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页岩纹层类型与测井表征方法研究

——以苏北盆地高邮凹陷阜宁组二段为例

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摘要:苏北盆地高邮凹陷阜宁组二段(以下简称阜二段)页岩岩相非均质性,纹层类型复杂且测井定量表征难度大,制约了页岩油“甜点”有利区带的优选。因此,基于阜二段不同沉积阶段的气候环境演化特征,结合岩心薄片、全岩衍射、元素录井、测井等资料,详细研究了高邮凹陷阜二段页岩纹层类型及纹层发育程度的测井定量表征方法。研究表明:高邮凹陷阜二段页岩主要发育长英质、黏土质、方解石和白云石条带等纹层类型,受古气候演化影响,阜二段各小层不同纹层类型占比存在差异,不同纹层类型的叠置耦合造成了纵向上页岩油差异富集,且纹层越发育,页岩油的富集程度越高。针对页岩纹层差异分布的地质特征,进一步通过电成像测井图像边缘检测和页岩沉积速率计算等方法综合分析,阜二段页岩IV-3—IV-7、V-6—V-8小层纹层发育程度高,为纵向上页岩油地质“甜点”层。其中基于电成像测井图像边缘检测的页岩纹层识别精度高,可适用于不同区块页岩油纵向“甜点”层的精细地质评价,而通过计算页岩沉积速率变化来表征纹层发育程度适用于开展页岩纹层发育程度的空间展布预测,指导页岩油的立体勘探。

关键词:高邮凹陷;阜二段;页岩纹层类型;气候演化;电成像测井;图像边缘检测;米兰科维奇旋回

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Research on shale lamination types and logging characterization methods: A case study of the Funing Formation Member 2 in Gaoyou Sag, Subei Basin

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Abstract: The shale lithofacies in the second member of the Funing Formation (hereafter referred to as Funing Formation Member 2) in the Gaoyou Sag of Subei Basin exhibits significant heterogeneity, with complex lamination types that are challenging to quantify using well logging, thus limiting the identification of favorable “sweet spots” for shale oil. Therefore, this study investigates the methods for quantitative characterization of shale lamination types and their development in Funing Formation Member 2 of Gaoyou Sag, by integrating data from core thin sections, whole rock diffraction, elemental logging, and well logging, based on the climatic and environmental evolution during different sedimentary stages. The results show that shale lamination types mainly include quartz-enriched, clay-enriched, calcite, and dolomite bands. Influenced by ancient climatic evolution, the proportions of different lamination types vary across intervals, and the vertical superposition and coupling of these lamination types lead to differential shale oil enrichment, with more developed laminations corresponding to higher oil enrichment. During the deposition of intervals V-6 to V-10, the sediments exhibit a high aridity index, low Sr/Cu ratio, significant variation in the Sr/Ba ratio, and high V/(V+Ni) ratio. These characteristics suggest a strongly reducing, semi-arid to arid saline water environment with fluctuating water depths and periodic variation in lake nutrients. Saline stratification and diagenesis facilitate the development of abundant bright calcite layers, fibrous calcite layers, and dolomite layers, providing favorable reservoir properties for shale oil. During the deposition of intervals V-1 to V-5, the Sr/Cu ratio increases significantly while the aridity index decreases. The overall environmental characteristics indicate a strongly reducing, arid saline water environment. The shale is predominantly composed of clay-rich to sandy-mixed lithology, with clay-enriched layers and clay-rich laminations as the dominant lamination types. Due to the influence of recrystallization degree, the proportion of bright calcite layers decreases while the proportion of mudstone-like calcite layers increases.

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During the deposition of intervals IV-5 to IV-8, the Sr/Cu ratio exhibits a periodic variation of “decrease followed by increase”, indicating a decrease in lake water salinity. The lithology primarily consists of clay-rich to sandy-mixed shale, with the development of clay-enriched layers, clay-rich laminations, bright calcite layers, fibrous calcite layers, and dolomite layers. These intervals demonstrate excellent reservoir properties and are regarded as high-quality sweet spot layers for shale oil. During the deposition of intervals IV 1- IV 4, the Sr/Cu ratio increases, indicating intensified arid conditions. The climate characteristics suggest a strongly reducing, arid saline environment. The recrystallization degree of calcite is higher, leading to the development of bright calcite, fibrous calcite, and dolomite layers. Additionally, the proportion of mudstone-like calcite layers increases, indicating a higher overall carbonate mineral content influenced by the depositional environment. During the deposition of the subinterval III, the climate alternates between humid and arid conditions, with a higher degree of calcite crystallization and the development of bright calcite layers. Subintervals II and I exhibit a significant decrease in Fe/Mn and Sr/Ba ratios, indicating intensified humid conditions. Water depth increases, and the shale gradually transitions to blocky structure. The content of gray and muddy minerals decreases, limiting the development of gray and muddy laminations. The study further confirms a positive correlation between the degree of shale lamination development and shale oil enrichment. Based on the geological characteristics of the shale lamination distribution, further analysis was conducted using methods such as edge detection from electrical imaging well logging and shale deposition rate calculation. The study identified intervals IV-3 to IV-7 and V-6 to V-8 in Funing Formation Member 2 as having well-developed laminations and higher total organic carbon (TOC) compared to other intervals, marking them as vertical shale oil sweet spot layers. The image edge detection method using electrical imaging well logging offers high accuracy for shale bedding identification and is suitable for detailed geological evaluation of vertical shale oil sweet spot layers in different blocks. Furthermore, as the climate change during shale deposition becomes more frequent and the sedimentation rate varies more drastically, the vertical heterogeneity and lamination development of shale increase. Thus, sedimentation rate variations can serve as an indicator of shale lamination development. An analysis of stratigraphic cycles in the Huazhuang area's Funing Formation Member 2 revealed that natural gamma MTM spectrum analysis of well Huaye 7 identified eight dominant frequencies, corresponding to cycle thicknesses of 39.84, 11.76, 9.43, 4.20, 3.19, 2.32, 2.13, 1.82 m. The ratio of cycle thicknesses is 21.91:6.47:5.19:2.13:1.76:1.28:1.17:1.00, which is close to the theoretical cycle ratio of 21.32:6.58:5.26:2.74:2.00:1.21:1.16:1.00 for this period. Therefore, the shale deposition process of the Funing Formation Member 2 is controlled by the Milankovitch astronomical cycle. The optimal sedimentation rate for this interval was determined to be 10.8 cm/kyr. Using this optimal rate, the eCOCO statistical method was applied to track and analyze sedimentation rate variations in the Funing Formation Member 2. The results indicate significant differences in sedimentation rates among different sub-layers of the Funing Formation Member 2 due to the influence of periodic climatic fluctuations. Moreover, the degree of lamination development indicated by the sedimentation rate variation correlates well with the overall proportion of lamination development obtained from thin section analysis, and is consistent with the lamination development detected by imaging logging in different intervals. Consequently, this method can predict the spatial distribution of lamination development, providing guidance for three-dimensional shale oil exploration. In summary, this study provides insight on the lithological heterogeneity and quantitative logging characterization of the Funing Formation Member 2 in the Gaoyou Sag, Subei Basin. These findings contribute to the identification and evaluation of shale oil sweet spot layers, promoting shale oil exploration and development.

Keywords: Gaoyou Sag; Funing Formation Member 2; shale lamination types; climate evolution; electrical imaging logging; image edge detection; Milankovitch cycles

近年来,中国石化通过加强陆相页岩油理论研究与技术攻关,在渤海湾盆地济阳拗陷、南襄盆地泌阳凹陷、江汉盆地潜江凹陷、苏北盆地溱潼凹陷和高邮凹陷等多个区块相继取得了页岩油的勘探突破^[1-3]。勘探实践表明:陆相咸化湖盆页岩具有矿物组分复杂、岩相类型多变、纹层发育、非均质性强等地质特点^[4],页岩油富集高产与保存条件、热演化程度、异常高压、断裂发育规模、页岩岩相等密切相关^[5-6]。其中,页岩纹层作为岩心纵向上肉眼可识别的最小岩性单元,单层厚度通常不超过10 mm^[7-9],微观上通过影响页岩油“四性”特征(生油性、储集物性与可动、可压性)加剧了页岩油地质工程“甜点”层的差异分布。由于页岩纹层常被视为古气候周期、地质事件再现,是研究古湖泊物理性质、古湖水化学特征及

古生产力演化的最佳对象^[10],因此,针对页岩纹层方面的研究目前主要是通过划分纹层类型来进行古气候环境变化与储集物性的差异性分析^[11-15],而缺乏对页岩纹层定量表征方法的研究,制约了纵向上页岩油“甜点”层的优选。

由于单一纹层厚度多为厘米—毫米级,常规测井分辨率仅为分米级,据岩心薄片统计,高邮凹陷阜宁组二段页岩纹层密度介于1 000~3 000条/m。纹层发育程度远超常规测井分辨率极限,常规敏感测井曲线交汇法难以直接表征页岩纹层发育程度。而目前已有学者在结合岩心薄片统计的基础上通过电成像、三分量感应及阵列声波等特殊测井方法进行页岩纹层测井定量表征方面开展了探索性研究^[16-17],其中,电成像测井方面,部分学者引入图像

分割、边缘检测等技术,在明确电成像测井图像的明暗条纹变化与纵向岩性差异的基础上利用Candy、Sobel及Roberts等多种边缘检测算法进行页岩纹层表征^[18]。基于Candy算法的电成像测井图像边缘检测法能通过识别测井图像的近水平方向的明暗条纹边缘来指示页岩地层的纹层发育程度,页岩纹层识别效果较好,其主要包括图像高斯滤波、图像增强、图像定位和边缘检测等多个关键技术^[19-20]。但受电成像测井资料精度、井筒环境、诱导缝分布及纵向地层电阻率变化影响(页岩油电成像测井长度多在100~400 m),直接对全井段电成像测井静态图像统一设置Candy算子颜色阈值进行边缘检测易受纵向电成像图像颜色阈值的影响,致使页岩纹层的定量表征结果出现误差。从页岩纹层成因上讲,纹层形成时气候变化频繁、水体震荡程度高、页岩沉积速率变化剧烈^[21-22],而常规测井中的自然伽马测井敏感曲线蕴含了高分辨率的古气候、沉积速率等信息,如自然伽马测井值较高时,表明地层中黏土含量较高,页岩沉积时气候相对较湿润;自然伽马测井值较低时,灰云质含量较高,气候干旱程度加剧。因此,通过自然伽马测井曲线对页岩开展地层米兰科维奇旋回沉积速率分析,并以页岩地层沉积速率变化来指示纵向纹层发育程度差异,可作为电成

像测井图像边缘检测的分段限制条件,提高页岩纹层识别精度。

研究以高邮凹陷花庄地区为例,在岩心观察、薄片统计、全岩矿物X射线衍射分析基础上深入剖析纵向上阜二段页岩纹层类型差异与沉积环境演化联系,并通过地层米兰科维奇旋回分析进行高分辨率沉积速率刻画、电成像测井图像边缘检测等手段建立起阜二段页岩纹层结构的测井定量识别方法,实现单井纵向上纹层发育程度的定量表征,为页岩岩相的地质表征提供理论依据。并作为电成像测井图像边缘检测Candy算子阈值约束条件来克服纵向地层电阻率变化等因素的影响,以提高电成像测井边缘检测表征纹层发育程度的精度。

1 地质背景

苏北盆地是下扬子地台古生界褶皱基底上发育的中、新生代断-坳复合型伸展盆地,南抵苏南隆起,北接鲁苏隆起,东与黄海相邻^[23-24](图1)。盆地自下而上发育了上白垩统泰二段、古近系阜二段及阜四段3套烃源岩^[25]。

苏北盆地高邮凹陷花庄地区阜二段页岩形成于构造

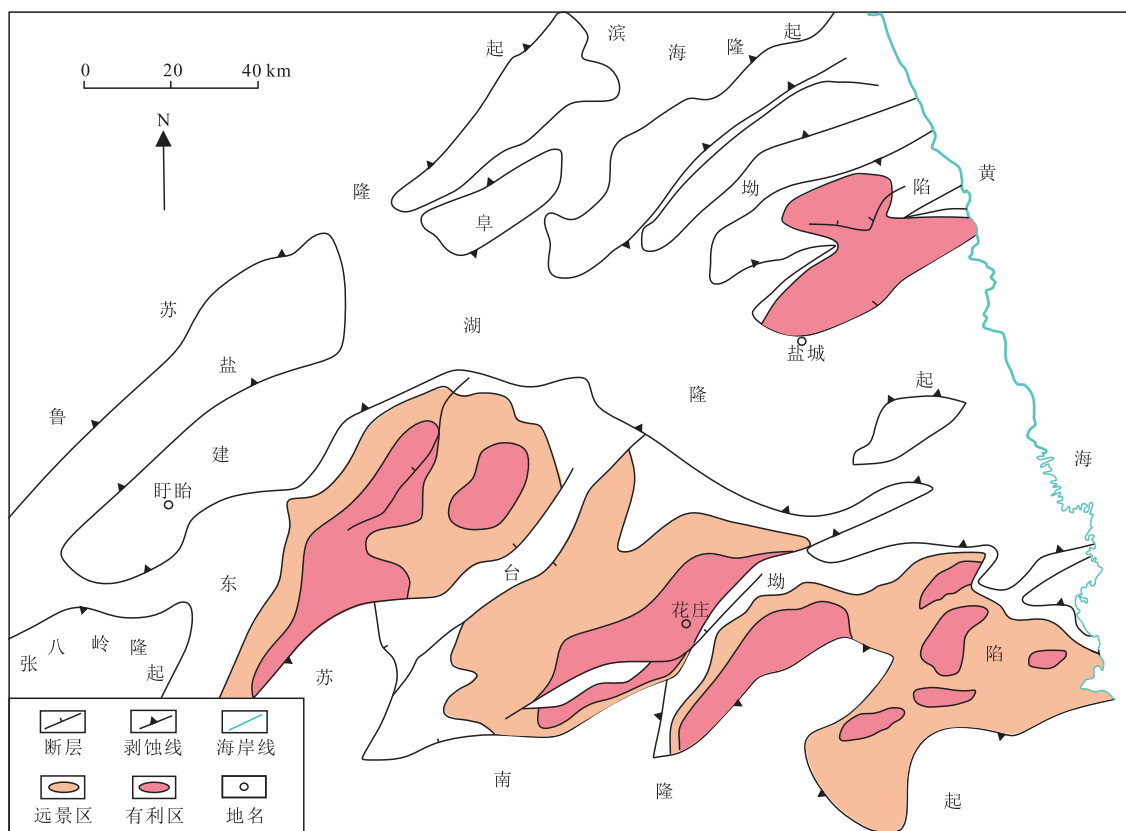


图1 苏北盆地高邮凹陷区域构造

Fig. 1 Regional structure of Gaoyou Sag, Subei Basin

稳定的盆地拗陷期,整体为一套半深湖—深湖相富含有机质泥页岩,分布范围广泛,沉积厚度大,有机质丰度高,热演化程度适中。根据沉积旋回、岩性与电性特征,纵向上阜二段页岩自上而下可分为页Ⅰ、页Ⅱ、页Ⅲ、页Ⅳ、页Ⅴ五个亚段,页岩油富集条件有利^[26-28],是苏北盆地陆相页岩油勘探实践的重点区带。近年来,江苏油田通过部署探井加大页岩油勘探开发力度,在花庄地区取得了阜二段页Ⅳ、页Ⅴ亚段的页岩油勘探突破,展现了苏北盆地阜二段陆相页岩油良好的勘探潜力。

2 页岩岩相及纹层类型特征

2.1 矿物组分特征与岩相类型

通过对花庄地区阜二段花页1井、花101井与花页7井3口取心井1083个页岩样品全岩衍射结果分析:阜二段页岩矿物组分以石英、长石、方解石、白云石与黏土为主,其中,长石石英、碳酸盐岩和黏土矿物含量比例分别为4:3:3,呈典型的混积页岩岩相特征。岩相类型主要包括长英质-黏土质混积页岩(Ⅳ¹)和长英质-灰云质混积页岩(Ⅳ²),其次为长英页岩(Ⅱ¹)、含灰云黏土质长英页岩(Ⅱ²)(图2a)。纵向上各亚段间矿物组分含量增减变化与页岩岩相类型呈明显“分段性”,反映了阜二段页岩矿物组分特征与沉积环境演化的周期性耦合(图2b)。

2.2 页岩纹层特征

岩心观察表明:阜二段页岩包括纹层状、层状和块状3种沉积构造。其中根据苏北盆地阜二段页岩沉积特征划分,阜二段页岩纹层状构造单一纹层厚度通常小于0.5 cm,层状构造单一纹层厚度介于1~2 cm,而块状构造单一纹层厚度大于2 cm^[29-30]。

进一步按矿物组分划分,阜二段主要发育黏土质、长英质、方解石(泥晶、亮晶、纤维状)和白云石条带等4种纹层类型。其中黏土质纹层分布稳定,单偏光下呈黑褐色,且与长英质纹层沉积差异性明显,纹层厚度介于50~500 μm;长英质纹层矿物粒径多为粉砂级,磨圆程度呈棱角-次棱角状,其中夹有细、薄的黏土矿物纹层(图3a);泥晶方解石纹层方解石晶粒细小,形态呈不规则透镜状,直径多小于5 μm,自形程度差,为原始沉积形成的泥晶碳酸盐岩颗粒,边缘界限模糊,单偏光下纹层形态呈现弯曲状、透镜状和平直状(图3b);亮晶方解石纹层方解石颗粒为亮晶-微亮晶级,厚度介于20~50 μm,结晶程度高,自形程度相对较好,单偏光性下纹层形态为平直连续状,纹层界限清晰,边缘光滑(图3c);纤维状方解石纹层方解石颗粒粗大,形态多呈垂直于纹层方向生长的纤维状或叠锥状。其中,单偏光下纤维状方解石纹

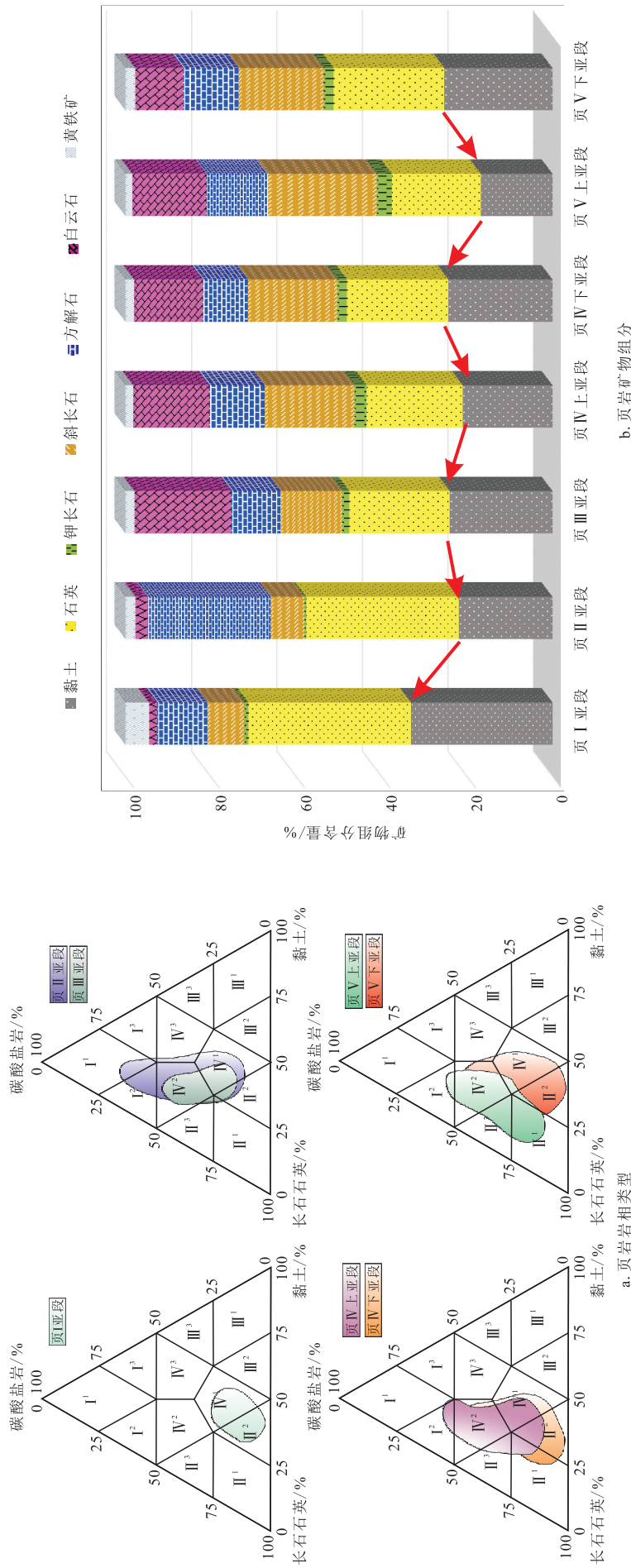
层中部多发育暗色中位面,中位面将两侧纤维状碳酸盐岩隔开,反映了纤维状方解石在中位面两侧生长速率的差异,单偏光下可以看到其中的纤维互相平行,几乎垂直于脉体边缘,与周围暗色泥质或有机质层之间具有明显的分界,是多期碳酸盐岩重结晶的结果,自形程度也相对较好^[31],纹层厚度介于50~200 μm(图3d、图3e);白云石条带是阜二段页岩中典型纹层类型之一,其白云石晶粒粗大,单一纹层厚度多大于500 μm,纹层平直连续,自形程度高(图3f),溶蚀孔洞发育,是阜二段页岩油良好的储集空间,主要分布在页Ⅳ亚段下部。

3 气候演化与纹层分布差异

前人研究表明:泥页岩中不同种类元素含量比值能有效反映古气候、古水深、古盐度、水体氧化还原性及陆源物质的输入,且与水深变化,水体分层、页岩岩相、纹层类型分布密切相关^[32-33]。东营、潜江、南堡等凹陷陆相泥页岩地层中微量元素含量变化与沉积环境的响应特征表明:当地层中Sr/Cu、Fe/Mn比值升高,干湿指数 $(Al+Fe)/(Ca+Mg)$ 、Sr/Ba比值降低,表明古气候由温暖湿润向寒冷干旱转变,湖盆收缩,水体相对较浅^[34-36]。而苏北盆地高邮凹陷阜二段页岩地层自下而上干湿指数逐渐增大,Fe/Mn比值逐渐减少,直至页Ⅰ亚段沉积时期达到峰值,反映了阜二段页岩形成时总体为一种“水深早浅晚深、气候早干晚湿、盐度早咸晚淡,生产力早低晚高”的沉积环境特征。同时,纵向上阜二段不同亚段、小层间Sr/Cu、Fe/Mn等比值呈多旋回增减性变化,进一步表明了总体“早干晚湿”的古气候背景下,阜二段不同小层页岩沉积时仍存在多期干湿气候的交替旋回变化,进而造成了页岩在矿物组分、岩相、纹层类型的周期性变化。其中页Ⅰ亚段沉积时气候湿润,黏土矿物含量升高,碳酸盐岩等脆性矿物含量最低,TOC(总有机碳)含量最高;而页Ⅳ、页Ⅴ亚段下部沉积时期,地层中Sr/Cu比值偏低,干湿指数相对略高,气候相对较湿润,长英质-黏土质混积页岩发育,TOC含量相对较高,有利于页岩油富集(图4a)。

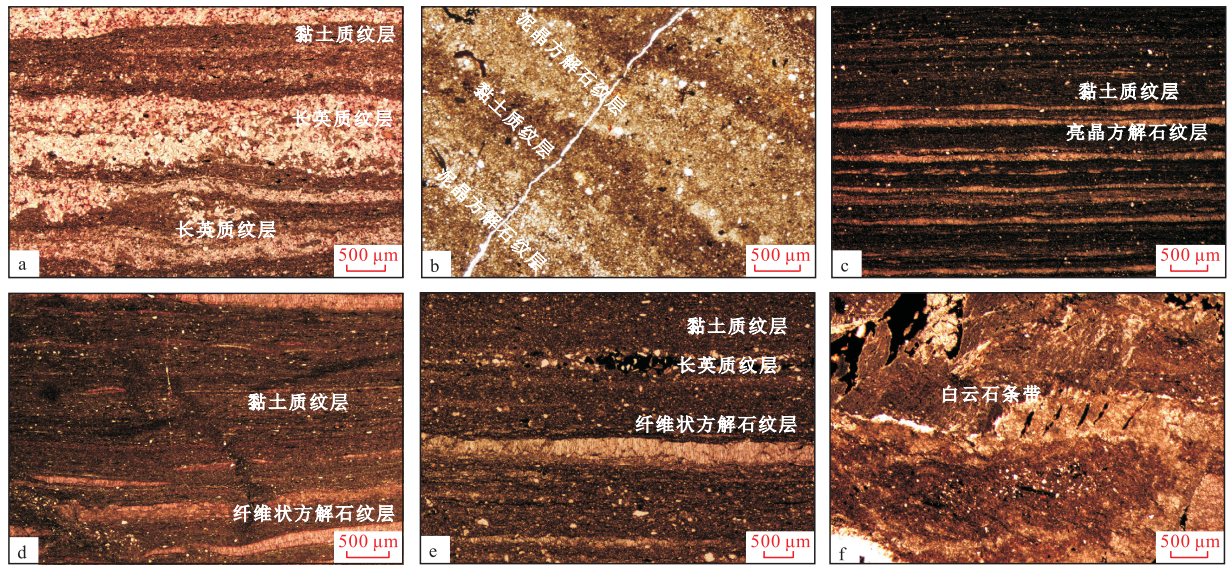
结合不同纹层类型镜下特征,薄片统计表明:花庄地区阜二段页岩以长英质纹层和黏土质纹层为主,且受古气候干湿变化、水体古盐度分层影响,不同小层碳酸盐岩类纹层占比存在较大差异,且呈弱周期变化(图4b)。

阜二段页Ⅴ-6—Ⅴ-10小层沉积时期,干湿指数较高,Sr/Cu比值较低、Sr/Ba比值变化剧烈、V/(V+Ni)比值高,表明为强还原性半干旱交替咸水环境,水深变化频繁,入湖营养物质呈周期性变化。受咸化水体分层及成岩作用影响,发育大量亮晶方解石纹层、纤维状方解石纹层及白云石条带,页岩油储集物性较好。



注：I¹为灰云页岩；I²为含黏土长英质灰云页岩；I³为长英页岩；II¹为含灰云黏土质长英页岩；II²为含黏土灰云质长英页岩；II³为含黏土质页岩；III¹为含灰云长英质黏土页岩；III²为含长英灰云质黏土页岩；III³为长英质-黏土质混积页岩；IV¹为长英质-黏土质混积页岩；IV²为长英质-黏土质混积页岩；IV³为长英质-黏土质混积页岩。

图2 苏北盆地高邮凹陷花庄地区阜宁组二段页岩岩相类型与页岩矿物组分特征
Fig. 2 Shale lithofacies characteristics and mineral composition of the Fuming Formation Member 2 in Huazhuang area of Gaoyou Sag, Subei Basin



注:a.花101井页V亚段黏土质-长英质纹层,纹层韵律明显,单偏光;b.花页1井页IV亚段泥晶方解石-黏土质纹层,纹层连续性好,泥晶方解石颗粒小,单偏光;c.花101井页IV亚段黏土质-亮晶方解石纹层,亮晶方解石纹层边界清晰,单偏光;d.花页1井页V亚段黏土质-纤维状方解石纹层,纤维状方解石纹层中间发育暗色中位面,方解石重结晶程度差异明显,单偏光;e.花页1井页V亚段黏土质-纤维状方解石纹层,纤维状方解石纹层呈叠锥、正弦状,方解石重结晶程度差异明显,是多期碳酸盐岩重结晶的结果,单偏光;f.花101井页IV亚段白云石条带-黏土质纹层,白云石条带周边同方解石重结晶颗粒,内部发育溶蚀孔、粒间孔,储集物性好。

图3 苏北盆地高邮凹陷花庄地区阜二段主要岩相岩心及普通岩石薄片镜下特征

Fig. 3 Microscopic characteristics of core samples and thin sections from the Funing Formation Member 2 in Huazhuang area of Gaoyou Sag, Subei Basin

页V-1—V-5小层沉积时期, Sr/Cu、Sr/Ba 比值显著上升, 干湿指数降低, 气候干旱程度加剧, 整体为强还原干旱咸水环境, 灰云质矿物含量上升, 以长英质-灰云质混积页岩岩相为主。页岩纹层类型主要为黏土质纹层、长英质纹层为主, 受重结晶程度影响, 亮晶方解石纹层占比减少, 泥晶方解石纹层占比增多。

页IV-5—IV-8小层沉积时期, Sr/Cu 比值呈“先减后增”旋回性变化, 反映沉积时期湖盆水体咸化程度降低, 气候相对页V亚段上部略湿润, 岩相以长英质-黏土质混积页岩为主, 主要发育黏土质-长英质纹层、亮晶方解石纹层、纤维状方解石纹层以及白云石条带, 储集物性好, 为页岩油优质“甜点”层段。

页IV-1—IV-4小层沉积时期, Sr/Cu 比值升高, 气候干旱程度加剧, 气候为强还原干旱咸水环境, 方解石重结晶程度高, 局部发育亮晶方解石纹层、纤维状方解石纹层及白云石条带, 同时泥晶方解石纹层占比提高, 表明受沉积环境影响, 整体碳酸盐岩矿物含量较多。

页III亚段沉积时期, 气候干湿频繁震荡, 方解石结晶程度高, 亮晶方解石纹层较发育。页II至页I亚段沉积时期, Fe/Mn 比值、Sr/Ba 比值明显降低, 气候湿润程度加剧, 沉积水深升高, 页岩逐渐过渡为块状结构, 灰云质矿物含量逐渐减少, 基本不发育灰云质纹层。

4 页岩纹层测井方法表征

4.1 电成像测井纹层表征

纹层发育程度影响页岩的生烃及储集物性, 且纹层越发育, 越有利页岩油富集^[37]。在目前已有的测井系列中, 电成像测井由于纵向分辨率最高(理论可达5 mm), 是开展页岩纹层发育程度定量评价时最重要、有效的测井资料。研究为具体量化阜二段页岩纹层发育程度, 结合前人研究, 引入纹层指数概念, 即25 cm深度段内图像边缘检测所确定的纹层条数^[20]。针对花庄地区阜二段多口井的电成像高精度测井图像, 基于Python3.6语言环境对电成像单极板彩色图像进行等间隔切割、灰度化及高斯滤波、边缘增强等图像处理, 进一步对单一电成像图像中明暗条纹数量精细统计, 用于指示该深度段内页岩纹层发育程度(图5)。同时根据岩心观察结果、电性特征及电成像测井图像颜色差异分段开展电成像测井图像的纹层边缘检测, 以量化阜二段纵向上页岩纹层发育程度。

以花页7井阜二段电成像测井图像纹层检测结果为例, 同时结合阜二段不同小层纹层发育占比(镜下岩心薄片统计)对比统计: 整体上阜二段不同小层的纹层指数与

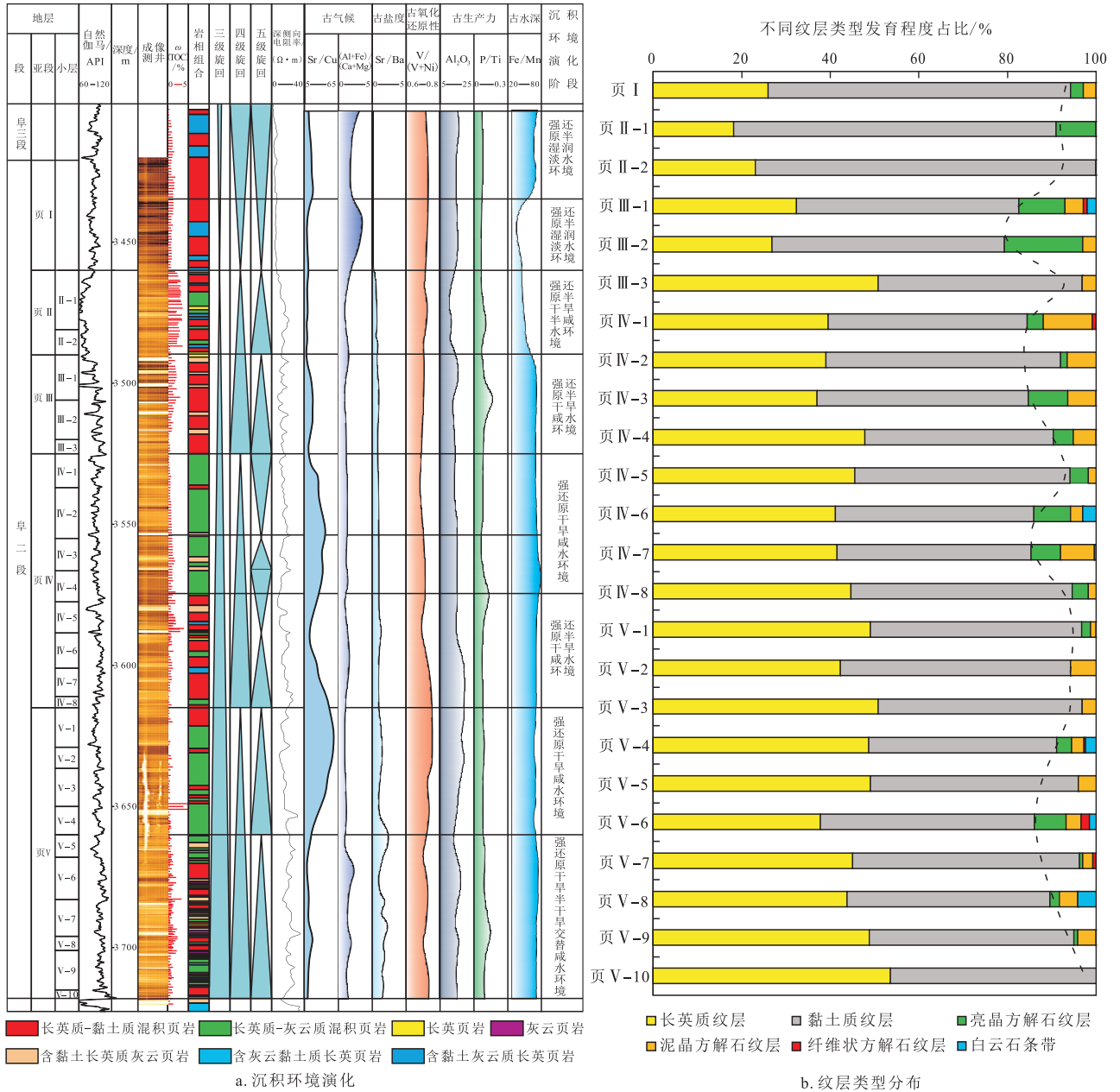


图4 苏北盆地高邮凹陷花庄地区阜二段沉积环境演化及纹层类型分布特征

Fig. 4 Evolution of depositional environments and distribution characteristics of lamination types of the Funing Formation Member 2 in Huazhuang area of Gaoyou Sag, Subei Basin

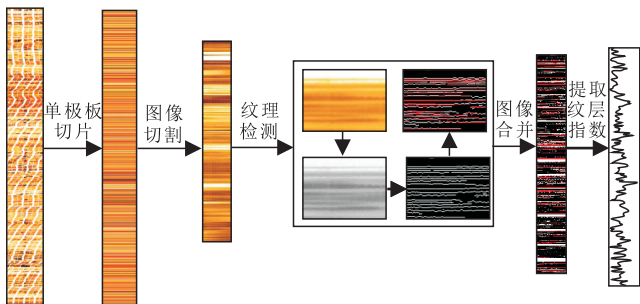


图5 基于电成像测井图像的页岩纹层发育程度识别方法
Fig. 5 Identification method for shale lamination development based on electrical imaging logging

岩心薄片统计的纹层发育段占比变化趋势基本一致。其中,阜二段页V亚段下部V-6、V-7与V-8小层纹层发育程度相对较高,纹层指数多大于20,岩屑录井揭示,该段 $\omega(\text{TOC})$ 平均为1.1%;页IV-4、IV-5、IV-6小层纹层指数多大于24, $\omega(\text{TOC})$ 介于1.1%~1.4%,平均为1.2%;该些小层均为阜二段地质“甜点”层(图6)。由于页岩纹层发育程度高,页岩油储层的可改造性强,工程压裂条件有利,因此,通过电成像测井图像进行页岩纹层发育程度的定量表征有助于对页岩油纵向“甜点”层差异分布特征进行精细地质评价。

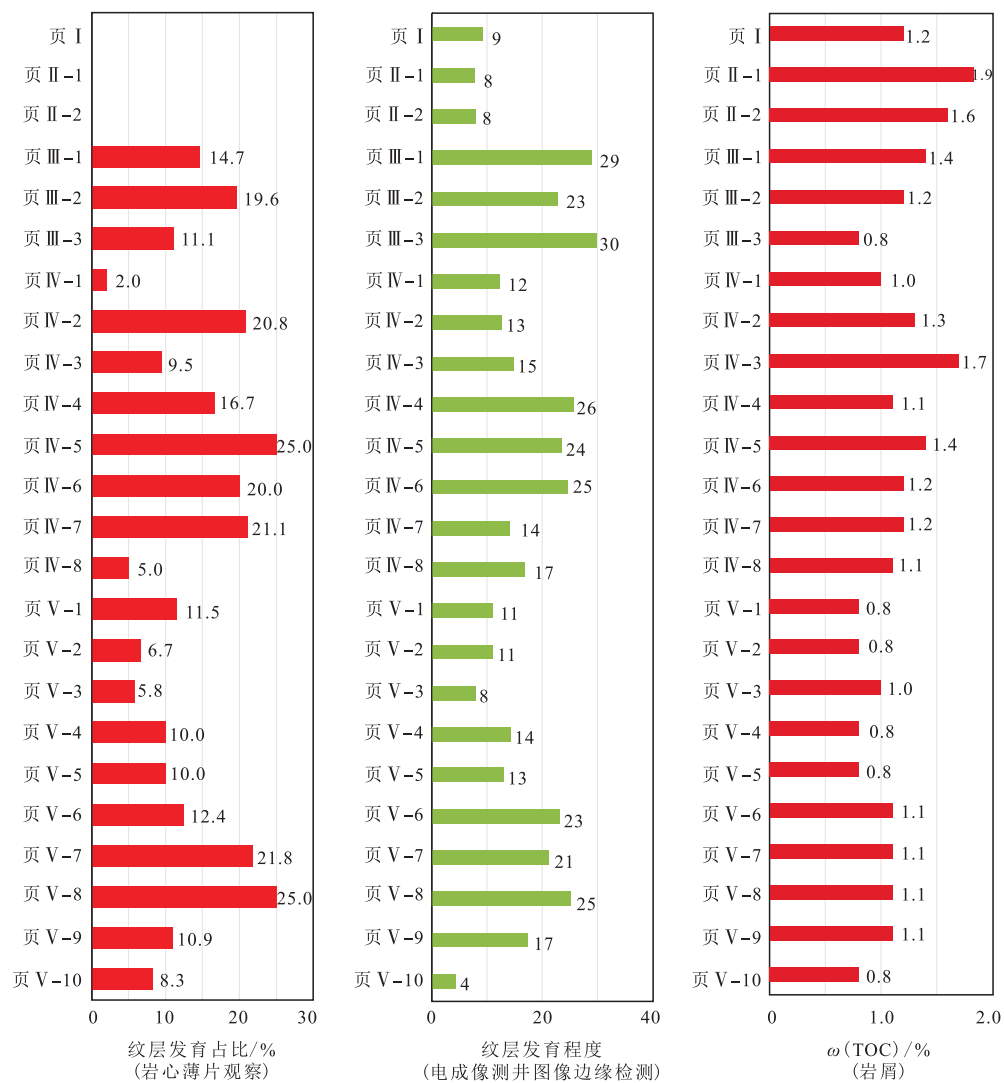


图6 花页7井阜二段页岩电成像测井纹层发育程度表征与岩心薄片统计对比

Fig. 6 Characterization of shale lamination development in the Funing Formation Member 2 from well Huaye 7 using electrical imaging logging compared with thin section statistics of core samples

4.2 常规测井纹层表征

电成像测井分辨率高,是开展页岩纹层定量表征的首选,但因探测成本昂贵,一般电成像专项测试的油井数量较少,而常规测井资料丰富,是进行页岩纹层定量表征的重要资料。

从页岩纹层成因分析,气候变化越频繁,页岩沉积速率变化越剧烈,纵向上非均质性强,纹层越发育。米兰科维奇旋回研究表明:湖盆页岩沉积时期,长偏心率、短偏心率、斜率和岁差地球轨道参数的周期变化通过影响地表日照量影响地球气候的周期性波动,进而造成页岩结构、构造及岩性变化的差异^[38]。因此,对常规测井中分辨率高、连续性好、对气候变迁最敏感的自然伽马测井数据

在进行米兰科维奇旋回信号提取和识别研究的基础上,通过计算不同小层页岩沉积速率变化情况来表征纹层发育程度。

研究的阜二段地层旋回分析流程是在基于 Matlab 平台的 AcycleV2.4.1(沉积旋回-古气候信号分析软件)实现的^[39]。主要方法与步骤如下:①进行数据预处理,删除偏离正常波动内异常值,并进行等间距线性插值;②深度域沉积速率分析;③MTM(多窗谱分析法)频谱分析识别米兰科维奇旋回:对自然伽马测井曲线进行频谱分析,寻找对应的米氏旋回频谱峰值,通过滤波分析提取相应频率信号,进而明确地球轨道参数偏心率、斜率和岁差的周期^[40]。一般而言,通过频谱分析获取的旋回厚度比与天文地球轨道参数的周期比一致,即认为沉积记录包含米

兰科维奇旋回。

花页7井阜二段自然伽马MTM频谱分析结果显示阜二段自然伽马存在8个优势频率,由此计算出谱峰对应的旋回厚度为39.84、11.76、9.43、4.20、3.19、2.32、2.13、1.82 m,其旋回厚度比为21.91:6.47:5.19:2.13:1.76:1.28:1.17:1.00,接近该时期21.32:6.58:5.26:2.74:2.00:1.21:1.16:1.00的天文周期比,表明花庄地区阜二段页岩沉积过程受地球轨道周期性变化控制,存在米兰科维奇旋回(表1)。

在阜二段页岩地层的MTM频谱分析基础上,进一步通过蒙特卡洛模拟来评价经ASM(采用零假设检验天文驱动信号的存在)统计法^[41]所识别的偏心率、斜率和岁差周期与理论值间的拟合程度,并用零假设检验的显著性水平来表达匹配结果,并得到湖相泥岩的最优沉积速率值^[42-44]。图7a为花页7井的ASM分析结果,表明阜二段的最优沉积速率为10.8 cm/kyr,且零假设检验的显著性水平低于0.01。基于这一最优沉积速率,进一步采用eCOCO(基于一系列可能的沉积速率,利用假设检验和蒙特卡洛模拟来追踪沉积速率的变化)统计法^[45]追踪评估阜二段页岩沉积速率的变化,跟踪气候敏感曲线自然伽马沿地层序列在沉积速率上的变化,以此表征页岩纹层发育程度。图7b显示:受气候周期性波动影响,阜二段不同小层的页岩沉积速率存在显著差异,沉积速率变化所表征的纹层发育程度与岩心薄片统计的纹层发育占比整体规律相关性较高,且与电成像测井图像边缘检测的不同层段纹层发育程度的变化规律较一致。其中,阜二段页IV-3、IV-5—IV-7、V-6、V-7小层沉积速率变化较快,页岩纹层发育程度高,且TOC含量高于其他层段,为

表1 花页7井阜二段自然伽马频谱分析与50 Ma地球轨道周期参数对比

Table 1 Comparison of natural gamma-ray spectrum analysis from the Funing Formation Member 2 in well Huaye 7 and Earth's orbital parameters at 50 Ma

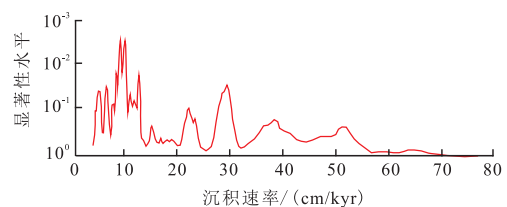
自然伽马频谱分析			50 Ma 地球轨道周期		地球轨道周期参数
主频率	旋回厚度/m	旋回厚度比	天文周期/kyr	天文周期比	
0.025 1	39.84	21.91	405	21.32	偏心率
0.085 0	11.74	6.47	125	6.58	
0.106 0	9.43	5.19	100	5.26	
0.238 0	4.20	2.31	52	2.74	
0.313 0	3.19	1.76	38	2.00	斜率
0.431 0	2.32	1.28	23	1.21	
0.469 0	2.13	1.17	22	1.16	岁差
0.550 0	1.82	1.00	19	1.00	

纵向上页岩油地质“甜点”层,因此,该方法适用于新区块页岩油勘探开发早期阶段,通过自然伽马进行页岩纹层发育程度的定量表征,可作为页岩油地质“甜点”评价时的重要地质参数,优选出页岩油“甜点”层靶窗。

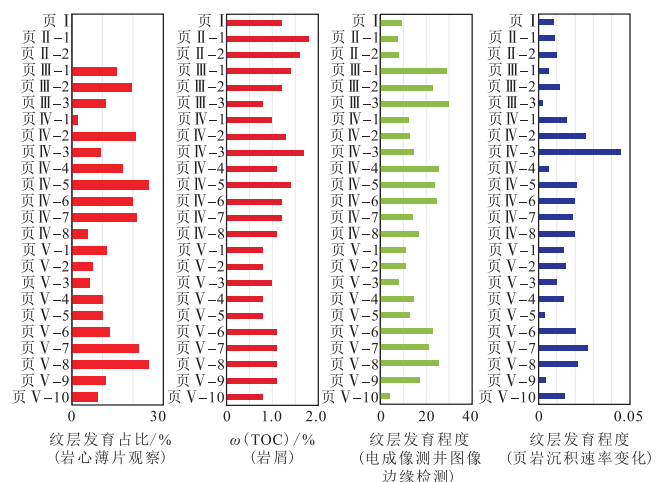
5 结论

1) 苏北盆地高邮凹陷阜二段页岩沉积时期为“水深早浅晚深、气候早干晚湿、盐度早咸晚淡,生产力早低晚高”的环境特征,且在多期干湿交替性气候变化影响下,纵向上阜二段不同小层页岩在矿物组分、岩相、纹层类型存在周期性变化,主要发育长英质、黏土质、泥晶方解石、亮晶方解石、纤维状方解石纹层类型和白云石条带。不同纹层叠置分布造成页岩优势生烃岩相与储集岩相的差异性耦合,加剧了阜二段页岩油“甜点”差异分布。

2) 基于电成像、常规等测井资料的阜二段页岩纹层发育程度定量表征结果表明:高邮凹陷阜二段页IV-3—IV-7、页V-6—V-8小层纹层发育程度高,页岩油富集条件有利。其中,基于电成像测井图像的页岩纹层表征方法可利用高精度电成像测井图像进行纵向上纹



a. 花页7井最优沉积速率估算



b. 花页7井纹层发育程度(沉积速率表征法)

图7 花页7井阜二段最优沉积速率估算与纹层发育程度定量表征

Fig. 7 Optimal deposition rate estimation and quantitative characterization of lamination development in the Funing Formation Member 2 of well Huaye 7

层发育程度的精细评价;而基于自然伽马测井-米兰科维奇旋回的时间序列分析法可通过评估不同层段页岩沉积速率变化来指示纵向页岩纹层发育程度差异,该方法适用于页岩油勘探开发早期阶段,通过常规测井进行页岩纹层发育程度表征,指导页岩油地质“甜点”层段的优选。

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(上接第27页)

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