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Review article

Unique vs. non-unique stratal geometries: Relevance to sequence stratigraphy

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ABSTRACT

The sequence stratigraphic architecture includes a complex array of stratal geometries with different degrees of stratigraphic significance. The 'non-unique' variability of the sequence stratigraphic framework (i.e., stratal geometries which are not diagnostic for the definition of systems tracts and bounding surfaces) is irrelevant to the workflow of sequence stratigraphy. What is relevant is the observation of the 'unique' stratal geometries that are diagnostic for the definition of units and surfaces of sequence stratigraphy. In downstream-controlled settings, these unique stratal stacking patterns relate to the forced regressive, normal regressive, and transgressive shoreline trajectories. Multiple controls interact during the formation of each type of stacking pattern, including accommodation, sediment supply, and the energy of the sediment-transport agents. This interplay explains the non-unique variability, but does not change the unique criteria that afford a consistent application of sequence stratigraphy. The distinction between unique and non-unique stratal geometries is critical to the sequence stratigraphic methodology. Failure to rationalize the non-unique variability within the context of unique stratal geometries is counterproductive, and obscures the simple workflow of sequence stratigraphy. This is the case with uncalibrated numerical modeling, which may overemphasize non-unique or even unrealistic stratigraphic scenarios. While useful to test the possible controls on stratigraphic architecture, modeling requires validation with real data, and plays no role in the sequence stratigraphic methodology.

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1. Introduction

1.1. Rationale

This work started as a Comment article (Catuneanu and Zecchin, 2016) on the numerical modeling results of Burgess and Prince (2015). The main point of our Comment was that numerical modeling can bring unnecessary confusion if: (1) the results are not calibrated with real data (e.g., overemphasis on upstream controls in downstream-controlled settings, due to an unrealistic selection of input parameters); and (2) the results are not placed in a proper context (i.e., failure to rationalize the non-diagnostic stratigraphic variability within a framework defined by diagnostic stratal geometries). The stratigraphic community needs clear guidelines on the workflow that affords the application of sequence stratigraphy to the rock record. Failure to distinguish between stratal geometries with different degrees of relevance to the definition of sequence stratigraphic units is a setback in the understanding of the method. Moreover, significant issues still remain to be clarified, including: (1) the meaning of 'unique' and 'non-unique' stratal geometries; and, related to this, (2) the difference between methodology and modeling in sequence stratigraphy. Clarification of these issues is of fundamental importance, and prompted us to expand our Comment into the present paper.

The meaning of 'unique' vs. 'non-unique' stratal geometries is a matter of semantics, but it can cause significant confusion if used differently by different authors. For example, these terms designate single ('unique') vs. multiple ('non-unique') *controls* on the stratigraphic architecture in the view of Burgess and Prince (2015), but diagnostic ('unique') vs. non-diagnostic ('non-unique') *criteria* for the identification of systems tracts in light of Catuneanu and Zecchin (2016). This different usage of terminology reflects the contrast between numerical *modeling* (i.e., whereby the various controls on the stratigraphic architecture are quantified as input parameters into the model; hence, the emphasis on controls: Burgess and Prince, 2015) and the sequence stratigraphic *methodology* which is based on the observation of stratal stacking patterns that afford the identification of systems tracts and bounding sequence stratigraphic surfaces, irrespective of the underlying controls on the stratigraphic architecture (hence, the emphasis on field criteria: Zecchin and Catuneanu, 2013; Catuneanu and Zecchin, 2013, 2016). Notably, *all* sequence stratigraphic units and bounding surfaces can have multiple origins, so the definition of 'non-unique' stratal geometries in the sense of Burgess and Prince (2015) becomes meaningless.

The sequence stratigraphic methodology is objective in the sense that no interpretation of the underlying controls is required in order to identify sequence stratigraphic elements (sequences, systems tracts, and bounding surfaces) on the basis of observed stratal stacking patterns. In fact, in many cases, it is difficult if not impossible to identify the underlying controls (e.g., eustasy vs. tectonics; allogenic vs. autogenic), or to quantify their relative contributions to the stratigraphic architecture. At the same time, the reliability of the interpreted sequence stratigraphic framework depends on: (1) the quality and amount of data available; and (2) the ability of the interpreter to restore stratal geometries at syn-depositional time, and to recognize the diagnostic stacking patterns. These are issues that may impact the outcome of the sequence stratigraphic work, but do not represent in any way a pitfall of the sequence stratigraphic methodology. These practical limitations are the reason why sequence stratigraphic models often require revisiting and improvements as new data or interpretation skills are acquired.

The sequence stratigraphic modeling is subjective in the sense that the input parameters (i.e., the controls on stratigraphic architecture) are selected by the modeler. Therefore, any stratigraphic scenarios (realistic or unrealistic) can be 'demonstrated' with numerical modeling. While this theoretical exercise can help understand how sedimentary systems may respond under variable conditions, numerical modeling does not replace or supplement the lack of field data, and has no bearing on the sequence stratigraphic workflow and methodology. The methodology solely relies on the observation of field criteria, regardless of the interpreted controlling mechanisms (e.g., single or multiple, allogenic or autogenic, etc.; Catuneanu and Zecchin, 2013); beyond this, there is no 'magic' involved (i.e., no data = no model). The resolution of the data available (e.g., seismic vs. outcrop) constrains the scale of observation, which is why the sequence stratigraphic workflow and methodology are independent of scale and need to remain consistent at all scales (e.g., Posamentier et al., 1992a; Csato et al., 2014).

When used in conjunction with real data, numerical modeling provides a useful tool for testing the possible controls on the stratigraphic architecture (e.g., Euzen and Joseph, 2004; Rabineau et al., 2005, 2006; Csato et al., 2013, 2015; Leroux et al., 2014). A critical parameter in the numerical model is the selection of the mode of sediment transport, deposition, and erosion. In different models (e.g., geometric vs. diffusive vs. process-based), this parameter is implemented in different ways, leading to very different results. Therefore, the selection of this parameter (e.g., the diffusive coefficient 'K' in the Dionisos modeling software) affects significantly the model results, to an extent that can even outweigh the selection of the 'tested' controls (i.e., eustasy, tectonics, sediment supply). This raises a significant note of caution, since this coefficient remains entirely subjective, and possibly unrealistic, unless calibrated and tuned with real data. The abusive use of numerical modeling, including the confusion of modeling with methodology, overshadows its potential positive contributions, and is a setback in sequence stratigraphy.

1.2. Methodology vs. modeling in sequence stratigraphy

Sequence stratigraphy evolved significantly since the 1970s, from a model-driven methodology (e.g., based on assumptions regarding the dominant role of eustasy on sequence development, and the consequent assertions about global correlations; Vail et al., 1977; Haq et al., 1987) to a data-based methodology which honors local data and local controls on sedimentation. The latter approach opened the door for more realistic interpretations of local stratigraphic architectures, which proved to be highly variable, not only from one sedimentary basin to another, but also between sub-basins of the same sedimentary basin (Catuneanu et al., 1999, 2002; Miall et al., 2008; Csato et al., 2013). For any practical purposes, field data remain the backbone of the sequence stratigraphic methodology. The scale of the sequence stratigraphic framework depends on the resolution of the data available (e.g., larger scale, low-resolution frameworks can be constructed with seismic data, whereas well-log and outcrop data afford the construction of high-resolution frameworks at sub-seismic scales). The realization of the full stratigraphic complexity that can be observed at intertwining scales relies on the integration of multiple data sets with different degrees of stratigraphic resolution.

Numerical stratigraphic forward modeling emerged as a tool to simulate the development of the stratigraphic architecture starting from various combinations of input parameters such as the rates of subsidence, sea level change, and sediment supply (e.g., Heller et al., 1993; Flemings and Grotzinger, 1996; Cross and Lessenger, 1999; Gawthorpe et al., 2003). The caveat is that the output of numerical modeling depends on the input parameters, so one needs to discern between what is realistic vs. unrealistic, common