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用“伞式解构”方法剖析致密储层微观各向异性

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摘 要:致密油气储层作为非常规油气储层的重要类型,具有孔隙尺度小,微观非均质性强等显著特征.目前在大幅提高资源动用率方面仍面临重大理论挑战,探索潜力广阔.本研究利用“伞式解构”方法定量解析了中国鄂尔多斯盆地陆相致密砂岩储层孔隙和矿物的微观各向异性特征.实例研究显示,八向伞式切片微观孔喉发育存在显著的微观各向异性,各向填隙物发育特征差异明显,随着取样角度的变化,呈现连续非稳态分布.八向伞式切片分形维数是孔隙率、渗透率和孔喉发育概率的良好表征.研究可为揭示致密储层储渗机理及“甜点”分布规律,指导致密油气有效开发提供重要的理论支撑与实践依据.

关键词:伞式解构;微观各向异性;致密储层;表征;孔隙;石油地质.

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Quantitative Analysis on the Microscopic Anisotropy Characteristics of Pore and Mineral in Tight Reservoir by “Umbrella Deconstruction” Method

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Abstract: As an important type of unconventional reservoirs, tight oil and gas reservoirs are characterized by small pore scale and obvious micro-heterogeneity. The exploration potential is vast despite the major theoretical challenges in greatly improving the recovery rate of resources. In this study, the micro anisotropic characteristics of pores and minerals in continental tight sandstone reservoirs in Ordos basin, China, are quantitatively analyzed by means of “umbrella deconstruction”. The case study shows that there is a significant micro anisotropy in the micro pore-throat development in eight directions, and the development characteristics of the anisotropic filler are obviously different. With the change of sampling angle, the micro pores show continuously unsteady distribution. The fractal dimension could characterize the porosity, permeability and pore-throat development probability. The study can provide important theoretical support and practical basis for revealing the mechanism of tight reservoir permeability, “sweet spot” distribution and guiding the effective development of tight oil and gas.

Key words: umbrella deconstruction; micro-anisotropy; tight reservoir; characterization; pore; petroleum geology.

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随着非常规油气资源的大量发现和上产，世界正经历着一场新的能源革命.致密油作为非常规油气的典型代表，具有准连续－连续型成藏，孔喉尺度小，非均质性更强，开采难度大等显著特征.其中，储层微观非均质性主要包括孔喉非均质性和矿物非均质性两个方面，具体包含孔喉形态及尺寸、连通程度、配置关系、分选程度以及矿物类型、含量、分布的非均质性.微观非均质性特征可直接影响注入剂的驱替效率，也是导致剩余油形成的根本原因之一（Kate *et al.*, 2006; Jia *et al.*, 2017; Wu *et al.*, 2019）.因此，对致密储层微观非均质性开展综合量化表征成为探索剩余油气分布机理的重要途径，是石油地质学领域极为重要的前沿科学问题（Du *et al.*, 2018a, 2018b）.

随着学科交叉的深入推进，Micro-CT、Nano-CT、FIB-SEM等高分辨率观测技术开始运用于非常规储层储集空间表征研究中，前人利用该系列技术针对非常规储层开展了大量卓有成效的研究工作，取得了一系列重要的研究结论（Du *et al.*, 2019a, 2019b）.但随着研究的深入和矿场实践的反馈，该技术逐渐暴露出费用高昂、CT阈值划分不合理易引起孔喉误判、样品尺度过小易引起代表性差等诸多核心问题.实际上，分辨率和代表性在实际观测研究中属于一对典型的矛盾体，很大程度上无法同时兼顾（Hajnos *et al.*, 2006; Hinai *et al.*, 2014; Gundogar *et al.*, 2016; Xiao *et al.*, 2016; Zheng *et al.*, 2018）.

观测分辨率与样品尺度是一对典型的矛盾体，现有技术条件下仍无法实现较大程度上的兼顾（Du *et al.*, 2018a, 2018b, 2019d; Lai *et al.*, 2018）.近年来，相关研究多数落脚于如何大幅提高观测精度，这在一定程度上忽略了观测精度越大则要求样品尺度越小，而样品尺度越小则非均质性越弱，从而偏离了非均质性研究的初衷（Alyafei *et al.*, 2016; Krakowska *et al.*, 2018）.Alyafei *et al.*（2016）通过研究图像分辨率大小对储层岩石孔隙度和渗透率估计精度的影响发现，渗透率变化最低可达25%，而孔隙度变化最高可达50%.Wang *et al.*（2016）采用多重分形方法研究发现，页岩中不同类型孔隙平均分形维数和平均宽度不同，微观非均质性程度高低依次为粒间孔、粒内孔与有机孔.Huang *et al.*（2017）认为微尺度空间的分形维数逐渐增加，纳米尺度空间中分形维数减少，表明微尺度空间的非均质性逐渐增强，而纳米尺度空间的非均质性逐渐减弱.Munawar *et al.*（2018）认为孔隙网络模型（PNM）预测岩石物理特性的成功依赖于图像分割、图像分辨率以及岩石是否均质3大因素，单尺度PNM方法无法解决致密储层的精细表征问题，亟需探索多尺度表征方法.

实际上，储层微观非均质性的量化表征研究应时刻着眼于有效甜点识别及提高采收率的最终目标，若偏离了该目标，往往容易“舍本逐末”.深入对比并剖析储层“二维”与“三维”表征方面的研究工作表明，随着CT技术和双束电镜（FIB-SEM）等高精度三维储层测试技术的引入，原先基于二维平面的储层表征技术受到了一定程度的冲击（Klaver *et al.*, 2016; Markussen *et al.*, 2019）.在短时间内无法解决诸如储层海量数据高精度扫描、存储、统计、分析处理以及在三维空间内较大程度兼顾分辨率－代表性等技术问题的大背景下，二维表征仍具有较大的探索和应用价值.而且，随着大视域成像技术的迅速发展，分辨率与代表性这一对矛盾体极有可能率先在二维空间内被解决（Silin *et al.*, 2003; Du *et al.*, 2018a, 2018b; Markussen *et al.*, 2019）.

当观测分辨率与样本尺寸在二维空间得到较大程度上的兼顾后，如何实现储层孔隙－喉道的精准判识与量化表征，对于开展致密油气储集、渗流能力的量化评价具有重要的基础理论意义.然而，对同一样品而言，由于各种孔喉量化测试分析技术的原理差异性较大，导致多种方法得到的孔隙和喉道信息匹配程度较低，可对比性较差，这在一定程度上造成了应用的困难.Silin *et al.*（2003），Dong（2007）基于岩石微米－纳米CT数据体，提出“最大球法（MB）”，实现了对孔喉的分割统计，随后Arand and Hesser（2017）根据储层研究对象的差异对MB法进行了算法改进或修正，进一步提升了孔喉判识表征的准确度.Rabbani *et al.*（2014）综合利用城市块距离函数和分水岭分割算法对多孔介质孔隙和喉道进行检测，分析网络的连通性和渗透性.Berrezueta *et al.*（2017）基于薄壁岩相显微镜提出一种自动图像处理方法用于检测和分析孔隙和喉道（分辨率为6.35 μm/pixel），进而开展孔喉分布曲线的构建与统计分析.

基于此，Du *et al.*（2019a, 2019b, 2019c, 2019d）已提出了“伞式解构”理念并进行了相关方

法和实验探究，并在此过程中不断拓展该方法的具体研究对象，取得了一系列的新认识．研究成果在一定程度上实现了分辨率与代表性的兼顾（Du *et al.*，2018a，2018b）．本文的着重点是利用这一方法对鄂尔多斯盆地新安边油田长7致密砂岩油储层开展微观各向异性的表征．

1　地质背景

鄂尔多斯盆地是位于华北陆块西部的大型多旋回克拉通盆地．从地层及含油气层系而言，主产层延长组以大面积湖泊三角洲前缘及三角洲平原为沉积特征，储油性与物性的相关性强，砂体平面展布范围控制着油藏的展布范围，从而有利于形成大规模岩性油藏．鄂尔多斯盆地延长组储层发育总体较为规律，砂泥岩界限总体平整且广泛延伸，较易区分出单砂体，厚度约3 m（图1），局部砂体尖灭现象较为明显，隔夹层广泛发育．致密砂岩储层原油分布呈现明显条带状，且条带迂曲度差异明显，孔喉大小、分布、结构等特征将在很大程度上决定原油储渗的非均质性（Du *et al.*，2019b，2019c，2019d）．

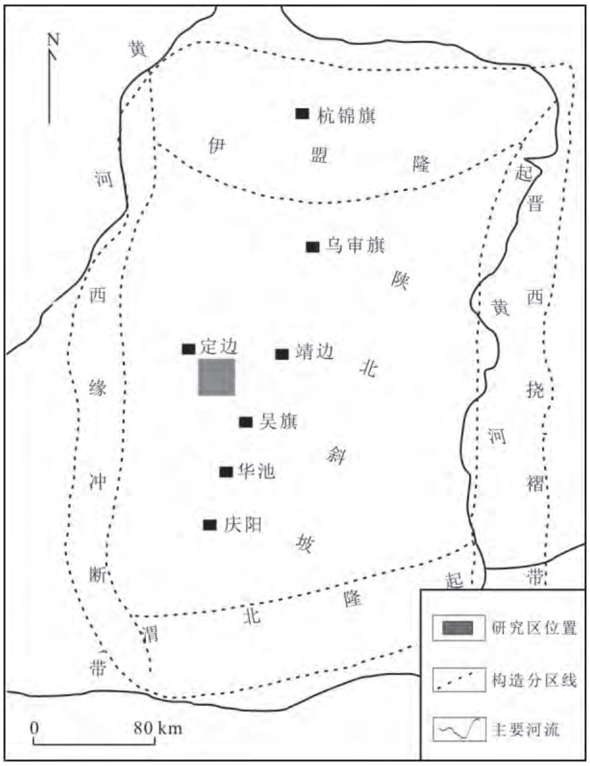

图1　研究区地理位置

Fig.1　Location of the study area

2　方法与结果

按照“伞式解构”理念及其系列改进方法的基本原理（Du *et al.*，2019a，2019b，2019c），本文选取了鄂尔多斯盆地长7段致密砂岩油储层样品的标准岩心钻柱，从端面垂直母线方向选择固定角度作为标志线，再沿该方向每隔固定角度步长（22.5°）顺时针旋转，依次选定8根标志线．沿8条标志线方向精准切片、磨片，岩石切片直径标准为25 mm．采用高分辨率场发射扫描电镜（FE-SEM）并结合大视域成像技术，对八向切片开展高分辨率成像．通过构建多个属性参数，对其微观非均质性及各向异性开展量化表征（图2）．

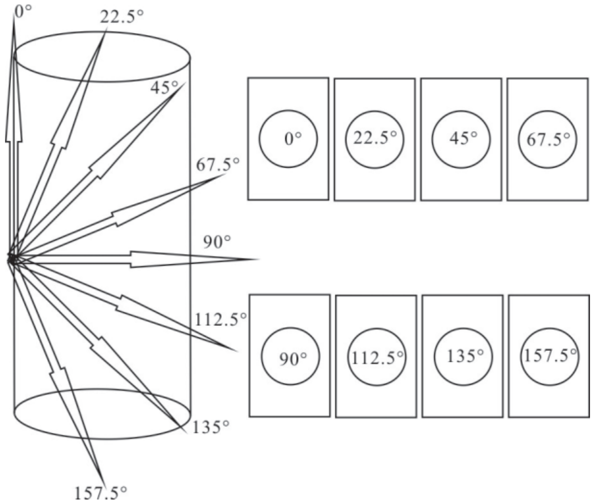

图2　“伞式解构”技术原理示意

Fig.2　Schematic diagram of “umbrella deconstruction” technology

据Du *et al.*（2018a，2018b）

3　应用实例

3.1　各向孔喉－矿物属性参数各向异性剖析

将每个样品8张伞式切片置于场发射扫描电镜（FE-SEM）下对样品开展高精度成像，以A1号样品伞式切片大视域图像为例，分别从孔喉及填隙物发育特征两个角度剖析长7致密储层微观各向异性．

对伞式切片孔隙－喉道开展分割，进而分别统计（图3～图4）．

依据平均孔隙、喉道半径将八向岩石分为高孔中喉、中孔粗喉、中孔细喉、低孔中喉、低孔细喉5类，孔隙、喉道的峰值半径等参数均有所差别，良好地表征了岩石不同方向微观孔喉发育的微观非均

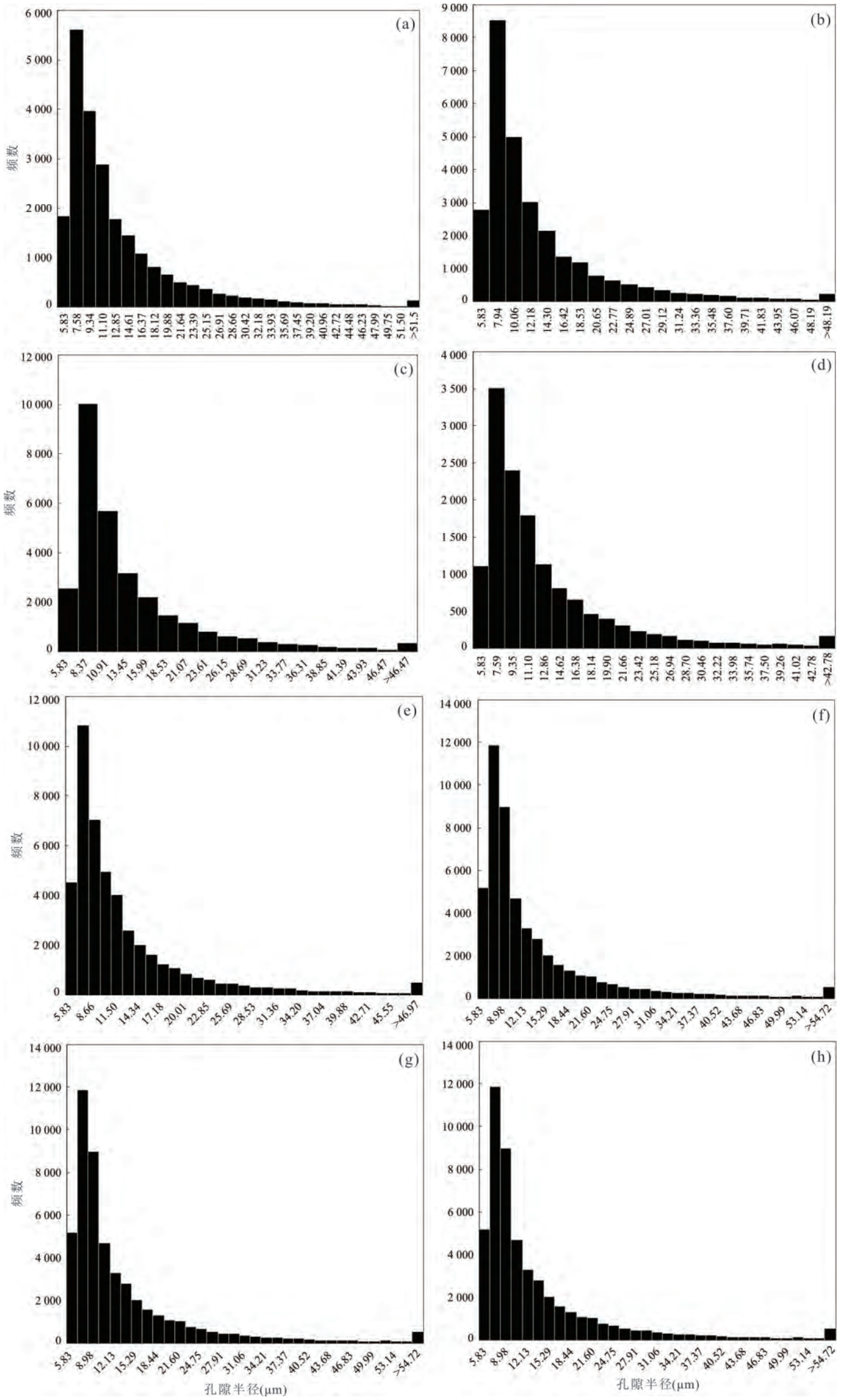

图 3　八向孔隙半径分布

Fig.3　Distribution of pore radius in eight directions

a.0°方向;b.22.5°方向;c.45°方向;d.67.5°方向;e.90°方向;f.112.5°方向;g.135°方向;h.157.5°方向

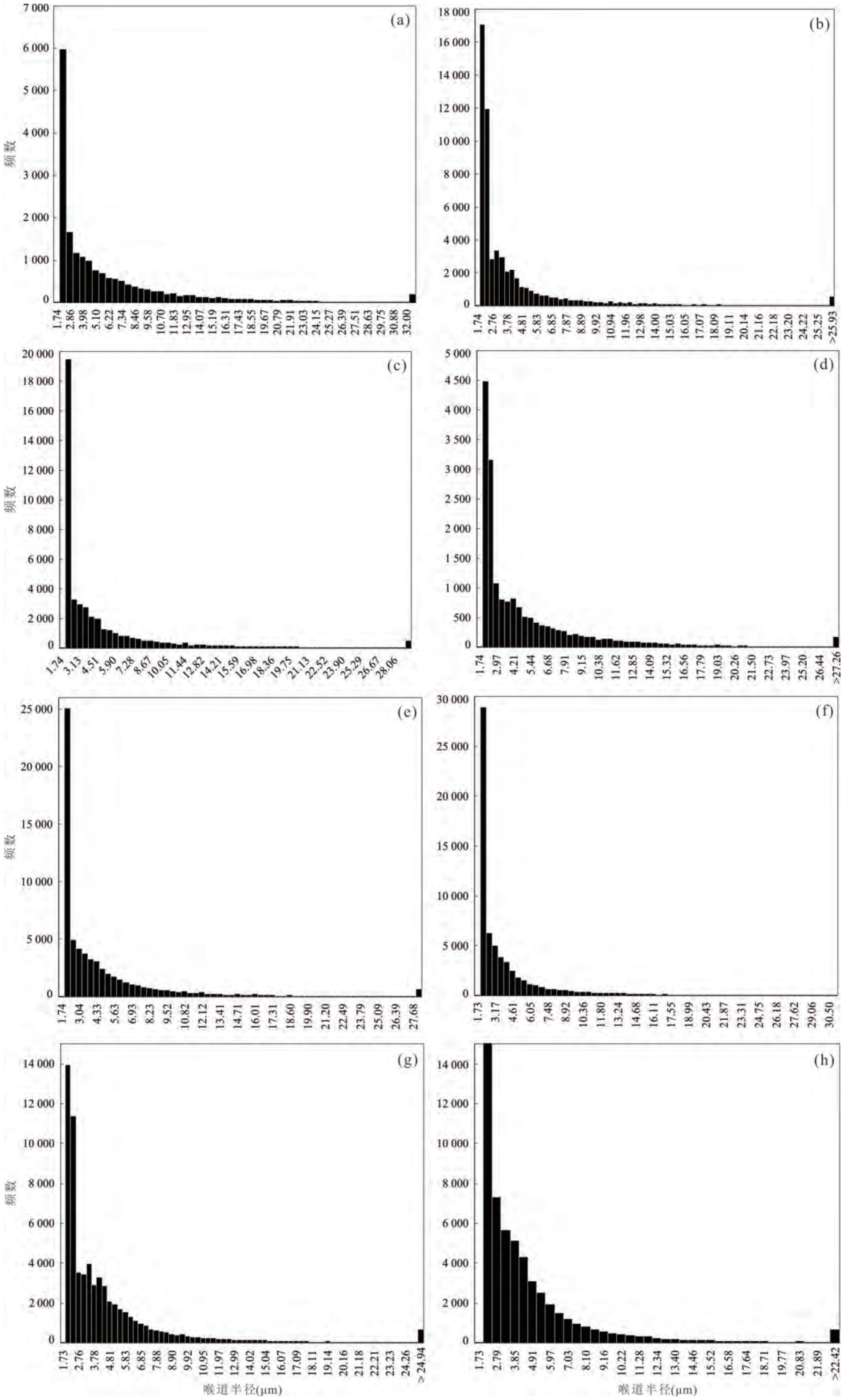

图4 八向喉道半径分布

Fig.4 Distribution of throat radius in eight directions

a.0°方向；b.22.5°方向；c.45°方向；d.67.5°方向；e.90°方向；f.112.5°方向；g.135°方向；h.157.5°方向

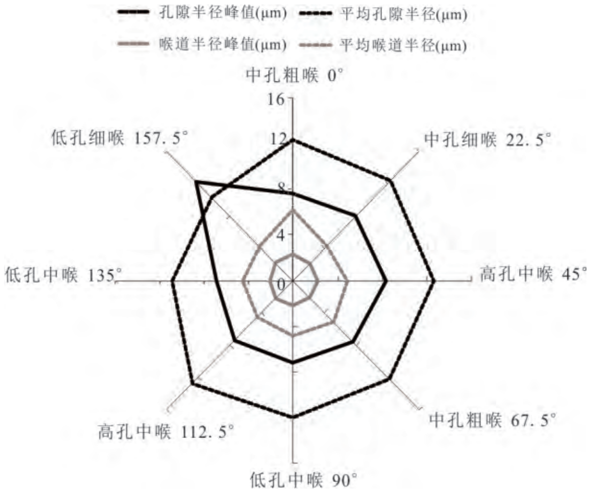

图 5　八向切片孔喉属性参数分布

Fig.5　Distribution of pore and throat parameters in eight direction

质性和各向异性(图 5).

以 A1 号样品为例,对其大视域图像开展高分辨率图像精细处理,八向切片孔喉各属性参数变化曲线如图 6 所示.

相似地,先对八向切片中的填隙物展开识别,再进行量化表征.八向切片填隙物条带各属性参数变化曲线如图 7 所示.

伞式切片孔喉和填隙物微观各向异性表征结果显示(图 7),无论是孔喉的宽度还是填隙物条带的宽度,各个方向上的差异均较为显著,且随着取样角度的变化呈现连续非稳态分布,充分展现了孔隙—矿物属性参数微观各向异性特征.

3.2　各向孔喉分形维数的物理意义

用盒维数法对 A1 号样品伞式切片开展分形维数计算.同时,为充分厘清孔喉分形维数在长 7 致密砂岩油储层中的物理意义,将分形维数分别与孔隙率、渗透率及单位面积孔喉数量做相关性交会.

相关性分析表明(图 8),计盒分形维数与孔隙率、渗透率和单位面积孔喉数量均呈良好线性相关关系.分形维数越大,单位面积孔喉数量、孔隙率、渗透率均呈增大趋势,这说明分形维数不仅能表征孔喉复杂程度,而且是孔隙率、渗透率和孔喉发育概率的良好表征.同时,单位面积孔喉数量即孔喉发育概率也直接影响了渗透率.

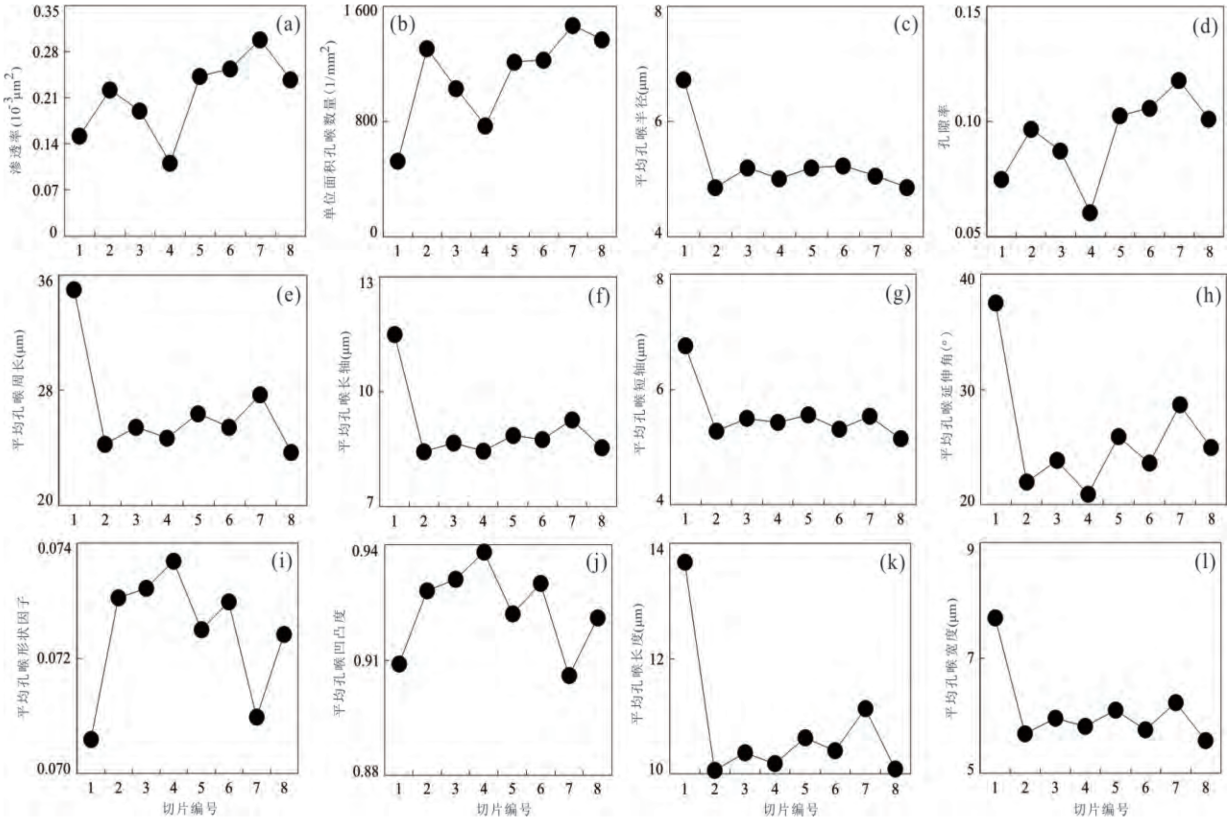

图 6　八向切片孔喉属性参数变化曲线

Fig.6　Change curve of pore and throat parameters in eight directions

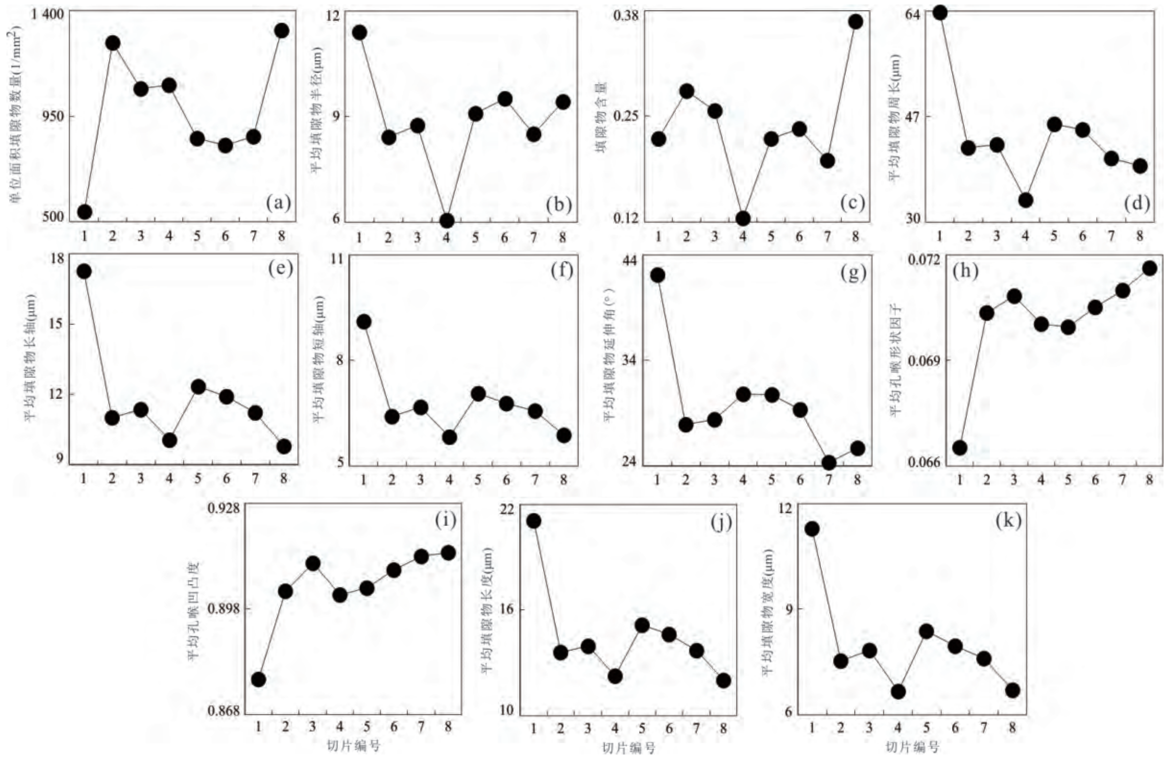

图 7　八向切片填隙物条带属性参数变化曲线

Fig.7　Change curve of parameters of interfilling strip properties in eight directions

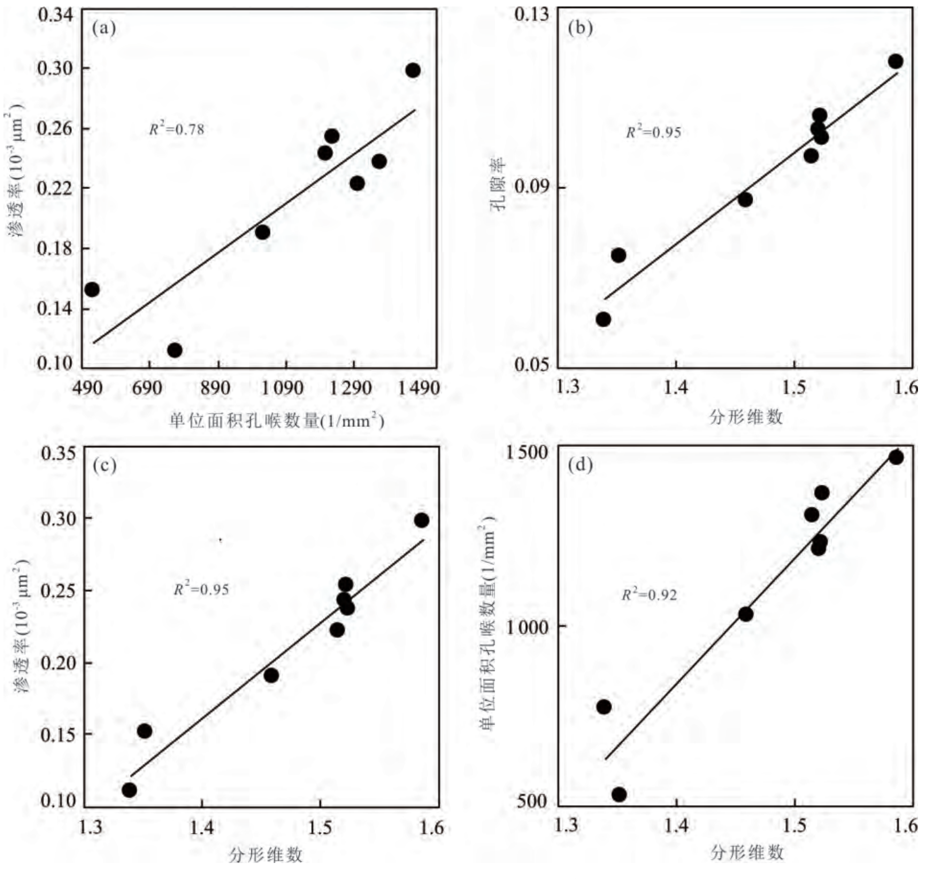

图 8　八向孔喉分形维数与孔喉属性参数相关性分析

Fig.8　Correlation analysis between pore-throat fractal dimension in eight directions and pore throat attribute parameters

4　结论

（1）与Micro-CT、Nano-CT、FIB-SEM等技术相比，“伞式解构”方法的特殊意义主要表现在两方面，一是对岩心标准钻柱力求“物尽其用”，二是在分辨率达到要求的前提下提高代表性进而实现二者兼顾.

（2）伞式切片微观各向异性表征结果显示，各向孔喉参数与填隙物差异明显，随着取样角度的变化，呈现连续非稳态分布.结果充分展现了填隙物参数在空间上各向异性的变化规律，其高次拟合公式可为岩石参数的各向异性提供连续计算方法和理论依据.

（3）计盒分形维数与孔隙率、渗透率和单位面积孔喉数量均呈良好线性相关关系.分形维数越大，单位面积孔喉数量、孔隙率、渗透率均呈增大趋势，这说明分形维数不仅表征孔喉复杂程度，而且是孔隙率、渗透率和孔喉发育概率的良好表征.同时，单位面积孔喉数量即孔喉发育概率也直接影响了渗透率.

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