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苏北盆地古近系阜宁组页岩七性关系与三品质测井评价

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内容提要:通过岩芯、薄片、扫描电镜等岩石物理实验结合常规、成像以及核磁共振等测井资料,对苏北盆地古近系阜宁组阜二段页岩“七性关系”和“三品质”进行研究。结果表明阜二段页岩储集空间包括粒间孔、颗粒溶孔、晶间孔、有机质孔以及微裂缝,不同孔径孔隙含油性均较好。根据物性参数、孔隙空间建立了储层品质划分标准,由Ⅰ类到Ⅳ类束缚水饱和度逐渐变大。阜二段烃源岩有机质类型好,*TOC* 基本都大于1%,根据自然伽马能谱测井 K 含量和 $\Delta \lg R$ 建立了 *TOC* 测井模型,并根据 *TOC* 大小实现烃源岩品质划分。地应力方向主要为北东—南西向,阜二段脆性指数基本都大于40%,可压裂性好,根据脆性指数实现工程品质划分。在“七性关系”研究基础上,通过对储层品质、烃源岩品质以及工程品质三者叠加完成了单井“甜点”段优选,甜点主要分布在泥脖子、七尖峰、四尖峰和上山字和中山字段,结果与试油资料相吻合。研究成果可为页岩油测井评价和甜点预测提供理论指导和技术支撑。

关键词:页岩油;七性关系;三品质;测井评价;阜宁组;苏北盆地

页岩油(广义)泛指蕴藏在富有机质页岩层系(包含页岩层系中的致密碳酸盐岩和碎屑岩夹层)中的石油资源(邹才能等,2015;金之钧等,2019;付金华等,2019;赵贤正等,2020)。狭义页岩油则指滞留于页岩层中尚未排出、相对原位存储的石油(赵贤正等,2020)。页岩油通常富集于有机质丰富的细粒沉积岩层系内,储层可为致密碎屑岩、碳酸盐岩和泥页岩,依靠常规开发技术难以开采,需通过压裂改造(邹才能等,2013;金之钧等,2019;付金华等,2019;杨智等,2021)。近年来,随着页岩油勘探开发理论和工程上的突破,页岩油在全球各个盆地获得广泛突破,如美国和加拿大交界处 Williston 盆地的巴肯页岩(Saidian and Prasad, 2015)、渤海湾盆地沧东凹陷孔店组孔二段(鄢继华等,2017;Guan Ming et al., 2020)、鄂尔多斯盆地延长组7段细粒沉积岩(邹才能等,2015;袁选俊等,2015;Lai Jin et al., 2016)、准噶尔盆地吉木萨尔凹陷二叠系芦草沟组(王小军等,2019;支东明等,2019;王剑等,2020)、苏北盆地古新统阜宁组阜二段(Liu Xiaoping et al., 2020)等,证实了页岩油具有巨大的资源勘探潜力(李晓光等,2019;邹才能等,2019;胡宗全等,2021)。

测井技术作为重要的技术手段在页岩油理论研究与勘探开发实践中发挥了不可替代的作用(蒋云箭等,2020;李宁等,2021)。众多专家学者针对页岩测井评价做了很多卓有成效的工作,在页岩层序地层(熊绍云等,2020)、岩相(匡立春等,2015;张超等,2017)、孔隙结构(Loucks et al., 2012)、裂缝识别(Lyu Wenya et al., 2016;吕文雅等,2021)、储层参数计算(张晋言,2012)、脆性指数(Lai Jin et al., 2015)、地层压力(钟淑敏等,2016)和源储配置关系(钟高润等,2016)等精细评价与测井表征取得系列

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成果。然而总体而言,非常规油气的快速兴起使得现今测井评价技术正面临不适应勘探开发对象的艰难时期(李浩等, 2015; 刘国强, 2021; 赖锦等, 2021)。致密、页岩油气评价提出的“七性关系”(岩性、物性、电性、含油性、脆性、烃源岩特性和地应力各向异性)和“三品质”(烃源岩品质、储层品质和工程品质)评价使测井评价技术面临多重挑战和全新探索(李浩等,2015;刘国强,2021;赖锦等,2021)。勘探目标的转变以及技术需求的提高对测井评价技术提出了新的要求(李宁等, 2020; 蒋云箭等, 2020),即由原来的常规储层“四性关系”研究逐渐转向非常规油气“七性关系”和“三品质”评价(赵政璋等,2012;闫伟林等,2014;蒋云箭等,2020;赖锦等,2021)。

然而目前缺乏一套可推广的针对页岩油的“七性关系”和“三品质”测井评价体系,本文基于以上研究现状和存在的问题,以苏北盆地古近系阜宁组阜二段典型狭义页岩油(Zhang et al., 2014)为例,首先分别阐明其岩性、物性、电性、含油性、脆性、烃源岩特性和地应力各向异性等七性特征,然后通过岩芯分析化验资料以及常规测井结合新技术测井资料实现页岩“七性关系”测井表征;在此基础上分别建立页岩油“三品质”分类标准与对应测井评价体系。以期为页岩油测井评价提供了新思路和新方法,并为非常规油气测井评价体系提供理论依据与技术示范。

1 区域地质概况

苏北盆地是在白垩系基底之上形成的中新生代断陷湖盆,行政区划上属于安徽和江苏地界,并向东延伸入黄海,其面积约 3.5×10^4 km^2(Qiao Xiaojuan et al., 2012;Quaye et al., 2019;李维等,2020)。苏北盆地构造演化可以分为 3 个阶段:早期拉伸断裂阶段、晚期断陷阶段以及坳陷阶段(Liu Chao et al., 2016)。形成现今的近东西向“一隆两坳”构造格局:盐阜坳陷、建湖隆起、东台坳陷(图 1)(骆卫峰

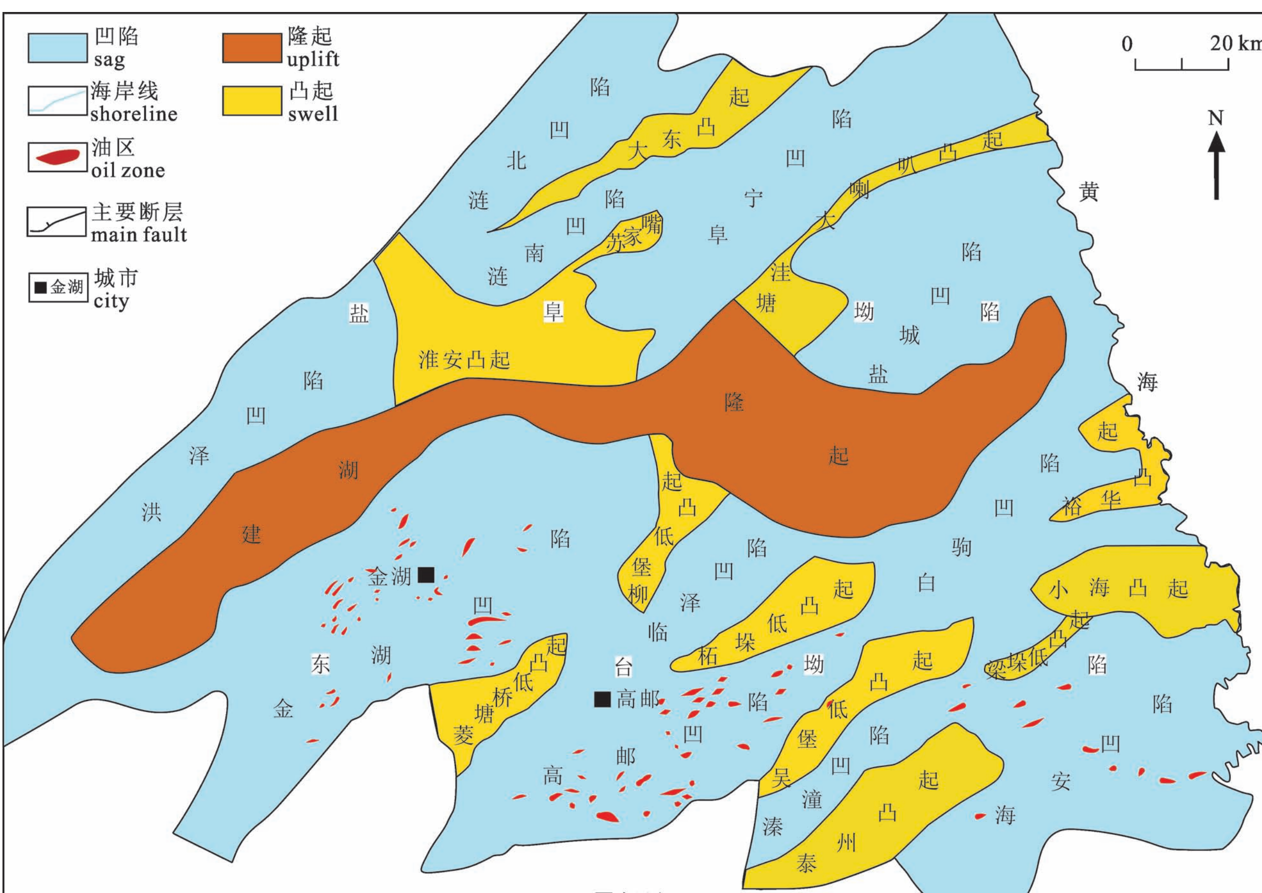


图 1 苏北盆地构造带划分图(据 Zhang et al., 2014; Liu Jingshou et al., 2018;王旭影和姜在兴,2021 修改)

Fig. 1 Tectonic location and units of Subei Basin (modified from Zhang et al., 2014; Liu Jingshou et al., 2018; Wang Xuying and Jiang Zaixing,2021&)

等,2018)。钻孔揭示苏北盆地中新生代沉积物厚度可达 7000 m,发育地层包括上白垩统泰州组(K_2t),古近系阜宁组(E_1f)、戴南组(E_2d)和三垛组(E_2s)以及新近系盐城组(N_2y)和第四系东台组(Qd)(Chen Liqiong, 2009; Qiao Xiaojuan et al., 2012;Liu Chao et al., 2016;李维等,2020)。

阜宁组自下而上可以划分为 4 段,即阜一—阜四段(E_1f_1—E_1f_4)(Qi Kun et al., 2018)。其中,阜一段和阜三段沉积以河流—三角洲相为主,其岩性主要为砂岩、粉砂岩;而阜二段和阜四段以湖泊相深灰色泥页岩为主,是苏北盆地广泛发育的烃源岩层(Qi Kun et al., 2018;王旭影和姜在兴, 2018;彭金宁等,2020;Liu Xiaoping et al., 2020)。近年来随着“进源找油”理论的革新以及水平井钻井、体积压裂等技术的进步,该套烃源岩层也逐渐成为产油的目的层并受到广泛关注(Cheng Qingsong et al., 2019; Liu Xiaoping et al., 2020)。目前在苏北盆地金湖凹陷和高邮凹陷钻遇的阜宁组(阜二段和阜四段)泥页岩层系 200 余井中见油气显示,试油有 4 口井累计产油在 1000 t 以上,显示了优越的页岩油聚集条件和良好的油气勘探前景(段宏亮等,2020;付茜等,2020)。

2　“七性关系”研究

2.1　岩性

岩性的识别与划分是进行页岩油甜点评价预测、探井部署的基础(赵贤正等,2017)。阜二段页岩主要形成于相对低能环境的深湖、半深湖沉积环境,且其细微的沉积环境以及沉积物来源变化也造成沉积构造、矿物组分特征等具有明显差异(李维等,2020;付茜等,2020)。结合现场岩芯描述、薄片鉴定和 XRD 分析,确定阜宁组阜二段岩性主要是灰黑色页岩(图 2a—c)、(灰质)泥页岩(图 2d—f;图 2g—i)、云质或粉砂质泥岩等(图 2j—l;图 2m—o)(Cheng Qingsong et al., 2019; Liu Xiaoping et al., 2020)。XRD 全岩分析表明主要矿物组成包括石英、长石、碳酸盐颗粒和黏土矿物(伊利石和伊蒙混层)以及黄铁矿(Liu Xiaoping et al., 2021)。

2.2　物性及孔隙结构

氦气孔隙度以及脉冲渗透率分析表明阜二段页岩油储层孔隙度介于 0.18% ~ 7.82%,平均仅 2.14%,渗透率平均 0.13×10^{-3} μm^2,分布在 0.000002 至 11.73×10^{-3} μm^2 之间(Liu Xiaoping et al., 2020)(图 3a)。核磁共振 T_2 谱分布基本表现为单峰状,部分 T_2 谱存在拖尾现象(图 3b)。说明其孔喉体系以细小的相对连续的孔隙空间为主,较少大孔径粒间孔等(图 3b)。

Loucks 等(2009,2012)研究指出页岩油孔隙空间基本为纳米级,且其孔隙类型包括粒间孔、粒内孔、有机质孔和微裂缝(Liu Xiaoping et al., 2021)。除微裂缝外,因此基于光学显微镜的铸体薄片难以探测到页岩油储层中的不同孔隙类型(图 2),扫描电镜在形貌及连通性等探测方面作用凸显(Zhang Pengfei et al., 2018)。扫描电镜观察表明阜二段纳米级孔隙广泛发育,包含(1)无机成因孔隙,如颗粒(石英、长石和碳酸盐颗粒)粒间孔(图 3c)、粒内(长石和白云石颗粒)溶孔(图 3d)、矿物(黏土矿物和白云石)晶间孔(图 3e,3f);(2)有机成因孔隙如有机质孔(图 3g);(3)微裂缝(图 3h)(Liu Xiaoping et al., 2020)。

2.3　含油性

页岩油微观含油性由孔隙类型及其组合特征以及矿物润湿性决定(Xi Kelai et al., 2019; Zhao Xianzheng et al., 2019;Liu Xiaoping et al., 2020)。荧光薄片视域下可见阜二段页岩全尺度孔隙均含油,矿物颗粒如长石、白云石等边缘发暗蓝或亮蓝色荧光(图 4a,b),长石以及亲油性白云石颗粒内部溶蚀形成的粒内孔隙暗蓝或亮蓝色荧光特征呈分散状分布(图 4a,b)(Liu Xiaoping et al., 2020)。部分陆源黏土矿物内部以及有机质内部也有分散蓝色荧光特征(图 4c,d),此外,未被充填的微裂缝暗色荧光特征也很明显(图 4e,f)。事实上,页岩油储层中哪怕孔径最小的有机质孔,由于其亲油性,往往也是含油的(Loucks et al., 2009; Li Maowen et al., 2019)。

2.4　电性/测井响应

页岩电测响应表现出明显的高伽马(>60 API)、高中子(>15%)、高声波时差(>250 μs/m)、低密度(<2.55 g/cm^3)、高电阻率的特征(图 6)。含油性好的页岩层段又表现出特定的响应,即相对低伽马、高电阻率、深浅电阻率存在幅度差、核磁共振 T_2 谱分布范围宽,且存在一定的拖尾现象。而相对不含油的页岩层段表现为相对高伽马、低电阻率(深浅电阻率基本重合)、高 Pe 值(>5 b/e)、高密度和低声波时差的特征(图 6)(Liu Xiaoping et al., 2020)。

2.5　烃源岩特性

评价烃源岩特性通常依赖地球化学分析测试方

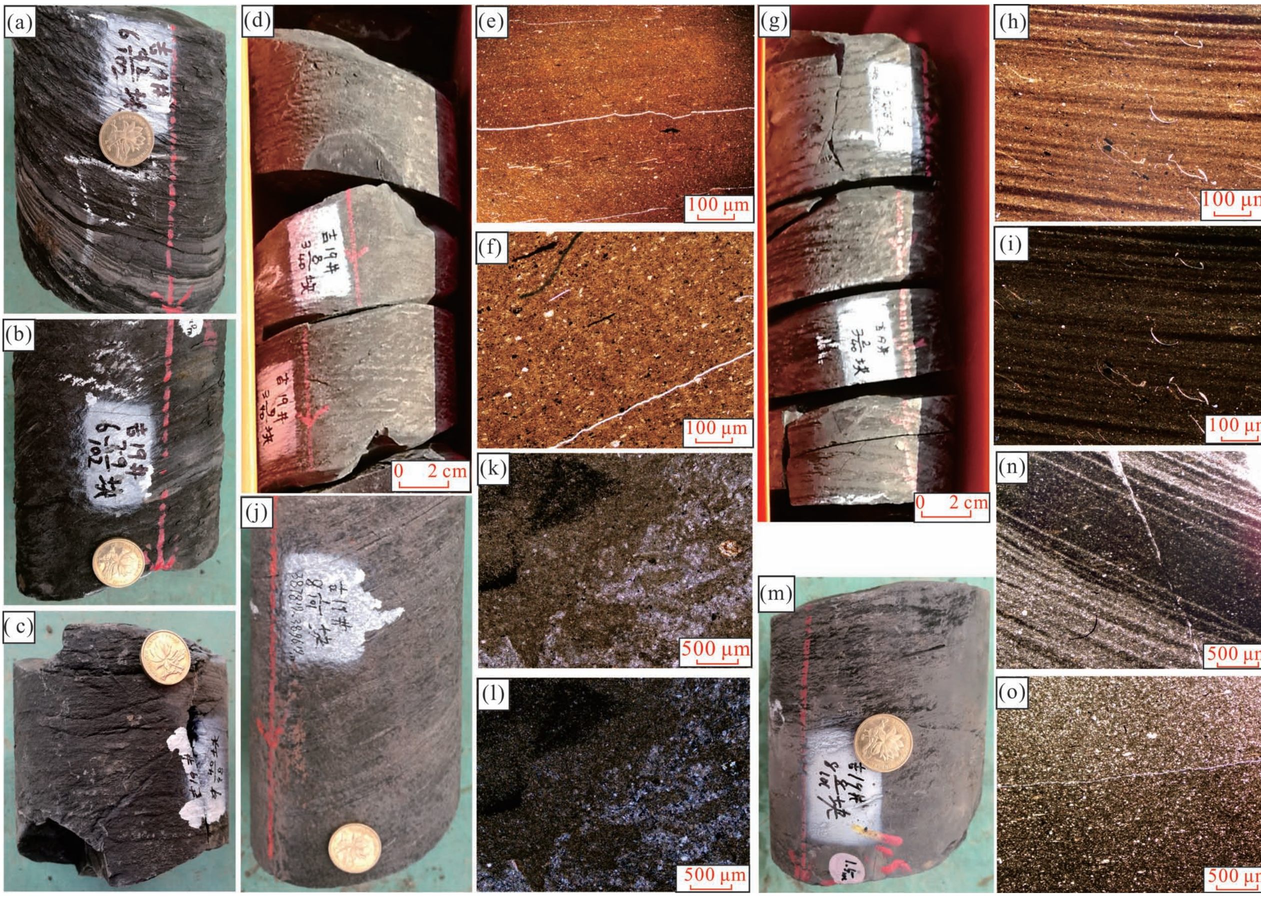


图 2 苏北盆地古近系阜宁组二段不同岩性岩芯及镜下薄片特征

Fig. 2 Core photos and thin section images of various lithogies of the Second Member of the Paleogene Funing Formation in Subei Basin

(a) 灰黑色页岩,Ji-19 井,3865.28 m;(b) 灰黑色页岩,Ji-19 井,3865.28 m;(c) 灰黑色白云质泥岩,Ji-19 井,3903.22 m;(d) 灰色泥岩,Ji-19 井,3826.22 m;(e) 泥岩,发育微裂缝;(f) 泥岩,发育微裂缝;(g) 灰色泥岩,Ji-19 井,3825.15 m;(h) 纹层状泥岩,纹层由泥质、长英质颗粒和碳酸盐颗粒构成,单偏光;(i) 纹层状泥岩,纹层由泥质、长英质颗粒和碳酸盐颗粒构成,正交光;(j) 灰黑色云质、粉砂质泥岩,Ji-19 井,3878.19 m;(k) 灰黑色云质、粉砂质泥岩,单偏光,Ji-19 井,3878.25 m;(l) 灰黑色云质、粉砂质泥岩,正交光,Ji-19 井,3878.25 m;(m) 灰黑色云质泥岩,Ji-19 井,3879.5 m;(n) 灰黑色纹层状云质泥岩,粉砂质和微晶白云石组分可成纹层状,Ji-19 井,3879.5 m;(o) 灰黑色纹层状云质泥岩,粉砂质和微晶白云石组分可成不显纹层状,Ji-19 井,3879.5 m

(a) grayish black shale, the Well Ji-19, 3865.28 m; (b) grayish black shale, the Well Ji-19, 3865.28 m; (c) gray black dolomitic mudstone, the Well Ji-19, 3903.22; (d) gray mudstone, the Well Ji-19, 3826.22 m; (e) gray mudstone with micro-fracture; (f) mudstone with micro-fracture; (g) gray mudstone, the Well Ji-19, 3825.15 m; (h) laminated mudstone, and the lamina are characterized by argillaceous, felsic and carbonate, plane polarized light; (i) laminated mudstone, and the lamina are characterized by argillaceous, felsic and carbonate, cross polarized light; (j) grayish black dolomitic and silty mudstone, the Well Ji-19, 3878.19 m; (k) grayish black dolomitic and silty mudstone, plane polarized light, the Well Ji-19, 3878.25 m; (l) grayish black dolomitic and silty mudstone, cross polarized light, the Well Ji-19, 3878.25 m; (m) grayish black dolomitic mudstone, the Well Ji-19, 3879.5 m; (n) grayish black laminated dolomitic mudstone, silts and microcrystalline dolomite can form lamina, the Well Ji-19, 3879.5 m; (o) grayish black lamina dolomitic mudstone, silts and microcrystalline dolomite have no laminated structure, the Well Ji-19, 3879.5 m

法,获得其中有机质类型、有机质丰度和成熟度等参数,其中的有机质丰度常用总有机碳含量(*TOC*)来表征(杨涛涛等,2013;Zhao Xianzheng et al.,2019)。但受到分析样品数量和成本的限制,单井纵向上连续评价 *TOC* 的工作通常难以开展,因此利用纵向分辨率高、连续性好的测井资料势在必行(王贵文等,2002;杨涛涛等,2013)。Schmoker(1981)利用对烃源岩有机碳响应比较灵敏的自然伽马、密度和声波时差等曲线建立了烃源岩定性识别方法。Passey 等(1990)提出了基于声波时差和

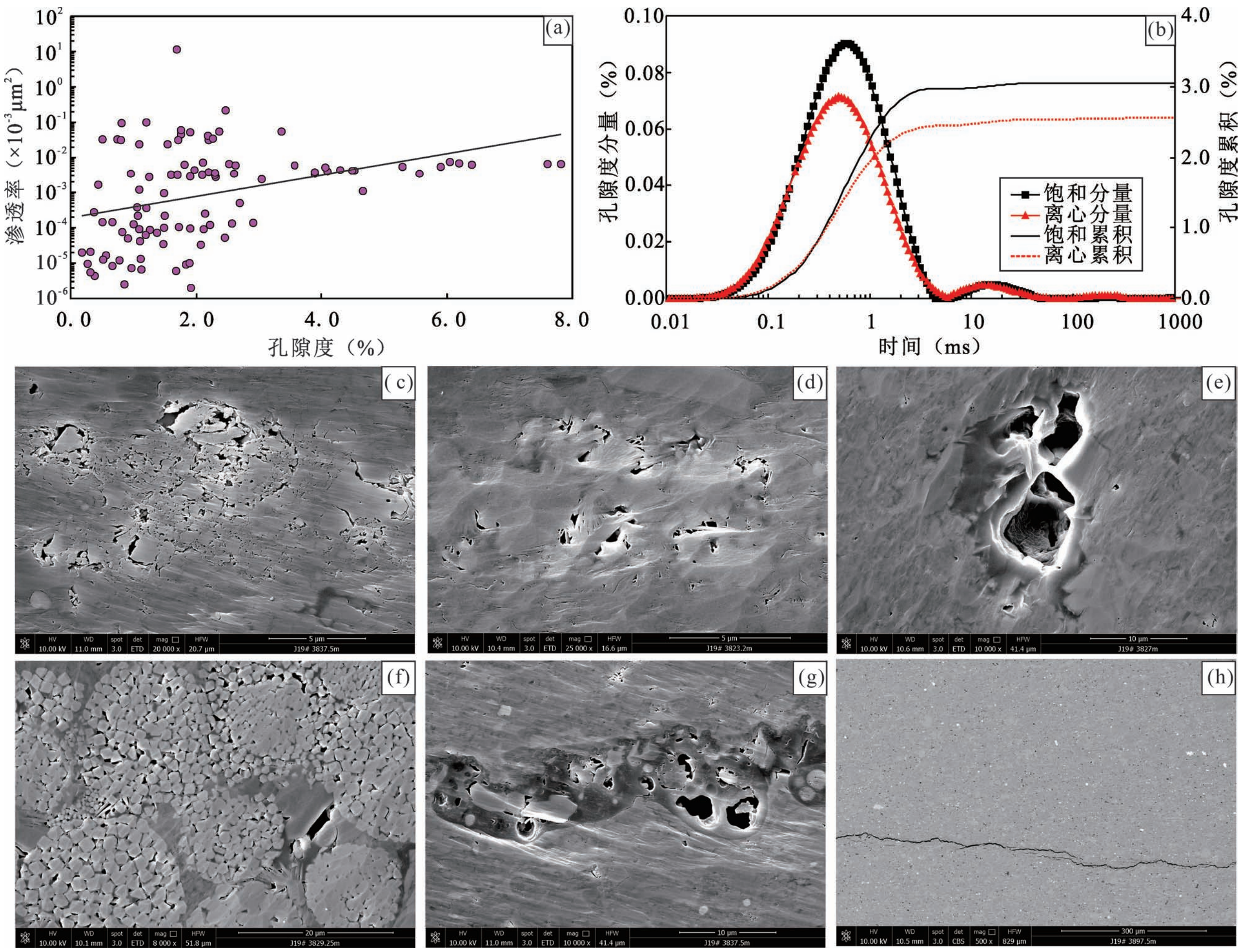


图 3 苏北盆地古近系阜宁组二段孔渗关系、核磁共振 T_2 谱以及不同储集空间扫描电镜照片

Fig. 3 Porosity—permeability crossplot, NMR T_2 spectrum and SEM images of various pore spaces of the Second Member of the Funing Formation in Subei Basin

(a) 苏北盆地古近系阜宁组二段孔渗交会图;(b) 核磁共振 T_2 谱;(c) 颗粒粒间孔;(d) 长石颗粒溶蚀形成粒内孔;(e) 黏土矿物晶间孔;(f) 黄铁矿晶间孔;(g) 有机质孔;(h) 微裂缝

(a) cross plot of porosity and permeability; (b) nuclear magnetic resonance T_2 spectrum; (c) interparticle pore; (d) intragranular pores formed by dissolution of feldspar particles; (e) intercrystalline pores of clay minerals; (f) intercrystalline pores of pyrite; (g) organic matter pores; (h) microfracture

电阻率曲线相叠合的 $\Delta \lg R$ 方法进行 *TOC* 测井计算(Passey et al., 1990),此后国内外学者在此基础上提出了基于不同电测响应具有不同适应性的 *TOC* 测井评价模型,并取得了广泛应用(王贵文等,2002;朱光有等,2003;Zhao Peiqiang et al., 2016;Shalaby et al., 2019;Godfray and Seetharamaiah,2019)。

$$\Delta \lg R=\lg(R/R_{基线})+0.02(\Delta t-\Delta t_{基线}) \quad (1)$$

$$TOC=\Delta \lg R\times 10^{(2.297-0.1688LOM)} \quad (2)$$

式(1)和(2)中,$\Delta \lg R$ 为声波和电阻率曲线分异幅度,它包含了岩石属性和烃源岩特性,R 为测井(深)电阻率,Ω·m;Δt 为实测声波时差,μs/ft (1 ft = 30.48 cm);$R_{基线}$ 和 $\Delta t_{基线}$ 为声波和电阻率基线对应的电阻率(Ω·m)和声波时差值(50 μs/ft)。*LOM* 为热变指数,是指示有机质成熟度的参数,与镜质体反射率(*Ro*)对应的常数。

实际操作过程中将声波时差(线性刻度)和电阻率测井曲线(对数刻度)叠合时通常每 50 μs/ft (164 μs/m)声波时差对应一个对数电阻率刻度(如电阻率从 1~10 Ω·m),在非烃源岩段两条曲线将重叠(基线处),而在二者分异处,即为烃源岩段,且分异幅度越大,一般指示有机质含量越丰富。当然

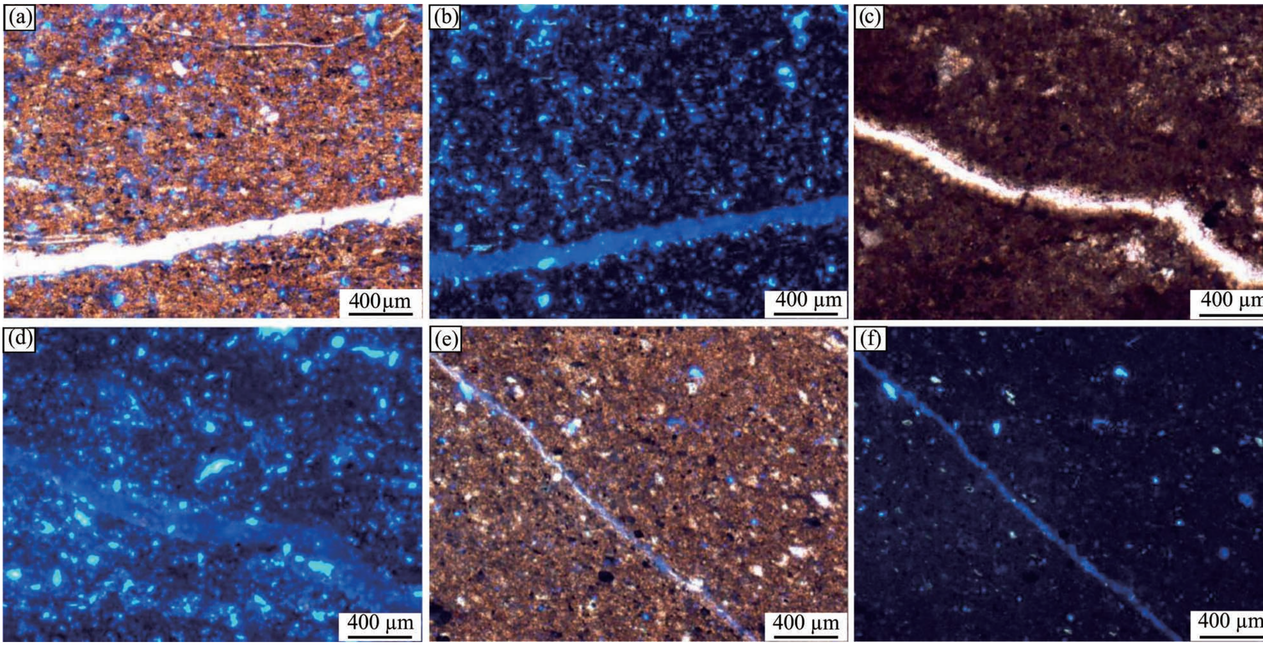


图 4 苏北盆地阜宁组二段不同孔隙微观含油性特征

Fig. 4 Oil-bearing property of various pore spaces of the Second Member of the Paleogene Funing Formation in Subei Basin

(a) 石英、白云石矿物颗粒分散分布,见生物碎屑,发育一条裂缝,Ji-19 井,3828.5 m;(b)矿物颗粒边缘分散暗蓝色荧光特征,a 视域荧光照片;(c) 成分主要为陆源黏土矿物(泥质),微晶方解石,有机质分散分布,发育微裂缝,Ji-19 井,3847 m;(d) 陆源黏土发斑点状蓝色荧光,有机质内部荧光呈分散状,c 视域荧光照片;(e) 石英长石等分散分布,有机物分散分布,发育一条微裂缝,Ji-19 井,3833 m;(f) 有机质荧光呈斑点状,微裂缝边缘含油,发暗蓝色荧光,e 视域荧光照片

(a) quartz, dolomite mineral particles are scattered distributed, and containing bioclasts, there is a microfracture, the Well Ji-19, 3825.5 m; (b) the edges of particle emit blue fluorescences, the same filed view of a under ultraviolet (UV) light; (c) the composition is dominantly detrital clay (mudrocks), microcrystalline calcite, and the organic matters are scattered distributed, there is a microfracture, the Well Ji-19, 3847 m; (d) the detrital clay emit scattered blue fluorescences, and there are scattered blue fluorescences in organic matters, the same filed view of c under ultraviolet (UV) light; (e) the quartz and feldspare as well as the organic matters are scattered distributed, and there is a micro-fracture, the Well Ji-19, 3833 m; (f) there are scattered blue fluorescences in organic matters, the edges of the microfractures are fluorescent (dark blue), he same filed view of e under ultraviolet (UV) light

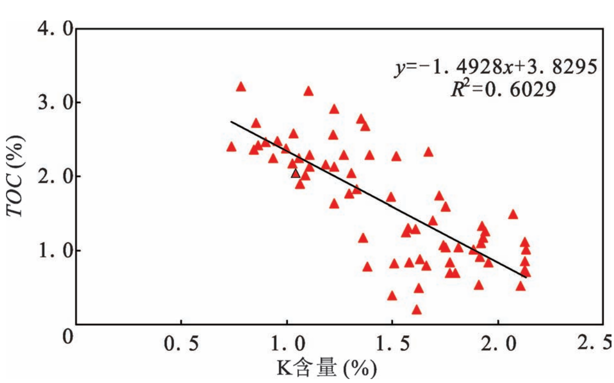


图 5 自然伽马能谱测井 K 含量与实测 *TOC* 交会图

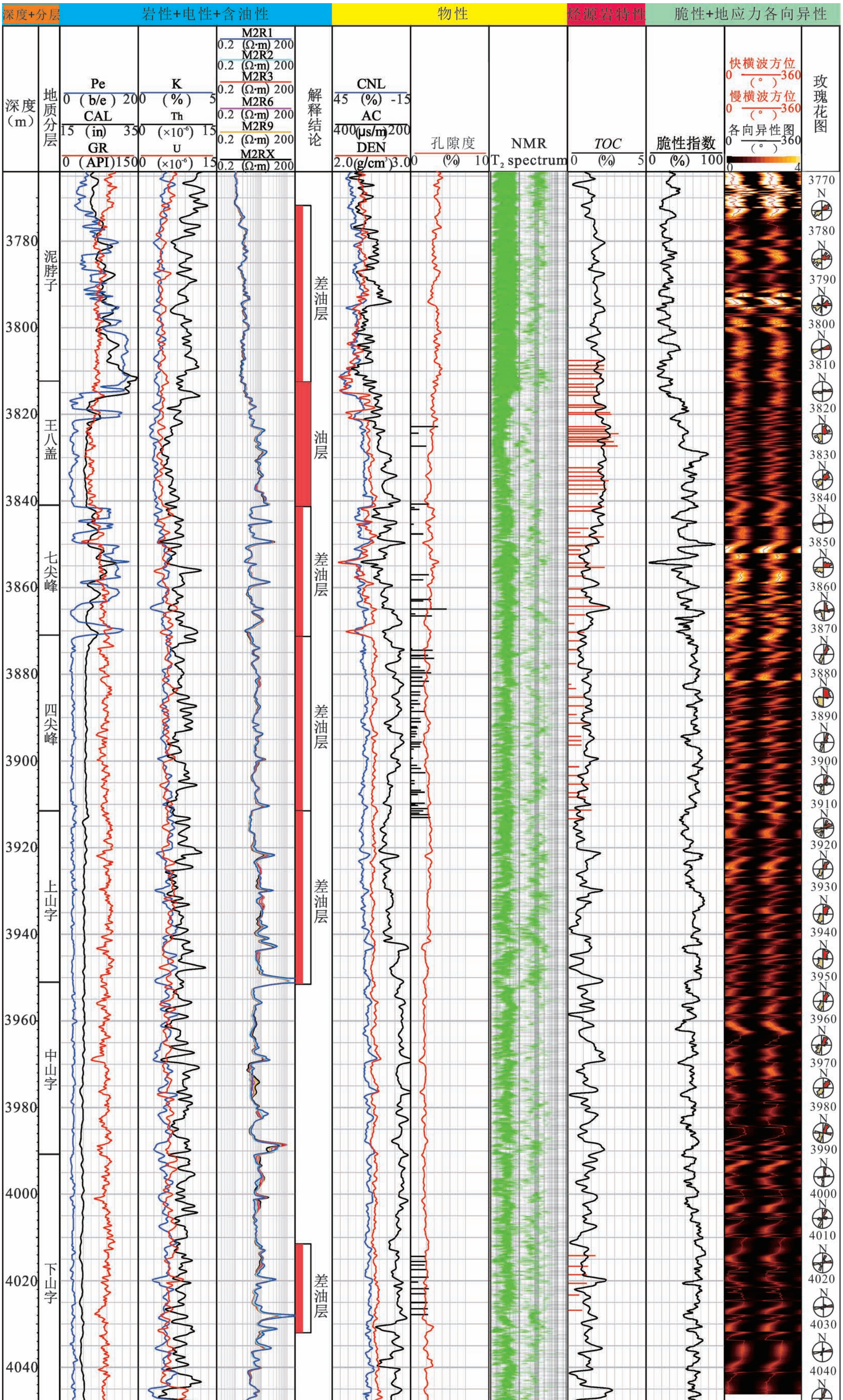
Fig. 5 Crossplot diagram of K element of natural gamma ray spectrum and the measured *TOC*

实际操作过程中还需利用自然伽马曲线等识别剔除蒸发岩、火成岩、致密层段或井壁垮塌严重层段(石玉江等,2012)。

考虑到 $\Delta \lg R$ 方法要找基线,可能存在误差,而研究表明自然伽马能谱测井能分别得到地层中铀元素、钍元素以及钾元素含量,因此也可利用自然伽马能谱测井可对烃源岩有机质丰度进行定量评价(陆巧焕等,2006)。本次研究发现其 *TOC* 含量与 K 元素具有良好的相关性(图 5),故本论文对于采集了自然伽马能谱测井的井采用自然伽马能谱测井 K 元素对 *TOC* 进行定量评价,而没有采集自然伽马能谱测井的井则采取 $\Delta \lg R$ 方法进行 *TOC* 测井计算。

2.6 脆性

页岩油储层致密,非均质性较强,要采取压裂改造等才能获得工业油流,因此岩石脆性评价对优选压裂增产层段至关重要(高辉等,2018)。针对非常规油气储集层而言,岩石脆性一般定义是其发生破



注：1 in =2.54 cm

图6 苏北盆地阜二段Ji-19井“铁柱子”七性关系综合图

Fig. 6 Comprehensive diagram of the seven relationships of template well “Tiezhuzi” in the Well Ji-19 of the second member of Paleogene Funing Formation in Subei Basin

裂前的瞬态变化难易程度,间接反映的是储层经压裂改造后所形成裂缝的复杂程度,一般可通过脆性指数来定量表征(袁俊亮等,2014;孙建孟等,2015;Avanzini et al., 2016;赖锦等,2016;Iqbal et al., 2018)。通常脆性高的层段可压裂性越好,在压裂作业中能够迅速形成复杂的网状裂缝,有利于油气开发(Guo Tiankui et al., 2015;赖锦等,2016;Iqbal et al., 2018;刘可禹和刘畅,2019)。脆性指数的计算方法可分为 3 种,一是基于岩石力学参数的泊—杨法(泊松比、杨氏模量法)(式 3、式 4、式 5);二是基于脆性矿物(石英、长石、碳酸盐等)含量计算矿物成分比值法(式 6、式 7);三是地区经验公式法(Jarvie et al., 2007;Lai Jin et al., 2015;赖锦等,2016;Iqbal et al., 2018;Zhao Xianzheng et al., 2019)。通常脆性矿物含量越高,将导致岩石力学参数中的泊松比减小而杨氏模量增大(Kumar et al., 2018),因此矿物组分法和泊松比—杨氏模量法二者紧密相连,矿物组分是岩石力学特征的物质基础与内因,岩石力学参数则是脆性的外在表现形式(董宁等,2013;赖锦等,2016)。

$$BI_{\mathrm{E}}=\frac{E-E_{\min}}{E_{\max}-E_{\min}} \tag{3}$$

$$BI_{\nu}=\frac{\nu-\nu_{\max}}{\nu_{\min}-\nu_{\max}} \tag{4}$$

$$BI=\frac{BI_{\mathrm{E}}+BI_{\nu}}{2}\times 100\% \tag{5}$$

$$BI=\frac{n(\mathrm{Qz})+n(\mathrm{Car})+n(\mathrm{Fels})}{n(\mathrm{Qz})+n(\mathrm{Car})+n(\mathrm{Fels})+n(\mathrm{Clay})}\times 100\% \tag{6}$$

$$BI=\frac{n(\mathrm{Qz})+n(\mathrm{Car})}{n(\mathrm{Qz})+n(\mathrm{Car})+n(\mathrm{Fels})+n(\mathrm{Clay})}\times 100\% \tag{7}$$

式中,BI 为脆性指数,%;Qz 为石英含量;Car 为碳酸盐含量;Fels 为长石含量;Clay 为黏土总量。E 为岩石的杨氏模量,GPa;ν 为岩石泊松比,无量纲;下标 min 和 max 分别代表该参数在某个地层段内的最小值和最大值。BI_{E} 和 BI_{ν} 分别为通过杨氏模量和泊松比所计算的脆性指数。

本次研究采取了泊松比—杨氏模量法计算脆性指数,计算结果表明,脆性指数介于 20%~80%(图 6)。

2.7 地应力各向异性

地应力是深度、岩性、孔隙压力、结构和构造的综合反映(唐振兴等,2019)。各向异性为岩石固有属性,通常可以通过正交偶极测井提取地层各向异性参数,并结合成像测井进行最大水平地应力方向判别、裂缝评价、水力压裂和射孔方案设计(赵军等,2005;魏周拓等,2012)。其中地应力各向异性评价在非常规油气井网布置、钻完井设计、压裂改造、井壁稳定性分析中起着举足轻重的作用(赵军等,2005;刘建伟等,2016;孟宪波等,2019)。地应力方向可通过成像测井拾取诱导缝和井壁崩落方位进行判别,二者分别指示现今最大和最小水平主应力方向(Lai Jin et al., 2018;Stadtmuller et al., 2018)。此外,在三轴应力(垂向、水平最大、水平最小应力)不均衡的各向异性地层中,横波传播时将分裂成快慢横波(横波分裂),且横波在最大水平主应力方向上传播速度最快,因此通过阵列声波测井提取快慢横波方位也可以进行地应力方位拾取(陆黄生,2012;Lai Jin et al., 2019)。Schlumberger 的偶极声波 DSI 和 Baker Hughes 的多极子声波 XMAC 均可用于横波方向的提取,同时可提供或计算①纵、横波速度;②岩石力学参数;③岩石破裂压力、地层压力、最大最小水平主应力(陆黄生,2012;Lai Jin et al., 2017;Iqbal et al., 2018)。

本次研究通过 DSI 提取的地层各向特征表明,单井水平最大主应力方向垂向上不断变化,但总体优势方位为北东—南西方向,偶见近东西向水平最大主应力方向(图 6)。

3 单井“铁柱子”建立

20 世纪 60 年代,大庆油田基于电测井序列,针对常规油气储集层,率先提出了“四性关系”(岩性、物性、含油性和电性)为依托的地层评价方法(孙建孟等,2013)。如今得益于非常规油气地质理论以及压裂改造工艺等技术的进步,致密油气、页岩油气逐渐成为勘探开发的重要目标(付金华等,2019)。勘探目标的转变以及技术需求的提高对测井评价技术提出了新的要求,即由原来的“四性关系”研究逐渐转向“七性关系”研究,因此亟需提取相关测井属性和信息,提供测井识别精度和扩展测井评价广度。当前针对非常规油气储集层,只有以大量高精度岩石物理实验为依托,刻度常规、成像和核磁等多尺度测井评价序列,建立全井段取芯、多序列测井的铁柱子井,才能实现非常规油气储集层“七性关系”综合评价(唐振兴等,2019)。如准噶尔盆地吉木萨尔凹陷芦草沟组页岩油吉 174 井(匡立春等,2015)、鄂尔多斯盆地延长组长 7 段页岩油的城 96 井(冉治

等,2016)以及准噶尔盆地玛湖凹陷风城组页岩玛页 1 井(Wang Song et al., 2021)等。

"铁柱子井"的岩石物理含义即是建立一口取芯和分析化验资料较全,同时测井采集序列也配套的标杆井,建立测井信息与地质信息的桥梁,明确甜点段在测井信息上的响应特征,后续的新井解释都可在"铁柱子井"指导下进行。铁柱子井的建立可为非常规致密、页岩油气测井评价搭建了测井和地质研究的桥梁,并可指导其他单井"七性关系"研究和"三品质"评价工作(匡立春等,2015)。本文通过综合研究,即实现了从岩性、物性、含油性、电性到脆性、烃源岩特性和地应力各向异性的 Ji-19 井铁柱子建立(图 6)。

铁柱子研究表明电性是岩性、物性和含油性的综合响应,阜二段最顶部的泥脖子段表现出典型的高伽马、低电阻的特征,为典型泥岩层。其孔隙度较低(3%~4%),测井计算 *TOC*(1.5%~2.5%)和脆性指数均较低(<40%),代表了岩性对其他六性的控制。而王八盖段以及下伏的七尖峰和四尖峰段为典型云质页岩的低伽马高电阻率的特征,测井计算和实测 *TOC* 均较高,实测和计算的孔隙度也较高,源岩和储层叠置发育,因此其为典型的好储集层和烃源岩层(图 6)。上山子、中山子和下山子段也为典型的烃源岩与储集层叠置发育段,其中的高伽马、高电阻层段为好烃源岩层,而低伽马、中—高电阻,且深浅电阻率明显具有分异特征的层段,则为储集层发育层段,通常也对应脆性较高层段(图 6)。总体上,Ji-19 井单井地应力各向异性特征较强,可以看到,水平最大主应力方向垂向上不断旋转变化,但总体以近北东—南西方向为主(图 6)。

4 "三品质"评价

4.1 三品质分类标准

针对非常规油气的"三品质"评价包括烃源岩品质评价、储层品质评价和工程品质评价。其中,烃源岩品质对应资源甜点区、储层品质对应物性甜点区,工程品质对应工程甜点区(张鹏飞等,2019)。"三品质"评价是非常规油气评价的重中之重,可以此为基础优选出致密油气物性和工程"甜点"分布(闫伟林等,2014;唐振兴等,2019;李晓光等,2019;付锁堂等,2020;王小军等,2019;匡立春等,2021)。

4.1.1 烃源岩品质

烃源岩品质评价主要依托七性关系研究中的烃源岩特性。烃源岩品质决定了油气的富集程度,因此烃源岩评价是基础(杜江民等,2016)。苏北盆地阜二段烃源岩有机质类型好,以 Ⅰ 型和 Ⅱ 型有机质为主,有机质丰度高,测井 *TOC* 计算可以看出阜二段 *TOC* 基本都大于 1%,由此根据烃源岩分类标准将研究区阜二段烃源岩划分为 3 种类型,其中好的烃源岩其 *TOC* 含量大于 2%,中等烃源岩 *TOC* 含量 1%~2%,差烃源岩 *TOC* 含量小于 1%。

4.1.2 储层品质

储层品质评价"岩性"、"物性"、"电性"和"含油性"(尹成芳等,2017)。本文选取页岩储层孔隙结构特征作为研究区阜二段页岩储层有效性的主要影响参数进而对页岩储层有效性进行研究。基于岩芯、薄片、扫描电镜分析基础上,将研究区阜二段储层孔隙结构根据毛管曲线及其参数、核磁共振 T_2 谱以及不可动流体体积参数 BVI(束缚水饱和度)将储层类型划分为四类(表 1)(Liu Xiaoping et al., 2020)。同时核磁共振测井可提供核磁孔隙度、束缚水饱和度等参数(Lai Jin et al., 2020; Wang Guiwen et al., 2020),因此可用于储层类型划分。

其中,Ⅰ类对应储层孔隙度>4%,渗透率大于 $0.02\times10^{-3}\ \mu m^2$,核磁孔隙度最高可达 6%,存在一定的基质孔隙,部分发育粒间孔和微裂缝,流体可动性好,束缚水饱和度值相对较低(<75%)(表 1)。

Ⅱ类对应储层孔隙度 2%~4%,渗透率 $0.002\times10^{-3}\ \mu m^2 \sim 0.02\times10^{-3}\ \mu m^2$,具有黏土矿物晶间孔和颗粒溶蚀孔形成的复杂孔隙结构特征,晶间孔主要形成于自生黏土矿物中,颗粒溶蚀孔主要为长石、白云石颗粒遭受溶蚀形成的不规则和锯齿状孔隙。核磁孔隙度可达 5%以上,具有中等束缚水饱和度值(表 1)。

Ⅲ类主要由有机质孔、粒内溶孔以及粒间孔构成,孔隙结构复杂,对应储层孔隙度 1%~2%,渗透率 $0.0001\times10^{-3}\ \mu m^2 \sim 0.01\times10^{-3}\ \mu m^2$,束缚水相对较高(表 1)。

Ⅳ类对应的孔隙度<1%,渗透率<$0.0001\times10^{-3}\ \mu m^2$,孔隙类型主要为有机质孔,虽然有机质孔较为

表 1 苏北盆地古近系阜二段储层类型划分表

Table 1 Reservoir type classification of the Second Member of the Funing Formation in Subei Basin

储层类型	Ⅰ类	Ⅱ类	Ⅲ类	Ⅳ类
孔隙度(%)	>4	4~2	2~1	<1
渗透率($\times10^{-3}\mu m^2$)	>0.02	0.02~0.002	0.0001~0.01	<0.0001
束缚水饱和度 BVI(%)	<75	75~80	>80	>80

发育,但其连通性较差,导致该孔隙结构类型具有较高束缚水饱和度值,难以成为有利储层(表 1)。

4.1.3 工程品质

工程品质评价主要指“脆性”和“地应力和各向异性”的评价(尹成芳等,2017)。工程品质评价最终的目的是评价储层的脆性、可压裂性(覃豪和杨小磊,2019)。工程甜点区位于地应力较低、脆性较强层段(高辉等,2018)。前已述及,Ji-19 井最大水平主应力方向主要为北东—南西向,而计算的脆性指数基本都大于 40%,整体脆性指数较高。根据脆性指数来对页岩工程品质进行分类,其中 I 类工程甜点区脆性指数>60%,Ⅱ类工程甜点区则脆性介于 40%~60%,Ⅲ类则脆性指数小于 40%层段。

4.2 单井“三品质”测井评价

页岩油有利区既是资源甜点区、物性甜点区,又是工程甜点区(Avanzini et al., 2016;张鹏飞等,2019)。其中页岩油“三品质”评价中,烃源岩品质对应资源甜点区、储层品质对应物性甜点区,工程品质对应工程甜点区(Zhao Xianzheng et al., 2019)。对单井页岩油甜点评价而言,物性甜点和工程甜点的优选尤为重要(付锁堂等,2020)。在以上“七性关系”铁柱子井建立的基础上,对于研究区其他单井,即可实现其“三品质”测井评价以及可依托“三品质”特征实现其甜点发育区带优选(Kumar et al., 2018)。

烃源岩品质可通过 $\Delta \lg R$ 法和自然伽马能谱统计回归法评价 *TOC*,从而寻找优质烃源岩,确定资源甜点区带(张鹏飞等,2019;付金华等,2019;付锁堂等,2020)。储层品质评价核心为宏观物性参数和微观孔隙结构,可依托常规孔隙度测井和核磁共振测井 T_2 谱来确定物性甜点区带(付金华等,2019;李晓光等,2019;付锁堂等,2020)。工程品质定量评价,基于阵列声波测井以及矿物组分比值法(元素俘获测井)计算岩石脆性指数,并依托成像和阵列声波测井实现地应力各向异性特征(包括现今最大水平主应力方向)的提取,确定工程甜点区带,为压裂设计优化提供技术支持(Iqbal et al., 2018;王小军等,2019;付金华等,2019;李晓光等,2019;付锁堂等,2020)。

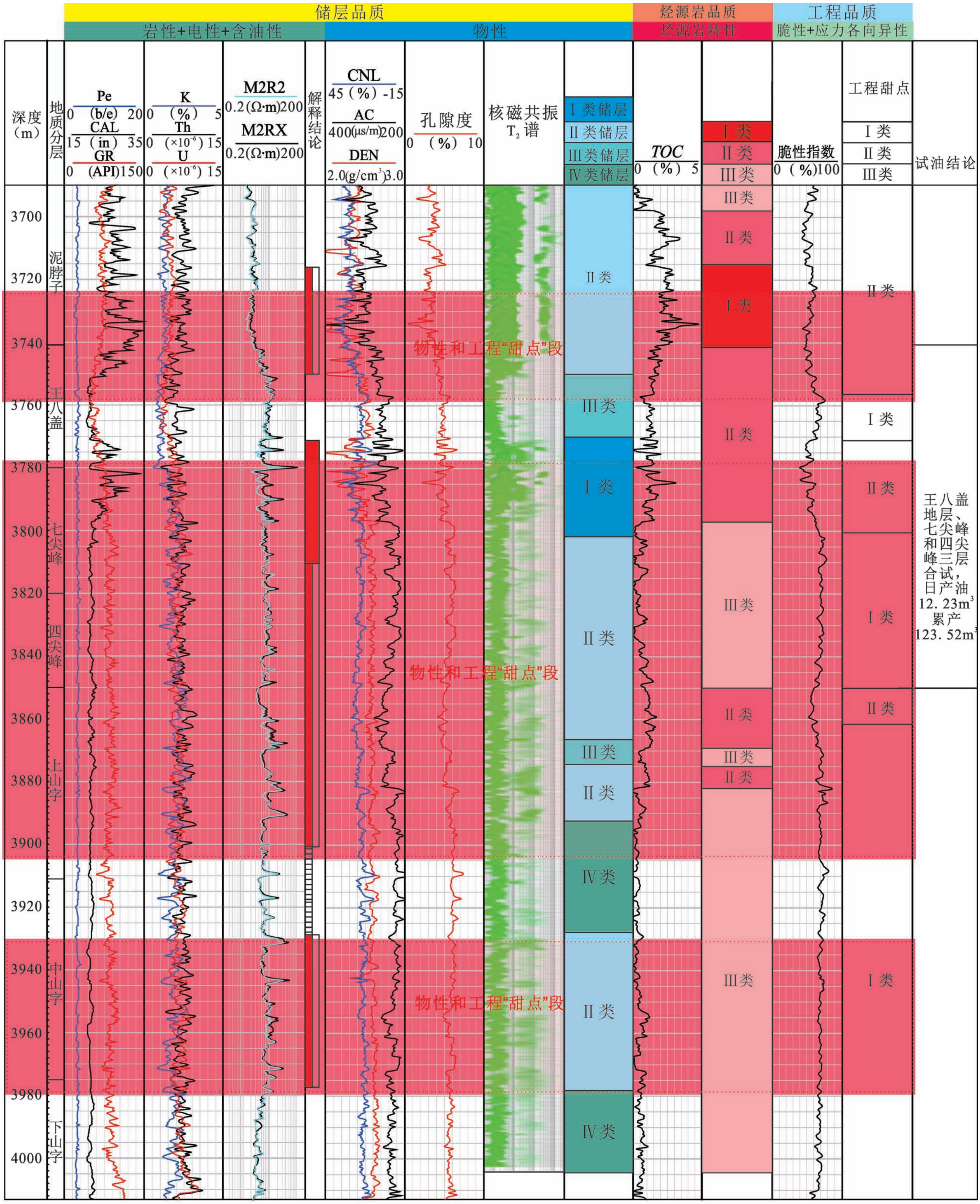
通过自然伽马能谱测井计算的 *TOC*,实现了吉 10 井单井烃源岩品质识别与划分,可以看到,好烃源岩段主要位于泥脖子、七尖峰和四尖峰段,为页岩油富集提供资源甜点(图 7)。通过测井计算孔隙度以及核磁共振 T_2 谱特征,确定了好的储集层段主要对应特征为测井解释孔隙度较高,同时具备较宽的核磁共振 T_2 谱,甚至部分层段还存在拖尾现象。此外,高分辨率阵列感应测井(M2R1—M2Rx 系列测井)往往具备明显的分异现象,即深浅电阻率具备明显的曲线幅度差(图 7)。通过测井计算的脆性指数实现了工程品质的划分,有利的工程甜点发育段往往对应脆性指数较高的层段(图 7)。

研究表明,页岩油物性“甜点”和工程“甜点”的有效结合体通常对应页岩油发育层段(蒋云箭等,2020;付锁堂等,2020)。通过储层品质和工程品质相耦合,最终划分出 Ji 10 井单井 3 个甜点(物性和工程甜点相叠加)发育段,主要分布在泥脖子、七尖峰、四尖峰和上山字和中山字段(图 7)。优选出的物性和工程甜点段与实际试油资料吻合较好,王八盖地层、七尖峰和四尖峰三小层合试,日产油 12.23 m^3,累产油 123.52 m^3,证实了三品质划分结果的准确性(图 7)。因此通过在“七性关系”研究的基础上,建立“三品质”的测井识别与评价标准,最终通过单井“三品质”划分优选页岩油甜点方法切实可行。

5 结论

苏北盆地古近系阜二段岩性主要是灰黑色页岩、(灰质)泥页岩、云质或粉砂质泥岩等,储集空间包括粒间孔、颗粒溶孔、晶间孔、有机质孔以及微裂缝,荧光薄片表明不同类型和不同孔径孔隙含油性均较好。核磁共振 T_2 谱分布基本表现为单峰状,且很少出现拖尾现象。说明其孔喉体系以细小的相对连续的孔隙空间为主,较少或缺失大孔径粒间孔等。测井曲线上页岩表现为高伽马(>60 API)、高中子(>15%)、高声波时差(>250 μs/m)、低密度(<2.55 g/cm^3)、高电阻率的特征。根据自然伽马能谱测井和 $\Delta \lg R$ 建立了 *TOC* 测井模型,结果表明阜二段烃源岩有机质类型好,*TOC* 基本都大于 1%。根据泊松比—杨氏模量法计算脆性指数,结果表明脆性指数介于 20%~80%。阵列声波测井提取的地应力各向异性特征表明,单井水平最大主应力方向垂向上不断变化,但总体优势方位为北东—南西方向。最终建立了包含岩性、物性、电性、含油性、脆性、烃源岩特性和地应力各向异性“七性关系”特征的铁柱子井。

根据 *TOC* 大小实现烃源岩品质划分,根据脆性指数实现工程品质划分。然后根据物性参数结合核磁共振 T_2 谱建立了储层品质划分标准。在“七性关



注:1 in =2.54 cm　油层 oil layer　差油层 poor oil layer　干层 dry layer

图 7 苏北盆地古近系阜二段 Ji 10 单井"三品质"测井评价

Fig. 7 Three property division of the Well Ji-10 of the Second Member of Paleogene Funing Formation in Subei Basin

系”研究基础上,通过对储层品质、烃源岩品质以及工程品质三者叠加完成了单井“甜点”段优选,结果表明单井甜点主要分布在泥脖子、七尖峰、四尖峰和上山字和中山字段,结果与试油资料相吻合。在“七性关系”研究基础上,通过建立“三品质”的测井识别与评价标准,可基于单井“三品质”划分优选页岩油甜点。研究结果可为页岩油甜点综合评价和预测提供理论指导和方法支撑。

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Well logging evaluation of seven kinds of relationships and three types of properties of Paleogene Funing Formation oil shales in Subei Basin

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Abstract: The interrelation between "seven kinds of relationships" and the characteristics of "three types of properties" of the Second Member of the Funing Formation in the Subei Basin (northern Jiangsu Basin) are investigated by integrating cores, thin sections, scanning electron microscope (SEM) and other petrophysical experiments, combined with conventional logs, image logs, and Nuclear Magnetic Resonance (NMR) logging data. The results reveal that the main storage spaces developed in the shale reservoirs of the Second Member of the Funing Formation, which are mainly oil-bearing, are intergranular pores, intragranular solution pores, intercrystal pores, organic matter pores and micro-fractures. Based on the physical parameters and pore spaces, the classification criteria for the quality of reservoir are established. The value of irreducible water saturation increases from type Ⅰ to type Ⅳ. It is concluded that the source rock of the Second Member of the Funing Formation, which *TOC* is basically greater than 1%, has good organic matter types. A well-log-based *TOC* calculation model is established based on natural gamma spectroscopy log data (K) and $\Delta\lg R$ method, the classification of source rock quality is achieved based on *TOC*. The direction of in-situ stress is mainly NE—SW, and the brittle index of the Second Member of the Funing Formation is basically greater than 40%, which means it can be easily fractured. The engineering quality is divided according to the brittle index. On the basis of the research on interrelation between "Seven Relationships", by considering the reservoir quality, source rock quality and engineering quality, the "sweet spot" of a single well is selected. It is concluded that the sweet spots are mainly distributed in the Nibozi, Qijianfeng, Sijianfeng, Shangshanzi and Zhongshanzi sections, which is consistent with the oil test data. The results can provide theoretical guidance and technical support for well log evaluation and sweet spot prediction of oil shales.

Keywords: shale oil; seven kinds of relationships; three types of properties; well log evaluation; Funing

Formation; Subei Basin(northern Jiangsu Basin)

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