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# 成因层序地层学的回顾与展望<sup>①</sup>

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**摘要** 回顾了以成因地层层序为基础的成因层序地层学的形成、发展与研究现状,对成因地层层序及其内部构成、高分辨率成因地层层序、成因地层层序的旋回性、非海相成因地层层序、成因地层层序与沉积物堆积速率等主要观点作了简略评述,并结合我国陆相沉积特征对成因层序地层学未来研究前景作了初步展望

**关键词** 成因层序地层学 回顾 展望

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## 1 引言

在1987年,以美国 Exxon 公司 Vail 研究组为代表建立的以沉积层序为基础的层序地层学的出现带来了地学界的一场革命。在1989年,以美国得克萨斯大学奥斯汀分校 W. E. Galloway 教授在《AAPG Bulletin》上发表的两篇关于成因地层层序的著名论文为标志<sup>(1,2)</sup>,代表着不同于 Exxon 公司的沉积层序分析的另一流派——成因层序地层学的诞生。本文的主要目的就是介绍与评述成因层序地层学的诞生、发展及其主要内容,为成因层序地层学在我国的普及推广与深化研究作出努力。

## 2 成因地层层序及其内部构成

在1974年,美国沉积学家 Frazier 提出了沉积幕的重要概念<sup>(3)</sup>。他认为每一个沉积幕由一个沉积复合体记录来确定,沉积复合体依次由若干个相序列(准层序)组成。每一沉积复合体是在气候和构造背景相对稳定的区间内由盆地边缘的所有点源所形成的若干准层序的复合体。沉积幕记录了两次最大洪泛事件之间的一个完整的相对海平面升降周期。

Galloway 在沉积幕的基础上提出了成因地层层序的模式<sup>(1)</sup>。他定义成因地层层序为沉积幕的沉积产物,由三个重要部分组成:即远超前积部分、上超海进部分、与反映最大洪泛作用的顶底界面。

远超前积部分包括(1)常为砂质的河流、三角洲平原以及反映沿岸平原加积作用的海湾泻湖相;(2)海滨带的前积沉积物(亦为砂质):朝陆地方向,它覆于先期沉积序列的泛滥沉积台地之上;朝海方向,则覆于同时沉积的远超大陆坡相之上;(3)加积的下陆坡与前积的上陆坡的混合相。

上超海进部分包括(1)滨线后退期间和之后沉积的经过改造的海滨带相和陆棚相;(2)受重力作用在坡脚重新沉积的上陆坡和陆架边缘沉积的裙状体。继大陆边缘的活跃的建造作用之后的海进期,是上陆坡和大陆边缘的广泛块体滑塌和再沉

积的良好时期,结果是一种独特的再沉积物质的裙状体上超于斜坡的坡脚之上。

成因地层层序以最大海泛面为界,它们是海进期间陆棚和陆坡的碎屑沉积物供给处于相对饥饿状态与随之而来的最大海泛期的记录。最大海泛面分开了下伏层序的上超海进部分与上覆层序的远超前积部分。在一个成因地层层序内部,用陆上间断侵蚀面来分开远超前积部分和上超海进部分。

Galloway 还描述了成因地层层序在墨西哥湾西北部新生代盆地中的应用,框架性地把该区的新生代地层划分为9个成因地层层序<sup>(2)</sup>。他认为,越过成因地层层序边界到下一个成因地层层序时,盆外河流体系及其相关的沉积中心大多发生明显的迁移。在每一个成因地层层序内,古地理条件保持相对稳定,但其远超前积部分与上超海进部分的沉积风格和形式常发生改变,因此,对这两部分分别编图是有益的。如下 Wilcox 层序的远超前积部分,河流能量的影响相对较强,三角洲体系多为河控鸟足状三角洲或波浪轻微改造的舌状三角洲;而层序的上超海进部分,盆地能量的影响相对较强,三角洲常为浪控的弓形或尖头状<sup>(4)</sup>。

## 3 高分辨率成因地层层序

在1995年,Xue 和 Galloway 在《AAPG Bulletin》第二期上发表了题为《得克萨斯滨岸平原古新世 Wilcox 群中段地层的高分辨率沉积框架》的论文<sup>(5)</sup>。作者以700余口井测井资料为基础,识别出顶、底为最大洪泛面所限定的 Wilcox 群中段地层是由两个平均持续时间为0.75~1.1 Ma 的两个高分辨率成因地层层序组成的,而这两个高分辨率层序是该区适用的作图单元。作者在文章中还讨论了成因地层层序内部的不整合面问题,认为如果在相对海平面变化足够大而迅速,导致明显的沉积相不连续情况下,选取这一成因地层层序作为一个作图单元是不合适的,至少应分为两个作图单元;另一种情况就是相对海平面变化影响小,沉积相不连续现象不明显,很难根据测井资料与地震资料识别出来,在这种情况下,以成因地层层序作

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为一个作图单元是可行的。

作者还讨论了利用测井资料进行高分辨率地层对比问题,认为最大洪泛面与海进面具较强的侧向连续性,因而易于识别,但选作沉积层序边界的不整合面与可与其对比的整合面由于侧向连续性差而难以识别,特别是陆棚地区更是如此,因此,利用测井资料进行高分辨率地层对比时成因地层层序分析显然要比沉积层序分析可靠。

在年代地层框架的详细对比基础上,作者分别以两个高分辨率成因地层层序为作图单元,详细作了地层等厚图、砂岩百分比图、测井相图,然后对沉积体系类型与分布进行了综合解释,第一次详细作出了该区 Wilcox 群中段两个层序的沉积体系图,为研究盆地的充填史提供了一个窗口。

另一个高频成因地层层序的研究实例是美国得克萨斯海岸平原始新世 Yegua 组的研究<sup>[6]</sup>。在 Galloway<sup>[3]</sup>识别出来的 Yegua 三级成因地层层序基础上,Meckel 和 Galloway 把 Yegua 层序进一步划为 6 个平均持续区为 0.8 Ma 的四级成因地层层序。形成这些四级层序的控制因素是不同的,有的是受可容空间控制,也有的受沉积物源供给控制。研究结果表明,穿过四级洪泛面,不会发生象穿过三级最大洪泛面所引起的沉积体系的古地理重大变化,但会引起沉积过程和沉积系统重要参数的变化。

## 4 成因地层层序的旋回性

在 1997 年,《AAPG Bulletin》第六期刊登了题为《得克萨斯州墨西哥湾盆地老第三纪 Wilcox 地层的沉积旋回与演化》的论文<sup>[7]</sup>。作者根据测井资料的详细地层对比识别出了 Wilcox 地层的两个沉积旋回,而这两个沉积旋回是物源区两个构造脉动的响应。

这两个沉积旋回都具有以下特点:①它们的沉积产物的顶、底界面均为最大洪泛面;②每个沉积旋回都有着沉积中心迁移的记录;③每一沉积旋回都伴随着陆棚边缘前积的过程;④沉积体系演化反映了从水退到水进沉积的序列;⑤持续的时间区间为几个百万年(分别为 3.6 与 7.5 Ma);⑥每一沉积旋回的产物可以进一步细分为两个以上的准层序组或高频成因地层层序,也就是次一级沉积旋回的产物。

沉积旋回性研究已经有很长的历史。过去的研究主要讨论一定的岩性或沉积相类型的重复现象,认为每一沉积旋回是由早期的水进相与晚期的水退相组成。这样,其沉积产物的顶、底界面即为不整合面或与之可对比的整合面。由于在本区的测井资料上很难识别区域性展布的不整合面,因此,该文选用了成因地层层序的模式来解释旋回性。除了讨论每一旋回的沉积体系演化外,还强调了每一旋回伴随的沉积中心的迁移与陆棚边缘的前积过程,为识别该级别的沉积旋回性提供了易于操作的标准。

## 5 非海相成因地层层序

### 5.1 湖相地层的成因地层层序分析

在 1993 年,《AAPG Bulletin》第十期发表了题为《松辽盆地上白垩统 QYN 成因层序地层格架、沉积风格与油气分布》的论

文<sup>[8]</sup>,首次将成因地层层序的理论扩展到湖相盆地。作者认为,根据海相盆地的研究发展起来的沉积幕与成因地层层序的概念同样适用于湖相盆地,并以松辽盆地上白垩统青山口组、姚家组和嫩江组(QYN)为例,进行了成因地层层序的分析。在这篇文章中,第一次明确地提出在存在明显的陆上不整合面和沉积相向盆地中心的相迁移的情况下,成因地层层序可以细分为前积体系域、低水位前积复合体和水进体系域。这里提出的三类体系域,不具有全球性海平面变化的内涵。在 Exxon 的沉积层序模式中,每一沉积层序都由三个体系域组成,即水进体系域、高水位体系域、低水位体系域或陆棚边缘体系域。沉积层序模式中的体系域主要是根据地层的几何特征和物理关系来定义,因此,Swift 等人认为 Exxon 的体系域是几何体系域,而不是沉积体系域<sup>[9]</sup>,因为该模式主要强调几何学特征而不是沉积相关系。Exxon 的模式又把这种几何体系域与全球海平面升降联系起来<sup>[10]</sup>,但在湖相盆地,显然这种几何体系域与全球海平面升降没有直接的联系,而构造活动与沉积物供应为主要的控制因素。为了简化和扩大几何体系域概念的应用,我们应用三个术语,即前积型体系域(Progradational Systems Tract)、低水位前积复合体(Lowstand Progradational Complex)和退积型体系域(Retrogradational Systems Tract)。文中“低水位”的含义,强调相对水平面的升降,既可能是全球海平面变化引起的,也可能是构造抬升等其它因素引起的。

### 5.2 含煤地层的成因地层层序分析

在 1994 年,Hamilton 和 Tadros 在《AAPG Bulletin》第二期上发表了题为《用煤层作非海相盆地中的成因地层层序边界》的论文<sup>[11]</sup>,提出在缺乏海泛面的情况下,需要不同的层序识别标准。区域展布的煤层具有成因地层层序边界的基本属性。它们是碎屑沉积物堆积间隔期间的生物化学沉积物,因此,它们记录了沉积物的中断。从概念上讲,煤层相当于 Frazier (1974)的沉积间断面,它记录了沉积事件或沉积幕的终结。局部或亚区域展布的煤是小规模间断面的例子,是限定 Frazier 相序或准层序的界面;相比之下,区域展布的煤层规模较大,相当于限定一个沉积幕的沉积复合体或成因地层层序的边界。

另一方面,虽然区域性展布的煤层可以作为成因地层层序的边界,但它与 Galloway(1989a)选用最大洪泛面作为成因地层层序的边界至少存在着两点差异。

第一,区域性展布的煤层不一定代表最大洪泛面,而可能是海进面或水进体系域内物源中断事件的产物<sup>[12]</sup>。特别是存在海相或湖相地层的情况下,选用煤层作为成因地层层序的边界应该慎重,因为海、湖相地层往往更可能是最大洪泛面的产物。

第二,在冲积-河流相为主的环境中,煤层是沉积物源中断的产物,但并不代表它在相对水平面变化中的位置<sup>[13]</sup>。因此,也就很难在这种成因地层层序内进行体系域的分析。

## 6 成因地层层序与沉积物堆积速率

Galloway 在第十一届 GCSSEPM 研究年会上介绍了墨西哥湾西北部老第三纪沉积幕、成因地层层序与沉积物堆积速率的研究成果<sup>[14]</sup>。他通过该地区四个沉积次凹的代表剖面计算

沉积物堆积速率,以此推测沉积物供应,从而发现成因地层层序是幕式的高沉积物供应的记录。成因地层层序的边界是低沉积物供应与随后的盆地边缘的海泛沉积的产物。在层序内,沉积速率随着相对于陆架边缘的位置,不同的沉积体系与不同的次凹而变。

Galloway 和 Willams 在 Galloway 的 1990 年工作基础上,详细总结了河流、三角洲、海滨带和陆棚沉积体系的沉积物堆积速率随着相对于陆架边缘位置远近的变化特点<sup>[15]</sup>,认为该区的河流体系的沉积物堆积速率在 30~150 m/Ma 之间,而三角洲体系变化较大,陆棚三角洲约为 30~120 m/Ma 陆棚边缘三角洲为 300~750 m/Ma 最大可达 1 400 m/Ma。海滨带体系及其伴生的泥质内陆棚沉积物的堆积速率变化也较大,从小于 100 m/Ma 直到大于 500 m/Ma 存在着向古陆棚边缘降低的趋势。陆棚体系主要以泥质为主,进积陆棚体系的沉积物堆积速率为 600 m/Ma 而海侵陆棚体系的堆积速率则较低,为 30~200 m/Ma。

在 1997 年,Liu 和 Galloway 通过对北海盆地 16 个成因地层层序的层序颗粒体积(即总层序体积减去胶结物体积和孔隙体积)的定量测定,计算出北海盆地在时间和空间上总沉积物补给的速率<sup>[16]</sup>。他们的研究发现,沉积物供给的重要变化阶段均与物源区的构造脉动相关联,而构造脉动则与北大西洋盆地的演化有关、与伴随着阿尔卑斯连续造山运动的板内应力变化有关或者与斯堪的纳维亚新生代后期的造陆上升有关,从而推断物源区地形起伏的变化史、所形成的地形坡度及盆地内沉积量的相关变化是北海盆地新生代层序发育的主要控制因素。

## 7 展望:冲积—河流相地层与多物源的挑战

综上所述,成因层序地层学分析在海相、湖相、含煤地层均有成功的应用实例,这些实例都具有一个共同特点:即存在反映最大海、湖泛或缺乏沉积物源供应的“饥饿”沉积界面。只有识别出这些“饥饿”沉积界面与不整合面,才能把盆地充填的沉积体分离成若干个成因地层单元。但是,在以多个沉积物源变化为主要控制因素的湖盆或冲积—河流相地层中,应用盆地范围内分布的“饥饿”沉积界面来划分成因地层单元具有很大的难度。

在多物源向湖盆供给沉积物时,大致有两种情况。一种是多个物源沉积物供给的变化大致同步,可能存在统一的“饥饿”沉积界面或与最大洪泛面相关的沉积层段。这种条件下可以进行成因地层层序分析。但大多数情况下,常见多个沉积物源的变化不是同期的而是此起彼伏,就不存在一个盆地内统一的“饥饿”沉积界面,也就失去了应用“饥饿”沉积界面划分成因地层单元的基础。这不仅是对 Galloway 成因地层层序学说的挑战,而且也是对 Exxon 沉积层序模式的挑战。

在冲积—河流相地层中,由于沉积物物源供应充足,砂岩发育,缺乏广泛分布的湖相泥岩、煤层、古土壤层,识别“饥饿”沉积界面存在很大困难。虽然河道透置型式能反映垂向“基准面”的变化,但往往仅代表局部地区,难以在区域上进行对比追

踪。

由此可见,成因层序地层的下一步研究目标应朝着两个方向努力;一是解决多物源不同步变化形成的盆地充填的年代地层框架建立问题,另一是解决冲积—河流相粗碎屑岩沉积物中的“饥饿”沉积面识别问题。可以预见,随着这两个问题的解决,必将把成因层序地层学研究推向一个新的阶段。

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## Looking back and ahead on Genetic Sequence Stratigraphy

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### Abstract

Genetic sequence stratigraphy on the basis of genetic stratigraphic sequence proposed by Galloway (1989) is a paradigm of Exxon's depositional sequence model. A genetic stratigraphic sequence is the sedimentary product of a depositional episode. The sequence consists of three important components: offlap components, onlap or transgressive components, and top and base bounding surfaces reflecting maximum marine flooding.

The model of genetic stratigraphic sequence is firstly applied to the northwest Gulf of Mexico Cenozoic basin, U. S. A. Galloway (1989) recognized nine genetic stratigraphic sequences for the Cenozoic strata of the basin. The extrabasinal fluvial systems and associated depocenters shift significantly from a genetic stratigraphic sequence to the following sequence. Within each genetic stratigraphic sequence, the paleogeography remains comparatively stable, but depositional styles and patterns between offlap components and onlap or transgressive components change as relative sea level changes.

Galloway (1990) studied the relationship among Paleogene depositional episodes, genetic stratigraphic sequences, and sediment accumulation rates NW Gulf of Mexico basin. He found that the genetic stratigraphic sequences record episodes of high supply, punctuated by intervals of low supply and consequent transgressive flooding of the basin margin. Within sequences, depositional rates vary with position relative to the contemporaneous shelf margin, with depositional system, and between subbasins. Liu and Galloway (1997) studied Tertiary sediment supply to the North Sea basin. They concluded that all episodes of Tertiary sediment supply correlate to source-terrain tectonic pulses. The history of changing source-area relief and resulting topographic grades and related changes in sediment yield into the basin was a principal control on North Sea Cenozoic sequence development.

The precepts of genetic sequence stratigraphy were developed from the study of marine basins, but they can be applied to nonmarine basins. The Qingshankou, Yaojia, and Nenjiang (QYN) formations in the Songliao basin can be used to illustrate the application of sequence analysis in a lacustrine setting (Xue and Galloway, 1993). They proposed that use of subaerial unconformity and transgressive surfaces allows further subdivision of the QYN sequence into a progradational systems tract, lowstand prograding complex, and retrogradational systems tract. Hamilton and Tadros (1994) chose the regional extensive coals as genetic stratigraphic sequence boundaries in coal-bearing strata in the Gunnedah basin, Australia. Regionally extensive coals can exhibit the essential attributes of sequence boundaries. Coals of regional extent require interruption in sediment supply at a basin-wide scale and can bound the sequences.

High-resolution sequences are also studied in genetic sequence stratigraphy. One example is the sequence analysis of the middle Wilcox subgroup in the Texas coastal plain (Xue and Galloway, 1995). Two high-resolution genetic stratigraphic sequences of the middle Wilcox were delineated within the interval time span of 1.5-2.2 m.y. based on detailed correlation of approximately 700 well logs. They discussed the issue of high-resolution stratigraphic correlation using well-log data and concluded that maximum flooding surfaces are easily recognizable

because of good lateral continuity whereas unconformities are difficult to identify due to poor lateral continuity, especially in shelf environment. The other example is case study of the Eocene Yegua Formation in Texas Gulf Coast (Meckel and Galloway, 1996). The Eocene Yegua Formation is made up of six fourth - order sequences, which have average durations of 0.8 million years or less. The formation of these sequences is controlled by accommodation or by sediment supply. The significant change seen in fourth - order sequences is the shift in overall regime ratio and reorganization of depositional processes.

Cyclicity of genetic stratigraphic sequences is another research topic. Two depositional cycles have been identified in the Wilcox strata of the Tertiary Gulf of Mexico. Two depositional cycles bounded by maximum flooding events were characterized by depocenter shifting, shelf - margin progradation, and depositional system evolution, and lasted several million years. Each of the two depositional cycles generally corresponds to a pulse of tectonism in sediment source area. Each depositional cycle is divided into four intervals separated by regional flooding events. The product of each interval is represented by a parasequence set or high - frequency genetic stratigraphic sequence.

As stated above, genetic sequence stratigraphic analysis has been applied to marine, lacustrine and coal - bearing strata. These examples display a common feature that "starved" sedimentary surfaces are present. The "starved" surfaces, recorded events of maximum marine or lacustrine flooding, or interruption in sediment supply at a basin - wide scale, can be chosen to separate sediment fills of basins into several genetic stratigraphic units. However, it is difficult to find such basin - wide "starved" surfaces in basins with multiple, variable sediment supplies and alluvial - fluvial basin.

In a basin with several sediment supply areas, there are no unified "starved" surfaces if sediment supply controls sequence development and several sediment supplies change differently. Thus, there is no basis to use "starved" surfaces to separate sediment fills into genetic stratigraphic units.

In alluvial - fluvial basins, there is lack of widely distributed lacustrine mudstones, coal beds, paleosol beds because of very high sediment supply. As a result, it is hard work to recognize "starved" surfaces. Although fluvial channel stacking patterns respond vertical changes of "base level", it is difficult to trace and correlate regionally.

Future study of genetic sequence stratigraphy combined with nonmarine sedimentary characteristics of China is towards two directions: one is to construct chronostratigraphic framework in basins with no synchronous changes of several sediment supplies, the other is to identify basin - wide "starved" surfaces or substitute surfaces in alluvial - fluvial basins.

**Key words** genetic sequence stratigraphy    looking back    looking ahead