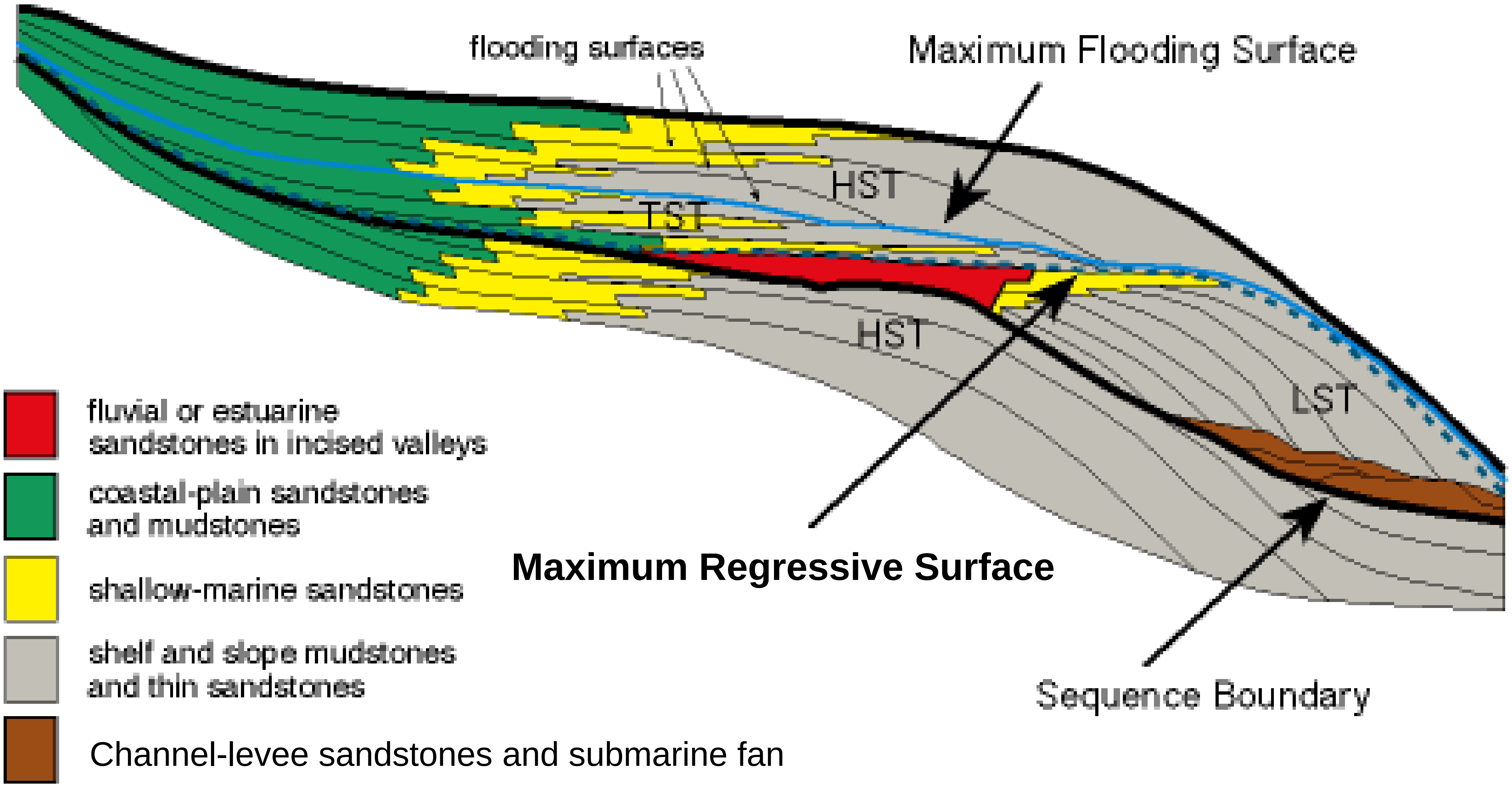
Sequence Stratigraphic Analysis



SECTOR OF HISTORICAL GEOLOGY - PALEONTOLOGY

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1.1 Introduction

Sequence Stratigraphy has been established over the past 40-45 years as a popular methodology for correlating sedimentary strata and constructing dynamic chronological frameworks for sedimentary regional basins, in order to understand the evolution of the basin's depositional systems through time. Such frameworks, in conjunction with the sedimentology of the strata, are fundamental for interpreting paleogeography and depositional trends caused by changes generated by the interplay between rates of sedimentation and the rates of increase or reduction of the space available for deposition (i.e., accommodation space) in the marine basins.

Such changes in accommodation space include: tectonic movements, isostatic subsidence due to sediment overloading, isostatic uplift due to the removal of loadings from land, eustatic sea level changes in response to changes in the volume of ocean water (due to climate changes) and the volume of ocean basins, and sediment compaction and consolidation. The sum of all these changes is commonly referred to as stratigraphic **base level** change.

Sequence Stratigraphy usually involves the subdivision of a sedimentary basin fill into individual sequences of deposition (hence the name), which can then be linked to changes in the two fundamental parameters of sediment supply and accommodation space. Hence, the main target is to reconstruct how sediments filled a basin and, therefore, how the stratigraphy was formed through space and time. This can help scientists and exploration geologists to figure out many important things like how sea level changed and where coarse- and fine-grained sediments are located (very important issue for the oil and gas industry). Over the years, Sequence Stratigraphy has developed into a widely used, methodological framework that encompasses many aspects of Sedimentology and Stratigraphy and has many useful applications and predictive capacities.

Sedimentary sequences refer to an amount of stratigraphy that was deposited during an episode of base level fall and subsequent rise. Commonly, such depositional sequences are further subdivided into so-called systems tracts (meaning a portion of stratigraphy linked to a position in base level). For instance, when base level falls during a glacial period and, then, subsequently rises during an interglacial period, one sequence is deposited consisting of a lowstand systems tract (LST), followed by a transgressive systems tract (TST) and, finally, a highstand systems tract (HST). The amount and type of systems tracts considered can differ among researchers and projects. Systems tracts are often distinct in their shape, size and type of sedimentary deposits. For instance, basin floor fans, usually form as part of the lowstand systems tract (sediments that were deposited when sea level was low or falling), while the boundaries between systems tracts are often marked by significant surfaces like sequence boundaries or maximum flooding surfaces.

However, like most things in Earth sciences, sequence stratigraphic models are always a simplification of the reality and Sequence Stratigraphy as a whole is infamous for being complicated and fraught with difficult terminology, numerous exceptions and additional complicating factors, many of which are unknown or poorly understood. Nevertheless, Sequence Stratigraphy has become an important branch of Stratigraphy and Sedimentology and has greatly helped the sedimentological community as well as economic geologists in better understanding sedimentary basins and their stratigraphy.

The fundamental starting point for Sequence Stratigraphy is the sedimentary facies, which is a lithostratigraphic body characterized by distinct lithological or fossil characteristics, generally reflecting a certain origin. A group of sedimentary facies genetically linked by common processes and environments comprises a depositional system. These depositional systems can be grouped together within a framework of unconformity-bounding relatively conformable stratigraphic packages to form the depositional sequences.

The modern era of Sequence Stratigraphy began with the milestone publication (1977) of the Exxon definitions and methodology. However, by 1990, it was apparent that two different approaches of the sequence stratigraphic methodology and classification were in use, termed as inductive and deductive, and that the existence of these two different approaches might well be contributing to methodological and communication problems. Indeed, long-standing controversial issues regarding the existing sequence stratigraphic terminology and methodology were arisen, but the application of Sequence Stratigraphy to the sedimentary basin analysis, mainly by the oil and gas industry, was unavoidable to be established as a tool of crucial significance.

The inductive approach of Sequence Stratigraphy, which is empirical and material-based, is readily applied using a wide variety of data sets, in order to generate a robust theory. This contrasts with the deductive approach, which generally relies on the availability of very specialized data in order to be applied in a scientific and reliable manner for the validation of an existing theory. It is critical that those engaged in sequence stratigraphic investigations are aware of the existence of these two distinctly different approaches and of the problems that might arise if one does not apply the most appropriate to its study.
However, the deductive approach, conceptual and somewhat model-driven, has dominated the sequence stratigraphic methodology and terminology for the past 30 years, since it remains highly interpretive, in its philosophical essence, far more than any other methodological branch of stratigraphy.

The roots of Sequence Stratigraphy can be traced far back in the classic principles of Sedimentary Geology, which established the fundamental guidelines of sedimentological and stratigraphic analyses. These “first principles” established the ground rules for the physics of flow and sediment motion, and the processes of sediment accumulation, bypass or erosion in relation to a shifting balance between relative sea-level changes, sediment supply and the energy of the transporting agent (Figs 1, 2). These principles still represent the scientific background of Sequence Stratigraphy, which allows old and modern concepts to blend into an evolving new way of looking at the sedimentary rock record.

Principles of flow and sediment motion

All natural systems tend toward a state of equilibrium that reflects an optimum use of energy. This state of equilibrium is expressed as a graded profile in fluvial systems, or as a base level in coastal to marine systems. Along such profiles, there is a perfect balance between sediment removal and accumulation(see image below).

Fluid and sediment gravity flows tend to move from high to low elevations, following pathways that require the least amount of energy for fluid and sediment motion.

Flow velocity is directly proportional to slope magnitude.

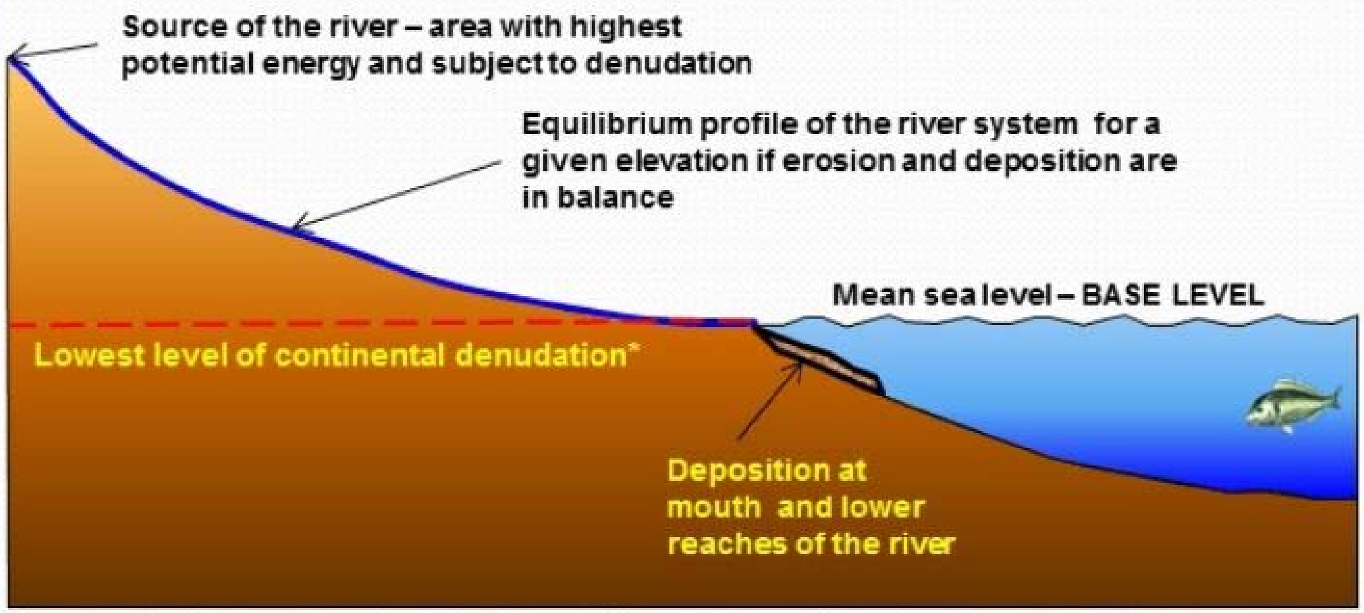
Flow discharge (subaerial or subaqueous) is equal to flow velocity times cross-sectional area.

Sediment load (volume) is directly proportional to the transport capacity of the flow, which reflects the combination of flow discharge and velocity.

The mode of sediment transport (bedload, saltation, suspension) reflects the balance between grain size/weight and flow competence.

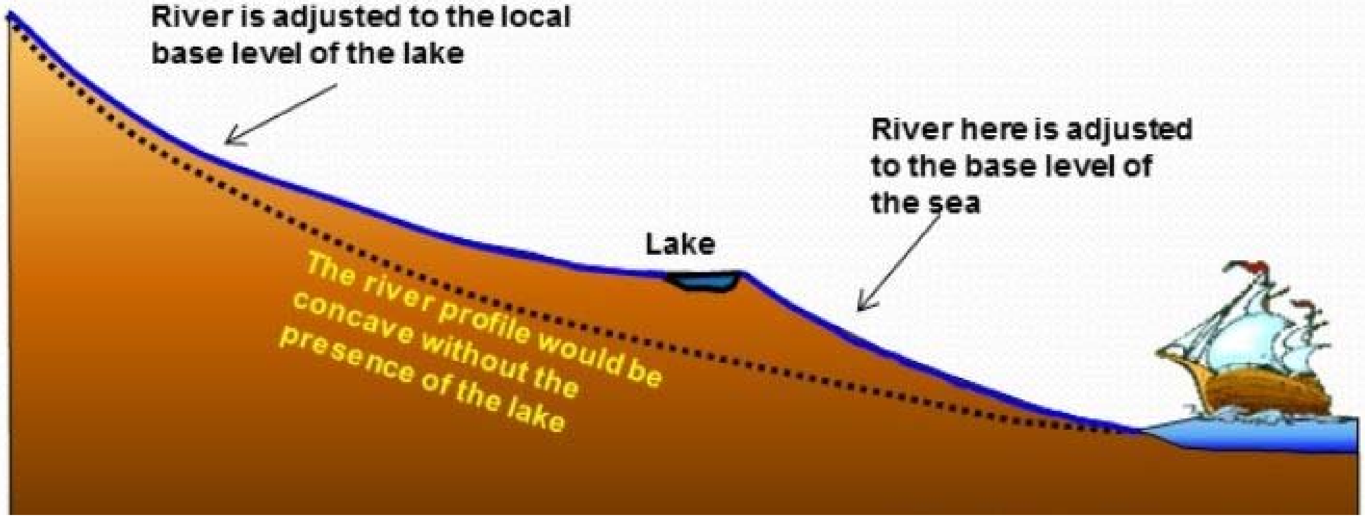
Fig. 1 *Key "first principles" of Sedimentary Geology that are relevant to Sequence Stratigraphy.*

IDEALISED GRADED RIVER



*Denudation is the combined effects of weathering, mass movement and erosion

RIVER GRADE WITH LOCAL CHANGES



Principles of sedimentation

Walther's Law: within a relatively conformable succession of genetically related strata, vertical shifts of facies reflect corresponding lateral shifts of facies.

The direction of lateral facies shifts (progradation, retrogradation) reflects the balance between sedimentation rates and the rates of change in the space available for sediment to accumulate.

Processes of aggradation or erosion are linked to the shifting balance between energy flux and sediment supply: excess energy flux leads to erosion, excess sediment load triggers aggradation.

The bulk of clastic sediments is derived from elevated source areas and is delivered to sedimentary basins by river systems.

As environmental energy decreases, coarser-grained sediments are deposited first.

Fig. 2 *Key "first principles" of Sedimentary Geology that are relevant to Sequence Stratigraphy.*

In conclusion, it is broadly recognized that Sequence Stratigraphy is a fresh technique for the analysis of sedimentary successions rather than a brand new method on its own. Of course, one cannot emphasize that a successful sequence stratigraphic study necessarily requires integration of various data sets and methods of data analysis into a unified, interdisciplinary approach (Fig. 3). But also this is not to say that Sequence Stratigraphy simply re-sells old concepts in a new package. In fact, the sequence stratigraphic technique allows for new insights into the genesis and architecture of sedimentary basin fills, which were not possible prior to the introduction of seismic stratigraphic concepts in the 1970s. The issues of how sedimentary facies are formed evolve and distributed in both mature and frontier hydrocarbon basins are good examples of such new insights, which were made possible by the sequence stratigraphic approaches, and are highly significant on both academic and economic grounds.

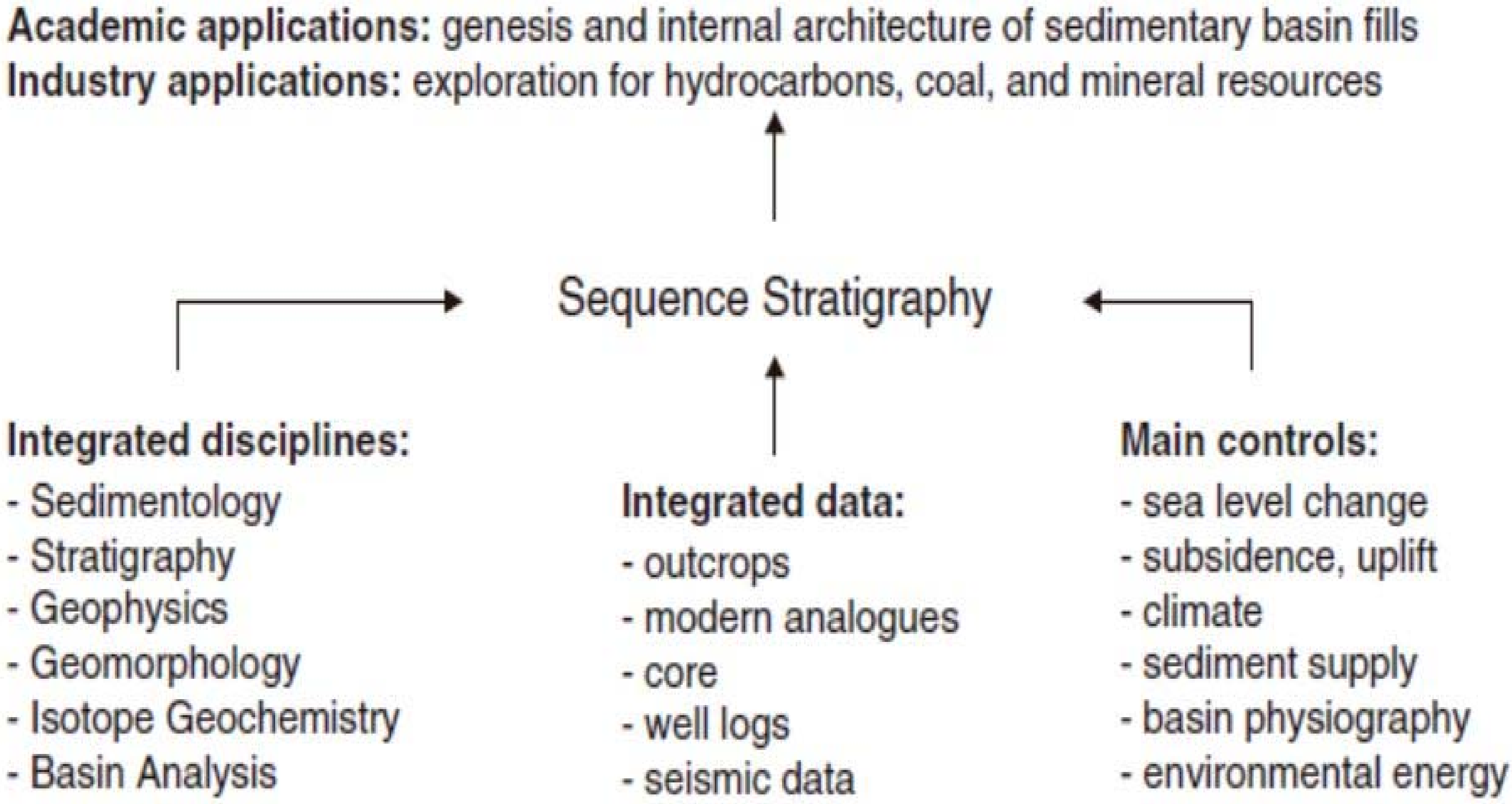
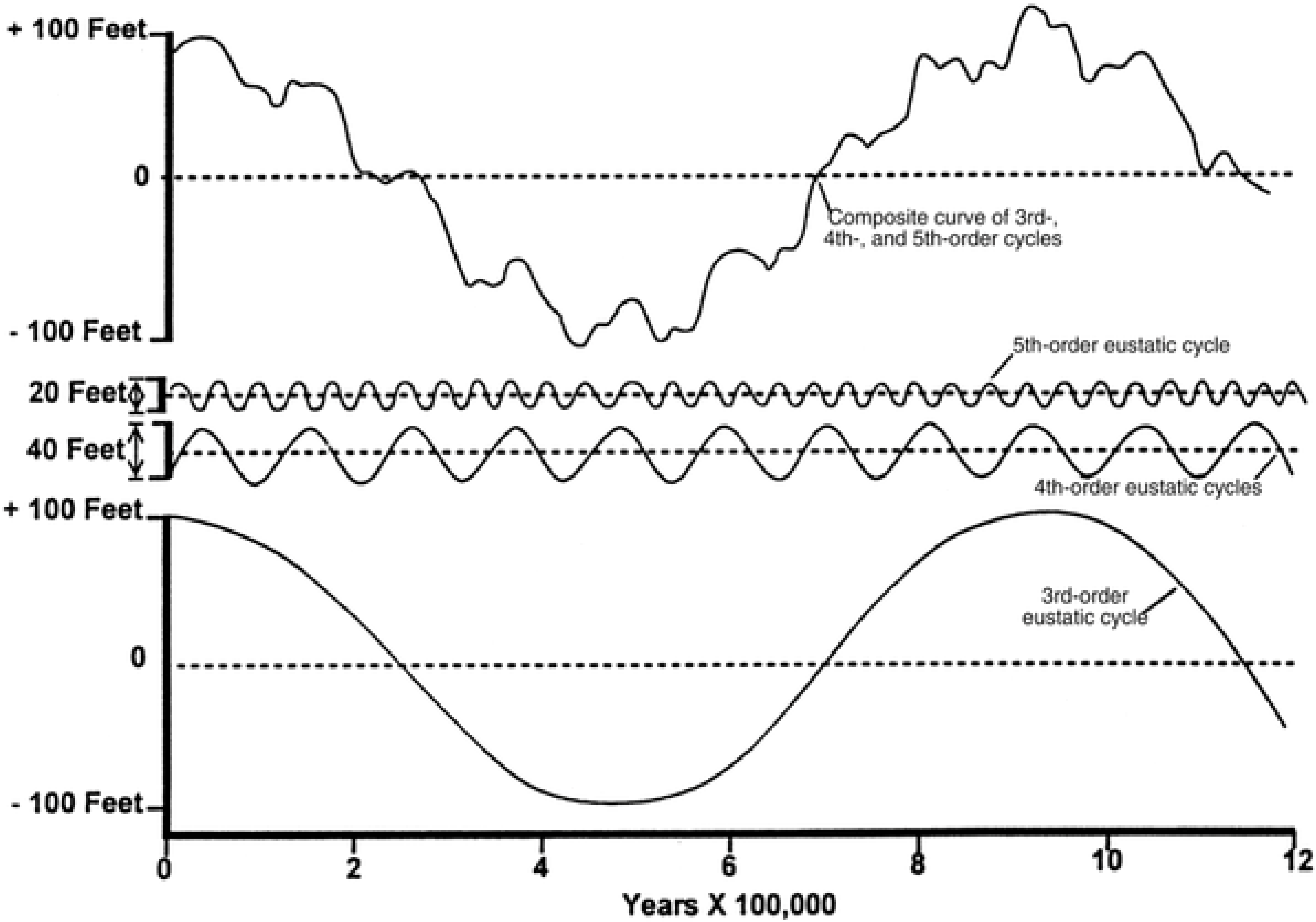


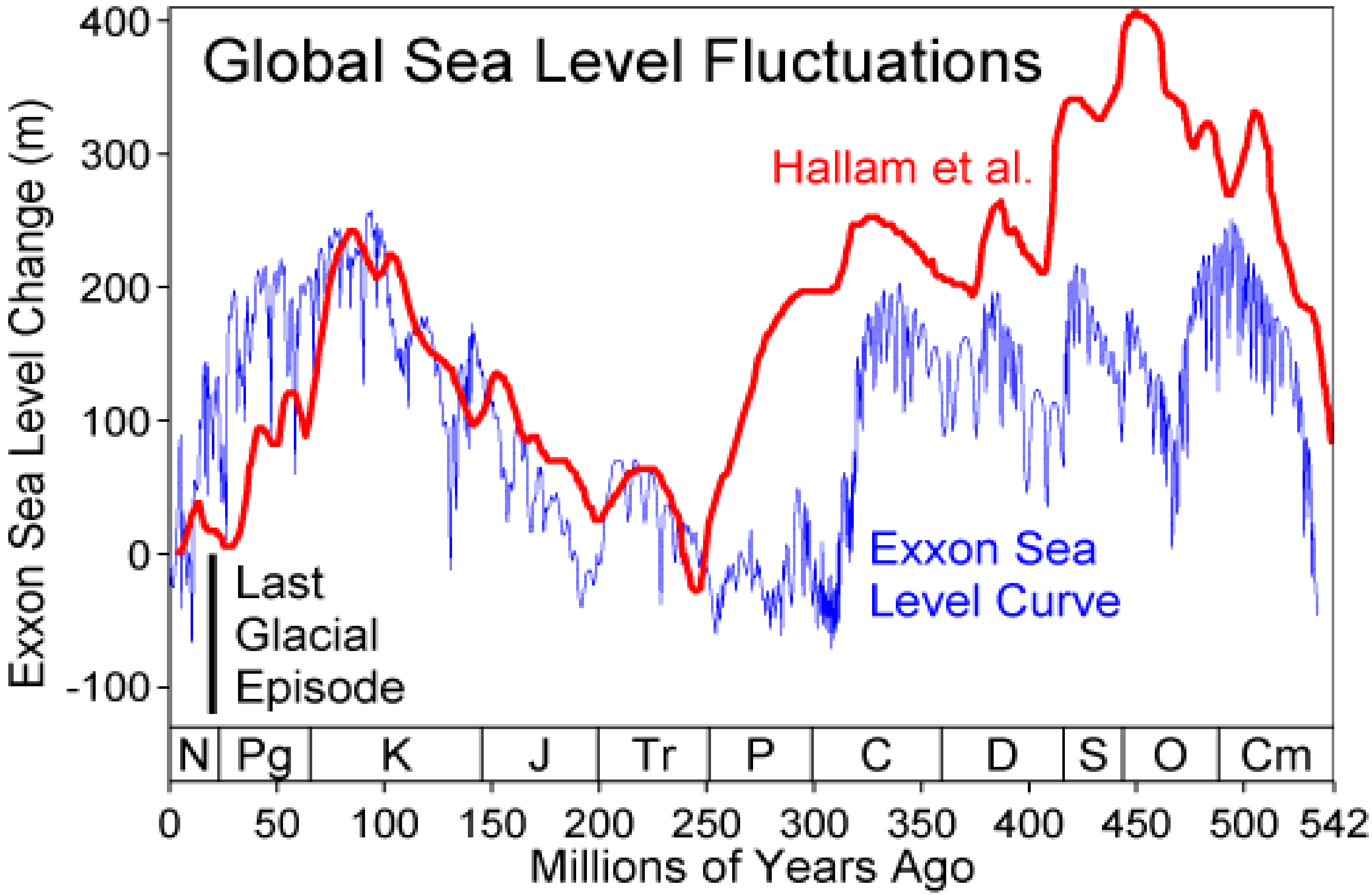
Fig. 3 *Sequence Stratigraphy in the context of interdisciplinary research. Main controls, integrated data sets and subject areas and applications.*

1.2 Deductive Approach of Sequence Stratigraphy

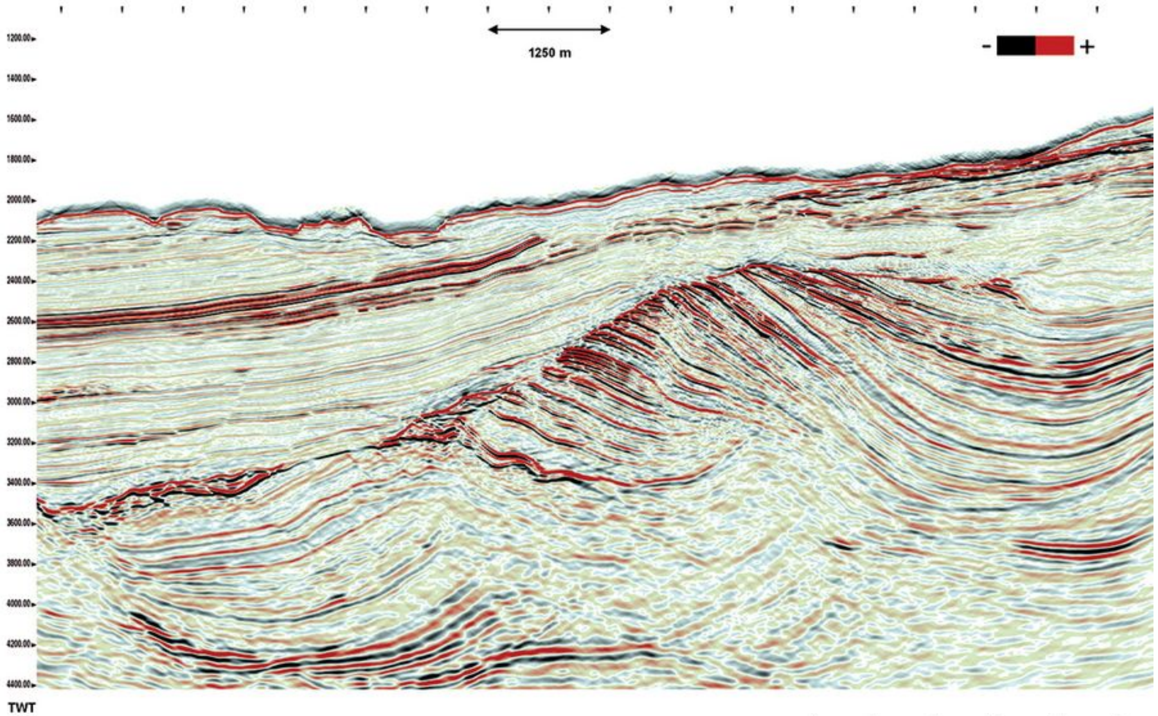
The deductive approach is based primarily on a mathematical, stratigraphic model, which was developed by Mac Jervey of Exxon in 1979 to provide a theoretical basis for seismic-based, sequence stratigraphic concepts presented by Exxon scientists in 1977. The model used a “sinusoidal” sea-level rise and fall (see images below), associated subsidence that increased basinward and a constant sediment supply as input parameters. Particularly, it predicted the occurrence of stacked, basin flank unconformities and downlap surfaces in central regimes of the basin, being the principal surfaces interpreted from seismic profiling (see images below).

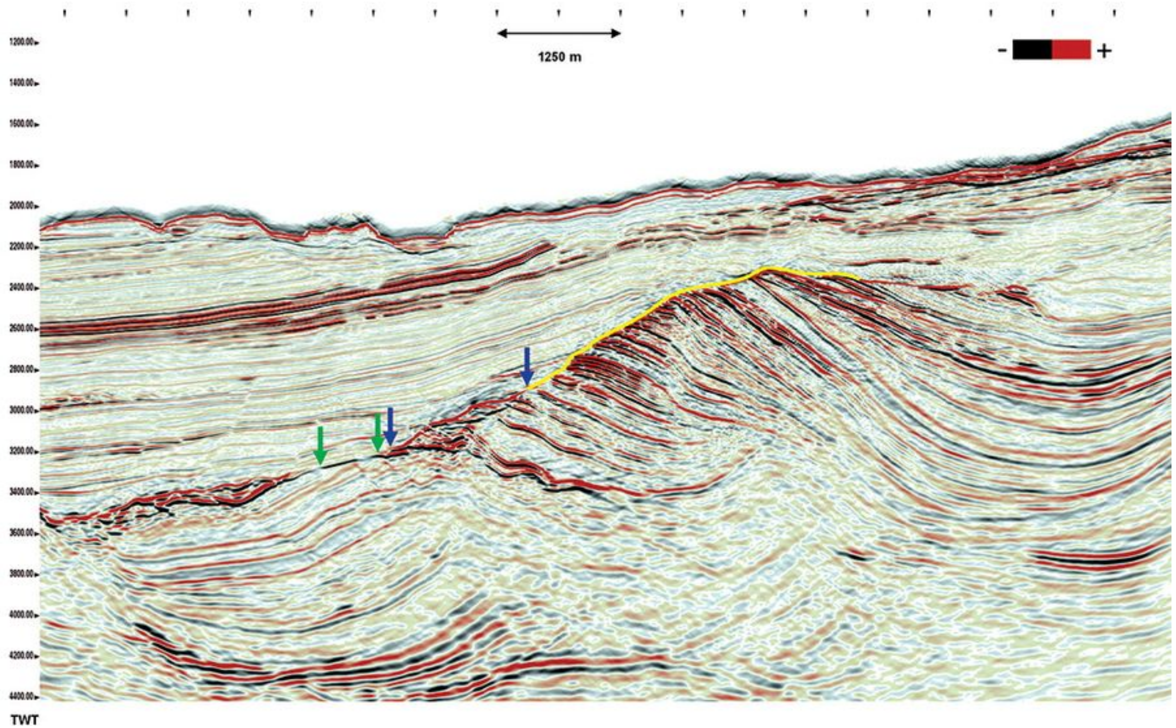


Composite curve created by adding third-, fourth- and fifth-order cycles together

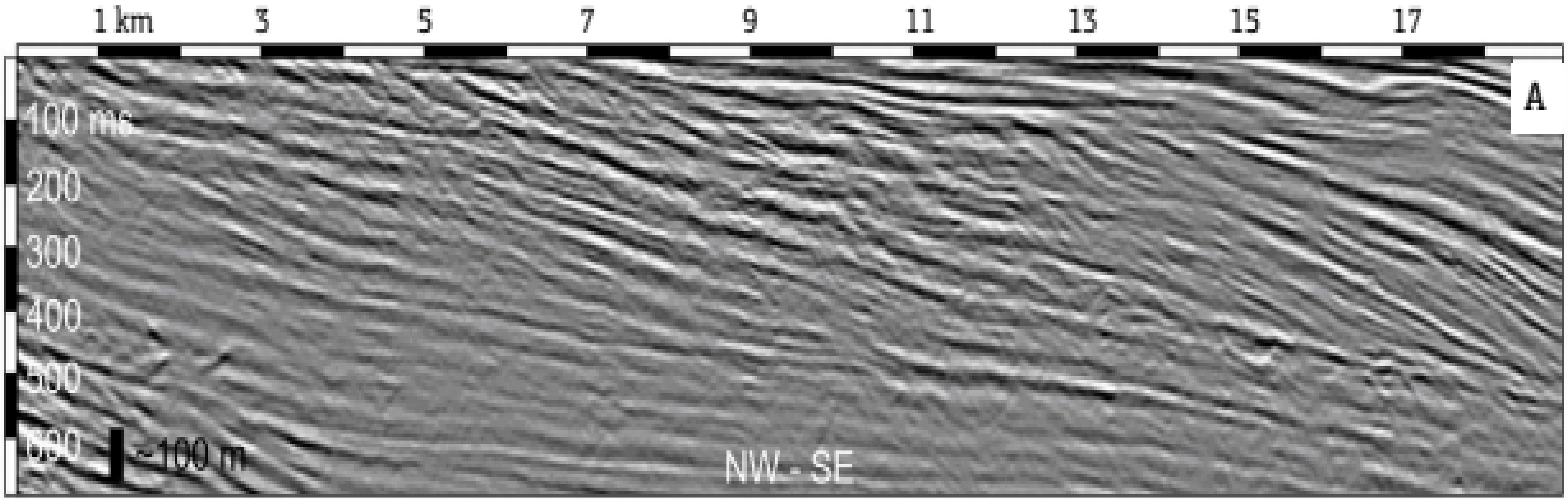


Sea level reconstructions during the last 500 million years (the scale of change during the last glacial/interglacial transition is indicated with a black bar)

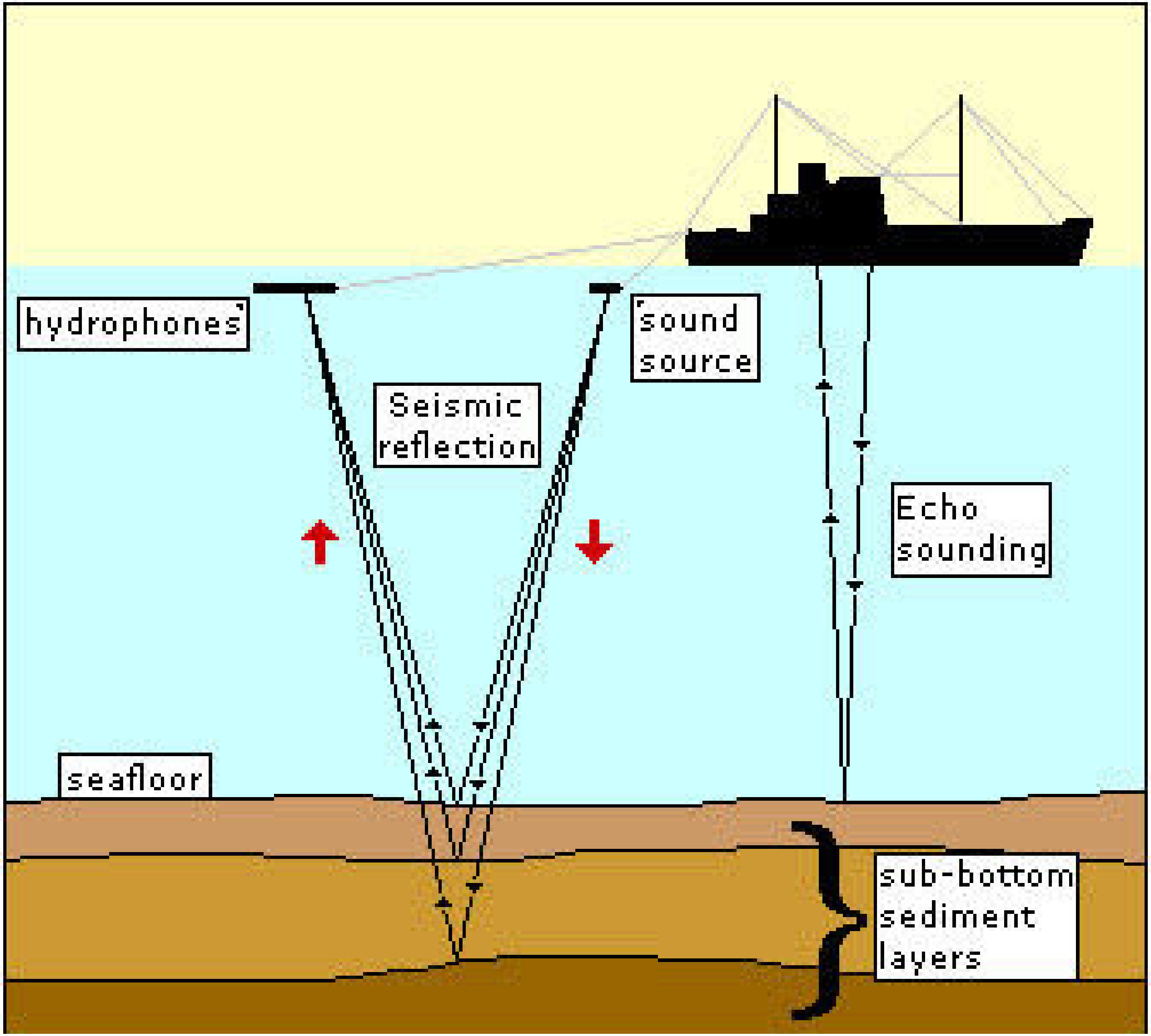




Example of angular unconformity

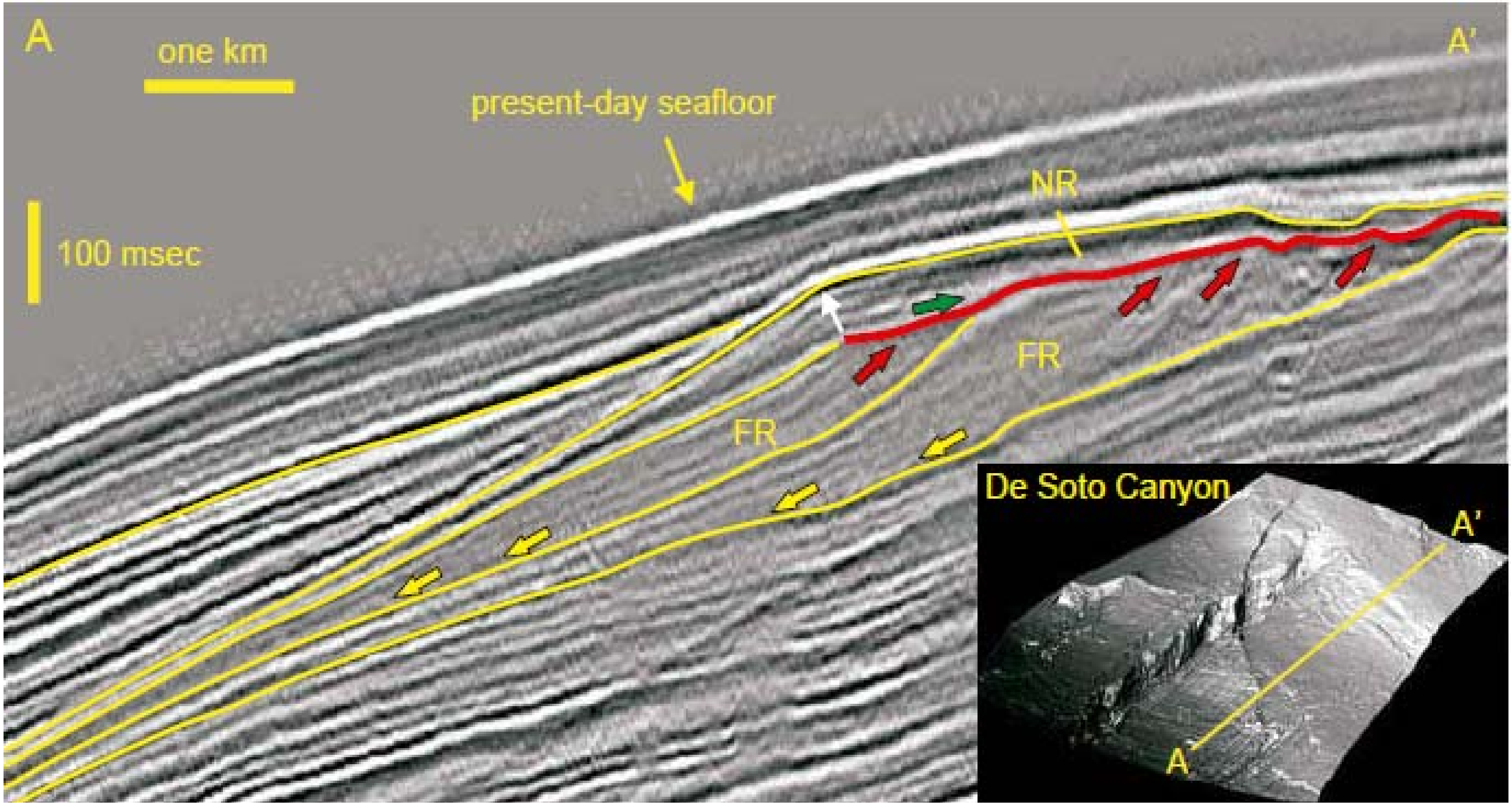


Example of downlap surfaces

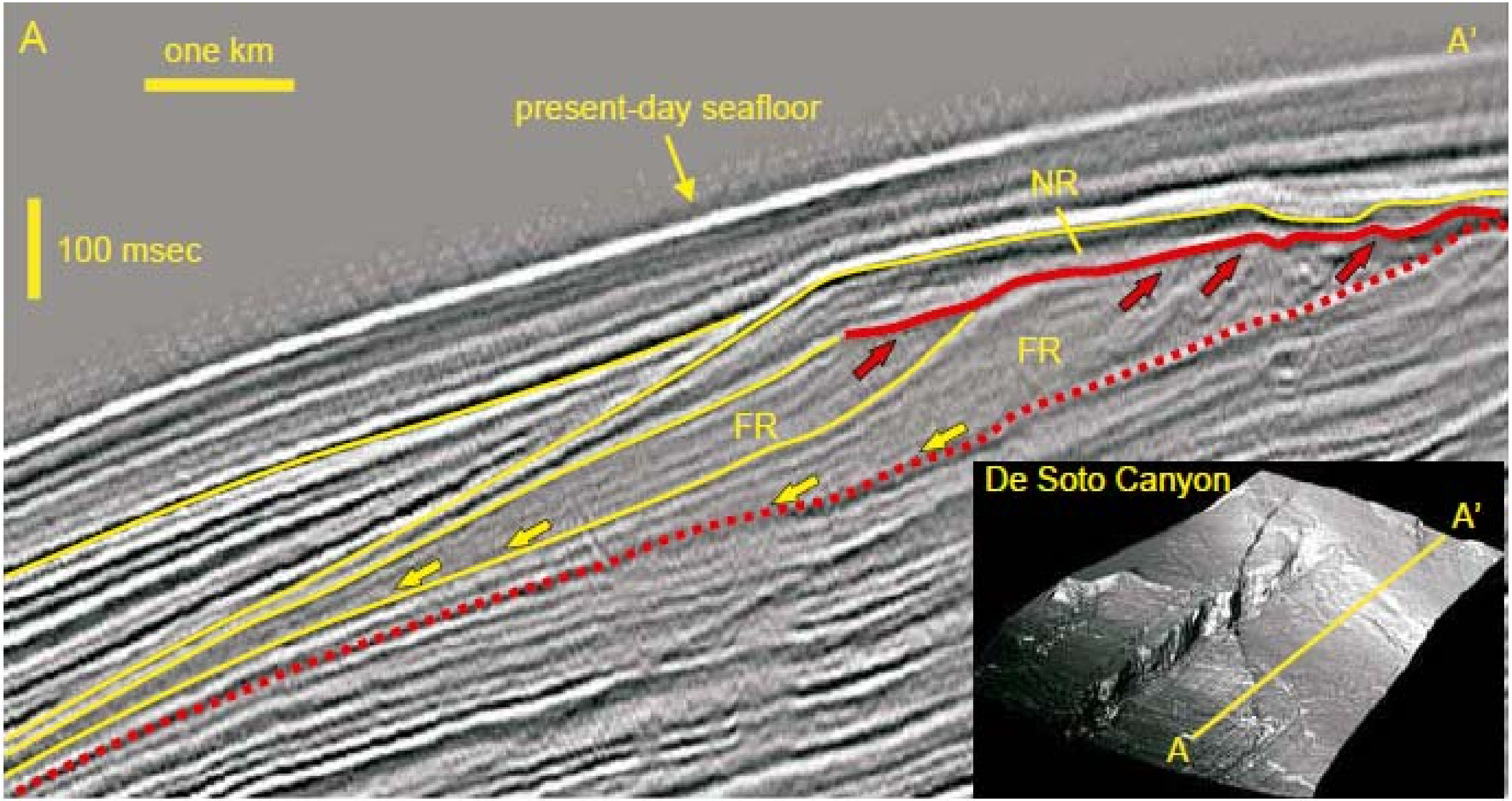

hydrophones
sound source
Seismic reflection
Echo sounding
seafloor
sub-bottom sediment layers

1.2.1 The Deductive Sequence Stratigraphic Surfaces

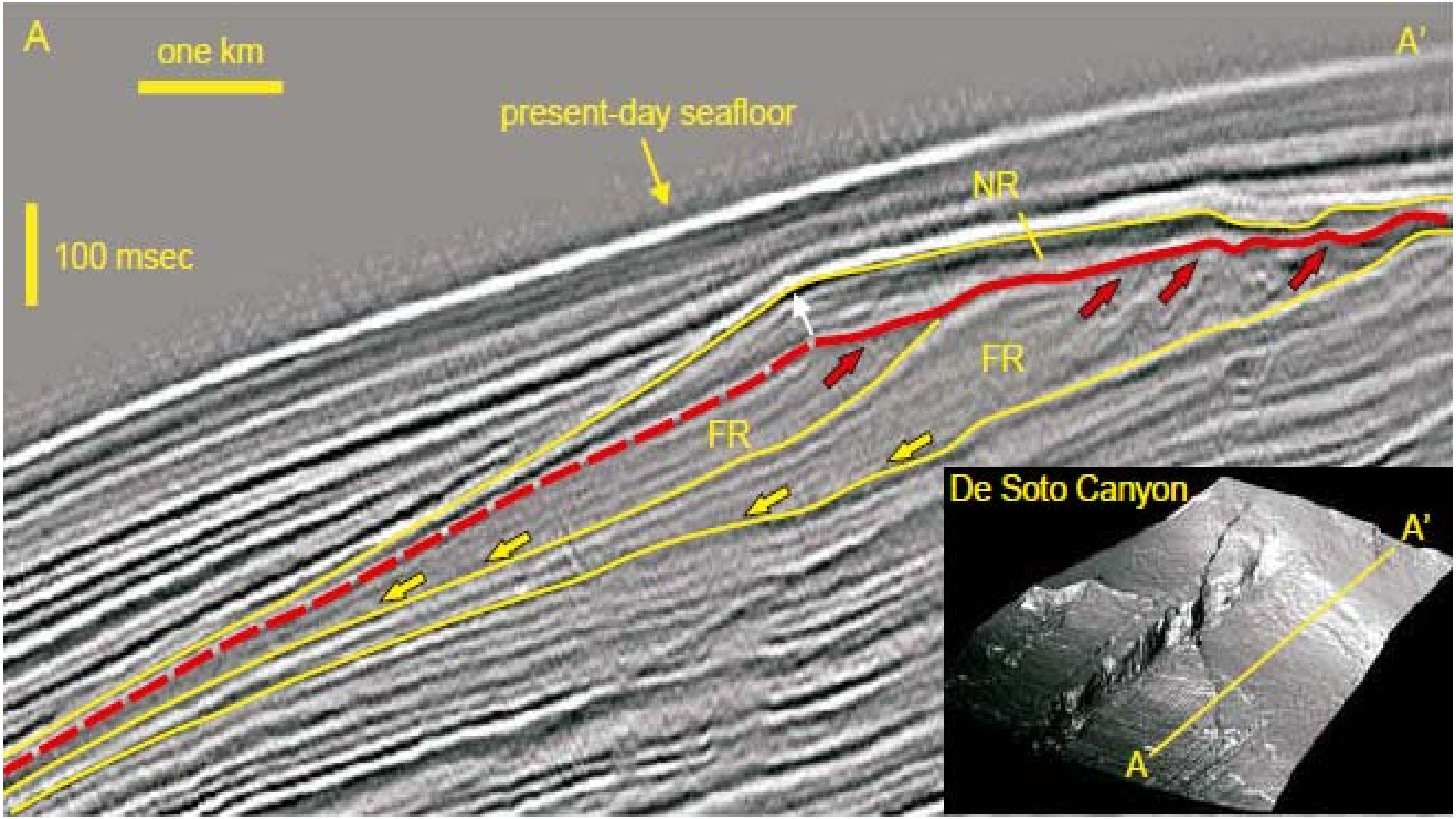
The deductive sequence stratigraphic approach recognizes the following surfaces: Subaerial Unconformity (SU), Shoreline Ravinement (SR), Regressive Surface of Marine Erosion (RSME), Maximum Regressive Surface (MRS), Maximum Flooding Surface (MFS), Basal Surface of Forced Regression (BSFR) and Correlative Conformity (CC) (see relevant images below).



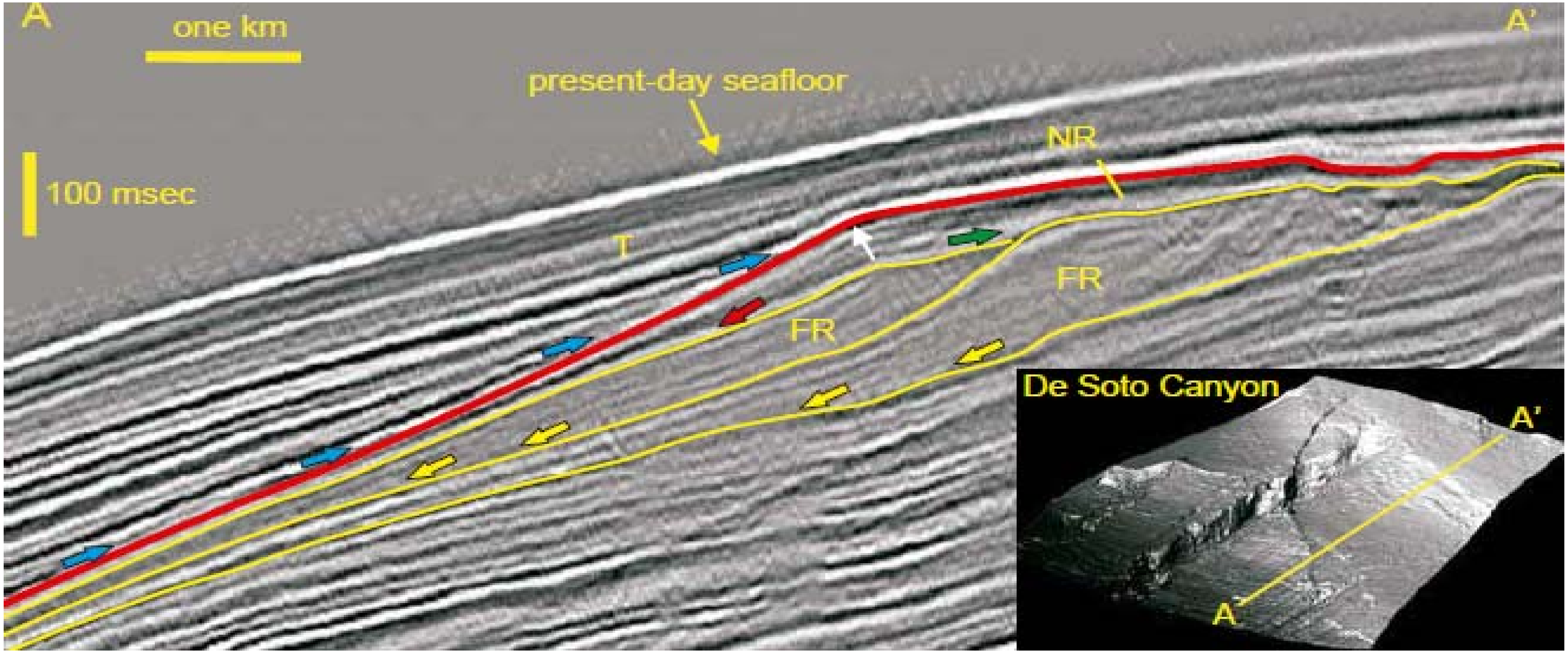
Subaerial Unconformity *(red line) on a dip-oriented, 2D seismic transect. Red arrows indicate truncation of the underlying forced regressive shallow-marine strata. Thinner yellow lines provide a sense of the overall stratal stacking patterns. Note that the subaerial unconformity is associated with offlap, decrease in elevation in a basinward direction and irregular topographic relief. The basinward termination of the Subaerial Unconformity indicates the shoreline position at the end of forced regression. Abbreviations: FR - forced regressive deposits; NR - normal regressive deposits.*



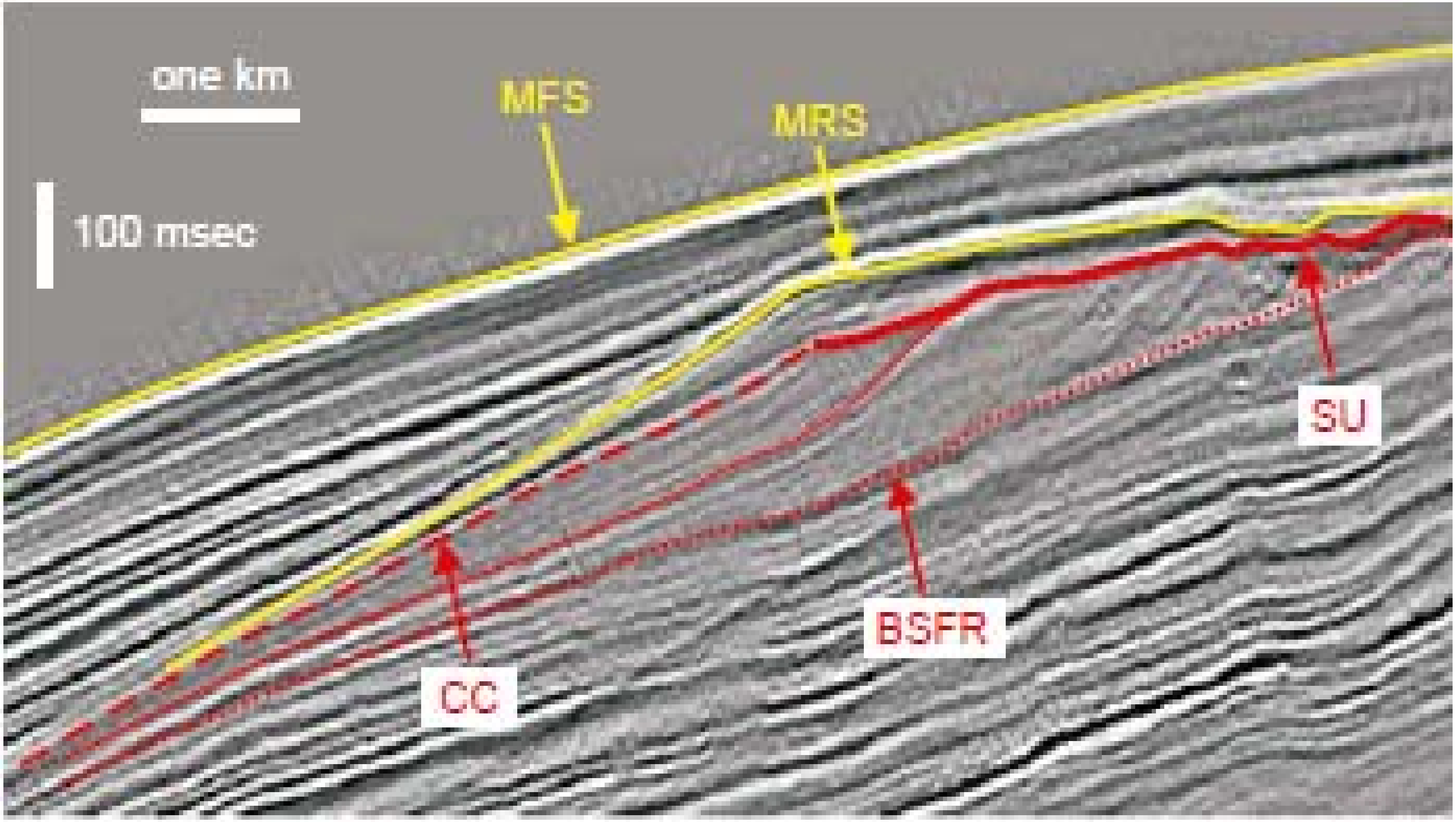
Basal Surface of Forced Regression *(red dotted line) on a dip-oriented 2D seismic transect. The solid red line shows the basinward portion of the Subaerial Unconformity that formed during forced regression. Thinner yellow lines provide a sense of the overall stratal stacking patterns. The Basal Surface of Forced Regression corresponds to the seafloor at the onset of forced regression. Red arrows indicate truncation of the shallow-marine forced regressive strata by the Subaerial Unconformity. The deep-water forced regressive deposits downlap the Basal Surface of Forced Regression (yellow arrows).*



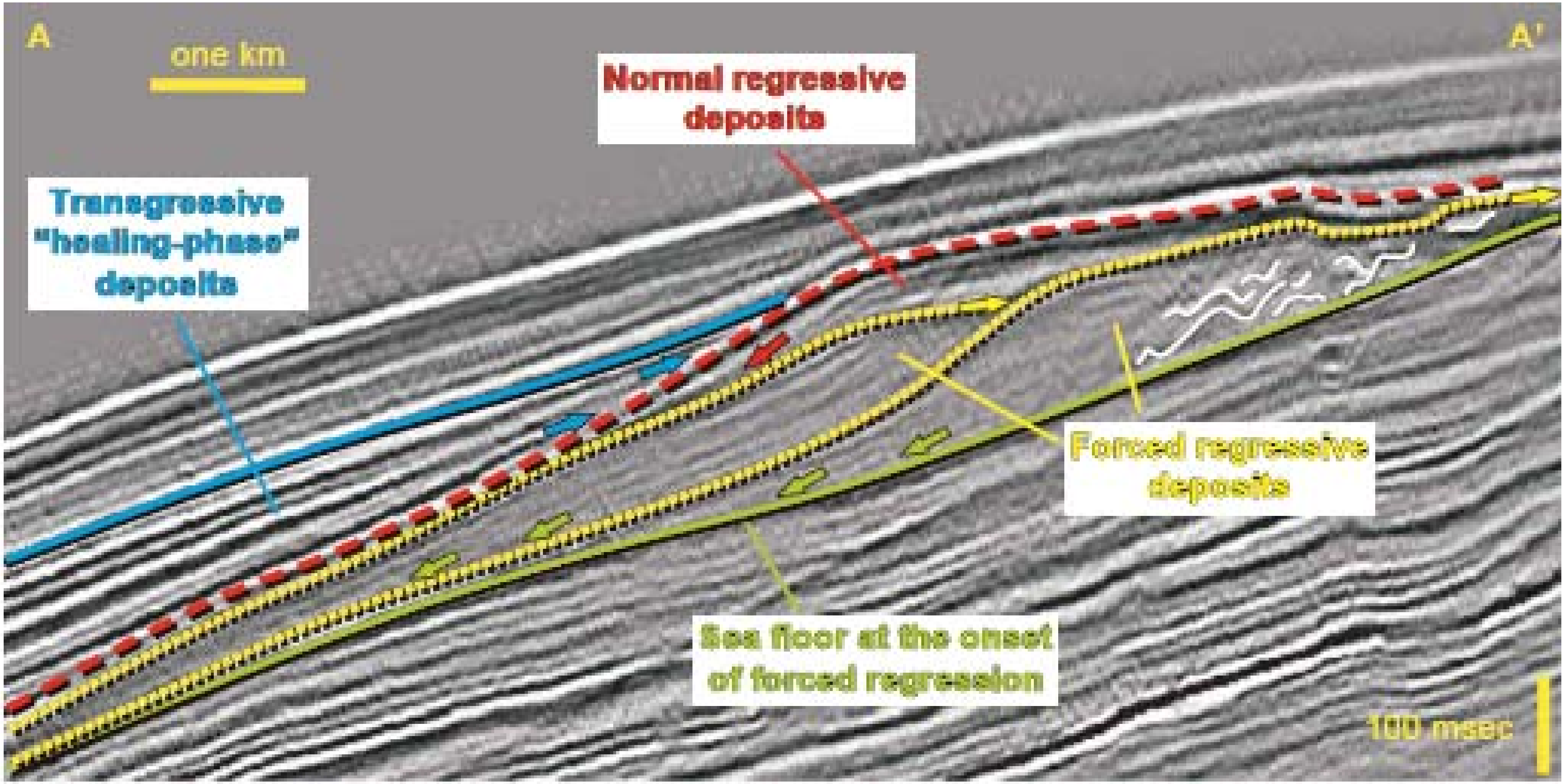
Correlative Conformity *(red dashed line) on a dip-oriented, 2D seismic transect The solid red line shows the Subaerial Unconformity, whose basinward termination meets the Correlative Conformity at the point that corresponds to the position of the shoreline at the end of forced regression. The Correlative Conformity is the youngest clinoform associated with offlap. Red arrows indicate truncation of the shallow-marine forced regressive strata by the Subaerial Unconformity.*



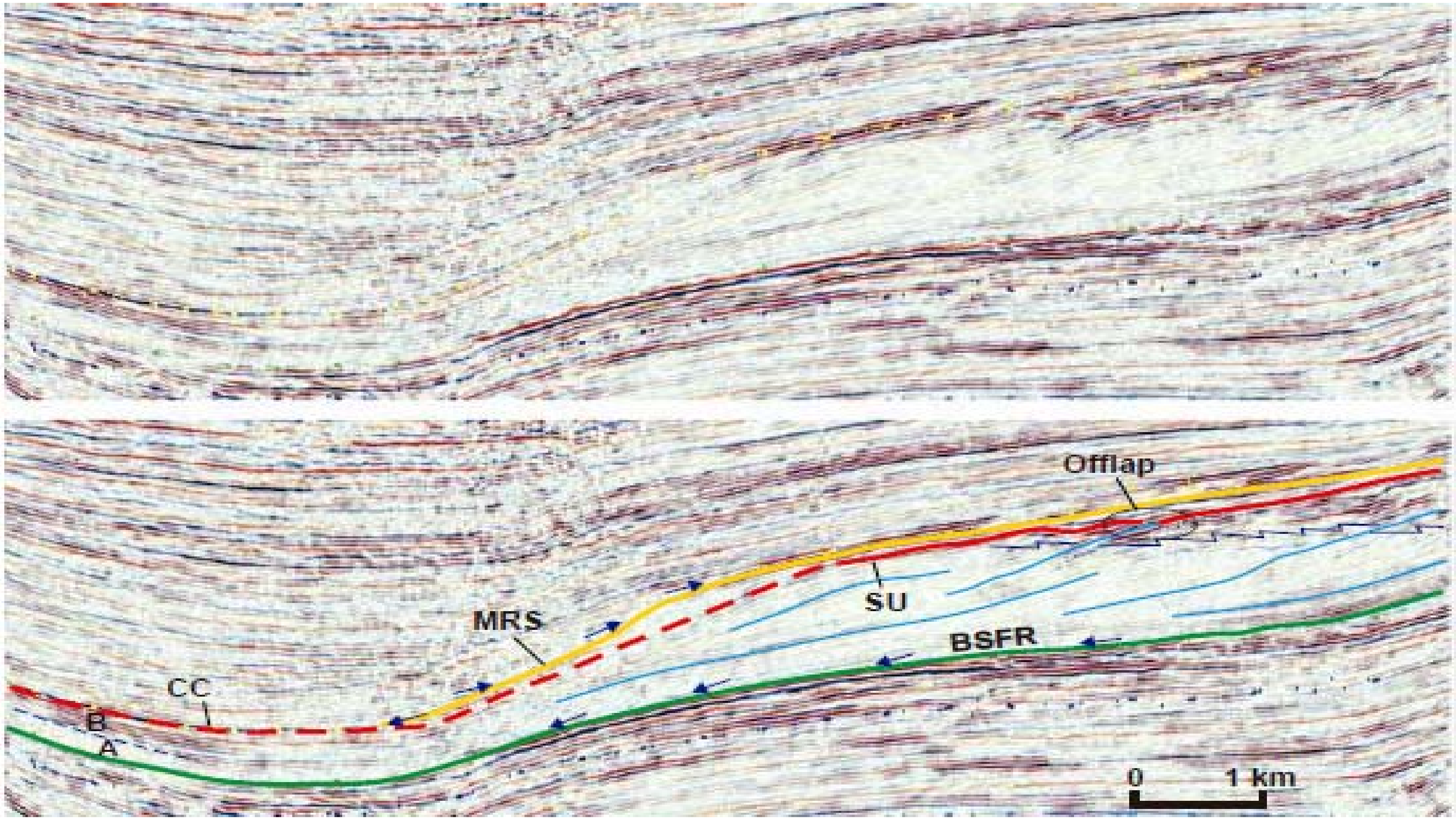
***Maximum Regressive Surface** (red line) on a dip-oriented, 2D seismic transect. This surface tops all fluvial to deep-marine strata that accumulate during lowstand normal regression. The maximum regressive surface may onlap the Subaerial Unconformity in a landward direction (fluvial onlap) and is onlapped by transgressive facies in the deep-water environment (marine onlap; blue arrows). The white arrow indicates the shoreline trajectory during lowstand normal regression. It is inferred that the normal regressive facies are marine seaward from the white arrow (downlapping the underlying forced regressive deposits; red arrow) and non-marine in the opposite direction (onlapping the Subaerial Unconformity; green arrow - fluvial onlap). In a marine environment, the Maximum Regressive Surface is the youngest clinoform associated with shoreline regression*.



*The **Maximum Flooding Surface** (MFS) is approximated with the modern seafloor in the seismic profile (Pleistocene to present day), but as the transgression still continues today, the actual MFS is yet to be formed.*

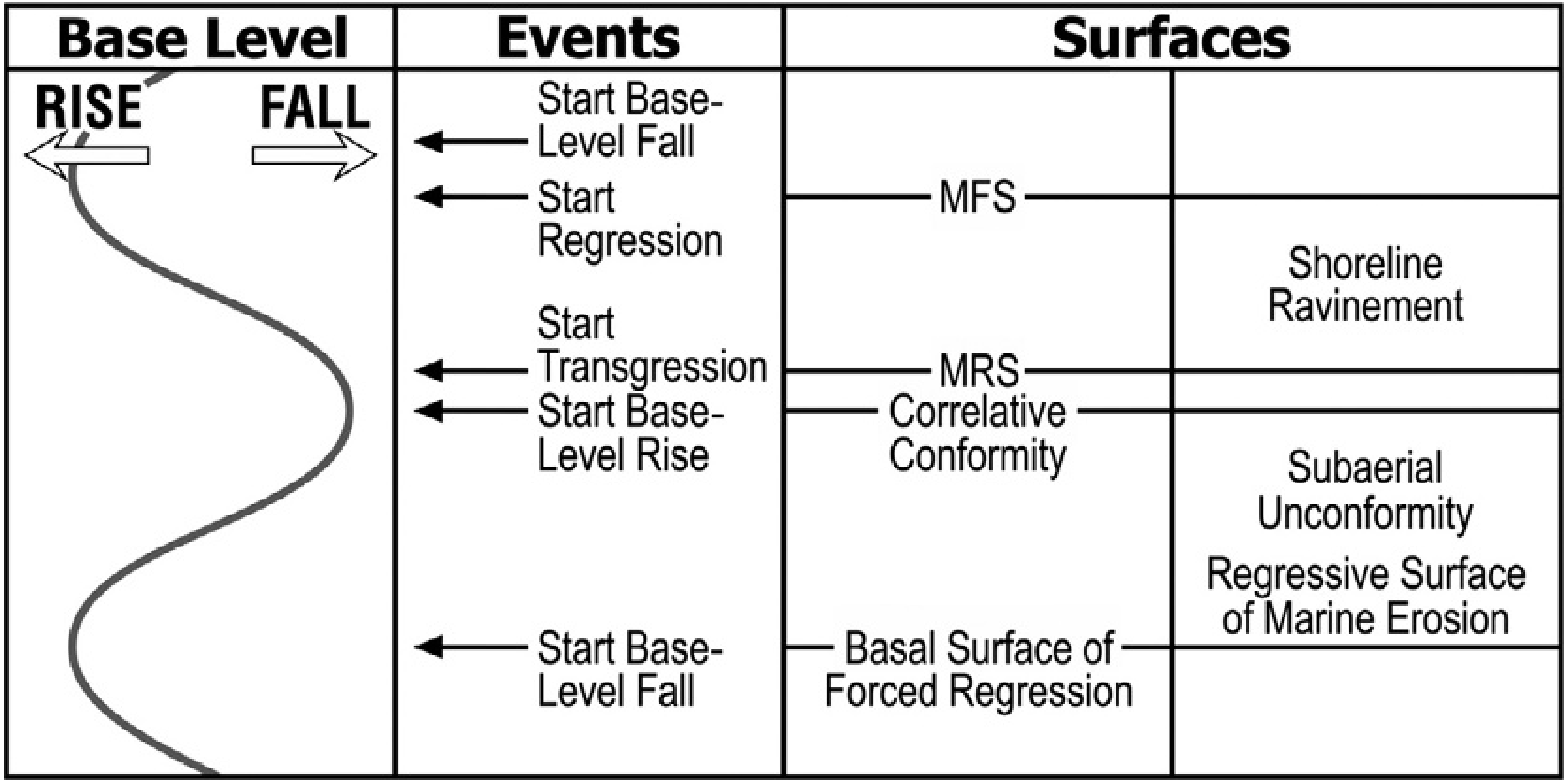


Shelf-edge and healing-phase deposits in the De Soto Canyon area of the Gulf of Mexico. The white wavy lines indicate possible slumping during forced regression. Regressive deposits (both normal and forced) downlap the seafloor (green and red arrows), whereas the transgressive deposits onlap the youngest prograding clinoform (blue arrows). The normal regressive deposits include an aggrading topset. The three genetic types of strata, i.e., forced regressive, normal regressive and transgressive, form the conceptual core of Sequence Stratigraphy as they control the formation and timing of all systems tracts.



Uninterpreted and interpreted seismic profile showing the contrast in facies between mudflow deposits (facies ***A*** *- early forced regressive) and turbidites (facies* ***B*** *- late forced regressive) in a deep-water setting. Note that the top of the coarser-grained facies of the submarine fan is marked by the extension within the basin of the youngest clinoform associated with offlap (i.e., the Correlative Conformity). In this example, the Maximum Regressive Surface downlaps the Correlative Conformity and, thus, no significant lowstand normal regressive deposits are present above the late forced regressive turbidites.*

The sequence stratigraphic surfaces used in the deductive approach are defined relative to the four main events of the base-level cycle (see below).



1.2.2 Base-Level Changes and Induced Depositional Trends

There are two main types of change in depositional trend which result from base level movements. These are 1) a change from sedimentation and accumulation to erosion or greatly reduced sedimentation and vice-versa and 2) the change from a regressive trend to a transgressive one and vice-versa. During a cycle of base level rise and fall, seven important changes of depositional trend, which represent variations of the two main types, occur. Four occur during base level rise and three during fall. These changes happen over either a short or long time interval when compared to the duration of the complete cycle. These seven changes in depositional trend are:

Base level rise

1) expansion of deposition and accumulation of nonmarine strata in a landward direction across a subaerial erosion surface.

2) change from a regressive trend to a transgressive one in a marine succession.

3) cessation of sedimentation along the shoreline and the migration of shoreface erosion landward during transgression.

4) change from a transgressive trend to a regressive one in nonmarine and marine strata.

Base level fall

5) cessation of sedimentation on the basin edge and the gradual basinward expansion of subaerial erosion

6) development of sea floor erosion on the inner shelf and gradual basinward migration of this erosional area

7) cessation of deposition on large portions of a marine slope.

During the initial stage of rise, enough sediment still reaches the marine area to allow the shoreline to continue to advance basinward (regression) as it had during the previous time of sea level fall. However such advancement occurs at a declining rate until finally the rate of base level rise at the shoreline exceeds the rate of sediment supply. At this time the shoreline ceases its seaward movement and begins to shift landward (transgression). This change from regression to transgression results in two major changes in depositional trend. Along the shoreline, net erosion occurs and this zone of shoreface erosion moves landward during the transgression. The resulting erosion surface is known as a **shoreface ravinement** and it develops during the entire time transgression occurs. Also with the initiation of transgression, finer sediment starts to be deposited at any given shelf locality due to the increasing distance from the sediment source as well as the overall reduced supply to the marine area. This results in a significant change from a coarsening upward trend that characterized the preceding regression to a fining-upward one. The horizon that marks this significant change is termed a **maximum regressive surface.**

Eventually the rate of base level rise slows and sedimentation at the shoreline once again exceeds the rate of removal by waves. The development of the shoreface ravinement stops and the shoreline reverses direction and begins to move seaward (regression). This results in increased sedimentation to the marine basin and coarser sediment begins to prograde across the shelf. This produces a change from a fining-upward trend to a coarsening-upward one and the horizon that marks this change in trend is termed a **maximum flooding surface.**

With the start of base level fall, sediment accommodation space begins to be reduced and sedimentation ceases on the basin margin. Subaerial erosion advances basinward during the entire time of fall and this produces a **subaerial unconformity** that reaches its maximum basinward extent at the end of base level fall. The seaward movement of the shoreline, which began in the waning stages of base level rise, continues throughout base level fall but at a faster pace. Also when base level starts to fall, the inner part of the marine shelf begins to be eroded. This is due to the regrading of the shelf as it attempts to equilibrate with falling base level. This inner shelf erosion surface migrates seaward during the entire interval of base level fall and is progressively covered by prograding shoreface deposits. This results in the **regressive surface of marine erosion.**

1.2.3 Systems Tracts with Greatest Trapping Potential

Data on the depositional setting of more than 2000 major conventional oil and gas fields in 200 transgressive and regressive wedges within 80 basins show that most hydrocarbons found in siliciclastic reservoirs occur in the base to middle of the wedge in generally lowstand deposits, or transgressive depositional facies where the sediment inputs into the basin are optimum (not excessive) and occur together with high organic content. This can be further attributed to the greater probability of effective top seal in contrast to the highstand systems tract.

The best potential reservoirs of the highstand stage tend to be associated with the shoreline to shoreface depositional systems, which concentrate the largest amounts of sand, with the highest sand/mud ratio. These reservoirs are usually meters to tens of meters thick and may display very good lateral continuity along the strike of the basin.

1.3 Facies Analysis: Outcrops, Cores and Modern Analogues

Facies analysis is a fundamental sedimentological method of characterizing bodies of rocks with unique lithological, physical and biological characteristics relative to all adjacent deposits. This method is commonly applied to describe the sediments and/or sedimentary rocks observed in outcrops, sediment cores, or modern environments.

Facies analysis is of paramount importance for any sequence stratigraphic study, as it provides critical clues for paleogeographic and paleoenvironmental reconstructions as well as for the definition of the sequence stratigraphic surfaces. As such, facies analysis is an integral part of both Sedimentology and Sequence Stratigraphy, which justifies the partial overlap between these disciplines.

In the context of Sequence Stratigraphy, facies analysis is particularly relevant to the study of cyclic changes in the processes that form individual depositional systems in response to base-level shifts.

1.3.1 Concepts of Depositional Systems, Facies and Facies Models

A depositional system is the product of sedimentation in a particular depositional environment. Hence, it includes the three-dimensional assemblage of strata whose geometry and facies lead to the interpretation of a specific paleo-depositional environment.

Depositional systems form the building blocks of *systems tracts*, the latter representing an essential concept for stratigraphic correlation and the genetic interpretation of the sedimentary basin fill.

The study of depositional systems is closely related to the concepts of facies, facies associations and facies models, which are defined in Fig. 4.

Facies (Bates and Jackson, 1987): the aspect, appearance, and characteristics of a rock unit, usually reflecting the conditions of its origin and differentiating the unit from adjacent or associated units.

Facies (Walker, 1992): a particular combination of lithology, structural and textural attributes that defines features different from other rock bodies.

> *Facies are controlled by sedimentary processes that operate in particular areas of the depositional environments. Hence, the observation of facies helps with the interpretation of syn-depositional processes.*

Facies Association (Collinson, 1969): groups of facies genetically related to one another and which have some environmental significance.

> *The understanding of facies associations is a critical element for the reconstruction of paleo-depositional environments. In turn, such reconstructions are one of the keys for the interpretation of sequence stratigraphic surfaces*

Facies model (Walker, 1992): a general summary of a particular depositional system, involving many individual examples from recent sediments and ancient rocks.

> *A facies model assumes predictability in the morphology and evolution of a depositional environment, inferring "standard" vertical profiles and lateral changes of facies. Given the natural variability of allocyclic and autocyclic processes, a dogmatic application of this idealization introduces a potential for error in the interpretation.*

Fig. 4 *Concepts of facies, facies associations and facies models.*

In conclusion, facies analysis is an essential method for the reconstruction of paleodepositional environments as well as for the understanding of climatic changes and subsidence history of sedimentary basins. The understanding of facies and their associations are also essential for the correct interpretation of sequence stratigraphic surfaces. Facies analysis is, therefore, a prerequisite for any sequence stratigraphic study.

1.3.2 Classification of Depositional Environments

Depositional environments may be classified into three broad categories, as follows (Fig. 5): non-marine (beyond the reach of marine flooding), coastal or transitional (intermittently flooded by marine water) and marine (permanently covered by marine water). An illustration of the sub-environments that encompass the transition from non-marine to fully marine environments is presented in Fig. 6.

It should be emphasized that in coastal areas, the river-mouth environments (i.e., sediment entry points to the marine basin) are separated by stretches of open shoreline where the beach environment develops. The glacial environment is not included in the classification scheme displayed in Fig. 5 because it is climatically controlled and may overlap on any non-marine, coastal, or marine depositional environment.

1. Nonmarine environments

- **Colluvial and alluvial fans**
- **Fluvial environments**
- **Lacustrine environments**
- **Aeolian environments**

2. Coastal (marginal marine) environments

- **River mouth environments**
  - regressive river mouths: Deltas
  - transgressive river mouths: Estuaries
- **Open shoreline (beach) environments**
  - foreshore
  - backshore

3. Marine environments

- **Shallow marine environments**
  - shoreface
  - inner and outer shelf
- **Deep marine environments**
  - continental slope
  - abyssal plain (basin floor)

Fig. 5 *Depositional environments, based on the relative contributions of non-marine and marine processes. The coastal/marginal marine environments, also known as 'transitional', are intermittently flooded by marine water during tidal cycles and storms. Note that both types of coastal environments (river-mouth or open shoreline) may be transgressive or regressive. Depositional systems refer to products (bodies of rock in the stratigraphic record), whereas depositional environments refer to active processes in modern areas of sediment accumulation. The boundaries between the various coastal and shallow-marine environments are defined in Figs. 6,7.*

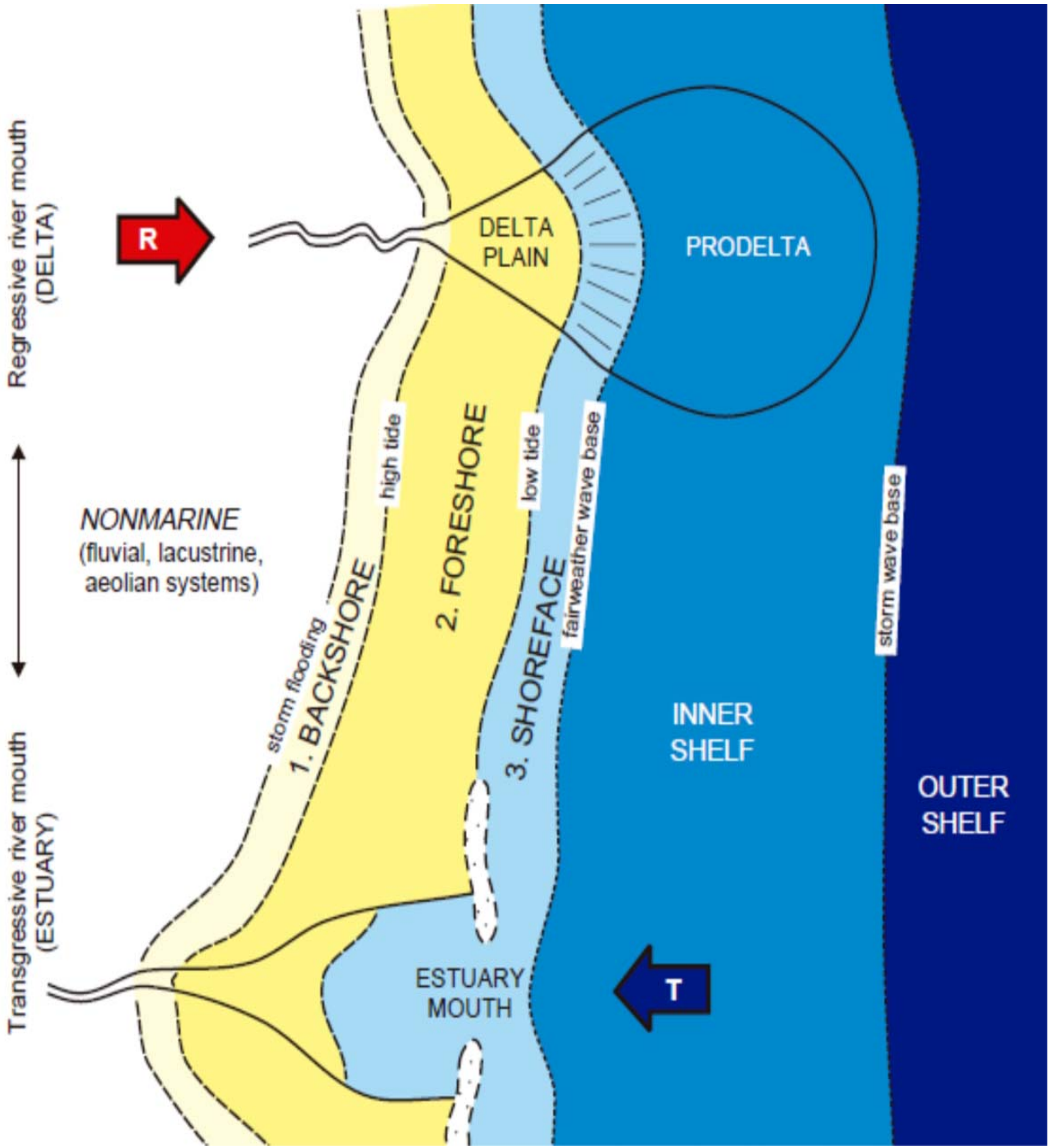


Fig. 6 *Transition from marine to non-marine environments. The large arrows indicate the direction of shoreline shift in the two river-mouth environments (R-regressive; T-transgressive). Between the river-mouth environments, the coastline is an open shoreline. The character of the shoreline (transgressive vs. regressive) may change along strike due to variations in subsidence and sedimentation rates.*

Within the non-marine portion of the basin, a distinction can be made between the steeper-gradient alluvial plain, which captures the upstream reaches of fluvial systems, and the gently sloping coastal plain that may develop within the downstream reaches of the fluvial environment (Fig. 7). “Coastal plain” is a geomorphological term that refers to a seaward progradation of a relatively flat area or emerged seafloor, bordering a coastline and extending inland to the nearest elevated land. Fig. 7 illustrates the situation where the coastal plain forms by processes of progradation, rather than seafloor emergence. In this case, the sediments that accumulate on the coastal plain during the progradation of the shoreline are part of the so-called “coastal prism”, which includes fluvial to shallow-water deposits. The coastal prism is wedge shaped and expands landward from the coastal environment by onlapping the pre-existing topography in an upstream direction. The landward limit of the coastal prism is termed “bayline” and it may shift upstream when the progradation of the shoreline is accompanied by aggradation.

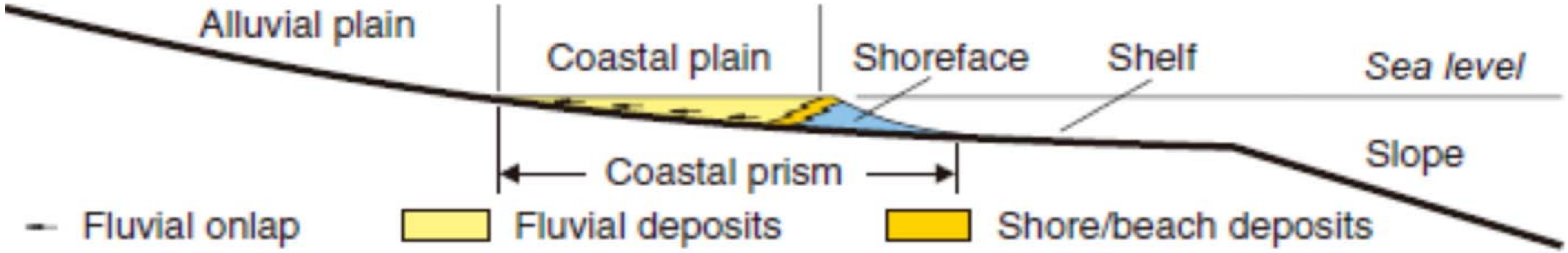


Fig. 7 *Dip-oriented profile illustrating the main geomorphic and depositional settings of a continental shelf: alluvial plain, coastal plain, coast (including the intertidal and supratidal environments) and shallow-marine (shoreface and shelf) environments. Note that coastal plains may form by either progradation or the emergence of the seafloor. This diagram illustrates the former situation, when a coastal prism of fluvial to shoreface deposits accumulates in the coastal plain to shallow-water settings. For scale, coastal plains may be tens to hundreds of kilometers wide, depending on sediment supply and the gradient of the onlapped floodplain surface. Coastal prisms are typically associated with lowstand and highstand normal regressions (systems tracts). A lowstand coastal prism may be scoured by tidal- and/or wave-ravinement processes during subsequent transgression, whereas a highstand coastal prism is typically incised by rivers during the subsequent base-level fall. Both lowstand and highstand coastal prisms may be preserved in the rock record, where the original thickness of the coastal prism exceeds the amount of subsequent erosion.*

Coastal environments are critical for Sequence Stratigraphy, as they record the history of shoreline shifts and are most sensitive in providing the clues for the reconstruction of the cyclic changes in depositional trends. In fact, the development of sequence stratigraphic concepts started in the first place with the study of the transition zone between marine and non-marine environments, where the relationship of facies and stratigraphic surfaces is easier to observe. From the shoreline, the application of Sequence Stratigraphy was gradually expanded in both landward and basinward directions, until a coherent basin-wide model that includes the stacking patterns expected in both fully fluvial and deep-marine successions was, finally, established. The importance of the shoreline, as link between the marine and non-marine portions of the basin, is also reflected by the fact that the reference curve of base-level changes, which is used to define the four main events of a stratigraphic cycle and, essentially, the timing of all systems tracts and stratigraphic surfaces, is centered in the displacements of the shoreline (Fig. 8).

Events \ Sequence model	Depositional Sequence II	Depositional Sequence III	Depositional Sequence IV	Genetic Sequence	T-R Sequence
	HST	early HST	HST	HST	RST
end of transgression					
	TST	TST	TST	TST	TST
end of regression					
	late LST (wedge)	LST	LST	late LST (wedge)	RST
end of base-level fall					
	early LST (fan)	late HST	FSST	early LST (fan)	
onset of base-level fall					
	HST	early HST	HST	HST	

sequence boundary

systems tract boundary

within systems tract surface

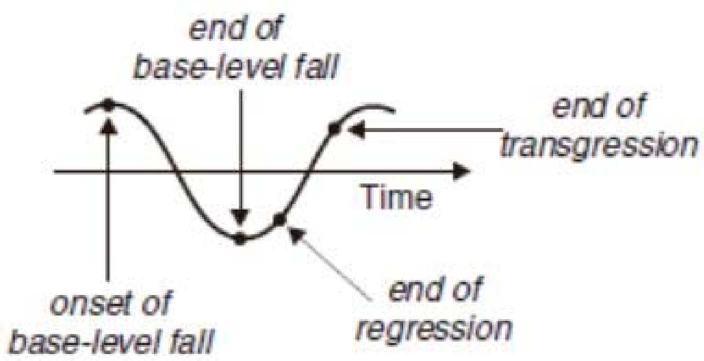


Fig. 8 *Timing of system tracts and sequence boundaries for the sequence models currently in use. Abbreviations: LST - lowstand systems tract; TST - transgressive systems tract; HST - highstand systems tract; FSST - falling-stage systems tract; RST - regressive systems tract; T-R - transgressive-regressive*.

Finally, a reality that is commonly overlooked is that coastlines may change their transgressive *vs.* regressive character along strike, as a function of the fluctuations in subsidence and sedimentation rates (Fig. 6). This means that the predictable architecture and age relationships of depositional systems and systems tracts presented in 2D cross-sections along dip may be altered in a 3D view, due to the high diachronicity that may potentially be imposed on systems tract boundaries by the strike variability in subsidence and sedimentation rates. One should, therefore, keep an open mind when trying to extrapolate the reality of one dip-oriented profile to other locations along the strike. In addition, autocyclic shifts in the distribution of energy and sediment within individual depositional environments, which could affect all environments presented in Fig. 5, are another reason why variations in stratigraphic geometry should be expected along strike from one dip-oriented profile to another.

1.3.3 Walther's Law

The connection between the vertical and lateral changes of facies observed in outcrops and underwater is made by Walther's Law (Figs 9, 10). This is a fundamental principle of stratigraphy, which allows the geologist to predict the lateral changes of facies based on the vertical profiles observed in sections such as small outcrops, sediment cores, or well logs. Vertical changes in litho- and bio-facies have long been used to reconstruct paleogeography and temporal changes in depositional environments and, using the Walther's Law, to interpret lateral shifts of these environments. However, such interpretations are only valid within relatively conformable successions of genetically related strata. Vertical changes across sequences bounded by unconformities most probably reflect major shifts of facies between successions that are genetically unrelated and, thus, such changes should not be used to reconstruct the paleogeography of one particular time slice in the stratigraphic record.

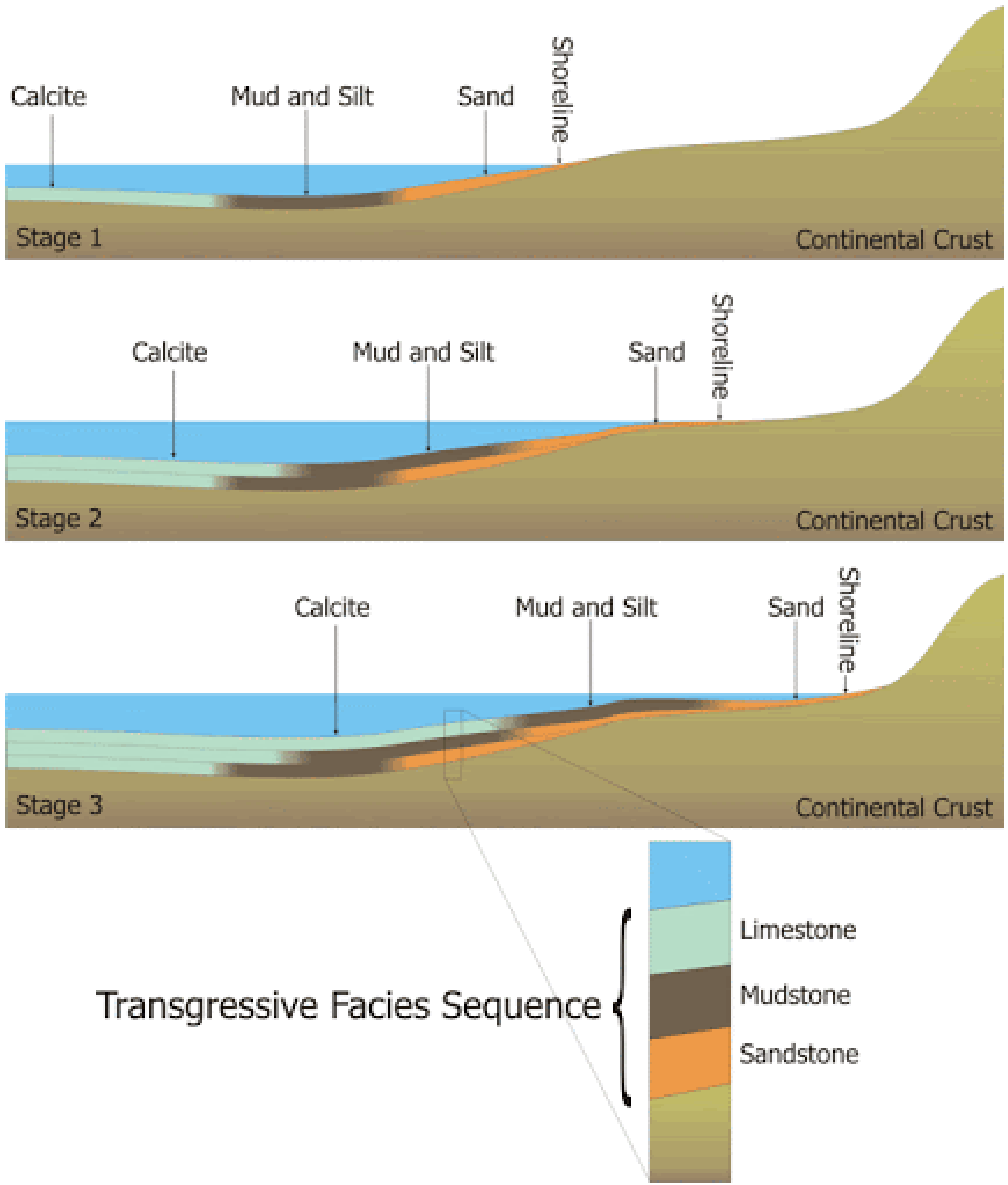


Fig. 9 *Walther's Law.*

Walther's Law (Middleton, 1973): in a conformable succession, the only facies that can occur together in vertical succession are those that can occur side by side in nature.

Walther's Law (Bates and Jackson, 1987): only those facies and facies-areas can be superimposed which can be observed beside each other at the present time.

Walther's Law (Posamentier and Allen, 1999): the same succession that is present vertically also is present horizontally *unless there is a break in sedimentation.*

In other words, a vertical change of facies implies a corresponding lateral shift of facies within a relatively conformable succession of genetically related strata.

Fig. 10 *Walther's Law: the principle that connects the lateral and vertical shifts of facies within a sequence (i.e., a relatively conformable succession of genetically related strata).*

A prograding delta is a good illustration of the Walther's Law concept. The deltaic depositional system includes prodelta, delta front and delta plain facies, which occur side by side in that order and the products of which occur together in the same order in vertical succession (Fig. 11).

The use of the depositional system based on the Walther's Law enables predictions to be made about the stratigraphy at larger scales, because it permits interpretations of the rocks in terms of broad paleoenvironmental and paleogeographic reconstructions. This technique has now become part of Sequence Stratigraphy, where sedimentary sequences are regionally correlatable packages of strata that record local or regional changes in the base level.

Cross-Section of a Delta

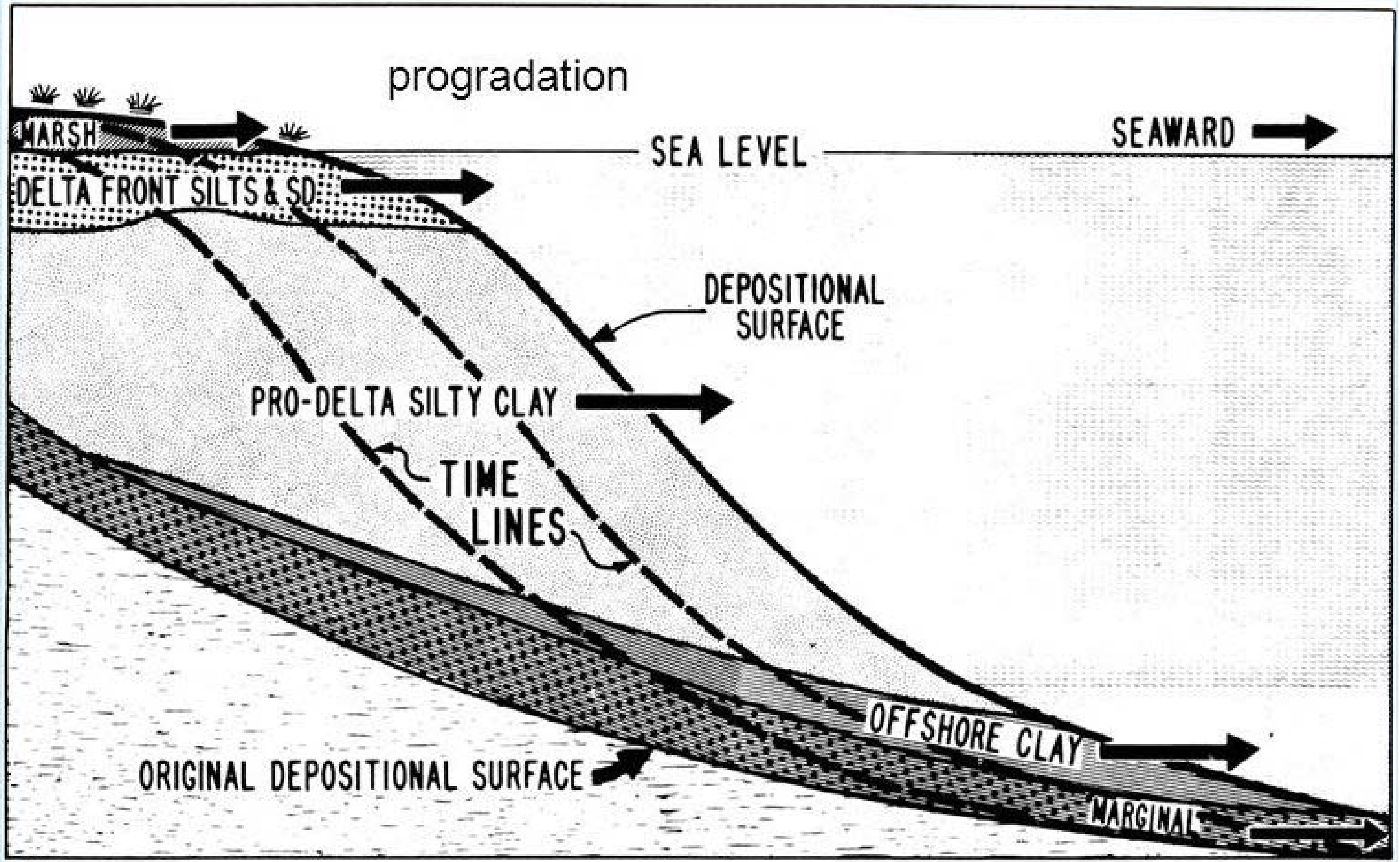


Fig. 11 *The constructional phase of the delta cycle.*

Beyond the scale of a depositional system, Walther’s Law is equally valuable when applied to systems tracts, as the internal architecture of each systems tract involves progradational or retrogradational shifts of facies which translate into corresponding facies changes along vertical profiles. Fig. 12 provides examples of how vertical profiles integrate and help to reconstruct the lateral facies relationships along dip-oriented sections.

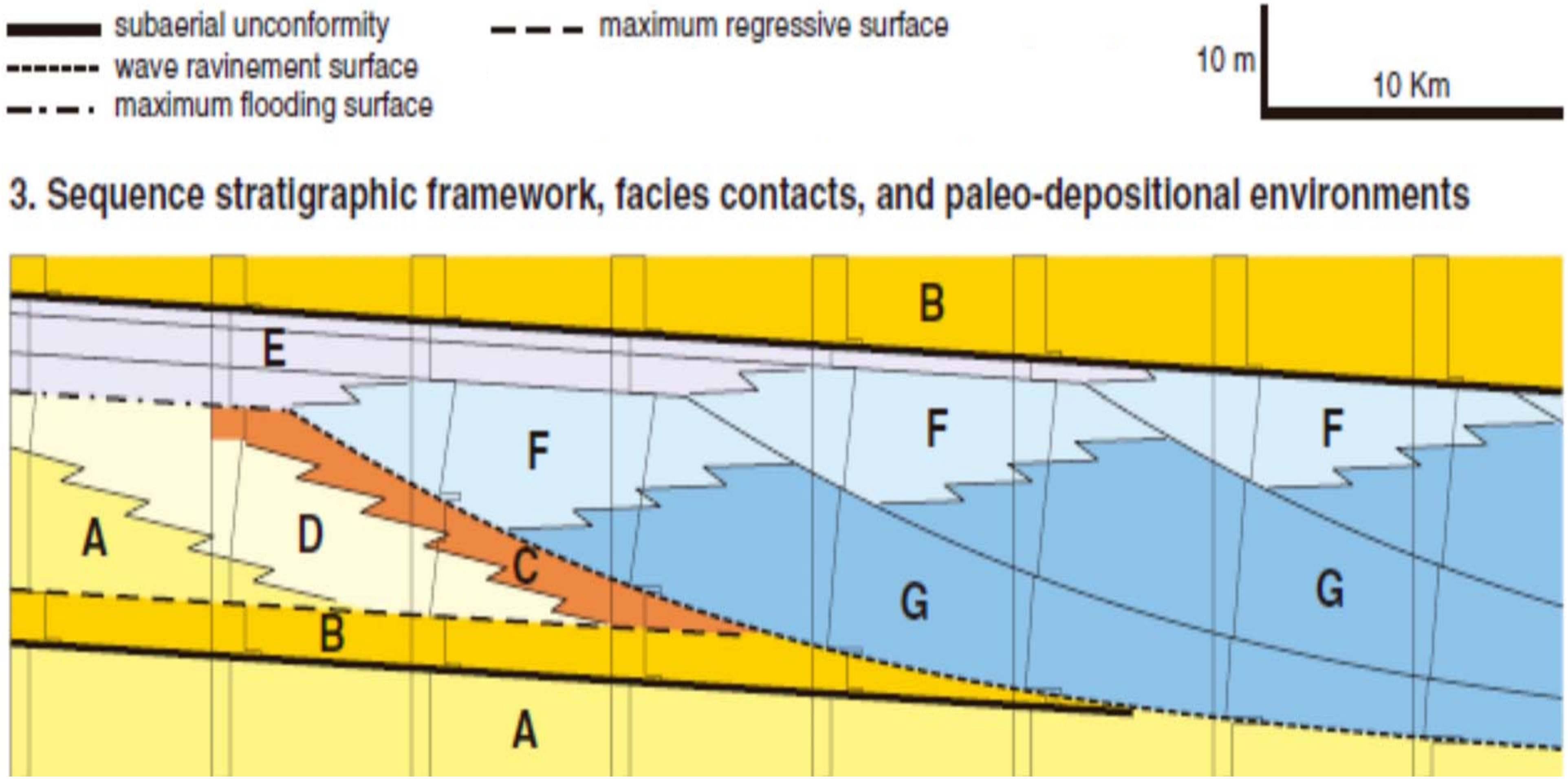


Fig. 12 *Sequence stratigraphic cross section, showing key surfaces, within-trend facies contacts and paleodepositional environments. Within-trend facies contacts, marking lateral changes of facies, are placed on the cross-section after the sequence stratigraphic framework is constructed. Facies codes: A - meandering system; B - braided system; C - estuary-mouth complex; D - central estuary; E - delta plain; F - upper delta front; G - lower delta front / prodelta.*

1.3.4 Sedimentary Petrography

The observation of sedimentary facies in outcrops or sediment cores is often enough to constrain the position of sequence-bounding unconformities, where such contacts bring together contrasting facies that are genetically unrelated (Fig. 13). The larger the stratigraphic hiatus associated with the sequence boundaries, the better the chance of mapping these surfaces by simple facies observations. There are, however, cases, especially in adjacent successions composed of coarse braided fluvial deposits, where "cryptic" subaerial unconformities are difficult to distinguish from other channel-scour surfaces. Such cryptic sequence boundaries may occur within thick fluvial successions consisting of unvarying facies and may well be associated with substantial breaks in sedimentation. In the absence of abrupt changes in facies and paleocurrent directions across these sequence boundaries, petrographic studies of cements and framework grains may provide the only solid criteria for the identification and mapping of sequence-bounding unconformities.

Fig. 13 *Subaerial unconformity (arrows) at the contact between the Burgersdorp Formation and the overlying Molteno Formation (Middle Triassic, Dordrecht-Queenstown region, Karoo Basin). The succession is fluvial, with an abrupt increase in energy levels across the contact. Note the change in fluvial styles from meandering (with lateral accretion) to amalgamated braided depositional systems. The unconformity is associated with a ~7 Ma stratigraphic hiatus and, thus, separates fluvial sequences that are genetically unrelated.*

Braided stream system

Meandering river system and lateral accretion

Besides changes in provenance and the related composition of framework grains, subaerial unconformities may also be identified by the presence of secondary minerals that replace some of the original sandstone constituents via processes of weathering under subaerial conditions. For example, it has been documented that subaerial exposure, given the availability of sufficient amounts of K, Al and Fe that may be derived from the weathering of clays and feldspars, may lead to the replacement of calcite cements by secondary glauconite. Glauconite-bearing sandstones may, therefore, be used to recognize sequence-bounding unconformities, where the glauconite formed as a replacement mineral. Hence, a distinction needs to be made between the syndepositional glauconite of marine origin (framework grains in sandstones) and the secondary glauconite that forms under subaerial conditions (coatings, cements), which can be resolved via petrographic analysis.

Also, the vertical distribution pattern of early diagenetic clay minerals, such as kaolinite, smectite, palygorskite, glaucony and berthierine, may indicate changes in the accommodation space and the position of sequence stratigraphic surfaces. Changes in the relative sea level and sediment supply/sedimentation rates, together with the climatic conditions prevalent during and immediately after the deposition of sediments, control the type, abundance and spatial distribution of clay minerals by influencing the pore-water chemistry and the duration over which the sediments are submitted to a certain set of geochemical conditions (Fig. 14).

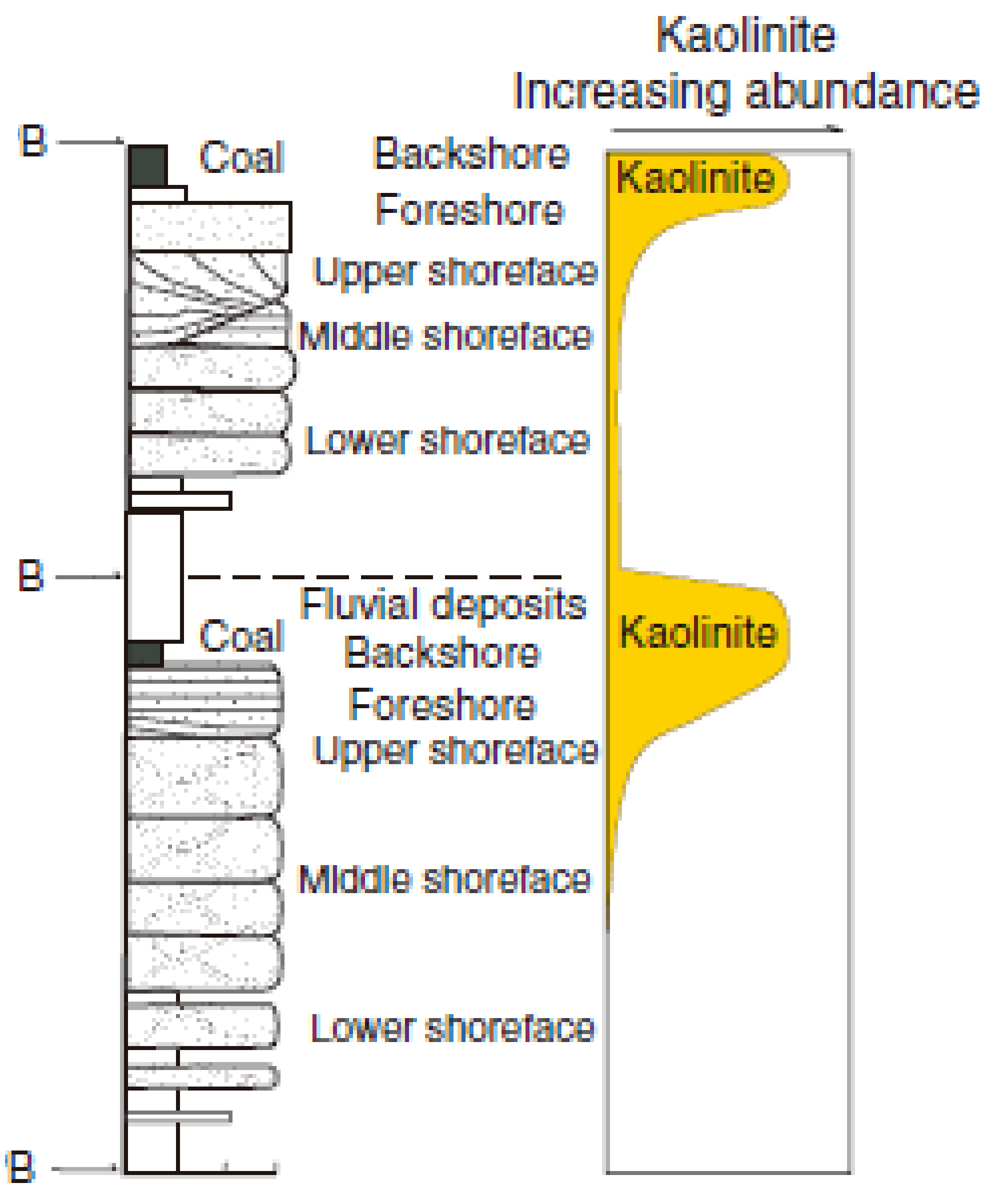


Fig. 14 *Kaolinite content increases toward the top of the sequences, where continental facies are exposed to extensive meteoric water flushing under semi-humid to humid climatic conditions. B: Sequense Boundary.*

Petrographic studies may also be used to emphasize grading trends (fining- *vs.* coarsening-upward) in vertical successions (outcrops, sediment cores). Vertical profiles are a vital part of the sequence stratigraphic analyses and are commonly used to discern between progradational and retrogradational trends in marine successions, or to outline fluvial depositional sequences in non-marine deposits.

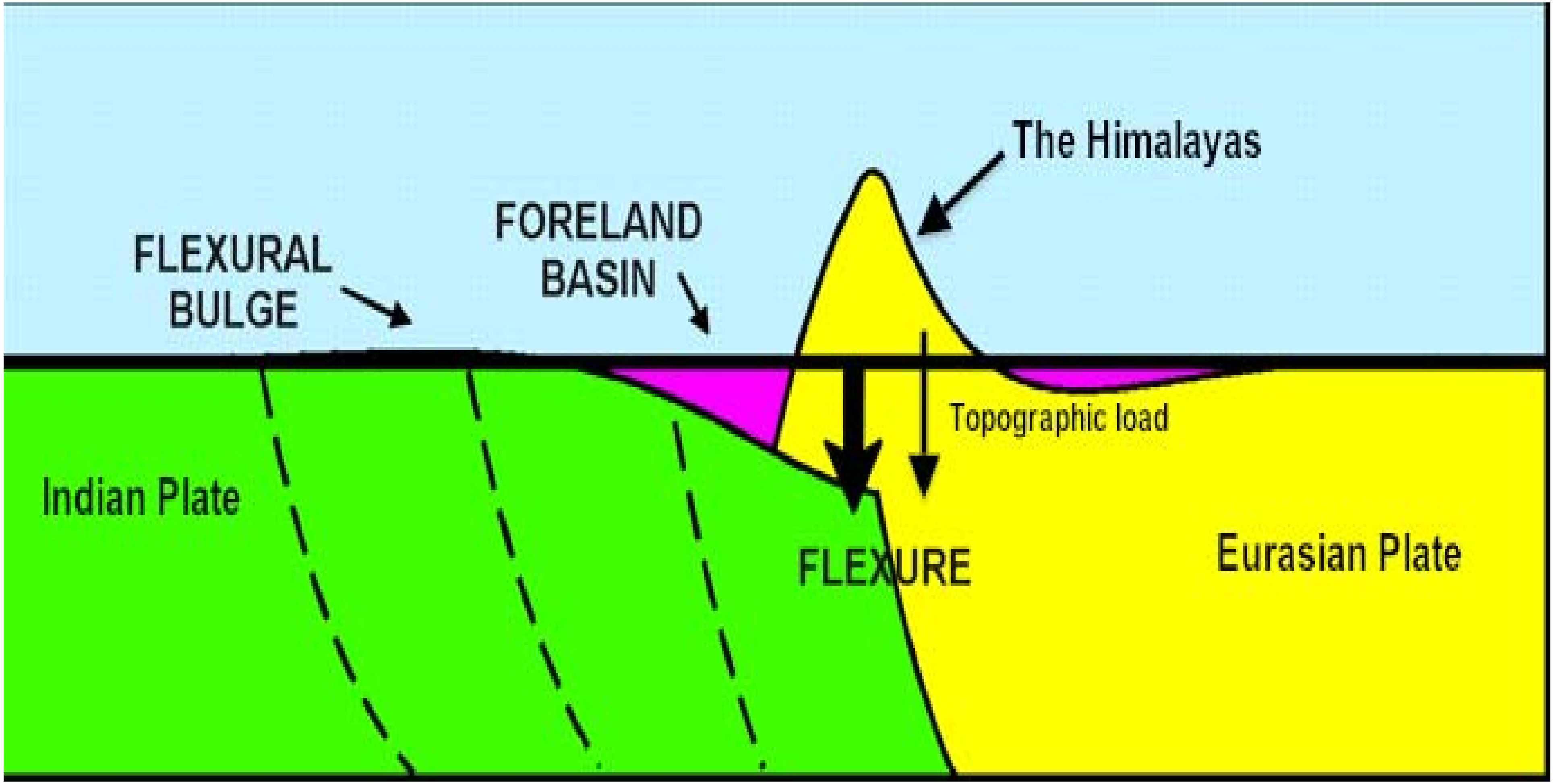
Fluvial sequences, for example, often show overall fining-upward trends that reflect aggradation in an energy-declining environment. From a sedimentological perspective, sequence boundaries (e.g., subaerial unconformities) in such fluvial successions are commonly picked at the base of the coarsest units, usually represented by amalgamated channel fills.

However, changes in sedimentation patterns across a basin due to variations in subsidence and sediment supply make it difficult to know which cyclic stratigraphic sequences are age equivalent when comparing vertical profiles from different sections. Under ideal circumstances, the availability of age data (biostratigraphic, magnetostratigraphic, radiometric, marker beds) represents the perfect solution to this problem. But often such age data are missing, especially in the study of older successions, and in the absence of time control other sedimentological observations have to be integrated with the petrographic data in order to validate geological interpretations.

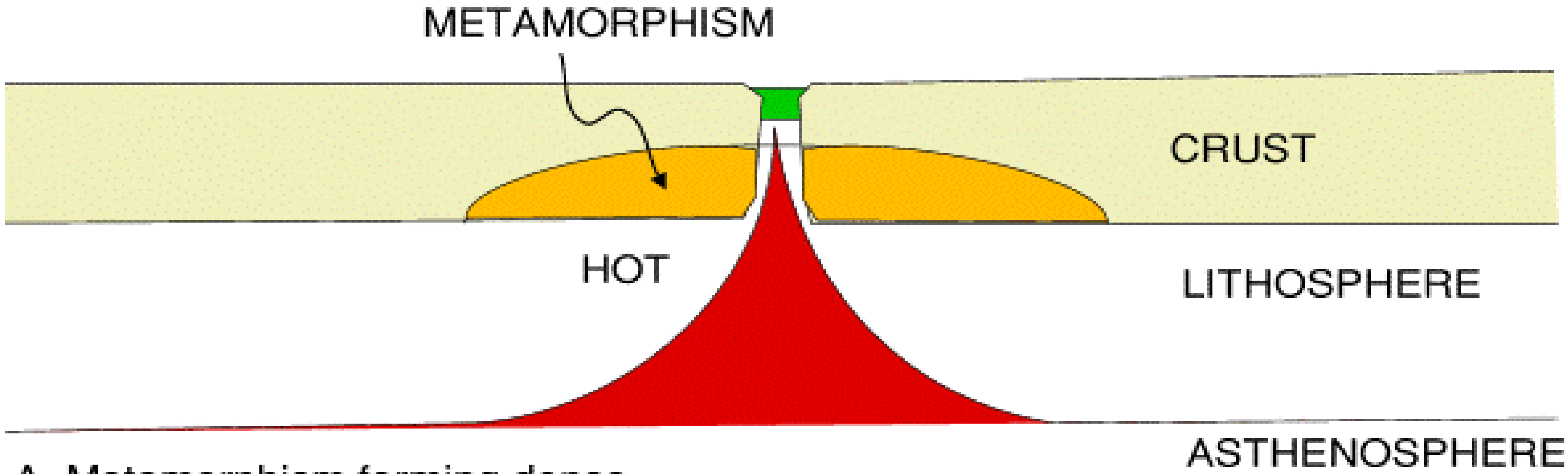
Hence, paleocurrent measurements, derived from unidirectional flow-related bedforms, can be particularly useful as a complementary tool to the petrographic data analysis, because they can provide a record of the tectonic tilt in the basin, which usually triggers hiatuses in the stratigraphic record.

1.3.5 Paleocurrent Directions

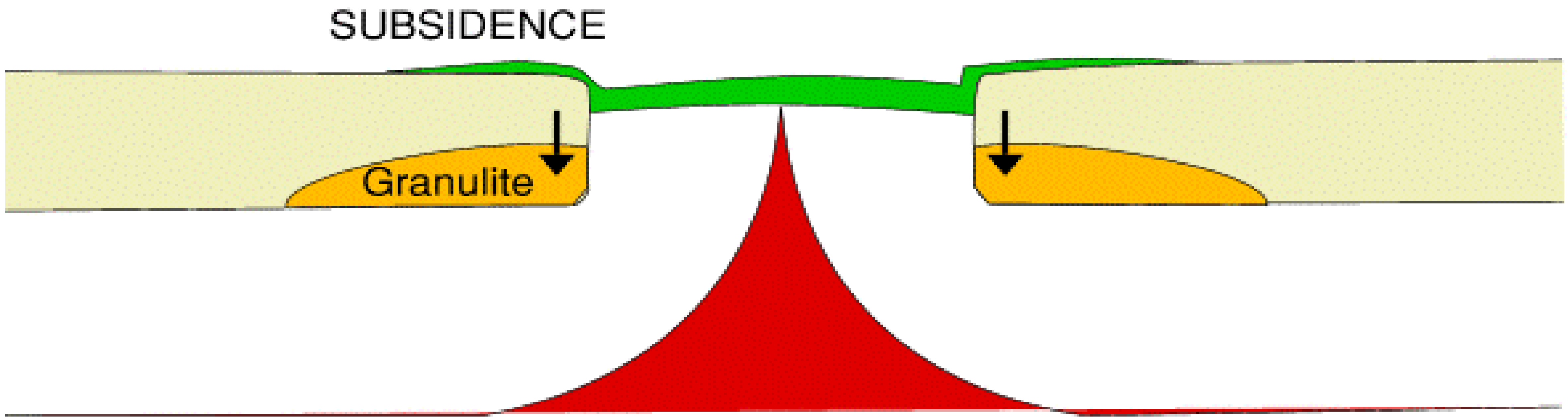
The major breaks in the stratigraphic record are potentially associated with stages of tectonic reorganization of sedimentary basins and, thus, with changes in tilt direction across sequence boundaries. This is often the case in tectonically active basins, such as grabens, rifts, or foreland systems, where stratigraphic cyclicity is commonly controlled by cycles of subsidence and uplift triggered by various tectonic, flexural (see image below) and isostatic mechanisms (https://www.britannica.com/video/81405/theory-isostasy). Other basin types, however, such as 'passive' continental margins or intracratonic sag basins, are dominated by long-term thermal subsidence (see image below) and, thus, they may show little change in the tilt direction through time. In such cases, stratigraphic cyclicity may be mainly controlled by fluctuations in sea level and paleocurrent measurements may be of little use to constrain the position of sequence boundaries.



The Himalayas
FOREL AND
BASIN
FLEXURAL
BULGE
Topographic load
Indian Plate
FLEXURE
Eurasian Plate



A. Metamorphism forming dense granulites in lower crust



B. Subsidence as lithosphere cools

Overfilled foreland basins represent a classic example of a depositional environment where fluvial sequences and bounding unconformities form in isolation from eustatic influences, with a timing controlled by orogenic cycles of tectonic loading (thrust) and unloading. In such foredeep basins, fluvial aggradation takes place during stages of differential flexural subsidence, with higher rates towards the center of loading, whereas bounding stratigraphic surfaces form during stages of differential isostatic rebound. Renewed thrusting in the orogenic belt marks the onset of a new depositional episode. Due to the strike variability in orogenic loading, which is commonly the normal condition rather than the exception, abrupt changes in the tilt direction are usually recorded across sequence boundaries. Such changes in tectonic tilt may be used to outline fluvial sequences with distinct drainage patterns and to map their bounding surfaces (Fig. 15).

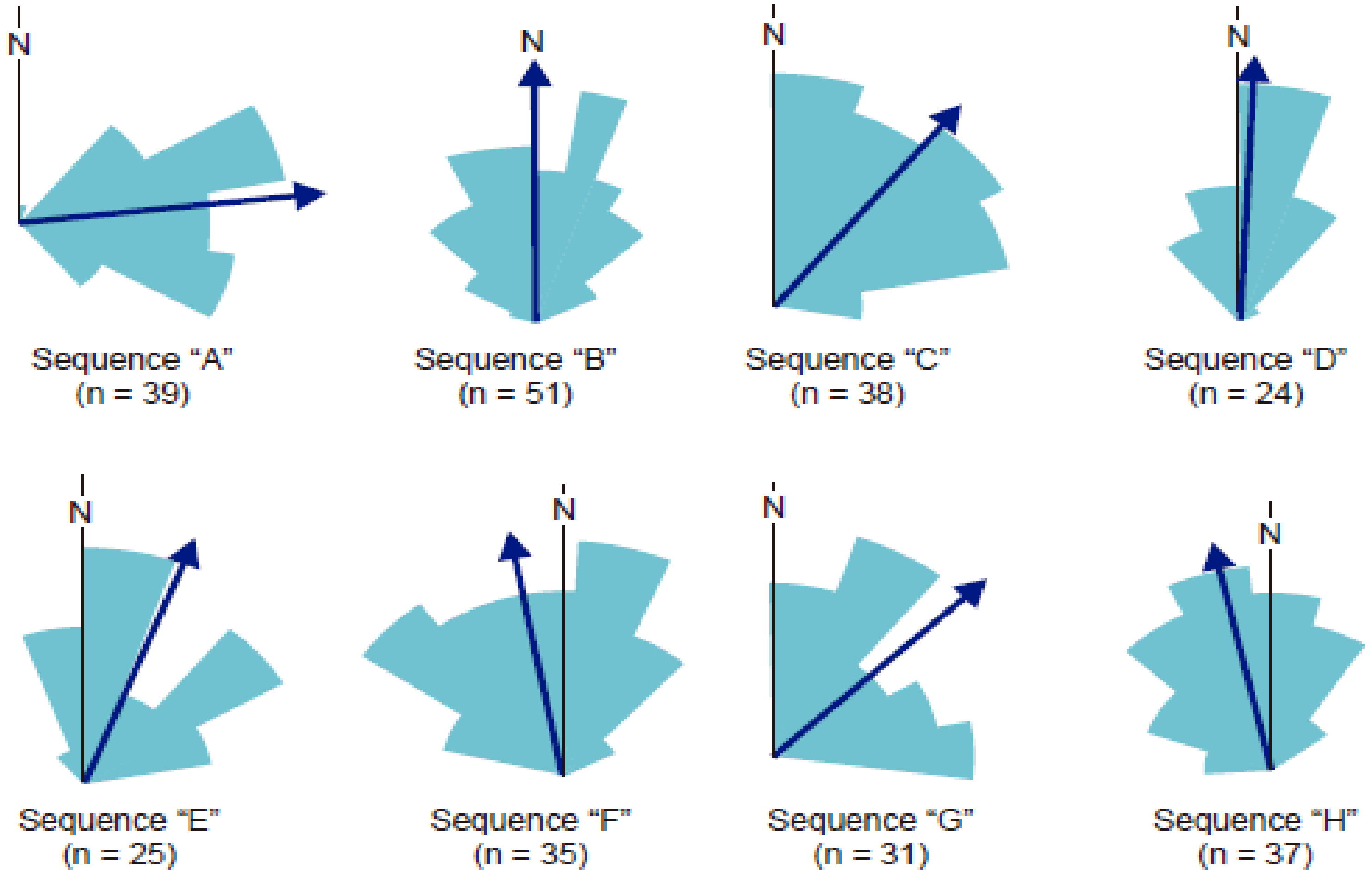
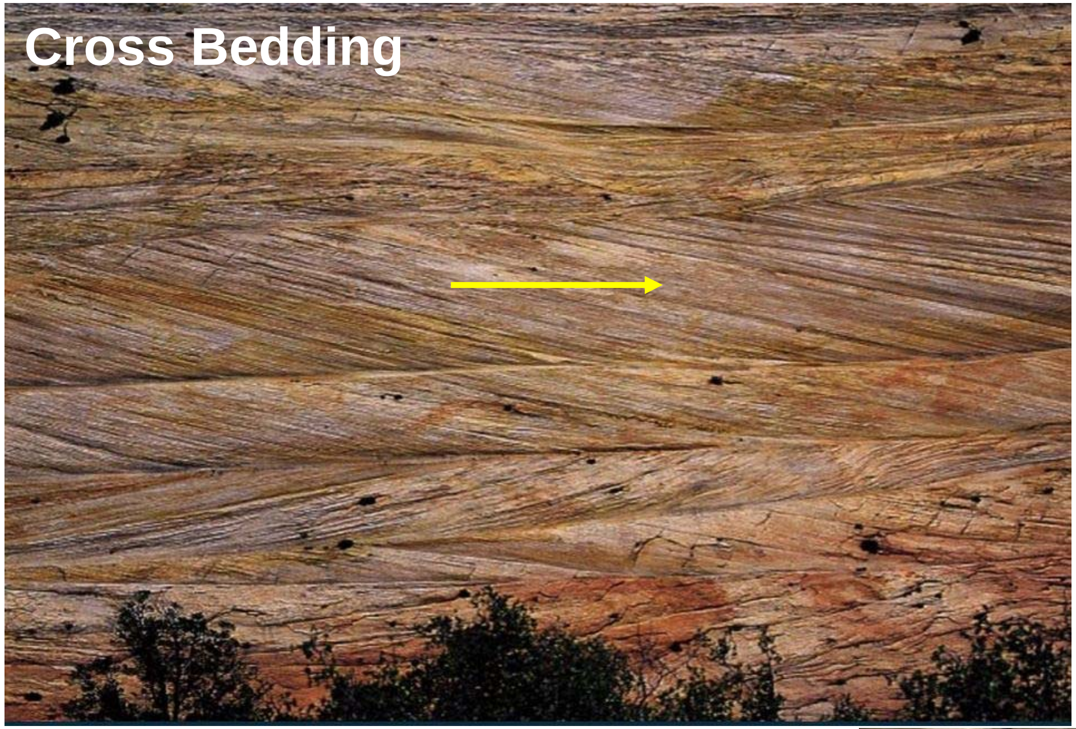
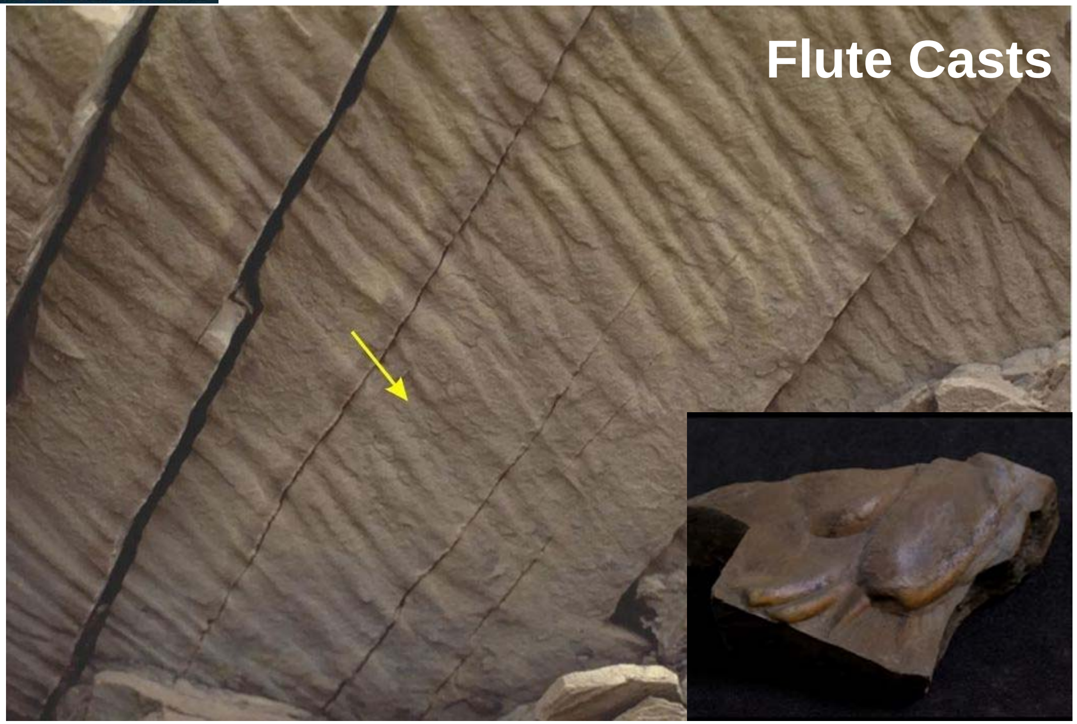


Fig. 15 *Paleoflow directions for the eight third-order depositional sequences of the Koonap-Middleton fluvial Formations in the Karoo foredeep. The succession spans a time interval of 5 Ma during the Late Permian and measures a total thickness of 2630 m. The 'n' represents the number of paleoflow measurements used to construct the rose diagram for each sequence. In this case study, sequence boundaries are marked not only by a change in tectonic tilt, but also by an abrupt change in fluvial styles and associated lithofacies.*





Examples of paleoflow direction indicators

1.3.6 Pedology

Pedology (soil science) deals with the study of soil morphology, genesis and classification. The formation of soils refers to the physical, biological and chemical transformations that affect sediments and rocks exposed to subaerial conditions. Paleosols (i.e., fossil soils) are buried or exhumed soil horizons that formed in the geological past on ancient landscapes. Pedological studies started with the analysis of modern soils and Quaternary paleosols, but have been vastly expanded to the pre-Quaternary record in the 1990s due to their multiple geological applications: (1) interpretations of ancient landscapes, from local to basin scales; (2) interpretations of ancient surface processes (sedimentation, non-deposition, erosion), including sedimentation rates and the controls thereof; (3) interpretations of paleoclimates, including estimations of mean annual precipitation rates and mean annual temperatures; and (4) stratigraphic correlations and determination of the cyclic change in soil characteristics in relation to base-level changes.

The complexity of soils, and, thus, of paleosols, can only begin to be understood by looking at the high diversity of environments in which they may form, the variety of surface processes to which they can be genetically related and the practical difficulties to classify them.

Paleosols have been described from an entire range of non-marine environments, including alluvial, palustrine and eolian environments, but also from coastal settings and even marginal-marine to shallow-marine settings, where stages of base-level fall led to the subaerial exposure of paleo-seafloors.

Irrespective of the depositional environment, soils may form in connection with different surface processes, including sediment aggradation (as long as sedimentation rates do not outpace the rates of pedogenesis), sediment bypass (non-deposition) and sediment reworking (as long as the rate of scouring does not outpace the rate of pedogenesis).

Soils formed during stages of sediment aggradation occur within conformable successions, whereas soils formed during stages of non-deposition or erosion are associated with stratigraphic hiatuses, marking diastems or unconformities in the stratigraphic record. These issues are particularly important for Sequence Stratigraphy, as it is essential to distinguish between paleosols with the significance of sequence boundaries, playing the role of subaerial unconformities, and paleosols that occur within the sequence and systems tracts.

However, theoretical and field studies have shown that the paleosol types observed in the rock record change with a fluctuating base level, thus, allowing one to assess their relative importance and significance from a sequence stratigraphic perspective. For example, the sequence boundaries of the Upper Carboniferous cyclothems in the Sydney Basin of Nova Scotia are marked by mature calcareous paleosols (calcretes; see Fig. 16) formed during times of increased aridity and lowered base level, whereas vertisols occur within sequences, being formed in aggrading fluvial floodplains during times of increased humidity and rising base level (see Fig. 17).

Fig. 16 *Top: calcrete with strong nodular texture; note the non-disrupted nature of the siltstone below. Bottom: calcrete exposed on wave-cut platform, with strong vertic fabric (scale 50 cm).*

Fig. 17 *Top: lowstand calcrete paleosols (sequence boundary; see arrow) pass upward into dryland vertisols, probably marking the renewal of clastic supply to the coastal plain as accommodation was made available by base-level rise. Bottom: grey coastal siltstones at lower left (see arrows) pass upward in meter-thick calcrete; the calcrete is overlain by red vertisols and thin splay sandstones, as sedimentation resumed on the dryland coastal plain, possibly as transgression allowed sediment storage on the floodplain.*

The types of paleosols that may form in relation to the interplay between surface processes (sedimentation, erosion) and pedogenesis are illustrated in Fig. 18.

Stages of non-deposition and/or erosion, typically associated with sequence boundaries, result in the formation of mature paleosols along unconformity surfaces.

Stages of sediment accumulation, typically associated with the deposition of a sequence, result in the formation of less mature and, generally, aggrading paleosol, whose rates of aggradation match the sedimentation rates.

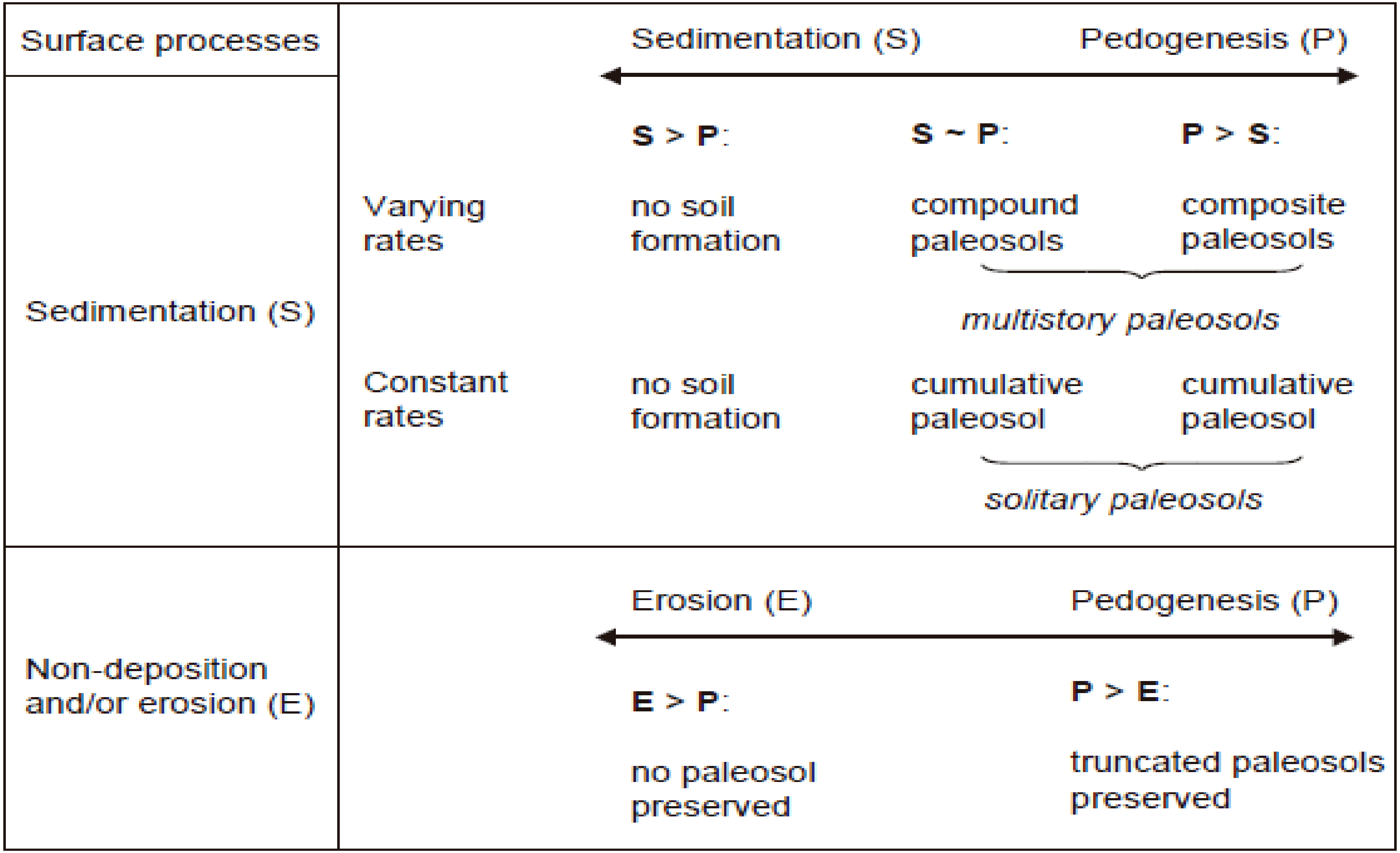


Fig. 18 *Interplay of pedogenesis and surface processes. Compound, composite and cumulative paleosols occur within conformable successions, hence, within the depositional sequences. Truncated paleosols are associated with stratigraphic hiatuses and, therefore, mark diastems or unconformities.*

Paleosols associated with sequence boundaries are generally strongly developed and well-drained, reflecting prolonged stages of sediment cut-off and a lowered base level (low water table in the non-marine portion of the basin. Besides base level, climate may also leave a strong signature on the nature of sequence-bounding paleosols (e.g., a drier climate would promote evaporation and the formation of calcic paleosols).

However, base level and climate are not necessarily independent variables, as climatic cycles driven by orbital forcing (e.g., eccentricity, obliquity and precession cycles), with periodicities in a range of tens to hundreds of thousands of years (Fig. 19) are a primary control on sea-level changes (Milankovitch cycles). In such cases, stages of base-level fall may reflect times of increased climatic aridity. On the other hand, base-level changes may also be driven by tectonism, independent of climate changes, in which case base-level cycles may be modified independently to the climatic fluctuations.

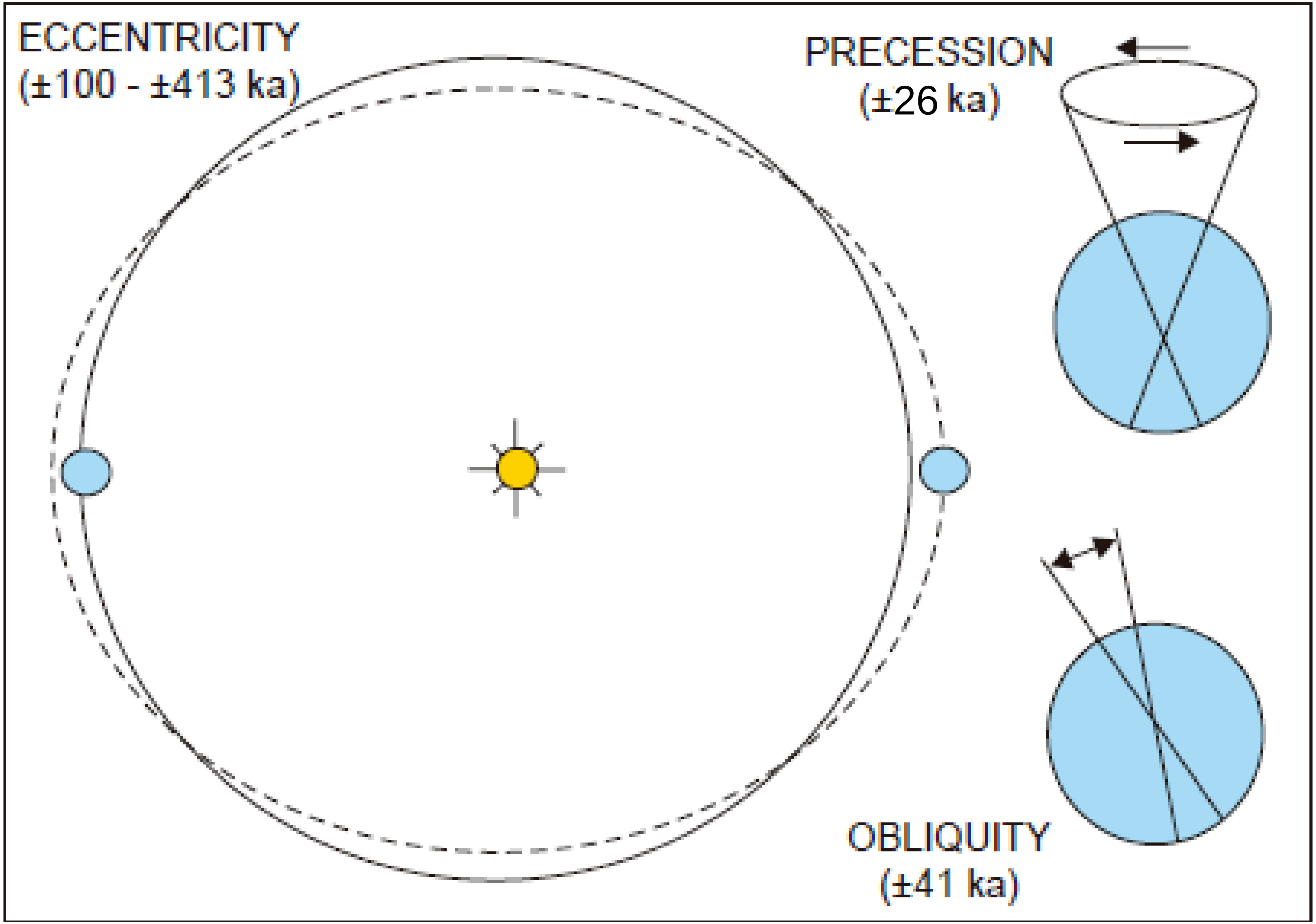


Fig. 19 *Main components of orbital forcing, showing the causes of Milankovitch-band (10^4–10^5 years) cyclicity.*

Sequence-bounding unconformities are commonly regional in scale (caused by allogenic processes), as opposed to the more localized diastems related to autogenic processes, and, depending on paleo-landscape, can be surfaces with highly irregular topographic relief along which the amount of missing time may vary considerably. **Therefore, accordingly, the paleosol associated with a sequence-bounding unconformity** can show lateral changes that may be used to interpret lateral variations in topography and missing time.

In contrast, paleosols that form within sequences may be weakly to well-developed, but are generally less mature than the sequence-bounding paleosols (Fig. 20). They form during stages of base-level rise (higher water table in non-marine environments), when surface processes are dominated by sediment aggradation. As a result, these paleosols tend to be ‘wetter’ relative to the sequence-bounding paleosols, to the extent of becoming hydromorphic (gleysol type) around the maximum flooding surfaces, which mark the timing of the highest water table in the non-marine environment. Such ‘wetter’ and immature paleosols form over relatively short time scales and are often seen in close association with coal seams (Fig. 20). Fig. 21 synthesizes the main contrasts between the sequence bounding paleosols and the paleosols that form within sequences. The latter type may show aggradational features, often with a multistory architecture due to unsteady sedimentation rates, but may also be associated with hiatuses where autogenic processes, such as channel avulsion, led to a cut-off of sediment supply in overbank areas.

Fig. 20 *Wet and immature paleosol of gleysol type, formed in close association with a coal seam during an overall stage of base-level rise. This example displays amalgamated braided fluvial channel fills, interpreted as a lowstand systems tract. Such immature paleosols develop within depositional sequences, commonly over short time scales of 10^3 years or less. The formation of wet and immature soils vs. coal seams is most likely a function of fluctuations in climatic conditions and fluvial discharge (subaerial exposure vs. flooding of overbank environments) rather than marine base-level changes.*

Features \ Paleosol type	Sequence-bounding paleosols	Paleosols within sequences
maturity	strongly developed	weakly to well-developed
soil saturation	well-drained	wetter
hiatus	10^4 yr or more	0-10^3 yr
hiatus controls	allogenic	autogenic (e.g., avulsion)
hiatus extent	regional	local
significance	unconformity	diastem
accommodation	negative	positive
surface process	bypass or erosion	aggradation
water table	low	higher
architecture	solitary	commonly multistory

Fig. 21 *Comparison between sequence-bounding paleosols and the paleosols developed within sequences.*

In conclusion, Fig. 22 illustrates a generalized model of paleosol development in relation to a cycle of base-level change. As a matter of principle, the higher the sedimentation rates in the floodplain the weaker developed the paleosol is. Hence, the most mature paleosols are predicted along sequence boundaries (zero or negative sedimentation rates) and the least developed paleosols are expected to form during transgressions, when the fluvial aggradation rates in the non-marine environment and the water table are highest. Due to the high water table in the non-marine environments during transgression, hydromorphic paleosols are often associated with regional coal seams.
It can be concluded that paleosols are highly relevant to Sequence Stratigraphy, complementing the information acquired via different methods of data analysis. Pedologic studies are routinely performed on outcrops and sediment cores and to a lesser extent on well logs, and may be applied to a wide range of stratigraphic ages, including strata as old as the Early Proterozoic.

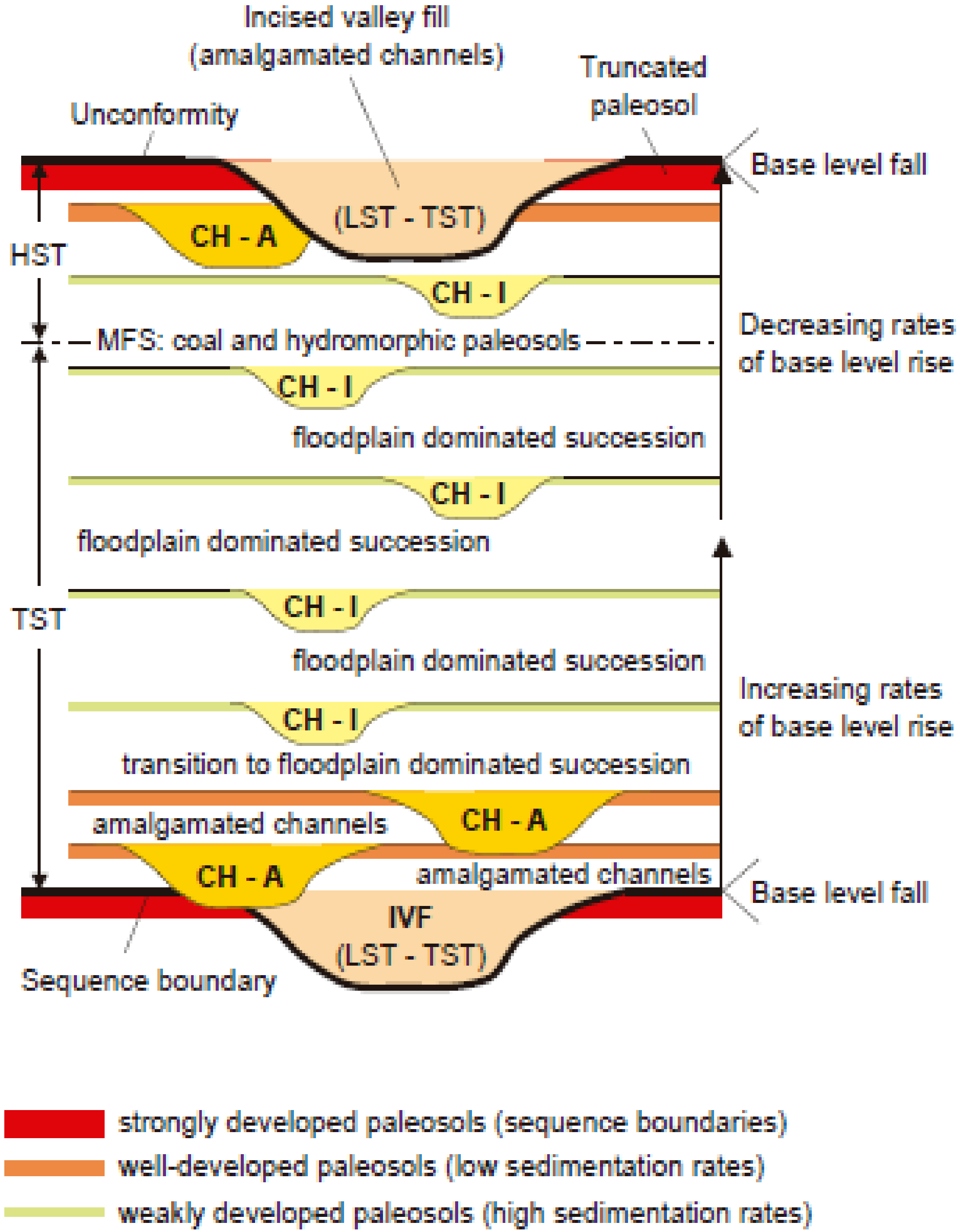
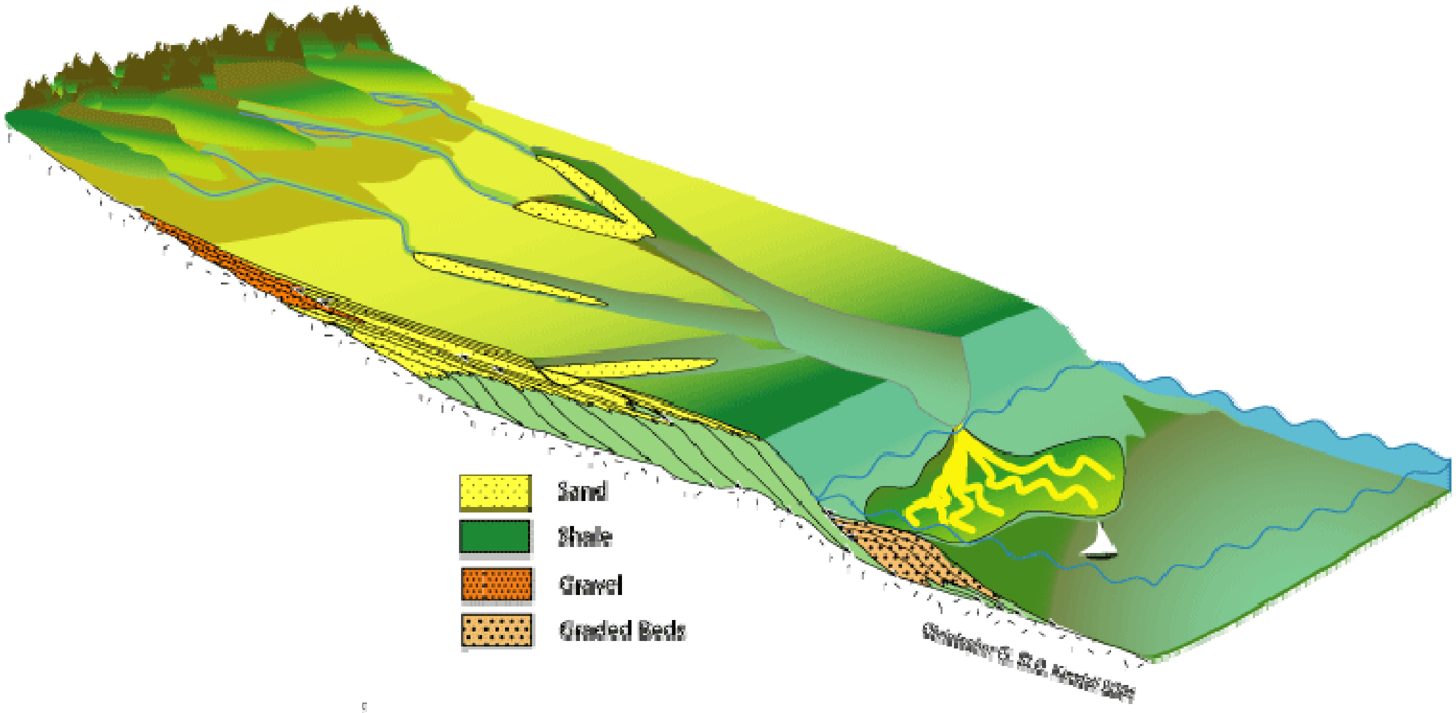
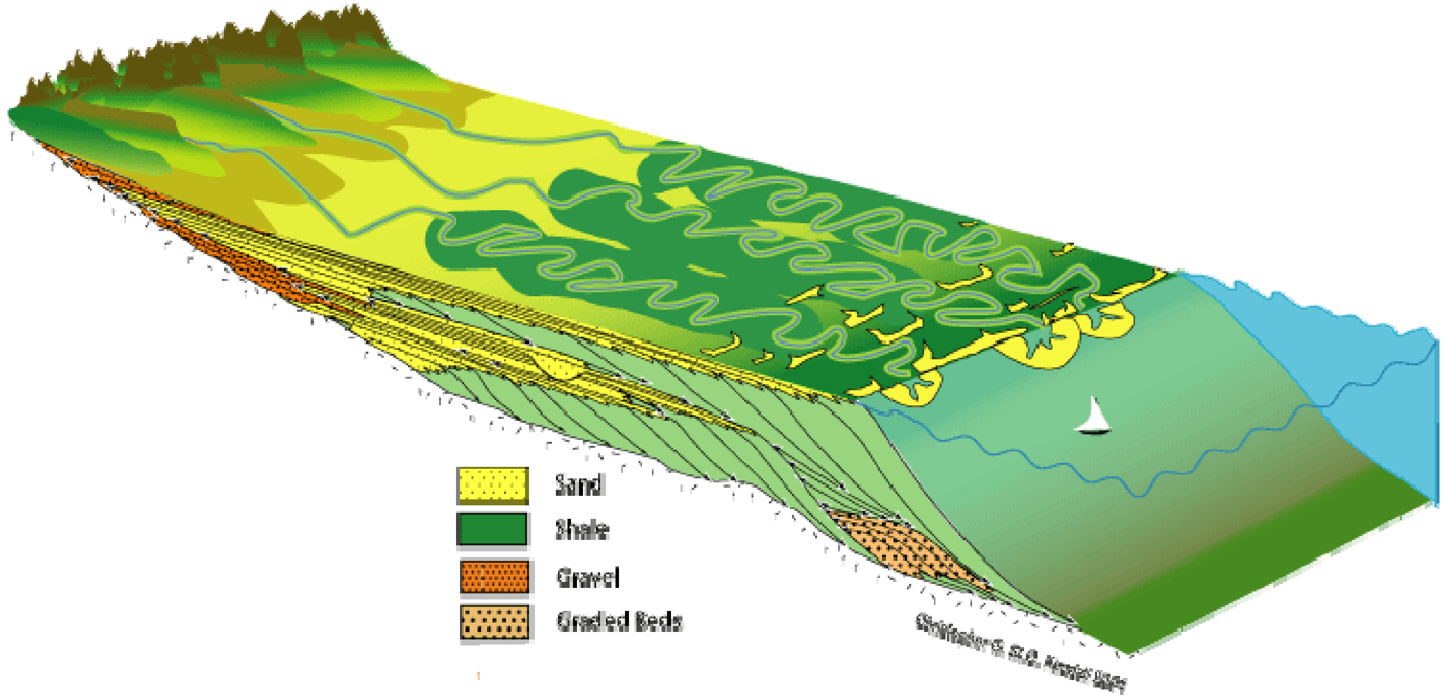


Fig. 22 *Generalized model of paleosol development in relation to a base-level cycle. In this model, the rates of fluvial aggradation (and indirectly the degree of channel amalgamation and the paleosol maturity) are directly linked to the rates of base-level rise. Note that low sedimentation rates (early and late stages of base-level rise) allow for channel amalgamation and the formation of well-developed paleosols. High sedimentation rates favor the formation of weakly developed paleosols within a succession dominated by floodplain deposits.*


Sand
Shale
Gravel
Graded Beds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1.3.7 Ichnology

General Principles

Ichnology is the study of traces made by organisms, including their description, classification and interpretation. Such traces may be ancient (trace fossils - the object of study of paleoichnology) or modern (recent traces - the object of study of neoichnology) and, generally, reflect basic behavior patterns (e.g., resting, mobility, dwelling or feeding), which can be directly linked to a number of ecological controls (e.g., substrate coherence, water energy, sedimentation rates, nutrients, salinity, oxygenation, light or temperature) and indirectly to particular depositional environments.

Trace fossils include a wide range of biogenic structures where the results of organism activities are preserved in sediments or sedimentary rocks, but not the organisms themselves or any body parts thereof. Ichnofossils also exclude molds of the body fossils that may form after burial, but include imprints made by body parts of active organisms. Trace fossils are often found in successions that are otherwise unfossiliferous and bring a line of evidence that can be used towards the reconstruction of paleoecological conditions and paleodepositional environments. As with any independent research method, the information brought by ichnology may be ambiguous in some cases (e.g., when two or more different organisms contribute to the formation of one trace, or when one organism generates different structures in the same substrate due to changes in its behavior; Fig. 23a, b), so it is best that ichnological data be used in combination with other clues provided by classical paleontology and sedimentology to better validate paleoenvironmental interpretations.

Trace fossils generally reflect the activity of *soft-bodied organisms*, which commonly lack hard (preservable) body parts. In many environments, such organisms represent the dominant component of the biomass.

Trace fossils may be classified into structures reflecting *bioturbation* (disruption of original stratification or sediment fabric: e.g., tracks, trails, burrows); *biostratification* (stratification created by organism activity: e.g., biogenic graded bedding, biogenic mats); *biodeposition* (production or concentration of sediments by organism activity: e.g., fecal pellets, products of bioerosion); or *bioerosion* (mechanical or biochemical excavation by an organism into a substrate: e.g., borings, gnawings, scrapings, bitings).

Fig. 23a *Basic principles of ichnology.*

Trace fossils are sensitive to water energy (hence, they may be used to recognize and correlate event beds), substrate coherence, and other *ecological parameters* such as salinity, oxygen levels, sedimentation rates, luminosity, temperature, and the abundance and type of nutrients.

Trace fossils tend to be *enhanced by diagenesis*, as opposed to physical or chemical structures which are often obliterated by dissolution, staining or other diagenetic processes.

An individual trace fossil may be the product of *one organism* (easier to interpret), or the product of *two or more different organisms* (composite structures, more difficult to interpret).

An individual organism may generate *different structures* corresponding to different behavior in similar substrates, or to identical behavior in different substrates. At the same time, *identical structures* may be generated by different organisms with similar behavior.

Fig. 23b *Basic principles of ichnology.*

The fossil record of an ichnocoenose, which is an association of environmentally related traces, is defined as an *ichnofacies.* Furthermore, besides the actual types of trace fossils, their abundance and arrangement are also used to characterize the texture and internal structure of a deposit, which defines the concept of *Ichnofabric.* Lateral and vertical shifts in ichnofacies and ichnofabrics are generally used to interpret changes in space as well as through time in paleodepositional environments, based on inferred shifts in paleoecological conditions

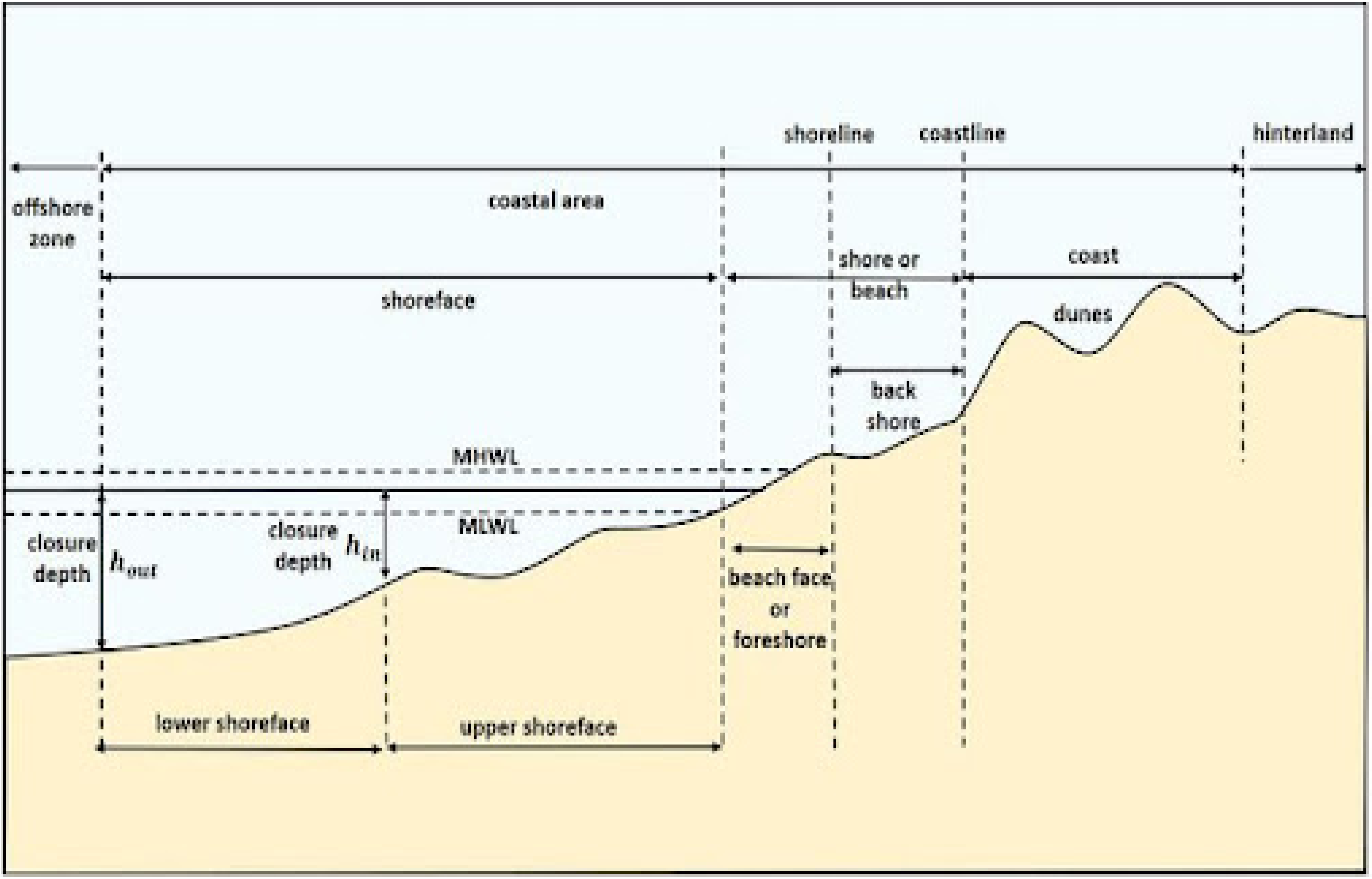
The concept of ichnofacies, which is central to ichnology, was originally developed based on the observation that many of the environmental factors that control the distribution of traces change progressively with increased water depth. It is important to realize, however, that the ecology of an environment reflects the interplay of a multitude of factors (Fig. 23) and, therefore, the types and number of organisms that inhabit a particular area (and subsequently the resultant ichnofacies and ichnofabrics) do not necessarily translate into specific water depths, distance from shore, or tectonic or physiographic setting. For example, the *Zoophycos* ichnofacies, typically formed under deeper-marine conditions, below the storm wave base, may also be found in other oxygen-poor settings such as restricted lagoons in coastal environments. This suggests that caution needs to be used when attempting to interpret absolute or relative paleobathymetry based on ichnofacies sequences, or to establish the syndepositional transgressive or regressive shifts of the shoreline.

Ichnofacies Classification

The classification of trace fossil assemblages (i.e., ichnofacies) is primarily based on the substrate type and coherence, while it has a direct connection with paleoenvironmental conditions. The ichnofacies presented in Fig. 24 are listed in order of increasing marine influence, from fully non-marine to marginal-, shallow- and deep-marine environments. The basic substrate types used in the classification of ichnofacies include *softgrounds* (either shifting or stable, but generally unconsolidated), *firmgrounds* (semi-consolidated substrates, which are firm but unlithified), *hardgrounds* (consolidated or fully lithified substrates) and, finally, *woodgrounds* (i.e., in situ and laterally extensive carbonaceous substrates, such as peats or coal seams).

Substrate	Ichnofacies	Environment		Trace fossils
Softground, *nonmarine*	Termitichnus	Subaerial	No flooding: paleosols developed on low watertable alluvial and coastal plains	*Termitichnus, Edaphichnium, Scaphichnium, Celliforma, Macanopsis, Ichnogyrus*
	Scoyenia	Freshwater	Intermittent flooding: shallow lakes or high watertable alluvial and coastal plains	*Scoyenia*, vertebrate tracks
	Mermia		Fully aquatic: shallow to deep lakes, fjord lakes	*Mermia, Gordia, Planolites, Cochlichnus, Helminthopsis, Palaeophycus, Vagorichnus*
Woodground	Teredolites	Marginal marine	Estuaries, deltas, backbarrier settings, incised valley fills	*Teredolites, Thalassinoides*
Softground, *marginal marine*	Psilonichnus		Backshore ± foreshore	*Psilonichnus, Macanopsis*
Hardground	Trypanites	Marginal marine to marine	Foreshore - shoreface - shelf	*Caulostrepsis, Entobia*, echinoid borings (unnamed), *Trypanites*
Firmground	Glossifungites			*Gastrochaenolites, Skolithos, Diplocraterion, Arenicolites, Thalassinoides, Rhizocorall.*
Softground, *marine*	Skolithos	Marine	Foreshore - shoreface	*Skolithos, Diplocraterion, Arenicolites, Ophiomorpha, Rosselia, Conichnus*
	Cruziana		Lower shoreface - inner shelf	*Phycodes, Rhizocorralium, Thalassinoides, Planolites, Asteriacites, Rosselia*
	Zoophycos		Outer shelf- slope	*Zoophycos, Lorenzinia, Spirophyton*
	Nereites		Slope - basin floor	*Paleodictyon, Helminthoida, Taphrhelminthopsis, Nereites, Cosmorhaphe, Spirorhaphe*

Fig. 24
Classification of ichnofacies based on substrate type and conherence as well as depositional environment.



Coastal environment

Fig. 24 shows that only three ichnofacies are substrate dependent (or *substrate-controlled*), being associated with a specific substrate type (i.e., the *Teredolites* ichnofacies forms only on woodgrounds; the *Trypanites* ichnofacies is diagnostic for hardgrounds; and the *Glossifungites* ichnofacies indicates firmgrounds), whereas the rest of eight ichnofacies form on a variety of softground substrates, ranging from non-marine to marginal marine and fully marine, as a function of ecological conditions. In practice, ichnofacies (see Figs 25-29) may, therefore, be broadly classified into two main groups, i.e., a softground-related group and a substrate-controlled group.

A

B

Fig. 25 *Skolithos ichnofacies comprise burrows (made from worm-like animals) ranging in age from early Cambrian to the present and are found throughout the world. They occur in sediments and sedimentary rocks, primarily sands and sandstones. They are typically marine in origin and are commonly associated with high-energy environments close to the shoreline. A: Skolithos traces (Mississippian Etherington Formation, Jasper National Park, Alberta). B: Ophiomorpha traces on a bedding plane in shoreface to wave-dominated delta front deposits of Eocene Epoch (Sunset Cove Bay, Oregon).*

A

B

C

Fig. 26 *Zoophycos ichnofacies produced by moving and feeding polychaete worms. A, B, C: Zoophycos trace fossils concordant with bedding planes in the Mississippian Etherington Formation (Jasper National Park, Alberta), Mississippian Shunda Formation (Jasper National Park, Alberta) and Cretaceous Wabiskaw Member of the Clearwater Formation (Fort McMurray, Alberta), respectively.*

Fig. 27 *Glossifungites ichnofacies at the base of a tidal channel fill (arrow). The photograph shows Thalassinoides burrows, produced by decapod crustaceans, descending into the underlying intertidal deposits (Pleistocene section, Willapa Bay, Washington). The Glossifungites facies represents an assemblage of burrows (vertical, U-shaped, or sparsely branched) that occur in firm, but not lithified, siliciclastic and/or carbonate muds and silts of the intertidal and shallow marine areas where scouring has often removed the unconsolidated layers at the sediment surface. The surfaces on which Glossifungites occur are interpreted to have formed following a regression and sea level fall and just after the initial transgressive phase immediately following sea level lowstands.*

Fig. 28 *Trypanites ichnofacies, produced by bivalve molluscs, in a modern intertidal environment.The hardground occurs as a scour cut into Triassic bedrock by tidal currents and has the significance of a transgressive tidal-ravinement surface. Boring density may locally exceed 1250 borings per square meter. Location is near Economy, Nova Scotia (Bay of Fundy, Minas Basin).*

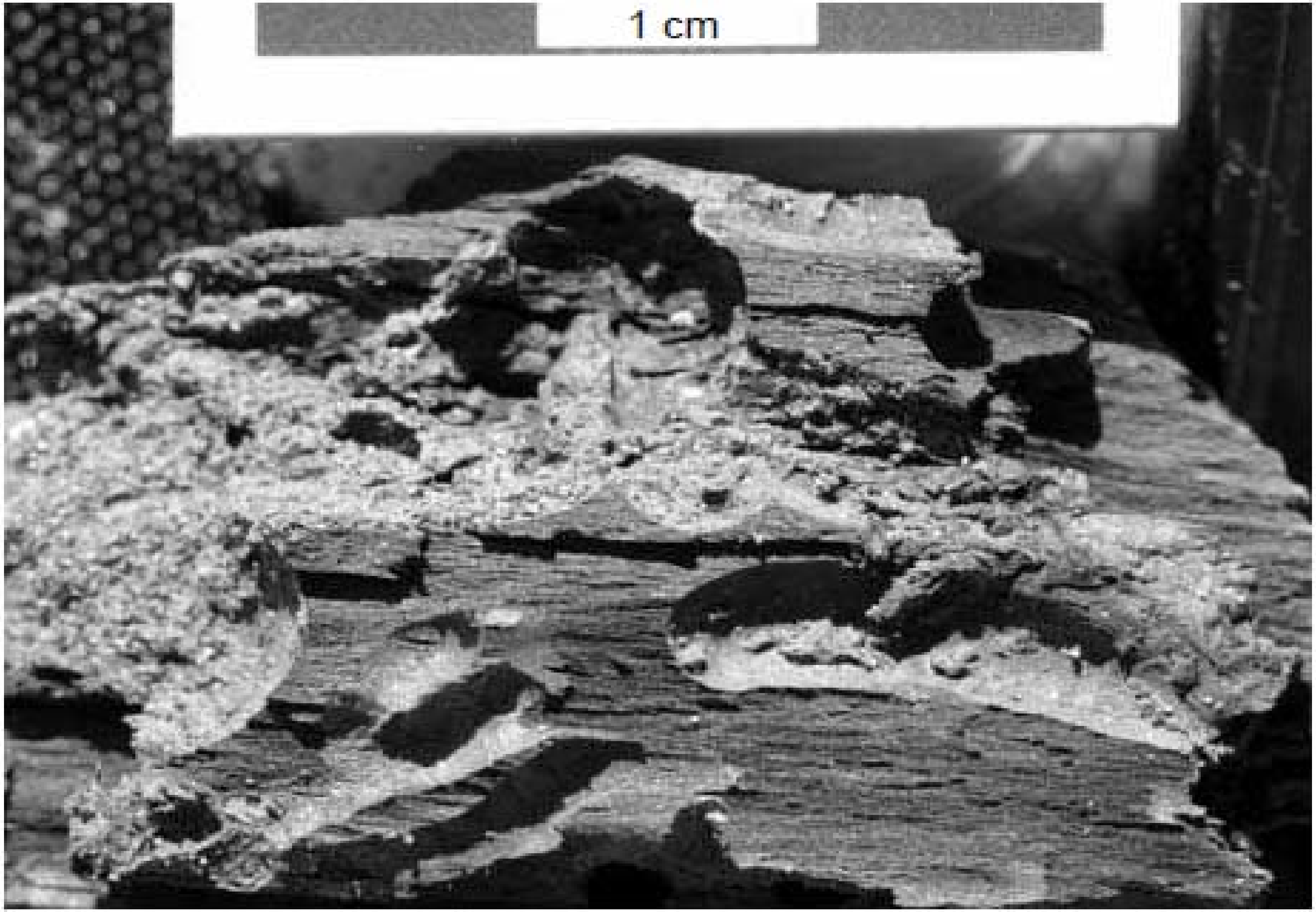


Fig. 29 *Teredolites ichnofacies in a modern intertidal environment (Willapa Bay, Washington). The borings are sand-filled, which provides their typical mode of preservation, and are made by the bivalve Bankia. The woodground has the significance of a transgressive tidal-ravinement surface. The association between Teredolites and transgressive coastlines is generally valid for both in situ and allochthonous woodgrounds.*

Major Remarks

It is important to note that many individual trace fossils are common among different ichnofacies. For example, *Planolites* may be part of both *Mermia* (freshwater) and *Cruziana* (seawater) assemblages or *Thalassinoides* may populate softground, firmground and woodground substrates. Hence, the assemblages of trace fossils, coupled with additional clues provided by physical textures and structures, need to be used in conjunction for the proper interpretation of stratigraphic surfaces and paleodepositional environments.

The importance of ichnology to Sequence Stratigraphy is two-fold: (1) *Softground-related ichnofacies*, which generally form in conformable successions, assist with the interpretation of paleodepositional environments and changes thereof with time. The vertical shifts in softground assemblages are governed by the same Walther's Law that sets up the principles of lateral and vertical facies variability in relatively conformable successions of strata and, therefore, can be used to decipher paleodepositional trends (progradation *vs.* retrogradation) in the rock record. The recognition of such trends, which in turn relate to the regressions and transgressions of paleoshorelines, is central to any sequence stratigraphic interpretation.

(2) *Substrate-controlled ichnofacies* are genetically related to stratigraphic hiatuses and can be conveniently used as unconformities in the rock record, thus, being of crucial importance for the sequence stratigraphic analysis. The actual type of the unconformable sequence stratigraphic surface can be further evaluated by studying the nature and relative shift directions of the facies which are in contact across such omission surfaces.

1.4 High-Resolution Sequence Stratigraphy: The East Coulee Delta (Alberta, Canada)

1.4.1 East Coulee Delta General Description

The East Coulee fan delta (Fig. 30) formed along the margin of a large puddle within a roadside drainage ditch during a period of high runoff following a rain storm. The delta measured 2.3 m across and 1.8 m along dip. The ditch within which it formed was 2.8 m wide and 30 m long. Its depth at the center was 50 cm at its maximum and 10 cm at its minimum. Varying puddle level (i.e., base level) resulted in a succession of systems tracts including a highstand, transgressive and two lowstand systems tracts. In addition, other features such as ravinement surfaces, longshore drift associated “beach deposits”, wave-cut bevels and “incised valleys” were recognized. This example confirms that sequence stratigraphic principles are scale- and time-independent.

Fig. 30 *Fan delta at East Coulee (Alberta, Canada).*

The East Coulee fan delta comprised at least three progradational lobes that created an arcuate plan view (Figs 30, 31), built by streams characterized by a braided pattern. The grain size distribution within each of these lobes was silt to very fine sand. The delta lobes were progressively younger in a basinward direction. A stream-cut gully (“incised valley” y in Fig. 31) was cut across the largest and landwardmost delta front (Unit A in Fig. 31), originating at the fan delta apex and continuing across to the basinwardmost delta lobe. The depth of incision was greatest across Unit A and diminished downdip. This stream-cut gully served as the conduit for sediment that fed the two smaller delta lobes (Units C and D on Fig. 31). Two strike-parallel “escarpments” (i.e., 1 and 2 in Fig. 31) had formed atop the largest delta front, while one “incised valley” were terminated at these “escarpments” (e.g., “incised valley” x in Fig. 31).

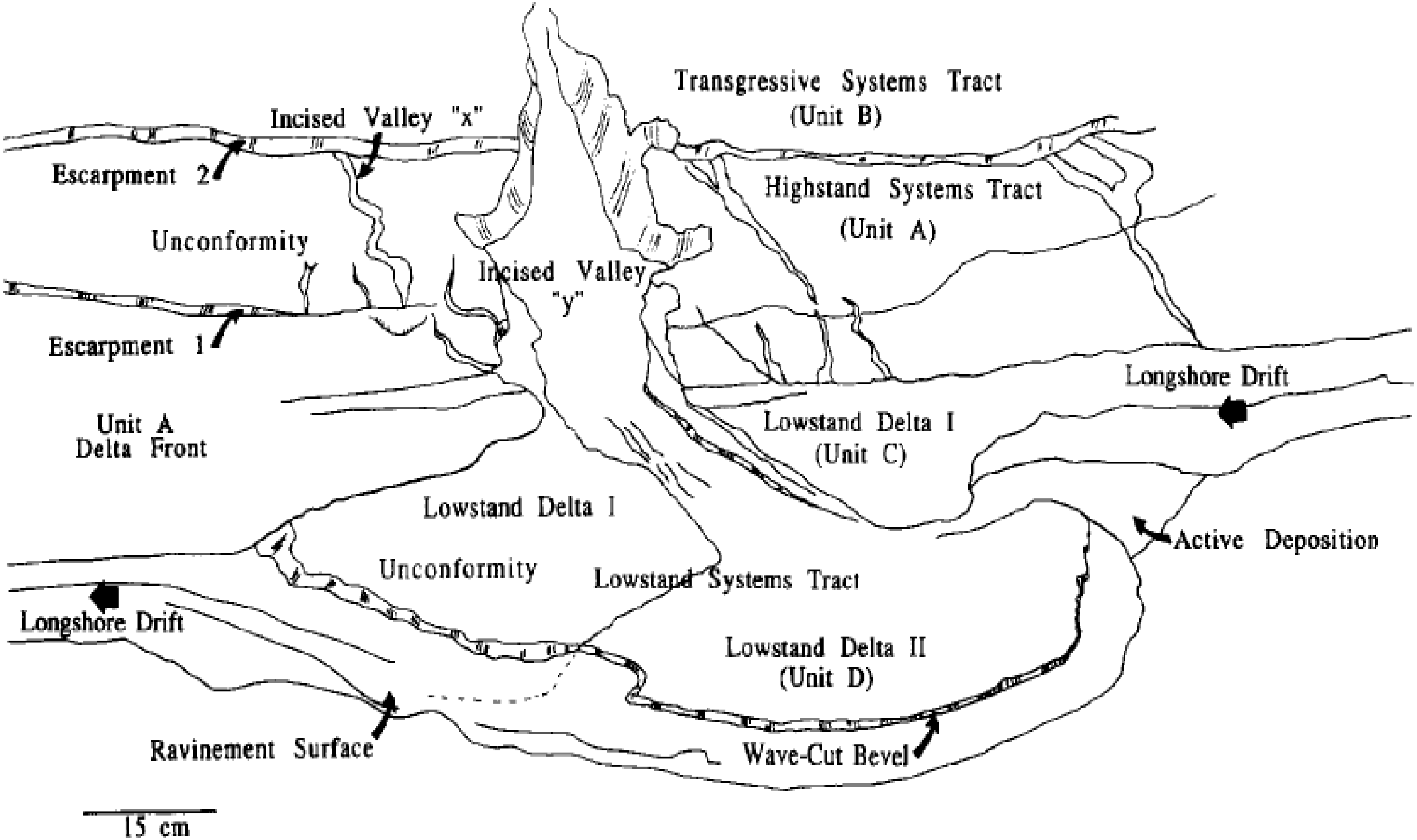


Fig. 31 *The delta measured 2.3 m across and 1.8 m along dip and prograded into a roadside drainage ditch 2.8 m wide and 30 m long during a short interval following a rain storm. Highstand, transgressive and two lowstand systems tracts were recognized.*

1.4.2 Highstand and Transgressive Systems Tracts

The deposition of the East Coulee delta was initiated during and immediately after a period of heavy rain in April 1989 near the central Alberta (Canada), community of East Coulee. Because it was not possible for the internal stratal patterns to be examined (since an effort of trenching triggered significant slope instability due to the high degree of saturation), the physical stratigraphy was based on observations of the external morphology.

The visible deposits of the earliest delta front (Unit A in Fig. 31) were inferred to have been associated with higher stands of puddle level. It is reasonable to assume that delta sedimentation was initiated shortly after the onset of rainfall (i.e., at an initially lower puddle level). During the resulting rising puddle level, the delta could have prograded or retrograded, depending on the ratio between sediment flux and the rate of accommodation space increase associated with the puddle level rise. In either case, aggradation would have occurred, resulting in coastal onlap.

The occurrence of “escarpment” 1 (Fig. 31) is interpreted as a wave-cut bevel associated with transgression of the shoreline. A subsequent acceleration of the puddle level rise resulted in an overstepping of the bevel and a rapid landward migration of the shoreline to a landward position at “escarpment” 2 (Fig. 31). It is possible that the bevel formation was followed by minor puddle level fall. Evidence for this interpretation is the occurrence of a small “incised valley” (“incised valley” x in Fig. 31) atop Unit A feeding a small delta just seaward of “escarpment” 1.
Following these events, a major flooding resulted in shoreline migration back towards the apex of Unit A. Then, a decrease in the rate of puddle level rise led to shoreline regression and progradation of Unit B (Fig. 31). The evidence for Unit B being a younger progradational unit is the disappearance of the “incised valley” x beneath Unit B at “escarpment” 2.

1.4.3 Lowstand Systems Tracts

During the puddle level fall, the delta plain of Unit B ceased to be an active depocenter and became a zone of bypass. As puddle level continued to fall, the steeper slopes of the delta front were exposed. The longitudinal profile of the principal stream was extended by an additional freshly exposed and steeper stream segment. Hence, the principal stream responded to the new steeper segment by downcutting to re-establish its graded or equilibrium profile, thus, excavating the “incised valley” y. For the same reason, small-scale “incised valleys” associated with “escarpment” 2 (see Fig. 31) developed.

The “incised valleys” fed the lowstand deposits (i.e., the lowstand systems tract) that developed seaward of the highstand delta plain (Unit A) and onlapped the delta front of Unit A (Fig. 31). This seaward migration of the shoreline strictly due to base-level fall constitutes a **forced regression**. This type of regression is in marked contrast to seaward migrations of the shoreline resulting from an excess of sediment supply relative to shelf space available (i.e., accommodation). This latter type of regression results from continual progradation and is termed a **normal regression**. The **forced regression** is characterized by discrete seaward jumps of the shoreline. The lowstand delta lobe comprising Unit C is an example of this type of regression (Fig. 31). Note that the location of the shoreline of Unit C occurred significantly basinward of the immediately preceding shoreline of Unit B located at or near “escarpment” 2.

The puddle level probably stabilized at this time, allowing Unit C to prograde. The puddle depth was at this time significantly less than during the preceding highstand and transgressive systems tracts times (Units A and B). The slope of the Unit C delta front most probably was lower, since the delta was prograding into shallower water. Hence, a renewed puddle-level fall resulted in another forced regression, but with limited incision than previously (due to being only slightly out of grade), causing the deposition of Unit D (see Lowstand Delta II lobe in Fig. 31).

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