孔隙尺度下岩性分类及参数粗化

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摘要 随着孔隙尺度流动模拟研究深入, 基于数字图像可对岩石性质进行模拟计算, 但计算结果并不能反映宏观岩样性质, 因此急需合理参数粗化方法. 本文建立了孔隙尺度下处理岩性分类以及参数粗化的一整套方法. 对于岩相学岩性分类, 计算闵可夫斯基形态学函数值, 采用 K 均值聚类得到水平层理, 并通过空间插值和 K 均值聚类确定出岩石不规则层理. 对于水动力学岩性分类, 计算逾渗几何参数, 使用有监督无监督高斯混合模型进行分类, 分类结果与连通孔隙结构性质匹配良好. 基于层状层理、不规则层理、水动力学岩性分类结果提出相应参数粗化公式, 计算局部岩样渗透率、电导率反推整体岩样渗透率、电导率. 研究结果发现基于水动力学岩性分类结果建立的参数粗化公式获得的整体岩样渗透率、电导率最为准确.

关键词 岩性分类, 参数粗化, 闵可夫斯基函数, 逾渗几何, K 均值, 高斯混合模型

岩性分类是研究孔隙级流动模拟和宏观油藏数值模拟的基础^[1], 它将岩体的几何性质和流动过程中反映的水力性质联系起来^[2,3]. 岩性概念最早由 Archie^[4]于1950年提出, 但 Archie 提出的岩性概念太广. Porras 等人^[5]提出了3种岩性单元: 水动力学单元、岩相学单元、沉积相单元. Rushing 等人^[6]基于3种岩性单元提出了3种岩性分类概念: 沉积学岩性分类、岩相学岩性分类、水动力学岩性分类. 沉积学岩性分类主要基于沉积环境、地层层序、地质结构进行分类; 岩相学岩性分类主要基于岩石层理、孔隙结构进行分类; 水动力学岩性分类主要基于孔隙结构反映的流动性(孔渗关系)进行分类. Aranibar^[7]基于测井数据和岩心测量参数采用无监督人工神经网络方法在油藏尺度下进行岩相学岩性分类. 岩心尺度下岩相学分类主要基于压汞测试数据以及核磁共振获

得的孔径分布数据^[8], Al-Owihan 等人^[9]通过沿岩心剖面CT成像获得孔隙度以及矿物组成和含量信息, 采用交会图法在岩心尺度下进行沉积学岩性分类. 油藏尺度下沉积学岩性分类主要基于测井数据^[10], Xu 等人^[11]通过孔隙度和不可动流体饱和度在油藏尺度下进行水动力学岩性分类. 岩心尺度下水动力学岩性分类主要基于实验室岩心测试获得的孔隙度和渗透率关系^[12].

岩性分类主要在岩心尺度和油藏尺度下进行研究. 由于NMR测井存在弛豫扩散作用以及经验公式划分的不确定性^[8], 导致岩心尺度和油藏尺度下的岩性分类结果并不准确. 随着CT成像以及数字岩心技术的发展^[13,14], 储层岩石孔隙结构可通过数字图像准确刻画, 因此在孔隙尺度下准确划分岩石性质具有重要意义.

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目前研究参数粗化均在油藏尺度下对网格参数进行处理^[15-17]。随着孔隙级流动模拟技术研究的深入,基于数字岩心可以对岩石物性参数进行计算^[18-22],但基于岩石数字图像微观模拟方法对计算机硬件有很高要求,大尺寸岩样计算时间较长。由于岩石的非均质性,基于直接微观模拟方法得到的岩石物性计算结果并不能与岩心实验结果进行直接对比。因此急需合理的参数粗化方法,通过直接微观模拟得到的局部岩样物性参数计算结果反推得到整体岩样的物性参数。

本文提出了孔隙尺度下处理岩相学岩性分类、水动力学岩性分类以及参数粗化问题的一整套方法。对于岩相学岩性分类,计算闵可夫斯基形态学函数值,采用 K 均值聚类确定水平层理,并通过空间插值和 K 均值聚类确定岩石不规则层理。对于水动力学岩性分类,计算逾渗几何参数,使用有监督无监督高斯混合模型进行分类。基于层状层理、不规则层理、水动力学岩性分类结果,选择合理尺寸的局部岩样,计算局部岩样渗透率、电导率,建立对应参数粗化公式,对整体岩样渗透率电导率进行求解。

1 岩样描述

研究岩样为薄层砂岩,大小为3 cm×7.5 mm×7.5 mm。通过CT扫描、图像滤波、二值化处理后,扫描岩样被划分为孔隙相和骨架相。测量得到孔隙度为18.2%,图像大小为1193×1514×176,分辨率为3.864 μm。本次研究使用大小900×900×1760,在本文中将三维岩样取二维剖面进行可视化,如图1所示。

2 岩相学岩性分类

2.1 闵可夫斯基形态学函数计算

对于岩相学岩性分类,采用闵可夫斯基形态学函数描述孔隙几何结构。三维光滑连续物体(骨架颗粒)的几何特征可由闵可夫斯基形态学函数完全描述^[23]。基于格子方法计算闵可夫斯基形态学函数理论由Mecke^[24]提出,进而被应用到分析三维数字图像的几何结构中^[25]。闵可夫斯基形态学函数具体表达形式如下^[26]:

$$V_0(Y) = V, \quad (1)$$

$$V_1(Y) = \int_{\partial Y} ds, \quad (2)$$

图1 (网络版彩色)(a) Xray-CT设备; (b) 滤波后的二维岩石剖面; (c) 二值化后的二维岩石剖面

Figure 1 (Color online) (a) Xray micro-CT facility; (b) 2D cross-sections of the tomogram after applying AD filters; (c) 2D cross-sections of the tomogram after binarization

$$V_2(Y) = \int_{\partial Y} \frac{1}{2} \left(\frac{1}{r_1(s)} + \frac{1}{r_2(s)} \right) ds, \quad (3)$$

$$V_3(Y) = \int_{\partial Y} \frac{1}{r_1(s)r_2(s)} ds, \quad (4)$$

其中 Y 指骨架表面, $r_1(s)$, $r_2(s)$ 指互相垂直的主曲率半径; $V_0(Y)$ 为骨架体积, $V_1(Y)$ 为孔隙表面积, $V_2(Y)$ 为积分平均曲率, $V_3(Y)$ 为积分高斯曲率。积分平均曲率 $V_2(Y)$ 用来描述岩石颗粒表面凹凸程度, 积分平均曲率 $V_2(Y)$ 绝对值越大, 反映岩石越致密; 积分高斯曲率 $V_3(Y)$ 反映岩石胶结程度, 负值表示胶结良好, 正值表示岩石颗粒松散。实际计算中采取下述公式计算闵可夫斯基形态学函数^[24]:

$$v_i = \frac{V_i(Y)}{V_0}, \quad i = 0, 1, 2, 3. \quad (5)$$

2.2 表征单元体分析

考虑该岩样层理为层状层理, 选取合适大小的表征单元体。从上至下移动表征单元体, 每移动1个体素计算一次表征单元体内的闵可夫斯基函数值 $v_i(i=0,1,2,3)$ 。计算得到的闵可夫斯基函数值 $v_i(i=0,1,2,3)$ 反映表征单元体内的几何性质。表征单元体 X 方向长度为900体素, Y 方向长度为900体素。为确定表征单元体 Z 方向长度, 首先采用最大球法^[27]计算研究岩样的孔径分布, 得到该岩样最大孔隙直径为32体素(图2)。表征单元体尺寸应大于最大孔隙尺寸以保证计算得到的闵可夫斯基函数值准确性。考虑立方体含有最大孔隙直径的球体并且孔隙度与研究岩样相同, 则该立方体边长体素为

$$L_{\text{cubic}} = \sqrt[3]{\frac{V_{\text{sphere}}}{\phi}} = \sqrt[3]{\frac{\pi d^3}{6\phi}} = 48, \quad (6)$$

图2 (网络版彩色)孔隙半径分布二维剖面图

Figure 2 (Color online) 2D cross section of the covering radius transform

因此选取48体素作为表征单元体Z方向长度,则表征单元体大小为900×900×48.如图3所示,从上至下每移动1个体素计算一次闵可夫斯基函数值,共获得1713组闵可夫斯基函数值.

2.3 层状层理岩相学岩性分类及参数粗化

采用K均值方法^[28]对计算得到的1713组闵可夫斯基函数值进行聚类,并匹配闵可夫斯基函数值计算位置,划分3种不同岩性:分选良好大孔区域、微

图3 (网络版彩色)计算方法示意图(Z方向剖面显示,矩形框表示表征单元体剖面,从上至下每移动1个体素计算一次闵可夫斯基函数值)

Figure 3 (Color online) Illustration of calculation method moving along the Z-axis of the core with $\Delta z=1$ voxel to calculate Minkowski function

孔区域以及过渡区域.根据闵可夫斯基函数值的平均值 $\mu_1^{(0)}, \mu_2^{(0)}, \dots, \mu_k^{(0)}$, 任意给一系列的质心,将闵可夫斯基函数值依据式(7)归类

$$V_i^{(t)} = \left\{ v_p : \|v_p - \mu_i^{(t)}\|^2 \leq \|v_p - \mu_j^{(t)}\|^2 \forall 1 \leq j \leq k \right\}, \quad (7)$$

式中, $V_i^{(t)}$ 为第*i*类中所有的闵可夫斯基函数值; k 为分类数量, 值为3; t 为迭代次数; v_p 为闵可夫斯基函数值 $v_j=(v_0, v_1, v_2, v_3)$; $\mu_i^{(t)}, \mu_j^{(t)}$ 分别为第*i*类和第*j*类闵可夫斯基函数第*t*次的平均值.

式(8)重新计算并更新各组质心,直至质心不再发生改变^[29]

$$\mu_i^{(t+1)} = |V_i^{(t)}|^{-1} \sum_{v_p \in V_i^{(t)}} v_p, \quad (8)$$

分类结果与实际物理模型匹配良好,如图4所示.

按照划分结果,将各层按照不同岩性标注(图5).对每一层采用LBM D3Q19模型^[30]计算水平渗透率 k_h 、垂向渗透率 k_v . 为满足达西流动要求, LBM模拟中入口/出口之间的压力差设定为0.0005 Pa, 而松弛时间为1^[31]; 同时考虑到复杂多孔介质中流-固面上无滑动效应^[32], 因此选择完全反弹边界模型. 通过求

解Laplace方程^[33,34]计算水平有效电导率 $\left(\frac{\sigma_{\text{eff}}}{\sigma_0}\right)_h$ 、垂

向有效电导率 $\left(\frac{\sigma_{\text{eff}}}{\sigma_0}\right)_v$. 采用如下公式^[35,36]进行参数

粗化, 计算该岩样的整体性质. 计算得到岩样水平渗透率为 $0.8804 \mu\text{m}^2$, 垂向渗透率为 $0.6494 \mu\text{m}^2$, 水平有效电导率 $\left(\frac{\sigma_{\text{eff}}}{\sigma_0}\right)_h$ 为0.035, 垂向有效电导率 $\left(\frac{\sigma_{\text{eff}}}{\sigma_0}\right)_v$ 为0.0346.

$$k_h = \frac{\sum_{i=1}^{n_t} k_{hi} T_i}{T_i}, \quad (9)$$

$$k_v = \frac{T_i}{\sum_{i=1}^{n_t} \frac{T_i}{k_{vi}}}, \quad (10)$$

$$\left(\frac{\sigma_{\text{eff}}}{\sigma_0}\right)_h = \frac{\sum_{i=1}^{n_t} \left(\frac{\sigma_{\text{eff}}}{\sigma_0}\right)_{hi} T_i}{T_i}, \quad (11)$$

$$\left(\frac{\sigma_{\text{eff}}}{\sigma_0}\right)_v = T_i / \sum_{i=1}^{n_t} \frac{T_i}{\left(\frac{\sigma_{\text{eff}}}{\sigma_0}\right)_{vi}}, \quad (12)$$

图4 (网络版彩色)基于K均值方法岩石类型划分结果。(a) 孔隙体积; (b) 孔隙表面积; (c) 积分高斯曲率; (d) 积分平均曲率
Figure 4 (Color online) K-means rock typing result. (a) Total volume; (b) surface area; (c) integral of Gaussian curvature; (d) integral of mean curvature

图5 (网络版彩色)层状层理岩性表征图
Figure 5 (Color online) Rock sample visualization based on rock type

其中, T_i 表示岩样Z方向厚度1713; T_i 表示划分出的各层水平岩层厚度; n_i 表示划分出的层数13; k_{hi} , k_{vi} ,

$(\sigma_{\text{eff}}/\sigma_0)_{hi}$, $(\sigma_{\text{eff}}/\sigma_0)_{vi}$ 分别表示第*i*种岩性的水平渗透率、垂向渗透率、水平有效电导率、垂向有效电导率。

2.4 不规则层理岩相学岩性分类及参数粗化

表征单元体大小更改为 $300 \times 300 \times 48$, 由于整体岩样大小为 $900 \times 900 \times 1760$, 因此从上至下每移动1个体素分9个区域同时计算9组闵可夫斯基函数值, 如图6和7所示. 采用最小曲率法^[37,38]对每次同时计算得到的9组闵可夫斯基函数值进行空间插值以保证插值数据的光滑性(图8).

采用前述K均值方法对插值后的闵可夫斯基值进行聚类, 将岩性划分成3类, 并匹配空间对应计算位置, 最终得到不规则层理(图9). 通过图9中得到的不规则层理可以找到地层尖灭, 说明在成岩过程中由于风力作用导致沉积颗粒运移.

图6 (网络版彩色)测量方法XY方向, 9组测量窗

Figure 6 (Color online) Measurement method in X and Y direction, nine measurement windows

图7 (网络版彩色)测量方法Z方向剖面示意图

Figure 7 (Color online) Measurement method in Z direction

在划分好不规则层理的岩样中选取 $100 \times 100 \times 1713$ 体素局部岩样(图10), 按照不同岩性逐层采用LBM D3Q19模型计算水平渗透率、垂向渗透率, 模型参数与前述相同. 通过求解Laplace方程计算水平有效电导率、垂向有效电导率. 提出如下参数粗化公式计算整体岩样渗透率、电导率性质. 计算得到岩样水平渗透率为 $1.2369 \mu\text{m}^2$, 垂向渗透率为 $0.6230 \mu\text{m}^2$, 水平有效电导率 $(\sigma_{\text{eff}}/\sigma_0)_h$ 为0.0368, 垂向有效电导率 $(\sigma_{\text{eff}}/\sigma_0)_v$ 为0.0260.

$$k_h = \frac{N_1}{N_t} \frac{\sum_{i=1}^{n_1} k_{hi}}{n_1} + \frac{N_2}{N_t} \frac{\sum_{i=1}^{n_2} k_{hi}}{n_2} + \frac{N_3}{N_t} \frac{\sum_{i=1}^{n_3} k_{hi}}{n_3}, \quad (13)$$

$$k_v = \frac{N_t}{\frac{N_1}{\sum_{i=1}^{n_1} k_{vi}} + \frac{N_2}{\sum_{i=1}^{n_2} k_{vi}} + \frac{N_3}{\sum_{i=1}^{n_3} k_{vi}}}, \quad (14)$$

$$\left(\frac{\sigma_{\text{eff}}}{\sigma_0} \right)_h = \frac{N_1}{N_t} \frac{\sum_{i=1}^{n_1} \left(\frac{\sigma_{\text{eff}}}{\sigma_0} \right)_{hi}}{n_1} + \frac{N_2}{N_t} \frac{\sum_{i=1}^{n_2} \left(\frac{\sigma_{\text{eff}}}{\sigma_0} \right)_{hi}}{n_2} + \frac{N_3}{N_t} \frac{\sum_{i=1}^{n_3} \left(\frac{\sigma_{\text{eff}}}{\sigma_0} \right)_{hi}}{n_3}, \quad (15)$$

$$\left(\frac{\sigma_{\text{eff}}}{\sigma_0} \right)_v = \frac{N_t}{\frac{N_1}{\sum_{i=1}^{n_1} \left(\frac{\sigma_{\text{eff}}}{\sigma_0} \right)_{vi}} + \frac{N_2}{\sum_{i=1}^{n_2} \left(\frac{\sigma_{\text{eff}}}{\sigma_0} \right)_{vi}} + \frac{N_3}{\sum_{i=1}^{n_3} \left(\frac{\sigma_{\text{eff}}}{\sigma_0} \right)_{vi}}}, \quad (16)$$

$i=1$ 表示分选良好大孔区域, $i=2$ 表示微孔区域, $i=3$ 表示过渡区域. N_t 表示岩样Z方向厚度1713, N_i 表示在 $900 \times 900 \times 1713$ 岩样中对应第*i*种岩性的厚度. n_i 表示在 $100 \times 100 \times 1713$ 局部岩样中对应第*i*种岩性的岩层数量. k_{hi} , k_{vi} , $(\sigma_{\text{eff}}/\sigma_0)_{hi}$, $(\sigma_{\text{eff}}/\sigma_0)_{vi}$ 分别表示第*i*种岩性的水平渗透率、垂向渗透率、水平有效电导率、垂向有效电导率.

3 水动力学岩性分类

3.1 逾渗几何参数计算

对于水动力学岩性分类, 首先对孔隙进行连通性分析, 剔除孤立孔隙, 在连通孔隙系统中计算逾渗

图8 (网络版彩色) 闵可夫斯基函数值空间插值示意图. (a) 骨架体积; (b) 孔隙表面积; (c) 积分平均曲率; (d) 积分高斯曲率
Figure 8 (Color online) Spatial interpolation of Minkowski function value. (a) Total volume; (b) surface area; (c) integral of mean curvature; (d) integral of Gaussian curvature

几何参数. 逾渗几何参数包括5个几何参数: 骨架体积、孔隙表面积、积分平均曲率、积分高斯曲率以及临界半径. 临界半径为连通孔隙系统中能够自由通过的最大球体半径, 也就是非润湿相流体驱替润湿相流体对应的逾渗阈值, 相关计算方法可参考文献[27], 在本文中以 l_c 表示. 逾渗几何参数在流体流经的孔隙表面计算得到, 因此为动态几何参数.

3.2 表征单元体分析

岩石孔隙结构性质由于非均质性影响会随岩样尺寸变化而变化^[39]. 在岩样上切割不同尺寸立方体, 计算逾渗几何参数、渗透率、有效电导率, 以选择能够表征岩石连通孔隙结构性质的合理尺寸. 由图11

可以看出当立方体大小为 $200 \times 200 \times 200$ 时, 岩石对应性质趋于稳定. 选取 $200 \times 200 \times 200$ 立方体作为该岩样的表征单元体.

3.3 水动力学岩性分类及参数粗化

采用高斯混合模型进行水动力学岩性分类. 高斯混合模型由不同高斯分布的密度函数加权构成^[40], 是基于概率密度函数的分类方法. 某种特定孔隙结构计算得到的逾渗几何参数对应一种高斯分布密度函数. 整体岩样计算得到的逾渗几何参数的概率密度函数可以视为由不同孔隙结构对应的逾渗几何参数的高斯分布密度函数加权形成. 岩样具有 k 种不同孔隙结构的逾渗几何参数概率密度函数可表示为

图9 (网络版彩色)不规则层理岩性表征图

Figure 9 (Color online) Dipping interface rock sample visualization

$$p(v) = \sum_{i=1}^k w_i g_i(v | \mu_i, \Sigma_i), \quad (17)$$

$v \in \mathbb{R}^5$, 表示一组逾渗几何参数, $w_i \in \mathbb{R}$ 表示混合权重, 其中

$$\sum_{i=1}^k w_i = 1, \quad (18)$$

$$g_i(v | \mu_i, \Sigma_i) = \frac{1}{(2\pi)^{5/2} |\Sigma_i|^{1/2}} \exp \left\{ -\frac{1}{2} (v - \mu_i)^T \Sigma_i^{-1} (v - \mu_i) \right\}, i = 1, \dots, k, \quad (19)$$

$g_i(v | \mu_i, \Sigma_i)$ 表示高斯分布密度函数, 均值 $\mu_i \in \mathbb{R}^5$, 协方差 $\Sigma_i \in \mathbb{R}^5 \times \mathbb{R}^5$, 本次研究 k 取 3.

采用期望最大算法^[41]求解权重 w_i 、均值 μ_i 、协方差 Σ_i , 每组逾渗几何参数 $v_j (j=1, \dots, N)$ 通过概率最大原则确定所属孔隙结构 $c_j \in \{1, \dots, k\}$

$$c_j = \arg \max_{i=1, \dots, k} (w_i g_i(v_j)). \quad (20)$$

在原始 $900 \times 900 \times 176$ 岩样中心切割出 $800 \times 800 \times 1600$ 岩样, 将 $800 \times 800 \times 1600$ 岩样划分为 $4 \times 4 \times 8$ 个 $200 \times 200 \times 200$ 表征单元体, 如图 12 所示. 底部 $4 \times 4 \times 4$ 个表征单元体计算逾渗几何参数、水平渗透率、垂向渗透率、水平有效电导率、垂向有效电导率. 参数计算方法与前述相同. 利用逾渗几何参数进行无监督高斯混合模型分类, 获得对应 3 种岩性的逾渗几何参数高斯分布的均值 $v = (l_c, v_0, v_1, v_2, v_3)$ 、协方差 Σ (表 1). 分类结果见图 13 和 14. 顶部 $4 \times 4 \times 4$ 个表征单元体计算逾渗几何参数, 并利用底部 $4 \times 4 \times 4$ 表征单元体求得的代表 3 种岩性逾渗几何参数高斯分布的均值 $v = (l_c, v_0, v_1, v_2, v_3)$ 、协方差 Σ , 进行有监督高斯混合模型分类, 分类结果见图 15 和 16.

从图 13~16 中可以看出, 分选良好大孔表征单元体临界半径大, 骨架体积和表面积小, 积分平均曲率低, 高斯曲率为正值, 渗透率、有效电导率高. 致密微孔表征单元体体现出相反的性质. 因此水动力学岩性分类结果与联通孔隙结构性性质匹配良好. 基于水动力学岩性分类结果, 提出如下参数粗化公式计

图10 (网络版彩色)100×100×1713 体素局部岩样

Figure 10 (Color online) Selected subsample 100×100×1713 voxel

图 11 (网络版彩色)岩石连通孔隙结构性质随立方体边长变化. (a) 临界半径; (b) 骨架体积; (c) 孔隙表面积; (d) 积分平均曲率; (e) 积分高斯曲率; (f) 渗透率; (g) 有效电导率, 前 5 个统称为逾渗几何数据

Figure 11 (Color online) Pore structure parameter change with cubic size. (a) Critical diameter; (b) total volume; (c) surface area; (d) integral of mean curvature; (e) integral of Gaussian curvature; (f) permeability; (g) effective conductivity. The first five parameters are percolation geometry data

图 12 (网络版彩色)岩样划分示意图. 底部表示采用无监督高斯混合模型, 顶部表示采用有监督高斯混合模型

Figure 12 (Color online) Illustration of the subsample selection, bottom blocks- unsupervised GMM, top blocks-supervised GMM

算整体岩样性质. 计算得到岩样水平渗透率为 $0.9925 \mu\text{m}^2$, 垂向渗透率为 $0.6025 \mu\text{m}^2$, 水平有效电导率 $(\sigma_{\text{eff}}/\sigma_0)_h$ 为 0.0388, 垂向有效电导率 $(\sigma_{\text{eff}}/\sigma_0)_v$ 为 0.0315.

$$k_h = \frac{N_1}{N_t} \sqrt{\prod_{i=1}^{n_1} k_{hi}} + \frac{N_2}{N_t} \sqrt{\prod_{i=1}^{n_2} k_{hi}} + \frac{N_3}{N_t} \sqrt{\prod_{i=1}^{n_3} k_{hi}}, \quad (21)$$

$$k_v = \frac{N_t}{\frac{N_1}{\sqrt{\prod_{i=1}^{n_1} k_{vi}}} + \frac{N_2}{\sqrt{\prod_{i=1}^{n_2} k_{vi}}} + \frac{N_3}{\sqrt{\prod_{i=1}^{n_3} k_{vi}}}}, \quad (22)$$

$$\left(\frac{\sigma_{\text{eff}}}{\sigma_0}\right)_h = \frac{N_1}{N_t} \sqrt{\prod_{i=1}^{n_1} \left(\frac{\sigma_{\text{eff}}}{\sigma_0}\right)_{hi}} + \frac{N_2}{N_t} \sqrt{\prod_{i=1}^{n_2} \left(\frac{\sigma_{\text{eff}}}{\sigma_0}\right)_{hi}} + \frac{N_3}{N_t} \sqrt{\prod_{i=1}^{n_3} \left(\frac{\sigma_{\text{eff}}}{\sigma_0}\right)_{hi}}, \quad (23)$$

$$\left(\frac{\sigma_{\text{eff}}}{\sigma_0}\right)_v = \frac{N_t}{\frac{N_1}{\sqrt{\prod_{i=1}^{n_1} \left(\frac{\sigma_{\text{eff}}}{\sigma_0}\right)_{vi}}} + \frac{N_2}{\sqrt{\prod_{i=1}^{n_2} \left(\frac{\sigma_{\text{eff}}}{\sigma_0}\right)_{vi}}} + \frac{N_3}{\sqrt{\prod_{i=1}^{n_3} \left(\frac{\sigma_{\text{eff}}}{\sigma_0}\right)_{vi}}}}, \quad (24)$$

其中 $i=1$ 表示分选良好大孔表征单元体, $i=2$ 表示致密微孔表征单元体, $i=3$ 表示过渡表征单元体. N_i 表示在

表1 水平方向和垂直方向得到的逾渗几何数据 3组高斯混合模型标准化均值分布

Table 1 Standardized centroid of percolation geometry data for three Gaussian mixture models in horizontal direction and vertical direction

岩性	临界半径		骨架体积		表面积		平均曲率		高斯曲率	
	水平	垂直	水平	垂直	水平	垂直	水平	垂直	水平	垂直
致密微孔	-0.849	-0.431	1.02	0.006	1.04	0.171	0.658	0.412	-0.825	0.216
分选良好大孔	1.1	0.72	-0.321	-0.479	-0.636	-0.661	-0.886	-0.692	-0.216	0.364
过渡	-0.184	-1.23	-0.526	1.21	-0.305	1.44	0.167	1.19	0.775	-1.22

图13 (网络版彩色)底部表征单元体水平方向无监督高斯混合模型分类结果。(a) 临界半径; (b) 骨架体积; (c) 孔隙表面积; (d) 积分平均曲率; (e) 积分高斯曲率; (f) 有效电导率; (g) 渗透率

Figure 13 (Color online) Histograms of parameter value of the bottom blocks in horizontal direction (unsupervised). (a) Critical diameter; (b) total volume; (c) surface area; (d) integral of mean curvature; (e) integral of Gaussian curvature; (f) effective conductivity; (g) permeability

4×4×8个表征单元体中对应第*i*种岩性的表征单元体数量, n_i 表示在底部4×4×4个表征单元体中对应第*i*种岩性的表征单元体数量; N_i 为所有表征单元体数量128; k_{hi} , k_{vi} , $(\sigma_{eff}/\sigma_0)_{hi}$, $(\sigma_{eff}/\sigma_0)_{vi}$ 分别表示底部4×4×4表征单元体中第*i*种岩性的水平渗透率、垂向渗透率、水平有效电导率、垂向有效电导率。

为比较不同参数粗化方法计算结果准确性, 采用LBM D3Q19模型和求解Laplace方程在计算机集群

对900×900×1760体素岩样直接计算渗透率和有效电导率。模型参数设置与前述相同, 计算得到岩样水平渗透率为1.0150 μm^2 , 垂向渗透率为0.4100 μm^2 , 水平有效电导率 $(\sigma_{eff}/\sigma_0)_h$ 为0.0397, 垂向有效电导率 $(\sigma_{eff}/\sigma_0)_v$ 为0.0268。将渗透率和有效电导率精确值与基于层状层理岩相学岩性分类参数粗化结果、基于不规则层理岩相学岩性分类参数粗化结果、基于水动力学岩性分类参数粗化结果进行对比, 基于水动力

图 14 (网络版彩色)底部表征单元体垂直方向无监督高斯混合模型分类结果. (a) 临界半径; (b) 骨架体积; (c) 孔隙表面积; (d) 积分平均曲率; (e) 积分高斯曲率; (f) 有效电导率; (g) 渗透率

Figure 14 (Color online) Histograms of parameter value of the bottom blocks in vertical direction (unsupervised). (a) Critical diameter; (b) total volume; (c) surface area; (d) integral of mean curvature; (e) integral of Gaussian curvature; (f) effective conductivity; (g) permeability

学岩性分类参数粗化得到整体岩样渗透率、电导率值最为准确。

4 结论

岩性分类能实现储层几何特征同运输属性的关联, 可为微观流动运移行为模拟及宏观油藏数值模拟提供支撑, 具有重要的现实意义. 而目前岩性分类的研究主要在油藏宏观尺度下进行, 本文着重探讨了孔隙尺度下岩性分类及参数粗化方法, 并发现基于水动力学岩性分类结果的参数粗化方法获得的宏观岩样渗透率、电导率参数最为准确. 主要结论如下:

(1) 计算闵可夫斯基形态学函数值, 通过 K 均值聚类得到水平层理, 并且通过最小曲率插值和 K 均值聚类确定出岩石微观不规则层理. 基于岩相学岩性

分类结果可对岩石颗粒沉积进行分析, 但基于岩相学岩性分类的参数粗化结果并不准确, 这是由于岩相学岩性分类结果只考虑了孔隙结构的几何特征并没有考虑孔隙间的联通性.

(2) 计算逾渗几何参数, 使用有监督无监督高斯混合模型进行水动力学岩性分类. 水动力学岩性分类考虑了连通孔隙的几何性质以及水力性质, 因此基于水动力学岩性分类的参数粗化结果也最为准确.

(3) 目前基于数字图像模拟计算岩石性质很大程度受目前计算机内存以及计算能力制约. 本文提出的参数粗化方法可减少计算时间, 降低计算需求, 通过计算局部岩样性质反推整体岩样性质, 为准确预测宏观岩样性质提供了可行的途径.

图 15 (网络版彩色)顶部表征单元体水平方向有监督高斯混合模型分类结果. (a) 临界半径; (b) 骨架体积; (c) 孔隙表面积; (d) 积分平均曲率; (e) 积分高斯曲率

Figure 15 (Color online) Histograms of parameter value of the top blocks in horizontal direction (supervised). (a) Critical diameter; (b) total volume; (c) surface area; (d) integral of mean curvature; (e) integral of Gaussian curvature

图 16 (网络版彩色)顶部表征单元体垂直方向有监督高斯混合模型分类结果. (a) 临界半径; (b) 骨架体积; (c) 孔隙表面积; (d) 积分平均曲率; (e) 积分高斯曲率

Figure 16 (Color online) Histograms of the parameter value of the top blocks in vertical direction (supervised). (a) Critical diameter; (b) total volume; (c) surface area; (d) integral of mean curvature; (e) integral of Gaussian curvature

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Summary for “孔隙尺度下岩性分类及参数粗化”

Pore scale rock typing and upscaling

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Rock-typing is an important part for micro pore scale flow simulation and macro scale reservoir simulation. It is the linkage between pore geometries and fluid flow properties. Recent research advances on pore scale flow simulation enable rock properties to be calculated based on the digital images. But the calculation results doesn't reflect the properties of whole rock sample. Therefore a suitable upscaling method is needed. In this study we first illustrate three different rock types: depositional rock type, petrographic rock type and hydraulic rock type. Depositional rock type is defined within the context of the large-scale geologic framework and represent those original rock properties present at deposition. Petrographic rock type is also described in the context of the geological framework established from the depositional rock types, but is based on a pore-scale microscopic imaging. Hydraulic rock types is also quantified on the pore scale but represent the physical rock flow and storage properties as controlled by the pore structure.

Then we introduce a work flow process that accurately solves the problem of rock typing and upscaling. The reservoir rock is a thin-bedded sandstone from an aeolian environment. For petrographic rock typing, we suppose thin-bedded rock sample as a layer system and define a measurement window moving along the z -axis of the core with $\Delta z=1$ voxel, perpendicular to the bedding direction. Minkowski functions namely total volume, surface area, integral of mean curvature, and integral of Gaussian curvature, are calculated based on the measure windows and kmeans clustering is applied to detect layer interface. Furthermore, the integration of spatial interpolation and kmeans clustering is proved to detect the dipping interface successfully. The classification results match well with corresponding properties and stratigraphic pitch-out can be found, which reflects the aeolian process, e.g., the activity of the winds to enable sediment transport. For hydraulic rock typing, the size, geometry, and distribution of pore throats, as determined by capillary pressure measurements, control the magnitude of porosity and permeability for a given rock. Therefore dynamic geometrical properties during the physical rock flow should be considered and we use percolation test data which includes critical diameter and Minkowski functions. All of these data are calculated based on the pore throats, which the fluid flows on it. The key to successful and efficient characterization is to exploit natural scales. Values and variability of each property are function of scale due to heterogeneities. Therefore, representative elementary volumes should be selected suitably to stabilize the data measurements. We first choose different sizes of subsample and measure corresponding percolation test data, permeability and effective conductivity. After selecting suitable representative elementary volumes, bottom blocks of subsamples are used for unsupervised Gaussian mixture model clustering and top blocks of subsamples are used for supervised Gaussian mixture model clustering based on the calculated centroid which means the mean value and covariance matrix of the percolation test data for each rock type in bottom blocks. The results demonstrate that different rock types are well separated with each other and match well with the corresponding geometrical properties and petrophysical properties. Three formulas which are based on layer system, undulating surfaces and hydraulic rock typing results, are developed to do upscaling. Local permeabilities and effective conductivities are computed to predict whole rock sample's permeabilities and effective conductivities. The results indicate that upscaling formula based on the hydraulic rock typing results is most accurate.

rock-typing, upscaling, Minkowski functional, percolation geometry, K means, Gaussian mixture model

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