

鄂尔多斯盆地姬塬地区延长组长4+5 低阻油层成因及识别方法

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摘要:近年来在鄂尔多斯盆地姬塬地区延长组长4+5油层组发现了大量低阻油层,但由于其成因机理及识别方法在理论和技术方面存在问题,导致其常被错判或遗漏。为此,根据岩心观察、薄片鉴定、扫描电镜观察、X衍射和高压汞分析等多种技术手段,结合测井资料及试油、试采等数据,对姬塬地区延长组长4+5低阻油层的成因及识别方法进行研究。结果表明,构造幅度低、油水关系复杂、不动水饱和度和地层水矿化度高是长4+5低阻油层的主要成因,其中,不动水饱和度高主要受颗粒粒度细、泥质含量高及孔隙结构复杂等因素控制。实例分析表明,定性识别低阻油层的邻近储层对比法、以泥质含量-孔渗比-不动水饱和度三维模型为基础定量识别低阻油层的可动水分析法及快速直观识别低阻油层的交会图版法为长4+5低阻油层识别的3种有效方法,使研究区低阻油层的解释结论与试油结果的符合率得以提高。

关键词:低阻油层 成因 识别方法 长4+5油层组 姬塬地区 鄂尔多斯盆地

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Genetic mechanism and identification methods of low resistivity oil reservoirs in Chang4+5 member of Yanchang Formation in Jiyuan area, Ordos Basin

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Abstract: In recent years, a large number of low resistivity oil reservoirs have been discovered in Chang4+5 member of Yanchang Formation of Jiyuan area, Ordos Basin. But there are many theoretical and technical problems in the genetic mechanism and identification methods, which often results in misidentification or loss of oil reservoirs in the study area. To study the genetic mechanism and identification methods of low resistivity oil reservoirs in Chang4+5 member of Yanchang Formation in Jiyuan area, a series of measurements and analysis such as core and thin section observation, SEM observation, XRD and mercury injection tests etc., combining with data of logging, oil testing and production, were used. The result shows that low amplitude structure, complex relationship between oil and water, high immobile water saturation and high formation water salinity are the main causes of low resistivity oil reservoirs in Chang4+5 member. Among which, the high immobile water saturation in the study area is controlled by fine particle size, high clay content and complex pore structure.

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The case study shows that three methods of identifying low resistivity oil reservoirs were proposed in this paper: a qualitative contrast method of identifying reservoirs adjacent to low resistivity oil reservoirs; a quantitative identification method of analyzing mobile water of low resistivity oil reservoirs based on a three dimensional model of the relationship among clay content, ratio of porosity to permeability and immobile water saturation; and a crossplot method of identifying low resistivity oil reservoirs fast and accurately. These methods can improve the coincidence rate between the interpretation results and the oil test results.

Key words: low resistivity oil reservoir; genetic mechanism; identification methods; Chang4+5 member; Jiyuan area; Ordos Basin

低阻油层属于非常规储层,在电性特征上主要表现为2种类型:一类是绝对低阻油层,即电阻率绝对值较低,一般小于 $5 \Omega \cdot \text{m}$;另一类是相对低阻油层,即同一油水系统内油层与纯水层的电阻率比值较低,一般小于 $2^{[1-6]}$ 。低阻油层成因复杂多样,主要受构造幅度、不动水饱和度、粘土矿物附加导电性、油水层矿化度、泥浆侵入及测井仪器分辨率等内、外因素影响^[5-11],再加上理论和技术方面的问题,导致低阻油层的评价和识别工作滞后于勘探开发进展。近年来,低阻油层作为老油田增产挖潜的目标之一逐渐受到关注^[12-13]。

鄂尔多斯盆地姬塬地区延长组长4+5低阻油层处于开发初期。H50井区于2016年5月作为研究区最先被发现的低阻油层区块,该区块油层的电阻率为 $3 \sim 11 \Omega \cdot \text{m}$,主要为相对低阻油层。前人对姬塬地区延长组长4+5低阻油层的成因及识别的研究程度较低且不全面,仅基于“四性”分析低阻油层成因,浅析低阻油层的定性识别方法^[14],造成研究区较多低阻油层的遗漏。为此,通过综合分析低阻油层的构造和沉积作用、储层特征及地层水矿化度等因素,创新性建立适合研究区的泥质含量-孔渗比-不动水饱和度三维模型,针对性地提出定性、定量快速识别低阻油层的方法,并确定低阻油层测井解释下限,以期为研究区低阻油层进一步挖潜提供借鉴。

1 区域地质背景

姬塬地区位于鄂尔多斯盆地中西部,横跨伊陕斜坡和天环坳陷两大一级地质构造单元,整体构造平缓,仅局部可见鼻状构造。姬塬地区长4+5油层组为浅水三角洲沉积,主要发育三角洲前缘亚相,油藏主要受控于沉积相带,分布在三角洲前缘亚相的水下分流河道和河口坝储集砂体中,以岩性油藏为主^[15-20]。姬塬地区长4+5油层组地层厚度相对稳定,主要为 $80 \sim 94 \text{ m}$,发育一套砂、泥岩薄互层沉积。储层岩石类型以细一极细粒岩屑质长石砂岩

为主,长石含量为 34.45% ,石英含量为 31.15% ,岩屑含量平均为 12.33% ,泥质含量平均高达 10.10% ,粘土矿物成分以高岭石和绿泥石为主,碎屑颗粒以次棱角状为主,粒度分选性中等—好,整体上矿物成熟度较低。研究区长4+5油层组埋深达 $2\ 200 \sim 2\ 700 \text{ m}$,成岩作用较为复杂,主要包括压实、胶结和溶蚀作用等。

2 低阻油层成因分析

2.1 构造幅度低、油水关系复杂

姬塬地区构造十分平缓,仅局部可见鼻状构造,主要发育岩性油藏,受构造高点的影响不大^[21-23]。圈闭幅度较小,主要为 $10 \sim 15 \text{ m}$ 。对研究区低阻油井进行油藏剖面分析表明,其油层电阻率为 $3.78 \sim 7.47 \Omega \cdot \text{m}$,平均为 $5.95 \Omega \cdot \text{m}$,油藏圈闭幅度小于 15 m ,以岩性油藏为主。试油结果显示储层内油水关系复杂,低幅度构造形成的圈闭中浮力对油气的运移作用有限,导致油水分异不彻底,油水边界不明显,常解释为油水同层,甚至出现油水关系倒置的现象。在低幅度构造背景下形成的复杂油水关系,造成储层含油饱和度降低,电阻率下降,进而形成低阻油层。因此,构造幅度低、油水关系复杂是长4+5低阻油层形成的主要因素之一。

2.2 不动水饱和度高

一般情况下,不动水由岩石颗粒表面被吸附的薄膜滞留水和微细毛管孔中的毛管滞留水组成^[6],其中薄膜滞留水的含量主要受控于颗粒比表面积和岩石亲水性,毛管滞留水主要受控于孔隙结构(内因)及压差(外因)。影响不动水饱和度的主要因素包括岩石类型、颗粒粒度、泥质含量、粘土类型及孔隙结构等储层岩石本身的性质。

核磁共振测井法通常为不动水饱和度最有效的求取方法,但由于研究区缺少实测资料,故采用高压压汞相关数据近似确定不动水饱和度。一般认为,当孔隙半径小于 $0.15 \mu\text{m}$ 时,孔隙内所含水难以在地层压力条件下流动,因此把这部分孔隙体积

占有有效孔隙体积的百分数近似作为储层的不动水饱和度^[24]。研究表明,长4+5低阻油层不动水饱和度较高,为36.09%~97.84%,平均为68.57%。由不动水饱和度与电阻率关系(图1)可以看出,随着不动水饱和度的增加,电阻率呈减小趋势,二者呈负相关,说明不动水饱和度高是长4+5低阻油层形成的主要因素之一。

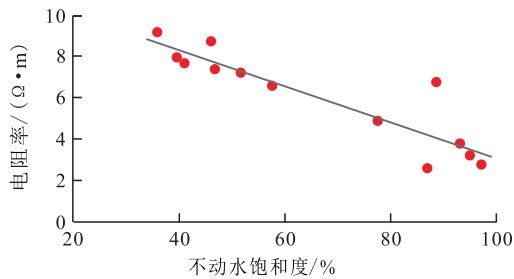


图1 姬塬地区长4+5低阻油层不动水饱和度与电阻率关系

Fig.1 Relationship between the immobile water saturation and resistivity of low resistivity oil reservoirs in Chang4+5 member in Jiyuan area

2.2.1 颗粒粒度细

姬塬地区长4+5低阻油层形成于浅水三角洲前缘低能环境,水动力较弱,形成的岩石颗粒粒度细,杂基含量高,岩性以细砂岩为主,颗粒粒度普遍较小,粒径主要为0.10~0.25 mm(图2)。岩石颗粒粒度细,不仅会造成岩石比表面增大,在颗粒表面吸附更多的薄膜滞留水;还导致孔隙弯曲度增大,形成大量的微小毛管孔隙,使得孔隙中含有较高含量的毛管滞留水,二者共同作用导致不动水饱和度增高,而不动水饱和度越高,在储层中越容易形成良好的离子导电网络,储层的导电性越强,越容易形成低阻油层^[14,25]。

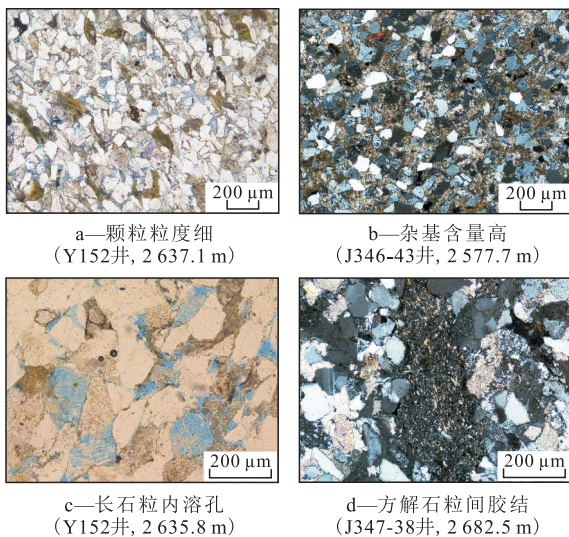


图2 姬塬地区长4+5低阻油层铸体薄片照片

Fig.2 Photographs of casting thin section of low resistivity oil reservoirs in Chang4+5 member in Jiyuan area

2.2.2 粘土矿物含量高

姬塬地区长4+5低阻油层粘土矿物含量较高。由X衍射分析结果表明,其泥质含量主要为6.0%~17.2%,平均为10.1%,其中,以高岭石(含量为37.8%)和绿泥石(含量为32.7%)为主,其次是伊利石(含量为24.3%)和伊/蒙混层(含量为5.1%)。从扫描电镜照片可以看出,粘土矿物多以分散质点状充填于粒间孔隙或者贴附在颗粒表面(图3)。

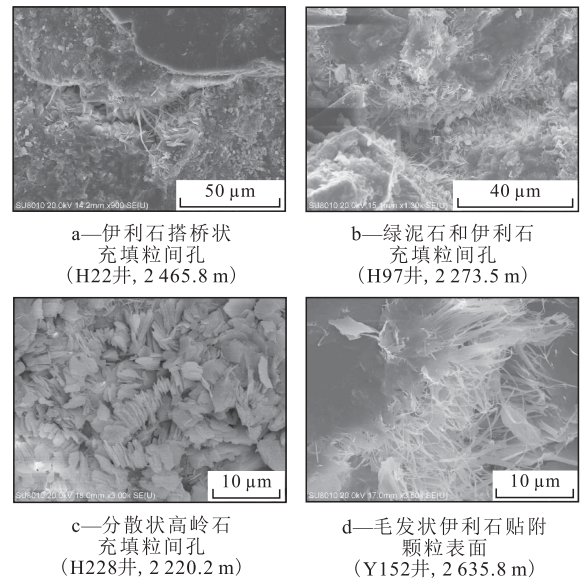


图3 姬塬地区长4+5低阻油层粘土矿物扫描电镜照片

Fig.3 Scanning electron microscopy images of clay minerals of low resistivity oil reservoirs in Chang4+5 member in Jiyuan area

粘土矿物含量和产状影响不动水饱和度。高含量的粘土矿物对孔隙结构改造强烈,粘土矿物的产状决定其分子间作用力和亲水性,疏松分布的粘土矿物,一方面导致分子间作用力变弱,粘土矿物易随流体迁移,进而堵塞孔喉,导致微孔隙发育,使得毛管滞留水含量增高;另一方面导致晶格间距变大,亲水性变强,易在颗粒表面形成薄膜滞留水,2方面共同作用导致地层中不动水饱和度升高,形成十分发达的不动水离子导电网络,从而降低地层电阻率^[26]。因此,研究区发育的高含量和分散状的粘土矿物为形成高不动水饱和度提供物质基础。

由研究区长4+5低阻油层泥质含量与不动水饱和度关系(图4)可以看出,随着泥质含量的增多,不动水饱和度呈增加趋势,二者呈正相关,说明泥质含量高是形成不动水饱和度高的主要因素之一。

2.2.3 孔隙结构复杂

姬塬地区长4+5油层组埋深较大,由于压实、胶结和溶蚀等成岩作用及储层岩石学特征共同作用使得储层孔隙结构更加复杂^[27](图2)。扫描电镜观

察结果表明,长4+5低阻油层孔隙类型以粒间孔(图3)和粒内溶孔(图5)为主。压汞曲线特征分析表明,储层以细孔微喉为主,孔喉渗流能力差,属于典型低孔超低渗透储层^[28](图6)。复杂的孔隙结构容易导致毛管排驱压力增大,毛管中的地层水部分残留在微小孔喉中,导致不动水饱和度增加。

孔渗比反映储层的孔隙结构,其比值越小,孔隙结构越复杂^[29]。由研究区长4+5低阻油层孔渗比

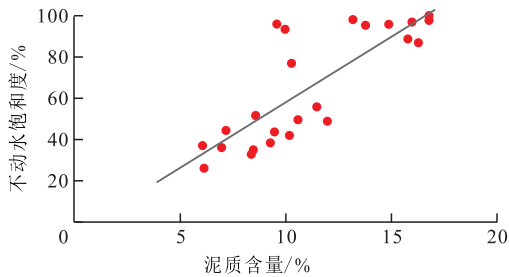
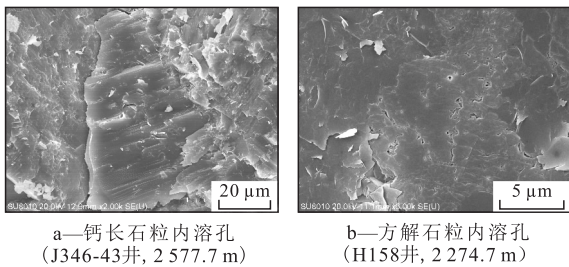


图4 姬塬地区长4+5低阻油层泥质含量与不动水饱和度关系

Fig.4 Relationship between clay content and immobile water saturation of low resistivity oil reservoirs in Chang4+5 member in Jiyuan area



a—钙长石粒内溶孔 (J346-43井, 2 577.7 m) b—方解石粒内溶孔 (H158井, 2 274.7 m)

图5 姬塬地区长4+5低阻油层扫描电镜照片

Fig.5 Scanning electron microscope images of low resistivity oil reservoirs in Chang4+5 member in Jiyuan area

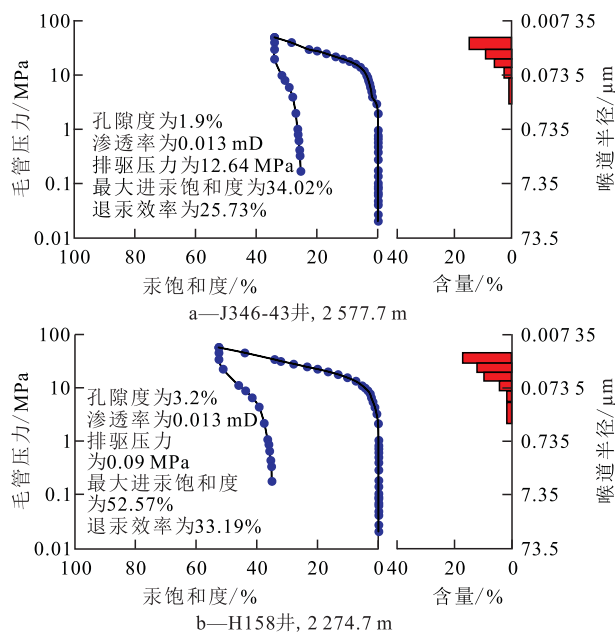


图6 姬塬地区长4+5低阻油层压汞曲线

Fig.6 Mercury injection curve of low resistivity oil reservoirs in Chang4+5 member in Jiyuan area

与不动水饱和度关系(图7)可以看出,孔渗比和不动水饱和度之间具有较好的负相关性,当孔渗比小于0.05 mD/%时,随着孔渗比的增大,不动水饱和度快速降低;当孔渗比大于0.05 mD/%时,随着孔渗比的增大,不动水饱和度缓慢降低,说明孔隙结构越复杂,对不动水饱和度的影响越大。

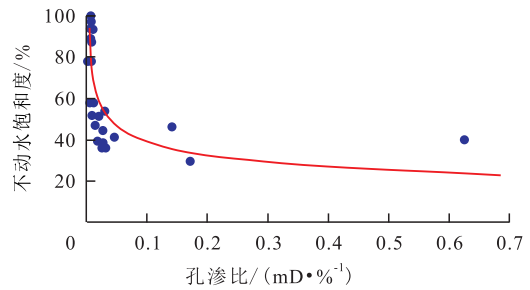


图7 姬塬地区长4+5低阻油层孔渗比与不动水饱和度关系

Fig.7 Relationship between ratio of porosity to permeability and immobile water saturation of low resistivity oil reservoirs in Chang4+5 member in Jiyuan area

2.3 地层水矿化度高

油层电阻率除受岩石类型和物性影响外,还受地层水矿化度影响。高矿化度地层水具有较高的电解质浓度,会造成导电性较强的离子相互连通构成离子导电网络,进而导致油层的电阻率降低,最终形成低阻油层^[8,30]。

姬塬地区长4+5油层组地层水以CaCl₂型为主,但研究区地层水矿化度在不同的油层类型中存在差异,低阻油层地层水矿化度为30.5~100.1 g/L,平均为62.4 g/L;高阻油层地层水矿化度为16~58 g/L,平均为39.7 g/L。研究区长4+5低阻油层不同类型油层地层水矿化度与电阻率关系(图8)表明:低阻油层的地层水矿化度明显高于高阻油层的地层水矿化度;低阻油层和高阻油层的电阻率均随着地层水矿化度的增大而降低,且在高阻油层中的降低速率大于低阻油层。这些特征均说明地层水矿化度

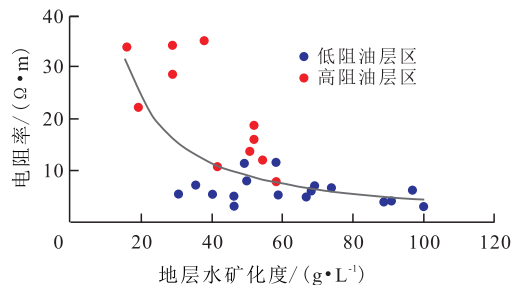


图8 姬塬地区长4+5低阻油层不同类型油层地层水矿化度与电阻率关系

Fig.8 Relationship between formation water salinity and reservoir resistivity in different oil pay types of low resistivity oil reservoirs in Chang4+5 member in Jiyuan area

高是导致研究区长4+5低阻油层形成的主要因素之一。

3 低阻油层识别方法

在对低阻油层地质背景及成因机理分析的基础上,通过对大量测井资料和试油结果的对比分析,提出3种有效识别低阻油层的方法:定性识别低阻油层的邻近储层对比法、以泥质含量-孔渗比-不动水饱和度三维模型为基础定量识别低阻油层的可动水分析法,以及快速直观识别低阻油层的交会图版法,并确定其测井解释下限。

3.1 邻近储层对比法

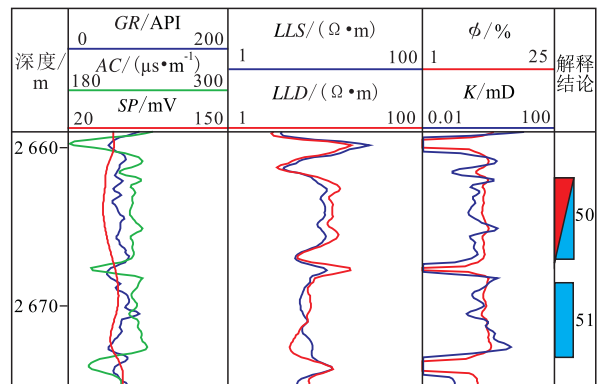
在掌握地质背景的基础上,结合测井资料及试油、试采数据等资料,分析测井曲线的响应特征及其组合关系,重点对比分析储层电性与岩性、物性、含油性及水性之间的匹配关系,进而客观准确地识别低阻油层^[27]。通过对研究区大量低阻油层实例分析,认为邻近储层电性对比法和邻近储层水性对比法对长4+5低阻油层的识别是有效可行的。

3.1.1 电性对比法

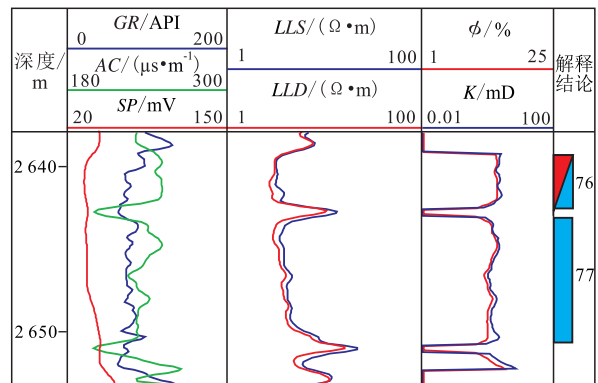
当目的层的物性和岩性与邻近水层接近,且其电阻率与邻近水层电阻率的比值小于2时,可以将其解释为油层或油水同层。如J347-41井,顶部储层(50号)和底部储层(51号)的孔隙度和渗透率接近,说明其物性相近,自然电位负异常幅度一致说明水性也很接近,但电阻率存在较大差异(图9a),即50号储层电阻率($9.79 \Omega \cdot m$)是51号储层电阻率($6.26 \Omega \cdot m$)的1.56倍,故将50号储层解释为油水同层,试油获产油量为2.68 t/d,解释结论与试油结果一致。

3.1.2 水性对比法

油气评价工作往往容易忽略水性对电阻率的影响,易将低阻油层误判为水层。因此,当相邻2套储层物性和岩性相近时,地层水矿化度高的低电阻率储层可识别为油层或油水同层,且油层的电阻率值远高于油水同层。如H23-68井,顶部76号储层电阻率($3.2 \Omega \cdot m$)略小于底部77号储层($3.5 \Omega \cdot m$),解释物性曲线和自然伽马测井曲线认为,这2套储层的物性和岩性接近。但自然电位负异常幅度存在较大差异(图9b),说明其地层水性质存在差异,地层水分析结果表明,76号储层地层水矿化度(100.1 g/L)大于77号(85.2 g/L),故将76号储层解释为油水同层,与试油结果(产油量为15.9 t/d,产水量为9.9 t/d)吻合。



a—J347-41井



b—H23-68井

图9 姬塬地区长4+5低阻油层邻近储层对比法

Fig.9 Contrast memthod of identifying reservoirs adjacent to low resistivity oil reservoirs in Chang4+5 member in Jiyuan area

3.2 可动水分析法

可动水分析法是根据地层中是否有可动水来确定储层产液性质^[14-15]。可以通过分析储层含水饱和度(S_w)和不动水饱和度(S_{wi})确定可动水饱和度(S_{wm})^[31],即 $S_{wm}=S_w-S_{wi}$ 。统计分析表明,低阻油层可动水饱和度与产液性质之间具有如下关系:当储层中 $S_w \approx S_{wi}$ 时,几乎无可动水,储层只产油不出水,为油层;当储层中 $S_w > S_{wi}$,即 $S_{wm} > 0$ 时,可动水含量适中,油水均出,为油水同层;当储层中 $S_w \geq S_{wi}$,且 $S_{wm} \rightarrow 1$ 时,可动水占据大部分储集空间,以出水为主,偶见油花,为水层或含油水层。

对研究区长4+5低阻油层成因机理分析结果表明,低阻油层不动水饱和度受泥质含量(V_{sh})和孔隙结构影响,根据已有的不动水饱和度数据建立泥质含量-孔渗比-不动水饱和度三维模型(图10),并得出其相应的拟合公式。由模型可以看出,泥质含量越高,孔渗比越小,不动水饱和度越大,相关系数也高,可达0.84,说明该模型拟合效果很好。因此,可以根据该拟合公式快速计算不动水饱和度,进而求出可动水饱和度。如J351-41井,埋深为2529~2534 m,泥质含量为13.03%,孔渗比为0.36 mD/%,

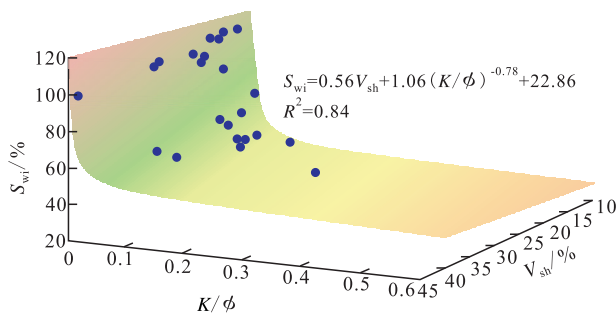


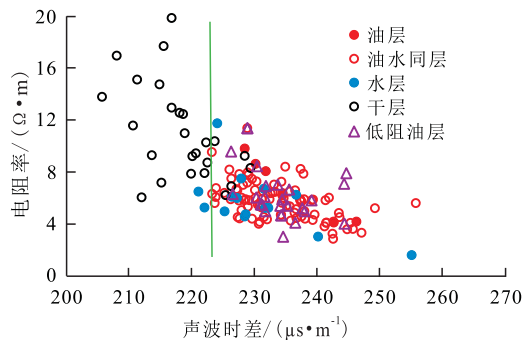
图10 姬塬地区长4+5低阻油层泥质含量-孔渗比-不动水饱和度的三维模型

Fig.10 A three-dimensional model related to clay content, ratio of porosity to permeability and immobile water saturation for low resistivity oil reservoirs in Chang4+5 member in Jiyuan area

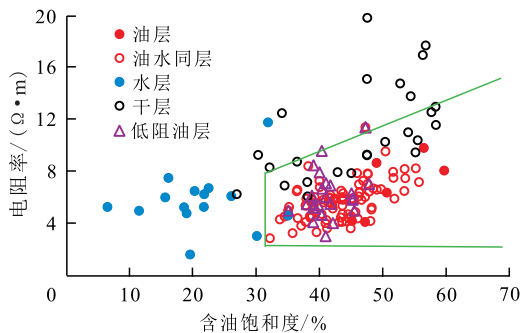
含水饱和度为49.32%,由拟合公式计算得出其不动水饱和度为32.52%,可动水饱和度为16.8%,故将其解释为油水同层,试油获产油量为8.88 t/d,产水量为6.42 t/d,解释结论与试油结果一致。

3.3 交会图版法

交会图版法是识别流体性质常用的1种快速有效的方法,从交会图版中可直观地看出油层、水层的电性和物性特征^[32](图11)。声波时差与电阻率、含水饱和度与电阻率交会图版法在识别研究区低阻油层方面效果较好,并在此基础上确定低阻油层的测井解释下限。



a—声波时差与电阻率交会图版



b—含水饱和度与电阻率交会图版

图11 姬塬地区长4+5低阻油层交会图版

Fig.11 Crossplots for identification of low resistivity oil reservoirs in Chang4+5 member in Jiyuan area

对姬塬地区长4+5低阻油层的137个数据点进行统计分析,结果表明:声波时差与电阻率交会图版可确定出低阻油层的声波时差下限为223 μs/m,含水饱和度与电阻率交会图版可确定出低阻油层含水饱和度下限为32%,电阻率下限为2.5 Ω·m。长4+5低阻油层26个经试油结果验证的低阻油层数据点与交会图版的吻合率高达92%,这表明交会图版法可以有效识别低阻油层。

对低阻油层不同识别方法的实例分析结果表明,以上3种识别方法的原理和思路虽然存在较大差异,但都能提高解释结论与试油结果的符合率。

4 结论

姬塬地区长4+5油层组构造幅度低、地形平缓,主要发育浅水三角洲前缘亚相,低能沉积环境下发育的储层具有颗粒粒度细、泥质含量高和矿物成熟度低的岩石学特征,储层埋深大,成岩作用复杂,孔隙类型以细孔微喉为主,属于典型的低孔超低渗透储层。姬塬地区长4+5低阻油层成因主要包括构造幅度低、油水关系复杂、不动水饱和度和地层水矿化度高。其中,不动水饱和度高受颗粒粒度细、泥质含量高及孔隙结构复杂等因素影响。

通过对研究区大量测井资料和试油结果的对比分析,提出了3种有效识别低阻油层的方法,分别为定性识别低阻油层的邻近储层对比法,以泥质含量-孔渗比-不动水饱和度三维模型为基础定量识别低阻油层的可动水分析法,以及快速直观识别低阻油层的交会图版法。实例分析表明以上3种方法对长4+5低阻油层的识别均取得较好的效果,提高了解释结论与试油结果的符合率。因此,综合使用以上识别方法有助于指导研究区低阻油层的进一步挖潜。

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