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Cyclicity and hierarchy in sequence stratigraphy: an integrated approach

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Abstract

With standardized methodology and nomenclature, the sequence stratigraphy aims to characterize multi-scale cyclical units of genetically related rocks into a hierarchical chronostratigraphic framework. From facies to basin scale, the stacking patterns and stratigraphic surfaces are recognized as sequence elements. In parallel, Earth sciences have developed a sophisticated understanding of geological processes (tectonic, climatic, and eustatic) that produce the main cyclicity observed in the sedimentary rock record. This review paper discusses how the elaboration of hierarchical stratigraphic frameworks that incorporate the knowledge of these periodic geological processes — from high- to low-frequencies — as the control of generation and preservation of sequences — from high- to low-resolutions — guarantees objective results in predicting vertical recurrence and the lateral correlation of genetic stratigraphic units. This interpretive approach of cyclic stratigraphic analysis supports the development of effective observable criteria to identify and rank sequences in multiple scales, based on cycle anatomy, recurrence, vertical trends, and mappability. This methodological improvement reduces the inaccuracies and contradictions of traditional conceptual models based on fully preserved three-dimensional depositional systems.

KEYWORDS: sequence stratigraphy; cyclicity; hierarchy.

INTRODUCTION

Since the definition of "sequence" was provided by Sloss *et al.* (1949), a significant theoretical and technological evolution allowed the formulation of sequence stratigraphy in the current terms (*e.g.*, Sloss 1963, Mitchum 1977, Johnson and Murphy 1984, Posamentier *et al.* 1988, Van Wagoner *et al.* 1988, Galloway 1989, Embry and Johannessen 1992, Hunt and Tucker 1992, Catuneanu *et al.* 2011). Due to its academic scope and industrial applicability, sequence stratigraphy is recognized as the primary research program for stratigraphic analysis. The contributions in recent years have promoted the standardization of methodology and nomenclature (Catuneanu *et al.* 2010, 2011). Its modern application offers powerful tools for describing the observable record from facies cycle to basin scale, through the definition of sequences within a hierarchical chronostratigraphic framework (*e.g.*, Catuneanu 2019a). Notably, the sequential analysis on the outcrop scale has received special attention from the scientific community, increasingly improving what is known as high-resolution stratigraphy (*e.g.*, Magalhães *et al.* 2020).

During the last centuries, precursor and complementary research lines to sequence stratigraphy, that investigate the external and internal dynamics of the planet, provided a sophisticated comprehension of periodic eustatic, tectonic, and climatic processes, and their respective cyclical records observed in sedimentary sections. Thus, while sequence stratigraphy aims to identify and correlate cycles of genetically related rocks in the stratigraphic record, the study of geological processes contributes to elaborating robust conceptual models, which control the spatial and temporal distribution of sedimentary units. Such integrated solutions are critical, for example, for the evolution of modern three-dimensional stratigraphic-sedimentological forward modeling (*e.g.*, Faria *et al.* 2017).

However, aiming to universalize its application, recent publications have assigned to sequence stratigraphy a descriptive emphasis, based on the observation of stratal stacking patterns in the rock record, disassociating the methodology from the underlying sedimentary controls (*e.g.*, Catuneanu and Zecchin 2013, Catuneanu 2019a, 2019b). Although the segregation between description and subsequent interpretation seems prudent for practical functionality, it is crucial to keep in mind that, in a geological investigation, geologists do not always find completely objective data or information "purely given", but the way they analyze the record is always shaped by previous conceptions,

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expectations, and values (Frodeman 1995). In this sense, does the revised and updated knowledge about the geological processes that control sedimentation and, especially, the preservation of the sedimentary record have no role in developing the sequence stratigraphy workflow and methodology?

This paper is a review based on more than two decades of successful experience of the Petrobras School of High-Resolution Stratigraphy developed in cooperation with researchers from Brazilian and international universities, bringing together some relevant works produced on the subject. Following the concepts of sequence stratigraphy, the objective is to present: A brief conceptual discussion on the fundamental importance of preserving the cyclical sedimentary record in paleoenvironmental reconstructions; The main cyclic controls of sedimentary deposits that derive from periodic eustatic, tectonic, and climatic processes; The methodological advantages of integrating the most up-to-date knowledge of cyclic controls on sedimentation in defining a predictive logic that supports the identification of low- and high-resolution sequences organized in a hierarchical framework.

PHILOSOPHICAL FOUNDATION

The interdependence between description and interpretation in sequence stratigraphy

Sequences were originally designed to define stratigraphic units bounded by unconformities, mapped on continental scales "greater than the hierarchy of group or supergroup" (Sloss *et al.* 1949, Sloss 1963). Later, this definition was incorporated in seismic interpretation to outline smaller scale units (Vail 1992, Dott 2014). In this adaptation, the seismic recognition of sequences considered both subaerial unconformities and their marine extensions of correlative conformities (Mitchum 1977).

From 1970 to 1990, different proposals for definitions and models of sequences produced a profusion of propositions and jargon in the literature (Catuneanu 2006). Among some reasons for the origin of such a diversity of models are the use of different databases, the different sedimentary and geotectonic contexts, and the premises on primary sedimentation controls (Catuneanu 2006). Despite these differences, all models have been linked to base-level changes, and presented stratigraphic surfaces as the essential descriptive criterion in defining sequences (Fig. 1).

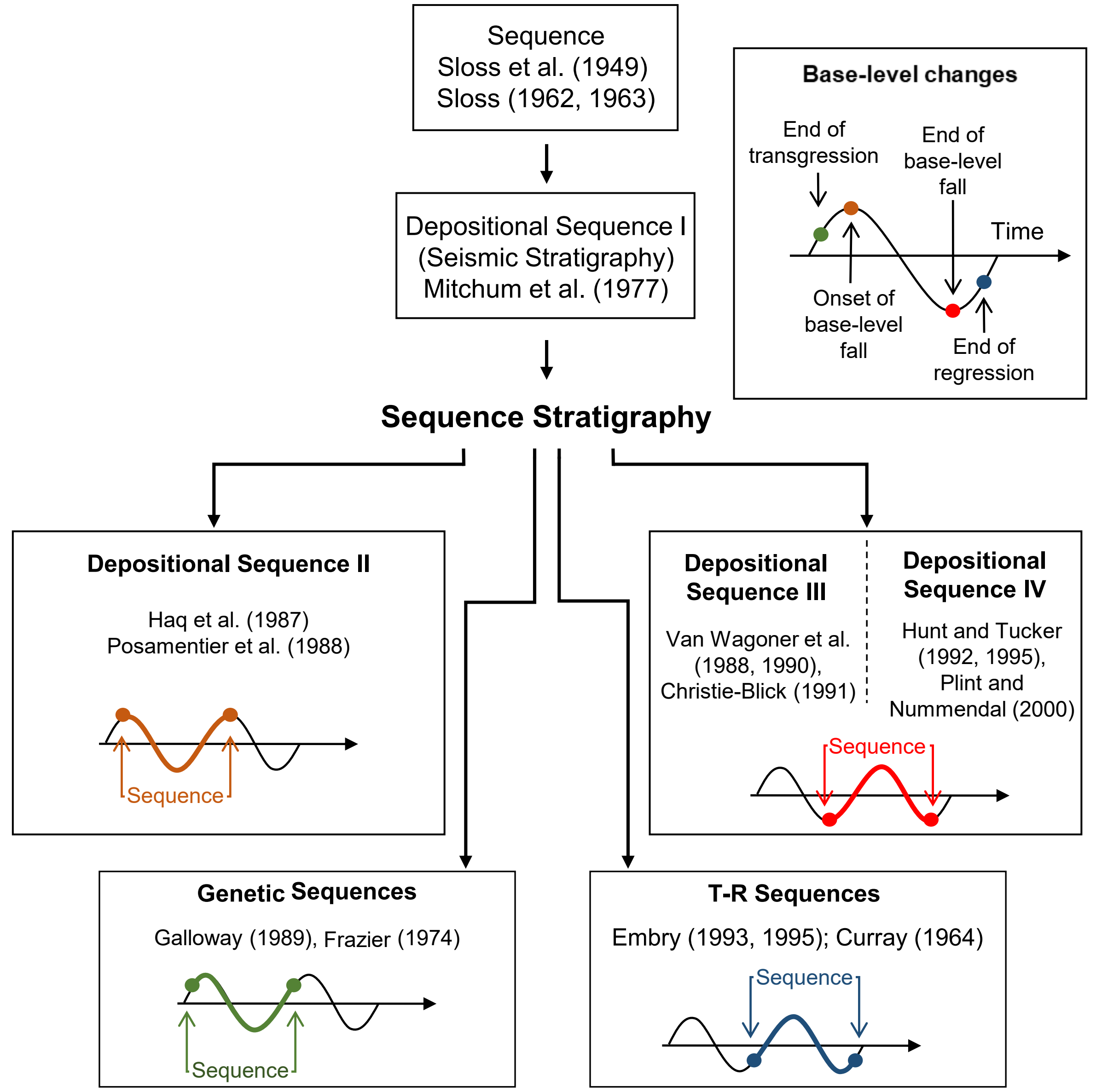
After the 2000s, methods and terms in sequence stratigraphy analysis were standardized (Miall 2016). In this context, Catuneanu *et al.* (2009, p. 19) defined a sequence as "a succession of strata deposited during a full cycle of changes in accommodation or sedimentary supply". This generic, yet advanced definition is independent of temporal and spatial scales and suitable for all previously proposed sequence models. However, despite its full acceptance by the community (*e.g.*, Catuneanu *et al.* 2011), this definition presented a possible weakness, once it did not offer objective criteria to describe sequences from a real dataset. Thus, Catuneanu and Zecchin (2013, p. 27) presented a revised definition of a sequence as "a cycle of change in stratal stacking patterns, dividable into systems tracts and bounded by sequence stratigraphic surfaces".

Catuneanu and Zecchin (2013), Catuneanu (2019a, 2019b) advocate that the concepts and methodology of sequence stratigraphy must be focused on observational field criteria of stratal stacking patterns in the rock record, regardless of the interpretation of the primary controls on sequence development. The main argument of these authors is that most elements of the sequences can be developed similarly as a product of different sedimentary processes. Thus, although the interpretation of the underlying controls may be at the base of the elaboration of a stratigraphic sequence framework, it "plays no role in the sequence stratigraphic workflow and methodology" (Catuneanu 2019a, p. 314).

Dissociation of accurate description from the subsequent interpretation seems prudent when so many variables are involved in building the stratigraphic record. For this reason, the definition of a sequence proposed by Catuneanu and Zecchin (2013) is valid and opportune. Keeping the methodology focused on observational field criteria is an advantage for stratigraphic sequence nomenclature and methodology. However, observation in geology differs substantially from other sciences that have an experimental and analytical basis (Fantinel 2005). Due to the complexity of the spatial and temporal scales involved in the stratigraphic investigation, one of the most significant methodological challenges is to give meaning to both the sedimentary record and the gaps (*e.g.*, Miall 2017). In this way, geologists are forced to fill in the gaps with reasonable interpretations (Frodeman 1995).

According to Catuneanu (2019a), the shoreline trajectory is a key element for describing progradation and retrogradation stacking patterns and associated systems tracts in downstream-controlled areas. However, the paleoenvironmental reconstruction, which determines transgressions and regressions at each stage of shoreline trajectory changes, is systematically and vertically interrupted by every non-gradual contact of the sedimentary succession. In this sense, the definition of stacking patterns, which is a basic descriptive task in the sequence stratigraphy practice, depends on the ability of geologists to properly bind the various interpreted paleoenvironmental fragments by assigning meaning to the gaps in the record (see item "General Problem on Conceptual Depositional System"). This is an elementary example of how the geological methodology, although based on well-defined descriptive criteria, will always have some subjectivity and dependence on interpretation.

The crucial point here is, instead of enhancing the antagonism, to propose a complementary view to rescue the simultaneous descriptive and interpretive approaches in sequence stratigraphy. In other words, the best definition of descriptive criteria for any stratigraphic framework results from the interpretation of how their respective organization could be developed (and vice versa). It is a dynamic dependency that does not end in the visualization of the geological record itself, but continues in a spiral between the descriptive experience and the interpretation, through the contact with new knowledge, new investigative contexts, and further investigation tools (Fantinel 2005). This approach does not weaken the



Depositional Sequence: Limited by subaerial unconformities and their marine correlative concordances

Genetic Sequences: Limited by maximum flood surfaces.

T-R Sequences: Limited by composite surfaces that includes by subaerial unconformities and the marine portion of the maximum regression surface.

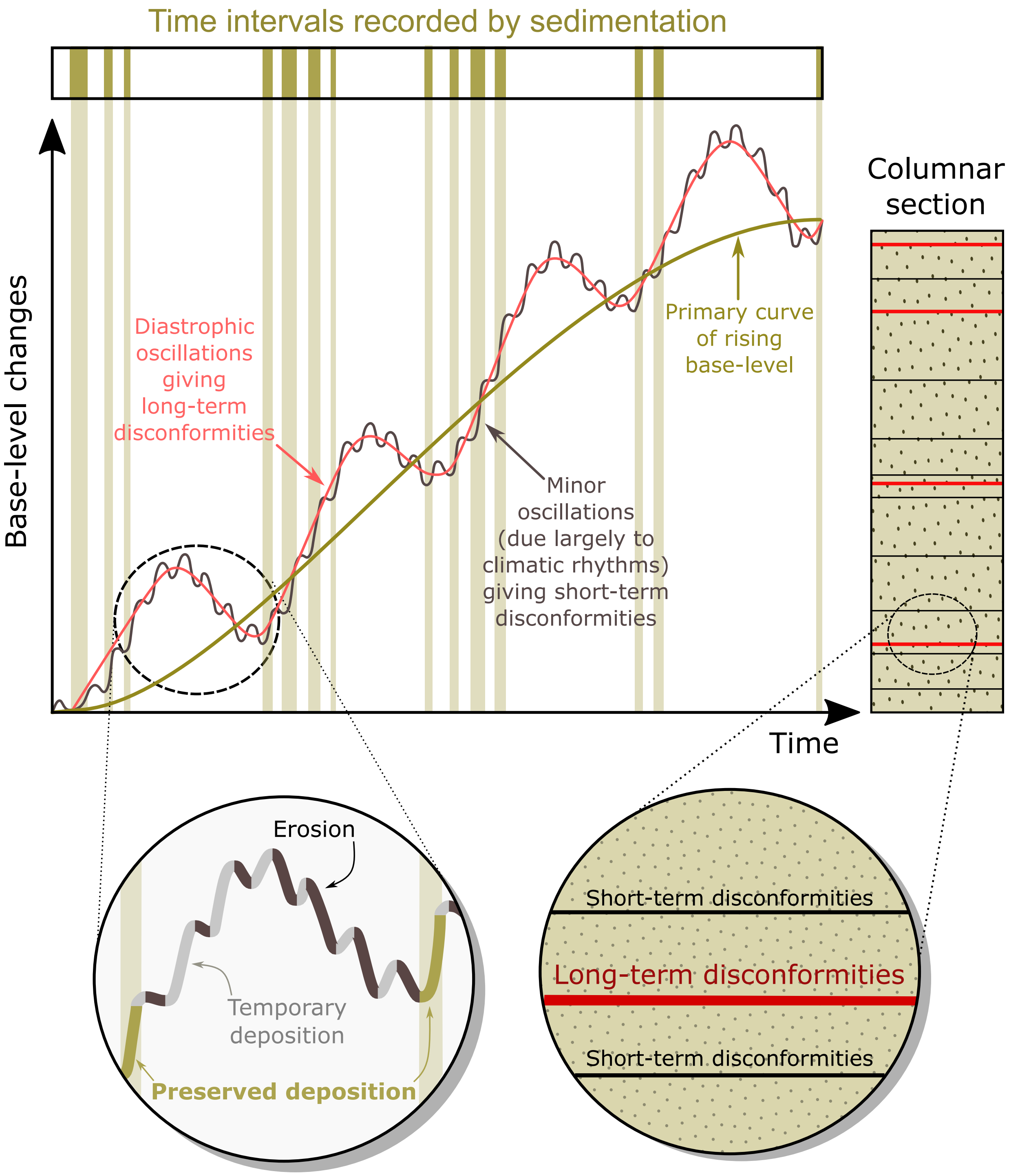
Source: modified from Catuneanu (2006).

Figure 1. Historical evolution of sequence stratigraphy models (modified from Catuneanu 2006). The nature of the separation of depositional sequence models III and IV is only semantic, relative to the systems tracts' distinct nomenclature with identical sequence limits.

observational field criteria on sequence stratigraphy analyses. On the contrary, the interpretative proposal advocated here associates the fundamental concepts of sequence stratigraphy (see item "Conceptual Foundation") with updated knowledge of periodic geological processes that control sedimentation, and especially, the preservation of the cyclical sedimentary record (see item "Allogenic Sequence-Generating Mechanisms"). This approach helps to define a predictive logic that supports improvements in the workflow and in the methodology of sequence stratigraphy at all scales permitted by the available data (see item "Sequence Hierarchy").

General problem on conceptual depositional system: the "Frankenstein models" vs. the preservation of cyclical sedimentary record

It is common sense that the hiatuses encompass much more time than the sedimentary rock record (*e.g.*, Dott 1983, Ager 1993, Miall 2017). According to Barrell (1917), the recurrent pattern of stratigraphic organization, which includes the rock record and the gaps, is a product of the rise and fall, in multiple amplitudes and frequencies, of the base level (Fig. 2). In this sense, the preserved sedimentary record corresponds to a tiny



Source: modified from Barrell (1917).

Figure 2. Graph represents the sedimentary stacking as a product of harmonic fluctuations of multiple frequencies of base-level changes. In this view, the low preservation of deposits (only one-sixth of the time) results in large gaps (unrecorded time is shown in the upper portion of the figure) and materialized as surfaces in the record.

fraction of the geological time, and its completeness is a function of the observation scale, whose control deteriorates as short as timescales (increased resolution) are considered (Sadler 1999).

Given the lack of tools or parameters for measuring so many time gaps, which are defined by high-resolution analysis, conceptual sedimentary models are traditionally elaborated from a controversial uniformitarian point of view. Thus, models are built based on the assumption that observations made on short time scales, accessible to human observation, can be reliably compared with sedimentary records that represent very long-time intervals (Miall 2015). Consequently, it is assumed that the geographic arrangement of architectural elements can represent fully preserved three-dimensional depositional systems. However, analyzing the shoreline shifts during the last glacial period (~ 20,000 years ago, Fig. 3) it is clear to deduce how sedimentary environments are ephemeral and susceptible to significant transformations.

Both the generation and preservation of sedimentary deposits in the stratigraphic record are dependent on processes operating during base-level fluctuations, promoting

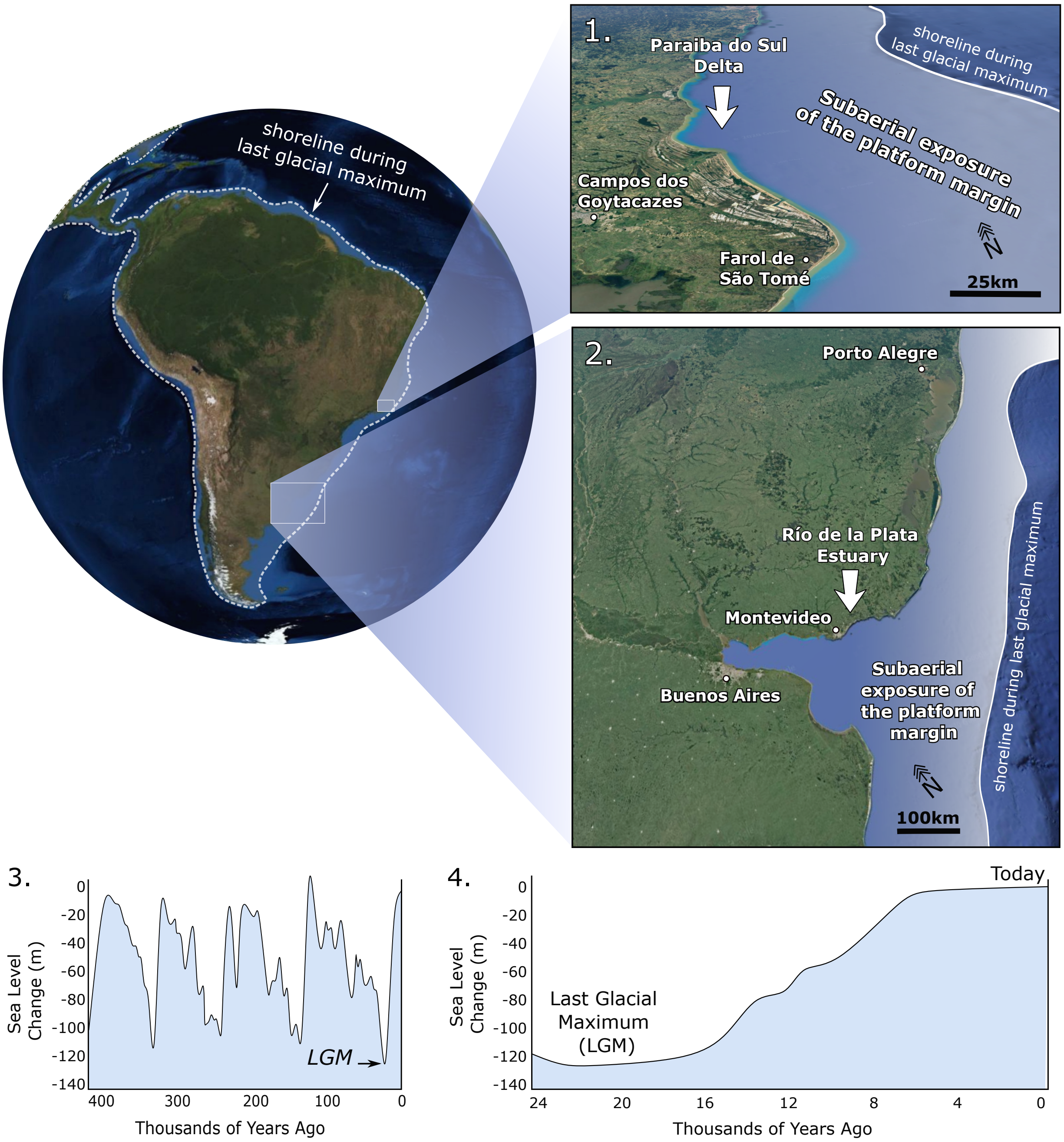


Figure 3. Simplified representation of the shoreline's mean position and the continental platform exposed in South America during the last glacial maximum (LGM) (based on Gautney 2018). Examples of modern environments, and indications of the approximate location of the shoreline during the LGM: (1) Delta of Parnaíba do Sul (State of Rio de Janeiro, Brazil); (2) Estuary of the Rio de la Plata (between Argentina and Uruguay). Below are models for the global variation in sea level over the past 400,000 (3 from Waelbroeck *et al.* 2002) and 24,000 years (4 from Wright *et al.* 2020).

the high-frequency overlap of different paleogeographies (*e.g.*, Magalhães *et al.* 2016, Silveira 2020). Such an alternation prevents the complete and idealized distribution of sedimentary environments in the geological record, limiting the application of Wather's law. Consequently, due to the inconsistencies in making the principle of actualism compatible with long-term processes, "Frankenstein Models" are proposed. "Frankenstein Models" is considered here as the unrealistic simplification of the geological record based on fragmentary information belonging to different geographic and temporal realities, usually alternating, and mistakenly assembled in supposedly complete depositional systems, developed, and preserved by a continuous process of sedimentation (Fig. 4).

To guarantee more realistic representations, conceptual models must incorporate the principles of high-frequency paleogeographic evolution, in which both the gaps and the preserved record occur in predictable and orderly stratigraphic patterns (Fig. 4) at all time scales (Miall 2017). Thus, the classical sedimentary approaches inherited from the lithostratigraphy, used in regional geological mapping, and the interpretation of sequences restricted to the seismic scale (low-resolution) need to be systematically revised. These large (low-resolution) mappable units usually brought together into "Frankenstein Models"

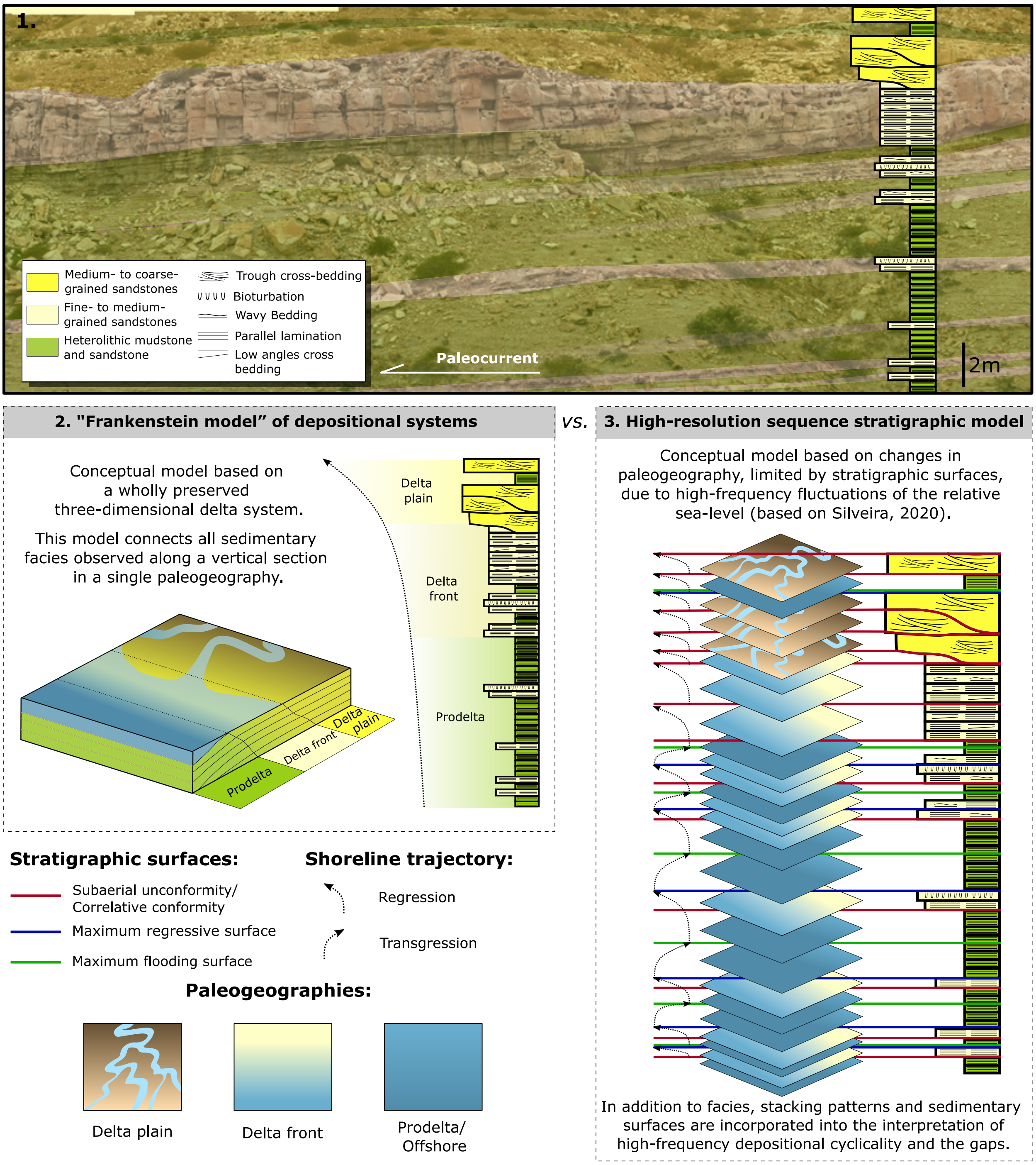


Figure 4. Difference between paleoenvironmental reconstructions of the same stratigraphic data: (1) Interpreted section of the Lajas Formation (Jurassic of Neuquen Basin, Argentina), showing prograding deltaic clinoform, including sedimentary log; (2) "Frankenstein model", based on fragmentary information mistakenly assembled in a wholly preserved three-dimensional depositional system; (3) the interpretation elaborated by the concepts of sequence stratigraphy, which considers both cyclic deposition and the gaps (example based on Silveira 2020).

are nothing more than the materialization of high-frequency trends during the evolution of long-term cyclic processes.

CONCEPTUAL FOUNDATION

Autogenic and allogenic processes

Autogenic and allogenic processes describe the controls of sedimentary dynamics. Autogenic processes are produced by the natural distribution of energy and sediments promoted by the intrinsic dynamics of the depositional environments. The occurrence of these processes is either quasi-periodic or episodic. Channel migration, lateral avulsion of delta lobes, and catastrophic sedimentary events are examples of autogenic dynamics. Such processes are commonly studied by conventional sedimentology of facies analysis and physical and numerical modeling (*e.g.*, Fick *et al.* 2017).

Allogenic processes correspond to forces external to the sedimentary environments, traditionally related to climatic, eustatic, and tectonic dynamics (see item "Allogenic

Sequence-Generating Mechanisms"). The effect of such processes represents the main control on accommodation (see item "Accommodation and Preservation") over large portions of a sedimentary basin, which supports stratigraphic correlations by depositional trends (Catuneanu 2006, Miall 2010, Catuneanu *et al.* 2011).

Distinguishing the record of these processes has been a matter of great discussion (*e.g.*, Trampush *et al.* 2017, Hajek and Straub 2017). Part of this discussion should consider how a given factor, alone or interactively, interferes with sedimentation and may influence the energy distribution of a given depositional system. Some authors argue that independent autogenic or allogenic effects may produce similar elements of sequences that characterize the anatomy of the sequence, such as stacking patterns and respective stratigraphic surfaces (*e.g.*, Catuneanu and Zecchin 2013). However, Schwarzacher (2000, p. 61) emphasized that "the practice of classifying the repetitive sediment sequences as 'autocyclic', without identifying a proper mechanism which causes the observed cyclicity, is highly unsatisfactory".

The repetition of allogenic processes is key for the comprehension of the stratigraphic framework based on regular and hierarchical patterns (Holbrook and Miall 2020). Thus, although the autogenic processes are inherent to the formation of any sedimentary succession (Hajek and Straub 2017), the knowledge about the frequency of allogenic processes provides essential prediction to sequence stratigraphy paradigms (*e.g.*, Shanley and McCabe 1994, Miall 2015).

Sedimentary supply and sedimentation rate

Any stratigraphic record can be described by its facies and sedimentary surfaces. In the final analysis, every sedimentary surface represents non-recorded time (Ager 1993). In turn, sedimentary facies correspond to the preserved product of erosion, transport, and depositional processes (*e.g.*, Schumm 1977, Reading and Levell 1996, Allen 2008). Sedimentary supply corresponds to the influx of sedimentary particles and solutes into the basin. The sedimentation rate varies by many orders of magnitude and may concern extrabasinal (allochthonous) or intrabasinal (autochthonous) sediment origin.

The extrabasinal sedimentary supply is linked to the production and distribution of terrestrial material. Sediment supply variation over time is closely related to continuous or catastrophic autogenic processes (*e.g.*, Einsele and Seilacher 1982, Dott 1983, Reading and Levell 1996). Nevertheless, allogenic influence can also affect sediment supply, such as tectonic processes in the source area and climatic variations (*e.g.*, Castelltort and Van Den Driessche 2003, Miall 2016, Romans *et al.* 2016).

The intrabasinal sedimentary supply can be produced by chemical, biochemical, and biological processes. The production of marine and lake carbonate and evaporite, for example, is mainly controlled by water geochemistry and temperature, influencing the nature and the productivity of the biota (*e.g.*, Reading and Levell 1996). Recycling is also in charge of the intrabasinal sedimentary supply, responsible for transporting particles between different domains of the basin (*e.g.*, Auchter *et al.* 2020).

Unlike sedimentary supply, which refers to the deposition process, the sedimentation rate is determined from the preserved accumulation. Therefore, estimates of sedimentation rates depend on the magnitude of the analyzed stratigraphic intervals (*e.g.*, Sadler 1999, Schlager, 2004, 2005, 2010, Miall 2015). Regardless of the depositional context, sedimentation rates systematically decrease with the increased analyzed time intervals (Sadler 1999; Fig. 5.1). In other words, the longer the measured time interval, the lower the sedimentation rate, since in very long stratigraphic intervals, several gaps are added to the time of deposition (Schlager 2005; Fig. 5.2). In this

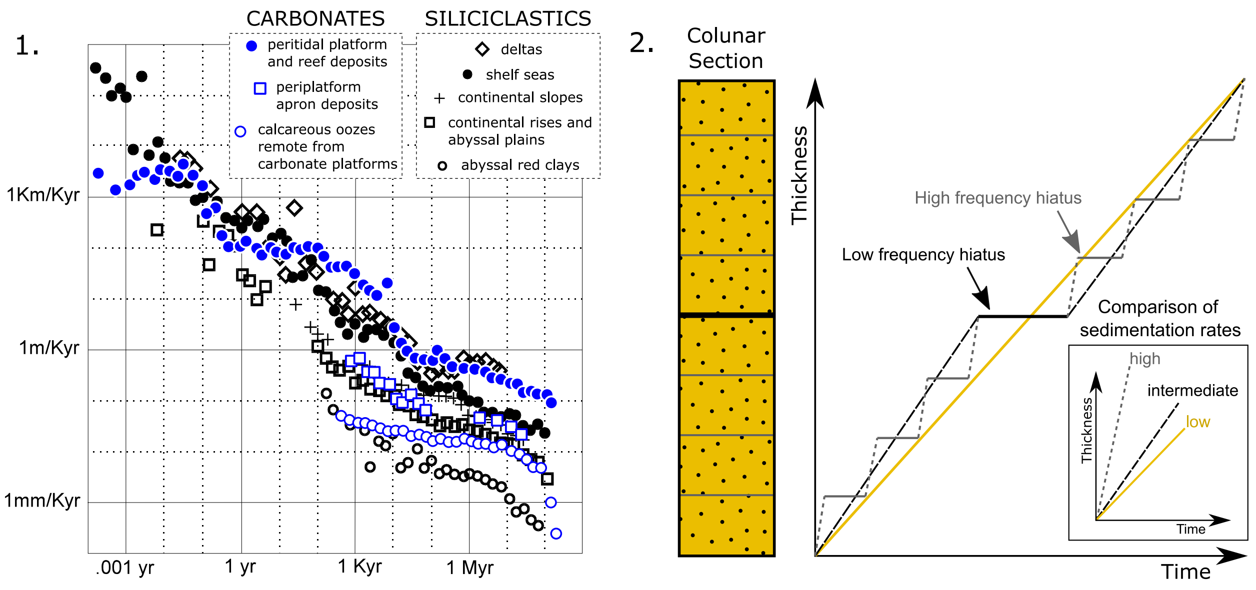


Figure 5. Sedimentation rates as a function of time intervals: (1) Mean accumulation rates for siliciclastic and carbonate sediments empirically determined as a function of time intervals (modified from Sadler 1999); (2) Schematic graph of time x stratigraphic thickness indicating how the calculated sedimentation rates are dependent on the length of the analyzed intervals between gaps (based on Schlager 2005).

sense, although it is possible to differentiate sedimentation from sediment supply and sedimentation rates, to analyze the stratigraphic record, it is essential to understand the controls of preservation at different scales using the variations in accommodation over geological time.

Accommodation and preservation

Jervey (1988) originally defined accommodation as the space below the base level (above which erosion will occur) available for sediments to fill. According to Jervey (1988), the base level is controlled by the sea, and, ultimately, is equivalent to the sea level. Although this accommodation concept is most used in sequence stratigraphy, some authors emphasize the need for improvements.

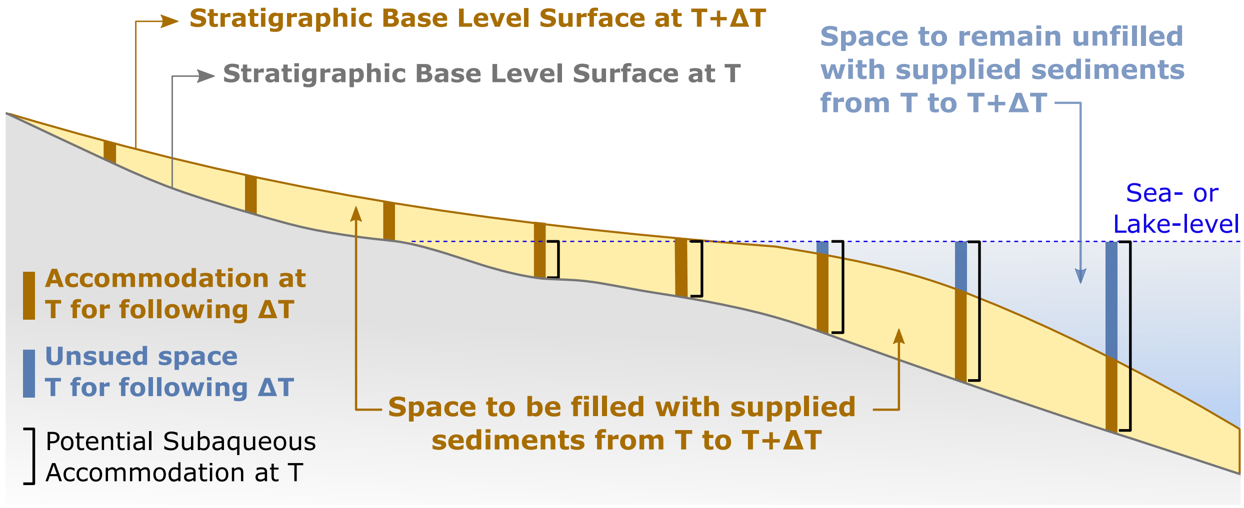
Muto and Steel (2000) proposed accommodation as "thickness, measured at a specified site and time, of a space which becomes filled with sediments during a specified time interval" (Fig. 6). In this sense, accommodation is treated objectively as a result rather than a potential. Exclusively in subaqueous environments, the "potential accommodation" can be analyzed in relation to the lateral paleogeographic variations over the same time interval, considering the bathymetry (Muto and Streel 2000; Fig. 7). In this sense, at a given time (correlatable stratigraphic interval), it is possible to assess, for example, that the "potential accommodation" is more significant in the center of any subaqueous environment than in its margins.

Accommodation variations can be described as relative (positive and negative) rates, which serve to analyze a time interval preserved in the record between each pair of chosen stratigraphic surfaces. This idea is fully compatible with the depositional base-level concept, as defined by Jervey (1988) and presented in the Barrell diagram (Fig. 2). Furthermore, as time is incorporated into the concept, it avoids the common mistake of considering accommodation as a discrete variable, comparable to absolute measurements of bathymetry.

The distribution and the dynamics of relative accommodation rates in a sedimentary basin, during its evolution in geological time, are influenced mainly by allogenic processes (*e.g.*, Shanley and McCabe 1994, Reading and Levell 1996, Coe *et al.* 2003, Fig. 7). The allogenic influence on accommodation establishes limits to the autogenic process of generating and preserving sequences (Fig. 8). This understanding is particularly crucial for stratigraphic correlations since, in most cases, the effect of allogenic processes can be identified over large areas within a basin or even in different ones (*e.g.*, Pittet and Strasser 1998).

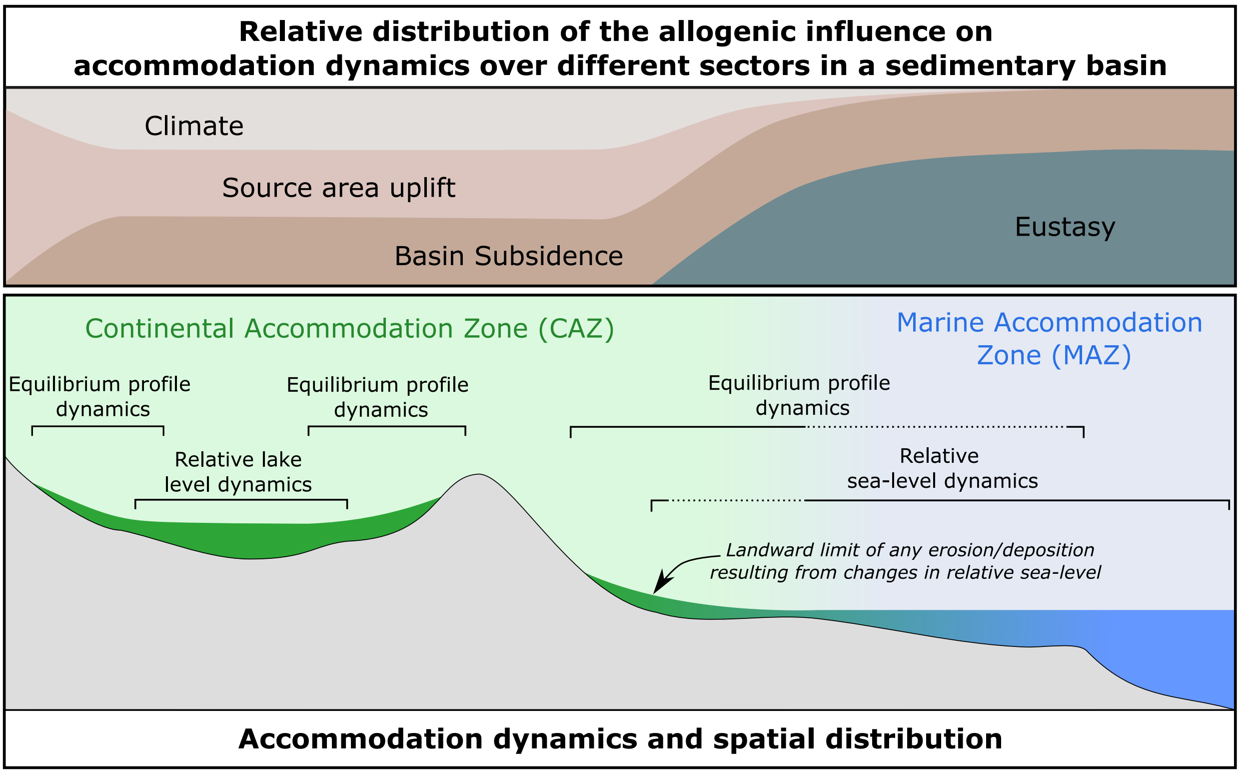
In general, the environments distributed over different sectors of a sedimentary basin can be subdivided into marine (MAZ) and continental (CAZ) accommodation zones (Fig. 7). In MAZ, which extends from the open ocean to transitional environments close to the shoreline, variations in accommodation are primarily controlled by basin tectonics and, mainly, by eustasy, whose integration results in the relative sea level (*e.g.*, Hunt and Tucker 1992). It is essential to consider that eustasy is not an independent factor, and a large part of its dynamics corresponds to a climatic effect (see items "Conceptual Foundation" and "Allogenic Sequence-Generating Mechanisms"). For this reason, in Figure 7, the "pure" climate process loses influence as the eustatic process becomes prevailing. In CAZ, the same reasoning for sea level can be adapted in lakes settings. The dynamics of accommodation in lake systems are due to tectonic and climatic variations (*e.g.*, Bohacs *et al.* 2000). The region between the uplifted areas and the sea or lake level is connected mainly by fluvial systems. Variations in accommodation in this region are associated with the dynamics of the equilibrium profile (*e.g.*, Miall 1996, Posamentier and Allen 1999), and all allogenic processes (tectonics of source area, basin subsidence, climate, and eustasy), intrinsically combined with autogenic processes, can promote changes in sedimentation patterns (Catuneanu 2006).

There is no way to define the end of the MAZ and the beginning of the CAZ since it is a gradual and variable limit in geological time. Throughout this transition, eustasy exerts



Source: modified from Muto and Steel (2000).

Figure 6. Accommodation can be considered as the resulting amount of space filled by sediments in each ΔT. The potential accommodation, that is, the maximum possible magnitude of accommodation that considers bathymetry, should be evaluated only within a specific time (T) and does not apply to subaerial environments.



Source: based on Shanley and McCabe (1994) and Coe *et al.* (2003).

Figure 7. Dynamics and spatial distribution of accommodation over the different sedimentary environments — marine (Marine Accommodation Zone — MAZ) and continental (Continental Accommodation Zone — CAZ). The dynamic of accommodation is strongly controlled by allogenic factors (climate, eustasy, subsidence of the basin, and elevation of the source area), but their relative influence varies along the basin. The main difference is in eustasy, which gradually loses its influence towards the Continental Accommodation Zone, where other controlling factors prevail.

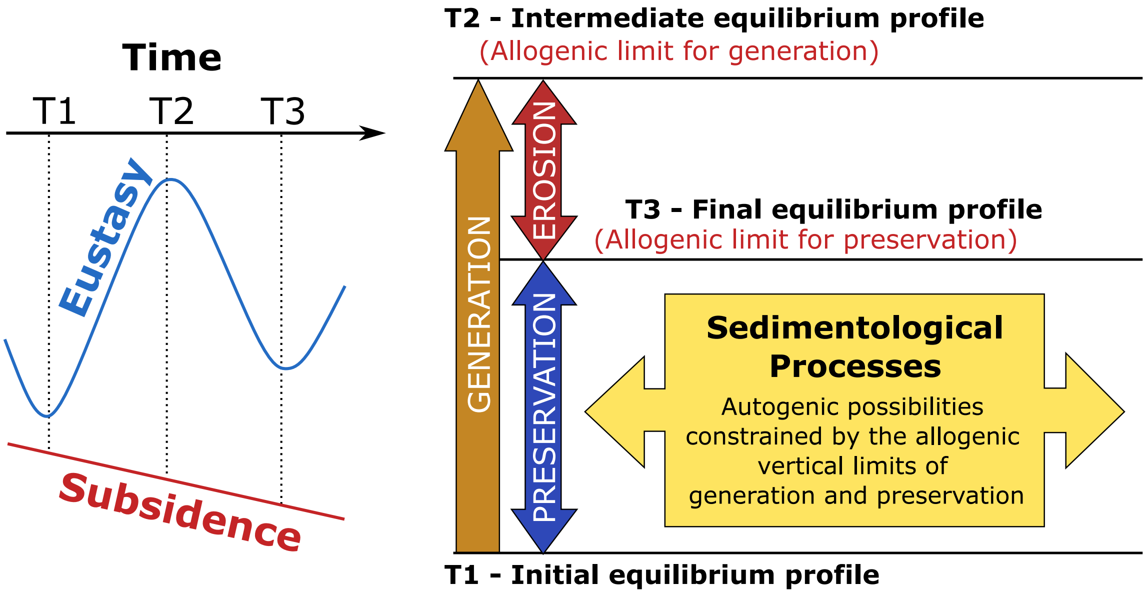


Figure 8. Interaction and contribution of allogenic and autogenic factors in the development of sequences of any scale. The generation (in T2) and preservation (in T3) resulting from eustasy and tectonic phenomena will always stratigraphically limit the preserved product of the continuous deposition governed by autogenic factors.

control — primary or secondary — in the deposition and preservation of marine and continental strata. The sequence stratigraphy literature has dedicated itself so much to analyze the sedimentary record over this transition that its nomenclature is primarily associated with shoreline trajectories (*e.g.*, Embry 1993). However, it is crucial to consider that what is observed in the sedimentary record are the preserved progradational and retrogradational stacking patterns and stratigraphic surfaces used to interpret regression and transgression trends of the shoreline. For the characterization of stacking patterns, variations in accommodation rates and sedimentary supply are considered together (*e.g.*, Catuneanu 2006).

Stacking patterns: the accommodation/sediment supply (A/S) ratio concept

The stacking patterns correspond to the record of organized sedimentary successions, where sedimentation trends are identified. Its concept underlies basic principles when defining stratigraphic units and sequence stratigraphy surfaces, regardless of scale (Catuneanu *et al.* 2011).

The criteria for defining stacking patterns range from facies relationships and layer geometry to reflector termination patterns seen in seismic data. They can be descriptive, regarding observations of the relationships between texture (coarsening and fining upward) and thickness (thickening and thinning upward) of sedimentary facies. However, they can also be interpretative, based on proximality and distality relationship (shallowing-upward and deepening-upward).

Stacking patterns can be understood as the record of paleogeographic evolution during fluctuations in accommodation (A) and sediment supply (S) rates (*e.g.*, Shanley and McCabe 1994; Fig. 9). When accommodation rates are positive ($A > 0$), stacking patterns can be aggradation (A/S ratio = 1), progradation ($0 < A/S < 1$) or retrogradation ($A/S > 1$). From these stacking patterns, the displacement of depositional systems and the shoreline trajectory are interpreted. Thus, retrogradation records shoreline transgression (*i.e.*, the landward migration of depositional systems), and progradation records shoreline regression (*i.e.*, the basinward migration of depositional systems). Aggradational stacking patterns correspond to a hypothetical situation in which the shoreline remains stationary. However, this term is most often used generically, describing vertical layer recurrence in any situation where $A > 0$ (*e.g.*, fluvial topset; Catuneanu 2006).

The A/S ratio concept can also be satisfactorily used to define stacking patterns in fluvial systems, regardless of sea or lake level influence (*e.g.*, Martinius *et al.* 2014). In general, the degree of amalgamation of channels in proportion to the overbank facies and the development of paleosols are used to characterize patterns of low-accommodation (or high-amalgamation; $0 < A/S < 1$) and high-accommodation (or low-amalgamation; $A/S > 1$) (*e.g.*, Wright and Marriott 1993, Shanley and McCabe 1994, Currie 1997, Martinius *et al.* 2014).

Regressions also occur when accommodation rates are negative ($A < 0$) during the base-level fall (*i.e.*, forced regression). At these times, large areas are eroded at the margin of the basin with concomitant deposition in relatively deep waters. The shoreline trajectory during $A < 0$ is called forced regression, in contrast to the normal regression interpreted when $A > 0$.

Correlations based on stacking patterns imply that depositional controls acted synchronously in many portions of the basin. However, it is necessary to consider that, in many cases, different stacking patterns can develop simultaneously due to different A/S rates along the depositional area. This condition is more critical at high-frequency analysis in tectonically active contexts, such as in foreland (reciprocal stratigraphy sense Cantueanu *et al.* 1999) and rift basins (*e.g.*, Howell and Flint 1996, Kuchle and Scherer 2010, Holz *et al.* 2017; Fig. 10). For this reason, understanding the geological processes that control variations in accommodation, sedimentary supply, and the preservation of stacking patterns is essential to describe and interpret the stratigraphic record. This comprehension provides robustness in the development of chronostratigraphic conceptual models in the most diverse depositional contexts, including, for example, glacial (*e.g.*, Powell and Cooper 2002), eolian (*e.g.*, Bállico *et al.* 2017), and deep water (*e.g.*, De Gasperi and Catuneanu 2014) environments.

ALLOGENIC SEQUENCE-GENERATING MECHANISMS

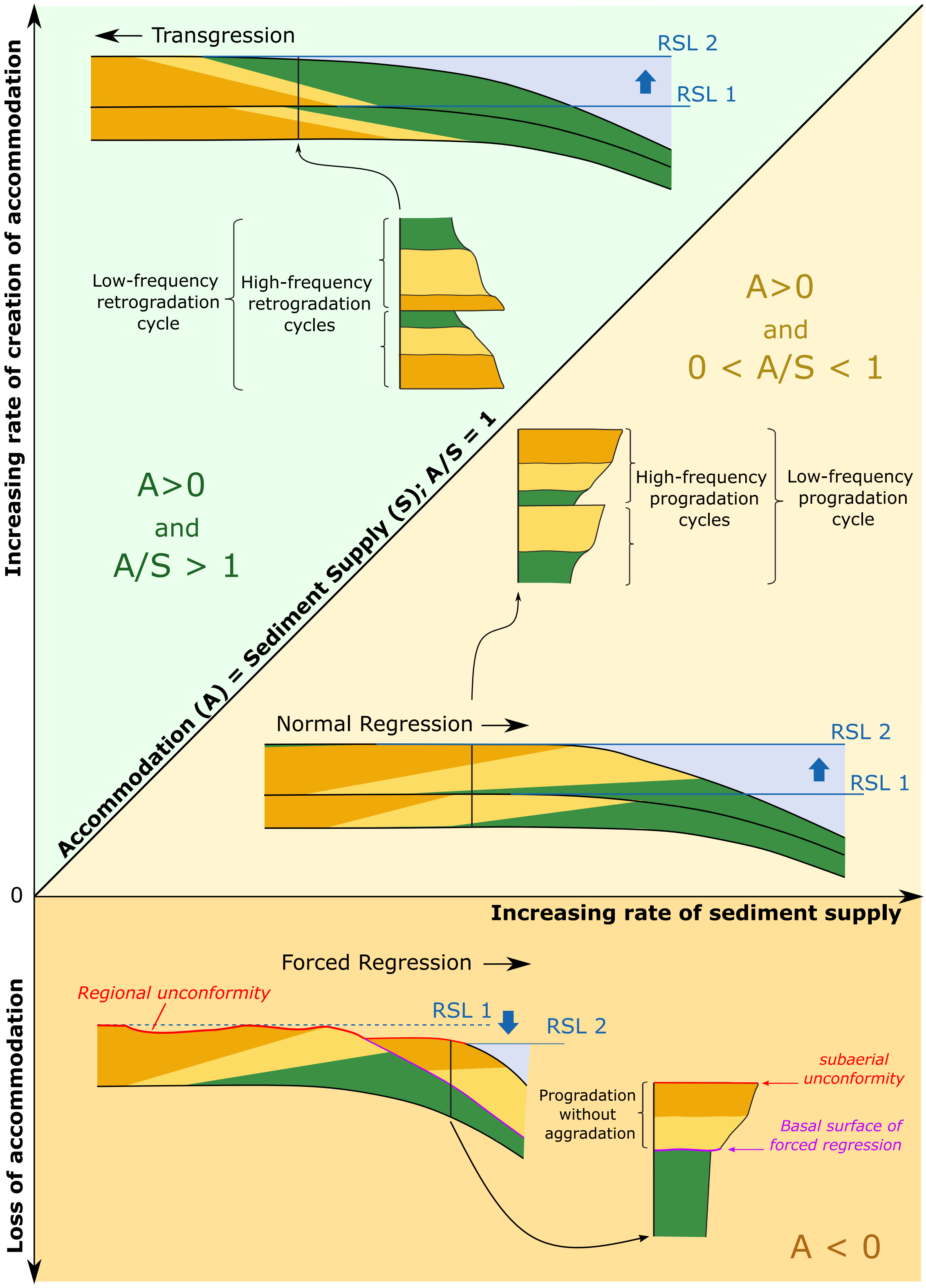
Eustasy

Eustasy is understood as a process of variation of the global sea level, measured to a fixed datum, commonly the Earth center (*e.g.*, Conrad 2013). During the 1970s and 1980s, seismic stratigraphy emphasized the importance of eustasy as the dominant control in stratigraphic architecture (Miall 2010). Climatic controls on eustasy (glacio-eustasy) were mainly associated with the generation of sequences (*e.g.*, Frazier 1974). However, the diastrophic (tectonic) impact is related to eustatic fluctuation since its conception (Miall 2010). The most accepted understanding is that eustasy is the combination of tectonic and climatic processes that cause changes in the ocean water volume and the average container volume (capacity) of ocean basins (*e.g.*, Sames *et al.* 2016, Sames *et al.* 2020, Fig. 11).

The variations in the available volume of ocean basins correspond to "long-term" processes (greater than 1 Ma), related mainly to the internal dynamics of the Earth that promote changes in the geometries and dimensions of the basins, as well as in their respective magmatic or sedimentary filling (*e.g.*, Sames *et al.* 2016, Ray *et al.* 2019). The controls of change in the ocean water volume include the processes of thermal expansion (thermo-eustasy) and the storage of water on the continents, either in the form of ice (glacio-eustasy) or underground and surface reservoirs (aquifer-eustasy) (*e.g.*, Sames *et al.* 2020). Such processes are "short-term" (up to 1 – 3 Ma), driven mainly by astronomical/climatic cyclicity (*e.g.*, Pittet and Strasser 1998). In addition, there is also the possibility of exchanging water between the ocean and the Earth's mantle, which involves higher time scales (*e.g.*, Ni *et al.* 2017, Nakagawa *et al.* 2018).

Tectonics

Although eustatic phenomena have been particularly vital to broadening the discussion on global chronostratigraphic correlations, their role, as proposed in the early days of seismic stratigraphy (*e.g.*, Payton 1977), proved to be insufficient to describe all sea-level variations observed in different contexts or scales (Miall 2016). This conclusion was crucial for developing the "relative sea level" concept (*e.g.*, Wilgus *et al.* 1988). Local tectonics, coupled with eustatic changes, cause significant sea-level variations, operating changes in accommodation

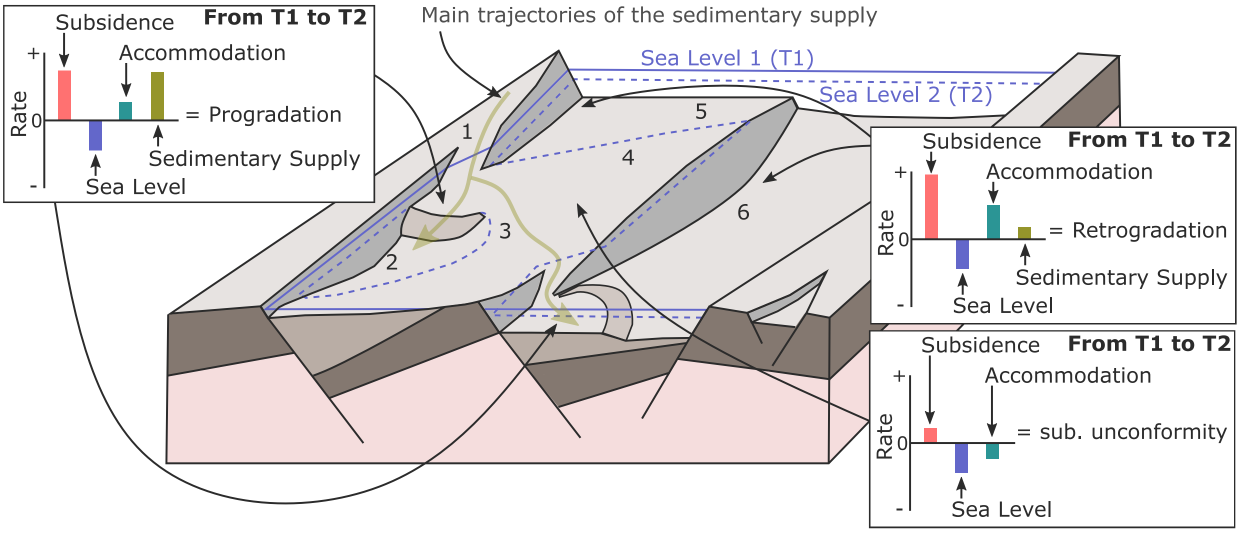


Source: modified from Shanley and McCabe (1994).

Figure 9. Schematic graph illustrating stacking patterns resulting from the balance between variations in accommodation (A, in this case, controlled by relative sea level — RSL) and sedimentary supply (S) rates (modified from Shanley and McCabe 1994). When accommodation rates are positive (A > 0), stacking patterns (progradation and retrogradation) and shoreline trajectories (normal regression and transgression, respectively) depend on the relationship with sedimentary supply rates (A/S). When the accommodation rate is negative (A < 0), erosion occurs landwards, and sedimentation advances to the depocenter, developing forced regression.

rates with various amplitudes and frequencies (*e.g.*, Matenco and Haq 2020).

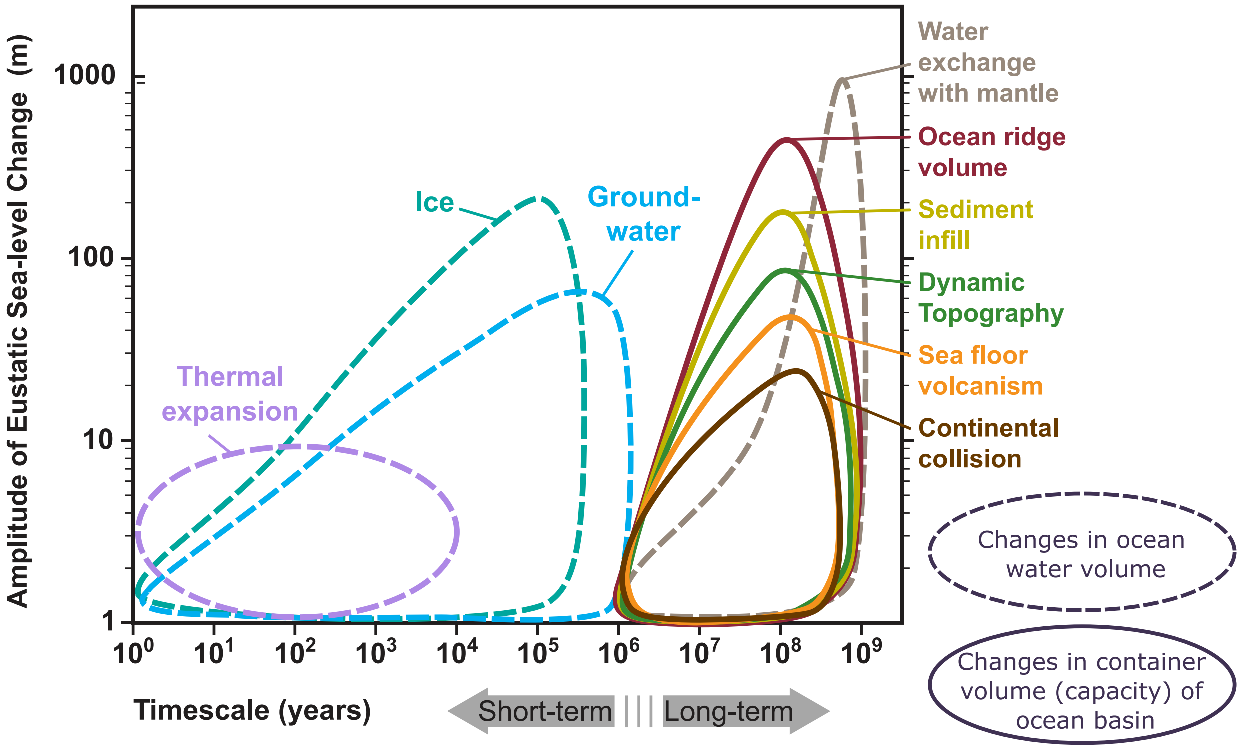
As mentioned, tectonics contributes globally to changes in the container volume (capacity) of the ocean basins. The tectono-eustasy (Fairbridge 1961) occurs over very long-time scales, producing deformation of ocean basins during the opening and closing of the oceans during the Supercontinent Cycles (or Wilson Cycles). However, beyond the changes in the volume of the ocean basin, the tectonic dynamics responsible for the "Supercontinent Cycles" during the Phanerozoic



1. Transfer zone at fault offset. Sediment input point. / 2. Hangingwall trough. / 3. Significant change in shoreline orientation following sea level fall. / 4. Localized ramp geometry oblique to general depositional dip direction./ 5. Localized shelf/slope break at fault scarp. / 6. Maximum subsidence in center of fault ellipse.

Source: modified from Howell and Flint (1996).

Figure 10. Schematic diagram showing different stacking patterns and surfaces developed simultaneously along a rift basin.

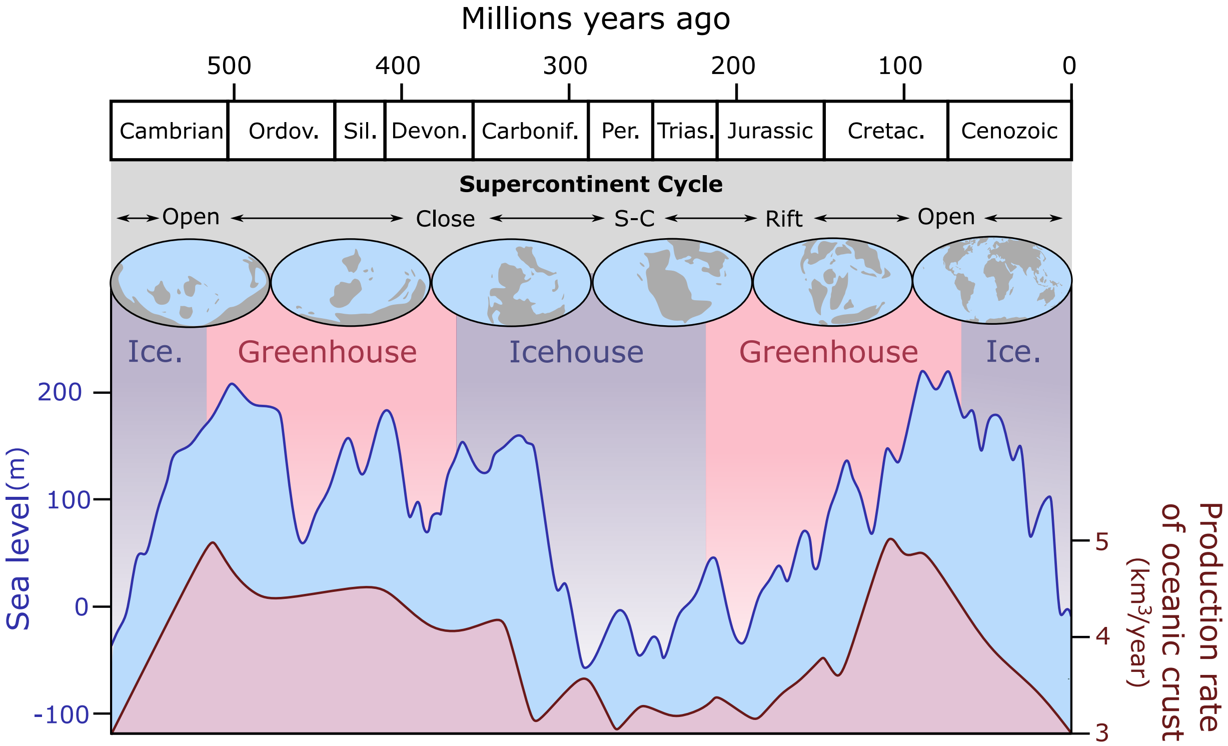


Source: modified from Sames *et al.* (2016) and Sames *et al.* (2020).

Figure 11. Log-scale diagram of the timing and amplitudes of the main mechanisms that control eustasy (modified from Sames *et al.* 2016 and Sames *et al.* 2020). The values represented must be considered as average dimensions.

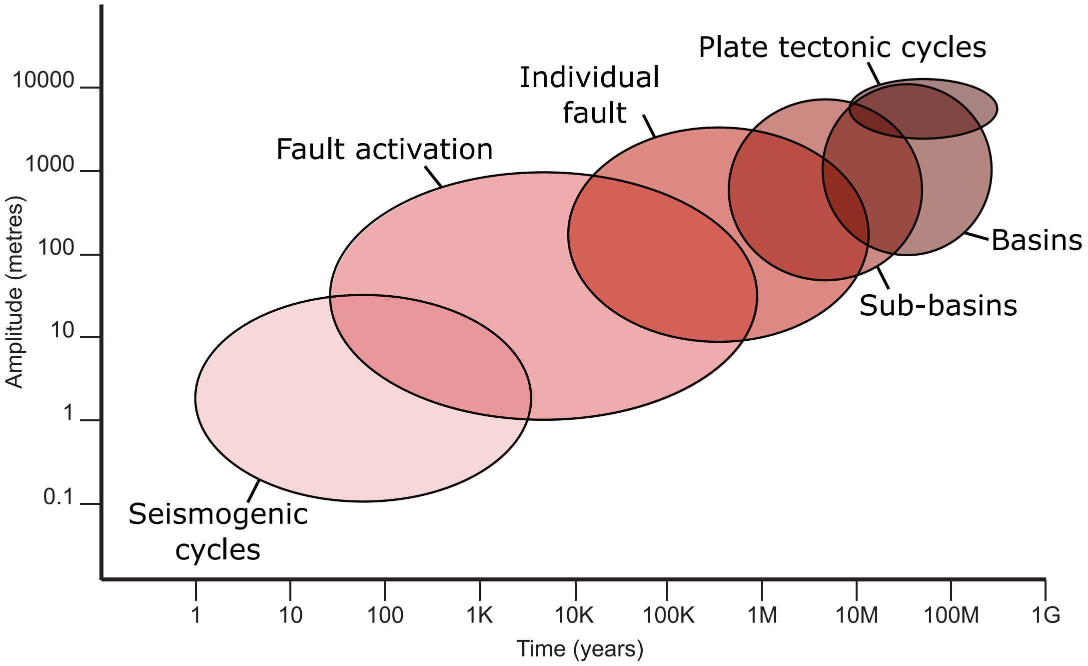
also influenced the Earth's climate, causing alternation between the Icehouse and Greenhouse stages (Fischer 1981, Kidder and Worsley 2010; Fig. 12).

During Icehouse, ice retains part of the ocean water. Conversely, during Greenhouse, high temperature inhibits ice formation on the continents. The association of these long-term climatic stages with tectonic dynamics and eustatic variations results in long-term oscillations in the eustatic level (*i.e.*, high during Greenhouse and low during Icehouse). It is necessary to consider that, despite wide variations in eustasy, changes in sedimentary environments throughout this cycle will only be preserved if local subsidence rates allow the balance of accommodation to be positive (*e.g.*, Strasser *et al.* 1999). Besides that, changes in accommodation rates due to tectonic activity can be more significant than any other forcing factor at any spatial and temporal scale (Matenco and Haq 2020; Fig. 13).



Source: based on Worsley *et al.* (1984), Takashima *et al.* (2006) and Nance *et al.* (2014).

Figure 12. Supercontinent (S-C) cycles during the Phanerozoic, including the alternation between Greenhouse and Icehouse stages, sea-level changes, and oceanic crust production rates.



Source: modified from Matenco and Haq (2020).

Figure 13. Log-scale diagram of the timing and amplitudes of the main tectonic mechanisms that promote accommodation changes, ranging from plate tectonic cycles to basins, sub-basins, individual faults, fault activation moments, and seismogenic cycles.

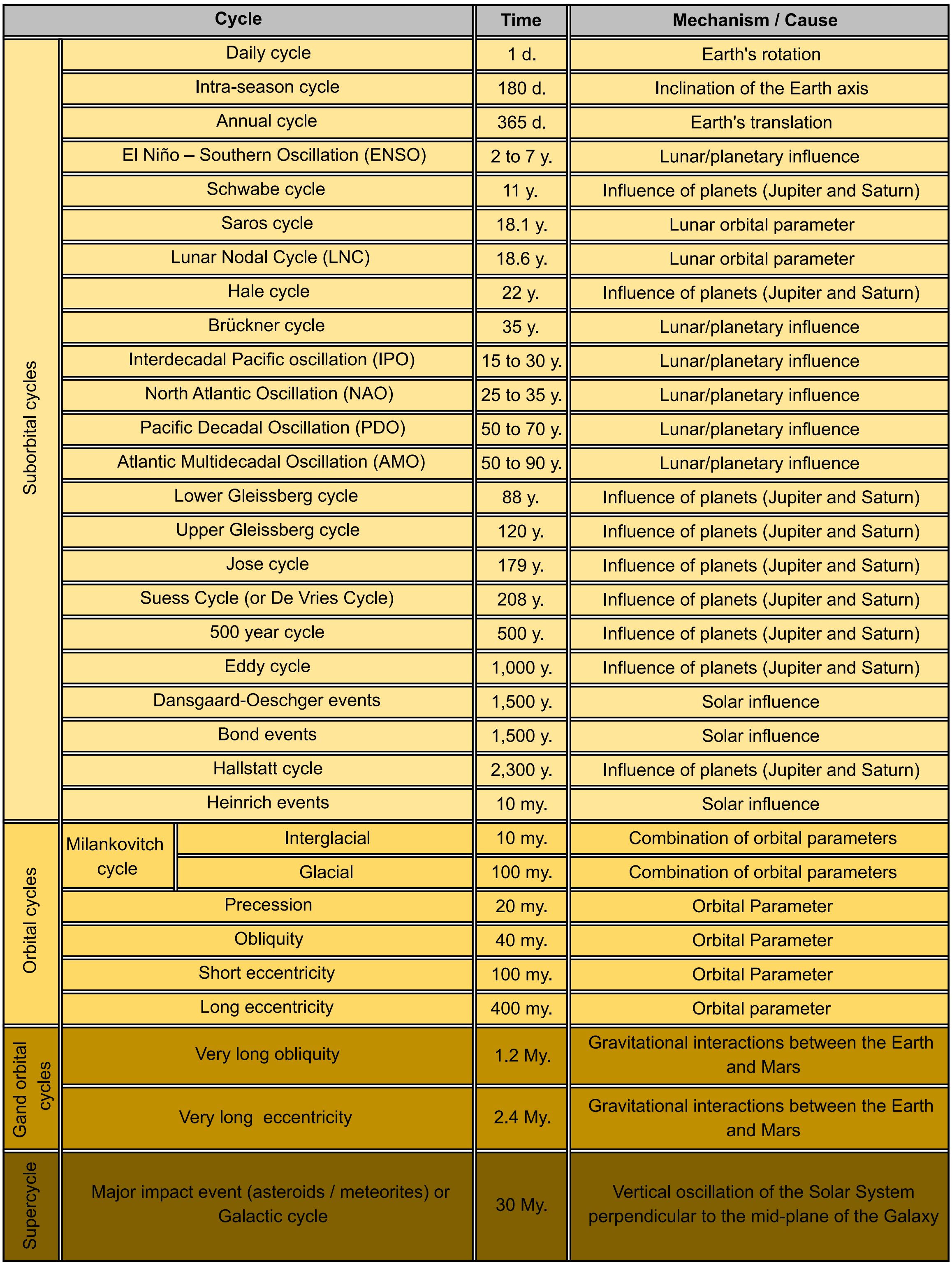
It is noteworthy that many processes that promote the development of deformations and shifts in topography, engendering changes in accommodation rates that are not directly related to geotectonics, such as halokinesis (*e.g.*, Rojo *et al.* 2020), sedimentary compaction (*e.g.*, Khani and Back 2015), and glacio-isostatic adjustment (*e.g.*, Dietrich *et al.* 2018).

Climate

As previously mentioned, planetary climate changes present a natural cyclic and regular dynamics, and many processes have the potential to leave their stratigraphic record preserved. Such processes have a wide range of known time frequencies, from daily scales to recurrences over millions of years.

In addition to the global changes related to tectonic dynamics (*e.g.*, Greenhouse and Icehouse; Fig. 12), astronomical cycles have been referred to in the literature as the main responsible for the planetary climate changes observed in the geological record (*e.g.*, Strasser *et al.* 2007).

Even if not perfectly conservative, astronomical cycles are the most regular oscillation known in nature. For this reason, they are used as a geochronological reference in cyclostratigraphic research (see item "High-resolution Sequence Stratigraphy"). Astronomical cycles are multiple and periodic events (simple or compound) that range from Earth's rotation, recorded in tidal deposits (tidal bundles), to the oscillation and revolution cycles of the Solar System in the galaxy, which also impress a recognizable sign in the geological record (House 1995, Hinnov 2013, Oliveira *et al.* 2017; Fig. 14). Most investigations in cyclostratigraphy attribute



Cycle			Time	Mechanism / Cause
Suborbital cycles	Daily cycle		1 d.	Earth's rotation
	Intra-season cycle		180 d.	Inclination of the Earth axis
	Annual cycle		365 d.	Earth's translation
	El Niño – Southern Oscillation (ENSO)		2 to 7 y.	Lunar/planetary influence
	Schwabe cycle		11 y.	Influence of planets (Jupiter and Saturn)
	Saros cycle		18.1 y.	Lunar orbital parameter
	Lunar Nodal Cycle (LNC)		18.6 y.	Lunar orbital parameter
	Hale cycle		22 y.	Influence of planets (Jupiter and Saturn)
	Brückner cycle		35 y.	Lunar/planetary influence
	Interdecadal Pacific oscillation (IPO)		15 to 30 y.	Lunar/planetary influence
	North Atlantic Oscillation (NAO)		25 to 35 y.	Lunar/planetary influence
	Pacific Decadal Oscillation (PDO)		50 to 70 y.	Lunar/planetary influence
	Atlantic Multidecadal Oscillation (AMO)		50 to 90 y.	Lunar/planetary influence
	Lower Gleissberg cycle		88 y.	Influence of planets (Jupiter and Saturn)
	Upper Gleissberg cycle		120 y.	Influence of planets (Jupiter and Saturn)
	Jose cycle		179 y.	Influence of planets (Jupiter and Saturn)
	Suess Cycle (or De Vries Cycle)		208 y.	Influence of planets (Jupiter and Saturn)
	500 year cycle		500 y.	Influence of planets (Jupiter and Saturn)
	Eddy cycle		1,000 y.	Influence of planets (Jupiter and Saturn)
	Dansgaard-Oeschger events		1,500 y.	Solar influence
	Bond events		1,500 y.	Solar influence
	Hallstatt cycle		2,300 y.	Influence of planets (Jupiter and Saturn)
	Heinrich events		10 my.	Solar influence
Orbital cycles	Milankovitch cycle	Interglacial	10 my.	Combination of orbital parameters
		Glacial	100 my.	Combination of orbital parameters
	Precession		20 my.	Orbital Parameter
	Obliquity		40 my.	Orbital Parameter
	Short eccentricity		100 my.	Orbital Parameter
	Long eccentricity		400 my.	Orbital parameter
Gand orbital cycles	Very long obliquity		1.2 My.	Gravitational interactions between the Earth and Mars
	Very long eccentricity		2.4 My.	Gravitational interactions between the Earth and Mars
Supercycle	Major impact event (asteroids / meteorites) or Galactic cycle		30 My.	Vertical oscillation of the Solar System perpendicular to the mid-plane of the Galaxy

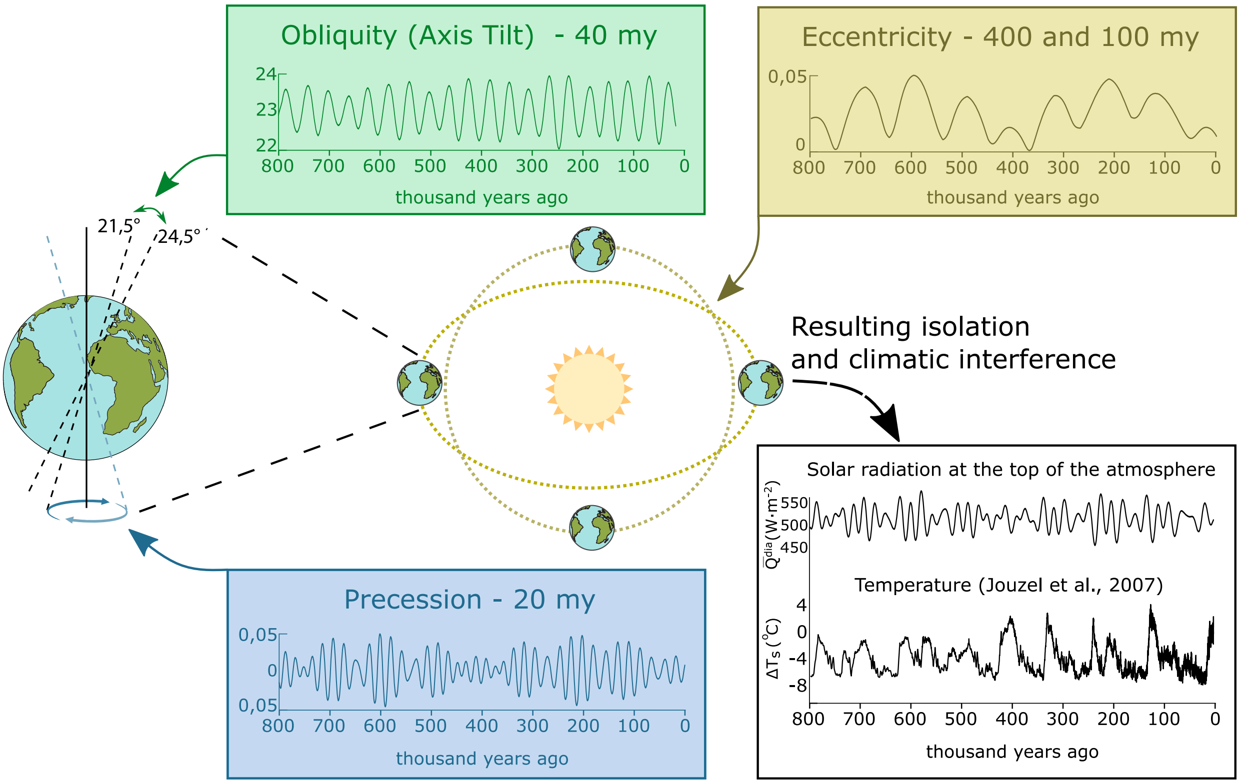
Legend: d = day(s); y = year(s); my = thousands of years; My = Millions of years.

Source: modified from Oliveira *et al.* (2017).

Figure 14. Synthesis of climatic cycles, their timing, and the related astronomical mechanisms.

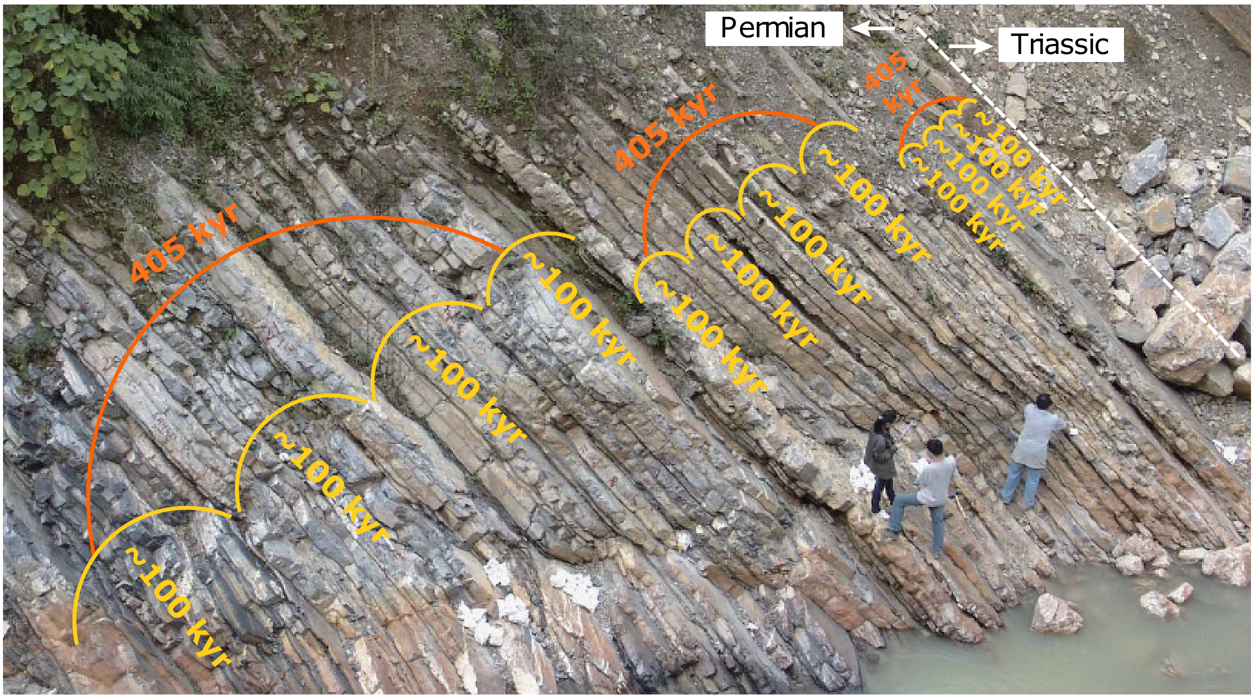
to the Milankovitch cycles (Fig. 15) the main recurrences observed in the stratigraphic record in outcrop and core scale (*e.g.*, Wu *et al.* 2013; Fig. 16). However, higher-resolution studies have shown that orbital signals are commonly superimposed by higher frequency cycles (sub-orbital cycles) with the recurrence spectrum from centennial to annual scale (*e.g.*, Li *et al.* 2019; Fig. 17).

The success of the theory presented by Milankovitch (1941) derives from his precise calculations that demonstrated how the orbitally driven variability in the solar



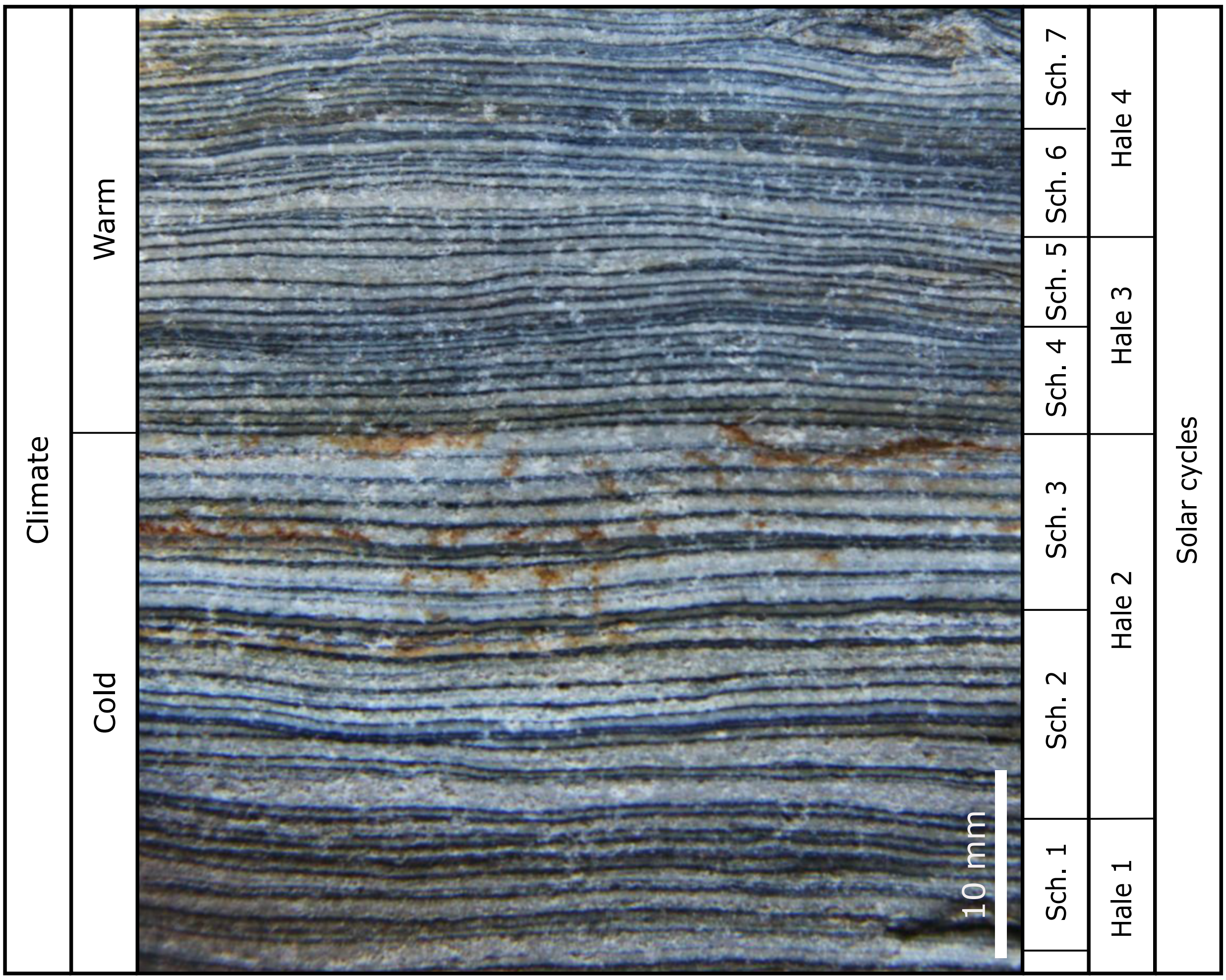
Source: modified from Oliveira *et al.* (2017) and Jouzel *et al.* (2007).

Figure 15. Orbital parameters (Milankovitch cycles) and the result of the solar radiation at the top of the atmosphere in the subsequent control of global temperature in the last 800 thousand years.



Source: modified from Wu *et al.* (2013).

Figure 16. Visual identification of Milankovitch cycles in an outcrop of Permian marine carbonates from the Dalong Formation, China (modified from Wu *et al.* 2013). Note the groups of layers identified as a product of precession forming cycles of 100 kyr (short eccentricity) regrouped in cycles of 405 kyr (long eccentricity).



Source: from Li *et al.* (2018).

Figure 17. Schwabe (Sch. 1 to 7) and Hale (1 to 4) cycles (see Fig. 14 for references) identified in shallow marine deposit with microbial influence of the Wuqiangxi Formation, Neoproterozoic (810-715 Ma) in South China.

radiation received by the Earth over time determines the glacial/interglacial cycles during Icehouse stages. Currently, the orbital parameters satisfactorily explain the main climatic cycles in geological time, being a reference to determine, for example, the short-term eustatic changes in both the Icehouse and Greenhouse stages (*e.g.*, Sames *et al.* 2020; Fig. 11).

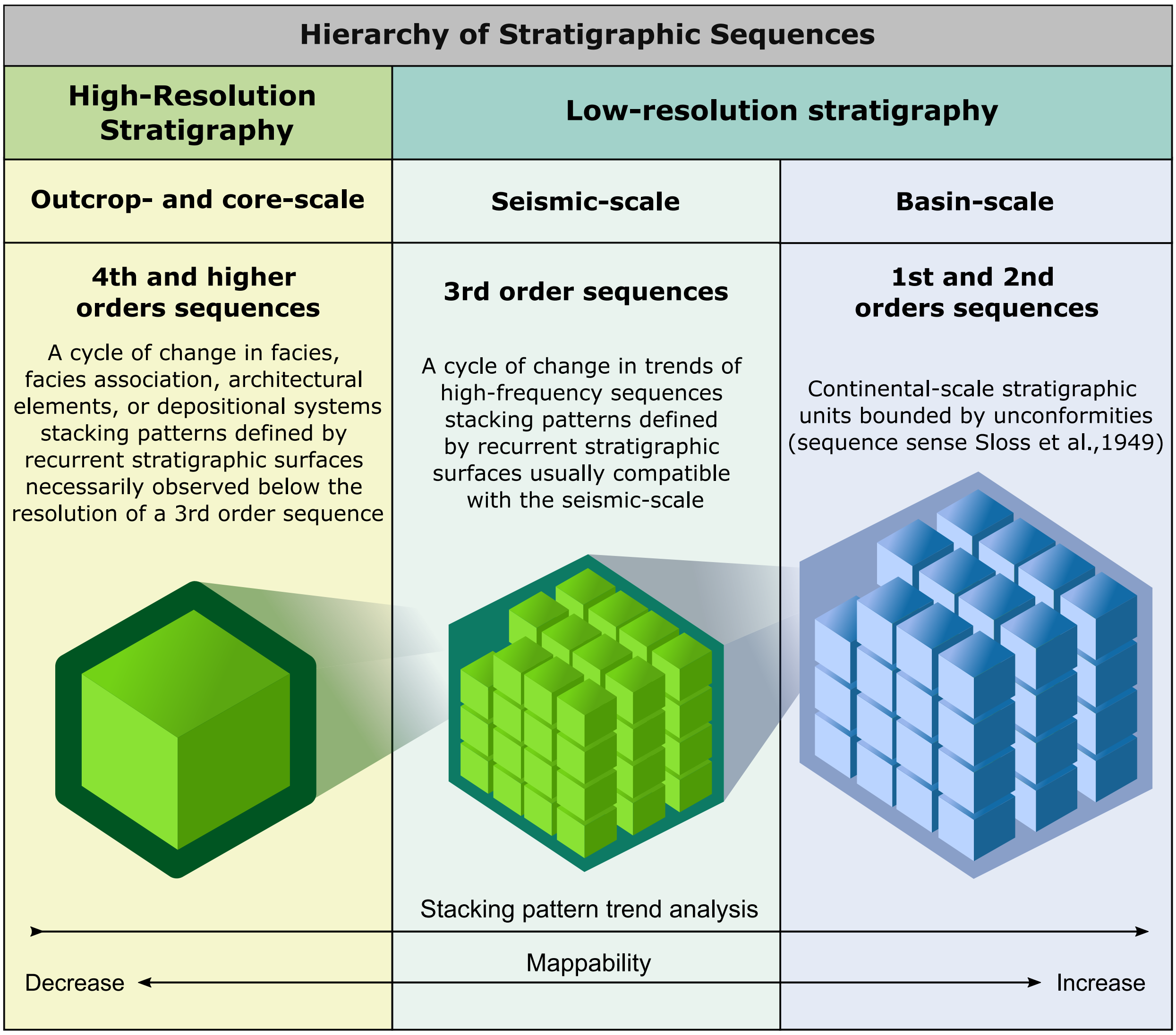
Besides eustatic changes, the constant variations in insolation result in climatic impacts that, ultimately, exert an influence of different magnitudes not only on accommodation rates in continental environments but also on the sedimentary supply rates of organic and inorganic sediments (Li *et al.* 2019). Furthermore, as climate and tectonics are coupled systems, feedback effects can occur at different scales. For example, the intensity of erosion promoted by the climate on a tectonically deformed crust can stimulate faults motion due to reducing lithostatic load (Allen 2008). Therefore, a systematic analysis is always required to understand the boundary conditions of sedimentation and preservation in the stratigraphic record, and a multi-frequency sequence stratigraphic analysis can be a satisfactory way to achieve a solution.

SEQUENCE HIERARCHY

Accordion effect of resolution on stratigraphic analysis

Characterizing and understanding the multi-scale cyclical behavior of the sedimentary record has been one of the most critical aspects of stratigraphic analysis (Schwarzacher 1993, 2000). In the context of sequence stratigraphy, the stratigraphic cyclicity observed at different scales can be described as sequences from different hierarchical levels, in which the stacking pattern of a higher order is composed of an organized amalgamation of lower rankings sequences (Catuneanu 2006, 2019a, Magalhães *et al.* 2020; Fig. 18).

The most accepted hierarchical sequence classification starts with a basin-fill reference (Catuneanu 2006). Thus, a first-order sequence is defined as the complete filling of a sedimentary basin developed within a specific tectonic configuration. Therefore, a first-order sequence can be subdivided into second and subsequently lower orders. As a corollary, the magnitude of correlation should decrease, and, inversely, the recurrence of stratigraphic surfaces should increase toward the lower hierarchical level.



Hierarchy of Stratigraphic Sequences		
High-Resolution Stratigraphy	Low-resolution stratigraphy	
Outcrop- and core-scale	Seismic-scale	Basin-scale
4th and higher orders sequences A cycle of change in facies, facies association, architectural elements, or depositional systems stacking patterns defined by recurrent stratigraphic surfaces necessarily observed below the resolution of a 3rd order sequence	**3rd order sequences** A cycle of change in trends of high-frequency sequences stacking patterns defined by recurrent stratigraphic surfaces usually compatible with the seismic-scale	**1st and 2nd orders sequences** Continental-scale stratigraphic units bounded by unconformities (sequence sense Sloss et al.,1949)

Source: modified from Magalhães *et al.* (2020).

Figure 18. Hierarchy of stratigraphic sequences based on cycles observed at different scales.

Each sequence hierarchy observed in a sedimentary succession can be understood as a product of accommodation variation in different magnitudes and durations (*e.g.*, Neal and Abreu 2009). An analogy proposed here to understand the resolution in sequence analysis resulting from a variable spectrum of accommodation is named the "accordion effect". A gain of resolution in detecting the high-frequency signal of fluctuations in the A/S ratio (short duration) occurs at times of high rates of long-term accommodation. In this sense, it is like the expansion of accordion's folds (Fig. 19.1). When the increase in long-term accommodation is not significant, there is a decrease in the high-frequency sequence resolution (Fig. 19.2). Jerolmack and Paola (2010) describe this phenomenon as "signal shredding", when there is the removal of evidence of short-term fluctuation in the A/S ratio of the sedimentary record as a consequence of the energetic and dispersive action of the sedimentary processes, generating missing beats (*e.g.*, Hardie *et al.* 1986, Steinhauff and Walker 1995, Strasser 2015). On the other hand, the lack of definition for high-frequency stratigraphic analysis can also happen when potential accommodation is high and sedimentation rates are very low, as is the case of condensed sections (Strasser 2015). Hence, as accommodation rates are continually changing, the visible "accordion effect" in the vertical scale of low-frequency analysis occurs from hiatus zones to condensation zones, and vice versa. In correlations, the resolution of the stratigraphic analysis varies according to the "potential accommodation" (sense Muto and Steel 2000; Fig. 7). At each correlatable interval, there will be a relative increase in the resolution of stratigraphic analysis (accordion effect) toward the down-dip of paleogeographic variations (Fig. 20).

In general, the long- and short-term relationship is arbitrary, and this sequence subordination analysis is valid for all observable scales. Thus, the possibilities for generating and preserving stacking patterns of any frequency are controlled by the vertical limits of accommodation and preservation of a higher hierarchical level, engendering the preservation of every high-frequency cycle.

An example of resolution for different sequence hierarchies (1st- to 4th-order) is observed in the Mesoproterozoic Tombador

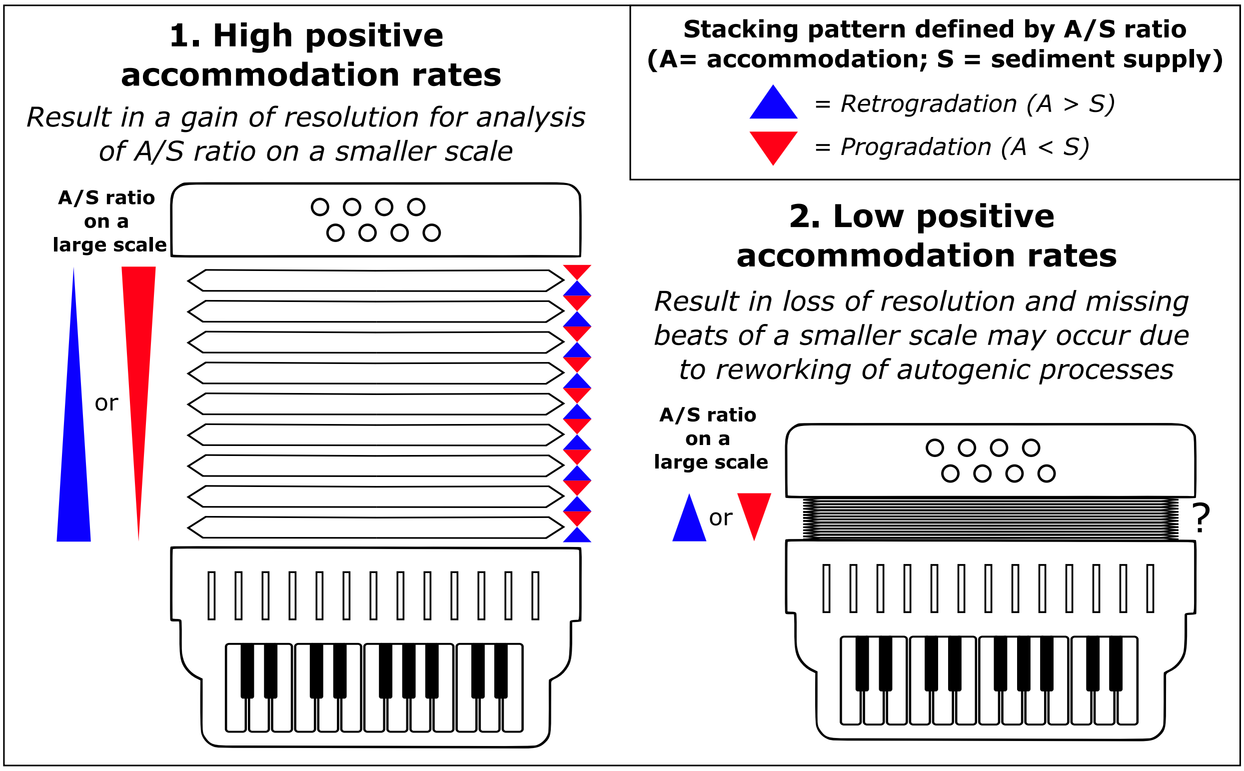
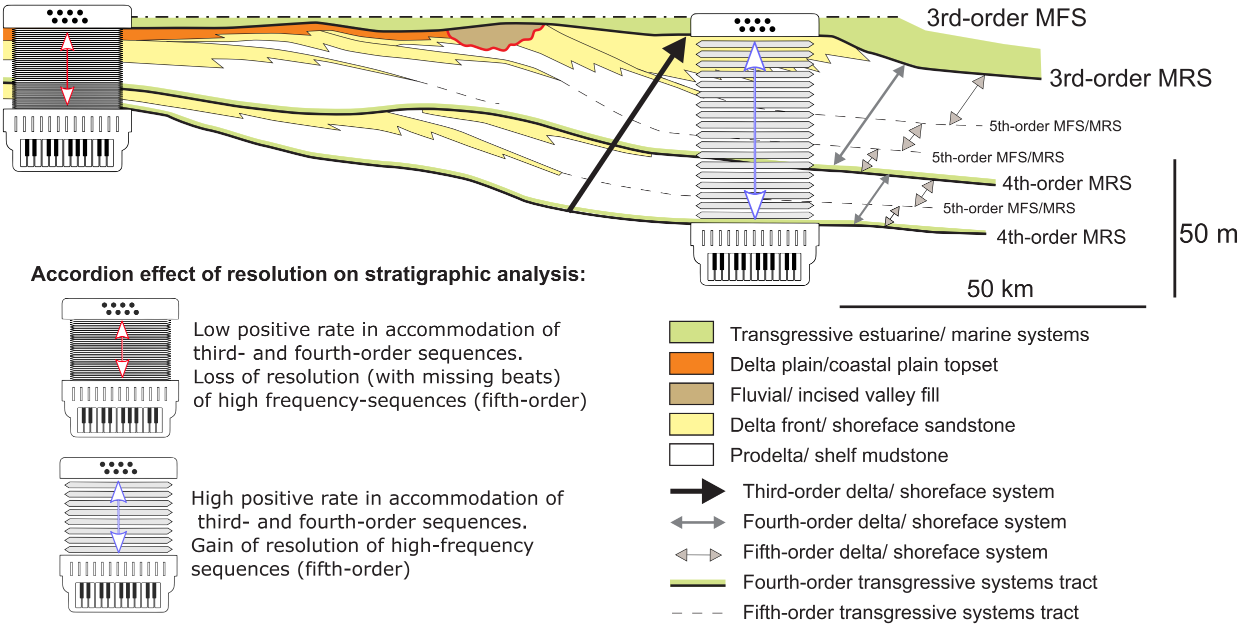


Figure 19. Accordion effect of resolution on stratigraphic analysis. Relative values of high (1) or low (2) rates in long-term (positive rate) accommodation define the possibilities of generation and preservation of the stacking pattern resulting from the high-frequency fluctuation in the A/S ratio.



Source: modified from Bhattacharya (1993) and Catuneanu (2019b).

Figure 20. Sequences, systems tracts, and depositional systems observed at different scales (i.e., hierarchical levels), generated by the fluctuation in the A/S ratio, in a stratigraphic architecture of a prograding system.

Formation, northeastern Brazil (Magalhães *et al.* 2016). At the Tombador Formation base, third-order sequences are characterized by alternating estuarine/marine and continental deposits (Fig. 21). The highest sequence resolution (4th-order) occurs in the estuarine intervals within the third-order transgressive systems tract (high accommodation rate), involving contrasting facies associations. However, the resolution for high-frequency sequences in the third-order continental intervals (lower accommodation rate) is poorer, which is pronounced by the aggradation of monotonous successions of fluvial sandstone deposits.

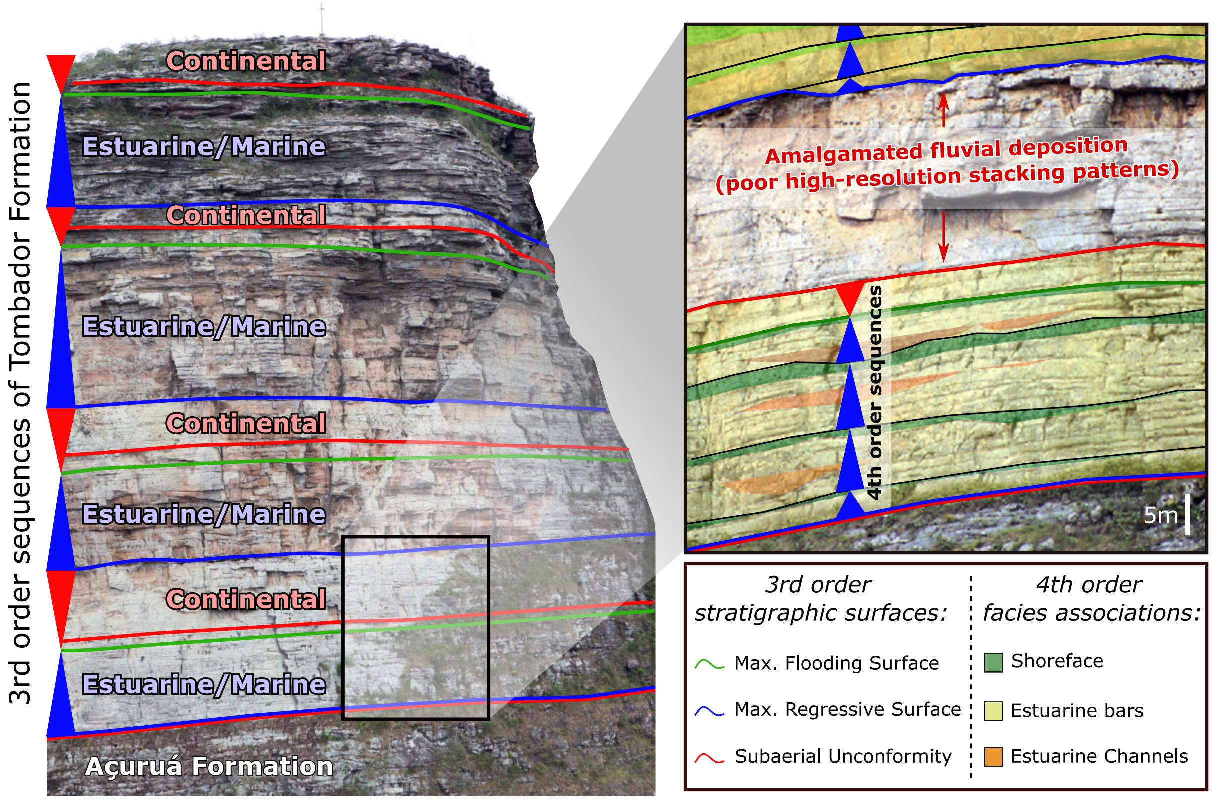


Figure 21. Stratigraphic framework of the third- and fourth-order sequences of the Tombador Formation (Mesoproterozoic, Brazil; Magalhães *et al.* 2016). The fourth-order sequences (highest resolution), characterized by the alternation of estuarine and shoreface facies associations, are well observed in the third-order transgressive intervals (high accommodation setting). In the low accommodation setting of the regressive continental intervals, high-resolution sequences are poorly identified.

It is interesting to note that the energetic and dispersive effect of sedimentary processes is, in general, more intense in allochthonous than in autochthonous sedimentation. For this reason, carbonate and evaporitic contexts tend to have higher resolution for the analysis of stacking patterns, as observed in the case of the lacustrine carbonate deposits of the Salta Basin (*e.g.*, Bento Freire 2012, Bunevich 2016, Bunevich *et al.* 2017, Fig. 22).

Criteria for identifying sequences in a hierarchical framework

The premises here are: any displacement of facies in terms of proximity and laterality, intrinsic to their respective depositional systems, within correlatable intervals of equivalent stacking patterns, is controlled by the A/S ratio; and different limits of accommodation constrain distinct preservation potential. In this sense, the cycles' anatomy, recurrence, vertical trends, and the mappability of stacking patterns and stratigraphic surfaces are the observable criteria for identifying sequences, at any scale and rank, within a hierarchical stratigraphic framework (Fig. 23).

The analysis of cycle anatomy is a primary and robust descriptive criterion for the proposal of a sequence. At any scale of observation, a sequence must have a typical internal Transgressive-Regressive pattern (T-R cycle) bounded by the maximum flooding surface (end of transgression) or by the maximum regressive surface (end of regression) (*e.g.*, Embry 1995, 2009). The subdivision of sequences in facies or system tracts can be more complex (*e.g.*, Van Wagoner *et al.* 1990) depending on the scale (seismic or outcrop) and context (*e.g.*, basin morphology). However, as all types of sequences (Fig. 1) exhibit the T-R pattern, this is the minimum requirement for anatomy analysis in low- and high-resolution. The T-R cycles may be asymmetric, and one of the terms may even be missing (Fig. 23.1).

Recurrence is the fundamental characteristic of a cycle (Fig. 23.2). This pattern indicates that a regular mechanism controlled sedimentation. Its frequency allows the interpreter to speculate what could be that mechanism (long or short-term — *e.g.*, Pittet and Strasser 1998). Also, the frequency is inversely proportional to the hierarchy (*e.g.*, Magalhães *et al.* 2016, Melo *et al.* 2020). Thus, the higher the frequency of a cycle candidate to be a sequence, the lower its hierarchy and the duration of its generating mechanisms (*e.g.*, Pedrinha *et al.* 2015).

Since the recurrence of sequences does not establish a random pattern, the consequent upward trend is also an important criterion to be observed (*e.g.*, Schlaich and Aigner 2017). Upward trends of stacking patterns occur due to short-term modulation by long-term processes in changes in the A/S ratio (accordion effect). The upward trend is fundamental for hierarchy. The vertical arrangement of stacking patterns that determine the high-frequency sequences is the basis for defining and constructing the stacking patterns of immediately

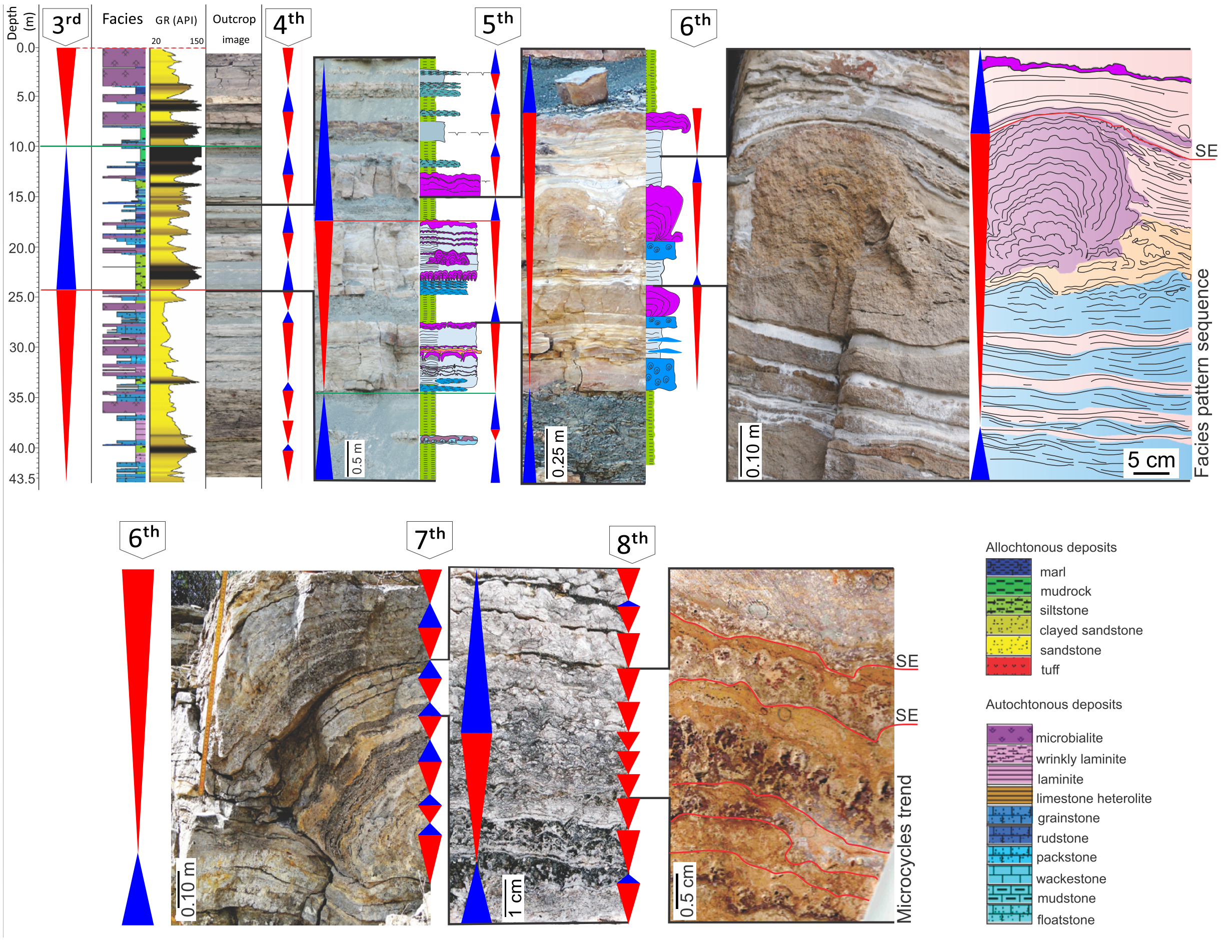


Figure 22. Cyclicity hierarchies observed in the Yacoraite Formation, Danian from the Salta Basin (Bento Freire 2012, Bunevich 2016, Bunevich *et al.* 2017). Stacking patterns are shown from the 3rd- to the 8th-order sequences, always composing superior hierarchies. Note the 7th and 8th order sequences, characterized by the rhythmic alternation of thickening and thinning trends during the stromatolite growth at a thin-section scale.

higher-order sequences (*e.g.*, Turner *et al.* 2012, Pedrinha *et al.* 2015, Gomes *et al.* 2020).

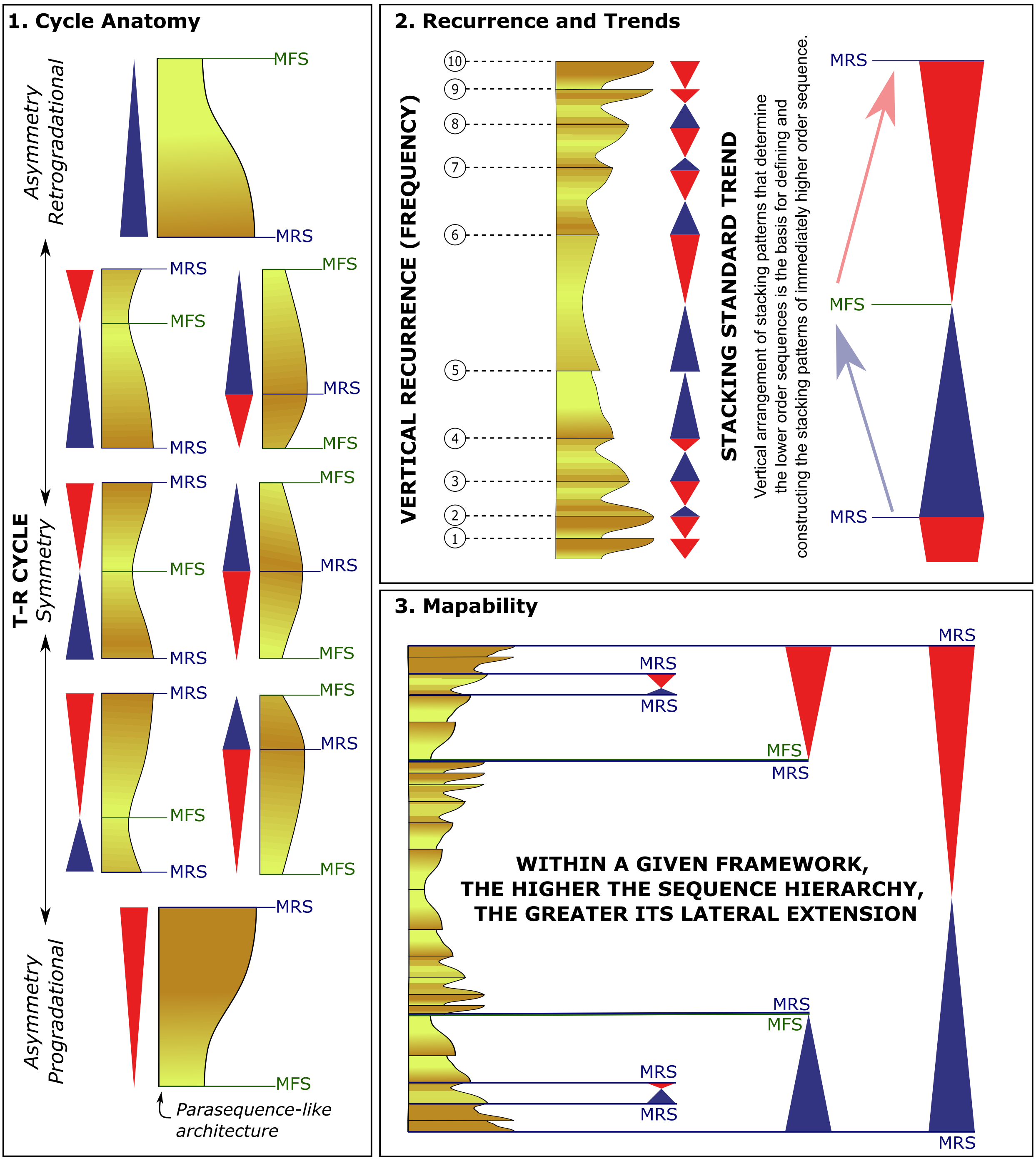
The change in any deposition trend is always marked by a stratigraphic surface (*e.g.*, Catuneanu 2006). According to Magalhães *et al.* (2020), stratigraphic surfaces of any hierarchy are always anchored to the lowest rank. Lower rank surfaces may be a candidate to belong to a higher hierarchy. The fundamental importance of ranking stratigraphic surfaces is to determine the turning point of long-term transgressive or regressive trends and, thereby, to identify the boundaries that separate systems tracts from higher-ranking sequences.

The last criterion refers to the mappability of stacking patterns and their respective bounding stratigraphic surfaces. Within a given framework, mappability is greater the higher the sequence rank (Fig. 23.3 — *e.g.*, Embry 2009, Magalhães *et al.* 2016, Melo *et al.* 2020). This criterion is based on the analysis related to time and the evolution of depositional topography. The higher-frequency sequences are formed in short periods, with a low potential to modify the inherited depositional topography. Thus, its preservation occurs only in local and discontinuous depocenters, resulting in poor correlations. This phenomenon is not only related to the amplitude but, above all, to the duration of base-level variation. Besides, as mentioned earlier, local variations in the A/S ratio are common in short-term periods, decreasing the relative potential for long-distance correlations of high-resolution sequences. In relatively longer periods, the high potential for changes in the depositional topography and the general trend imposed on the A/S ratio allow the development of lower-resolution sequences with considerable correlations over large areas.

The sequence mappability criterion reinforces that one-dimensional observations of depositional trends and sedimentation breaks in a single vertical section are not sufficient for stratigraphic analysis. However, even though the lateral correlation is mandatory for identifying a sequence of any hierarchy, sparse data can preclude it in the case of high-frequency sequences due to its limited spatial occurrence. For this reason, even if an individual high-frequency sequence is not mapped, their statistical representativeness in terms of vertical recurrence and trends analysis, for the construction of correlatable medium- and low-frequency sequences, guarantees an overall reliable sequential approach.

Low-resolution sequence stratigraphy

In general, sequence stratigraphy frameworks can be divided into low- and high-resolution (Fig. 19).



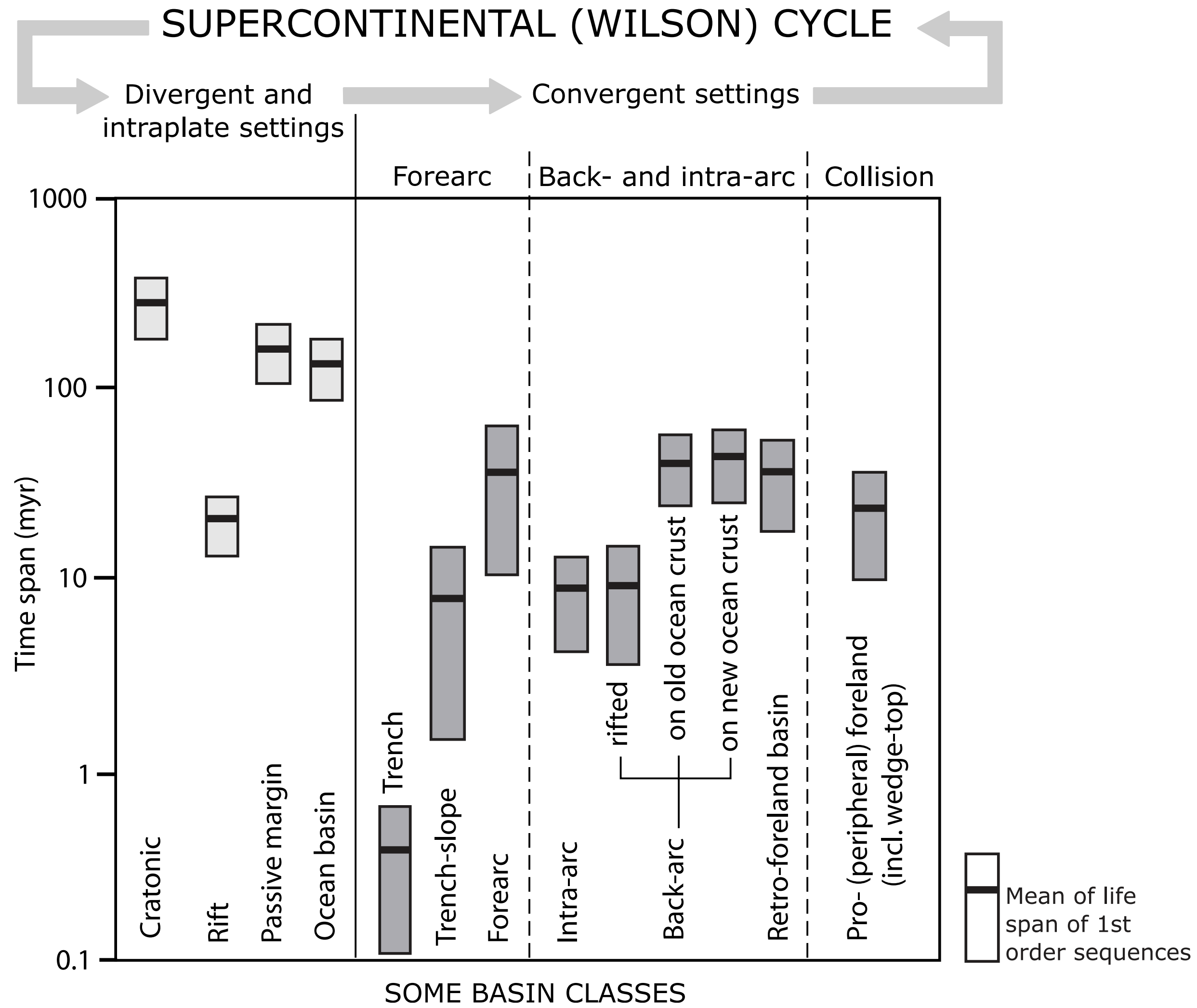
MFS: maximum flooding surface; MRS: maximum regressive surface.

Figure 23. Observable criteria for identifying sequences in the hierarchical framework: (1) Different architectures (cycle anatomy) of T-R cycles (modified from Zecchin 2007 and Catuneanu and Zecchin 2013). (2) Vertical recurrence of individual cycles and trends in the cycles stacking pattern (modulation of the smallest by the highest hierarchy). (3) The lateral extension (mappability) of the stacking patterns and stratigraphic surfaces, within a given framework, that is more significant the higher is the hierarchy.

The low-resolution is related to the definition of the regional stratigraphic framework, which involves basin- and seismic-scale analysis.

First-order sequences are consensually interpreted as corresponding to endogenous basin formation processes that compose a global supercontinent cycle (*e.g.*, Woodcock 2004, Allen *et al.* 2015; Fig. 24). In a "polyphasic" basin, the record of each evolution phase, related to a specific subsidence mechanism, corresponds to a first-order sequence.

Second-order sequences correspond to the record of the main paleogeographic changes in the balance between accommodation and sediment supply related to basin scale (*e.g.*, Catuneanu 2006). These paleogeographic changes are generally expressed in major transgressions and regressions within the stratigraphic evolution of any basin. Their origin is closely associated with regional and global tectonic processes (*e.g.*, Catuneanu and Eriksson 1999, Eriksson *et al.* 2005). However, on this scale, the influence of long-term



Source: modified from Woodcock (2004).

Figure 24. Origin and longevity of first-order sequences (related to the subsidence mechanisms) within the supercontinental Wilson cycle.

climate processes (*e.g.*, greenhouse-icehouse cycles) cannot be neglected.

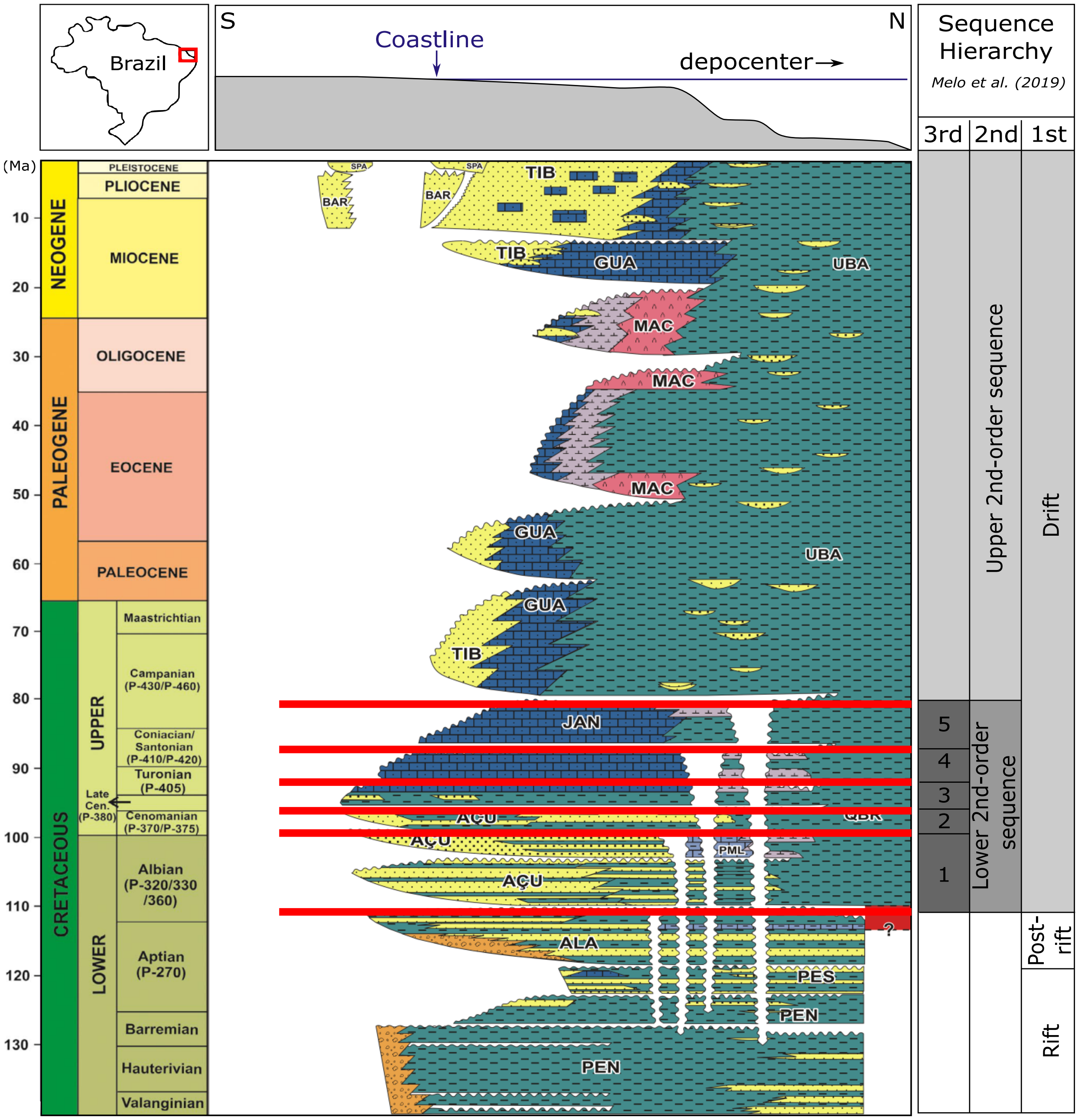
Melo *et al.* (2020) presented an example of a low-resolution stratigraphic framework for the Potiguar Basin, located on the Brazilian equatorial margin (Fig. 25). The tectonic phases (rift, post-rift, and drift) of this basin evolved during the opening of the South Atlantic Ocean and are classified as first-order sequences. Melo *et al.* (2020) defined two second-order sequences within the drift phase, which correspond to the most considerable paleogeographic changes in the basin scale for this interval. In the lower sequence, from Albian to late Campanian, the authors interpreted five third-order sequences mainly based on seismic data (Fig. 26).

The seismic-scale cycles (Fig. 19) correspond to the sequences interpreted from the alternation of seismic reflection termination patterns, whose relationship with depositional timelines offered the first tests for sequence stratigraphy (*e.g.*, Vail *et al.* 1977, Galloway 1989). In general, seismic-scale cycles are considered third-order sequences (*e.g.*, Melo *et al.* 2020). Although this definition is partially inconsistent, since it depends on data acquisition and processing techniques, the stratigraphic units imaged by seismic are always intermediate between the resolution of the sedimentary basin fill and the outcrop and core scale. These cycles are probably generated by the combination of tectonic (regional and global) and climatic controls, both influencing the eustatic pulse (e.g., Strasser *et al.* 2000).

The success of seismic stratigraphy in the oil industry is associated with the effective prediction of reservoirs and seals. The principles and practice of sequence stratigraphy were mainly built from the evolution of studies on seismic scale to recognize sequences, systems tracts, and stratigraphic surfaces (Fig. 27). Several general principles developed by the Exxon group in the 1970s are still in use in sequence stratigraphy. However, adjustments on the "seismic sequences" concept were improved in other scales, especially in the definition of high-frequency sequences associated with outcrop analysis, cores, and well logs data, generally attributed to high-resolution stratigraphy (*e.g.*, Magalhães *et al.* 2016, Catuneanu and Zecchin 2013, Magalhães *et al.* 2020).

High-resolution sequence stratigraphy

High-resolution stratigraphy is traditionally related to the scale that exceeds seismic resolution, being determined in



AÇU: Açu Formation; PML: Ponta do Mel Formation; JAN: Jandaíra Formation; QBR: Quebradas Formation.

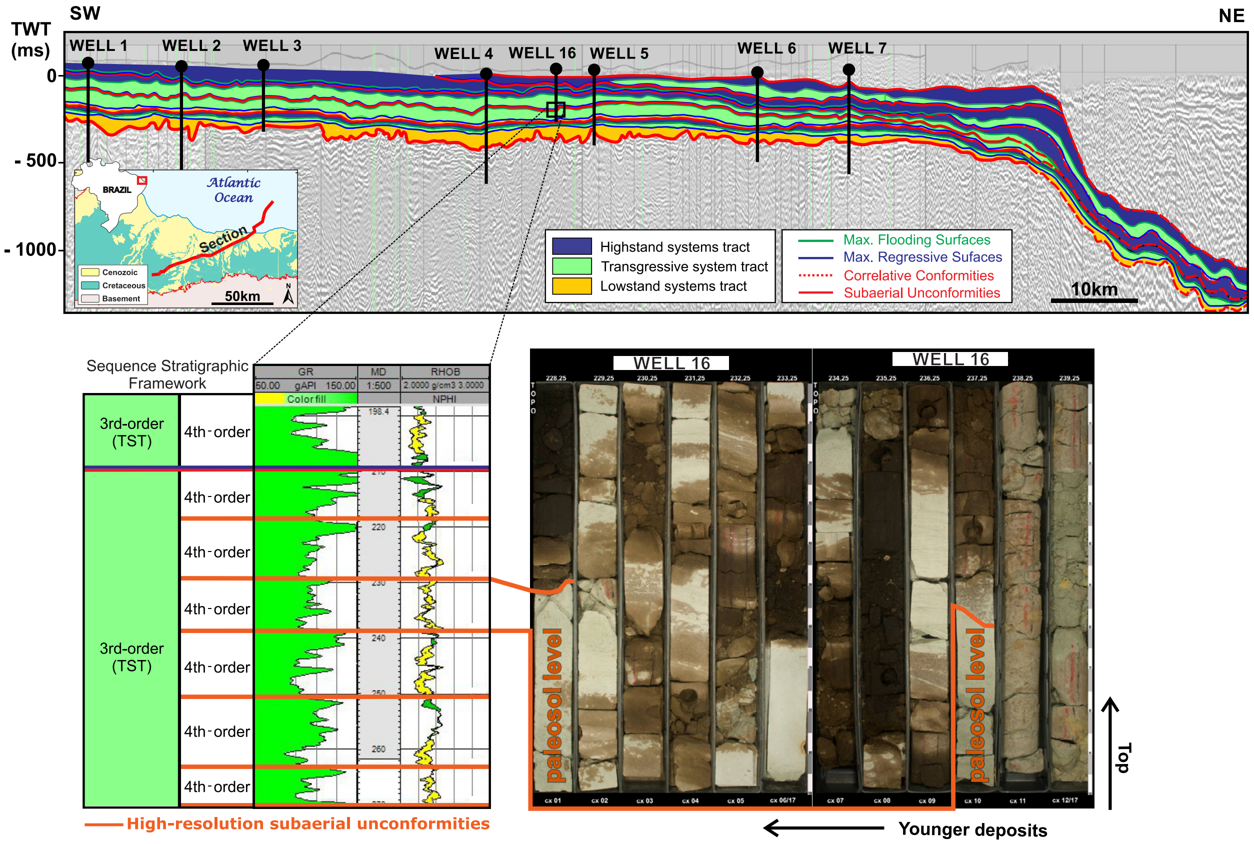
Source: modified from Pessoa Neto *et al.* (2007).

Figure 25. Stratigraphic chart of the Potiguar Basin illustrating the proposed sequence hierarchy (Melo *et al.* 2020). The phases of tectonic evolution are first-order sequences. The drift phase is subdivided into two second-order sequences. The lower second-order sequence, from Albian to Campanian, is subdivided into five third-order sequences.

cores, well logs, and outcrops (*e.g.*, Mitchum and Van Wagoner 1991). Some examples are presented by: Silveira (2020), in a deltaic deposit of Lajas Formation (Fig. 4); Magalhães *et al.* (2016), in estuarine strata of Tombador Formation (Fig. 21); Bento Freire (2012), Bunevich (2016), Bunevich *et al.* (2017), and Gomes *et al.* (2020), in lacustrine carbonate from Yacoraite Formation (Fig. 22); and Melo *et al.* (2020), in a fluvial interval of Açu Formation (Fig. 26).

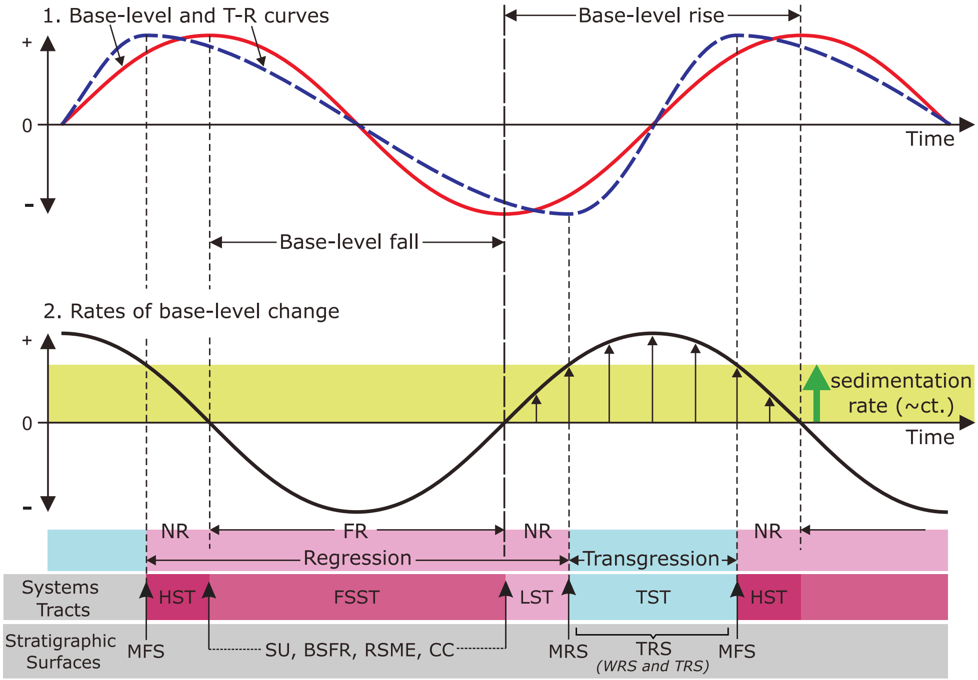
For the oil industry, the applied high-resolution sequence stratigraphy is undoubtedly very relevant for reservoir geology (*e.g.*, Zecchin and Catuneanu 2015). Magalhães *et al.* (2020) presented an extensive review, explaining in detail the high-resolution sequence stratigraphy methodology applied to reservoir zonation and characterization, showing how it better defines the critical heterogeneities that control the fluid flow observed during oil and gas production.

In general, the effort to standardize and define stratigraphic sequence orders (*e.g.*, Catuneanu *et al.* 2011, Catuneanu 2019a, 2019b, Magalhães *et al.* 2020) has shown that the methodology of sequence stratigraphy is independent of scale and the resolution of the data available. The stratigraphic record can be organized in sequences with an ordered pattern. At each observation scale, the building blocks are represented by sequences of different hierarchical levels (Catuneanu 2019b).



Source: modified from Melo *et al.* (2020).

Figure 26. Third- and fourth-order sequences from the Potiguar Basin (modified from Melo *et al.* 2020). A strike-oriented seismic section showing the sequences unconformity boundaries (red lines). Below, a closer view of well data showing the high-frequency fourth-order sequences identified in fluvial systems, bound by subaerial unconformities placed at the top of paleosols (detailed in core data).



FR: forced regression; NR: normal regression; HST: highstand systems tract; FSST: falling-stage systems tract; LST: lowstand systems tract; TST: transgressive systems tract; MFS: maximum flooding surface; SU: subaerial unconformity; BSFR: basal surface of forced regression; RSME: regressive surface of marine erosion; CC: correlative conformity; MRS: maximum regressive surface; TRS: transgressive ravinement surfaces; WRS: wave-ravinement surface; TRS: tidal-ravinement surface.

Source: modified from Catuneanu 2006.

Figure 27. System tracts and stratigraphic surfaces development in response to base-level changes as a function of time (modified from Catuneanu 2006). Above, base-level and transgressive–regressive (T–R) curves, and below, rates of base-level change and sedimentation rate. All sequence stratigraphic surfaces and system tracts can be defined with these curves. These definitions are perfectly adaptable for the seismic interpretation of sequences (especially in basins with the continental shelf and slope physiography). Adaptations are necessary for sequences above and below seismic resolution.

According to Schlager (2004), since stratigraphic sequences are essentially shaped by the relationship between the rates of accommodation and the sediment supply, and both have fractal properties, it is not surprising that the resulting sequence record inherits this fractal attribute.

A relevant discussion about the fractal nature of stratigraphic sequences (Schlager, 2004) is related to the concept of depositional system. Some authors argue that the sequence architecture is largely invariable in scale and, therefore, changes in the systems tracts must be observed at all scales (*e.g.*, Catuneanu 2019a, 2019b). Zecchin *et al.* (2017), for instance, differentiate sequences from sedimentological cycles using the concept of depositional systems. For these authors, sedimentological cycles occur within the same depositional system, whereas sequences encompass different systems, usually of greater thickness and duration.

It should be considered that, in a low-resolution scale involving large stratigraphic units, changes in depositional systems are easily perceived by the dominance of specific facies associations over others, either in vertical profile or in seismic data. Thus, facies changes in the depositional systems should be simply interpreted as the corresponding local record of the long-distance migration of the systems tracts toward the depocenter or toward the source area. In a high-resolution framework, even though high-frequency cycles promote paleogeographic changes involving different depositional systems, the extreme variations in facies associations may not necessarily be generated or preserved all over the basin as high-resolution stacking patterns. This issue refers to the previous discussion of Frankenstein models (see item "General Problem on Conceptual Depositional System"). The recognition of the transition from one depositional system to another would be more assured by observing the stacking trend of higher-resolution sequences enclosed within a single lower-resolution sequence. After all, the vertical trend is the main component for elaborating a hierarchical stratigraphic framework (Fig. 23).

In summary, the interpreter must always mitigate the proposal that imposes the condition of changing depositional systems to grant a stratigraphic value to the sedimentary succession, thus defining "sequences". In a high-resolution framework, the change in the depositional system is dependent on three factors:

- the location of the section containing the high-resolution sequences in relation to the shoreline — either nearby, where the system transitions occur more frequently, or faraway (extremely continental or deep sea), where vertically the systems tend to remain the same;
- how subordinated are the amplitudes in accommodation of short- and long-term geological processes;
- how detailed the high-resolution sequences are.

Thus, although changes in depositional systems are not seen in many contexts (*e.g.*, fluvial — Melo *et al.* 2020; Fig. 26) and scales (*e.g.*, 5th to 8th-order sequences — Bunevich *et al.* 2017; Fig. 22), some cyclical records are validly representative terms of the high-resolution framework, as they present all the observable criteria for the identification of sequences (Fig. 23). In these cases, naming cyclical entities using geographic terms (system tracts) may not be appropriate, and the term "facies tracts" (*e.g.*, Matenco and Haq 2020) is an alternative to compose high-frequency sequences.

Regarding genesis, it is known that short-term tectonic and deformational processes, which occur during the development of individual faults and folds (*e.g.*, Raja Gabaglia 1991, Dickinson *et al.* 1994, Matenco and Haq 2020), can affect the parameters of accommodation and sediment supply for the development of high-frequency sequences. This is, undoubtedly, a field to be further explored by stratigraphic research. However, climate change is probably the chief mechanism for the origin of most of the cyclicity observed in outcrops and cores. In this sense, cyclostratigraphy has been used to investigate periodic climatic processes, potentially responsible for the genesis of the various observable cycles in the geological record (*e.g.*, Wu *et al.* 2013; Fig. 16). Using this approach at different ages and depositional contexts, a growing number of cases have consistently demonstrated the relationship between high-frequency cyclical successions and climatic/astronomical processes (Hilgen *et al.* 2015), which fully conforms to the sequence stratigraphy approach (Schwarzacher 2000).

The detection of the preserved orbital signal in the stratigraphic record is achieved by a frequency analysis of the paleoclimatic proxies obtained in the section of interest. There are many proxies used in the cyclostratigraphic analysis, but the most frequent are:

- gamma-ray (*e.g.*, Mendes 2005);
- magnetic properties of the rocks (*e.g.*, Ellwood *et al.* 2012);
- relative paleobatimetry defined by the facies succession (*e.g.*, Olsen and Kent 1996);
- thickness of the layers (Tucker *et al.* 2009);
- color pattern of the sediments (*e.g.*, Franco *et al.* 2011).

Li *et al.* (2019) presented an extensive and updated review of the concepts, methodological use, and interpretation of these main proxies in cyclostratigraphy.

Different mathematical techniques are also used for signal processing to determine and analyze a set of sequential data periodicity (Weedon 2003, Kodama and Hinnov 2014). Despite the mathematical solutions observed in many cyclostratigraphic works, the analyses of the temporal stratigraphic sign can be imprecise and subject to many misinterpretations if accurate geochronological information is not integrated. Thus, cyclostratigraphy is currently applied in conjunction with several other methods that assist the paleoenvironmental interpretation, improving the focus on paleoclimate proxies, but, above all, offering geochronological precision for temporal calibration.

Integrated stratigraphy is the combined application, for high-resolution stratigraphic analysis, of multiple stratigraphic subdisciplines, including cyclostratigraphy, biostratigraphy, magnetostratigraphy, chemostratigraphy, isotopic geochronology, especially when this practice is related to geological time (*e.g.*, Coccioni *et al.* 2012, Hilgen *et al.* 2015). Once the astronomical signal detection is demonstrated, a temporal calibration with exceptional precision and resolution can be established. Hence, the climatic, oceanographic, sedimentary, biological, and diagenetic processes can be evaluated with higher accuracy than traditional geochronological approaches (Strasser *et al.* 2007). A refinement of the conceptual geological model for high-frequency paleogeographic and paleoecological variations applying integrated stratigraphic studies authorizes long-distance chronocorrelations between cyclical successions of different depositional systems and allows astronomical tuning by mathematical solutions (*e.g.*, Hilgen *et al.* 2015; Fig. 28).

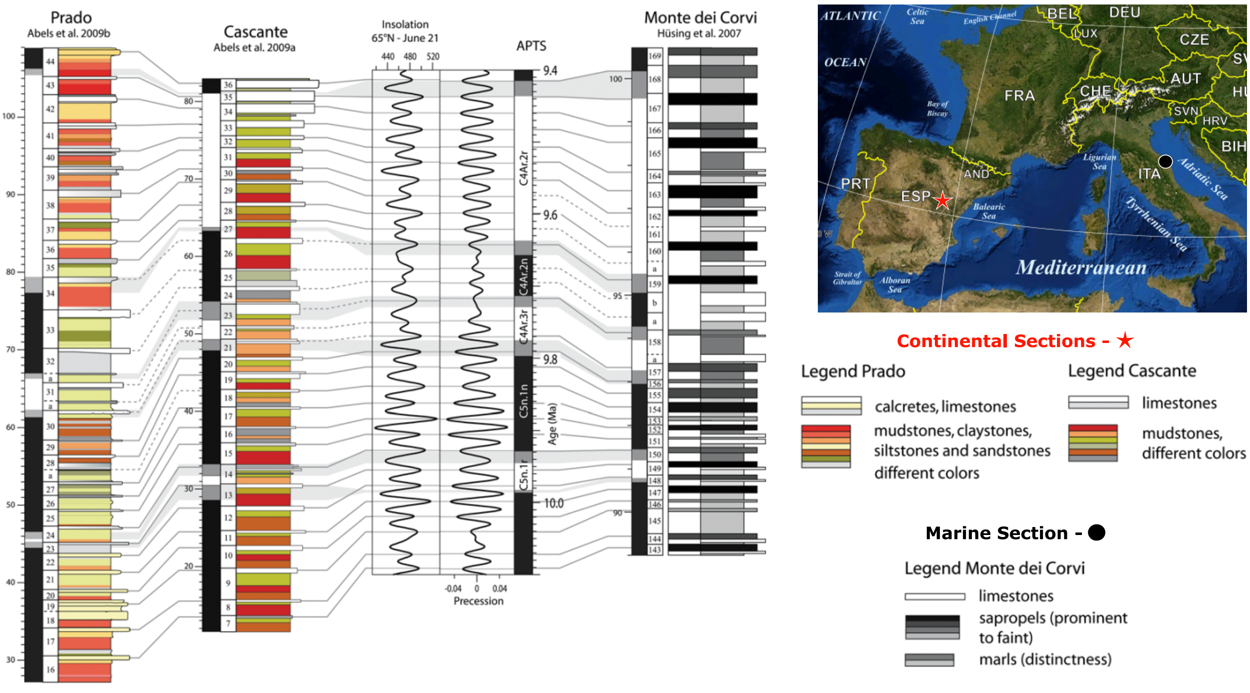
FINAL REMARKS

The advances in sequence stratigraphy have contributed mainly to the consolidation of applicable methodology to describe the observable record at different scales, defining sequences within a chronostratigraphic hierarchical structure (*e.g.*, Catuneanu *et al.* 2011, Catuneanu 2019a, 2019b, Magalhães *et al.* 2020). However, sequence stratigraphy is still in a state of flux, and attempts to standardize the method should leave ample room for the evolution of concepts (Schlager 2010).

The experience accumulated in many years of research and application by Petrobras School of High-Resolution Stratigraphy (*e.g.*, Raja Gabaglia 1991, Bento Freire 2012, De Gasperi and Catuneanu 2014, Pedrinha *et al.* 2015, Roemers-Oliveira *et al.* 2015, Magalhães *et al.* 2016, Bunevich *et al.* 2017, Melo *et al.* 2020, Gomes *et al.* 2020, Magalhães *et al.* 2020, Silveira 2020) reinforces the importance of the interdependence between description and interpretation for the development of sequence stratigraphy principles and practice. Supported by the conceptual basis available in the literature, especially for the understanding of stratigraphic preservation, it is here proposed an integrated analysis of four observable criteria that identify and rank sequences at all scales permitted by the available data: cycle anatomy, recurrence, vertical trends, and mappability (Fig. 23). These characteristics imply the existence of a regular cyclical mechanism that controls their generation and preservation.

The interpretative approach advocated here considers that allogenic mechanisms are the major reference to explain cyclicity in the generation and preservation of sedimentary deposits (*e.g.*, Miall 2017), providing the principles for understanding the regularity of stratigraphic record at multiple scales (accordion effect), their hierarchical nature and, ultimately, supporting any sequential analysis. The association of the fundamental concepts of sequence stratigraphy with updated knowledge of tectonic (*e.g.*, Matenco and Haq 2020) and climatic processes (*e.g.*, Strasser *et al.* 2007), and their interrelationships with eustasy (*e.g.*, Sames *et al.* 2020), supports a workflow that starts from the recognition of elementary units to their stratigraphic clusters, which occur organized in vertical succession and horizontal correlations (Fig. 29).

In summary, for theoretical and practical purposes, the concept of sequence is definitively connected to allogenic mechanisms. Even if the autogenic factor necessarily occurs for the genesis of any sedimentary deposit, the eventual and isolated internal changes in the sedimentary system are not sufficient to explain the generation of stratigraphic cyclical units that make up a hierarchical and predictive framework. In other words, it is not recommended to define a sequence based only on the cycle pattern observed in a single vertical



Source: modified from Hilgen *et al.* (2015).

Figure 28. High-resolution cyclostratigraphic correlations (at precession-scale) and tuning of the continental sections of Prado and Cascante (Spain) and the marine section of Monte dei Corvi (Italy). The correlations and tuning are tightly constrained by magnetostratigraphy in all sections.

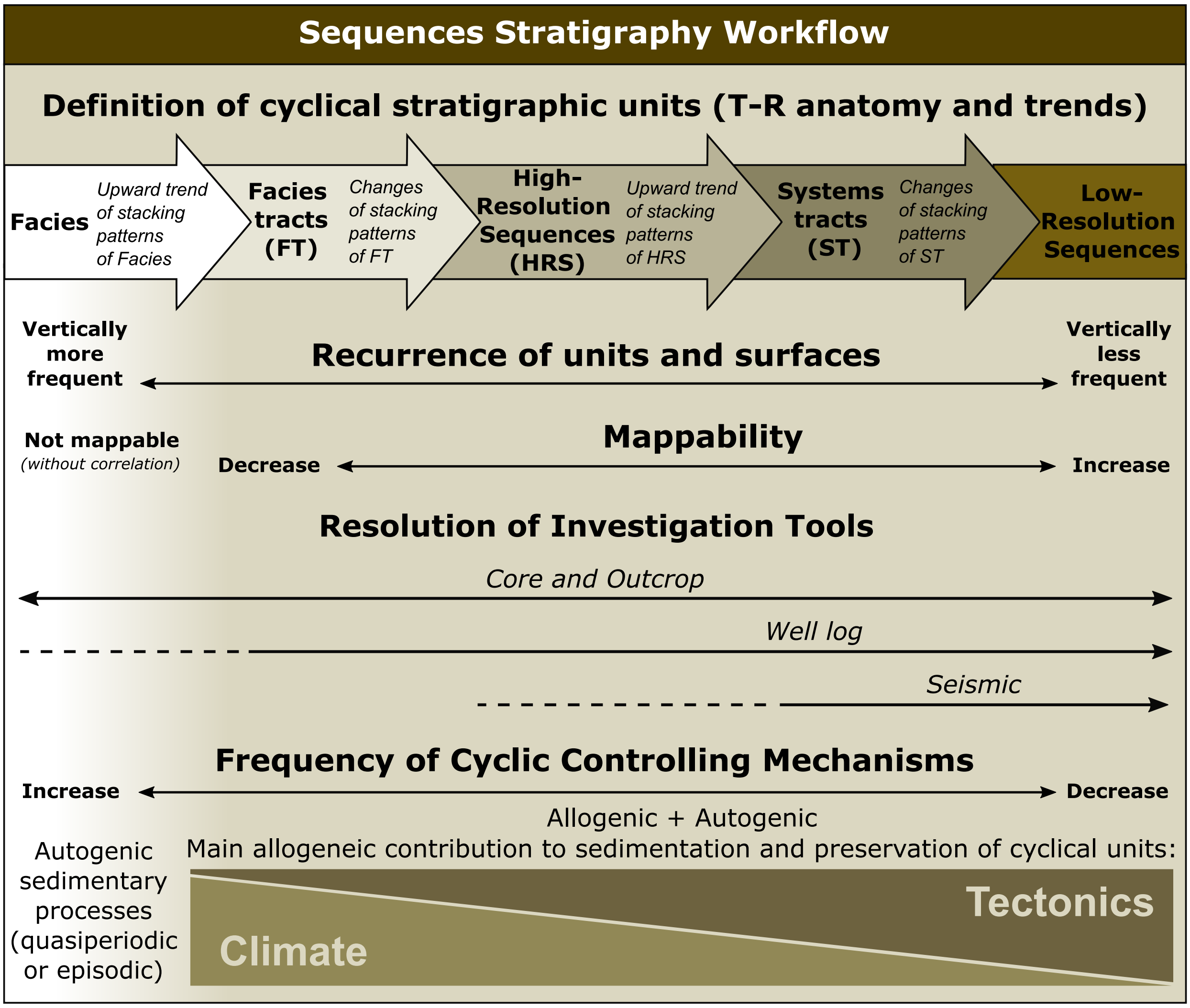


Figure 29. Sequence stratigraphy workflow that starts from recognizing elementary units to their stratigraphic clusters, that occur organized in mappable vertical successions. Stratigraphic stacking patterns that define T-R cycle anatomies can be observed at different scales, depending on the resolution of the investigation tool. Except for sedimentary facies, produced purely by autogenic processes, all recurring stacking patterns that make up the hierarchical framework, are a product of the autogenic and allogenic processes interaction. The highest stratigraphic frequencies are composed of facies tracts, whose changes in stacking patterns give rise to high-resolution sequences. These sequences tend to have less mappability and are predominantly controlled by climatic processes modulated by tectonics. System tracts can be recognized as an organization of high-resolution sequences in an upward trend of stacking patterns, with the preponderant representation of given facies associations and arrangements. Changes in system tracts make up low-resolution sequences. These units have wider mappability and are controlled predominantly by tectonics, modeled at different intensities by the climate.

section, even if that arrangement is similar to the T-R cycle. Such cycles alone do not offer a prediction, precisely because they have several possibilities of origin. Thus, recurrence, vertical trends, and mappability are fundamental features to define sequence, and compose a hierarchical framework. When mappability is not demonstrable on a very detailed scale due to lack of data, other parameters coherent with lower-resolution scale characterization guarantee the prediction of the sequential analysis.

Conceptual models elaborated with a hierarchical stratigraphic framework, which incorporate the knowledge of geological processes — from low to high frequency — in the generation and preservation of sequences — from low- to high-resolution —, reduce the inaccuracies and contradictions of their counterparts based on simple sedimentary accumulation, which traditionally considers the existence of fully preserved three-dimensional depositional systems (the “Frankenstein models”). The methodological gain is materialized in more realistic representations, ensuring objective results in predicting vertical recurrence and lateral correlation of stratigraphic units. This analysis is fundamentally useful in its application in the oil industry (*e.g.*, Melo *et al.* 2020, Magalhães *et al.* 2020).

Relevant advances in stratigraphic research are currently identified within the sequence stratigraphy context, especially in the high-resolution analysis. High-resolution tectono-stratigraphy is an example of a study field not yet explored. Moreover, few studies have combined the progress in high-resolution sequence stratigraphy with the integrated stratigraphy/cyclostratigraphy. The methodology of high resolution instigates the comprehension of the geological evolution of the basin filling, considering sedimentary evolution complexity related to the generation, preservation, and to the measurements and meaning of the innumerable temporal gaps. This perspective allows to:

- Identify and correlate multi-scale sequences through the direct description of the rock record (stacking patterns and stratigraphic surfaces);
- Characterize the high-resolution hierarchy;
- Dispose of a stratigraphic framework to define the principal deposition controlling mechanisms (and time scales involved) through the quantitative analysis of frequencies of sedimentary parameters (proxies).

The definition of the main controlling factors enables a better estimation of the rates of generation and preservation of any sedimentary succession. Consequently, a hierarchical chronostratigraphic framework can be developed, with sequences correlated to varying distances within a basin. The methodological gain is the development of more robust conceptual models. In other words, advances in this research direction will reduce the inaccuracies of the purely qualitative sequential analysis and offer potential correlations for the vertical analysis of the cyclostratigraphy.

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