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含部分封闭断层油藏水驱优势渗流通道演化规律

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摘要:含部分封闭断层油藏作为一种常见的油藏类型,低序级断层引起的断层部分封闭导致其与完全封闭油藏具备不同的流体渗流及剩余油分布规律。现有技术难以定量刻画整个水驱进程中油藏深部的优势渗流通道演化规律,进而影响了该类油藏的高效开发。因此,设计制作了含部分封闭断层油藏物理模型并开展水驱油实验,根据模型参数及实验结果建立数值反演模型。基于标准化过流量算法定量表征优势渗流通道,利用数值反演模型与无断层油藏优势渗流通道演化规律进行对比,揭示了含部分封闭断层油藏物理模型优势渗流通道演化规律。研究表明:断层遮挡区域采出井累积产油量较低、产油速度较慢,断层不连续处过流面积减小导致该处采出井见水最早。处于断层另一侧采出井虽初期产油量接近,但断层对注入水阻挡作用导致强阻挡区采出井分流率较高且后期产油速度最高。在无水采油期发育对驱油起积极作用的优势渗流区,该区域经过垂向均衡展布、“指状”展布发育形成油藏底部“纺锤体状”优势渗流通道。各井见水后除在强阻挡区外区域形成由注水井至生产井井底的优势渗流通道,随着注入量增大,该通道在垂向及采出井井周发育且对驱油起消极作用。与无断层油藏相比,部分封闭断层使优势渗流通道在强阻挡区发育滞后且强阻挡区注入水波及困难,导致各区域剩余油分布差异较大,集中分布于强阻挡区上部及强阻挡区断层附近。

关键词:部分封闭断层;水驱;优势渗流通道;物理模拟;数值反演

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Evolution law of dominant flow channel of water flooding in partially enclosed fault reservoir

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Abstract: A partially enclosed fault reservoir is a common reservoir type. The partially enclosed faults caused by low-order faults lead to different fluid flow and distribution laws of remaining oil between partially enclosed fault reservoirs and completely enclosed reservoirs. Through the existing technology, it is difficult to quantitatively describe the evolution law of the dominant flow channel in the deep part of the reservoir in the whole process of water flooding, which affects the efficient development of this kind of reservoir. Therefore, the physical model of a partially enclosed fault reservoir was designed and fabricated, and the water flooding experiment was carried out. The numerical inversion model was established according to the model parameters and experimental re-

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sults. The dominant flow channel was quantitatively characterized based on the standardized flow rate algorithm. Then, the numerical inversion model was used to compare with the evolution law of the dominant flow channels in fault-free reservoirs and reveal the evolution law of the dominant flow channel in the physical model of the partially enclosed fault reservoir. The results show that the accumulative oil yield and the oil production rate of the production well in the fault-occluded area were low. The reduction of the flow area in the fault discontinuity led to the earliest breakthrough in the production well. Although the production wells on the other side of the fault had close oil production in the early stage, the blocking effect of the fault on injection water led to a higher flow diversion rate and the highest oil production rate in the late stage in the strongly fault-occluded area. During the anhydrous oil production period, a dominant flow area played a positive role in oil displacement, which developed into a spindle-shaped dominant flow channel at the bottom of the reservoir through vertical equilibrium distribution and “finger-shaped” distribution. After water production in each well, a dominant flow channel was formed from the injection well to the bottom of the production well, except for the strongly fault-occluded area. With the increase in injection volume, this channel developed in the vertical direction and around the production well and played a negative role in oil displacement. Compared with fault-free reservoirs, partially enclosed faults made the development of dominant flow channels lag in strongly fault-occluded areas and difficult water sweep in strongly fault-occluded areas, resulting in significant differences in the distribution of remaining oil in each area, and the remaining oil is concentrated in the upper part of the strongly fault-occluded area and near the faults in strongly fault-occluded areas.

Key words: partially enclosed fault; water flooding; dominant flow channel; physical simulation; numerical inversion

断层油藏是中国分布较广的一种油藏类型^[1-4], 由于受到不同封闭性断层的影响, 常具有数量多、差异大、不规则等特点, 具备复杂的流体渗流规律。此类油藏的开发研究集中于不同性质断层的不同作用形式对油气运聚^[5]及剩余油分布^[6-7]的影响, 却忽略了对低序级断层^[8]等导致的部分封闭断层的研究。在胜利油田多个复杂断块油田中, 局部发育的低序级断层形成的部分封闭断层对井间连通性产生较大影响。水驱作为该类油藏的主要开发方式^[9-11], 鲜有学者关注断层尤其是含部分封闭断层油藏在整个开发过程中优势渗流通道的演化规律^[12]。

优势渗流通道的发育及展布为影响水驱效率的重要因素之一, 现今学者主要采用生产动态分析^[13]、示踪剂监测^[14]、机器学习^[15]、试井^[16-17]、注入井压降曲线监测等方法识别、刻画优势渗流通道, 但存在成本高、依赖现场经验等缺点, 较难表征油藏深部的优势渗流通道。优势渗流通道的发育及展布受流体性质差异^[18]、注采制度^[19]、储层性质^[20-21]等影响。而对于断层油藏, 断层使得该类油藏具有复杂的渗流规律, 除了上述因素的影响外, 断层的封闭程度对优势渗流通道的发育影响较大。采用常规方法较难表征具有复杂渗流规律的断层油藏。

笔者以含部分封闭断层油藏为研究对象, 设计制作了物理模型并进行水驱油实验。根据物理模型参数, 建立数值反演模型。基于标准化过流量计算方法定量表征优势渗流通道。该方法不仅能够揭示含部分封闭断层油藏水驱优势渗流通道演化规律, 还能应用于油田现场其他类型油藏, 为高含

水期水驱改善措施的制定提供理论支撑。

1 水驱物理模拟实验

1.1 模型设计

为增强物理模型的普适性, 在研究断层封闭性对水驱油藏流场演化规律的影响时忽略实际油藏中断层两侧构造高度的差异性。将能够使油气各向密封不逸散的断层特征化, 设计制作了具备部分封闭断层的物理模型(图1a), 模型尺寸为31 cm×31 cm×21 cm。对于断裂系统较为发育的油田, 即使按照规则井网部署, 部分封闭断层仍会影响井组内的渗流场。故采用规则的五点井网, 将各井预埋后, 使用环氧树脂浇注制作物理模型(图1b)。基于量纲分析法, 依据几何相似、运动相似、动力相似原理, 推导得到: 模型渗透率为0.7~0.8 D; 孔隙度为0.16~0.18; 注入速度为1~5 mL/min; 注采压差为0.1~0.5 MPa; 含油饱和度为0.6~0.75; 原油黏度为10~15 mPa·s。

1.2 实验器材及步骤

实验材料 实验温度为45 °C, 注入水为蒸馏水(密度为997 kg/m³, 黏度为1 mPa·s), 用油为15号白油(密度为800 kg/m³, 黏度为12 mPa·s)。

实验装置 实验装置主要包括驱替系统(恒速注入泵及中间容器)、计量系统(主要为各量程量筒)、温度控制系统(恒温箱)(图2)。

实验步骤 实验步骤包括: ①根据模型设计方案, 制作目标物性参数的人造岩心。采用环氧树脂浇注密封。②注入气体检查物理模型的气密性, 依

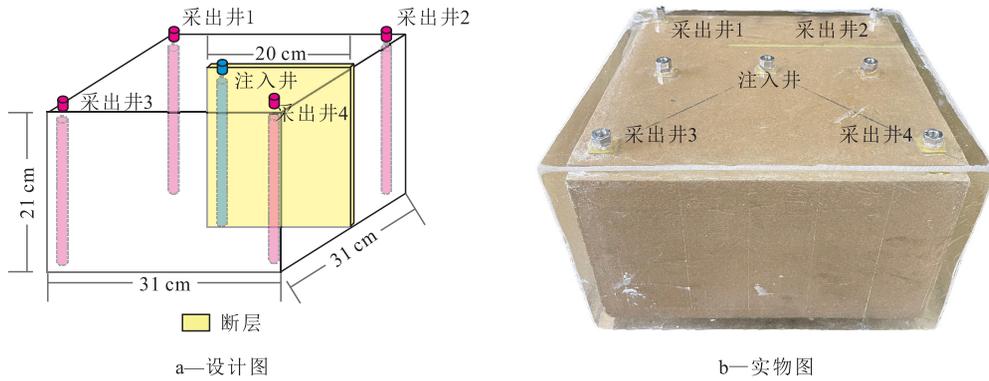


图1 含部分封闭断层油藏物理模型

Fig. 1 Physical model of partially enclosed fault reservoir

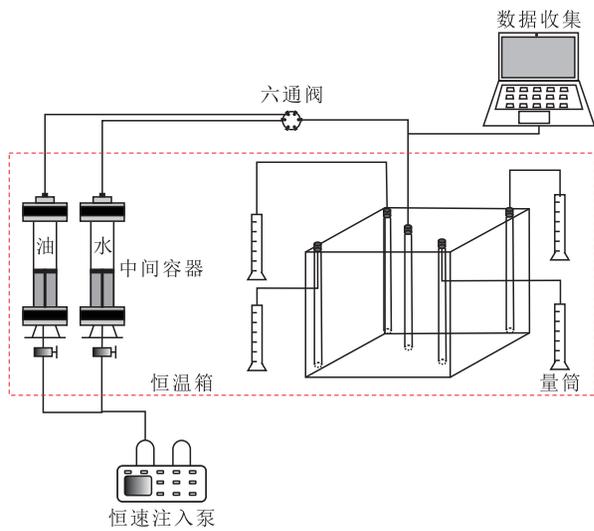


图2 水驱物理模拟实验流程

Fig.2 Physical simulation experiment of water flooding

据图2连接实验装置并抽真空。③将实验装置置于45 °C恒温箱内,以1 mL/min速度对物理模型饱和油、水。采用各井分别注入、交替采出的方法,避免受断层影响导致饱和不均匀。④将预热至45 °C的蒸馏水以3 mL/min的速度注入含部分封闭断层油藏的物理模型,计量各井采出液量。⑤待水驱至某口井含水率达到98%时,停止实验。⑥在物理模型不同区域沿各方向钻取岩心,依据测量标准^[22]测定其垂向渗透率为0.649 3D,水平渗透率为0.753 6D,孔隙度为0.171,含油饱和度为72.5%,各参数符合含部分封闭断层油藏物理模拟实验设计要求。

1.3 实验结果

物理模拟实验全程计量各采出井的累积注入量、累积产油量和累积产水量,处理各生产数据得到水驱油动态变化(图3,图4)。分析认为,采出井2受断层遮挡作用最强,注入水在初期较难波及至采出井2的井周区域,所以水驱产油速度最慢、累积产油量最低。虽然采出井1处于断层未发育区域,但该井与注入井渗流通道受到断层较弱的遮挡作用,

而且流向采出井2的流体流经采出井1井周区域,所以该井见水最快,导致中后期产油速度较低,采出井1的累积产油量略高于采出井2。由于采出井3、采出井4未受到断层的遮挡作用,注入水会在断层的阻挡作用下主要流向这两口井,所以,其累积产油量远高于其他2口井。尤其是采出井4,部分本应直接流向采出井2的注入水在断层的作用下进入采出井4,使得该井分流率始终最高,且水驱后期累积产油量最高。采出井3含水率先达到98%时停止实验,水驱采出程度为32.93%。

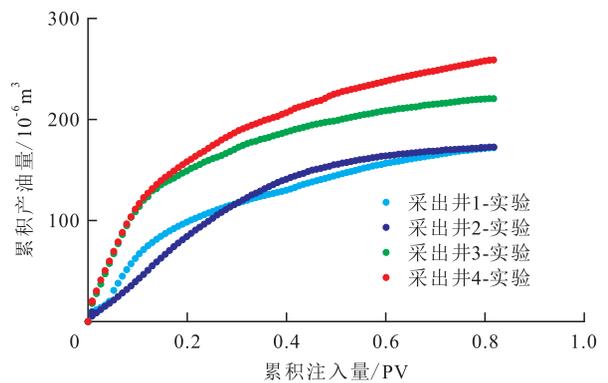


图3 物理模拟单井累积产油量变化

Fig.3 Cumulative oil production of single well in physical simulation

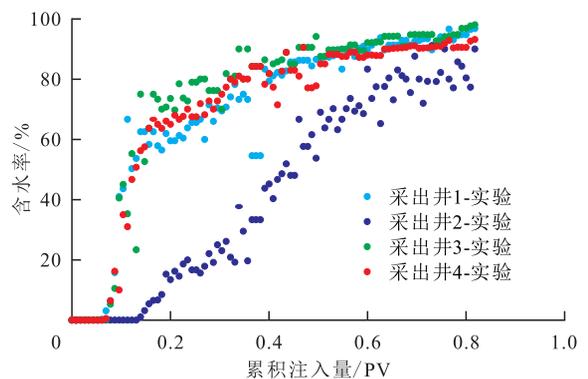


图4 物理模拟单井含水率变化

Fig.4 Water cuts of single well in physical simulation

由图4可见,当累积注入量为0.04 PV时,采出井1、采出井3相继见水后,采出井4见水。原因为采出井1较采出井2受到的断层遮挡作用较弱,而采出井3较采出井4受断层阻挡作用较弱,因断层不连续处注入水的过流面积较小,导致在生产压差相同情况下,该区域水的渗流速度较快,故采出井1见水时间略早。在断层影响下,采出井2注入水的渗流距离最远,使得采出井2见水最晚(累积注入量为0.13 PV时见水)。

2 数值反演模型

2.1 模型建立

为真实反演含部分封闭断层油藏,数值反演模型完全按照物理模型中岩石及流体性质、井网配置等建立(图5a),模型网格数为 $31 \times 31 \times 21$,网格步长为 $0.01 \text{ m} \times 0.01 \text{ m} \times 0.01 \text{ m}$,岩石压缩系数为 $2.5 \times 10^{-4} \text{ MPa}^{-1}$,顶深为 0.01 m ,有效厚度为 0.1 m 。对数值反演模型进行分区(图5b),采出井1和采出井2所在的两个区域受到断层不同程度的遮挡作用,导致注入水难以进入采出井1和采出井2,故将两个区域分别划分为弱遮挡区和强遮挡区。注入水在采出井3和采出井4所在区域内受到断层的阻挡,较难从这两个区域流出,故将这两个区域相应地分别划分为弱阻挡区和强阻挡区。

2.2 模型验证

基于水驱油实验后测量得到的物理模型参数,通过调整油水相对渗透率,拟合不同时刻的单井累积产油量和含水率的动态变化(图6)。因物理模型制作及计量误差,物理模拟与数值模拟结果不能完全契合,但总体拟合效果良好,说明该数值反演模型能够真实表征含部分封闭断层油藏。

3 水驱优势渗流通道演化规律

3.1 定量表征方法

因地质构型、储层非均质性、注采制度、黏度差异等因素使油藏渗流场中同一等势面的流体速度不同,形成了各等势面的优势渗流区域,故可以通过刻画各等势面的优势渗流区域得到整个油藏的优势渗流通道。但是等势面面积的差异会干扰该表征方法,因此,提出了标准化过流量 Q_w 消除等势面面积差异造成的速度差异,第 n 个等势面的第 m 点的标准化过流量表达式为:

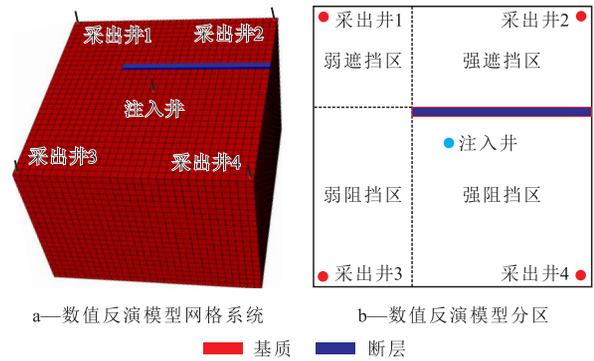


图5 数值反演模型网格系统与分区

Fig.5 Grid system and division of numerical inversion model

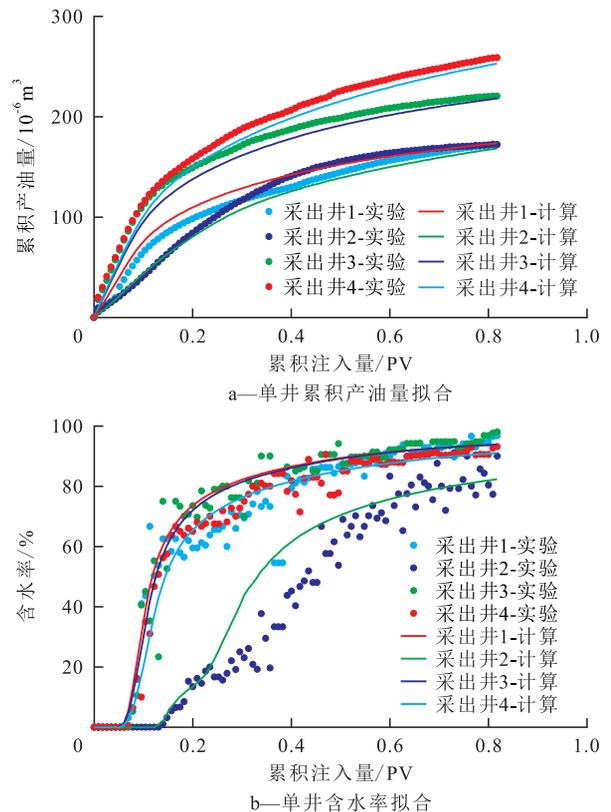


图6 数值反演模型拟合

Fig.6 Numerical inversion model fitting

$$Q_{wnm} = v_{nm} A_n \quad (1)$$

(1)式中 v_{nm} 一般使用较易获得的驱替相的流速。各等势面的过流面积(即各等势面的面积)是表征优势渗流通道的关键。与一源(或一汇)渗流场中等势面呈规则的球状不同,地质特征复杂的油藏具有不规则的等势面,需要借助油藏数值模拟软件计算结果得到等势面,然后通过计算得到等势面面积。

将优势渗流通道定义为油藏中最高标准化过流量点的 α ($\alpha < 1$)倍,且要求同一油藏在整个开发过程中 α 取值相同且大于等于0.5,则有:

$$Q_{ws} \geq \alpha Q_{wmax} \quad (2)$$

图7为不同累积注入量时, α 的不同取值与优势渗流通道占比(即优势渗流通道占整个油藏的比例)的关系。分析发现, α 取值大于0.5时, 各累积注入量下优势渗流通道占比较为稳定, 说明 α 取值为0.5可以用于计算各生产时刻优势渗流通道体积变化。

3.2 演化规律分析

3.2.1 含部分封闭断层油藏

基于优势渗流通道定量表征方法计算水驱全程各区域(强遮挡区、弱遮挡区、强阻挡区、弱阻挡区)优势渗流通道体积分别与全区域体积的比值, 得到优势渗流通道占比变化(图8), 结合各区域采出程度变化(图9a)及优势渗流通道演化(图10), 含部分封闭断层油藏措施前水驱阶段优势渗流通道发育分为以下阶段:

优势渗流区发育阶段 无水采油期初期(累积注入量为0~0.04 PV), 没有形成完整的注采井间优势渗流通道, 而是发育以水驱前缘为边界的优势渗流区, 并且垂向展布较为均匀, 体积增长迅速(图10a)。无水采油期后期, 在重力作用下优势渗流区在油藏底部快速发育(图10b), 尤其是处于部分断层遮挡的弱遮挡区。该阶段优势渗流区的发育对驱油起到积极作用, 各区域采出程度上升较快。

优势渗流通道快速发育阶段 累积注入量为0.05~0.06 PV, 采出井1、采出井3、采出井4依次见水, 在重力及油水黏度差异作用下, 仅在储层底部发育“指状”优势渗流通道(图10c)。累积注入量为0.07~0.10 PV, 在各区域底部形成“纺锤体状”优势渗流通道(图10d), 向上发育形成注入井至各采出井井底的优势渗流通道(图10g)。

优势渗流通道缓慢发育阶段 累积注入量为0.11~0.20 PV, 注入水主要沿受断层影响较弱的其他3个区域渗流, 导致强遮挡区仍然以优势渗流区

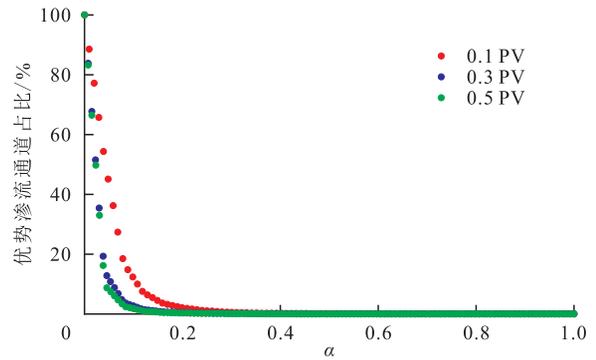


图7 不同累积注入量时优势渗流通道占比与 α 的关系
Fig.7 Relationship between proportion of dominant flow channels and α at different cumulative injection amounts

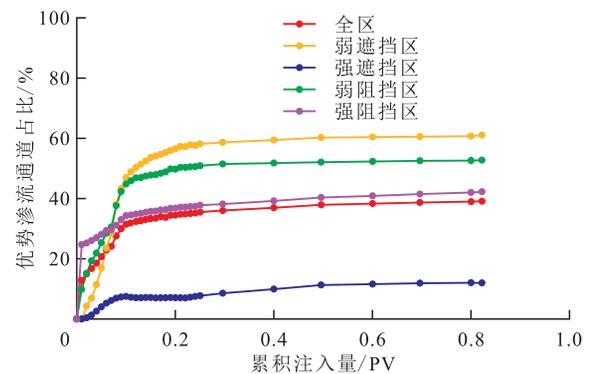


图8 含部分封闭断层油藏各区域优势渗流通道占比变化
Fig.8 Proportion of dominant flow channels in different areas of partially enclosed fault reservoir

的形式缓慢发育, 即使采出井见水(图10i)后也仅沿储层底部缓慢发育“纺锤体状”优势渗流通道。采出程度从此阶段开始增速放缓, 优势渗流通道对驱油起到消极作用。

优势渗流通道稳定发育阶段 累积注入量为0.21 PV, 在形成由注入井井口至采出井1、采出井3、采出井4井底的、稳定的优势渗流通道后, 强遮挡区的优势渗流区开始向上再次发育, 直至采出井3含水率到达98%停止模拟, 强遮挡区优势渗流通道仍然主要集中在储层底部及采出井的井周, 其他区

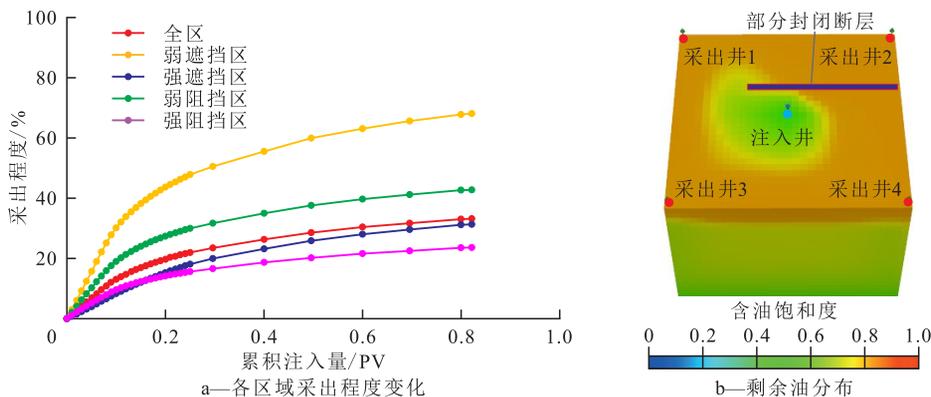


图9 含部分封闭断层油藏各区域采出程度变化及剩余油分布
Fig.9 Oil recoveries in different areas and remaining oil distribution of partially enclosed fault reservoir

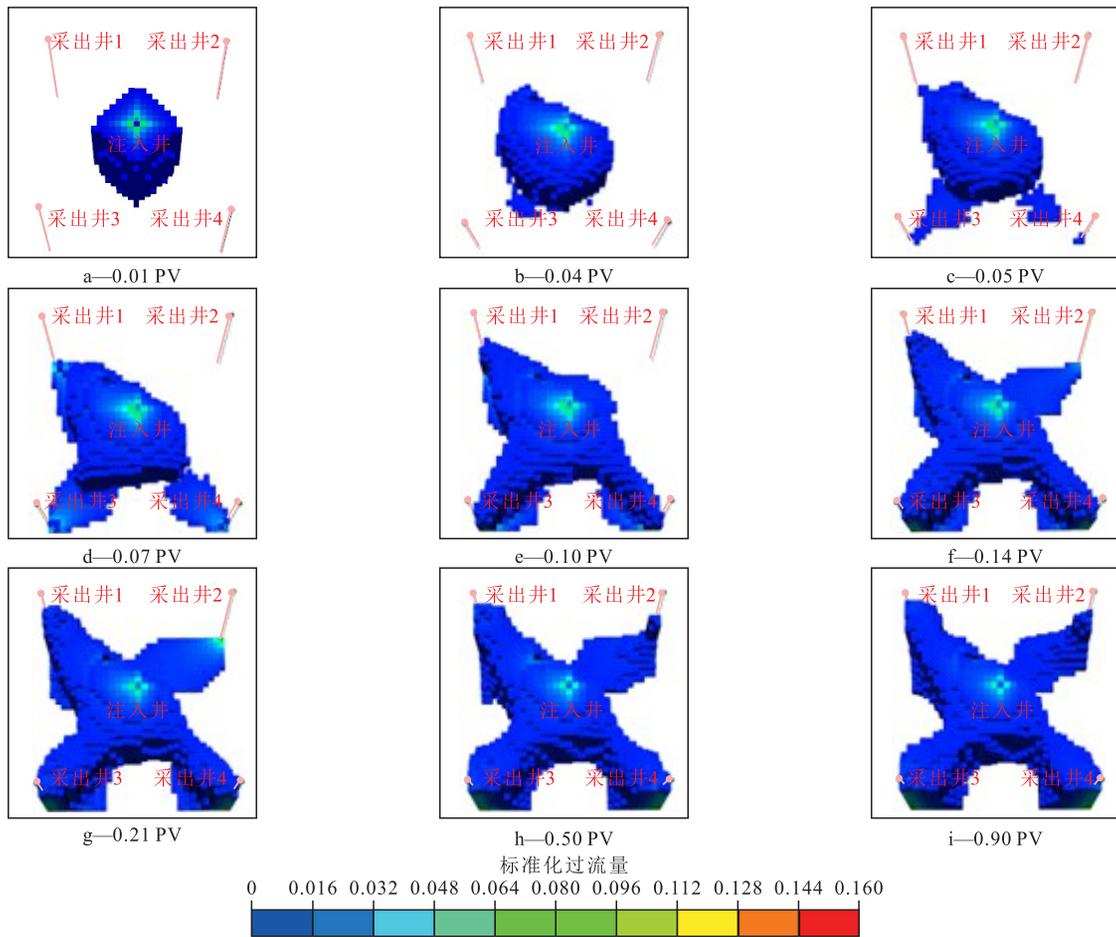


图10 不同累积注入量下含部分封闭断层油藏优势渗流通道演化

Fig.10 Evolution of dominant flow channels in partially enclosed fault reservoirs at different cumulative injection amounts

域沿垂向及采出井井周发育。如图9b所示,部分封闭断层导致各区域的剩余油分布差异较大,主要分布于强遮挡区顶部及强阻挡区的断层附近以及其他区域顶部。

3.2.2 无断层油藏

为明确部分封闭断层对优势渗流通道演化规律的影响,建立了与含部分封闭断层油藏参数相同的无断层油藏数值模型。为了清晰对比两者的差异,采用相同的区域划分,计算无断层油藏各区域优势渗流通道占比变化(图11)、采出程度变化(图12)及优势渗流通道演化(图13)。

对比图10与图13发现,无断层油藏与含部分封闭断层油藏相比,两种油藏都是由优势渗流区发育为优势渗流通道,且体积变化趋势基本相同。但含部分封闭断层油藏的强遮挡区与其他区域相比,优势渗流通道发育滞后,但无断层油藏却不存在该现象,各区域的优势渗流通道发育均衡。由于不受断层影响,无断层油藏的见水时间较晚,且各井见水时间相同。如图11和图12所示,无断层油藏各区域的优势渗流通道体积占比及采出程度较均匀,

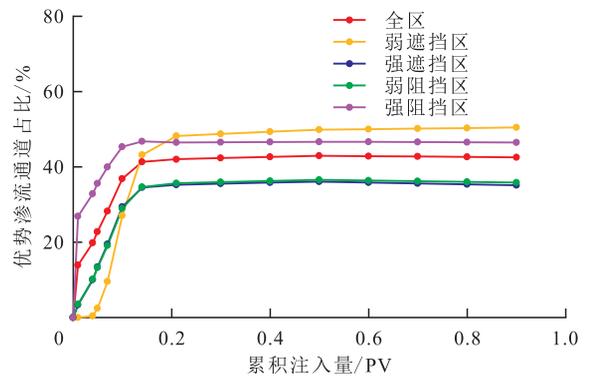


图11 无断层油藏各区域优势渗流通道占比变化

Fig.11 Proportion of dominant flow channels in different areas of fault-free reservoir

各区域间优势渗流通道体积及采出程度存在较小的差异,这是由于区域的划分导致的。如图12b所示,无断层油藏在重力作用下,剩余油仅均匀分布在油藏的顶部。

4 结论

依据含部分封闭断层油藏水驱物理模拟结果

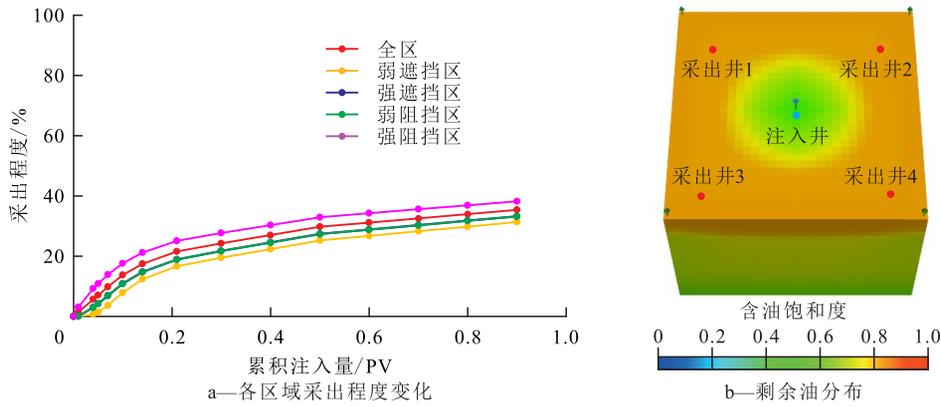


图 12 无断层油藏各区域采出程度变化及剩余油分布

Fig.12 Oil recoveries and remaining oil distribution in different areas of fault-free reservoir

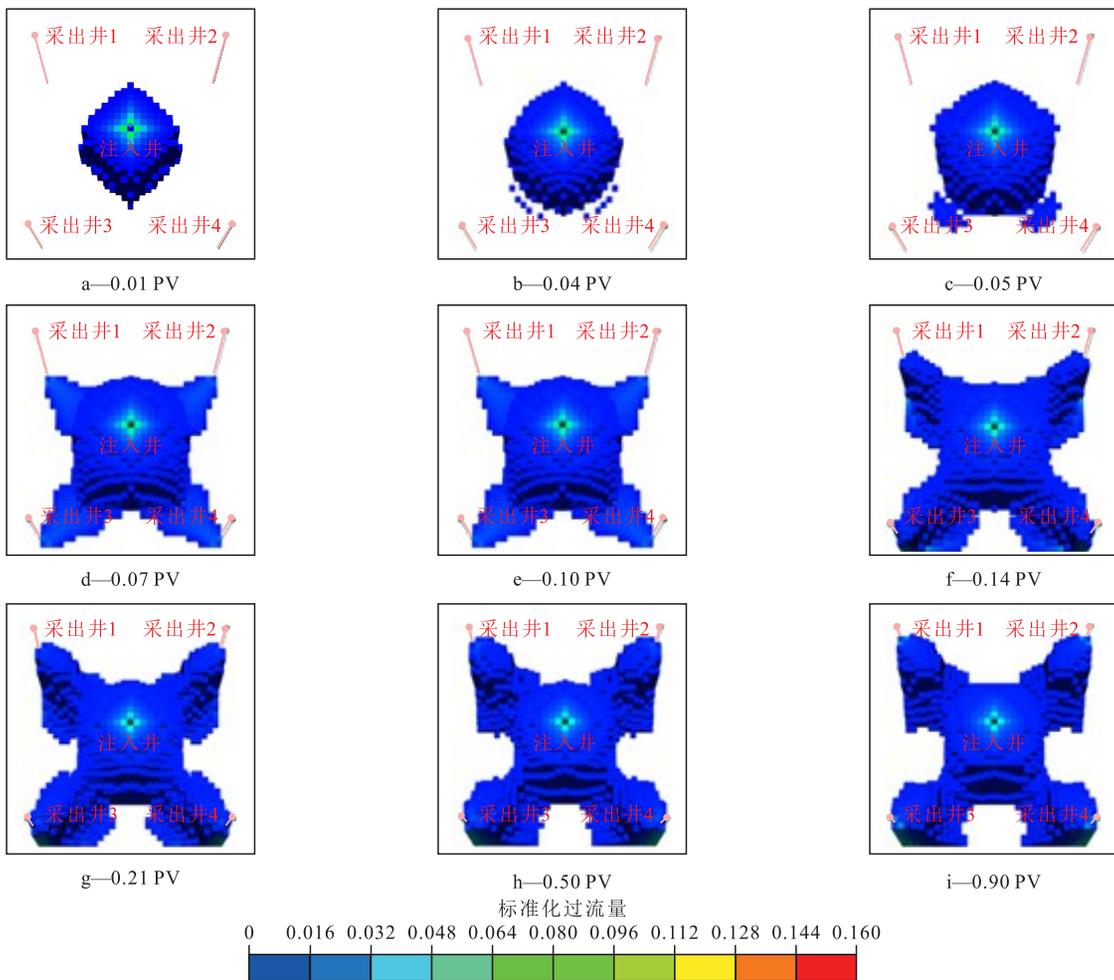


图 13 不同累积注入量下无断层油藏优势渗流通道演化

Fig.13 Evolution of dominant flow channels in fault-free reservoir at different cumulative injection amounts

建立数值反演模型,采用标准化过流量算法定量表征优势渗流通道,探索了该油藏措施前水驱阶段优势渗流通道发育分为优势渗流区发育阶段、优势渗流通道快速发育阶段、优势渗流通道缓慢发育阶段及优势渗流通道稳定发育阶段。

含部分封闭断层油藏物理模型无水采油期累积注入量为0.04 PV,受断层遮挡作用的2口井累积

产油量最低,而强阻挡区采出井由于较高的注入水分流率导致水驱后期累积产油量高于受断层影响最小的弱阻挡区采出井。无水采油期形成以水驱前缘为边界的优势渗流区,优势渗流区发育阶段优势渗流区体积快速增长且对驱油起积极作用。各井见水后首先形成由注入井至生产井底的优势渗流通道,然后主要沿垂向及采出井周围发育。发育

完善的优势渗流通道导致注入水无效循环,使得各区域采出程度增速变缓。

与无断层油藏相比,含部分封闭断层油藏优势渗流通道体积占比变化趋势相同,但断层导致强遮挡区优势渗流区/通道发育滞后,以及强阻挡区断层附近注入水波及困难,最终强遮挡区仅在储层底部及采出井井周形成优势渗流通道。断层使各区域剩余油分布差异较大,集中分布在强遮挡区顶部及强阻挡区断层附近。而无断层油藏各区域优势渗流通道及采出程度变化均匀。

符号解释

- A_n ——渗流场中第 n 个等势面的过流面积, m^2 ;
 Q_{wmax} ——全场标准化过流量最大值, m^3/d ;
 Q_{wnm} ——第 n 个等势面的第 m 点的标准化过流量, m^3/d ;
 Q_{ws} ——优势渗流通道中各点的标准化过流量, m^3/d ;
 v_{nm} ——第 n 个等势面的第 m 点的流速, m/d ;
 α ——标准化过流量差异容忍度。

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