

## 9(b). Sequence stratigraphic context of microbial mat features

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#### Introduction: Microbial mats in the rock record

Microbial mats may form in a wide range of depositional environments, from fully marine to continental (section 9(a)), and their presence in the rock record is established for most of geological time (e.g., Seilacher, 1999; Eriksson et al., 2000; Watanabe et al., 2000; Noffke et al., 2003a; Banerjee and Jeevankumar, 2005). The earliest evidence of microbial mat formation has been reported from the 3.2 Ga siliciclastic marine strata of the Moodies Group of the Barberton greenstone belt in South Africa (Noffke et al., 2006b), while the earliest inferred continental example comes from the 1.8 Ga palaeodesert deposits of the Waterberg Group, also in South Africa (Eriksson et al., 2000).

The abundance of microbial mats within depositional environments has changed through geological time (section 9(a)), with the highest proliferation during the Mesoproterozoic (Pfluger and Sarkar, 1996; Eriksson et al., 2000; Schopf, 2004; Altermann, 2004; Sarkar et al., 2005). The Proterozoic dominance of these micro-organisms was followed by a sharp decline at the onset of the Phanerozoic with the rapid growth of grazing metazoan communities (Grotzinger, 1990). The effect of microbial mats on stratigraphic architecture is thus more evident for Proterozoic successions than for strata accumulated during the Phanerozoic.

Numerous types of microbial structures have been described in siliciclastic and carbonate rocks, as summarized in recent publications (e.g., Gerdes et al., 2000a; Noffke et al., 2001a; Schieber, 2004; Sarkar et al., 2004; Banerjee and Jeevankumar, 2005; and this volume). Depositional and post-depositional processes associated with most sedimentary environments, particularly those of marine affinity, favour the preservation of microbial mat structures in carbonate systems, while the evidence for microbial activity in siliciclastic environments is often indirect and circumstantial. Laboratory experiments (see Chapter 2) have contributed significantly to improving understanding of mats forming in clastic settings. The low preservation potential of microbial mats in siliciclastic rocks is explained by processes such as syn-depositional wave and current reworking of unconsolidated sediment, the degradation of microbial textures soon after burial in the absence of early cements, or by a variety of deeper-burial diagenetic processes (Banerjee and Jeevankumar, 2005). However, indirect signatures of microbial growth and decay are often recognizable in the field, and materialize in sedimentary features such as wrinkle structures, sand cracks, roll-up structures, gas domes, petee structures, palimpsest ripples, and others (e.g., Noffke, 1998a; Schieber, 1999, 2004; Eriksson et al., 2000; Gerdes et al., 2000; Noffke et al., 2001a; Banerjee and Jeevankumar, 2005).

The influence of microbial mats on sedimentation has been investigated in numerous publications, particularly from the point of view of process sedimentology and the mechanisms of formation of microbial activity-related sedimentary structures. At larger scales of observation, however, the stratigraphic context of microbial mats is less understood, and the relationship

between the occurrence of microbial mats and the architecture of the stratigraphic record has only begun to be documented (e.g., Sarkar et al., 2005). This paper examines the current understanding of the position and role of microbial mats within a sequence stratigraphic framework.

## **The standard sequence stratigraphic model**

### *Definition and basic concepts*

Sequence stratigraphy studies the sedimentary response to changes in base level, and the depositional trends that emerge from the interplay of accommodation (i.e., space available for sediments to fill) and sedimentation. These depositional trends refer to aggradation, erosion, progradation and retrogradation. The applications of sequence stratigraphy are tremendous, from deciphering the Earth's geological record of local to global changes, to improving the success of economic exploration and production. Multiple data sets are integrated for this purpose, and insights from several disciplines are required (Fig. 9(b)-1).

The predictive aspect of sequence stratigraphy is the key to its appeal and success, as models of facies relationships and development can be constructed from local to regional scales. The predictable association of depositional systems into sequences and component systems tracts is made possible by the fact that processes in all depositional environments respond to a common control: base-level changes. In turn, changes in base level depend on the interplay of allogenic controls such as eustasy, tectonism, and climate. Base level is therefore the link that 'synchronizes' depositional processes in all environments across a sedimentary basin, bringing coherence to the sequence stratigraphic model. The complex interplay of allogenic controls, and the variability added to the sequence stratigraphic model by the contribution of independent factors such as autogenic processes, rock types in the source areas, sediment supply and basin physiography, have been discussed in a number of syntheses including Payton (1977), Wilgus et al. (1988), Emery and Myers (1996), Galloway and Hobday (1996), Miall (1997), Gradstein et al. (1998), Shanley and McCabe (1998), Posamentier and Allen (1999), Coe (2003), Schlager (2005) and Catuneanu (2006).

The concept of 'base level' defines a dynamic and imaginary surface of balance between erosion and deposition, i.e. the highest level up to which a sedimentary succession can be built (Twenhofel, 1939; Sloss, 1962). A rise in base level creates accommodation, whereas a fall in base level destroys accommodation. The base level is commonly approximated with the sea level (e.g., Jervey, 1988; Schumm, 1993; Posamentier and Allen, 1999), and it is generally used in the context of marine environments. The equivalent concept in the alluvial realm is the fluvial graded profile. Even though the marine base level and the fluvial graded profile are often in a process-response relationship (see full discussion in Catuneanu, 2006), the two concepts may be amalgamated into one 'stratigraphic base level' that marks the surface of equilibrium between sedimentation and erosion in all depositional environments (Cross and Lessenger, 1998). A base level positioned below the topographic profile (seascape or landscape) is referred to as 'negative'

accommodation, and triggers downcutting, whereas a base level above the topographic profile marks ‘positive’ accommodation, and it is accompanied by sediment accumulation.

Changes in accommodation, and their interplay with the rates of sedimentation, control the manifestation of all types of depositional trends in the stratigraphic record. Figure 9(b)-2 depicts the complex relationship between all main controls on stratigraphic architecture, and the definition of basic concepts such as sea-level changes (fluctuations in the position of the sea level relative to the centre of the Earth), relative sea-level changes (fluctuations in the position of the sea level relative to a datum that records the rates of subsidence or uplift), base-level changes (fluctuations in the position of the base level relative to the same datum that records the rates of subsidence or uplift), and the transgressive and regressive shifts of the shoreline. Furthermore, regressive shoreline shifts are classified into ‘forced regressions’ (progradation during base-level fall, driven by negative accommodation) and ‘normal regressions’ (progradation during base-level rise, driven by sediment supply).

### ***Building blocks of the sequence stratigraphic framework***

The building blocks of the sequence stratigraphic framework include sequences, systems tracts, and parasequences. A ‘sequence’ is a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities (Mitchum, 1977). A sequence corresponds to a full cycle of base-level changes. The definition of a sequence is independent of temporal and spatial scales. The relative importance of sequences is resolved via the concept of hierarchy, whereby higher-rank sequences may consist of two or more lower-rank sequences.

The addendum to the original definition of Mitchum (1977) that a sequence corresponds to a full cycle of base-level changes is required to separate a sequence from component systems tracts. As more than one sequence stratigraphic surface may have unconformable portions, the package of strata between two consecutive unconformities in the rock record is likely to correspond to only one stage of a full cycle of base-level changes, i.e. to a systems tract. The bounding unconformities and correlative conformities referred to in the definition of a sequence have to be consistently represented by the same type(s) of sequence stratigraphic surfaces, albeit not specified in the definition.

A sequence is subdivided into component systems tracts, which consist of a linkage of contemporaneous depositional systems that accumulate during a particular stage of shoreline shifts (Brown and Fisher, 1977). The timing of systems tract boundaries is set by the four main events of the base-level cycle, i.e. the onset of base-level fall at the shoreline, the end of base-level fall at the shoreline, the end of shoreline regression and the end of shoreline transgression (Catuneanu, 2006; Fig. 9(b)-3). Systems tracts are interpreted based on stratal stacking patterns, position within the sequence, and types of bounding surfaces. Figure 9(b)-4 illustrates a generalized model for the types and distribution of depositional systems within the various systems tracts.

Parasequences are stratigraphic units bounded by ‘flooding surfaces’ (Van Wagoner et al., 1988, 1990), which, depending on circumstances, may be represented by transgressive ravinement

surfaces, maximum flooding surfaces, maximum regressive surfaces, or facies contacts within the transgressive systems tract (see Catuneanu, 2006, for a recent discussion and examples). Consequently, parasequences are not just smaller-scale sequences, as parasequence boundaries may be represented by surfaces other than sequence boundaries.

Parasequences are commonly used to describe individual prograding lobes in coastal to shallow-water systems, where evidence of abrupt water deepening (i.e., documentation of flooding surfaces) is easiest to demonstrate. Confusions regarding the meaning of parasequences arose with the application of the term to all shoaling-upward stratal units, whether or not they were bounded by flooding surfaces, which is beyond the original intent of Van Wagoner et al. (1988, 1990). The applicability and the usefulness of the 'parasequence' concept in fully fluvial and deep-water systems have been questioned by Posamentier and Allen (1999). The restriction of parasequences to coastal and shallow-water systems marks another difference between the concepts of sequence and parasequence.

### *Variability of the sequence stratigraphic model*

Lessons learned from sequence stratigraphic work over the past two decades show that no single template can provide the optimum solution for the interpretation of every data set. The variability of the sequence stratigraphic model is caused by at least two different factors, one related to the fact that allogenic mechanisms are not the only controls on sedimentation, and another related to the change in subsidence patterns and basin physiography from one tectonic setting to another.

The role of fluctuating base level is central to sequence stratigraphy, and places emphasis on the allogenic controls on sedimentation. While allowing for the construction of a basic predictable stratigraphic framework, this approach generates a 'static sea' model whereby any other stratigraphic events (e.g., the effects of earthquakes or other short-term events on sediment supply and depositional processes) are ignored. However, one should keep in mind that autocyclic controls or short-term events may leave an equally important imprint on the architecture of the stratigraphic record. At the scale of individual depositional environments, the tendency to self organization toward the most energy-efficient state of equilibrium may generate stratigraphic signatures similar to the ones produced by allogenic mechanisms. The inclusion of autocyclic controls and stratigraphic events in sequence analysis may explain the unpredictable distribution of some depositional elements within the basic sequence stratigraphic framework. This full-spectrum analysis of long- and short-term controls on sedimentation translates into a 'dynamic sea' approach, which requires a case-by-case study for the construction of any sequence stratigraphic model.

Changes in tectonic setting may also explain variability in the relative contribution of systems tracts to the make-up of a sequence. Each tectonic setting is unique in terms of tectonics, subsidence rates, sediment flux, physiography and topographic gradients within the basin and along the basin margins, and as a result differences in stratal architecture and the development and preservation of particular depositional systems are expected. As pointed out by Diessel et al. (2000) and Davies and Gibling (2003), the subsidence history of any sedimentary basin controls the distribution of accommodation in time and space, and as a result, the stratal architecture of

each basin-fill reflects the unique regional and temporal variations in subsidence rates that characterize different types of tectonic settings. The basic contrasts between low- and high-gradient settings in terms of the resulting stratigraphic architecture of the basin-fill have been discussed by Catuneanu (2006) (Fig. 9(b)-5).

### **Influence of microbial mats on sequence architecture**

The implications of microbial mats for sequence architecture are most evident for Proterozoic successions, as the proliferation of microbial activity was highest during that time (Pfluger and Sarkar, 1996; Eriksson et al., 2000; Schopf, 2004; Altermann, 2004; Sarkar et al., 2005). Recently, strong evidence for microbial mats influencing clastic sedimentation during the Mesozoic to Neoproterozoic period has also been found (e.g., Noffke et al., 2003a, 2006a, b); however, the broad siliciclastic shelf environments that accompanied Proterozoic continental and supercontinental environments (e.g., Eriksson et al., 2004) vastly expanded suitable marine settings conducive to flourishing microbial mat communities. The strong evolution of grazing metazoan communities at the onset of the Phanerozoic marked a corresponding decline in the relative role of microbial mats on sedimentation (Grotzinger, 1990). As sequence stratigraphy developed as a new method of stratigraphic analysis based primarily on Phanerozoic case studies, the influence of microbial mats on sequence architecture remained largely overlooked and poorly understood until recently. The exceptional preservation of some Precambrian sedimentary-basin-fills, such as in South Africa and India (e.g., work by Eriksson et al., 2000; Noffke et al., 2003a, 2006b; Banerjee and Jeevankumar, 2005; Sarkar et al., 2005) has allowed for more insights into the role of microbial mats on sedimentation within a sequence stratigraphic framework, which are summarized below.

The influence of microbial mats on the sedimentary record may be analyzed from both sedimentological and stratigraphic perspectives. From a process sedimentology standpoint, the organic binding of sediments afforded by microbial mats increases the cohesiveness of the depositional surface and results in the formation of particular sedimentary structures that provide direct or indirect evidence of syn-depositional microbial activity (Chapters 3, 4 and 5). Examples of such microbial activity-related features include the wrinkle structures described by Banerjee and Jeevankumar (2005) from the Palaeoproterozoic strata of the Vindhyan Basin in central India. The formation of these structures requires an interaction of physical processes (e.g., traction currents or gas escape) with a cohesive substrate 'cemented' by microbial mats. The distribution of microbial structures within the sedimentary basin may be used to infer the change in the nature and relative energy of physical processes that operated in different depositional environments during geological time. For example, microbial-related wrinkle structures that formed in the Proterozoic are best preserved within the shelf system (below the fairweather wave-base), which is contrary to modern trends that show a better preservation potential within the intertidal to subtidal zones (Banerjee and Jeevankumar, 2005; see, however, section 7(a) where Noffke argues for a close association of mat-related features and tidal settings in the Archaean). This fact suggests that wind energy and associated wave erosion may have been stronger in the Precambrian, affecting preferentially the coastal to shoreface environments, and leading to the observed inversion in the locus of preservation of wrinkle structures across the

Precambrian – Phanerozoic boundary. A greater polarization of Earth's thermal zones (Rautenbach, 2001) combined with enhanced global rotation in the Precambrian (Williams, 2004) help to explain this inferred greater wind (and concomitant wave) energy. This conclusion is also supported by the fact that the proliferation of grazing organisms in the shallow subtidal environment only took place following the onset of the Phanerozoic, thus contributing toward trends that are opposite relative to those preserved in the rock record. This means that the importance of wave energy to the preservation of microbial features in the shallow-water areas outpaces the effects of grazing organisms, as the latter would tend to decrease, rather than increase, the preservation potential of microbial features in the subtidal environment.

From a stratigraphic perspective, the inferred changes in wave energy with geological time, based on the distribution of preserved microbial structures, are important to understand the differences between the architecture of Proterozoic and Phanerozoic sequences, and in particular, the relative contribution of systems tracts to the make-up of a sequence. Notably, the Precambrian sequences lack well-developed transgressive systems tracts, and are dominated by stacked highstand systems tracts that may be separated by thin veneers of transgressive deposits, often reduced to transgressive lags only (e.g., Sarkar et al., 2005). In contrast, many Phanerozoic sequences include fully developed transgressive systems tracts, which consist of all depositional systems from fluvial, to coastal (particularly estuarine) and fully marine. Whether this trend can be generalized or not, still requires further research. It is possible that insufficient Precambrian successions have been studied so far to draw meaningful conclusions. Even for the Phanerozoic, changes in the tectonic setting may generate significant departures from the 'standard' sequence stratigraphic template, and the relative development of systems tracts may vary significantly between low- and high-gradient settings (Fig. 9(b)-5; Catuneanu, 2006). This may also be the case with the Precambrian. However, evidence so far suggests that physical processes, particularly stronger wave energy, combined with a greater proliferation of microbial mats may explain the lesser development of transgressive systems tracts during the Precambrian.

Work on the Palaeoproterozoic and Neoproterozoic successions of central and western India (Banerjee and Jeevankumar, 2005; Sarkar et al., 2005) has documented the poor representation of transgressive systems tracts in comparison with the well-developed underlying and overlying normal regressive deposits. A transgressive systems tract consists, in a most general scenario, of transgressive fluvial to coastal facies scoured at the top by the transgressive wave-ravinement surface, which in turn is overlapped by transgressive shallow-marine strata. The absence (or poor development) of the fluvial to coastal section of the Precambrian transgressive systems tracts may be attributed to the inferred strong wave scouring in the upper shoreface during transgression, which may have removed much of the underlying section in the processes of shoreline backstepping. This also explains why microbial mats are not documented commonly from coastal to shoreface systems of Precambrian age, even though grazing organisms (common in the shoreface environment during the Phanerozoic) were not present during that time. The amount of erosion associated with the transgressive wave ravinement surfaces is generally within a range of 20 m for the Phanerozoic (Demarest and Kraft, 1987), with exceptional values of 40 m recorded along the coastline of the present-day Canterbury Plains (Leckie, 1994). The latter magnitude of erosion may have been the norm in the pre-Phanerozoic time, thus explaining the poor preservation of the fluvial to coastal portion of the Precambrian transgressive systems

tracts. The transgressive wave-ravinement processes may, however, not be used to explain the poor development of the marine shale portion of the Precambrian transgressive systems tracts (e.g., Catuneanu and Eriksson, 1999; Sarkar et al., 2005), as the transgressive shales accumulate on top of wave-ravinement surfaces. The issue of the thin or absent transgressive shales of Precambrian sequences has been tackled by Sarkar et al. (2005), who interpreted that low sea-floor gradients, promoting rapid transgressions, coupled with a low sediment supply, may explain the observed lack of significant development of transgressive shales in the studied Proterozoic sections. In these case studies, the transgressive systems tract is typically reduced to a transgressive lag, which is preserved between stacked normal regressive systems tracts (interpreted as 'highstand' by Sarkar et al., 2005) of prograding and aggrading deposits. Aggradation under normal regressive conditions, in spite of the low sediment supply, was attributed to the prolific growth of microbial mats below the fairweather wave-base (within the shelf environment) which prevented deeper-water current reworking of sediments by the organic binding of particles (Sarkar et al., 2005). The preferential preservation of microbial mat-related structures within the deeper (shelf) portions of parasequences has also been documented by Banerjee and Jeevankumar (2005).

## Conclusions

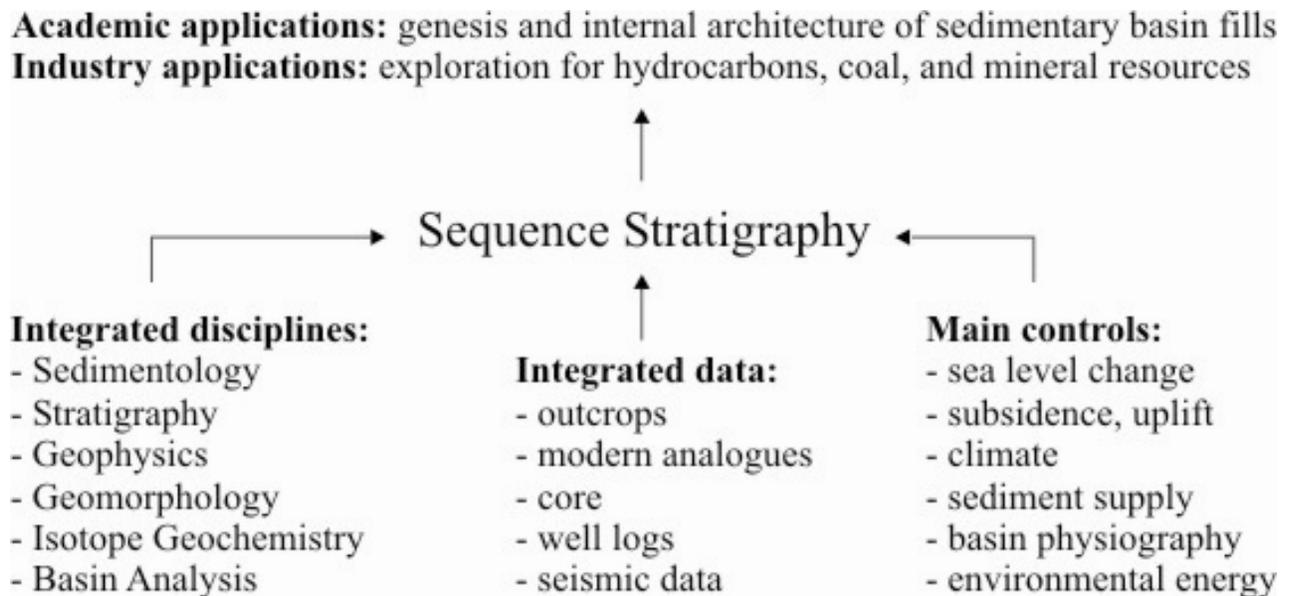
1. Microbial mats influenced sedimentary processes and the architecture of the stratigraphic record for at least the past 3.2 Ga of geological time. The relative importance of microbial activity on sedimentation changed through time as a function of changing environmental-energy conditions and the evolution of competing groups of organisms.
2. The influence of microbial mats on sequence architecture is most evident for Proterozoic successions, as the proliferation of microbial mat activity was highest during that time. The strong evolution of grazing metazoan communities following the onset of the Phanerozoic marked a corresponding decline in the relative role of microbial mats on sedimentation.
3. From a sedimentological viewpoint, the organic binding of sediments afforded by microbial mats increases the cohesiveness of the substrate and results in the formation of particular sedimentary structures that provide direct or indirect evidence of syn-depositional microbial activity.
4. The distribution of microbial structures within a sedimentary basin may be used to infer the change in the nature and relative energy of physical processes that operated in different depositional environments during geological time. It is inferred that coastal to shoreface wave erosion may have been stronger in the Precambrian, leading to the preferential preservation of microbial structures within shelf systems. This is contrary to modern trends, where most evidence of microbial activity is preserved in coastal to shoreface environments.
5. Research so far indicates that Precambrian sequences lack well-developed transgressive systems tracts, and are dominated by stacked systems tracts of normal regressive deposits that may be separated by thin veneers of transgressive deposits, often reduced to transgressive lags.

This is in contrast to many Phanerozoic sequences, which include fully developed transgressive systems tracts consisting of all depositional systems from fluvial, to coastal and fully marine.

6. The absence (or poor development) of the fluvial to coastal section of the Precambrian transgressive systems tracts may be attributed to the inferred strong wave scouring in the upper shoreface during shoreline transgression. The lack of significant development of transgressive shales above wave ravinement surfaces may be attributed to low sea-floor gradients, promoting rapid transgressions, coupled with a low sediment supply.

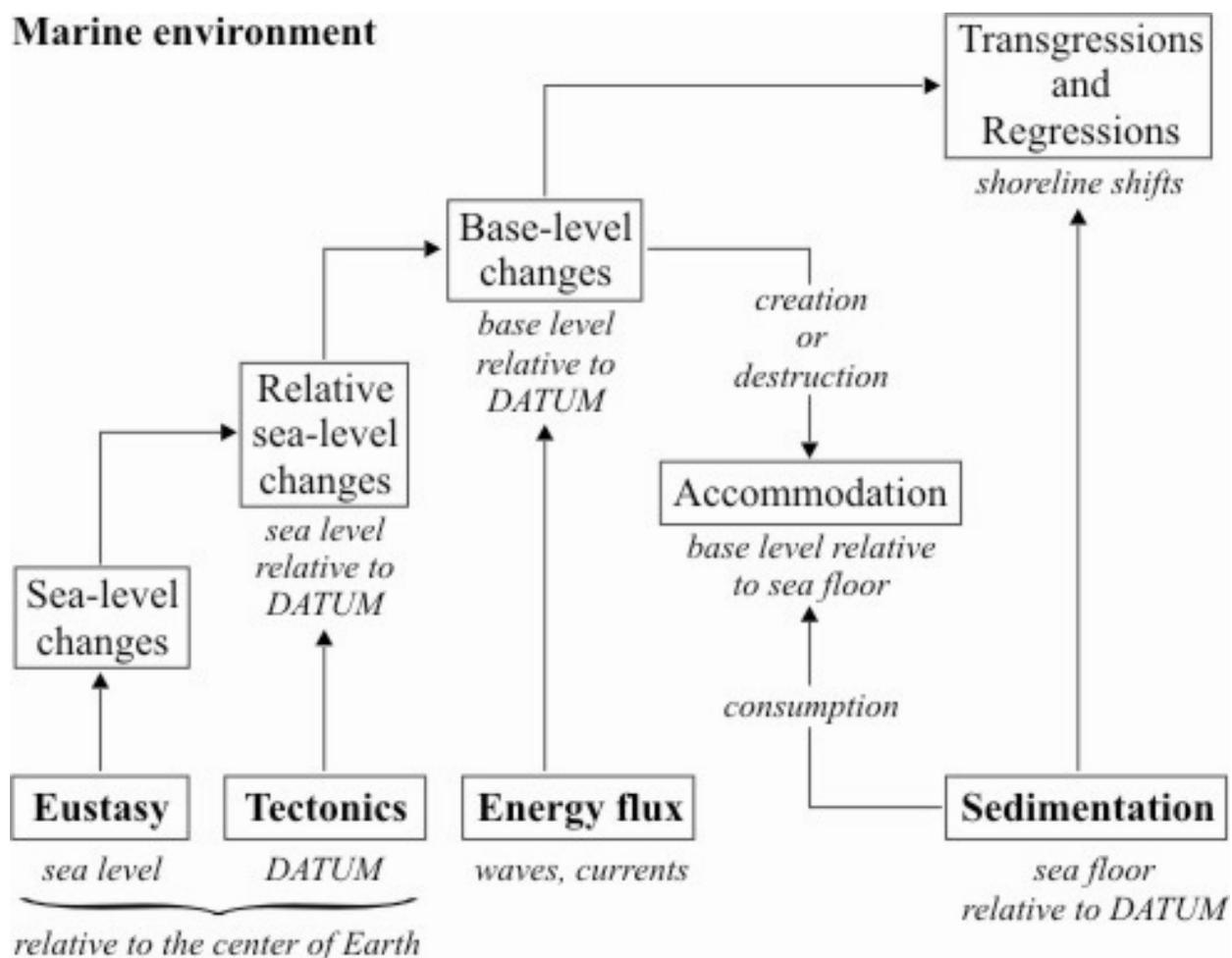
7. Within Precambrian sequences, the aggradation of normal regressive deposits in spite of the low sediment supply may be explained by the prolific growth of microbial mats below the fairweather wave-base (within the shelf environment) which prevented deep-water current reworking of sediments, by the organic binding of clastic particles. As such, microbial structures are preferentially preserved within the deeper-water portions of parasequences.

## Figures Chapter 9(b)



**Fig. 9(b)-1:**

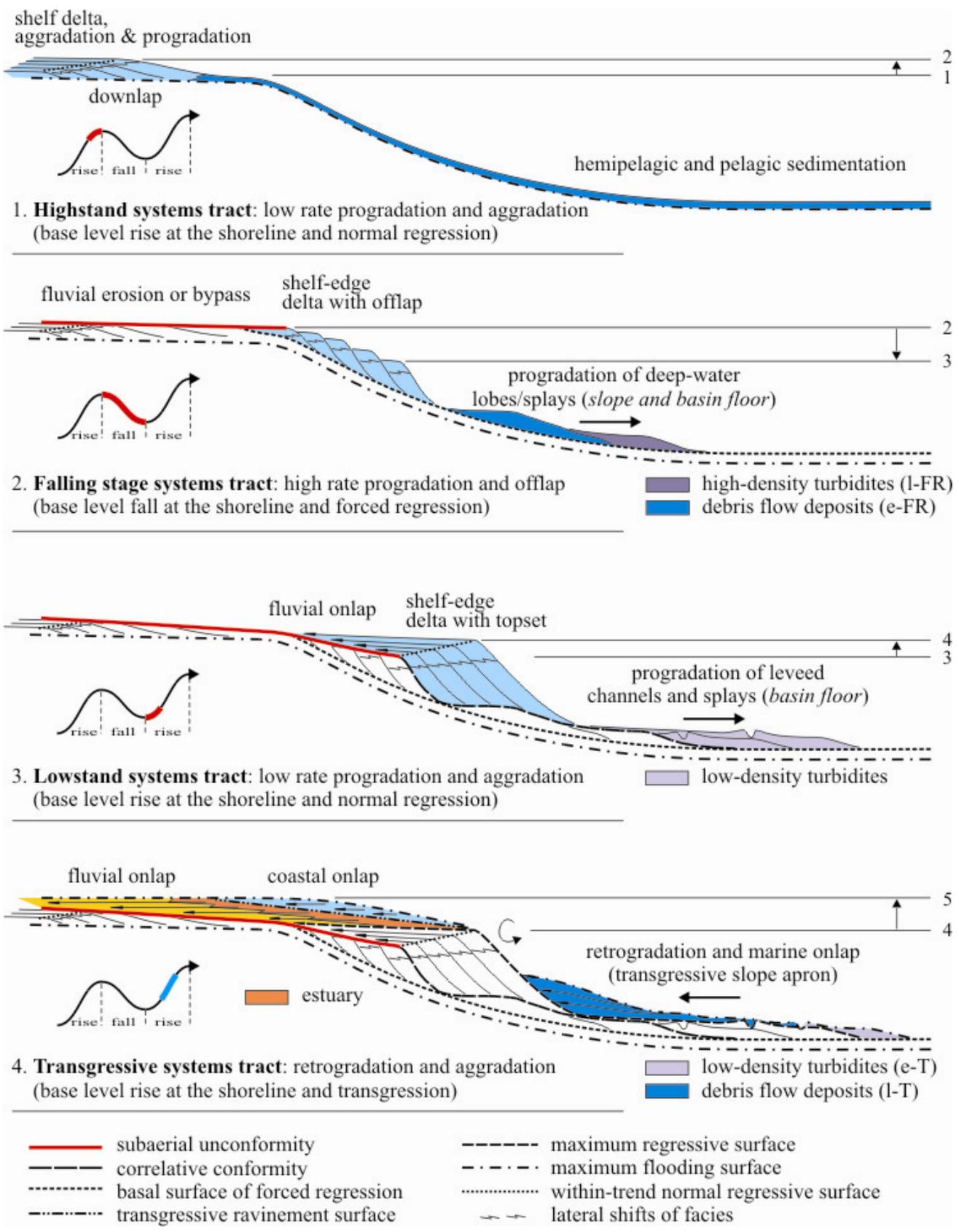
Sequence stratigraphy in the context of interdisciplinary research: main controls, integrated data sets and subject areas, and applications (from Catuneanu, 2006).



**Fig. 9(b)-2:**

Controls on accommodation and shoreline shifts in a marine environment (from Catuneanu, 2006). The ‘DATUM’ is a reference horizon, independent of sedimentation, which monitors tectonic motions (subsidence, uplift) relative to the centre of the Earth. See Catuneanu (2006) for additional definitions and explanations.





In: *Atlas of microbial mat features preserved within the clastic rock record*, Schieber, J., Bose, P.K., Eriksson, P.G., Banerjee, S., Sarkar, S., Altermann, W., and Catuneau, O., (Eds.), Elsevier, p. 276-283. (2007)

**Fig. 9(b)-4:**

Regional architecture of depositional systems, systems tracts and sequence stratigraphic surfaces (from Catuneanu, 2006). The systems tract nomenclature follows the scheme of Hunt and Tucker (1992). Systems tracts are defined by stratal stacking patterns and bounding surfaces, with an inferred timing relative to the reference curve of base-level changes at the shoreline.

| Basin types<br>Shoreline shifts | <b>Low-gradient ('shelf') settings</b><br>(continental shelves, filled foreland basins, intracratonic basins)  | <b>High-gradient ('ramp') settings</b><br>(continental slopes, underfilled forelands, rift and strike-slip basins)   |
|---------------------------------|--|--|
| Transgressions                  | Estuaries are likely to form. The preservation of estuarine facies is a function of the rates of base-level rise and wind/wave energy.   | Estuaries are unlikely to form, due to the steep topography, higher fluvial energy, wave erosion, and slope instability.   |
| Normal regressions              | Deltas have diagnostic topsets, as a result of aggradation in the delta plains. Fluvial aggradation extends over a relatively large distance upstream (inconspicuous onlap onto the subaerial unconformity at lowstand). | Deltas have diagnostic topsets, as a result of aggradation in the delta plains. Fluvial aggradation is restricted to a relatively small area adjacent to the shoreline (pronounced onlap). Fluvial strata have low preservation potential. |
| Forced regressions              | Deltas have diagnostic offlapping geometries (delta plain erosion or bypass). The regressive surface of marine erosion forms in the lower shoreface in wave-dominated settings.  | Deltas have diagnostic offlapping geometries (delta plain erosion or bypass). No erosion in the lower shoreface, as the sea floor is already steeper than the shoreface equilibrium profile.   |

**Fig. 9(b)-5:**

Contrasts between low- and high-gradient tectonic settings, in terms of processes and products of transgressions, normal regressions and forced regressions (from Catuneanu, 2006).

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