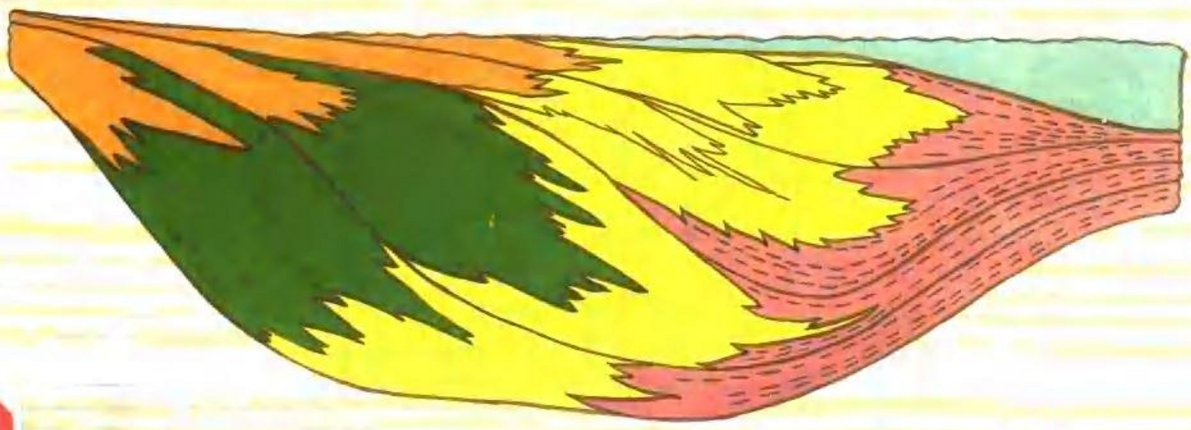
陆相断陷湖盆

层序地层学

纪友亮　张世奇等　编著



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内 容 提 要

本书是我国第一部系统介绍陆相断陷湖盆层序地层学理论模式的专著，全书共分七章。它主要讨论了湖平面变化的研究方法、层序发育的控制因素、层序边界的形成机理和层序边界的识别标志。总结出了适合我国陆相断陷湖盆特点的层序类型、体系域组成和密集段特征，探讨了河流(陆上)环境、深水环境中准层序的划分方法。最后研究了济阳坳陷东部地区下第三系层序地层学特征。

本书可供从事层序地层学、沉积学以及石油地质勘探事业的科研、技术人员及大专院校的师生参阅。

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序　言

地震剖面是地壳对地震波的响应，地下的地层界面只是造成这种响应的多种因素之一。地质学家和地球物理学家们在认识地震反射层时也注意到了地震波的微小变化，认为这些变化反映地层学、沉积学的现象。早在50年代——光点地震技术时代——我们已经有了这样的认识，在某些地区曾经做出了有效的解释。数字地震技术开始以来，地震信息的准确性与精细程度不断地提高，信息量日益丰富，使我们有条件利用地震的各种属性资料较为全面地认识地下的地层和沉积现象。这样，地震地层学就应运而生了。美国Exxon公司P.R.Vail等在1977年推出了地震地层学这一新的理论，随即迅速在全球推广应用。当然，中国也以很快的速度应用到全国石油勘探领域中。

大约在1977～1987年十年间。Vail等人不断修改完善地震地层学，特别是在研究了美国德克萨斯州西北部的野外露头及相应的地震剖面与测井曲线后发现：(1)从一个不整合面到下一个不整合面之间的地层分布具有一定规律；(2)这种规律在全球范围内具有普遍意义；(3)在地震资料与测井曲线上均有反映这一地层分布规律的明显特征。据此，Vail等人认为有必要建立层序地层学的概念来完善、提高原有的地震地层学。层序地层学是从岩石成因上考虑的，故此，R.G.Walker把它归属到成因地层学。Vail认为层序地层学是地质学中的一场革命，它正在向传统的沉积学、地层学挑战(与Vail谈话记录，1991)。

最近几年国内也已普遍应用了层序地层学的概念在许多含油气盆地做了解释。石油大学纪友亮教授对华北盆地中的济阳坳陷东部地区下第三系地层做了层序地层学的研究。他从理论上对陆相湖盆的演化特点进行了分析，提出一套适合我国陆相断陷盆地沉积特点的层序地层模式和研究思路，撰写了这本理论结合实际并有所创新的著作。书中提出了不少新的观点，修改和完善了层序地层学的某些内容。值得中国的层序地层研究者思考与推敲。主要有：

1.陆相湖盆可分为敞流湖盆、闭流湖盆两种类型，两种湖盆具有不同的相对湖平面变化特征，分别控制了不同的地层沉积格式。

2.陆相湖盆地层层序的形成及特征受构造运动、气候变化、沉积物供应和湖平面变化的控制。其中前两者为主导因素，后两者为影响因素，依据前两个因素可

将层序类型划分为构造层序和气候层序两种。构造层序又可分为简单断坳层序、同生断坳层序和多期断坳层序三类。

3. 对陆相湖盆中不同类型层序所包含的体系域做了归纳，同生断坳层序由低水位体系域、湖泊扩张体系域、湖泊收缩体系域和非湖泊体系域组成(低水位体系域与非湖泊体系域可以不出现)；简单断坳层序只发育巨厚的湖泊收缩体系域(进积式准层序组)，多期断坳层序由多期进积式准层序组成；气候层序由低水位体系域、湖泊扩张体系域、高水位体系域与湖泊收缩体系域组成。

4. 密集段(缓慢沉积段)可分布在一个层序的中部、底部，有时一个在层序内可多次出现。

5. 在准层序研究方面，突出了河流和深湖环境中的准层序划分。

纵观当前国内外的层序地层学研究，从结合油气勘探的实际出发。尚需进一步细致地划分层序，由现在的层序→准层序组→准层序三级层序发展为四级、五级甚至七级层序，以适应油藏表征的要求；也需要进一步综合地震、测井、岩性、古生物、微量元素等多方面的信息。

中国的含油气盆地有多种类型，亟需分别归纳各自的层序地层学模式及研究思路。纪友亮教授的这本书给我们提出了一套针对东部断陷湖盆的研究思路，当然还需要进一步提高完善，其中某些论点也可能仍需进一步商榷。同时也应及时总结西部海相盆地研究成果，以尽快地形成适合中国含油气盆地特点的层序地层学理论及方法。

袁秉衡

1995 年 10 月 26 日

Abstract

Through the studies of sequence stratigraphy of early Tertiary in the east part of Jiyang depression (mainly in Dongying sag), the characteristics of sequence evolution in continental basin of fault depression were analyzed theoretically, and a series of sequence stratigraphy patterns and study methods that are suitable to the continential fault depression were summed up. The following are several main contents:

1. Studies of lake level changes

According to hydrogeologic characters, lacustrine basins can be divided into open and closed basin with different characters of relative lake level changes. The relative lake level was defined and its controlling factors were studied in this book. The changes of relative lake level control the changes of the sublake accommdation space which influences the sedimentary patterns of lacustrine basin.

The changes of relative lake level can be determined in two methods: one is by geologic data in drilled holes and the other is by seismic sections. When seismic data are used, the lake level changes is determined by the characters of uplap, toplap and truncation. When geologic data are used, two steps are required. The first is to obtain ancient water depth by the distribution characters of sediments, sedimentary structures, palaeobiogeographic sets and ecology, authigenous minerals and minor elements, biological differentiation. The second step is to obtain original thickness of sediments by using stratigraphic decompaction adjustment. Thus, curve of lake level changes can be obtained by adding up the ancient water depth and the original thickness.

The changes of the lake level are mainly controlled by tectonic up-down warping and marine invasion in open basin. While it is controlled by climate changes and input of sediment in closed basin.

2. Studies of controlling factors of sequence development

The formation and the characters of the continental fault depression are controlled by tectonic movements, climate changes, sediment supplies and lake level changes. The former two are the main controlling factors, and the later two are the secondary controlling factors. Sequence is divided into tectonic sequence and climatic sequence according to the controlling factors.

In early Tertiary, Jiyang depression was a fault depression basin. The tectonic movements are mainly episodic movements of fault. According to the age of strata that was cutted by fault, they are divided into basement faults, secondary basement faults and cap rock faults. And according to the stage of the fault activation they are divided into the first Jiyang

episodic, the second Jiyang episodic and the first Dongying episodic. A megasequence was formed in each episodic movement and is named as early fault depression megasequence, intense fault depression megasequence, stable fault depression megasequence. The active patterns of the basin's boundary fault are different too. The manifestations of fault activation are mainly an instant intense rift, synsedimentary rift and multi-time rift, which control the development of simple, synsedimentary and multi-time fault depression sequence separately. These three sequenses are all tectonic sequences, and there are corresponding response characteristics on seismic sections.

The changes of ancient climate appear periodically too. In closed basin, the periodic changes of the climate influence the periodic changes of the basin's drainage rate and the relative lake level, and further influence the development of sequence. The sequence controlled by the changes of climate is named as climatic sequence, which is often developed in condition of drought climate and enough basin accommodation space. Studies and analyses of the R-Q-mode factor for the pore-pollen and the index of the fault movement in Jiyang depression of early Tertiary strata make it clear that when the second member of Shahejie Formation was deposited the condition was satisfied.

In most time, tectonic movement and climate changes control the sequence simultaneously. Open lacustrine basin and closed lacustrine basin often transform each other at different periods of basin's development. Moreover, sediment supplies and lake level changes also influence the range, thickness, evoluation stage of sequence development and the formaton of the sequence boundary.

3. Studies of sequence boundary

Sequence characters mainly include boundary characters and interior reflection structure characters of sequence. Boundary characters are principal marks to identify sequcence types. Sequence boundary of continental fault depression basin is formed because sedimentary surface is higher than depositional base level (lake level) or base level which results in degradation of sediments and non-deposition.

The mechanisms of formation of sequence boundary are the cease of the movement of boundary fault, upwarp movement of fault block, uplift of whole lacustrine basin and the fall of lake level.

Sequence boundary has obvious marks on seismic sections, log curves, outcrop sections and lithological characters, lithofacies, palaeontological combination, minor elements changes in drilling sections. On seismic sections, corresponding with sequence boundary there are uplap, erosion truncation, toplap and corresponding conformable reflection. Nearby sequence boundary there are sudden changes of species and amounts of palaeobiology. Near the boundary, the geochemistry characters, such as the content of brown hematite and the ratio of Fe^{2+}/Mn^{2+}, have clearly crest value. At the respects of sedimentology, the sudden facies change, the appearance of palaeosoil, and microinformation (diagenetic information) connected with unconformity or sedimentary break all indicate the

exist of sequence boundary . The mutation of arrow patterns of the dip log, the mutation of the average thoriam, uranium and potassium on the natural gamma-ray spectrometry log, and the mutation of the natural potential log, natural gamma-ray log, apparent resistivity log, etc, are all connected with the exist of sequence boundary.

During the actural studying process of sequence stratigraphy, the indentification of sequence boundary depends on the overall analyses of the different informations.

4. Sequence types and their compositions of systems tracts.

Because of the difference of the classification standards, the sequence types are divided differently. We selected the way of classification of formation mechanism and divided sequcence into two types —— tectonic sequence and climatic sequence.

Tectonic sequence is a series of originaly related strata controlled by tectonic movement in its whole movement period. Its top and bottom boundaries are erosion surface casused by tectonic uplift or non-depositional surface caused by ceasement of subsidence of the basin basement. Tectonic sequence of continental faul-tdepression lacustrine basin is the sequence controlled by basin boundary fault. According to the discrepance of fault movement styles, tectonic sequence was divided into synsedimentary fault depression sequence, simple fault depression sequence and multi-time fault depression sequence.

Synsedimentary fault depression sequence is the most general and representative sequence type in continental lacustrine basin. A complete synsedimentary fault depression sequence includes lacustrine lowstand system tracts (LLST), lacustrine extension system tracts (LEST), lacustrine contraction system tracts (LCST) and non-lacustrine system tracts (NLST). LLST is formed in early time of the sequence development during which the rate of increasing accommodation space is roughly equal to the rate of deposition and water depth is shallow. In the later stage of the sequence development, tectonic subsidence is gentle and the rate of sediment supplies is higher chronically than the rate of new space added. The lacustrine is about to vanish, but deposition is still carried on slowly and NLST is formed. LLST ad NLST don't develop sometimes. When the rate of subsidence (V_{sub})is higher than the rate of sediment supplies (V_{sup}), the lacustrine area is extended and water depth is deepened and LEST is formed. LEST is mainly composed of retrogrational parasequence sets. When V_{sub} is lower than V_{sup}, companying with contraction of lacustrine and water-depth' changing from deep to shallow, LCST is formed. LCST is composed of aggradational and progradational parasequence sets. LEST and LCST are the main components of synsedimentary fault depression sequence. There are no LLST and LEST in simple fault depression sequence. There is only a large-thickness LCST which is composed of a progradational parasequence sets. Multi-time fault depression sequence only includes a large-thickness LCST too, which is composed of several progradational parasequence sets.

Climatic sequence refers to a series of strata developed in the process during which lake level changed from low to high and then to low because of climate periodic changes. Climatic sequence developed in closed lacustrine basin that is similar to sea basin in hydrodynamic

conditions and can be treated as minor sea basin. So the characters climatic sequence's systems tract are similar to the characters of marine sequence's too. They include LLST, LEST, Lacustrine Highstand system tracts (LHST) and LCST.

5. Studies of lacustrine condensed sections

Lacustrine condensed sections refer to sections of low depositional rate associating with the maximum non-compensable surface resulted from the wide extentent of water. The condensed sections featured by the appearance of thin and continuous strata seriously modified by burrows. The main types of rock are deep-gray, deep-brown mud rock, oil shale and carbonate rock such as marl, dolomite, etc, including abundent benthonic, planktonic micropaleobiology fossils and organic matter. Although condensed sections are always very thin with low depositional rate, the sedimentation is continuous.

Studies of condensed sections of different depressions in Dongying Sag make it clear that condensed sections includes four types of internal textures: Ⅰ-type, Ⅱ-type, Ⅲ-type, Ⅳ-type; They are all main places to find the stratigraphic-lithologic oil-gas reserviors and stuctural-lithologic oil-gas reserviors.

Condensed sections may appears at the middle or bottom of the sequence. Sometimes there are many condensed sections in a sequence appearing both at the middle and the bottom of the sequence. The concrete position depends on the type of the sequence. At the initiantive of the development of simple fault depression sequence, the area of the lacustrine and the water depth is at its maximum, the sediment compensates unsufficiently at the basin centre, fine grain sediments deposit slowly in most area, and thus the condensed sections were formed and were located at the bottom. There is a good correlatation between the condensed sections and the activation time of basin boundary fault in multi — time fault depression sequence. There are often several condensed sections in one sequence ditributed at the middle and bottom of the sequence. Only its scope is a little more simple than the scope of simple fault depression sequence. The condensed sections of synsedimentary fault depression sequence and climatic sequence are located at the middle of the sequences. The former is located between lacustrine extension system tracts and lacustrine constraction system tracts, and the latter is located at the middle of the sequence.

Condensed sections are clearly displayed on lithology, electric behavior and geochemistry marks. On seismic sections, condensed sections always correspond with high reflective event with the characters of low frequency, high continuum, widely distribution, etc; And on the boundary, there's often downlap reflective textures. Lithology has the characters of fining granularity, deep color, developing bedding structure responded quiet water condition, and there's piecemeal distributed pynite ball responded close, half-close deep water environment. On the surface of condensed sections mud rock, develops ichnolites such as protopaleodictyon, horizental fodichnia and preserves abundent biology fossils such as calareous nannonfossils, foram with the characters of low differentiation, little shell, high abundance, and euryhalinous Ostracode, etc. At the respect of geochemistry, condensed

sections have the characters of high content of organic matter and good type of kerogen, and microelement, isotope responding deep water environment are relatively abundent. Beyond these, condensed sections have the characters of low sedimentation rate.

With the characters of thin, distributing widly, having obvious features and high content of organic matter, condensed sections have important significance in stratigraphic correlation, oil and gas resource evaluation and sequence interpretation.

6. Studies of Parasequence

A parasequence is a relatively comformable succession of generatically related beds or bed sets bounded by marine (or lacustrine) flooding surfaces or their correlative surface. Three different mechanisms can generate boundaries of parasequence. One is the relatively rapid increase in water depth caused by compaction of prodelta mudstones in a delta lobe. A second mechanism for the formation of a parasequence boundary is a rapid relative rise in lake level caused by subsidence along tectonically active faults. The third is a rise of lake level caused by climate changes.

A parasequence is easy to identify in the lake shore plain, deltaic, shore-lake, shallow-lake, or estuarine shallow-water-environments and there are two kinds of parasequence: upward-coarsening and upward-fining. The former is usually found in the sand lake-shore and delta environments. The later is formed in the muddy swapy-shore-lake environment.

The identifications of parasequense in fluvial and deepwater environments always are the different problems in sequence stratigraphy studies. In this study, we searched for response of fluvial balance section on lake level changes, and the changes of depositional characters during the process which was from a abrupt deepening of lake-water-depth to shallow upward. Then founded the real fluvial parasequence pattern, and solved the difficult problem of stratigraphy correlation between the fluvial to the shallow-lake environment.

In the study of deep water parasequence division, considering that lithologic indexes are little influenced by water depth, the marks of microelement (such as the ratio of Fe^{2+}/Mn^{2+}, the content of Co. ,etc), paleobiology features (such as biology combinations, changes of biology quantities and shell decorations, etc) and turbidite fans, etc, which are sensible to changes of water depth, are selected to seek the new approach, new way of parasequence division in deep water.

7. Sequence Stratigraphy Studies of DonyYing Sag of early Tertiary

On the base of former theories of continental lacustrine basin sequence stratigraphy, according to the comprehensive studies using seismic data explanations, log analyses, drilling or Paleobiology or core or ecologic and geochemical characters, depending on archaeomagnetism analyses, sequence stratigraphy special-purpose processing of seismic data, spectroscopic analysis methods, analyses of single-well sequence stratigraphy and section correlation, nine 3th grade sequence were identified in Dongying Sag of early Tertiary. The 1st, 2nd, 8th, 9th sequence of them are synsedimentary fault depression

sequence. The 3rd and 5th are simple fault depression sequences. The 4th is multi—time falut depression sequence. The 6th and 2th are climatic sequences.

Every sequence evolution is the result of sedimentary input to the basin under the certain tectonic setting. So different kinds of sequences had different space distribution and evolution characters, and includes different systems tracts types. After finishing the studies of sigle wells and sections correlation sequence stratigraphy, and on the base of the correlations of sequences, systems tracts, parasequence sets, and parasequences of the whole area, we analyzed the space-time distribution of systems tracts of every sequence and combinational features of systems tracts. Then determined the three-dimensional strata structures of every sequence and system tracts.

At last, we discussed the relation between every kind of system tracts to oil-gas source-reservoir-seal assemblage and deliberated the relation between hydrocarbon distribution to sequence stratigraphy.

前　言

“层序地层学”是70～80年代在国外逐渐发展起来的一门新学科，它的出现引起了全世界地质学家的关注。近年来，我国广大的科技工作者在科研和生产过程中，也引用层序地层学的观点，并取得了一定的效果，同时也发现了不少问题。陆相与海相盆地毕竟有相当大的区别，我国东部主要大油气田都位于断陷和断坳盆地中，因此，总结我国东部陆相断陷湖盆层序地层学演化模式，研究断陷湖盆和断坳湖盆中层序发育的控制因素、形成机制、层序类型、体系域类型及其组合等，是非常必要的。为此，石油大学(华东)在中国石油天然气总公司石油科技中青年创新基金的支持下，开展了“陆相断陷湖盆层序地层学”研究。本专著是该项目研究成果的一部分，它试图回答以下的关键问题：

1）两种类型层序界面和两种沉积体系域组合在中国陆相断陷盆地中应该是怎样的？

2）建立陆相湖盆层序地层学的理论，确定陆相湖盆中层序的发育主要受哪几个因素的控制，气候起着什么样的作用？

3）不同的构造背景，对层序的发育和发展有什么影响？

4）缓慢沉积段(C·S段)，在陆相盆地中有几个？分几个层次？在不同的环境下呈什么状态？

5）确定陆相湖盆中可以划分出几个体系域？各种体系域中沉积体系的组合特征如何？

6）层序的划分应向着精细的方向发展，努力把层序划分到7级，即层序(一、二、三级层序)、准层序组、准层序、层组、纹层等，划分厚度可达十几米，还有深水准层序的划分及识别等。

通过两年来的科技攻关，充分利用地震、测井和岩心描述等资料和地震资料的特殊处理，将济阳坳陷下第三系划分出3个二级层序，9个三级层序，对准层序的形成机理、准层序组的组合方式进行了探讨。研究认为济阳坳陷的下第三系地层可划分出构造层序和气候层序两类。在敞流湖盆中层序的发育主要受构造因素控制，这些层序称为构造层序；而闭流湖盆中，层序的发育主要受气候因素的控制，所发育的层序称为气候层序。在济阳坳陷下第三系以断坳为主的这个盆地中，将构造层序划分为简单断坳层序、多期断坳层序和同生断坳层序。简单断坳层序仅由一个进积式准层序组组成。简单断坳层序和多期断坳层序只发育湖泊收缩体系域。完整的同生断坳层序由低水位体系域、湖泊扩张体系域、湖泊收缩体系域和非湖泊体系域组成。完整的气候层序由低水位体系域、湖泊扩张体系域、高水位体系域和湖泊收缩体系域组成。研究中发现，C·S段可以划分为5个层次和4种结

构类型，它不仅可以出现在层序的内部，而且可以分布在层序的底部。研究过程中探讨了构造背景、物源方向、物源供应速率对层序边界形成的控制作用。

本项目的研究先后得到石油大学重点基金项目、中国石油天然气总公司石油科技中青年创新基金和山东省自然科学基金项目的资助。石油大学的纪友亮、张世奇、李红南、张立强、王永刚、杜世通、曹辉兰、钱峥、王志欣、白刚、李明升、汪焰、薄其众、何立华、王金友、刘忠军，胜利石油管理局的郭汝泰、宋国奇、张善文、张继田、田波、王文林等参加了本项目的研究工作。

本专著第一章由纪友亮编写，第二章由纪友亮、曹辉兰编写，第三章由纪友亮、张世奇编写，第四章由张世奇编写，第五章由张世奇、纪友亮编写，第六章由纪友亮、张世奇、李红南编写，第七章由张世奇、纪友亮、张立强、王永刚编写，最后由纪友亮、张世奇整理统稿。

李俐敏清绘了全部图件。在整个项目的研究过程中，始终得到中国石油天然气总公司科技局领导、石油大学校领导和石油大学勘探系领导的关心和帮助。得到胜利油田地质科学院、物探公司广大科技人员的配合和支持，在此表示深切的感谢！

作　者

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目　录