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# 细粒岩天文旋回识别及在精细地层划分上的应用 ——以辽河西部凹陷雷家地区沙四段为例

李阳<sup>1,2</sup>, 李晓光<sup>1</sup>, 张廷山<sup>2</sup>, 邹丙方<sup>1</sup>, 陈昌<sup>1</sup>, 李金鹏<sup>1</sup>, 周晓龙<sup>1</sup>, 王高飞<sup>1</sup>, 刘洋<sup>1</sup>,  
戚雪晨<sup>1</sup>, 郭美伶<sup>1</sup>, 高洋<sup>2</sup>

1. 中国石油辽河油田分公司, 辽宁盘锦 124010

2. 西南石油大学地球科学与技术学院, 成都 610500

**摘要** 【目的】渤海湾盆地辽河坳陷西部凹陷雷家地区沙四段以黏土、长英质、碳酸盐及方沸石矿物混合的湖相细粒沉积岩, 为该区油气赋存的主要载体, 但混合细粒岩成分复杂且横向变化快, 导致储层非均质性强, 为优质储层预测带来一定困难。【方法】以西部凹陷雷家地区雷15井、雷14井和雷61井为例, 基于时间序列分析方法、高精度碳酸盐U-Pb定年及自然伽马测井数据对沙四段混合细粒岩进行旋回地层学分析。【结果】(1)以相关系数法估算雷15井、雷14井和雷61井的最佳沉积速率, 发现最佳沉积速率依次增大, 分别为10.57 cm/kyr、11.40 cm/kyr和13.93 cm/kyr; (2)对古气候替代指标(自然伽马)进行频谱分析, 与标准偏心率、斜率、岁差合成曲线(ETP曲线)数据频谱分析结果进行对比, 识别雷15井、雷14井和雷61井混合细粒岩中的天文旋回信号, 并利用405 kyr长偏心率进行天文调谐, 以雷14井2766.61 m处年龄 $43.4 \pm 1.7$  Ma为锚点, 建立绝对天文年代标尺; (3)沙四段中识别出6个405 kyr长偏心率周期, ~17个~129 kyr短偏心率周期, 结合地球轨道周期与高频层序之间的联系, 建立偏心率尺度的精细地层划分对比格架。【结论】通过对雷家地区沙四段开展旋回地层学研究, 有效识别沙四段中天文旋回信号, 以量化方式建立具备时间属性的精细地层划分对比格架, 对该区油气进一步勘探具有重要指导作用, 并且有望拓宽旋回地层学在渤海湾盆地的适用性。

**关键词** 混合细粒岩; 天文旋回; 沉积速率; 精细地层划分; 西部凹陷

**第一作者简介** 李阳, 男, 1988年出生, 博士, 沉积储层及数据挖掘, E-mail: 7891235@qq.com

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## 0 引言

随着页岩油气等非常规油气勘探的兴起, 储层岩石粒度研究从“粗一中粒”向“细粒”发展, 细粒沉积物成分一般为粒径小于 $62.5 \mu\text{m}$ 的黏土、长英质、碳酸盐、硫化物和有机质等<sup>[1-11]</sup>, 不同成分的细粒沉积物以混合、互层、夹层或横向相变等形式堆积和演化进而形成混合细粒沉积岩序列<sup>[12-17]</sup>。国外学者对混合细粒沉积岩的研究多集中在海相沉积环境中的页岩, 如死海地区上更新统<sup>[18]</sup>、芬兰地区全新统<sup>[19]</sup>和北美地区始新统<sup>[20]</sup>等均有发现, 而国内混合细粒沉

积岩多发育在陆相湖盆中, 在渤海湾盆地古近系<sup>[8-9, 12-14, 16, 21]</sup>、准噶尔盆地二叠系<sup>[15, 22]</sup>、四川盆地侏罗系<sup>[6]</sup>、柴达木盆地古近系<sup>[23]</sup>、鄂尔多斯盆地三叠系<sup>[24]</sup>及松辽盆地白垩系<sup>[25]</sup>等均有分布。与海洋环境相比, 陆相湖盆范围小、物源类型多(陆源、内源、火山源及混合来源), 自我调节及净化能力较弱, 盆内沉积物具有颜色多样、矿物种类复杂、岩石类型丰富、相变快等特征, 并伴有纹层及揉皱等沉积构造<sup>[26-31]</sup>。湖相混合细粒岩相比于传统碎屑岩和碳酸盐岩体系, 其形成具有更为复杂的地质条件, 在地质构造作用影响较小的情况下, 古气候条件为决定混合细粒岩形成的重要外部

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因素,地球轨道参数的变化可以影响古气候(季风、日照量等),对湖相混合细粒岩地层开展旋回地层学研究以及识别其中的天文旋回信号显得尤为重要。

旋回地层学是以米兰科维奇理论为基础的一门地层学分支学科,主要研究受天文轨道力驱动的具有周期性变化的沉积记录,研究的主要周期为~20 kyr~2.4 Myr,广泛应用于湖相混合细粒岩地层沉积速率和沉积时限分析、天文年代标尺建立、精细等时地层划分对比以及优质烃源岩沉积规律分析中,并取得了较好的应用效果<sup>[9,32-43]</sup>。Berger *et al.*<sup>[44-46]</sup>、Laskar *et al.*<sup>[47-48]</sup>和Waltham<sup>[49]</sup>给出了天文周期(偏心率、斜率和岁差)的解决方案,以此可计算不同时代的偏心率(eccentricity)、斜率(obliquity 或 tilt)和岁差(precession)的主要周期,其中405 kyr长偏心率周期是250 Ma以来最稳定的天文轨道周期,被称为精准的“沉积物钟”,为开展旋回地层学研究提供了基础条件<sup>[50-53]</sup>。混合细粒岩因沉积连续而不发育不整合面,一般难以识别层序界面,不利于开展层序地层学研究<sup>[54-55]</sup>,不同学者将层序级别的划分与天文旋回联系起来,发现高频层序(四级、五级、六级层序)与米兰科维奇旋回周期密切相关,即天文轨道力驱动气候变化导致海/湖平面周期性变化使得地层具有旋回性沉积,四级层序反映了405 kyr长偏心率周期以及可能的~160~200 kyr的斜率调制周期,五级层序对应~100 kyr短偏心率周期,六级层序与岁差(~20 kyr)及斜率(~40 kyr)周期有关<sup>[52,56-58]</sup>,结合细粒混合沉积矿物的定年技术,便可以将建立的等时地层格架赋予时间属性。

渤海湾盆地辽河拗陷西部凹陷雷家地区沙四段发育一套以湖泊相为主的混合细粒沉积岩,储层岩性成分复杂且横向上变化快,导致储层孔隙结构复杂及非均质性强,为优质储层预测及水平井钻探等带来了一定的困难。目前对雷家湖相碳酸盐岩已从多方面进行了攻关,如沉积环境<sup>[59-61]</sup>、烃源岩特征<sup>[62-63]</sup>、储层特征<sup>[26,64]</sup>、白云岩和方沸石成因<sup>[21,26,65-67]</sup>及油藏特征<sup>[68-70]</sup>,均取得了较好的研究成果,但基于旋回地层学等时地层划分对比的基础性研究仍有所欠缺。本文基于旋回地层学理论基础,选取雷家地区三口探井沙四段为研究对象,通过对自然伽马曲线进行频谱分析识别出不同天文轨道周期,进行天文调谐,结合雷14井碳酸盐U-Pb定年结果,进一步探讨了雷家地区沙四段沉积时限。利用高频层序与天

文轨道周期之间的关系,建立天文旋回周期尺度的高精度地层划分对比格架,可为富有机质页岩发育规律、混合细粒岩分布特征、优质储层预测及水平井设计提供地质依据<sup>[35,56,71]</sup>。

## 1 地质概况

辽河拗陷位于渤海湾盆地东北部,是在华北地台基础上,受中—新生代区域拉张作用形成的多旋回新生代大陆裂谷盆地,具有“三凸三凹”的构造格局,西部凹陷是辽河拗陷内最大的次级负向构造单元,呈北东向展布,为东断西超、东陡西缓的狭长箕状断陷,雷家地区位于西部凹陷中北部,包括陈家、台安两个次级洼陷<sup>[26,72]</sup>(图1),分析探井紧邻陈家洼陷二级构造带,沙四时期以发育半深湖—深湖亚相为主,末期见扇三角洲相,沉积岩性成分一般较为复杂,多为碳酸盐、黏土矿物及长英质混合,在杜三层可见方沸石矿物混入,具有典型的细粒混合特征<sup>[26,66-67,72]</sup>。沙四段分为高升油层和杜家台油层,高升油层以泥岩、页岩、泥质碳酸盐岩为主,杜家台油层主要产油层集中在杜三层,以泥—粉晶白云岩、陆源混杂云岩以及方沸石质云岩沉积为主,常见纹层及揉皱等沉积构造,脆性矿物含量高,储层裂缝及溶蚀孔隙发育且具有较好的油气显示。本次研究选用的雷14井、雷15井及雷61井,多数位于湖盆沉积中心,受断裂影响较小,沉积地层连续性好,适合开展旋回地层学分析。

## 2 旋回地层学分析方法简介

目前多数学者以时间序列分析法进行旋回地层学研究,选取合理古气候替代指标(岩石物性、磁性、古生物、同位素以及测井等数据)进行频谱分析,识别古气候替代指标中的天文轨道周期信号,分析过程包括数据预处理、频谱分析、滤波和天文调谐等步骤<sup>[35]</sup>(数据处理和分析可在北京大学李明松老师开发的Acycle2.8软件中实现,下载地址为:<https://acycle.org>)。

古气候替代指标数据中应确保每个旋回中最少需要4个采样点来进行约束<sup>[40]</sup>,数据预处理包括数据去极值、插值、去趋势和预白化等,去趋势可以消除采样数据逐渐上升或者逐渐下降的趋势变化,选取合适窗口长度(一般为数据长度的35%),使用LOWESS(局部加权回归散点平滑法)、rLOWESS(稳



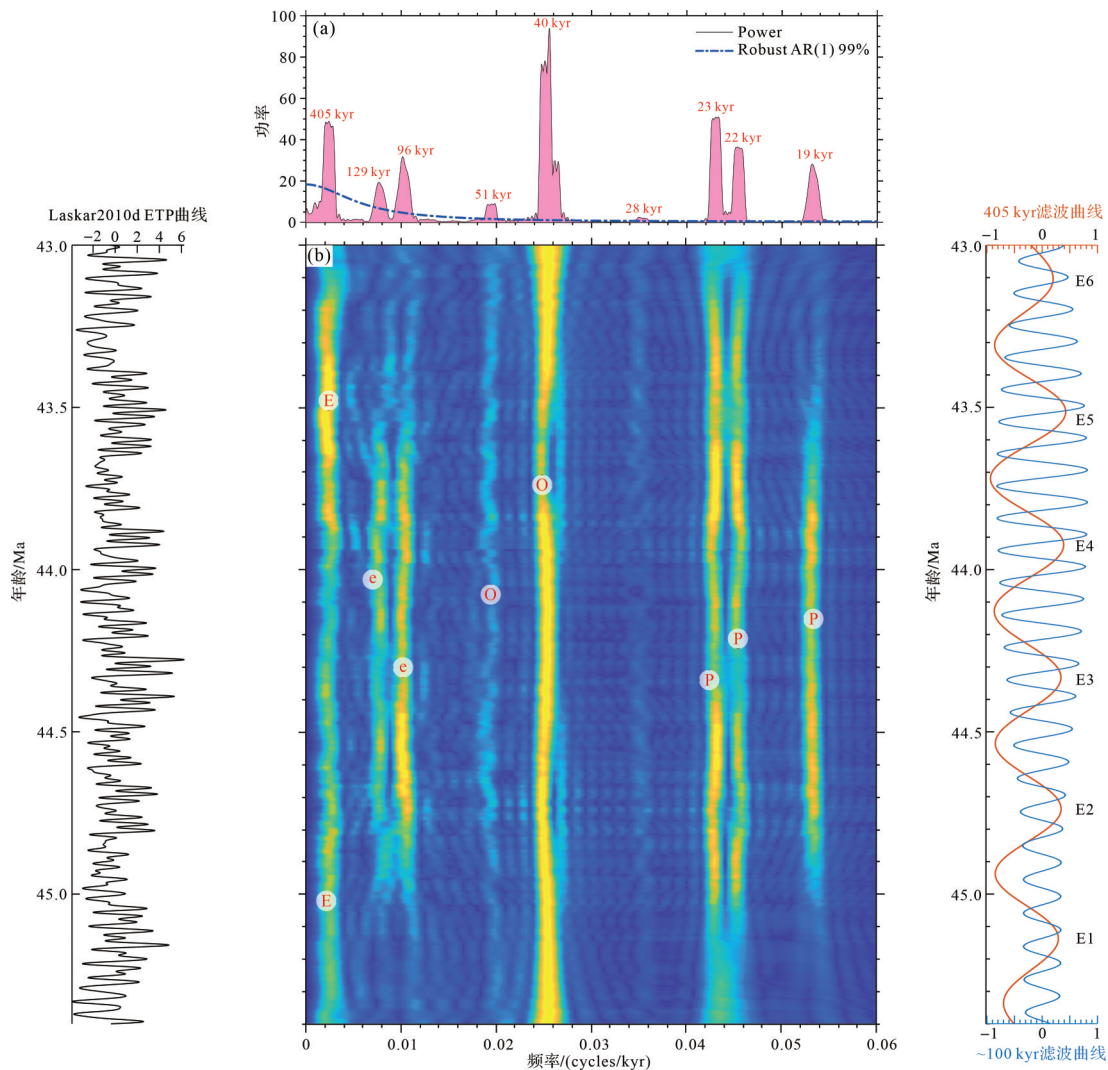


图2 Laskar2010d在43~45.4 Ma的ETP理论曲线的频谱分析图及~100 kyr和405 kyr的长短偏心率周期的滤波曲线图  
(a)MTM频谱图;(b)eFFT方法滑动频谱图

Fig.2 Spectral analysis of the standard eccentricity, tilt, and precession composite curve (ETP curve) theoretical curve of Laskar2010d at 43.0-45.4 Ma and filter curves of the long and short eccentricity periods of ~100 kyr and 405 kyr  
(a)  $2\pi$  Multi-Taper Method (MTM) spectrum analysis; (b) Evolutionary Fast Fourier Transform (eFFT) analysis

变分模态分解 (Variational Mode Decomposition, VMD) 亦可选取特定的频率分量<sup>[77-80]</sup>。将频谱分析过程中获取的天文轨道周期信号调谐到理论的天文轨道周期上,即将沉积记录或古气候替代指标的旋回记录对比到岁差、斜率、偏心率或(和)日照量变化曲线上,从而建立天文年代标尺,此过程为天文调谐。

评估沉积速率往往需要结合研究层段的沉积年代的天文轨道参数周期时限,主要方法有平均频谱误差<sup>[81]</sup>(Average Spectral Misfit, ASM)、相关系数方法<sup>[35]</sup>(Correlation Coefficient, COCO)以及年代标尺优化<sup>[82]</sup>(Time Scale Optimization, TimeOpt)。演化相关系

数 (Evolutionary Correlation Coefficient, eCOCO) 可以使用滑动地层窗口来追踪替代性指标序列变化的沉积速率<sup>[35]</sup>。这些方法均为将对应的古气候替代指标的信号与理论轨道信号对比,识别地层旋回序列中的天文驱动力参数旋回周期,以及准确评估沉积速率,同时使用 Monte Carlo 模拟方法评估没有天文驱动力的零假设<sup>[35-36]</sup>。

### 3 雷家地区旋回地层学分析

自然伽马测井可测量沉积地层中放射性元素衰变过程中自然伽马射线强度,其强度大小取决于岩

石中的铀(U)、钍(Th)和钾(K)元素的含量,自然伽马曲线可以反映地层中的泥质和有机质含量,一般温暖湿润环境下自然伽马表现为高值,干旱的环境下自然伽马常为低值,本文选用自然伽马数据作为古气候替代指标来对雷家地区的三口探井进行旋回地层学分析。对自然伽马数据去极值,并以0.125 m间隔对自然伽马数据进行线性插值,使用稳健局部加权回归散点平滑法(gLOWESS)对自然伽马数据去除趋势。使用相关系数法对沙四段沉积速率进行估算,采用窗谱分析方法(MTM)对雷14井、雷61井及雷15井的自然伽马数据进行频谱分析,并与ETP频谱结果进行对比,识别各井中的天文旋回周期信号,利用高斯带通滤波器提取天文周期,进而进行天文调谐,建立浮动天文年代标尺,最后建立长偏心率尺度和短偏心率尺度的精细地层划分对比格架。

### 3.1 ETP 频谱分析结果

从Laskar2010d ETP曲线的MTM频谱分析图和演化频谱分析图中可以明显看到此段沉积时期具有~405 kyr长偏心率周期、~129 kyr和~96 kyr短偏心率周期、~51 kyr和~40 kyr斜率周期以及~23 kyr、~22 kyr和~18.8 kyr岁差周期,所对应的周期频率分别为~0.002 469 cycles/kyr、~0.007 752 cycles/kyr、~0.010 416 cycles/kyr、~0.019 608 cycles/kyr、~0.025 641 cycles/kyr、~0.043 478 cycles/kyr、~0.045 455 cycles/kyr和0.053 394 cycles/kyr。与ETP曲线频谱分析结果进行对照,有利于识别雷家地区探井沙四段中的天文

旋回周期信号(图2)。

### 3.2 最佳沉积速率估算

沉积速率估算主要使用相关系数法,COCO不需要严格的年龄“锚点”进行限定,是一种客观确定最佳沉积速率的方法<sup>[35-36]</sup>。沉积速度分析范围为1~25 cm/kyr,沉积速度间隔为0.1 cm/kyr,采用Robust AR1模型对数据去除红噪,相关方法为Pearson, Monte Carlo模拟次数为5 000次,中值年龄为44 Ma,进而估算三口井的最佳沉积速率。从分析结果中可以发现,三口井都存在两个主要的沉积速率,其中低值部分在3.3~4.6 cm/kyr变化,高值部分在10~14 cm/kyr变化,高值部分的相关系数和零假设置信度均优于低值部分,故雷15井、雷14井及雷61井最佳沉积速率分别为10.57 cm/kyr、11.40 cm/kyr和13.93 cm/kyr,依次增大,可能与该区北东高—南西低的古构造格局有关<sup>[26,72]</sup>(图3)。

目前针对西部凹陷沙四段沉积速率的研究鲜有报道,但雷家地区与渤海湾盆地古近纪沙河街沉积时期的其他湖盆具有相似沉积速率。如王淳等<sup>[83]</sup>分析东营凹陷LY1井沙三—沙四上亚段沉积速率约为7.54 cm/kyr;石巨业等<sup>[84]</sup>对樊页1井磁化率指标进行ASM分析,计算出沙四上亚段最优沉积速率为13.14 cm/kyr;栾旭伟等<sup>[33]</sup>计算FY1井沙四上亚段的沉积速率为9.83~15.76 cm/kyr;孙善勇等<sup>[37]</sup>计算东营凹陷NY1井沙四上亚段沉积速率介于8.45~14.62 cm/kyr;金忠慧等<sup>[85]</sup>计算沙四上纯上亚段沉积

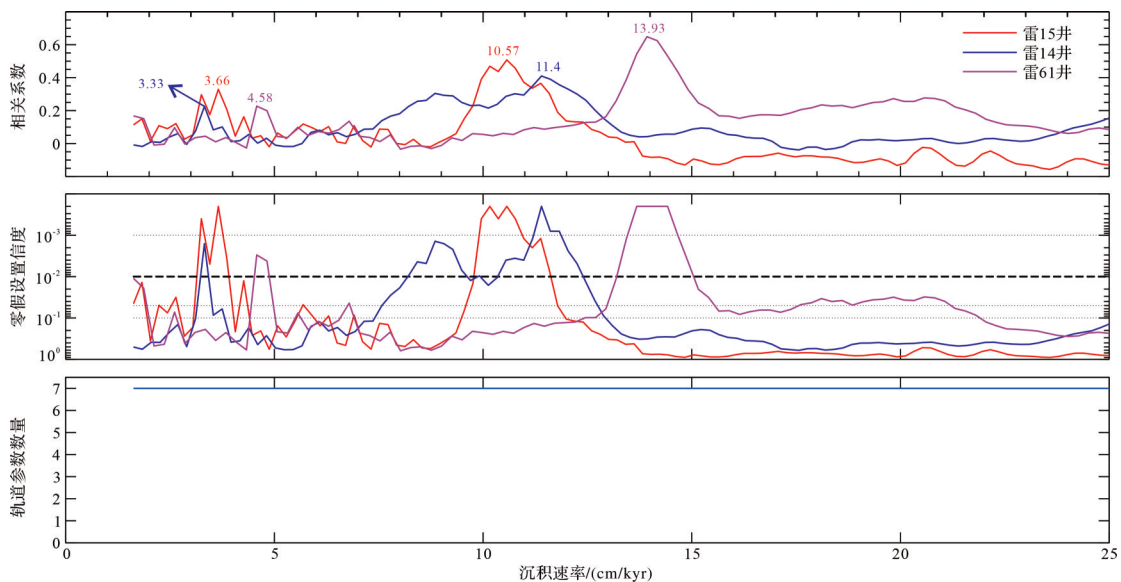


图3 雷15井、雷14井和雷61井基于相关系数法最佳沉积速率估算

Fig.3 Estimation of optimal sedimentary rate based on correlation coefficient method for wells Lei 15, Lei 14, and Lei 61

速率为9~11 cm/kyr,沙四上纯下亚段沉积速率为10.5~14.7 cm/kyr;彭军等<sup>[86]</sup>亦计算东营凹陷樊页1井沙四上亚段沉积速率偏小,为6.9 cm/kyr。

### 3.3 雷家地区探井频谱分析

雷14井和雷61井沙河街组顶部发育扇三角洲相,同时雷61井顶部亦见火山岩发育,对雷14井2 720~2 983 m井段、雷15井2 530~2 783 m井段和雷61井2 930.0~3 234.5 m井段的自然伽马数据进行频谱分析(表1、图4)。从eFFT频谱中可见偏心率信号较为连续,雷15井长偏心率超过90%置信度的峰值为52.682 3 m、42.145 8 m和35.121 5 m,雷14井存在59.715 9 m、43.791 7 m、36.493 1 m三个峰值,雷61井存在69.176 1 m、54.352 7 m和44.761 0 m三个峰值。结合上文基于COCO计算的各井最佳沉积速率,同时参照ETP曲线长偏心率中三个峰值的比值,可确定各井405 kyr长偏心率周期对应的峰值,雷15井、雷14井和雷61井分别为42.145 8 m、43.791 7 m及54.352 7 m。进而利用偏心率、斜率和岁差之间的比值识别各井中的短偏心率、斜率和岁差信号,雷15井中14.206 5 m、10.715 0 m、5.290 3 m、4.682 9 m、2.257 8 m和2.059 2 m峰值分别对应~129 kyr、~100 kyr、~51 kyr、~40 kyr、~22 kyr和~18.8 kyr;雷14井中14.279 9 m、5.614 3 m、4.499 1 m、2.341 8 m和2.036 8 m峰值分别对应~129 kyr、~51 kyr、~40 kyr、22 kyr和~18.8 kyr;雷61井中18.117 6 m、7.571 5 m、3.112 2 m和2.762 02 m峰值分别对应~129 kyr、~51 kyr、23 kyr和~21 kyr。

分别对雷15井、雷14井和雷61井偏心率周期进

行高斯带通滤波,三口井均识别出6个长偏心率周期,结果与ETP曲线提取的长偏心率周期个数一致,雷14井识别出17个短偏心率周期,雷15井和雷61井均识别出16个短偏心率周期,ETP曲线提取出完整的短偏心率周期~18个。沙四段沉积初期具有隆凹相间的古地貌格局,导致部分水上隆起发生沉积缺失,各井短偏心率周期个数的缺失可能与此有关<sup>[26,72]</sup>(图2,4)。在此基础上对长偏心率信号进行天文调谐,分别建立三口井的浮动天文年代标尺,其中雷15井沙四段沉积时限~2.30 Ma,雷14井沙四段沉积时限~2.34 Ma,雷61井沉积时限~2.30 Ma。从时间域的MTM频谱分析图及滑动频谱分析图中可以发现,三口井中存在显著的偏心率周期信号,斜率信号和岁差信号在各井的中下部较为显著(图5)。

对雷14井2 766.61 m碳酸盐岩样品进行碳酸盐U-Pb同位素定年,测试在西南石油大学国家重点实验室使用LA-ICP-MS完成(LA-ICP-MS由Resolution LR 193 nm ArF准分子激光剥蚀系统和Thermo iCAP TQ组成),得到年龄为43.4±1.7 Ma,以此年龄作为时间锚点,通过计数方式确定405 kyr长偏心率调谐GR滤波曲线的顶底年龄为43.03±1.7 Ma和45.34±1.7 Ma,这与姚益民等<sup>[73]</sup>和梁鸿德等<sup>[74]</sup>通过辽河坳陷古近系K-Ar火山岩同位素年龄测定的结果一致(图5d、图6)。

## 4 偏心率尺度精细地层划分对比

国际地层委员会利用稳定的405 kyr长偏心率周

表1 雷15井、雷14井和雷61井MTM频谱分析结果

Table 1  $2\pi$  MTM spectrum analysis results of wells Lei 15, Lei 14, and Lei 61

ETP 置信度超90%周期/kyr	雷15井		雷14井		雷61井	
	置信度超90%峰值/m	峰值比	置信度超90%峰值/m	峰值比	置信度超90%峰值/m	峰值比
521.957 0	52.682 3	506.250 5	59.715 9	552.272 2	69.176 1	515.454 1
405.000 0	42.145 8	405.000 0	43.791 7	405.000 0	54.352 7	405.000 0
343.000 0	35.121 5	337.500 0	36.493 1	337.500 2	44.761 0	333.529 1
129.086 0	15.052 1	144.643 1	15.276 2	141.279 3	19.264 2	143.543 9
96.814 5	14.206 5	136.517 3	14.279 9	132.065 2	18.117 6	135.000 2
51.523 6	10.715 0	102.965 8	5.614 3	51.923 1	7.571 5	56.417 9
39.883 7	5.290 3	50.836 8	4.499 1	41.609 5	3.112 2	23.190 2
28.651 6	4.682 9	45.000 0	4.170 6	38.571 4	2.762 0	20.580 7
23.265 5	2.913 3	27.995 5	2.341 8	21.657 7	/	/
21.987 2	2.257 8	21.696 4	2.139 7	19.788 3	/	/
18.846 2	2.059 2	19.788 0	2.036 8	18.837 2	/	/

注:峰值比=(405/λ<sub>405 kyr</sub>)×λ式中λ<sub>405 kyr</sub>为各井405 kyr长偏心率周期对应的峰值,λ为峰值。

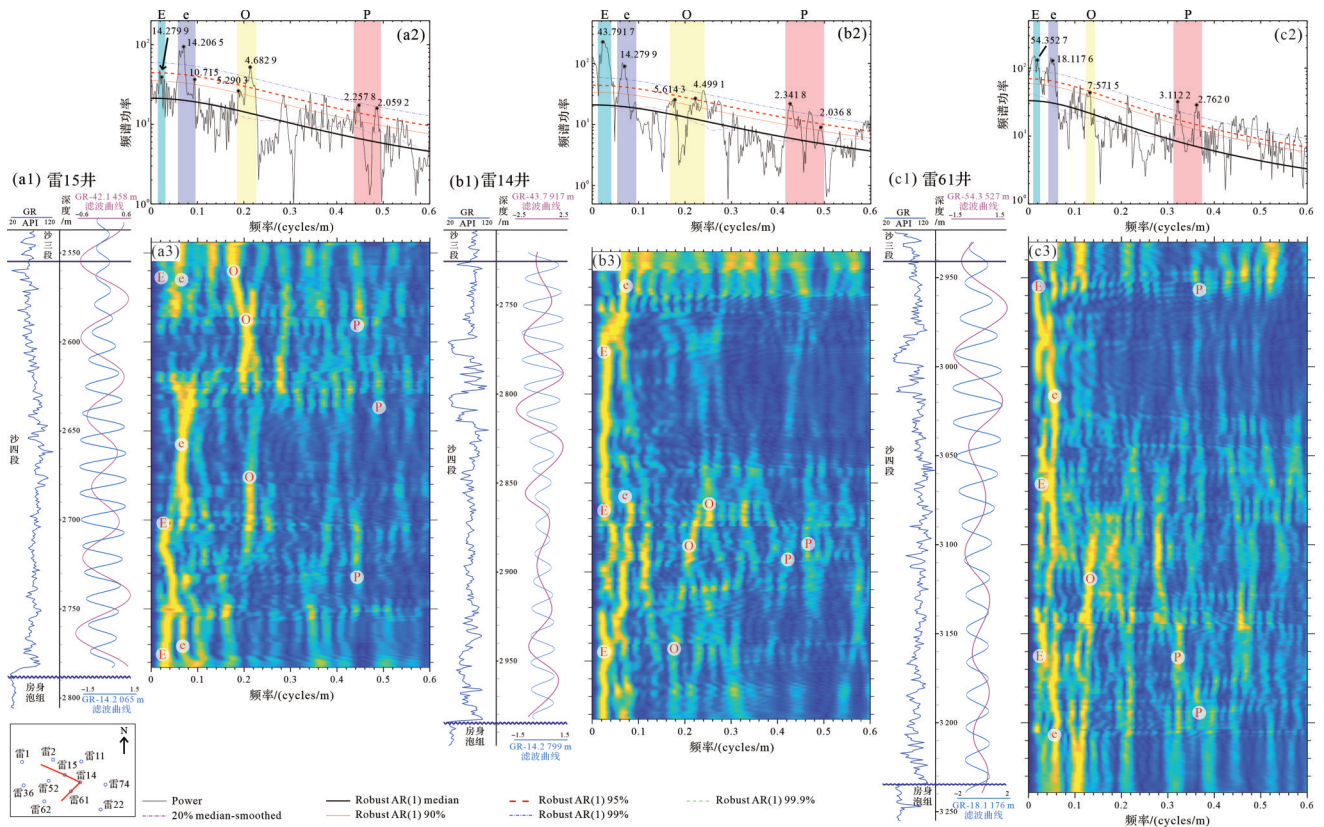


图4 雷15井、雷14井和雷61井沙四段深度域频谱及滑动窗口分析

(a1~c1)分别为雷15井、雷14井和雷61井GR曲线和滤波曲线,长偏心率滤波带宽分别为 $0.023\ 726\ 5 \pm 0.003\ 905\ 5$  cycles/m、 $0.022\ 791\ 5 \pm 0.005\ 178\ 5$  cycles/m和 $0.018\ 398\ 4 \pm 0.003\ 713\ 0$  cycles/m,短偏心率滤波带宽分别为 $0.070\ 389\ 0 \pm 0.004\ 607\ 0$  cycles/m、 $0.070\ 030\ 5 \pm 0.005\ 019\ 5$  cycles/m和 $0.055\ 595\ 5 \pm 0.004\ 421\ 5$  cycles/m;(a2~c2)分别为雷15井、雷14井和雷61井GR曲线频谱分析图;(a3~c3)分别为雷15井、雷14井和雷61井GR曲线滑动窗口频谱图,滑动窗口分别为50.55 m、52.5 m和61.85 m

Fig.4  $2\pi$  MTM spectrum analysis and eFFT analysis of wells Lei15, Lei14, and Lei61 in the depth domain

(a1-c1) are the gamma ray (GR) curves and filter curves of wells Lei 15, Lei 14, and Lei 61, respectively. The long eccentricity filter bandwidths are  $0.023\ 726\ 5 \pm 0.003\ 905\ 5$ ,  $0.022\ 791\ 5 \pm 0.005\ 178\ 5$ , and  $0.018\ 398\ 4 \pm 0.003\ 713\ 0$  cycles/m, respectively. The short eccentricity filter bandwidths are  $0.070\ 389\ 0 \pm 0.004\ 607\ 0$ ,  $0.070\ 030\ 5 \pm 0.005\ 019\ 5$ , and  $0.055\ 595\ 5 \pm 0.004\ 421\ 5$  cycles/m, respectively; (a2-c2) are the GR  $2\pi$  MTM spectrum analysis of wells Lei 15, Lei 14, and Lei 61, respectively; (a3-c3) are the eFFT of the GR curves of wells Lei 15, Lei 14, and Lei 61, respectively. The sliding windows are 50.55 m, 52.5 m, and 61.85 m, respectively

期作为基本地质计时单位建立国际地质年代表,古近纪天文年代表可以调谐至100 kyr短偏心率周期<sup>[87]</sup>,开展旋回地层学研究并提取古气候替代指标中的偏心率信号可将地层划分对比量化,并赋予时间属性。

雷15井、雷14井和雷61井每口井沙四段均提取405 kyr长偏心率周期6个,可以划分E1~E6六个小层,大致与四级层序相对应,小层厚度介于40~55 m,雷15井和雷61井均提取~129 kyr短偏心率周期16个,雷14井提取短偏心率周期17个,可划分~17个小层,小层厚度介于10~19 m,大致与五级层序相对应,其中每个长偏心率周期中包含~3.14个短偏心率周期(与405 kyr长偏心率周期和~129 kyr短偏心率周期的比值相当),从雷15井、雷14井和雷61井的

MTM频谱图和滑动窗口频谱图中可观察到,偏心率信号连续且显著,基于偏心率信号滤波建立的精细地层对比格架是可靠的(图4,5)。结合自然伽马和电阻率曲线,分析滤波曲线与测井曲线之间的关系,发现滤波曲线极大值点指示每个旋回水体最深的位置,雷家地区沙四段具有一个较好的对比标志层,为发育在高升油层上部的一套泥岩段—(“泥脖子”),是最大湖泛期的产物,各钻井中均有发现,全区稳定发育<sup>[26,72]</sup>,据此判断E3周期极大值点可能为最大湖泛面的位置(e7与e8分界线),地层对比格架中三角形箭头朝上代表水体由浅变深的半旋回(湖侵体系域),三角形箭头朝下代表水体由深变浅的半旋回(高位体系域),箭头相交处代表洪泛面,代表旋回中水体最深(图7)。

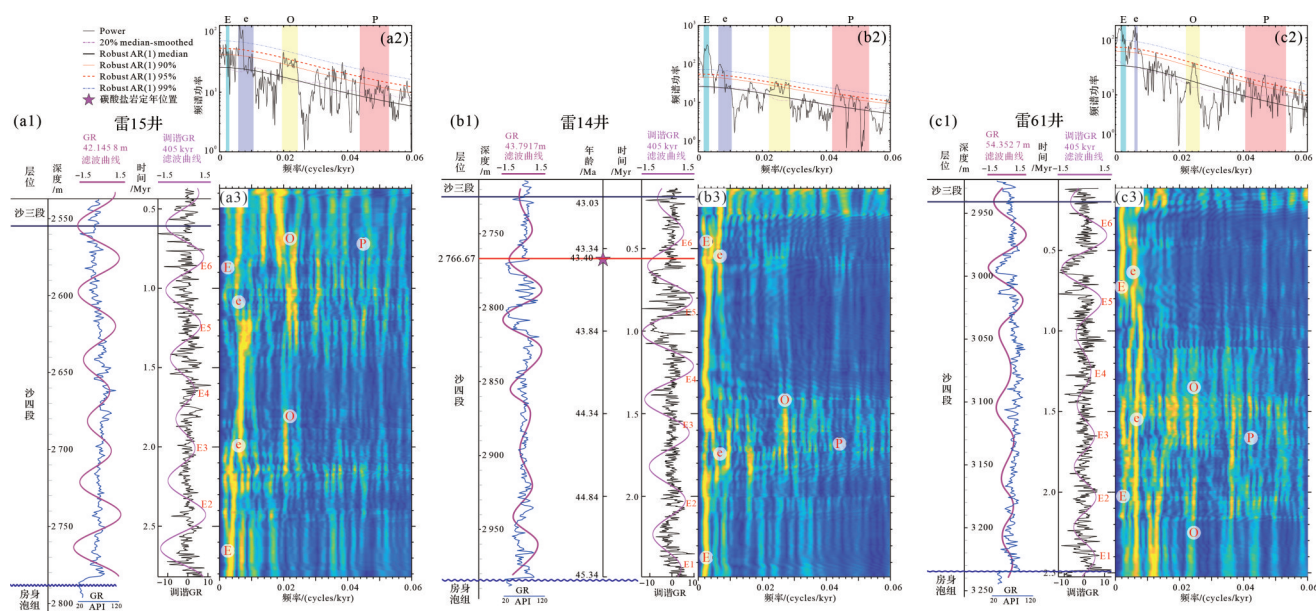


图5 雷15井、雷14井和雷61井沙四段时间域频谱、滑动窗口分析及天文年代标尺

(a1~c1)分别为雷15井、雷14井和雷61井GR、调谐GR曲线和滤波曲线,长偏心率滤波带宽分别为 $0.023\ 726\ 5 \pm 0.003\ 905\ 5$  cycles/m、 $0.022\ 791\ 5 \pm 0.005\ 178\ 5$  cycles/m和 $0.018\ 398\ 4 \pm 0.003\ 713\ 0$  cycles/m,调谐GR长偏心率滤波带宽分别为 $0.002\ 448\ 45 \pm 0.000\ 480\ 45$  cycles/kyr、 $0.002\ 465\ 05 \pm 0.000\ 346\ 15$  cycles/kyr和 $0.002\ 515\ 45 \pm 0.000\ 554\ 75$  cycles/kyr;(a2~c2)分别为雷15井、雷14井和雷61井调谐GR曲线频谱分析图;(a3~c3)分别为雷15井、雷14井和雷61井调谐GR曲线滑动窗口频谱图,滑动窗口均为600 kyr

Fig.5  $2\pi$ MTM spectrum analysis, eFFT analysis, and astronomical time scale of wells Lei15, Lei14, and Lei61 in the time domain (a1~c1) are the GR, tuning GR, and filtering curves of wells Lei 15, Lei 14, and Lei 61, respectively. The long eccentricity filter bandwidths are  $0.023\ 726\ 5 \pm 0.003\ 905\ 5$ ,  $0.022\ 791\ 5 \pm 0.005\ 178\ 5$ , and  $0.018\ 398\ 4 \pm 0.003\ 713\ 0$  cycles/m, respectively. The tuned GR long eccentricity filter bandwidths are  $0.002\ 448\ 45 \pm 0.000\ 480\ 45$ ,  $0.002\ 465\ 05 \pm 0.000\ 346\ 15$ , and  $0.002\ 515\ 45 \pm 0.000\ 554\ 75$  cycles/kyr, respectively; (a2~c2) are the spectrum analysis diagrams of the tuned GR curves of wells Lei 15, Lei 14, and Lei 61, respectively; (a3~c3) are the sliding window spectrograms of the tuned GR curves of wells Lei 15, Lei 14, and Lei 61, respectively. The sliding windows are all 600 kyr

根据辽河油田对杜家台油层和高升油层划分的规则<sup>[72]</sup>,高升油层中的高一层、高二层和高三层分别与E1、E2和E3三个长偏心率周期对应,杜家台油层中的杜三层与E4和E5长偏心率周期对应,杜二层和杜一层包括E6长偏心率周期,因此可判断高升油层和杜家台油层界限年龄为 $44.19 \pm 1.7$  Ma(图5d)。结合雷15井、雷14井和雷61井的油气显示资料,可以发现杜三油层(E4和E5长偏心率周期,e9~e14短偏心率周期,年龄介于 $43.4 \pm 1.7$  Ma~ $44.19 \pm 1.7$  Ma)油气显示较好,因为该段地层发育碳酸盐岩及方沸石质混合细粒岩,此类岩性脆性大且裂缝发育,同时裂缝受溶解作用进一步扩大改变,溶孔、溶洞常常沿着裂缝发育,为该区的优质储层,基于偏心率尺度的精细地层划分,为横向追踪这套优质储层提供重要的地质依据(图7)。

辽河拗陷西部拗陷沙四段与济阳拗陷东营拗陷沙四上亚段相对应<sup>[73-74]</sup>,不同学者对东营拗陷沙四上亚段进行旋回地层学分析时选用的沉积年龄主要为40~45 Ma,石巨业等<sup>[56]</sup>提取樊120井、樊页1井和梁758井沙四纯上亚段6个405 kyr长偏心率周期,20个

~100 kyr短偏心率周期,建立偏心率尺度等时地层对比格架;王淳等<sup>[83]</sup>提取东营拗陷LY1井沙四上亚段5.5个405 kyr长偏心率周期及24个~100 kyr短偏心率周期;彭军等亦对东营拗陷樊页1井识别出6个405 kyr长偏心率周期和22个~100 kyr短偏心率周期<sup>[86]</sup>。文中针对雷家地区沙河街组四段提取出6个405 kyr长偏心率周期,即可将沙四段划分为6个四级层序,与以上学者研究成果相似,但由于雷家地区沙四段中~129 kyr短偏心率周期信号较为明显,~100 kyr短偏心率周期信号弱且不明显,使用~129 kyr短偏心率周期滤波后得到~17个短偏心率周期。将本文的研究成果与东营拗陷沙四上亚段的研究成果进行对比分析,可拓宽旋回地层学分析在渤海湾盆地的适用性。

## 5 结论

(1) 使用相关系数法估算雷15井、雷14井和雷61井最佳沉积速率,分别为10.57、11.40和13.93 cm/kyr,与渤海湾盆地古近纪沙河街组其他湖



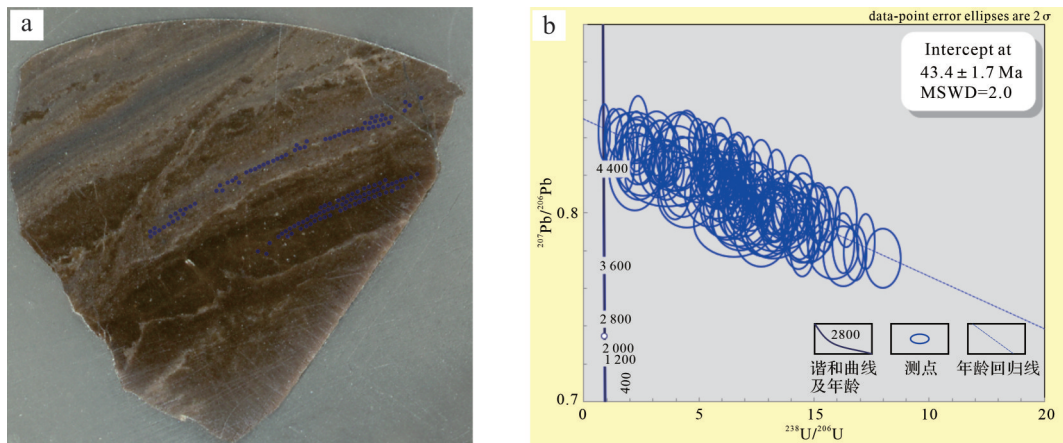


图6 雷14井2766.61 m碳酸盐岩U-Pb定年年龄

(a)激光靶及测点位置(共135个点);(b)碳酸盐U-Pb同位素年龄为43.4±1.7 Ma

Fig.6 TU-Pb dating age of carbonate rocks at 2766.61 m in well Lei 14

(a) laser target and measuring point locations (135 points in total); (b) carbonate U-Pb isotope age is 43.4±1.7 Ma

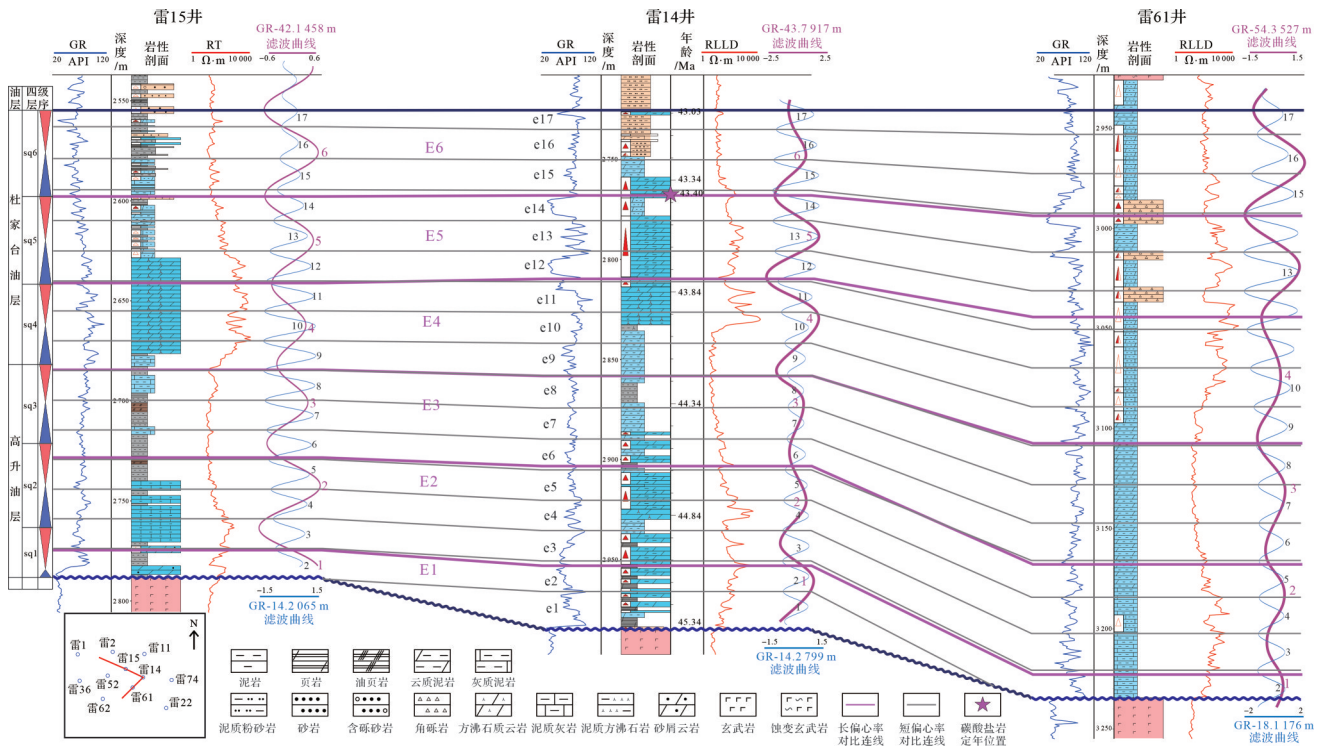


图7 偏心率尺度精细地层划分对比

Fig.7 Fine stratigraphic division and correlation at the eccentricity scale

盆相当。在最优沉积速率和ETP对比基础上, 42.15 m、43.79 m、54.35 m峰值对应405 kyr长偏心率周期, 14.21 m、14.28 m、18.12 m峰值对应约129 kyr短偏心率周期。

(2) 共识别6个405 kyr长偏心率周期和约17个129 kyr短偏心率周期。基于405 kyr滤波结果对雷15、雷14和雷61井进行天文调谐, 三口井沉积时

限约为2.30 Ma、2.34 Ma和2.30 Ma;以雷14井碳酸盐U-Pb年龄为时间锚点, 其顶、底年龄分别为43.03±1.7 Ma和45.34±1.7 Ma。

(3) 旋回地层学方法在渤海湾盆地适用性良好。将雷家地区沙四段划分为6个四级层序(长偏心率)和约17个五级层序(短偏心率), 每个四级层序平均含约3.14个五级层序, 实现了地层划分与对比的定

量化。建立的精细等时地层格架为富有机质页岩发育规律、混合细粒岩分布特征、优质储层预测及水平井部署提供了地质基础。

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# Identification of Astronomical Cycles in Fine-grained Rocks and Their Application in Fine Stratigraphic Division: A case study of the Fourth member of the Shahejie Formation in the Leijia area, Western Sag of the Liaohe Depression

LI Yang<sup>1,2</sup>, LI XiaoGuang<sup>1</sup>, ZHANG TingShan<sup>2</sup>, ZOU BingFang<sup>1</sup>, CHEN Chang<sup>1</sup>, LI JinPeng<sup>1</sup>, ZHOU XiaoLong<sup>1</sup>, WANG GaoFei<sup>1</sup>, LIU Yang<sup>1</sup>, QI XueChen<sup>1</sup>, GUO MeiLing<sup>1</sup>, GAO Yang<sup>2</sup>

1. PetroChina Liaohe Oilfield Company, Panjin, Liaoning 124010, China

2. School of Geoscience and Technology, Southwest Petroleum University, Chengdu 610500, China

**Abstract:** [Objective] Lacustrine fine-grained sedimentary rock mixed with clay, felsic, carbonate and analcite minerals, developed in the Fourth member of the Shahejie Formation of the Leijia area in the Western Sag of the Liaohe Depression in the Bohai Bay Basin, is the main carrier of oil and gas in the region. Owing to the complex composition and rapid lateral changes of mixed fine-grained rocks, the reservoirs are highly heterogeneous, which brings certain difficulties to the prediction of high-quality reservoirs. [Methods] Taking wells Lei 15, Lei 14, and Lei 61 in the Leijia area of the Western Sag as an example, and based on time series analysis method, high-precision carbonate U-Pb dating, and natural gamma ray (GR) logging data, the mixed fine-grained rocks of the Fourth member of the Shahejie Formation were analyzed using cyclostratigraphy. [Results] (1) The optimal sedimentation rates of wells Lei 15, Lei 14, and Lei 61 were estimated by Correlation Coefficient (COCO), the optimal sedimentation rates increased sequentially and were 10.57, 11.4, and 13.93 cm/kyr, respectively. (2) We performed spectrum analysis on the paleoclimate proxy indicator (GR) and compared it with the data spectrum analysis results of the standard eccentricity, slope, and precession (ETP) composite curve, identifying the astronomical cycle signals in mixed fine-grained rocks in wells Lei 15, Lei 14, and Lei 61. Then, we used the 405-kyr long eccentricity cycle for astronomical tuning. We set the age  $43.4 \pm 1.7$  Ma at 2 766.61 m in well Lei 14 as the anchor point to establish an absolute astronomical time scale. (3) 6 long eccentricity cycles of 405 kyr and ~17 short eccentricity cycles of ~129 kyr were identified in the Fourth member of the Shahejie Formation. Combining the connection between the Earth's orbital period and high-frequency sequences, a fine stratigraphic division and correlation at the eccentricity scale was established. [Conclusions] By conducting cyclostratigraphic research on the Fourth member of the Shahejie Formation in the Leijia area, its astronomical cycle signals can be effectively identified. This method quantitatively establishes a fine stratigraphic division and comparison framework with time attributes, which plays an important role in guiding further oil and gas exploration in the area and broadens the applicability of cyclostratigraphy in the Bohai Bay Basin.

**Key words:** mixed fine-grained sedimentary rock; astronomical cycle; sedimentation rate; fine stratigraphic division; Western Sag