

# WHZ油田致密储层微观特征及介质变形敏感实验

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**摘要:**致密储层普遍存在应力敏感现象,会造成油井生产一段时间后产量大幅递减。针对WHZ油田致密储层开发过程中存在的问题,利用岩心核磁共振 $T_2$ 测试方法,得到孔喉半径及 $T_2$ 截止值等参数,分析了WHZ油田致密储层岩石组成、孔喉结构及孔渗分布等微观特征,基于岩心流动实验及统计分析方法,得到升、降围压过程中随围压变化的渗透率,研究了致密储层无因次渗透率与无因次围压之间的函数关系,分析了致密储层介质变形影响因素,并结合矿场实际分析不同开发方式下的油田生产情况。结果表明:WHZ油田致密储层多孔介质经过升、降围压后,渗透率将产生不可逆损失,且压力降低会影响孔喉结构的重新分布,即使补充能量也难以恢复至初始值,存在储层介质永久性伤害。WHZ油田实际资料表明,降压开采使产能受损,同期产能同步注水开发高于未注水开发。因此,在油田开发过程中应尽量保持合理的地层压力,避免因储层介质变形引起产量损失。

**关键词:**致密储层 微观特征 应力敏感性 核磁共振 介质变形 围压

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## Microscopic characteristics and sensitivity experiment of medium deformation in the tight reservoirs of WHZ oilfield

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**Abstract:** Common phenomenon of stress sensitivity in the tight reservoirs may result in great decline of production after producing for some time for the oil wells. According to the development problem of the tight reservoirs in WHZ oilfield,  $T_2$  testing method through core NMR was applied to obtain pore-throat radius and  $T_2$  cutoff value and other parameters. The microscopic characteristics of rock composition, the pore-throat structure and the distribution of porosity and permeability in the tight reservoirs of WHZ oilfield were analyzed. Based on the experiment of core flooding and the method of statistical analysis, the variation of core permeability with the confining pressure was understood, and the function relationship between dimensionless permeability and dimensionless confining pressure for the tight reservoirs was researched. Influencing factors on medium deformation for the tight reservoirs were analyzed and the oilfield production situation under various development modes was analyzed combined with the actual field situation. The result shows that the permeability damage of porous medium is irreversible under loading and unloading confining pressure for the tight reservoirs in WHZ oilfield, and the re-distribution of pore-throat structure may be affected in the process of pressure drop. It's hard to recover the initial value and permanent damage may form for the reservoir even if energy is supplemented. Actual data of the WHZ oilfield show that the productivity loss may occur under pressure drop and the productivity with synchronous water flooding may be higher than that with no water flooding. Therefore, a reasonable formation pressure is necessary in the process of oilfield development, which may avoid production loss resulted from medium deformation of the reservoirs.

**Key words:** tight reservoir; microscopic characteristics; stress sensitivity; NMR; medium deformation; confining pressure

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致密储层孔喉结构复杂,在油藏开采前,储层岩石受上覆地层压力、孔隙流体压力以及岩石骨架应力等综合作用,一般处于平衡状态。但随着注入水的进入或地层流体的采出,岩石骨架的受力情况可能发生变化,导致其变形,从而影响储层的物性参数,这种性质称为岩石的应力敏感性<sup>[1-5]</sup>。薛永超等进行了不同级别渗透率岩心应力敏感实验,认为应力敏感性的存在使得岩石渗透率发生不可逆变化,将最终影响油井产能和油藏开发效果<sup>[6]</sup>。但目前关于应力敏感性对油田生产的影响还缺乏定量研究,难以指导油田的合理开发。为此,笔者利用岩心核磁共振(NMR)测试和岩心流动实验方法,结合矿场实际生产数据,分析了WHZ油田致密储层微观孔隙结构及介质变形特征,以期为合理开发致密储层的方案制定提供理论和实验依据。

## 1 基于NMR测试的致密储层微观特征

### 1.1 矿物组成及微观孔喉结构

实验岩心取自WHZ油田某致密储层,气测渗透率为 $0.019 \times 10^{-3} \sim 0.793 \times 10^{-3} \mu\text{m}^2$ ,孔隙度为3.44%~17.7%,属于低孔致密油藏。岩石矿物以石英为主,占整个矿物组分的58.2%,长石次之,占18.8%,粘土占10.3%。通常在外力作用下,硬度越低越容易发生变形或破碎并发生位移,使储层介质的孔隙体积缩小,甚至堵塞孔隙和喉道,降低了致密储层介质的有效孔隙度和渗透率。

由绘制的气测渗透率与孔隙度关系曲线(图1)可以看出,该致密储层随着岩石渗透率的增大,孔隙度也相应增大,二者具有良好的指数关系。

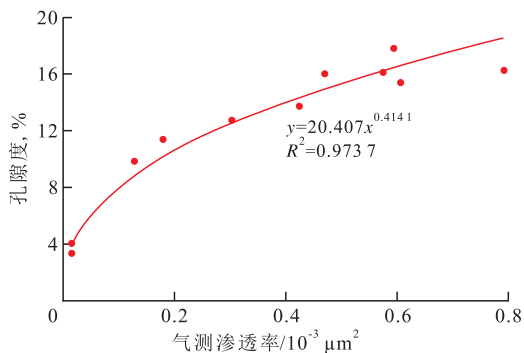


图1 WHZ油田某致密储层气测渗透率与孔隙度的关系  
Fig.1 Relationship between permeability and porosity in the tight reservoirs of WHZ oilfield

致密储层岩石孔隙结构通常为小孔和细孔型,大孔隙的体积占岩心总孔隙体积的比例很小。选

择3块岩心(表1)进行测试,得到喉道半径和孔隙半径分布结果。结果(图2)表明:致密储层中喉道半径和孔隙半径分布规律相似,均呈近似正态分布特征;几何尺寸绝对值较小的孔隙组成了致密岩心的有效孔隙。具体表现在:①岩心单位体积有效孔道个数越多,其气测渗透率越高;②当岩心单位体积有效孔隙个数相近时,喉道和孔隙半径越大,渗透率越大。反之,喉道和孔隙半径越小,渗透率越小;③岩心喉道和孔隙数量越多,该岩心的孔隙体积相对越大。

表1 岩心流动实验基本参数

Table 1 Basic parameters of the flow experiment of rock samples

编号	气测渗透率/ $10^{-3} \mu\text{m}^2$	岩心体积/ $\text{cm}^3$	孔隙体积/ $\text{cm}^3$
H1	0.424	1.359	0.167
H2	0.235	1.745	0.220
H3	0.727	2.019 7	0.339 7

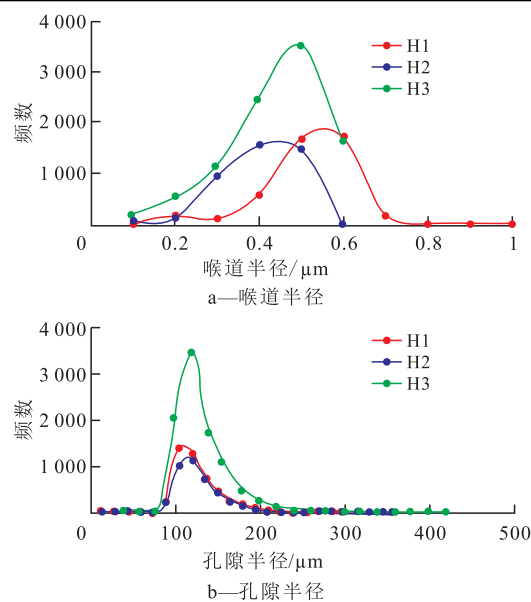


图2 WHZ油田某致密储层喉道半径和孔隙半径分布结果  
Fig.2 Throat radius and pore radius distribution in the tight reservoirs of WHZ oilfield

### 1.2 岩心流体饱和度

油藏中流体在储层多孔介质中以束缚和可动两类状态存在。储层孔隙空间的可动流体百分数越大,意味着束缚流体百分数越小,则储层的渗流能力就越好。因此,流体可流动能力从某种程度上决定了油田实际开发潜力<sup>[7-9]</sup>。

由6块致密砂岩岩心常规孔隙度和核磁孔隙度测定结果(表2)可以看出,当回波间隔为0.5 ms时,核磁孔隙度大多略微小于常规孔隙度,常规孔隙度平均值为12.42%,核磁孔隙度平均值为12.34%。

NMR标准 $T_2$ 截止值作为区分可动流体与束缚

表2 致密砂岩岩心核磁共振实验结果  
Table2 NMR results of the tight sandstone cores

编号	气测渗透率/ 10 <sup>-3</sup> μm <sup>2</sup>	孔隙度,%		束缚水饱 和度,%	可动流体 饱和度,%	T <sub>2</sub> 截止 值/ms
		常规	核磁			
L1	0.577	15.96	15.63	59.03	40.97	28.86
L2	0.183	11.42	11.61	71.19	28.81	28.86
L3	0.594	17.63	17.99	62.34	37.66	34.65
M4	0.793	16.24	16.04	52.67	47.33	34.65
M5	0.019	3.43	3.28	69.02	30.98	6.69
M8	0.131	9.81	9.46	73.23	26.77	28.86

流体的关键参数,其准确与否直接关系到束缚水饱和度和渗透率计算结果的准确性。6块致密砂岩岩心核磁共振可动流体饱和度测试结果(表2)表明:可动流体饱和度与岩心渗透率、孔隙度具有一定的相关性;该致密储层可动流体饱和度平均为26.77%~47.33%,核磁共振测试确定可动流体时,岩心的T<sub>2</sub>截止值平均为27.09 ms,可将该值作为WHZ油田致密储层T<sub>2</sub>截止值。

## 2 储层介质变形特征

### 2.1 实验方法

依据SY/T 5358—2010<sup>[10]</sup>,对WHZ油田某致密储层的8块岩心(表3)进行室内岩心流动实验,测定不同围压下的岩心渗透率,通过改变岩心围压模拟储层岩石受到的上覆压力变化,并分析岩心渗透率随围压的变化规律。实验用水为矿化度为9 525 mg/L、粘度为1.005 mPa·s的地层水。应力敏感实验的步骤包括:①按照图3安装实验流程,在温度为25℃的条件下,保持岩心两端压力梯度恒定;②设定初始围压为5 MPa,将围压依次增至10,15,20,30,40和50 MPa,每个围压点保持30 min,测定升压过程中不同围压下的渗透率;③根据选择的围压变化区间,再依次将围压由50 MPa降至40,30,20,15,

表3 应力敏感实验所用岩心基本参数  
Table3 Basic parameters of the rock samples in the stress sensitivity experiments

编号	气测渗透率/10 <sup>-3</sup> μm <sup>2</sup>	孔隙度,%	孔隙体积/cm <sup>3</sup>
M1	0.094	7.7	1.846
M2	0.307	12.7	3.596
M3	0.606	15.3	4.298
M4	0.793	16.2	4.209
M5	0.019	3.4	0.966
M6	0.425	13.7	3.964
M7	0.577	16.0	3.821
M8	0.131	9.8	2.477

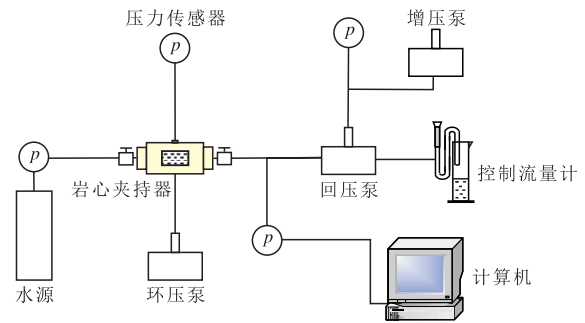


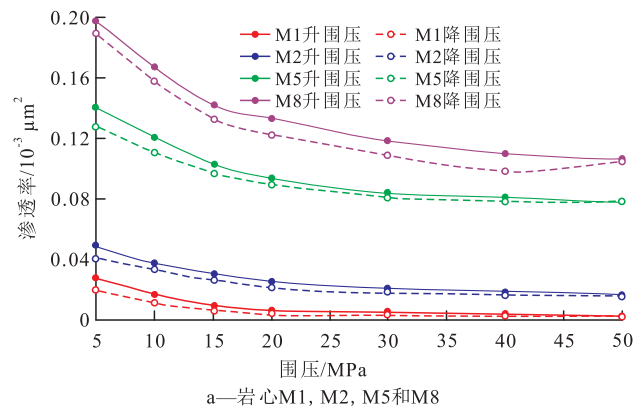
图3 应力敏感实验流程

Fig.3 Flowchart of stress sensitivity experiments

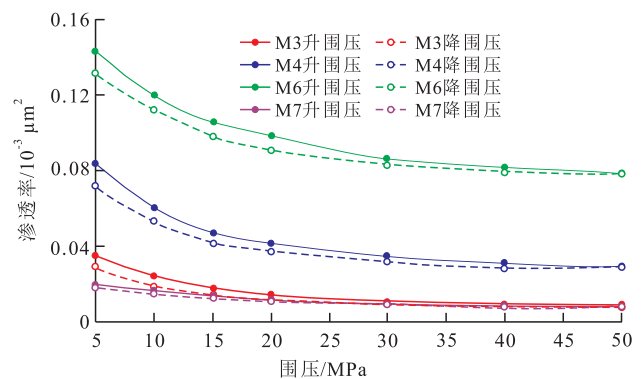
10和5 MPa,每个围压点保持1 h,测定降压过程中不同围压下的岩心渗透率;④对于每块岩心,均通过重复步骤②和③来模拟开采过程中地层降压后又升压的过程。

### 2.2 围压对岩石渗透率的影响

由8块致密岩心测得的渗透率与围压的关系曲线(图4)可以看出:①无论升压还是降压过程,随着围压的增大岩心渗透率均下降;②经过升压和降压过程后,渗透率均会产生损失,且该过程是不可逆的;③当围压为5~20 MPa时,渗透率随围压降低幅度较大,且渗透率最终不可逆损失率也较大;当围压为20~50 MPa时,渗透率随围压降低幅度较小,渗透率最终不可逆损失率也较小,为2%~4%。



a—岩心M1, M2, M5和M8



b—岩心M3, M4, M6和M7

图4 岩心渗透率随围压的变化关系

Fig.4 Variations of rock sample permeabilities with the confining pressure

### 2.3 应力敏感系数

应力敏感系数可以定量表征储层渗透率随应力变化的敏感程度,其值越大说明储层对压力越敏感<sup>[11-13]</sup>。将8块岩心的渗透率及围压进行无因次化处理,分别绘制两者的关系曲线(图5),利用乘幂数学式对曲线进行拟合,所得拟合方程形式与Zhu-Suyang等研究结果<sup>[14-16]</sup>相同,且相关系数较高,为0.981 1~0.997 1,得到的渗透率与围压的关系式为

$$\frac{K_s}{K_i} = \alpha \left( \frac{\sigma_s}{\sigma_i} \right)^{-\beta} \quad (1)$$

式中:  $K_s$  为某一围压下的渗透率,  $10^{-3} \mu\text{m}^2$ ;  $K_i$  为围压为 5 MPa 时的初始渗透率,  $10^{-3} \mu\text{m}^2$ ;  $\alpha$  和  $\beta$  均为系数;  $\sigma_s$  为围压, MPa;  $\sigma_i$  为初始围压, MPa。

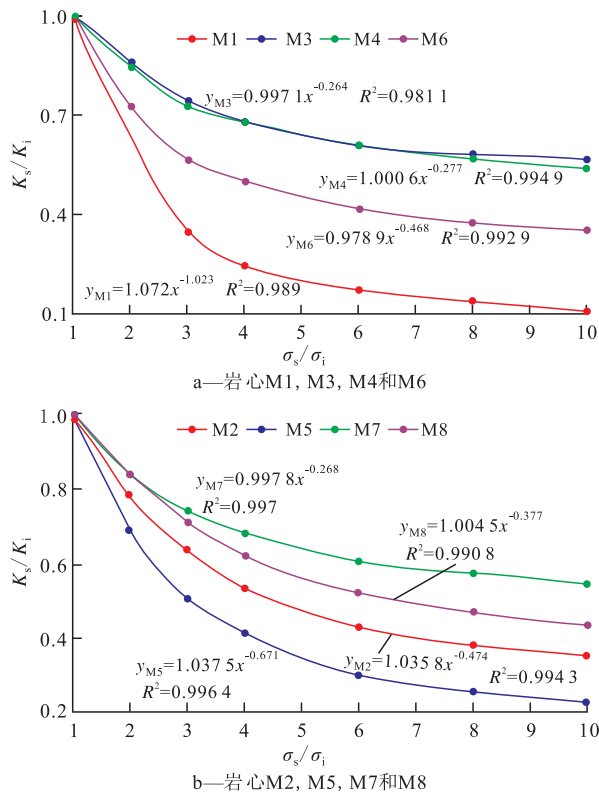


图5 实验岩心  $K_s/K_i$  与  $\sigma_s/\sigma_i$  的关系

Fig.5 Relationship between  $K_s/K_i$  and  $\sigma_s/\sigma_i$  of rock samples

笔者将式(1)中的  $\beta$  定义为应力敏感系数,8块致密岩心的应力敏感系数为0.264~1.023。

岩石的渗透率和孔隙度均随着应力条件变化而变化,但是孔隙度的变化幅度远小于渗透率的变化幅度。根据图1中孔隙度与渗透率的关系,假设应力敏感系数与初始渗透率和孔隙度的关系为

$$\beta = f(\phi K^{0.4141}) \quad (2)$$

式中:  $\phi$  为孔隙度;  $K$  为气测渗透率,  $10^{-3} \mu\text{m}^2$ 。

根据WHZ油田8块致密岩心的孔隙度、渗透率和应力敏感系数,绘制  $\beta$  与  $\phi K^{0.4141}$  的关系曲线,拟

合得到相关性较高的幂函数关系为

$$\beta = 0.7785(\phi K^{0.4141})^{-0.338} \quad (3)$$

分析初始渗透率、孔隙度与应力敏感系数的关系可知,岩心初始渗透率与孔隙度对应应力敏感系数影响较大。渗透率和孔隙度越小,对应的应力敏感系数越大,且在一定范围内应力敏感系数变化较大;当渗透率和孔隙度较大时,应力敏感系数变化较小。对于致密储层,压力的下降会影响孔喉结构的重新分布,造成渗透率和孔隙度的大幅损失,即使补充能量也难以恢复至初始值,即存在永久性伤害。这种伤害与孔喉微观结构及有效应力密切相关,油藏开发过程中压力下降越快,渗透率损失越大,产量递减越快,对油田稳产增产越不利。

### 3 实例分析

WHZ油田原始地层压力为50 MPa,渗透率为  $0.2 \times 10^{-3} \mu\text{m}^2$ ,储层厚度为24 m,地层原油粘度为  $0.78 \text{ mPa}\cdot\text{s}$ 。井组A采用同步注水开发方式,井组B采用天然能量开发方式,2井组储层渗透率接近。由2个井组平均单井产油量曲线(图6)可知:油藏开发初期,2个井组产能损失明显,产油量均递减较快,开采5 a的递减率均约为50%;但同步注水开发效果明显好于天然能量开发,同期产能同步注水开发高于天然能量开发,井组A注水见效后,油藏压力恢复,产油量上升明显,后期产油量下降趋势比较缓慢,开采10 a后,产油量稳定在4 t/d左右,而井组B,由于地层能量一直下降,产油量一直低于井组A,且一直处于递减状态。因此,在油田开发过程中应尽量保持合理的地层压力,避免因储层介质变形引起产量损失。

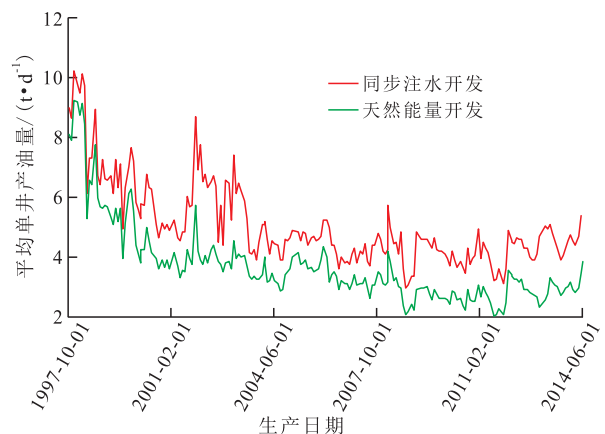


图6 注水和未注水井组平均单井产油量对比曲线

Fig.6 Comparison of average daily oil production curves between well groups with and without water flooding

## 4 结论

WHZ油田致密储层孔隙结构以几何尺寸绝对值较小的小孔和细孔型为主,喉道半径和孔隙半径分布规律相近,均呈近似正态分布特征;油藏平均可动流体饱和度为25%~45%,且可动流体饱和度随着岩心渗透率与孔隙度的增大而增大。在进行核磁共振确定可动流体时,可将27.09 ms作为WHZ油田致密储层 $T_2$ 截止值。岩石渗透率在升、降围压过程中存在一定的应力敏感性,当围压为0~20 MPa时,渗透率降低幅度大;当围压为20~50 MPa时,渗透率降低幅度小。升围压过程中孔喉结构重新分布,介质发生变形,造成渗透率大幅损失,且在经先升围压再降围压的过程后,渗透率产生不可逆的损失,即使地层压力再升高渗透率也难以恢复至初始值。因此,高效开发致密油藏应保持合理的地层压力,避免因储层介质变形引起油井产量的损失。

### 参考文献:

- [1] 许涛,黄海龙,修德艳,等.低渗透油藏应力敏感评价新方法[J].特种油气藏,2014,21(6):126-129.  
Xu Tao, Huang Hailong, Xiu Deyan, et al. New method for stress sensitivity evaluation aimed at low permeability oil reservoirs [J]. Special Oil & Gas Reservoirs, 2014, 21(6): 126-129.
- [2] 游利军,王巧智,康毅力,等.压裂液浸润对页岩储层应力敏感性的影响[J].油气地质与采收率,2014,21(6):102-106.  
You Lijun, Wang Qiaozhi, Kang Yili, et al. Influence of fracturing fluid immersion on stress sensitivity of shale reservoir [J]. Petroleum Geology and Recovery Efficiency, 2014, 21(6): 102-106.
- [3] 苏玉亮,栾志安,张永高.变形介质油藏开发特征[J].石油学报,2000,21(2):51-55.  
Su Yuliang, Luan Zhian, Zhang Yonggao. A study on development characteristics for deformed reservoir [J]. Acta Petrolei Sinica, 2000, 21(2): 51-55.
- [4] Zeng Zhengwen, Grigg Reid B, Gupta D B. Laboratory investigation of stress-sensitivity of non-Darcy gas flow parameters [C]. SPE 89431, 2004.
- [5] 肖开华,冯动军,李秀鹏.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[J].石油实验地质,2014,36(1):77-82.  
Xiao Kaihua, Feng Dongjun, Li Xiupeng. Micro pore and throat characteristics and moveable fluid variation of tight sandstone in 4th member of Xujiahe Formation, Xinchang Gas Field, western Sichuan Basin [J]. Petroleum Geology & Experiment, 2014, 36(1): 77-82.
- [6] 薛永超,程林松.不同级别渗透率岩心应力敏感实验对比研究[J].石油钻采工艺,2011,33(3):38-41.  
Xue Yongchao, Cheng Linsong. Experimental comparison study on stress sensitivity of different permeability cores [J]. Oil Drilling & Production Technology, 2011, 33(3): 38-41.
- [7] Lei Qun, Xiong Wei, Yuang Jiangru, et al. Analysis of stress sensitivity and its influence on oil production from tight reservoirs [C]. SPE 111148, 2007.
- [8] 刘顺,何衡,贺艳祥,等.低渗透油藏应力敏感实验数据处理方法对比[J].油气地质与采收率,2012,19(4):71-73.  
Liu Shun, He Heng, He Yanxiang, et al. Data processing correlation on stress sensitivity experiment for low-permeability reservoirs [J]. Petroleum Geology and Recovery Efficiency, 2012, 19(4): 71-73.
- [9] 王培玺,刘仁静.低渗透储层应力敏感系数统一模型[J].油气地质与采收率,2012,19(2):75-77.  
Wang Peixi, Liu Renjing. Universal model of stress sensitive coefficient for low permeability reservoir [J]. Petroleum Geology and Recovery Efficiency, 2012, 19(2): 75-77.
- [10] 曲岩涛,房会春,朱健,等.SY/T 5358—2010储层敏感性流动实验评价方法[S].北京:石油工业出版社,2010.  
Qu Yantao, Fang Huichun, Zhu Jian, et al. SY/T 5358—2010 Formation damage evaluation by flow test [S]. Beijing: Petroleum Industry Press, 2010.
- [11] 朱苏阳,李传亮,董凤玲.基于三维地应力的渗透率转换方法[J].油气地质与采收率,2013,20(4):69-71.  
Zhu Suyang, Li Chuanliang, Dong Fengling. Conversion calculation of reservoir permeability from laboratory data based on 3D strata stresses [J]. Petroleum Geology and Recovery Efficiency, 2013, 20(4): 69-71.
- [12] 陈明强,任龙,李明,等.鄂尔多斯盆地长7超低渗透油藏渗流规律研究[J].断块油气田,2013,20(2):191-195.  
Chen Mingqiang, Ren Long, Li Ming, et al. Study on seepage law of Chang7 ultra-low permeability reservoir in Ordos Basin [J]. Fault-Block Oil & Gas Field, 2013, 20(2): 191-195.
- [13] 罗瑞兰.关于低渗透致密储层岩石的应力敏感问题——与李传亮教授探讨[J].石油钻采工艺,2010,32(2):126-128.  
Luo Ruilan. Discussion of stress sensitivity of low permeability and tight reservoir rocks [J]. Oil Drilling & Production Technology, 2010, 32(2): 126-128.
- [14] Zhu Suyang. Experiment research of tight sandstone gas reservoir stress sensitivity based on the capillary bundle mode [C]. SPE 167638, 2013.
- [15] 李传亮.储层岩石的应力敏感问题——答罗瑞兰女士[J].石油钻采工艺,2006,28(6):86-88.  
Li Chuanliang. Discussion on the stress sensitivity of reservoir rocks—Reply to Ms Luo Ruilan [J]. Oil Drilling & Production Technology, 2006, 28(6): 86-88.
- [16] 章敬,李佳琦,徐江涛,等.准噶尔盆地高闭合应力致密储层改造技术研究及应用[J].油气地质与采收率,2014,21(2):98-101.  
Zhang Jing, Li Jiaqi, Xu Jiangtao, et al. Stimulation techniques study and application for tight reservoir with high closure stress, Junggar basin [J]. Petroleum Geology and Recovery Efficiency, 2014, 21(2): 98-101.