

# The future of the sequence stratigraphy paradigm: Dealing with a variable third dimension

Peter M. Burgess

Department of Earth, Ocean and Ecological Sciences, University of Liverpool, Jane Herdman Building, 4 Brownlow Street, Liverpool L69 3GP, UK

Sequence stratigraphy is a method and a model, and perhaps actually a paradigm, to make observations, interpretations, and predictions about strata, with important applications, from the search for hydrocarbons to an understanding of the geological history of global climate change. The method applies to strata across a range of scales, from basin margin stacking patterns to bed-by-bed heterogeneity. The model makes predictions founded on understanding of processes ranging from sediment transport dynamics, to organic sediment production, to the interplay of changes in accommodation and sediment supply that control stratal patterns, also across a wide range of scales. In this issue of *Geology*, Madof et al. (2016, p. 319) present a modified approach to sequence stratigraphic analysis of nearshore strata that better accounts for along-strike variability in stacking patterns. Madof et al. address important issues of how to observe and describe stratal architectures more complex than typically depicted in predominantly two-dimensional (2-D) conceptual models. This new research is a contribution to the ongoing development of sequence stratigraphy, and raises the important question of how sequence stratigraphic methods and conceptual models will develop.

## A BRIEF HISTORY OF SEQUENCE STRATIGRAPHY

Some aspects of sequence stratigraphy are as old as geology, but the core originated in the work of early to mid 20<sup>th</sup> century stratigraphers like Barrell (1917) and Wheeler (1964) and Sloss et al. (1949). The subject gained important traction when adapted and applied to seismic data in the late 1970s (Mitchum et al. 1977). Subsequent work emphasized concepts of relative sea-level variations controlling accommodation (Posamentier et al. 1988) and applied these ideas to outcrop-scale systems (Van Wagoner et al., 1990). More recent developments include new attempts to standardize sequence stratigraphy with well-defined nomenclature and to focus on defining a sequence stratigraphic method to generate objective observations, independent of model assumptions (Catuneanu, 2006; Catuneanu et al., 2009; Neal and Abreu, 2009). These observations can then be interpreted within the framework of a sequence stratigraphic model to generate useful, testable predictions.

## IS SEQUENCE STRATIGRAPHY A METHOD, MODEL, OR PARADIGM?

So is sequence stratigraphy a method, or a model, or both? Following on from this it is important to ask, after just over 50 years of development since the original work of Sloss (1949), how should the method and model continue to develop? To answer these questions, it is perhaps useful to think of sequence stratigraphy as a paradigm; that is, a framework of theories, methods, postulates, and standards for what constitutes a legitimate contribution to a field of science (Kuhn, 1962). As a paradigm, sequence stratigraphy is both method and model, and it is certainly possible in this case to progress from careful, objective observation to interpretation following certain theoretical models. However, it is also possible, as Kuhn (1962) points out, that the paradigm dominates thinking and observation, to the extent that it can make sufficiently objective observation and independent testing of the model elements difficult. In which case, it is very

important to constantly review the various elements of the paradigm to check that they are performing well, and to encourage modifications or additional elements, to include new developments from theory and experiment, and to address relatively weak areas. Madof et al. is an example of a possibly useful additional element to the method, and this and other areas for possible modification are discussed here.

## ACCOMMODATION AND SUPPLY: DO WE GIVE THEM EQUAL SPACE?

Schlager (1993) showed that changes in sediment supply be considered as a control on stratal stacking patterns alongside and interacting with changes in the rate of accommodation creation. This idea has been adopted in sequence stratigraphic models (e.g., Catuneanu, 2006) and it has been formalized to a degree in the concept of the accommodation supply ratio (Muto and Steel, 1997). However, being recognized as important and being frequently and equally applied in interpretations of strata are not necessarily the same thing. Catuneanu (2006) uses the word “accommodation” 554 times, and the word “supply” only 264 times. Other examples give even less precedence to supply variations (e.g., Neal and Abreu, 2009; 37 uses of “accommodation” but only 2 uses of “supply”). This simple evidence suggests that accommodation variations still dominate how we think about stratal architectures.

Perhaps related to this, while supply is more straightforward as a volume rate, it remains difficult to define accommodation precisely (Muto and Steel, 2000), especially when accommodation does not relate simply to sea level, making it difficult to progress with our understanding of controls on stratal stacking. Analogue and numerical modeling seem likely to be the way forward to develop this aspect of the sequence stratigraphic paradigm. Another important step forward would be work to determine how often sequence development and cyclicity arises from variations in sediment supply; this is included in the sequence definition given in Catuneanu et al. (2009), but there are little data as yet showing how often supply-driven sequences occur, and how interplay of accommodation and supply works in three dimensions.

## SYSTEMS TRACTS: THE IMPORTANCE OF NEUTRAL DESCRIPTIVE TERMINOLOGY

Is it problematic to use systems tract terminology that often appears to assume dominant control by accommodation variations even where this is not clear, for example, with “falling stage” and “lowstand” systems tract strata in deep-water settings (Covault and Graham, 2010)? Distinction between observational method and interpretations derived from a model is critical (Miall and Miall, 2004; Catuneanu et al., 2009; Neal and Abreu, 2009), so if this is blurred by use of particular terminology, that terminology may not be ideal. The accommodation succession method of Neal and Abreu (2009) that emphasizes observed aggradational and progradational elements following a particular pattern through a cycle of accommodation creation may be a more neutral, and therefore more effective, approach, particularly since it links directly to the accommodation supply ratio concept (Muto and Steel, 1997).

## MULTIPLE CONTROLS: HOW MUCH COMPLEXITY CAN WE DEAL WITH?

Control by rate of accommodation creation has dominated interpretations since the beginning of sequence stratigraphy. While there has been a move away from this more recently with explicit inclusion of sediment supply as a controlling factor (e.g., Catuneanu et al., 2009) there is much evidence that variable rate of creation of accommodation remains the favored interpretation, even in “best practice” examples of sequence stratigraphy (see previous comments about accommodation above). It is increasingly important that the more complex controls observed in numerical and analogue model results are fully incorporated into sequence stratigraphic models and accounted for in all the interpretations we make (Martin et al. 2009; Burgess and Prince, 2015; Kim et al. 2014). Part of the reason for single control interpretations may be that generating multiple interpretations encompassing multiple controls has been time-consuming and complex. This is less true now, when numerical forward models can quickly generate multiple scenarios and allow us to assess their outcomes (e.g., Burgess et al., 2006).

## COMPLEXITY, AUTOGENIC PROCESSES AND THREE-DIMENSIONAL SEQUENCE STRATIGRAPHY

How well do the current sequence stratigraphic method and models deal with 3-D variability in strata? The important of this variability has been understood for a long time (Martinsen and Helland-Hansen, 1995) and it is certainly acknowledged in the sequence stratigraphic paradigm (e.g., Catuneanu, 2006, their figure 5.52). However, Catuneanu (2006) also claims that autogenic processes producing complex 3-D heterogeneity are less important on the basin scale because it is allogenic processes that “control the larger-scale architecture of the basin fill.” In contrast Paola (2016) argues that “the autogenic imprint on the stratigraphic record is stronger and more complex than once thought,” and this point is supported by other observational and experimental data (Kim et al. 2014).

The current sequence stratigraphic model places little emphasis on 3-D stratal complexity in the sense of along-strike variability. For example, Catuneanu (2006) is the key textbook reference on sequence stratigraphy, and contains 349 figures. Of those, only 20 are 3-D diagrams that could accurately represent both down-dip and along-strike variability together, and most of them do not. In contrast, 173 of Catuneanu’s figures are 2-D diagrams and seismic and outcrop images, suggesting that 2-D thinking is still a preferred approach. Some of the 2-D seismic sections do show significant variability, as do many of the 78 maps figures in Catuneanu (2006) but again, little of this heterogeneity is incorporated into the 3-D conceptual diagrams. Madof et al. is particularly useful in this respect because they fully embrace the existence of along-strike variability and offer a trajectory analysis method to quantitatively record the variability. Addition of methods and concepts like this are helpful to determine how much 3-D complexity is present in strata, and to record and understand that complexity.

## SUMMARY

Science is about a progression of ideas, methods, and data, and even well-established paradigms change, sometimes through evolution, and sometimes through rapid revolution. Given this, it seems highly unlikely that sequence stratigraphy will stay as it is. More likely is that it will evolve and change as our knowledge and understanding grows, particularly through new methods that lead to new data and new understanding. Read Madof et al. (2016) with this in mind.

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