Periodic Law Patterns of Sequence Stratigraphy

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Method Article

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Abstract

Based on the current theory of sequence stratigraphy, this study employs stillstand normal regression (SNR) to replace the method of highstand normal regression (HNR) to establish shoreline trajectory and sediment supply models of off-lap and onlap-type sequences, respectively. The basic principle of the digital model-driven approach in this study is to decompose the shoreline trajectory (*f*st) and sediment supply trajectory (*f*ss) into their vertical and horizontal projection vectors to establish periodic sufficient condition of shoreline trajectory and sediment supply trajectory, aiming to obtain the remnant maximum flooding surface (RMFS) and/or its intersecting subaerial unconformity (ISU) sequence model: HST (SNR)-FSST (FR)-LST (LNR)-TST (T). This model established the synchronic necessary condition of shoreline trajectory and sediment supply trajectory and obtained the periodic law patterns of sequence stratigraphy, proposed as "two rhombuses sandwiching one subaerial unconformity". This study defines a sequence as: a sequence is a stratigraphic unit constrained by periodic sufficient condition and synchronic necessary condition of shoreline and sediment supply trajectories and is composed of a relatively conformable succession of genetically interrelated strata bounded at their top and base by RMFS and/or intersecting subaerial unconformities (ISU). Moreover, the periodic laws of sequence stratigraphy show that the RMFS is almost potentially correlative to the lower boundary of the stage B (global boundary stratotype section and point) of chronostratigraphic units and close to the biohorizon or first appearance datums (first appearance datums) of biostratigraphic units.

1. Introduction

Sequence stratigraphy has developed five contrasting approaches and four definitions of sequence boundary over the years (Catuneanu, 2009). The first definition of sequence stratigraphy was proposed in the 1940s (Sloss et al., 1949). It was then developed into a two-division sequence stratigraphic model (comprising lowstand systems tract (LST) and highstand systems tract (HST)) developed in the 1970s (Mitchum et al., 1977; Vail et al., 1977a; Vail et al., 1977b) and a three-division model (comprising a LST, transgressive systems tract (TST), and HST) developed in the 1980s (Haq et al., 1987; Vail et al., 1987; Van Wagoner et al., 1987, 1988, 1990; Cross, 1988; Embry, 1988; Jervey, 1988; Kendall and Lerche, 1988; Plint, 1988; Posamentier et al., 1988; Posamentier and Vail, 1988; Sarg, 1988; Cant, 1989). The four-division model (comprising a LST, TST, HST, and falling-stage systems tract (FSST)) was established in the 1990s (Christie-Blick, 1991; Vail, 1991; Hunt and Tucker, 1992; Posamentier and Allen, 1992; Helland-Hansen and Gelberg, 1994; Plint and Nummedal, 2000). Other models include transgressive-regressive (T-R) (Johnson and Murphy, 1984; Embry and Johannessen, 1992) and genetic sequences (Frazier, 1974; Galloway, 1989). Subsequently, 15-member International Subcommission on Stratigraphic Classification (ISSC) Working Group on Sequence Stratigraphy reviewed the basic concepts and terminology not only of sequence stratigraphy but of all unconformity-related units (Salvador, 2001a; ISSC, 2003). A five-person ISSC Task Group on Sequence stratigraphy was assigned to review the sequence stratigraphic literature, make recommendations regarding practical and scientifically valid methods and terminology for sequence stratigraphy, and to provide input to a revised edition to the International Stratigraphic Guide (Embry et al., 2007). Later, a 28-member International Working Group on Sequence Stratigraphy published standardization of sequence stratigraphy (Catuneanu et al., 2009). In recent years, a series of important achievements on sequence stratigraphy such as methodology and nomenclature of sequence stratigraphy (Catuneanu et al., 2011) and ISSC guideline for sequence stratigraphy (Catuneanu, 2012, 2017) have been published successively.

However, the debates or different perspectives over sequence stratigraphy (Miall, 1991; Kolla et al., 1995; Miall, 1995; Wilson, 1998; Yoshida et al., 1998; Van Wagoner ,1998; Yoshida, 2000; Miall and Miall, 2001; Donovan, 2001, 2010; Salvador, 2001a, 2001b; Posamentier, 2001; Christie-Blick et al., 2007; Embry, 2009, 2010) have been accompanied by the entire development process of sequence stratigraphy. Up to now, sequence stratigraphic nomenclature still remains informal and debatable (Owen, 2009). "The continuing controversy among sequence stratigraphers is also described as a controversy between a geometry-based approach and an outcrop-stratigraphy based approach" (ISSC, 2013), computation-based approach (i.e., computational model in this paper), describing both geometry and outcrops in mathematical language, may be one way to resolve this controversy.

The concept of sequence stratigraphy originated from the compounding ideas of regressive and transgressive overlap (Grabau, 1906) and was established based on a cratonic sequence bounded by regional unconformities (Sloss et al., 1949; Sloss, 1963). Despite the difference of scales, the idea of a depositional sequence bounded by unconformities and their correlative conformities still uses the original concept of an unconformity (Grabau, 1906; Sloss et al., 1949); that is, the occurrence of coastal onlap with marine transgression (deepening) and regression (shallowing) above the unconformity (Vail et al., 1977a). Genetic sequence bounded by maximum flooding surfaces (MFS) and their correlative conformities "does not rely on widespread development of subaerial erosion surfaces caused by eustatic falls of sea level to define (genetic) sequence boundaries" (Galloway, 1989). The T-R sequence constitutes T-R cycles (Johnson and Murphy, 1984) or a stratigraphic unit composed of a lower transgressive systems tract and an overlying regressive system tract bounded at its top and base by unconformities and transgressive surfaces or their correlative surfaces (Embry and Johannessen, 1992). Thus, transgression, regression, and unconformity have become the key issues of concerns in sequence stratigraphic studies.

The above three aspects have become important geological problems for a long time, and extensive empirical interpretations have been performed on these topics. Such research has always emphasized the application of empirical methods and terms to avoid theoretical concepts without the support of empirical approach. In essence, sequences of all scales belong to the category of data-driven approaches, that is, the application of empirical methods and terms. In addition to the application of empirical methods and terms, geologists from Exxon also pioneered a model-driven approach as a theoretical basis of depositional sequences in the 1980s (Plint and Nummedal, 2000). It is worth emphasizing that many efforts have been made with this model-driven approach to verify all existing terms in sequence stratigraphy to test their applications in stratigraphy studies, except for highstand normal regression (HNR).

2. Basic principle of the model-driven approach in sequence stratigraphy

Basic model-driven approaches focusing on transgression, regression, and unconformities include Barrell's equation and curve of harmonic oscillations in base level and climatic rhythms (Barrell, 1917), Wheeler's diagram (Wheeler, 1958), the deductive model of accommodation (Jervey, 1988), Cant's equation (Cant, 1989) and points of shoreline trajectory (Cant, 1990), relative changes of sea level as a function of eustacy and subsidence (Posamentier and Vail, 1988), the superposition curves of the 3rd -, 4th - and 5th -order cycles (Van Wagoner et al., 1990), the regression and transgression equation (Posamentier et al., 1992), and the concept of shoreline trajectory (Helland-Hansen and Gjelberg, 1994) or shoreline break (Vail et al., 1991). The sequence stratigraphy family has five schools and four types of sequence boundaries (Catuneanu, 2002; Catuneanu et al., 2009). From the perspective of geometry, the current concepts of sequence boundaries are almost impossible to unify, and multiple contrasting approaches coexist in the single base-level curve (vertical component of shoreline trajectory) with no constraints. In order to improve the model-driven approach, the constrained condition for the various sequence stratigraphy boundary definitions should be unified through the principle of vector decomposition of shoreline trajectory and sediment supply trajectory. The sequence stratigraphic model also needs to combine the inductive (or data-driven) and the deductive (model-driven) approaches so as to strictly follow the principles of mathematics and physics, rather than relying solely on empirical methods and terms that define on a single base-level curve.

There are currently two pitfalls in the model-driven approach to depositional sequence. (1) Non-periodicity: On the same base-level curve, five sequence stratigraphic approaches can be marked as LST, TST, HST, FSST, T-R. Because of the unreasonable design of HNR, it makes that the vertical component (base-level curve) and horizontal component (R&T curve) of the shoreline trajectory are not within the same periodicity (see Catuneanu (2002)'s Fig. 18), which is called the non-periodicity of sequence stratigraphy (Li and Jia, 2011). Li (2011) proposed that HNR should be replaced by stillstand normal regression (SNR) to avoid this non-periodicity existing in sequence stratigraphy for many years. (2) Unreasonable midpoint symmetric slip method: In sequence stratigraphy, the vertical component of the shoreline trajectory is essentially base-level curve or relative change of sea level (Haq et al., 1987; Vail et al., 1977b) and is used to explain the sequence development process and mark the system tracts. Posamentier and Vail (1988) took the inflection point and extreme point on the cosine curve as the midpoint and slip symmetrically toward both sides to obtain the interval of each system tract. They first assigned four intervals on cosine curve to three systems tracts: (a) intervals symmetrical to the left inflection point and lowest point, (b) interval symmetrical to the right inflection point, and (c) interval symmetrical to highest point, which were assigned to LST, TST, and HST respectively (Posamentier and Vail, 1988). Indeed, the midpoint symmetric slip method causes the mathematical significance of the inflection points and extreme points on the cosine curve and cannot play an important role in the sequence stratigraphy model-driven approach, because the first derivatives (-1, 0, and 1) of above points are the change rate of the base-level curve that are more suitable for definition of systems tracts. Hunt and Tucker (1992) subdivided the original LST of the Exxon Group into two fans (the slope fan and basin floor fan) as the underlying force regressive wedge system tract (FRWST) (i.e., FSST) and the lowstand wedge as the overlying LST; this work brought sequence stratigraphy into the stage of the four-division model. However, the midpoint symmetric sliding method remained unchanged in subsequent sequence stratigraphic studies. The three rising intervals on the right cosine curve of the base level are still designated to LST, TST, and HST. The midpoint symmetric sliding method causes the non-periodicity of the sequence stratigraphy. Therefore, two adjustments can be made as follows: (a) the interval of HNR must be mathematically replaced by SNR, and (b) the inflection point on the right side of the base-level cosine curve is used to separate LST and TST while ensuring that both the vertical component (base-level curve) and horizontal component (R&T curve) of the shoreline trajectory maintain the same periodicity.

By comprehensively analyzing and utilizing prior studies obtained with the preceding model-driven approaches, this study aims to unify the current sequence stratigraphic approaches that bind four system tracts with different sequence boundaries. It is the periodic sufficient condition and synchronic necessary condition of the shoreline trajectory and sediment supply trajectory that jointly constrain the sequences bounded by the remnant maximum flooding surface (RMFS) and/or intersecting subaerial unconformity (ISU).

3. Methods

Figure 1. Workflow of the model-driven approach based on the vector decomposition of the shoreline trajectory (s.t.) and sediment supply trajectory (s.s.). RMFS- remnant maximum flooding surface; ISU-intersecting subaerial unconformity.

Step 1

According to the compound T-R overlap sequences (Grabau, 1906), the sequence is geometrically divided into offlap-type and onlap-type sequences. Moreover, the sequence types include tectonic-driven sequences (Sloss, 1963), eustacy-driven sequences (Grabau, 1906), and climate-driven rhythms (Barrell, 1917). Regional tectonic unconformities can then be used to separate the underlying offlap-type sequences from the overlying onlap-type sequences.

Step 2: Models of offlap- and onlap-type sequences include the followings: the sequence model (Figs. 2a, 5a), systems tract model (Figs. 2b, 5b), entity model of shoreline trajectory and sediment supply trajectory (Figs. 2c, 5c) with the entity data model of shoreline trajectory and sediment supply trajectory (Figs. 2d, 5d).

There are two changes made in the sequence stratigraphic model in this study. First, HNR was replaced by SNR to avoid the current non-periodicity that results in that the base-level curve and the R&T curve are not within the same periodicity. Second, the sediment supply trajectory is first defined as the cross-section of the fair-weather wave base migration path along the depositional dip (Helland-Hansen and Gjelberg, 1994), which is an approximate boundary separating the shoreface and offshore deposits and represents the maximum position that can be reached by terrigenous sandy sediments. Therefore, the sediment supply trajectory combined with shoreline trajectory is used to approximately characterize "sediment flux delivered to the shoreline exceeds (or is lower than) the amount of space generated (i.e., new accommodation) for sediment to fill" (Posamentier et al., 1992), i.e., Posamentier et al (1992)'s regression and transgression equation.

Table 1

Coordinates (x, y) on shoreline trajectory (*f*st) and sediment supply trajectory (*f*ss) in the entity model of offlap-type sequence (panel c of Fig. 2).

Point	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	*f*st
x_{st}n	10.126	17.746	29.803	46.013	64.082	79.270	90.962	97.951	105.790	114.352	97.474	84.139	72.741	
y_{st}n	17.788	17.788	17.788	17.788	10.404	4.943	1.814	3.190	5.592	8.812	11.999	14.355	15.736	
Point	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**P11**	**P12**	**P13**	***f*ss**
x_{ss}n	19.975	26.749	37.698	51.755	68.387	82.422	93.325	100.079	107.122	114.352	99.158	87.122	76.889	
y_{ss}n	12.533	12.791	13.114	13.466	7.099	2.390	(0.304)	1.475	4.602	8.812	10.890	12.537	13.794	
t	24.926	32.546	40.166	47.786	55.406	63.026	70.646	78.266	85.886	93.506	101.126	108.746	116.366	

Table 2

Coordinates (x, y) on shoreline trajectory (*f*st) and sediment supply trajectory (*f*ss) in the entity model of onlap-type sequences (panel c of Fig. 5).

Point	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	*f*st
x_{st}n	38.390	46.016	54.106	63.857	74.715	83.862	90.967	95.181	99.617	104.256	62.958	26.928	1.201	
y_{st}n	14.310	14.310	14.310	14.310	8.442	4.095	1.601	3.400	6.442	10.351	14.047	17.407	19.742	
Point	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**P11**	**P12**	**P13**	***f*ss**
x_{ss}n	45.320	52.207	59.526	68.435	78.603	87.112	93.597	96.968	100.544	104.256	68.176	36.701	14.149	
y_{ss}n	10.547	10.742	10.995	11.270	5.728	1.635	-0.707	1.565	5.412	10.351	13.011	15.474	17.102	
t	24.926	32.546	40.166	47.786	55.406	63.026	70.646	78.266	85.886	93.506	101.126	108.746	116.366	

Step 3

Based on the offlap-type and onlap-type sequences, the computational models constrained by the periodic sufficient condition of the shoreline trajectory and sediment supply trajectory and by their synchronic necessary condition are used together to construct a model-driven approach with periodic sufficiency and synchronic necessary conditions to improve and unify the current five schools of sequence stratigraphy.

The basic principle of this step is to decompose the shoreline trajectory f_{st} and sediment supply trajectory f_{ss} into vertical and horizontal vectors meeting Pythagoras theorem Hypotenuse^2 = Perpendicular^2 + Base^2 (i.e., $\Delta S^2=\Delta H^2+\Delta L^2$), as shown in Fig. 2c and Fig. 5c, and derive their vertical and horizontal components (periodicity) and change rates (synchronicity) with time, as shown in Figs. 3–4, and Figs. 6–7.

(1) Considering periodici sufficiency condition, the vertical and horizontal components can be expressed by the following formulas:

$f_{stY}(t) = y_{st}n$ (n = 1, 2…13) (1)

where t1 = 24.926, t (n + 1) = 24.926 + n×7.62 (n = 1, 2…12) (the same below)

The vertical vectors $f_{stY}(t)$ (blue; base-level curve) of the shoreline trajectory in Fig. 3a and Fig. 6a.

$f_{ssY}(t) = y_{ss}n$ (n = 1, 2…13) (2)

The vertical vectors $f_{ssY}(t)$ (orange) of the sediment supply trajectory in Fig. 3a and Fig. 6a.

$f_{stX}(t) = x_{st}10 - x_{st}n$ (n = 1, 2…13) (3)

The horizontal vectors $f_{stX}(t)$ (blue; R&T curve) of the shoreline trajectory in Fig. 3b and Fig. 6b.

$f_{ssX}(t) = x_{ss}10 - x_{ss}n$ (n = 1, 2…13) (4)

The horizontal vectors $f_{ssX}(t)$ (orange) of the sediment supply trajectory in Fig. 3b and Fig. 6b.

(2) Regarding synchronic necessary condition, the rate of vertical and horizontal components can be expressed by the following formulas:

$f_{stY}(t)/\Delta t=[y_{st}(n+1) - y_{st}n]/\Delta t$ (n = 1, 2…12) (5)

The rates of the vertical vectors $f_{stY}(t)/\Delta t$ (blue) of the shoreline trajectory in Fig. 4a and Fig. 7a.

$f_{ssY}(t)/\Delta t=[y_{ss}(n+1) - y_{ss}n]/\Delta t$ (n = 1, 2…12) (6)

The rates of the vertical vectors $f_{ssY}(t)/\Delta t$ (blue) of the sediment supply trajectory in Fig. 4a and Fig. 7a.

$f_{stX}(t)/\Delta t$ =[x_{st}n-x_{st}(n + 1)]/Δt (n = 1, 2…12) (7)

The rates of the horizontal vectors $f_{stX}(t)/\Delta t$ (blue) of the shoreline trajectory in Fig. 4b and Fig. 7b.

$f_{ssX}(t)/\Delta t$ =[x_{ss}n-x_{ss}(n + 1)]/Δt (n = 1, 2…12) (8)

The rates of the horizontal vectors $f_{ssX}(t)/\Delta t$ (orange) of the sediment supply trajectory in Fig. 4b and Fig. 7b.

When HNR is replaced by SNR, the sequence stratigraphic model meets the requirement of maintaining both the vertical and horizontal vectors of the shoreline trajectory and sediment supply trajectory with the same periodicity (i.e., periodic sufficiency condition), thus avoiding the non-periodicity issue faced when the base-level curve and the R&T curve do not share the same periodicity due to the unreasonable design of HNR in the present sequence stratigraphic model.

Based on the rule extension of the regression equation (Posamentier et al., 1992), if $f_{ssY}(t)/\Delta t > f_{stY}(t)/\Delta t$ and $f_{ssX}(t)/\Delta t > f_{stX}(t)/\Delta t$, the shoreline trajectory and sediment supply trajectory are synchronic regression; otherwise, synchronic transgression occurs. Therefore, this sequence stratigraphic approach can obtain the synchronic necessary condition for maintaining the following conditions: (1) vertical synchronicity. The rates of the vertical vectors $f_{stY}(t)/\Delta t$ (blue) of the shoreline trajectory and the rates of the vertical vectors $f_{ssY}(t)/\Delta t$ (orange) of the sediment supply trajectory shown in Fig. 2a and Fig. 5a represent vertically synchronic effects of regression and transgression, respectively; and (2) horizontal synchronicity. The rates of the horizontal vectors $f_{stX}(t)/\Delta t$ (blue) of the shoreline trajectory and the rates of the horizontal vectors $f_{ssX}(t)/\Delta t$ (orange) of the sediment supply trajectory shown in Fig. 2b and Fig. 5b represent horizontally synchronic effects of regression and transgression, respectively. Therefore, this study successfully constrained the order of systems tracts in sequence stratigraphy with two conditions, rather than using single base-level curve to identify systems tracts.

4. Results

4.1. RMFS and/or ISU bounded sequences

The periodic condition of the shoreline trajectory and sediment supply trajectory in Fig. 3 and Fig. 6 is sufficient to fix both the offlap- and onlap-type sequences bounded by RMFS and/or ISU. Then, a sequence can only be composed of HST(SNR)-FSST(FR)-LST(LNR)-TST(T), whereas the system tract boundaries are the basal surface of forced regression (BSFR), the extension of subaerial unconformity (ESU), and the maximum regressive surface (MRS) occurring sequentially, as shown in Fig. 2a and Fig. 5a. Both the regressive surface of marine erosion (RSME) within FSST and the transgressive surface of marine erosion (TSME; i.e., transgressive ravinement surface) within the TST become obvious in most outcrops, but they could be easily misidentified as systems tract boundaries or even sequence boundaries. The identification of these two key surfaces is, to some extent, the source of confusion in the study of sequence stratigraphy due to a lack of the periodic law patterns of sequence stratigraphy. Li (2010) defined a sequence as a relatively conformable succession of genetically related strata bounded by RMFS and/or their correlative subaerial unconformities (CSU). After the presentation of a large number of diagrams and calculations of model-driven approaches, sequence boundaries should be described as remnant RMFS and/or their intersecting subaerial unconformities (ISU). In this study, a sequence is redefined as: a sequence is a sequence stratigraphic unit constrained by periodic sufficient condition and synchronic necessary condition of shoreline trajectory and sediment supply trajectory, and is composed of a relatively conformable succession of genetically related strata and bounded at its top and base by RMFS and/or their ISU.

RMFS and/or ISU bounded sequence inherit the scientific contributions of sequence stratigraphic schools as followings: (1) concept of subaerial unconformity in the depositional sequence that is distinguished from ISU as sequence boundary and ESU as systems tract boundary; (2) MFS in the genetic sequence that is named as RMFS finally intersects with subaerial unconformity so as to avoid excluding subaerial unconformity as genetic sequence boundary; (3) regressive systems tracts (e.g., combination of HST, FSST, and LST upward) in the T-R sequence; and (4) correlative conformity (Posamentier and Allen, 1999) is essentially BSFR. Therefore, based on the model-driven approach constrained by periodic sufficient condition in this study, SNR replacing HNR will reactivate and bring sequence stratigraphy to be integrated with other time-honoured stratigraphic disciplines. In essence, top and base sequence boundaries RMFS and/or ISU combing with key sequence stratigraphic surfaces (BSFR, ESU, and MRS) are used to bound HST(SNR)-FSST(FR)-LST(LNR)-TST(T) that obeys sequence periodic law patterns “two rhombuses sandwiching one subaerial unconformity”.

4.2. Sequence periodic law patterns: “two rhombuses sandwiching one subaerial unconformity”

Based on both the vertical and horizontal rates with time of vectors, the synchronic condition of the shoreline trajectory and sediment supply trajectory in Fig. 4 and Fig. 7 is necessary to fix both the offlap- and onlap-type sequences not only vertically but also horizontally as synchronic effects of regressions and transgressions.

According to the condition of an equal time interval (Δt, in this study, Δt = 7.62), if each rate of the vertical and horizontal vectors of the sediment supply trajectory times its Δt, i.e., absolute values$|(f_{stY}(t)/\Delta t)$ - $(f_{ssY}(t)/\Delta t)|\times\Delta t$ and $[(f_{stX}(t)/\Delta t)$ - $(f_{ssX}(t)/\Delta t)|\times\Delta t$, respectively, in the shaded areas in Fig. 4 and Fig. 7, then they are equal to the vertical thicknesses and horizontal lengths of the sediment supply trajectory, i.e., the thickness and lengths of the parasequence or parasequence set. As a result, we can obtain the following sequence periodic law patterns: “two rhombuses sandwiching one subaerial unconformity”. The two rhombuses are shown as follows: the underlying rhombus increases in thickness upwards in the HST during SNR and decreases in thickness upwards in the FSST during forced regression. In comparison, the overlying rhombus increases in thickness upwards in the LST during lowstand normal regression and decreases in thickness upwards in the TST during transgression. The subaerial unconformity separates these two rhombuses (the substratum and superstratum, respectively; the former provides erosional sediments for the latter, and this process is irreversible). The sequence periodic law patterns are derived from both the inductive and data-driven approach emphasizing empirical scientific observations and the deductive or model-driven approach based on parameters in Fig. 2 to Fig. 7, both of which are indispensable.

5. Discussion

Sequence stratigraphy belongs to the family of stratigraphy. However, up to now, sequence stratigraphy units are not eligible for entry into International Stratigraphic Guide. Three ISSC Working Groups on Sequence Stratigraphy (Salvador, 2001a; Embry et al., 2007; Catuneanu et al., 2009) have not been able to unify the schools of sequence stratigraphy, nor can they provide a single sequence stratigraphic unit for entry into the future international Stratigraphic Guide-the dream of several generations of sequence stratigraphers.

ISSC Working Group on Sequence Stratigraphy (1996–2002) "favors to abandon the use of the terms 'allostratigraphic units' and 'synthem', and to unify the terminology of unconformity-related units by recognizing a single term –'sequence'– for all such units" (Salvador, 2001a; ISSC, 2003), which leaves room for sequence stratigraphic units to replace unconformity-bounded units in the second International Stratigraphic Guide (Salvador, 1994). However, the coexistence of depositional sequence stratigraphic unit, genetic sequence stratigraphic unit, and T-R sequence stratigraphic unit makes it impossible to replace present unconformity-bounded units. RMFS and/or ISU bounded sequence, which unifies, inherits, and absorbs the beneficial basis of depositional sequence, genetic sequence, and T-R sequence, may have potential in this regard as a sequence stratigraphic unit.

The RMFS may be close to the lower boundary of stage B (Global boundary stratotype section and point), as defined by Hedberg (1976) and Salvador (1994) in Fig. 8, so the RMFS may be used as a marker surface to help optimize the stratotype boundaries of chronostratigraphic units. It is not clear whether the RMFS located at the boundary of the sequence stratigraphic unit is exactly consistent with the lower boundary of the chronostratigraphic unit, which requires further research by biostratigraphers in the future. The first appearance datums (FADs) appearing in most stratigraphic profiles are highly likely to be higher or lower than RMFS, so finding a Global boundary stratotype section and point located in line with RMFS is almost as difficult as climbing the sky.

The periodic law patterns of sequence stratigraphy— "two rhombuses sandwiching one subaerial unconformity"—also correspond to Radiation-Extinction and Radiation-Innovation sandwiching one subaerial unconformity in Walliser's (1996) diagram (Fig. 9). Ri (radiation after an innovation event) and Re (radiation after an extinction event) may be correlated to RMFS and MRS, respectively, as shown in Fig. 9. Moreover, FADs are close to RMFS rather than MRS (Fig. 9). It is this different periodic law patterns of sequence stratigraphy that brings a new perspective to sequence stratigraphy and plays an important role in optimizing the stratotype boundary of a chronostratigraphic unit and the biohorizons (or FADs) of biostratigraphic units.

Sequence stratigraphic characteristics of modern geomorphology should attract attention in sequence stratigraphy research. In the field of geological surveys for many years, we often climb steep cliffs and reach to single sided mountain. However, to date, we have not fully realized that these cliffs are, in most cases, characterizing FSST sedimentary rocks with strong weathering resistance (Fig. 8), whereas the eroded gentle slope on single sided mountain is almost entirely the locations of unconformities due to their weak weathering resistance (Fig. 8). The Fig. 2 in International Stratigraphic Guide (Salvador, 1994) clearly shows the aforementioned geomorphic features of unit-stratotype and boundary-stratotypes for a lithostratigraphic unit and boundary-stratotype for a chronostratigraphic unit. When we see rocks rather than the overall framework of stratum in outcrops, we often empirically believe that a subaerial unconformity divides the two rhombuses of a complete sequence periodic law patterns into two different sequences. Indeed, the extension of tectonic-driven unconformity is far greater than the extension of sea level-driven unconformity; the former can be judged by strata contact relationship, while the latter can be identified by strata thickness change to deduce the location of sea level-driven unconformity and even which systems tract is missing.

The grain-, depth- and thickness-variations of sequence stratigraphic tools as well as application of sequence periodic law patterns should be used together in sequence stratigraphy study. There are currently accepted grain-variation trends (finer upwards and coarsening upwards) of depositional sequences (Fig. 18 of Catuneanu 2002), depth-variation trends (deepening and shallowing) of T-R or genetic sequences, as well as three types of parasequence stacking patterns in parasequence set (Van Wagoner et al., 1988). These patterns were almost obtained from empirical data-driven approaches and lack true mathematical derivations such as vectors decomposition meeting Pythagoras theorem. This makes that the key characteristic of thickness decreasing upward of FSST have been empirically mistaken for grain coarsening upward. This problem can only be discovered by jointly constraining the derivation of the shoreline trajectory and the sediment supply trajectory in this study. Unfortunately, empirically grain coarsening upward of FSST directly leads two correlative conformities (Hunt and Tucker, 1992; Posamentier and Allen, 1999) at its top and bottom, where they should be essentially ESU and BSFR respectively in periodic law patterns of sequence stratigraphy. Both vertical grain variation of sediment and depth variation of water belongs to the sedimentary facies attribute, whereas thickness variation of systems tract belongs to sequence stratigraphy. Sedimentary facies research should be conducted within the sequence stratigraphic framework, rather than relying on sedimentary facies migration to interpret key sequence stratigraphic surfaces.

Therefore, the sequence periodic law patterns of "two rhombuses sandwiching one unconformity", derived from Pythagoras theorem, can be applied on outcrop, to preliminarily identify sequence stratigraphic key surfaces such as the RMFS, BSFR, ESU, MRS as well as RSME and TSME, which can be helpful for both lithostratigraphic, chronostratigraphic, and biostratigraphic units. Although, testing this hypothesis (sequence stratigraphy) is beyond the resolution of current biostratigraphic and chronostratigraphic techniques (Wilson, 1998), the periodic law patterns in this study can potentially match the boundary-stratotype for a chronostratigraphic unit (Fig. 8) or even with boundary-stratotype for a lithostratigraphic unit. The discipline of sequence stratigraphy should be qualified to use sequence stratigraphic units replace the current unconformity-bounded units in the future to enter the new International Stratigraphic Guide and perform its duty for the stratigraphy family.

6. Conclusions

In the context of highstand normal regression being replaced by stillstand normal regression, a computational model-driven approach was used to decompose the shoreline trajectory and sediment supply trajectory into their vertical and horizontal vectors, respectively, to:

1. Establish the periodic sufficient condition of the shoreline trajectory and sediment supply trajectory to obtain the RMFS and/or its ISU-bounded sequence model as follows: HST (SNR)-FSST (FR)-LST (LNR)-TST (T).
2. Establish the synchronic necessary condition of the shoreline trajectory and sediment supply trajectory to obtain the sequence periodic law proposed as "two rhombuses sandwiching one subaerial unconformity".

Declarations

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Declaration of Competing Interest

The author declare that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Figures

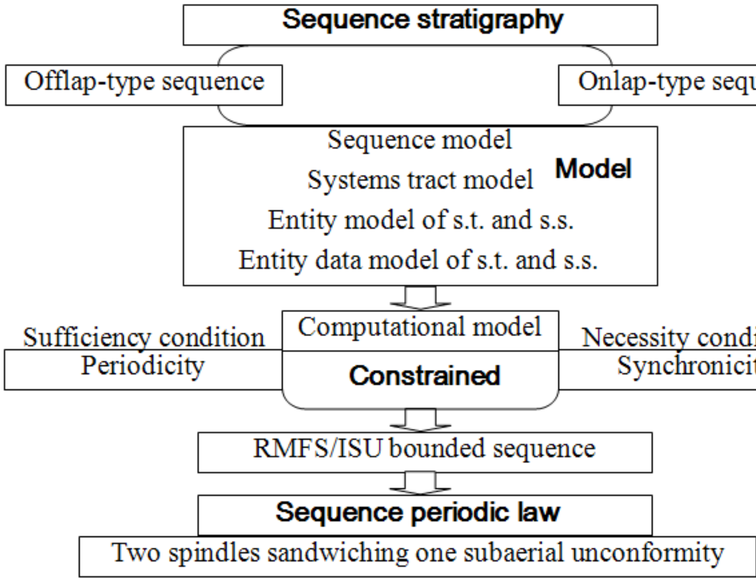

Figure 1

Workflow of the model-driven approach based on the vector decomposition of the shoreline trajectory (s.t.) and sediment supply trajectory (s.s.). RMFS-remnant maximum flooding surface; ISU-intersecting subaerial unconformity.

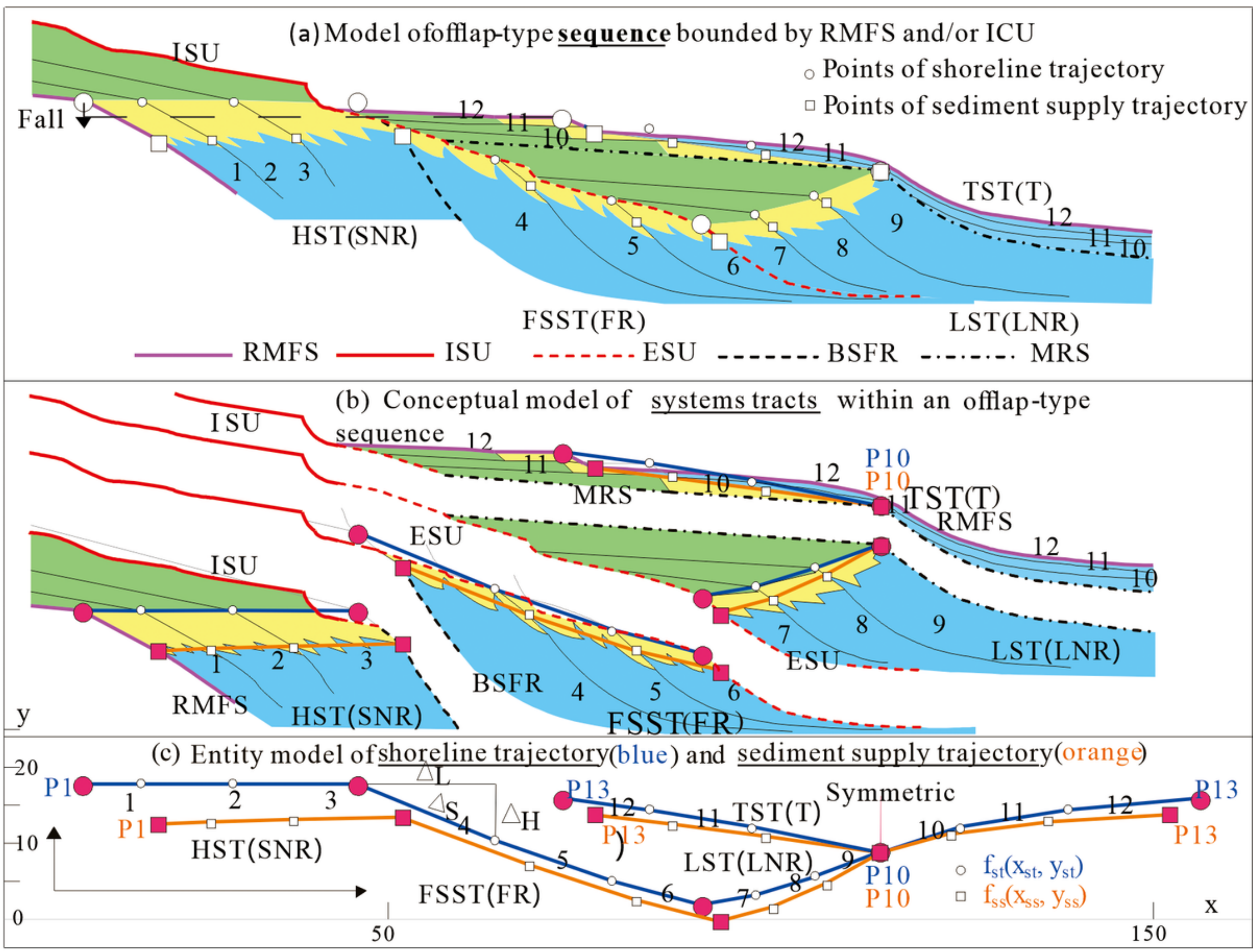

Figure 2

Models related to the offlap-type sequence. (a) model of off-type sequence; (b) conceptual model of systems tract; and (c) entity model of the shoreline trajectory and sediment supply trajectory. LST-lowstand systems tract; TST-transgressive systems tract; HST-highstand systems tract; FSST-falling-stage systems tract; RMFS- remnant maximum flooding surface; ISU-intersecting subaerial unconformity; ESU-extension of subaerial unconformity; SNR- stillstand normal regression; FR-forced regression; LNR-lowstand normal regression; MRS-maximum regressive surface.

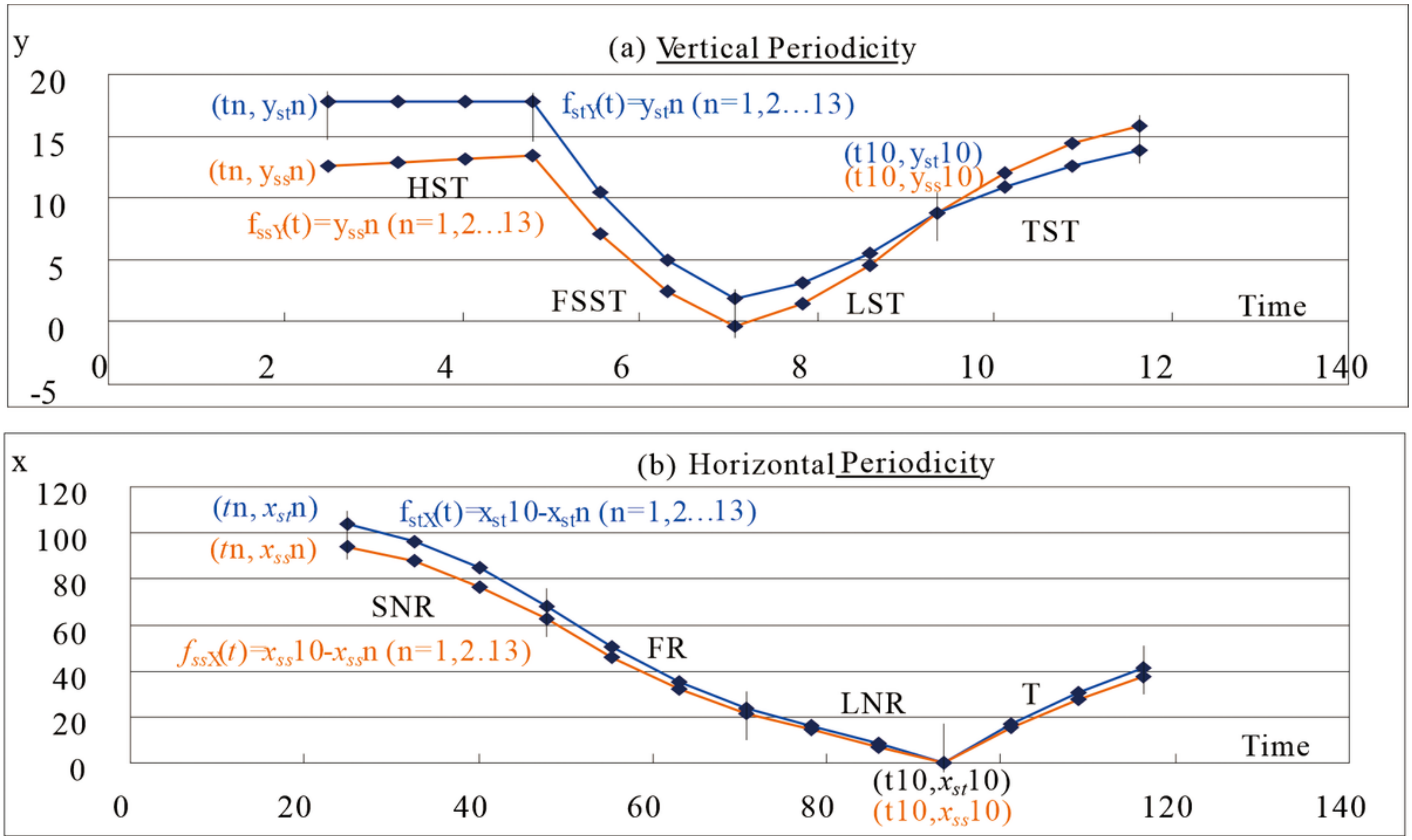

Figure 3

Periodicity related to the offlap-type sequences, (a) Vertical periodicity. The vertical vectors $f_{stY}(t)$ (blue; i.e., base-level curve) of the shoreline trajectory and vertical vectors $f_{ssY}(t)$ (orange) of the sediment supply trajectory in Figure 2 share the same vertical periodicity; (b) Horizontal periodicity. The horizontal vectors $f_{stX}(t)$ (blue; i.e., R&T curve) of the shoreline trajectory and the horizontal vectors $f_{ssX}(t)$ (orange) of the sediment supply trajectory in Figure 2 share the same horizontal periodicity. LST-lowstand systems tract; TST-transgressive systems tract; HST-highstand systems tract; FSST-falling-stage systems tract; SNR-stillstand normal regression; FR-forced regression; LNR-lowstand normal regression.

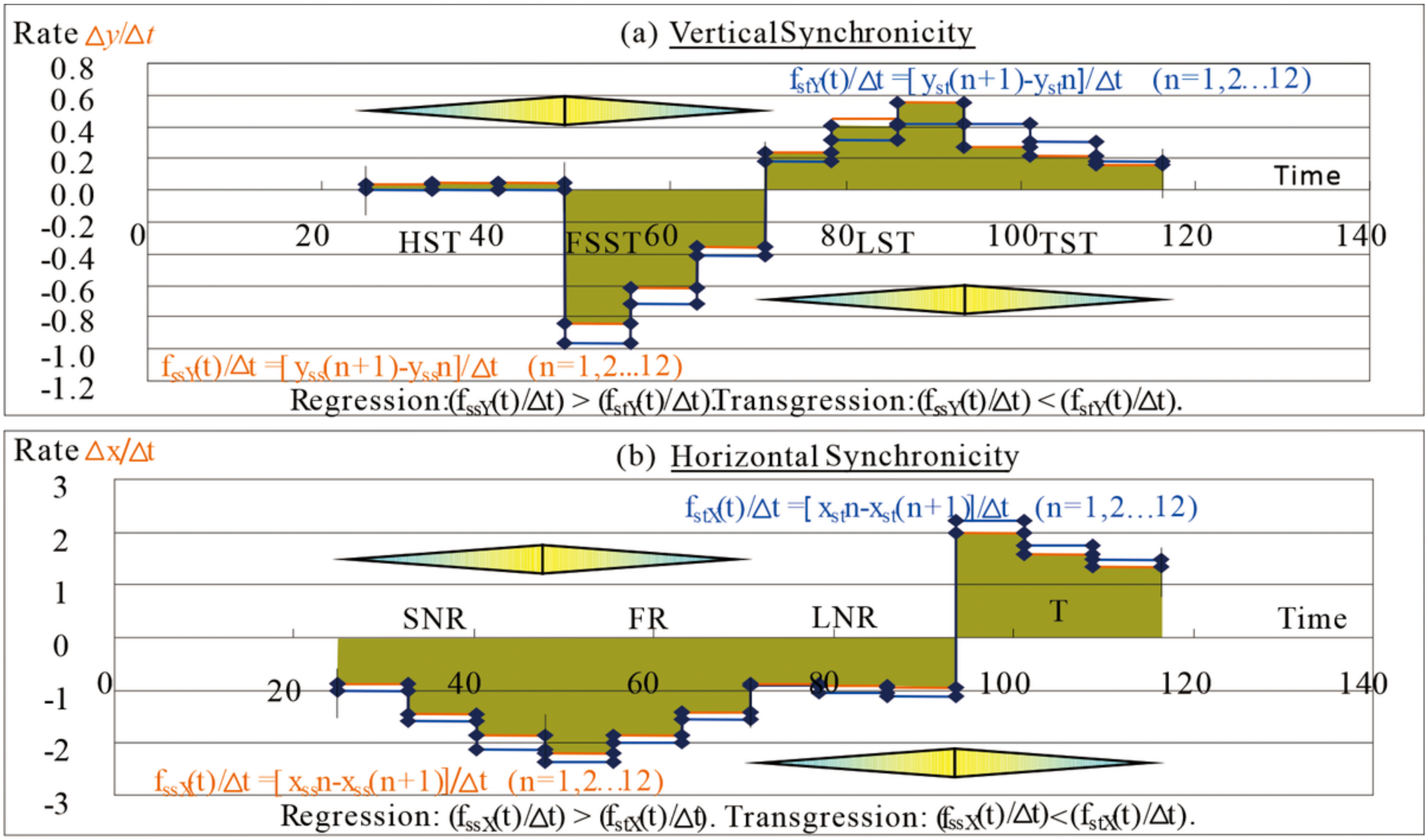

Figure 4

Synchronicity related to the offlap-type sequences, (a) Vertical synchronicity. The rates of the vertical vectors $f_{stY}(t)/\Delta t$ (blue) of the shoreline trajectory and the rates of the vertical vectors of the sediment supply trajectory $f_{ssY}(t)/\Delta t$ (orange) in Figure 2 express vertically synchronic regression and transgression; (b) Horizontal synchronicity. The rates of the horizontal vectors $f_{stX}(t)/\Delta t$ (blue) of the shoreline trajectory and the rates of the horizontal vectors $f_{ssX}(t)/\Delta t$ (orange) of the sediment supply trajectory in Figure 2 express horizontally synchronic regression and transgression. LST-lowstand systems tract; TST-transgressive systems tract; HST-highstand systems tract; FSST-falling-stage systems tract; SNR-stillstand normal regression; FR-forced regression; LNR-lowstand normal regression.

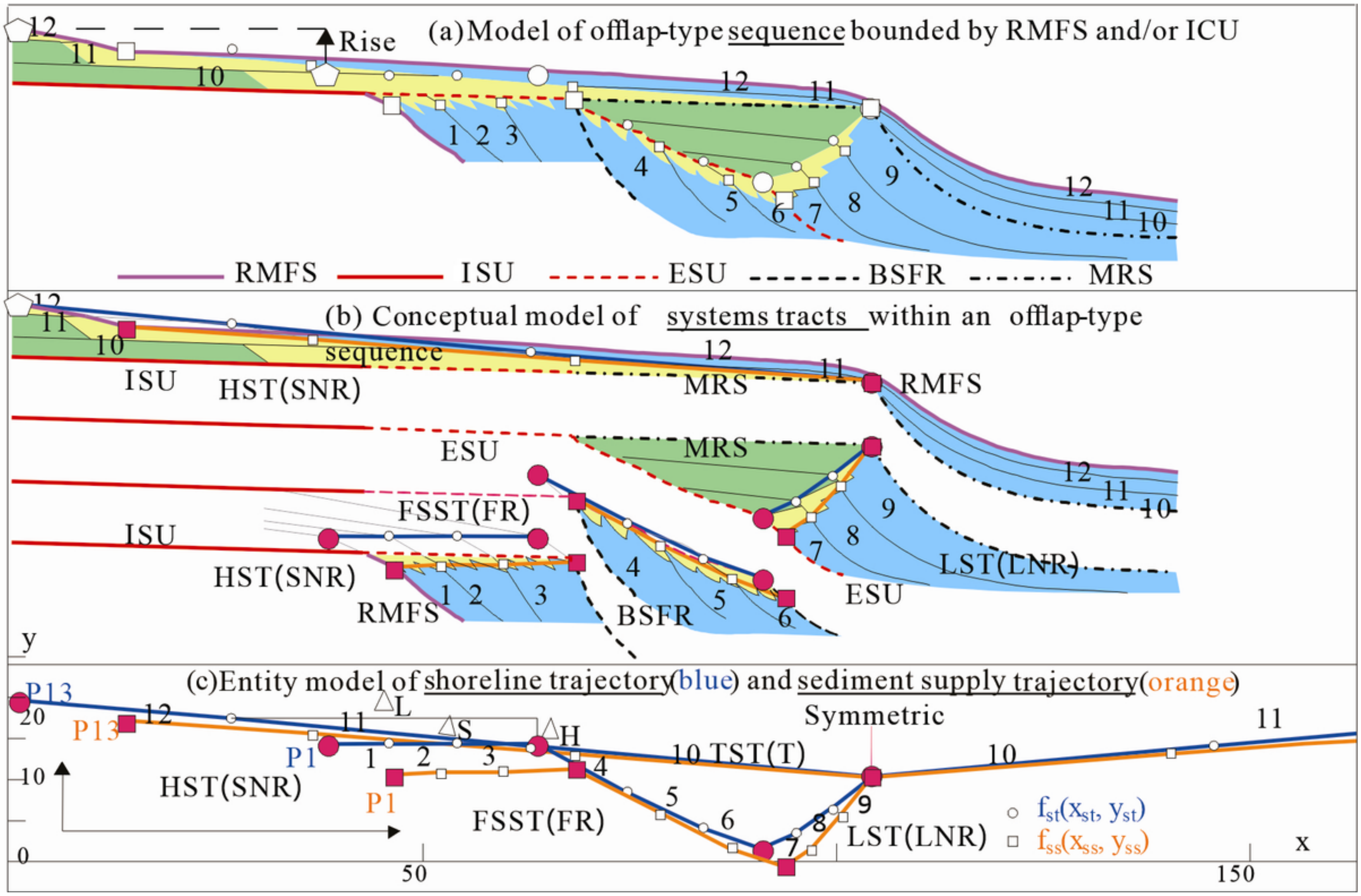

Figure 5

Models related to the onlap-type sequences, including (a) model of onlap-type sequence, (b) conceptual model of systems tract, and (c) entity model of the shoreline trajectory and sediment supply trajectory. LST-lowstand systems tract; TST-transgressive systems tract; HST-highstand systems tract; FSST-falling-stage systems tract; RMFS- remnant maximum flooding surface; ISU-intersecting subaerial unconformity; ESU-extension of subaerial unconformity; SNR-stillstand normal regression; FR-forced regression; LNR-lowstand normal regression; MRS-maximum regressive surface.

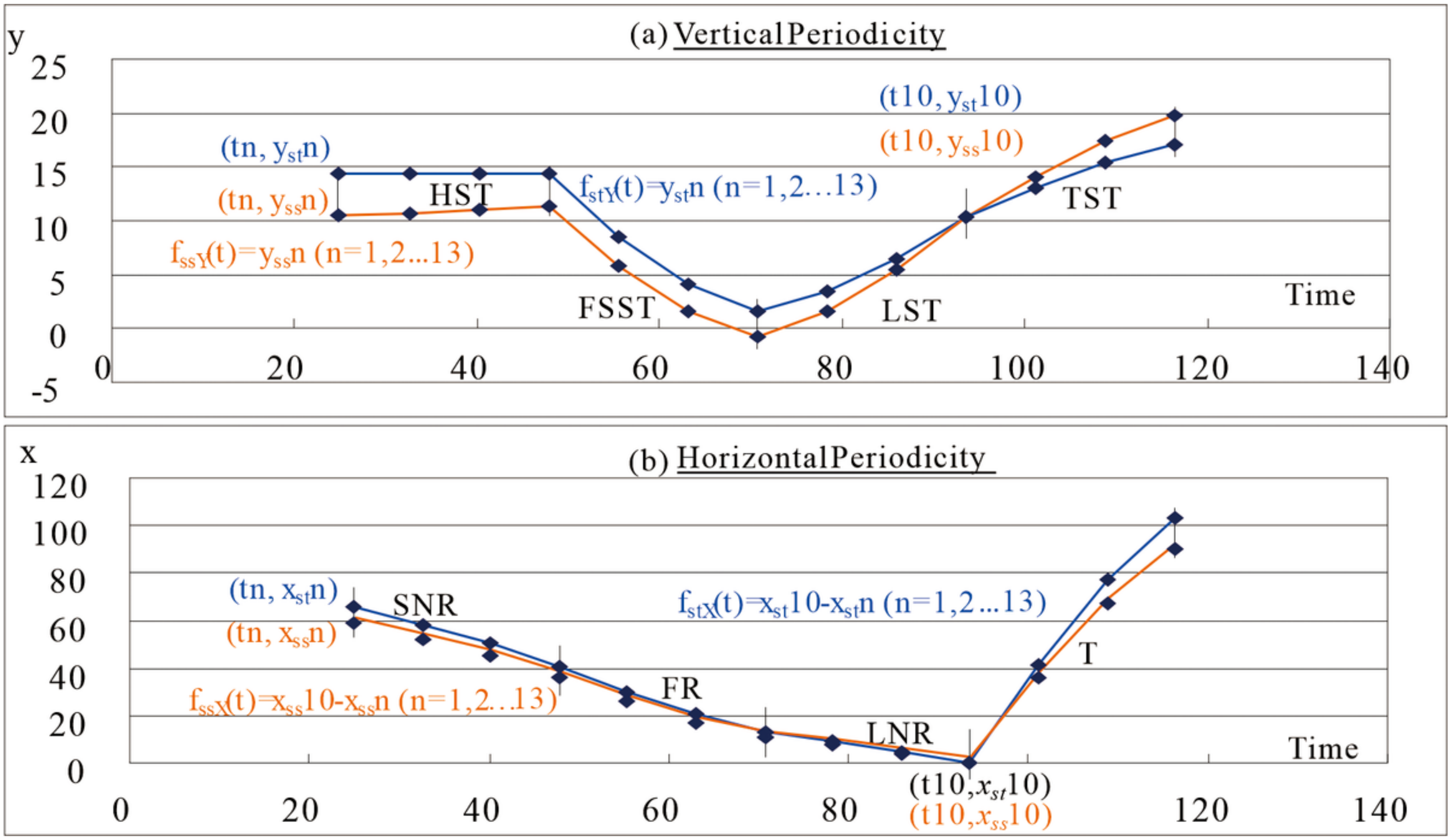

Figure 6

Periodicity related to the onlap-type sequences, (a) Vertical periodicity. The vertical vectors $f_{stY}(t)$ (blue; i.e., base-level curve) of the shoreline trajectory and the vertical vectors $f_{ssY}(t)$ (orange) of the sediment supply trajectory in Figure 5 share the same single vertical periodicity; (b) Horizontal periodicity. The horizontal vectors $f_{stX}(t)$ (blue; i.e., R&T curve) of the shoreline trajectory and the horizontal vectors $f_{stX}(t)$ (orange) of the sediment supply trajectory in Figure 5 share the same single horizontal periodicity. LST-lowstand systems tract; TST-transgressive systems tract; HST-highstand systems tract; FSST-falling-stage systems tract; SNR- stillstand normal regression; FR-forced regression; LNR-lowstand normal regression.

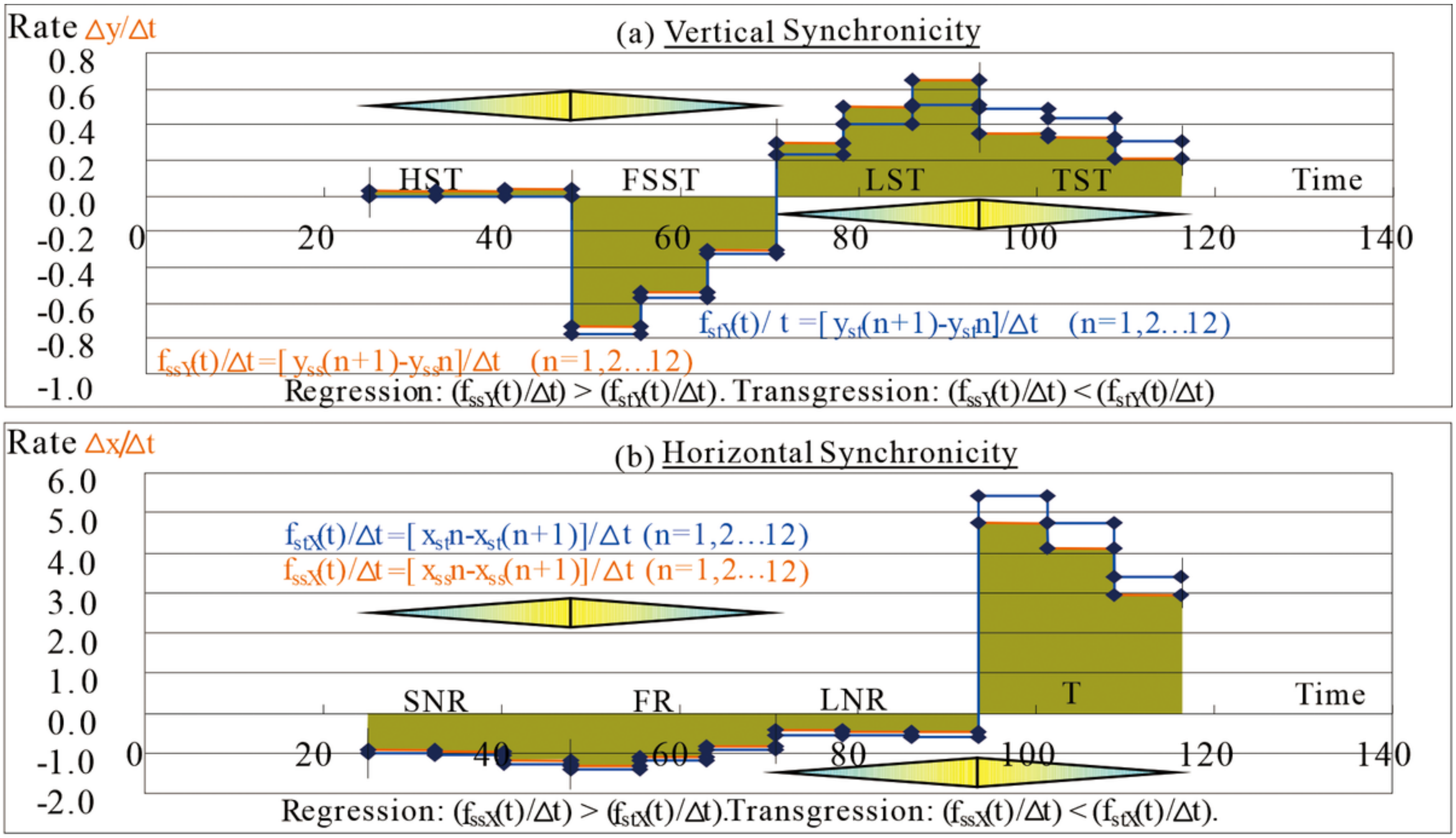

Figure 7

Synchronicity related to the onlap-type sequences, (a) Vertical synchronicity. The rates of the vertical vectors $f_{stY}(t)/\Delta t$ (blue) of the shoreline trajectory and the rates of vertical vectors of the sediment supply trajectory $f_{ssY}(t)/\Delta t$ (orange) in Figure 5 express vertically synchronic regression and transgression; (b) Horizontal synchronicity, the rates of the horizontal vectors $f_{stX}(t)/\Delta t$ (blue) of the shoreline trajectory and the rates of the horizontal vectors $f_{ssX}(t)/\Delta t$ (orange) of the sediment supply trajectory in Figure 5 express horizontally synchronic regression and transgression. LST-lowstand systems tract; TST-transgressive systems tract; HST-highstand systems tract; FSST-falling-stage systems tract; SNR- stillstand normal regression; FR-forced regression; LNR-lowstand normal regression.

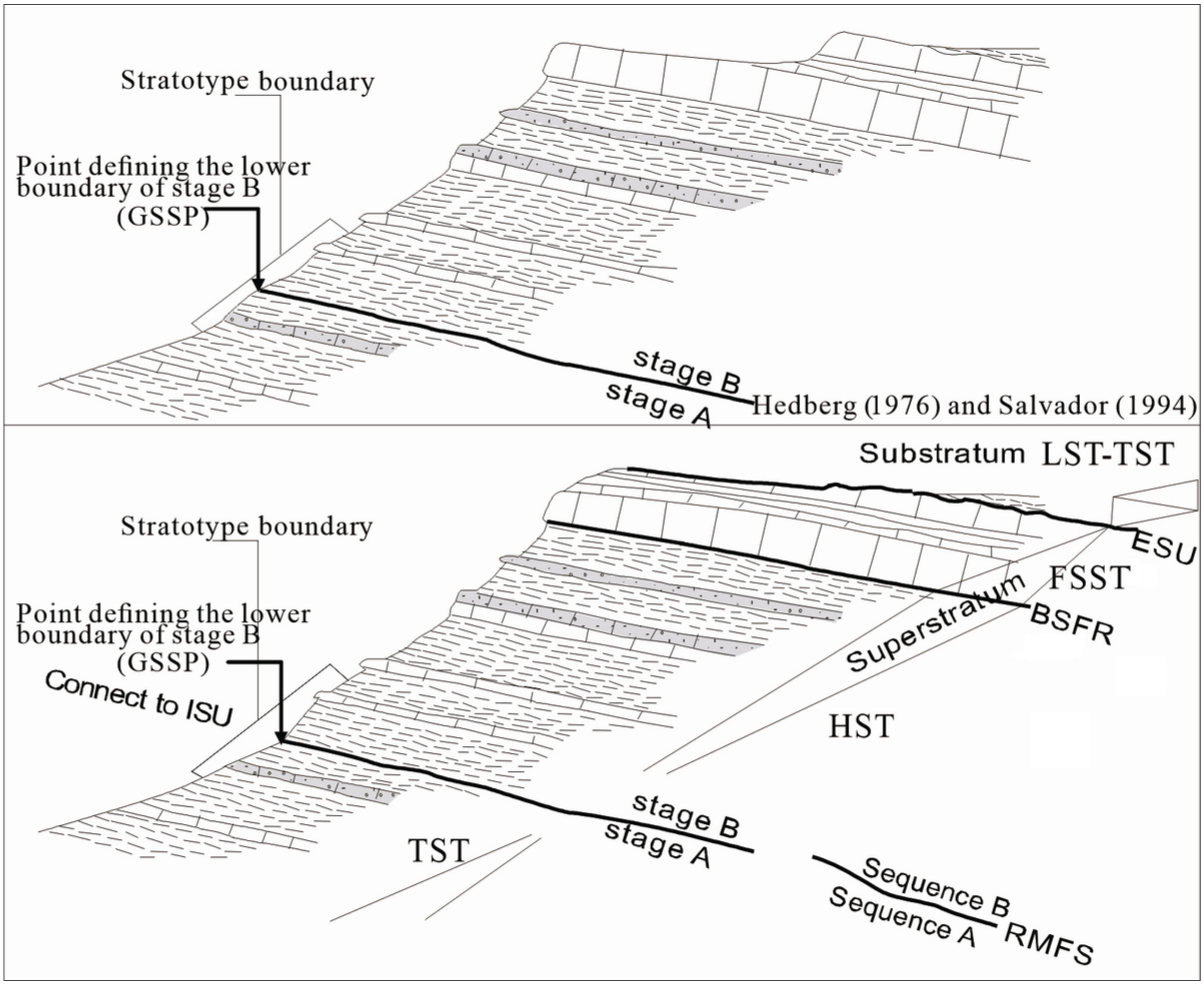

Figure 8

Stratotype boundary in a chronostratigraphic unit and the potentially matching remnant maximum flooding surface that bounds the future sequence stratigraphic units. Modified from Li et al. (2017). LST-lowstand systems tract; TST-transgressive systems tract; HST-highstand systems tract; FSST-falling-stage systems tract; ISU-intersecting subaerial unconformity.

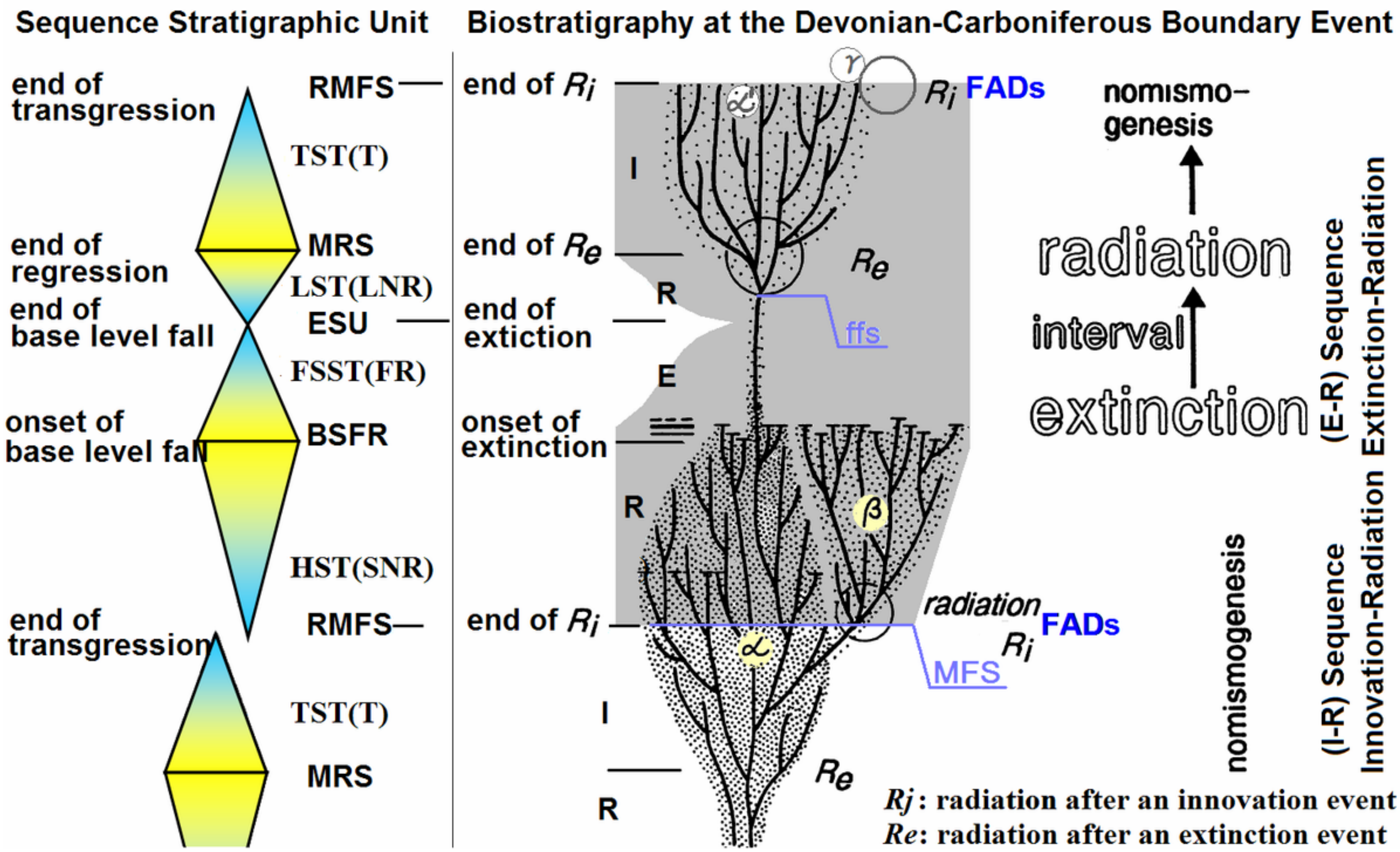

Figure 9

The “two rhombuses sandwiching one subaerial unconformity” pattern potentially corresponds tothe general pattern of evolutionary changes caused by an extinction event (Walliser, 1996). The maximum flooding surface (MFS) and transgressive surface (ts) are labelled by Wang (1999). LST-lowstand systems tract; TST-transgressive systems tract; HST-highstand systems tract; FSST-falling-stage systems tract; RMFS- remnant maximum flooding surface; ISU-intersecting subaerial unconformity; SNR- stillstand normal regression; FR-forced regression; LNR-lowstand normal regression. R-radiation; I-innovation; E-extinction; *Ri*-radiation after an innovation event; *Rj*-radiation after an extinction event.