

引用格式:梁岳立,葛家旺,赵晓明,等.鄂尔多斯盆地东缘山西组2段海陆过渡相页岩高分辨率层序划分及勘探地质意义[J].天然气地球科学,2022,33(3):408-417.

LIANG Yueli, GE Jiawang, ZHAO Xiaoming, et al. High-resolution sequence division and geological significance of exploration of marine-continental transitional facies shale in the 2<sup>nd</sup> Member of Shanxi Formation, eastern margin of Ordos Basin[J]. Natural Gas Geoscience, 2022, 33(3): 408-417.

DOI: 10.11764/j.issn.1672-1926.2021.10.021

## 鄂尔多斯盆地东缘山西组2段海陆过渡相页岩 高分辨率层序划分及勘探地质意义

梁岳立<sup>1,2</sup>, 葛家旺<sup>1,2</sup>, 赵晓明<sup>1,2</sup>, 张 喜<sup>1,2</sup>, 李树新<sup>3</sup>, 聂志宏<sup>3</sup>

(1. 西南石油大学地球科学与技术学院, 四川 成都 610500;

2. 西南石油大学天然气地质四川省重点实验室, 四川 成都 610500;

3. 中国石油煤层气有限责任公司, 北京 100028)

**摘要:**针对鄂尔多斯盆地东缘山西组海陆过渡相页岩单层厚度薄、岩性复杂且频繁互层导致地层横向对比多解性强的难题,建立了一种将高分辨率层序地层与旋回地层相结合的地层划分方法。主要通过测井曲线辅助岩心及野外露头等资料,采用最大熵频谱分析技术对测井曲线处理得到的INPEFA曲线,结合小波变换提取的时频特征,完成了山西组2段(山2段)海陆过渡相页岩高分辨率层序界面识别及多井等时对比。相比常规自然伽马曲线(GR),GR-INPEFA曲线的整体和局部趋势拐点可明显提高中期及短期旋回界面识别的准确度;不同尺度因子的小波系数曲线和时频图谱分析则能够实现中期及短期旋回界面的识别与对比。综合INPEFA曲线和小波变换技术将山2段划分为3个中期旋回(自下而上依次为MSC1、MSC2和MSC3)及12个短期旋回(自下而上依次为SSC1—SSC12),3个中期旋回与山西组内部山<sub>2</sub><sup>1</sup>—山<sub>2</sub><sup>3</sup>亚段对应较好,短期旋回与沉积相序演化特征耦合关系较好。高分辨率层序、矿物成分及储层特征的耦合研究表明MSC1中期旋回中SSC1短期旋回对应优质页岩富集层段。通过多尺度多方法融合测井技术对岩性复杂区构建层序地层格架具有一定借鉴意义。

**关键词:**INPEFA曲线;小波变换;山西组;海陆过渡相页岩;鄂尔多斯盆地

**中图分类号:**TE121.3

**文献标志码:**A

**文章编号:**1672-1926(2022)03-0408-10

### 0 引言

伴随着高速发展的全球页岩气勘探开发进程,我国相继在四川盆地、渤海湾盆地、柴达木盆地及鄂尔多斯盆地发现海陆过渡相页岩气<sup>[1-2]</sup>;页岩层系位于石炭系—二叠系,资源量占比约为25%<sup>[3]</sup>,展现出极大的勘探前景。目前海陆过渡相页岩气基础地质研究主要集中于沉积环境、沉积模式及储层特征等方面<sup>[2-4]</sup>,但针对高精度层序地层格架的研究相

对薄弱,实际上,细粒沉积因其看似均质的特征往往使得页岩段层序划分变得异常困难<sup>[5-6]</sup>。

前人<sup>[7-9]</sup>针对页岩段层序地层格架已开展过一些研究,认为TOC、V、Cr等有机与无机地球化学指标与相对海平面变化有关,地球化学指标及矿物成分特征等也可作为层序识别的依据,但该类方法划分指标相对单一并且往往受制于样品精度;SINGH<sup>[10]</sup>依据自然伽马曲线(GR)划分了Barnett组海相页岩伽马准层序GRP(Gamma Ray Parase-

收稿日期:2021-09-15;修回日期:2021-10-27;网络首发日期:2021-12-27.

基金项目:中国石油—西南石油大学创新联合体项目(编号:2020CX030104)资助.

作者简介:梁岳立(1993-),男,湖北黄冈人,硕士研究生,主要从事开发地质研究.E-mail:liangyl6855@gmail.com.

通信作者:葛家旺(1988-),男,湖北枝江人,讲师,博士,主要从事层序地层学、沉积学和开发地质学科研及教学工作.

E-mail: gjwddn@163.com.

quence),国内学者<sup>[11]</sup>亦利用此方法构建了东营凹陷陆相页岩层序格架。相对于海相页岩和陆相页岩,海陆过渡相页岩具有沉积环境及岩相高频变化、岩性复杂且频繁互层等特点,加剧了海陆过渡相页岩高精度层序界面识别难度。

近年来,鄂尔多斯盆地东缘山西组多套海陆过渡相页岩压裂测试均获得工业气流,初步实现了海陆过渡相页岩的勘探突破。山西组划分为2个长期旋回和6个中期旋回,分别对应山1段、山2段2个段和山<sub>1</sub><sup>1</sup>—山<sub>2</sub><sup>3</sup>共6个亚段<sup>[12-13]</sup>。但受限于地震资料分辨率等因素,且山西组海陆过渡相页岩具有单层薄、岩性叠置多样等特征,上述划分方案并不能满足海陆过渡相页岩的勘探开发需求。本文拟通过小波变换和INPEFA技术对海陆过渡相页岩进行高精度层序识别,即对测井曲线进行处理得到不同

趋势形态的曲线,判断沉积环境的变化并确定层序界面,实现高分辨率层序划分和对比<sup>[14-15]</sup>,为海陆过渡相页岩勘探开发提供技术支撑。

1 区域地质概况

鄂尔多斯盆地位于华北克拉通西部,东连吕梁山,西至滕里格沙漠,北起阴山,南至秦岭,整体呈南北走向<sup>[16]</sup>。根据构造特征鄂尔多斯盆地可划分为6个一级构造单元,西部为天环坳陷及西缘逆冲带,中部为伊陕斜坡,东部为晋西挠褶带,南北则依次为渭北隆起和伊盟隆起。研究区大宁—吉县地区则位于东部晋西挠褶带上,构造特征比较明显,为“一隆一凹两斜坡”<sup>[17]</sup>,即东部、西部发育斜坡带[图1(a)],中部发育蒲县凹陷带和桃园背斜带,地层总体呈南北走向。

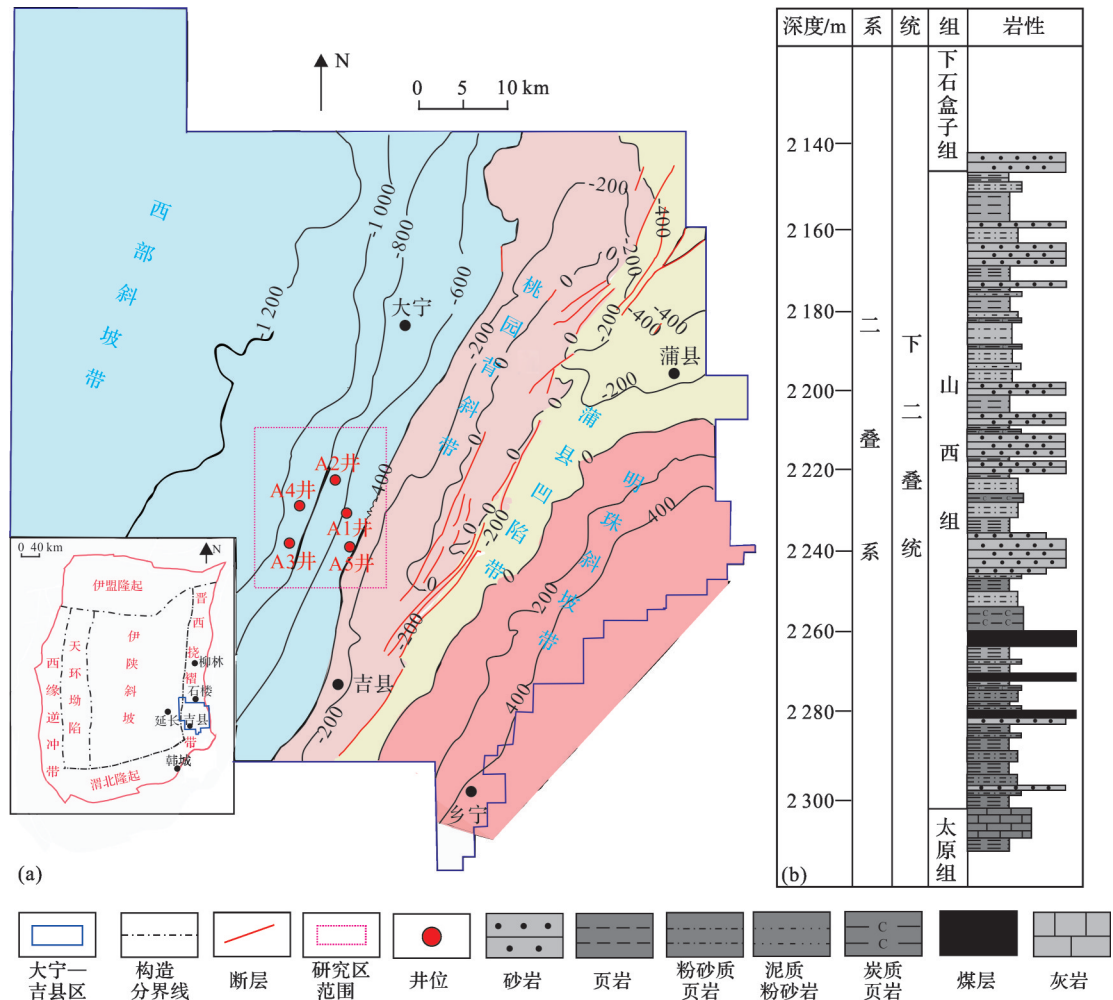


图1 鄂尔多斯盆地东缘构造特征及井位分布图(据文献[17],有修改)  
Fig.1 The structural characteristics and well location distribution in the eastern margin of Ordos Basin (modified after Ref.[17])

研究区内上古生界自下而上发育石炭统本溪组、下二叠统太原组、山西组及中二叠统石盒子组[图1(b)]。鄂尔多斯盆地东缘山西组整体为一套陆相三角洲、近海三角洲与陆表海过渡相沉积的页岩层系<sup>[18-19]</sup>,太原组沉积末期—山西组沉积早期,海水从鄂尔多斯盆地东西两侧逐渐减退,盆地由海相沉积逐渐变为陆相沉积,研究区大宁—吉县地区为南北物源过渡带,属于三角洲前缘—滨海沉积环境<sup>[2]</sup>,为典型的海陆过渡相沉积环境。其中山西组分为山1段和山2段。大量勘探资料证实,山1段和山2段均发育页岩沉积,其中山2段页岩厚度大,夹层少,最大厚度可达50 m,并根据相关井的岩心观察,山2段识别出下部浅海海湾相页岩、中部潮控三角洲平原相黑色页岩及上部三角洲平原相黑色页岩共3种类型页岩组合<sup>[2]</sup>,且山2段页岩TOC值相对较高,约为1%~3%,整体上勘探潜力较大。

## 2 高分辨率层序地层识别与划分

### 2.1 基于岩性及测井层序界面识别与划分

CROSS<sup>[20]</sup>基准面旋回理论认为地层的基准面旋回、可容空间等在一定地质时期内会留下“痕迹”,高分辨率层序地层学便根据这些“痕迹”分析不同级次的基准面旋回进行层序界面的识别与划

分<sup>[12]</sup>。长期基准面旋回界面为不整合面或与之对应的整合面,在测井、岩心方面存在较明显的识别标志,其通常在测井曲线上反映为GR曲线突变,同时也反映了岩性的突变<sup>[21]</sup>。当层序界面存在不整合面或较大沉积间断面时,测井曲线响应特征较为明显,反映为数值上存在较大变化;当层序界面位于下切谷内的下切河道时,在测井曲线上表现为箱型或钟形曲线<sup>[22]</sup>。山西组顶底界面均为盆地边缘构造抬升形成的不整合面<sup>[12]</sup>,其顶部与下石盒子组下伏骆驼脖子砂岩分界,砂岩厚度约为10 m[图2(a)],在测井曲线上表现为箱型曲线特征;山西组底界与下伏东大窑灰岩分界,测井曲线上响应特征为低GR、低AC值。虽然前人<sup>[23-24]</sup>认为山西组以北盆沟砂岩为底界,但在实际划分过程中均划在太原组顶部东大窑灰岩[图2(b)],这是由于当山西组底部北盆沟砂岩不发育时,太原组顶部灰岩之上发育的薄层泥岩与山西组底部泥岩不易区分,因此将山西组底界划在太原组顶部灰岩<sup>[12]</sup>。陈洪德等<sup>[25]</sup>依据经典地层学理论将鄂尔多斯盆地东缘山西组自下而上划分为山2段和山1段,对应2个长期旋回,层序界面发育典型的河道下切面<sup>[26]</sup>,界面底部发育铁磨沟砂岩<sup>[27-28]</sup>,以箱形测井曲线为特征,岩性上表现为一套砂岩叠置于厚层泥岩之上(图3)。

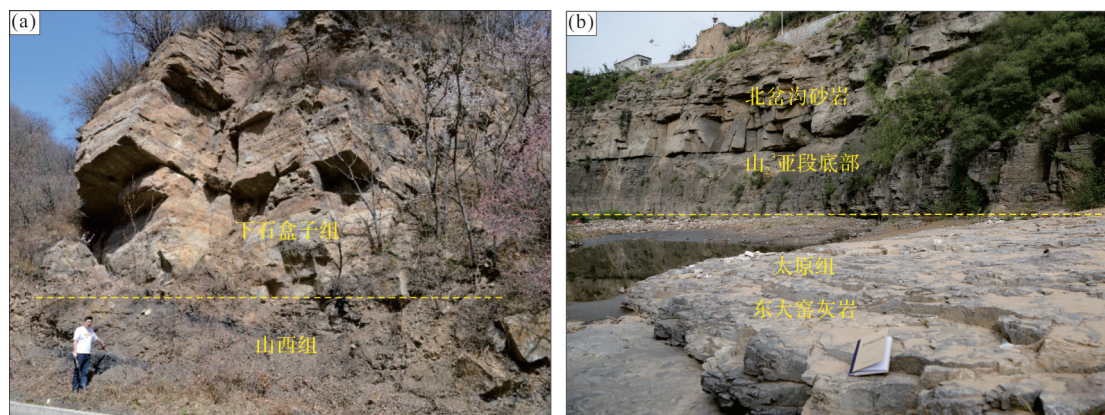


图2 鄂尔多斯盆地东缘山西组顶底界面野外剖面特征

Fig.2 Field profile characteristics of the top-bottom interface of Shanxi Formation in the eastern margin of Ordos Basin

(a)乡宁台头剖面,下石盒子组与山西组分界面;(b)柳林成家庄剖面,山西组与太原组分界面

山西组山2段自下而上可分为3个亚段,分别为山<sub>2</sub><sup>3</sup>亚段、山<sub>2</sub><sup>2</sup>亚段及山<sub>2</sub><sup>1</sup>亚段,对应MSC1、MSC2及MSC3共3个中期旋回。此类界面一般为结构转换面<sup>[12]</sup>,也为中期旋回界面,一般是2个下粗上细的正向结构的转换。山2段存在2个这样的结构转换面,其中MSC3和MSC2旋回岩性分界以

MSC3旋回底部发育灰色细砂岩[图4(c)]与MSC2旋回顶部发育深灰色泥岩分界,GR值由低值(63 API)突变为高值(137 API),GR曲线呈箱型;MSC2与MSC1旋回岩性分界以MSC2旋回底部发育灰黑色炭质泥岩与MSC1旋回顶部发育黑色煤层[图4(d)]分界,GR值由高值(153 API)突变为低值



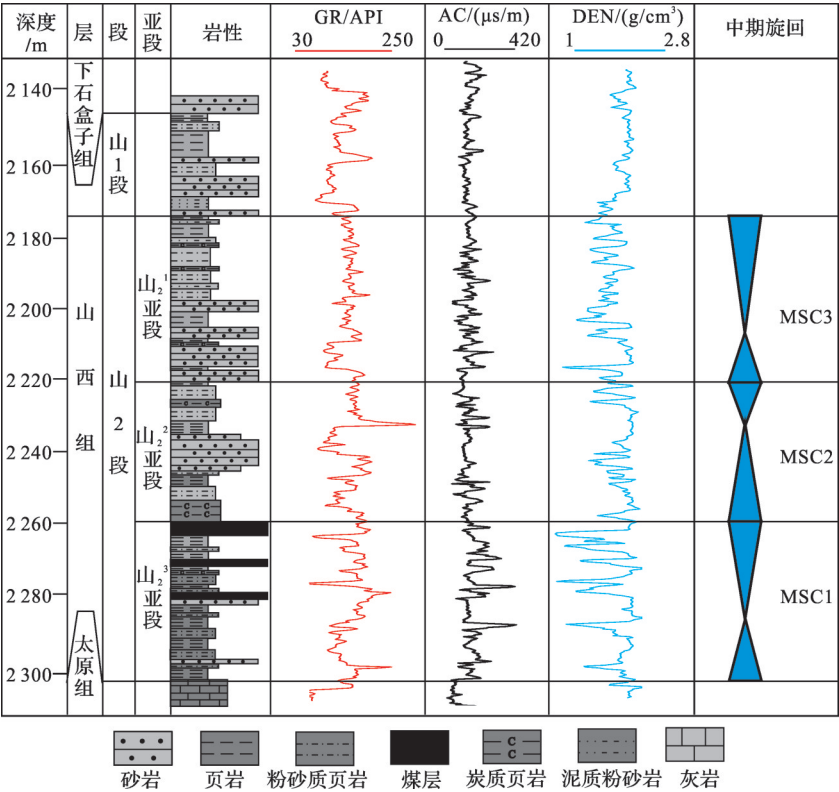


图3 鄂尔多斯盆地东缘A1井岩性界面及测井界面特征

Fig.3 Characteristics of lithology interface and logging interface of Well A1 in the eastern margin of Ordos Basin

(35 API), 山<sub>2</sub>亚段砂泥互层频繁, GR曲线多呈箱型或钟型; MSC1旋回顶部界面为5<sup>#</sup>煤层, 在研究区广泛且稳定分布, 底界发育黑色页岩[图4(e)]与太原组顶部发育东大窑灰岩[图4(f)]分界。

2.2 基于INPEFA曲线层序识别与划分

INPEFA (Integrated Prediction Error Filter

Analysis)曲线的拐点反映了不同级别的层序界面, 基于层序地层学原理可通过此曲线快速识别不同级别的层序界面<sup>[29]</sup>。首先, 通过最大熵频谱分析(MESA-GR)处理测井曲线得到估计值<sup>[30]</sup>[图5(b)], 随后通过测井实际值减去估计值便可得到预测误差滤波分析曲线<sup>[31]</sup>(Prediction Error Filter Analysis, PEFA)

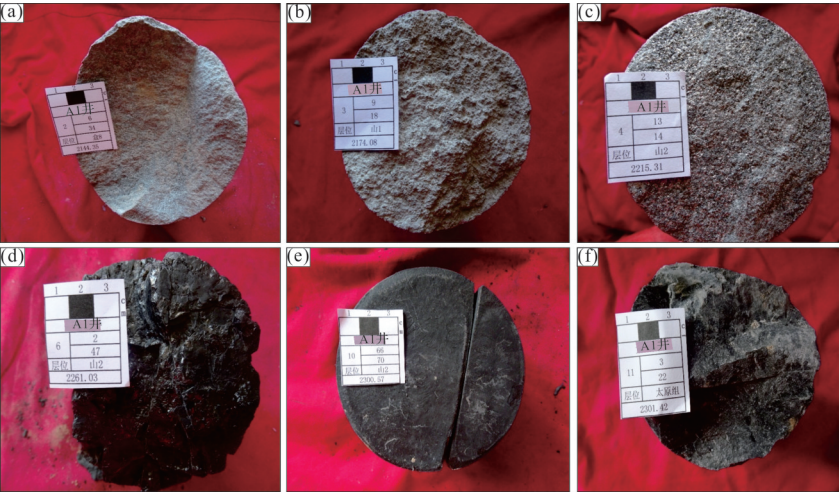


图4 鄂尔多斯盆地东缘A1井山西组层序界面岩心特征

Fig.4 Rock core characteristics of sequence interface of Shanxi Formation of Well A1 in the eastern margin of Ordos Basin

(a)下石盒子底部灰色细砂岩; (b)山1段底部灰色中砂岩; (c)山<sub>2</sub>亚段底部灰色细砂岩;  
(d)山<sub>2</sub>亚段顶部5<sup>#</sup>煤层; (e)山<sub>2</sub>亚段底部黑色页岩; (f)太原组顶部灰黑色灰岩

[图 5(c)],在 PEFA 曲线的基础上对其进行积分得到 INPEFA 曲线[图 5(d)],使得趋势不太明显的 PEFA 曲线变成 INPEFA 曲线,从而使趋势变得更加明显,由于一个趋势反映的层段与由或多或少几个转折点反映的反趋势层段是分开的,因此 INPEFA 值向上增加为正趋势,向上减小为负趋势,其中正趋势代表一个时间间断,在该时间间断上,曲线值比预测值含有更多的页岩,这可能是海侵阶段或洪泛阶段;负趋势代表一个时间间断,在该时间间断上,曲线值比预测值含有更多的砂岩,这可能是海退阶段或浅滩阶段。

应用 GR-INPEFA 曲线对 A1 井山 2 段的层序界面的级次进行识别与划分,从而实现基准面约束下的地层划分与对比<sup>[32]</sup>。以山 2 段顶底界面的深度为起止处理窗口长度,对 A1 井 GR 曲线进行积分变换后得到 INPEFA 曲线的拐点和趋势变化特征,识别出山 2 段内部的沉积旋回界面,自下而上依次划分为 3 个中期旋回(MSC1—MSC3)及 12 个短期旋回(SSC1—SSC12)[图 6(f),图 6(g)]。其中, MSC3 旋回底界以灰色细砂岩与 MSC2 旋回顶界深灰色泥岩区别,GR-INPEFA 曲线上的界面对应拐

点处,此界面为中期旋回界面。此时为中期基准面上升阶段,水体逐渐加深,以粒度较大的细砂岩为主,其顶部出现泥岩层和细砂岩,此时基准面上升结束,由细砂岩过渡为厚层泥岩及煤层等。基准面上升与下降构成一个对称旋回<sup>[33]</sup>,类似的, MSC2 旋回与 MSC1 旋回同样对应拐点处[图 6(d)]。因此,根据 GR-INPEFA 曲线趋势的呈现,可以看出在 2 219 m 和 2 261 m 这 2 个中期旋回界面的拐点趋势较为明显,级次较大,进一步验证了利用 INPEFA 曲线特征对层序地层进行研究的可行性与准确性<sup>[34]</sup>。

在进行短期旋回界面识别时,结合 INPEFA 曲线局部趋势拐点变化和岩性变化特征,将 MSC1、MSC2 及 MSC3 旋回进一步分别划分为 4 个短期旋回,即山 2 段识别出 12 个短期旋回 SSC1—SSC12[图 6(f)]。而 INPEFA 拐点预示着沉积环境的变化,因此结合沉积相序列的演化特征,以 MSC1 旋回为例,其中 SSC1 旋回为无障壁型浅海陆棚沉积体系,向上 SSC2 旋回逐渐演化为浅海—障壁型滨岸沉积体系的过渡带,SSC3 旋回和 SSC4 旋回则为障壁型滨岸沉积体系,进一步佐证了 INPEFA 曲线

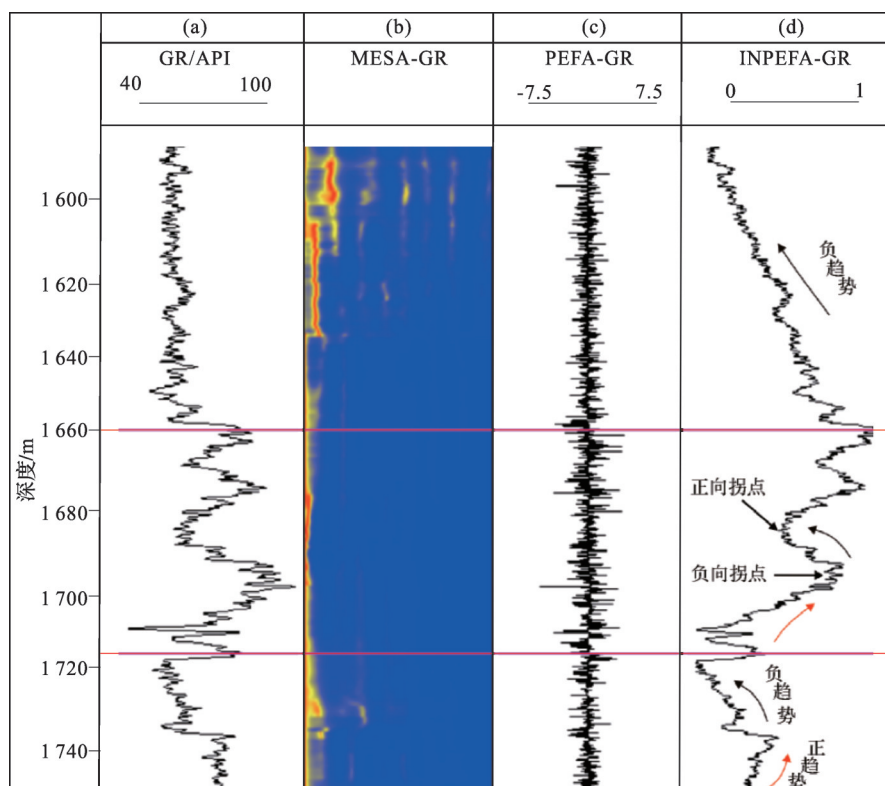


图 5 INPEFA 曲线合成图(据文献[31],有修改)

Fig.5 Composite graph of INPEFA curve(modified after Ref.[31])

(a)GR 原始曲线;(b)最大熵频谱分析;(c) PEFA 曲线;(d)INPEFA 曲线

拐点为层序界面。

### 2.3 基于小波变换层序识别与划分

小波分析可以通过自动伸缩、平移把信号分解成不同的尺度成分,进而将信号分解为不同周期的旋回<sup>[35]</sup>。多尺度分析的特点是:小波分析具有多分辨率性<sup>[36-37]</sup>,即不同的尺度因子代表了不同的时间周期。尺度因子的变化大小不同,信号中的不同周期信息得以显现,因此能够观察出测井信号中不同级别的沉积旋回信息,那么选取不同的尺度因子便能进行不同级别的层序划分。小波系数曲线峰谷交界处可作为地层突变界面,反映了沉积环境的改变,可作为层序界面,而小波变换的多尺度分析思想与地层的多级旋回性相似,通过多尺度小波系数曲线的周期性震荡特征,可分析地层的旋回性。

根据小波系数曲线周期性振荡趋势特征,在不同的尺度因子下划分中期旋回界面及短期旋回界面<sup>[38]</sup>。以山2段的顶底界深度作为处理窗口的起止长度,对A1井GR曲线进行不同尺度因子下的连续小波变换[图6(e)],以尺度因子 $a=64$ 及 $a=32$ 处分别划分出3个中期旋回及12个短期旋回,其中振荡较剧烈段对应砂岩发育的地方,振荡平缓段为泥页岩相对发育地方。在尺度因子 $a=64$ 的小波变换下,A1井山<sub>2</sub>亚段小波系数曲线顶底振荡性较强,

中间较弱,时频特征表现出能量团从下至上逐渐减小再增大的特征[图6(h)],代表一个大尺度沉积旋回。在尺度因子 $a=64$ 的小波变换下存在3个明显的周期旋回,并与INPEFA曲线具有很好的耦合性。在小尺度因子 $a=32$ 的小波变换下,其周期性变化与短期旋回具有良好的对应性,且小波系数曲线变化比INPEFA曲线的局部趋势变化更为明显。在尺度因子 $a=32$ 小波系数曲线下MSC1—MSC3旋回都存在4个明显的周期性振荡[图6(f)],振荡拐点处多为砂岩相变泥岩相或煤层等地层突变界面。

以MSC3旋回为例,根据小波变换的周期震荡性划分出SSC9—SSC12共4个短期旋回,其中SSC9旋回多为砂岩,其顶部由页岩与突变为SSC10旋回底部砂岩,代表水体环境由浅至深再变浅、沉积物粒度由粗到细再变粗、水动力由强逐渐减弱再增强的沉积环境,SSC10旋回顶部与SSC11旋回底部为砂岩突变为粉砂质页岩等,代表水体环境由深至浅再变深的沉积环境。据此GR曲线被划分为12个各自周期独立的沉积旋回,并且与INPEFA曲线局部趋势拐点具有较好的耦合性,证实了利用小波变换进行层序地层研究的准确性。此外,在研究区A2井、A3井、A4井及A5井中也识别出3个中期旋回与12个短期旋回,与A1井基本保持一

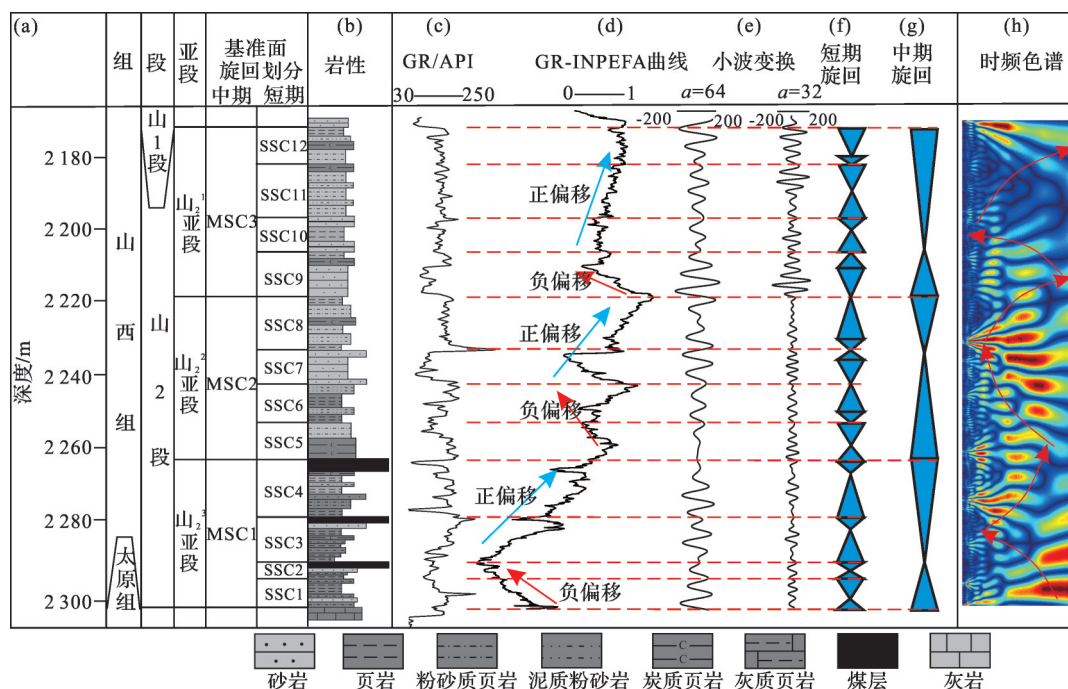


图6 鄂尔多斯盆地东缘A1井山西组山2段层序地层划分综合图

Fig.6 The comprehensive map of sequence stratigraphic division of the Shan2 Member of the Shanxi Formation in Well A1 in the eastern margin of Ordos Basin

(a)地层层序划分;(b)岩性;(c)GR曲线;(d)GR-INPEFA曲线;(e)不同尺度因子的小波变换;(f)短期旋回;(g)中期旋回;(h)时频色谱图





约为 $1.60 \text{ m}^3/\text{t}$ )及孔隙度(平均约为 $4.73\%$ )等特征,勘探潜力巨大。

#### 4 结论

(1) INPEFA 技术和小波变换均可识别常规测井信息无法识别的周期性变化特征,其不同幅度变化特征对应不同层序的级次性,且2种方法在层序划分中可相互验证,使各层序界面更直观准确。

(2)通过 INPEFA 技术和小波变换提取研究区山2段 GR 曲线,识别出3个中期旋回和12个短期旋回。小波变换曲线在尺度因子 $a=64$ 下与 INPEFA 曲线整体趋势拐点耦合性较好,并对应中期旋回界面,在尺度因子 $a=32$ 下与 INPEFA 曲线局部趋势拐点耦合性较好,并对应短期旋回界面。

(3)通过高分辨率层序界面的构建为识别海陆过渡相页岩优势富集段及储层段提供了技术支撑。结合 TOC、矿物组分及孔隙度变化等特征,识别出 MSC1 旋回为优势页岩富集段,其中 SSC1 旋回为优质页岩储层段,勘探潜力巨大。

#### 参考文献(References)

- [1] 郭旭升,胡东风,刘若冰,等.四川盆地二叠系海陆过渡相页岩气地质条件及勘探潜力[J].天然气工业,2018,38(10):17-24.  
GUO X S, HU D F, LIU R B, et al. Geological conditions and exploration potential of Permian transitional shale gas in the Sichuan Basin[J]. Natural Gas Industry, 2018, 38(10): 17-24.
- [2] 匡立春,董大忠,何文渊,等.鄂尔多斯盆地东缘海陆过渡相页岩气地质特征及勘探开发前景[J].石油勘探与开发,2020,47(3):435-446.  
KUANG L C, DONG D Z, HE W Y, et al. Geological characteristics and development potential of transitional shale gas in the east margin of the Ordos Basin, NW China[J]. Petroleum Exploration and Development, 2020, 47(3): 435-446.
- [3] 董大忠,王玉满,李新景,等.中国页岩气勘探开发新突破及发展前景思考[J].天然气工业,2016,36(1):19-32.  
DONG D Z, WANG Y M, LI X J, et al. Breakthrough and prospect of shale gas exploration and development in China[J]. Natural Gas Industry, 2016, 36(1): 19-32.
- [4] 董大忠,邱振,张磊夫,等.海陆过渡相页岩气层系沉积研究进展与页岩气新发现[J].沉积学报,2021,39(1):29-45.  
DONG D Z, QIU Z, ZHANG L F, et al. Progress on sedimentology of transitional facies shales and new discoveries of shale gas[J]. Acta Sedimentologica Sinica, 2021, 39(1): 29-45.
- [5] 姜在兴.层序地层学研究进展:国际层序地层学研讨会综述[J].地学前缘,2012,19(1):1-9.  
JIANG Z X. Advances in sequence stratigraphy: A summary from international workshop on sequence stratigraphy[J]. Earth Science Frontiers, 2012, 19(1): 1-9.
- [6] 姜在兴,梁超,吴靖,等.含油气细粒沉积岩研究的几个问题[J].石油学报,2013,34(6):1031-1039.  
JIANG Z X, LIANG C, WU J, et al. Several issues in sedimentological studies on hydrocarbon-bearing fine-grained sedimentary rocks[J]. Acta Petrolei Sinica, 2013, 34(6): 1031-1039.
- [7] CREANEY S, PASSEY Q R. Recurring patterns of total organic carbon and source rock quality within a sequence stratigraphic framework[J]. AAPG Bulletin, 1993, 77: 386-401.
- [8] SMITH M G, BUSTIN R M. Late Devonian and Early Mississippian Bakken and Exshaw black shale source rocks, western Canada sedimentary basin: A sequence stratigraphic interpretation[J]. AAPG Bulletin, 2000, 84(7): 940-960.
- [9] 张喜,张廷山,赵晓明,等.天文轨道周期及火山活动对中上扬子区晚奥陶世—早志留世有机碳聚集的影响[J].石油勘探与开发,2021,48(4):732-744.  
ZHANG X, ZHANG T S, ZHAO X M, et al. Astronomical and volcanic organic-carbon during Later Ordovician-Early Silurian in the upper Yangtze area, South China[J]. Petroleum Exploration and Development, 2021, 48(4): 732-744.
- [10] SINGH P. Lithofacies and Sequence Stratigraphy Framework of the Barnett Shale, Northeast Texas[D]. Oklahoma City: University of Oklahoma, 2008.
- [11] 杜学斌,刘辉,刘惠民,等.细粒沉积物层序地层划分方法初探:以东营凹陷樊1井沙三下一沙四上亚段泥页岩为例[J].地质科技情报,2016,35(4):1-11.  
DU X B, LIU H, LIU H M, et al. Methods of sequence stratigraphy in the fine-grained sediments: A case from the upper fourth sub-member and the lower third sub-member of the Shahejie Formation in Well Fanye 1 of Dongying Depression[J]. Geological Science and Technology Information, 2016, 35(4): 1-11.
- [12] 刘朋波.鄂尔多斯盆地延长探区山西组沉积相研究与地震储层识别[D].西安:西北大学,2010.  
LIU P B. Study of Sedimentary Phases and Seismic Reservoir Identification in the Shanxi Formation in the Yanchang Exploration Area of Ordos Basin[D]. Xi'an: Northwestern University, 2010.
- [13] 彭海燕,刘家铎,陈洪德,等.鄂尔多斯盆地东部山西组高分辨率层序地层与天然气聚集研究[J].石油物探,2008,47(5):519-525.  
PENG H Y, LIU J D, CHEN H D, et al. High-resolution sequence stratigraphy and gas accumulation of Shanxi Formation in east Ordos Basin[J]. Geophysical Prospecting for Petroleum, 2008, 47(5): 519-525.
- [14] 路顺行,张红贞,孟恩,等.运用 INPEFA 技术开展层序地层研究[J].石油地球物理勘探,2007,42(6):703-708.  
LU S X, ZHANG H Z, MENG E, et al. Application of INPEFA technique to carry out sequence-stratigraphy study[J]. Oil Geophysical Prospecting, 2007, 42(6): 703-708.
- [15] 袁野,王黎,谢锐杰. INPEFA 技术在层序地层划分中的应用——以苏北盆地溱潼凹陷南华区块阜三段为例[J].石油实验



- 地质, 2018, 40(6): 871-876.
- YUAN Y, WANG L, XIE R J. Application of INPEFA technology to sequence stratigraphic of the third member of Funing Formation, Nanhua Block, Qintong Sag, north Jiangsu Basin[J]. *Petroleum Geology and Experiment*, 2018, 40(6): 871-876.
- [16] 高云飞. 大宁—吉县区块东、西部山2段砂岩储层特征差异与控制因素[D]. 北京: 中国地质大学(北京), 2020.
- GAO Y F. Characteristics and Controlling Factors Differences of Sandstone Reservoir of Shan 2 in the East and West of the Daning-Jixian Block[D]. Beijing: China University of Geosciences(Beijing), 2020.
- [17] 赵龙梅, 文桂华, 李星涛, 等. 鄂尔多斯盆地大宁—吉县区块山西组2~3亚段致密砂岩气储层“甜点区”评价[J]. *天然气工业*, 2018, 38(S1): 5-10.
- ZHAO L M, WEN G H, LI X T, et al. Evaluation of the “sweet spot” of dense sandstone gas reservoir in sub-member 2-3 of Shanxi Formation in Daning-Jixian Block, Ordos Basin[J]. *Natural Gas Industry*, 2018, 38(S1): 5-10.
- [18] LI Y, TANG D Z, XU H, et al. Geological and hydrological controls on water co-produced with coalbed methane in Liulin, eastern Ordos Basin, China[J]. *AAPG Bulletin*, 2015, 99(2): 207-229.
- [19] DU W, JIANG Z X, ZHANG Y, et al. Sequence stratigraphy and sedimentary facies in the lower member of the Permian Shanxi Formation, northeastern Ordos Basin, China[J]. *Journal of Earth Science*, 2013, 24: 75-88.
- [20] CROSS T A. Controls on Coal Distribution in Transgressive-Regressive Cycles, Upper Cretaceous, Western Interior, U.S. A[M]. Tulsa: SEPM Special Publication, 1988: 371-380.
- [21] 于兴河. 碎屑岩系油气储层沉积学[M]. 北京: 石油工业出版社, 2002: 55-59.
- YU X H. Clastic Petroleum Reservoirs Sedimentology [M]. Beijing: Petroleum Industry Press, 2002: 55-59.
- [22] 于兴河, 王香增, 王念喜, 等. 鄂尔多斯盆地东南部上古生界层序地层格架及含气砂体沉积演化特征[J]. *古地理学报*, 2017, 19(6): 935-954.
- YU X H, WANG X Z, WANG N X, et al. The stratigraphic framework of the Upper Paleozoic sequence and the sedimentary evolution of gas-bearing sands in the southeastern Ordos Basin[J]. *Journal of Paleogeography*, 2017, 19(6): 935-954.
- [23] 廖志伟. 鄂尔多斯盆地富县地区山西组一下石盒子组沉积相及储层特征研究[D]. 成都: 成都理工大学, 2012.
- LIAO Z W. The Research on Sedimentary Facies and Reservoir Characteristic of Shanxi Formation-Lower Shihezi Formation, Fuxian Area, Ordos Basin[D]. Chengdu: Chengdu University of Tecnology, 2012.
- [24] 董良. 大宁—吉县太原组一盒八段主要砂体沉积特征分析[D]. 青岛: 山东科技大学, 2018.
- DONG L. Study of Sedimentary Characteristics of Main Sand Bodies in Taiyuan Formation to Eight Member of Shahezi Formation in Daning-Jixian Area[D]. Qingdao: Shandong University of Science and Technology, 2018.
- [25] 陈洪德, 李洁, 张成弓, 等. 鄂尔多斯盆地山西组沉积环境讨论及其地质启示[J]. *岩石学报*, 2011, 27(8): 2213-2229.
- CHEN H D, LI J, ZHANG C G, et al. Discussion of sedimentary environment and its geological enlightenment of Shanxi Formation in Ordos Basin[J]. *Acta Petrologica Sinica*, 2011, 27(8): 2213-2229.
- [26] 刘畅. 鄂尔多斯盆地临兴地区上古生界层序地层格架及沉积模式[J]. *非常规油气*, 2019, 6(1): 23-33.
- LIU C. Sequence stratigraphic framework and sedimentary model of Upper Paleozoic in Linxing area, Ordos Basin[J]. *Unconventional Oil & Gas*, 2019, 6(1): 23-33.
- [27] 杨勇, 雷卞军, 冯永玖, 等. 鄂尔多斯盆地子洲及邻区山西组二段高分辨率层序地层和煤沉积模式[J]. *石油与天然气地质*, 2013, 34(1): 58-67.
- YANG Y, LEI B J, FENG Y J, et al. High-resolution sequence stratigraphic and coal sedimentary modes of member 2 of Shanxi Formation in Zizhou and its adjacent areas[J]. *Oil & Gas Geology*, 2013, 34(1): 58-67.
- [28] 苏飞飞. 临兴地区山西组沉积体系研究[D]. 青岛: 中国石油大学(华东), 2018.
- SU F F. Investigation on the Sedimentary System of Shanxi Formation in Linxing Area[D]. Qingdao: China University of Petroleum(East China), 2018.
- [29] NIO S D, BROUWER J, SMITH D, et al. Spectral trend attribute analysis: Applications in the stratigraphic analysis of wireline logs[J]. *First Break*, 2005, 23(4): 71-75.
- [30] 刘洛夫, 徐敬领, 高鹏, 等. 综合预测误差滤波分析方法在地层划分及等时对比中的应用[J]. *石油与天然气地质*, 2013, 34(4): 564-572.
- LIU L F, XU J L, GAO P, et al. Application of comprehensive prediction error filter analysis to stratigraphic division and isochronous correlation[J]. *Oil & Gas Geology*, 2013, 34(4): 564-572.
- [31] 王梦琪, 谢俊, 王金凯, 等. 基于INPEFA技术的高分辨率层序地层研究——以埕北油田东营组二段为例[J]. *中国科技论文*, 2016, 11(9): 982-987, 994.
- WANG M Q, XIE J, WANG J K, et al. Research of high-resolution sequence stratigraphic using INPEFA: A case study in the second member of Dongying Formation of Chengbei Oil-field[J]. *China Sciencepaper*, 2016, 11(9): 982-987, 994.
- [32] 郑荣才, 彭军, 吴朝容. 陆相盆地基准面旋回的级次划分和研究意义[J]. *沉积学报*, 2001, 19(2): 249-255.
- ZHENG R C, PENG J, WU C R. Grade division of base-level cycles of terrigenous basin and its implications[J]. *Acta Sedimentologica Sinica*, 2001, 19(2): 249-255.
- [33] 邓宏文. 美国层序地层研究中的新学派——高分辨率层序地层学[J]. *石油与天然气地质*, 1995, 16(2): 89-97.
- DENG H W. A new school of thought in sequence stratigraphic studies in U.S.A.: High-resolution sequence stratigraphic[J]. *Oil & Gas Geology*, 1995, 16(2): 89-97.
- [34] 李建棋. INPEFA技术在川西源内层序和优质储层识别中的应用[D]. 武汉: 长江大学, 2019.
- LI J Q. Application of INPEFA Technology in Recognition of Source Sequence and Quality Reservoirs in Western Sichuan

- [D].Wuhan: Yangtze University, 2019.
- [35] 陈钢花,余杰,张孝珍.基于小波时频分析的测井层序地层划分方法[J].新疆石油地质,2007,28(3):355-358.  
CHEN G H, YU J, ZHANG X Z. Logging sequence stratigraphic division based on wavelet time-frequency analysis [J]. Xinjiang Petroleum Geology, 2007, 28(3): 355-358.
- [36] 周建.小波变换在兴城地区营四段层序地层划分研究中的应用[D].大庆:东北石油大学,2014.  
ZHOU J. Application of Wavelet Transform in the Studies of Sequence Stratigraphic of  $K_{1Y_4}$  of Xingcheng Area [D]. Daqing: Northeast Petroleum University, 2014.
- [37] 任金锋,廖远涛,孙鸣,等.基于小波变换的高精度层序地层定量划分研究及其应用[J].地球物理学进展,2013,28(5): 2651-2658.  
REN J F, LIAO Y T, SUN M, et al. A method for quantitative division of sequence stratigraphic with high-resolution based on wavelet transform and its application [J]. Progress in Geophysics, 2013, 28(5): 2651-2658.
- [38] 周亚伟,杜玉洪,谢俊,等.INPEFA技术与小波变换在层序地层划分中的应用与对比——以饶阳凹陷大王庄地区东营组三段为例[J].中国科技论文,2021,16(5):494-501.  
ZHOU Y W, DU Y H, XIE J, et al. Application and comparison of INPEFA technique and wavelet transform in sequence stratigraphic division: A case study in the third member of Dongying Formation in Dawangzhuang area, Raoyang Sag [J]. China Sciencepaper, 2021, 16(5): 494-501.

### High-resolution sequence division and geological significance of exploration of marine-continental transitional facies shale in the 2<sup>nd</sup> Member of Shanxi Formation, eastern margin of Ordos Basin

LIANG Yueli<sup>1</sup>, GE Jiawang<sup>1,2</sup>, ZHAO Xiaoming<sup>1,2</sup>, ZHANG Xi<sup>1,2</sup>, LI Shuxin<sup>3</sup>, NIE Zhihong<sup>3</sup>

(1. School of Geoscience and Technology, Southwest Petroleum University, Chengdu 610500, China;

2. Southwest Petroleum University, Natural Gas Geology Key Laboratory of Sichuan Province, Chengdu 610500, China;

3. PetroChina Coalbed Methane Company Limited, Beijing 100028, China)

**Abstract:** The shale of marine-continental translational facies is characterized by thin bedded layers, various lithology and multiple interstratifications. Aiming at the high-resolution sequences correlations of these shales, we establish a stratigraphic delineation method combining high-resolution stratigraphic sequence and cyclic stratigraphy. Using the data from logging curve-assisted rock cores and field section, the INPEFA curve obtained from the processing of logging curve and the time-frequency features extracted by wavelet transform, the high-resolution stratigraphic interface identification and multi-well isochronous comparison of the transitional shale in the 2<sup>nd</sup> Member of the Shanxi Formation were obtained. Compared with the conventional natural GR, the medium and short-term cycles points of the GR-INPEFA curve can significantly improve the identification accuracy of sequences interfaces. Wavelet coefficient curves and time-frequency mapping analysis with different scale factors can achieve the identification and comparison of medium-term and short-term cycle interfaces. Integrated INPEFA and wavelet transform technology, the 2<sup>nd</sup> Member of the Shanxi Formation is divided into three mid-term cycles (from bottom to top: MSC1, MSC2 and MSC3) and 12 short-term cycles (from bottom to top: SSC1-SSC12). The three medium-term cycles correspond to Sha<sub>2</sub><sup>1</sup>, Shan<sub>2</sub><sup>2</sup> and Shan<sub>2</sub><sup>3</sup> sub-members respectively. The short-term cycle are well coupled with the evolution of higher-order sequences and strata development. Finally, the coupling relationship of high-resolution sequence, mineral composition associated with reservoir characteristics is analyzed. It showed that SSC1 in lowest part of MSC1 is prone of excellent shale reservoirs. The medium-term and short-term cycles held significant implications for further stratigraphic correlations and exploration activities. The technic integration of multi-scale based logging cycles shows advantages for stratigraphic framework construction in a lithologically-complex shale interval.

**Key words:** INPEFA curve; Wavelet transform; Shanxi Formation; Marine-continental transitional facies shale; Ordos Basin

**Foundation item:** The CNPC-Southwest Petroleum University Innovation Consortium Project (Grant No. 2020CX030104).