

川东北元坝地区须家河组三段基于相控的相对优质储层预测

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摘要:川东北元坝地区须家河组三级储量规模大,但储量探明率低、试采效果差。其主要原因是致密砂岩储层非均质性强,相对优质储层分布不明。因而采用了先精准预测砂砾岩,然后在砂砾岩中寻找相对优质储层的思路开展研究。在单井沉积微相划分基础上,通过岩性逐级识别,实现岩性准确解释;进而分析须家河组三段各砂组顶、底界面处岩性组合及其地震响应特征,明确地震剖面上波峰和波谷的地质含义,同时考虑井-震分层的差异,多方法确定提取地震属性时的合理时窗,进而提取相应范围内、不受上、下地层影响的多种地震属性,以钻井结果为比照,优选对砂砾岩最为敏感的地震属性,井-震结合,刻画须三段砂砾岩的展布。为了进一步搞清楚砂砾岩中相对优质储层段,应用岩心资料,对砂砾岩细分岩石相,明确了须三段发育中-粗粒钙屑砂岩和砂质细砾岩两类相对优质储层,建立其测井解释标准,在砂砾岩展布的约束下,精细刻画了两类相对优质储层的分布,为须三段气藏下一步规模有效开发奠定了坚实基础。

关键词:地震属性;岩石相;沉积微相;优质储层;致密砂岩;储层预测;须家河组;川东北元坝地区

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Lithofacies-based prediction of relatively high-quality reservoirs of the Xu 3 Member in Yuanba area, northeastern Sichuan Basin

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Abstract: The 3P reserves of the Xujiahe Formation are large in scale in Yuanba area. However, due to the strong heterogeneity of tight sandstones, and less understanding on the distribution of relatively high-quality reservoirs, the proportion of proven reserves is low in the 3P reserves and the production tests are poor in effect. It is necessary to accurately predict the distribution of coarse siliciclastic rocks, from which relatively high-quality reservoirs are to be discovered. On the basis of sedimentary microfacies division by using well data, precise lithologic interpretation is achieved by gradual lithologic identification. The geological significance of peaks and troughs on seismic sections is clarified by analyzing the lithological associations on the top and bottom surfaces for various sand groups in the 3rd member of Xujiahe Formation (hereinafter referred to as Xu 3 Member); meanwhile, multiple methods are applied to select proper time window for extracting seismic attributes given the gap in seismic-well layering, and several seismic attributes that are not influenced by the overlying and underlying formations are extracted within the time window. In regard of the drilling data, we select the seismic attributes that are the most sensitive to coarse siliciclastic rocks and use them to map the distribution of the coarse siliciclastic rocks via seismic-well tie. On the other hand, to identify the relatively high-quality reservoirs within coarse siliciclastic rocks, we sub-divide the coarse siliciclastic rocks in lithology with core data, confirming that there are two categories of high-quality reservoirs well developed in the Xu 3 Member, that is, the medium-to-coarse-grained calcarenaceous sandstone reservoir and fine-grained arenaceous conglomerate reservoir. Furthermore, the distribution of the two categories of high-quality reservoirs is finely depicted under the constraint of the coarse siliciclastic rock distribution while establishing well logging interpretation criteria. The results serve to lay a sound

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basis for the large-scale development of the Xu 3 Member gas pools in high efficiency.

Key words: seismic attributes, lithofacies, sedimentary microfacies, high-quality reservoir, tight sandstone, reservoir prediction, Xujiahe Formation, Yuanba area in northeastern Sichuan Basin

川东北元坝地区须家河组已提交规模巨大的三级储量,主要分布在须家河组二段和三段;探明储量极少。须家河组试采效果差,多数井递减快,仅须三段气藏的两口井初产高、递减慢,具有一定效果。致密砂岩气藏稳产的关键因素是相对优质储层^[1-5],明确其发育的有利区是须三段气藏有效开发的关键因素之一。

元坝区块位于四川盆地东北部的川北低缓构造带^[6](图1a),须三段沉积时期受多物源控制,其西部沉积物来源于西北方向的龙门山北段,母岩以碳酸盐岩为主,中东部来源于东北方向的古大巴山^[7](图1b);元坝西部须三段从西北向东南呈楔形体分布,厚度变化大,西北部厚达325 m,东南减薄为117 m。须三段划分为 $Tx^{3(1)}$ – $Tx^{3(5)}$ 5个砂组。地震上追踪了 Tx^3 顶、 $Tx^{3(2)}$ 底、 $Tx^{3(3)}$ 底和 Tx^3 底4套层位,提取 $Tx^{3(1)}$ 砂组地震属性时,缺少其底层位;由于地层厚度变化大,应用相邻层位等时漂移的方法不能产生与实际相符的 $Tx^{3(1)}$ 底地震层位。同时,由于相变快^[8-11],泥岩、砂岩和砾岩互层,导致研究区内 $Tx^{3(3)}$ 底等界面

处岩性组合及其地震响应特征复杂。在提取各砂组的地震属性时,需采用不同方法确定时窗,才能获得符合地下实际情况的砂砾岩预测结果。此外,由于元坝西部须三段碳酸盐岩岩屑含量高,其中的砂砾岩方解石胶结严重,物性差,岩心分析孔隙度平均值仅为1.92%,在超致密的地层中寻找相对优质储层难度大。

本研究在单井沉积微相研究、岩性解释以及高精度合成记录制作的基础上,分析 Tx^3 顶、 $Tx^{3(2)}$ 底、 $Tx^{3(3)}$ 底和 Tx^3 底界面处的岩性组合及其地震响应特征,针对各界面的特征确定相应的开窗方法,进而提取了多种地震属性。通过井点位置砂砾岩厚度和各种地震属性的相关性分析,明确敏感属性,准确地预测了砂砾岩的分布。然后对取心井段开展了岩石相划分,结合物性分析资料,明确了块状中-粗粒钙屑砂岩和砂质细砾岩两类有利岩石相,建立其测井识别标准,结合其控制因素,明确了相对优质储层的分布,为元坝须三段气藏的井位部署和有效开发提供了依据,也为致密砂岩的优质储层预测提供了新的思路。

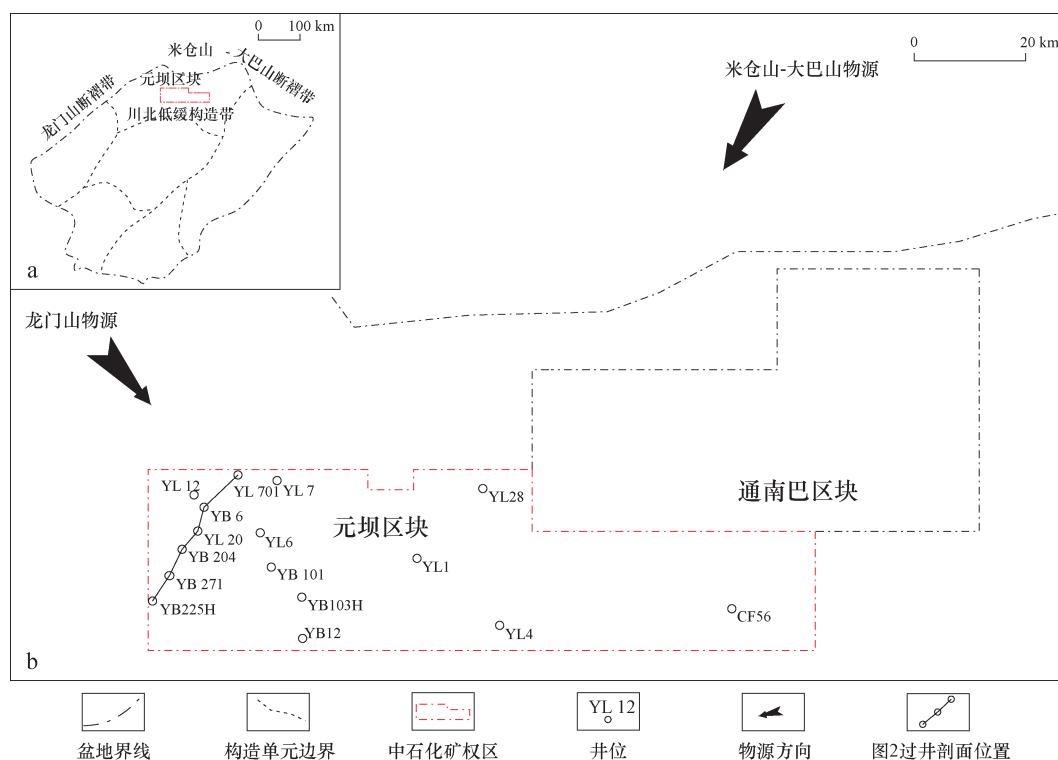


图1 川东北元坝区块位置(a)与须三段沉积时期物源方向(b)(据文献[6]和[7]有修改)
Fig. 1 Location of the Yuanba block(a) and the provenance during the Xu 3 Member deposition(b), northeastern Sichuan Basin (modified after references[6-7])

1 单井沉积-砂体特征

1.1 沉积微相类型

结合前人认识,通过研究区取心井段沉积微相研究,须三段为辫状河三角洲沉积^[12-15],主要发育三角洲平原亚相的辫状河道和泛滥平原(分流间洼地)微相,局部发育决口扇,及三角洲前缘亚相的水下分流河道和分流间湾微相,局部为河口坝和席状砂;在总结每种沉积微相的测井曲线特征的基础上,完成了单井沉积微相划分。从须三段沉积微相对比剖面(垂直物源方向)看,相变快,部分地区各砂组下部以河道砂砾岩为主,向上过渡为分流间湾或泛滥平原泥岩;部分地区河道砂砾岩局部发育,或基本泥岩为主,这就造成了须三段各砂组底界面附近复杂的岩性接触关系(图2)。

1.2 复杂岩性逐级识别

须三段岩性多样,考虑粒度和成分,可细分为17种类型。通过分析不同岩性测井响应特征,考虑测井识别精度及研究的需要,合并为8类岩性。结合岩心薄片,应用GR,CNL,AC,DEN和RD曲线,以交会图为基础建立了岩性逐级识别方法,首先完成了煤、泥岩、砂岩和砾岩等大类的识别;然后完成了砾岩中含砂砾岩和砂质砾岩,以及砂岩中含炭屑砂岩、中-粗粒钙屑砂岩、细粒钙屑砂岩、钙屑粉砂岩和岩屑砂岩小类的进一步识别。

2 基于沉积背景的砂砾岩体预测

2.1 须三段关键界面特征

在钻井合成记录制作基础上,综合沉积微相、岩屑录井和岩性解释结果,对 Tx^3 顶、 $Tx^{3(2)}$ 底、 $Tx^{3(3)}$ 底和 Tx^3 底4套地震层位对应井分层处的岩性组合进行了统计,并分析界面处地震响应特征。

须三段顶界面处岩性组合简单,界面之上为须四段底部的砾岩或含砾粗砂岩,表现为高阻抗,之下为须三段顶部的泥岩或粉砂岩,为低阻抗,地震上表现为一套连续性较好的中-强波谷, $Tx^{3(2)}$ 底界面处特征与之相似,不再赘述。

$Tx^{3(3)}$ 砂组底附近发育4种岩性组合。①工区西北部:界面之上为砂砾岩,之下为泥岩,地震上表现为连续的中-强波谷。②东南部:界面之上为泥岩,之下为砂岩,地震上表现为连续的中-强波峰,此波峰为 $Tx^{3(4)}$ 砂组上部砂岩的响应(图3a,b)。③YL25井附近:界面上、下均为泥岩,地震上对应不连续波谷-波峰转换处。④YB1井附近:界面之上为砂砾岩,之下为薄层泥岩与砂岩,地震上对应不连续弱波峰-波谷转换处。通过分析,明确了地震层位处波峰或波谷的地质含义,为提取地震属性时如何确定时窗奠定了基础。

须三段底界面处主要发育2种岩性组合。①西北部:界面之上为分流间湾泥岩,之下为水下分流河道砂岩,地震上表现为连续的中-强波峰,此波峰为须二段

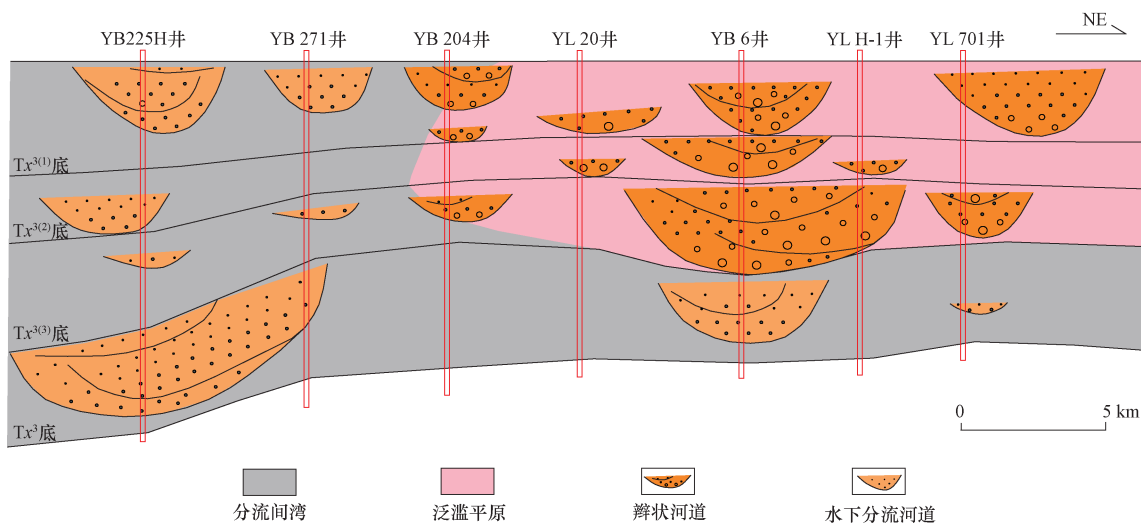


图2 川东北元坝地区北东向沉积微相连井对比剖面(剖面位置见图1)

Fig.2 NE-trending well-tied section for correlation of sedimentary micro-facies in Yuanba area, northeastern Sichuan Basin
(see Fig.1 for the section location)

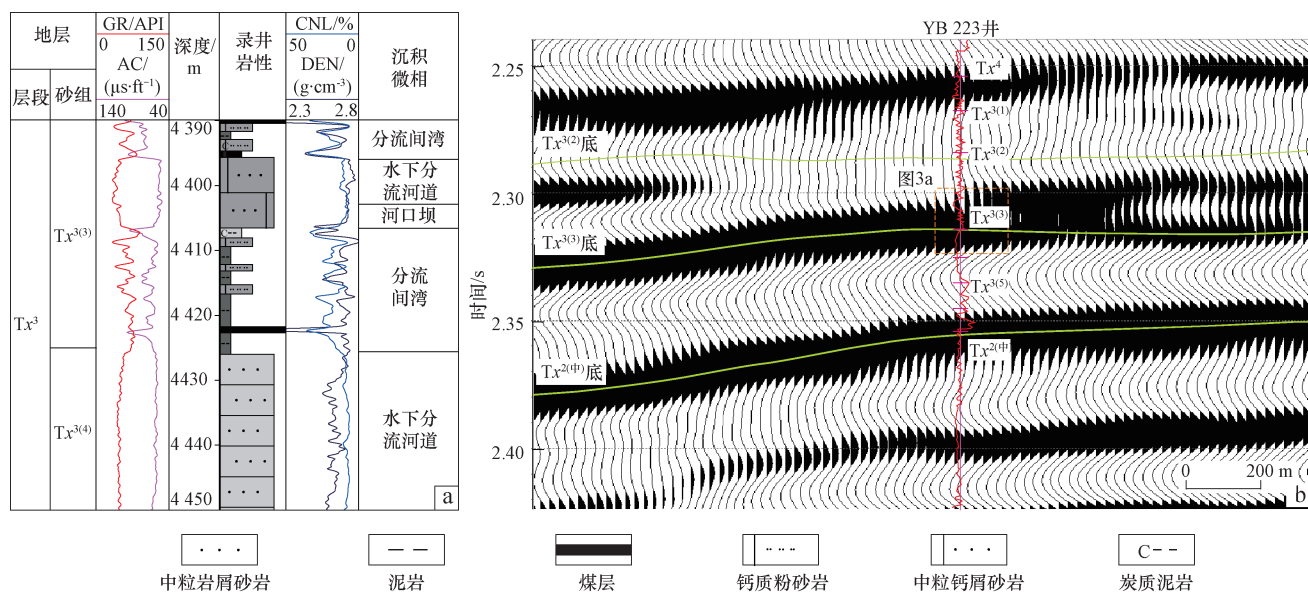


图3 川东北元坝地区 YB223 井 $Tx^{3(3)}$ 底界面特征

Fig.3 Lithologic assemblage and seismic response characteristics at the bottom of $Tx^{3(3)}$ sand group in Well YB223 in Yuanba area, northeastern Sichuan Basin

a. 底界面处岩性组合; b. 地震剖面

上部砂岩的响应。② 东南部: 界面之上为水下分流河道砂岩, 之下为滨浅湖相泥岩; 地震上表现为连续的中-强波谷。所以在提取 $Tx^{3(5)}$ 砂组地震属性时需分西北和东南两个区分别确定时窗。

2.2 提取属性时合理时窗的确定方法

考虑界面处岩性组合的差异, 提取须三段各砂组地震属性时, 采用多种方法确定时窗。

1) 须三段顶和 $Tx^{3(2)}$ 砂组底

两套地震层位均表现为较连续的中-强波谷, 依据合成记录, 统计工区内 48 口井地震层位与井分层的时间差异, 将两套地震层位分别上下漂移相应的时间, 从而确定提取相关砂组地震属性的时窗。

2) $Tx^{3(3)}$ 砂组底和须三段底

$Tx^{3(3)}$ 砂组底地震层位在研究区东南对应波峰, 其为 $Tx^{3(4)}$ 砂组砂岩的响应, 在提取 $Tx^{3(3)}$ 砂组波峰类属性时, 需消除其影响。本研究在该区域应用波峰自动扫描技术, 将该区域 $Tx^{3(3)}$ 砂组底层位调整到此波峰之上。而西北区对应波谷, 根据井震分层差异, 将原层位上移 5 ms 形成一个新层位, 将东南区和西北区的新层位组合作为提取 $Tx^{3(3)}$ 砂组地震属性的底界面 (图 4)。在提取 $Tx^{3(5)}$ 砂组属性时, 须三段底采用与 $Tx^{3(3)}$ 砂组底相似的方法。

3) $Tx^{3(1)}$ 砂组底

统计研究区钻井钻遇 $Tx^{3(1)}$ 砂组厚度占 $Tx^{3(1)}$ 和 $Tx^{3(2)}$ 砂组累计厚度的比值, 利用 Tx^3 顶和 $Tx^{3(2)}$ 砂组

底 2 套层位, 依据比值形成 $Tx^{3(1)}$ 底层位, 与井分层对比后, 一致性较好, 保证准确提取 $Tx^{3(1)}$ 和 $Tx^{3(2)}$ 砂组的地震属性。

2.3 砂砾岩预测及其分布

在确定了须三段各砂组合理时窗基础上, 提取了波峰平均值、波峰最大值、波峰总能量、均方根振幅、平均能量、平均瞬时频率、瞬时相位及波谷类地震属性, 并开展波阻抗反演; 其中波峰总能量属性连续性最好, 能够较好地刻画分流河道展布 (图 5a—c)。通过分析单井钻遇砂砾岩厚度与地震属性的相关性, 波峰总能量相关性最好, 能较好地预测砂砾岩 (图 6a—d)。

以井点砂砾岩厚度为基础, 结合波峰总能量属性, 通过克里金插值, 编制须三段各砂组砂砾岩 (砂岩和砾岩) 厚度图 (图 7a, b)。从图上看, 砂砾岩呈 NW—SE 向条带状分布, 向东南减薄; 过 YL702—YL12—YB6—YL22—YL6—YB101—YB1 井区的条带上砂砾岩各砂组均发育, 过 YL701—YL7—YL26 井区的条带上砂砾岩也较发育。

3 基于岩石相的优质储层预测

元坝地区须三段砂砾岩孔隙度为 0.60% ~ 5.25%, 渗透率为 $(0.002 \sim 44.600) \times 10^{-3} \mu m^2$, 砂砾岩段中仅部分层段为有效储层, 有待进一步细分岩石

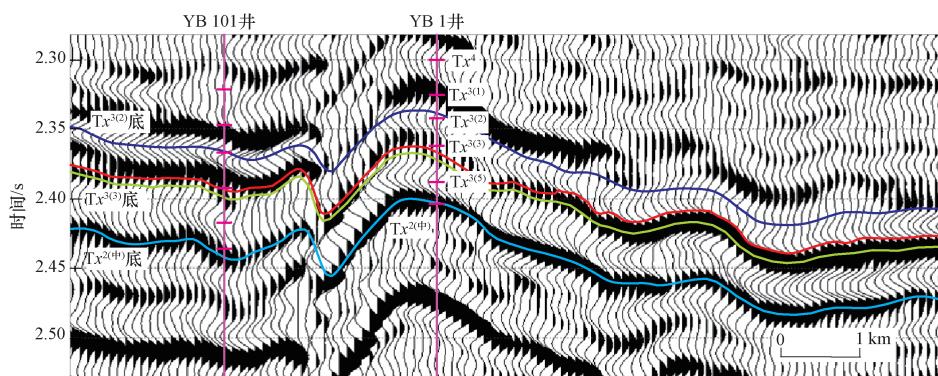


图4 川东北元坝地区 $\text{Tx}^{3(3)}$ 砂组底(绿色)和提取属性所用层位(红色)

Fig.4 Original layer (green) at the bottom of and the layer for seismic attribute extraction (red) of the $\text{Tx}^{3(3)}$ sand group in Yuanba area, northeastern Sichuan Basin

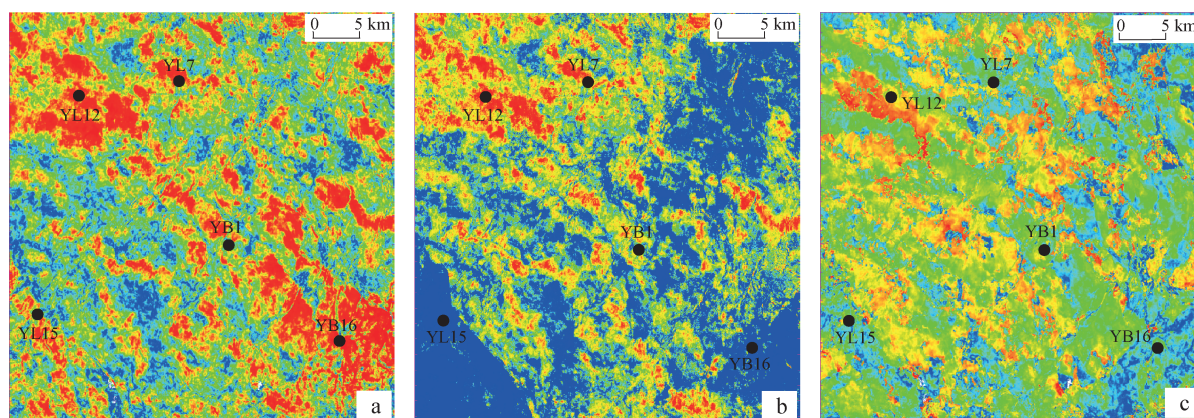
图5 川东北元坝地区 $Tx^{3(3)}$ 砂组地震属性

Fig. 5 Seismic attributes of the Tx³⁽³⁾ sand group in Yuanba area, northeastern Sichuan Basin

a. 均方根振幅;b. 波峰总能量;c. 平均瞬时频率

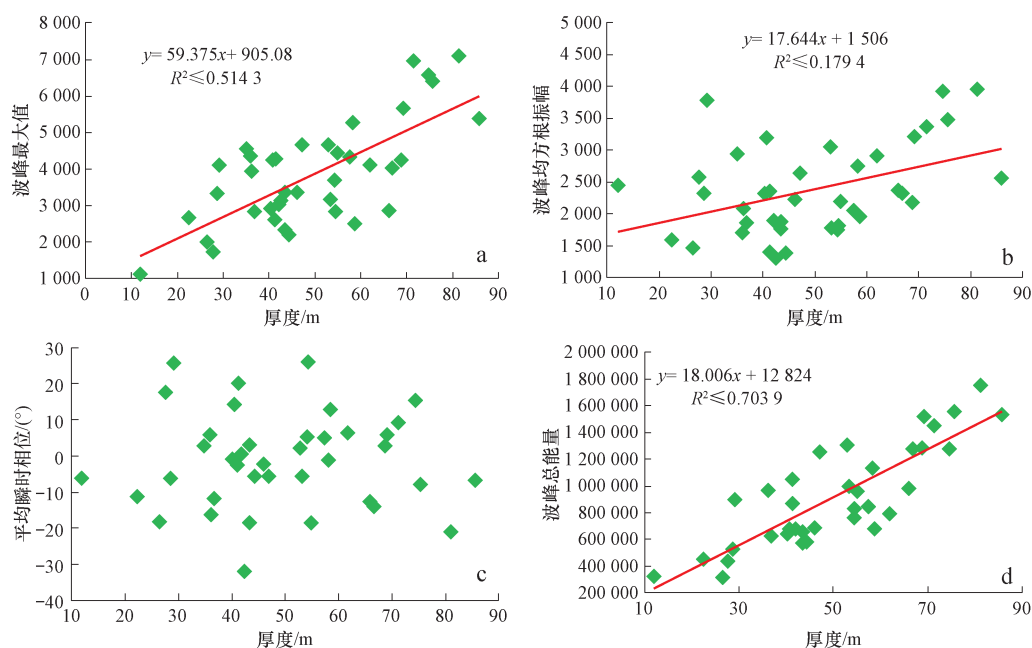


图6 川东北元坝地区井点位置砂砾岩厚度与地震属性交会图

Fig.6 Cross correlation showing the seismic attributes and the thickness of coarse siliciclastic rocks in Yuanba area, northeastern Sichuan Basin

a. 波峰最大值; b. 波峰均方根振幅; c. 平均瞬时相位; d. 波峰总能量

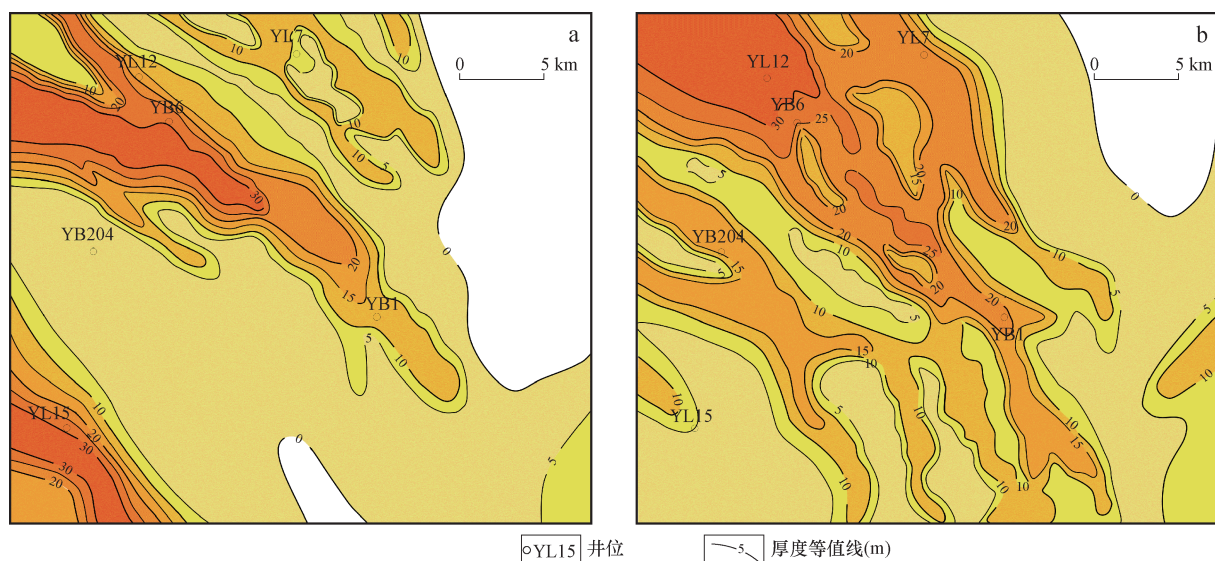


图7 川东北元坝地区须三段 $Tx^{3(2)}$ - $Tx^{3(3)}$ 砂组砂砾岩展布

Fig. 7 The thickness of sandstone and conglomerate of $Tx^{3(2)}$ and $Tx^{3(3)}$ sand groups in the Xu 3 Member, Yuanba area, northeastern Sichuan Basin

a. $Tx^{3(2)}$ 砂组; b. $Tx^{3(3)}$ 砂组

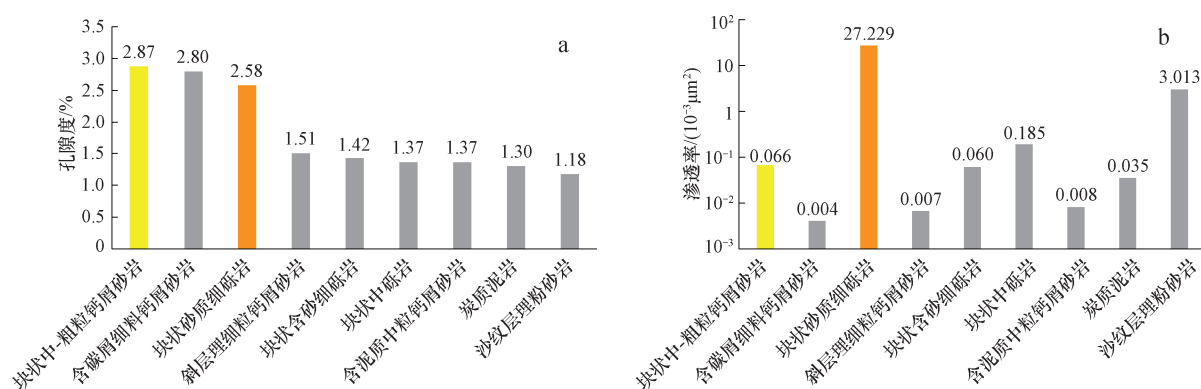


图8 川东北元坝地区须三段岩石相物性直方图

Fig. 8 Histograms of average porosity and permeability of different lithofacies in the Xu 3 Member, Yuanba area, northeastern Sichuan Basin

a. 岩心分析平均孔隙度 (311 个样品); b. 岩心分析平均渗透率 (309 个样品)

单元。而岩石相是指具有相同沉积构造和岩性、反映特定水动力条件的基本成因单元。Miall^[16-18] 倡导的岩石相划分方法,用岩石相编码将岩石的沉积构造和岩性统一起来,为沉积相研究提供了方便。岩石相分析是沉积砂体建筑结构要素分析的基础^[19-25]。裘亦楠^[26] 提出,岩石相与储集物性关系密切,致密砂岩虽经历了复杂的成岩作用,但是成岩作用是在沉积作用形成的岩石结构和矿物成分基础上进行的,且在一定的区域和一定层段内具有普遍影响的共性。通过成岩作用改造的储集物性,仍然可以与沉积结构建立较好

的关系。中国大量的储层实例都已证明了这一点^[27-31]。基于此认识,本研究利用岩石相开展有效储层预测,在须三段 13 口取心井岩心观察的基础上,划分了取心段的岩石相,须三段共发育 10 种岩石相类型。

3.1 有利岩石相类型

结合岩心物性分析数据,统计不同岩石相的平均孔隙度和渗透率(图 8a,b),块状中-粗粒钙屑砂岩、含炭屑细粒钙屑砂岩和块状砂质细砾岩孔隙度均大于

① 中国石油化工股份有限公司勘探南方分公司. 元坝气田须家河组三段上、中亚段气藏新增天然气预测储量报告[R]. 重庆:中国石油化工股份有限公司勘探南方分公司,2012.

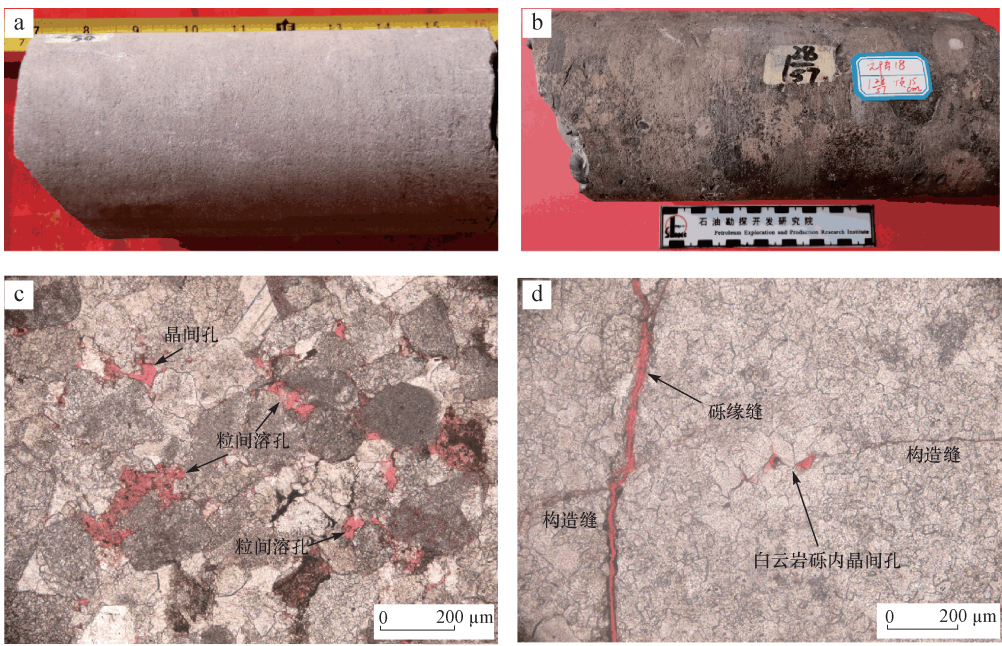


图 9 川东北元坝地区须三段两类有利岩石相典型照片和孔隙类型

Fig. 9 Typical core pictures and micrographs showing pore types of two favorable lithofacies of the Xu 3 Member, Yuanba area, northeastern Sichuan Basin

a. 块状中粒钙屑砂岩, YL20 井, 埋深 4 142.36 m; b. 块状砂质细砾岩, YL18 井, 埋深 4 524.80 m; c. 中粒钙屑砂岩发育粒间溶孔和粒内溶孔, 及少量晶间孔, YL15 井, 埋深 4 275.13 m; d. 砂质细砾岩中发育白云石砾内晶间孔, 砾缘缝和构造缝, YL6 井, 埋深 4 178.04 m

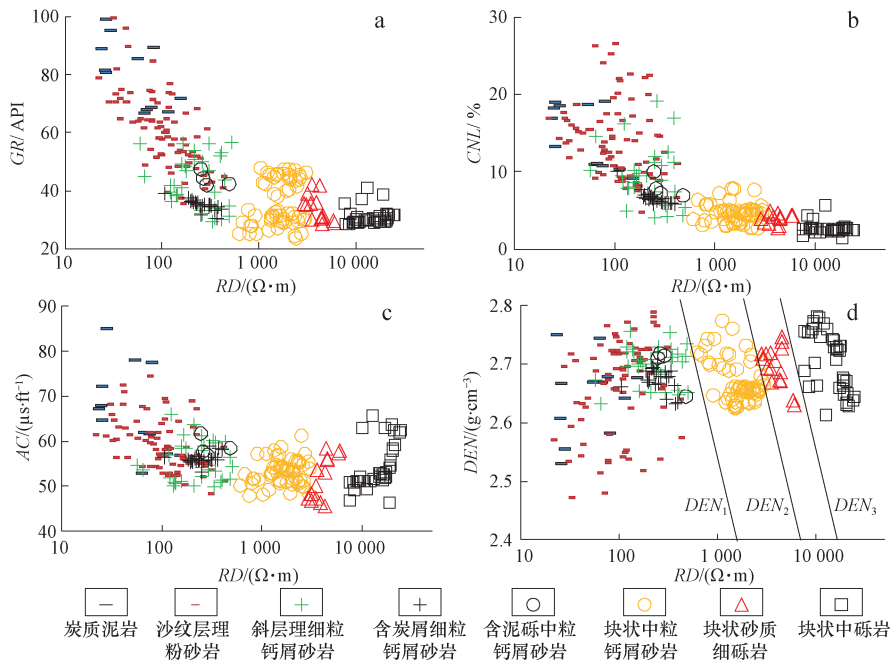


图 10 川东北元坝地区须三段取心段不同岩石相各种测井值交会图

Fig. 10 Cross correlation showing various well log parameters of different lithofacies in the Xu 3 Member, Yuanba area, northeastern Sichuan Basin

a. $RD - GR$; b. $RD - CNL$; c. $RD - AC$; d. $RD - DEN$

2%,达到了有效储层标准^①,但含炭屑细粒钙屑砂岩渗透性差,所以元坝须三段发育块状中-粗粒钙屑砂岩和砂质细砾岩两类有利岩石相(图 9a,b)。块状中-粗粒

钙屑砂岩的溶蚀孔较其他岩石相发育,所以储集性好(图 9c);而砂质细砾岩发育白云岩砾内晶间孔、砾缘缝和构造缝,所以渗透性好,且具有一定孔隙度(图 9d)。

表1 川东北元坝地区须三段有利岩石相测井识别标准

Table 1 Well logging identification criteria of favorable lithofacies of the Xu 3 Member, Yuanba area, northeastern Sichuan Basin

有利岩石相	测井解释标准
	$GR/API, CNL/\%, AC/(\mu s \cdot ft^{-1}), DEN/(g \cdot cm^{-3})$
块状砂质细砾岩	$GR < 42, CNL < 5, AC > 45, DEN_2 < DEN < DEN_3$
块状中-粗粒钙屑砂岩	$GR < 48, CNL < 8, AC > 47, DEN_1 < DEN < DEN_2$

注: $DEN_1 = -0.46 \lg RD + 3.99, DEN_2 = -0.46 \lg RD + 4.23, DEN_3 = -0.46 \lg RD + 4.44$ (图 10d)。

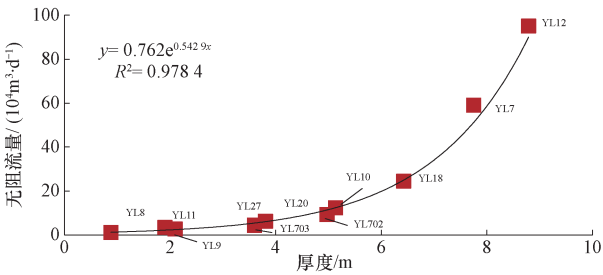


图 11 川东北元坝地区须三段测试井无阻流量与(相对优质储层与裂缝段)厚度交会图

Fig. 11 Cross correlation showing the open-flow potential test and the thickness of relatively high-quality reservoir and intervals with well-developed fractures in the Xu 3 Member, Yuanba area, northeastern Sichuan Basin

3.2 有利岩石相测井标准

为了在全井段识别出块状中-粗粒钙屑砂岩和砂质细砾岩,在岩心归位基础上,统计取心段各种岩石相的测井值,制作测井曲线交会图(图 10a—d),建立有利岩石相识别标准(表 1)。

应用上述标准,对元坝西部 48 口井块状中-粗粒钙屑砂岩和细砾岩进行识别。通过对须三段试采井的产能主控因素分析,无阻流量与相对优质储层和裂缝累计厚度呈正相关性(图 11),高产井 YL7 井和 YL12 井两类储层较发育,有必要刻画两类岩石相的分布。

3.3 有利岩石相分布

通过分析,纵向上,两类优质储层主要分布于辫状河道中部和水下分流河道中下部。平面上,靠近物源区,水动力强,以沉积中砾岩为主;靠近水下分流河道末端,水动力弱,以细砂岩为主。中-粗粒钙屑砂岩主要分布在平原/前缘亚相界线附近远物源区的一侧,砂质细砾岩多分布在平原/前缘亚相界线附近近物源区一侧。在沉积微相和砂砾岩分布的约束下,结合其控制因素,明确了各砂组两类相对优质储层分布。

$Tx^{3(2)}$ 砂组中-粗粒钙屑砂岩厚度以 5 ~ 10 m 为主,呈条带状分布,主要位于 YB6—YL22—YL6—YB101 井区和 YB225H—YL15—YB224 井区附近,受分流河道控制明显(图 12a),向物源区和半深湖方向均呈减薄趋势,其他砂组具有类似的特征。而砂质细砾岩相对中-粗粒钙屑砂岩欠发育,平均厚度为 3.0 ~ 4.5 m(图 12b)。

为了验证优质储层预测结果的可靠性,本研究统计了须三段气藏 8 口试采井的射孔段两类有利岩石相厚度,如果构造缝发育,则适当增加射孔段上下储层的厚度,分析其与累产气量相关性(图 13),优质储层越发育,累产气量越大。同时在预测的优质储层较发育的井区,优选了 YB6 井开展老井挖潜,截至 2020 年 12

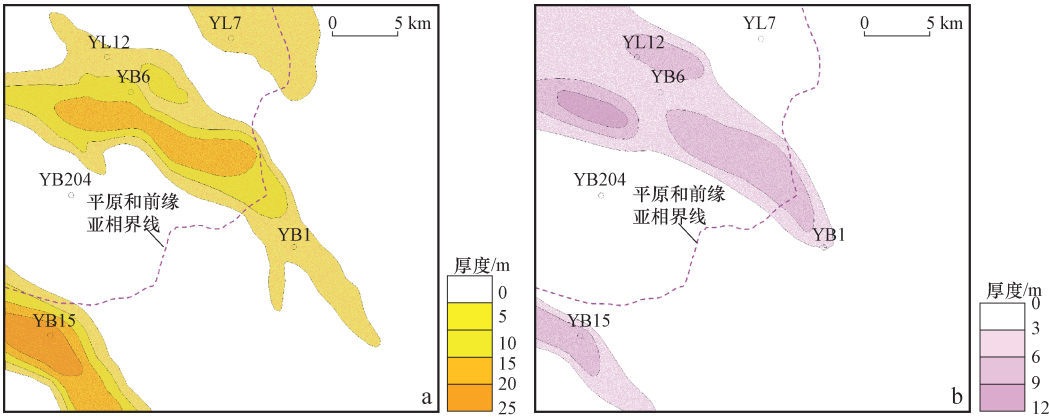


图 12 川东北元坝地区 $Tx^{3(2)}$ 砂组有利岩石相厚度

Fig. 12 Isopach map of favorable lithofacies of the $Tx^{3(2)}$ sand group in Yuanba area, northeastern Sichuan Basin

a. 中-粗粒钙屑砂岩; b. 砂质细砾岩

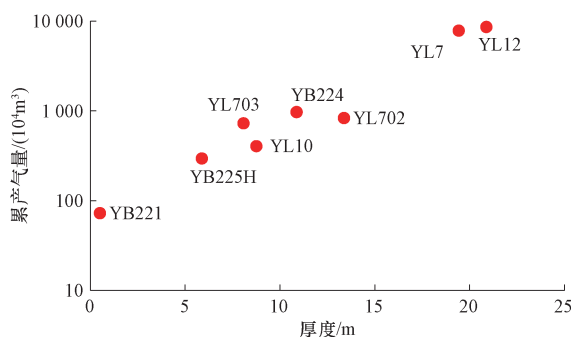


图13 川东北元坝地区须三段气藏试采井累产气量与有利岩石相厚度交会图

Fig. 13 Cross correlation showing the cumulative gas production and thickness of favorable lithofacies in well test in the Xu 3 Member, Yuanba area, northeastern Sichuan Basin

月1日,已累产气 $1\ 102 \times 10^4\ \text{m}^3$,且目前油压 14 MPa,显示了较强的稳产能力,优质储层的预测取得了良好的天然气成果,为下一步井位部署和规模有效开发提供了重要依据。

4 结论

1) 元坝地区须三段沉积微相变化快,岩性组合多样;地层界面之上为砂砾岩,之下为泥岩时,地震上对应波谷,提取界面之上砂组地震属性时仅需考虑井震分层差异;当界面之上为泥岩,之下为砂岩时,对应波峰,在提取界面之上砂组波峰类属性时则要消除其影响,据此形成了多种提取地震属性时确定时窗的方法。

2) 在振幅、频率和相位类地震属性中,波峰总能量与井上砂砾岩厚度相关性最好,最能反映分流河道砂砾岩分布。

3) 须三段各砂组砂砾岩呈 NW-SE 向条带状分布,向东南减薄,过 YL702-YL12-YB6-YL22-YL6-YB101 井区的条带上砂砾岩较发育。

4) 须三段发育块状中-粗粒钙屑砂岩和砂质细砾岩两类优质储层,两类优质储层受分流河道控制,中-粗粒钙屑砂岩主要分布在平原/前缘亚相界线附近远离物源区的一侧,砂质细砾岩多分布在平原/前缘亚相界线附近靠近物源区一侧。

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