

<https://doi.org/10.3799/dqkx.2022.246>



西湖凹陷平湖斜坡有利相带内储层非均质性成因新认识

谢晓军,熊连桥,韩雅坤,李鑫*,陈莹

中海油研究总院有限责任公司,北京 100028

摘要: 河流—潮汐双向水流沉积环境中,水体方向、动力、化学属性变化频繁,储层矿物基础、成岩过程复杂多变、物性非均质性强,一直是制约其勘探开发的难点.以中国东海西湖凹陷平湖组为例,针对河流—潮汐背景中潮道和水下分流河道两种高能沉积微相,通过岩心观察、孔渗测试、光镜等方法,从物质基础、物性规律、主控因素 3 个方面开展研究.结果表明:(1)潮道中上部物性好,孔隙度平均 18%、渗透率平均 120 mD ($1 \text{ mD} \approx 10^{-3} \mu\text{m}^2$),而潮道底部致密,孔隙度平均 4%、渗透率平均 0.05 mD;呈现非均质性的主要原因是碳酸盐胶结导致底部致密;(2)水下分流河道上部物性好,孔隙度平均 5%、渗透率平均 70 mD,而水下分流河道底部致密,孔隙度平均 1%、渗透率平均 0.01 mD;呈现非均质性的主要原因是高岭石充填导致底部致密.上述研究明确了西湖凹陷平湖组 2 种优势微相的非均质性成因,对深化河流—潮汐背景下储层非均质性规律及成因机制具有重要的理论指导意义;技术方法、研究成果可应用于东海盆地低渗砂岩储层油气勘探,对于中国近海、国外区块的深层碎屑岩储层油气勘探亦具有重要推广借鉴意义.

关键词: 近海;深层;非均质性;碳酸盐岩;高岭石;石油地质学.

中图分类号: P618

文章编号: 1000-2383(2024)04-1400-11

收稿日期: 2022-02-12

New Insights into Reservoirs Heterogeneous Genesis of Favorable Facies in Pinghu Formation, Xihu Depression

Xie Xiaojun, Xiong Lianqiao, Han Yakun, Li Xin*, Chen Ying

Research Institute Ltd., China National Offshore Oil Corporation, Beijing 100028, China

Abstract: Flow direction, dynamic and chemical properties change frequently in fluvial and tidal sedimentary environment, the reservoir mineral foundation and diagenetic process are complex and changeable, and the physical property is strong heterogeneity, which has always been the difficulty restricting its exploration and development. In this paper, Pinghu Formation in Xihu Depression of East Sea, China was taken as an example. Material basis, materiality pattern and main controlling factors were investigated in two high-energy sedimentary microphases, namely tidal channel and submerged divergent river channel. Methods include core observation, pore penetration test, light microscopy, isotope and inclusions. The results show follows. (1) The upper/middle part of tidal channel possessed good physical properties with an average porosity of 18% and permeability of 120 mD, while the bottom of tidal channel was dense with an average porosity of 4% and permeability of 0.05 mD. The main reason for the inhomogeneity is that the bottom is dense due to carbonate cementation. (2) The upper part of submerged diversion channel had

基金项目:“十三五”国家科技重大专项(No. 2016ZX05024002);中国博士后科学基金(No. 2021M693543).

作者简介:谢晓军(1978—),男,博士,高级工程师,主要从事沉积与储层地质研究工作. ORCID: 0000-0001-7768-1586. E-mail: xiexj@cnooc.com.cn

* **通讯作者:**李鑫(1988—),男,博士后,工程师,主要从事沉积与储层地质研究工作. ORCID: 0000-0001-6334-0369. E-mail: lixin71@cnooc.com.cn

引用格式:谢晓军,熊连桥,韩雅坤,李鑫,陈莹,2024. 西湖凹陷平湖斜坡有利相带内储层非均质性成因新认识. 地球科学, 49(4): 1400-1410.

Citation: Xie Xiaojun, Xiong Lianqiao, Han Yakun, Li Xin, Chen Ying, 2024. New Insights into Reservoirs Heterogeneous Genesis of Favorable Facies in Pinghu Formation, Xihu Depression. *Earth Science*, 49(4): 1400-1410.

good physical properties with an average porosity of 5% and permeability of 70 mD, while the bottom of submerged diversion channel was dense with an average porosity of 1% and permeability of 0.05 mD. The main reason for the inhomogeneity is that the bottom is dense due to kaolinite filling. The above analysis has important theoretical guiding significance to deepen the law and formation mechanism of reservoir heterogeneity under fluvial and tidal background. The technical methods and research results can be applied to the oil and gas exploration of low permeability sandstone reservoirs in the East China Sea basin, and have important reference significance for the oil and gas exploration of deep clastic reservoirs in offshore China and foreign blocks.

Key words: offshore; deep-buried; non-homogeneous; carbonate; kaolinite; petroleum geology.

在全球油气资源供应日趋紧张的形势下,随着浅层油气勘探开发不断深入,难度日益加大,将目标转向深层(埋深 $>3\ 500\text{ m}$)已成为必然趋势(钟大康等,2008;胡文瑞等,2013;冯佳睿等,2016).全球深层资源潜力巨大,探明和控制可采储量的63.3%分布于碎屑岩,是重要的勘探开发目标(童晓光等,2014;杨海军等,2019).然而,深层碎屑岩储层大多经历了复杂的演化过程和强烈的成岩改造,在深埋藏、强非均质性、低孔渗背景下,寻找相对优质储层难度较大(操应长等,2013;张凯逊等,2016;姜平等,2021;张莉等,2021;吴克强等,2023).

深层碎屑岩储层物性控制因素研究表明:沉积作用控制着储层原始物性,而成岩改造增加了储层的复杂性(于兴河和李胜利,2009;潘荣等,2014;杨文霞等,2023).优质储层形成受构造运动、沉积环境、埋藏方式等背景条件下的温度、压力、流体因素控制,具体包括:原始沉积物的成分、结构、构造等,演化过程中异常高压、烃类注入、热循环对流、膏盐效应等伴随的压实、胶结、溶解作用等(孙龙德等,2013;张功成等,2019;Gong *et al.*,2023).

中国东海盆地西湖凹陷油气勘探已历时40余年,中浅层油气勘探程度相对较高(顾惠荣等,2002;蒋海军等,2011;刘金水等,2012),深层已成为下一步勘探的潜力区.西湖凹陷生烃潜力大(高伟中等,2015;吴嘉鹏等,2017),但探明大中型油气田少,油气分布具有“小而散”的一般特征(胡明毅等,2013;周心怀等,2019).钻井成本高、探井预测成功率低,限制了研究区勘探开发的商业价值.

研究区前期工作发现,沉积因素不能完全解释现今储层非均质性的成因:相邻井位、相同沉积微相物性、产能均存在差异,且砂体内部往往“气—干互层”、纵向变化大.这一现象表明深层碎屑岩成岩期经受强烈改造,储层非均质性进一步增强.就潮道和 underwater 分流河道而言,属于水陆交互环境沉积的

高能相带,具有粒度粗、分选好的沉积特征,是碎屑岩中优质储层的典型代表(谢晓军等,2021).然而,潮道和 underwater 分流河道两种高能微相储层物性存在极强的非均质性,标志着以优质沉积相为有利预测目标的井位部署思路在深层勘探中并不完全适用,不能满足深层碎屑岩储层地质复杂性和特殊性的需求,存在极大的预测风险.

因此,本文针对深层碎屑岩储层非均质性强、成因不清的问题,以中国东海西湖凹陷平湖组为例,通过岩心描述、孔隙率和渗透率测试、光学、电学观察等实验方法,重点讨论3个问题:(1)储集物质基础特征;(2)储层非均质性规律;(3)储层非均质性成因.以此,揭示有效储层发育控制因素和作用机理,对深化深层油气勘探开发具有重要的理论指导意义和实际生产价值.技术方法、研究成果可应用于东海盆地低渗砂岩储层油气勘探,对于中国近海、国外区块的深层碎屑岩储层油气勘探亦具有重要推广借鉴意义.

1 区域地质概况

本文以东海盆地西湖凹陷平湖斜坡始新统平湖组砂岩为研究对象,研究区位于东海盆地西湖凹陷平湖斜坡(图1),目的层埋深普遍在 $3\ 500\sim 4\ 500\text{ m}$ 范围内,是典型的深层碎屑岩储层(于水,2020).构造上,西湖凹陷总体为张应力背景形成的复杂半地堑,构造背景具有断陷、断拗转换、拗陷及沉降的多期叠合特征(周心怀等,2019).沉积上,平湖组砂岩沉积于断拗转换期,总体属于西北陆缘、东岛阻隔、南部开口的半封闭海湾环境;西侧高部位物源注入,东侧低部位潮汐改造(周心怀等,2019).河流与潮汐共同控制沉积体展布,沉积环境主要为三角洲和潮坪,共发育5种微相类型:水下分流河道、河口坝、砂坪、潮道及混合坪.

其中,以潮道、水下分流河道发育最普遍且物

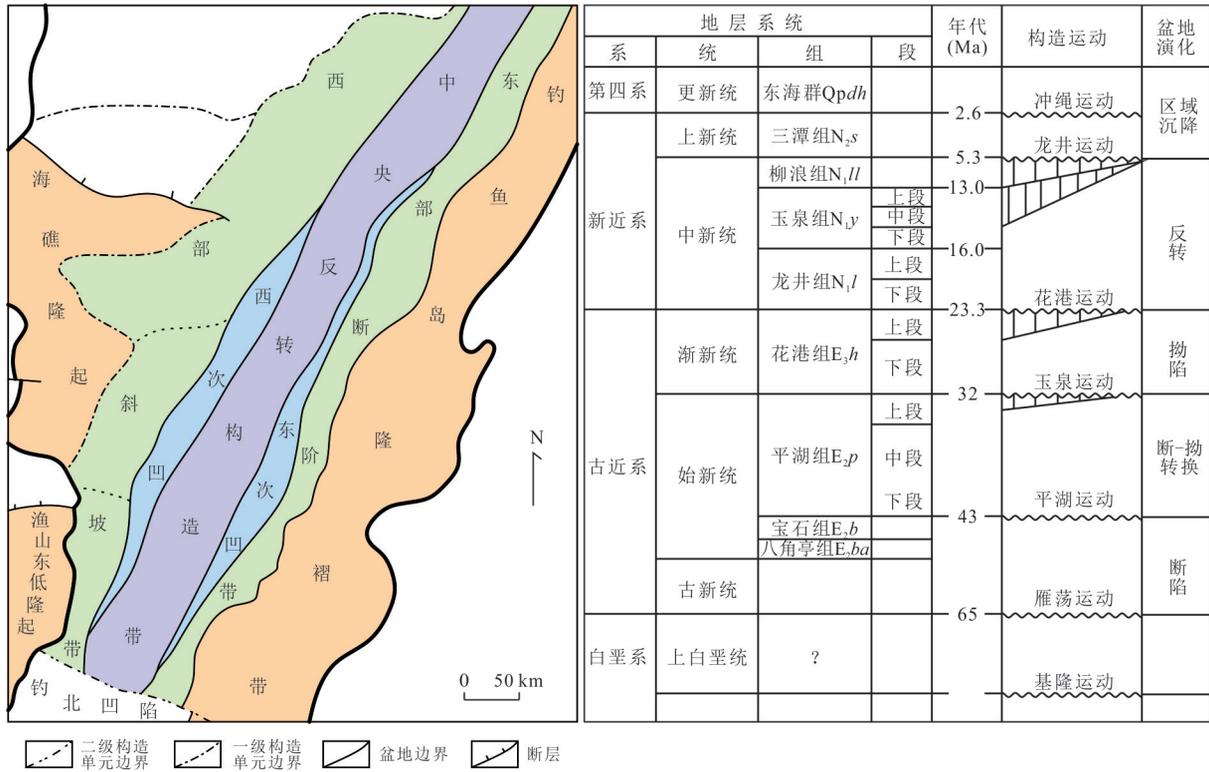


图 1 西湖凹陷区域位置

Fig. 1 Regional location map of Xihu depression

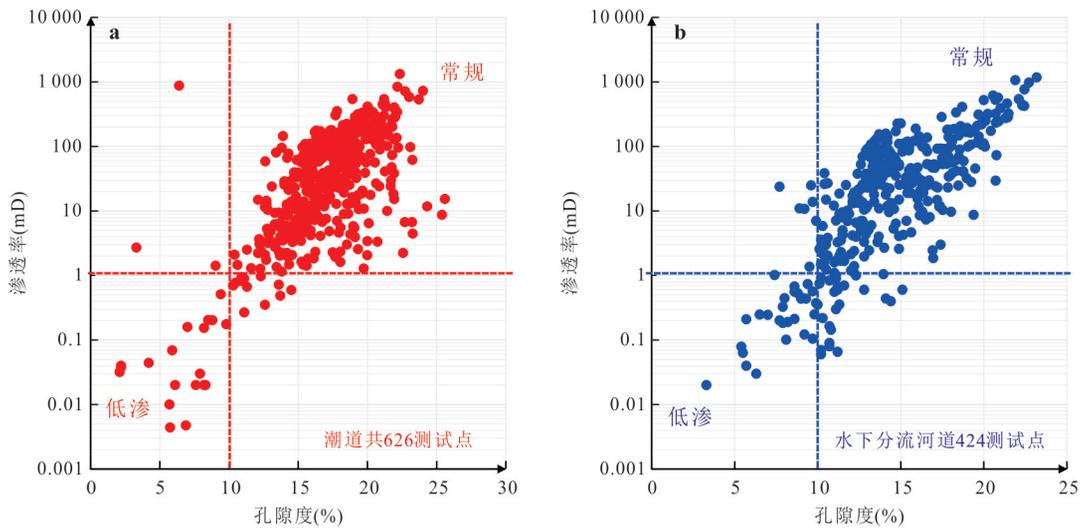


图 2 西湖凹陷平湖组潮道

Fig. 2 Physical properties of Pinghu Formation in Xihu sag

a. 潮道孔隙度与渗透率相关性统计图; b. 水下分流河道孔隙度与渗透率相关性统计图. $1 \text{ mD} \approx 10^{-3} \mu\text{m}^2$

性最优(谢晓军等, 2021). 然而, 通过物性分析发现: 虽然潮道和水下分流河道物性相对较好, 但其本身仍具有极强非均质性(图 2), 这严重阻碍了有利储层优选. 因此, 本文针对潮道、水下分流河道 2 种优势微相开展研究, 探索其非均质性规律和成因机

制, 以此深入认识西湖凹陷平湖组储层属性.

2 储集物质基础特征

2.1 潮道

潮道岩性以灰白色中砂岩、细砂岩为主; 测井

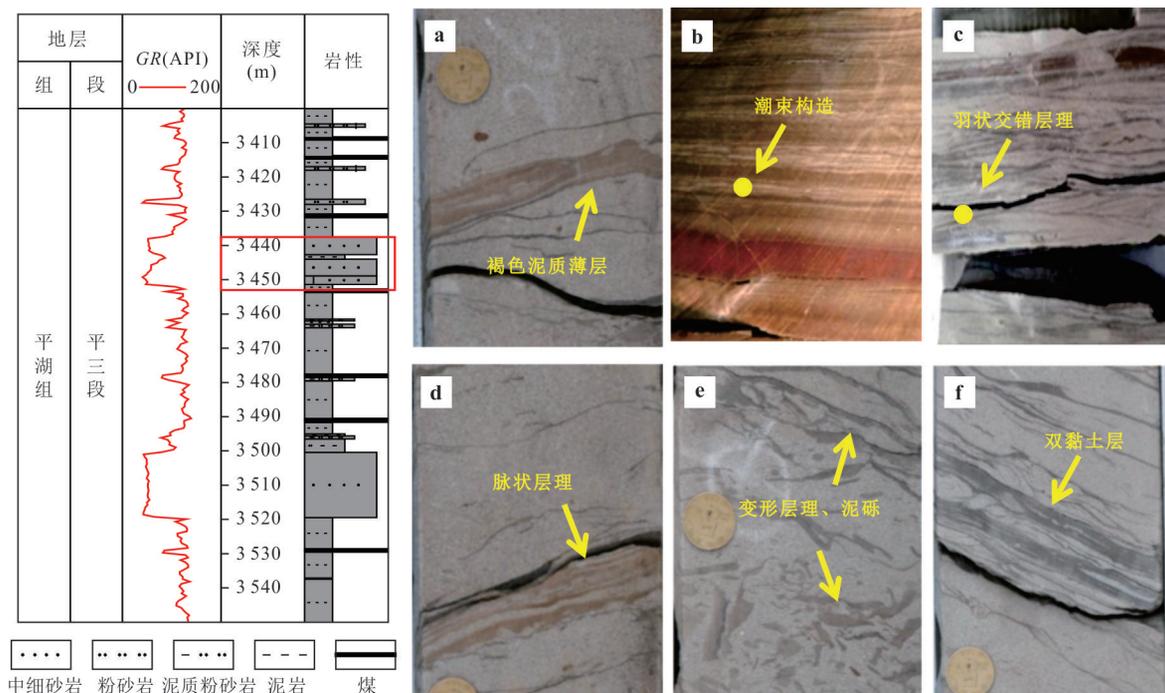


图3 潮道微相岩心柱状图及典型沉积构造特征(A1井)

Fig. 3 Core histogram and typical sedimentary structure of tidal channel (Well A1)

a. 3 445.57 m, 褐色泥质薄层; b. 3 442.40 m, 潮束构造; c. 3 443.55 m, 羽状交错层理; d. 3 445.27 m, 脉状层理; e. 3 441.72 m, 变形层理、泥砾; f. 3 440.62 m, 双黏土层

GR曲线呈现明显的箱型特征;沉积构造可见块状、交错、脉状、透镜状层理发育,双黏土层和羽状交错层理是潮道微相的指示性标志(图3)。原始矿物组成和沉积构造均一,表明了同一沉积环境岩石学特征的均一性质。

2.2 水下分流河道

水下分流河道岩性主要为灰白色中砂岩、含砾中砂岩;测井GR曲线表现为箱型;沉积构造方面,平行层理、槽状、楔状交错层理、冲刷面等均体现出河道的沉积特征(图4)。岩性和沉积构造具有典型的韵律性,指示水下分流河道的多期叠加特征;同时,黏土矿物(高岭石)在水下分流河道底部含量明显增高,也呈现周期性规律(见3.2部分)。

3 储层非均质性规律

3.1 潮道

整体上,潮道呈中上部物性好,而底部致密的非均质现象。潮道中上部孔隙度平均为18%、渗透率平均为120 mD($1 \text{ mD} \approx 10^{-3} \mu\text{m}^2$),物性较好;潮道底部孔隙度平均仅为3.8%,渗透率平均仅为0.04 mD,呈现致密特征(图5a)。从潮道底部孔渗资料可以看出,孔隙度、渗透率、面孔率迅速降低,在

0.5 m以内的深度范围,由高孔渗的优质储层转变为致密的非储层(图5b)。

3.2 水下分流河道

水下分流河道物性亦呈现一定的周期性特征,单期水下分流河道自上到下孔隙度、渗透率、面孔率降低。通过与沉积微相叠合分析可知,物性和黏土矿物(高岭石)的周期性增减规律与水下分流河道周期性叠加规律具有一致性。研究发现,水下分流河道中上部物性好,孔隙度平均为5%、渗透率平均为70 mD,而水下分流河道底部致密,孔隙度平均仅为1%、渗透率平均仅为0.01 mD(图6)。

4 储层非均质性成因分析

4.1 潮道

从物质基础来看,潮道的原始矿物组成、沉积构造均表现出均一性(图3),由此推断,潮道的原始储集空间也应该是均一的。然而,潮道却呈现了中上部物性好而底部物性差的强非均质性特征。这表明,深层碎屑岩成岩期经受强烈改造,沉积因素不能完全解释现今储层非均质性的成因。统计发现,碳酸盐胶结物含量与孔隙度、渗透率具有强负相关性(图7),随着碳酸盐胶结物的增加,储层物性具有

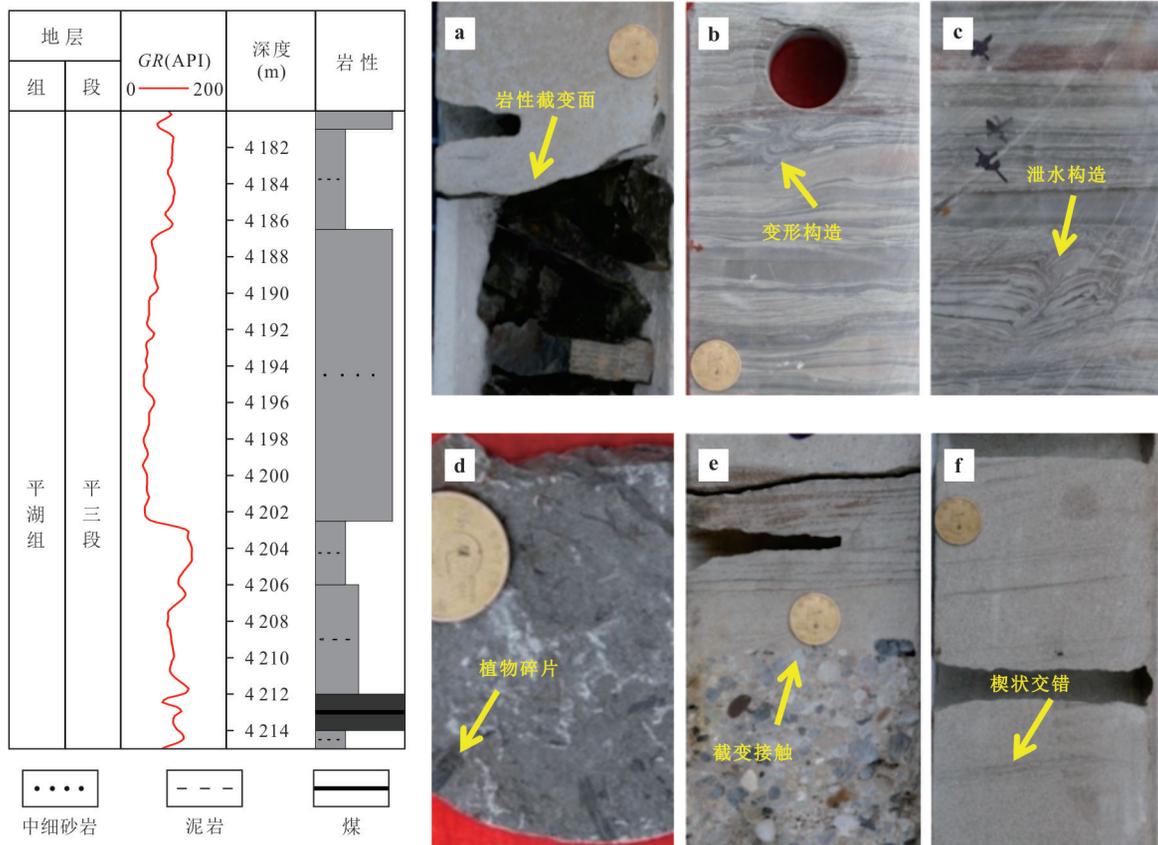


图 4 研究区水下分流河道微相储层岩心柱状图(A3井)

Fig. 4 Core histogram of underwater distributary channel (Well A3)

a. 4 202.75 m, 岩性截变面、冲刷面; b. 变形构造; c. 4 207.60 m, 泄水构造; d. 4 206.70 m, 植物碎片; e. 4 201.70 m, 截变接触、低角度交错; f. 4 201.40 m, 楔状交错层理

明显下降趋势,且碳酸盐胶结物含量均在潮道底部呈现高值.由此推断,碳酸盐胶结导致了潮道底部致密化,是潮道物性呈现非均质性的主要原因.

显微镜下同样能够观察到潮道物性的非均质特征(图8).潮道上部,颗粒以线接触方式排布,表明压实作用强,发育溶蚀孔隙,从溶蚀残余矿物具有长石的特征,表明孔隙是长石溶蚀后的产物;孔隙度达到21%,渗透率达到140 mD,表现出高孔高渗特征.潮道中部,颗粒以悬浮方式排布,表明压实作用弱,能够观测到长石溶蚀后的铸模孔,且碳酸盐晶体发育,偏光下无色透明、正交光为高级白,具自形菱形切面,证明为白云石,孔隙度降低到11%,渗透率降低到0.25 mD,表现出中孔低渗特征.潮道底部,颗粒仍然以悬浮方式排布,而白云石胶结物含量增加,孔隙不发育,表现出低孔低渗特征.研究表明:白云石胶结物可能来源有长石溶蚀、黏土矿物转化、碳酸盐岩岩屑溶蚀、铝硅酸盐矿物水化以及淡水混合效应等(Morad *et al.*, 2000).前4种来

源白云石均具有形成时期晚且含量低的特点,故淡水混合效应更符合显微镜下岩矿特征以及潮道海陆交互环境的地质背景.成岩序列表明,碳酸盐胶结物(白云石)形成时期早于压实时期,使得潮道底部迅速致密化,也阻碍了后期与流体之间的水岩作用,次生孔隙亦不发育.

4.2 水下分流河道微相

从物质基础来看,水下分流河道的原始矿物组成、沉积构造均表现出周期性特征(图4),指示了多期水下分流河道叠加的特征.同时,叠加的多期水下分流河道也具有周期性特征,单期水下分流河道自上到下物性降低,呈现上中部孔渗较高而底部致密的强非均质性特征.统计发现,高岭石含量与孔隙度、渗透率具有强负相关性(图9),随着高岭石的增加,储层物性具有明显下降趋势,且高岭石含量均在潮道底部呈现高值.由此推断,高岭石导致了水下分流河道底部致密化,是水下分流河道物性呈现非均质性的主要原因.

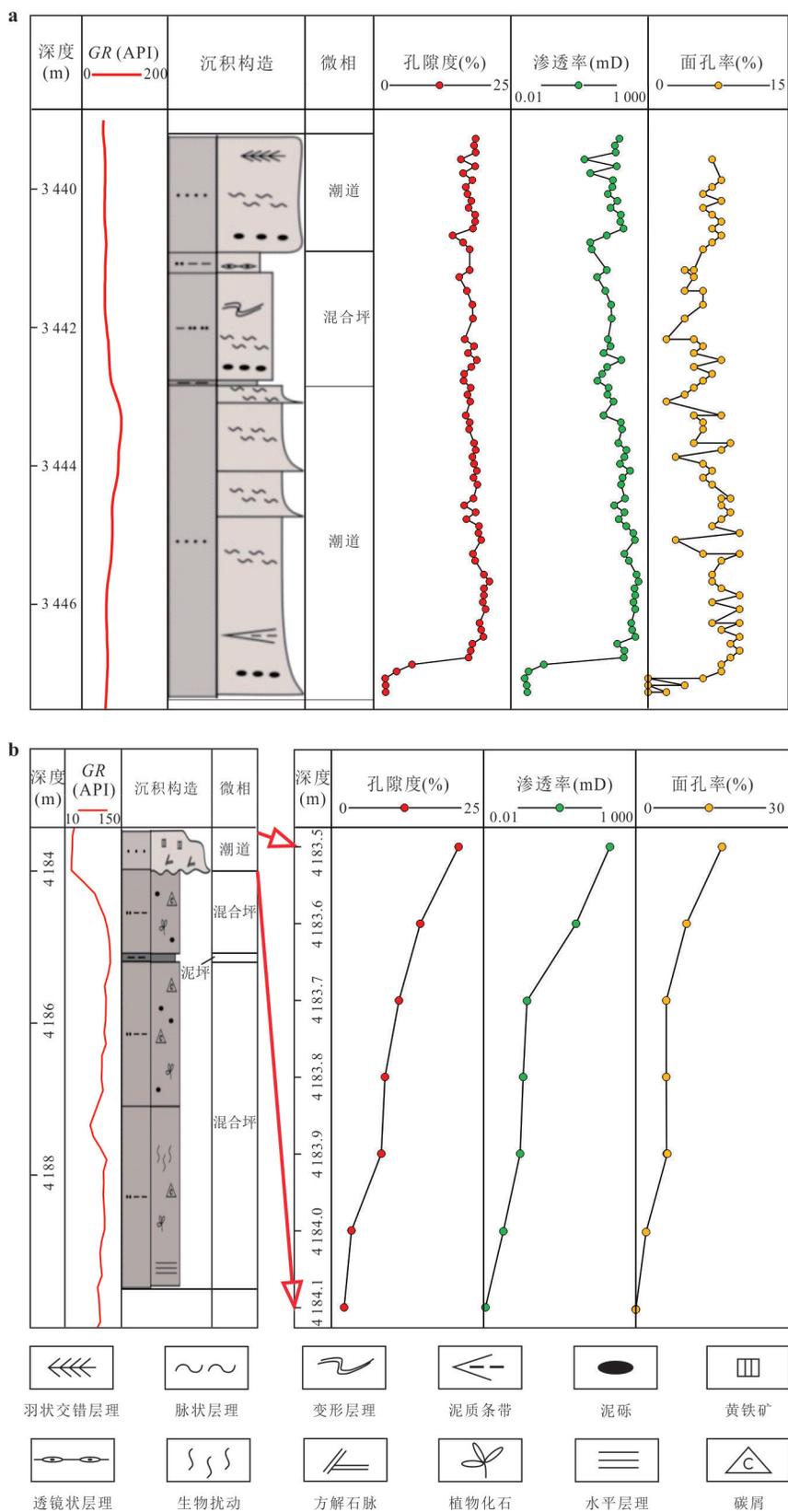


图 5 研究区潮道微相储层孔渗性随深度的变化规律

Fig. 5 Variation of porosity and permeability of tidal channel

a. A1 井, 3 439.19~3 447.38 m; b. A2 井, 潮道底部 0.50 m

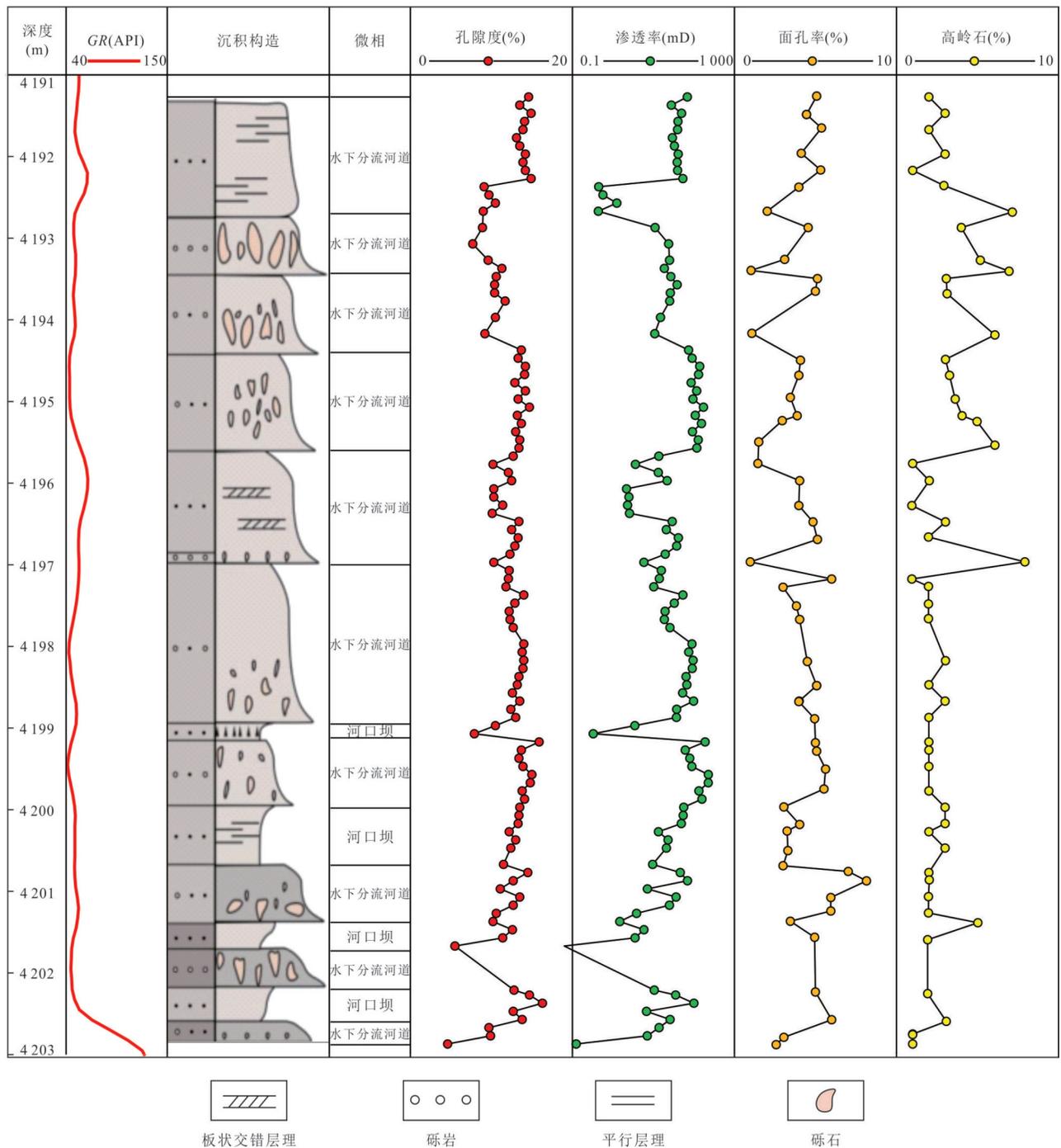


图6 研究区水下分流河道微相储层孔渗性随深度的变化规律
 Fig. 6 Variation of porosity and permeability of underwater distributary channel
 A3井, 4 191.27~4 202.87 m

显微镜下同样能够观察到水下分流河道物性的非均质特征(图 10). 水下分流河道中上部, 颗粒之间多以线接触方式为主、黏土矿物含量低、孔隙以溶蚀孔隙为主, 可见长石溶蚀残余、石英加大、碳酸盐胶结物. 水下分流河道底部, 颗粒多以悬浮方式接触, 颗粒间被黏土矿物充填, 通过光镜、电镜观

察判定, 黏土矿物主要为书页状/手风琴状的高岭石. 同时, 颗粒压实、溶蚀、胶结、次生加大等成岩现象均未有发现, 黏土矿物充填粒间孔隙的时期, 早于物理成岩和化学成岩, 阻止了颗粒的压实和水岩反应的发生, 是导致水下分流河道底部致密化的主要原因. 通过显微镜下岩矿特征可以看出, 高岭石

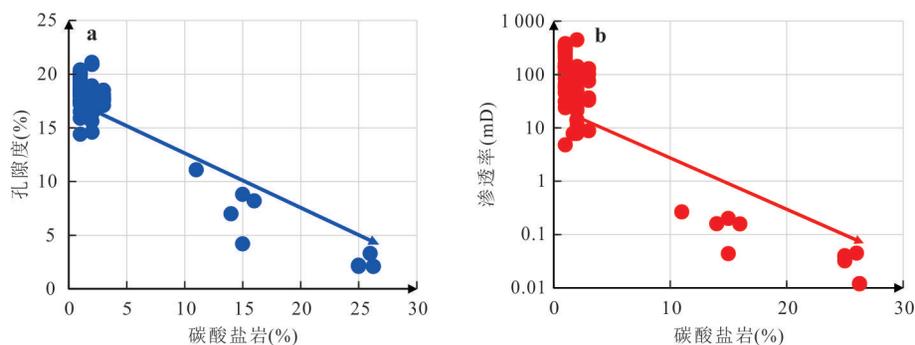


图 7 潮道碳酸盐胶结物与孔隙度相关性统计图(a)和碳酸盐胶结物与渗透率相关性统计图(b)

Fig. 7 Correlation between carbonate cement and porosity (a) and correlation between carbonate cement and permeability (b) in tidal channel

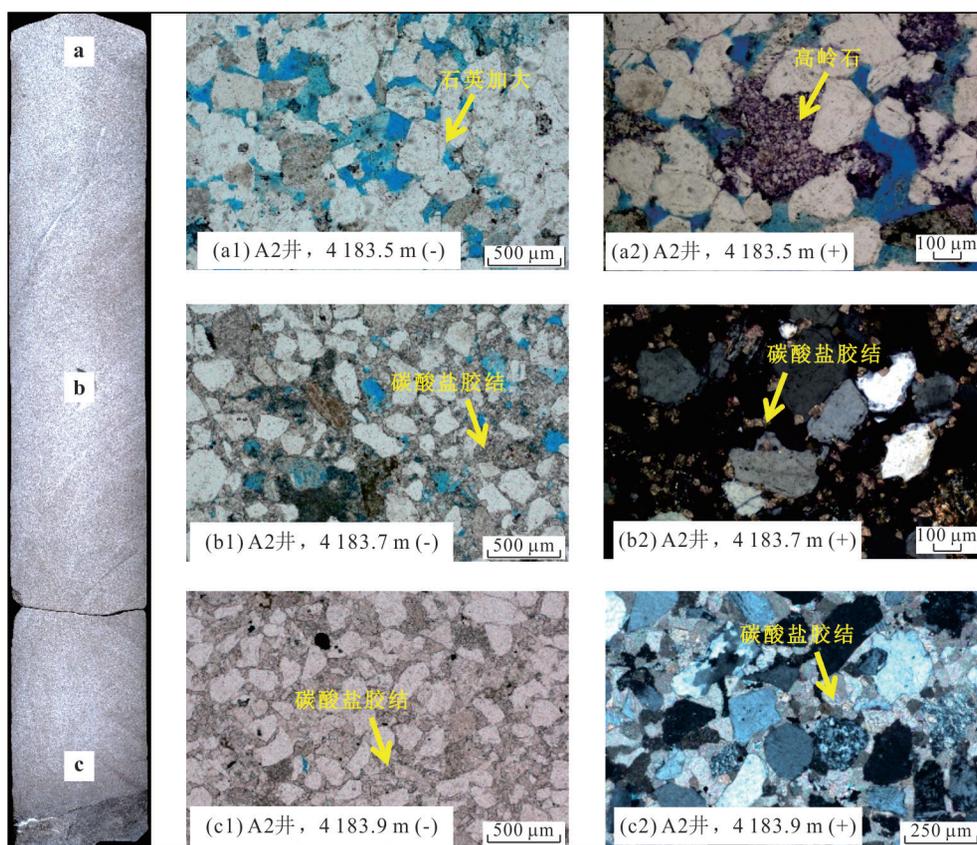


图 8 潮道微相储层矿物组成特征及孔隙类型

Fig. 8 Mineral composition characteristics and pore types of tidal channel

具有水下分流河道底部发育、孔隙充填形势产出、书页状/手风琴状晶型等特征,推测高岭石是水下分流河道沉积时期强水体下切早期沉积泥质而重结晶产物.

5 结论

中国东海西湖凹陷平湖组潮道和水下分流河道两种高能微相储层物性存在极强的非均质性,标

志着以优质沉积相带为有利预测目标的井位部署思路在深层勘探中并不适用,不能迎合深层碎屑岩储层地质复杂性和特殊性的需求,存在极大的预测风险.因此,本文针对潮道、水下分流河道 2 种优势微相开展研究.研究表明:潮道中上部物性好,孔隙度平均 18%、渗透率平均 120 mD,而潮道底部致密,孔隙度平均 4%、渗透率平均 0.05 mD,呈现非均质性的主要原因是碳酸盐胶结导致底部致密;水下分流河道中上部物性好,孔隙度平均 5%、渗透率平

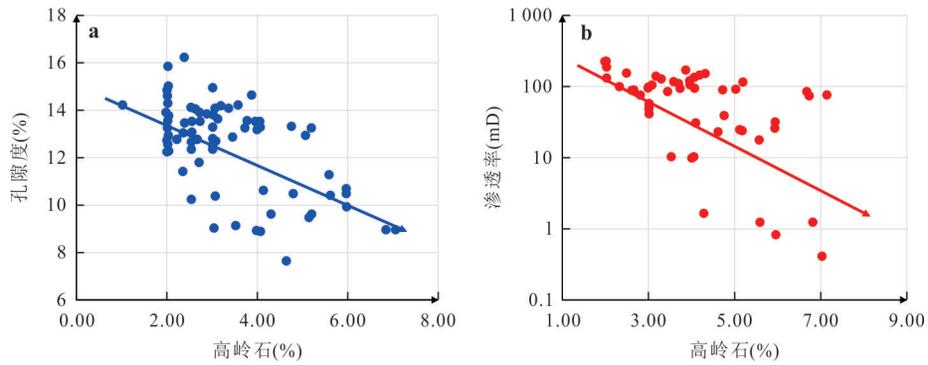


图 9 高岭石与孔隙度(a)和渗透率(b)相关性统计

Fig. 9 Correlation statistics of kaolinite with porosity (a) and permeability (b)
高岭石含量据 A3 井薄片统计

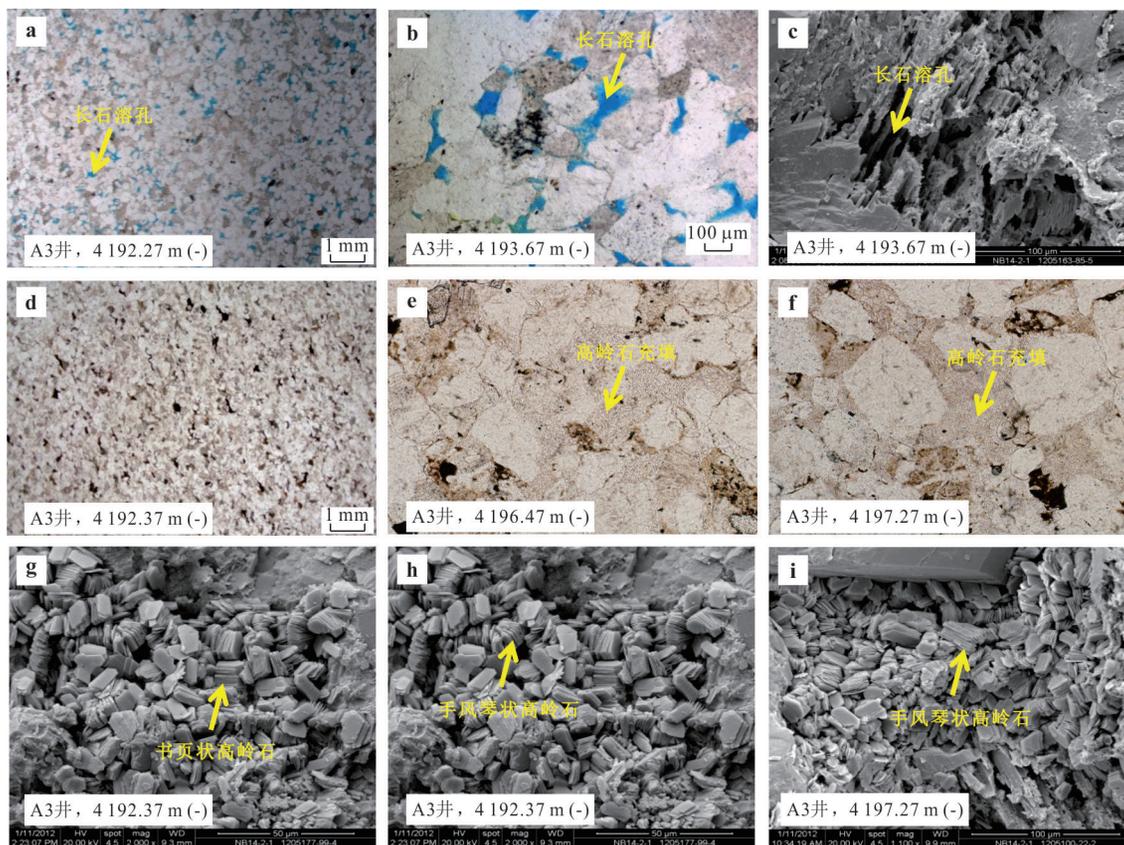


图 10 水下分流河道微相孔隙类型及矿物充填特征(A3 井)

Fig. 10 Pore types and mineral filling characteristics of underwater distributary channel (Well A3)

a~c. 河道上部高孔渗带:长石溶蚀孔,其中 b 为 a 局部放大;d~f. 河道底部低孔渗带:高岭石充填;g~i. 书页状、手风琴状高岭石形态特征

均 70 mD,而水下分流河道底部致密,孔隙度平均 1%、渗透率平均 0.01 mD,呈现非均质性的主要原因是高岭石充填导致底部致密.上述研究明确了西湖凹陷平湖组 2 种优势微相的非均质性成因,对深化河流—潮汐背景下储层非均质性规律及成因机制具有重要的理论指导意义;技术方法、研究成果可应用于东海盆地低渗砂岩储层油气勘探,对于中

国近海、国外区块的深层碎屑岩储层油气勘探亦具有重要推广借鉴意义.

References

Cao, Y.C., Yuan, G.H., Li, X.Y., et al., 2013. Types and Characteristics of Anomously High Porosity Zones in Paleogene Mid-Deep Buried Reservoirs in the Northern

- Slope, Dongying Sag. *Acta Petrolei Sinica*, 34(4): 683—691(in Chinese with English abstract).
- Feng, J.R., Gao, Z.Y., Cui, J.G., et al., 2016. The Exploration Status and Research Advances of Deep and Ultra-Deep Clastic Reservoirs. *Advances in Earth Science*, 31(7): 718—736(in Chinese with English abstract).
- Gao, W.Z., Yang, C.H., Zhao, H., 2015. Reservoir Formation and Modification Controlled by Thermal Events in the Xihu Sag, East China Sea Basin. *Petroleum Geology and Experiment*, 37(5): 548—554(in Chinese with English abstract).
- Gong, L., Gao, X. Z., Qu, F. T., et al., 2023. Reservoir Quality and Controlling Mechanism of the Upper Paleogene Fine-Grained Sandstones in Lacustrine Basin in the Hinterlands of Northern Qaidam Basin, NW China. *Journal of Earth Science*, 34(3): 806—823. <https://doi.org/10.1007/s12583-022-1701-6>
- Gu, H.R., Jia, J.Y., Ye, J.R., 2002. Characteristics of Oil and Gas Bearing System in Xihu Lake Depression in the East China Sea. *Oil & Gas Geology*, 23(3): 295—297, 306(in Chinese with English abstract).
- Hu, M.Y., Shen, J., Hu, D., 2013. Reservoir Characteristics and Its Main Controlling Factors of the Pinghu Formation in Pinghu Structural Belt, Xihu Depression. *Oil & Gas Geology*, 34(2): 185—191(in Chinese with English abstract).
- Hu, W.R., Bao, J.W., Hu, B., 2013. Trend and Progress in Global Oil and Gas Exploration. *Petroleum Exploration and Development*, 40(4): 409—413(in Chinese with English abstract).
- Jiang, H.J., Hu, M.Y., Hu, Z.G., et al., 2011. Sedimentary Environment of Paleogene in Xihu Sag: Microfossil as the Main Foundation. *Lithologic Reservoirs*, 23(1): 74—78 (in Chinese with English abstract).
- Jiang, P., Wang, Z.Z., Zou, M.S., et al., 2021. Development Characteristics of Carbonate Cement and Its Influence on Reservoir Quality in Sandstones from Zhuhai Formation in Wenchang A Depression. *Earth Science*, 46(2): 600—620(in Chinese with English abstract).
- Liu, J.S., Cao, B., Xu, Z.X., et al., 2012. Sedimentary Facies and the Characteristics of Tight Sandstone Reservoirs of Huagang Formation in Xihu Depression, East China Sea Basin. *Journal of Chengdu University of Technology (Science & Technology Edition)*, 39(2): 130—136(in Chinese with English abstract).
- Morad, S., Ketzer, J.M., De Ros, L.F., 2000. Spatial and Temporal of Diagenetic Alterations in Siliciclastic Rocks: Implications for Mass Transfer in Sedimentary Basins. *Sedimentology*, 47: 95—120.
- Pan, R., Zhu, X.M., Wang, X.X., et al., 2014. Advancement on Formation Mechanism of Deep Effective Clastic Reservoir. *Lithologic Reservoirs*, 26(4): 73—80(in Chinese with English abstract).
- Sun, L.D., Zou, C.N., Zhu, R.K., et al., 2013. Formation, Distribution and Potential of Deep Hydrocarbon Resources in China. *Petroleum Exploration and Development*, 40(6): 641—649(in Chinese with English abstract).
- Tong, X. G., Zhang, G. Y., Wang, Z. M., et al., 2014. Distribution and Potential of Global Oil and Gas Resources. *Earth Science Frontiers*, 21(3): 1—9(in Chinese with English abstract).
- Wu, K.Q., Xie, X.J., Liao, J.H., et al., 2023. The Rules of Reservoir Characteristics and Dissolution of Paleogene Clastic Rocks in Offshore China. *Earth Science*, 48(2): 385—397(in Chinese with English abstract).
- Wu, J.P., Zhang, L., Wan, L.F., et al., 2017. Provenance Analysis of Pinghu Formation in Xihu Sag. *China Petroleum Exploration*, 22(2): 50—57(in Chinese with English abstract).
- Xie, X.J., Xiong, L.Q., Chen, Y., et al., 2021. Low Permeability Reservoir Characteristics and Controlling Factors of “Sweet Points” of Pinghu Formation in Xihu Sag. *Science Technology and Engineering*, 21(30): 12890—12900(in Chinese with English abstract).
- Yang, H.J., Li, Y., Tang, Y.G., et al., 2019. Discovery of Kelasu Subsalt Deep Large Gas Field, Tarim Basin. *Xinjiang Petroleum Geology*, 40(1): 12—20(in Chinese with English abstract).
- Yang, W.X., Gui, L.L., Zhou, H., et al., 2023. Diagenesis and Accumulation Process of Silurian Sandstone Reservoir in Keping Area, Northwest Tarim Basin. *Earth Science*, 48(11): 4103—4116(in Chinese with English abstract).
- Yu, S., 2020. Depositional Genesis Analysis of Source Rock in Pinghu Formation of Western Slope, Xihu Depression. *Earth Science*, 45(5): 1722—1736(in Chinese with English abstract).
- Yu, X. H., Li, S.L., 2009. The Development and Hotspot Problems of Clastic Petroleum Reservoir Sedimentology. *Acta Sedimentologica Sinica*, 27(5): 880—895(in Chinese with English abstract).
- Zhang, G.C., Tian, B., Xie, X.J., et al., 2019. A Full-Life-Cycle Research Methodology of Deep High-Quality Clastic Rock Reservoir. *Acta Petrolei Sinica*, 40(S2): 13—28(in Chinese with English abstract).
- Zhang, K.X., Bai, G.P., Cao, B.F., et al., 2016. Geologi-

- cal Features of Siliciclastic Reservoirs in Deep Petroleum Accumulations. *Chinese Journal of Engineering*, 38(1): 1–10(in Chinese with English abstract).
- Zhang, L., Shu, Z.g., He, S., et al., 2021. Reservoir Characteristics and Differential Evolution Process of Xujiahe Formation in Jiannan Area, East Sichuan. *Earth Science*, 46(9): 3139–3156(in Chinese with English abstract).
- Zhong, D.K., Zhu, X.M., Wang, H.J., 2008. Reservoir Characteristics and Formation Mechanism of Deep High-Quality Clastic Rocks in China. *Science in China (Ser. D)*, 38(S1): 11–18(in Chinese).
- Zhou, X.H., Gao, S.L., Gao, W.Z., et al., 2019. Formation and Distribution of Marine-Continental Transitional Lithologic Reservoirs in Pingbei Slope Belt, Xihu Sag, East China Sea Shelf Basin. *China Petroleum Exploration*, 24(2): 153–164(in Chinese with English abstract).
- ### 中文参考文献
- 操应长, 远光辉, 李晓艳, 等, 2013. 东营凹陷北带古近系中深层异常高孔带类型及特征. *石油学报*, 34(4): 683–691.
- 冯佳睿, 高志勇, 崔京钢, 等, 2016. 深层、超深层碎屑岩储层勘探现状与研究进展. *地球科学进展*, 31(7): 718–736.
- 高伟中, 杨彩虹, 赵洪, 2015. 东海盆地西湖凹陷热事件对储层的改造及其机理探讨. *石油实验地质*, 37(5): 548–554.
- 顾惠荣, 贾健谊, 叶加仁, 2002. 东海西湖凹陷含油气系统特征. *石油与天然气地质*, 23(3): 295–297, 306.
- 胡明毅, 沈娇, 胡蝶, 2013. 西湖凹陷平湖构造带平湖组砂岩储层特征及其主控因素. *石油与天然气地质*, 34(2): 185–191.
- 胡文瑞, 鲍敬伟, 胡滨, 2013. 全球油气勘探进展与趋势. *石油勘探与开发*, 40(4): 409–413.
- 蒋海军, 胡明毅, 胡忠贵, 等, 2011. 西湖凹陷古近系沉积环境分析: 以微体古生物化石为主要依据. *岩性油气藏*, 23(1): 74–78.
- 姜平, 王珍珍, 邹明生, 等, 2021. 文昌 A 凹陷珠海组砂岩碳酸盐胶结物发育特征及其对储层质量的影响. *地球科学*, 46(2): 600–620.
- 刘金水, 曹冰, 徐志星, 等, 2012. 西湖凹陷某构造花港组沉积相及致密砂岩储层特征. *成都理工大学学报(自然科学版)*, 39(2): 130–136.
- 潘荣, 朱筱敏, 王星星, 等, 2014. 深层有效碎屑岩储层形成机理研究进展. *岩性油气藏*, 26(4): 73–80.
- 孙龙德, 邹才能, 朱如凯, 等, 2013. 中国深层油气形成、分布与潜力分析. *石油勘探与开发*, 40(6): 641–649.
- 童晓光, 张光亚, 王兆明, 等, 2014. 全球油气资源潜力与分布. *地学前缘*, 21(3): 1–9.
- 吴嘉鹏, 张兰, 万丽芬, 等, 2017. 西湖凹陷平湖组物源分析. *中国石油勘探*, 22(2): 50–57.
- 吴克强, 谢晓军, 廖计华, 等, 2023. 中国近海古近纪碎屑岩储层特征与溶蚀作用规律. *地球科学*, 48(2): 385–397.
- 谢晓军, 熊连桥, 陈莹, 等, 2021. 西湖凹陷平湖组低渗储层特征及“甜点”主控因素分析. *科学技术与工程*, 21(30): 12890–12900.
- 杨海军, 李勇, 唐雁刚, 等, 2019. 塔里木盆地克拉苏盐下深层大气田的发现. *新疆石油地质*, 40(1): 12–20.
- 杨文霞, 桂丽黎, 周慧, 等, 2023. 塔里木盆地柯坪地区志留系砂岩储层成岩与成藏过程. *地球科学*, 48(11): 4103–4116.
- 于水, 2020. 西湖凹陷西斜坡平湖组烃源岩沉积成因分析. *地球科学*, 45(5): 1722–1736.
- 于兴河, 李胜利, 2009. 碎屑岩系油气储层沉积学的发展历程与热点问题思考. *沉积学报*, 27(5): 880–895.
- 张功成, 田兵, 谢晓军, 等, 2019. 深层优质碎屑岩储层全生命周期分析方法论. *石油学报*, 40(增刊2): 13–28.
- 张凯逊, 白国平, 曹斌风, 等, 2016. 深层碎屑岩含油气储层发育特征. *工程科学学报*, 38(1): 1–10.
- 张莉, 舒志国, 何生, 等, 2021. 川东建南地区须家河组储层特征及其差异演化过程. *地球科学*, 46(9): 3139–3156.
- 钟大康, 朱筱敏, 王红军, 2008. 中国深层优质碎屑岩储层特征与形成机理分析. *中国科学(D辑)*, 38(S1): 11–18.
- 周心怀, 高顺莉, 高伟中, 等, 2019. 东海陆架盆地西湖凹陷平北斜坡带海陆过渡型岩性油气藏形成与分布预测. *中国石油勘探*, 24(2): 153–164.