

四川盆地侏罗系常规与非常规油藏类型探讨

金 涛 白 蓉 郭蕊莹 周春林 邓 燕 李秀清 刘 敏 李育聪

中国石油西南油气田公司勘探开发研究院, 四川 成都 610041

摘 要:四川盆地侏罗系油藏勘探开发思路经历了常规孔隙型油藏、裂缝型油藏、裂缝—孔隙型油藏,到目前非常规致密油和页岩油的转变,油藏类型的划分引起了极大争议。由于四川盆地侏罗系油藏是不受构造圈闭控制、大面积连续分布的油藏,在烃源分布范围内,油藏富集主要受控于储层和裂缝,储集体主要为砂岩、灰岩和页岩混层。因此,油藏分类方法首先参照国家标准中主要储集体渗透率界线划分常规油藏和非常规油藏;然后根据各类储层中石油贮藏量占比不同,再细分常规油藏为孔隙型、裂缝型、裂缝—孔隙型和孔隙—裂缝型四类油藏,非常规油藏为致密油和页岩油两类油藏。在此基础上,重新梳理四川盆地侏罗系油藏分类,油藏以页岩油为主,其次为致密油,只发现一处常规孔隙—裂缝型油藏;页岩油主要分布在凉高山组、大安寨段和东岳庙段富有机质页岩层系中,沙一段、凉下段和珍珠冲段河道砂油藏为致密油,致密灰岩和致密粉砂岩主要为隔夹层或顶底板。分类结果对勘探开发具有重要意义。

关键词:四川盆地;侏罗系;油藏类型;致密油;页岩油;导管引流

DOI:10.3969/j.issn.1006-5539.2021.03.012

Discussion on conventional and unconventional Jurassic reservoir types in Sichuan Basin

JIN Tao, BAI Rong, GUO Ruiying, ZHOU Chunlin, DENG Yan, LI Xiuqing, LIU Min, LI Yucong

Exploration and Development Research Institute of PetroChina Southwest Oil and Gas

Field Company, Chengdu, Sichuan, 610041, China

Abstract: The exploration and development ideas of Jurassic reservoir in Sichuan Basin have experienced the transition from conventional pore reservoir, fractured reservoir, fracture-pore reservoir, to unconventional tight oil and shale oil, and the classification of reservoir types has aroused great controversy. The Jurassic reservoir in Sichuan Basin is a large and continuous reservoir that is not controlled by structural traps. In the range of hydrocarbon source distribution, reservoir enrichment is mainly controlled by reservoirs and fractures, and the reservoirs are mainly mixed layers of sandstone, limestone and shale. Therefore, the reservoir is divided into conventional and unconventional reservoirs according to the permeability boundaries of major reservoirs in the national standard. Then, according to

收稿日期:2020-11-12

基金项目:国家科技重大专项“四川盆地致密油资源潜力、甜点区预测与关键技术应用”(2016ZX05046-006-008)

作者简介:金 涛(1969-),男,四川自贡人,高级工程师,学士,主要从事测井、油气勘探及地质研究。E-mail:jint@petrochina.

com.cn

the different proportion of oil reserves in different reservoirs, the conventional reservoirs are subdivided into four types: pore, fracture, fracture-pore and pore-fracture, and the unconventional reservoirs are subdivided into tight oil and shale oil. On this basis, the Jurassic reservoirs in Sichuan Basin were reclassified. The reservoirs were mainly shale oil, followed by tight oil. Only one conventional pore-fracture reservoir was found. Shale oil is mainly distributed in organic-rich shale layers of Lianggaoshan Formation, Da'anzhai Member and Dongyuemiao Member. Channel sand reservoirs of Shaximiao 1 Member, Lower Member of Lianggaoshan Formation and Zhenzhuchong Member are tight oil, while tight limestone and tight siltstone are mainly interbedded or roof-to-floor. Such classification is of great significance to exploration and development.

Keywords: Sichuan Basin; The Jurassic; Reservoir type; Tight oil; Shale oil; Drainage by catheter

0 前言

四川盆地侏罗系油藏经过60多年勘探开发,前期经历了孔隙型、裂缝型和裂缝—孔隙型等常规油藏的勘探开发,高峰期年产量达 20.7×10^4 t,获得探明储量 $7\,338 \times 10^4$ t,但探明率、转化率均极低,不到10%^[1]。后期引入非常规石油概念后,进行致密油攻关,获得部分成果认识,但还是未止住年产量下滑的趋势;目前页岩油的研究还未见到明显效果,但却引起油藏分类的极大争议。致密灰岩被当作主要的油藏储集体^[2],但资源量与产量的过大差距,以及二次采油难以为继,特别是成藏主控因素之一为裂缝,常常怀疑侏罗系油藏主要为裂缝型油藏;由于湖相页岩连续性差、岩相丰富,储集体主要为砂岩、灰岩和页岩混层,因此对致密油、页岩油划分有争议,有人认为厚层灰岩和砂岩中贮藏有致密油^[1-2],有人认为厚层灰岩和砂岩为顶底板,顶底板间富有机质页岩层系贮藏有页岩油气^[3];而“十三五”油气资源评价认为大安寨段、凉上段的厚层灰岩和砂岩油藏为储层甜点型页岩油,认为东岳庙段、大安寨段和凉上段为源内成藏的页岩油,珍珠冲段和沙一段为源外成藏的致密油。而关于致密油、页岩油纵向分布层位位置以及常规油藏存在与否等问题,只有确定了油藏类型,对今后的勘探开发思路才有指导意义。笔者根据国家标准进行定量解释来探讨油藏类型。

1 地质背景

四川盆地侏罗系主要为一套以碎屑岩为主,夹介壳灰岩的三角洲—内陆湖泊相淡水沉积,残厚2 000~3 000 m。纵向上发现了珍珠冲段、东岳庙段、大安寨段、凉高山组 and 沙一段五套含油气层系,四套主力烃源岩为珍珠冲段、东岳庙段、大安寨段和凉高山组,位于侏罗系下部,自生自储特征明显。已勘探开发的石油主要分布在盆地中部的大川中地区,面积 4.2×10^4 km²,已发现5

个油田和18个含油构造。

2 油藏分类方案

四川盆地侏罗系储层主要为特低孔隙度、特低渗透率的致密储层。油藏不受构造圈闭控制、大面积连续分布,控制因素主要为烃源、储层和裂缝。因此,油藏以非常规油藏为主,存在少量常规油藏。非常规油藏是指大面积连续分布,在现今经济技术条件下,难以完全用常规技术进行经济、有效开发的油藏^[4-5]。目前四川盆地侏罗系已发现的非常规油藏有致密油和页岩油^[6],由于湖相页岩连续性差、岩相丰富,单一储集体难以达到致密油和页岩油国家标准(GB/T 34906—2017《致密油地质评价方法》和GB/T 38718—2020《页岩油地质评价方法》)中连续厚度下限;而致密油和页岩油的主要储集体(石油贮藏量占比超过50%的储集体)覆压基质渗透率一般不大于 $0.1 \times 10^{-3} \mu\text{m}^2$,需要水平井加砂压裂等工艺改造才能获得工业产能;因此,笔者建议用不同岩石、有机质富集段中石油贮藏量占比来区分致密油和页岩油^[7]。致密油可定义为赋存于主要储集体覆压基质渗透率不大于 $0.1 \times 10^{-3} \mu\text{m}^2$ 的致密砂岩、碳酸盐岩等非富有机质储集层中石油^[8-9](未包括稠油)占比超过50%的油藏;页岩油则定义为赋存于主要储集体覆压基质渗透率不大于 $0.1 \times 10^{-3} \mu\text{m}^2$ 的富有机质页岩层系中石油占比不小于50%的油藏,见表1。

常规石油也可以进行量化定义,常规石油定义为赋存于覆压基质渗透率大于 $0.1 \times 10^{-3} \mu\text{m}^2$ 的砂岩、碳酸盐岩和泥页岩等储集层中石油占比超过50%的油藏。从油藏富集规律和历史原因考虑,参考李欢油气藏分类标准(2013年),常规油藏按储集空间类型分类,分为孔隙型、裂缝型、裂缝—孔隙型和孔隙—裂缝型,四川盆地侏罗系油藏早期就是按常规油藏的勘探开发思路,经历了孔隙型、裂缝型和裂缝—孔隙型的摸索。

表 1 四川盆地侏罗系油藏分类划分表

Tab. 1 Classification of Jurassic reservoirs in Sichuan Basin

分类	次级分类	石油贮藏量占比	主要储集体渗透率 / (10 ⁻³ μm ²)
常规油藏	孔隙型	孔隙≥90%	覆压渗透率>0.1 或空气渗透率≥1.0
	裂缝型	裂缝≥90%	
	裂缝—孔隙型	孔隙>裂缝>10%	
	孔隙—裂缝型	裂缝>孔隙>10%	
非常规油藏	致密油	致密灰岩、砂岩>50%	覆压渗透率≤0.1 或空气渗透率<1.0
	页岩油	富有机质页岩层系≥50%	

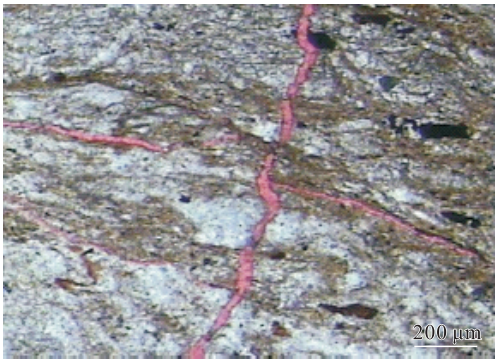
3 侏罗系油藏分类

3.1 常规油藏

四川盆地侏罗系油藏经历过孔隙型、裂缝型、孔隙—裂缝型和裂缝—孔隙型的研究,而目前能证实的只有常规孔隙—裂缝型油藏,是否存在其他常规油藏还存在争议。

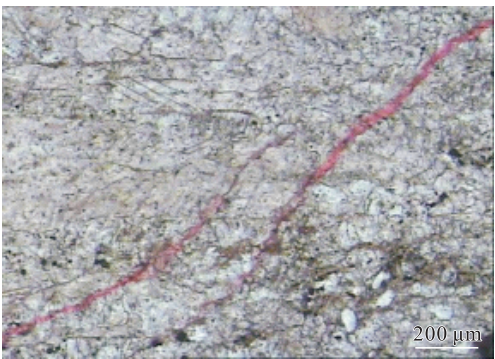
3.1.1 孔隙—裂缝型和裂缝型油藏

从野外剖面、岩心、薄片、测井、地震等描述来看,侏罗系主要发育单裂缝,裂缝密度大多极低,半径 10 m 范围内偶见 1 条毫米级以上裂缝,1 口取心井发育数百条微米级裂缝,且裂缝多被充填或半充填,见图 1,其裂缝空间不足以支撑万吨级以上的石油产出。



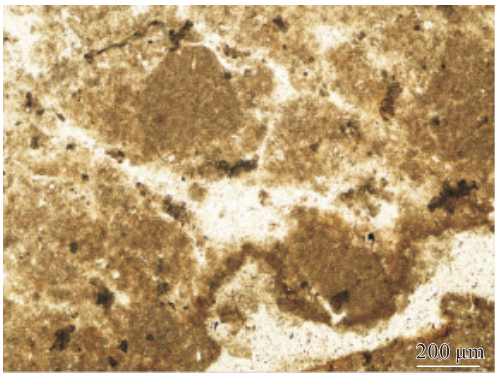
a) 大安寨段,构造缝分叉呈网状延伸,宽约 0.03 mm,铸体单偏光×25

a) Da'anzhai Member, the structural fractures are branched and extended in a network, about 0.03 mm wide, casting single-polarized light ×25



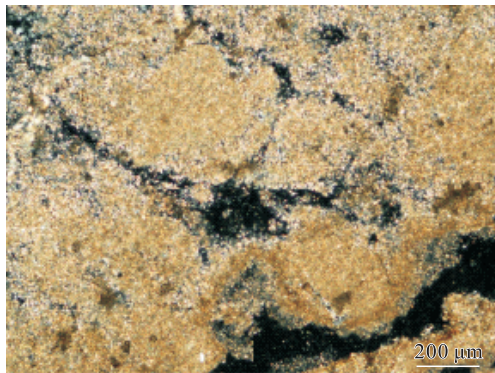
b) 大安寨段,构造微裂缝,宽约 0.01 mm,斜交切割介壳,铸体单偏光×50

b) Da'anzhai Member, structural microfracture, about 0.01 mm wide, oblique cut shell, casting single-polarized light ×50



c) X3 井,大安寨段,砂屑泥晶云岩,发育粒间溶孔,单偏光

c) Well X3, Da'anzhai Member, clastic micritic dolomite with intergranular dissolved pores and single-polarized light



d) X3 井,大安寨段,砂屑泥晶云岩,发育粒间溶孔,正交偏光

d) Well X3, Da'anzhai Member, clastic micritic dolomite with intergranular dissolved pores and orthogonal polarization

图 1 大安寨段薄片照片

Fig. 1 Slice of Da'anzhai Member

在岩石不发生大破碎的情况下,针对大安寨段油藏按上述描述假设,半径10 m范围内,平均发育1条平面延展10 m、垂向延展30 m(灰岩厚度)、有效缝宽5 mm的垂直缝,发育10 000条0.1 m长、0.05 m宽、有效缝宽0.03 mm的微裂缝,则在井控半径500 m的范围内,计算的裂缝空间体积为 $3\,754\text{ m}^3$,即使不考虑含油饱和度、体积系数、采收率等,裂缝空间体积也不到累产万吨以上石油体积的一半,而大安寨段油藏有148口万吨油井^[2],且从地震看,产油区大断裂极少,因此裂缝不是主要的储集空间。从试井、生产数据等分析,侏罗系油藏显然也不是以裂缝型油藏为主,不过局部地区存在孔隙—裂缝型油藏,如广安地区的凉高山组油藏。

广安地区凉高山组构造为背斜,发育多条平行轴线的断层。钻井在凉高山组多见井漏显示,漏失量可达 $1\,000\text{ m}^3$ 以上。凉高山组岩心破碎严重,砂岩被裂缝切割成块片状,泥页岩多呈碎块状,3口井的凉高山组岩心上见裂缝361条,其中有效缝340条,洞68个,擦痕65条,裂缝密度高达2条/m以上,裂缝渗透率大于 $1 \times 10^{-3}\text{ }\mu\text{m}^2$ 。广安地区凉高山组油藏多为低压,地层压力系数低至0.6 MPa/100 m,除初期个别井自喷外,主要为抽汲生产,气油比低至 $10\text{ m}^3/\text{m}^3$ 以下,增产措施以清蜡、热油洗井为主。笔者认为,广安地区紧邻西南—东北走向的华莹山大断裂西侧,而广安地区在侏罗系形成的背斜构造走向为北西—南东向,两组垂直方向的主应力在广安地区凉高山组形成网状裂缝,凉高山组岩层被网状裂缝切割,裂缝不仅切割致密砂岩,还切穿烃源岩,烃源气溢散后,溶解残余烃源气的石油充满裂缝及孔洞空间,形成低压油藏。因此,广安地区局部凉高山组油藏推断为孔隙—裂缝型油藏,见图2①类。

四川盆地侏罗系下部多为挤压断层,形成的断层、裂缝空间有限。烃源层又多与灰岩、砂岩互层分布,且介壳类生物发育,砂岩地层中钙质含量也较高^[10]。在有机酸的作用下,裂缝发育的地方,溶蚀孔洞也发育,见图3-a)、图2⑦类,因此,很难存在纯粹的裂缝型油藏。

3.1.2 裂缝—孔隙型和孔隙型油藏

从图3野外剖面和岩心观察发现,大安寨段在局部地区发育溶蚀孔洞,其分布非均质较强。在大安寨段介壳滩微相“西环带”边缘发现灰岩有白云石化现象,形成较稳定的溶蚀孔洞层,在厚2.5 m左右的白云石化带,溶蚀孔洞段孔隙度可高达5%以上,平均3%,按500 m井控半径计算,溶蚀孔洞体积空间近 $6 \times 10^4\text{ m}^3$,可以作为主要的储集空间,见图2②类。

X3井通过水平井钻探钻遇白云石化带170 m,钻遇

孔隙度大于3%的优质储层70 m,优质储层电阻率呈现“箱形”正差异,孔隙度曲线呈“钟形”,薄片见溶孔发育,测试获日产油超过50 t,从测井、地震和生产曲线上均未发现明显裂缝,为典型孔隙型储层。X3井因砂堵等原因产量突然下降,停产修井后,再无油气流产出,且测井渗透率大多小于 $1 \times 10^{-3}\text{ }\mu\text{m}^2$,有学者认为是致密油。但笔者认为测井渗透率是由基质灰岩孔渗关系式计算的,而X3井薄片观察的溶蚀孔喉为微米级,远好于基质纳米孔喉(前者多为常规油气藏,后者多为非常规油气藏^[11]),测井计算渗透率偏低,只是突然停产引发了对其溶蚀空间大小、烃源侧向运移距离的担忧,能否形成常规孔隙型油藏还需要深入研究。

部分井中也发现多处溶蚀孔洞层,厚度多为0.3 m左右,孔隙度为1%~5%,并偶见缝宽1 cm左右的半充填缝,只是厚度较薄,多作为页岩油的补充,有学者^[1-2,12]称为致密油的“甜点”,见图2⑦、⑧类。如果溶蚀加深,发育大量溶洞,则储集和渗透能力增大,有可能形成常规孔隙型油藏,再有裂缝配合,也可能形成常规裂缝—孔隙型油藏,如果有须家河组的烃源断层,还能形成气顶油藏,见图2③类,八角场地区大安寨段油气藏就是实例,因此寻找常规油藏还需要深入研究。

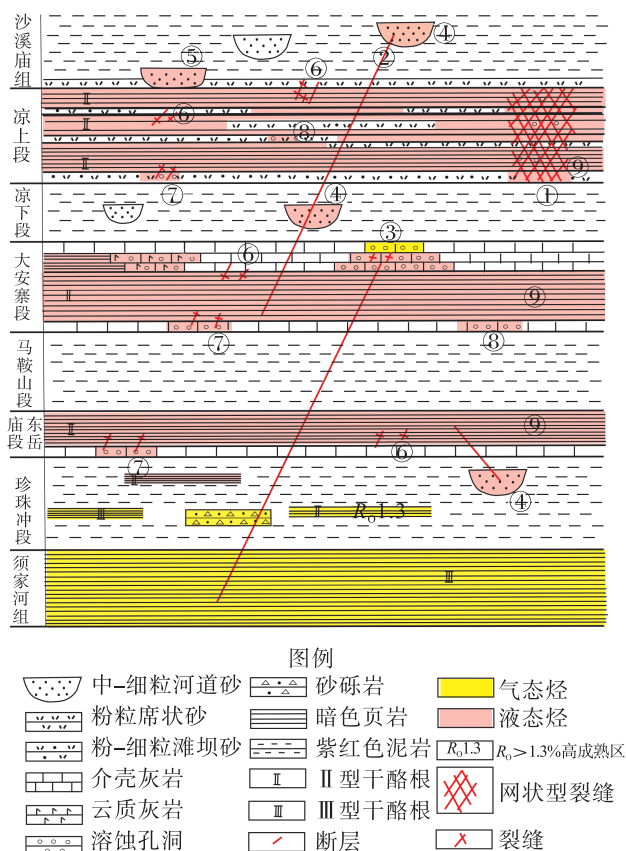


图2 四川盆地侏罗系石油成藏剖面图

Fig. 2 Petroleum accumulation profile of Jurassic in Sichuan Basin



a) 大一亚段, 介屑灰岩中构造缝充填的方解石溶蚀后形成溶蚀缝洞

a) Da'anzhai 1 Sub-member, the calcite filled by structural fractures in mesoclastic limestone dissolved and formed the dissolution fracture cave



b) 大一亚段, 3 854. 36 ~ 3855. 16 m, 介壳灰岩夹灰色泥岩, 发育溶蚀孔洞

b) Da'anzhai 1 Sub-member, 3 854. 36 ~ 3 855. 16 m, shell limestone interbedded with gray mudstone and developed with dissolution pores



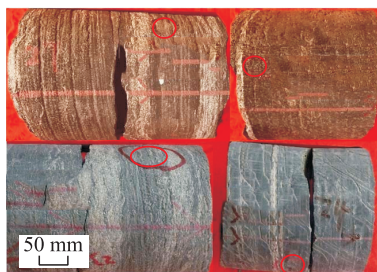
c) 大安寨段, 介壳灰岩, 发育溶蚀孔洞, 见油迹、有油味

c) Da'anzhai Member, crustal limestone with dissolution pores, oil traces and oil smell



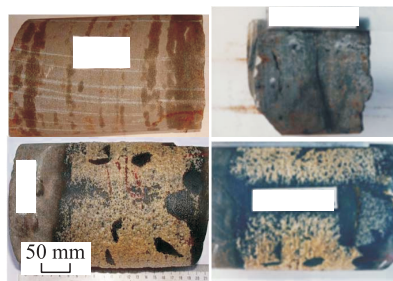
d) 大桥村剖面, 大安寨段, 厚层灰岩中的溶洞

d) Daqiao Village Section, Da'anzhai Section, karst cave in thick limestone



e) 大安寨段, 深灰色页岩夹灰白色灰岩条带, 岩心含气试验, 红圈为冒气处

e) Da'anzhai Member, dark gray shale with gray limestone strip, core gas bearing test, the red circle located the gas escaping place



f) 沙一段, 中—细砂岩, 河道砂体含油, 低角度缝和水平层理面两侧见油侵

f) The first member of the Shaximiao 1 Formation, medium-fine sandstones, and the channel sandbody is oil-bearing. Oil invasion can be seen on both sides of low angle fractures and horizontal bedding planes

图 3 岩心及野外剖面溶蚀孔洞照片

Fig. 3 Photos of dissolution holes in crop and field profile

3.2 非常规油藏

3.2.1 隔夹层和顶底板

四川陆相页岩油的岩石组合为泥页岩与粉砂岩、碳酸盐岩互层^[13], 粉砂岩、碳酸盐岩的单层厚度常大于 5 m, 页岩被分成若干不连续的小层段, 页岩孔隙度主要分布在 1% ~ 5% 之间, 高于致密灰岩 1% 左右孔隙度, 也高于致密粉砂岩 2% 左右的孔隙度, 见图 4 ~ 8, 页岩中页岩等水平缝较发育, 且页岩的破裂压力也远低于致密灰岩和致密粉砂岩, 因此油气更易在页岩中脉冲式运移富集。

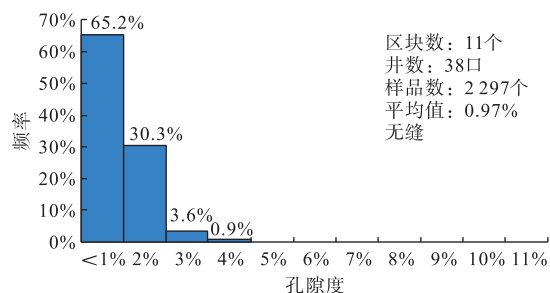
大安寨段灰岩储层孔隙度多小于 1%, 孔喉半径峰值为 19 ~ 72 nm, 主要为纳米孔, 理论上孔喉充注下限为 32 nm^[12], 实际上由于启动压力梯度的阻碍, 往厚层灰岩内部充注会越来越困难^[14], 含油饱和度也变低, 油气多以浓度差扩散形式在纳米孔中形成油膜, 因此无裂缝沟通, 石油极难充注与产出; 各项研究^[1-2, 12]也证实裂缝是油井高产的关键, 而且高产油井的薄片、扫描电镜等只见到裂缝、微裂缝沟通部分孔隙, 连通孔隙空间极为有限, 说明灰岩储层的油产量贡献较少。沙一段底部和凉

上段粉砂岩孔隙度在 2% 左右, 为致密粉砂岩, 如果无裂缝沟通, 则油水在 2% 的低孔砂岩中呈流体束缚状态^[15]或不含油, 见图 9。因此, 致密粉砂岩、碳酸盐岩大多为非储层^[16]。中石化常把大安寨段顶、底厚层灰岩作为油藏的顶、底板^[3], 阻挡油气溢散, 如大安寨段岩心冒气处被限制在紧靠致密灰岩层的页岩中, 见图 3-e), 也就是说致密灰岩阻止了页岩中油气的进一步运移。

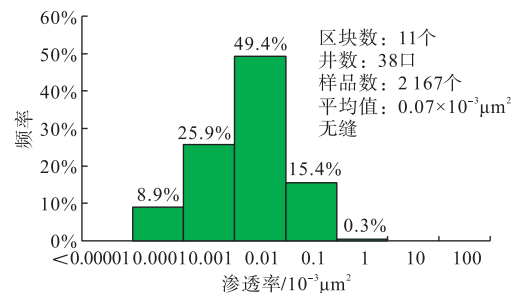
过去侏罗系油藏的开采大多与裂缝有关, 这些裂缝不是起到连通致密粉砂岩、致密碳酸盐岩中孔隙空间作用, 而是延伸到富有机质页岩中, 裂缝作为渗流通道^[17], 连通井筒与页岩储集空间, 生产时主要起引流页岩储集空间中石油的作用, 笔者形容为“导管引流”, 见图 2⑥、⑦类。

3.2.2 河道砂油藏多为致密油

沙一段河道砂油藏主要分布在沙一段中、下部, 少数分布在沙一段底部和凉下段, 见图 2④、⑤类, 主要为中、细砂岩, 图 3-f) 砂岩岩心见油浸, 砂体厚度在 20 m 左右, 测井曲线上多表现为“箱形”或“钟形”, 孔隙度一般大于 3%, 孔隙度峰值在 3% ~ 6%, 烃源主要来自于大安



a) 大安寨段石灰岩孔隙度分布直方图



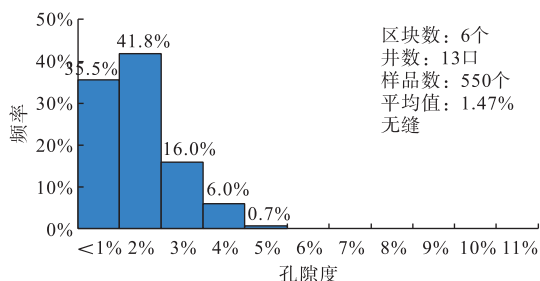
b) 大安寨段石灰岩渗透率分布直方图

a) Histogram of porosity distribution of limestone in Da'anzhai Member

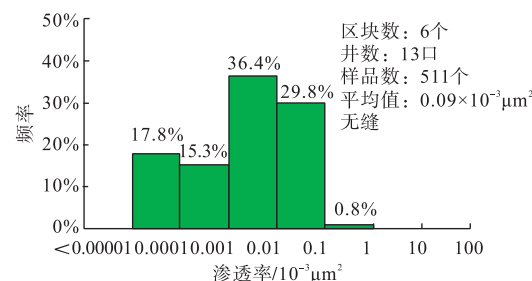
b) Histogram of permeability distribution of limestone in Da'anzhai Member

图4 大安寨段石灰岩物性分布直方图

Fig. 4 Histogram of physical property distribution of limestone in Da'anzhai Member



a) 凉高山组粉砂岩孔隙度分布直方图



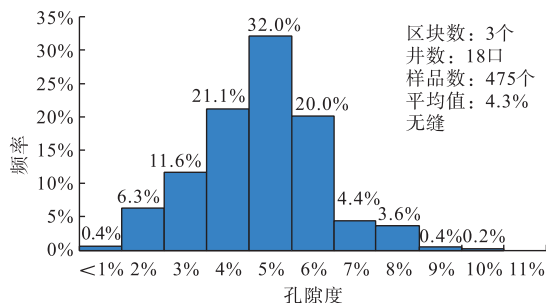
b) 凉高山组粉砂岩渗透率分布直方图

a) Histogram of siltstone porosity distribution in Lianggaoshan Formation

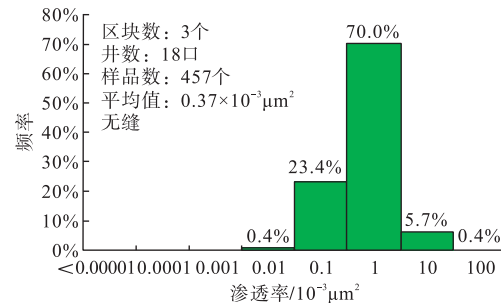
b) Histogram of siltstone permeability distribution in Lianggaoshan Formation

图5 凉高山组粉砂岩物性分布直方图

Fig. 5 Histogram of physical property distribution of siltstone in Lianggaoshan Formation



a) 沙一段中—细砂岩孔隙度分布直方图



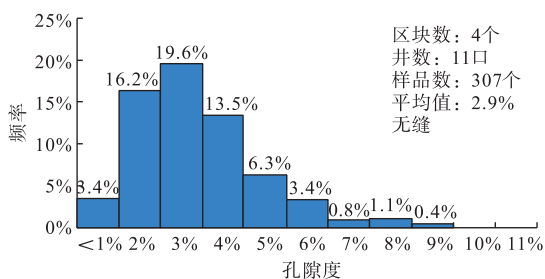
b) 沙一段中—细砂岩渗透率分布直方图

a) Histogram of porosity distribution of medium-fine sandstone in Shaximiao 1 Member

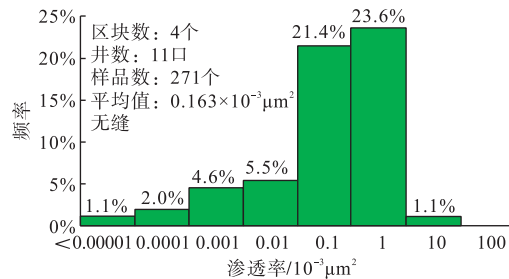
b) Histogram of permeability distribution of medium-fine sandstone in Shaximiao 1 Member

图6 沙一段中—细砂岩物性分布直方图

Fig. 6 Histogram of physical property distribution of medium-fine sandstone in Shaximiao 1 Member



a) 沙一段粉砂岩孔隙度分布直方图



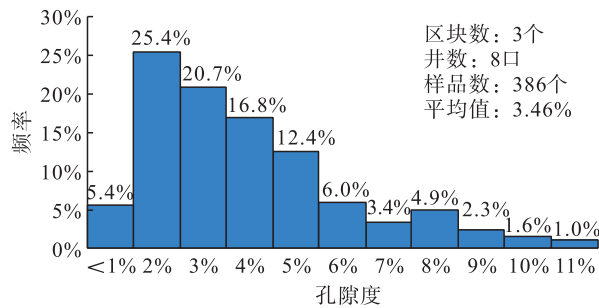
b) 沙一段粉砂岩渗透率分布直方图

a) Histogram of siltstone porosity distribution in Shaximiao 1 Member

b) Histogram of siltstone permeability distribution in Shaximiao 1 Member

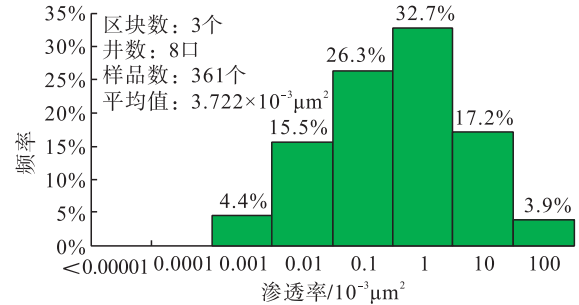
图7 沙一段粉砂岩物性分布直方图

Fig. 7 Histogram of physical property distribution of siltstone in Shaximiao 1 Member



a) 侏罗系页岩孔隙度分布直方图

a) Histogram of porosity distribution in Jurassic shale

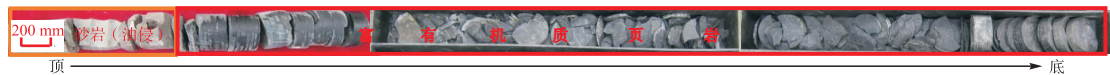


b) 侏罗系页岩渗透率分布直方图

b) Histogram of permeability distribution in Jurassic shale

图 8 侏罗系页岩物性分布直方图

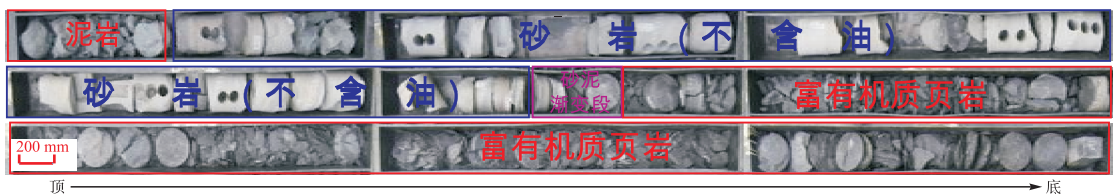
Fig. 8 Histogram of physical property distribution in Jurassic shale

a) X7 井, 沙一段底部中一细砂岩含油, 砂岩孔隙度 3.47%, 渗透率 $0.26 \times 10^{-3} \mu\text{m}^2$, 排驱压力 1.09 MPa; 凉上段顶部灰黑色页岩 TOC 2.33%

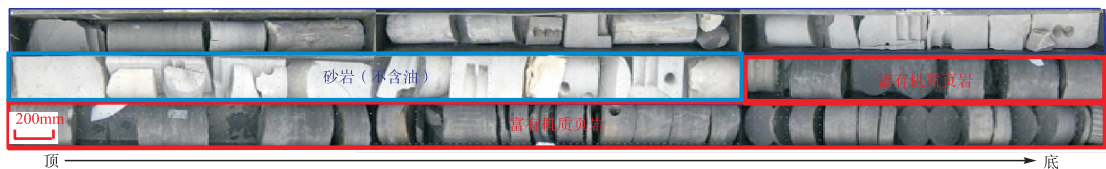
a) Well X7, medium to fine sandstone at the bottom of the first member of Shaximiao 1 Member is oil-bearing, with porosity of 3.47%, permeability of $0.26 \times 10^{-3} \mu\text{m}^2$ and displacement pressure of 1.09 MPa. The gray black shale at the top of the Upper Lianggaoshan Formation section TOC 2.33%

b) X5 井, 沙一段底部细砂岩含油, 细砂岩孔隙度 2.25%, 渗透率 $0.163 \times 10^{-3} \mu\text{m}^2$; 凉上段顶部灰黑色页岩 TOC 1.4%; 细砂岩与页岩之间夹 0.3 m 的泥质粉砂岩, 孔隙度 1.73%, 见裂缝发育

b) Well X5, fine sandstone at the bottom of the first member of Shaximiao 1 Member is oil-bearing, with porosity of 2.25% and permeability of $0.163 \times 10^{-3} \mu\text{m}^2$; TOC 1.4% of gray black shale at the top of the Upper Lianggaoshan Formation section; The 0.3 m argillaceous siltstone is sandwiched between the fine sandstone and the shale with a porosity of 1.73%, showing fracture development

c) X4 井, 沙一段底部细砂岩不含油, 细砂岩孔隙度 3.84%, 渗透率 $0.78 \times 10^{-3} \mu\text{m}^2$, 排驱压力 0.93 MPa; 凉上段顶部灰黑色页岩 TOC 1.28%; 细砂岩与页岩之间夹 0.3 m 的泥质粉砂岩, 孔隙度 1.75%

c) Well X4, fine sandstone at the bottom of the first member of Shaximiao 1 Member is oil-free, with porosity of 3.84%, permeability of $0.78 \times 10^{-3} \mu\text{m}^2$ and displacement pressure of 0.93 MPa; TOC 1.28% of the gray black shale at the top of the Upper Lianggaoshan Formation section; A 0.3 m argillaceous siltstone is sandwiched between fine sandstone and shale, with a porosity of 1.75%

d) X8 井, 沙一段底部粉砂岩不含油, 粉砂岩孔隙度 1.69%, 渗透率 $0.19 \times 10^{-3} \mu\text{m}^2$, 排驱压力 8.73 MPa; 凉上段顶部灰黑色页岩 TOC 1.94%

d) Well X8, there is no oil in siltstone at the bottom of the first member of Shaximiao 1 Member. The porosity of siltstone is 1.69%, the permeability is $0.19 \times 10^{-3} \mu\text{m}^2$, and the displacement pressure is 8.73 MPa. The gray black shale at the top of the Upper Lianggaoshan Formation section TOC 1.94%

图 9 沙一段一凉上段岩心柱子中砂岩与富含有机质页岩接触关系图

Fig. 9 Contact relationship between sandstone and organic-rich shale in core pillars of Shaximiao 1 Member to Upper Lianggaoshan Formation

寨段、凉上段,大多由烃源断层输导的远源成藏模式^[18]。公山庙油田公1号断层为逆断层,在断层上盘2 km范围内大安寨段油井产能极低^[19],且不产水,而沙一段在3 km左右构造高部位的油井产能较高,也就是说,目前烃源断层是封闭的,沙一段开采的石油主要来自于河道砂的储集空间,由于空气渗透率小于 $1 \times 10^{-3} \mu\text{m}^2$,因此,沙一段河道砂油藏主要为致密油。

针对公山庙油田沙一段河道砂,通过地震预测河道砂组,实施水平井钻探河道砂,采用体积加砂压裂,有2口井均获得日产油20 t以上的高产。

3.2.3 珍珠冲段油气藏

珍珠冲段油井集中分布在珍珠冲段烃源区外的遂宁地区,油源主要来自于东岳庙段烃源的倒灌,“十三五”油气资源评价把源外成藏的珍珠冲段油藏作为致密油,见图2④类。

珍珠冲段优质烃源岩主要分布在开江—大竹—广安—南充—绵阳—南江—万源区域内,大多位于 $R_o > 1.3\%$ 的高成熟度区^[20],有机质类型除了Ⅱ型,还有大量Ⅲ型,Ⅱ型有机质的烃源岩大多 $TOC < 2\%$,Ⅲ型有机质的烃源岩大多 $TOC > 2\%$,甚至高达10%以上。因此,珍珠冲段烃源以生气为主。另外,珍珠冲段直接覆盖在须家河组之上,还有大量来源于须家河组的气源,如九龙山珍珠冲段砾岩气藏。

珍珠冲段烃源岩纵向上分布大多较分散,目前没有发现像凉高山组、大安寨段和东岳庙段的烃源岩集中分布段,且研究程度较低,其资料有限,因此,珍珠冲段油气藏目前研究困难较大,还需要深入研究。

3.2.4 凉高山组页岩油

沙一段底部席状砂与凉高组顶部烃源岩常间隔一段0.3 m左右的粉砂质泥岩、泥质粉砂岩间隔层,这套间隔层若无裂缝沟通,则紧邻的砂岩不含油^[14],如X4井,如果有裂缝发育,则紧邻的砂岩含油,如X5井,在X5井中,沙一段底部席状砂裂缝发育段岩心见油侵,裂缝不发育段岩心仅见荧光显示,在井深2 501~2 502 m处发育较大规模裂缝,钻井见井涌显示,测试日产油6.5 t,累产油1 500 t,测试段砂岩孔隙度最低0.8%,最高3.6%,平均1.7%,从钻井显示、岩心描述、物性及测试情况看,油产量主要是通过裂缝的“导管引流”,直接引流来自凉高山组烃源岩中石油获得的产量。因此沙一段底部席状砂(无裂缝发育)主要是作为凉高山组页岩油顶板,同样,凉上段底部粉砂岩作为底板。顶、底板间富有机质页岩连续厚度在20 m以上,石油大部分保存在富有机质页岩中,形成页岩油,见图2⑨类。

3.2.5 大安寨段页岩油

大安寨段顶、底均为致密灰岩,灰岩基质孔隙度1%

左右,电阻率值高达10 000 Ωm 左右,局部发育裂缝、微裂缝,中部为大段厚层富有机质页岩夹薄层介壳灰岩,富有机质页岩连续厚度多在30~40 m之间^[21],X6井在顶、底灰岩段测试日产油7.3 t,累产油约13 000 t,灰岩段多处见裂缝发育,石油产量主要通过裂缝、微裂缝的“导管引流”,直接引流来自大安寨段烃源岩中石油获得。因此,大安寨段顶、底致密灰岩为大安寨段油藏的顶、底板,使得生成的石油大部分保存在富有机质页岩中,形成页岩油,见图2⑨类。

3.2.6 东岳庙段页岩油

同大安寨段和凉高山组页岩油一样,东岳庙段底部也有致密灰岩作为底板,马鞍山段底部泥岩作为顶板,为东岳庙段页岩油提供良好的保存条件,见图2⑨类,只是川中地区东岳庙段富有机质页岩厚度多在10 m左右,要获得工业油流较困难,这也是川中地区东岳庙段未获得累产上万吨油井的主要原因。不过川东地区东岳庙段富有机质页岩连续厚度可达20 m左右,最大厚度超过30 m,只是川东地区有机质成熟度较高,大多处于凝析油—生气阶段,以湿气为主,产少量凝析油,如中石化在涪页X7井东岳庙段测试日产气 $15 \times 10^4 \text{ m}^3$ 左右,日产油不到 10 m^3 。川东地区由于高山峡谷纵横,山顶的侏罗系多被剥蚀,山谷间大多发育断层,峡谷面积又较小,油气保存条件较差^[21],增加了川东地区勘探开发难度,也是川东地区侏罗系勘探开发程度较低的原因之一。

4 结论

1) 四川盆地侏罗系油藏以页岩油为主,其次为致密油。只发现一处常规孔隙—裂缝型油藏。

2) 在沙一段底部席状砂、凉上段粉砂岩、大安寨段和东岳庙段介壳灰岩中开采的石油,主要是通过裂缝的“导管引流”获取富有机质页岩中的页岩油。

3) 沙一段、凉下段和珍珠冲段河道砂油藏为致密油。

4) 沙一段底部席状砂、凉上段底部粉砂岩、大安寨段顶底厚层灰岩、东岳庙段底部灰岩多为页岩油顶、底板,而凉高山组、大安寨段和东岳庙段顶、底板间富有机质层系中油藏为页岩油。

参考文献:

- [1] 邹娟,乐园,金涛,等.川中地区侏罗系致密砂岩储集层成因及“甜点”预测[J].新疆石油地质,2018,39(5):555-560.
- ZOU Juan, LE Yuan, JIN Tao, et al. Genesis of Jurassic tight sandstone reservoirs in central Sichuan region and prediction of “dessert” [J]. Xinjiang Petroleum Geology,

- 2008, 39 (5): 555-560.
- [2] 黄东, 杨光, 杨智, 等. 四川盆地致密油勘探开发新认识与发展潜力[J]. 天然气地球科学, 2019, 30 (8): 1212-1221.
- HUANG Dong, YANG Guang, YANG Zhi, et al. New understanding and development potential of tight oil exploration and development in Sichuan Basin [J]. Natural gas geoscience, 2019, 30 (8): 1212-1221.
- [3] 魏祥峰, 黄静, 李宇平, 等. 元坝地区大安寨段陆相页岩气富集高产主控因素[J]. 中国地质, 2014, 41 (3): 970-987.
- WEI Xiangfeng, HUANG Jing, LI Yuping, et al. The main factors controlling the enrichment and high production of Da'anzhai member continental shale gas in Yuanba area [J]. Geology in China, 2014, 41 (3): 970-987.
- [4] 时筱淞, 林伶, 李洪香, 等. 沧东凹陷孔二段斜坡演化及控砂控藏机制[J]. 天然气与石油, 2018, 36(3): 65-70.
- SHI Xiaosong, LIN Ling, LI Hongxiang, et al. Slope evolution and sand control and reservoir control mechanism of the second member of Cangdong sag [J]. Natural Gas and Oil, 2012, 36 (3): 65-70.
- [5] 贾承造. 论非常规油气对经典石油天然气地质学理论的突破及意义[J]. 石油勘探与开发, 2017, 44(1): 1-11.
- JIA Chengzao. On the breakthrough and significance of unconventional oil and gas to the classical petroleum and natural gas geology [J]. Petroleum Exploration and Development, 2017, 44 (1): 1-11.
- [6] 黄鑫, 董秀成, 肖春跃, 等. 非常规油气勘探开发发现及发展前景[J]. 天然气与石油, 2012, 30(6): 38-41.
- HUANG Xin, DONG Xiucheng, XIAO Chunyue, et al. Observation and discovery of unconventional gas exploration and development prospect [J]. Natural Gas and Oil, 2012, 30 (6): 38-41.
- [7] 王礼常, 王志章, 陶果. 致密砂岩气藏储层分类新方法[J]. 科技导报, 2011, 29(24): 47-50.
- WANG Lichang, WANG Zhizhang, TAO Guo. New method for reservoir classification of tight sandstone gas reservoirs [J]. Science and Technology Bulletin, 2011, 29 (24): 47-50.
- [8] 赵政璋, 杜金虎. 致密油气[M]. 北京: 石油工业出版社, 2012.
- ZHAO Zhengzhang, DU Jinhu. Tight oil and gas [M]. Beijing: Petroleum Industry Press, 2012.
- [9] 邱振, 施振生, 董大忠, 等. 致密油源储特征与聚集机理——以准噶尔盆地吉木萨尔凹陷二叠系芦草沟组为例[J]. 石油勘探与开发, 2016, 43(6): 928-939.
- QIU Zhen, SHI Zhensheng, DONG Dazhong, et al. Tight oil source reservoir characteristics and aggregation mechanism: a case study of the permian Lucaogou formation in Jimsar sag, Junggar Basin [J]. Petroleum Exploration and Development, 2016, 43 (6): 928-939.
- [10] 黄东, 段勇, 李育聪, 等. 淡水湖相页岩油气有机碳含量下限研究——以四川盆地侏罗系大安寨段为例[J]. 中国石油勘探, 2018, 23(6): 38-45.
- HUANG Dong, DUAN Yong, LI Yucong, et al. Study on the toc lower limit of shale oil and gas of freshwater lake facies: a case study on the Jurassic Da'anzhai member in the Sichuan Basin [J]. China Petroleum Exploration, 2018, 23 (6): 38-45.
- [11] 邹才能, 杨智, 陶士振, 等. 纳米油气与源储共生型油气聚集[J]. 石油勘探与开发, 2012, 39(1): 13-26.
- ZOU Caineng, YANG Zhi, TAO Shizhen, et al. Nano-hydrocarbon and the accumulation in coexisting source and reservoir [J]. Petroleum Exploration and Development, 2012, 39 (1): 13-26.
- [12] 杨跃明, 杨家静, 杨光, 等. 四川盆地中部地区侏罗系致密油研究新进展[J]. 石油勘探与开发, 2016, 43 (6): 873-882.
- YANG Yueming, YANG Jiajing, YANG Guang, et al. New research progress of Jurassic tight oil in central Sichuan Basin [J]. Petroleum Exploration and Development, 2016, 43 (6): 873-882.
- [13] 朱彤, 俞凌杰, 王烽. 四川盆地海相、湖相页岩气形成条件对比及开发策略[J]. 天然气地球科学, 2017, 28 (4): 633-641.
- ZHU Tong, YU Lingjie, WANG Feng. Comparison of marine and lacustrine shale gas formation conditions and development strategies in Sichuan Basin [J]. Natural Gas Geoscience, 2017, 28 (4): 633-641.
- [14] 金涛, 白蓉, 邹娟, 等. 致密油含油厚度定量计算方法[J]. 天然气与石油, 2019, 37(3): 51-55.
- JIN Tao, BAI Rong, ZOU Juan, et al. Methods for quantitative calculation of oil thickness in tight oil [J]. Natural Gas and Oil, 2019, 37 (3): 51-55.
- [15] 金涛, 邹娟, 周春林, 等. 致密油碎屑岩储层分类方法探讨[J]. 天然气与石油, 2017, 35(4): 58-62.
- JIN Tao, ZOU Juan, ZHOU Chunlin, et al. Study on the classification methods of tight oil clastic rock reservoirs [J]. Natural Gas and Oil, 2017, 35 (4): 58-62.
- [16] 巨世昌, 刘博峰, 李闻东, 等. 致密砂岩储集层物性下限确定方法浅析[J]. 天然气与石油, 2017, 35(3): 62-67.
- JU Shichang, LIU Bofeng, LI Wendong, et al. A brief analysis of methods for determining the lower limit of physical properties of tight sandstone reservoirs [J]. Natural Gas and Oil, 2017, 35 (3): 62-67.

- Xi'an Petroleum University (Natural Science Edition), 2001, 16 (4): 79-84.
- [26] PHAN V T, CHOO S Y. A combination of augmented reality and google earth's facilities for urban planning in idea stage [J]. International Journal of Computer Applications, 2010, 4 (3): 26-34.
- [27] 孙敏, 陈秀万, 张飞舟, 等. 增强现实地理信息系统[J]. 北京大学学报(自然科学版), 2004, 40(6): 906-913.
SUN Min, CHEN Xiuwan, ZHANG Feizhou, et al. Augment reality geographical information system [J]. Acta Scientiarum Naturalium Universitatis Pekinensis, 2004, 40 (6): 906-913.
- [28] 常勇, 何宗宜. 户外增强现实技术及其在地下管网3D可视化中的应用[J]. 测绘通报, 2005(11): 57-60.
CHANG Yong, HE Zongyi. Technology of augmented reality and its application in 3D visualization of underground pipeline [J]. Bulletin of Surveying and Mapping, 2005 (11): 57-60.
- [29] 周玲, 陈强. 城市地下管网增强现实系统研究[J]. 计算机工程与应用, 2020, 56(1): 251-256.
ZHOU Ling, CHEN Qiang. Research on augmented reality system of urban underground pipe network [J]. Computer Engineering and Applications, 2020, 56 (1): 251-256.
- [30] 何波, 张慎, 邱文航, 等. 增强现实技术在工程施工中的应用综述[J]. 土木工程与管理学报, 2020, 37 (2): 93-98.
HE Bo, ZHANG Shen, QIU Wenhong, et al. Overview on application of augmented reality technology in engineering construction [J]. Journal of Civil Engineering and Management, 2020, 37 (2): 93-98.
- [31] 闫婉, 任玲, 宋光红, 等. 数字化协同设计对智能油气田建设的支持[J]. 天然气与石油, 2018, 36(3): 110-115.
YAN Wan, REN Ling, SONG Guanghong, et al. Digital collaborative design supports the construction of intelligent oil & gasfields [J]. Natural Gas and Oil, 2018, 36 (3): 110-115.
- [32] 汤晓勇, 孙子杰, 王鸿捷, 等. 智能油气田标准体系研究[J]. 天然气与石油, 2019, 37(5): 115-118.
TANG Xiaoyong, SUN Zijie, WANG Hongjie, et al. Research on standardization system of intelligent oil and gas fields [J]. Natural Gas and Oil, 2019, 37 (5): 115-118.
- [33] 王鸿捷. 智能油气田数字化交付研究[J]. 天然气与石油, 2020, 38(3): 108-111.
WANG Hongjie. A study on digital delivery of smart oil and gas field [J]. Natural Gas and Oil, 2020, 38 (3): 108-111.
- [34] 李遵照, 王剑波, 王晓霖, 等. 智慧能源时代的智能化管道系统建设[J]. 油气储运, 2017, 36(11): 1243-1250.
LI Zunzhao, WANG Jianbo, WANG Xiaolin, et al. Construction of intelligent pipeline system in the era of smart energy [J]. Oil & Gas Storage and Transportation, 2017, 36 (11): 1243-1250.
- [35] 李海润. 智慧管道技术现状及发展趋势[J]. 天然气与石油, 2018, 36(2): 129-132.
LI Hairun. The status quo & development trend of smart pipeline technology [J]. Natural Gas and Oil, 2018, 36 (2): 129-132.



(上接第 81 页)

- [17] 唐邦忠,沈 华,才 博,等.束鹿泥灰岩致密油水平井体积压裂技术研究[J].天然气与石油,2014,32(4):43-45.
TANG Bangzhong, SHEN Hua, CAI Bo, et al. Research on volume fracturing technique in horizontal tight oil wells of bunge marl [J]. Natural Gas and Oil, 2019, 32 (4): 43-45.
 - [18] 黄 东,李育聪,刘 敏,等.川中地区中侏罗统沙溪庙组一段油气藏特征及勘探潜力评价[J].中国石油勘探,2017,22(2):44-49.
HUANG Dong, LI Yucong, LIU Min, et al. Oil and gas reservoir characteristics and exploration potential evaluation of the first member of the Shaximiao formation, middle Jurassic, central Sichuan region [J]. China Petroleum Exploration, 2017, 22 (2): 44-49.
 - [19] 金 涛,陈 玲,郭蕊莹,等.四川盆地公山庙油田大安寨段致密油刻度区地质解剖[J].天然气勘探与开发,2014, JIN Tao, CHEN Ling, GUO Ruiying, et al. Geological anatomy of the tight oil scale area in the Dayanzhai section, Gongshanmiao oilfield, Sichuan basin [J]. Natural Gas Exploration and Development, 2014, 37 (3): 19-23.
 - [20] 李登华,李建忠,张 斌,等.四川盆地侏罗系致密油形成条件、资源潜力与甜点区预测[J].石油学报,2017,38 (7):740-752.
LI Denghua, LI Jianzhong, ZHANG Bin, et al. Formation condition, resource potential and sweet-spot area prediction of Jurassic tight oil in Sichuan basin [J]. Acta Petrolei Sinica, 2017, 38 (7): 740-752.
 - [21] 邹 娟,金 涛,李雪松,等.川东地区下侏罗统勘探潜力评价[J].中国石油勘探,2018,23(4):30-38.
ZOU Juan, JIN Tao, LI Xuesong, et al. Evaluation of lower jurassic exploration potential in the eastern Sichuan region [J]. China Petroleum Exploration, 2012, 23 (4): 30-38.