater distributary channel, estuary bar, far sand bar, and semi-deep to deep lake mudstone-equivalent sedimentary microfacies. The main diagenetic facies are unstable component dissolution facies, clay mineral infill, carbonate cementation and compacted dense facies. The fractures are mainly either horizontal or low-angle. By analyzing the relationships between different types of sedimentary microfacies, diagenetic and fracture facies and reservoir quality parameters, it is concluded that high-quality reservoirs were formed from dissolution facies in the underwater distributary channel and mouth bar in a high-energy depositional environment. The presence of fractures has also significantly improved reservoir quality. Four types of reservoir are classified by integrating the three controlling factors (sedimentary microfacies + diagenetic facies + fracture facies) and combining them with four important reservoir property parameters. The conclusions from oil and gas interpretation and oil test data indicate that the proposed method effectively evaluates and predicts favorable reservoir layers. **[Conclusions]** This study provides theoretical guidance for increasing the number of reservoirs and the production of oil and gas from the Liushagang Formation in the Fushan Sag. It also provides insights into the detailed description of reservoirs and the prediction and evaluation of high-quality reservoirs.

Key words: Liushagang Formation; sedimentary microfacies; diagenetic facies; fracture facies; controlling factors; high-quality reservoir prediction