

有限充注动力背景下致密储层油水差异成藏再认识 ——以鄂尔多斯盆地华池地区延长组8段为例

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摘要:鄂尔多斯盆地西南部延长组8段致密储层已发现如西峰和姬塬等油藏连片富集区,但在进一步勘探部署时亦发现如华池和城壕等油水差异富集区,储层中油藏的主控因素和分布规律不明。通过对华池东西部烃源岩条件、源储接触关系、砂体规模、储层物性及非均质性的对比解剖,探讨了油水差异富集区原油的成藏主控因素和富集规律。研究表明,源储压差作为致密油的主要成藏动力,其在倒灌运移模式下所能提供的原油充注动力有限。造成华池东西部油水差异富集的主控因素有源储间发育的泥质隔层、砂体发育规模和储层非均质性。其中泥质隔层决定了原油能否向下运移,砂体规模决定了原油能否侧向封堵,储层非均质性决定了单砂体中原油的差异性富集。在有限的充注动力背景下,规模大、整体物性好、均质性强的储层不利于致密油的富集,反而规模小、整体物性较差、非均质性较强的储层因容易形成岩性和物性遮挡而更利于致密油的富集。结果不同以往“好砂带找油”的观点,对鄂尔多斯盆地油水差异富集区下一步的勘探具有一定的参考价值。

关键词:主控因素;差异富集;致密油;长8段;鄂尔多斯盆地

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Further understanding of differential accumulations of oil and water in tight sandstones with limited charging power: A case study of Chang 8 member in Huachi area, Ordos Basin, China

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Abstract: Batches of tight oil reservoirs including Jiyuan and Xifeng reservoirs were found in the 8th member of Yanchang Formation (Chang 8 member) in southwest Ordos Basin. Further exploration in the place reveals some areas with differential accumulations of oil and water such as Huachi and Chenghao areas. Nevertheless, the main controlling factors and distribution patterns of these accumulations are unknown. Based on a detailed discussion on source rock quality, source-reservoir contact relationship, sand body scale, physical properties and heterogeneity of reservoir in eastern and western Huachi area, this study explores the controlling factors and accumulation patterns of oil reservoirs in the differential areas. The results show that the pressure difference between source and reservoir is the main driving force of tight oil accumulations, but provides only limited charging power with backward migration. The factors controlling the differential accumulation of oil and water in eastern and western Huachi area are the argillaceous barriers grown between source and reservoir, sand body size and reservoir heterogeneity, of which, the argillaceous barriers control the downward migration of crude oil, the size of sand body serves as the lateral sealing for crude oil, and the reservoir heterogeneity

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determines the differential accumulation of crude oil in a single sand body. Given the limited charging power, reservoirs that are large in scale, good in physical properties and strong in homogeneity, are not ideal harbors for oil to accumulate. On the contrary, reservoirs that are small in scale, poor in physical properties and strong in heterogeneity, are more readily to provide lithological or physical barriers to stop the escape of oil. This understanding, quite different from the previous viewpoint that “high-quality sands indicate good oil traps”, may serve to shed light on the further exploration in the differential areas of the Ordos Basin.

Key words: main controlling factor, differential accumulation, tight oil, Chang 8 member, Ordos Basin

近年来,世界范围内有关非常规油气藏的研究热度不断增加,鄂尔多斯盆地由于其独特的沉积环境和构造特征,在中国致密油气勘探开发领域处于重要地位^[1-4]。前期的勘探实践表明鄂尔多斯盆地延长组具有良好的油气成藏条件,并在各层系中均发现了油气藏的存在,这在很大程度上完善并发展了中国致密油气源内、近源和远源成藏理论^[5-8]。在国内致密油成藏方面,前人做了大量的研究,并提出不少值得借鉴的理论:如赵靖舟等^[9]认为优质烃源岩、“甜点区”、成藏动力和近源聚集是中国陆相致密油成藏的主要条件;杨华等^[10]提出丰富的微尺度孔隙是稠油富集的前提;陈世加等^[11-12]发现源储之间泥质隔夹层对原油的运移起到阻碍作用;任战利等^[13]则认为沉积微相、优质储层控制了延长组致密油藏的形成和富集。但在将这些理论运用于实际生产中时却出现新的问题,如在大量的研究中发现致密储层中油水差异富集的现象,而油藏的成藏主控因素和富集规律不明^[14-16]。鄂尔多斯盆地华池地区东西部相距较近,砂体规模、连续性和储层物性较差的华池东部主要为油井,而砂体规模、连

续性和储层物性更好的华池西部却出大水(图1),油水分布关系主要受何种因素的控制目前还没有成熟的理论对此做出解释。本文在前人研究的基础上,从烃源岩条件、源储接触关系、砂体发育规模和储层物性及非均质性等方面入手,探讨了华池地区油水差异富集的成藏规律,以求对未来相似领域的勘探开发起到参考作用。

1 研究区成藏背景

鄂尔多斯盆地华池地区延长组8段(长8段)储层以浅水三角洲前缘亚相为主,重要的储集体为三角洲前缘水下分流河道^[17-18]。长8段作为延长组三大主力油层组之一,属于低孔、低渗储层,其与上覆长7段的厚层优质烃源岩形成近源“倒灌”成藏模式。这种模式下,源岩和下伏储层之间的压差和输导断裂是造成油气倒灌运移的主要原因,而源岩超压值大小决定着油气垂向倒灌运移的距离和分布范围^[19-20]。姚泾利等^[21]利用测井声波资料计算得出长7段烃源岩与长8

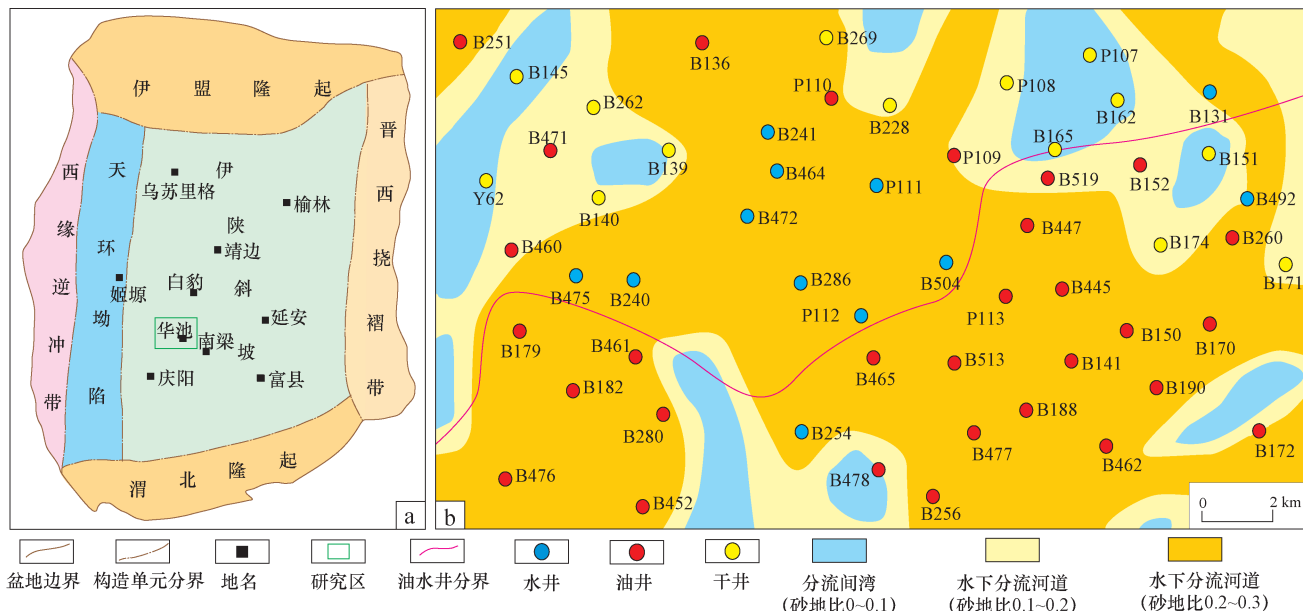


图1 鄂尔多斯盆地位置示意图(a)及华池地区油藏分布(b)

Fig. 1 Schematic diagram showing the location of the Ordos Basin (a) and the reservoir distribution in the Huachi area (b)

段储层之间存在着4~10 MPa的过剩压力差;郭秋麟等^[22]用“膨胀流驱动论”模拟延长组致密油聚集量时得出75 m厚的长8段储层中油柱高度为15.5 m,显示源储间的过剩压力差在长8段致密储层中所能引起的原油充注距离有限。笔者通过该区的声波测井资料计算亦发现长7段烃源岩与长8段储集层之间的剩余压差达到6~18 MPa,但其所能提供的原油充注动力有限。

以Z256井为例,虽然长8段储集层与长7段烃源岩紧邻,但由于储层致密(平均孔隙度7.34%,平均渗透率 $0.16 \times 10^{-3} \mu\text{m}^2$),原油只能够向下运移7~9 m的距离,在岩心上反映为长8段块状砂岩从上到下含油性依次减弱,由油浸、油斑逐渐变为不含油(图2)。华池地区靠近湖盆中心,河道摆动大、持续时间短、分叉严重,造成了储层垂向和平面上强的非均质性。有限的充注动力和复杂的沉积环境,使得华池地区长8段储层中油水差异富集情况频繁出现。

2 成藏控制因素

2.1 烃源岩条件

据前人的研究^[23-24],鄂尔多斯盆地长7段发育有一套优质烃源岩,其厚度达到40 m以上,有机质丰度高,生烃能力强,分布范围广,干酪根类型为I型和II型,属腐泥型有机质,且已达到成熟-高成熟阶段,处在强排烃阶段,为延长组各层系组提供了充足的油源支

撑。长7¹亚段、长7²亚段和其他层位的薄层烃源岩和黑色泥岩生烃能力有限,长8段储层中的原油主要来自于上覆的长7³亚段烃源岩^[25-26]。华池地区处于湖盆中心地带,其东西部相距近,沉积环境相同,在烃源岩质量和异常高压方面无明显的区别,烃源岩条件和异常高压不是造成华池东西部油水差异聚集的主要控制因素。

2.2 源-储接触关系

长8段储层与长7段源岩之间构成倒灌成藏模式,这种模式下原油充注动力随深度急剧减小,源、储之间发育的泥质隔层对原油向下运移产生重要影响。从华池东西部井的测井曲线上来看(图3),油水井的源、储接触关系明显不同,出水井的源、储之间存在明显的GR曲线高值段,普遍发育粉砂质泥岩、泥岩等隔层,阻碍油气大规模向下运移;而油井源、储之间GR曲线无明显变化,有利于长7³亚段烃源岩生成的油气向下运移。图3显示,虽然华池西部出水井的长8段储层与长7³亚段底界面相距较近,甚至是紧挨着,但是由于在长7段底部存在一套或多套有别于长7³亚段烃源岩的泥质隔层,导致原油不能够顺利的向下运移,长8¹亚段储层普遍不含油。相反,华池东部出油井长7³亚段为整套的烃源岩,在其下部未见有明显的隔层存在,使得原油可以向下运移,并在长8¹亚段的储层中聚集成藏,下伏储层普遍含油。可见,源、储之间泥质或粉砂质隔层的存在,对油藏的平面分布起到关键的控制作用。

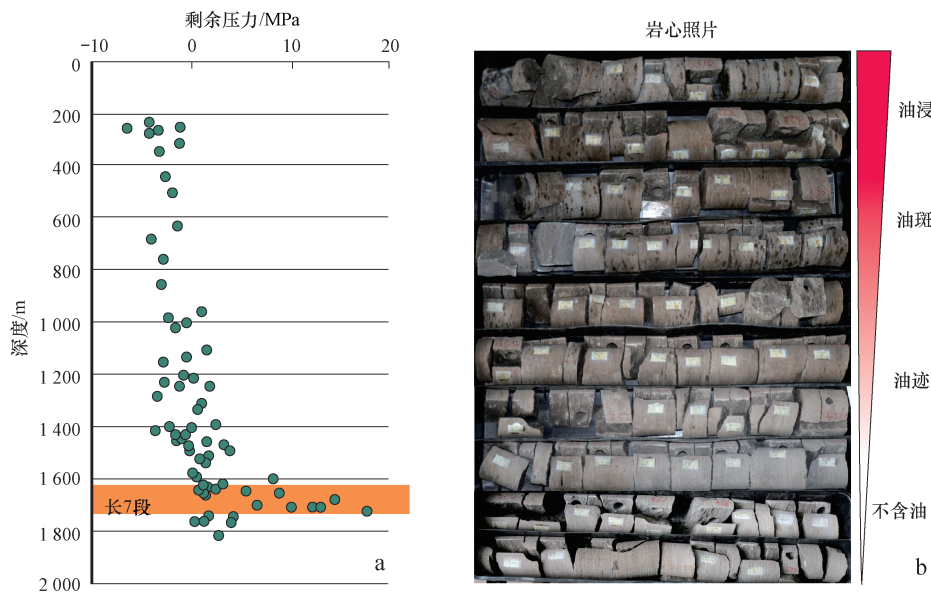


图2 鄂尔多斯盆地西南部Z256井剩余压力及岩心含油性特征

Fig. 2 Point diagram showing the residual pressure (a) of and images showing oil-bearing cores (b) from Well Z256 in southwest Ordos Basin

a. 等效深度法测井计算的剩余压力随深度变化;b. 长8¹亚段(埋深1 701.26~1 711.65 m)岩心照片

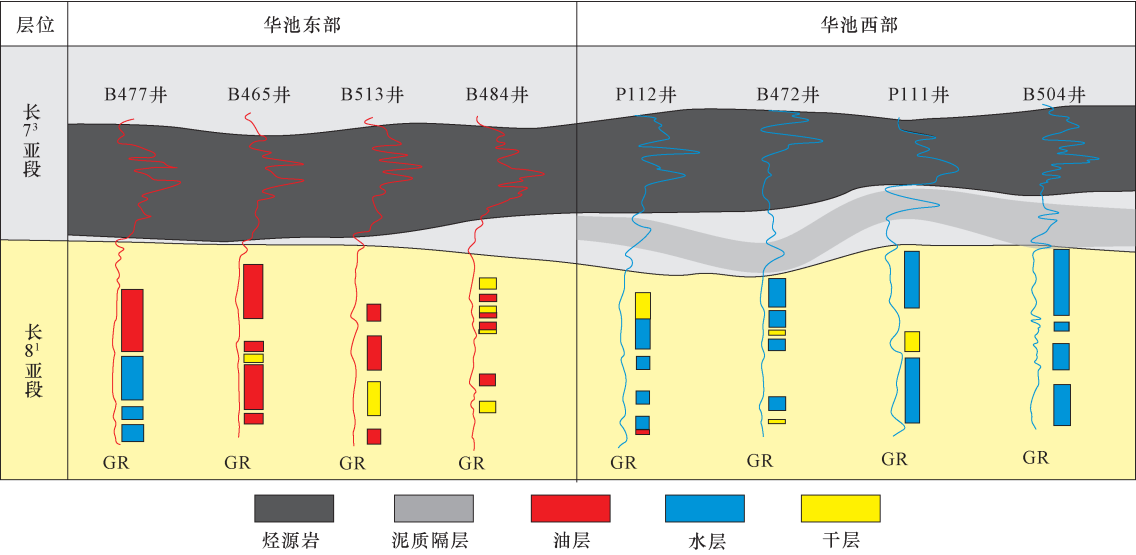


图 3 华池东西部源储之间泥质隔层发育差异

Fig. 3 Differences of argillaceous barriers between source and reservoir in the eastern and western parts of the Huachi area

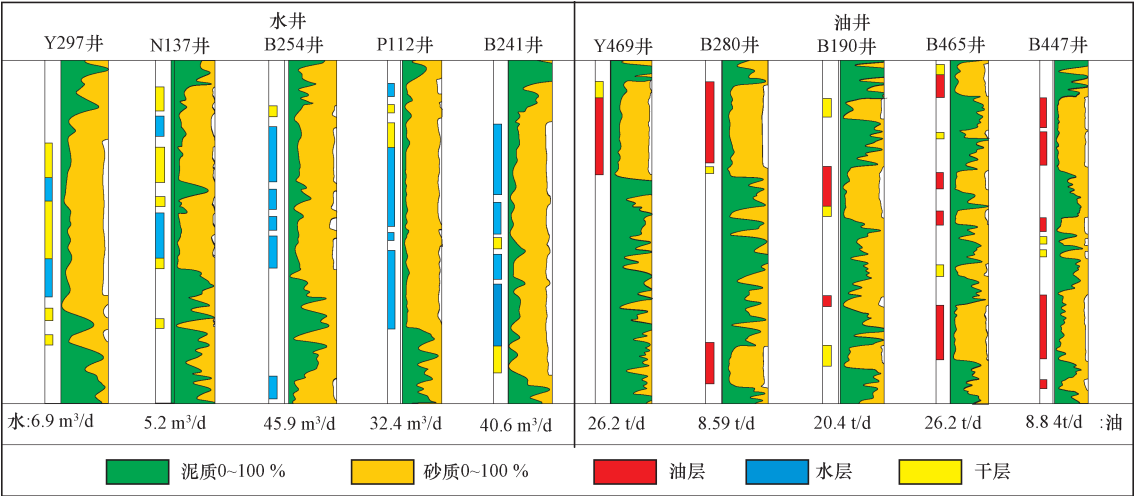


图 4 华池地区长 8¹ 亚段砂体发育规模与储层含油性之间的关系

Fig. 4 Relationship between sand body size and oil-bearing property of the Chang 8¹ submember in the Huachi area

2.3 砂体发育规模

华池地区大量出现物性好的厚砂体不出油而薄砂体出油的情况,通过岩心观察和试油资料发现,华池西部的 P112、B504 和 B241 等井砂体发育规模大,砂体厚度达到 21 m,中间无明显的岩性变化,平均日产水 40.6 m³;而华池东部的 B465 和 B447 等井砂体发育规模较小,砂体厚度小于 10 m,多见泥质粉砂岩或泥岩的互层,平均日产油 26.18 t。将华池东西部的测井资料行分类,发现普遍存在厚砂体出水而薄砂体出油的情况(图 4)。此现象与以往“原油主要聚集于好砂带”的认识相违背,体现了华池地区长 8 段储层油水富集的特殊性。分析认为,原油主要富集于薄砂层,主要得

益于薄砂层侧向容易尖灭而利于形成砂体尖灭型岩性油气藏,较厚的砂层侧向延伸远,原油可以经过长距离的运移而不易于保存。

2.4 储层物性差异

分别统计华池东西部长 8¹ 亚段储层中油、水、干层的孔隙度和渗透率(图 5),显示水层的物性好于油层好于干层。其中,水层的平均孔隙度为 10.14%,平均渗透率为 $1.01 \times 10^{-3} \mu\text{m}^2$;油层的平均孔隙度为 9.29%,平均渗透率为 $0.56 \times 10^{-3} \mu\text{m}^2$;干层的平均孔隙度为 7.79%,平均渗透率为 $0.51 \times 10^{-3} \mu\text{m}^2$ 。华池西部水井的储层物性整体好于东部地区的油井。华池地区长 8¹ 亚段储层中物性较好的储层出水,物性较差

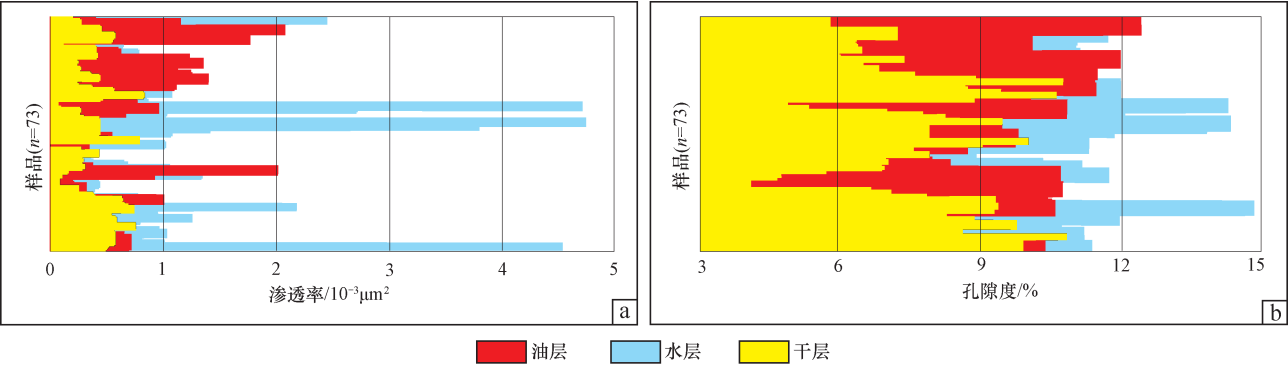


图 5 华池地区长 8¹ 亚段油、水、干层储层物性条形图

Fig. 5 Physical properties of oil, water and dry layers of the Chang 8¹ submember in the Huachi area

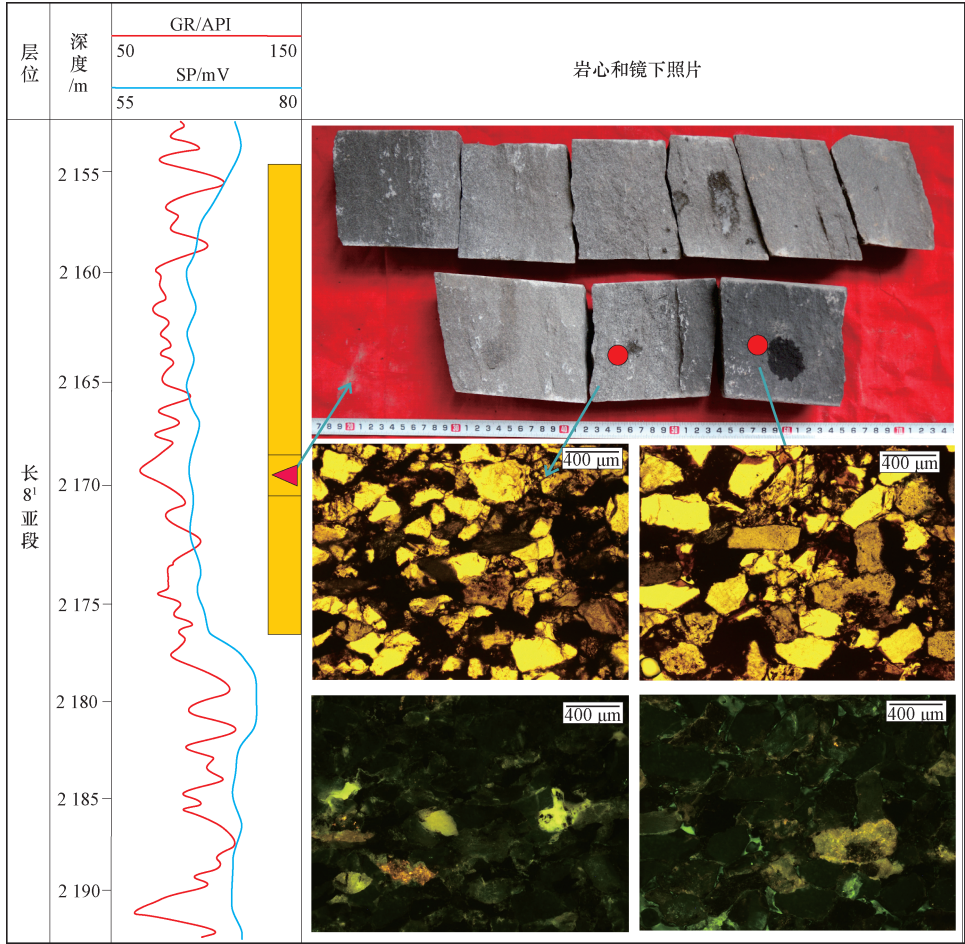


图 6 华池地区 P112 井长 8¹ 亚段单砂体中油水差异富集

Fig. 6 Differential accumulations of oil and water in a single sand body of Chang 8¹ submember in Well P112 in Huachi area

的储层却出油,这与以往的认知不符,也是华池地区致密油藏的特殊之处,故储层物性亦不是华池地区长 8 段油藏的主控因素。

2.5 储层非均质性

2.5.1 单砂体内部结构差异

在华池地区大量发现如 P112 井长 8¹ 亚段同一套

砂体中油水差异富集的现象(图 6)。这种由斜层理、平行层理、砂纹交错层理和块状层理组合起来的厚层复合砂体中包含了多套油层与干、水层的纵向叠置体,而原油往往只富集于均质性更强的块状砂体中,非均质性较强的含纹层砂体充当了相对盖层的作用,经过地层水长时间的浸泡而钙化^[27]。对比认为,相对于非均质性强的砂体来说,均质性强的块状砂体更易于原油充注和富集。

2.5.2 河道构型差异

除了砂体内部存在差异外,砂体构型也是影响储层非均质性的重要因素^[28-38]。根据砂体构型的相关理论^[39-41],将河道划分为河道主体和河道侧翼两个河道构型单元,并对不同河道构型砂体的物性做了对比:由岩心及其配套资料可以看出(图 7),河道主体为细砂岩,发育块状或平行层理,孔隙式胶结,颗粒较大,分选磨圆较好;而河道侧翼为粉砂岩或粉细砂岩,包含泥质团块,发育斜层理和砂纹交错层理等,基底式胶结,颗粒粒度较小,分选磨圆较差。

通过对不同构型岩样进行压汞分析,发现河道主体与侧翼的孔喉结构差距明显(图 8):河道主体的排

驱压力为 1.105 MPa,中值半径为 0.326 μm,最大汞饱和度为 92.4%;而河道侧翼对应值分别为 5.736 MPa、0.033 μm 和 87.75%。河道主体砂的门槛压力和中值压力较河道侧翼砂低,说明河道侧翼相比主体具有更强的微观非均质性,河道主体的物性远好于河道侧翼。

华池西部砂体规模大,储层物性好,河道侧翼砂体在整个河道砂体中的占比较小,储层的均质性整体较强。相反,华池东部砂体规模小,储层物性差,河道侧翼砂体在整个河道砂体中的占比较大,储层的非均质性较强。总之,砂体规模、储层物性和非均质性等因素互相消长、相互制约,共同控制着华池地区油藏的分布。

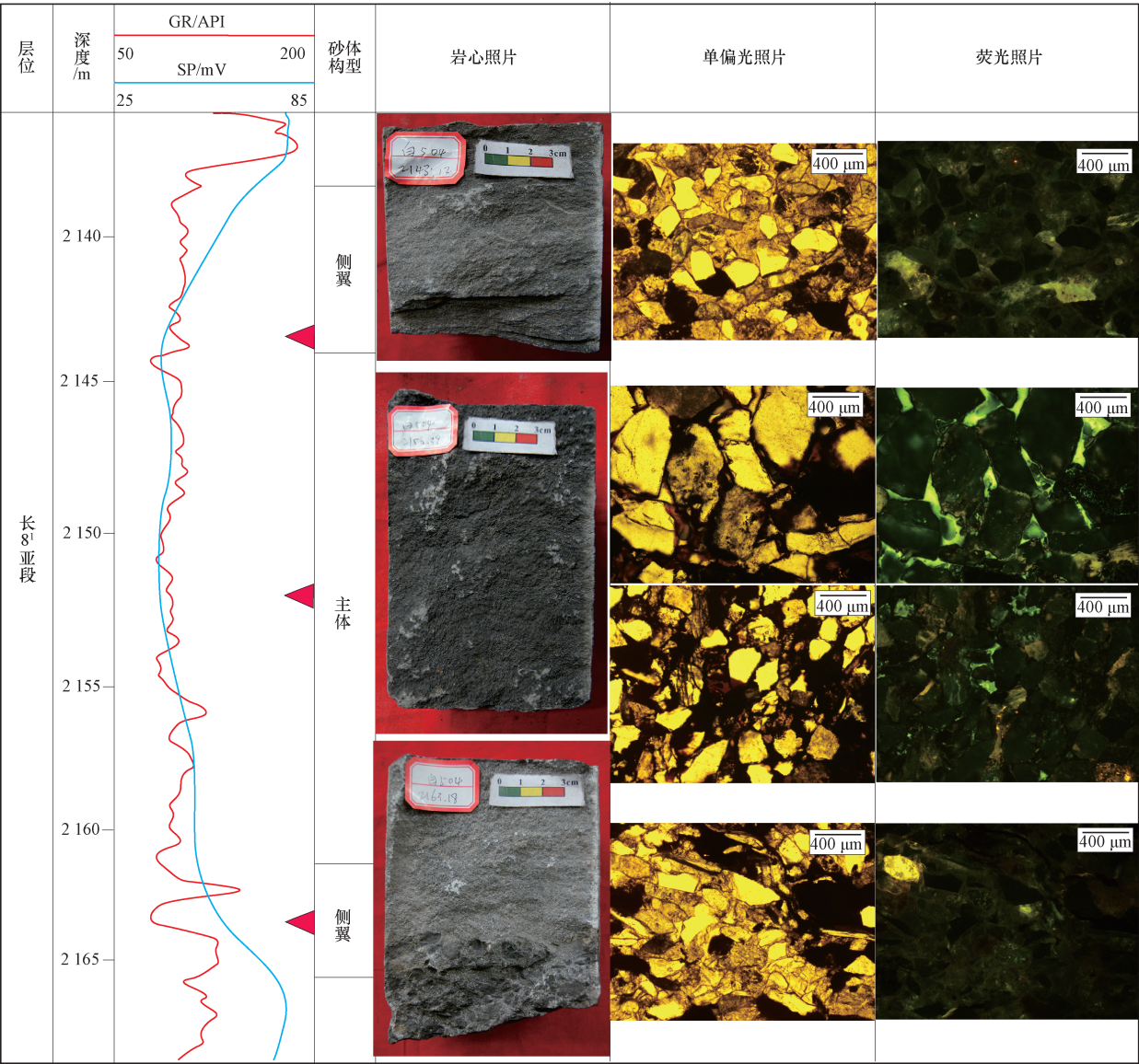


图 7 华池地区 B504 井长 8¹ 亚段河道主体与河道侧翼对比
Fig.7 Comparison of the main body and flanks of channels of Chang 8¹ submember in Well B504 in Huachi area

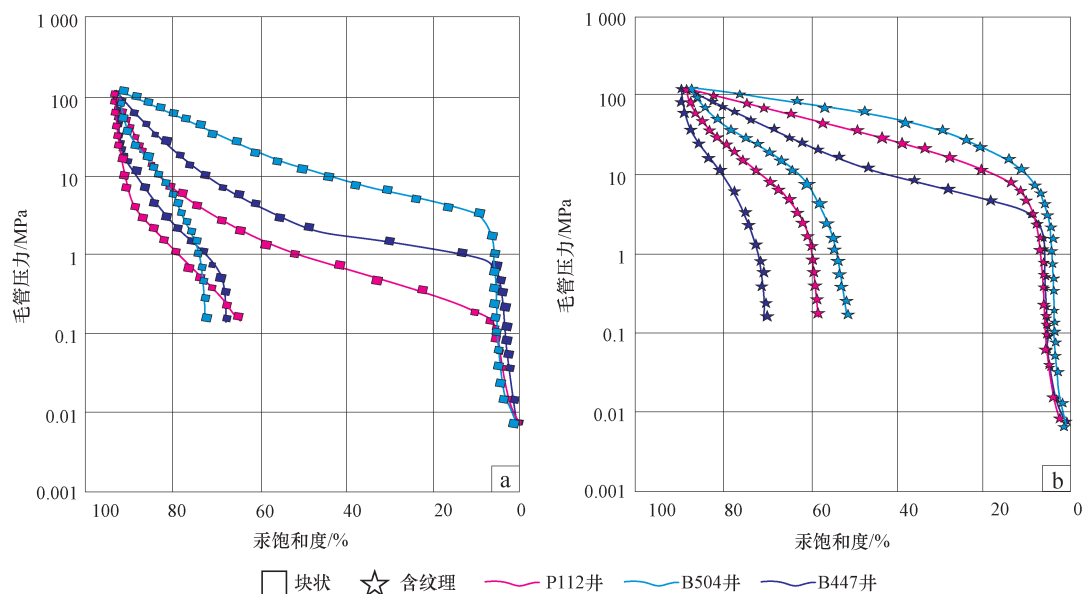


图8 华池地区长8¹亚段河道主体与侧翼压汞曲线

Fig.8 Curves obtained from mercury intrusion porosimetry of the main body and flanks of channels of Chang 8¹ submember in Huachi area
a. 河道主体;b. 河道侧翼

3 成藏机理

根据以上成藏控制因素的分析,排除了烃源岩条件与储层物性对华池地区油水差异性富集的影响,并认为长7段烃源岩形成的异常高压所能提供给原油向长8段储层中倒灌的动力有限。源、储之间的泥质隔层、砂体的发育规模和储层非均质性是引起华池东西部油水差异聚集的主要控制因素。

3.1 泥质隔层决定原油能否进入储层

源储之间的泥质和粉砂质隔层决定了原油能否倒灌下来。在有限的充注动力背景下,源储之间的隔夹层对原油倒灌运移的动力起到急速的衰减作用。相比华池东部地区,华池西部源储之间泥质隔层更发育,不易于原油的倒灌运移,故多数井以出水为主,而华池东部地区由于具有更好的源-储接触关系而利于原油向下运移成藏。

3.2 砂体规模决定原油能否侧向封堵成藏

在原油能运移进入储层的基础上,砂体的规模决定了原油能否侧向封堵成藏。无明显内部结构变化的厚层砂体物性较好,侧向延伸距离远,不易于原油的封堵而变为原油侧向运移的通道,反之则容易形成岩性上倾尖灭圈闭,对原油具有侧向的封堵作用,利于形成岩性油气藏。华池西部地区砂体厚度达到

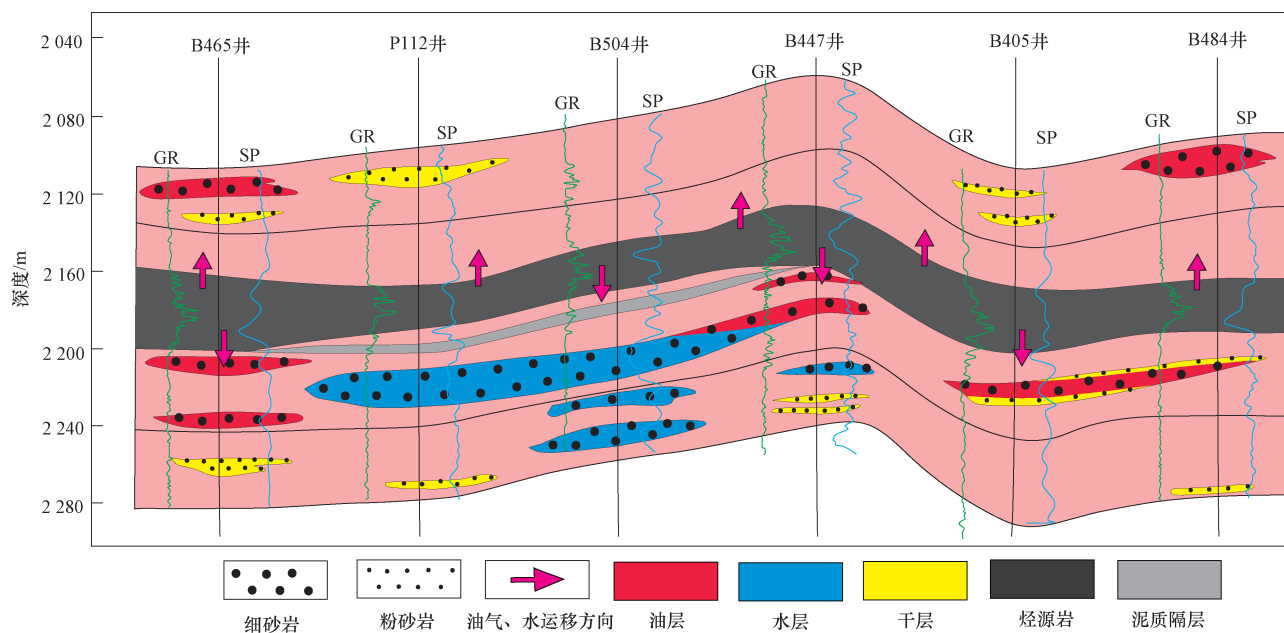
20 m 以上,原油会沿着河道长距离运移在砂体的尖灭处或是构造的高部位成藏,华池东部薄砂体很容易发生侧向尖灭,平面上延伸不远,更利于原油的封堵和成藏。

3.3 储层非均质性决定单砂体内部原油差异富集

具有内部结构变化的厚层河道砂亦可成藏,其与储层的非均质性有很大关系。砂体侧翼和含纹理构造的砂体在理论上起到减小砂体规模相同的作用。具有纹理的砂体或河道侧翼砂由于物性较差和非均质性更强,往往起到对原油相对封堵的作用,在有限充注动力下,原油不能够突破此岩性界面而在砂体均质性更强的部位成藏。

3.4 成藏模式

基于上述成藏主控因素,认为华池西部因为源储间存在泥质隔层,阻挡了原油的大规模向下运移,少量的原油在规模大、物性好、均质性强的储层中不易于侧向封堵(图9, P112井和 B504井),原油会沿着大套的河道砂向其他部位运移,最后在河道尖灭处或构造的高部位聚集成藏(图9, B447井)。华池东部则与其相反,因为没有源储之间隔挡层的影响,原油利于向下倒灌,加之储层规模小、非均质性强,原油不能侧向长距离运移,反而更利于原油的运聚成藏,在物性相对较好的薄砂体中聚集形成岩性油气藏(图9, B465井、B405井和 B484井)。

图9 华池地区长8¹亚段油藏成藏模式Fig.9 Hydrocarbon accumulation patterns in Chang 8¹ submember in Huachi area

4 结论与认识

1) 在倒灌成藏模式有限的充注动力条件下,华池西部源、储之间普遍发育的泥质隔层阻碍了原油向下运移,其长8段储层均质性强、物性好、砂体规模大,从长7段烃源岩生成并运移下来的少量原油不能侧向封堵而沿着河道砂体远距离运移,在构造的高部位或河道尖灭处聚集成藏;华池东部源、储之间无明显泥质隔层存在,原油易于向下运移,其长8段砂体规模小、储层非均质性强,原油不易侧向运移而就地成藏。故华池东部皆为油井而西部皆为水井。

2) 以往认为规模大、物性好和均质性强的砂带不利于华池地区长8段致密储层中原油的保存。充注动力有限背景下油水复杂区的成藏研究,应该摒弃“好砂带找油”的常规思想,反而规模小、非均质性强的“差砂带”更利于充注动力有限背景下油水复杂区原油的封堵和成藏。

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