

川西新场须四段致密砂岩 储层微观孔喉与可动流体变化特征

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摘要: 为了评价川西新场须四段致密砂岩储层, 应用恒速压汞及核磁共振实验方法对储层微观孔喉与可动流体变化特征进行定量分析。结果表明, 须四段致密砂岩储层可动流体参数、喉道特征参数及孔隙参数变化幅度大。微裂隙发育的致密砂岩储层孔隙对可动流体参数的影响较喉道要更大一些, 在微观上可动流体参数主要受孔隙控制。孔喉半径比较大、分布范围宽是致密砂岩储层可动流体含量低、可动用程度差的主要原因之一。微裂隙发育的致密砂岩储层具有喉道进汞饱和度较孔隙进汞饱和度和高的特点, 说明新场须四段致密砂岩储层的储集空间类型主要为孔隙—裂缝型。

关键词: 可动流体参数; 孔喉特征; 核磁共振; 恒速压汞; 致密砂岩储层; 川西

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Micro pore and throat characteristics and moveable fluid variation of tight sandstone in 4th member of Xujiahe Formation, Xinchang Gas Field, western Sichuan Basin

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Abstract: In order to evaluate the tight sandstone reservoirs in the 4th member of the Xujiahe Formation in the Xinchang area of the western Sichuan Basin, nuclear magnetic resonance and constant-rate mercury intrusion experiments have been carried out to quantitatively analyze micro pore and throat and moveable fluid variation characteristics. Studies have indicated that the moveable fluid parameters, throat parameters and pore parameters of tight sandstones vary largely. In micro-fractured tight sandstones, pores have an advantage over throats affecting the moveable fluid parameters, and the moveable fluid parameters are mainly controlled by pores. Low moveable fluid content and low producing degree of tight sandstones are mainly caused by the relatively long radius and wide distribution of pores and throats. In micro-fractured tight sandstones, the mercury saturation in throats is higher than that in pores, indicating that the dominant type of reservoir space is pore-fracture type in the 4th member of the Xujiahe Formation, the Xinchang Gas Field.

Key words: moveable fluid parameter; pore and throat characteristics; nuclear magnetic resonance; constant-rate mercury intrusion; tight sandstone reservoir; western Sichuan Basin

致密砂岩储层孔喉结构复杂, 可动流体变化大, 这一观点已得到普遍认同^[1-9]。然而, 这一结论多数都是在单一的孔喉或可动流体特征研究中得到的, 事实上孔喉特征的差异会直接导致可动流体参数变化, 但可动流体参数变化主要受孔隙或喉道影响尚不明确。基于这一考虑, 将核磁共振和恒速压汞技术相结合, 对川西新场地区须四段致密砂岩储层微观孔喉与可动流体变化特征进行了定量

分析评价。

1 实验介绍

恒速压汞技术以非常低的进汞速度(通常为 0.000 05 mL/min)将汞注入岩石孔隙体积内, 根据进汞压力的升降将岩石内部的喉道和孔隙分开, 可直接获取孔隙、喉道的数量分布^[10-12], 并得到孔隙、喉道半径和孔喉半径比分布等岩石微观特征参

数,这更利于对孔喉性质差异较大的致密储层进行研究。当孔隙半径足够小时,孔隙中的流体将被毛细管力或黏滞力所束缚而无法流动。核磁共振(NMR)技术利用孔隙大小与氢核弛豫率的反比关系,根据核磁共振谱(T_2 谱)的截止值将可动流体与不可动流体分开,获取可动流体参数。

为保证实验结果的准确性,核磁共振和恒速压汞实验采用同一块样品,先进行核磁共振测试,然后再进行恒速压汞实验。

2 实验结果

根据 13 个样品的物性分析,样品的孔隙度介于 1.70%~10.90%,平均为 6.22%;渗透率分布于 $(0.02\sim 2.81)\times 10^{-3} \mu\text{m}^2$ 范围内,平均为 $0.396\times 10^{-3} \mu\text{m}^2$,属于典型致密储层。实验分析中,将孔径大于截止孔径的孔隙体积占岩样总孔隙体积的百分数称为可动流体百分数,而将孔隙度与可动流体百分数的乘积称为可动流体孔隙度,可动流体百分数是可动用储量的上限,而可动流体孔隙度则反映单位体积样品内的可动流体量。孔隙半径与喉道半径之比称为孔喉半径比,孔隙进汞饱和度与喉道进汞饱和度之和等于总进汞饱和度。

3 储层物性和孔隙结构特征

本次 13 个实验样品的孔隙度为 1.70%~10.90%,渗透率为 $(0.02\sim 2.81)\times 10^{-3} \mu\text{m}^2$ (图 1),表明储层的非均质性较强。图 1 中前 6 个样品为须四上亚段,孔隙度为 5.90%~10.90%,平均值为 8.22%,渗透率为 $(0.16\sim 2.81)\times 10^{-3} \mu\text{m}^2$,平均为 $0.72\times 10^{-3} \mu\text{m}^2$;后

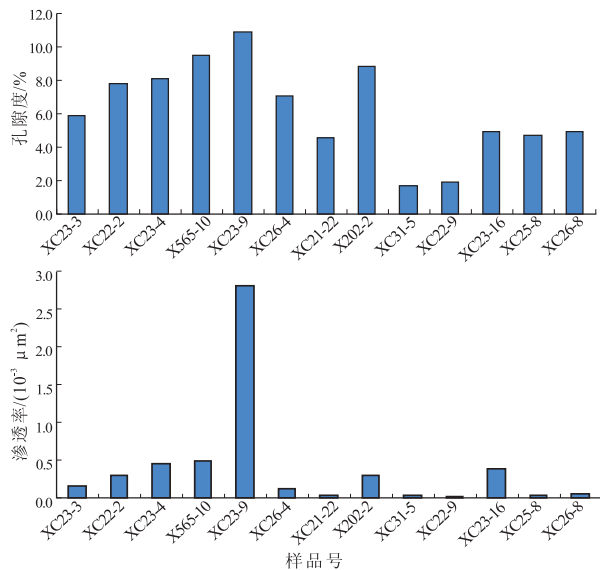


图 1 实测样品孔隙度、渗透率直方图

Fig.1 Porosity and permeability histogram of samples

7 个样品为须四下段,孔隙度为 1.70%~8.80%,平均值为 4.50%,渗透率为 $(0.03\sim 0.38)\times 10^{-3} \mu\text{m}^2$,平均为 $0.119\times 10^{-3} \mu\text{m}^2$,显然须四上亚段的物性较须四下亚段好。

岩石的孔隙度与平均孔隙半径、主流孔隙半径关系密切,而与平均喉道半径、孔喉半径比的相关性相对较弱(图 2)。岩石的渗透性与主流喉道半径、平均喉道半径关系密切^[13],而与平均孔隙半径、孔喉半径比的相关性相对较弱(图 3)。岩石排

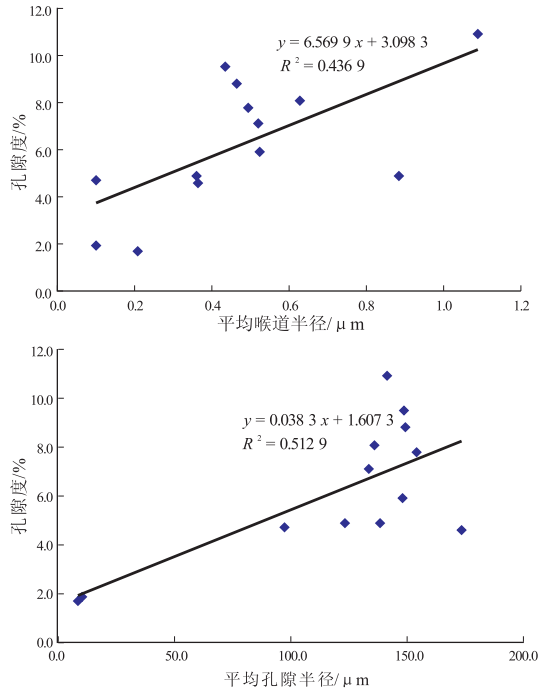


图 2 孔隙度与孔隙半径、喉道半径的相关关系

Fig.2 Relation between porosity and radius of pore and throat

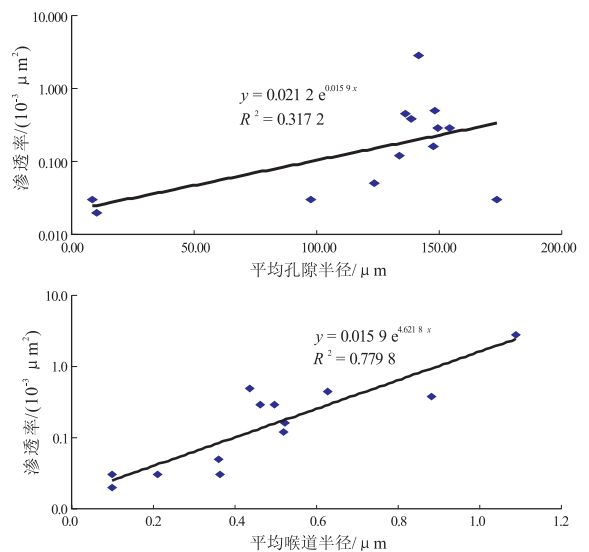


图 3 渗透率与孔隙半径、喉道半径的相关关系

Fig.3 Relation between permeability and radius of pore and throat

驱压力与渗透率关系密切,而与岩石孔隙度相关性相对较弱。

4 孔喉特征对可动流体参数的影响

根据恒速压汞和核磁共振实验结果参数,可以从 3 个方面分析微观孔喉特征与可动流体参数的变化关系。

4.1 孔喉半径的影响

13 个实测样品的孔隙半径分布在 8.72~173.32 μm 之间,喉道半径分布在 0.100~1.088 μm 之间,孔隙半径和喉道半径均差异较大。可动流体饱和度在 10.55%~49.45%,而可动流体孔隙度分布范围为 0.15%~2.49%,可以看出可动流体参数之间变化幅度也较大。为了表征孔隙、喉道对可动流体参数的影响,选取了平均孔隙半径、平均喉道半径、主流喉道半径参数来进行分析。

13 个样品的平均孔隙半径介于 8.72~173.32 μm,其中 10 个样品的平均孔隙半径集中在 123.46~173.32 μm 之间,级差仅为 1.4,表明不同渗透率级别样品孔隙之间差异不大。从平均孔隙半径与可动流体参数的相关关系可以看出(图 4),可动流体百分比与平均孔隙半径之间的相关性非常差,可动流体孔隙度与平均孔隙半径之间的相关性相对较好,说明孔隙对可动流体参数具有较大影响。

喉道是连通孔隙之间的相对狭窄部分,喉道的形状、大小直接关系孔隙之间连通性的好坏,进而也就影响可动流体参数的变化^[14]。实验结果表明,

13 个样品的平均喉道半径分布范围为 0.100~1.088 μm,变化幅度较大,级差达到了 10.88。可动流体百分比与平均喉道半径之间的相关性非常差,可动流体孔隙度与平均喉道半径值之间的相关性相对较好(图 5)。依据泊稷叶定理,喉道半径越大,对渗透率的贡献越大。定义渗透率贡献达到 95%时的所有喉道加权平均值为主流喉道半径,该参数体现的是储集层主要渗流空间的大小。13 个实测样品的主流喉道分布于 0.10~0.904 μm,可动流体参数与主流喉道半径的相关性和与平均喉道半径的相关性具有同样的规律(图 6)。

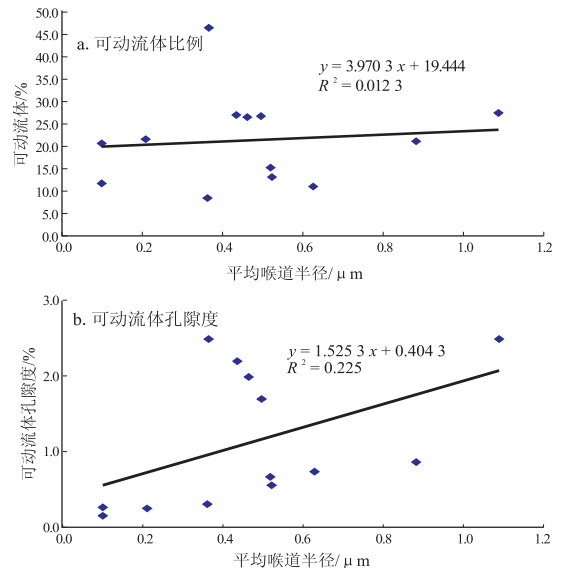


图 5 平均喉道半径与可动流体参数的相关关系
Fig.5 Relation between movable fluid parameters and average throat radiuses

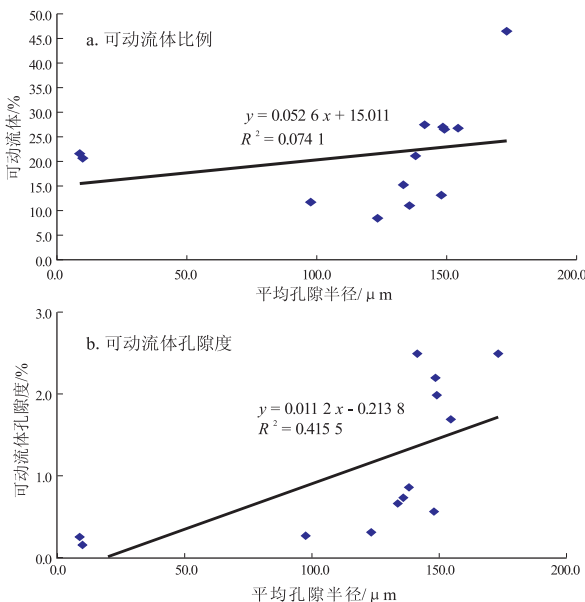


图 4 平均孔隙半径与可动流体参数的相关关系
Fig.4 Relation between movable fluid parameters and average pore radiuses

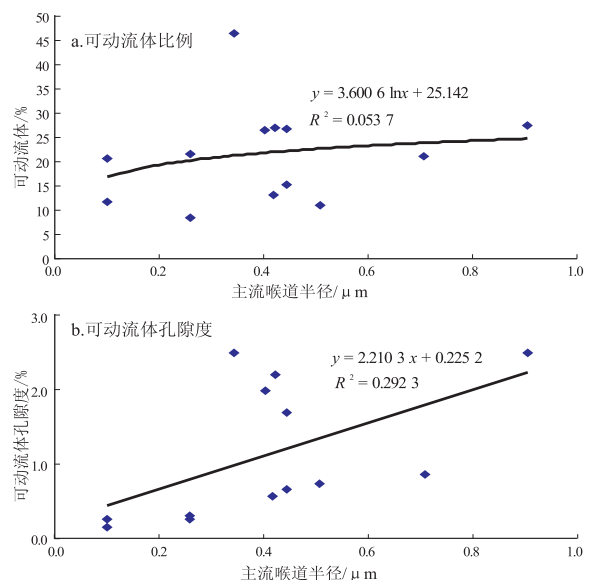


图 6 主流喉道半径与可动流体参数的相关关系
Fig.6 Relation between movable fluid parameters and main throat radiuses

通过对可动流体参数与平均孔隙半径、平均喉道半径及主流喉道半径的相关性对比分析可见,可动流体参数与平均孔隙半径的相关性要比可动流体参数与平均喉道半径及主流喉道半径的相关性略好,与常规孔隙型砂岩储层的规律相反,表明储层喉道发育;而电镜分析结果表明新场须四段致密砂岩微裂隙发育,说明喉道主要是微裂隙。因此在致密储层评价中,孔隙度参数的权重应适当减小,重视裂缝对储层性能的影响。

4.2 孔喉半径比的影响

由孔喉半径比与可动流体参数之间的相关关系可知(图 7),孔喉半径比与可动流体孔隙度的相关性好于其与可动流体百分数的相关性。实测 13 个样品的平均孔喉半径比介于 6.3~616.8,孔喉半径比越大,且分布范围宽,孔隙中流体被束缚的可能性就越大,可动流体含量就越小。气田开发过程中,孔喉半径比的大小决定着流体是发生卡断式驱替还是活塞式驱替,如果孔喉半径比大,较大孔隙被较小的喉道所包围,驱替时易发生卡断,使连续的天燃气相遭到破坏,增加了渗流阻力,减小了天然气可流动性,这也是特低渗储层可动天然气含量低,可动用程度差的主要原因之一。

4.3 孔喉体积的影响

孔、喉体积是孔隙、喉道半径及孔隙、喉道数的函数。岩样的孔隙、喉道半径越大,孔隙、喉道数越多,孔隙、喉道体积越大。喉道发育程度越高,流体越容易渗流^[15]。利用恒速压汞技术得到的孔隙、喉道进汞饱和度可以从一定程度上定量反映孔隙、喉道的体积大小。13 个实测样品的孔隙、喉道进汞

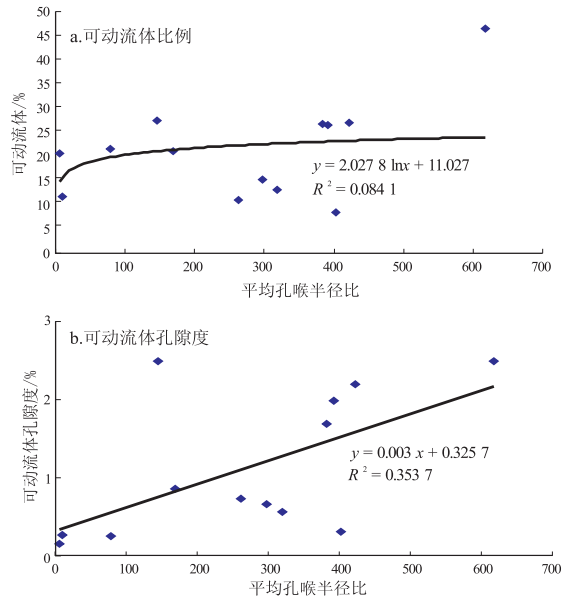


图 7 孔喉半径比与可动流体参数的相关关系
Fig.7 Relation between movable fluid parameters and radius ratio of pore and throat

饱和度分布范围分别为 0.04%~29.23%和 10.54%~46.45%,各样品孔隙进汞饱和度变化较大(级差为 730.5),说明储层非均质性强,而喉道进汞饱和度的差异相对较小(级差为 4.4),这与上述孔喉半径的分析结果一致。13 个样品中除 1 个样品外,其余 12 个样品的喉道进汞饱和度均较孔隙进汞饱和度高,主要是由于新场须四段致密砂岩储层微裂隙发育所致^[16-17],也说明其储集空间类型主要为孔隙—裂缝型。

由孔隙、喉道进汞饱和度与可动流体参数的相关关系可知(图 8),孔隙进汞饱和度与可动流体参

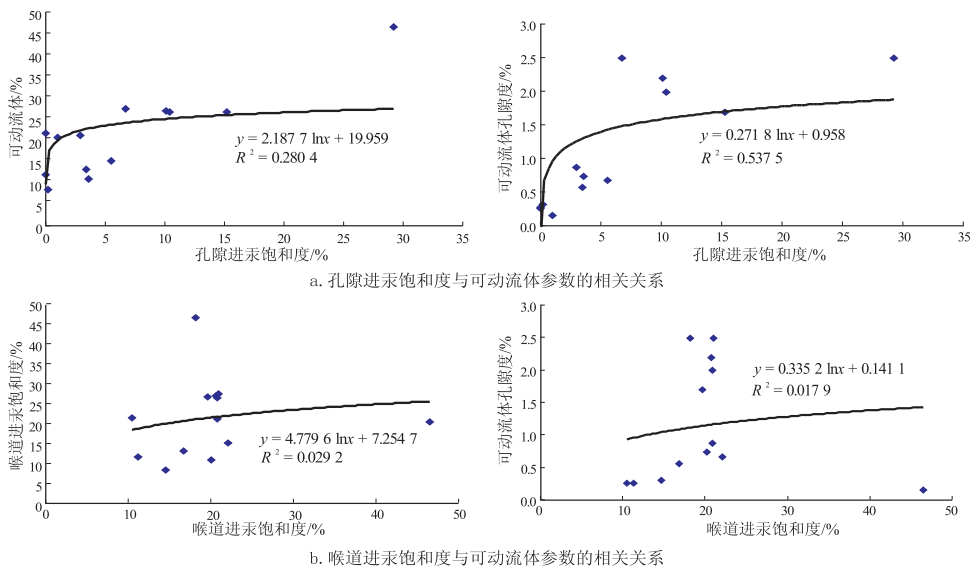


图 8 孔隙、喉道进汞饱和度与可动流体参数的相关关系

Fig.8 Relation between movable fluid parameters and mercury saturations of pore and throat

数的相关性稍好一些,这也再次验证了新场须四段致密砂岩储层的孔隙对可动流体参数的影响程度较喉道更大一些。孔喉体积是孔喉半径、长度及孔喉个数的函数,孔喉体积的大小与这3个参数成正比关系。样品的孔喉体积越大,则反映出孔隙空间和喉道半径增大,有效渗流空间和渗流通道增大,岩石颗粒表面对孔喉中流体的拉拽力减弱,流体被束缚的几率也会随之减小,可动流体参数相应增大。

5 结论

(1)利用恒速压汞和核磁共振实验,可定量评价致密砂岩储层微观孔喉半径、孔喉半径比、孔喉体积参数对可动流体参数的影响程度。

(2)致密砂岩储层具有可动流体参数、喉道特征参数、孔隙特征参数差异较大的特点。

(3)微裂隙发育的致密砂岩储层孔隙对可动流体参数的影响较喉道要更大一些,在微观上可动流体参数主要受孔隙控制,孔隙和喉道半径越小,可动流体参数衰减越快;储层孔喉半径比较大,且分布范围宽,是致密砂岩储层可动流体含量低,可动用程度差的主要原因之一。

(4)微裂隙发育的致密砂岩储层具有喉道进汞饱和度均较孔隙进汞饱和度高的特点,说明新场须四段致密砂岩储层的储集空间类型主要为孔隙—裂缝型。

参考文献:

- [1] 朱永贤,孙卫,于锋.应用常规压汞和恒速压汞实验方法研究储层微观孔隙结构:以三塘湖油田牛圈湖区头屯河组为例[J].天然气地球科学,2008,19(4):553-556.
Zhu Yongxian, Sun Wei, Yu Feng. Application of high pressure Hg injection and rate-controlled Hg penetration experimental technique to studying reservoir microscopic pore structure: taking Toutunhe formation in Niuanquhu area of Santanghu oilfield as an example[J]. Natural Gas Geoscience, 2008, 19(4): 553-556.
- [2] 王金勋,杨普华,刘庆杰,等.应用恒速压汞实验数据计算相对渗透率曲线[J].石油大学学报:自然科学版,2003,27(4):66-69.
Wang Jinxun, Yang Puhua, Liu Qingjie, et al. Determination of relative permeability curves using data measured with rate-controlled mercury penetration[J]. Journal of the University of Petroleum, China, 2003, 27(4): 66-69.
- [3] 王为民,赵刚,谷长春,等.核磁共振岩屑分析技术的实验及应用研究[J].石油勘探与开发,2005,32(1):56-59.
Wang Weimin, Zhao Gang, Gu Changchun, et al. Experiment and application of NMR technology on cuttings[J]. Petroleum Exploration and Development, 2005, 32(1): 56-59.
- [4] 李太伟,郭和坤,李海波,等.应用核磁共振技术研究页岩气储层可动流体[J].特种油气藏,2012,19(1):107-109.

- Li Taiwei, Guo Hekun, Li Haibo, et al. Research on movable fluids in shale gas reservoirs with NMR technology[J]. Special Oil & Gas Reservoirs, 2012, 19(1): 107-109.
- [5] 时宇,齐亚东,杨正明,等.基于恒速压汞法的低渗透储层分形研究[J].油气地质与采收率,2009,16(2):88-90.
Shi Yu, Qi Yadong, Yang Zhengming, et al. Fractal study of low permeability reservoir based on constant-rate mercury injection[J]. Petroleum Geology and Recovery Efficiency, 2009, 16(2): 88-90.
- [6] 刘德新,岳湘安,侯吉瑞.孔隙介质中边界流体动态特性实验研究[J].大庆石油地质与开发,2008,27(5):58-61.
Liu Dexin, Yue Xiang'an, Hou Jirui. Experimental studies on dynamic characteristics of boundary fluids in porous media[J]. Petroleum Geology & Oilfield Development in Daqing, 2008, 27(5): 58-61.
- [7] 王为民,郭和坤,叶朝辉.利用核磁共振可动流体评价低渗透油田开发潜力[J].石油学报,2001,22(6):40-44.
Wang Weimin, Guo Hekun, Ye Chaohui. The evaluation of development potential in low permeability oilfield by the aid of NMR movable fluid detecting technology[J]. Acta Petrolei Sinica, 2001, 22(6): 40-44.
- [8] 郝明强,刘先贵,胡永乐,等.微裂缝性特低渗透油藏储层特征研究[J].石油学报,2007,28(5):93-98.
Hao Mingqiang, Liu Xiangui, Hu Yongle, et al. Reservoir characteristics of micro-fractured ultra-low permeability reservoirs[J]. Acta Petrolei Sinica, 2007, 28(5): 93-98.
- [9] 王瑞飞,陈明强.特低渗透砂岩储层可动流体赋存特征及影响因素[J].石油学报,2008,29(4):558-561.
Wang Ruifei, Chen Mingqiang. Characteristics and influencing factors of movable fluid in ultra-low permeability sandstone reservoir[J]. Acta Petrolei Sinica, 2008, 29(4): 558-561.
- [10] 李珊,孙卫,王力,等.恒速压汞技术在储层孔隙结构研究中的应用[J].断块油气田,2013,20(4):485-487.
Li Shan, Sun Wei, Wang Li, et al. Application of constant-rate mercury injection technology in reservoir pore structure study[J]. Fault-Block Oil & Gas Field, 2013, 20(4): 485-487.
- [11] 高永利,张志国.恒速压汞技术定量评价低渗透砂岩孔喉结构差异性[J].地质科技情报,2011,30(4):73-76.
Gao Yongli, Zhang Zhiguo. Valuation on Difference of pore throat structure of low permeability sandstone by Constant-rate mercury penetration technique[J]. Geological Science and Technology Information, 2011, 30(4): 73-76.
- [12] 李卫成,张艳梅,王芳,等.应用恒速压汞技术研究致密油储层微观孔喉特征:以鄂尔多斯盆地上三叠统延长组为例[J].岩性油气藏,2012,24(6):60-65.
Li Weicheng, Zhang Yanmei, Wang Fang, et al. Application of constant-rate mercury penetration technique to study of pore throat characteristics of tight reservoir: A case study from the Upper Triassic Yanchang Formation in Ordos Basin[J]. Lithologic Reservoirs, 2012, 24(6): 60-65.
- [13] 高辉,敬晓峰,张兰.不同孔喉匹配关系下的特低渗透砂岩微观孔喉特征差异[J].石油实验地质,2013,35(4):401-406.
Gao Hui, Jing Xiaofeng, Zhang Lan. Difference of micro-pore throat characteristics in extra-low permeability sandstone of different pore throat matching relationship. Petroleum Geology &

Experiment, 2013, 35(4) :401-406.

[14] 高辉,孙卫,高静乐,等.特低渗透砂岩储层微观孔喉与可动流体变化特征[J].大庆石油地质与开发,2011,30(2) :89-93.
Gao Hui, Sun Wei, Gao Jingle, et al.Characteristic of micro-pore throat and movable fluid in Super-Low Permeability Sandstone Reservoir [J]. Petroleum Geology & Oilfield Development in Daqing, 2011, 30(2) : 89-93.

[15] 王瑞飞,沈平平,宋子齐,等.特低渗透砂岩油藏储层微观孔喉特征[J].石油学报,2009,30(4) :560-563,569.
Wang Ruifei, Shen Pingping, Song Ziqi, et al.Characteristics of micro-pore throat in ultra-low permeability sandstone reservoir [J]. Acta Petrolei Sinica, 2009, 30(4) : 560-563, 569.

[16] 麦发海,孟万斌,李敏,等.孝泉—新场地区须四段砂岩储层微观孔隙结构特征[J].中国西部科技,2011,10(33) :28-30.
Mai Fahai, Meng Wanbin, Li Min, et al.Characteristic of Micro-Pore Structure in sandstone reservoir of fourth member of Xujiahe Formation in Xiaquan - Xinchang area [J]. Science and Technology of West China, 2011, 10(33) : 28-30.

[17] 王志文,葛祥,张筠.新场气田须四下亚段岩屑砂岩储层评价[J].西部探矿工程,2011,23(5) :59-61.
Wang Zhiwen, Ge Xiang, Zhang Jun.Evaluation of rock-fracture-ment sandstone reservoir in lower sub section of Xujiahe Formation in Xinchang area [J]. West-China Exploration Engineering, 2011, 23(5) : 59-61.

(编辑 黄娟)

(上接第 69 页)

[13] Allan U S.Model for hydrocarbon migration and entrapment within faulted structures [J]. AAPG Bulletin, 1989, 73(7) : 803-811.

[14] 刘书会,王宝言,刘成鑫.西湖凹陷平湖地区平湖组沉积相的再认识[J].油气地质与采收率,2009,16(3) :1-4.
Liu Shuhui, Wang Baoyan, Liu Chengxin.Study on the sedimentary facies of Pinghu Fm in Pinghu area of Xihu Depression [J]. Petroleum Geology and Recovery, 2009, 16(3) : 1-4.

[15] 徐发,张建培,张田,等.西湖凹陷输层体系特征及其对油气成藏的控制作用[J].海洋地质前沿,2012,28(7) :24-29.

Xu Fa, Zhang Jianpei, Zhang Tian, et al.Transportation layer systems and their controlling Role on Hydrocarbon Accumulation in Xihu Depression [J]. Offshore Geology Leading, 2012, 28(7) : 24-29.

[16] 罗群,庞雄奇.海南福山凹陷顺向和反向断裂控藏机理及油气聚集模式[J].石油学报,2008,29(3) :363-367.
Luo Qun, Pang Xiongqi.Reservoir controlling mechanism and petroleum accumulation model for consequent fault and antithetic fault in Fushan depression of Hainan area [J]. Petroleum Journal, 2008, 29(3) : 363-367.

(编辑 徐文明)

(上接第 76 页)

[16] 钱勤,严伟,王雪玲.元坝气田长兴组未开发气藏采收率初探[J].石油实验地质,2012,34(6) :653-655.
Qian Qin, Yan Wei, Wang Xuelling.Primary study of recovery rate of undeveloped gas reservoir in Changxing Formation, Yuanba gas field [J]. Petroleum Geology & Experiment, 2012, 34(6) : 653-655.

[17] 冯明刚,严丽,王雪玲,等.元坝气田长兴组气藏有效储层物性下限标准研究[J].石油实验地质,2012,34(5) :535-538.
Feng Minggang, Yan Li, Wang Xuelling, et al.Lower limit for physical property of effective reservoir in Changxing Formation, Yuanba gas field [J]. Petroleum Geology & Experiment, 2012, 34(5) : 535-538.

[18] 罗开平,黄泽光,蒋小琼,等.川东北地区优质碳酸盐岩储层改造机制探讨[J].石油实验地质,2011,33(6) :559-563.
Luo Kaiping, Huang Zeguang, Jiang Xiaoqiong, et al.Reformation

mechanism of high-quality carbonate reservoirs in northeastern Sichuan Basin [J]. Petroleum Geology & Experiment, 2011, 33(6) : 559-563.

[19] 张元春,邹华耀,李平平,等.川东北元坝地区长兴组流体包裹体特征及油气充注史[J].新疆石油地质,2010,31(3) :250-251.
Zhang Yuanchun, Zou Huayao, Li Pingping, et al.Fluid inclusion feature and hydrocarbon charge history of Changxing formation in Yuanba area in Northeastern Sichuan basin [J]. Xinjiang Petroleum Geology, 2010, 31(3) : 250-251.

[20] 吴群,彭金宁.川东北地区埋藏史及热史分析:以普光 2 井为例[J].石油实验地质,2013,35(2) :133-138.
Wu Qun, Peng Jinning.Burial and thermal histories of northeastern Sichuan Basin: A case study of Well Puguang 2 [J]. Petroleum Geology & Experiment, 2013, 35(2) : 133-138.

(编辑 黄娟)