Contributions to Sequence Stratigraphy from Analogue and Numerical Experiments

Tetsuji Muto[1*], Ron J. Steel[2], Peter Burgess[3]

[1]*Department of Environmental Science, Nagasaki University, Nagasaki 852-8521, Japan*
[2]*Department of Geological Science, University of Texas at Austin,*
Austin, Texas, USA
[3]*Department of Earth Sciences, Royal Holloway University of London, Egham Hill, Surrey, TW20 0EX, UK*
**Corresponding author (e-mail: tmuto@nagasaki-u.ac.jp)*

Abstract: The sequence stratigraphic model, though no longer focused on eustasy and accommodation, has been up until recently based largely on observation and interpretation of outcrop and subsurface data. This approach may be restrictive if the current model places limits on what is observed and how observations are interpreted.To make progress in our understanding of strata, the sequence stratigraphic model and method should be tested against and fully incorporate theoretical and experimental results that provide new knowledge of (1) autogenesis, (2) intrinsic stratigraphic responses, (3) alluvial grade, and (4) scales appropriate to individual depositional systems evolving with relative sea level changes. More extensive Inclusion of analogue and numerical experimental results could lead to significant modification and refinement of existing sequence stratigraphic models.

The emergence of the seismic and sequence stratigraphy method and model in the 1970s, is often described as a revolution in the science of stratigraphy, and has been compared to the origination and establishment of plate tectonics theory (e.g. Miall 1995; Catuneanu 2006). Certainly, sequence stratigraphy, especially through the use of seismic data, has had a huge impact on the study and interpretation of strata in the late 20th century. It showed that sedimentary strata imaged on seismic data were commonly organized into discrete, repetitive unconformity bounded onlapping-to-downlapping depositional sequences The early model utilised long-standing ideas that made eustasythe best-known repetitive driving mechanismto create sequences. However, a simple eustasy-based interpretation of the repetitive stratal packages attracted criticism (e.g. Christie-Blick *et al*. 1988, 2007; Miall & Miall 2001, and references therein) and the more recent sequence stratigraphic models (e.g. Wilgus *et al*. 1988; Posamentier & James 1993; Walker & James 1994; Christie-Blick & Driscoll 1995; Myers & Milton 1996; Catuneanu 2006; Embry 2009; Catuneanu *et al*. 2009) represent a more balanced understanding of combined control by eustasy, tectonics and sediment supply variations.

However, in the last decade or so a new discipline of experimental stratigraphy has developed, and has significant potential to contribute to our understanding of strata. Experimental stratigraphy comprises both analogue and numerical forward modelling of sedimentary systems. Its key strength is generation of insight into evolution of depositional systems without restrictive assumptions. We suggest that evolution of the sequence stratigraphic should integrate these experimental results as much as possible. For example, analogue and numerical modelling may reveal much about autogenic behavior (*sensu* Muto *et al*. 2007) that thus far is not commonly included in sequence stratigraphic interpretations (Muto et al., 2007; Kim and Paola, 2007; Burgess et al., 2008; Paola et al., 2009; Steel and Milliken, 2013). Results from these models, combined with a source-to-sink approach to depositional systems has already influenced the sequence stratigraphic model and method, especially in terms of ideas about sediment bypass in deep-water (e.g. (Burgess and Hovius, 1998; Muto and Steel, 2002; Dixon et al., 2012) and the de-coupling of the linkage between systems tracts and sea-level behavior, so that usage of lowstand and highstand adjectives referring to systems tracts is gradually being discontinued (Abreu et al., 2009; Abreu et al this volume).

This article reviews recent conceptual developments arising largely from experimental stratigraphy, and argues that these concepts and newly identified processes should be included into an evolved sequence stratigraphic model.

Autogenesis and allogenesis

When a depositional environment is regarded as a *system*, it must have a distinct spatial extent and an outside boundary. Any process acting from outside the depositional system is regarded as *external forcing*. Evidently, sediment and water supply from the upstream reaches of the sediment routing system are part of dynamic external forcing since they are input of material from the drainage basin, outside of the depositional system. In the discipline of stratigraphy it is not very meaningful to consider an environment where neither sediment nor water is supplied to the system and thus no sediment accumulation/erosion occurs there. From this point of view, any *active* depositional system will be prone to at least one form of dynamic external forcing.

What is more important with an active depositional system is to what degree the operating dynamic external forcing is reasonably steady (i.e. rate constant) or unsteady (i.e. rate variable). In this context, the term *autogenic* should refer to the origin of stratal and/or geomorphic features (surfaces, hiati, stacking patterns etc.) that arise as stratigraphic responses despite relatively steady dynamic external forcing (static external forcing too; see Muto & Steel 2014). In other words, if the magnitude of system change is greater than the magnitude of external forcing, autogenic processes may be responsible. Conversely, the term *allogenic* refers to stratigraphic and/or geomorphic responses generated as a result of the dynamic external forcing being unsteady. In the conventional understanding of sequence stratigraphy, much attention has been paid to whether the forcing is internal or external, but this may be misleading; both probably operate all of the time, the question is what contribution does each type of forcing make to stratal patterns.

It is often assumed in sedimentology and stratigraphy that autogenesis merely operates at sub-depositional system scales, and that only allogenesis is directly relevant to the larger-scale architecture of basin fill (Catuneanu 2006). In this view autogenesis is commonly believed to be associated with responses of the depositional system that are local (i.e. a small part of the system), stochastic and cyclic, such as typically illustrated with channel avulsion and lateral shifting of deltaic lobes. However, autogenesis is more than this; there is another type of autogenesis that encompasses the entire system,that is deterministic and noncyclic. In fact, the concept of *large-scale deterministic autogenesis* (Muto & Steel 2002a; Paola *et al.* 2009; Muto *et al*. 2012) can account for broader spatial and temporal changes in stratigraphic successions, such as a regressive to transgressive turnaround as a result of autogenic response to steady rise of relative sea level (*autoretreat*; see Muto & Steel 1992; Muto 2001; Petter *et al*. 2009; Leva-López *et al*. 2013), highstand regressive shelf-delta transits as a process of self-regulated equilibrium regression (Burgess *et al.* 2008) and the aggradational-to-degradational transition of deltas as an autogenic response to steady fall of relative sea level (*autoincision*; see Muto & Steel 2004; Swenson & Muto 2007). It has generally become accepted that large-scale autogenesis of depositional systems can play a key role in building distinctive stratigraphic architectures, leaving an important imprint on stratigraphy (Muto 2001; Kim & Paola 2007; Martin *et al.* 2009; Paola *et al.* 2009; Steel & Milliken 2013). As a consequence of these various forms of autogenesis we suggest that some existing sequence stratigraphic studies require re-examination.

Although the continued enquiry for a precise understanding of autogenesis will affect the validity of some allogenic sequence stratigraphic interpretations, this should not negate the importance of further exploring allogenesis. Knowledge of autogenesis will rather enhance stratigraphic studies of allogenesis-related processes and products. To confidently detect allogenic signals from the geological record, we strongly suggest a procedure, following the principle of Occam's Razor, that first attempts to explain stratigraphic responses only in terms of autogenic processes. Allogenic interpretation should then be incorporated after confirming that autogenic interpretation is insufficient for what was observed. Without this procedure, any interpreted allogenic responses of dynamic external forcing can be overestimated or underestimated. Autostratigraphic analysis was applied by Muto & Steel (2002) who detected a decelerating sea level rise from an Early Eocene regressive shoreline succession in the Central Tertiary Basin on Spitsbergen.

Intrinsic stratigraphic responses

Equilibrium stratigraphic response is a type of response by which steady external forcing results in a steady stratigraphic configuration, for example development of a particular stratal-stacking pattern. Conversely, an interrupted or unsteady stratigraphic configuration is routinely attributed to unsteady external forcing. This view of stratigraphic responses is probably accepted by most stratigraphers and plays a fundamental role in sequence stratigraphic analyses (e.g. Catuneanu 2006).

The following example statements are consistent with this hypothesis of equilibrium response.

(a) A depositional system maintains a particular stratigraphic and/or geomorphic behavior if external forcing does not change with time;

(b)

(c) There can exist a balanced state between the effect of relative sea level rise and the effect of sediment supply to any system. Sustained vertical aggradation along a stationary shoreline represents such a balanced state;

(d) Regression or transgression occurs according to the imbalance between sediment supply and relative sea level rise;

(e) Transition from regression to transgression is primarily due to accelerated relative sea level rise, decreased sediment supply and/or increased tectonic subsidence;

However, this hypothesis of equilibrium response is insufficient to capture the whole picture of intrinsic stratigraphic responses. Steady external forcing not only produces steady stratigraphic configuration but also unsteady stratigraphic configuration, by the response referred to in Fig. 2 as *nonequilibrium response* (Muto *et al.* 2012). Typical examples of nonequilibrium response include shoreline autoretreat and subsequent autobreak with constant sea level rise (Muto 2001), and an inevitable transition from aggradational regime to degradational regime with constant sea level fall (Swenson & Muto 2007). Another example of non-equilibrium responses, in exploring the relationship between sedimentation and tectonics, was provided by Leva-Lopez et al. (2013), who showed differing autogenic responses in rate and direction of shoreline migration despite constant external forcing during the development of the subsidence pattern characteristic of foreland basins. It is also possible that steady stratigraphic configuration results from unsteady external forcing, as illustrated by the allogenic attainment of alluvial grade (Muto & Swenson 2005a; see below). Although equilibrium response is possible, it can be effective only under limited conditions (Muto & Swenson 2006). It is nonequilibrium response that generally holds true under steady external forcing. Thus, we suggest that stratigraphic models should be examined in terms of nonequilibrium responses.

A primary mechanism of nonequilibrium response is the progressive spatial expansion of the depositional system, usually recorded as progradation. For example, the entire surface of an incipient delta can be fully covered with supplied sediment, but after the delta has prograded some distance, sediment supply of the same amount is insufficient to cover the whole topset and foreset surface. Consequently the delta is unable to sustain progradation, so even with steady dynamic forcing, a depositional system generally fails to sustain a constant and uniform stacking pattern. This mutual feedback of the progressive spatial growth of depositional systems and its effect on stratigraphic responses may go undetected because the growth of a depositional system is commonly “reset” after each cycle of sea level change and does not have a “memory” of sedimentation that took place during the preceding cycle (e.g. Posamentier *et al.* 1988). Without full recognition of nonequilibrium responses, the sequence stratigraphic method is unlikely to accurately detect allogenic events in the stratigraphic record.

Alluvial grade

Grade, referring to the state of river that conveys sediment without net deposition and net erosion, is a dynamic equilibrium state of the river in terms of sediment balance. This concept was originally advocated by Gilbert (1877) and has been presented as the long-term, equilibrium state of a river system subject to steady external forcing by stationary base level (Davis 1902; Green 1936; Kesseli 1941; Leopold & Bull 1979; Posamentier & Vail 1988; Thorne & Swift 1991; Johnson & Beaumont 1995; Muto & Steel 2000; Holbrook *et al*. 2006). A correct understanding of alluvial grade is fundamental to stratigraphy, because grade represents the critical condition that discriminates between aggradational and degradational regimes in a river system, and also because grade is a key to the exploration of fluvial response to base level forcing.

It is a common assumption in stratigraphic studies that (1) stratigraphic responses of an alluvial river to base level changes are controlled by the graded profile of the river, (2) rivers basically aggrade in response to base level rise and degrade in response to base level fall (though sustained alluvial aggradation during base level fall has also been proposed by Petter and Muto, 2008)), and (3) grade is the final, stable state of a river system that is attained by equilibrium response to stationary base level (e.g. Posamentier *et al*. 1988; Posamentier & Vail 1988; Thorne & Swift 1991a; Holbrook *et al*. 2006). This view of alluvial grade holds true if the downstream end of the river was fixed for example by a weir, so that the delta could not prograde basinward in spite of continuing sediment supply. This scenario can certainly work in natural settings where the delta perches at a shelf break, where the basinward slope is too steep to contain the delta's foreset deposits (Kim *et al.* 2013), but not in normal shelf settings where prograding deltas are fed by rivers.

If the downstream end of the delta is not fixed (i.e. it is a moving boundary), the feeder alluvial river has no chance to attain grade with stationary base level (Muto *et al.* submitted). Numerical models have shown that alluvial grade can be realized by three different mechanisms (Table 1): (1) *autogenic grade* attained by equilibrium response to constant sea level fall in a moving-boundary setting (Muto & Swenson 2006), (2) *allogenic grade* attained by non-equilibrium response to decelerating sea level fall in a moving-boundary setting (Muto & Swenson 2005a), and (3) *forced grade* attained by equilibrium response to stationary sea level in a downstream-fixed boundary setting (Table 1; Muto & Swenson 2005b; Postma 2006; Cantelli & Muto 2014). These three different processes of attaining grade are also affected by geomorphic conditions, particularly alluvial slope ([illegible]e[illegible] [illegible]*et al*. 2012). In case of a moving-boundary setting (both cases of autogenic and allogenic grade), the critical condition to discriminate between aggradation and degradation is not stationary sea level, but falling sea level. Thus, alluvial rivers can continue to aggrade, even though sea level continues to fall, as long as sea level curve stays above the grade curve. The geometrical pattern of this grade curve can vary significantly, dependent on the geomorphic conditions of the delta and the basin (Petter & Muto 2008; Muto *et al.* 2012).

Recent 3D experimental study on forced grade suggests that at the moment of grade attainment with stationary base level, the feeder alluvial river abruptly, but inevitably, becomes degradational in association with incision of a valley that is stabilized in the axial part of the delta plain (Kim *et al.* 2013). Thus, the alluvial plain, which was previously aggrading with stationary base level, undergoes valley incision in the late stage of approaching grade. It is after the completion of valley incision that the alluvial river becomes graded. Once the feeder alluvial system has attained a graded state, autocyclic lateral shifting of delta distributary channels is suppressed by being inside the valley. In a moving-boundary setting with falling sea level, on the other hand, a channel-lobe system at autogenic grade can simply extend basinward without lateral shifting (Muto *et al.* 2012). The above new views of alluvial grade cast doubt on the rationale of the conventional grade model that has played an important role in some sequence stratigraphic models.

I don't know about this. Accommodation still seems to me a central but poorly thought through concept in most, if not all, sequence strat analyses e.g. 22 uses of accommodation in Catuneanu & Zecchin 2013, 31 in Neal et al, this volume. And surely the A/S ratio is still a really useful idea in principle, but actually currently limited by this problem of how accommodation is defined? So I think actually we are duty bound to highlight these issues with the term, but maybe this can be done in less than 2 pages?

The accommodation concept

Accommodation, originally defined as "the space made available for potential sediment accumulation" (Jervey 1988), has been one of the fundamental concepts forming the framework of sequence stratigraphy. A basic assumption in sequence stratigraphy is that a balanced (or imbalanced) state between rate of sediment supply to the basin (S) and rate of change of accommodation (A) controls the basic stratigraphic architecture of a coastal depositional system (e.g. Sloss 1962; Curray 1964; Curtis 1970; Swift 1975; Vail et al. 1977; Shanley & McCabe 1994), such as: A/S >> 1 for nondeltaic rapid transgression, A/S > 1 for deltaic transgression, A/S = 1 for vertical aggradation with laterally-stationary shoreline, 0 < A/S < 1 for "normal" regression, A = 0 for grade, and A < 0 for forced regression with valley incision. This view of stratigraphic control of accommodation, known as the "A/S ratio concept" (Muto & Steel 1997), is based on the hypothesis of equilibrium response and thus takes no account of nonequilibrium response. Even apart from this latter problem, the accommodation concept is flawed (Muto & Steel 2000).

A serious flaw with the accommodation concept is that it cannot be objectively specified, measured and quantified as 3D *space* (2D in cross section). For accommodation to be objectively specified, it must be distinguished strictly from *anti-accommodation* (Muto & Steel 2000), the space in which no supplied sediment can accumulate, or the space made unavailable for sediment accumulation. However, it is inherently difficult to identify the spatial boundary between accommodation and adjacent anti-accommodation, partly because the original definition of accommodation tells nothing about the lateral (basinward) extent of the space. A counter argument might be offered that accommodation is all about relative sea-level change and that its lateral extent has little to do with the definition. If this latter were correct, accommodation would be substantially the same as the thickness of a water mass measured at a specified location in a basin. But this would raise a serious confusion as to dimensions: i.e. A and S have different dimensions (A in LT^{-1}, S in L^3T^{-1}) and thus cannot be in the magnitude relationship. It would be meaningless to argue which one of A and S is larger than the other, and the A/S ratio concept would be unusable.

There is an alternative idea that S, to be compared with A, is not rate of sediment supply to the depositional system but local rate of sedimentation (e.g. Van Wagoner 1988; Catuneanu 2006; ref. Curray, 1964). S defined in this way avoids the dimensional confusion and does not violate the magnitude relationship with A (rate of increase in water depth), but creates another problem. Sedimentation rate (S) may well change by location in the depositional system and also with time. If S at a particular location is assumed to be constant with time, the total amount of sediment supplied to the depositional system is required to increase in proportion to the square to cubic of elapsed time t (i.e. $S \propto t^n$, $2 \leq n \leq 3$), particularly when the system is progradational and progressively expanding. This latter version of the A/S ratio concept would be valid only in cases considering a very small part of the depositional system (e.g. only in the vicinity of the river mouth) for a very short time interval, and where depositional processes are in equilibrium with forcing.

The original accommodation concept by Jervey (1988) does not merely refer to some water depth, but implies a somewhat *special* space that must have some potential of being filled with sediments. This point of view makes it unclear if accommodation is truly independent from sedimentation. If A is not independent of S (now, rate of sediment supply), the following notions will hold: (1) accommodation does not exist without sediment availability, (2) two deltaic systems in front of the same bathymetry have different magnitudes of accommodation if they have different magnitudes of S, and (3) the space to be filled with sediment is inevitably equal to the volume of the sediment to be supplied; i.e. A = S at any time (but this would make the A/S ratio concept null). If accommodation were truly independent of sedimentation, on the other hand, it could include the entire ocean into which the delta is prograding and thus would suffer from the anti-accommodation issue, as noted above.

Accommodation is extended to subaerial environments using concepts of graded stream profiles. This “subaerial accommodation” is defined as space between the existing fluvial or coastal plain and the position in space of the graded profile (Posamentier *et al.* 1988; Posamentier & Allen 1999). However, the grade concept on which existing sequence stratigraphic models are based is the conventional one that alluvial grade is attained by equilibrium response to stationary base level. As noted above, recent research has shown that there cannot exist a graded state in an alluvial river feeding a prograding delta as long as relative sea level remains stationary or is rising (Muto & Swenson 2005b). With rising or stationary base level, subaerial accommodation cannot be defined, i.e. the alluvial river has no limit in vertical aggradation if only sediment is available. Subaerial accommodation can be defined only during sea level fall and only under a particular geomorphic condition (□□≤□□□□□

In the case where the downstream end of a feeder river is fixed (i.e. the delta cannot prograde despite substantial sediment supply to the coast), the river can become graded with stationary base level (forced grade; see above). Even in this latter case, however, careful consideration of subaerial accommodation is necessary because the coastal plain undergoes significant valley incision at the moment of grade attainment (Kim *et al.* 2013; see above), i.e. space right above the alluvial river profile that is supposed to be part of accommodation in the late stage of approaching grade becomes anti-accommodation.

In summary, we suggest that the accommodation concept, both subaqueous and subaerial, is impossible to apply rigorously. The accommodation concept originated from Jervey's (1988) suggestion that "in order for sediments to accumulate, there must be space available below base level." What is precisely meant by "base level" here is *erosional* base level, and the function of sea level as the boundary surface to limit the top of potential sediment accumulation is emphasized. It is well known, however, that sediment can accumulate above sea level, stay there for a long time and eventually be preserved as geological record.

It is thus our considered view that the accommodation concept cannot be treated objectively as a physical quantity, and that sequence stratigraphy has become burdened by it. The internal structure of a stratigraphic sequence does not require this concept; it simply reflects the intrinsic stratigraphic responses to external forcing.

Scales proper to coastal depositional systems

In the framework of the early version of sequence stratigraphy, sequences were believed to occur over periodicities ranging through five orders of magnitude, from 10^4 year to 10^8 years (Vail *et al.* 1977), though this five-fold hierarchy is subjective and very approximate (Drummond & Wilkinson 1993). The key notion to be mentioned here is that the orders of relative sea level cycles are not necessarily reflected in the scales of depositional cycles.

Any coastal depositional system growing under the control of sea level has particular length and time scales that are referred to as the autostratigraphic length scale Λ and autostratigraphic time scale τ, calculated with:

$$L = \sqrt{\frac{Q_s}{|R_{slr}|}} \qquad \text{(in 3D consideration)} \qquad (1)$$

$$t = \frac{L^2}{u} = a\frac{Q_s}{{R_{slr}}^2} \qquad (2)$$

where R_{slr} is rate of sea level rise, Q_s is rate of sediment supply, and □is rlinear diffusion constant for alluvial sedimentation given by:

$$u = \frac{Q_s}{a} \quad (3)$$

(Muto *et al.* 2007; ref. Paola *et al.* 1992). This □This . This stant for alluvial sedimentatiotime required for the manifestation of individual large-scale autogenic events and also affects how well the nonequilibrium response comes out. For a physically plausible range of sediment and water supply and rate of sea-level change, these length and time scales can vary by orders of magnitude between coastal depositional systems. Because of this, even if they experience the same relative sea level rise (and the same tectonic subsidence), their response can be significantly different dependent on magnitudes of Q_s and □□(see also Parker *et al.* 2008a, b). Given a period T for sea level change (a rise or a fall), the depositional system will have prominent signals of nonequilibrium response to the sea level forcing when $T >> \tau$, and might show equilibrium response when $T << \tau$ (Muto & Steel 1997, 2014). In this case where $T << \tau$, a delta will be able to maintain a progradational behavior even during the entire period of sea level rise (T), and an aggradational behavior even during the period of sea level fall (T). Thus, the time scale □□□ffects the formation of an unconformable boundary in response to base level fall.

It is therefore important to note that the recognizable generation of non-equilibrium response depends on the length of T relative to □. As noted before, sequence stratigraphy is based on the hypothesis of equilibrium response, the application of which is generally limited to a short time interval (T << □thin a small part of the depositional system. This can be an important problem in sequence stratigraphy where we have to deal with spatially and temporally large-scale sedimentation events (T >> □T using ideas that may be valid only for local-scale sedimentation (T << □ed

Discontinuous boundaries and non-unique solutions

Recognition of a hiatal discontinuity (unconformity, in a broad sense) is important in sequence stratigraphic analysis, because it leads to identification of sequence boundaries and systems tract boundaries (Vail *et al*. 1977; Posamentier *et al.* 1988; Galloway 1989; Rogers 1994). Such boundaries are commonly believed to be allogenic responses, i.e. attributed to a significant change in dynamic external forcing, especially relative sea-level changes (Loutit & Kennett 1981; Kidwell 1988; Strong & Paola 2008), tectonic activity (Ford *et al.* 1997; Suppe *et al.* 1997; Els 2000; Rafini & Mercier 2002; Dickinson *et al.* 2002), or a combination of both (Li *et al.* 2004). However, a change in river discharge can also result in the formation of widespread erosion surfaces, potentially sequence-bounding unconformities (Milana & Tietze 2002, 2007; Burgess & Prince 2015).

A deltaic succession produced in a tank-flume experiment conducted by Tomer *et al.* (2010), developed a sediment-starved surface, produced by constant sea-level rise, then unconformably overlain by a younger delta that prograded during subsequent sea-level stillstand (Fig 4A). This discontinuous boundary was generated as follows. In the early stage of sea-level rise, the deltaic shoreline retreated landward after a regressive stage (i.e. autoretreat) and then reached an autobreak point, after which the existing subaqueous slope began to be starved of sediment (became a shelf surface), i.e. lost its clear delta-front configuration. During the subsequent (i.e. nondeltaic) transgression, the sediment-starved surface progressively extended landward with continuing sea-level rise. After sea level had come to stillstand, the sediment-starved surface became overlain unconformably by foreset deposits of the newly reactivated delta, whereby a hiatal boundary had been generated. Alluvial beds right below the boundary accumulated during sea level rise, whereas the delta's subaqueous deposits right above the boundary accumulated with stationary sea level. This boundary is definitely allogenic, because it resulted from the temporal change in sea level forcing (rising sea level stopped). Unsteady external forcing can certainly generate hiatal discontinuities in stratigraphic successions.

Notably, apparently the same hiatal boundary can be produced by purely autogenic processes. Figure 4B shows a deltaic succession created in another experiment where a relatively long period of sea level stillstand was followed by constant sea level rise. In the late stage of this latter sea level rise, a hiatal boundary was generated which, in the limited window of observation, looks to be substantially the same as the allogenic one. The alluvial beds right below the boundary accumulated during constant base level rise, and the delta's subaqueous deposits right above the boundary also accumulated during base level rise of the same constant rate. Since there was no change in the dynamic external forcing through the accumulation of these two distinct stratigraphic units, the intervening boundary can be regarded as autogenic, representing the product of nonequilibrium response of the alluvial system to steady sea level rise.

The mechanism of this autogenic hiatal boundary can be explained in terms of critical alluvial length. Any alluvial river aggrading with sea level rise has a critical magnitude of downstream length (L_{crt}). When alluvial length L exceeds L_{crt}, the river can no longer maintain deltaic sedimentation. L_{crt} is given by:

$$L_{crt} = L \frac{g\sqrt{1+a^2}}{g - a} \qquad (4)$$

where □here)y deltaic sedimentation. f donlapped by the alluvial deposit (Tomer *et al.* 2012). Note that L_{crt} is approximately equal to □□□□□□□□□□□. In the case of the first experiment (Fig. 4A), there was no pre-existing deposit before sea level began to rise, i.e. L = 0 at the onset of the run. As sea level rose, L progressively increased and eventually became equal to L_{crt}, when the autobreak event occurred. This is the reason why the depositional system is nondeltaic after the attainment of autobreak. With this initial condition, nondeltaic transgression in the late stage of sea level rise is inevitably preceded by deltaic transgression, deltaic aggradation, and deltaic regression, illustrating a nonequilibrium response.

What if a delta prograded basinward for a significantly long distance before sea level begins to rise, so that L has far exceeded L_{crt} that is specified with the rate of subsequent sea level rise? In this case, the depositional system becomes nondeltaic as soon as sea level begins to rise. There subsequently occurs nondeltaic rapid transgression without being preceded by deltaic transgression and/or regression. As nondeltaic shoreline migrates landward leaving a sediment-starved surface, the alluvial river becomes shorter and shorter with time, and eventually shorter than L_{crt}. At the same time the depositional system recovers deltaic sedimentation. This is because sediment supplied is now sufficient for the entire alluvial river to aggrade and also available for building a foreset slope. Thereby, the existing sediment-starved surface is progressively overlain by the delta's subaqueous deposit, i.e. an autogenic hiatal boundary is generated.

An important implication from these experiments is that (1) a hiatal discontinuous boundaries can be produced autogenically, and (2) apparently the same hiatal boundaries can be generated by different types of sea level forcing and through different stratigraphic responses. It will be hard to distinguish between an allogenic boundary and an autogenic boundary by appearance, unless a sufficiently large window of the entire stratigraphic profile is available (Fig. 4). Different types of external forcing or different types of stratigraphic responses can certainly bring quite similar stratigraphic configuration, in appearance or in substance, representing an issue of non-uniqueness (Burgess et al., 2006; Burgess & Prince 2015). Another example of such non-unique solutions to stratigraphic configuration was provided by Leva-Lopez et al (2013) in the discussion of subsidence vs supply-dominated sediment-wedge generation.

Does sequence stratigraphy require evolution or revolution?

The arguments above imply that some of the key concepts in sequence stratigraphy can be refined, perhaps extensively, to include the autostratigraphic perspectives of depositional systems and their response to external forcing. Existing sequence stratigraphic models can be greatly strengthened by incorporating autostratigraphic notions including (1) an appreciation of autogenesis, particularly of large-scale deterministic autogenesis, (2) the current new knowledge and understanding of intrinsic stratigraphic responses, (3) the autostratigraphic view of alluvial grade, and (4) a full consideration of time scales proper to individual depositional systems, as defined with R_{slr} and Q_s. Such modifications may seem like a revolution, changing the model and perhaps also the method beyond easy recognition.

However, autostratigraphy is not an alternative to sequence stratigraphy. Both are about explaining stratal architectures, and trying to make predictions away from data points , for example to predict lithology that is not shown directly in seismic images, or lithology away from well or outcrop sections. So surely what is required is an evolution to combine both approaches into the kind of useful conceptual models that have been so successful in sequence stratigraphy already over the last 30 years. It may also be necessary to do more numerical forward modelling as part of the interpretation process to properly understand stratigraphic data, but the refined conceptual models collected in one paper and presented as easy-to-follow diagrams would be a good start. In reality, sequence stratigraphy cannot be free from autostratigraphy, because stratigraphic responses and products are the compound products arising from both allogenesis and autogenesis. An improved knowledge of autogenesis will certainly provide a better understanding of the formation of sequences and the stratigraphic effects of external forcing.

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Caption

Table 1. Comparison of the alluvial grade concept between conventional sequence stratigraphy and an autostratigraphic view.

Fig. 1. The methodology of autostratigraphic analysis. To detect allogenic components in stratigraphic products, we should first try to explain stratigraphic features as far as possible in terms of autogenic processes or steady external forcing. Without this procedure, sequence stratigraphic analysis can lead to overestimation, and possibly underestimation, of the effect of unsteady external dynamic forcing. After Muto and Steel (2014).

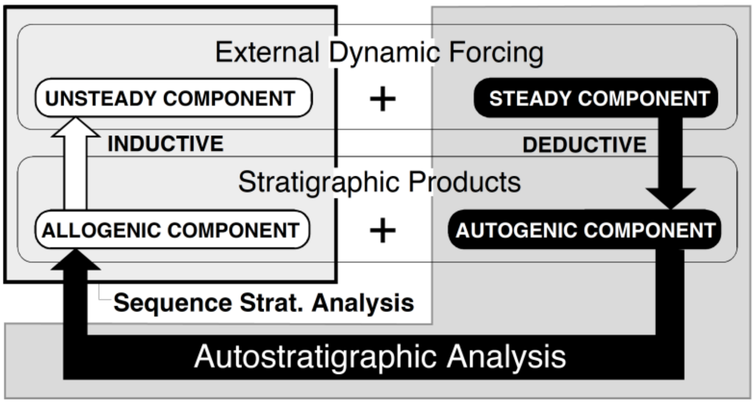
Fig. 2. Different views of the intrinsic stratigraphic response of a depositional system to dynamic external forcing. Conventional sequence stratigraphy prefers to assume that for steady dynamic external forcing, equilibrium response holds true in general, and thus commonly attributes any unsteady stratigraphic features to unsteady dynamic external forcing. The autostratigraphic view is that there are two more types of response should be considered; autogenic nonequilibrium response (unsteady stratigraphic configuration by steady forcing) and allogenic nonequilibrium response (steady stratigraphic configuration by unsteady forcing) (after Muto and Steel, 2014).

Fig. 3. Shoreline trajectories obtained from a series of numerical simulations where sea level (*h*) was raised in two different patterns with time (*t*): one with a constant rate (*h* = *t*), the other in a sinusoidal curve described with a sine function (*h* = 0.5sin□=*t*-0.5)+0.5). Autostratigraphic length scale □length scale hic sinusoidal curve described with a sine fu□□th steady sea level rise, shoreline tends to migrate with a curved trajectory owing to nonequilibrium response, (2) the occurrence of an autobreak event depends on magnitudes of □□□have no relation to the occurrence of autobreak events and maximum flooding.

Fig. 4. Tank-flume experiments conducted by Tomer *et al.* (2011), where deltas were built under different base-level conditions. (**A**) Constant base level rise was followed by a period of stillstand, whereby a hiatal discontinuous boundary was allogenically produced. (**B**) Base level stillstand was followed by constant rise, whereby apparently the same boundary was autogenically produced. Note that the two boundaries resemble each other. See Tomer *et al.* (2011) for detailed experimental conditions.

Table 1. Comparison of the views of alluvial grade between sequence stratigraphy and autostratigraphy

	sequence stratigraphy	**autostratigraphy**		
		forced grade	**allogenic grade**	**autogenic grade**
downstream boundary	moving	fixed	moving	moving
sea level forcing	stationary	stationary	fall at a decelerating rate	fall at a constant rate
geomorphic condition	not specified	very deep water in front	alluvial slope < basin slope	alluvial slope = basin slope
stratigraphic response	equiibrium	equiibrium	nonequilibrium	equiibrium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UNSTEADY COMPONENT
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AUTOGENIC COMPONENT
Sequence Strat. Analysis
Autostratigraphic Analysis

Fig. 1.

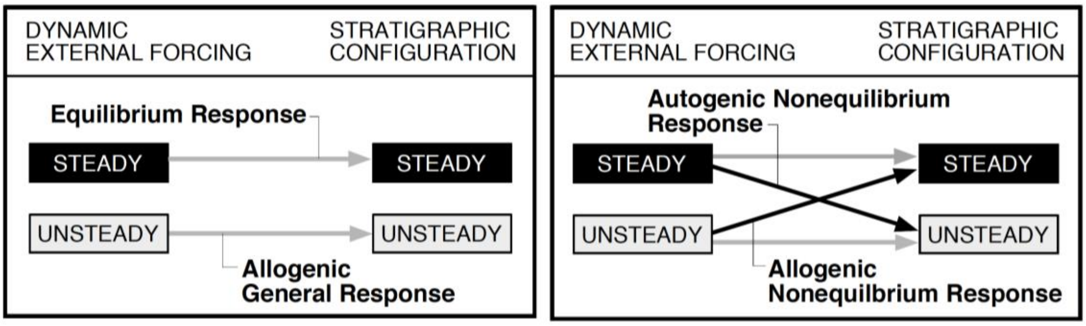
DYNAMIC
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Fig. 2.

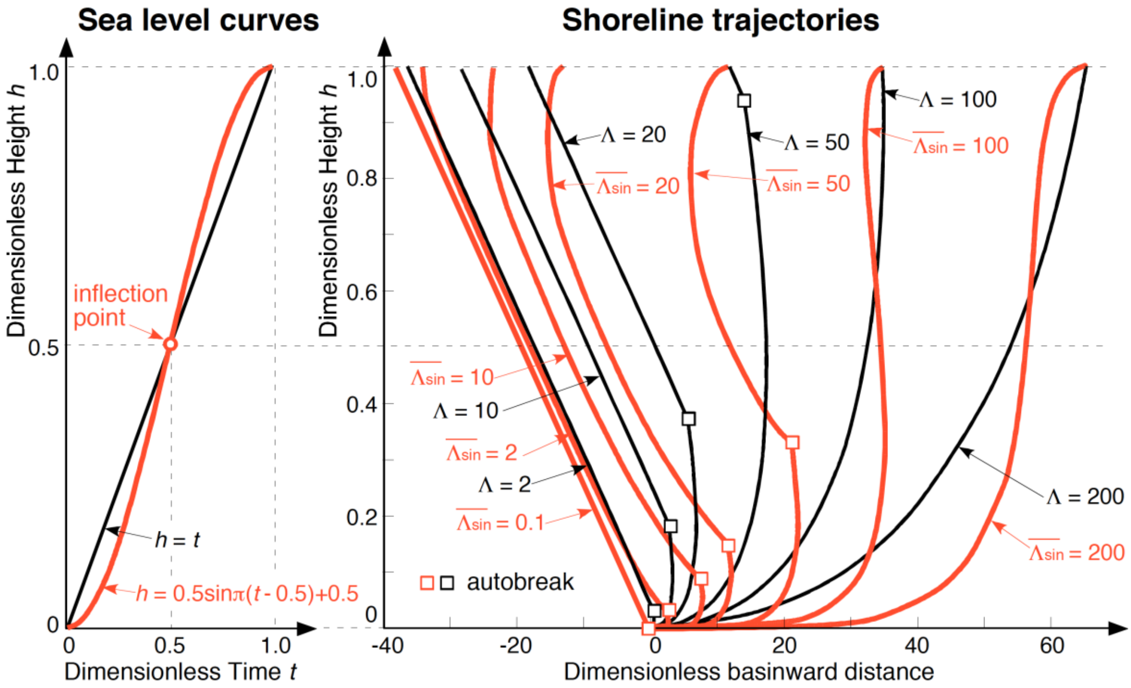

Fig. 3. Shoreline trajectories obtained from a series of numerical simulations where sea level (h) raised in two different patterns with time (t): one with a constant rate ($h = t$), the other in a sinusoidal curve described with a sine function ($h = 0.5\sin\pi(t\text{-}0.5)+0.5$). Autostratigraphic length scale Λ is dimensionless in this particular simulation. Because Λ changes with time when rate of sea level rise is not constant, its average for the entire period of sea level rise is considered (Λsin with bar). Note that (1) even with steady sea level rise, shoreline tends to migrate with a curved trajectory owing to nonequilibrium response, (2) the occurrence of an autobreak event depends on magnitudes of Λ (Λsin, too), and (3) the inflection point in the sea level curve appears to have no relation to the occurrence of autobreak events and maximum flooding.

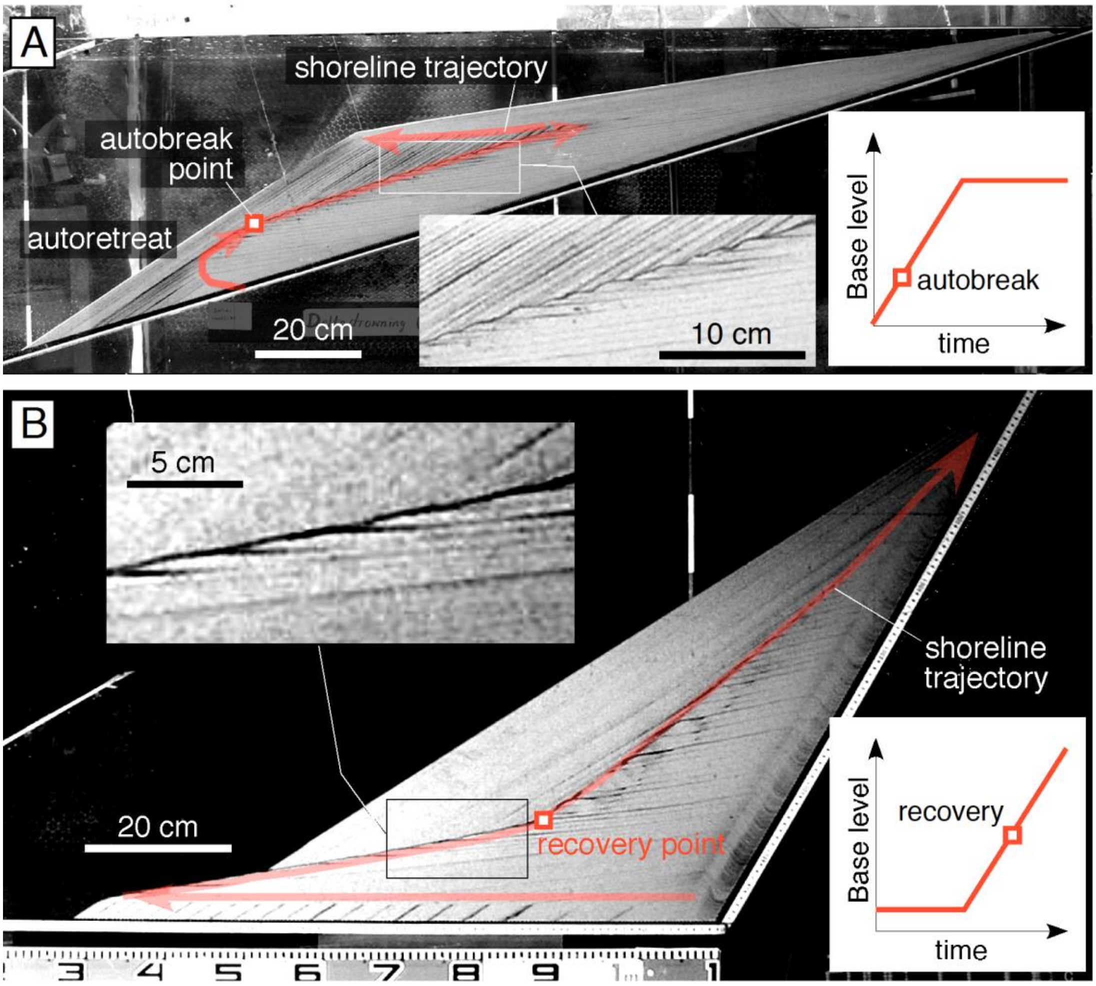

Fig. 4. Tank-flume experiments conducted by Tomer *et al.* (2011), where deltas were built under different base-level conditions. (**A**) Constant base level rise was followed by a period of stillstand, whereby a hiatal discontinuous boundary was allogenically produced. (**B**) Base level stillstand was followed by constant rise, whereby apparently the same boundary was autogenically produced. Note that the two boundaries appear to resemble with each other. See Tomer *et al.* (2011) for detailed experimental conditions.