

# 全油气系统源储侧接式致密油藏 主控因素及成藏模式 ——以玛南斜坡区风城组二段为例

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**摘要:**玛南斜坡区是准噶尔盆地非常规油气勘探的重要接替领域。根据研究区测录井、分析化验和生产测试等资料,明确油藏类型及分布规律,研究玛南斜坡区风城组二段致密油藏主控因素及成藏模式。结果表明:玛南斜坡区风城组二段( $P_1f_2$ )油藏为全油气系统背景下的致密油藏,源储侧向对接,具有整体含油、局部富集的特征,甜点主要分布于风城组二段二砂组二小层( $P_1f_2^{2-2}$ )和三小层( $P_1f_2^{2-3}$ )。油藏受储层品质、源储配置和异常高压等因素控制,储层品质控制油气富集程度,研究区储层分为三类,其中Ⅰ类储层岩性粒度较粗,孔喉结构好,是油气优先富集区;厚储薄源型配置中的薄层烃源岩的发育既为油藏形成提供物质基础,又改变储层润湿性或受生烃增压而形成微裂缝,为油气成藏提供条件;异常高压控制含油性及产能平面分布,超压区水平井含油率及产能更高。研究区为源储侧接、优储控富、超压驱动的成藏模式。该结果为研究区和类似区块的后续开发建产提供指导。

**关键词:**准噶尔盆地;玛南斜坡;风城组;全油气系统;源储侧接;致密油藏;主控因素;成藏模式

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## 0 引言

玛湖凹陷蕴藏丰富的油气资源,是中国油气增储上产的重要领域之一。玛湖凹陷风城组勘探经历两个阶段,第一阶段为2018年及以前,按照“由源到圈”的勘探思路,在盆缘构造高部位发现二叠系风城组常规砂砾岩油藏,但向斜坡区外推时普遍见水,勘探效果未达预期;第二阶段为2019年至今,勘探思路转向“近源勘探”,构建常规—非常规有序分布模式,在第一阶段认为的“水区之下”发现源储紧邻致密油气,于凹陷区碱湖中心发现源储一体页岩油气<sup>[1-3]</sup>,极大丰富了全油气系统地质理论。玛湖凹陷二叠系风城组油藏成为全油气理论与勘探实践结合的典型案例<sup>[4]</sup>。

人们研究玛湖凹陷风城组全油气系统理论与成藏机理<sup>[1-5]</sup>、宏观沉积演化及储层展布<sup>[5-9]</sup>等,阐述烃源岩生排烃到油气运移再到聚集成藏的全过程。玛湖凹陷风城组发育一套广泛分布的碱湖相烃源岩,为全油气系统成藏提供重要的物质基础<sup>[5,7]</sup>,斜坡区发育冲积扇—扇三角洲—半深湖沉积体系控制下的全序多类型储层,孔喉结构的差异控制常规一致密—页岩油气藏的有序聚集<sup>[8-9]</sup>。已有研究集中于盆缘常规油气藏和玛湖凹陷北斜坡页岩油领域,基本明确油藏特征、高产控制因素及富集模式<sup>[10-12]</sup>。玛南斜坡区风城组致密油为夹在高部位常规油藏和低部位页岩油藏之间的过渡领域,具有特殊性,与典型致密油案例(如鄂尔多斯延长组、四川盆地须家河组和松辽盆地青山口组等)普遍存在的上源下储、下源上储和源储互层等源储配置模式不同<sup>[13-14]</sup>。玛南斜坡区风城组埋藏较深且沉积相带具有有序性,同层系中的致密砂岩储层与烃源岩呈齿状交错,油气在烃源岩中生成且未运移至其他层系,在层内侧向运移至与源岩对接的砂岩储层,为源储侧接式致密油<sup>[1,4]</sup>。何文军等<sup>[15]</sup>研究风城组致密储层成因,风城组烃源岩演化过程中释放有机酸,可促进储层溶蚀并改善储集空间,构造缝和成岩收缩缝为油气提供运移通道;单祥等<sup>[16]</sup>研究致密油藏储集特征及控制因素,优势岩相是储层形成的基础,溶蚀作用控制次生孔隙的形成,裂缝是高产的必

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要条件。这些研究缺乏油藏主控因素及成藏模式探讨。

玛南斜坡区致密油藏领域油水关系复杂,前期勘探阶段试油属于纯油层井,在试采过程中普遍存在油水同出,含油率差异明显,特别是提产试验水平井产量差异大,高产富集规律不清,制约精细评价及效益开发。基于研究区测录井、试油试采及分析化验资料,明确致密油藏类型及分布规律,分析致密油藏主控因素,建立成藏模式,为研究区和类似区块的致密油评价开发提供参考。

### 1 区域地质概况

玛湖凹陷位于准噶尔盆地西北缘,是盆地重要的富油凹陷之一。玛南斜坡区处于西北缘向凹陷中心的过渡带(见图 1(a)),整体为一大型单斜构造,接受大量的盆地边缘碎屑沉积。在二叠纪至白垩纪的沉积演化过程中,斜坡区形成多套储盖组合,成为油气聚集成藏的有利区位。玛南斜坡区在十余个层系获得油气发现,累计提交三级石油地质储量  $1.24 \times 10^9 \text{ t}^{[17]}$ 。

二叠系风城组自下而上分为风城组一段(风一段)、二段(风二段)和三段(风三段),受不同类型物源供给和沉积水体盐度的影响,各层段岩石类型存在差异<sup>[17-21]</sup>。风二段可分为一砂组( $P_1f_2^1$ )和二砂组( $P_1f_2^2$ ),其中, $P_1f_2^1$ 为火山活动时期形成的溢流相玄武岩; $P_1f_2^2$ 为扇三角洲前缘—湖泊沉积背景下形成的一套凝灰质中粗砂岩—粉细砂岩,局部夹灰色、灰黑色泥岩,砂体厚度为 96~233 m,平均为 165 m,为主要研究目的层,根据旋回特征可进一步细分为风二段二砂组一至三小层( $P_1f_2^{2-1}$ 、 $P_1f_2^{2-2}$  和  $P_1f_2^{2-3}$ ) (见图 1(b))。

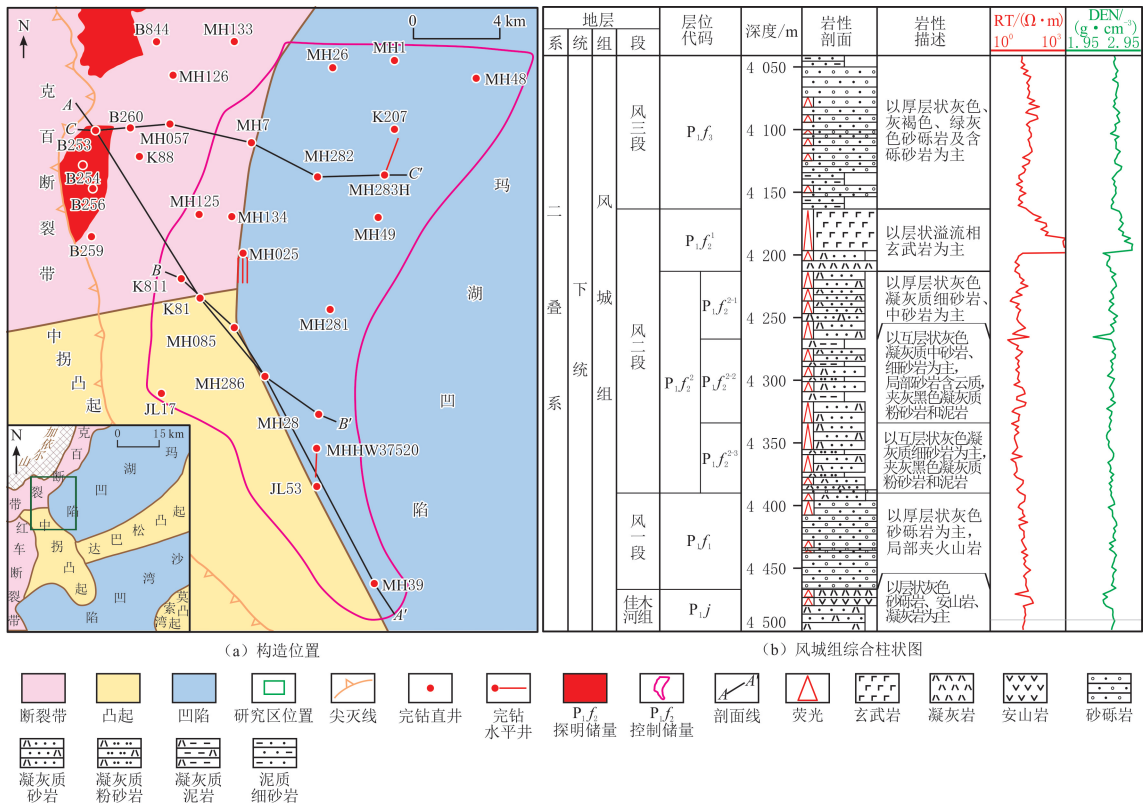


图 1 玛南斜坡构造位置及风城组综合柱状图  
Fig. 1 Tectonic setting and stratigraphic column of the southern slope of Mahu Sag

玛南斜坡区风城组勘探始于 20 世纪 90 年代,早期发现的油藏集中在构造高部位尖灭线附近。近年来,在全油气系统理论的指导下,开展老井复试及新井钻探,发现多个油藏,2020 年提交控制石油地质储量为  $1.45 \times 10^8 \text{ t}$ ,含油面积为 238.7 km<sup>2</sup>(见图 1(a))。为实现控制储量升级及后续建产,部署多口试验水平井。其中,控制储量区北部水平井——MH283H 井邻近碱湖发育区,频繁发生盐堵而生产受限,需要探索配套采油工艺;南部实施的 MH025 试验水平井组及 MHHW37520 井表现较好的生产效果,是现阶段

段建产的重要接替领域。

## 2 油藏类型及分布规律

### 2.1 油藏类型及特征

#### 2.1.1 沉积特征与源储关系

玛南地区凤城组自高部位到凹陷中心依次发育冲积扇、扇三角洲平原、扇三角洲前缘、半深湖和深湖沉积体系,相带的有序性决定沉积物粒度由粗到细的序次变化,孔喉由大到小依次分布<sup>[3-4]</sup>。凹陷中心发育古老碱湖烃源岩,有机质丰度高且处于生烃高峰阶段,具有强大的供烃能力<sup>[17]</sup>。在浮力成藏和自封闭成藏作用的驱动下,发育常规油、致密油和页岩油 3 种类型油藏,空间展布与相带匹配,常规油藏集中发育于近源区冲积扇和扇三角洲平原相,致密油藏集中发育于扇三角洲前缘相,页岩油藏集中发育于半深湖相,呈有序分布特征(见图 2)。

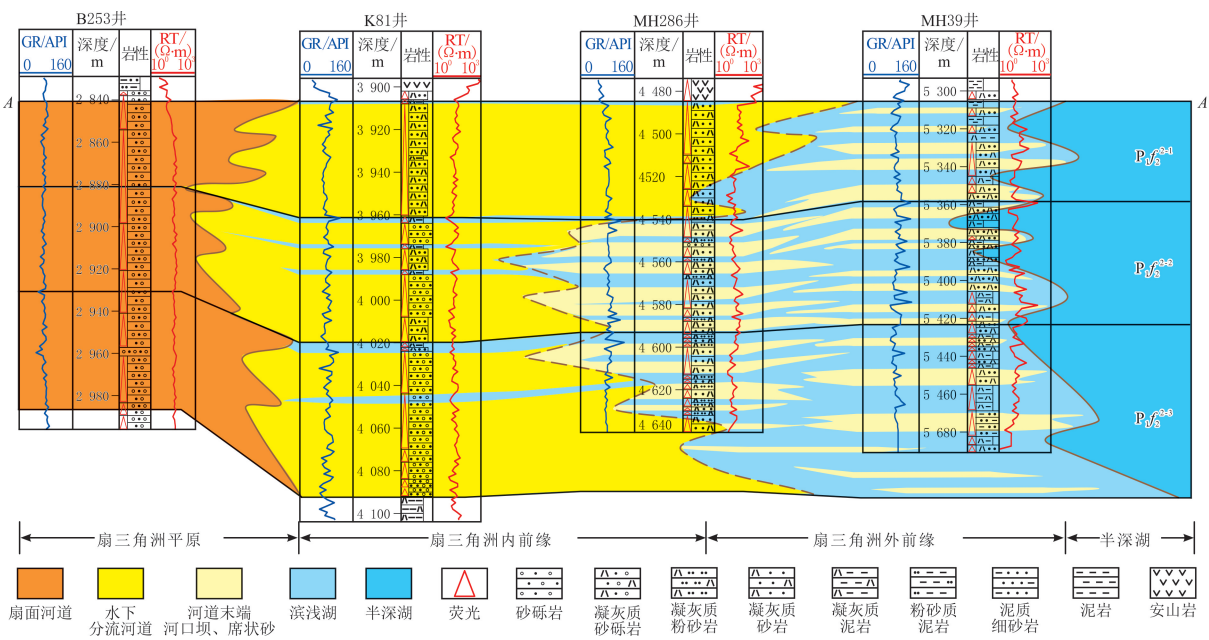


图 2 玛南斜坡风二段沉积相剖面(位置见图 1(a))

Fig. 2 Sedimentary facies profile of the second member in the Fengcheng Formation, southern slope of Mahu Sag(location is shown in Fig. 1(a))

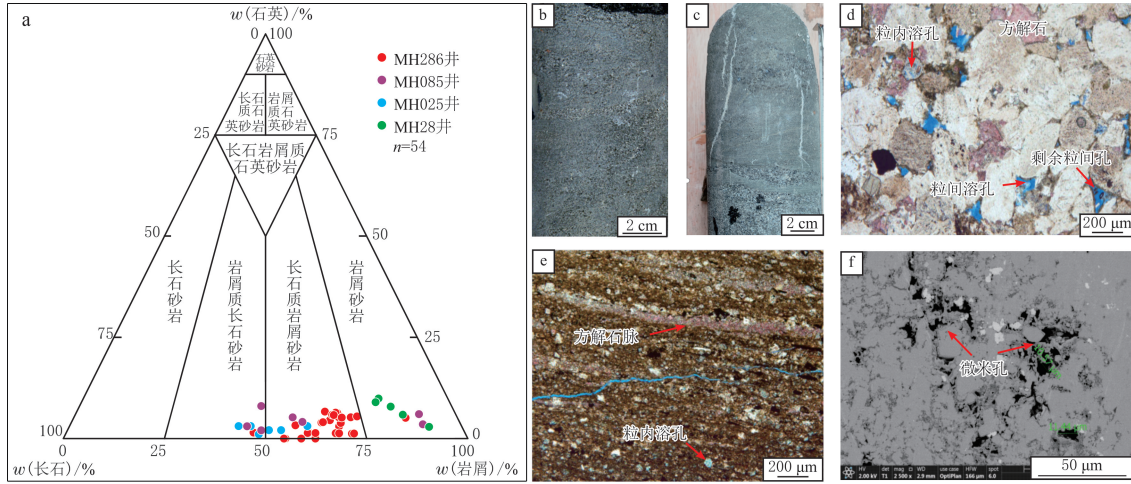
MH28 区块为全油气系统背景下的致密油藏区域,沉积相带主要为扇三角洲前缘相,可细分为内前缘和外前缘相,远离物源方向,沉积微相依次为水下分流河道、河口坝、席状砂、半深湖,砂体厚度逐渐减薄,砂体结构由厚层状逐渐变为薄互层,富有机质泥岩以夹层形式嵌在储层内部。沉积相带决定储层向烃源岩渐变过渡和齿状接触,越靠近凹陷中心,烃源岩越发育,储层与烃源岩为侧向对接关系,烃源岩生成的油气在源储压差的驱动下侧向运移进入致密储层,具有就近成藏的优势。

#### 2.1.2 储层特征

储层岩石类型以长石质岩屑砂岩和岩屑砂岩为主(见图 3(a)),碎屑组分中的岩屑质量分数占主导,平均为 51.2%,岩屑组分以凝灰岩、流纹岩和安山岩岩屑为主;长石质量分数平均为 30.6%,石英质量分数平均为 3.5%;填隙物质量分数为 14.7%,其中,火山凝灰质量分数平均为 7.6%,绿泥石质量分数平均为 3.3%,泥质质量分数平均为 1.5%,含少量方解石、自生钠长石、铁白云石和黄铁矿等。储层岩性以粗中砂岩和粉细砂岩为主(见图 3(b-c)),粒径一般为 0.05~0.50 mm,最大粒径为 2.00 mm。

储层孔隙度为 0.21%~9.60%,中值为 4.52%,渗透率为  $(0.01\sim 1.21)\times 10^{-3} \mu\text{m}^2$ ,中值为  $0.04\times 10^{-3} \mu\text{m}^2$ ,为典型的致密储层。储集空间主要为剩余粒间孔、粒内溶孔、粒间溶孔和晶间微孔等。粗粒级储层在显微镜下见宏孔,孔隙之间具有一定的连通性,微裂缝基本不发育(见图 3(d));细粒级储层在显微

镜下见少量宏孔,微裂缝较为发育(见图 3(e)),在扫描电镜下见粒内溶孔及晶间孔(见图 3(f))。



(a) 岩石矿物组分三元图; (b) 灰色凝灰质中细砂岩, MH025井, 4 369.90 m; (c) 灰色粗砂岩向上过渡为细砂岩, 方解石脉发育, MH286井, 4 534.10 m; (d) 含凝灰质中粗砂岩, 剩余粒间孔占比为50%, 粒间溶孔占比为40%, 粒内溶孔占比为10%, MH025井, 4 307.63 m; (e) 灰黑色凝灰质泥质粉砂岩, 粒内溶孔占比为60%, 微裂缝占比为40%, MH286井, 4 540.50 m; (f) 凝灰质细砂岩, 微米孔发育, MH28井, 4 931.40 m

图 3 玛南斜坡风二段储层特征

Fig. 3 Reservoir characteristics of the second member in the Fengcheng Formation, southern slope of Mahu Sag

### 2.1.3 含油性与生产特征

研究区油藏呈整体含油、局部富集的特征,油藏边界受岩性和物性控制。纵向上,测录井资料可见大套连续油气显示,气测全烃与密度曲线响应特征具有一致性,甜点纵向集中发育;平面上,探评井显示见油,产量存在较大差异,部分井在试油期间为纯油,在试采期间油水同出,整体表现为试油初期含油饱和度高,含油率为 70%~100%,试采期间油水比逐渐稳定,含油率为 35%~80%,生产特征指示为典型致密油藏。

### 2.2 甜点表征及分布规律

采用研究区常规测井曲线评价含油性难度大,受岩石成分多样、孔隙结构多变的影响,油层识别符合率低;核磁共振测井受岩性影响小,可直观、准确反映孔隙和流体性质,广泛应用于致密油、页岩油等复杂储层的物性、含油性解释。基于核磁共振测井变频技术,将核磁共振  $T_2$  谱分解成束缚水、可动水、束缚油及可动油 4 种状态的流体,实现流体定量识别<sup>[22-25]</sup>。建立以含油孔隙度为核心参数的研究区甜点评价方法,含油孔隙度的地质意义为有效孔隙度与含油饱和度的乘积,代表岩石中的含油体积占比,在核磁共振测井上为束缚油和游离油部分,通过核磁共振  $T_2$  截止值表征。

开展岩心核磁共振实验,确定含油孔隙度  $T_2$  截止值。样品 1 饱和水后水信号分量明显增加,集中分布在  $T_2$  截止值 10 ms 前(见图 4(a)),样品 2 饱和油后油信号分量明显增加,集中分布在  $T_2$  截止值 10 ms 后(见图 4(b)),确定含油孔隙度  $T_2$  截止值为 10 ms。开展全区核磁共振测井解释,结合 JL46、MH134、MH025、MH085、K811、MH286 和 MH28 等井试油生产数据,建立含油孔隙度与试油强度交会图(见图 5),以米产油指数衡量试油强度,其为试油单井日产油量与射孔厚度之比。由图 5 可见,含油孔隙度与米产油指数具有良好的正相关关系,当含油孔隙度小于 1.0%时,不具备工业产油能力;随含油孔隙度的增大,试油强度逐渐变强,当含油孔隙度为 4.0%时,米产油指数为 1.4 t/m。

研究区纵向发育 5 套甜点(见图 6),其中,  $P_1 f_2^{2-1}$  发育 3 套薄层甜点,平均厚度为 7.2 m,分散分布;  $P_1 f_2^{2-2}$  和  $P_1 f_2^{2-3}$  各发育 1 套甜点,厚度大,平均分别为 29.3 m 和 31.5 m,集中分布,平面展布稳定,多口试井获工业油流,局部水平井提产试验效果良好。

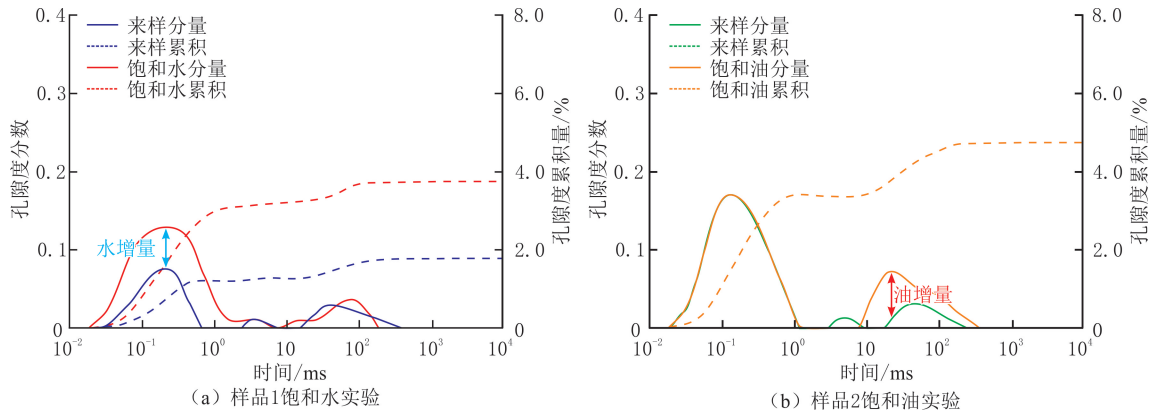


图 4 玛南斜坡风二段岩心核磁共振实验结果

Fig. 4 NMR experiments on cores from the second member of the Fengcheng Formation, southern slope of Mahu Sag

### 3 成藏主控因素

在生烃膨胀力的作用下,致密油藏油气克服毛细管压力,在储层内聚集成藏,控制因素包括烃源岩质量差异、与烃源岩的距离、源储配置类型、储层条件、有无裂缝疏导和充注动力等<sup>[26]</sup>。根据甜点分布特征及试油试采资料,研究区成藏主控因素为储层品质、源储配置和异常高压。

#### 3.1 储层品质

致密油藏油气充注受源储压差驱动影响,在同等充注压力下,储层孔喉越大、连通性越好,油气充注阻力越小,越容易聚集成藏<sup>[27-29]</sup>。根据研究区高压压汞资料,对孔喉结构进行表征,将储层划分为三类(见表 1、图 7)。

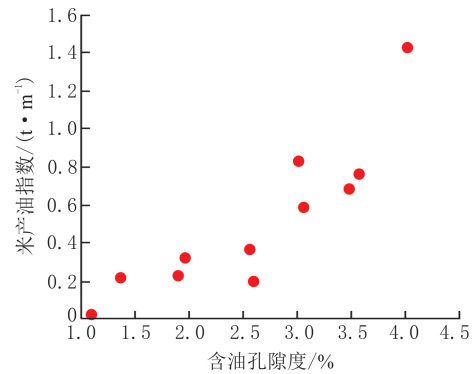


图 5 玛南斜坡风二段含油孔隙度与试油强度交会图

Fig. 5 Crossplot of oil-bearing porosity and oil test intensity of the second member in the Fengcheng Formation, southern slope of Mahu Sag

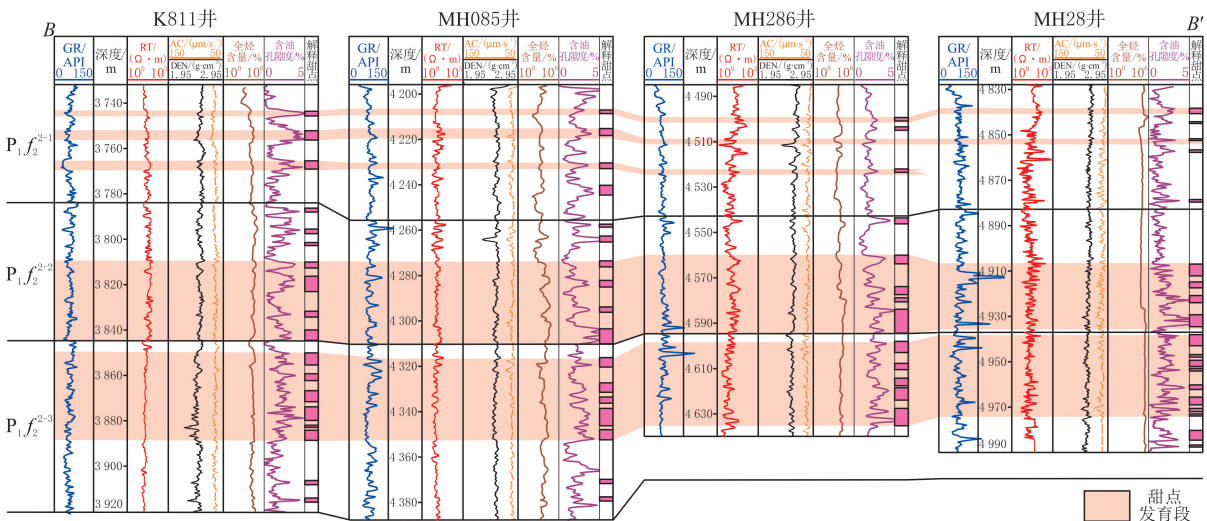


图 6 玛南斜坡风二段甜点分布(位置见图 1(a))

Fig. 6 Sweet spot distribution of the second member in the Fengcheng Formation, southern slope of Mahu Sag(location is shown in Fig. 1(a))

表1 玛南斜坡风二段不同储层类型孔喉结构参数

Table 1 Pore-throat structure parameters of different reservoir types of the second member in the Fengcheng Formation, southern slope of Mahu Sag

储层类型	排驱压力/ MPa	毛细管半径/ $\mu\text{m}$	中值压力/ MPa	中值半径/ $\mu\text{m}$	最大进汞饱和度/ %	退汞效率/ %
I类	0.80~4.63 2.42	0.06~0.17 0.11	8.47~18.18 13.85	0.04~0.09 0.06	79.79~98.94 89.15	24.06~29.98 29.03
II类	3.10~9.33 5.77	0.02~0.08 0.04	22.07~74.68 39.52	0.01~0.04 0.03	56.85~85.89 69.59	16.47~27.67 22.55
III类	0.67~34.18 13.26	0.01~0.10 0.02	26.55~146.99 61.23	0.01~0.03 0.015	55.99~96.89 78.25	11.85~26.37 18.81

注:  $\frac{\text{最小} \sim \text{最大}}{\text{平均}}$ 。

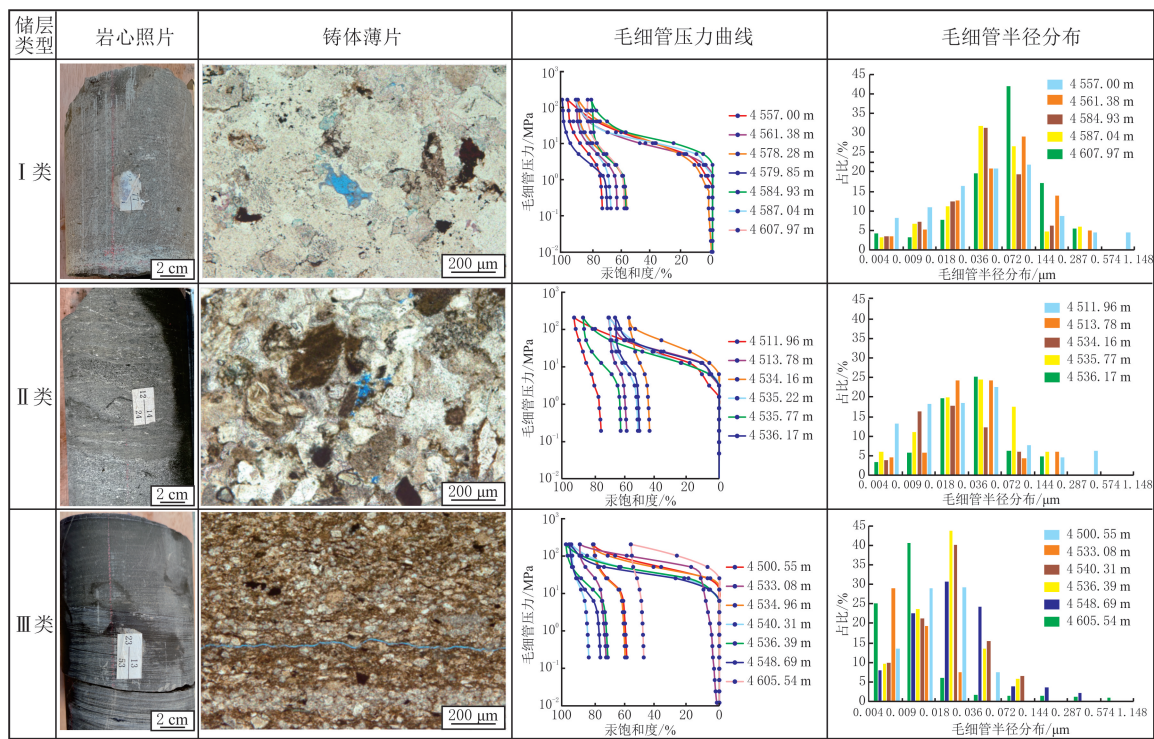


图7 玛南斜坡风二段储层类型特征

Fig. 7 Reservoir type characteristics of the second member in the Fengcheng Formation, southern slope of Mahu Sag

I类储层孔喉结构最好,排驱压力和中值压力低,平均分别为2.42和13.85 MPa,毛细管半径大,平均为0.11  $\mu\text{m}$ ,退汞效率高,平均为29.03%,呈孔径大、连通性好、渗流能力好的特征。储层孔隙度为4.2%~9.6%,平均为5.8%,渗透率为 $(0.022 \sim 0.141) \times 10^{-3} \mu\text{m}^2$ ,平均为 $0.051 \times 10^{-3} \mu\text{m}^2$ 。镜下孔隙发育明显,主要为粒间孔。岩性主要为低凝灰质中粗砂岩类,粒度粗,碎屑组分占比高,凝灰质质量分数低(8.4%),是孔喉结构好的主要原因。储层纵向上分布于  $P_1f_2^{2-2}$  和  $P_1f_2^{2-3}$ ,是甜点集中发育段。

II类储层孔喉结构次之,排驱压力和中值压力较高,平均分别为5.77和39.52 MPa,毛细管半径小,平均为0.04  $\mu\text{m}$ ,退汞效率中等,平均为22.55%。储层孔隙度为3.9%~6.0%,平均为4.8%,渗透率为 $(0.017 \sim 0.043) \times 10^{-3} \mu\text{m}^2$ ,平均为 $0.029 \times 10^{-3} \mu\text{m}^2$ 。镜下孔隙发育较少,以粒间孔和粒内溶孔为主。岩性为高凝灰质中粗砂岩类,属于中粗砂岩类,凝灰质质量分数高(16.2%),是导致孔喉结构差的主要原因。一方面,凝灰质组分易在压实过程中发生塑性变形并占据孔隙空间,加剧压实减孔;另一方面,凝灰质组分易在埋藏过程中发生蚀变作用而生成高岭石和绿泥石等黏土矿物,在粒间原地堆积,部分黏土矿物以包壳形式存在于碎屑颗粒表面,增加孔喉结构复杂性<sup>[30-32]</sup>。储层纵向上分布于  $P_1f_2^{2-1}$ ,甜点段发育薄而

分散。

Ⅲ类储层孔喉结构最差,排驱压力和中值压力最高,平均分别为 13.26 和 61.23 MPa,毛细管半径小,平均为 0.02  $\mu\text{m}$ ,采收效率最低,平均为 18.81%。储层孔隙度为 0.2%~5.4%,平均为 2.8%,渗透率为  $(0.010\sim 0.067)\times 10^{-3} \mu\text{m}^2$ ,平均为  $0.020\times 10^{-3} \mu\text{m}^2$ 。镜下未见明显孔隙,部分样品微裂缝发育,扫描电镜下见长石和白云石溶蚀孔。储层纵向上分布于  $P_1f_2^{2-1}\sim P_1f_2^{2-3}$ ,以薄层形式出现,为非甜点发育段。

根据取心井——MH286 井分析化验结果,研究区储层类型的纵向分布具有一定的规律性(见图 8),  $P_1f_2^{2-1}$  以发育Ⅱ类储层为主,凝灰质质量分数高;  $P_1f_2^{2-2}$  和  $P_1f_2^{2-3}$  以发育Ⅰ类储层为主,凝灰质质量分数低;局部发育薄层Ⅲ类储层。火山活动的强弱和湖平面的变化在一定程度上影响储层纵向分布特征。风二段自下而上火山活动持续增强,  $P_1f_2^1$  为火山活动形成的一套安山玄武岩地层。  $P_1f_2^{2-3}$  至  $P_1f_2^{2-2}$  沉积期,火山活动较弱,湖平面较高,陆源碎屑中凝灰质质量分数少,沉积物入湖后经过水体淘洗而具有一定分选性,形成的储层质量较好;  $P_1f_2^{2-1}$  沉积期,火山活动较强,产生大量的凝灰质物质,同时湖平面开始下降,沉积物入湖后快速沉积,分选较差,凝灰质后期蚀变形形成黏土矿物,储层孔喉结构进一步复杂化。

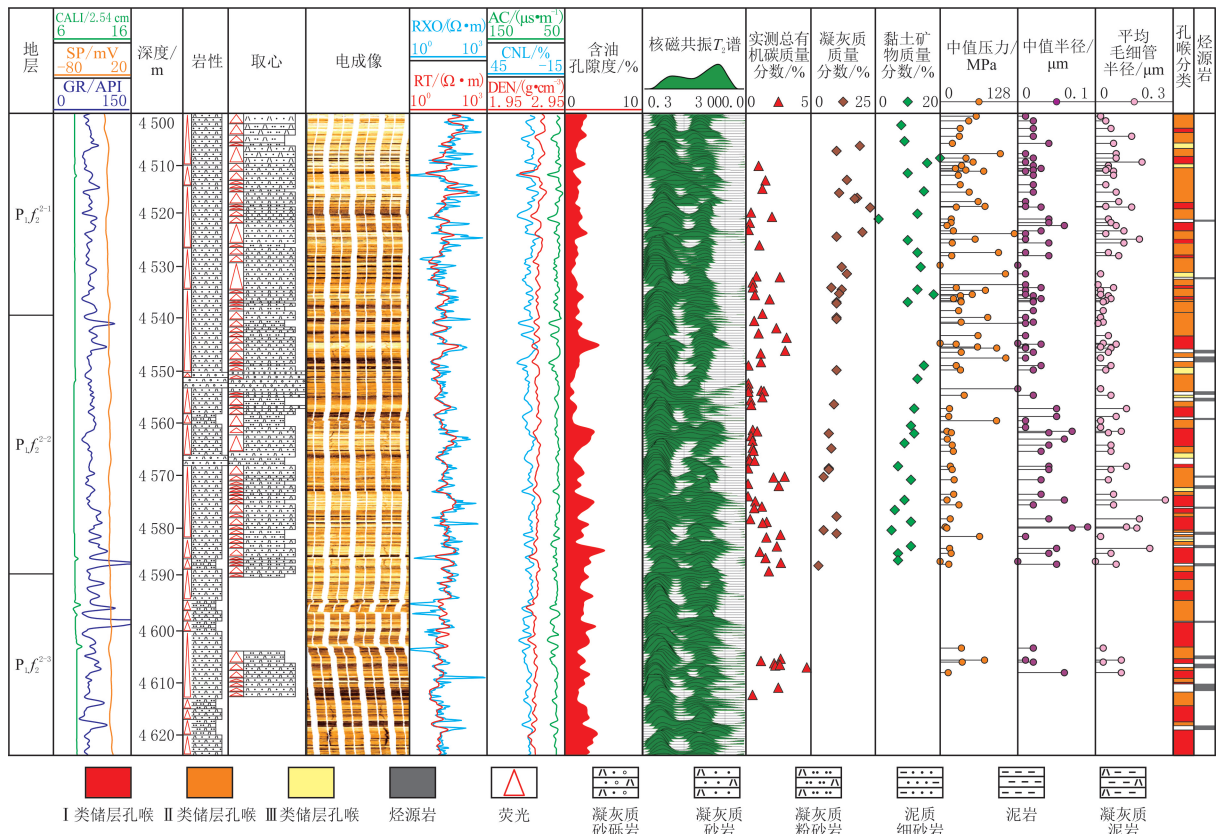
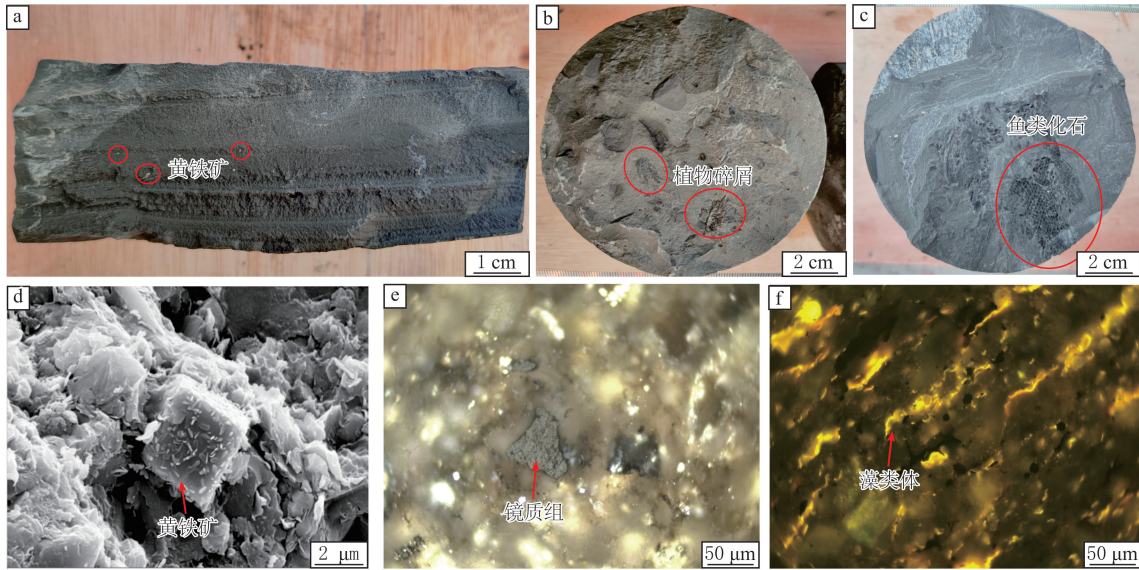


图 8 玛南斜坡风二段 MH286 井储层纵向分布特征

Fig. 8 Vertical characteristics of the reservoir in well MH286 of the second member in the Fengcheng Formation, southern slope of Mahu Sag

### 3.2 源储配置

优质烃源岩的发育控制致密油的整体分布,良好的源储配置对油气分布有一定的控制作用。玛南地区油气主要来源于凹陷中心的古老碱湖烃源岩<sup>[17]</sup>,在扇三角洲外前缘相向湖相交互沉积过程中,斜坡区低部位薄层烃源岩发育。岩性为灰黑色泥岩,发育水平层理,见植物碎屑、鱼类化石及黄铁矿,反映深水还原环境(见图 9);总有机碳质量分数为 0.33%~5.82%,平均为 1.51%,S1+S2 为 0.23~21.02 mg/g,平均为 4.71 mg/g,氯仿沥青“A”质量分数为 0.02%~1.26%,平均为 0.34%,为好—很好烃源岩。镜下见高等植物组分及藻类体(见图 9),有机质类型以Ⅱ类为主;镜质体反射率为 0.84%~1.58%,平均为 1.23%,处于成熟演化阶段。



(a) 灰黑色泥岩, 水平层理, 见黄铁矿晶粒, MH286井, 4 584.50 m; (b) 深灰色粉砂质泥岩, 见植物碎屑, MH286井, 4 582.30 m; (c) 灰黑色泥岩, 见鱼类化石, MH286井, 4 563.20 m; (d) 粒间自生黄铁矿, MH286井, 4 581.70 m; (e) 有机质显微组分(镜质组), MH28井, 4 937.00 m; (f) 有机质显微组分(藻类体), MH085井, 4 319.70 m

图 9 玛南斜坡风二段烃源岩特征

Fig. 9 Source rock characteristics of the second member in the Fengcheng Formation, southern slope of Mahu Sag

研究区薄层烃源岩主要发育源储分离型和源储互层型配置。平面上,受相带控制,远离凹陷中心,沉积相带以内前缘相为主,发育源储分离型配置;靠近凹陷中心,沉积相带以外前缘相为主,水侵时期过渡至湖相沉积,发育源储互层型配置,具体形式为厚储夹多套薄源,源储比小于 30%。研究区更低部位发育源储比更高的源储互层型配置,直至过渡至页岩油藏。

纵向上,受沉积纵向演化控制, $P_1f_2^{2-1}$ 以源储分离型配置为主, $P_1f_2^{2-2}$ 和  $P_1f_2^{2-3}$ 以源储互层型配置为主。 $P_1f_2^{2-2}$ 砂组顶部发育最大湖泛面(见图 10),以最大湖泛面为界,风二段纵向划分为 2 个长期旋回,最大湖泛面之上  $P_1f_2^{2-1}$ 为典型的砂体进积水退体系域,泥质夹层欠发育,随水体变浅,有机质难以保存,基本不发育烃源岩,油气侧向运移,为源储分离型配置;最大湖泛面之下  $P_1f_2^{2-2}$ 和  $P_1f_2^{2-3}$ 受水进体系域控制,自下而上水体逐渐加深,砂体以加积形式呈层状产出,泥质夹层较发育,且深水环境有利于细粒沉积物中有机质的保存,烃源岩以夹层形式与储层叠置出现,形成源储互层型配置。

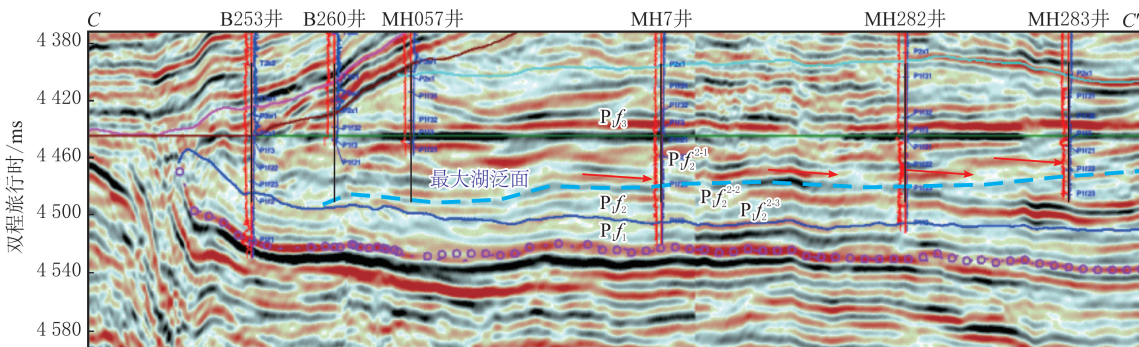


图 10 过 B253—B260—MH057—MH7—MH282—MH283 井地震相剖面( $P_1f_3$  底拉平)(位置见图 1(a))

Fig. 10 Interpreted seismic facies profile along the well tie of B253-B260-MH057-MH7-MH282-MH283, flattened on the base of the  $P_1f_3$  to reveal depositional architecture(location is shown in Fig. 1(a))

源储互层型配置更有利于油气富集,薄层烃源岩既为油藏形成提供物质基础,又对油气富集起促进作用。这是因为烃类吸附于颗粒表面而形成油膜,将储层的润湿性由水润湿转变为油润湿,有效降低邻源油气充注阻力,促进油气在储层中高效聚集<sup>[33-34]</sup>;同时,生烃增压产生的微裂缝能够增加储层的渗透性,为

油气运移提供优势通道<sup>[27-29,35]</sup>。

### 3.3 异常高压

压力对油气运移及富集具有重要作用,控制含油性及产能的平面差异。根据研究区试油统计结果,试油强度与压力因数呈明显正相关关系(见图 11)。不同压力因数的水平井试采差异大,构造高部位 MH025 井组(MH-HW37271、MHHW37272、MHHW37273 等井)压力因数约为 1.21,试采一年,压力下降快,落零即转抽,日产油 15.8 t,含水率较高,平均为 63.0%;构造低部位 MHHW37520 井压力因数约为 1.40,试采效果远好于 MH025 井组的,试采期间的压力下降慢,目前套压为 21 MPa,具备自喷生产能力,平均日产油 24.0 t,含水率低,平均为 21.9%(见图 12)。

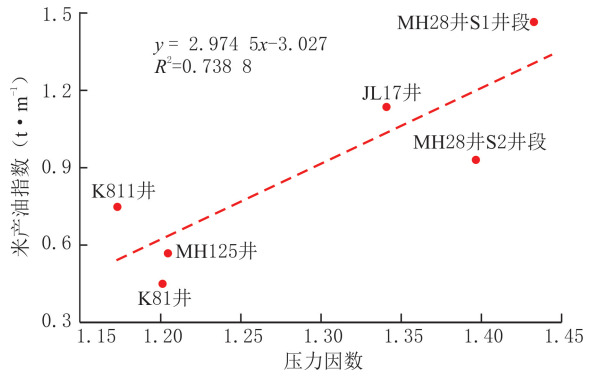


图 11 玛南斜坡风二段压力因数与试油强度关系  
Fig. 11 Relationship between pressure coefficient and oil test intensity of the second member in the Fengcheng Formation, southern slope of Mahu Sag

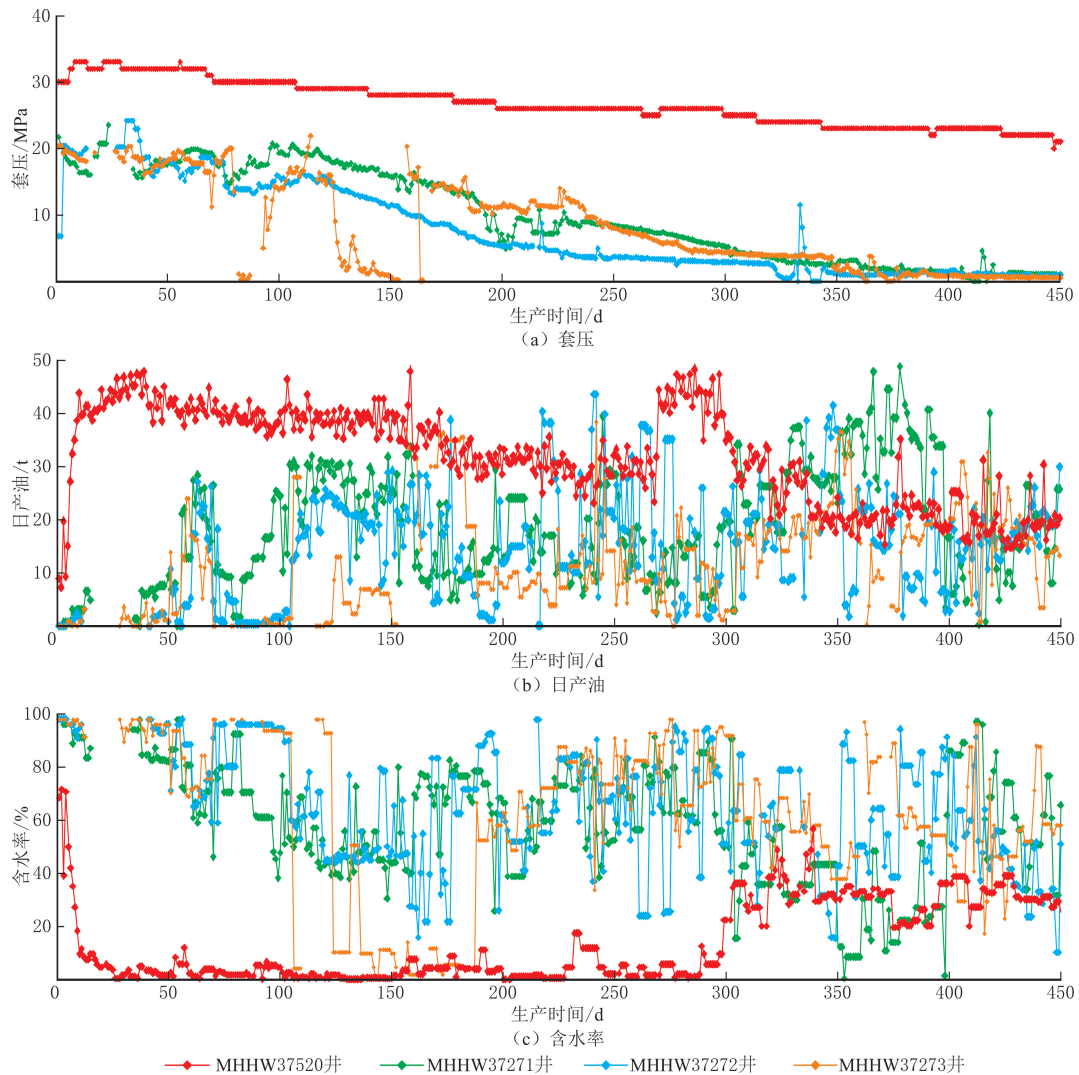


图 12 玛南斜坡风二段 MH025 水平井组与 MHHW37520 井试采数据  
Fig. 12 Production test comparison between the MH025 horizontal well pad and well MHHW37520 of the second member in the Fengcheng Formation, southern slope of Mahu Sag

地层压力是影响试采结果的重要因素。常见的异常高压成因包括欠压实机制、流体膨胀机制、构造挤压机制和伊/蒙转化机制等。根据测井曲线分析异常高压成因,其中声波速度—密度交会图分析法是广泛应用于识别异常高压成因的方法之一,特别是对由流体膨胀引起的超压。在正常压实的地层中,随深度增加,孔隙度减小,地层垂直应力与声波速度逐渐增加,沉积物处于持续加载的过程;对于由流体膨胀作用引起的异常高压,孔隙流体承压,声波速度降低的同时,密度基本不变,密度与声波速度的投影处于卸载曲线<sup>[36-38]</sup>。研究区MH281和MH085井声波速度—密度交会图(见图13)显示,上乌尔禾组和百口泉组的声波速度—密度散点主要落在加载曲线上,夏子街组和下乌尔禾组的部分散点表现为加载特征,部分散点表现为卸载特征。根据研究区正常压实的地层测井曲线特征,风二段散点呈密度增加而声波速度增加的趋势,实际上风二段的散点主要以卸载特征为主,具有声波速度减小而密度基本保持不变的特征,指示研究区风二段异常高压主要为生烃膨胀成因。

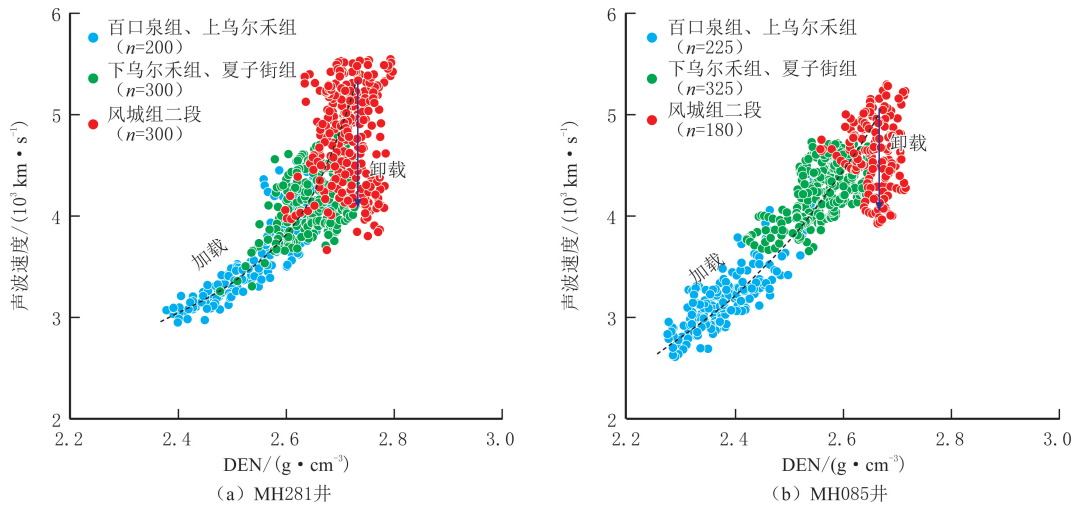


图13 MH281和MH085井声波速度—密度交会图  
Fig. 13 Acoustic velocity-density crossplot of wells MH281 and MH085

生烃膨胀作用对地层超压的贡献率为卸载机制对地层超压的贡献比率<sup>[36-37]</sup>。越向研究区东北部,流体膨胀对地层超压的贡献率越高(见图14),与区域烃源岩展布趋势一致,表明研究区东北部靠近生烃中心,发育源储一体油藏。基于地震数据建立压力预测模型,明确地层压力平面展布特征,研究区地层压力自南西向北东方向逐渐升高,其中,蓝色区域为正常压带,压力因数为1.00~1.15;绿色区域为过渡带,压力因数为1.15~1.30;黄色与红色区域为超压带,压力因数为1.30~1.60(见图15)。

异常高压对致密油富集具有重要控制作用,特别是由生烃膨胀引起的异常高压有利于油气克服毛管压力,在储层内聚集成藏,局部形成高含油饱和度区;同时,在油藏开发过程中提供较高的地层能量,有利于油气产出。

#### 4 成藏模式

玛南斜坡区致密油藏受储层品质、源储配置及异常高压等因素控制,整体为源储侧接、优储控富、超压驱动成藏模式,为夹在常规油藏与页岩油藏之间的过渡领域,低部位凹陷中心发育主力烃源岩,是研究区油气主要来源(见图16)。沉积相带的有序分布使得岩性序次发生变化,储层与烃源岩呈齿状侧接,烃源岩生成的油气侧向运移至邻近的储层。优质储层控制油气富集程度, $P_1f_2^{2-1}$ 为最大湖泛面之上的高位体系域,发育大套厚层砂体,受火山活动影响,凝灰质质量分数高,孔喉结构差,油气充注强度低,油层发育薄而分散; $P_1f_2^{2-2}$ 和 $P_1f_2^{2-3}$ 为最大湖泛面之下的水进体系域,振荡环境的水体对砂体有一定的淘洗作用,受火山作用影响弱,凝灰质质量分数低,孔喉结构好,同时发育源储互层型配置,薄层烃源岩的发育具有改善润湿性、降低充注压力的叠加优势,油气富集程度高,是油层集中发育层段。凹陷中心烃源岩由生烃膨胀引起的异常高压为油气充注提供动力,远离烃源岩方向,压力因数的降低导致油气充注程度逐渐减弱,

含油饱和度逐渐降低。异常高压为油藏开发提供充足的能量,高压区水平井长期试采压力稳定,含油率高;低压区水平井长期试采压力下降快,含水率相对高。

研究区致密油藏富集规律为:纵向上, $P_1f_2^{2-2}$  和  $P_1f_2^{2-3}$  为主力含油层系,油层发育稳定且累积厚度大;平面上,低部位异常高压区油气富集程度更高,开发过程中的含油率及压力更为稳定,可作为效益建产及升级探明的先行试验区块。

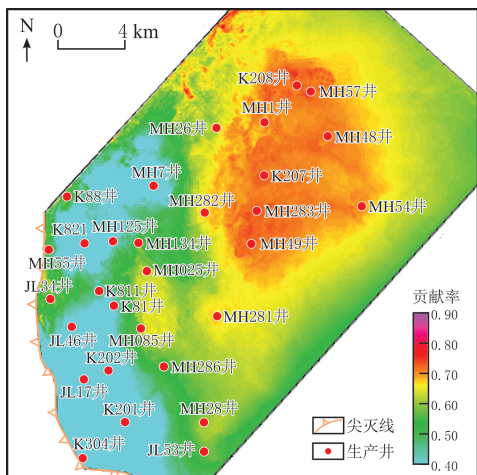


图 14 玛南斜坡风二段流体膨胀作用对地层超压贡献率

Fig. 14 Contribution of fluid expansion to overpressure for the second member of the Fengcheng Formation, southern slope of Mahu Sag

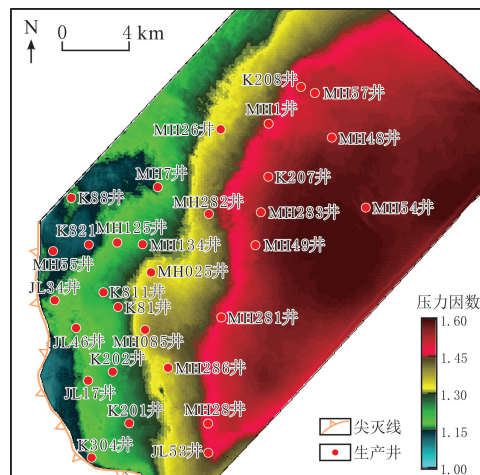


图 15 玛南斜坡风二段地层压力预测

Fig. 15 Formation pressure prediction for the second member of the Fengcheng Formation, southern slope of Mahu Sag

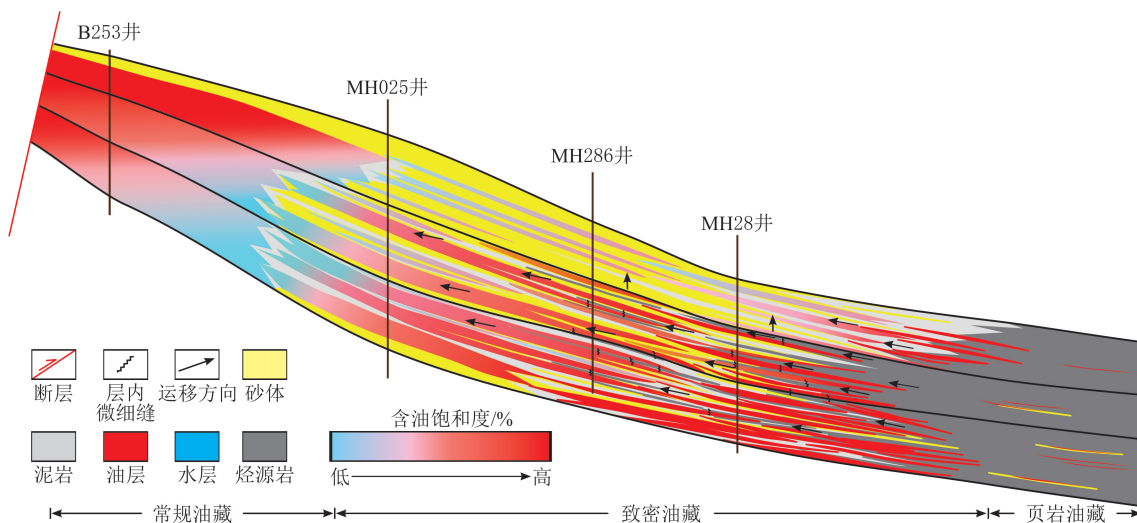


图 16 玛南斜坡区风城组致密油藏成藏模式

Fig. 16 Tight oil accumulation model of the Fengcheng Formation in the southern slope of Mahu Sag

## 5 结论

(1) 准噶尔盆地玛南斜坡区风二段油藏为全油气系统背景下的致密油藏,沉积相带决定储层向烃源岩过渡,源储侧向呈齿状对接。储层以粗中砂岩和粉细砂岩为主,物性差,油藏呈整体含油、局部富集特征。

(2) 研究区油藏受储层品质、源储配置和异常高压等因素控制,储层品质控制油气富集程度,储层分为三类,其中 I 类储层岩性较粗,孔喉结构好,是油气优先富集区;源储互层型配置中薄层烃源岩的发育进一步降低油气充注阻力,为油气成藏提供条件,形成较高的含油饱和度;异常高压控制含油性及产能平面分

布,超压区水平井含油率及产能更高。

(3)研究区致密油藏的成藏模式为源储侧接、优储控富、超压驱动,纵向上, $P_1f_2^{2-2}$ 和 $P_1f_2^{2-3}$ 为甜点主力发育层系;平面上,低部位异常高压区油气富集程度更高,可作为后续开发建产的有利区块。

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mental shale oil enrichment result centered on the concept of “Enrichment dominated by sweet spot interlayers (Calcareous-Dolomitic Shale), accumulation supported by hydrocarbon-prone matrix (Mixed Shale), and preservation sealed by tight interlayers(Felsic Shale)”. This result provides significant theoretical guidance for shale oil exploration in the Subei Basin and analogous geological settings.

**Key words:** Gaoyou Sag; Paleogene; second member of Funing Formation; shale oil; lithofacies assemblages; enrichment model; pore structure; oil-bearing characteristics; hydrocarbon mobility

**The main controlling factors and accumulation model of laterally connected source-reservoir tight oil reservoirs in the whole oil and gas system: a case study of the second member of Fengcheng Formation in Manan Slope Area/2026,50(2):81-94**

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**Abstract:** The southern slope of the Mahu Sag is a critical replacement area for unconventional oil and gas exploration in the Junggar Basin. Based on data from well logging, core analysis, laboratory tests, and production tests in the study area, research was conducted on the main controlling factors and accumulation model of tight oil reservoirs in the second member of the Fengcheng Formation( $P_1f_2$ ) in the southern slope area, according to reservoir types and distribution patterns. The results indicate that the  $P_1f_2$  reservoirs in the southern slope are tight oil accumulations within a total petroleum system, characterized by lateral source-reservoir juxtaposition, overall oil-bearing potential, and local enrichment. Sweet spots are primarily distributed in the second sub-layer( $P_1f_2^{2-2}$ ) and the third sub-layer( $P_1f_2^{2-3}$ ) of the second member interval of  $P_1f_2$ . The reservoirs are jointly controlled by reservoir quality, source rock thickness, and abnormal pressure. Reservoir quality governs the degree of hydrocarbon enrichment. Based on pore-throat structure, the reservoirs can be classified into three categories, with class I reservoirs having coarser grain size and better pore-throat structure, serving as the preferred areas for hydrocarbon enrichment. In the thick-reservoir and thin-source assemblage, the development of thin-layer source rocks not only provides the material basis for reservoir formation but also facilitates accumulation by altering reservoir wettability or generating microfractures through hydrocarbon-generation pressurization. Abnormal high pressure controls the spatial distribution of oil-bearing potential and productivity, with overpressured zones exhibiting higher oil saturation and productivity in horizontal wells. The accumulation model in the study area is defined as lateral source-reservoir juxtaposition, high-quality reservoirs controlling enrichment, and overpressure-driven charging. These findings provide guidance for subsequent development and production in the study area.

**Key words:** Junggar Basin; Manan Slope; Fengcheng Formation; the whole oil and gas system; laterally connected source-reservoir; tight oil reservoir; main controlling factors; accumulation mode

**Microscopic pore-fracture structure characterization of medium-high rank coal reservoirs from eastern margin of Ordos Basin/2026, 50(2):95-108**

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**Abstract:** The development of deep coal reservoirs is the key approach to increasing reserves and production of coalbed methane. The Benxi Formation 8th coals in eastern margin of Ordos Basin were taken as the research object, based on the coal quality parameter test, experiments such as low pressure CO<sub>2</sub> adsorption, low temperature N<sub>2</sub> adsorption, high pressure mercury injection and micron CT scanning were carried out to characterize the pore-fracture structure of medium-high coal reservoirs with a full scale, the characteristics of pore-fracture structure at different scales were comprehensively evaluated, and the influence of metamorphism degree on the development of pore-fracture at different scales was also discussed. The results show that the coal volume type in the study area is mainly characterized by a dual-peak pattern of micropores and fractures, featuring the coexistence of micropores and fractures, and the pore size is mainly concentrated in the range of 0.3–1.5 nm and greater than 1 000 μm. The average volume of micropores, mesoporous pores, macropores and fractures accounted for 70.8%, 16.0%, 8.1% and 5.1% of the total pore volume, respectively. Micropores contribute 98.8% of specific surface area and are the main occurrence sites of adsorbed gas. There are significant differences in the pore-fracture structure of middle-high coal reservoirs. With the increase of coal rank, the metamorphism of coal rock was deepened, the volume of micropores increases steadily, and the volume of fractures increases first and then decreases and then increases, while the change of mesoporous and macro pores volume is not obvious. The coal reservoirs with higher coal rank has higher volume proportion of micropores and stronger adsorption. This result provides theoretical and data support for deep coalbed methane potential evaluation and exploration and development in Ordos Basin.

**Key words:** pore-fracture; structural characterization; coal reservoirs; middle-high coal rank; Benxi Formation; eastern margin of Ordos Basin