

# 准噶尔盆地中拐凸起南部佳木河组储层发育特征及演化序列

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**摘 要:**中拐凸起南部二叠统佳木河组,是准噶尔盆地西北缘重要的深层—超深层致密砂(砾)岩油气勘探热点区带。利用岩心薄片、高压压汞、电镜扫描及岩心三维 CT 扫描等测试分析技术,表征储层岩石学、储层物性和储集空间发育特点,探讨储层控制因素及演化过程。结果表明:研究区储层岩性为富含浊沸石胶结物的致密砾岩,储集空间以后期溶蚀类孔隙为主,具有中高孔隙度、低渗透率的特点,孔喉配位数较低,孔隙连通较差;扇三角洲前缘是储层发育的主要相带,压实作用和胶结作用导致储层致密化,浊沸石的溶蚀作用是致密储层成藏成储的主要内在因素;断裂、不整合通过增强溶蚀作用的广度和深度影响储层的去致密化过程;受构造抬升淋滤和烃源岩演化影响,储层经过地表弱酸性水、排烃初期有机酸和过成熟阶段原油裂解 CO<sub>2</sub> 分压上升三期溶蚀作用改造,地表弱酸性水淋滤是储层去致密化的主要原因。该结果为研究区和同类型储层勘探开发提供参考。

**关 键 词:**准噶尔盆地;中拐凸起;佳木河组;储层;发育特征;浊沸石;演化序列

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## 0 引言

随油气勘探技术的持续更迭及油气勘探进程的逐步深入,深层—超深层致密砂(砾)岩气在中国各大沉积盆地获得勘探发现和突破,成为油气增储上产的重要领域<sup>[1-3]</sup>。准噶尔盆地二叠系深层—超深层(中国中西部盆地深层埋深为 4 500~6 000 m,超深层埋深大于 6 000 m<sup>[2]</sup>)致密砂(砾)岩气资源潜力丰富,勘探潜力巨大,盆地多个区块陆续获得重大发现,落实一批储量可观、高产稳产的含油气区带<sup>[3-4]</sup>。盆地发育多套烃源岩和稳定分布的油气盖层<sup>[5-7]</sup>,储层发育是决定致密砂(砾)岩气形成规模油气藏的决定性因素<sup>[4,8-9]</sup>。

中拐地区二叠系佳木河组是准噶尔盆地西北缘重要的深层—超深层致密砂(砾)岩气勘探区带和勘探目标,范存辉等<sup>[10]</sup>研究储层主控因素,岩性岩相、构造运动及成岩作用共同控制储层的形成,但未深入研究储层的成岩演化过程;李道清等<sup>[11]</sup>分析最新三维地震资料,分析中拐凸起南部构造演化,断裂活动能够改善储层物性,控制优质储层平面展布,但未讨论储层岩性及成岩作用;韩宝等<sup>[12]</sup>分析研究区不整合类型及油气藏类型,明确不整合面距佳木河组储层的距离与储层物性具有显著的负相关关系,但未深入分析影响机理;王孝明<sup>[13]</sup>等分析岩心测试资料,探讨研究区成岩演化过程,明确成岩作用的控制因素,从成岩作用角度阐明佳木河组有利储层的形成机理。优质油气储层的形成是沉积作用、构造作用和成岩作用的综合结果。

研究区位于准噶尔盆地西部隆起中拐凸起南翼,累计完钻探井 14 口,普遍获得良好油气显示,表明中拐凸起南部佳木河组整体发育油气富集区。有关佳木河组储层发育特征缺乏系统阐述,受研究资料时限性影响,对研究区油气勘探的指导有限。根据岩心薄片和物性资料,利用高压压汞、电镜扫描和岩心三维 CT 扫描等实验方法,分析研究区岩性组合、沉积相带、成岩作用和构造演化等,明确佳木河组储层基本特征及控制因素,探讨储层成岩演化过程,为同类型储层研究及研究区勘探开发提供一定参考。

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# 1 地质概况

研究区北部以红 3 井东断裂为界,西部终止于红车断裂带,东南部紧邻玛湖凹陷、达巴松凸起、盆 1 井西凹陷和沙湾凹陷,整体表现为“三凹一凸”构造格局(见图 1(a))。沙湾凹陷作为研究区主要的供烃凹陷,与研究区整体东南倾的构造格局具有源—运—储等油气地质条件适配性良好的特点,成藏条件优越<sup>[14-16]</sup>。研究区地层发育较为齐全,自下而上发育上古生界石炭系、二叠系佳木河组和乌尔禾组,中生界三叠系、侏罗系、白垩系及新生界(见图 1(b)),地层展布相对稳定(见图 1(c)),其中二叠系佳木河组二段(佳二段  $P_{1j_2}$ )是研究区主要目的储层。

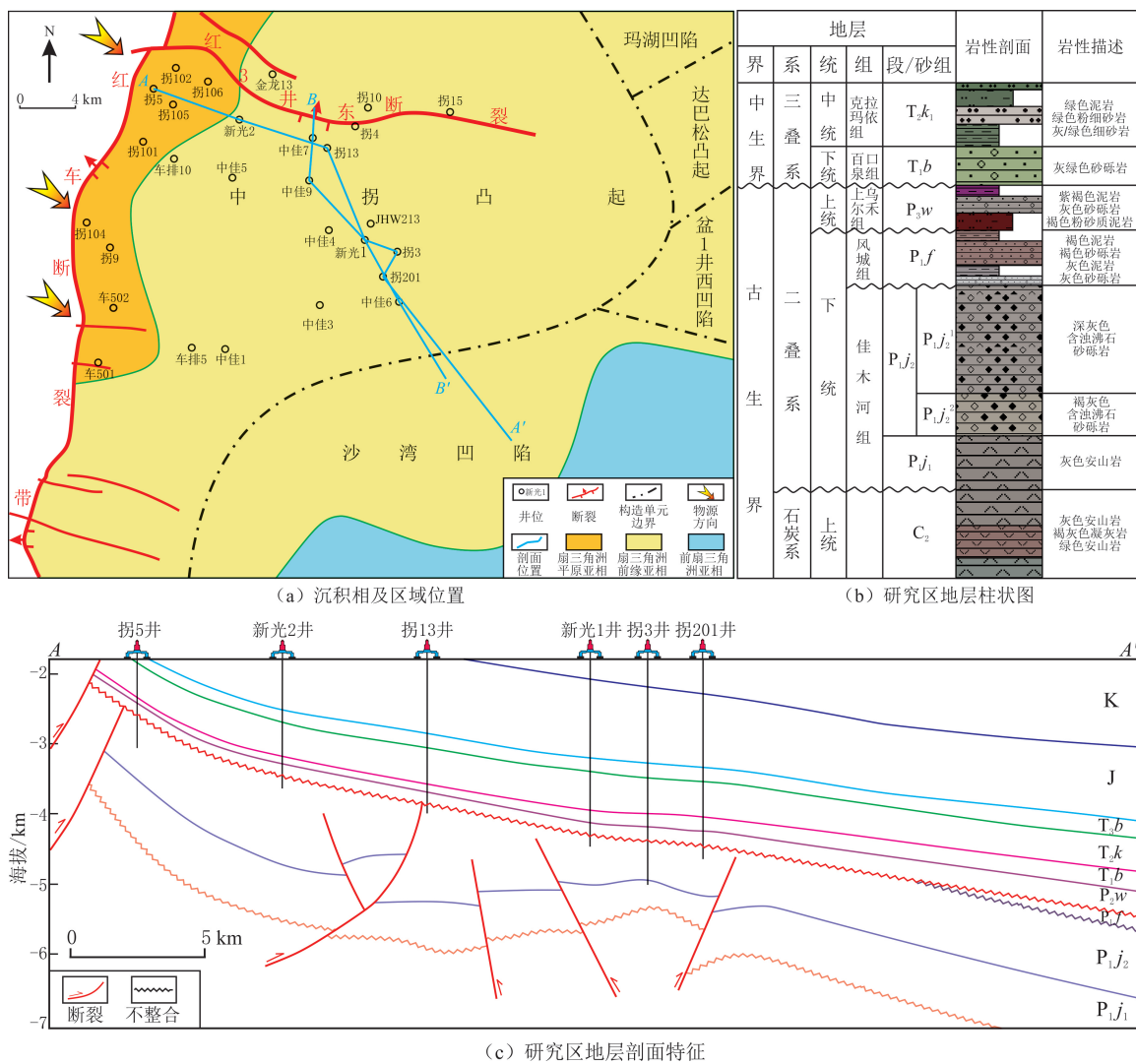


图 1 中拐凸起南部佳二段沉积相及地层发育特征

Fig. 1 Sedimentary facies and stratigraphic development characteristics of  $P_{1j_2}$  in the south of Zhongguai Uplift

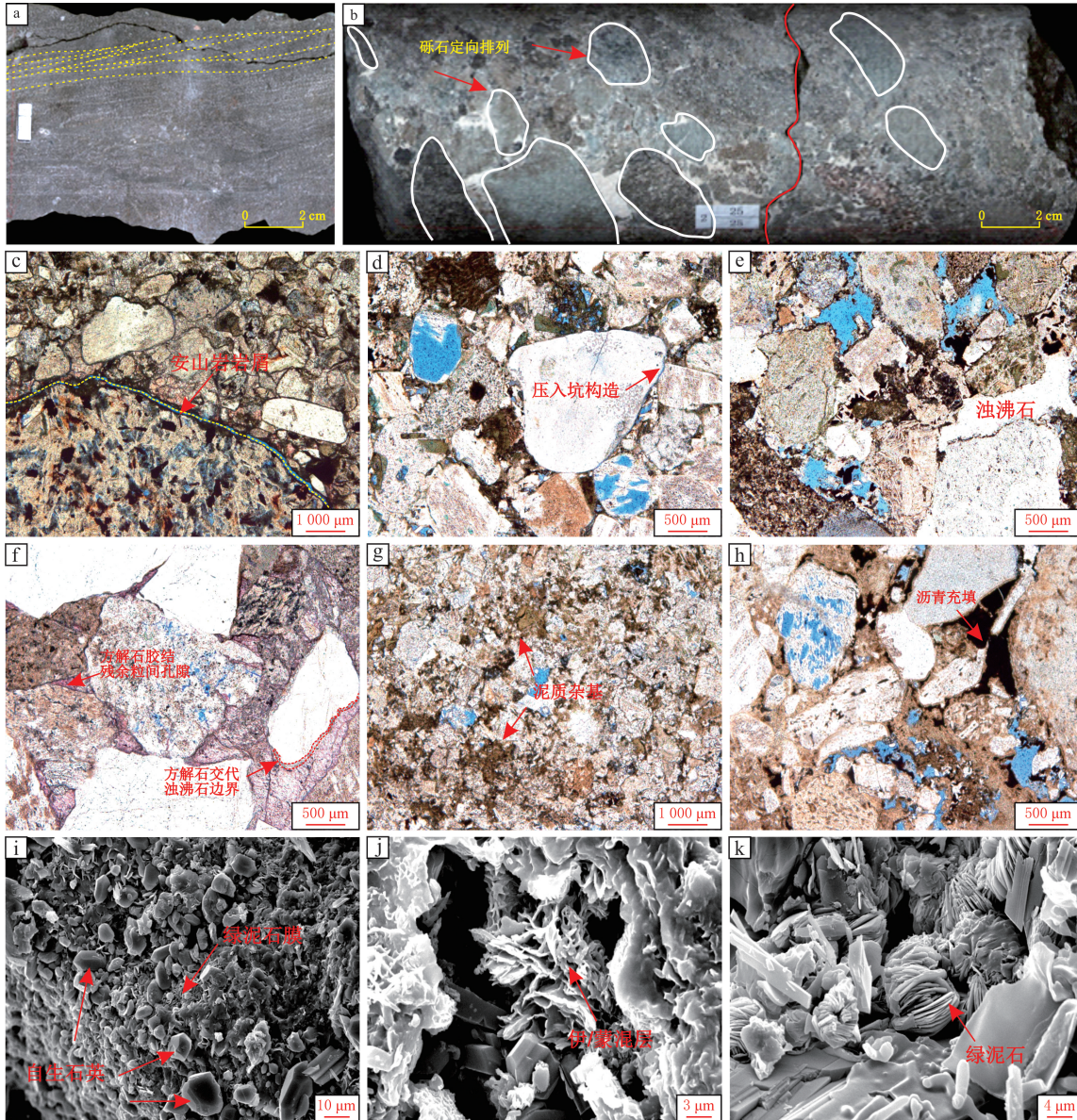
晚古生代石炭纪以来,准噶尔盆地经历海西构造幕、印支构造幕、燕山构造幕和喜马拉雅构造幕等构造演化阶段,构造应力性质和方向的变化造成现今盆地隆凹相间的复杂构造格局<sup>[17-18]</sup>。其中,中晚二叠世海西期—印支期挤压逆冲阶段是研究区目的储层去致密化的主要构造期次,构造运动形成下二叠统佳木河组—上二叠统乌尔禾组区域性不整合,是研究区油气运移、成藏的重要场所<sup>[11,19]</sup>。

# 2 储层基本特征

## 2.1 岩石学特征

研究区佳二段储层岩心多呈灰白色、浅灰色或灰绿色,发育楔状交错层理、波状层理和平行层理(见图

2(a)),与下伏岩层多为突变接触(见图2(b))。岩性以砂砾岩、含砂砾岩和砂质砾岩为主,砾石成分多为安山岩,其次为凝灰岩、霏细岩和花岗岩,分选中等—差,粒径差异较大,颗粒磨圆度呈次棱—次圆状,粒间以点—线接触和线接触为主(见图2(a-h))。粒度概率累积曲线显示,沉积物粒度差异大,悬浮组分占比小,滚动组分由北至南逐渐减少,跳跃组分升高(见图3)。整体上,反映研究区储层砂体具有近源、水动力较强且沉积速度较快的扇三角洲沉积特点。



(a) 岩性突变, JHW213井, 4 469.20 m; (b) 砾石定向排列, JHW213井, 4 470.30 m; (c) 安山岩砾石, 中佳4井, 4 468.13 m; (d) 颗粒点—线接触, 中佳5井, 3 886.05 m; (e) 浊沸石胶结, 中佳5井, 3 927.17 m; (f) 方解石、浊沸石胶结, 中佳5井, 3 997.38 m; (g) 泥质杂基, 中佳5井, 3 929.60 m; (h) 沥青充填, 中佳5井, 3 886.05 m; (i) 自生石英、绿泥石膜, 新光2井, 3 754.80 m; (j) 伊/蒙混层, 新光2井, 3 750.95 m; (k) 自生绿泥石, 新光2井, 3 754.80 m

图2 中拐凸起南部佳二段储层镜下特征

Fig. 2 Microscopic characteristics of  $P_{1j_2}$  reservoir in the south of Zhongguai Uplift

研究区孔隙胶结和基底胶结共存,填隙物体积分数占比高,以浊沸石、方解石和泥质杂基为主,少量为硅质、绿泥石和凝灰质(见图4(a))。浊沸石胶结物普遍发育(见图2(d-h)),分布不均匀,纵向分布差异较大,平均体积分数为8.45%,约占总填隙物的65.30%;其次为方解石和泥质杂基(见图2(f)),平均体积分数分别为4.40%、2.61%;硅质及其他胶结物平均体积分数占比小于2.00%,占比相对较小。X线衍射黏

土矿物分析结果显示,研究区储层黏土矿物以绿泥石为主(见图 2(i-k)),约占总黏土的 55.31%,其次为绿/蒙混层(21.10%)、伊/蒙混层(10.13%)和伊利石(9.25%),高岭石体积分数较低(4.22%)(见图 4(b))。

### 2.2 储集空间类型

储层铸体薄片分析显示,中佳区块二叠系佳木河组( $P_{1j_2}$ )储集空间类型多样,包括粒内溶孔(47.19%)(见图 2(d,f,h)、图 5(b))、粒间溶孔(29.02%)(见图 2(e,h))、铸模孔(8.13%)(见图 5(a))、剩余粒间孔(7.98%)(见图 2(h))及晶间孔(7.68%)(见图 5(c))。其中,粒内溶孔多为岩屑颗粒易溶物质溶蚀而形成的溶孔,粒间溶孔主要为胶结物的后期溶蚀形成的。储集空间以溶蚀类孔隙为主,是油气主要的赋存单元,反映储层后期溶蚀改造程度强烈。

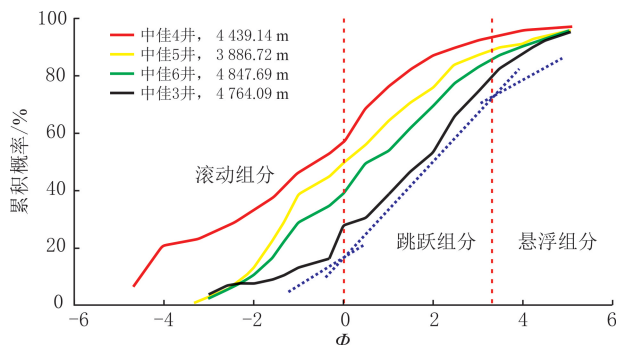


图 3 中拐凸起南部佳二段储层粒度累积曲线  
Fig. 3 Grain size accumulation curve of  $P_{1j_2}$  reservoir in the south of Zhongguai Uplift

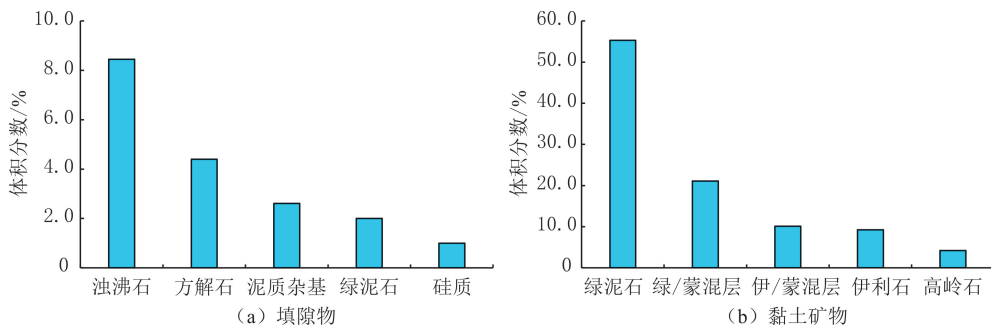


图 4 中拐凸起南部佳二段储层填隙物及黏土矿物体积分数  
Fig. 4 The content of interstitial material and clay mineral in  $P_{1j_2}$  reservoir in the south of Zhongguai Uplift

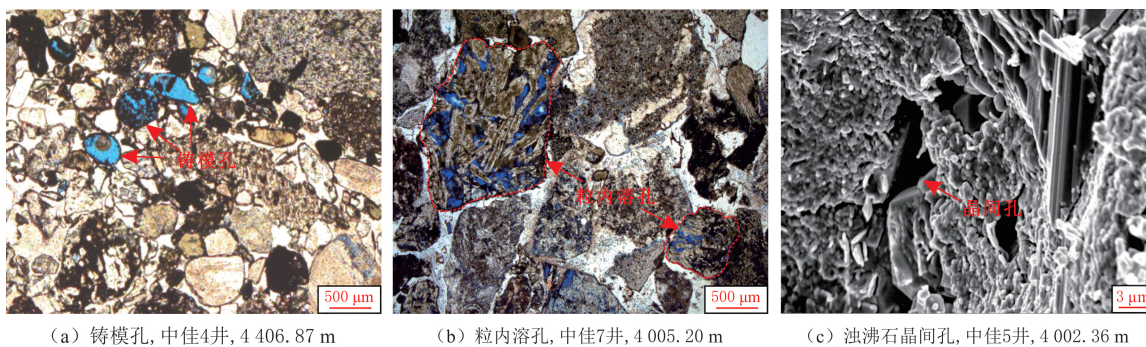


图 5 中拐凸起南部佳二段储集空间类型  
Fig. 5 Types of reservoir space of  $P_{1j_2}$  member in the south of Zhongguai Uplift

### 2.3 物性特征

根据中佳区块二叠系佳二段样品孔隙度分析,研究区有效储层孔隙度在 10.3%~20.9%之间,中值为 14.1%,平均为 13.9%;有效储层渗透率为  $(0.016 \sim 3430) \times 10^{-3} \mu\text{m}^2$ ,中值为  $11.490 \times 10^{-3} \mu\text{m}^2$ ,平均为  $221.890 \times 10^{-3} \mu\text{m}^2$ ,为中孔中高渗储层。铸体薄片观察发现,溶蚀/构造裂缝多表现为边缘粗糙、穿砾发育的特点(见图 6(a-c)),受样品加工过程中砾石松动、低密度浊沸石胶结物与高密度中基性火山熔岩屑由井筒取至地表造成的膨胀率差异影响<sup>[20]</sup>,导致大量发育具有未充填、无定向、粒缘发育等特点的假裂缝(见图 6(d))。大量发育的粒缘假裂缝提高岩石的渗流能力,导致岩心测试渗透率与试井渗透率出现显著差异(见图 6(e))。储层孔隙度为 8.4%~15.1%,平均孔隙度为 11.0%,渗透率为  $(0.002 \sim 0.321) \times$

$10^{-3} \mu\text{m}^2$ , 平均渗透率为  $0.050 \times 10^{-3} \mu\text{m}^2$  (见图 6(f)), 属于致密储层<sup>[20]</sup>。

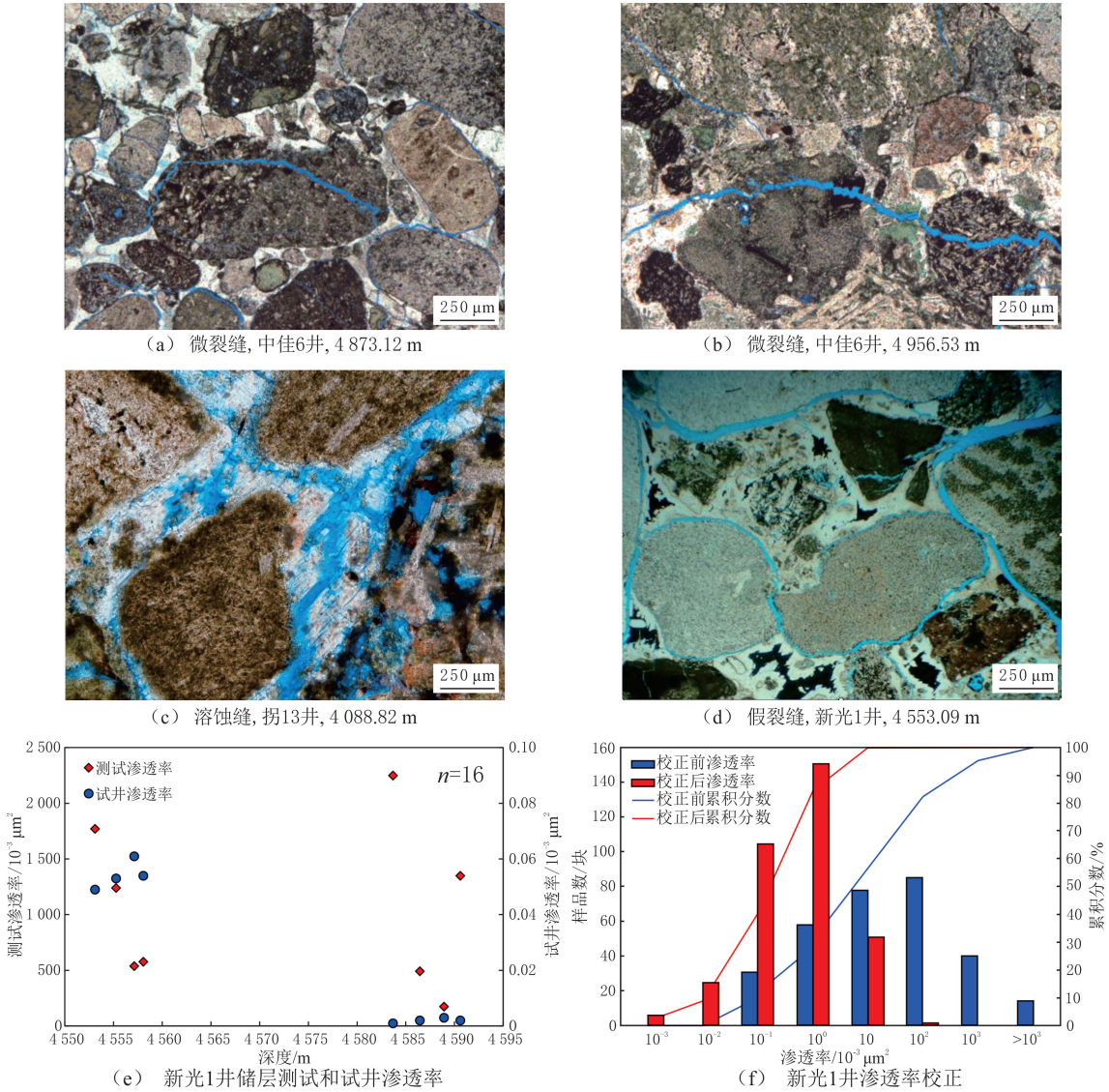


图6 中拐凸起南部佳二段储层物性校正

Fig. 6 Reservoir physical property correction of  $P_{1j_2}$  member in the south of Zhongguai Uplift

### 2.4 孔喉结构

薄片资料显示, 研究区目的层喉道类型有片状、弯片状、管束状及缩颈型(见图 2(d,f))。受填隙物及岩屑塑性强、储层埋深大的影响, 颗粒间点一线接触及线接触导致孔隙缩颈型喉道不发育, 多发育片状及弯片状喉道类型。典型井压汞资料显示, 毛细管压力曲线整体表现为偏细歪度、孔隙分选中等—较差, 具有细孔隙—微喉道特征, 渗流条件整体偏差(见图 7)。

利用岩心高精度 CT 扫描方法, 得到岩心基质三维结构显示, 相较于标准多孔介质 Berea 砂岩, 研究区储层基质孔隙连通性较差(见图 8(a))。孔隙喉道配位数分布在 0~10 个喉道之间, 集中分布在 1~3 个喉道之间, 占比为 64.2%; 17.6% 的孔隙喉道配位数为 4~10 个喉道; 孔隙喉道配位数值为 0 的孤立孔隙占 0.8%(见图 8(b)), 整体上孔喉配位数较低。

### 3 储层主控因素

综合岩心分析、铸体薄片等测试数据, 研究区沉积作用、成岩作用及构造作用是影响储层发育及质量的重要因素。

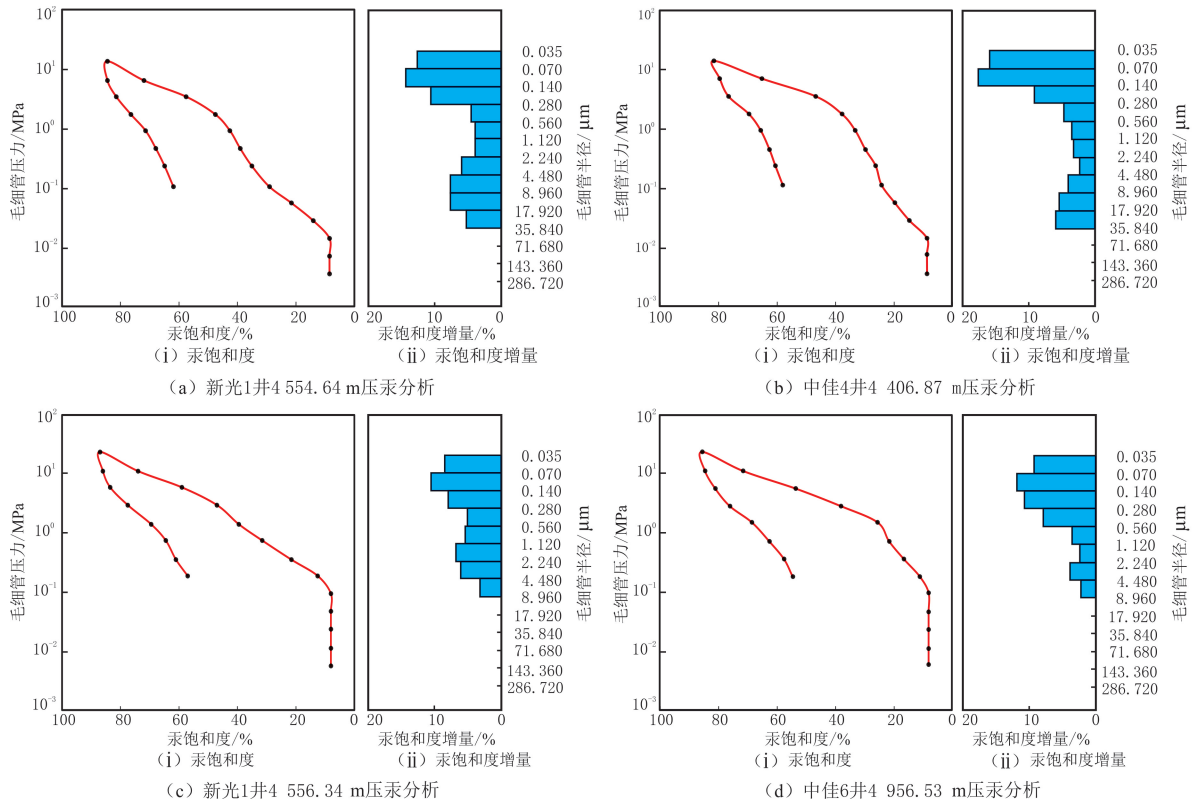


图 7 中拐凸起南部佳二段典型井压汞特征

Fig. 7 Mercury injection characteristics of typical wells in  $P_{1j_2}$  member in the south of Zhongguai Uplift

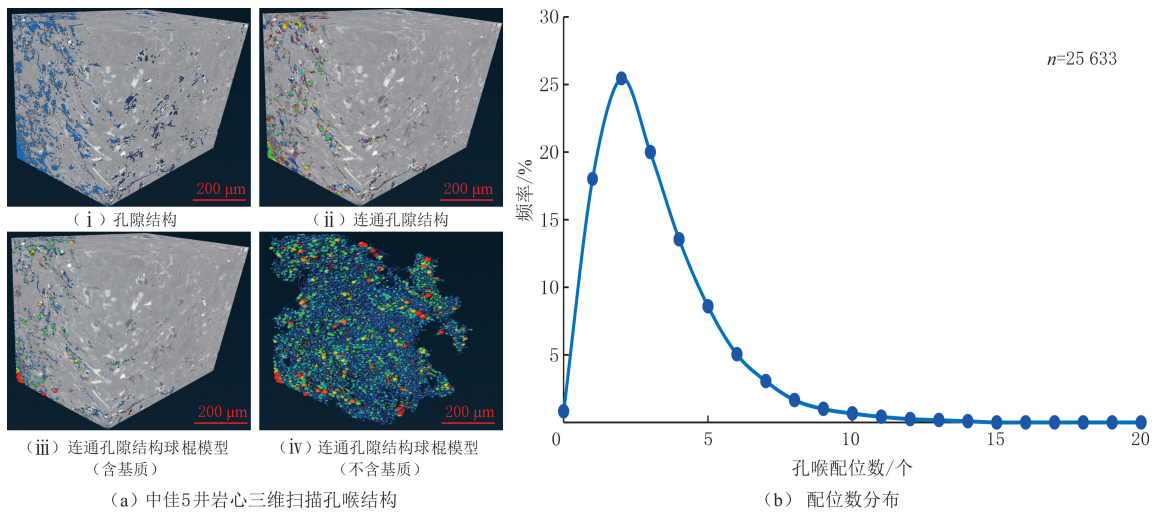


图 8 中拐凸起南部佳二段岩心孔喉结构特征

Fig. 8 The pore throat structure characteristics of the core of  $P_{1j_2}$  in the south of Zhongguai Uplift

### 3.1 沉积作用

沉积作用影响储层沉积期不同相带的岩石成分,控制储层发育。研究区整体属于扇三角洲沉积环境,物源来自西北部红车断裂带,顺物源方向为扇三角洲平原、扇三角洲前缘和前扇三角洲亚相,主体属于扇三角洲前缘亚相(见图 1(a))。

扇三角洲平原亚相沉积物搬运距离短,机械分异和化学分异不充分,导致岩石组分中的塑性凝灰岩岩屑、泥质等杂基体积分数占比多(见图 9(a)),胶结作用较弱,抗压实能力弱,不利于支撑保留前期孔隙结构。较高的中酸性凝灰岩岩屑及安山岩岩屑水解,易形成富  $\text{Na}^+$ 、 $\text{Ca}^+$  及硅质的环境,有利于形成高硅片沸石(见图 9(b))。受成分和晶体特征影响,片沸石耐酸性高,不易在后期酸性流体环境中发生溶蚀作用,

岩心分析孔隙度为 2.5%~11.2%，平均为 7.8%<sup>[21]</sup>。

相较于扇三角洲平原亚相，扇三角洲前缘亚相沉积物搬运距离较远，分异作用充分，岩石组分以刚性安山岩岩屑为主，杂基含量少(见图 9(c))，胶结物发育，抗压实能力强，一定程度上有利于保留沉积孔隙。中基性安山岩岩屑富含斜长石和中基性火山玻璃水解，易形成富钙低硅环境，形成浊沸石(见图 9(d))。浊沸石对温度、压力和有机酸等物理化学条件敏感，相较于片沸石更易发生后期溶蚀<sup>[22-23]</sup>，更有利于形成优质储层，岩心分析孔隙度为 7.4%~16.0%，平均为 10.3%<sup>[21]</sup>。

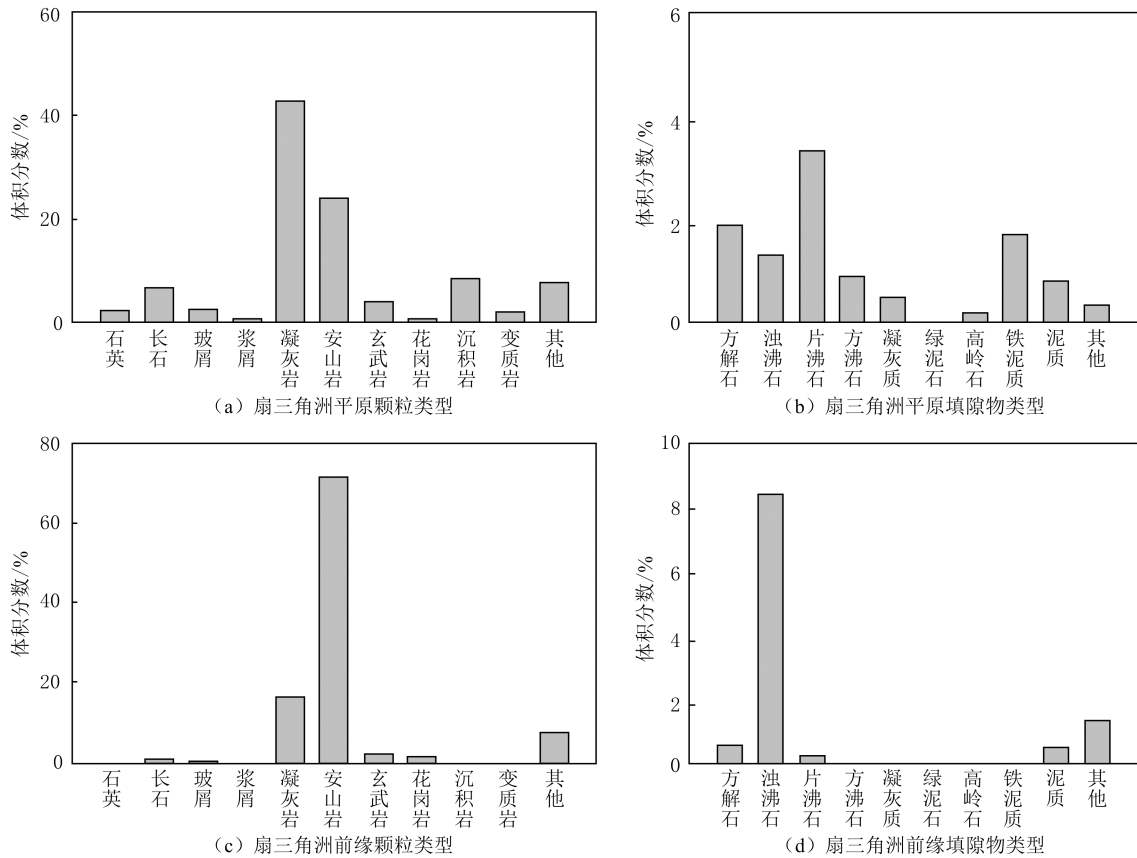


图 9 中拐凸起南部佳二段不同沉积相颗粒及填隙物类型特征

Fig. 9 Characteristics of different sedimentary facies particles and interstitial material types of P<sub>1j2</sub> in the south of Zhongguai Uplift

### 3.2 成岩作用

成岩作用从沉积初期至现今持续发生，多种成岩作用之间的强度差异是形成规模储层、优质储层的基础，对储层具有长时间、大规模和全方位的影响，是储层基本特征的决定性因素<sup>[8,10]</sup>，影响研究区储层发育的成岩作用主要包括压实作用、胶结作用和溶蚀作用。

#### 3.2.1 压实作用

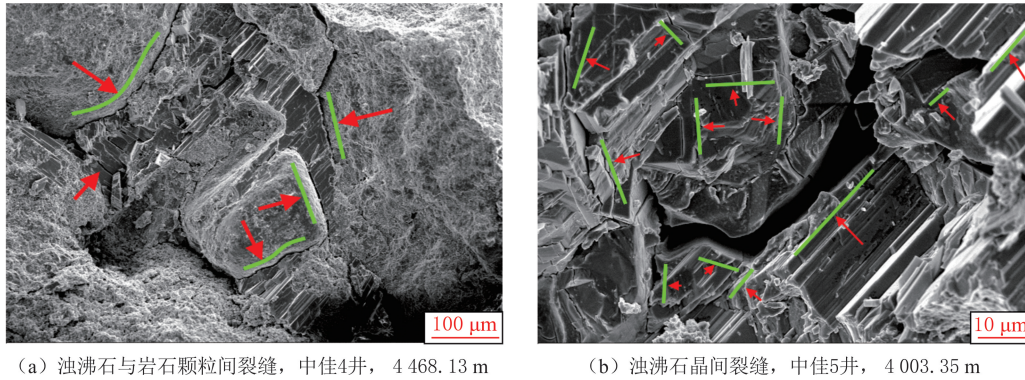
压实作用是典型的破坏性储层成岩作用，是导致储层致密化的主要控制因素。研究区受埋藏深度及构造挤压作用影响，压实作用明显，局部偶见压溶作用。压实作用在镜下主要表现为岩石颗粒以线接触和点一线接触为主(见图 2(d-f))，可见颗粒定向排列及部分岩石颗粒破裂缝(见图 2(b,d))；压溶作用表现为岩石颗粒间凹凸接触，形成压入坑构造(见图 2(d))。

#### 3.2.2 胶结作用

胶结作用对储层演化既存在破坏性，也存在建设性。研究区储层胶结作用主要表现为原生粒间孔隙受胶结物充填，胶结物以孔隙式胶结和基底式胶结为主。胶结物包括浊沸石胶结物、碳酸盐岩胶结物、硅质胶结物和黏土矿物胶结物(见图 2(f,i-k))。

浊沸石是研究区储层主要的胶结物类型，通常以孔隙胶结式和基底胶结式出现，呈连晶状(见图 2(c-

d)),主要发育于扇三角洲前缘亚相。浊沸石形成于高 pH 和富含中基性火山碎屑的碱性环境<sup>[22-23]</sup>,成岩作用初期的弱碱性沉积地层水,有利于浊沸石胶结物的形成。浊沸石胶结物对储层物性的改善具有两面性,早期的浊沸石胶结破坏原生孔隙结构,但增强储层的抗压能力,为后期的溶蚀作用提供物质基础<sup>[24-26]</sup>。沸石胶结物受自身结构影响,在沸石胶结物与颗粒边缘(见图 10(a))、沸石胶结物内部产生大量顺晶层的裂缝(见图 10(b)),胶结程度较弱,对致密储层的物性改善及贡献具有正向意义。



(a) 浊沸石与岩石颗粒间裂缝,中佳4井,4468.13 m

(b) 浊沸石晶间裂缝,中佳5井,4003.35 m

图 10 中拐凸起南部佳二段浊沸石胶结物微观特征

Fig. 10 Microscopic characteristics of laumontite cements of  $P_{1j_2}$  in the south of Zhongguai Uplift

碳酸盐岩胶结物发育程度较弱,在部分薄片可观察到方解石胶结。镜下可见较明显的两期发育的特点,第一期碳酸盐岩胶结物以充填浊沸石胶结残余孔为主,呈镶嵌状胶结;第二期碳酸盐岩胶结物以胶结浊沸石溶蚀孔隙为主,镜下表现为沿浊沸石不规则的颗粒溶蚀边缘胶结。浊沸石胶结物发育的储层通常伴随少量碳酸盐岩胶结物(见图 2(f)),浊沸石的形成对碳酸盐岩胶结物具有一定的抑制作用<sup>[25,27]</sup>。其次浊沸石溶解平衡需要的  $CO_2$  分压相对于方解石的较低<sup>[27]</sup>,成岩作用进入酸性阶段时,浊沸石更易发生溶解并产生高岭石和方解石等碳酸盐岩沉淀。碳酸盐岩胶结物体积分数占比小且后期溶蚀程度弱,导致碳酸盐岩胶结物对储层物性改善作用有限。

硅质胶结物和黏土胶结物含量较少。硅质胶结物多以自生石英微粒分布在孔隙中,对储层影响程度较弱(见图 2(i))。黏土矿物以绿泥石和伊/蒙混层为主,绿泥石多呈玫瑰花状充填于粒间孔隙或以片状垂直附着于颗粒表面而形成绿泥石膜,前者对孔隙有一定的破坏作用(见图 2(k)),后者一定程度上抑制颗粒压实作用,对储层物性改善具有一定的积极意义(见图 2(i));伊/蒙混层多呈丝片状充填于溶蚀孔隙(见图 2(g)),不利于储层物性改善。

### 3.2.3 溶蚀作用

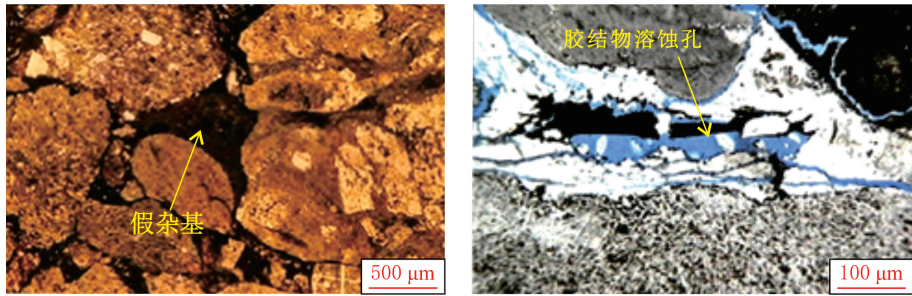
溶蚀作用是形成研究区优质储层最主要的建设性成岩作用。岩屑的差异化溶蚀形成大量的粒内溶孔、浊沸石胶结物的后期溶蚀形成大量的粒间溶孔,以及强烈溶蚀作用下形成的铸模孔,强烈的溶蚀作用是改善致密储层物性的决定因素(见图 2、图 5)。

## 3.3 构造作用

佳木河组沉积以来,研究区主要历经 4 期构造运动<sup>[11]</sup>,多期构造运动形成的断裂和不整合对储层的成岩成储过程影响显著,二者共同作用为致密储层物性改善提供基础。

### 3.3.1 断裂

研究区北部受限于红 3 井东断裂,西部终止于红车断裂带,区内次级逆冲断裂及压扭性走滑断裂发育,断裂对佳木河组储层改造作用显著<sup>[11]</sup>。断裂对研究区目的层的影响具有两面性。消极影响是在强烈的构造挤压背景下形成的逆断裂,使得压实作用强度增加,破坏储层质量。研究区西部近红车断裂带区域压实作用更强,颗粒接触强度显著大于其他区域的,塑性颗粒假杂基化(见图 11(a)),储层更加致密<sup>[13,28]</sup>;积极影响是在断裂发育区域,断裂不仅能作为流体优势运移通道(见图 12),纵向沟通地表水和有机酸,扩大储层宏观溶蚀范围(见图 11(b)),在埋深较大部分产生局部相对高孔渗区,发挥降低储层致密性的作用,同时断裂伴生缝也能直接改善储层孔渗条件(见图 12)<sup>[29-30]</sup>。



(a) 塑性颗粒假杂基化, 拐102井, 3 669.40 m (b) 裂缝、胶结物溶蚀孔, 新光1井, 4 558.06 m

图 11 中拐凸起南部佳二段不同断裂发育区储层微观特征  
Fig. 11 Microscopic characteristics of reservoirs in different fault development areas of  $P_{1j_2}$  in the south of Zhongguai Uplift

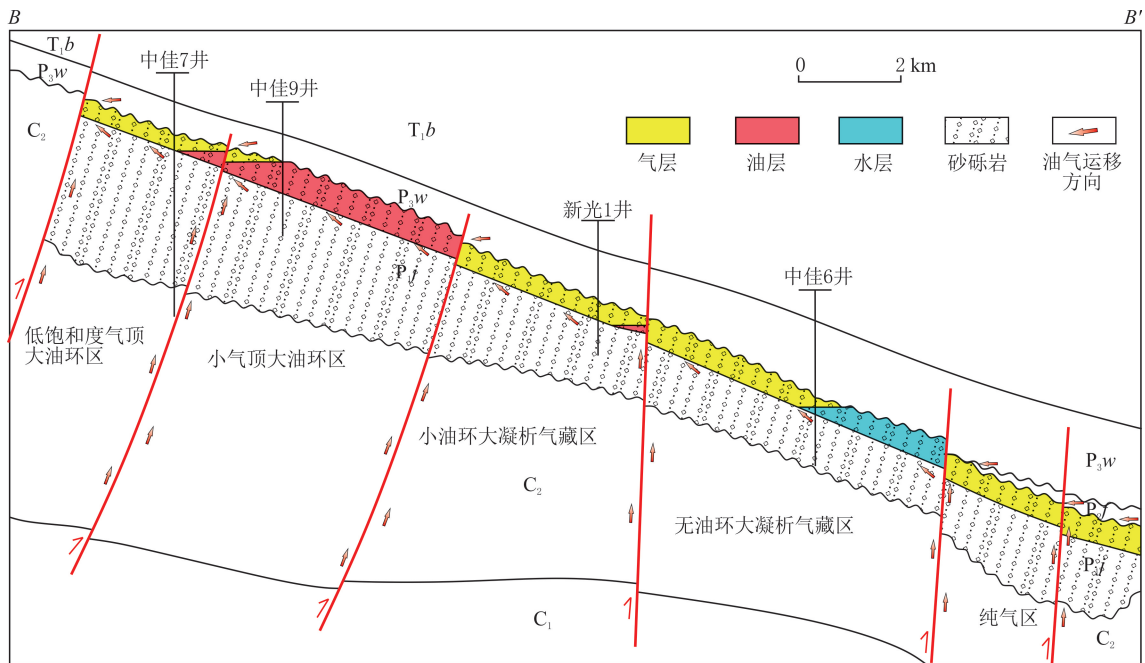


图 12 中拐凸起南部断裂与油气藏类型(据文献[11]修改, 剖面位置见图 1(a))

Fig. 12 Faults and reservoir types in the south of Zhongguai Uplift(modified by reference[11], section position is shown in Fig. 1(a))

### 3.3.2 不整合

不整合作为区域构造运动的产物,是油气储集单元和运移体系中的重要组成部分<sup>[31]</sup>。受早二叠世晚期挤压作用影响,研究区缺失中二叠世风城组,下二叠世佳木河组与上二叠世乌尔禾组直接接触,发育区域不整合<sup>[11]</sup>。在中二叠世风化剥蚀背景下,弱酸性地表水为佳木河组储层淋滤溶蚀作用提供物质条件,随深度增加,受原始储层致密及断层发育密度较低影响,地表水的纵向淋滤作用逐渐减弱,储层距不整合面距离越大,浊沸石胶结物体积分数占比越高,储层物性越差(见图 13)。在油气充注期,不整合作为油气优势运移通道(见图 12),能够引导有机酸对储层再次溶蚀改造。

## 4 储层成岩演化序列

研究区烃源岩测试  $R_o$  为 1.5%~2.5%,整体属于高一过成熟阶段。X 线衍射显示黏土矿物成分中不含蒙皂石,以绿泥石和伊利石为主,伊/蒙混层(I/S)平均体积分数为 6%,伊利石平均体积分数为 7%,绿泥石平均体积分数为 63%,反映佳木河组处于中成岩阶段 B 期早期(见图 14)。

早成岩期,快速埋藏压实作用下,火山玻璃及中基性火山岩屑发生水解蚀变,大量的  $Ca^{+}$ 、 $Na^{+}$  等碱性

离子富集,形成弱碱性地层水环境,以浊沸石为主的沸石胶结物开始沉淀,自生绿泥石膜开始生成,随方解石胶结物析出,原生孔隙遭受破坏,致使储层致密化(见图 13)。二叠世中期,受初次挤压隆升构造运动影响,目的层暴露于地表并接受剥蚀风化<sup>[11]</sup>,在接近不整合面的有限深度<sup>[32]</sup>内,弱酸性地表水对浊沸石胶结物产生普遍溶蚀,少量钙质、硅质及高岭石沉淀(图 14),溶蚀孔有效改善储层物性。

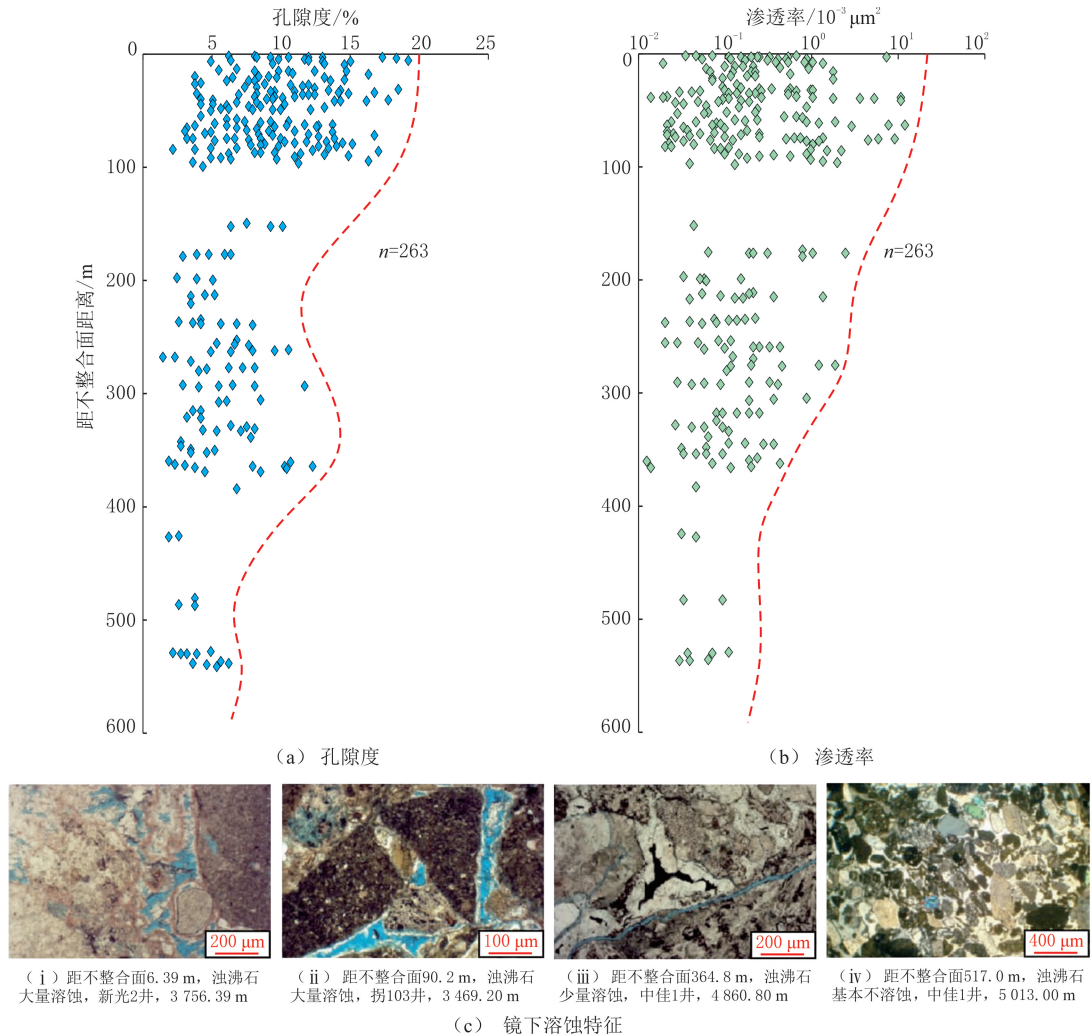


图 13 中拐凸起南部佳二段储层物性变化与距不整合面距离关系(据文献[13]修改)

Fig. 13 The relationship between the change of reservoir physical properties and the distance from unconformity of  $P_{1j_2}$  in the south of Zhongguai Uplift(modified by reference[13])

中成岩 A 期,烃源岩进入生排烃阶段,大量有机酸沿不整合—断裂体系运移至目的层,造成浊沸石的二次溶蚀,溶蚀形成的碱金属离子受储层较为致密的影响而原地富集<sup>[33]</sup>,随溶蚀作用的持续,酸性环境逐渐过渡至碱性环境,方解石胶结物沉淀(见图 13)。晚侏罗世二次生烃与第一次的相似<sup>[33]</sup>。

随埋藏加深,地层温度持续上升,成岩作用进入中成岩阶段 B 期,烃源岩进入过成熟生气阶段,随原油裂解, $CO_2$  分压上升,地层水转变为酸性环境,发生晚期溶蚀作用,随方解石、硅质等胶结物沉淀<sup>[29]</sup>,沥青逐步充填部分孔隙(见图 14)。相较于弱酸性地表水的淋滤改造作用,有机质演化形成的有机酸对含浊沸石致密储层的改造能力较弱,过成熟阶段原油裂解产生的  $CO_2$  的量有限,对致密储层的改善作用更弱。

总之,研究区压实作用与成岩早期的胶结作用是控制储层致密化的决定性因素,隆升剥蚀期弱酸性地表水对浊沸石胶结物溶蚀,是致密化储层物性改善的主要原因;近不整合的储层中的浊沸石胶结物受弱酸性地表水溶蚀消耗较多,深部储层致密,酸性流体难以造成影响,对储层改造程度较弱。

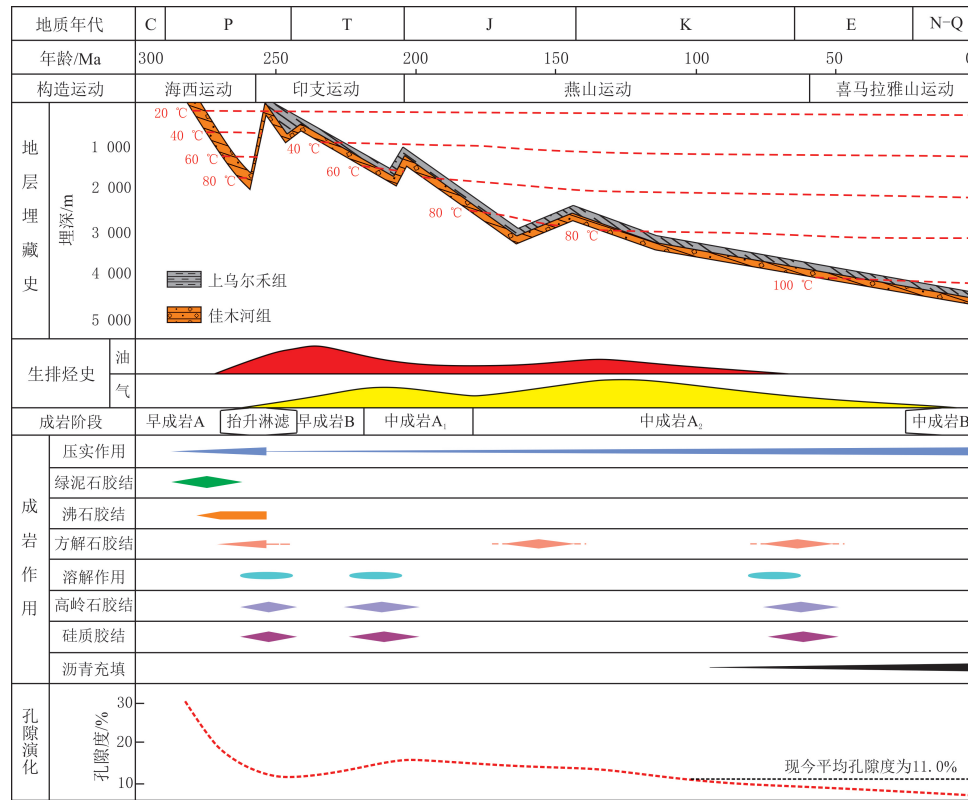


图 14 中拐凸起南部佳二段储层演化序列  
Fig. 14 The reservoir evolution sequence of P<sub>1j2</sub> in the south of Zhongguai Uplift

## 5 结论

(1) 准噶尔盆地中拐凸起佳木河组储层岩性以扇三角洲前缘沉积相的砾岩为主, 浊沸石胶结物发育, 储集空间以溶蚀型孔隙为主, 平均孔隙度为 11.0%, 平均渗透率为  $0.05 \times 10^{-3} \mu\text{m}^2$ , 孔喉半径较小, 孔隙结构较差, 孔喉配位数较低, 整体为中孔低渗储层。

(2) 沉积作用、成岩作用和构造作用对研究区储层的控制作用, 本质上是地质因素影响浊沸石的沉淀和溶解平衡。沉积作用不仅决定储层的原始品质, 也控制浊沸石的平面分布; 成岩作用主要影响储层质量, 压实作用与浊沸石的胶结作用导致储层致密化, 浊沸石的溶蚀作用是主要的建设性成岩作用; 构造作用形成的断裂和不整合为储层浊沸石的大面积溶蚀提供条件, 断裂伴生缝直接改善储层质量。

(3) 研究区储层处于中成岩阶段 B 期早期。成岩演化过程中, 压实作用和胶结作用导致储层致密化; 抬升淋滤、生烃初期及原油裂解期产生的弱酸性地表水与有机酸使得浊沸石胶结物发生 3 期溶蚀作用, 改善储层物性, 其中抬升淋滤期弱酸性地表水的淋滤溶蚀作用是改善储层致密化的主要因素。

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bars superimposed on earlier bar deposits. The single bars exhibit three stacking patterns: isolated, vertically superimposed, and laterally migrating. The architectural characteristics are controlled by hydrodynamic zonation of wave action: isolated bars develop in the swell zone, vertically superimposed bars form in the breaker and surf zones, and laterally migrating bars dominate in the swash zone. Influenced by high-frequency sea-level fluctuations and hydrodynamic differentiation, the internal accretionary units and interbeds within a single bar are distributed nearly horizontally nearshore and progressively stack seaward at low angles offshore. These results provide a basis for reservoir prediction and well pattern optimization during gas field development.

**Key words:** shore-shallow marine beach-bar; sandbody architecture; genetic model; single bar; accretionary body; Yinggehai Formation; Ledong 15D Gas Field; Yinggehai Basin

**Reservoir development characteristics and evolution sequences of Jiamuhe Formation in the south of Zhongguai Uplift, Junggar Basin**/2026,50(2):36-48

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**Abstract:** The Lower Permian Jiamuhe Formation in the south of Zhongguai Uplift is an important petroleum exploration hotspot of the deep-ultra-deep tight sandstone(conglomerate) in the northwestern margin of Junggar Basin. The reservoir petrology, reservoir physical properties and reservoir space development characteristics are characterized by using core thin section, high pressure mercury injection, SEM and core three-dimensional CT scanning, and reservoir control factors and evolution process are discussed. The results show that: the reservoir lithology in the study area is dense conglomerate rich in laumontite cement, which has the characteristics of medium-high porosity and low permeability. The reservoir space is dominated by late dissolution pores. The pore throat coordination number and the pore connectivity are bad. Fan delta front is the main facies belt of reservoir development. Compaction and cementation lead to reservoir densification. The dissolution of laumontite is the main internal factor of tight reservoir accumulation. The tectonic effects such as faults and unconformities affect the eliminating densification process of reservoirs by enhancing the breadth and depth of dissolution. Affected by tectonic uplift leaching and source rock evolution, the reservoir was modified by three stages of dissolution: weak acid water on the surface, organic acid in the early stage of hydrocarbon expulsion and partial pressure rise of CO<sub>2</sub> with crude oil cracking in the over-mature stage. Among them, the leaching of weak acid water on the surface is the main reason for reservoir eliminating densification. The results provide a reference for the exploration and development of the study area and the same type of reservoir.

**Key words:** Junggar Basin; Zhongguai Uplift; Jiamuhe Formation; reservoir; development characteristics; laumontite; evolution sequence

**Characteristics and main controlling factors of organic-rich shale reservoirs in the Long 1<sub>1</sub> Sub-member, Zigong Area, Sichuan Basin/2026,50(2):49-63**

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**Abstract:** The Lower Silurian Longmaxi Formation in the Southwestern Sichuan Basin represents a high-quality marine hydrocarbon source rock with significant exploration value. Focusing on organic-rich shale from the Long 1<sub>1</sub> Sub-member in the Zigong Area of the Sichuan Basin, this study employed techniques including total organic carbon mass fraction analysis, whole-rock X-ray diffraction, scanning electron microscopy, and CO<sub>2</sub> and N<sub>2</sub> adsorption to characterize reservoir properties, pore structure features, and their governing factors. Results indicate that the shale mineral composition in the study area is primarily clay minerals and quartz. Pore types in the organic-rich shale of the Long 1<sub>1</sub> Sub-member include organic pores, inorganic pores, and microfractures. Organic pores constitute the dominant pore type, accounting for 42.31%–93.04% of total porosity with an average of 66.88%. The total organic carbon (TOC) content in the organic-rich shale of the Long 1<sub>1</sub> Sub-member ranged from 0.16% to 5.05%, averaging 1.63%. The shale organic matter predominantly belonged to type I, with an average vitrinite reflectance of 2.30%. The shale's total porosity ranged from 0.018 0 to 0.031 0 cm<sup>3</sup>/g, with a total specific surface area ranging from 23.15 to 45.26 m<sup>2</sup>/g. The Long 1<sub>1</sub> Sub-member shale reservoirs predominantly developed mesopores, followed by micropores, which together accounted for approximately 95% of the total pore volume, while macropores constituted the smallest proportion. Organic matter abundance and maturity are the primary factors controlling organic pore development. Hydrocarbon generation promotes the formation of nanoscale pores, while high thermal maturity causes kerogen shrinkage and partial closure of organic pores. Clay mineral interconversion and compaction negatively impact pore development. Brittle minerals like quartz and calcite provide structural support for pore spaces during diagenesis, preserving intergranular pores and increasing porosity. These findings provide a basis for predicting sweet spots in deep marine shale gas exploration within the Sichuan Basin.

**Key words:** Sichuan Basin; Zigong Area; Longmaxi Formation; organic matter; deep marine shale; reservoirs characteristics; pore structure; quantitative characterization; main controlling factors