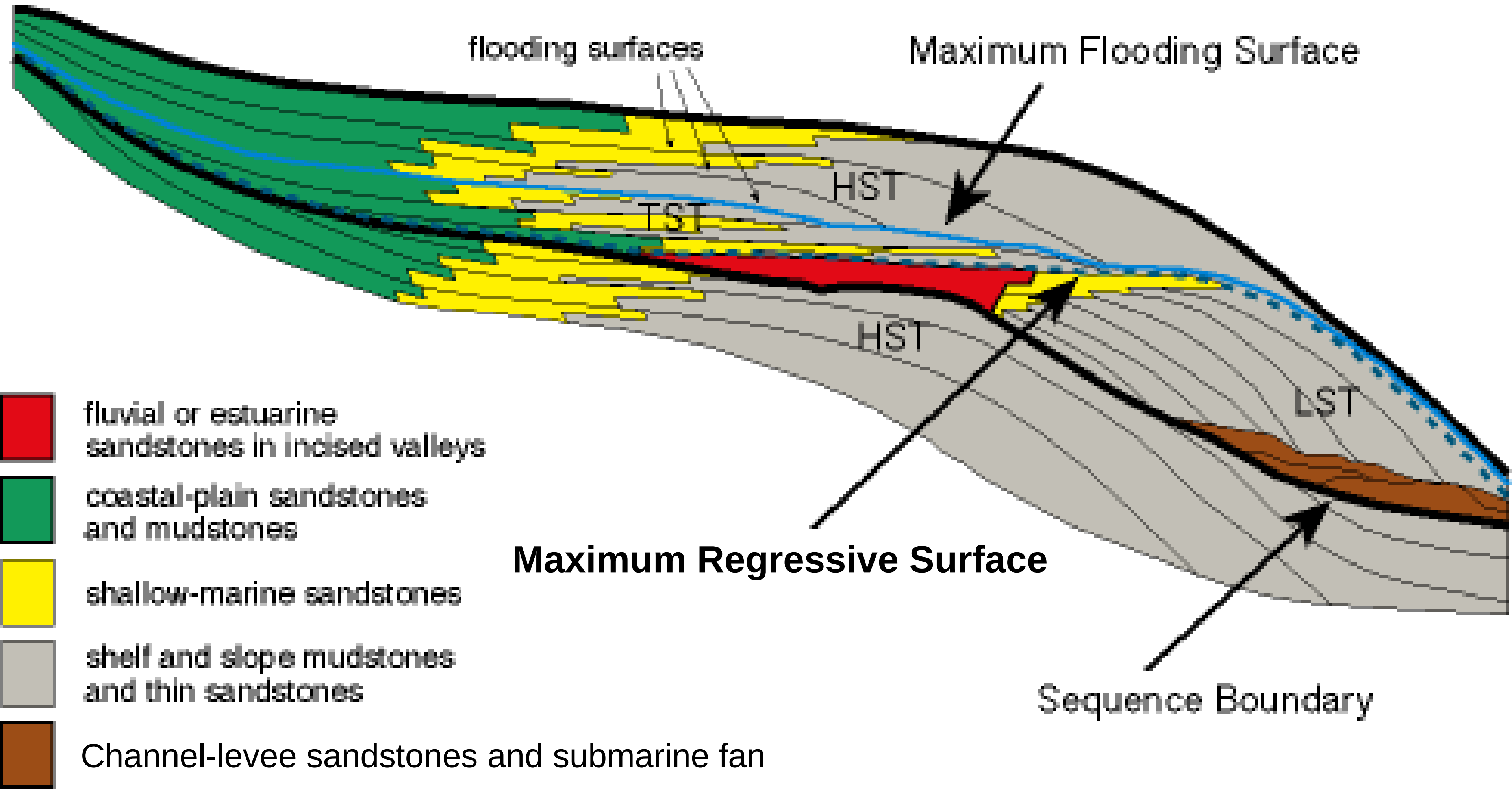
Sequence Stratigraphic Analysis



SECTOR OF HISTORICAL GEOLOGY - PALEONTOLOGY
Assistant Professor Ioannis Panagiotopoulos

1.1 Introduction

1.1.1 Environmental Sequence Stratigraphy

Sequence Stratigraphy has arguably **revolutionized stratigraphic analysis in the oil and gas industry since the 1970s**, but presently only **a few environmental companies have utilized this power tool**.

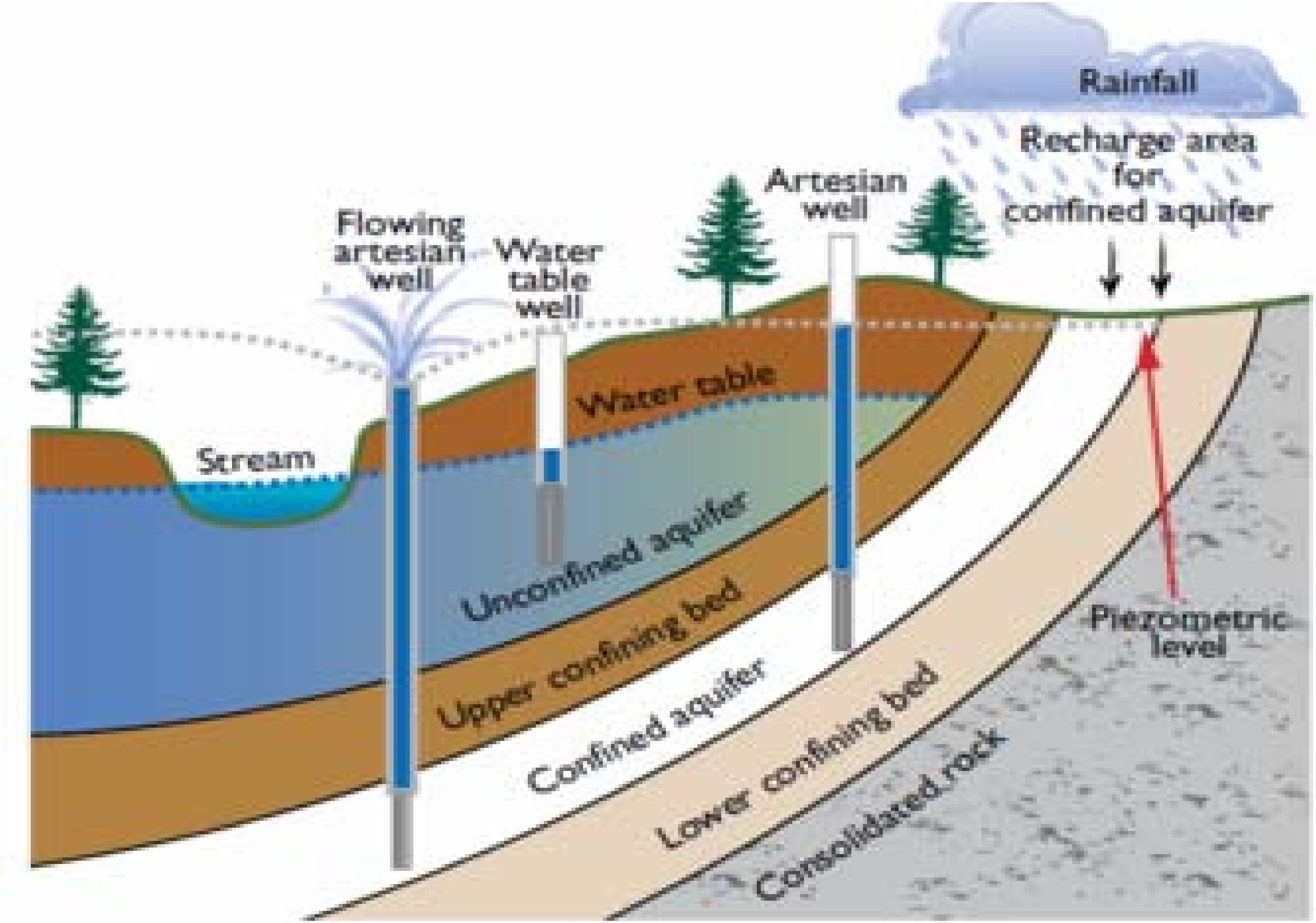
The **majority of the environmental companies** have mistakenly used only **lithostratigraphy**, without its parallel integration with the **sequence stratigraphic correlation techniques in order to define the subsurface stratigraphic heterogeneity**, which is vital for the **groundwater reserve analysis**.

But this has been significantly limiting their ability to **construct accurate conceptual site models and develop remedial strategies to effectively deal**, **especially**, **with groundwater contamination issues**.

The role of **Sequence Stratigraphy** in generating **robust and realistic hydrogeological models is vital**.

The application of this tool can effectively **identify the inherent lithologic heterogeneities**, **which control the groundwater flow paths**, **thu**s, **enhancing the effectiveness of the designed remedial measures in contaminated aquifers** as well as **the probability for the discovery of new aquifers** (see image below).

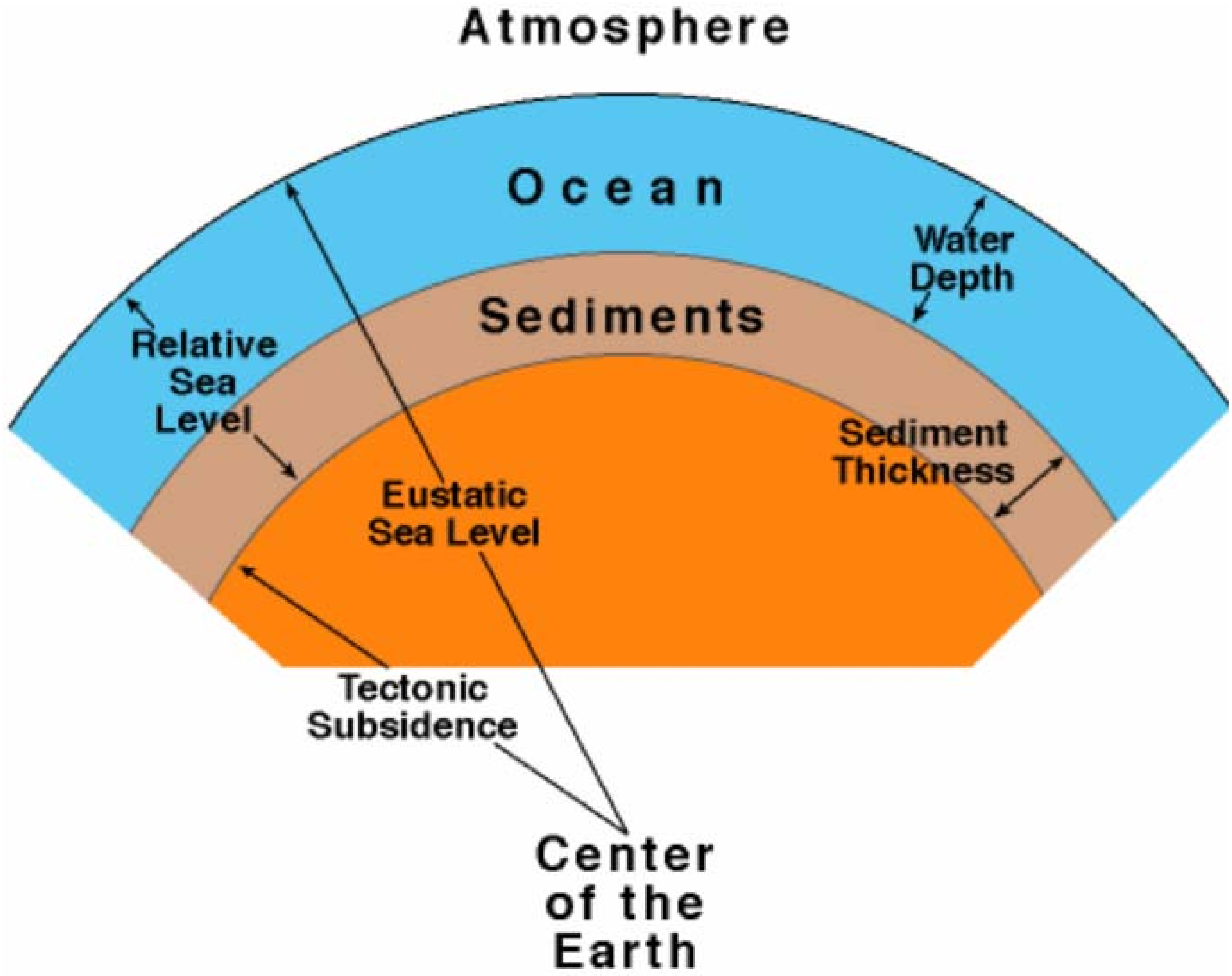
Therefore, the **Environmental Sequence Stratigraphy** approach can decisively strengthen the knowledge about the **hydrologic characteristics of the inland depositional environments throughout the geologic time** with the **mapping** and subsequent **prediction of the subsurface heterogeneous conditions in an entire drainage basin**.



Rainfall
Recharge area for confined aquifer
Artesian well
Flowing artesian well
Water table well
Water table
Stream
Unconfined aquifer
Upper confining bed
Confined aquifer
Lower confining bed
Consolidated rock
Piezometric level

1.1.2 The Sequence Stratigraphy Tool

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 regional** (**mainly**) **marine sedimentary basins**, in order to understand the evolution of the basin's **depositional systems** through time. Such frameworks, in conjunction with the **facies analysis of the depositional systems**, 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**, see image below) **in the marine basins**.



ACCOMODATION SPACE (10^5-10^8 years) → ESL + TS = ST + WD

Changes in **accommodation space** include:

(1) **Tectonic movements** (uplift, thermal subsidence, lithospheric flexure).

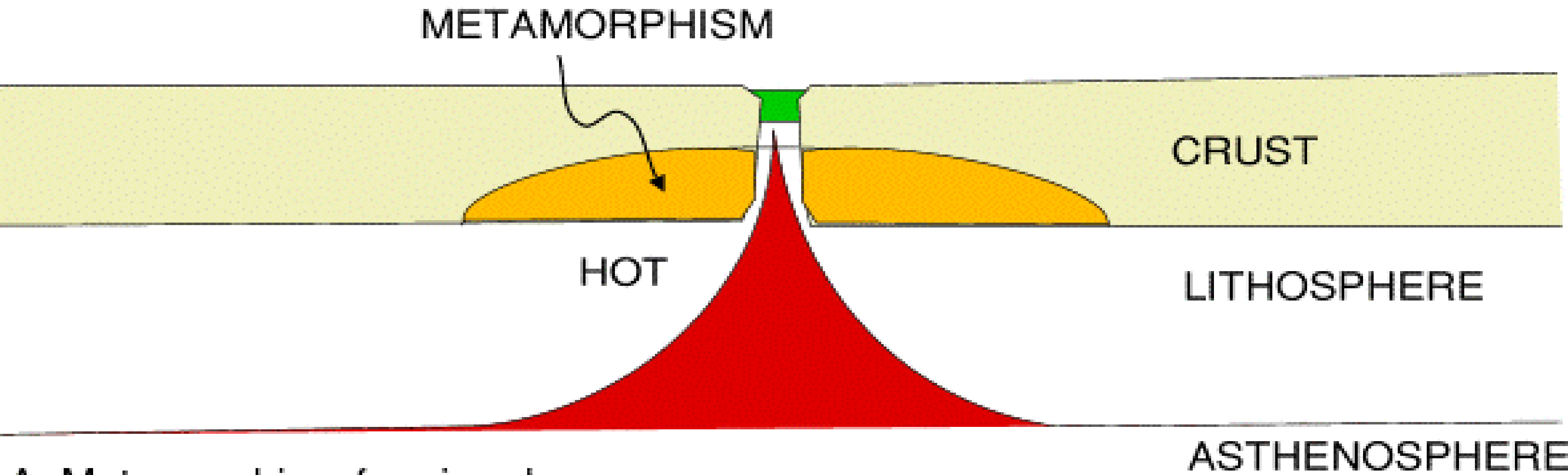
(2) **Isostatic subsidence** due to sediment overloading.

(3) **Isostatic uplift** due to the removal of loadings from land.

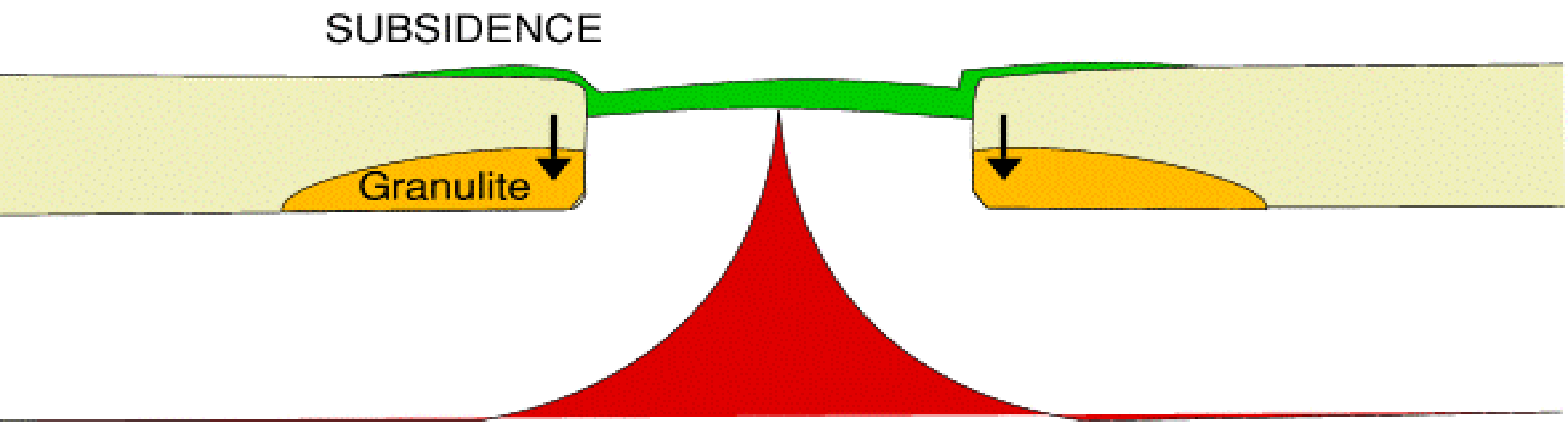
(4) **Eustatic sea level changes** in response to changes in the volume of ocean water (due to climate changes) and the volume of ocean basins (due to seafloor spreading, intense or weak magmatism).

(5) **Sediment compaction** and **consolidation**.

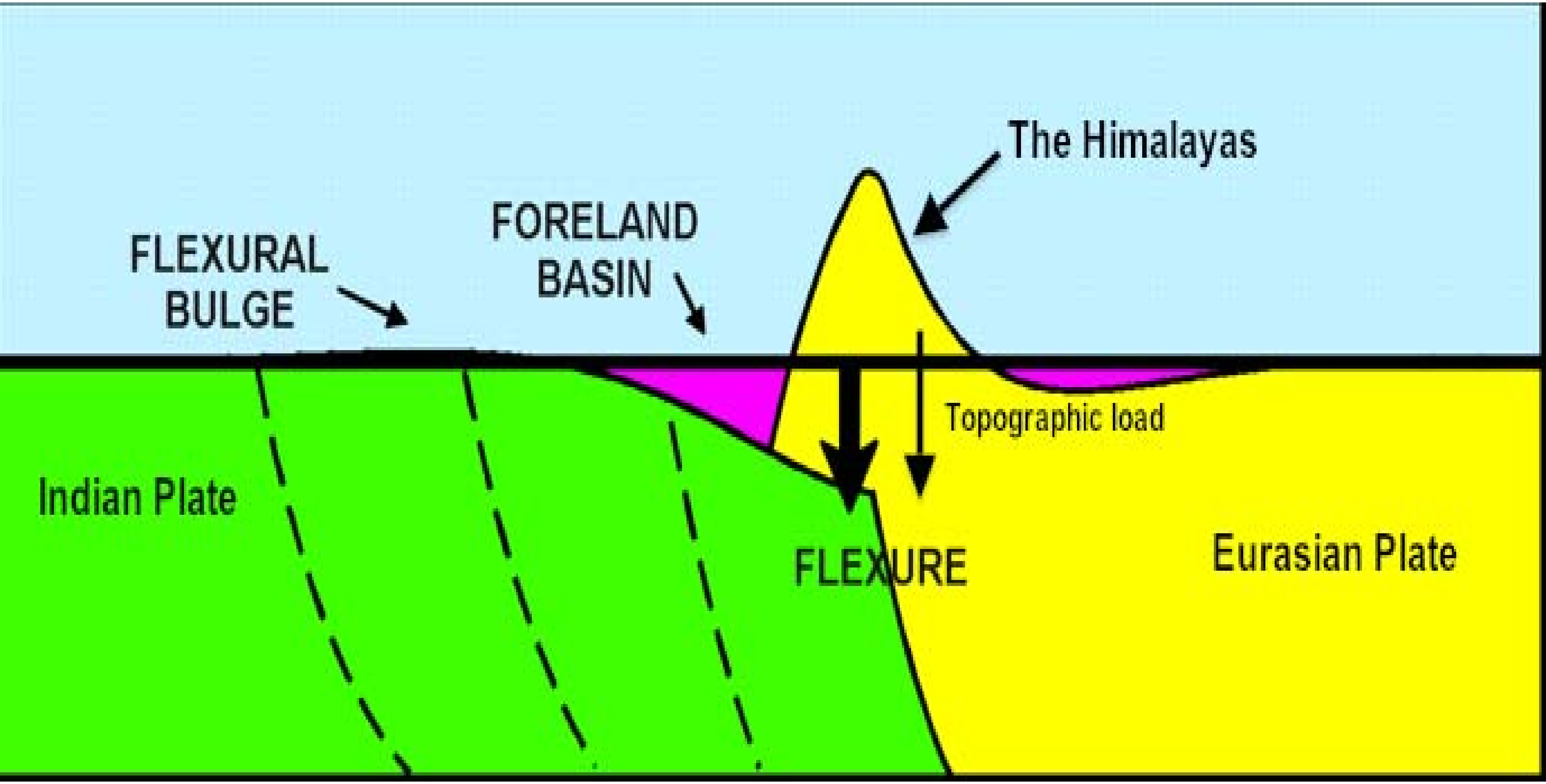
The sum of all the above changes is commonly referred to as stratigraphic **base** (**sea**) **level change**.



A. Metamorphism forming dense granulites in lower crust



B. Subsidence as lithosphere cools


The Himalayas
FORELAND
BASIN
FLEXURAL
BULGE
Topographic load
Indian Plate
FLEXURE
Eurasian Plate

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**.

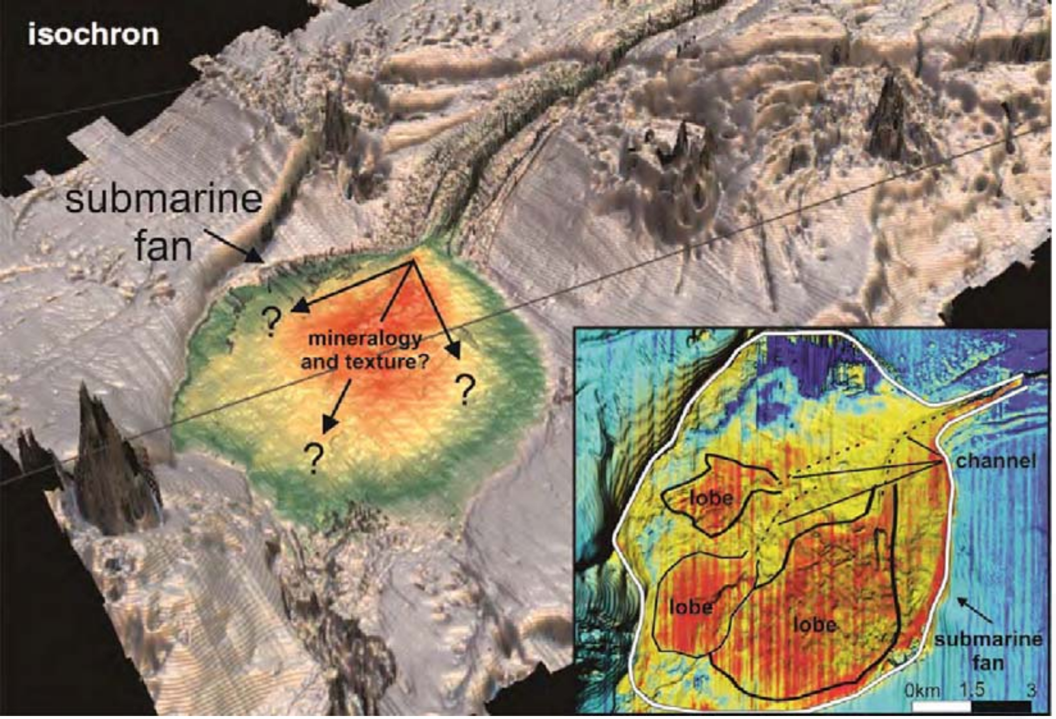
Hence, **the main target is to reconstruct the physical processes via which sediments filled a basin** and, therefore, how the stratigraphy was formed through space and time. This can help **scientists and exploration geologists** to figure out many important things like **how sea level changed** and **where coarse- and fine-grained sediments are located** (a very important issue for the **oil and gas industry** as well as for the **environmental sector too**, **dealing with hydrological issues**).

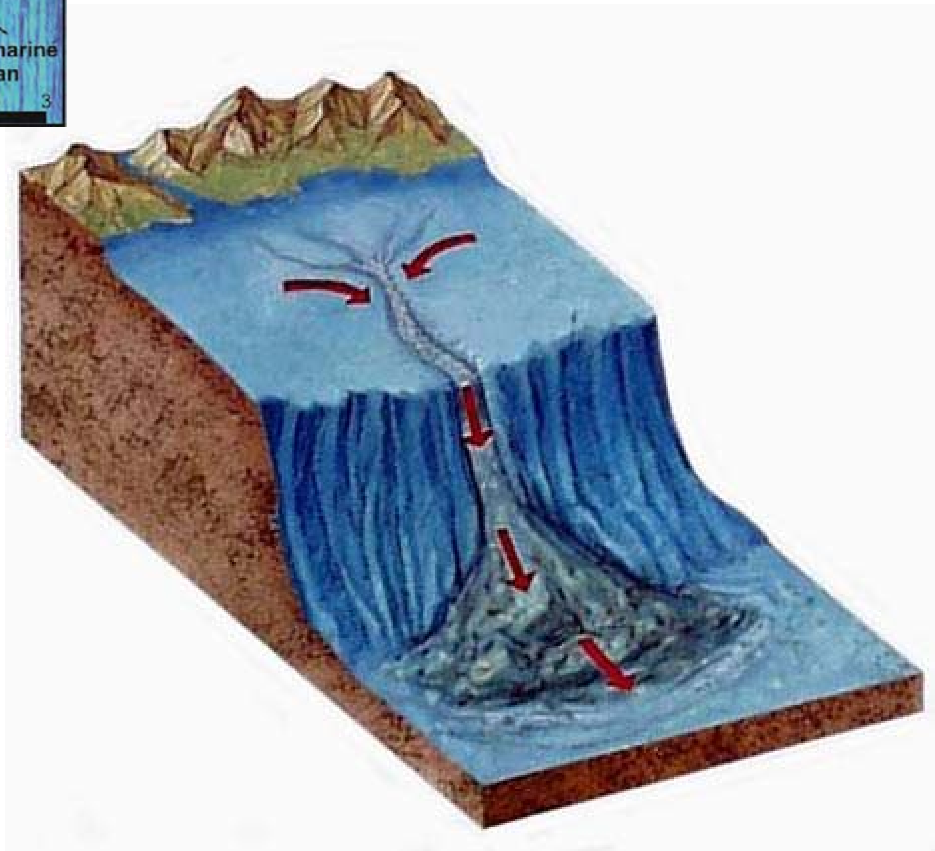
Over the years, **Sequence Stratigraphy** has developed into a widely used, methodological framework that encompasses many aspects of **Sedimentology and classic Stratigraphy** and has many useful applications and **predictive capacities in space**.

Sedimentary sequences refer to stratigraphic layers that were deposited during an episode of sea (base) level fall and subsequent rise.

Commonly, such depositional sequences are further subdivided into so-called **systems tracts** (i.e., a portion of the stratigraphy linked to a **specific position of sea level**). For instance, when **sea level falls** during a **glacial period** and, then, subsequently **rises** during an **interglacial period**, one stratigraphic sequence is deposited consisting of a **lowstand systems tract** (**LST**), followed by a **transgressive systems tract** (**TST**) and, finally, a **highstand systems tract** (**HST**).

Systems tracts are often distinct in their **shape**, **size and type of sedimentary deposits**. For instance, **basin floor fans** (see image below), usually develop as part of the **LST formation** (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**.


isochron
submarine fan
mineralogy and texture?
?
?
?
lobe
lobe
lobe
channel
submarine fan
0km 1.5 3



However, **like most things in Earth sciences**, the sequence stratigraphic models are always a **simplification of the reality** and **Sequence Stratigraphy** as a whole is infamous for being complicated and filled with **difficult terminology and additional complicating factors**, many of which are **unknown or poorly understood**.

Nevertheless, **Sequence Stratigraphy has become an important branch of classic Stratigraphy and Sedimentology**, and has greatly helped the **sedimentological community** as well as the **economic geologists** in the better **understanding of sedimentary basins and their dynamic evolution through time**.

The fundamental starting point for Sequence Stratigraphy is the **sedimentary facies**, which is a **unique layer/unit characterized by distinct lithological**, **textural**, **mineralogical and fossil characteristics**, generally reflecting a **certain sediment source** and/or **formation under the action of particular physical process/es in a specific depositional environment**.

A group of sedimentary facies genetically linked by common physical processes and environment comprises a depositional system.

Eventually, **the depositional systems can be grouped together within a framework of unconformity-bounding relatively conformable stratigraphic packages to form the stratigraphic 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 the two distinctly different approaches and of **the problems that might arise if one does not apply the most appropriate one 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 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 water 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** (see Figs 1, 2). The same 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.

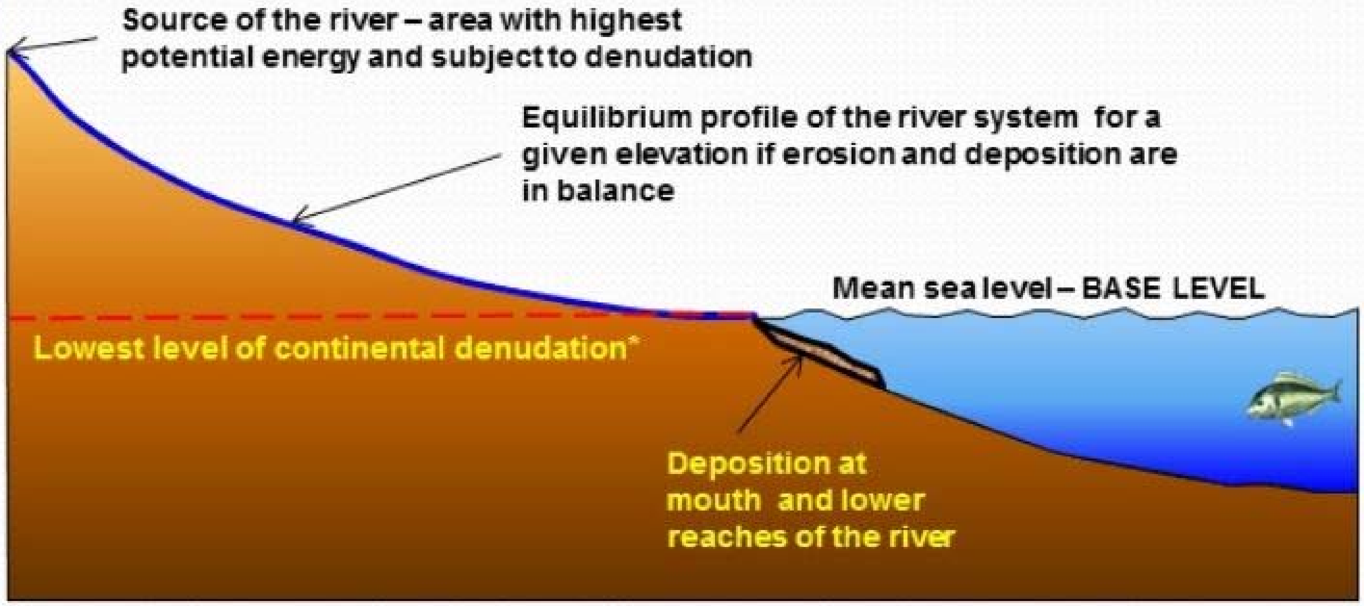
Flow discharge (subaerial or subaqueous) is equal to flow velocity times cross-sectional area.

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.

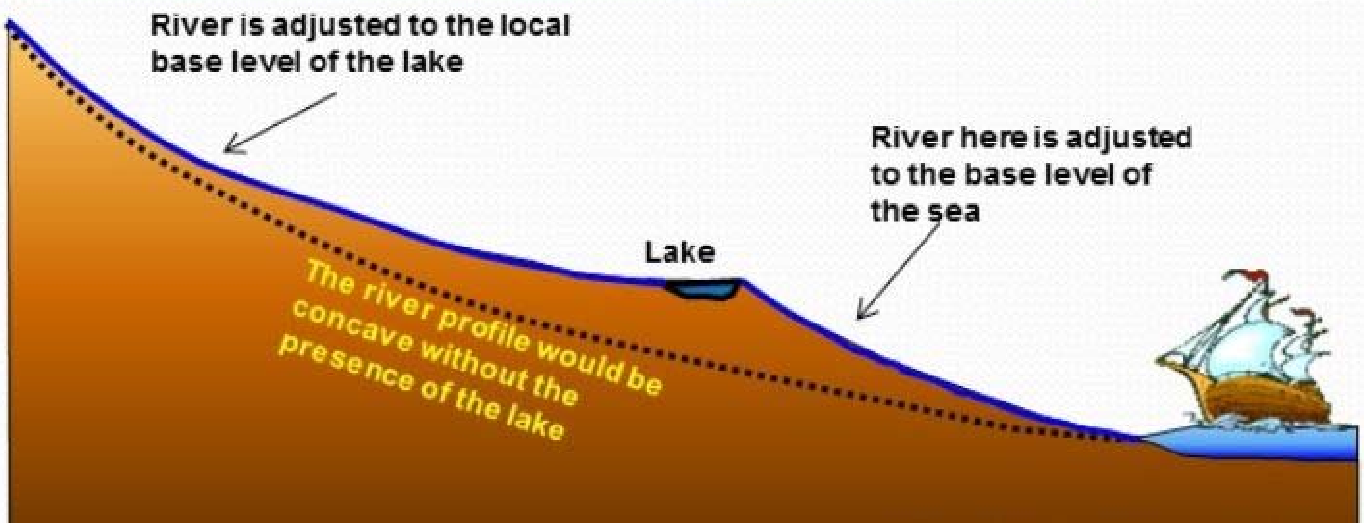
Fig. 1 *Key "**first principles**" of **Sedimentary Geology** that are relevant to **Sequence Stratigraphy**.*

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 the integration of a plethora of various datasets 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 techniques** in the **1970s**. The understanding 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 concepts**, and are **highly significant on both academic and economic grounds**.

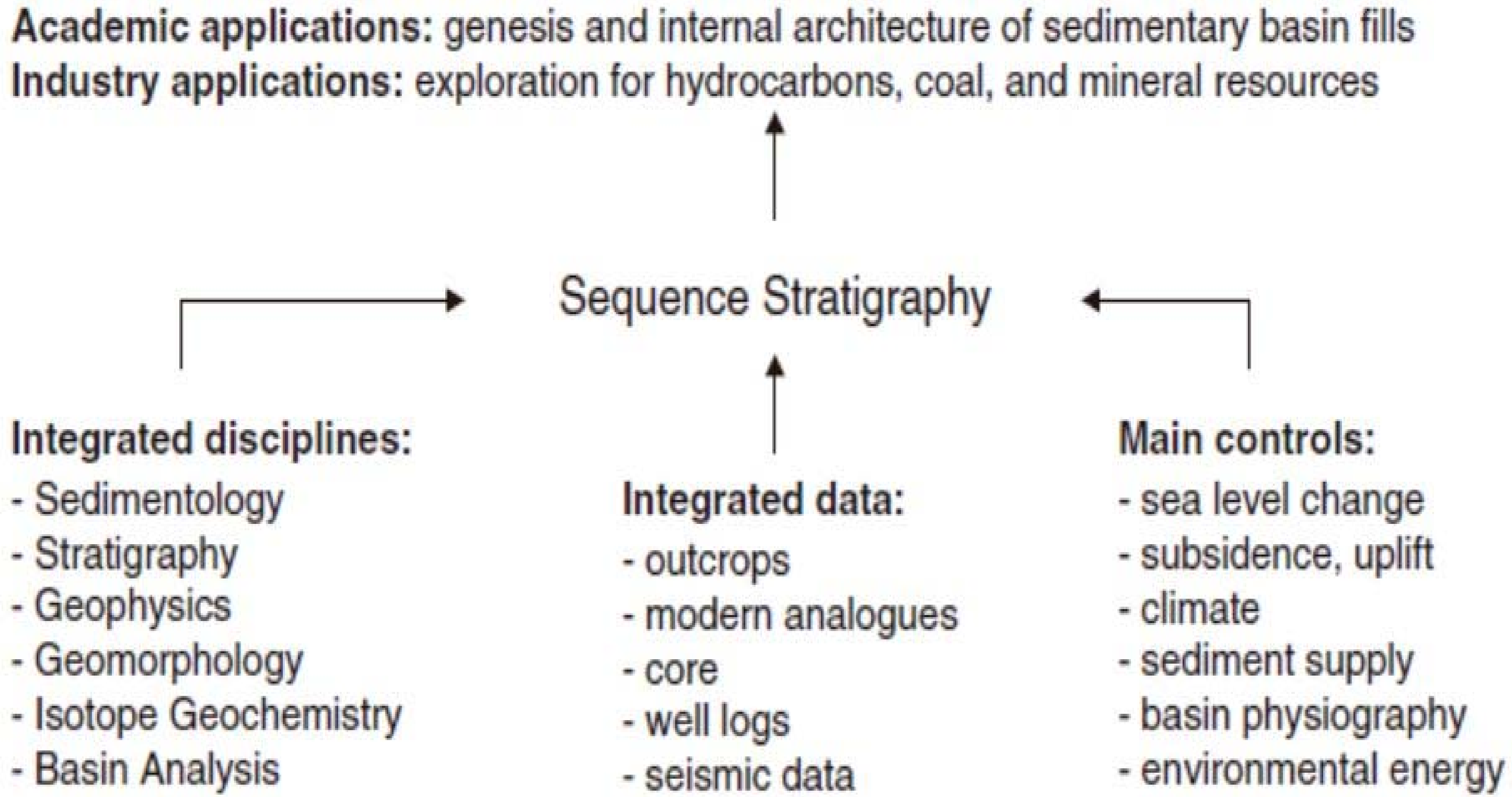
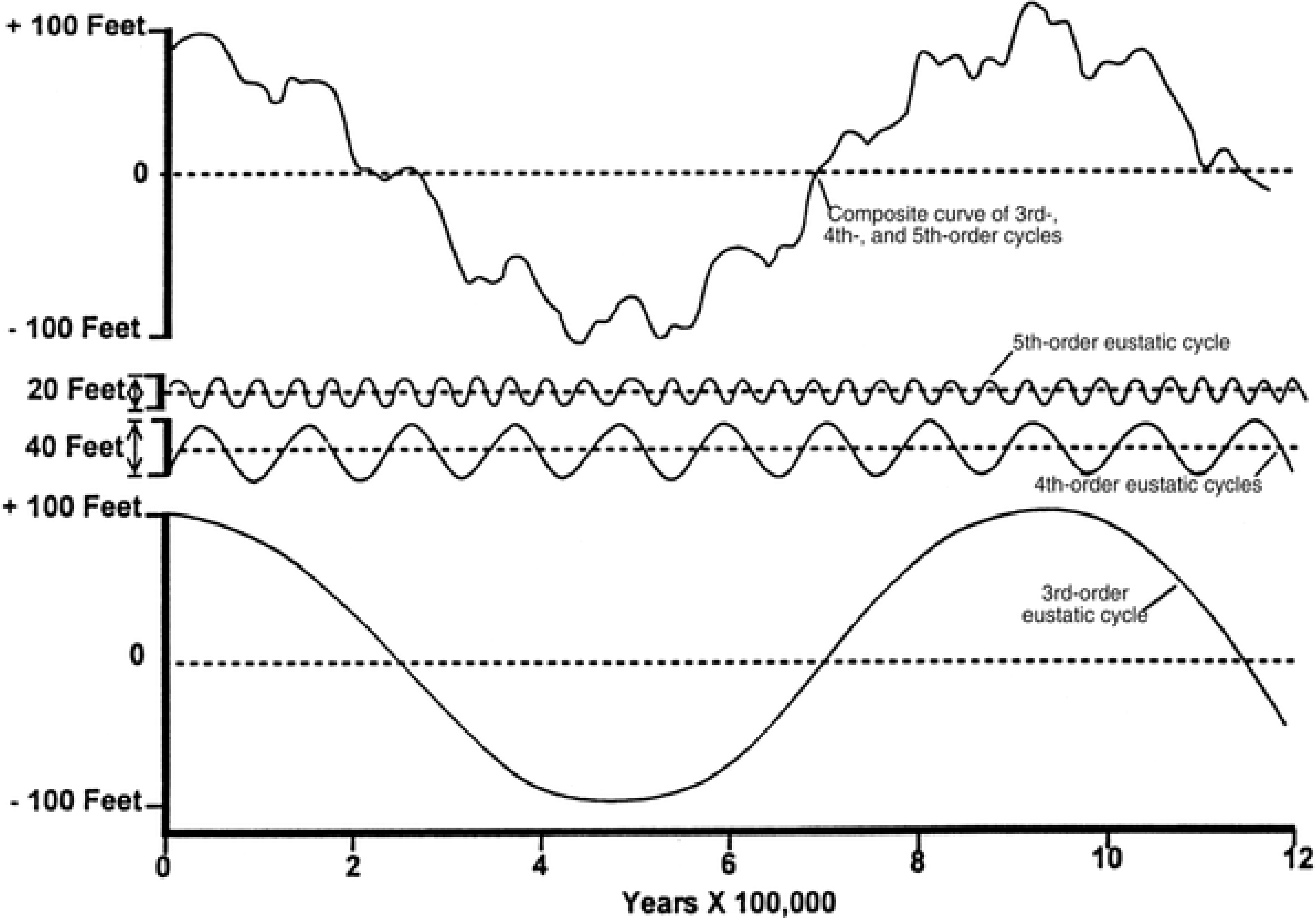


Fig. 3 ***Sequence Stratigraphy in the context of interdisciplinary research.***

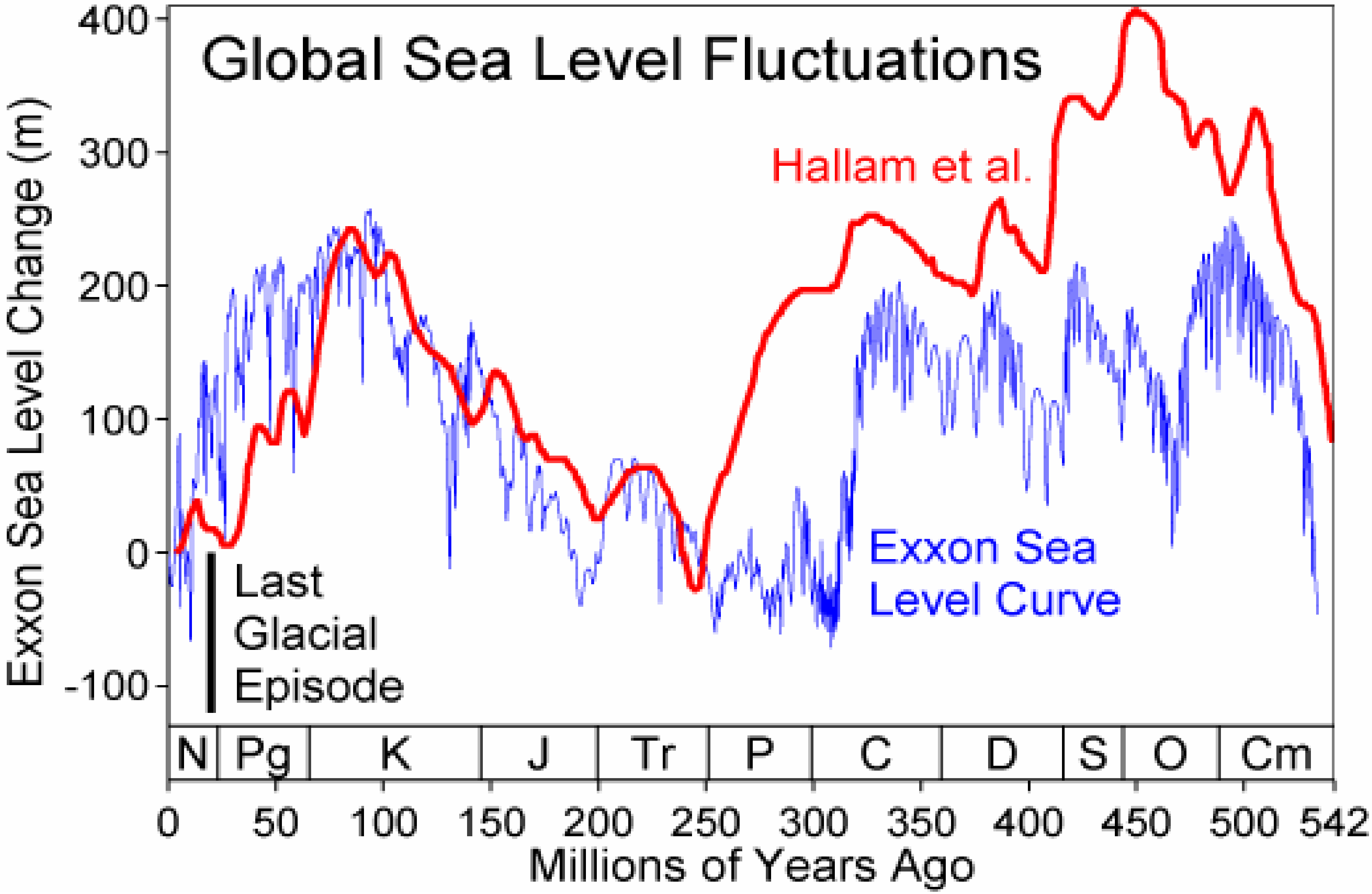
1.2 Deductive Approach of Sequence Stratigraphy

The **deductive approach** was primarily based 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**, concerning marine basins.

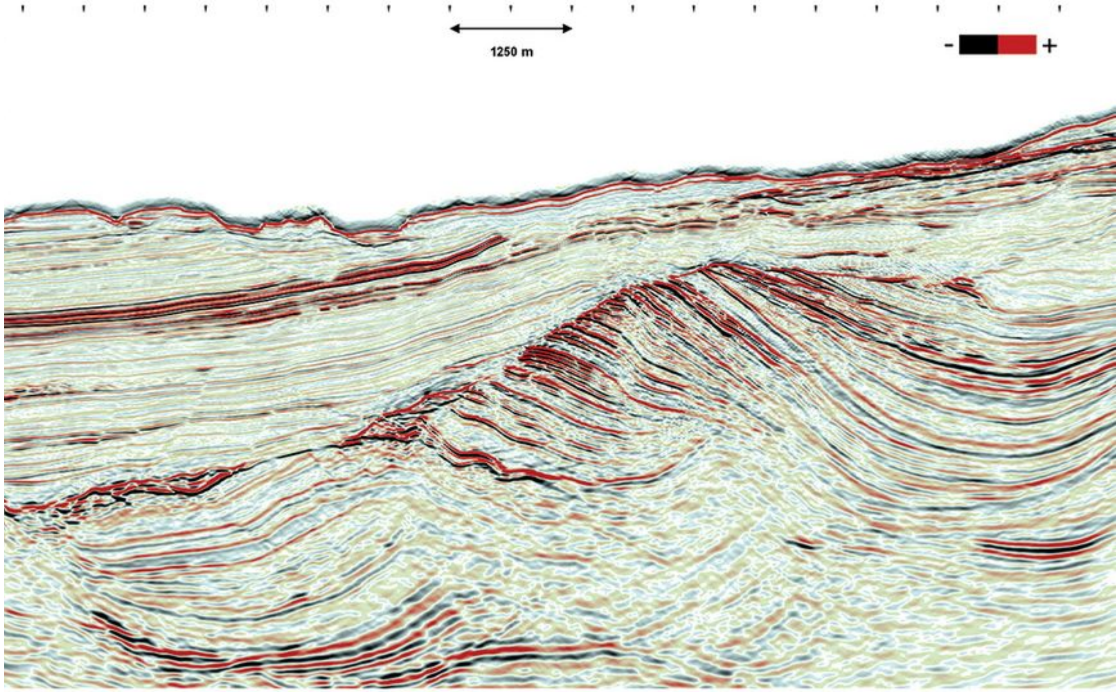
The model used a “**sinusoidal**” **sea level rise and fall** (see images below), **associated subsidence that increased basinward and a constant sediment supply as input parameters**. Particularly, **it predicted the occurrence of basin unconformities and downlap surfaces** in the central regimes of a sedimentary basin, which are major surfaces that can be identified from **seismic-reflection profiling** (see images below).



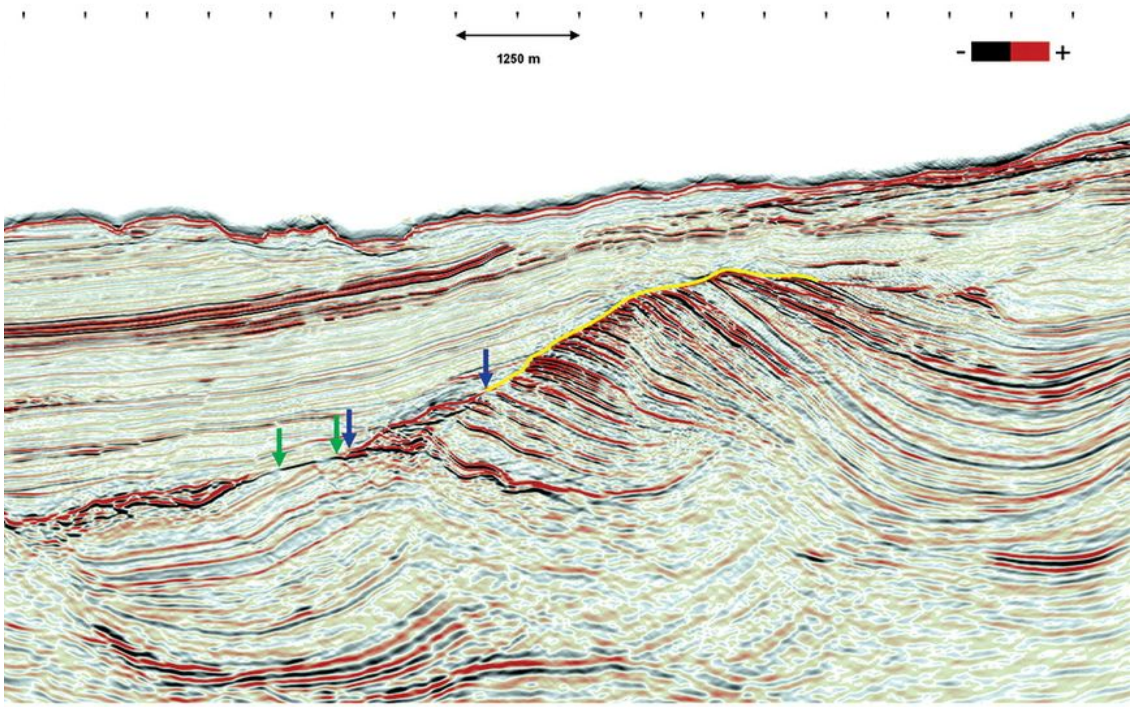
***Composite curve** created by adding **third-, fourth- and fifth-order cycles** together.*

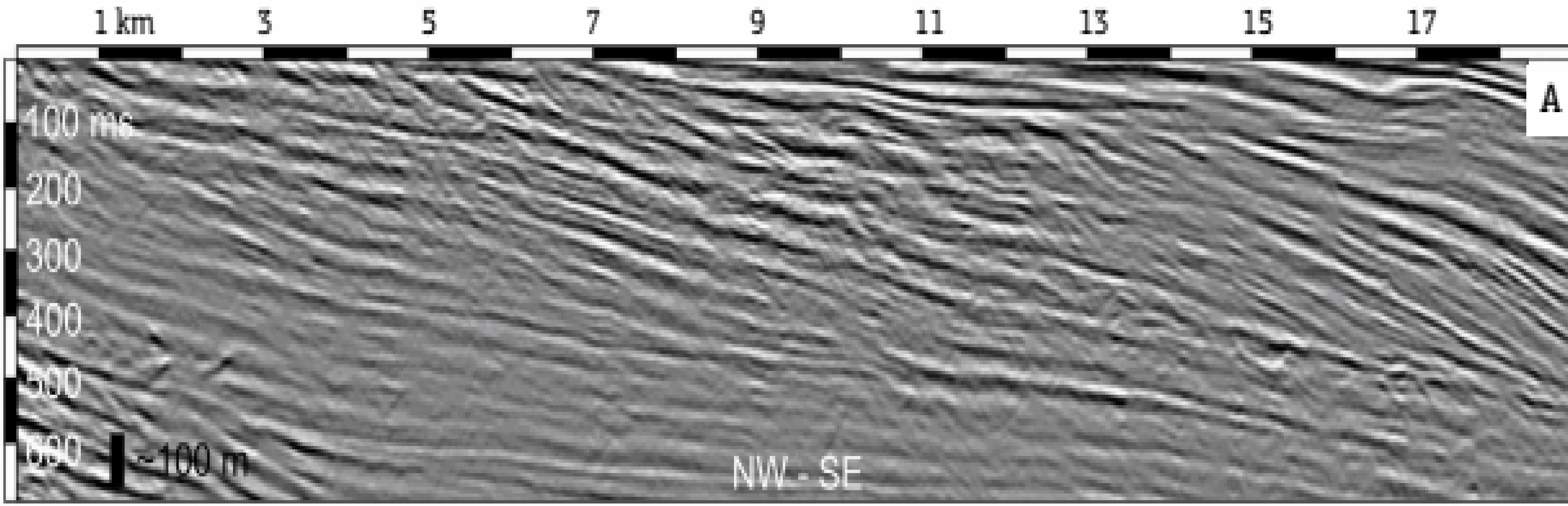


Sea level reconstructions during the last ***500 million years*** *(the scale of change during the* ***last major greenhouse/icehouse transition*** *is indicated with a* ***black bar****).*

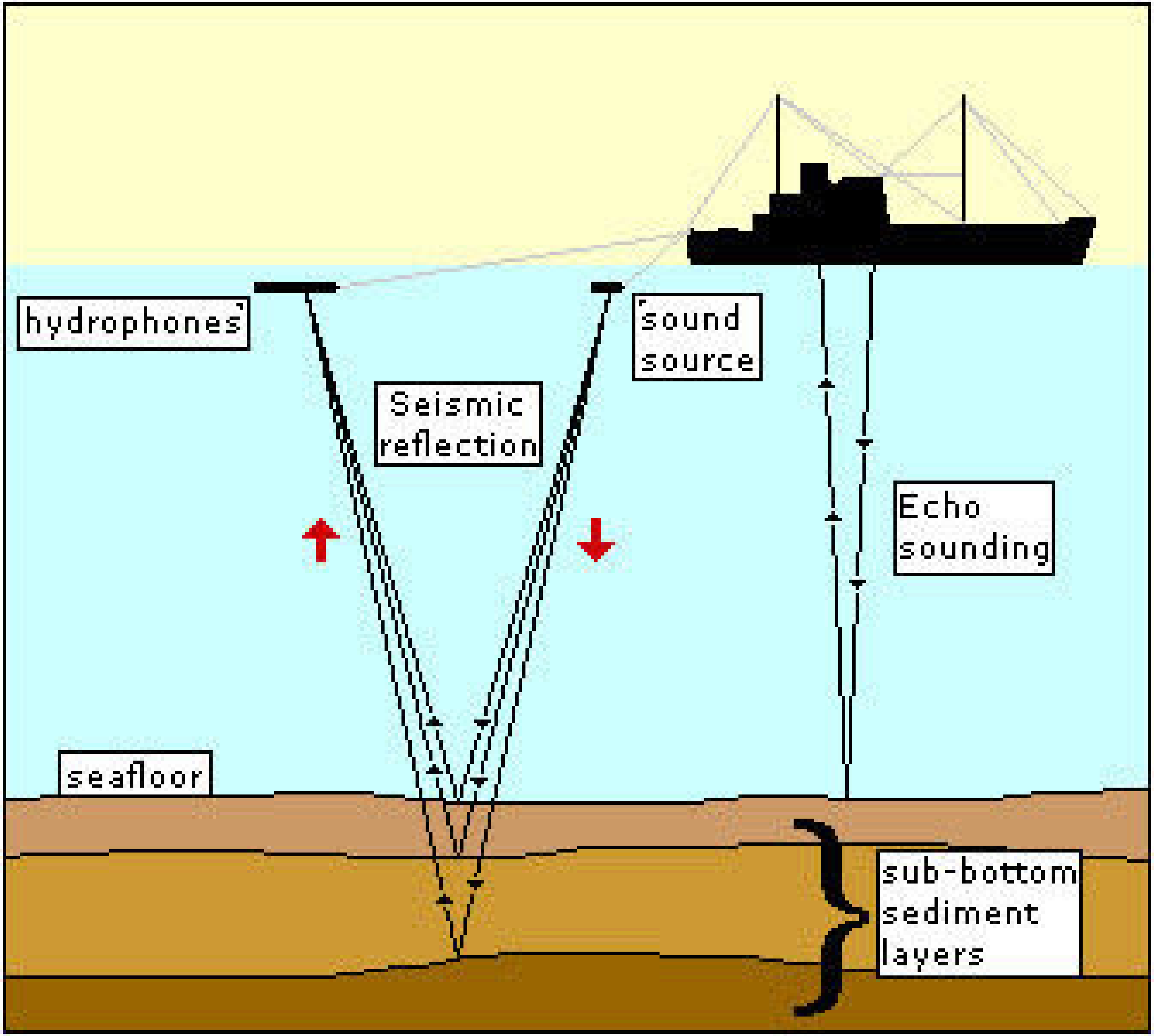


Example of ***angular unconformity***.





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 **stratigraphic surfaces** (see relevant images below):

(**1**) **Basal Surface of Forced Regression** (**BSFR**).

(**2**) **Regressive Surface of Marine Erosion (RSME)**.

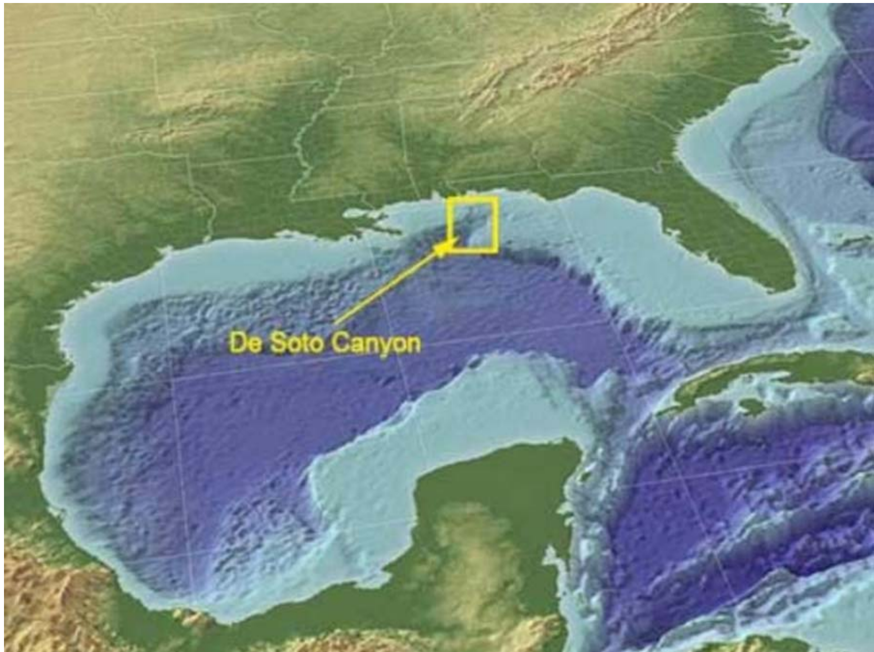
(**3**) **Subaerial Unconformity** (**SU**).

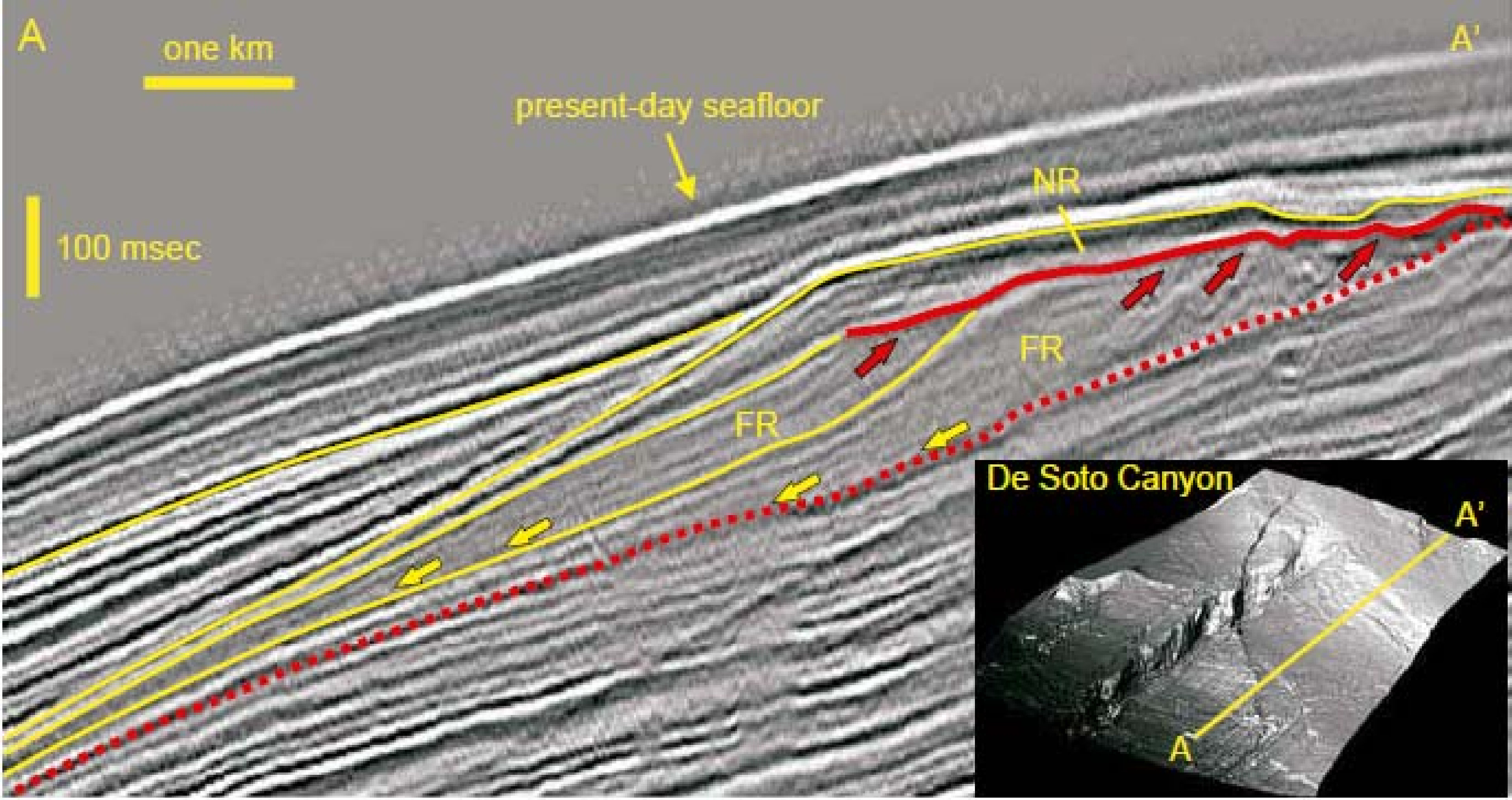
(**4**) **Correlative Conformity** (**CC**).

(**5**) **Maximum Regressive Surface** (**MRS**).

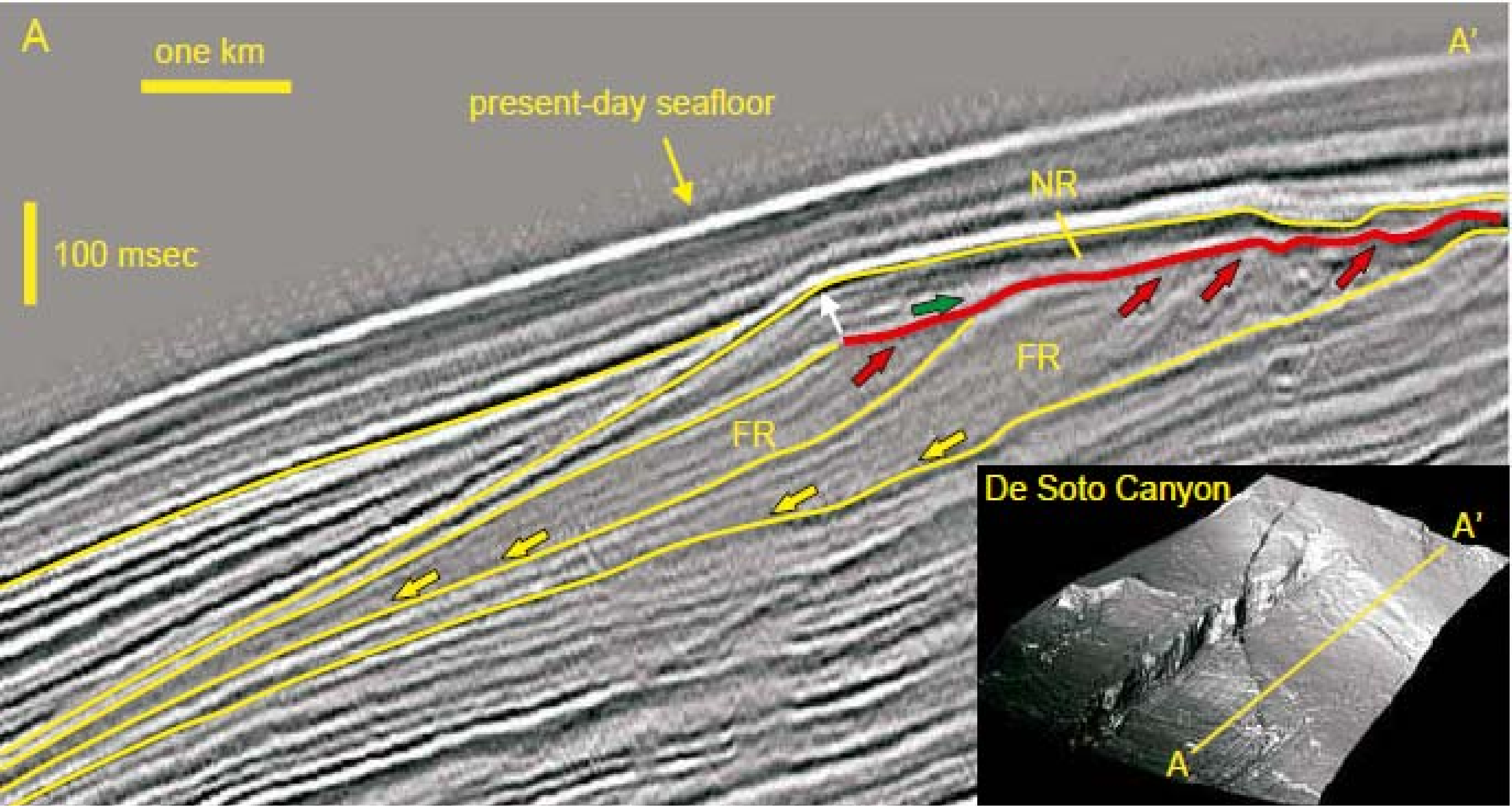
(**6**) **Shoreline Ravinement (SR)**.

(**7**) **Maximum Flooding Surface** (**MFS**).

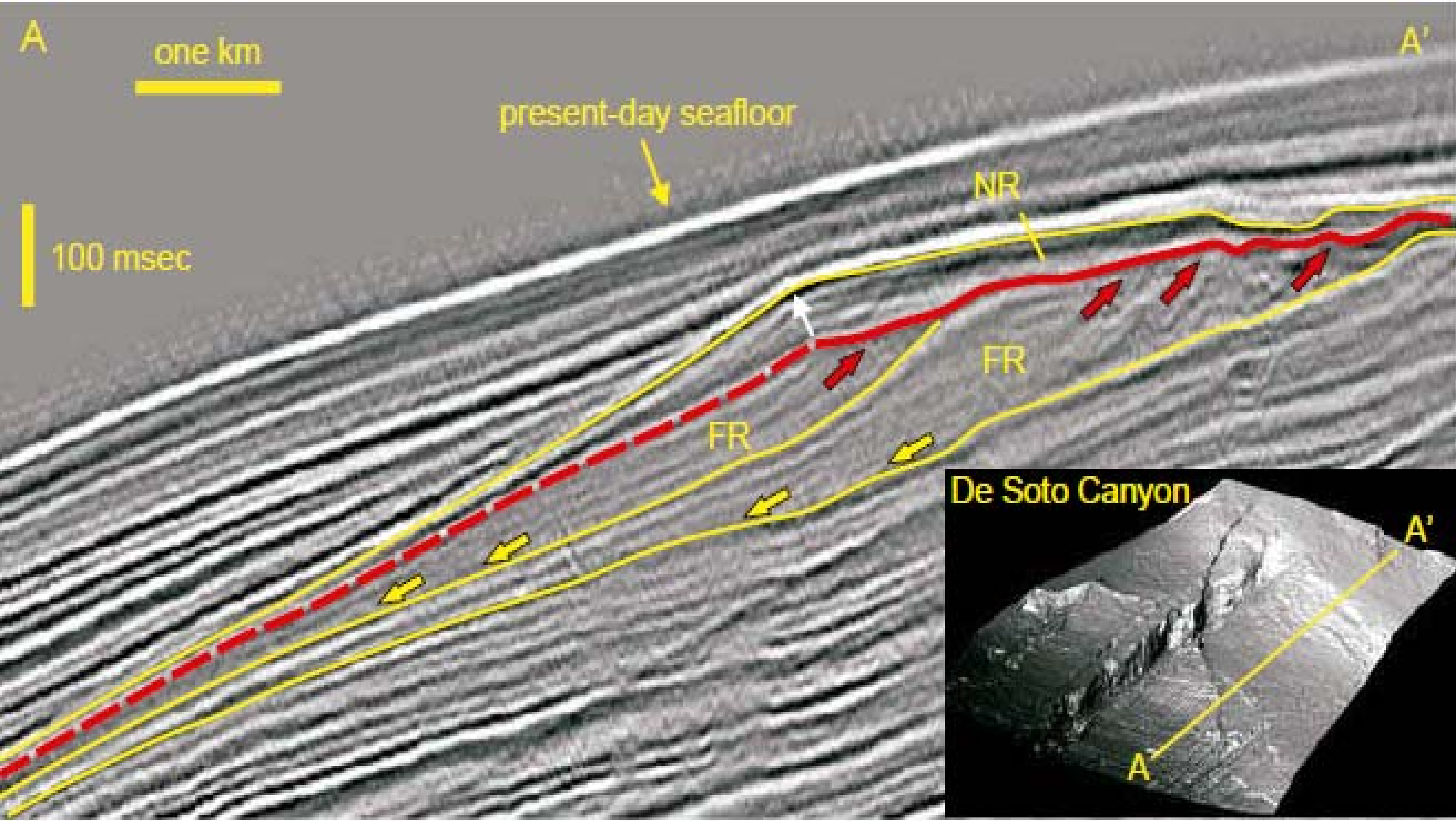




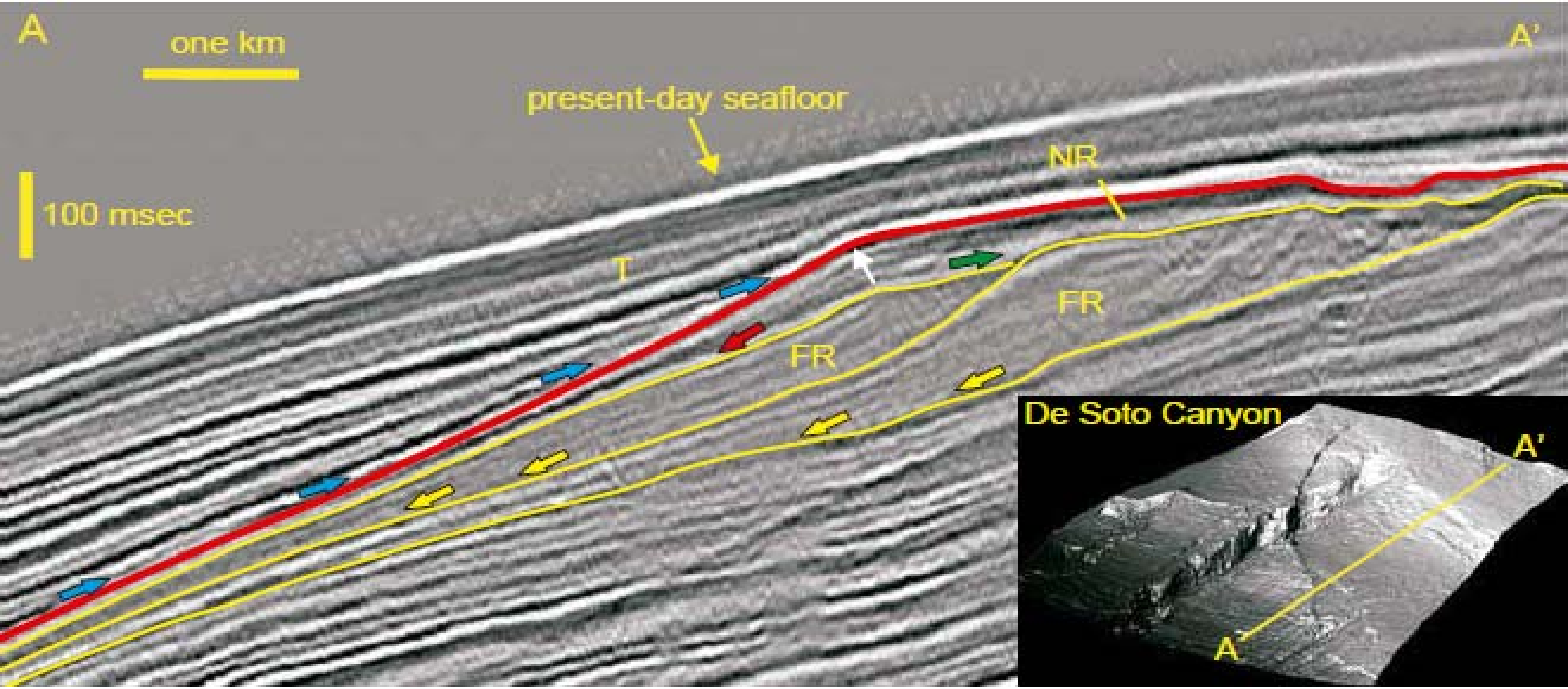
Basal Surface of Forced Regression (red dotted line) *on a dip-oriented 2D seismic transect. The* ***solid red line*** *shows the basinward portion of the* ***Subaerial Unconformity*** *that formed during* ***Forced Regression****. The* ***Basal Surface of Forced Regression*** *corresponds to the seafloor at the* ***onset of Forced Regression****. The* ***red arrows*** *indicate truncation (****offlap****) of the* ***shallow-marine forced regressive strata*** *(****FR****) by the* ***Subaerial Unconformity****. The* ***deep-water forced regressive deposits downlap the Basal Surface of Forced Regression*** *(see* ***yellow arrows****).*



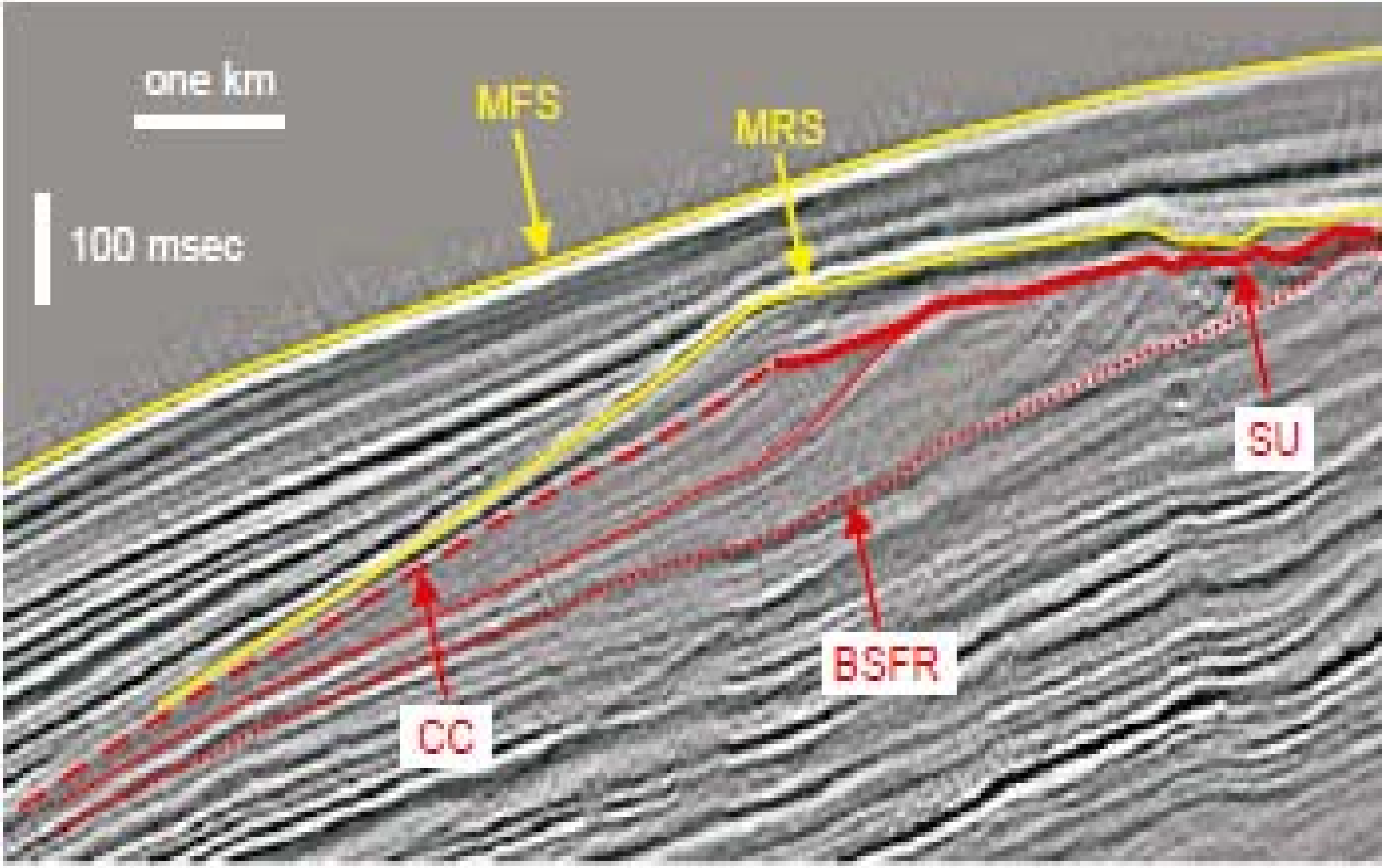
Subaerial Unconformity *(**red line**) on a dip-oriented, 2D seismic transect. The **thinner yellow lines** provide a sense of the overall **stratal stacking patterns**. The **Subaerial Unconformity** is associated with **offlap**, **decrease in elevation in a basinward direction and irregular topographic relief**. The basinward termination of the **Subaerial Unconformity** indicates the **shoreline position at the end of Forced Regression**.*



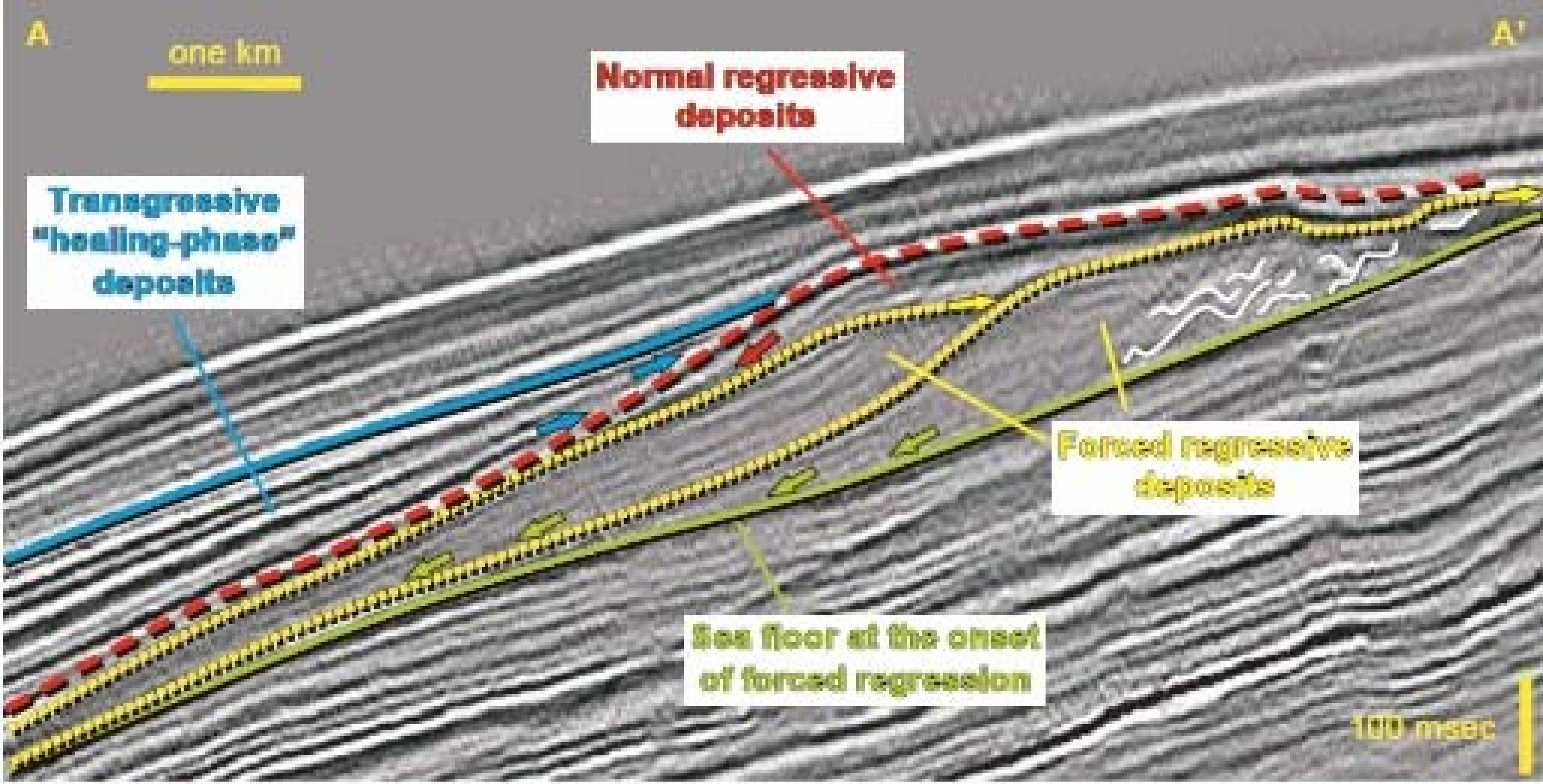
***Correlative Conformity** (**red dashed line**) on a dip-oriented, 2D seismic transect. The **solid red line** shows the **Subaerial Unconformity**, whose basinward termination meets the **Correlative Conformity** at the point that corresponds to the position of the **shoreline at the end of Forced Regression**.*



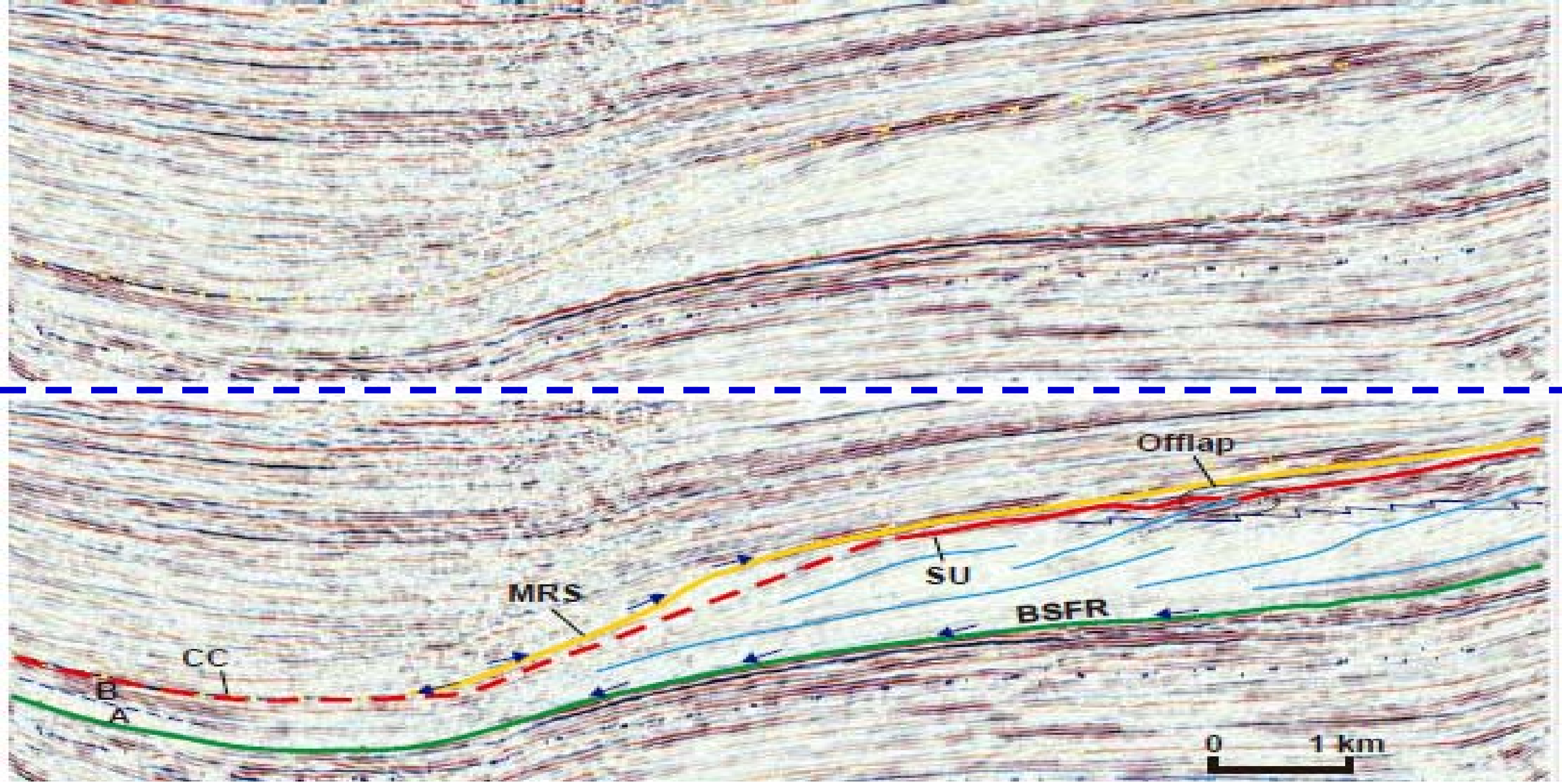
Maximum Regressive Surface *(**red line**) on a dip-oriented, 2D seismic transect. This surface tops all **fluvial to deep-marine strata** that accumulate during the **lowstand Normal Regression** (**NR**). The **Maximum Regressive Surface** may onlap the **Subaerial Unconformity** in a landward direction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



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

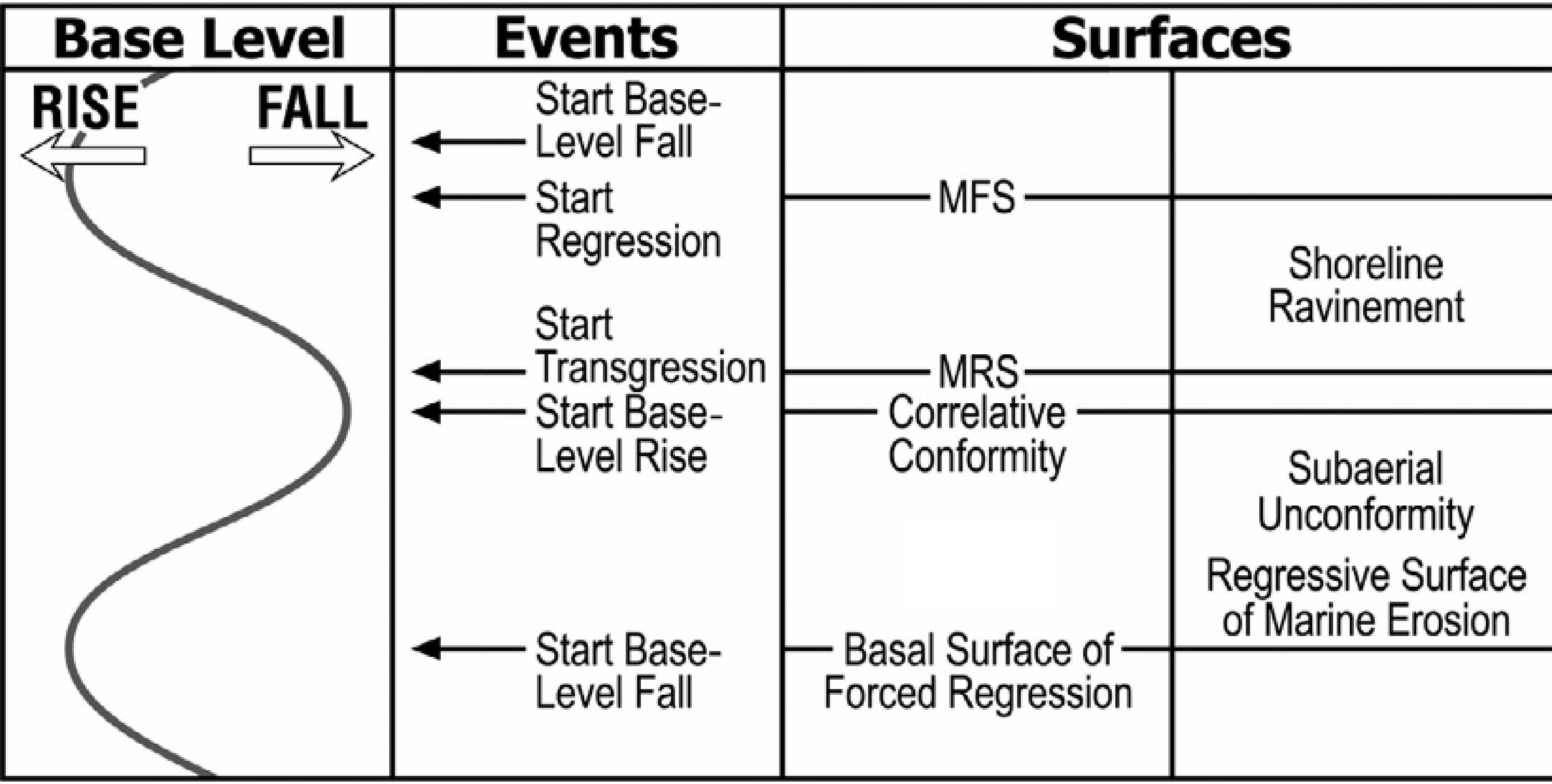


***Shelf-edge and healing-phase deposits** in the **De Soto Canyon** of the **Gulf of Mexico**. The **white wavy lines** indicate possible **slumping** during the **Forced Regression**. The **three genetic types of strata**, i.e., **forced regressive**, **normal regressive and transgressive**, **form the conceptual core of Sequence Stratigraphy as they configure the formation and timing of all systems tracts**.*



Uninterpreted *and* ***interpreted*** *seismic profile showing the contrast in facies between* ***mud deposits*** *(****facies A - early forced regressive****) and* ***turbidites*** *(****facies B - late forced regressive****) in a* ***deep-water setting****. The* ***top of the coarser-grained facies of the submarine fan*** *is marked by the extension within the basin of 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****.*

In conclusion, the **sequence stratigraphic surfaces used in the deductive approach** are defined relative to **four main events of the sea** (**base**) **level cycle**, as shown 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 a highly diachronous horizon known as the **regressive surface of marine erosion**.

1.2.3 Systems Tracts With the Greatest Hydrocarbon Trapping Potential

Data concerning the setting of more than 2000 major conventional oil and gas fields in 200 transgressive and regressive depositional systems within 80 marine sedimentary basins show that most siliciclastic hydrocarbon reservoirs occur in the base to middle of the wedge-shaped deposits of the lowstand systems tract (LST), or in the deposits of the transgressive systems tract (TST), where the terrestrial sediment inputs into the basin are optimum (not excessive) and occur together with high marine organic content.

The best reservoirs with hydrocarbon potential in the HST tend to be associated with the shoreline to shoreface deposits, which accumulate the largest amounts of sand, with the highest sand/mud ratio. These reservoirs usually range from meters to tens of meters in thickness 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**, **chemical 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**.

Hence, 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 (sea) level shifts**.

1.3.1 Concepts of Depositional Systems, Facies and Facies Models

A depositional system is the product of a sedimentation process or the product of various interacting processes 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**, with the latter representing an **essential concept for the 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**, with the relevant terminology shown 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 (Figs 5, 6): (**i**) **non-marine** (**beyond the reach of marine flooding**); (**ii**) **coastal or transitional** (**intermittently flooded by marine water**); and (**iii**) **marine** (**permanently covered by marine water**).

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 aforementioned classification scheme 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, i.e.,* ***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 the physical processes in areas of sediment accumulation****. The boundaries between the various coastal and shallow-marine environments are defined in Figs 6, 7.*

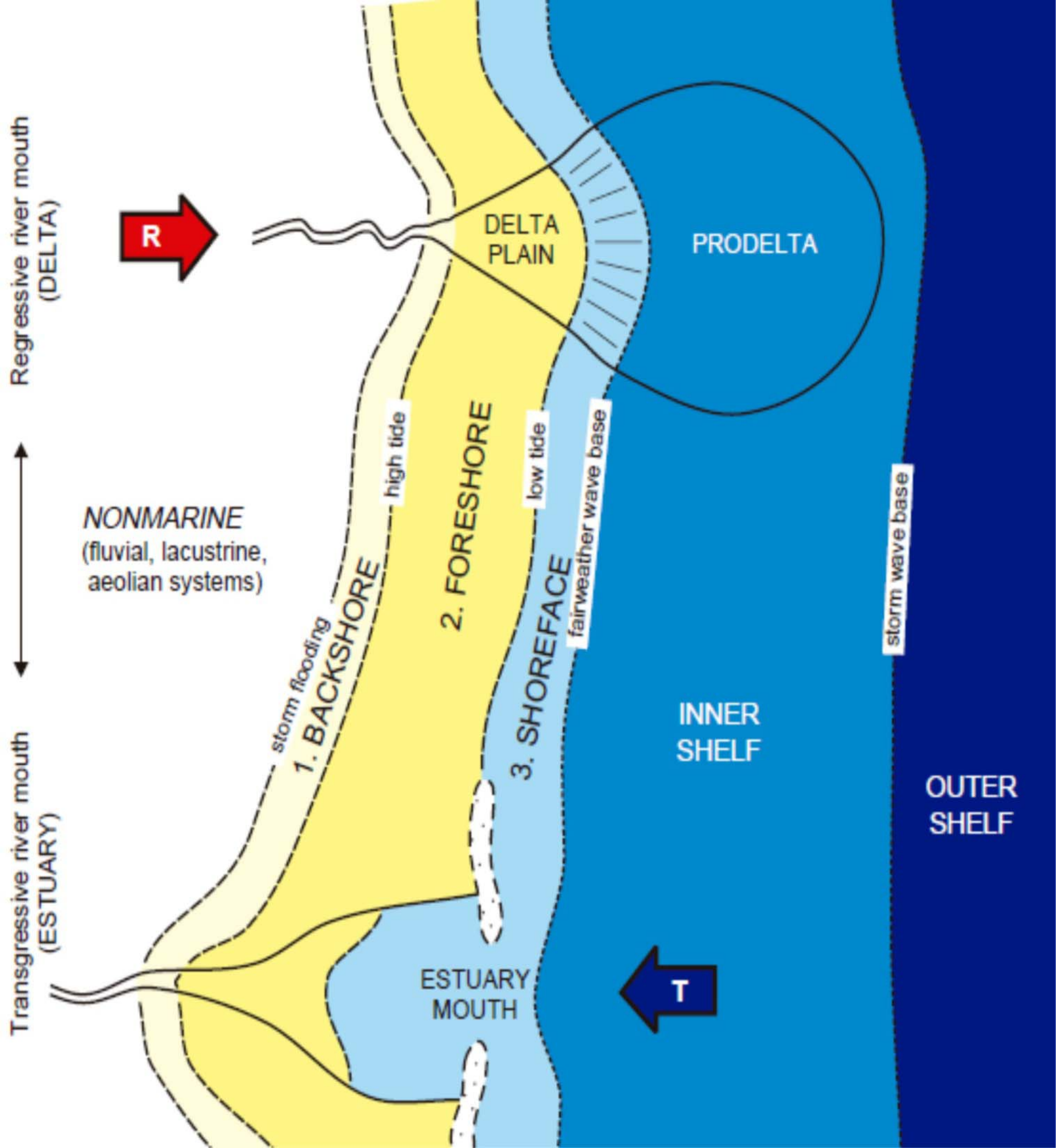


Fig. 6 *Transition from* ***marine*** *to* ***non-marine environments****. The large arrows indicate the direction of shoreline shift in the two river-mouth environments (****R****-regressive;* ***T****-transgressive). Between the river-mouth environments, the coastline is an open shoreline.* ***The 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**.

Many times the **coastal plain** is formed 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**" (Fig. 7), 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 upstream**. The landward limit of the coastal prism is termed "**bayline**".

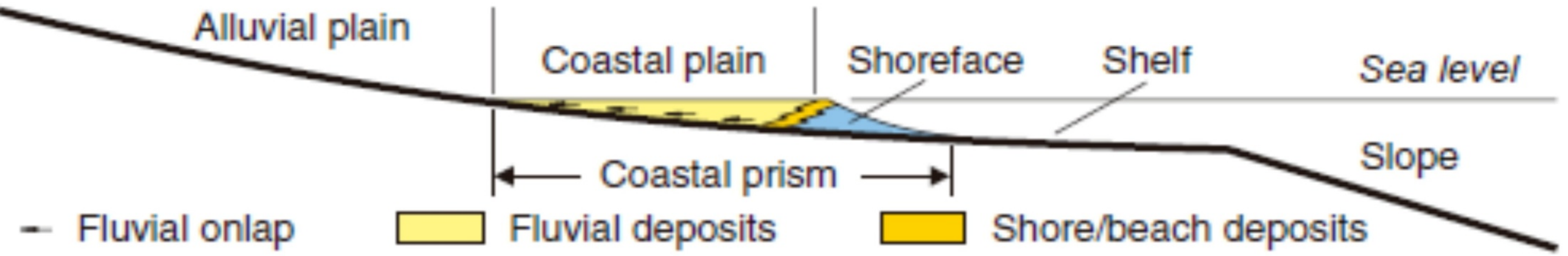


Fig. 7 ***Dip-oriented profile illustrating the main geomorphic and depositional settings of a continental shelf**: (**i**) **alluvial plain**; (**ii**) **coastal plain**; (**iii**) **coast** (including the intertidal and supratidal environments); and (**iv**) **shallow-marine** (shoreface and shelf) environments. 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 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**. 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**, when the **initial thickness of the coastal prism exceeds the amount of 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 **basin-wide model** that includes the accumulated strata 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 the 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 shoreline displacements** (Fig. 8).

Sequence model / Events	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

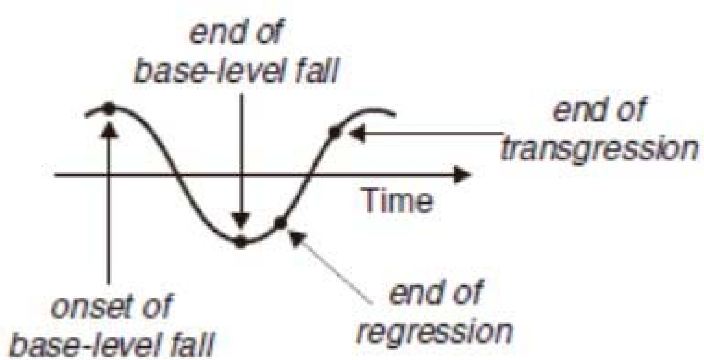


Fig. 8 ***Timing of system tracts*** *and* ***Sequence Boundaries for the Sequence Stratigraphy models currently in use****. Abbreviations:* ***LST*** *- lowstand systems tract;* ***TST*** *- transgressive systems tract;* ***HST*** *- highstand systems tract;* ***FSST*** *- falling-stage systems tract;* ***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 **false high diachronicity** that may be attributed to **systems tract boundaries**, caused by the **strike variability in subsidence** and **sedimentation rates**.
In addition, **autocyclic shifts** in the **distribution of energy and sediment** within individual **depositional environments**, which could affect all of them (see 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 The Walther’s Law

The connection between the vertical and lateral changes of facies observed in outcrops and underwater is made by the 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 in the past**.

However, **such interpretations are only valid within 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**.

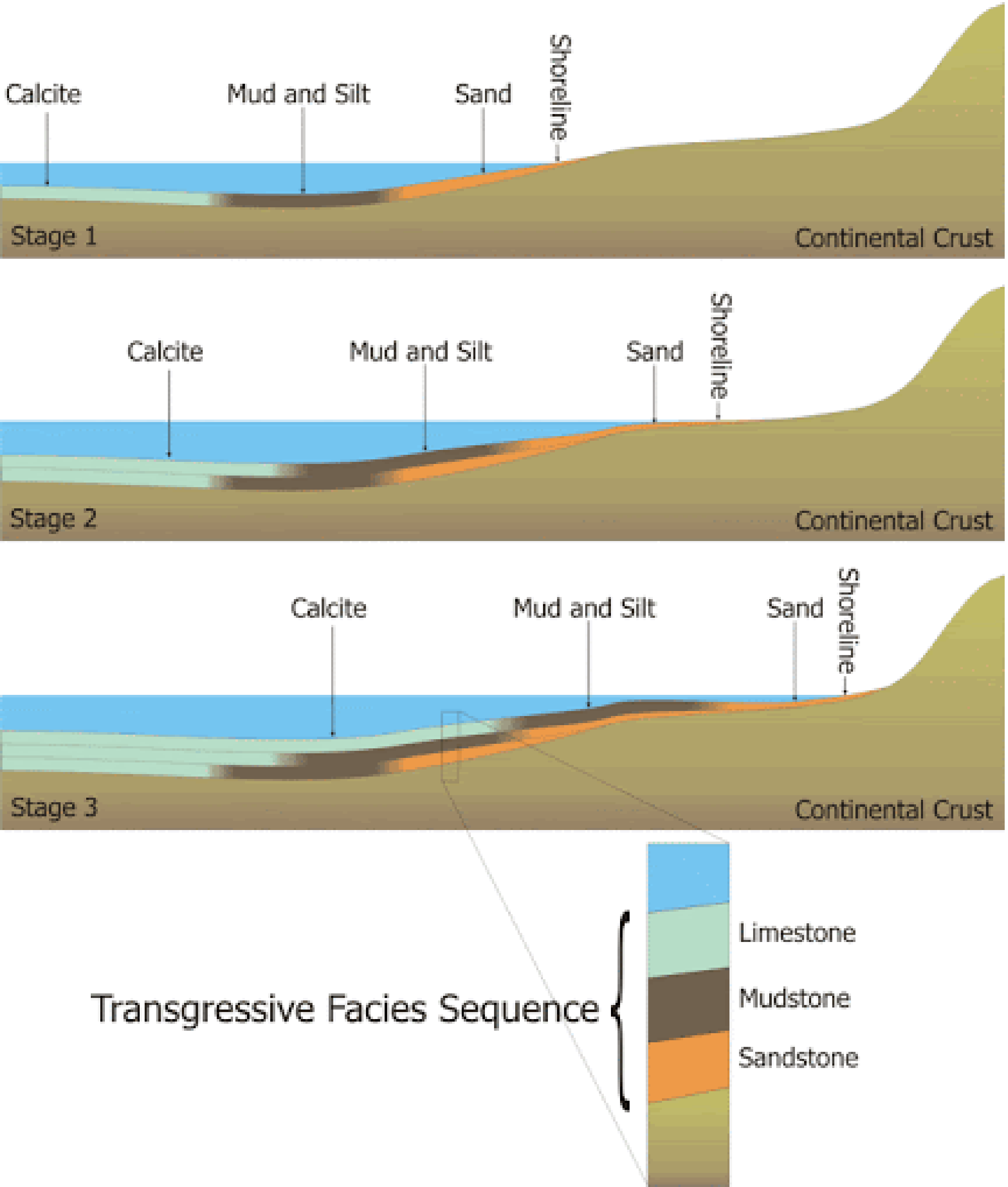


Fig. 9 *Walther's Law.*

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 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 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).

Cross-Section of a Delta

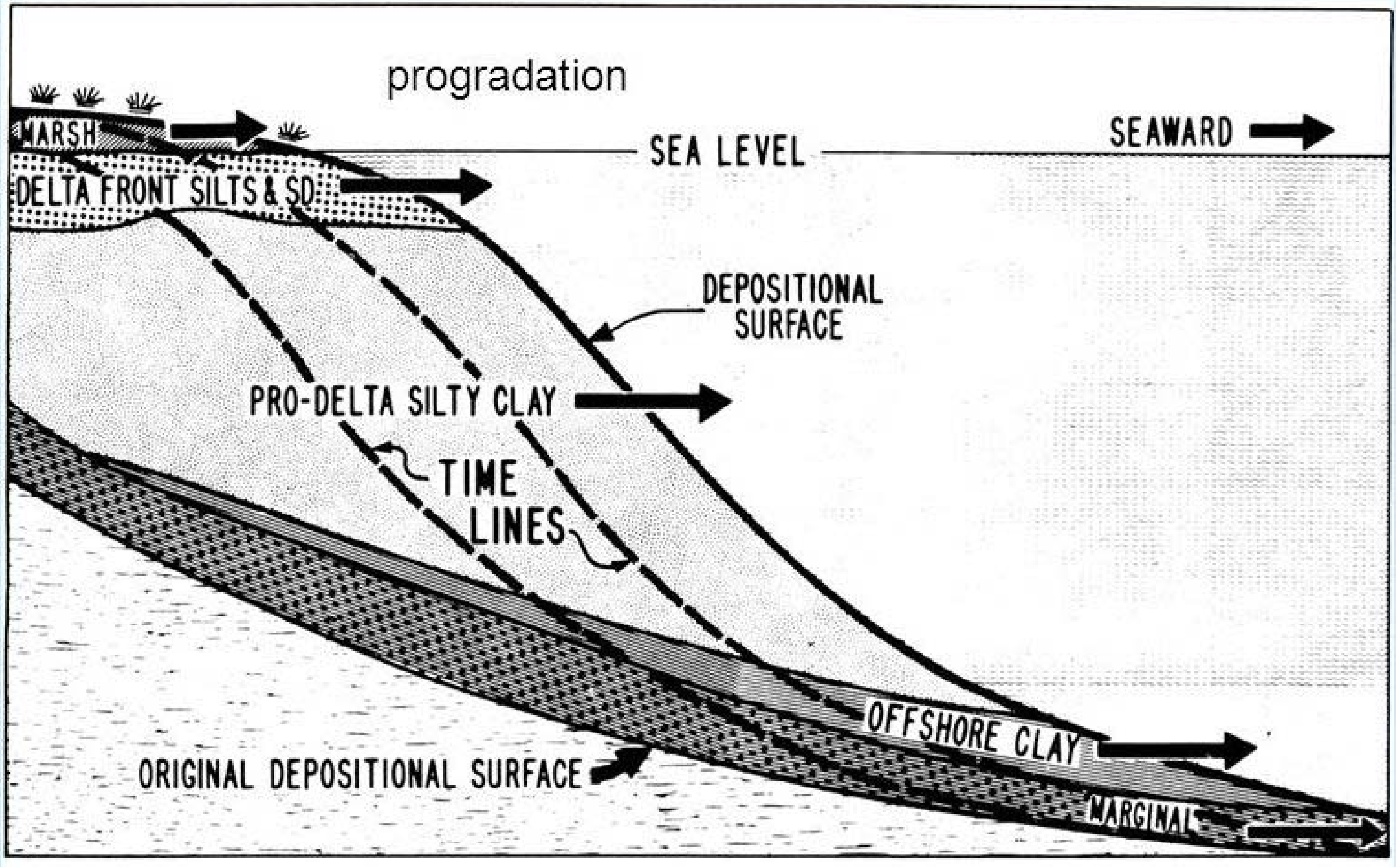


Fig. 11 ***The constructional phase of the delta cycle.***

The **statistical analysis** (e.g., **Markov Chain Analysis**) of a 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' formation in order to achieve **broad paleoenvironmental and paleogeographic reconstructions**.

This technique has now become a **crucial part of Sequence Stratigraphy**, when sedimentary strata, which record local or regional changes in the base level, are **conformable** (**hiatuses** and **diastems** are absent).

Hence, **beyond the scale of a depositional system** (e.g., **delta plain sedimentation**), the **Walther's Law** is equally valuable when applied **within 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 sections**.

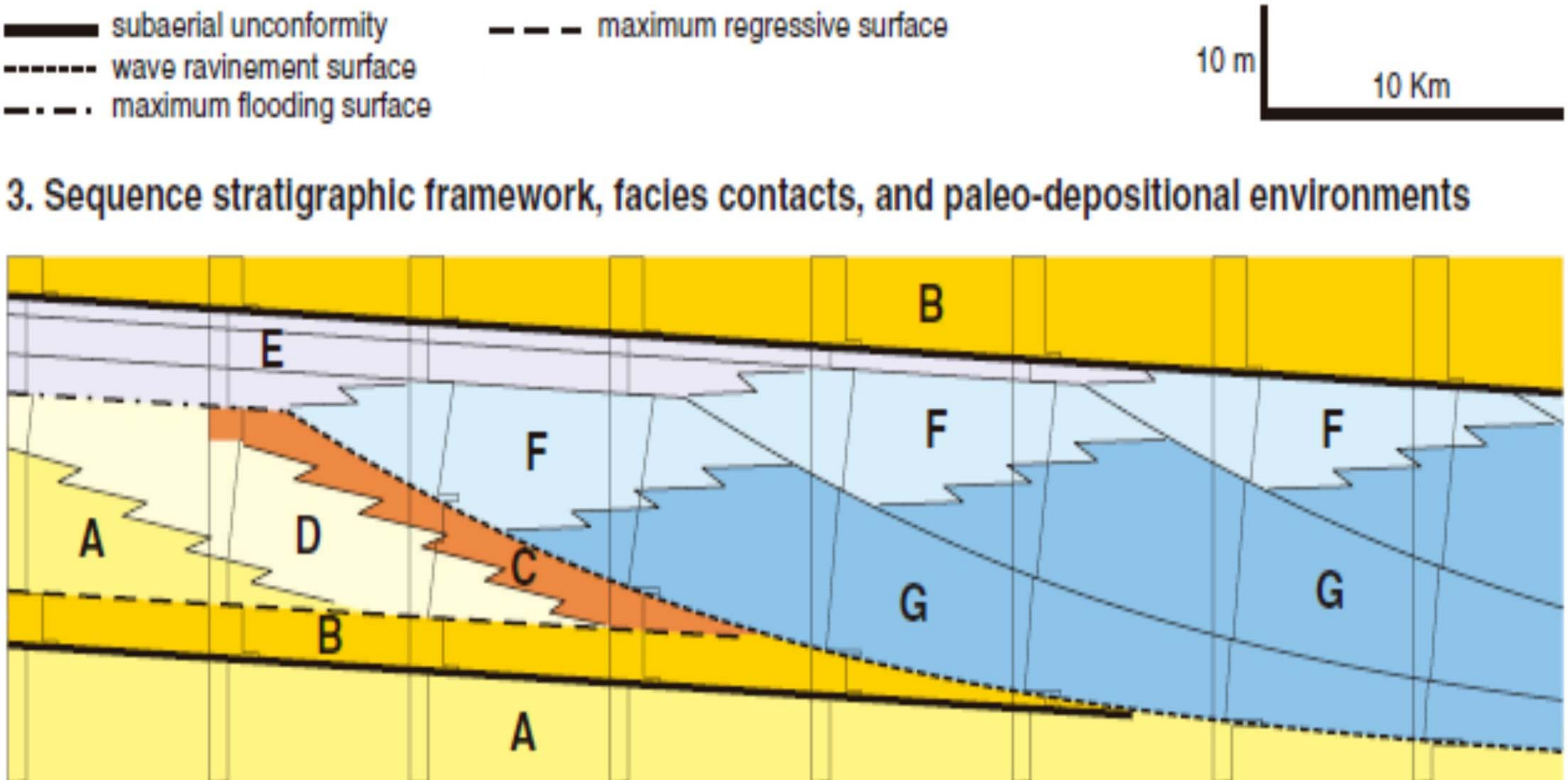


Fig. 12 *Sequence stratigraphic cross section,* ***showing key surfaces****,* ***facies contacts*** *and* ***paleodepositional environments****. Facies codes:* ***A*** *- meandering system;* ***B*** *- braided system;* ***C*** *- estuary-mouth complex;* ***D*** *- central estuary;* ***E*** *- delta plain;* ***F*** *- delta front;* ***G*** *- prodelta.*

1.3.4 Sedimentary Petrography

The observation of sedimentary facies in **outcrops** or **sediment cores** is often enough to identify 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**.

However, there are cases, especially in adjacent successions composed of **coarse braided fluvial deposits**, where "**cryptic**" **subaerial unconformities are difficult to be distinguished 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 across these **Sequence Boundaries**, the **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 the **changes in the facies provenance** based on the **composition of framework grains** detected via petrographic analysis, **subaerial unconformities** may also be identified by the **presence of secondary minerals that replace some of an original sedimentary rock** (e.g., sandstone) **constituents via processes of weathering under subaerial conditions**.

For example, it has been documented that **subaerial exposure of a deposit**, **given the availability of sufficient amounts of K**, **Al** and **Fe** that may be derived from the **weathering of clays** and **K-feldspars**, may lead to the **replacement of cements by secondary glauconite**. **Glauconite-bearing sandstones** may, therefore, be used to identify **Sequence-Bounding unconformities**, when 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**, which can be resolved via petrographic analysis.

Also, the vertical quantitative distribution pattern of **early diagenetic clay minerals**, such as **kaolinite**, **smectite**, **palygorskite**, **glauconite and berthierine**, may indicate the **base level stand** and the subsequent position of a **cryptic subaerial unconformity**.

In general, **changes in the base level and sediment supply/sedimentation rates**, together with the **climatic conditions** prevaling 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).

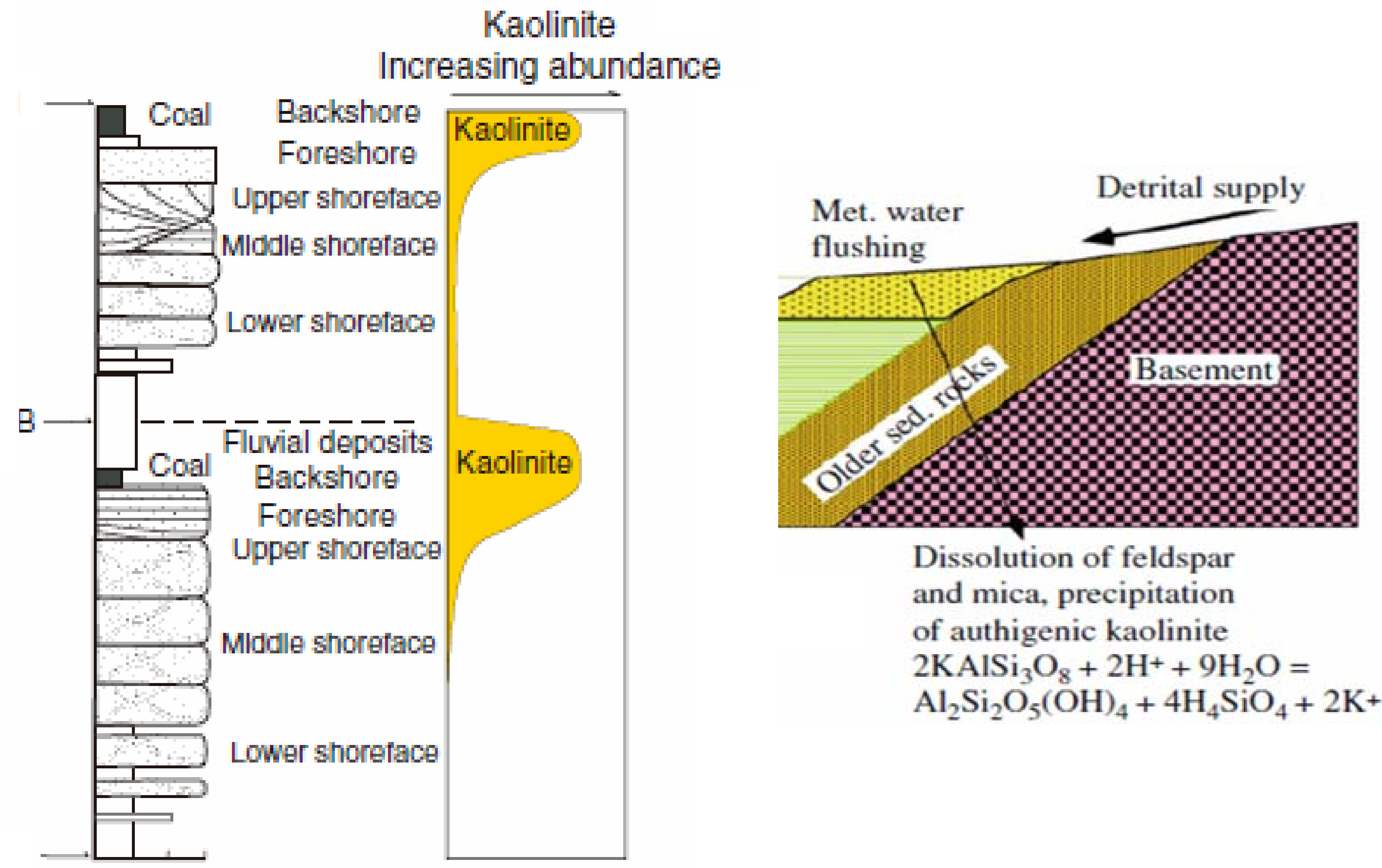


Fig. 14 ***Kaolinite content increases toward the top of the sequences, where continental facies are exposed to extensive meteoric water flushing*** *under semi-humid to humid climatic conditions. B: Sequense Boundary.*

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 differentiate progradational** from **retrogradational** trends in **marine successions**, or **to outline fluvial depositional sequences in non-marine deposits**.

For example, **fluvial sequences** often show overall **fining-upward trends** that reflect **aggradation in an energy-declining environment**. Hence, **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**.

1.3.5 Paleocurrent Directions

Major breaks in the stratigraphic record are potentially associated with **stages of tectonic reorganization of sedimentary basins** and, thus, with changes in the **strike** (**direction**) **across Sequence Boundaries**.

This is often the case in tectonically active basins, such as **grabens**, **rifts**, **or foreland basins**, where **stratigraphic cyclicity** is commonly controlled by cycles of **subsidence and uplift**, triggered by **tectonic activity** and **flexural and isostatic mechanisms in the lithosphere**.

Overfilled foreland basins represent a classic example of a depositional environment, **where fluvial sequences and their Bounding Unconformities form in isolation from eustatic influences**, with a timing **controlled by orogenic cycles of tectonic loading and unloading**. In such **foreland** (foredeep) **basins**, fluvial aggradation takes place during stages of differential **flexural subsidence**, with higher rates towards the center of the basin, while **Bounding Unconformities form during stages of differential isostatic rebound**, and a **renewed orogenic belt formation 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 **strike direction are usually recorded across Sequence Boundaries**. Such changes in the **strike variability** may be used to **outline fluvial sequences with distinct drainage patterns** and to **map their Bounding Unconformities** (Fig. 15).

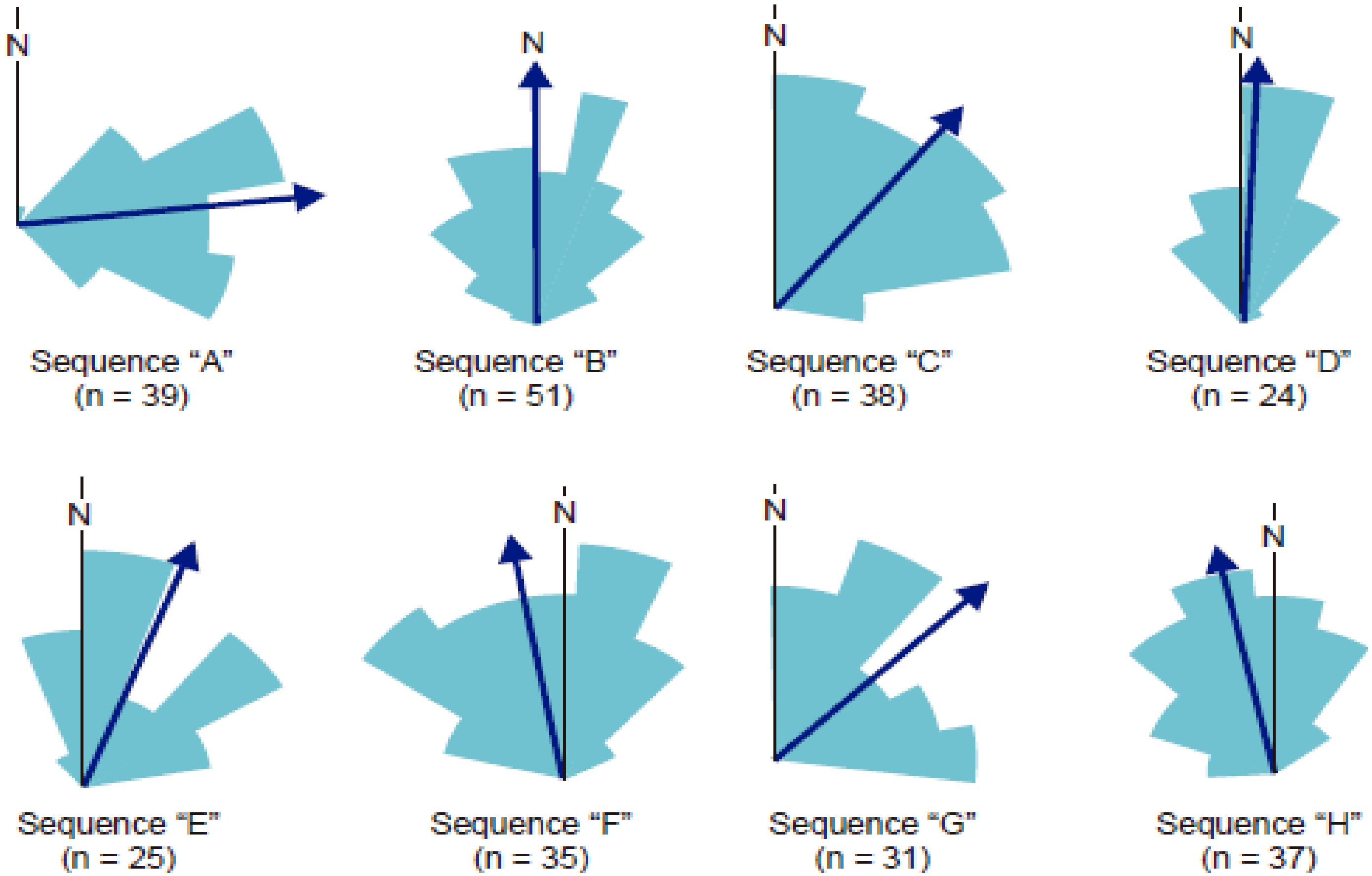
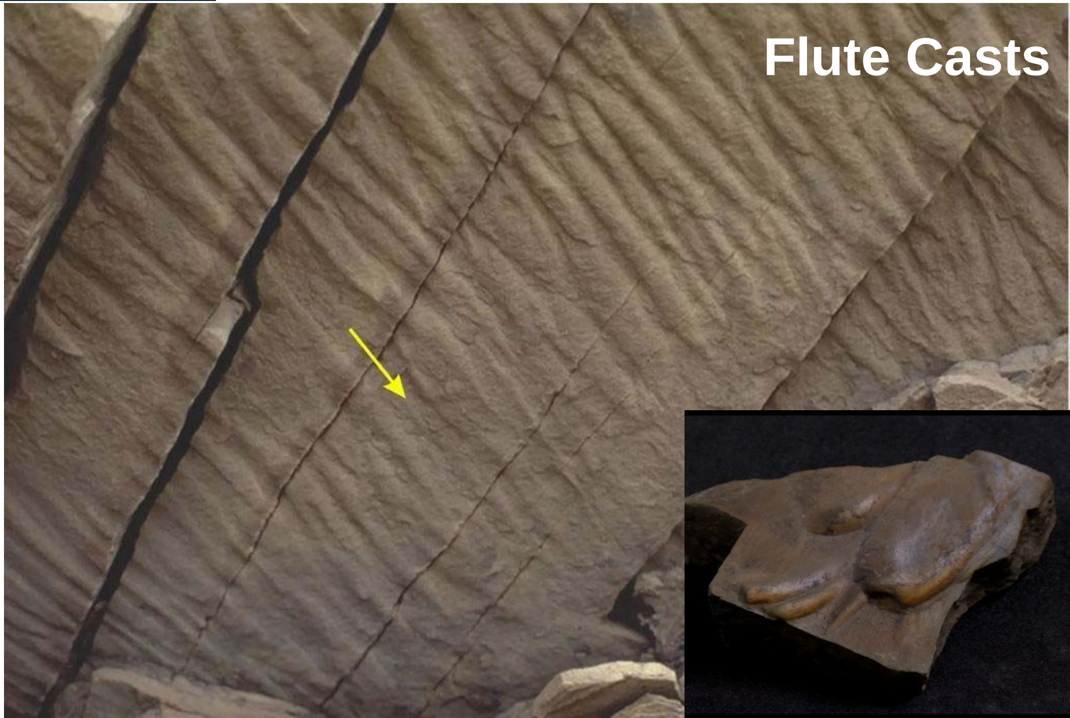


Fig. 15 ***Paleoflow directions*** *for the* ***eight third-order*** *depositional sequences of the* ***Koonap-Middleton fluvial Formations*** *in the* ***Karoo Foredeep****. The succession spans a time interval during the* ***Late Permian*** *and measures a total thickness of* ***2630 m****. The '****n****' 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 the*** **strike variability in orogenic loading** *, 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 were 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 **related controls**; (**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**.

Irrespectively 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 fluvial sediment aggradation occur within **conformable successions**, whereas **soils formed during stages of non-deposition or erosion are associated with stratigraphic unconformities** (i.e., **hiatuses** or **diastems** in the stratigraphic record).

These above 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 **systems tracts of a stratigraphic sequence**.

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 vertical fabric (scale of 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 (Fig. 18):

- **Stages of non-deposition and/or erosion, typically associated with Sequence Boundaries**, **result in the formation of mature paleosols corresponding to 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** (**accumulation**) **match the fluvial sedimentation rates**.

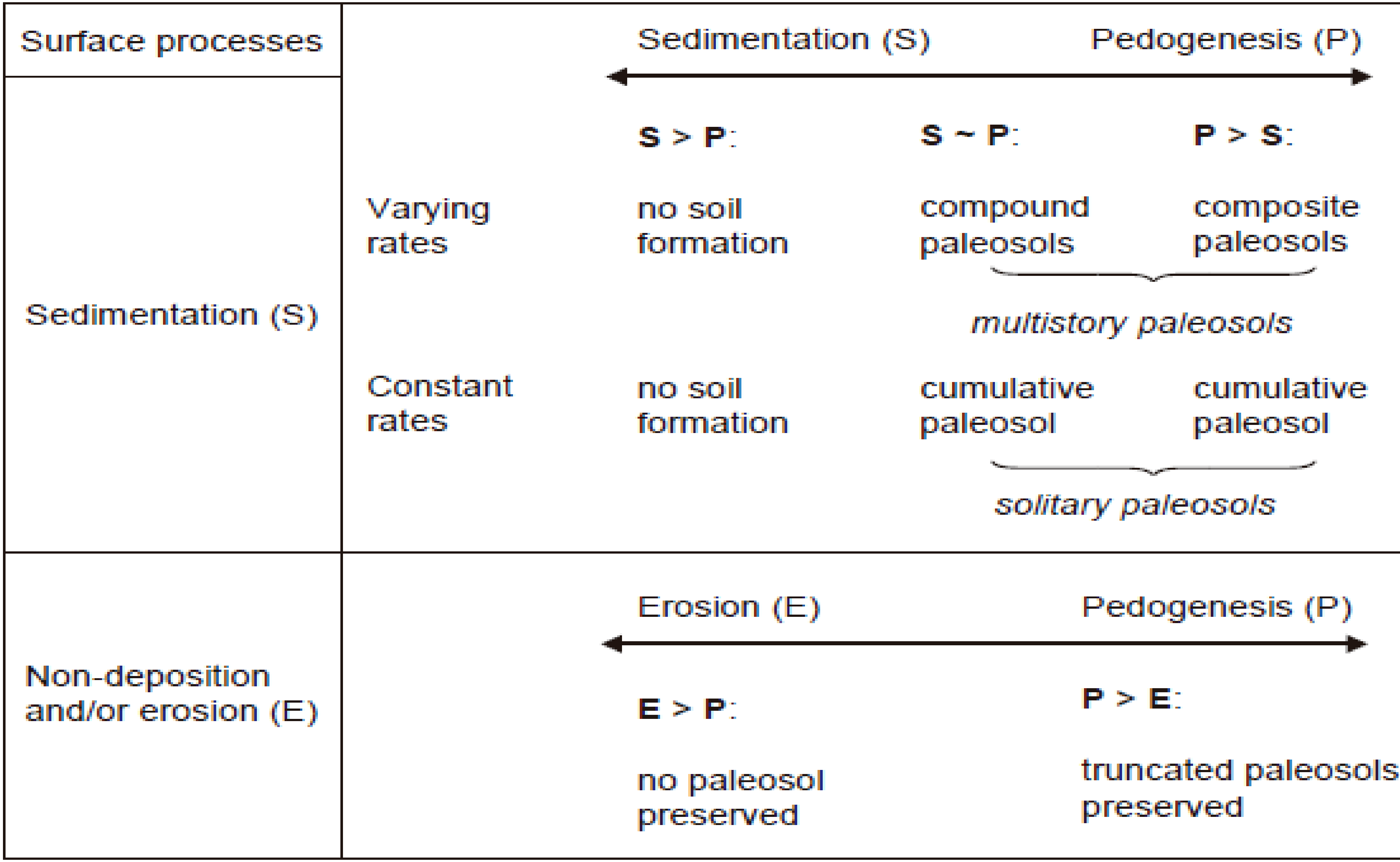


Fig. 18 ***Compound***, ***composite*** *and* ***cumulative*** *paleosols occur within* ***conformable successions****, hence, being within the depositional sequences.* ***Truncated paleosols are associated with stratigraphic unconformities*** *and, therefore,* ***mark hiatuses*** *or* ***diastems****.*

Paleosols associated with **Sequence Boundaries** are generally strongly developed and well drained, **reflecting prolonged stages of sediment cut-off** and a **lowered base level** (causing a **low water table** in the non-marine portion of the basin). However, besides the **climate-induced base level change**, **climate itself** 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**). On the other hand, **base level changes** may also be driven by **tectonism**, thus, **base level cycles** may be modified independently to the **climatic fluctuations.**

The **Sequence-Bounding unconformities**, **corresponding to hiatuses** (**i**) 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, and (**ii**) they can be surfaces with highly irregular topographic relief along which the amount of missing time may vary considerably. Therefore, accordingly, **a mature paleosol used as a Sequence-Bounding unconformity** can show **great lateral changes**, which may be used to **interpret great lateral variations** in **topography** and **missing time**.

In contrast, **paleosols that form within sequences** may be **weakly- to well-developed**, but they are generally **less mature than the Sequence-Bounding paleosols** (Fig. 19).

They **form during stages of base level rise** (causing a **higher water table** in non-marine environments), when surface processes are dominated by **fluvial sediment aggradation**. As a result, **these paleosols tend to be much wetter** relative to the **Sequence-Bounding paleosols**, to the extent of becoming **hydromorphic** (**gleysols**) as the **Maximum Flooding Surface** is, finally, completed, which also marks the timing of the **highest water table in the non-marine environment**.

Such **wetter paleosols** form over relatively short time scales and are often seen in close association with **coal seams** (Fig. 19).

Fig. 19 ***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. However, the* ***formation of wet and immature soils*** *vs.* ***coal seams*** *can, sometimes, be a* ***function of fluctuations in climatic conditions*** *rather than* ***marine base level rise****.*

The **main contrasts** between the **Sequence-Bounding paleosols** and the **paleosols that form within sequences** are shown in Fig. 20. The latter type may show **aggradational features**, often with a multistory architecture due to unsteady sedimentation rates, but may also be **associated with diastems** (small hiatuses) when **autogenic processes**, such as **channel avulsion**, lead to a **cut-off of sediment supply** in **overbank areas**.

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. 20 *Comparison between* ***Sequence-Bounding paleosols*** *and the* ***paleosols developed within sequences****.*

In conclusion, a generalized **model of paleosol development** in relation to a **cycle of base level change** can be described as follows (see Fig. 21 and the following image below): 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** with **zero or negative sedimentation rates**, while 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 the highest**. Due to the high water table in the non-marine environments during transgression, **hydromorphic paleosols are often associated with regional coal seams**.

Therefore, it can be concluded that paleosols are **highly relevant to Sequence Stratigraphy**, complementing the information acquired via different methods of data analysis.

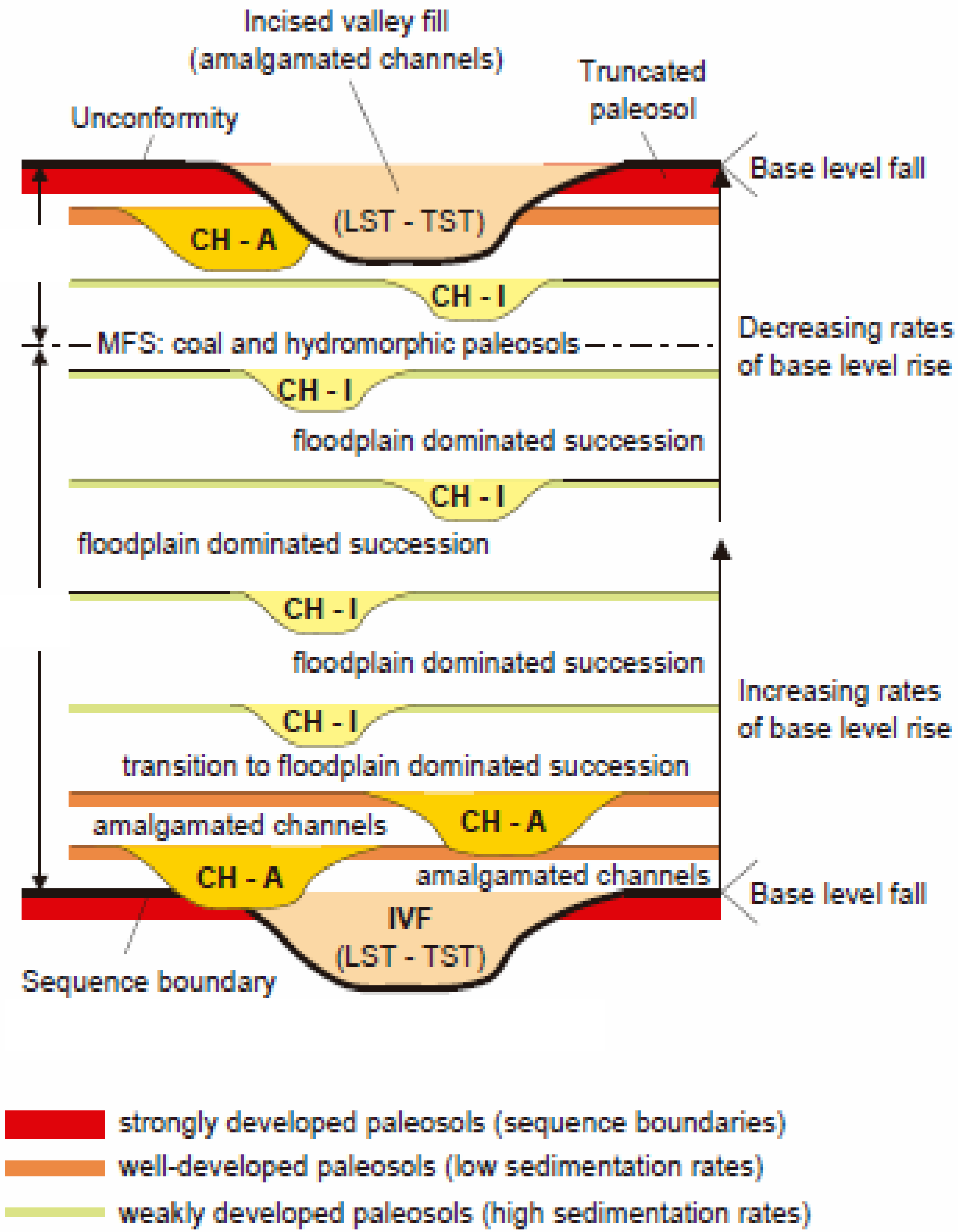
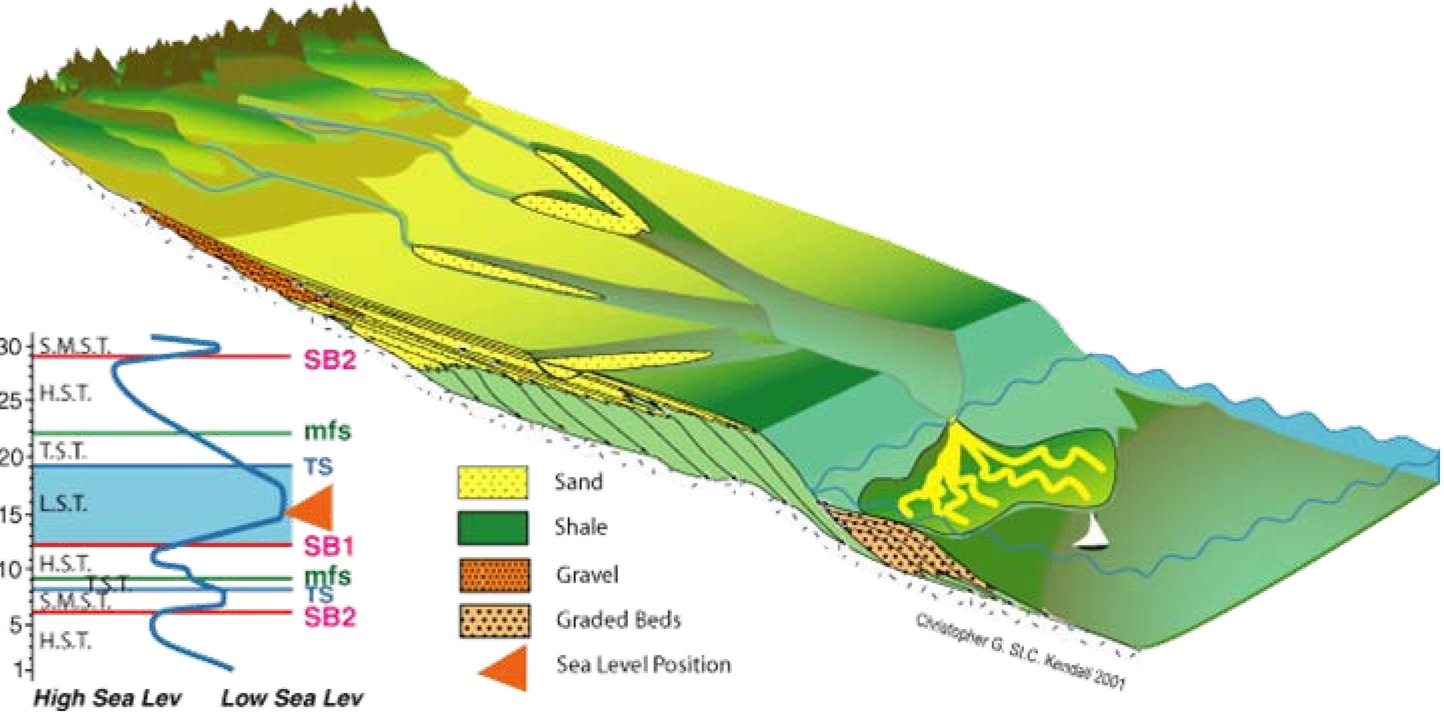


Fig. 21 *Generalized model of paleosol development in relation to a base level cycle. In this model, the rates of fluvial aggradation (and indirectly the degree of channel amalgamation and the paleosol maturity) are directly linked to the rates of base level rise. High non-marine sedimentation rates favor the formation of weakly-developed paleosols within a succession dominated by floodplain deposits.*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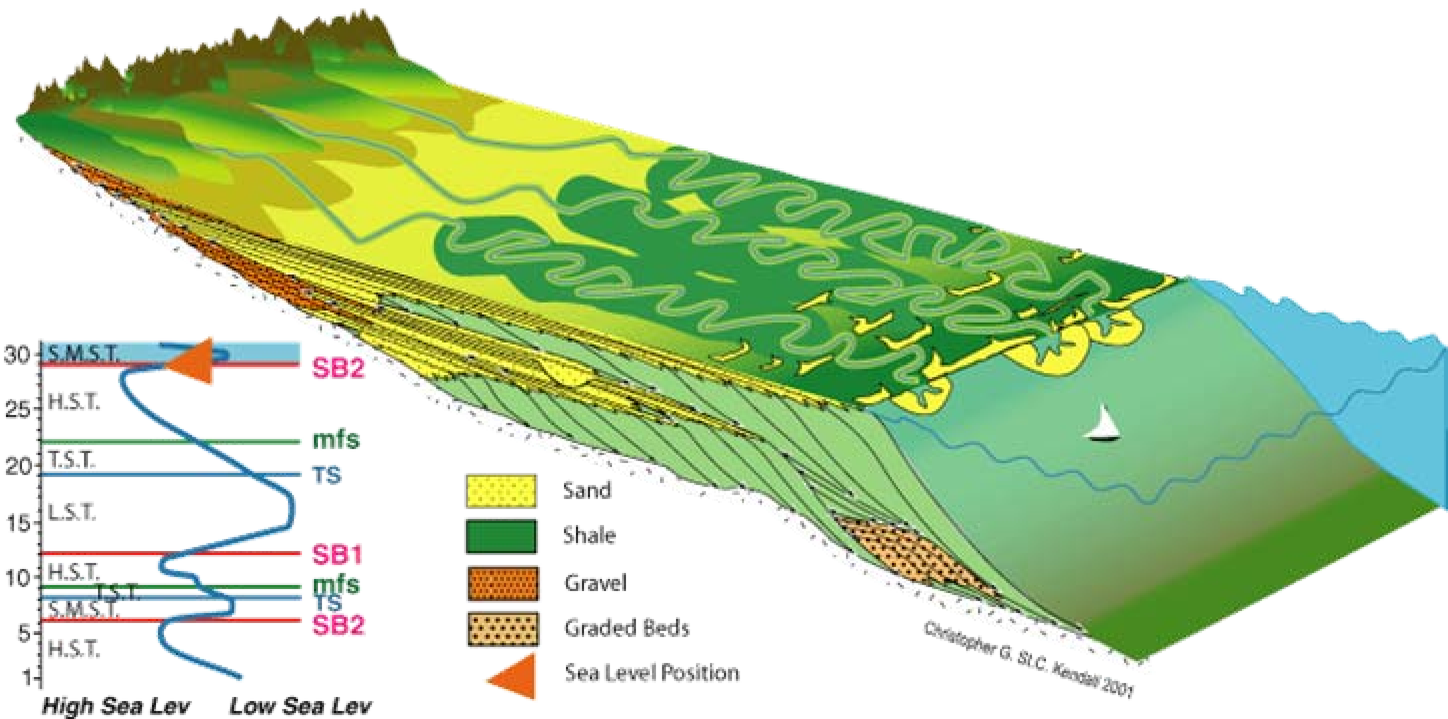
Sea Level Position
Christopher G. St.C. Kendall 2001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Sea Level Position
Christopher G. St.C. Kendall 2001

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** *of* the organisms **during their life span** (e.g., **resting**, **mobility**, **dwelling** or **feeding**), which can be directly linked to a number of **ecological controls** (e.g., **substrate strength**, **water flow energy**, **sedimentation rates**, **nutrient levels**, **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 alive 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 (see Fig. 22a, b), 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**.

Hence, **ichnological data** should be used in combination **with other clues** provided by **classical paleontology** and **sedimentology** to better **validate paleoenvironmental interpretations**.

1. 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.

2. 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).

3. Trace fossils reflect *behavior patterns*, and so they have *long temporal ranges*. This hampers biostratigraphic dating, but facilitates paleoecological comparisons of rocks of different ages. Basic behavior patterns include resting, locomotion, dwelling and feeding, all of which can be combined with escape or equilibrium structures.

Fig. 22a *Basic principles of ichnology.*

4. 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.

5. Behavior patterns depend on ecological conditions, which in turn relate to particular depositional environments. Hence, trace fossils tend to have a *narrow facies range*, and can be used for interpretations of *paleo-depositional environments*.

6. 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.

7. 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).

8. 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. 22b *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 the inferred shifts in the **paleoecological conditions**.

The **concept of ichnofacies**, which is central to ichnology, **was originally developed** based on the observation that **many of the environmental factors**, **which 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** 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 the **ichnofacies sequences**, or to establish the **transgressive** or **regressive shifts of the shoreline**.

Ichnofacies Classification

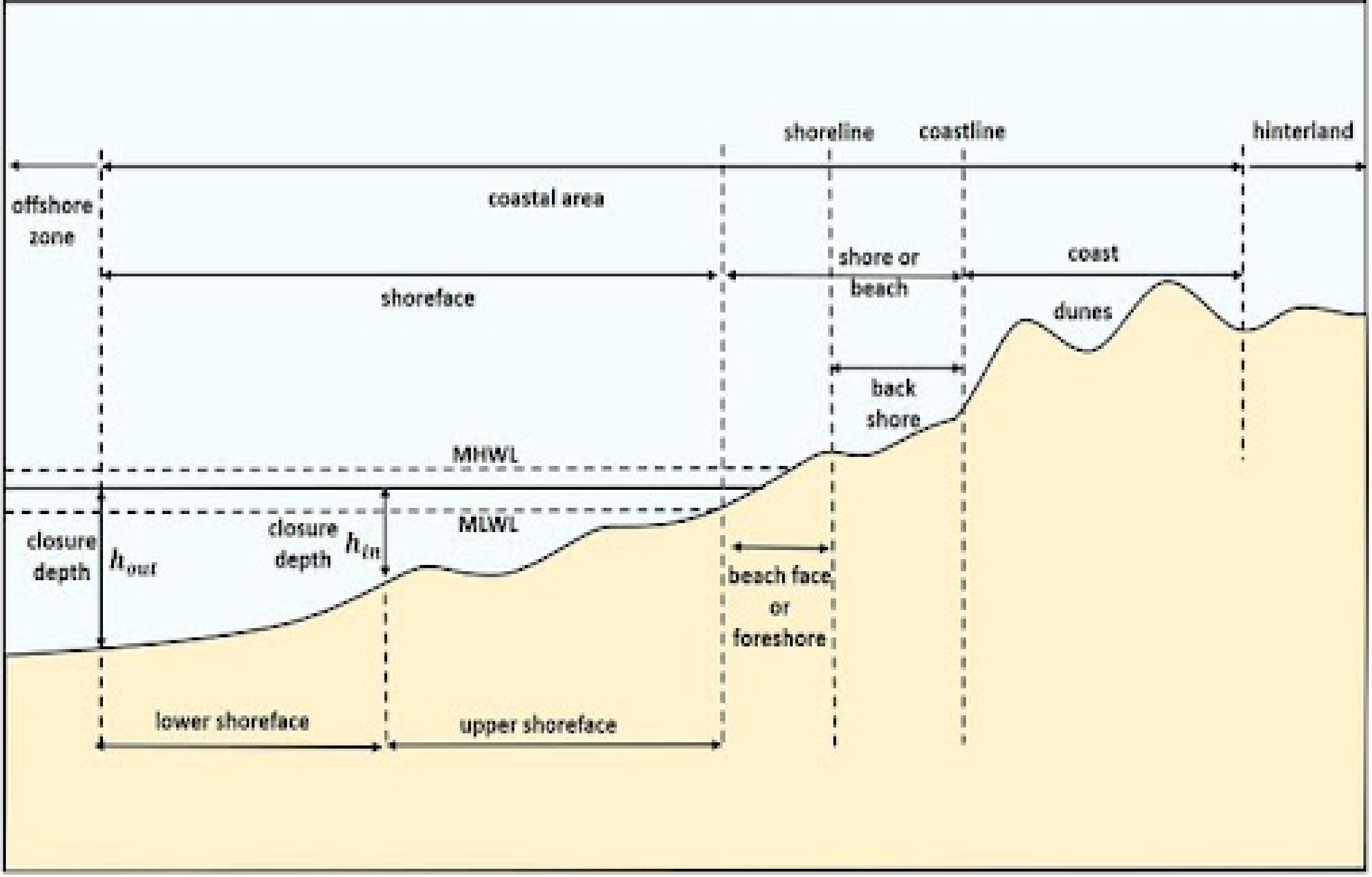
The classification of trace fossil assemblages (i.e., **ichnofacies**) is primarily based on the **substrate type and coherence**, while it has a direct connection with **paleoenvironmental conditions**.

The ichnofacies presented in Fig. 23 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** (generally unconsolidated), **firmgrounds** (semi-consolidated substrates, which are firm but unlithified), **hardgrounds** (consolidated or fully lithified substrates) and, finally, **woodgrounds** (i.e., 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, Rhizocorallium, Thalassinoides, Planolites, Asteriacites, Rosselia*
	Zoophycos		Outer shelf- slope	*Zoophycos, Lorenzinia, Spirophyton*
	Nereites		Slope - basin floor	*Paleodictyon, Helminthoida, Taphrhelminthopsis, Nereites, Cosmorhaphe, Spirorhaphe*

Fig. 23 ***Classification of ichnofacies based on the substrate type and its strength as well as on the depositional environment.***



Coastal environment

In general, **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**), while the rest eight ichnofacies of Fig. 23 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 may be broadly classified into two main groups**, **i.e.**, **a softground-related group** (see Figs 24, 25**)** **and a substrate-controlled group** (see Figs 26-28).

A

B

Fig. 24 ***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*** *(Sunset Cove Bay, Oregon).*

A

B

C

Fig. 25 ***Zoophycos* deep-water 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. 26 ***Glossifungites ichnofacies*** *reaching the base of a* ***tidal channel fill*** *(arrow).* ***Thalassinoides burrows****, produced by* ***decapod crustaceans****, descending into the* ***underlying intertidal deposits*** *(****Pleistocene****, 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 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. 27 ***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).*

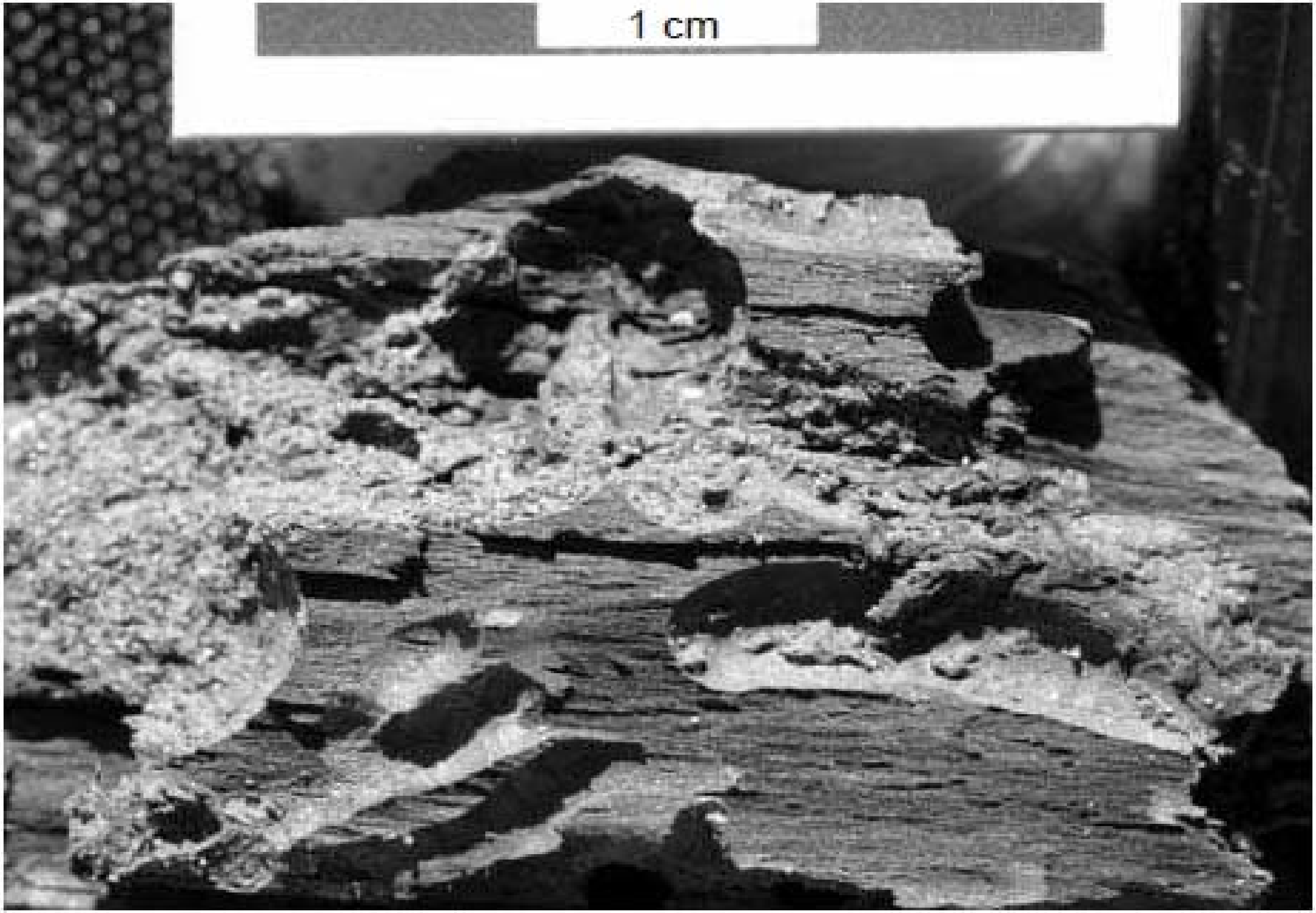


Fig. 28 ***Teredolites* ichnofacies** *in a* ***modern intertidal environment*** *(Willapa Bay, Washington). The* ***borings are sand-filled****, which provides their typical mode of preservation, and are made by the* ***bivalve Bankia****. The* ***woodground*** *has the significance of a* ***transgressive 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**) The **Softground-related ichnofacies**, which generally form in **conformable successions**, assist with the **interpretation of paleodepositional environments** and **their changes with time**. This is due to the fact that the **vertical shifts in softground assemblages are governed by the Walther's Law** and, therefore, they can be used to **decipher paleodepositional trends** (i.e., **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**) The **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**

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. 29) was formed along the margin of a **small pool 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. The varying pool level (i.e., **base level**) resulted in a succession of **systems tracts** including **one Highstand**, **one Transgressive** and **two Lowstand systems tracts**. In addition, other features such as “**ravinement surfaces**”, “**longshore drift associated with beach deposits**”, “**wave-cut**” **inclinations** and “**incised valleys**” were identified.

This example confirms that **sequence stratigraphic principles are scale- and time-independent**.

Fig. 29 *“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 29, 30), **built by fast streams**. 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** (see “**Incised Valley y**” in Fig. 30) **was cut across the largest and landwardmost** “**Delta Front**” (**Unit A** in Fig. 30), initially, 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 **main conduit for sediment that fed the smaller** “**delta**” **lobes** of **Units C** and **D** (Fig. 30).

Two strike-parallel “**Escarpments**” (i.e., see **1** and **2** in Fig. 30) had formed atop the largest “**Delta Front**”, while one “**Incised Valley**” was bounded by these two “**Escarpments**” (e.g., see “**Incised Valley x**” in Fig. 30).

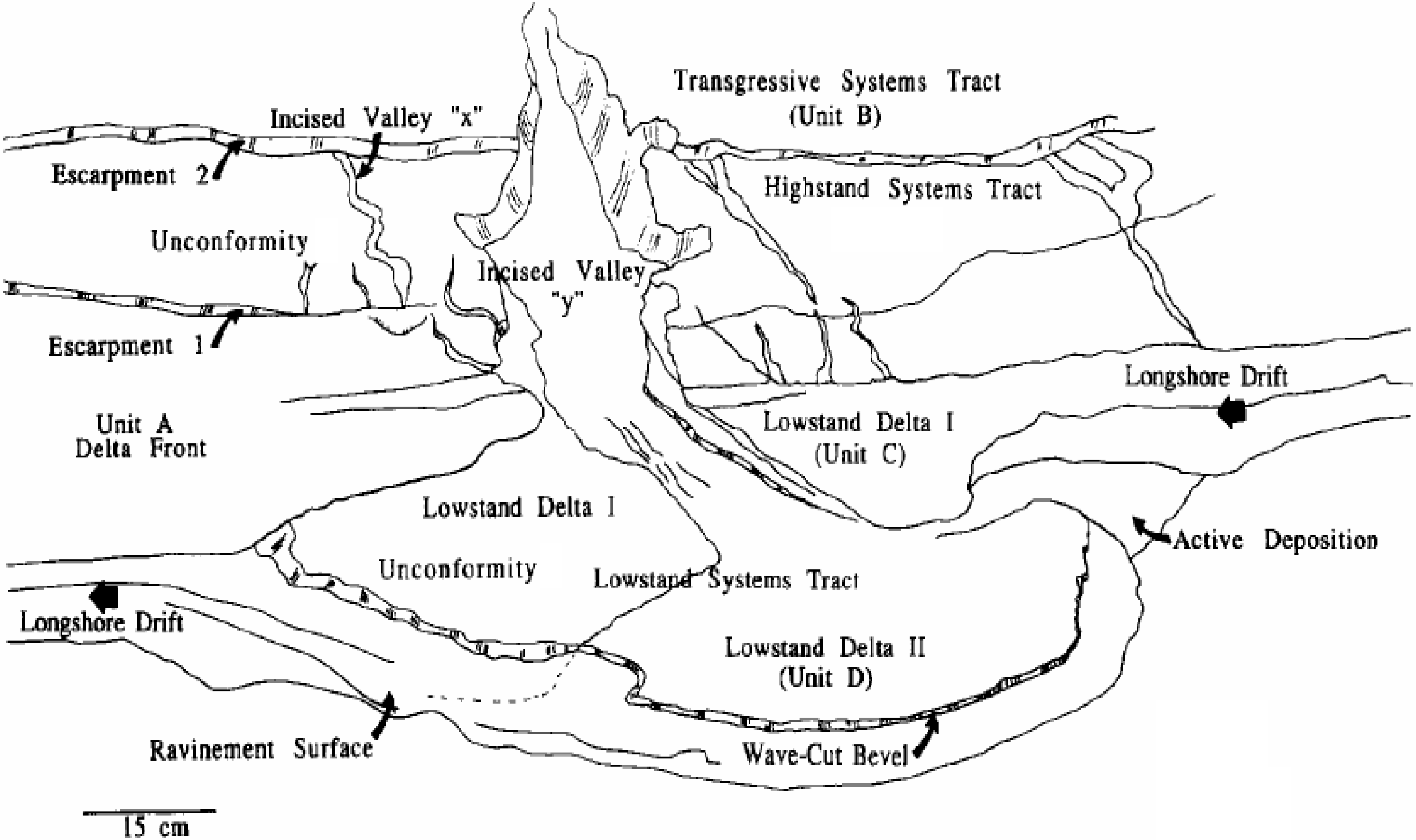


Fig. 30 *The "**delta**" measured **2.3 m** across and **1.8 m** along dip and prograded into a roadside drainage ditch **2.8 m** wide and **30 m** long during a short interval **following a rain storm**. **One Highstand**, **one Transgressive** and **two Lowstand systems tracts** were identified.*

1.4.2 Highstand and Transgressive Systems Tracts

The **deposition** of **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**.

It is reasonable to assume that “**delta**” sedimentation (see “**delta front**” of **Unit A** in Fig. 30) was **initiated shortly after the onset of rainfall** (i.e., at an initially lower pool level). **During the resulting rising pool level**, the “**delta**” should have initially **retrograded for a very short time** and, then, **prograded**, depending of course on the **ratio between sediment flux and rate of accommodation space increase** associated with the **pool level rise**.

The occurrence of “**Escarpment**” **1** (Fig. 30) is interpreted as a **wave-cut inclination** (**bevel 1**) associated with the **transgression** of the “**shoreline**”. A subsequent **acceleration** of the **pool level rise** resulted in an **overstepping** of the **bevel 1** and a **rapid landward migration** of the “**shoreline**” to “**Escarpment**” **2** (**bevel 2**) (Fig. 30). It is possible that the **bevel 2 formation** was followed by a **minor pool level fall**. Evidence for this interpretation is the occurrence of a small “**Incised Valley**” (i.e., “**Incised Valley x**” in Fig. 30) atop **Unit A** feeding a small “**delta**” just “**basinward**” of “**Escarpment**” **1**.

Following these events, soon a **major reflooding resulted in** “**shoreline**” **migration back beyond the apex of** “**Escarpment**” **2**.

Then, a **decrease in the rate of the pool level rise** led to “**shoreline**” **regression** and **progradation** of **Unit B** (Fig. 30).

1.4.3 Lowstand Systems Tracts

During the **pool level fall**, the "**delta plain**" of **Unit B** ceased to be an **active depocenter** and **became a zone of bypass**. As **pool level continued to fall**, the steeper slopes of the "**Delta Front**" were gradually exposed. Hence, the **longitudinal profile** of the **principal stream of bypass** was extended by an **additional freshly exposed and steeper stream segment**. Hence, the **principal stream of bypass 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 were developed** (see Fig. 30).

The “**incised valleys**” fed the **lowstand deposits** that developed “**basinward**” of the **highstand delta plain** and **onlapped the delta front** of **Unit A** (Fig. 30).

The “**basinward**” migration of the “**shoreline**” strictly due to **base level fall** constituted a **Forced Regression**, which was characterized by a **discrete basinward jump** of the **shoreline**.

Hence, the **lowstand** “**delta**” **lobes** (**Unit C**) was the result of **Forced Regression** (Fig. 30).

Eventually, the **pool level** probably **stabilized at this time**, allowing **Unit C to prograde**. The **pool depth** was at this time **significantly less** than during the **preceding time** of the **Transgressive** and **Highstand systems tracts**, respectively, thus, the **gradient** of the **Unit C** “**Delta Front**” was most probably **lower**, because the delta **was prograding** into **shallower water**.

Therefore, a **renewed pool level fall** resulted in another **Forced Regression**, but with **negligible incision** than previously (due to the occurring **much smoother gradient**), causing the deposition of **Unit D** (see “**Lowstand Delta II**” in Fig. 30).

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