Ciências da Terra (UNL)	Lisboa	Nº 18	pp. 65-68, 2 figs.	2013

Sequence Stratigraphy

Andy Davies

NEFTEX, 97 Milton Park, Abingdon, Oxfordshire, United Kingdom, OX14 4RY; andrew.davies@neftex.com

Summary

Sequence stratigraphy relies upon grouping sediments into discrete packages based upon the relative sea-level regime during the time of their deposition. In so doing it has revolutionised the way we understand the stratigraphic record. The technique significantly aids correlation allowing disparate data to be integrated effectively and dramatically improves predictive capability. This has been used to greatest effect in the hydrocarbon exploration industry to increase the economic success of exploration by successfully predicting the pre-drill presence of source rocks, reservoirs and seals. Recent studies have revealed fast paced, high amplitude global sea-level (eustatic) cycles even in intervals of time considered to be greenhouse climate states, which can be linked to warming and cooling trends. Understanding the driver for these enigmatic events is an important avenue for future research and may help with our predictions of the characteristics of an anthropogenically forced greenhouse world.

Keywords**:** Sequence stratigraphy, eustasy, paleoclimate, hydrocarbon exploration

Introduction

Over the past 4 decades, sequence stratigraphy has revolutionised the way we view the stratigraphic record and yet the precise method and terminology remain rich in controversy (e.g. Catuneanu *et al*., 2009). Despite this, the basic concepts of the discipline are simple to grasp; sedimentary systems respond to variations in base-level (relative sea-level or lake-level for instance) and the resulting packages of sediments can be identified based upon whether base-level was high, low, rising, falling or static. Such packages can be identified by analysing changes in depositional facies and stratal geometries and are divided by important chronostratigraphic horizons (Fig. 1). These horizons provide a "key" for correlating and integrating disparate data (e.g. seismic, wireline, outcrop, biostratigraphy), allowing the chronological order of basin filling and erosional events to be determined. By grouping sediments into packages a better understanding of the temporal and spatial relationships of sediments is developed in a way that is not possible using simple lithostratigraphic correlations. The technique also allows informed predictions of facies away from "hard" data control, which has helped to greatly increase the economic success of hydrocarbon exploration.

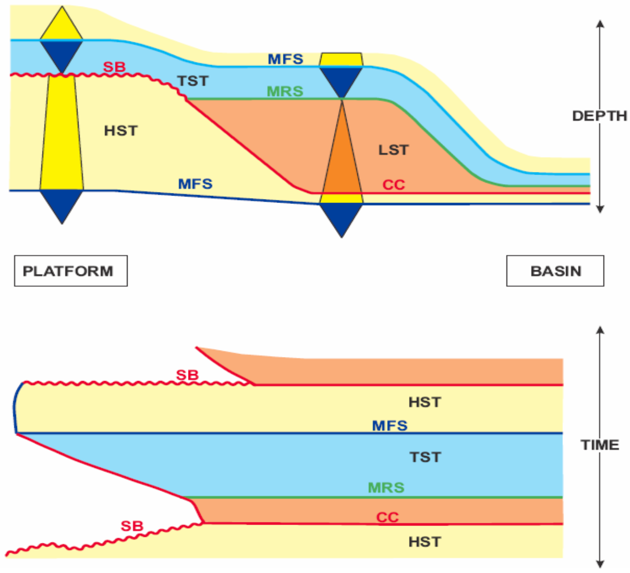

Fig. 1 – Simplification of common sequence stratigraphic terminology within the hydrocarbon industry in depth and time (chronostratigraphic chart), modified from Simmons, 2012. TST = transgressive systems tract, MFS = maximum flooding surface, HST = highstand systems tract, LST = lowstand systems tract, SB = sequence boundary, CC = correlative conformity, MRS = maximum regression surface.

The development of sequence stratigraphic concepts

Sequence stratigraphic methodology was pioneered by the geologists and geophysicists of Exxon (Vail *et al*., 1977), who identified packages of reflectors on seismic data, separated by what they termed "bounding surfaces". Progradation and retrogradation could be identified in the seismic reflectors, relating to the rise and fall of relative sea-level. Since this seminal work, a wide variety of sequence stratigraphic models have been developed by different groups (Fig. 2). These models have helped develop our understanding of the influence of different regimes (pace and magnitude) of relative base-level change on a wide variety of depositional settings. An unforeseen consequence of this has been the contrasting use of the same terminology – for example the term "sequence boundary". A careful examination of the terminology and concepts used by individual authors when trying to understand published sequence stratigraphic interpretations is therefore essential. Catuneanu *et al*. (2009) provides an important attempt to synthesise these models and define a standard use of sequence stratigraphic terminology. It is vital that practitioners of sequence stratigraphy continue to strive for this goal whilst also trying to reach consensus on the exact position of each of the sequence stratigraphic surfaces on a relative sea-level curve.

Global implications

Base-level fluctuations can be forced by a number of different factors including tectonic subsidence/uplift, changes in sediment supply (resulting from changes in hinterland relief or climate) and eustasy (global sea-level change). Whilst all of these factors are important for individual basins, the recognition of eustatic cycles holds the potential to facilitate high resolution global stratigraphic correlation (e.g. Simmons *et al*., 2007). Whilst related to sequence stratigraphy, eustasy is a separate concept that was first introduced by Suess (1888) and there have been advocates for its use as a primary tool of correlation ever since. Vail *et al*. (1977) noted that the sequences observed in their seismic, well and outcrop data were of the same age in the majority of basins they examined. They thus determined that eustasy was the key driver for the sequences they observed and that a eustatic sea-level curve could be constructed as a result. The first such curve was published by Vail *et al*. (1977) and this was later expanded upon for the Mesozoic and Cenozoic by Haq *et al*. (1987, 1988).

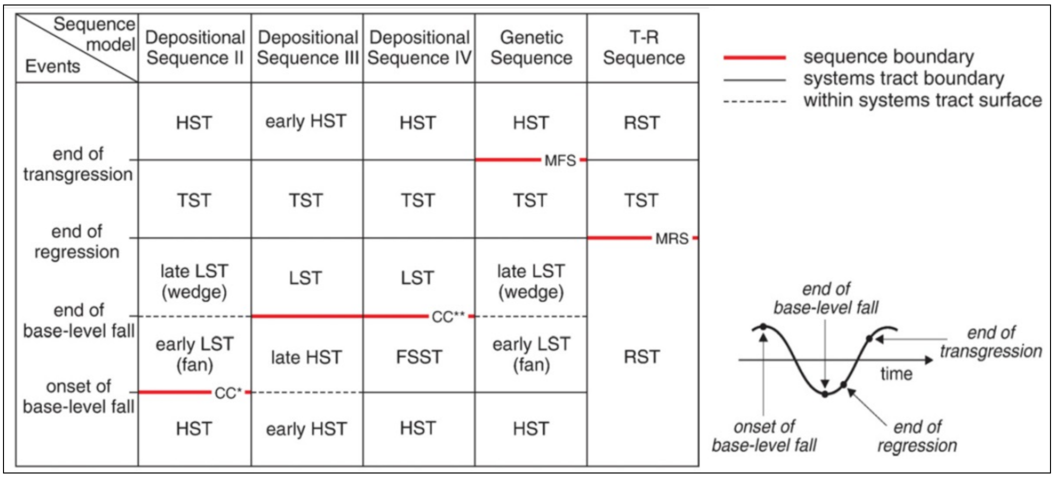

Fig. 2 – Diagram illustrating the key differences between a number of sequence stratigraphic models (modified from Catuneanu *et al*., 2009).

Eustatic cycles are observed throughout the stratigraphic column, raising an important question about their driving mechanism. For known glacial epochs (e.g. the Late Ordovician), a potential driver for large amplitude, rapid eustatic cycles is obvious, and yet such cycles are also observed in greenhouse climate systems. Miller *et al*., (2005) demonstrated that in data from the New Jersey margin, global sea-level fluctuated by 20-80m over time periods of <1 Ma during the Late Cretaceous to Miocene. A comparable study by Sahagian *et al*. (1996) on Middle Jurassic to Late Cretaceous data from the Russian Platform suggests similar magnitudes of sea-level change. The pace of these events can be determined by using Milankovitch cycles to generate a cyclostratigraphic chronology, allowing a resolution of up to ~20 Ka. One such succession is the Late Jurassic Kimmeridge Clay, exposed in southern England, where a 3rd order transgressive systems tract can be calculated as 456 Ka in duration. The rate of this event is relatively fast and lies within the realms assumed for glacio-eustatic transgression.

Comparisons of paleoclimate proxy data with sequence stratigraphic events provides a clear link between many large-scale maximum flooding events and paleoclimatic warming, and climatic cooling and lowstand intervals (e.g. Dera *et al*., 2011) hinting at a possible glacio-eustatic driver. In order to truly understand the driving forces behind these cycles it is imperative that additional sections with high chronostratigraphic resolution (e.g. biostratigraphic, cyclostratigraphic, chemostratigraphic) of sea-level change are identified, preferably with coincident paleoclimate proxy data. Likewise, additional information on the amplitudes of the eustatic cycles is needed, including sections where back-stripping has been performed. Ultimately we need to develop an understanding of whether these fast paced, high amplitude greenhouse cycles relate to glacio-eustasy, dynamic topography, variations in mid-ocean spreading rates, large igneous province activity or other more enigmatic mechanisms. A detailed, temporally precise and global view of the paleoclimate history of greenhouse periods will help to assess this, especially if conducted within a palinspastic framework. Amongst other benefits this will aid our predictions of the characteristics of an anthropogenically forced greenhouse world.

Industrial applications of the technique

In the hydrocarbon industry, sequence stratigraphy is routinely used as the primary method for the subdivision of strata for both intra- and inter-basin correlation and has been successfully applied at plate scales (Sharland *et al*., 2001). This is not surprising as the sequence stratigraphic interpretation and subsequent correlation can be reasonably clear in the seismic and well data that the industry has access to. As an example, geologists working in the North Sea of NW Europe will talk of the sequence stratigraphic scheme of Partington *et al*. (1993) in the same way as they talk of the standard units of geologic time. The sequence stratigraphic framework provides a means to understand the chronostratigraphic evolution of a basin/region often through the construction of chronostratigraphic charts (or Wheeler diagrams). Recently it has become possible to produce automated chronostratigraphic charts from seismic interpretation allowing deeper insight into basin evolution and its petroleum potential.

Sequence stratigraphic concepts also aid informed prediction of which facies are likely to occur basinward, landward and laterally in the depositional system. Therefore the occurrence of source rocks, reservoirs and seals may be inferred at a regional scale, even from relatively sparse datasets. This has played an important role in enabling successful hydrocarbon exploration in deep-water settings. For example, many of the deep-water fans currently being targeted around the Atlantic margin relate to periods of relatively low sea-level which can be inferred from, and correlated to, hiatuses in more data-rich shallow marine-settings. As easy to find resources continue to dwindle and hydrocarbon exploration continues to be forced into deeper waters, sequence stratigraphy will continue to play a vital role in securing future energy supplies. Pivotal to this will be the development of more detailed insights into the effects of relative base-level change on the plethora of depositional settings and how the characteristics of the base-level change has evolved over geological time.

References

CATUNEANU O., ABREU V., BHATTACHARYA J. P., BLUM M. D., DALRYMPLE R. W., ERIKSSON P. G., FIELDING C. R., FISHER W. L., GALLOWAY W. E., GIBLING M. R., GILES K. A., HOLBROOK J. M., JORDAN R., KENDALL C. G. ST. C., MACURDA B., MARTINSEN O. J., MIALL A. D., NEAL J. E., NUMMEDAL D., POMAR L., POSAMENTIER H. W., PRATT B. R., PRATT,J. F., SARG J. F., SHANLEY K. W., STEEL R. J., STRASSER A., TUCKER M. E. & WINKER C. (2009) – Towards the standardization of sequence stratigraphy. *Earth Science Reviews* 92, 1-33.

DERA G., NEIGE P. DOMMERGUES J. L. & BRAYARD A. (2011) – Ammonite paleobiogeography during the Pliensbachian–Toarcian crisis (Early Jurassic) reflecting paleoclimate, eustasy, and extinctions. *Global and Planetary Change* 78, 92-105.

HAQ B. U., HARDENBOL, J. & VAIL, P.R. (1987) – Chronology of fluctuating sea levels since the Triassic (250 million years ago to present). *Science* 235, 1156-1167.

HAQ B.U., HARDENBOL J. & VAIL P. R. (1988) – Mesozoic and Cenozoic chronostratigraphy and eustatic cycles. *In* WILGUS J. *et al*. (Eds.), Sea-level Changes: An Integrated Approach. *SEPM Special Publication* 42, 71-108.

MILLER K.G., KOMINZ M. A., BROWNING J. V., WRIGHT J. D., MOUNTAIN G. S., KATZ M. E., SUGARMAN P. J., CRAMER B. S., CHRISTIE-BLICK N. & PEKAR S. F. (2005) – The Phanerozoic record of global sea-level change. *Science* 310, 1293-1298.

PARTINGTON M. A., COPESTAKE P., MITCHENER B. C. & UNDERHILL J. R. (1993) – Biostratigraphic calibration of genetic stratigraphic sequences in the Jurassic - lowermost Cretaceous (Hettangian to Ryazanian) of the North Sea and adjacent areas. *In* PARKER J. R. (Ed.), *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*. Geological Society of London, 371 – 386.

SAHAGIAN D., PINOUS O., OLFERIEV A. & ZAKHAROV V. (1996) – Eustatic curve for the Middle Jurassic – Cretaceous based on Russian Platform and Siberian stratigraphy zonal resolution. *AAPG Bulletin* 80, 1433-1458.

SHARLAND P.R., ARCHER R., CASEY D. M., DAVIES R. B., HALL S. H., HEWARD A. P., HORBURY A. D. & SIMMONS M. D. (2001) – Arabian Plate Sequence Stratigraphy. *GeoArabia Special Publication* 2, 371p.

SIMMONS M. D., SHARLAND P. R., CASEY D. M., DAVIES R. B. & SUTCLIFFE O. E. (2007) – Arabian Plate sequence stratigraphy: Potential implications for global chronostratigraphy. *GeoArabia* 12, 101-130.

SIMMONS M. D. (2012.) – Sequence Stratigraphy and Sea-Level Change. *In* GRADSTEIN F. M., OGG J. G., SCHMITZ M. & OGG G. (Eds) - *The Geologic Time Scale 2012*. Elsevier, 239-267.

SUESS E. (1888) – *Das Antilitz der Erde*. Tempsky-Freytag, vol, 2, 703p.

VAIL P. R.; MITCHUM R. M. JR., TOOD R. G., WIDMIER J. M., THOMPSON S., SANGREE J. B., BUBB J. N. & HATLEID W. G. (1977) – Seismic stratigraphy and global changes of sea level. *In* PAYTON C. E. (Ed.), Seismic stratigraphy-applications to hydrocarbon exploration. *AAPG Memoir* 26, 49-212.