SEQUENCE STRATIGRAPHY

Course of Stratigraphy G301

Second semester (February-June2014)

Department of Geology

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Lecture 4 & 5

DEFINITION

- Sequence stratigraphy is a methodology that provides a framework for the elements of any depositional setting, facilitating paleogeographic reconstructions and the prediction of facies and lithologies away from control points.
- This framework ties changes in stratal stacking patterns to the responses to varying accommodation and sediment supply through time.
- Stratal stacking patterns enable determination of the order in which strata were laid down, and explain the geometric relationships and the architecture of sedimentary strata.
- The main tool used in sequence stratigraphic analysis is the stacking pattern of strata and the key surfaces that bound successions defined by different stratal stacking patterns.

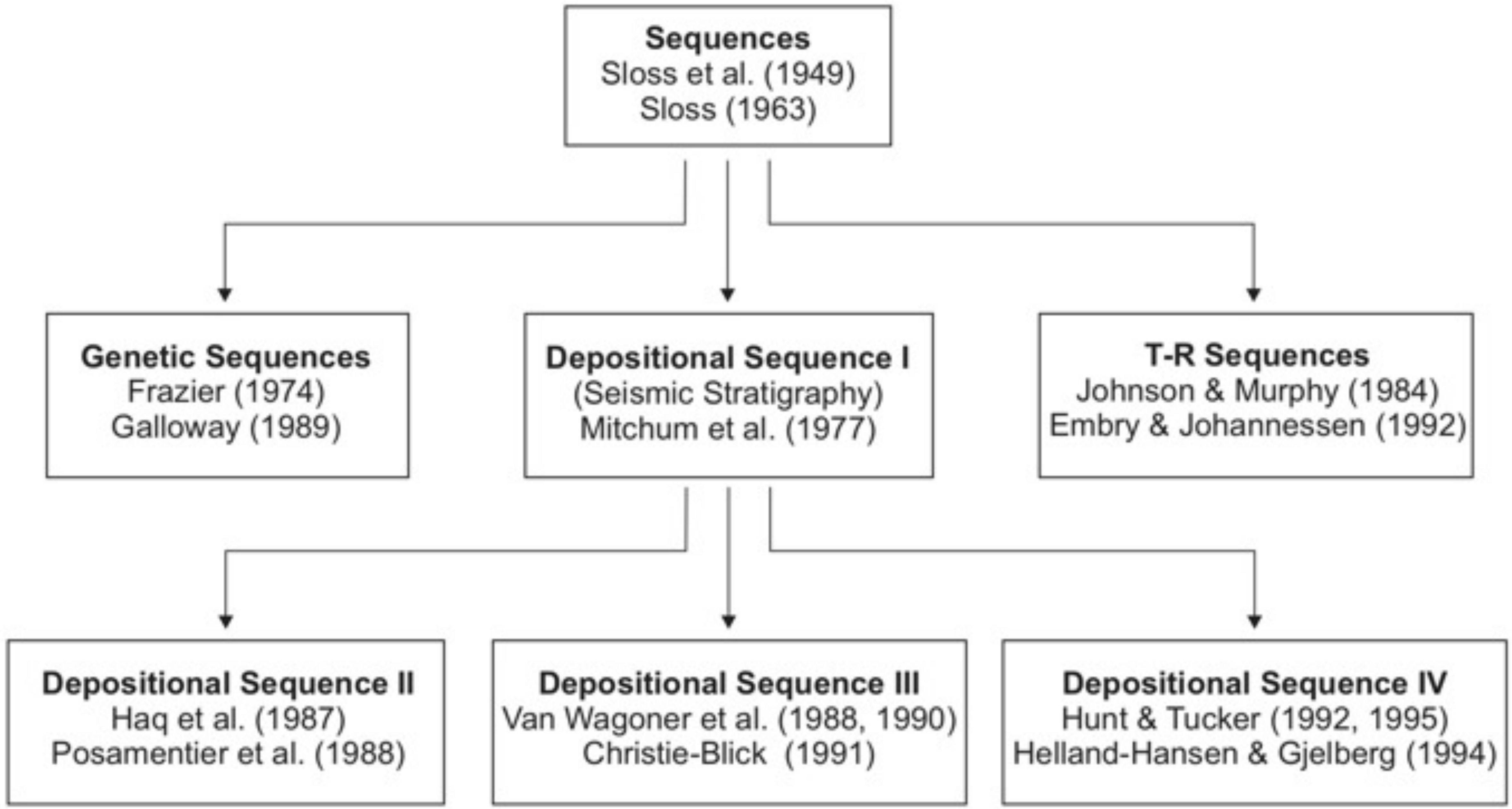
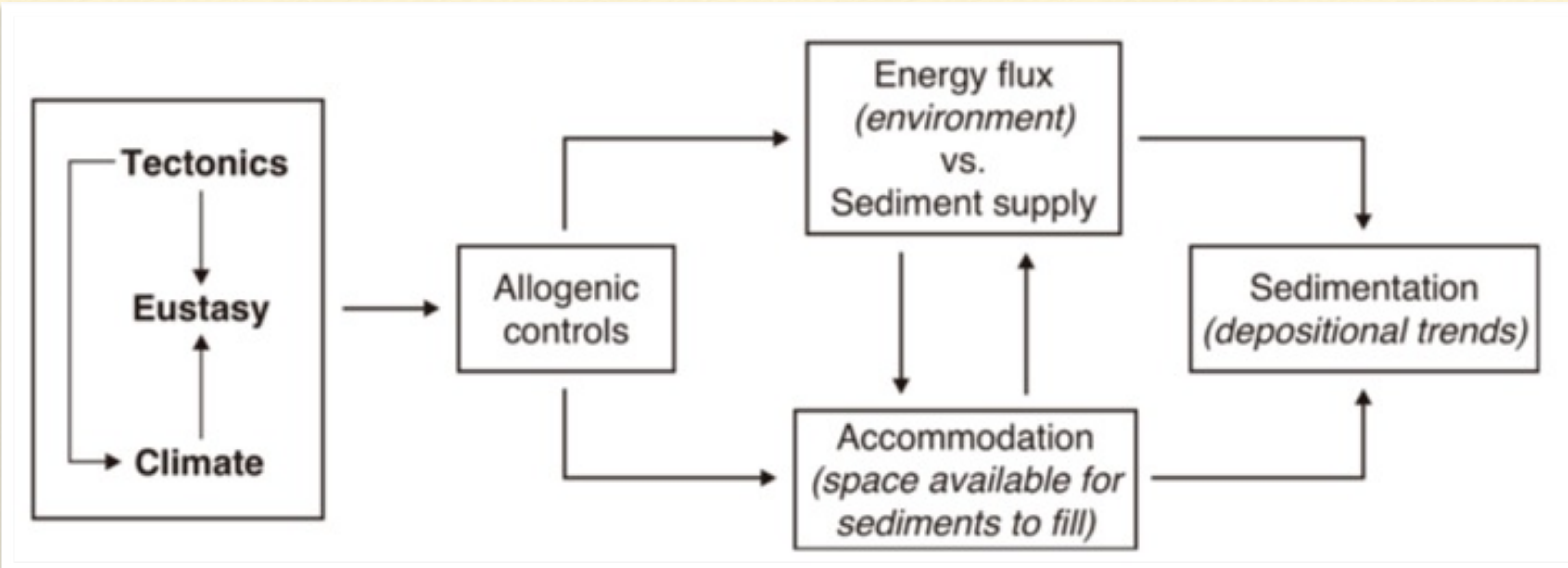


Fig. 1. Evolution of sequence stratigraphic approaches (from Catuneanu et al. 2010).

ACCOMMODATION

- The concept of ‘accommodation’ defines the space available for sediments to fill (Jervey 1988). Accommodation may be modified by the interplay between various independent controls which may operate over a wide range of temporal scales. Marine accommodation is controlled primarily by basin tectonism and global eustasy, and, over much shorter time scales, by fluctuations in the energy flux of waves and currents.

- Depositional trends of aggradation, erosion, progradation and retrogradation may be explained by changes in accommodation or by the interplay between accommodation and sediment supply. Positive accommodation promotes sediment aggradation, whereas negative accommodation results in downcutting.


Tectonics
Eustasy
Climate
Allogenic controls
Energy flux (environment) vs. Sediment supply
Accommodation (space available for sediments to fill)
Sedimentation (depositional trends)

Hierarchical order	Duration (My)	Cause
First order	200-400	Formation and breakup of supercontinents
Second order	10-100	Volume changes in mid-oceanic spreading centers
Third order	1-10	Regional plate kinematics
Fourth and fifth order	0.01-1	Orbital forcing

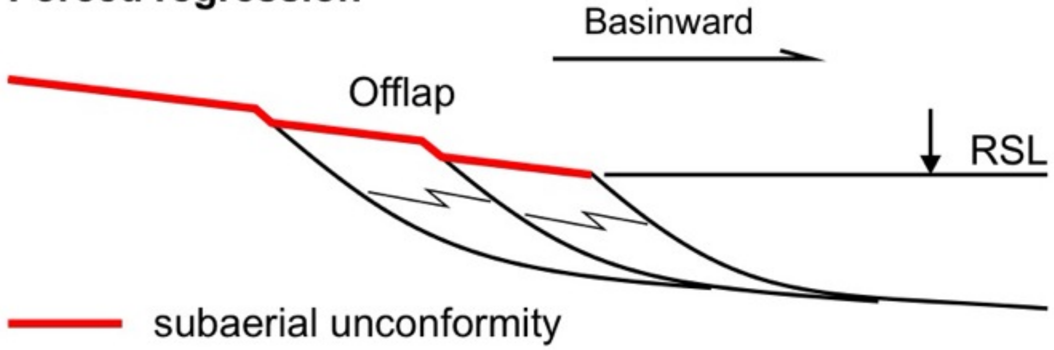
FIGURE 3.2 Tectonic and orbital controls on eustatic fluctuations (modified from Vail *et al.*, 1977, and Miall, 2000). Local or basin-scale tectonism is superimposed and independent of these global sea-level cycles, often with higher rates and magnitudes, and with a wide range of time scales.

STRATAL STACKING PATTERNS

- Stratal stacking patterns may be defined either in relation to or independently of shoreline trajectories. Criteria involved in the definition of stratal stacking patterns include geometries and facies relationships that arose from the interplay of available accommodation and sediment supply at syn-depositional time.

Strata Stacking Pattern

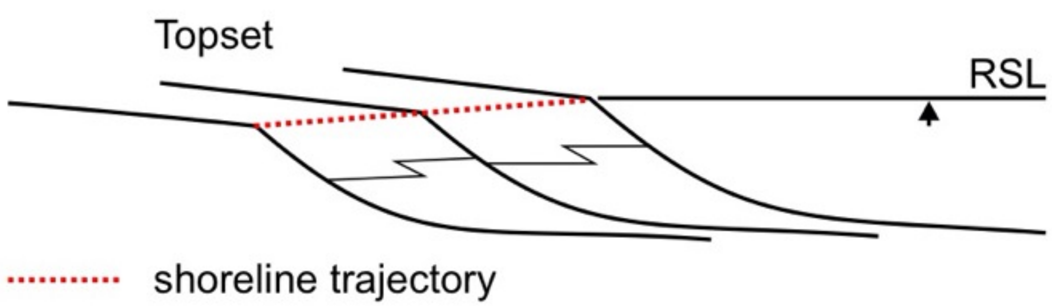
Forced regression



Stacking pattern: progradation with downstepping

Interpretation: progradation driven by relative sea-level fall (negative accommodation). The coastline is forced to regress, irrespective of sediment supply.

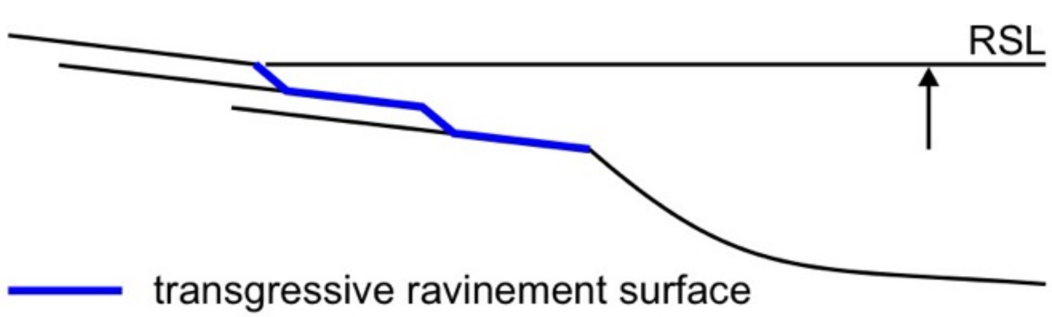
Normal regression



Stacking pattern: progradation with aggradation

Interpretation: progradation driven by sediment supply. Sedimentation rates outpace the rates of relative sea-level rise (positive accommodation) at the coastline.

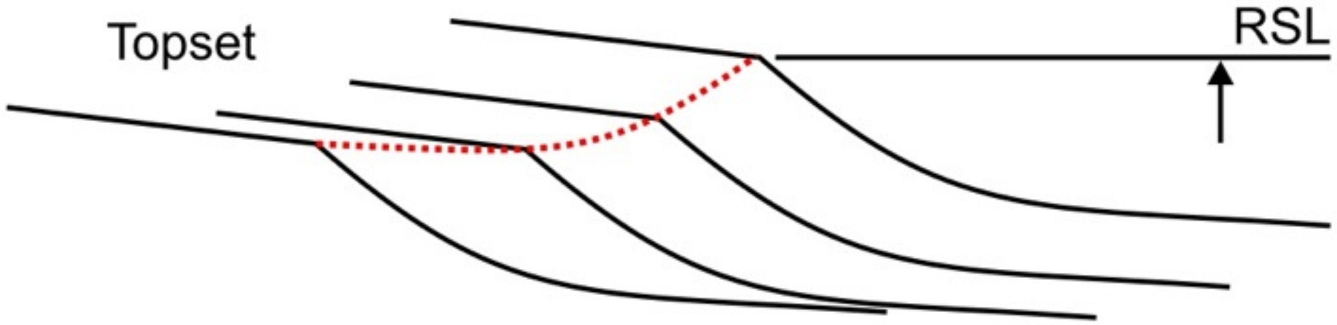
Transgression



Stacking pattern: retrogradation.

Interpretation: retrogradation (backstepping) driven by relative sea-level rise. Accommodation outpaces the sedimentation rates at the coastline.

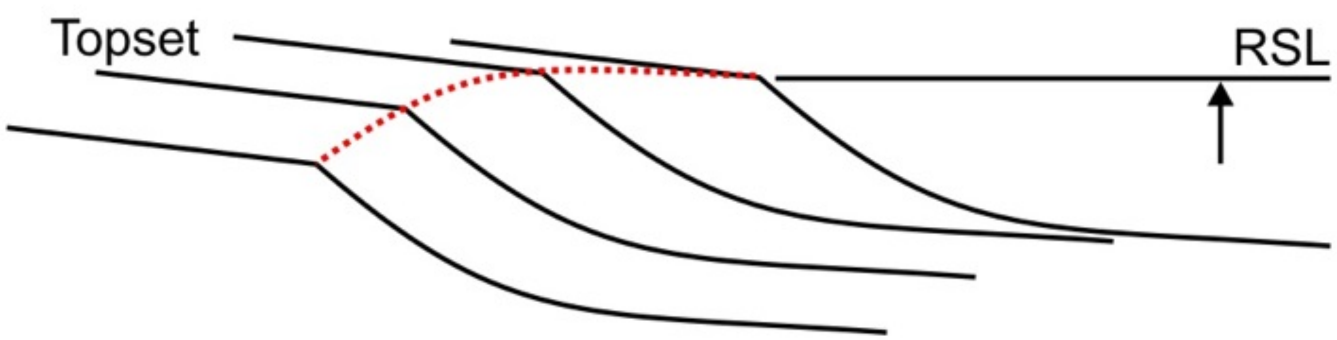
Lowstand normal regression (accelerating RSL rise)



The rates of progradation decrease with time, the rates of aggradation increase with time.

shoreline trajectory (concave up)

Highstand normal regression (decelerating RSL rise)



The rates of progradation increase with time, the rates of aggradation decrease with time.

shoreline trajectory (convex up)

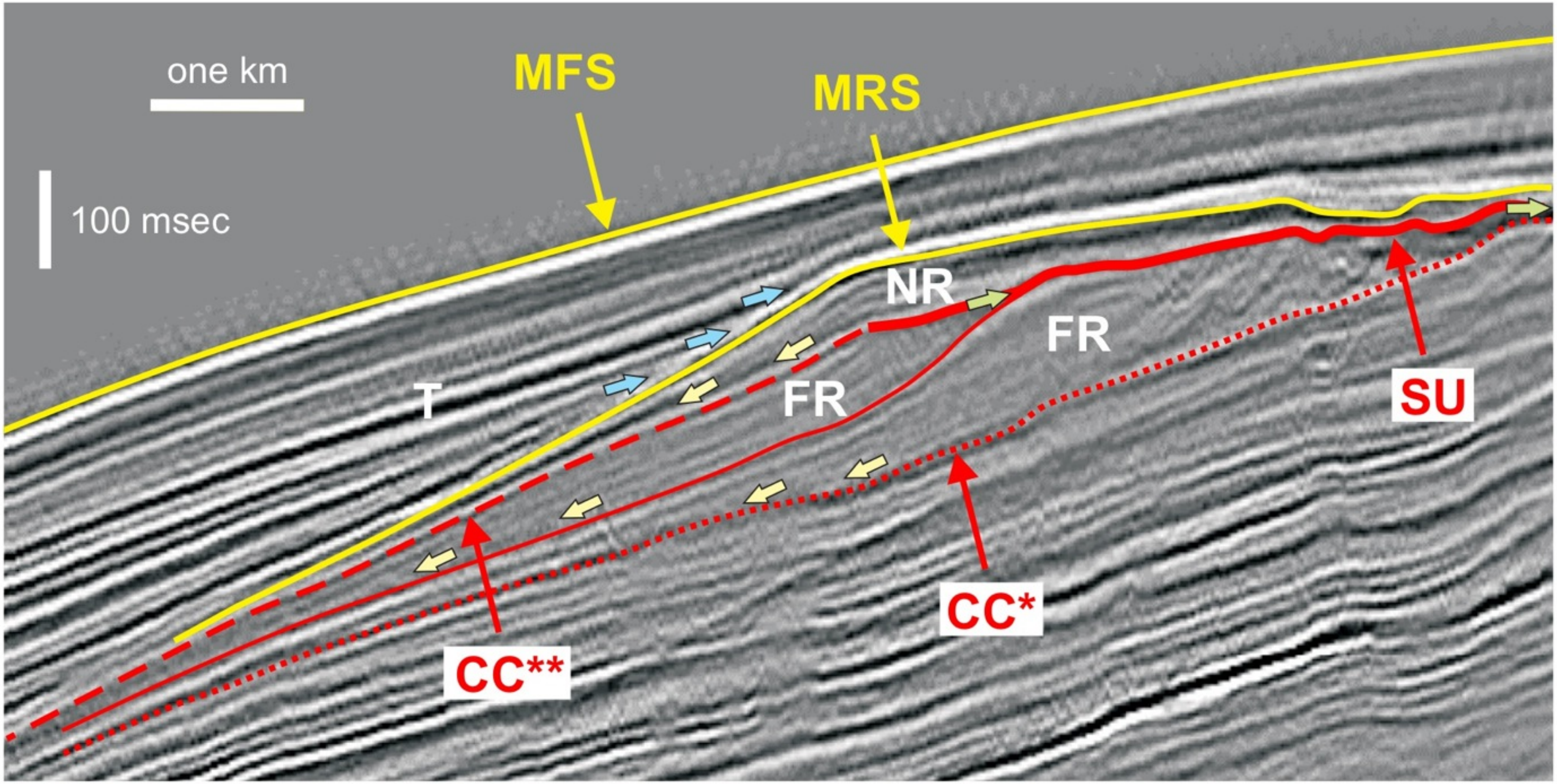
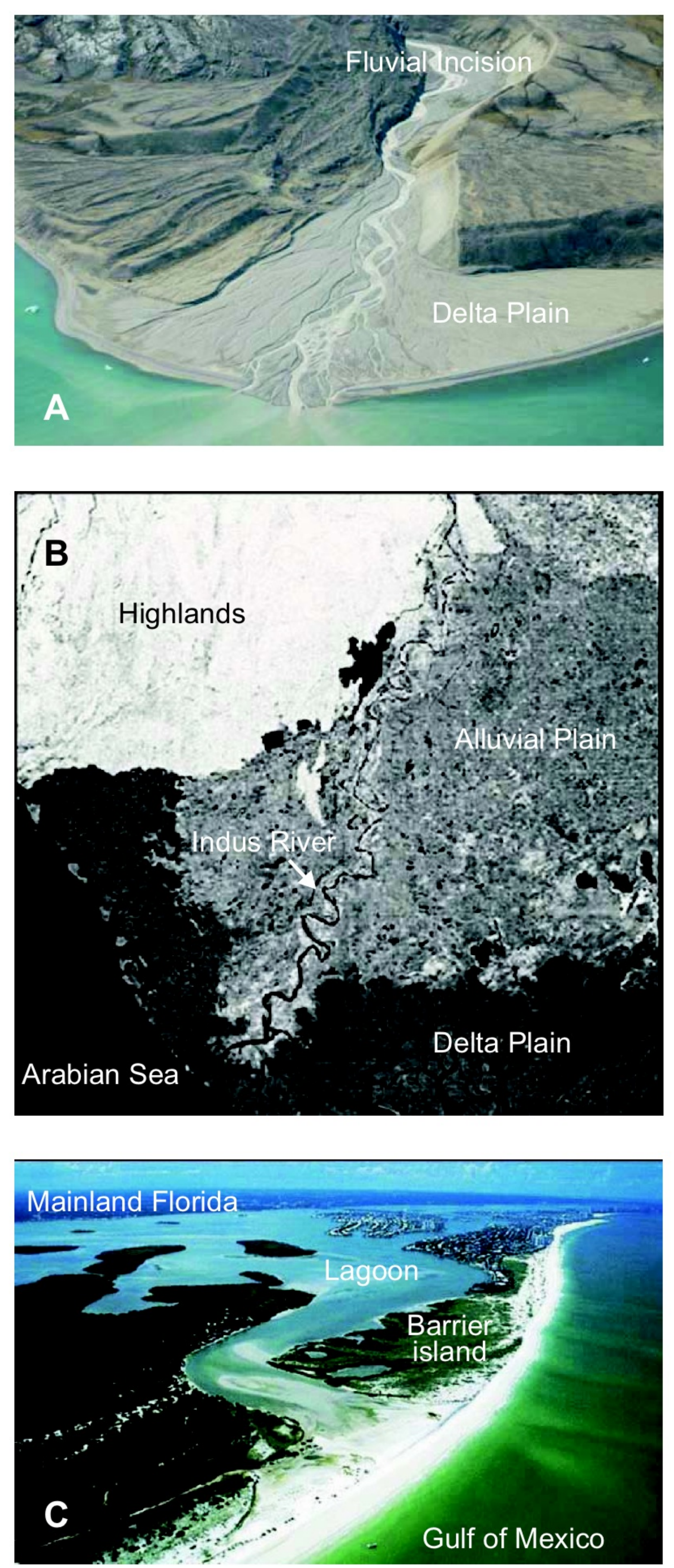
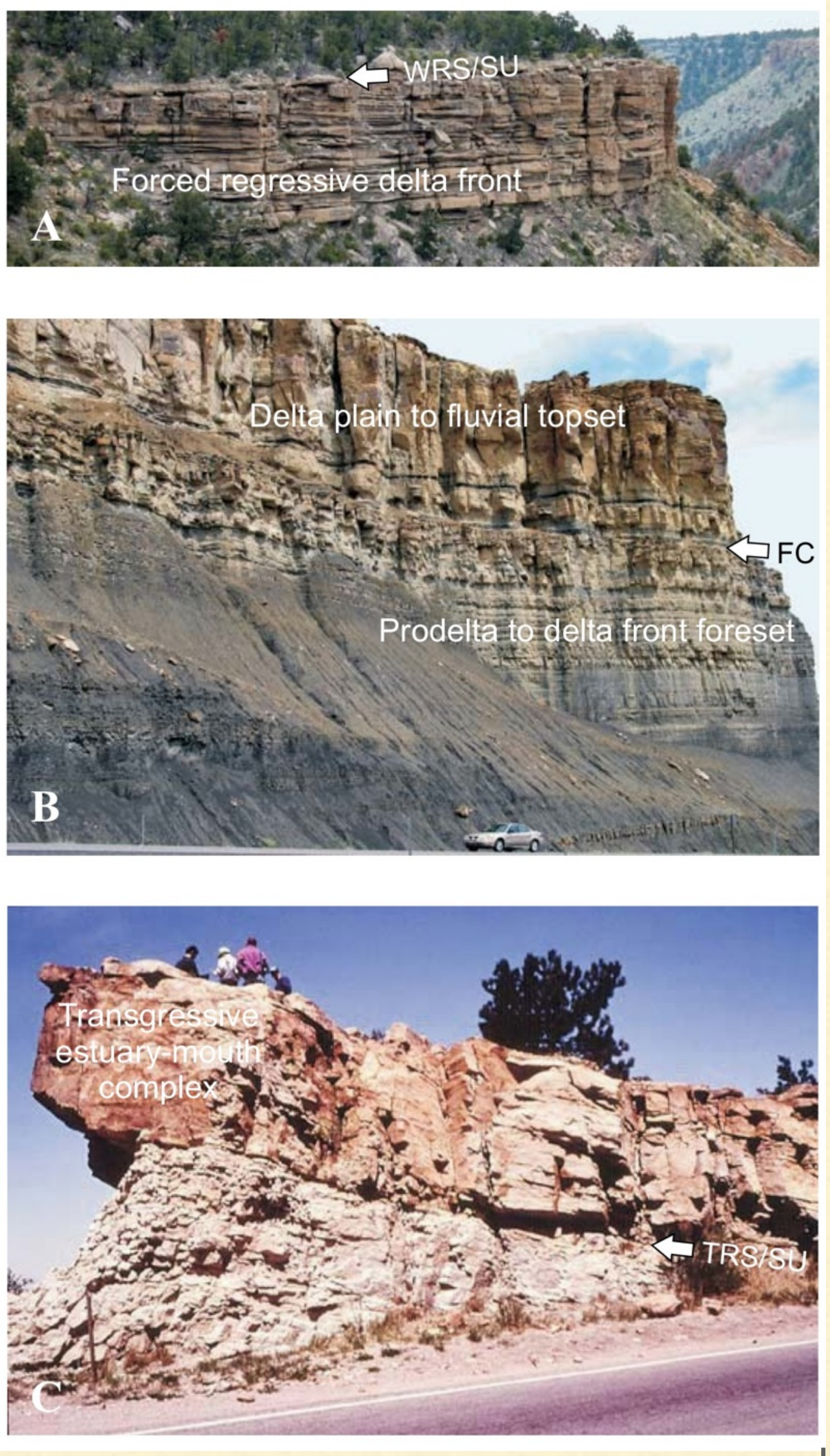


Fig. 8. Types of shoreline trajectory: seismic example (Plio-Pleistocene to Holocene, Gulf of Mexico; modified from Posamentier and Kolla 2003). Stratal terminations: green arrows – offlap; yellow arrows – downlap; blue arrows – onlap. Abbreviations: FR – forced regression; NR – normal regression; T – transgression; SU – subaerial unconformity; CC* – correlative conformity in the sense of Posamentier and Allen (1999) (= basal surface of forced regression); CC** – correlative conformity in the sense of Hunt and Tucker (1992); MRS – maximum regressive surface; MFS – maximum flooding surface.


Fluvial Incision
Delta Plain
A
B
Highlands
Alluvial Plain
Indus River
Arabian Sea
Delta Plain
Mainland Florida
Lagoon
Barrier island
C
Gulf of Mexico


WRS/SU
Forced regressive delta front
A
Delta plain to fluvial topset
FC
Prodelta to delta front foreset
B
Transgressive estuary-mouth complex
TRS/SU
C

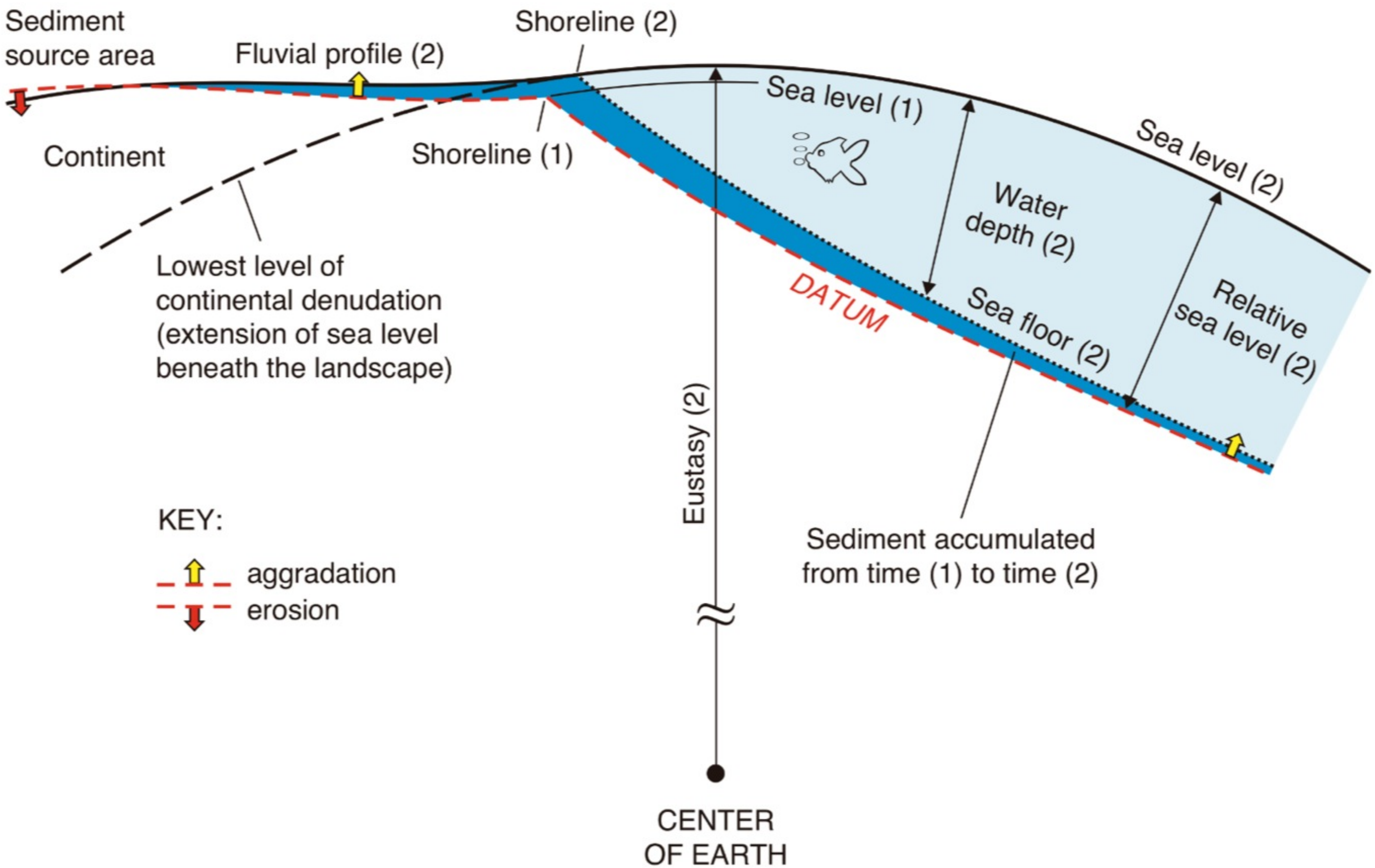


FIGURE 3.12 Eustasy, relative sea level, and water depth as a function of sea level, seafloor, and datum reference surfaces (modified from Posamentier *et al*., 1988). The datum is a subsurface reference horizon that monitors the amount of total subsidence or uplift relative to the center of Earth. In this diagram, the datum corresponds to the ground surface (subaerial and subaqueous) at time (1). Sedimentation (from time 1 to time 2 in this diagram) buries the datum, which, at any particular location, may be visualized as a G.P.S. that monitors changes in elevation through time (i.e., distance relative to the center of Earth).

Definition concepts of base level

Base level (Twenhofel, 1939): highest level to which a sedimentary succession can be built.

Base level (Sloss, 1962): an imaginary and dynamic equilibrium surface above which a particle cannot come to rest and below which deposition and burial is possible.

Base level (Bates and Jackson, 1987): theoretical limit or lowest level toward which erosion of the Earth's surface constantly progresses but rarely, if ever, reaches. The general or ultimate base level for the land surface is sea level.

Base level (Jervey, 1988): ... is controlled by sea level and, at first approximation, is equivalent to sea level ... although, in fact, a secondary marine profile of equilibrium is attained that reflects the marine-energy flux in any region.

Base level (Schumm, 1993): the imaginary surface to which subaerial erosion proceeds. It is effectively sea level, although rivers erode slightly below it.

Base level (Cross, 1991): a surface of equilibrium between erosion and deposition.

Base level (Cross and Lessenger, 1998): a descriptor of the interactions between processes that create and remove accommodation space and surficial processes that bring sediment or that remove sediment from that space.

Base level (Posamentier and Allen, 1999): the level that a river attains at its mouth (i.e., either sea level or lake level), and constitutes the surface to which the equilibrium profile is anchored.

There are two schools of thought regarding the concept of base level:

(1) Base level is more or less the sea level, although usually below it due to the action of waves and currents. The extension of this surface into the subsurface of continents defines the ultimate level of continental denudation. On the continents, processes of aggradation versus incision are regulated via the concept of graded (equilibrium) fluvial profile. Graded fluvial profiles meet the base level at the shoreline.

(2) The concept of base level is generalized to define the surface of balance between erosion and sedimentation within both marine and continental areas (the "stratigraphic" base level of Cross and Lessenger, 1998). In this acceptance, the concept of graded fluvial profile becomes incorporated within the concept of base level. The stratigraphic base level will thus include a continental portion (fluvial base level = graded fluvial profile) and a marine portion (marine base level ~ sea level).

The drawback of the second approach is that fluvial base-level shifts are controlled by marine base-level shifts, especially in the downstream reaches of the river system, and hence the two concepts are in a process/response relationship. This suggests that it is preferable to keep these two concepts separate as opposed to incorporating them into one "stratigraphic base level". This is the approach adopted in this book, where the fluvial base level is referred to as the fluvial graded profile, and the marine base level is simply referred to as the base level.

TYPES OF SEQUENCE

- 1- Depositional sequences

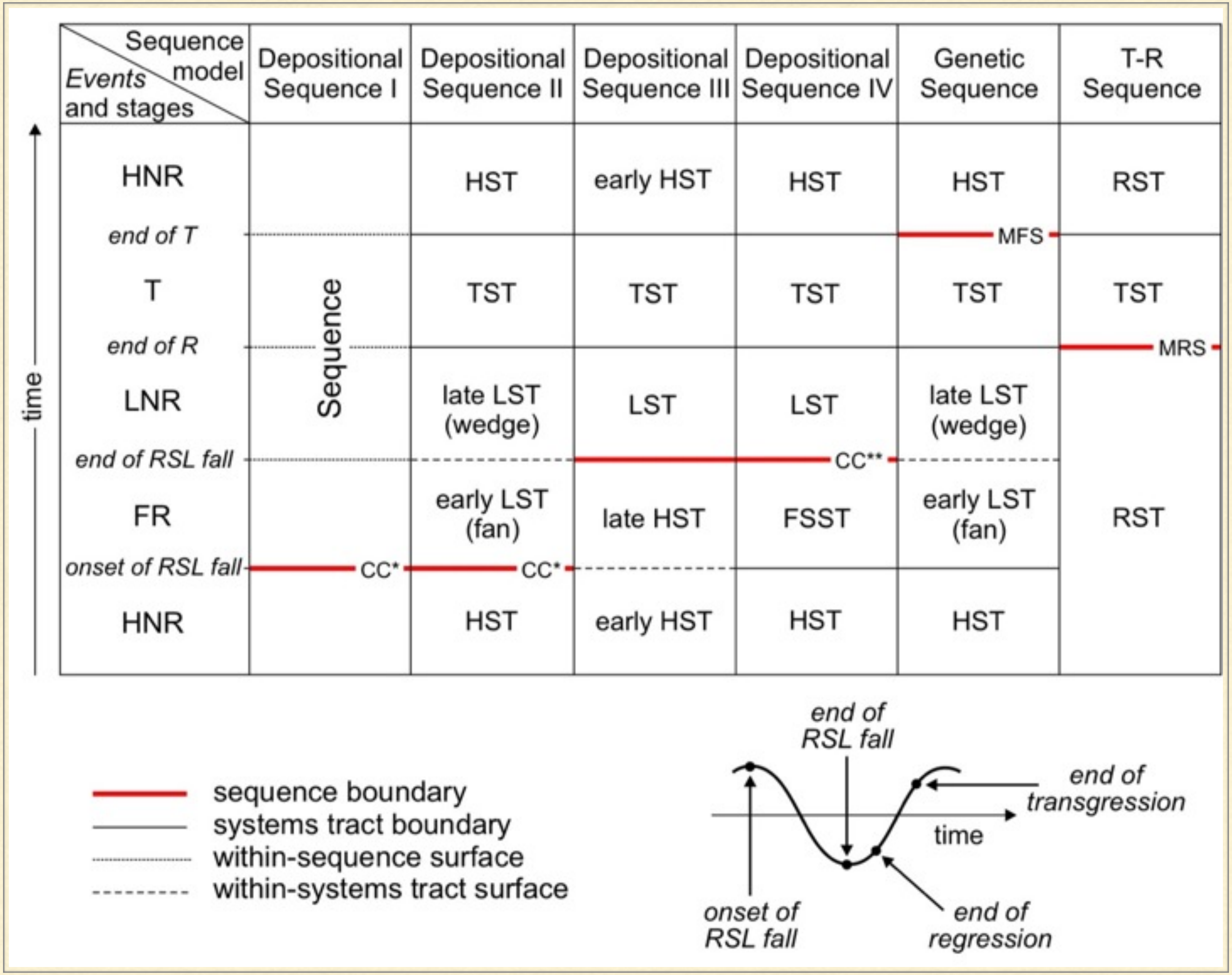
- A depositional sequence forms during a full cycle of change in accommodation, which involves both an increase (positive) and decrease (negative) in the space available for sediments to fill.

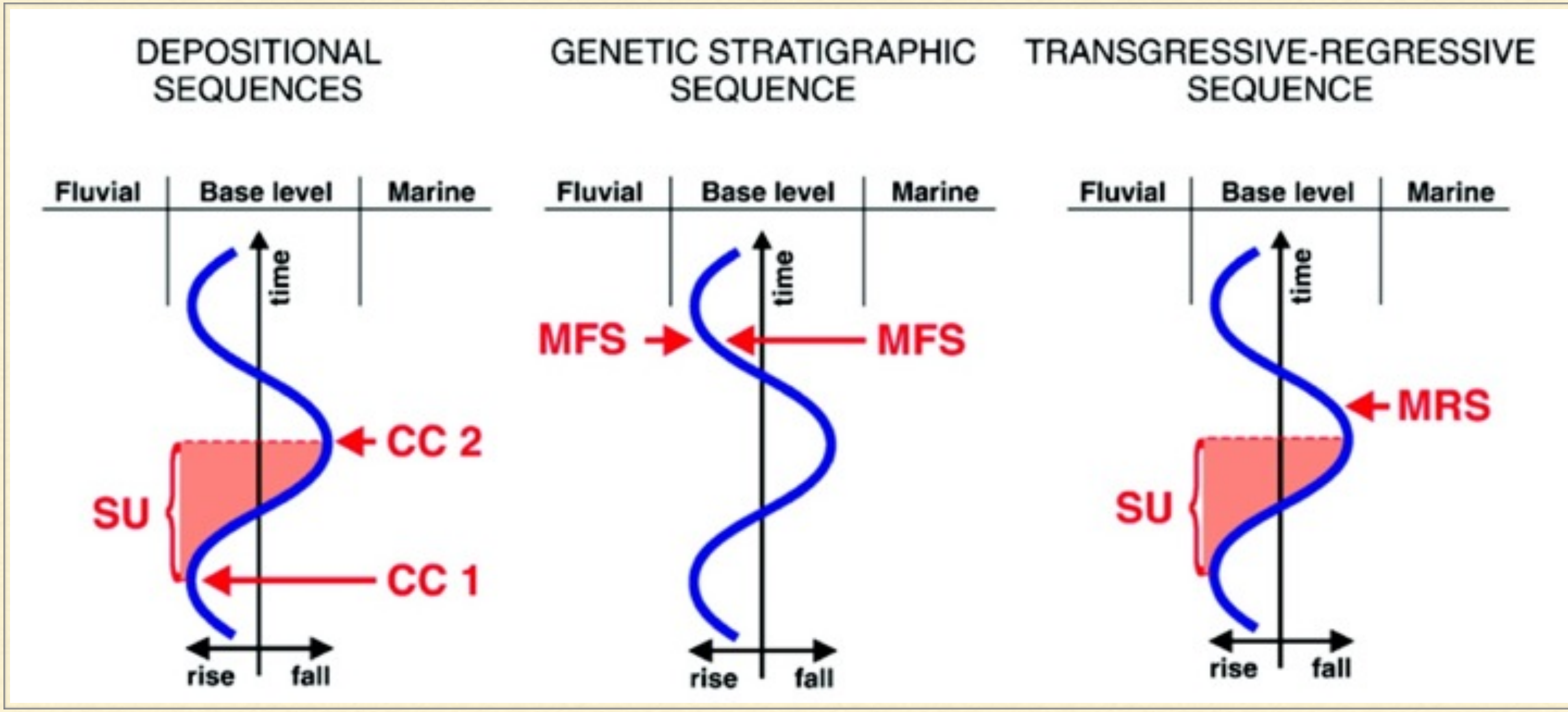
- 2-Genetic stratigraphic sequences

- The formation of genetic stratigraphic sequences depends on the development of maximum flooding surfaces, which form during times of positive accommodation. A genetic stratigraphic sequence may form during a full cycle of change in accommodation, as in the case of a depositional sequence, but it may also form during periods of positive accommodation in response to fluctuations in the rates of accommodation creation and/or sediment supply

TYPES OF SEQUENCE

- 3- Transgressive-regressive (T-R) sequences
- The original T-R sequence of Johnson and Murphy (1984) depends of maximum regressive surfaces, which form during times of positive accommodation. As in the case of genetic stratigraphic sequences, this type of sequence may form during a full cycle of change in accommodation, but it may also form during periods of positive accommodation as a result of fluctuations in the rates of accommodation and/or sediment supply.


Sequence model
Events and stages
Depositional Sequence I
Depositional Sequence II
Depositional Sequence III
Depositional Sequence IV
Genetic Sequence
T-R Sequence
time
HNR
end of T
T
end of R
LNR
end of RSL fall
FR
onset of RSL fall
HNR
Sequence
HST
TST
late LST (wedge)
early LST (fan)
HST
early HST
TST
LST
late HST
early HST
HST
TST
LST
FSST
HST
HST
MFS
TST
late LST (wedge)
early LST (fan)
HST
RST
TST
MRS
RST
CC*
CC*
CC**
sequence boundary
systems tract boundary
within-sequence surface
within-systems tract surface
end of RSL fall
end of transgression
time
onset of RSL fall
end of regression


DEPOSITIONAL SEQUENCES
GENETIC STRATIGRAPHIC SEQUENCE
TRANSGRESSIVE-REGRESSIVE SEQUENCE
Fluvial
Base level
Marine
time
SU
CC 2
CC 1
MFS
MRS
rise
fall

SEQUENCE STRATIGRAPHIC UNITS: SYSTEMS TRACTS

- A systems tract is "a linkage of contemporaneous depositional systems, forming the subdivision of a sequence" (Brown and Fisher 1977).
- The definition of a systems tract is independent of spatial and temporal scales.
- The internal architecture of a systems tract may vary greatly with the scale of observation, from a succession of facies (e. g., in the case of high-frequency sequences driven by orbital forcing) to a parasequence set or a set of higher frequency sequences.
- A systems tract consists of a relatively conformable succession of genetically related strata bounded by conformable or unconformable sequence stratigraphic surfaces.

- Systems tracts are interpreted on the basis of stratal stacking patterns, position within the sequence, and types of bounding surface.
- Systems tracts may be either shoreline-related, where their origin can be linked to particular types of shoreline trajectory, or shoreline-independent, where a genetic link to coeval shorelines cannot be determined.

1- SHORELINE-RELATED SYSTEMS TRACTS

- Shoreline-related systems tracts consist of correlatable depositional systems that are genetically related to specific types of shoreline trajectory (i. e., forced regression, normal regression, transgression). These systems tracts may be observed at different scales, and are defined by distinct stratal stacking patterns.

- Shoreline-related systems tracts are commonly interpreted to form during specific phases of the relative sea-level cycle.

FALLING-STAGE SYSTEMS TRACT (FSST)

- The FSST includes all the regressive deposits that accumulate after the onset of a relative sea-level fall and before the start of the next relative sea-level rise.
- The FSST is the product of a forced regression.
- The fall in relative sea level is evidenced by the erosion of the subaerially exposed sediment surface updip of the coastline at the end of forced regression, and the formation of a diachronous subaerial unconformity that caps the Highstand Systems Tract (HST).
- The subaerial unconformity may be onlapped by flu-vial deposits that belong to the lowstand or the trans-gressive systems tracts. The subaerial unconformity may also be reworked by a time-transgressive marine ravinement surface overlain by a sediment lag

LOWSTAND SYSTEMS TRACT (LST)

- The LST includes deposits that accumulate after the onset of relative sea-level rise, during normal regression, on top of the FSST and the corresponding up-dip subaerial unconformity.
- Stacking patterns exhibit forestepping, aggrading clinoforms that (in siliciclastic systems) thicken downdip, and a topset of fluvial, coastal plain and/or delta plain deposits.
- LST sediments often fill or partially infill incised valleys that were cut into the HST, and other earlier deposits, during forced regression.

TRANSGRESSIVE SYSTEMS TRACT (TST)

- The TST comprises the deposits that accumulated from the onset of transgression until the time of maximum transgression of the coast, just prior to the renewed regression of the HST.

- The TST lies directly on the maximum regressive surface formed at the end of regression (also termed a 'transgressive surface') and is overlain by the 'maximum flooding surface' (MFS) formed when marine sediments reach their most land-ward position.

- Stacking patterns exhibit backstepping, onlapping, retrogradational clinoforms that (in silici-clastic systems) thicken landward. In cases where there is a high sediment supply the parasequences may be aggradational.

HIGHSTAND SYSTEMS TRACT (HST)

- The HST includes the progradational deposits that form when sediment accumulation rates exceed the rate of increase in accommodation during the late stages of relative sea-level rise.

- The HST lies directly on the MFS formed when marine sediments reached their most landward position.

- This systems tract is capped by the subaerial unconformity and its correlative conformity sensu Posamentier and Allen (1999).

- Stacking patterns exhibit prograding and aggrading clinoforms that commonly thin downdip, capped by a topset of fluvial, coastal plain and/or delta plain deposits

REGRESSIVE SYSTEM TRACT (RST)

- The RST lies above a TST and is overlain by the ini-tial transgressive surface of the overlying TST. The complete sequence is known as a Transgressive-Regressive (T-R) Sequence (Johnson and Murphy 1984; Embry and Johannessen 1992).
- The sediments of this systems tract include the HST, FSST and LST systems tracts defined above.
- There are cases where the data available are insufficient to differentiate between HST, FSST an HST systems tracts. In such cases the usage of the Regressive Systems Tract is justified.

2- SHORELINE-INDEPENDENT SYSTEMS TRACTS

- Shoreline-independent systems tracts are stratigraphic units that form the subdivisions of sequences in areas where sedimentation processes are unrelated to shoreline shifts.

- These systems tracts are defined by specific stratal stacking patterns that can be recognized and correlated regionally, without reference to shoreline trajectories.

- In upstream-controlled flu-vial settings, fluvial accommodation may change in-dependently of changes in accommodation at the nearest shoreline and create sequences and component low- and high-accommodation systems tracts.

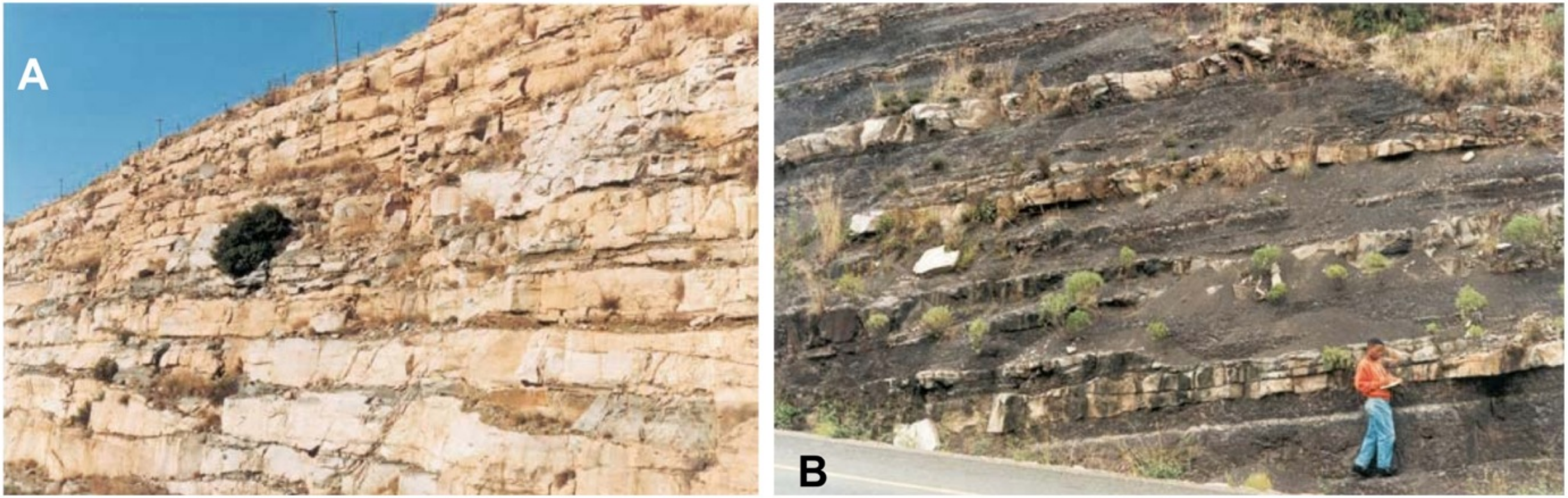
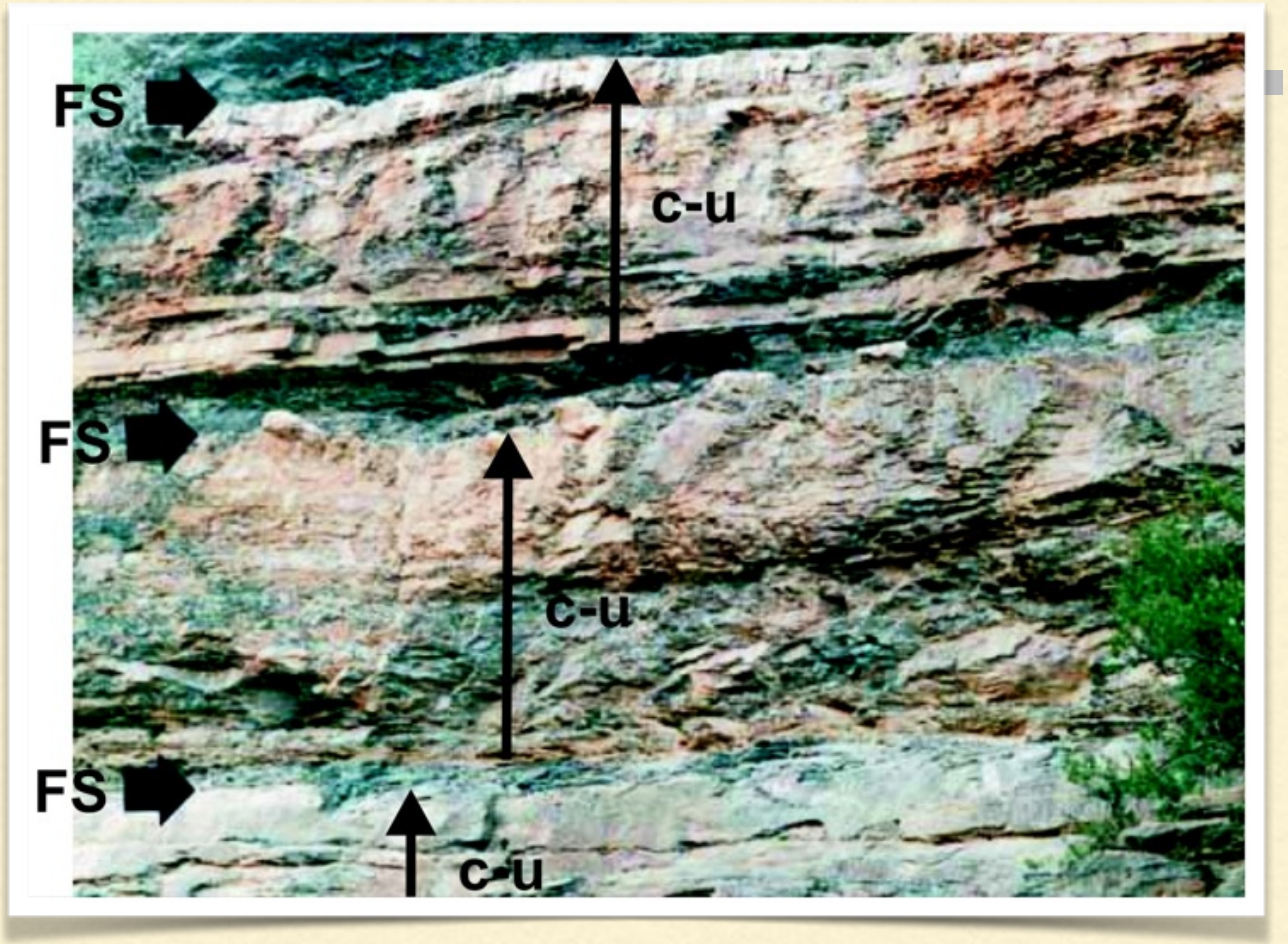


Fig. 9. Stratal stacking patterns in upstream-controlled fluvial systems. A – channel-dominated succession (low-accommodation setting: Katberg Formation, Early Triassic, Karoo Basin); B – overbank-dominated succession (high-accommodation setting: Burgersdorp Formation, Early-Middle Triassic, Karoo Basin).

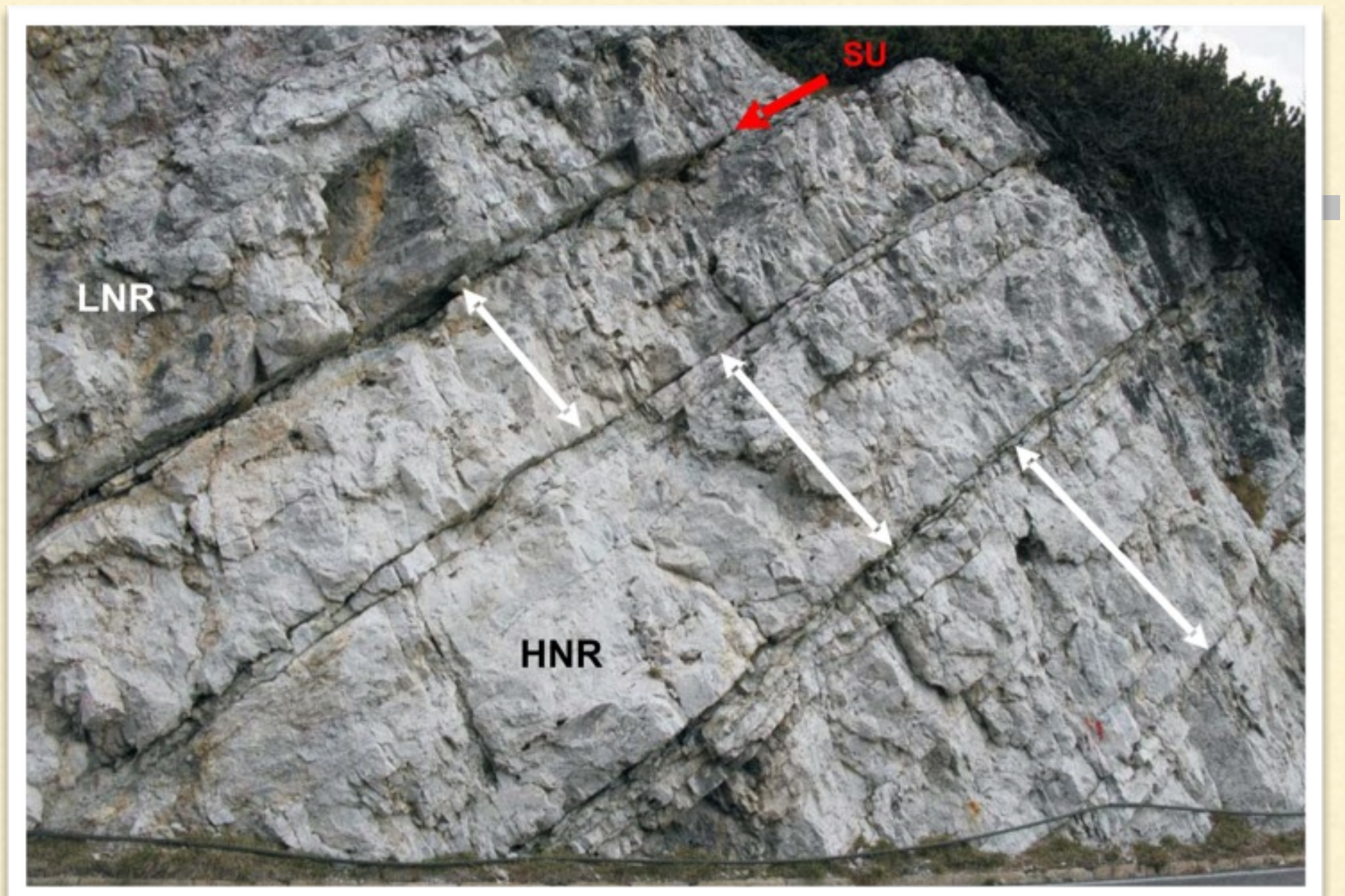
SEQUENCE STRATIGRAPHIC UNITS: PARASEQUENCES



Upstepping parasequences (Late Permian Water-ford Formation, Ecca Group, Karoo Basin).

- A parasequence in its original definition (Van Wagoner et al. 1988, 1990) is an upward-shallowing succession of facies bounded by marine flooding surfaces. A marine flooding surface is a lithological discontinuity across which there is an abrupt shift of facies that commonly indicates an abrupt increase in water depth.

SEQUENCE STRATIGRAPHIC UNITS: PARASEQUENCES

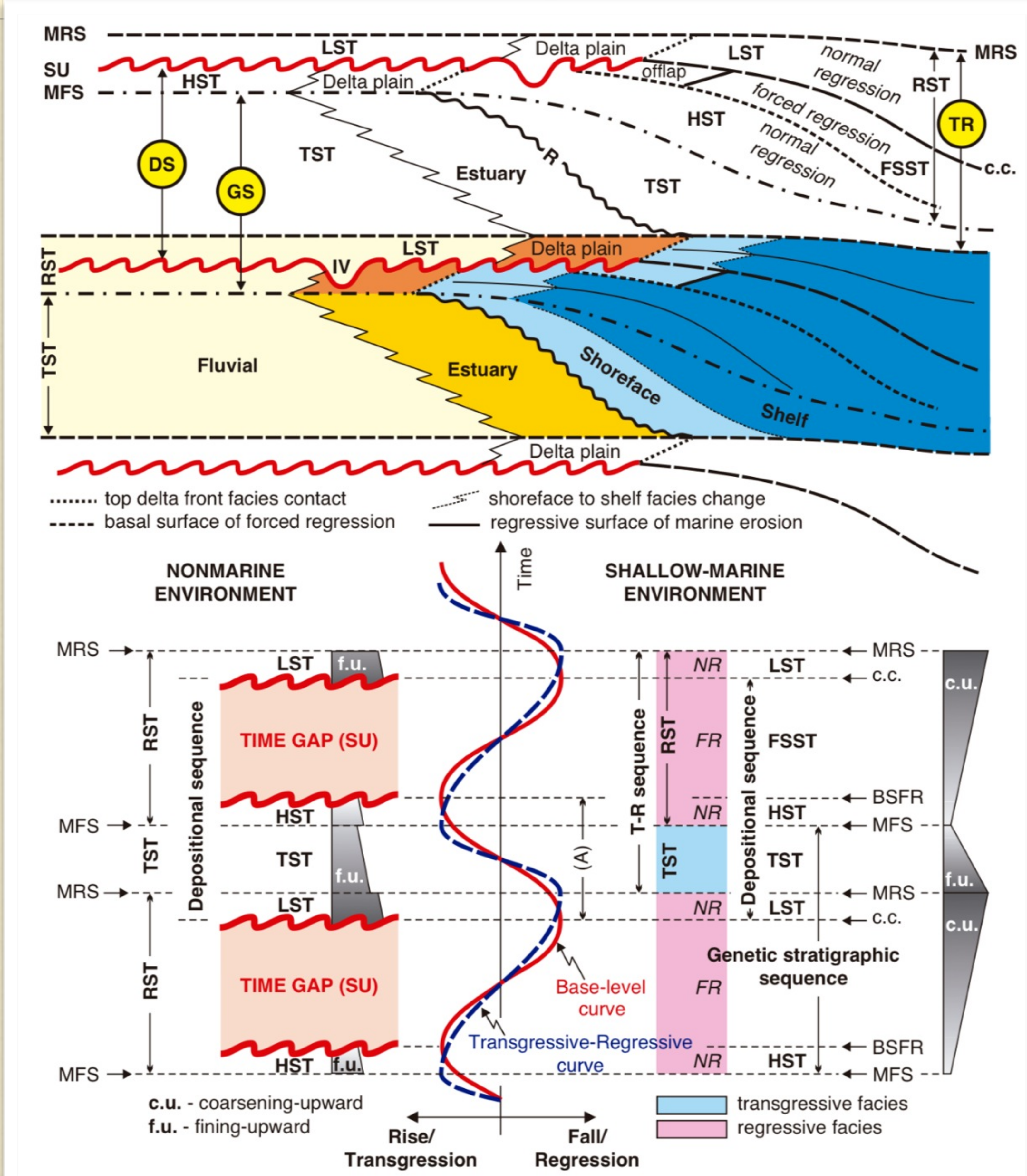


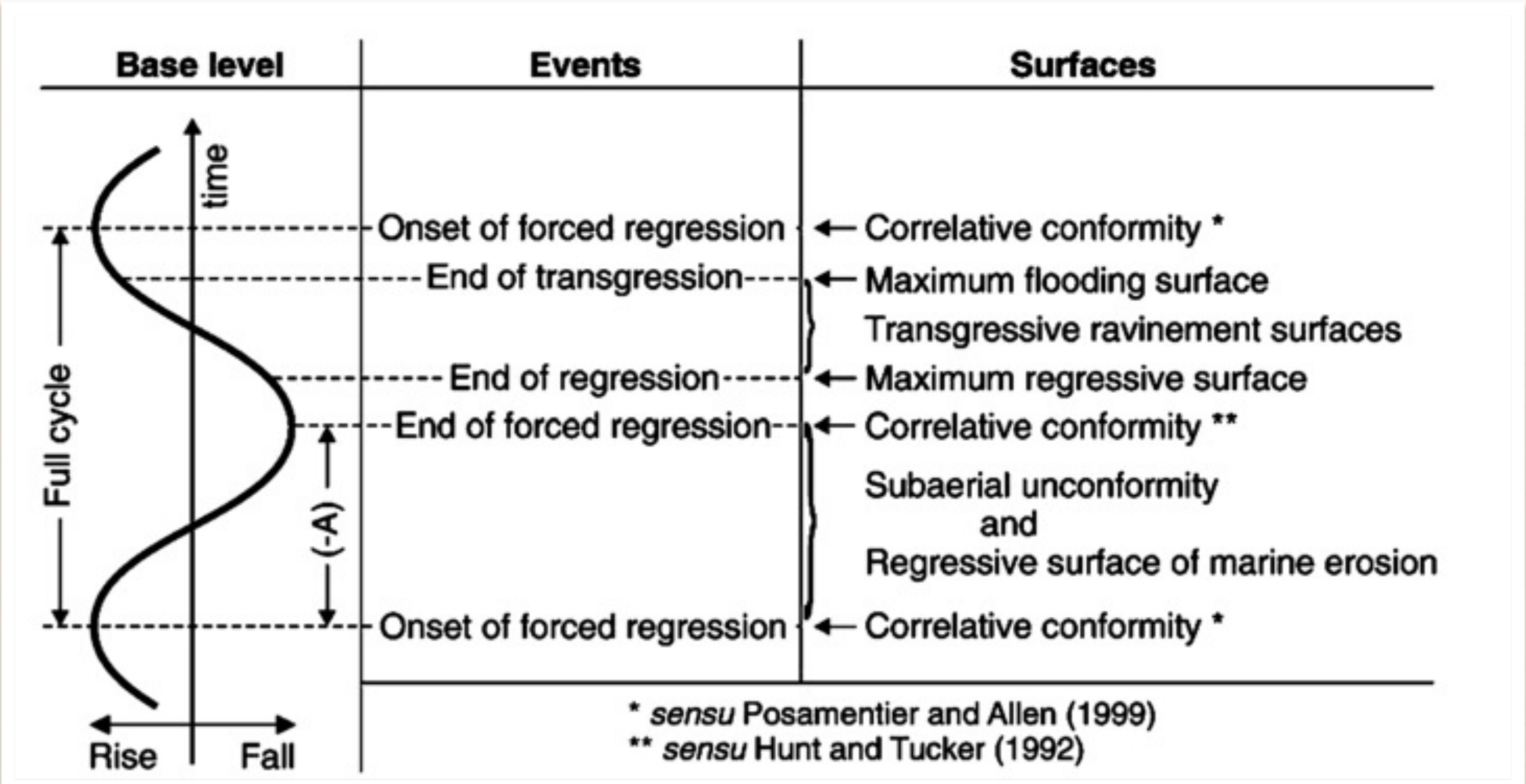
Peritidal cycles in a platform top setting (Triassic, The Dolomites, Italy).

- In carbonate settings, a parasequence corresponds to a succession of facies commonly contain-ing a lag deposit or thin deepening interval followed by a thicker shallowing-upward part, as for example in peritidal cycles

SEQUENCE STRATIGRAPHIC SURFACES

- Sequence stratigraphic surfaces mark changes in stratal stacking pattern. They are surfaces that can serve, at least in part, as systems tract boundaries. Sequence stratigraphic surfaces may correspond to 'conceptual' horizons (i. e., without a lithologic contrast) or physical surfaces, depending on their outcrop expression.
- Unconformable sequence stratigraphic surfaces typically have a physical expression.


MRS
SU
MFS
LST
HST
Delta plain
Delta plain
offlap
normal regression
forced regression
normal regression
RST
TR
c.c.
FSST
HST
TST
Estuary
R
TST
DS
GS
RST
TST
LST
IV
Delta plain
Fluvial
Estuary
Shoreface
Shelf
Delta plain
top delta front facies contact
basal surface of forced regression
shoreface to shelf facies change
regressive surface of marine erosion
NONMARINE ENVIRONMENT
Time
SHALLOW-MARINE ENVIRONMENT
MRS
LST
f.u.
TIME GAP (SU)
HST
RST
Depositional sequence
MFS
TST
TST
f.u.
MRS
LST
TIME GAP (SU)
RST
HST
f.u.
MFS
(A)
T-R sequence
RST
TST
NR
FR
NR
NR
FR
NR
LST
FSST
HST
TST
LST
HST
Depositional sequence
MRS
c.c.
BSFR
MFS
MRS
c.c.
BSFR
MFS
c.u.
f.u.
c.u.
Genetic stratigraphic sequence
Base-level curve
Transgressive-Regressive curve
c.u. - coarsening-upward
f.u. - fining-upward
Rise/ Transgression
Fall/ Regression
transgressive facies
regressive facies


Base level
Events
Surfaces
time
Full cycle
(-A)
Rise
Fall
Onset of forced regression
End of transgression
End of regression
End of forced regression
Onset of forced regression
Correlative conformity *
Maximum flooding surface
Transgressive ravinement surfaces
Maximum regressive surface
Correlative conformity **
Subaerial unconformity
and
Regressive surface of marine erosion
Correlative conformity *
* *sensu* Posamentier and Allen (1999)
** *sensu* Hunt and Tucker (1992)

1- SUBAERIAL UNCONFORMITY

- The subaerial unconformity (Sloss et al. 1949) is an unconformity that forms under subaerial conditions as a result of fluvial erosion or bypass, pedogenesis, wind degradation, or dissolution and karstification.
- Alternative terms include: 'lowstand unconformity' (Schlager 1992), 'regressive surface of fluvial erosion' (Plint and Nummedal 2000), and 'fluvial entrenchment/incision surface' (Galloway 2004).

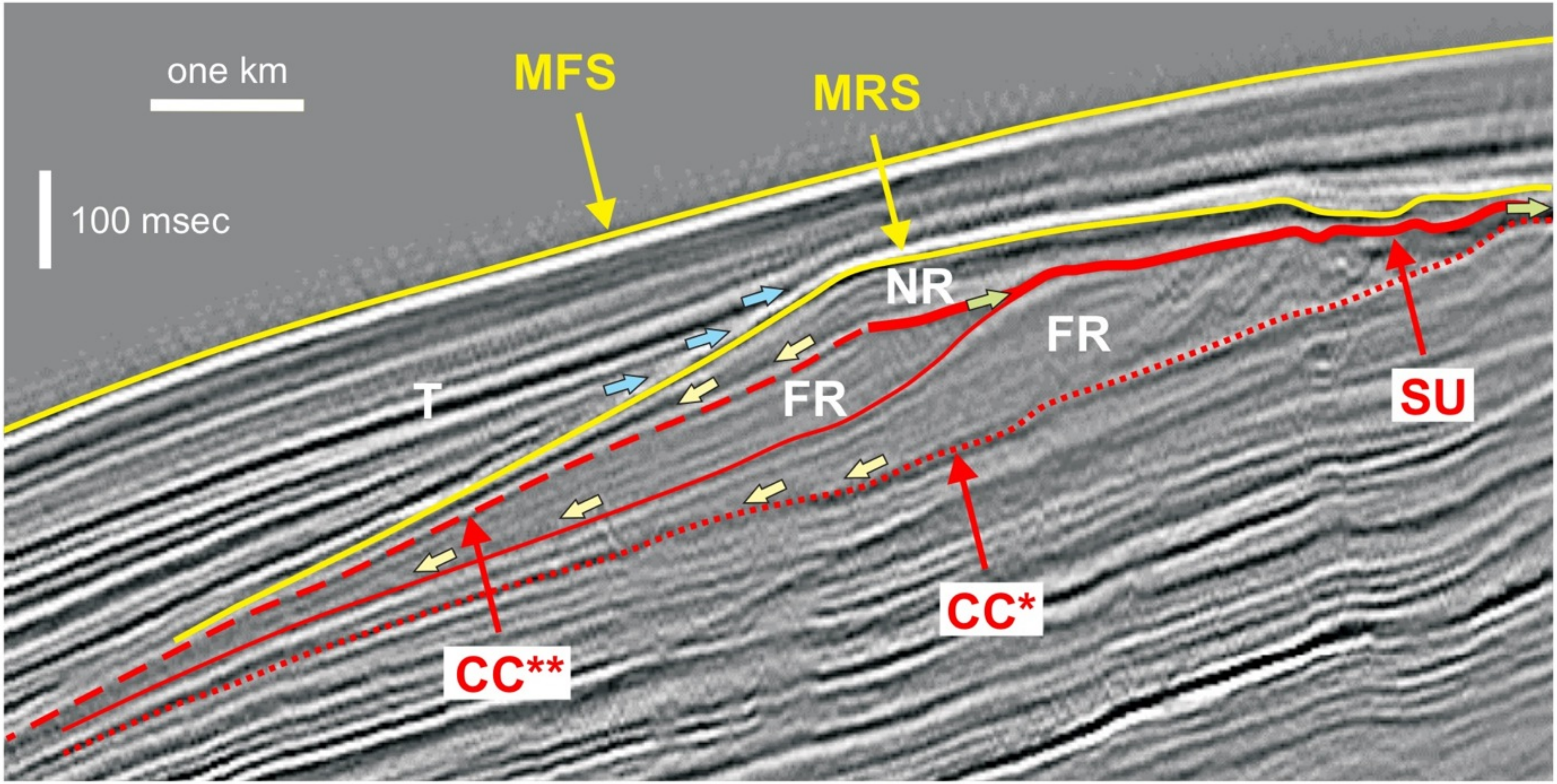
2- CORRELATIVE CONFORMITIES

- The correlative conformity in the sense of Posamentier et al. (1988) is a marine stratigraphic surface that marks the change in stratal stacking patterns from highstand normal regression to forced regression. It is the paleo-seafloor at the onset of forced regression. An alternative term is 'basal surface of forced regression' (Hunt and Tucker 1992).

- The correlative conformity in the sense of Hunt and Tucker (1992) is a marine stratigraphic surface that marks the change in stratal stacking patterns from forced regression to lowstand normal regression. It therefore records the paleo-seafloor at the end of forced regression.

3- MAXIMUM FLOODING SURFACE

- The maximum flooding surface (Frazier 1974; Posa-mentier et al. 1988; Van Wagoner et al. 1988; Gal-loway 1989) is a stratigraphic surface that marks a change in stratal stacking patterns from transgression to highstand normal regression.



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4- MAXIMUM REGRESSIVE SURFACE

- The maximum regressive surface (Helland-Hansen and Martinsen 1996) is a stratigraphic surface that marks a change in stratal stacking patterns from lowstand normal regression to transgression.
- It is the paleo-seafloor at the end of lowstand normal regression, and its cor-relative surface within the nonmarine setting.

5-TRANSGRESSIVE RAVINEMENT SURFACES

- The transgressive ravinement surfaces are erosional surfaces that form by means of wave scouring (i. e., wave-ravinement surfaces) or tidal scouring (i. e., tidal-ravinement surfaces) during transgression in coastal to shallow-water environments.
- Both types of transgressive ravinement surfaces are diachronous, younging towards the basin margin.

6- REGRESSIVE SURFACE OF MARINE EROSION

- The regressive surface of marine erosion is an erosional surface that forms typically by means of wave scouring during forced regression in wave-dominated shallow-water settings due to the lowering of the wave base relative to the seafloor.

- However, this scour may also form under conditions of high-energy normal regression, where the shoreline trajectory is horizontal (i. e., progradation during a stillstand of relative sea level) or rising at a low angle (i. e., prograda-tion during low rates of relative sea-level rise).

- The regressive surface of marine erosion is diachronous, younging basinward with the rate of shoreline regression.

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- Catuneanu, O., 2006. Principles of sequence stratigraphy. Elsevier, Amsterdam, 375P.

- Catuneanu, O., Galloway, W.L., Kendall, C.G.St.C., Miall, A.D., Posamentier, H.W., Strasser, A., Tucker, M.E. 2011. Sequence Stratigraphy: Methodology and Nomenclature. Newsletters on Stratigraphy, Stuttgart, Germany, Special Issue Vol. 44/3, pp. 173-245.