

陆相富碳酸盐页岩纹层组合对页岩油富集的控制作用

——以渤海湾盆地济阳坳陷古近系沙河街组页岩为例

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摘要:陆相页岩油勘探已取得突破,但页岩油富集高产的主控地质因素尚不清晰,制约着页岩油的高效开发。精细刻画不同纹层特征可揭示页岩油富集主控因素。本文以济阳坳陷古近系沙河街组富碳酸盐页岩为研究对象,通过薄片鉴定和场发射扫描电镜观察,剖析了典型纹层储集空间和含油性的特征,揭示了页岩纹层组合对页岩油富集的控制作用。研究发现,济阳坳陷沙河街组四段上亚段富碳酸盐页岩的纹层可划分为纤维状方解石纹层、泥晶方解石纹层、粉晶方解石纹层、富黏土矿物纹层和混合矿物纹层5种类型,主要发育“泥晶方解石纹层+富黏土矿物纹层+混合矿物纹层”和“纤维状方解石纹层+粉晶方解石纹层+富黏土矿物纹层+混合矿物纹层”2种纹层组合模式;富黏土矿物纹层和混合矿物纹层有机质含量高,是页岩油富集的物质基础;粉晶方解石纹层储集空间发育,是页岩油储集的优势纹层;富黏土矿物纹层与粉晶方解石纹层或泥晶方解石纹层叠置分布,可构成页岩油富集的最佳纹层配置,该类纹层组合的富碳酸盐页岩是页岩油勘探开发的重要目标。

关键词:富碳酸盐页岩;纹层组合;富集因素;页岩油;沙河街组;济阳坳陷;渤海湾盆地

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Controlling effects of lamina assemblages on shale oil enrichment for lacustrine carbonate-rich shales: A case study of shales in the Paleogene Shahejie Formation, Jiyang Depression, Bohai Bay Basin

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Abstract: Breakthroughs have been achieved in the exploration of lacustrine shale oil. However, the dominant geological factors controlling the enrichment and high yield of shale oil remain unclear, restricting its efficient exploitation. The fine characterization of various laminae can reveal the major factors controlling shale oil enrichment. This study focuses on the carbonate-rich shales of the Paleogene Shahejie Formation in the Jiyang Depression. Using thin section observations and field emission scanning electron microscopy (FE-SEM), we analyze the reservoir spaces and oil-bearing properties of typical laminae and reveal the controlling effects of the lamina assemblages of shales on oil enrichment. The results indicate that carbonate-rich shales in the upper sub-member of the 4th member of the Shahejie Formation (Es_4^u) within the Jiyang Depression contain five lamina types: fibrous calcite laminae, micritic calcite laminae, very fine crystalline calcite laminae, clay-mineral-rich laminae, and mixed laminae. Major lamina assemblages include the combination of micritic calcite laminae, clay-mineral-rich laminae, and mixed laminae, and

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the combination of fibrous calcite laminae, very fine crystalline calcite laminae, clay-mineral-rich laminae, and mixed laminae. The clay-mineral-rich and mixed laminae, among others, exhibit high organic matter content, serving as the material basis for shale oil enrichment. Meanwhile, the very fine crystalline calcite laminae, with well-developed reservoir spaces, act as preferential storage media for shale oil. Additionally, the superposition of clay-mineral-rich laminae with very fine crystalline or micritic calcite laminae forms the optimal lamina configuration for shale oil enrichment. Therefore, the carbonate-rich shales with the clay-mineral-rich laminae and very fine crystalline or micritic calcite laminae assemblage serve as an important target for shale oil exploration and exploitation.

Key words: carbonate-rich shale, lamina assemblage, enrichment factor, shale oil, Shahejie Formation, Jiyang Depression, Bohai Bay Basin

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中国丰富的陆相页岩油资源是重要的石油接替能源之一,目前已在多个盆地(如渤海湾、松辽、准噶尔和鄂尔多斯等盆地)重点层段开展了页岩油勘探与试采实践^[1-4],获得了重要突破,展示了陆相页岩油良好的发展前景。然而,中国页岩油的研究起步相对较晚,相较于北美海相页岩,中国陆相页岩存在沉积类型多样、矿物组成复杂和成熟度低等不利因素^[5],给页岩油勘探开发带来了巨大挑战。济阳页岩油经过50余年的探索,已在渤南、博兴、牛庄、民丰和利津等多个洼陷的古近系沙河街组四段上亚段(沙四上亚段)与沙河街组三段下亚段(沙三下亚段)取得产能突破^[6-8],并成功建立了陆相断陷湖盆页岩油国家级示范区。尽管济阳页岩油已取得战略性突破,高产井频现,但不同突破井之间产量差异较大,页岩油富集高产的主控地质因素还不明确,制约着济阳页岩油的高质量勘探。

页岩油能否富集高产与页岩储集空间、页岩油赋存状态和流动特征以及页岩油储层的可压裂性密切相关^[2, 9-10]。常用的研究方法是将页岩划分为不同类型岩相,分析不同岩相的物性、含油性、可动性和可压裂性等影响因素,确定有利岩相,指导页岩油勘探和开发,该方法在页岩油甜点区选取过程中被广泛应用^[11-12]。但随着勘探开发的不断推进,发现甜点区段不同位置产量存在差异,因此进一步精细评价是非常有必要的。前人研究认为影响页岩油富集的因素包括有机质的类型和丰度、热演化程度、无机矿物组分和微观孔隙结构等^[13-16]。在局部甜点区段,有机质的类型和丰度以及热演化程度的差异较小,而在无机组分和微观孔隙结构极强的非均质性的直接影响下,页岩微纳尺度孔隙中的烃类以不同的状态赋存和流动^[9]。因此,页岩的岩石组分和孔隙结

构特征研究,是页岩油富集评价的重要基础。

纹层作为最小的沉积单元^[17],不仅能够反映页岩储集层的微观结构特征和储集性能,更能揭示页岩储集层改造过程中压裂缝网的扩展规律及压裂效果^[18]。纹层的形成与沉积速率、沉积间断、物质供给和流态转换密切相关,通常是单一水流或沉积事件在几秒到几年的“地质时间的瞬间”形成的^[19-20]。不同成因纹层的物质组成(有机质和无机矿物)和微观孔隙结构(孔隙大小、孔隙形态和连通性等)存在差异。海相纹层形成的沉积环境相对稳定,通常为缺氧环境,主要受到平面波动、海洋流动和水体化学环境的控制^[21-22]。管全中等^[18]通过薄片观察、X射线衍射分析和古环境参数定量表征,将四川盆地五峰组–龙马溪组一段页岩纹层划分为硅质纹层、钙质纹层、黏土质纹层和有机质纹层4类。陆相湖盆沉积环境复杂,通常受到陆地气候变化和水文条件的影响。气候变化主要表现为干旱、湿润交替和季节性降水变化等,这导致沉积物的颗粒组成和沉积速率进行周期性波动^[20-23]。例如,松辽盆地青山口组为淡水湖,以陆源沉积为主,而渤海湾盆地沙河街组的半咸水–盐湖则利于碳酸盐沉淀^[24-25];在靠近物源的浅湖–半深湖区颗粒较粗,而远离物源的深湖区沉积环境稳定,颗粒较细^[20, 26];生物在温度较低的季节死亡会形成有机质纹层^[27]。王鑫等^[28]通过微区取样精细评价了古龙凹陷青山口组一段页岩不同纹层的储集性和含油性特征,发现相较于方解石纹层和长英质纹层,黏土矿物纹层具有更大的孔隙体积和孔隙比表面积,有机质含量高的纹层更有利于油气生成。陆相页岩通常是由多种纹层相互叠置,以纹层组合的形式呈现,可通过研究纹层中岩石组分特征、微观孔隙结构和烃类分布特征,

明确不同纹层在页岩油富集过程中的“角色”,结合纹层之间的叠合关系,确定有利于页岩油富集的纹层组合。

复杂的沉积环境和多样的物质来源形成了不同的陆相页岩类型,包括富长英质型、富黏土质型、富碳酸盐型和混合质型^[7]。济阳坳陷古近系沙河街组发育典型的富碳酸盐页岩,本次研究通过普通薄片观察、荧光薄片鉴定和场发射扫描电镜等多种实验手段,精细表征沙河街组富碳酸盐页岩不同纹层岩石组分、储集空间和孔隙流体特征以及典型的纹层组合,揭示富碳酸盐页岩中纹层对页岩油富集的控制作用,为济阳坳陷页岩油增储上产提供指导。

1 地质概况

济阳坳陷位于渤海湾盆地南部(图1a),是渤海湾盆地的次级构造单元,由惠民、东营、沾化和车镇等凹陷以

及陈家庄等位于凹陷间的隆起组成,西至埕宁隆起,北邻埕子口隆起,东接垦东隆起,南部为鲁西和广饶隆起(图1b),面积约为 $2.5 \times 10^4 \text{ km}^2$ ^[29-31]。济阳坳陷整体表现为由多个次一级北断-南超的半地堑凹陷组成,其内的凸起构造呈近北东向排列,单个隆起构造呈东西向展布,东西向构造为东营凹陷的主体构造方向,西部凹陷则为北东向展布^[32]。济阳坳陷发育古生代、中生代和新生代地层,主要经历古近纪裂陷期与新近纪拗陷期2个演化阶段,自下而上发育古近系孔店组(Ek)、沙河街组(Es)和东营组(Ed),新近系馆陶组(Ng)和明化镇组(Nm)以及第四系(Q)(图1c)^[33]。古近系发育沙三下亚段和沙四上亚段2套主力烃源岩,具有分布广、厚度大和有机质丰度高等特点,沉积环境为浅湖-半深湖相,二者有机质类型均为I型(总有机碳含量TOC介于1%~5%),沙四上亚段厚度稍薄,一般介于50~350 m,沙三下亚段烃源岩厚度一般在100~400 m,岩

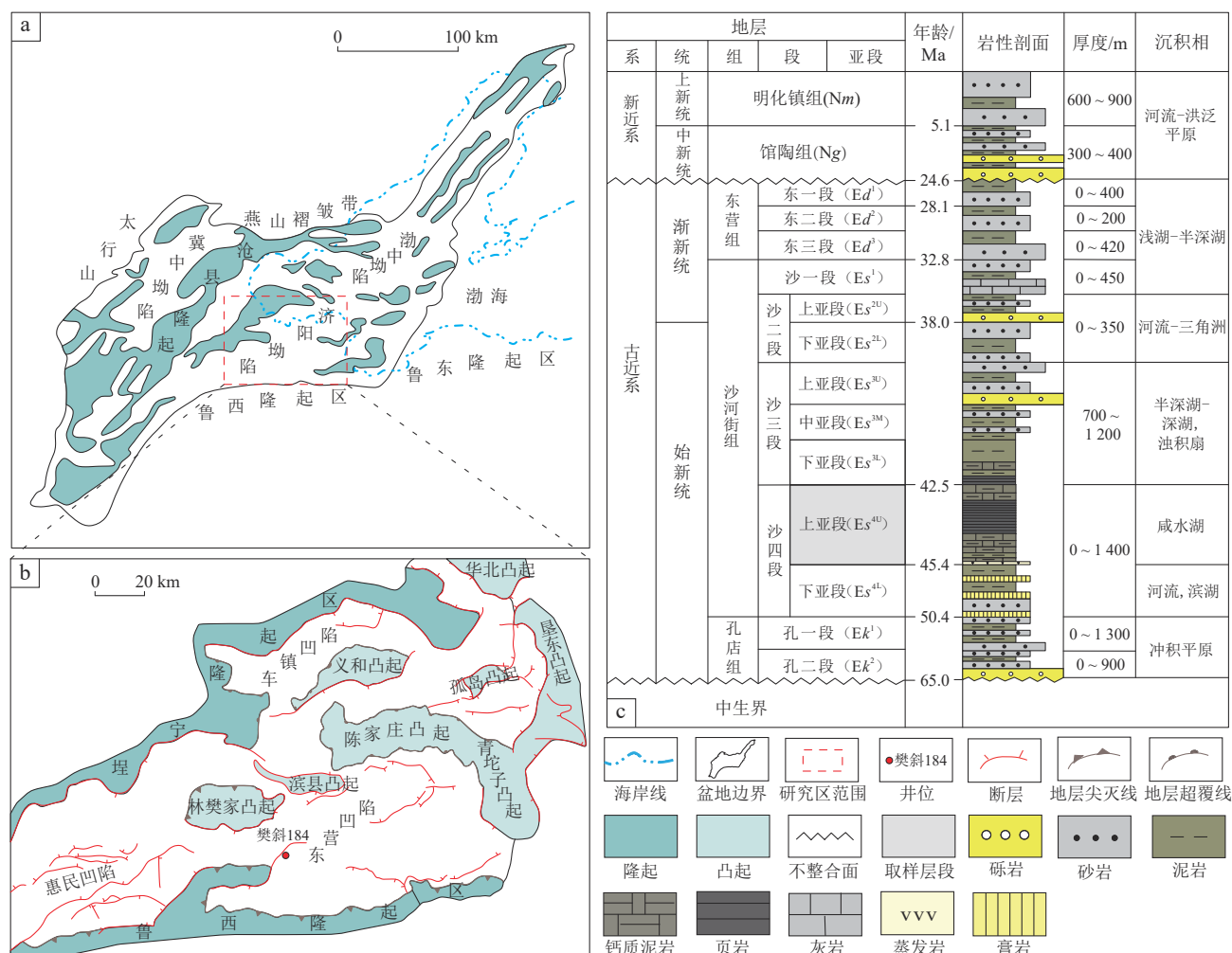


Fig. 1 Structural unit division and composite stratigraphic column of the Jiyang Depression, Bohai Bay Basin^[29,31]

a. 渤海湾盆地构造位置;b. 济阳坳陷构造单元划分;c. 济阳坳陷地层综合柱状图

相均以富有机质纹层状泥质灰岩和富有机质纹层状灰质泥岩为主,为页岩油勘探的有利靶区^[34-36]。

本次研究页岩样品取自济阳坳陷的樊斜184井,层位为沙(沙河街组)四段(图1)。

2 纹层划分

纹层是沉积物中肉眼可见的最小或最薄的原始沉积层^[37]。前人研究表明,单一纹层的结构和成分较为均一,但不同纹层和不同纹层组合之间的孔隙结构存在较大差异^[7, 38-40]。对东营凹陷出油井的统计结果显示,页岩油气主要产自富有机质纹层状岩相中,该类岩相占出油井段的70%左右^[36]。对工区纹层进行精细和有效的划分是刻画页岩储层及含油性的必要措施。通过结合前人对工区基础层的研究以及对樊斜184井6块岩心的薄片观察,首先依据矿物组分将富碳酸盐页岩的纹层划分为富黏土矿物纹层、富碳酸盐矿物纹层和混合矿物纹层;同时考虑到济阳坳陷沙河街组碳酸盐矿物产状、形态和结构等方面的差异,将富碳酸盐矿物纹层类型进一步划分为,纤维状方解石纹层、泥晶方解石纹层和粉晶方解石纹层等,白云石纹层在本次观察中极少见到,不作为本次讨论的主要对象。事实上,岩石的组分和粒径在成岩过程中具有一定的联系。具体表现为:富黏土矿物纹层和泥晶方解石纹层中矿物颗粒多为泥级;粉晶方解石纹层中矿物颗粒较粗,相对发育的岩石骨架可有效保障储集空间的发育;混合矿物纹层中矿物颗粒在成分和粒径上均呈现出较强的非均质性。

2.1 纤维状方解石纹层

前人对济阳坳陷富碳酸盐纹层成因做了大量研究,纤维状方解石纹层的形成过程反映了页岩中地层流体信息和水-岩作用特征^[41-42]。在有机质热演化成熟阶段,有机酸排出并溶解了页岩中的泥晶方解石,形成了富碳酸盐的流体^[43],在地层压力作用下,流体沿层理缝运移,并在一定条件下,方解石析出并结晶。

纤维状方解石纹层在显微镜下主要以脉状产出,不同纤维状方解石脉厚度变化较大,较厚层可达2.00 mm,在岩石薄片中具有明显的识别特征(图2a),较薄层厚度小于0.10 mm,平均厚度在0.20 mm。单条方解石脉多呈长条状和透镜状,薄片下观察呈干净的亮白色,不切穿层理。在研究区页岩中共识别出了2种形态的纤维状方解石,分别为单向生长方解石脉和双向生长方解石脉。单向生长方解石脉是富碳酸盐流体在层理缝中从一侧向另一侧连续结晶生长而成^[44],脉体中纤维状晶体连续性极好(图2b—e)。双向生长方解石脉为富碳酸盐流体在层理缝中背向或相向连续生长,往往会在脉体中间形成“中间线”(图2f),“中间线”主要成分为围岩组分^[45]。双向生长的纤维状方解石脉发育“叠锥状”交错接触带或未完全充填的孔-缝体系(图2c, g)。

2.2 泥晶方解石纹层

泥晶方解石纹层厚0.26~0.62 mm,常与富黏土矿物纹层互层或呈透镜状分散在富黏土矿物纹层中

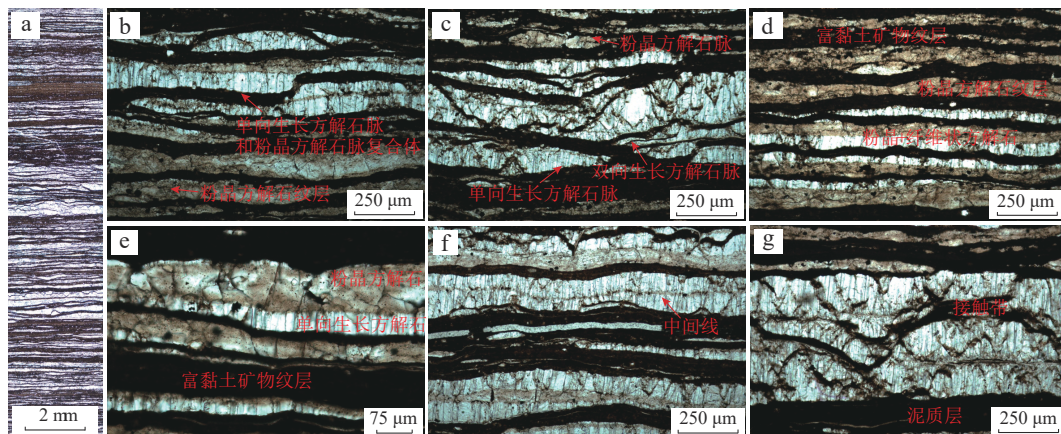


图2 济阳坳陷樊斜184井沙四上亚段页岩纤维状方解石脉产状特征单偏光普通薄片显微照片(埋深3 529.34 m)

Fig. 2 Thin-section micrographs under plane-polarized light showing the occurrence characteristics of fibrous calcite veins in the Es^{4U} shales in well FX184, Jiyang Depression

a. 纤维状方解石脉;b. 单向生长方解石脉和粉晶方解石脉复合体;c. 多种纤维状方解石的混合;d. 纤维状方解石与粉晶方解石的复合体;e. 纤维状方解石与粉晶方解石的复合体;f. 双向生长的纤维状方解石脉,脉体中间发育较为平直的中间线;g. 双向生长的纤维状方解石脉,脉体中间发育“叠锥状”交错接触带

(图3),是济阳坳陷页岩富碳酸盐纹层中发育规模最大的纹层,是碳酸盐矿物最主要的赋存形式。泥晶方解石的发育有多种成因,其中主要包括气候影响(干旱-半干旱易发育)、水体盐度浓缩沉积和生物化学沉积^[7]。脉体表面因黏土矿物的附着略显污浊,呈灰黄色(图3a,b)。泥晶方解石纹层发育脉体和透镜体2种形态,脉状泥晶方解石形态较为平直、横向连续性好,透镜状泥晶方解石大小差异较大(图3c)。局部与脉状泥晶方解石混合发育,反应动荡的水体环境(图3d),大多情况下,泥晶方解石透镜体堆积发育。泥晶方解石纹层晶粒粒度一般小于4 μm ,为泥晶或微晶结构(图3d),薄片镜下不易观察。泥晶方解石纹层的形态特征通常能够反映其形成时的水体环境,纹层越平直,水体环境越安静。泥晶方解石纹层发育的层段通常有机质丰度较高^[46],能够在纹层周围发现生物碎屑(图3e)。泥晶方解石矿物组成以泥晶方解石颗

粒为主,含有少量的石英和长石等矿物,发育较小的晶间孔(图3f)。

2.3 粉晶方解石纹层

粉晶方解石纹层厚0.15~0.17 mm,是页岩中泥晶方解石经过溶解作用和交代重结晶作用后形成的产物。其与纤维状方解石的异地重结晶不同的是,粉晶方解石基本继承了原始纹层的沉积形态(图4a),显微镜下方解石晶粒呈灰黄色,多为细-粉晶,少数可呈中晶(图4b)。部分粉晶方解石由于重结晶程度不均匀,会出现一部分重结晶成细-粉晶,另一部分仍然保持泥晶方解石的状态(图4c)。显微镜下观察发现,大部分粉晶方解石脉会发育较好的孔隙空间,且孔隙连通性好。部分重结晶程度较高的粉晶方解石脉体致密且横向连续性好,常与纤维状方解石脉复合出现(图2e,f)。

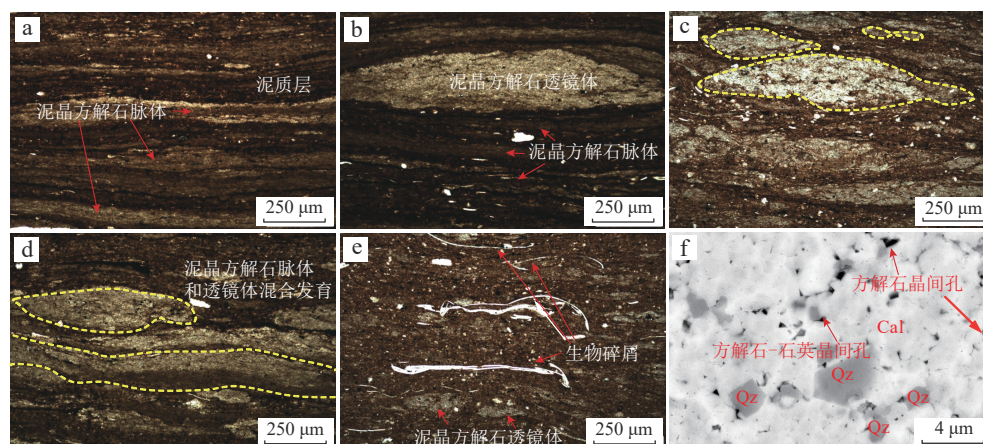


图3 济阳坳陷樊斜184井沙四上亚段页岩泥晶方解石纹层产状特征显微照片

Fig. 3 Micrographs showing occurrence characteristics of micritic calcite laminae in the Es^{4U} shales in well FX184, Jiyang Depression

a. 泥晶方解石纹层与富黏土矿物纹层的互层,泥晶方解石纹层呈灰黄色,与黏土层渐变接触,埋深3 550.35 m,单偏光,普通薄片;b. 透镜状泥晶方解石顺层发育在泥质纹层中,埋深3 550.35 m,单偏光,普通薄片;c. 堆积发育的泥晶方解石透镜体,埋深3 568.85 m,单偏光,普通薄片;d. 泥晶方解石透镜体与脉体混合发育,埋深3 550.35 m,单偏光,普通薄片;e. 泥晶方解石透镜体发育在富黏土矿物纹层中,层内可见较多的生物碎屑,埋深3 568.85 m,单偏光,普通薄片;f. 泥晶方解石矿物组成特征,埋深3 550.35 m,扫描电镜(Cal为方解石,Qz为石英)

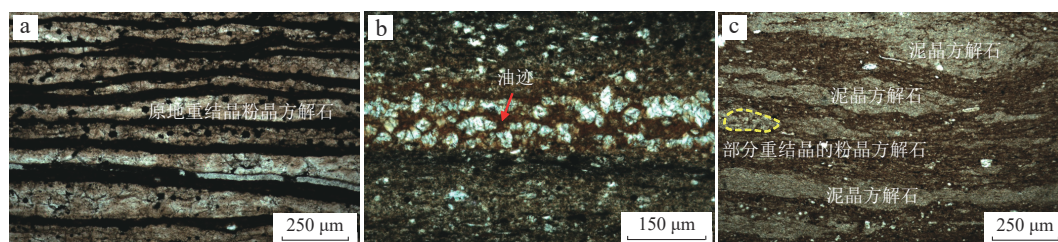


图4 济阳坳陷樊斜184井沙四上亚段页岩粉晶方解石纹层产状特征单偏光普通薄片显微照片

Fig. 4 Thin-section micrographs under plane-polarized light showing the occurrence characteristics of very fine crystalline calcite laminae in the Es^{4U} shales in well FX184, Jiyang Depression

a. 原地重结晶粉晶方解石脉,脉体因黏土矿物附着略显污浊,横向连续发育,埋深3 529.34 m;b. 粉晶方解石脉,晶型明显,脉体连通性好,可见油气运移痕迹,埋深3 667.60 m;c. 泥晶方解石部分重结晶形成的粉晶方解石颗粒,埋深3 553.50 m

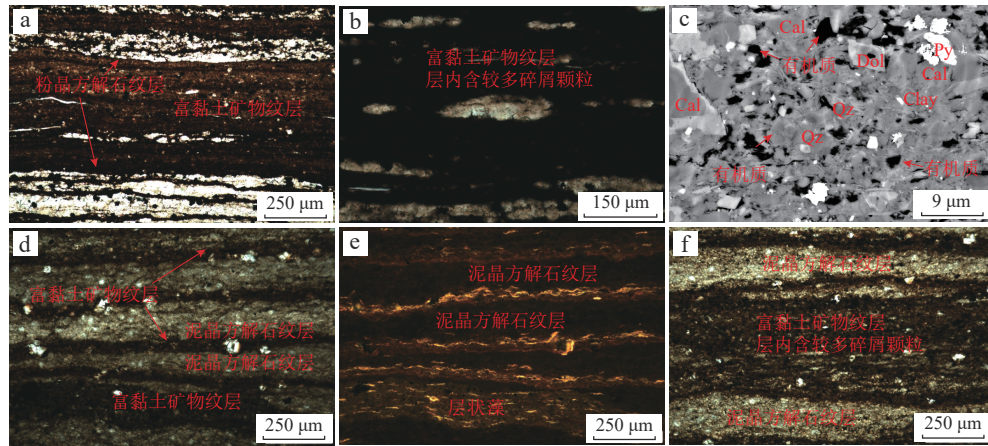


图5 济阳坳陷樊斜184井沙四上亚段页岩富黏土矿物纹层产状特征显微照片

Fig. 5 Micrographs showing the occurrence characteristics of clay-mineral-rich laminae in the Es^{4u} shales in well FX184, Jiyang Depression
a. 较纯的富黏土矿物纹层,含碎屑颗粒少,纹层表面平整,埋深3 529.34 m,单偏光,普通薄片;b. 含透镜体的富黏土矿物纹层,透镜体顺层发育,埋深3 529.34 m,单偏光,普通薄片;c. 富黏土矿物纹层矿物组成特征,大量有机质充填,埋深3 529.34 m,扫描电镜(Cal为方解石,Qz为石英,Dol为白云石,Py为黄铁矿,Clay为黏土矿物);d. 与泥晶方解石脉互层的富黏土矿物纹层,埋深3 358.20 m,单偏光,普通薄片;e. 富黏土矿物纹层中发育大量的层状藻,埋深3 358.20 m,荧光(与d图同视域),普通薄片;f. 碎屑颗粒含量较高的泥质层,受有机质含量影响,颜色较纯泥质层变淡,埋深3 358.20 m,单偏光,普通薄片

2.4 富黏土矿物纹层

页岩中富黏土矿物纹层主要与沉积环境、物质来源、沉积动力学条件和成岩过程有关^[47]。富黏土矿物纹层是黏土矿物与碎屑颗粒的组合物,以黏土矿物为主要矿物组分,含有碳酸盐、长英质和少量黄铁矿等其他矿物颗粒。黏土矿物多与有机质共同沉积,易形成黏土矿物-有机质复合体。在后期热演化过程中,黏土矿物-有机质复合体作为优势生烃纹层,黏土矿物进一步促进有机质生烃^[48-49]。富黏土矿物纹层有机质含量较高,镜下通常呈褐色或黑色(图5a,b),常以富碳酸盐纹层之间的夹层或与富碳酸盐纹层互层存在(图2f,图3a,图4a,图5a)。富黏土矿物纹层厚度大多为0.24~1.23 mm,而黏土矿物含量高的厚度可达3.25 mm,碎屑矿物颗粒粒径介于2~10 μm(图5c),属于泥级颗粒,难以通过肉眼区分。当碎屑颗粒含量较低时,纹层表面较为平整,与上、下围岩交接清晰(图5d),层内可见顺层分布的油迹残余(图5e)。当碎屑颗粒大量发育时,通常会以颗粒状随机分布或以小型透镜体状顺层分布在富黏土矿物纹层中,纹层表面凹凸不平(图5f)。富黏土矿物纹层是有机质的主要载体(图5c,e),具有大量生烃的基础,生烃潜力大,是工区重要的生油层。

2.5 混合矿物纹层

页岩中的混合矿物纹层是由多种沉积成因机制共

同作用形成的,包括沉积环境的波动、物质来源的差异、沉积动力条件的变化以及成岩过程中的矿物转化等^[10]。混合矿物纹层通常表现为不同成分物质(如黏土矿物、碳酸盐矿物、石英、长石和有机质等)的交替沉积,这反映了沉积环境的不稳定性和周期性或多来源物质输入的特点^[50-52]。混合矿物纹层相较于富黏土矿物纹层具有更高的长英质和碳酸盐矿物含量,黏土矿物含量较低,不同矿物颗粒大小均匀,无明显的层状特征。不同沉积期次的混合矿物纹层在组分上略有差异,镜下可见矿物颗粒大小有所区分(图6a)。混合矿物纹层较其他纹层厚度差异较大,单层厚度可达2 cm以上,既能以互层或夹层形式发育,也能够单独成层。显微镜下观察混合矿物纹层可见其岩性较为均一(图6),颜色受有机质含量影响,从棕色到深褐色均有发育,层内常见生物碎屑,具备一定的生烃能力。

3 不同纹层储集空间及含油性特征

页岩中不同类型纹层的孔隙组合特征受其沉积环境、矿物组成、微观结构和成岩作用的影响。纹层作为页岩中常见的沉积构造,其不同类型往往反映了不同的沉积动力学条件,而这些条件又决定了孔隙结构的发育情况和含油性特征。

3.1 纤维状方解石纹层

纤维状方解石形成过程中存在排他性,不包含生

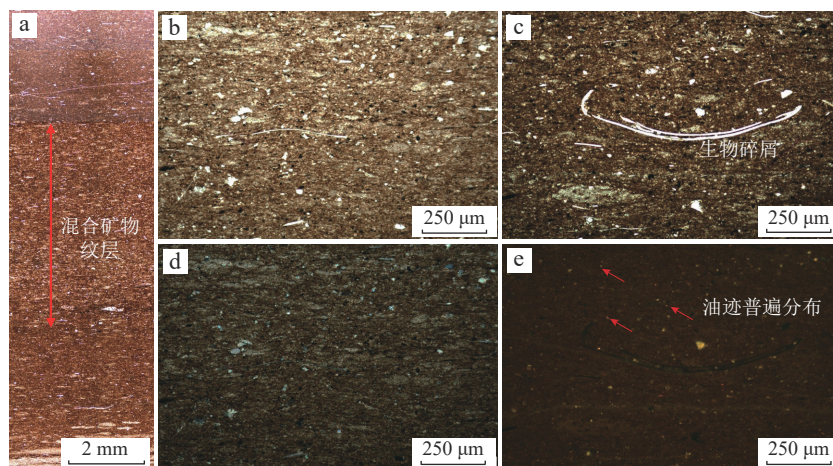


图6 济阳坳陷樊斜184井沙四上亚段页岩混合矿物纹层产状特征普通薄片显微照片(埋深3 553.50 m)

Fig. 6 Thin-section micrographs showing the occurrence characteristics of mixed laminae in the Es^{4U} shales in well FX184, Jiyang Depression

- a. 岩性均一,无明显层状特征,单偏光;b. 碳酸盐矿物和长英质矿物随机均匀分布,颗粒大小较为均一,单偏光;c. 含生物碎屑,单偏光;d. 正交光(与b图同视域);e. 含油迹,荧光(与c图同视域)

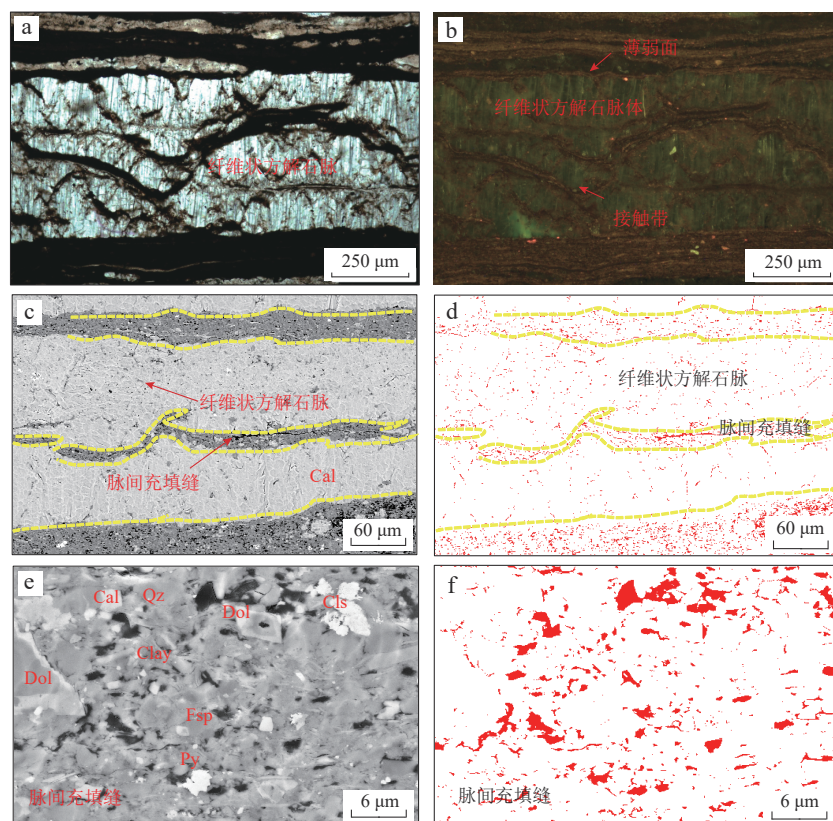


图7 济阳坳陷樊斜184井沙四上亚段页岩纤维状方解石纹层孔隙结构及含油性特征(埋深3 529.34 m)

Fig. 7 Micrographs showing the pore structure and oil-bearing properties of fibrous calcite laminae in the Es^{4U} shales in well FX184, Jiyang Depression

- a. 双向生长纤维状方解石脉,脉体间发育“叠锥状”交错接触带,单偏光,普通薄片显微照片;b. 纤维状方解石脉致密,接触带和薄弱面处具有较好的荧光显示,荧光(与a图同视域),普通薄片显微照片;c. 纤维状方解石脉体,扫描电镜照片;d. e图中提取的孔隙分布,面孔率为4.02%;e. 黏土层间的纤维状方解石脉体,扫描电镜照片;f. e图中提取的孔隙分布,面孔率为9.21%

(Cal为方解石;Qz为石英;Dol为白云石;Clay为黏土矿物;Py为黄铁矿;Fsp为长石;Cls为天青石。)

烃有机质,方解石结晶生长充分,晶体之间紧密接触,脉体内部较为致密,仅发育少量大孔,中孔零星分布。

孔隙多为重结晶后残余的粒内孔隙,以方解石粒内孔为主,连通性较差,荧光下和扫描电镜下观察脉体油气

呈零星分布(图7a—d)。纤维状方解石脉结晶生长过程中通常会在脉体和围岩之间发育一定的孔隙或裂缝,这类储集空间在荧光下具备较好的油气显示(图7e,f)。脉间充填缝中孔隙类型多为黏土-微晶(石英、长石和方解石等微晶颗粒)粒间孔,残余油充填其中,在荧光下可见较好的荧光显示(图7b)。同时,扫描电镜下也可观察到纤维状方解石脉体与脉间充填缝的残余油分布差异(图7d)。总体而言,纤维状方解石纹层含油性较差,脉体储集孔隙不发育,油气储集空间受限。双向生长方解石脉的“叠锥状”结构中具备较好的油气显示,但总体规模较小。

3.2 泥晶方解石纹层

泥晶方解石纹层常以连续或透镜状形式存在,内部较为均质,主要由泥晶方解石和石英微晶组成,石英微晶内嵌于泥晶方解石晶粒之间,方解石和石英晶粒

间易形成颗粒粒间孔(图8)。在页岩沉积过程中,泥晶方解石多为蒸发成因,微晶石英常以陆源输入的形式沉积于泥晶方解石之间^[53-54]。

泥晶方解石脉内部较为致密,孔隙度较低,以泥晶方解石-石英晶间孔为主,平均孔径为198 nm,部分方解石-石英晶间夹杂黏土矿物。泥晶方解石纹层组合以孔径300~400 nm的孔隙占比最高,孔径100~900 nm的中孔分布最为普遍(图8g)。此外,部分较大孔隙的残余油表面可见油膜。整体而言,泥晶状方解石纹层组合内部较为均一,且整体较为致密,孔隙度较低。孔隙类型以方解石和石英的粒间孔隙为主,矿物颗粒对孔隙的支撑性好,具有一定的油气储集能力。此外,泥晶方解石纹层与富黏土矿物纹层互层时常发育层间缝或穿层缝,可有效沟通上、下富黏土矿物纹层和方解石层的基质孔隙,互层越频繁,纹层厚度越薄,沟通效果越好,荧光下可见层间缝中油气残余(图8a,b)。

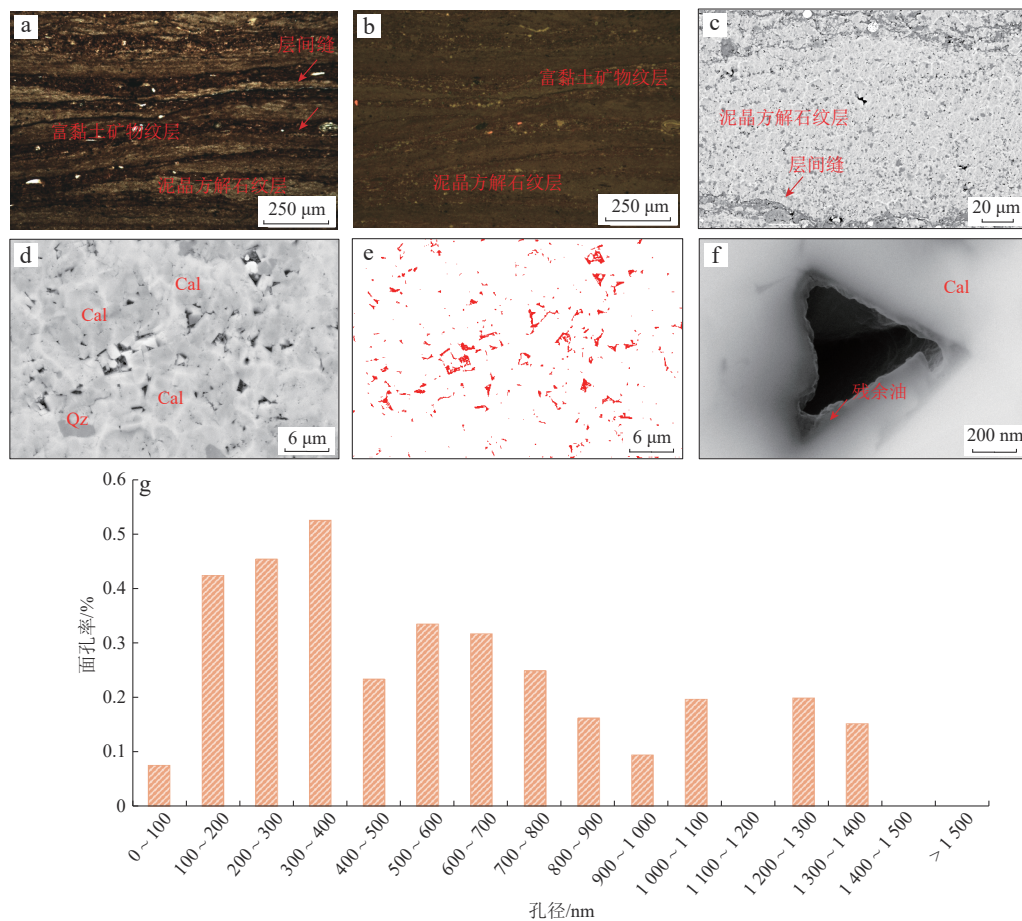


图8 济阳坳陷樊斜184井沙四上亚段页岩泥晶方解石纹层孔隙结构特征(埋深3 539.47 m)

Fig. 8 Micrographs showing the pore structure of micritic calcite laminae in the Es^{4u} shales in well FX184, Jiyang Depression

a. 泥晶方解石脉与富黏土矿物纹层互层,可见层间缝,单偏光,普通薄片显微照片;b. 泥晶方解石脉与富黏土矿物纹层互层,荧光,普通薄片显微照片;c. 泥晶方解石脉,可见层间缝,扫描电镜照片;d. 泥晶方解石纹层矿物组成,扫描电镜照片;e. d图视域内残留油分布,面孔率为3.30%;f. 泥晶方解石脉粒间孔隙,扫描电镜照片;g. d图视域内孔径与面孔率关系柱状图 (Cal为方解石;Qz为石英。)

3.3 粉晶方解石纹层

粉晶方解石纹层并不常见,仅少数样品可见。粉晶状方解石脉多在重结晶程度较低的阶段形成,方解石晶粒较大(可达几十微米),晶间孔隙较为发育。镜下粉晶粒间孔隙的连通性较好,且往往具有较大的孔隙空间。荧光条件下,粉晶方解石粒间荧光特征极为明显,这表明粒间含油性极佳。晶间的孔、缝可沟通临近的富黏土矿物纹层(主要生油层),形成油气运聚的重要通道。扫描电镜下粉晶方解石粒间孔、缝同样极为发育,具有孔隙度高、孔径大和含油丰富的特征,未完全结晶的残余孔隙中同样充填大量残余油(图9)。粉晶方解石纹层以粒间孔隙为主要孔隙类型,既可作为有效的储集层,也能够作为输导层,是优质的含油气纹层。

3.4 富黏土矿物纹层

富黏土矿物纹层中常见的孔隙包括黏土-微晶(石英、长石和方解石等)粒间孔和黏土矿物晶间孔(图10a—c)。通过扫描电镜可见富黏土矿物纹层孔隙内部多残余油附着,较大孔隙中的残余油壁面可见油膜。此外,黏土-微晶孔隙平面分布广,孔隙连通性好,是优势的储油空间和运移通道(图10c,d)。黏土矿物-有机质复合体中可见有机质收缩缝发育,且与相邻黏土-微晶孔隙相沟通,形成良好的生-储-运配置。部分黏土矿物内部可见黏土矿物晶间孔,多为狭长形孔隙,孔隙中未见油气充填,或为页岩中水的主要富集空间。整体平均孔径

为191 nm,其中孔径100~500 nm晶间孔隙最为发育,也发育有微米级孔、缝(图10e),它们是页岩中储油的主要载体。

3.5 混合矿物纹层

混合矿物纹层在透射光下多为棕褐色夹杂星点状亮斑,其中棕褐色多为黏土矿物-有机质复合体,星点状亮斑则为石英、长石和方解石等透光矿物。内部整体矿物分布较均一,未见明显层理结构(图11a)。扫描电镜下方解石、石英和长石等微晶颗粒较大,黏土矿物夹杂在微晶颗粒边缘,形成黏土-微晶粒间孔(图11c)。

扫描电镜下混合矿物纹层中孔隙以黏土-微晶粒间孔为主,中-大孔占比高,孔径500~600 nm孔隙贡献最大,平均孔径约为117 nm(图11e)。小孔多完全充填滞留油,较大孔隙残余油中心为残留孔隙,这部分残留孔隙原本以赋存易挥发油为主,随着页岩样品在地表的放置,易挥发组分优先散失,留下相对不易挥发的残留油附着于孔隙壁面(图11c)。长英质-灰质混积型页岩,粒间孔隙含油性较好,孔隙表面普遍存在残余油附着。

4 纹层组合对页岩油富集的控制作用

页岩储层是由多种纹层相互组合形成的,不同纹层在页岩油富集过程中扮演着不同的角色(图12)。富黏土矿物纹层中有机质广泛分布,是产生页岩油的

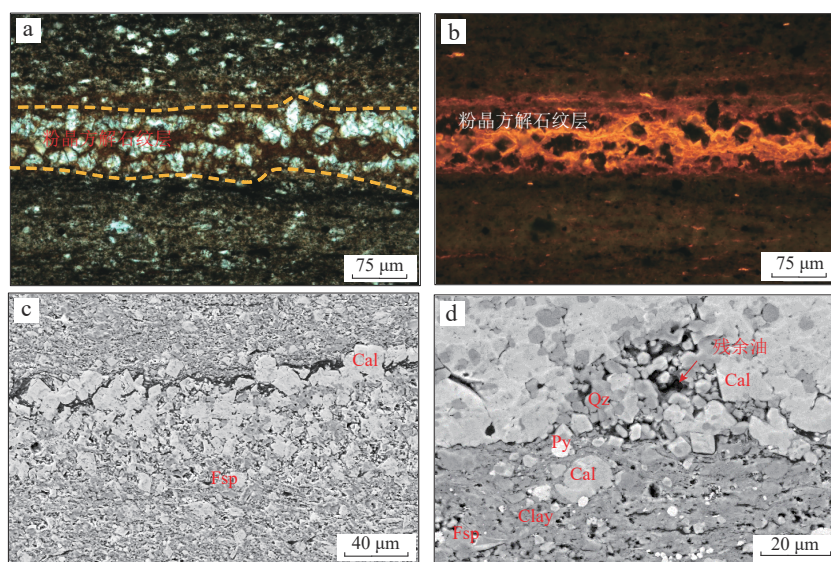


图9 济阳坳陷樊斜184井沙四上亚段页岩粉晶方解石纹层显微照片(埋深3 664.85 m)

Fig. 9 Micrographs of very fine crystalline calcite laminae in the Es^{4U} shale in well FX184, Jiyang Depression

a. 单偏光,普通薄片;b. 荧光,普通薄片;c. 扫描电镜;d. 粉晶方解石纹层含油孔隙,扫描电镜

(Cal为方解石;Qz为石英;Clay为黏土矿物;Py为黄铁矿;Fsp为长石。)

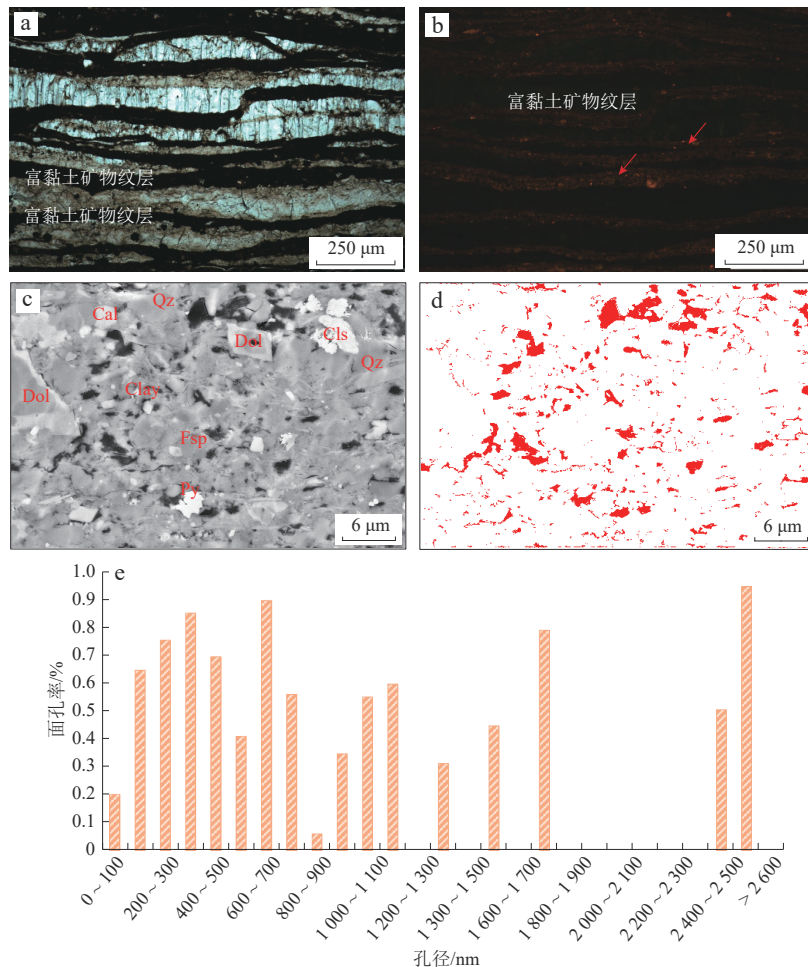


图10 济阳坳陷樊斜184井沙四上亚段页岩富黏土矿物纹层含油性、孔隙结构及孔径分布特征(埋深3 529.34 m)

Fig. 10 Oil-bearing properties, pore structure, and pore size distribution of clay-mineral-rich laminae in the Es^{4u} in well FX184, Jiyang Depression

a. 单偏光,普通薄片显微照片;b. a图同视域富黏土矿物纹层,荧光,普通薄片显微照片;c. 扫描电镜照片;d. c图视域内残留油分布,面孔率为8.77%;e. c图视域内孔径与面孔率关系柱状图

(Cal为方解石;Dol为白云石;Clay为黏土矿物;Py为黄铁矿;Fsp为长石;Cls为天青石。)

重要基础,纹层中的储集空间多被烃类充填,但孔径较小,且后期被压裂改造能力差,难以流出。泥晶方解石纹层中含有少量沉积成因的有机质碎屑,具备一定的生烃能力,孔隙类型以方解石粒间孔为主,具备自生自储的能力,但生烃能力与储集能力相对较弱。纤维状方解石纹层中脉体内部孔隙欠发育,脉体中间缝与富黏土矿物纹层类似,具有较高的油气显示,脉体缝中的黏土矿物与方解石脉体力学性质的差异使得缝体与脉体接触处发育微裂缝,可作为烃类的储集空间和流动通道。同时,方解石脉体的抗压性也可作为后期压裂改造提供支撑。粉晶方解石纹层虽自身不具备生烃潜力,但广泛发育的粒间孔以及较好的连通性,使得粉晶方解石纹层可作为较好的储油纹层。混合矿物纹层内多种有机组分和无机组分共存,具有源-储一体的特征,但生烃能力弱于富黏土矿物纹层、储集能力弱于粉晶方解石纹层。混合矿物纹层在纹层组合中扮演的角

色取决于相邻的纹层,例如当邻层具有较好的生烃能力时,混合矿物纹层可作为储油纹层。此外,由于方解石成因上的差异,泥晶方解石纹层和粉晶方解石纹层与富黏土矿物纹层通常呈突变式接触,易形成层间缝,成为页岩油渗流通道。

有机质是油气生成的重要基础,储集空间是油气储存的场所,两者共同控制着页岩中油气的富集。因此,同时存在有机质广泛分布的纹层和储集空间发育的纹层的富碳酸盐页岩其内油气更为富集。此外,储集空间发育的纹层通常以脆性矿物为主,后期改造能力强,因此这类页岩也具有较好的开发潜力。本次研究的富碳酸盐页岩主要发育有“泥晶方解石纹层+富黏土矿物纹层+混合矿物纹层”和“纤维状方解石纹层+粉晶方解石纹层+富黏土矿物纹层+混合矿物纹层”2种纹层组合(图12)。前者的3类纹层均具备生烃能力,但储集性较差;另一方面,泥晶方解石纹层和富

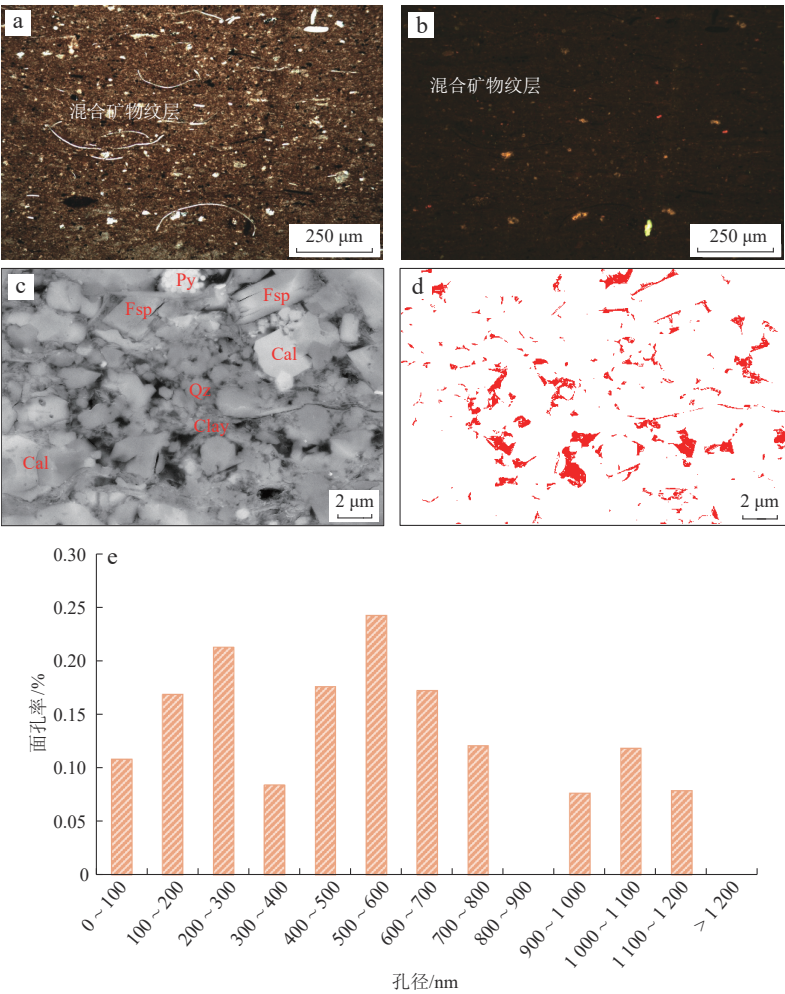


图 11 济阳坳陷樊斜 184 井沙四上亚段页岩混合矿物纹层含油性、孔隙结构及孔径分布特征(埋深 3 560.50 m)

Fig. 11 Oil-bearing properties, pore structure, and pore size distribution of mixed laminae in the Es^{4U} in well FX184, Jiyang Depression

a. 单偏光,普通薄片显微照片;b. 荧光,普通薄片显微照片;c. 扫描电镜照片;d. b图视域内残留孔分布,面孔率为 0.39%;e. b图视域内孔径与面孔率关系柱状图
(Cal 为方解石;Qz 为石英;Clay 为黏土矿物;Py 为黄铁矿;Fsp 为长石。)

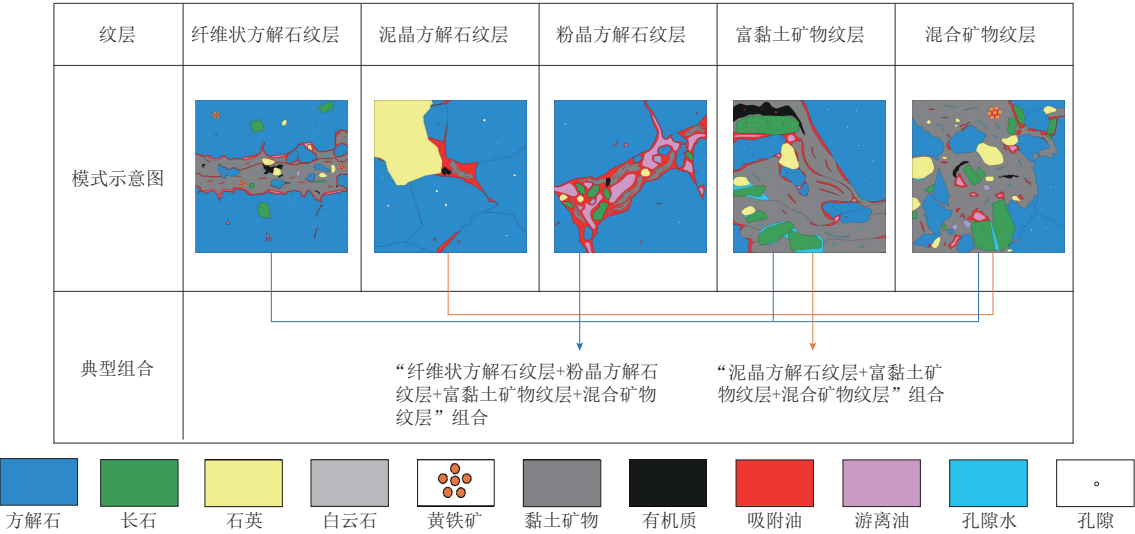


图 12 济阳坳陷樊斜 184 井沙四上亚段富碳酸盐页岩纹层特征与典型纹层组合

Fig. 12 Lamina characteristics and typical lamina assemblages of carbonate-rich shales in the Es^{4U} in well FX184, Jiyang Depression

黏土矿物纹层中矿物颗粒较小,压裂改造效果相对较低,开发潜力相对较低。后者“生(富黏土矿物纹层和混合矿物纹层)”“储(粉晶方解石纹层、混合矿物纹层和层间缝)”和“渗(粉晶方解石纹层和层间缝)”兼备,是富碳酸盐页岩中有利于页岩油富集和开发的纹层组合。

5 结论

根据纹层的矿物组成、成因及形态特征对沙河街组四段上亚段富碳酸盐页岩纹层进行类型划分,结合镜下观察和实验,对纹层进行精细刻画,揭示了页岩纹层组合对页岩油富集的控制作用。形成了以下主要认识:

1) 将济阳坳陷沙四上亚段的富碳酸盐页岩的纹层划分为纤维状方解石纹层、泥晶方解石纹层、粉晶方解石纹层、富黏土矿物纹层和混合矿物纹层5类,主要发育有“泥晶方解石纹层+富黏土矿物纹层+混合矿物纹层”和“纤维状方解石纹层+粉晶方解石纹层+富黏土矿物纹层+混合矿物纹层”2种纹层组合模式。

2) 富碳酸盐页岩的富黏土矿物纹层中有机质含量高,是重要的生油层;粉晶方解石纹层和混合矿物纹层储集空间最为发育,是页岩油富集的优势纹层。

3) “纤维状方解石纹层+粉晶方解石纹层+富黏土矿物纹层+混合矿物纹层”组合中生-储-渗兼备,是沙四上亚段富碳酸盐页岩油富集的最佳纹层配置。

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