Istituto Nazionale di Oceanografia e di Geofisica Sperimentale

# Università degli studi di Trieste

## LAUREA MAGISTRALE IN GEOSCIENZE

**Classe Scienze e Tecnologie Geologiche**

## Curriculum: Esplorazione Geologica

## Anno accademico 2021 - 2022

# Analisi di Bacino e Stratigrafia Sequenziale (426SM)

Docente: **Michele Rebesco**

| *Modulo* | Argomento | Docente | Data |
|---|---|---|---|
| ***1.1*** | introduzione al corso e argomenti | Rebesco | 05/10/21 |
| ***1.2*** | metodi (geofisica, affioramenti, geologia marina, ambienti attuali) | Volpi/Rebesco | 06/10/21 |
| ***1.3*** | meccanismi di formazione dei bacini (geodinamica, tettonica…) | Lodolo | 12/10/21 |
| ***1.4*** | Interpretazione sismica, facies e strutture primarie | Rebesco | 13/10/21 |
| ***6.1*** | visita a Rompighiaccio Laura Bassi (assieme a Geologia Marina) | Rebesco | 15/10/22 |
| | Martedì 19 Ottobre non c'è lezione | | |
| ***1.5*** | Energy storage e CCS | Volpi/Donda | 20/10/21 |
| ***2.1*** | Processi sedimentari nei fiumi e nei delta | Rebesco | 26/10/21 |
| ***2.2*** | Azione di maree e onde, del ghiaccio e del vento | Rebesco | 27/10/21 |
| | Martedì 2 Novembre non c'è lezione | | |
| | Mercoledì 3 Novembre non c'è lezione | | |
| ***2.3*** | Correnti di densità e correnti di fondo, trasporto di massa | Lucchi/Rebesco | 09/11/21 |
| ***3.1*** | pianure abissali (decantazione emipelagica) e margini continentali | Rebesco | 10/11/21 |
| ***3.2*** | Conoidi sottomarine (flussi gravitativi dalla scarpata continentale) | Lucchi/Rebesco | 16/11/21 |
| ***3.3*** | Sediment drifts (correnti di fondo lungo la scarpata continentale) | Rebesco | 17/11/21 |
| ***3.4*** | Mass transport deposits (accenni a risoluzione/penetrazione) | Ford | 23/11/21 |
| ***3.5*** | Piattaforme continentali (onde, tempeste, tsunami) | Rebesco | 24/11/21 |
| ***3.6*** | Sistemi deposizionali in ambiente polare | De Santis | 30/11/21 |
| ***3.7*** | Sistema di barriera | Rebesco | 01/12/21 |
| ***3.8*** | Depositi alluvionali | Rebesco | 07/12/21 |
| | Mercoledì 8 e martedì 14 Dicembre non c'è lezione | | |
| ***3.9*** | Laghi, deserti e ambienti carbonartici | Rebesco | 15/12/21 |
| ***3.10*** | faglie, vulcani e approfondimento conoidi | Rebesco | 21/12/21 |
| ***4.1*** | stratigrafia sequenziale: introduction | Rebesco | 22/12/21 |
| | Dal 23 Dicembre al 9 Gennaio non c'è lezione | | |
| ***4.2*** | stratigrafia sequenziale: closer view | Rebesco | 11/01/22 |
| ***4.3*** | stratigrafia sequenziale: applicazioni (es. reservoirs di idrocarburi) | Rebesco | 12/01/22 |
| ***5*** | esercitazione | Rebesco | 18/01/22 |
| ***6.2*** | visita a CoreLoggingLAB (assieme a Geologia Marina) | Rebesco | 19/01/22 |
| ***6.3*** | visita a OGS e SEISLAB (assieme a Geologia Marina) | Rebesco | 21/01/22 |

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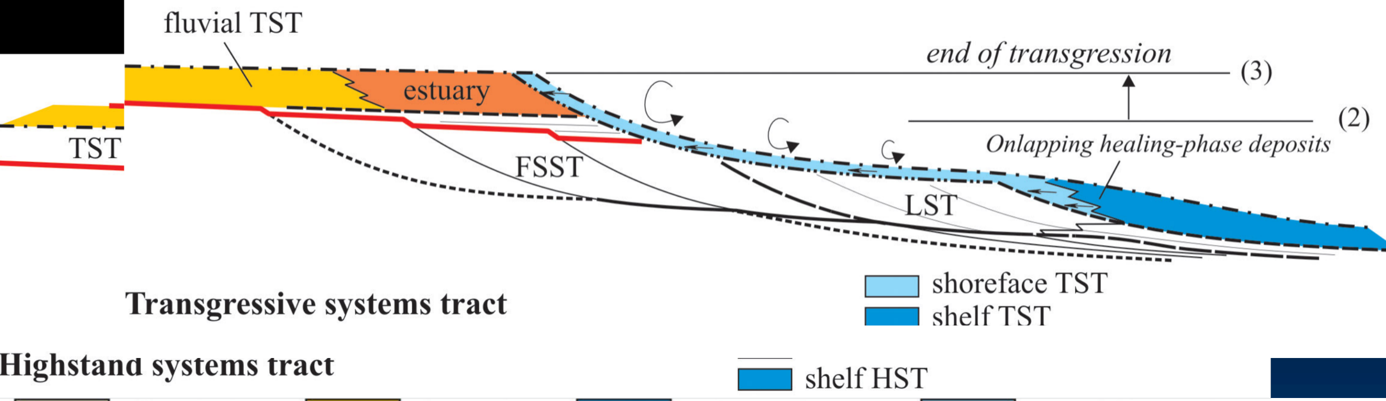
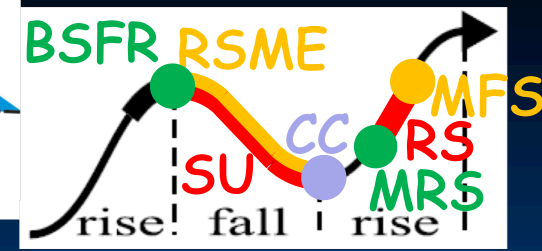
# Modulo 4.3
# Sequence stratigraphy – closer view

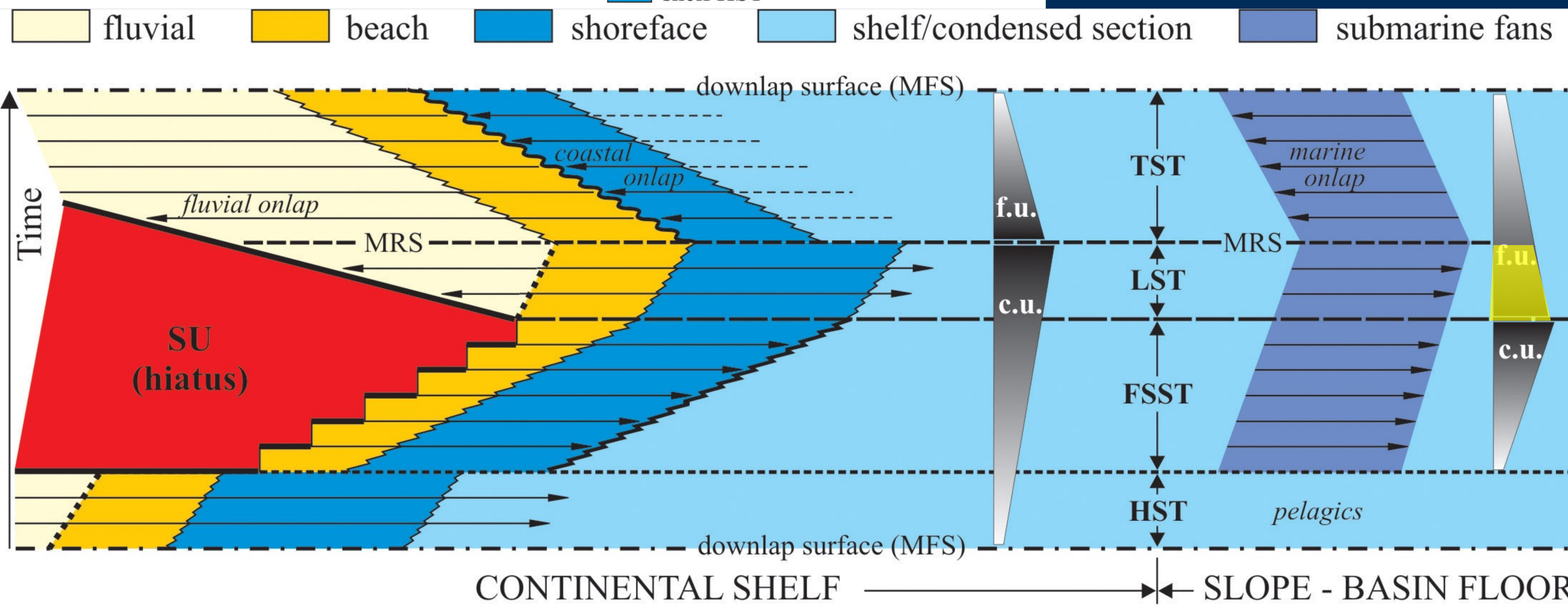
## Docente: Massimo Zecchin

Outline:
- Examples and Questions
- Sequence stratigraphic models
- Exercise
- Application to reservoir geology

<u>Question</u>:
chiarire i termini diacrona e isocrona.



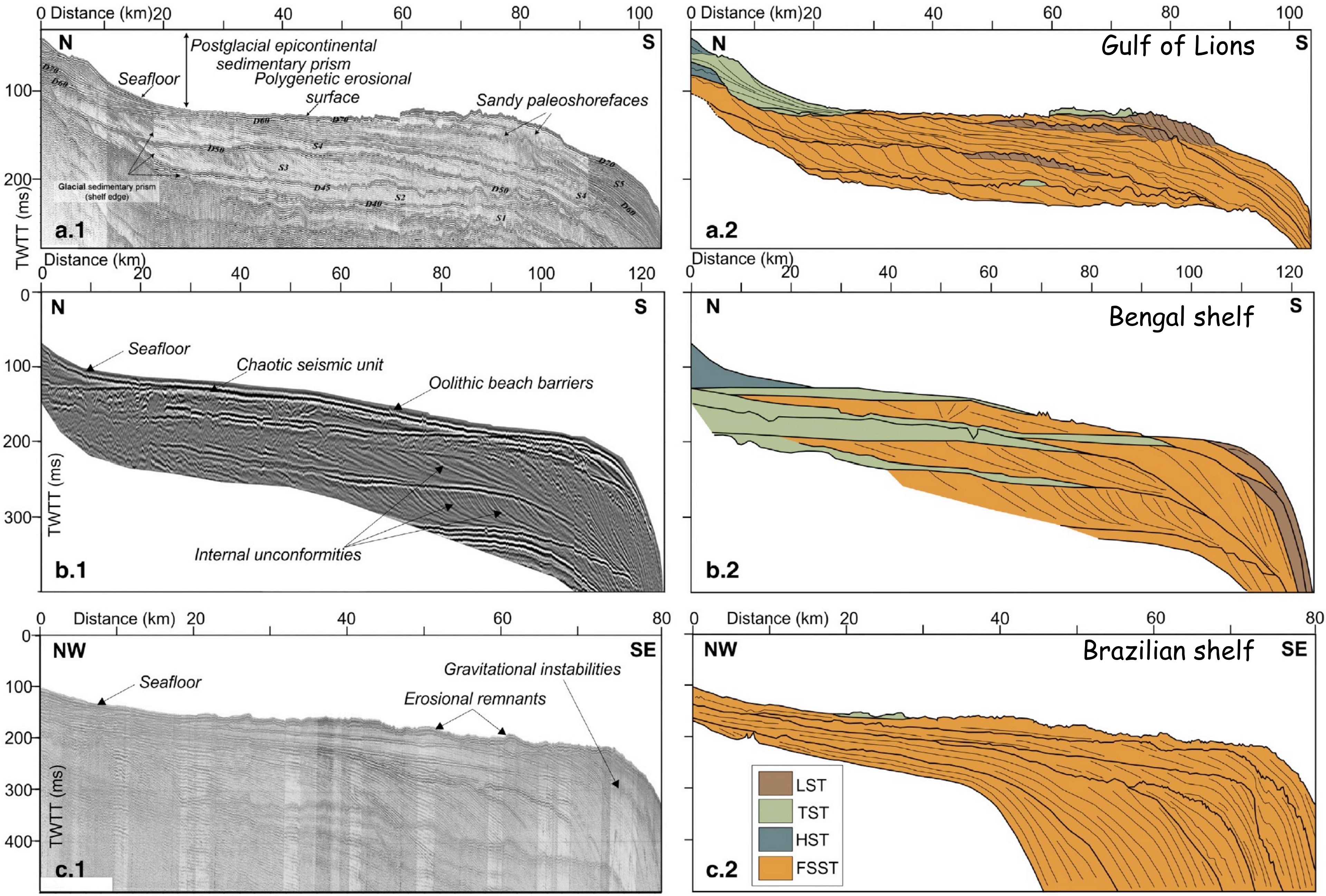




# Wheeler diagram

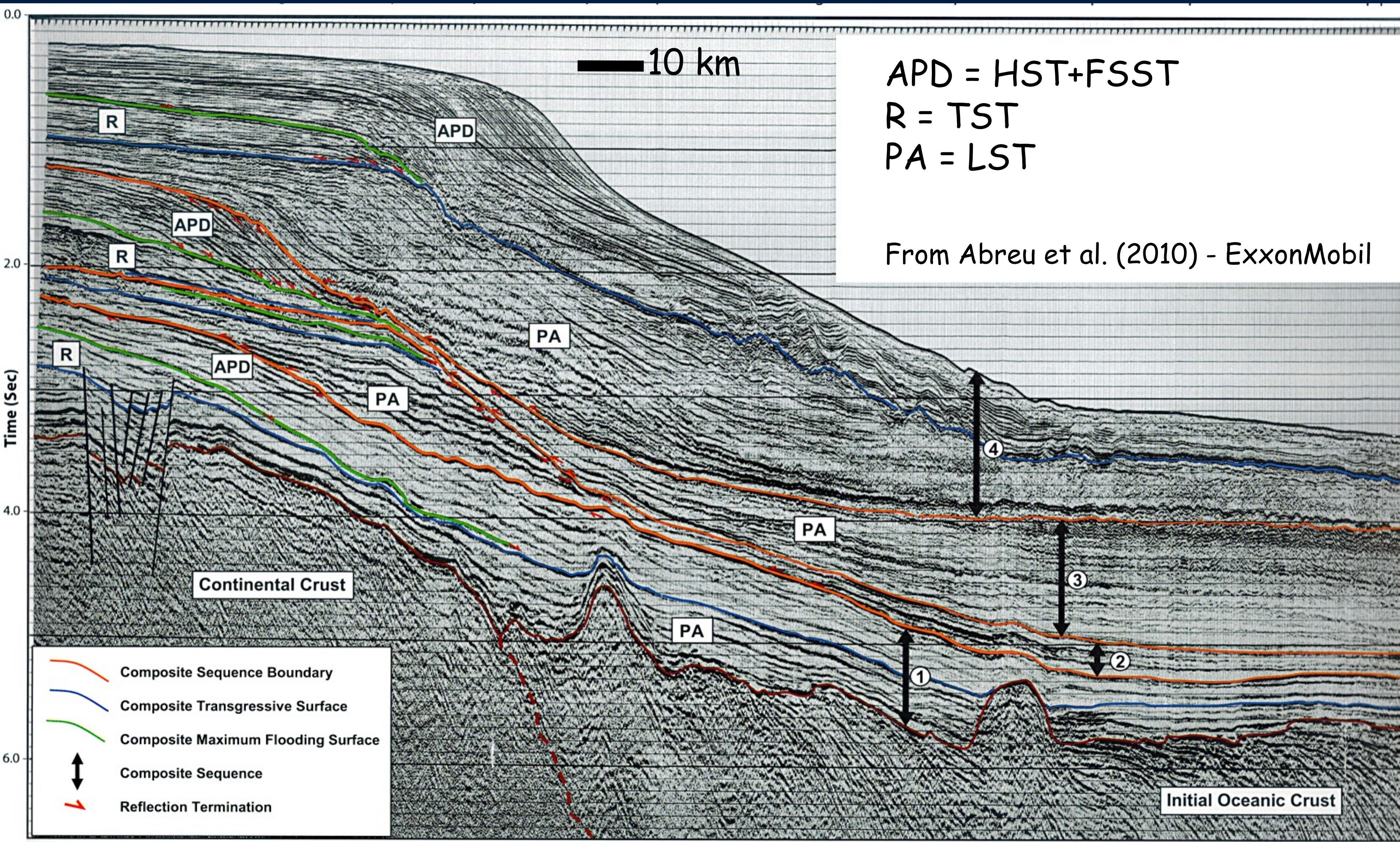
- subaerial unconformity
- correlative conformity
- regressive surface of marine erosion
- basal surface of forced regression
- onlap
- maximum regressive surface
- maximum flooding surface
- transgressive ravinement surface
- within-trend normal regressive surface
- downlap

# Upper Pleistocene shelf

From Lobo & Ridente (2013)



# Pelotas Basin (southern Brazil)
# Four sequences from Aptian to Present

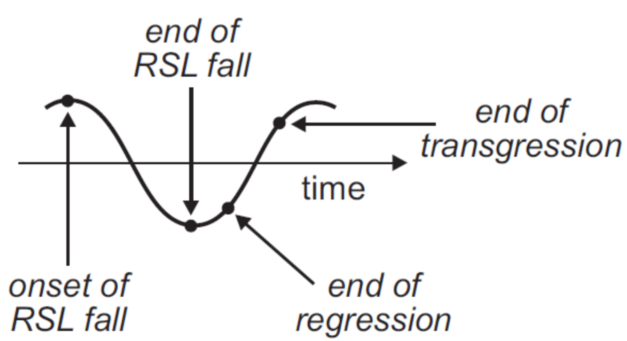


# Sequence stratigraphic models

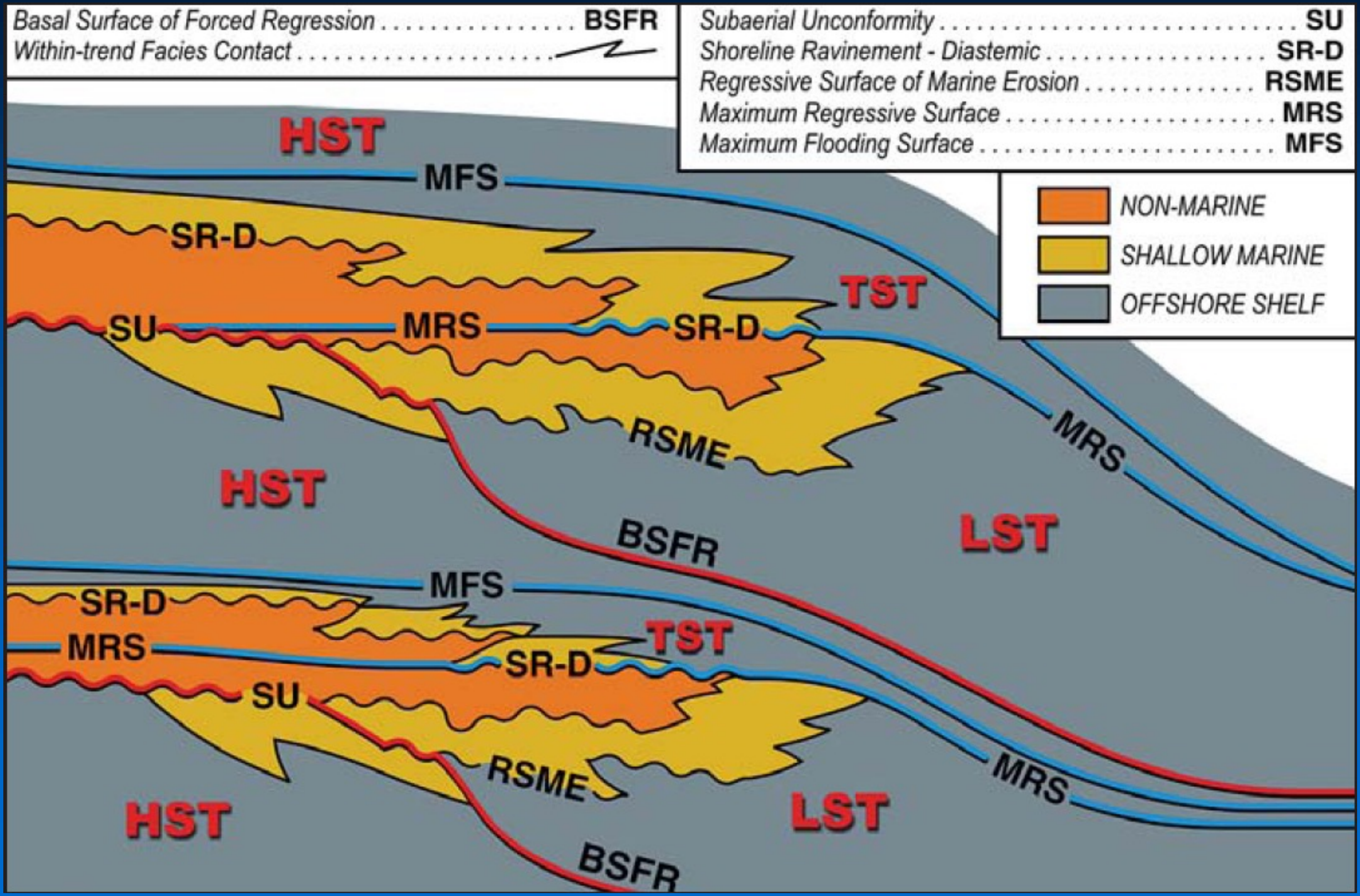
| Events and stages \ Sequence model | Mitchum et al. (1977): Depositional Sequence I | Posamentier et al. (1988): Depositional Sequence II | Van Wagoner et al. (1988): Depositional Sequence III | Hunt & Tucker (1992): Depositional Sequence IV | Galloway (1989): Genetic Sequence | Johnson & Murphy (1984): T-R Sequence |
|---|---|---|---|---|---|---|
| HNR | | HST | early HST | HST | HST | RST |
| *end of T* | | | | | MFS | |
| T | Sequence | TST | TST | TST | TST | TST |
| *end of R* | | | | | | MRS |
| LNR | | late LST (wedge) | LST | LST | late LST (wedge) | |
| *end of RSL fall* | | | | CC** | | |
| FR | | early LST (fan) | late HST | FSST | early LST (fan) | RST |
| *onset of RSL fall* | CC* | CC* | | | | |
| HNR | | HST | early HST | HST | HST | |

time

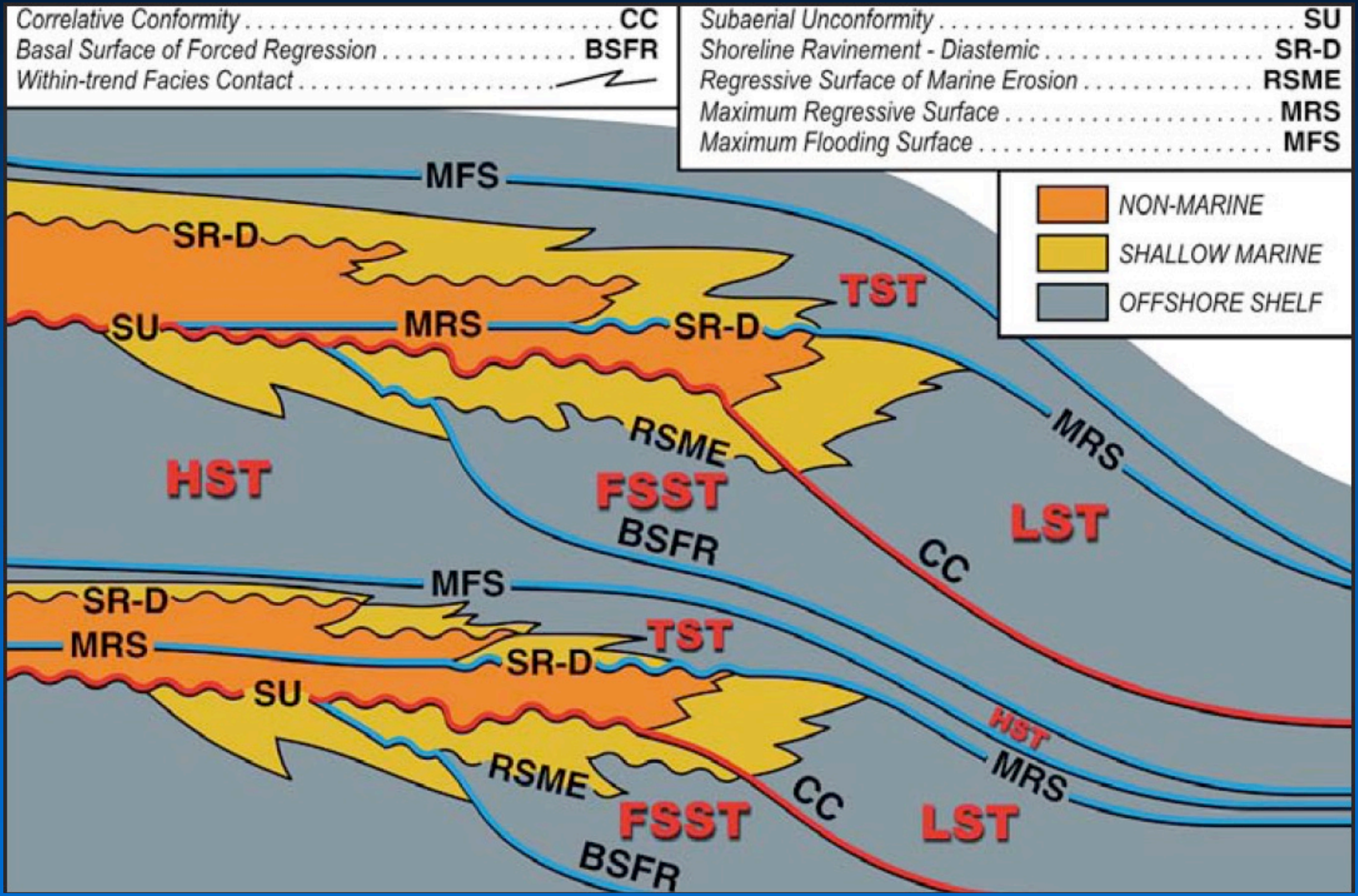
sequence boundary
systems tract boundary
within-sequence surface
within-systems tract surface



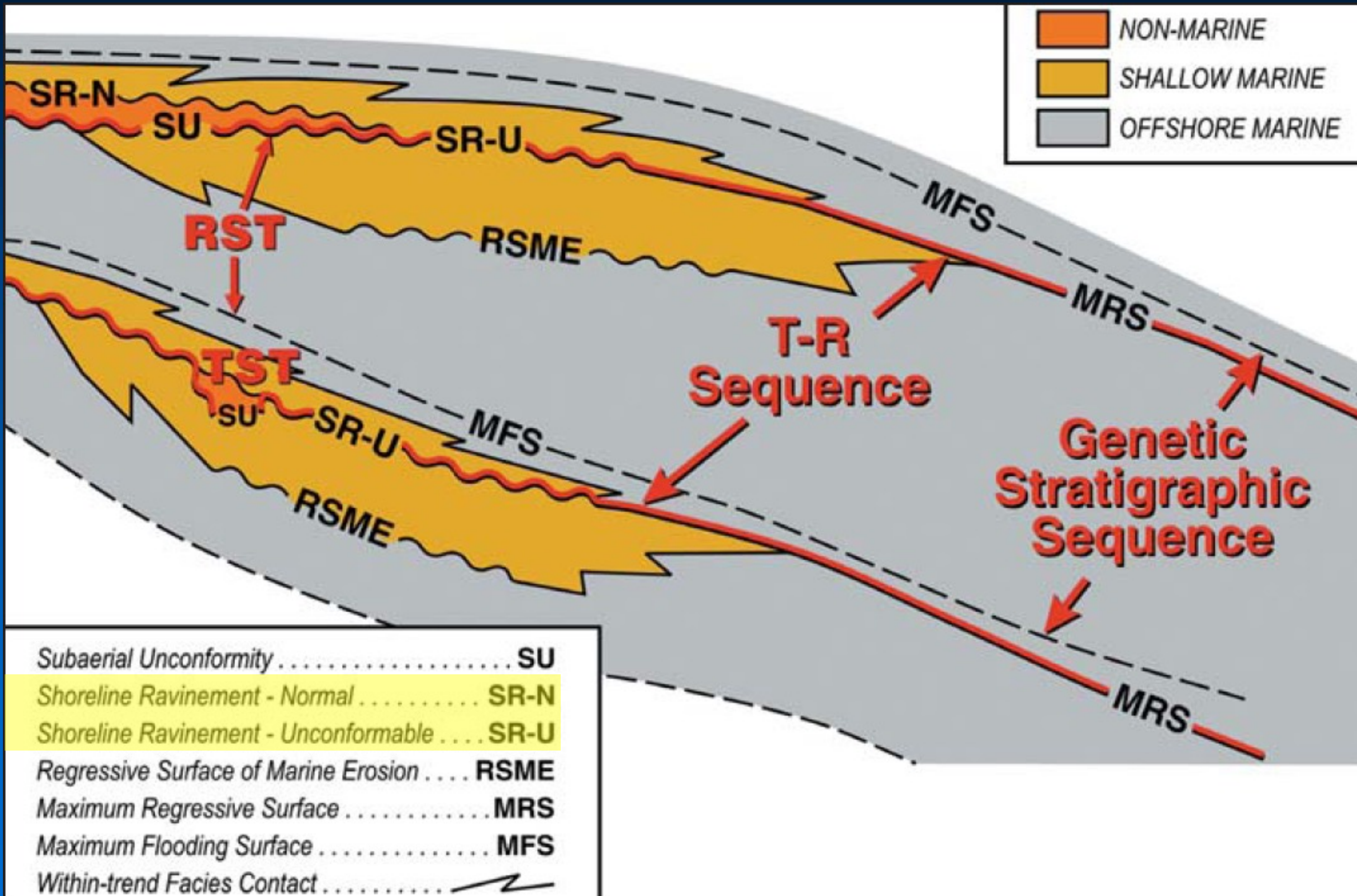
# Depositional sequence of Posamentier & Allen, 1999



# Depositional sequence of Hunt & Tucker, 1992 and Helland-Hansen & Gjelberg, 1994

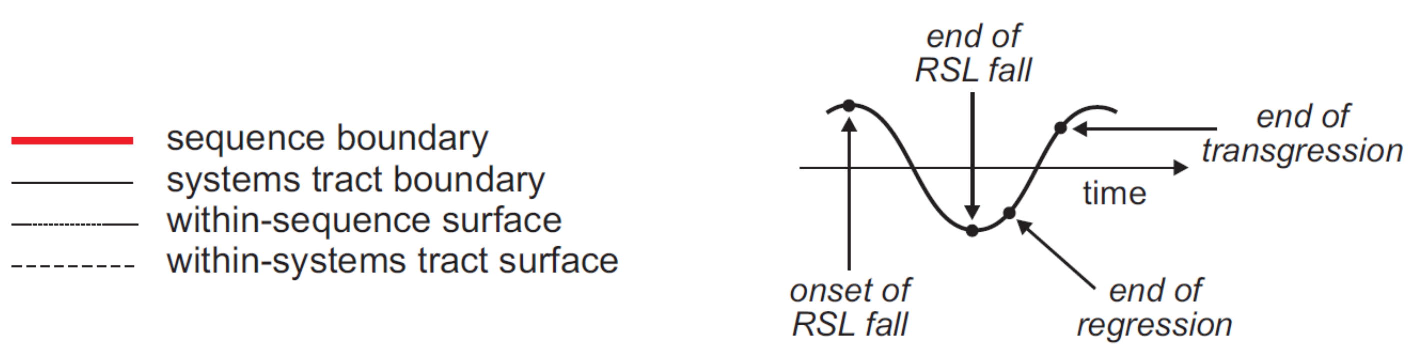


# T-R and genetic sequences

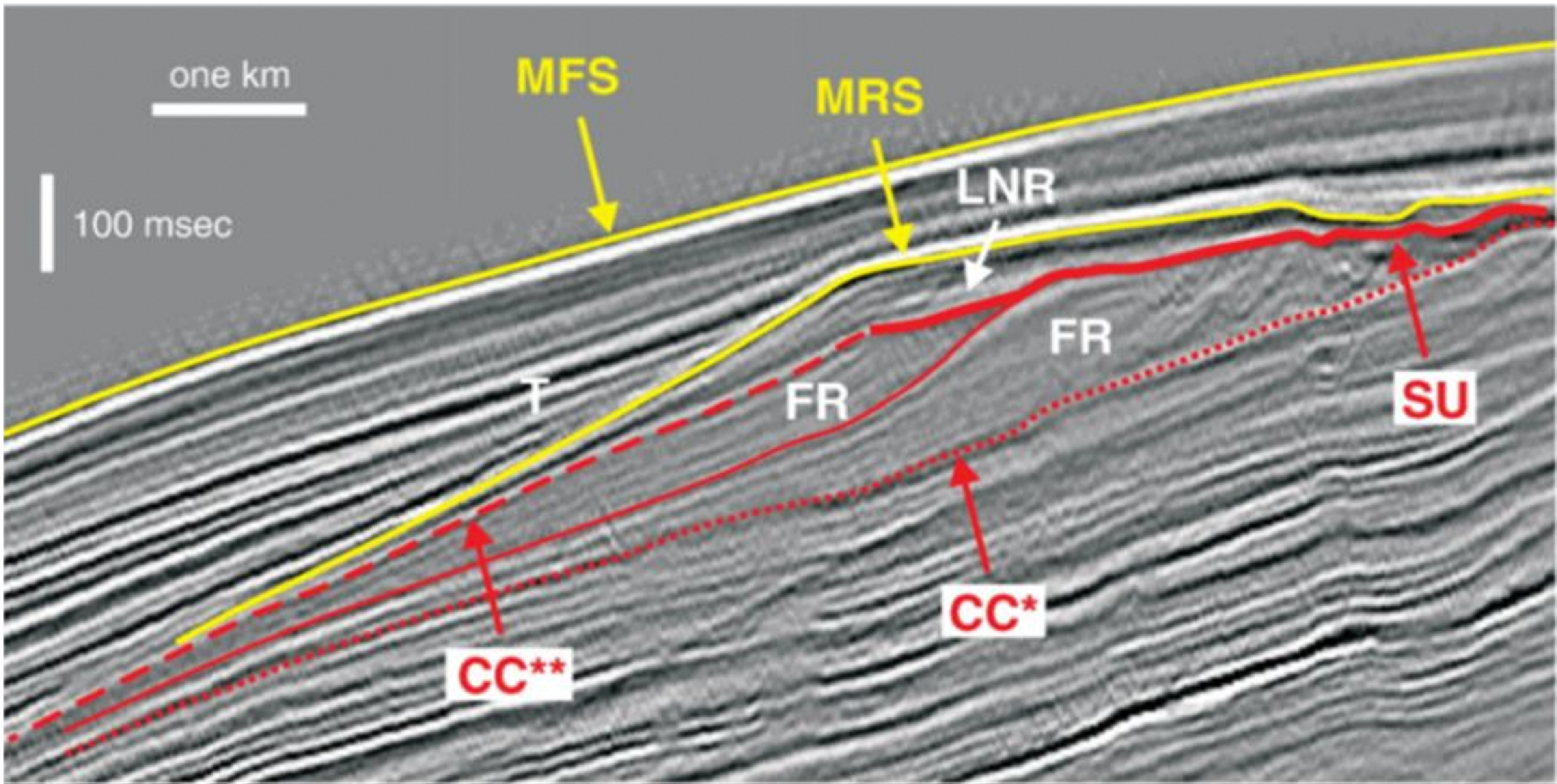


# Sequence stratigraphic models

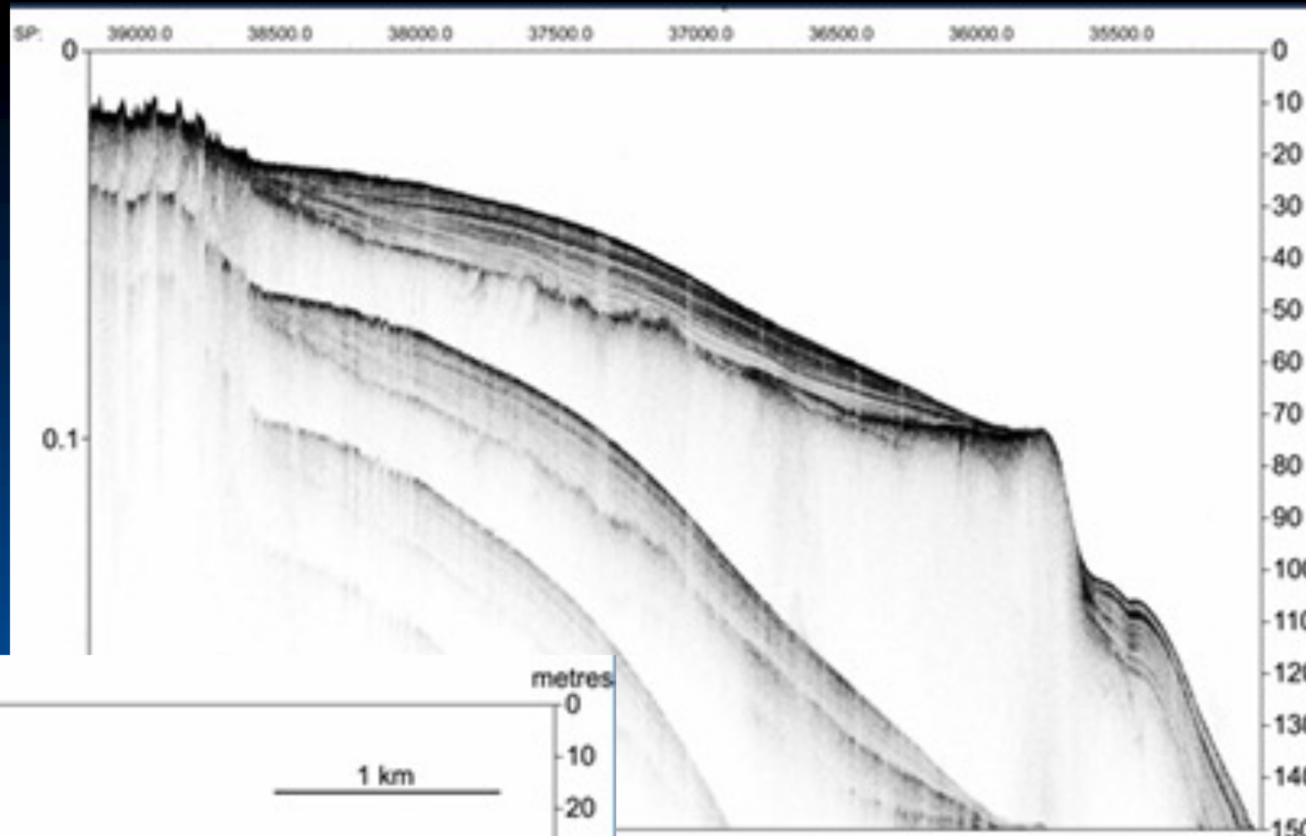
| Events and stages \ Sequence model | Depositional Sequence I (Mitchum et al. (1977)) | Depositional Sequence II (Posamentier et al. (1988)) | Depositional Sequence III (Van Wagoner et al. (1988)) | Depositional Sequence IV (Hunt & Tucker (1992)) | Genetic Sequence (Galloway (1989)) | T-R Sequence (Johnson & Murphy (1984)) |
|---|---|---|---|---|---|---|
| HNR | | HST | early HST | HST | HST | RST |
| *end of T* | | | | | MFS | |
| T | Sequence | TST | TST | TST | TST | TST |
| *end of R* | | | | | | MRS |
| LNR | | late LST (wedge) | LST | LST | late LST (wedge) | RST |
| *end of RSL fall* | | | | CC** | | |
| FR | | early LST (fan) | late HST | FSST | early LST (fan) | |
| *onset of RSL fall* | CC* | CC* | | | | |
| HNR | | HST | early HST | HST | HST | |

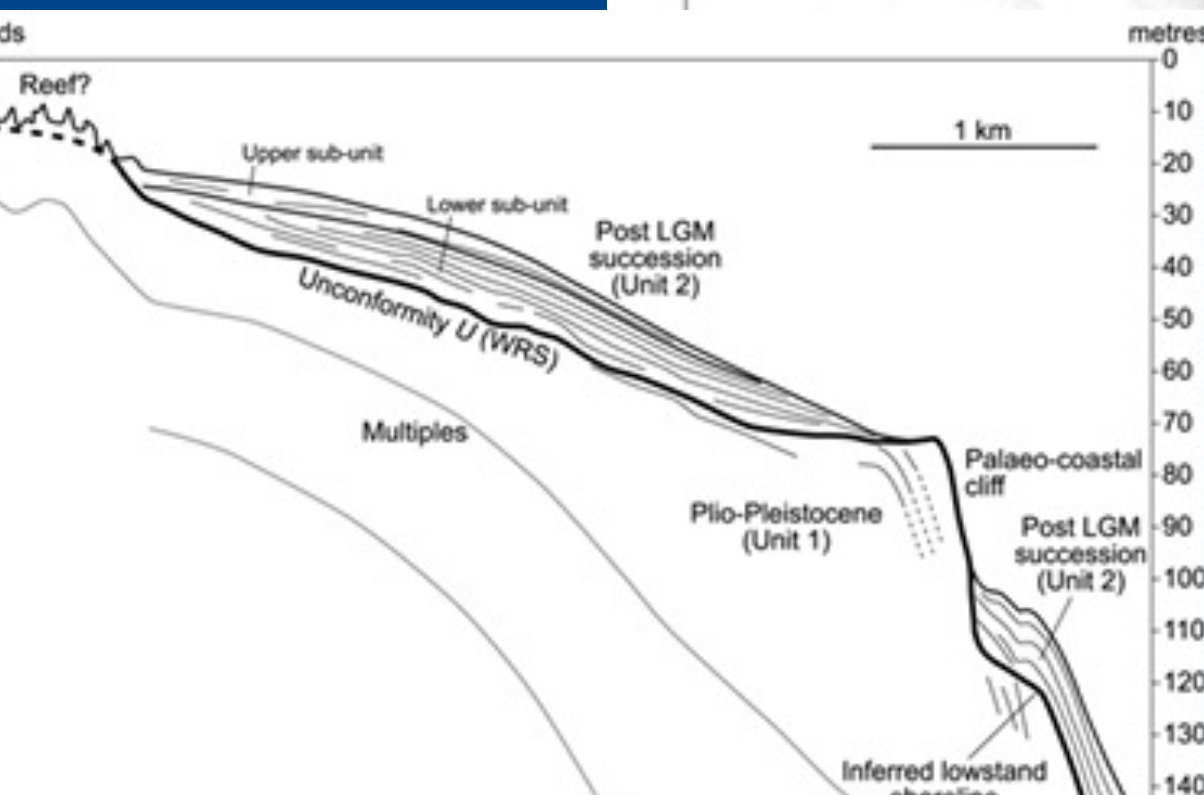


# Esercizio:tentare voi di identificare i system tracts e segnare le superfici stratigrafiche



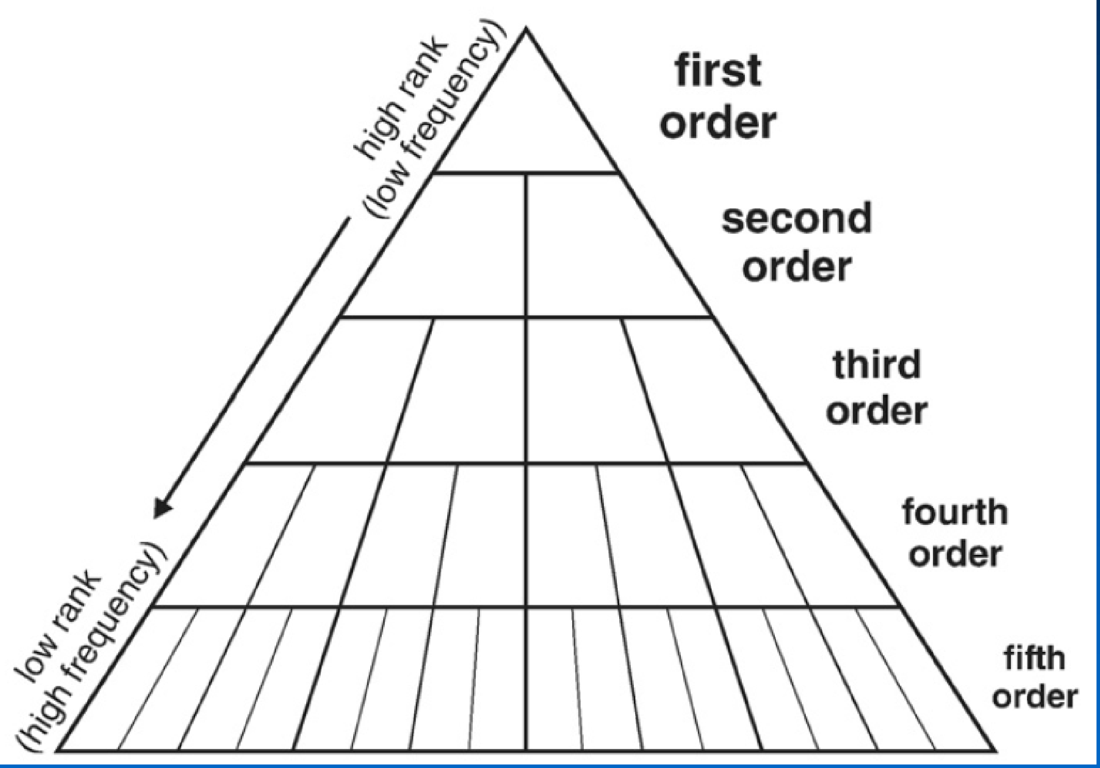
# Ravinement surface (RS)




Off Crotone
Zecchin et al. (2011)
Amendolara bank

# Sequence hierarchy

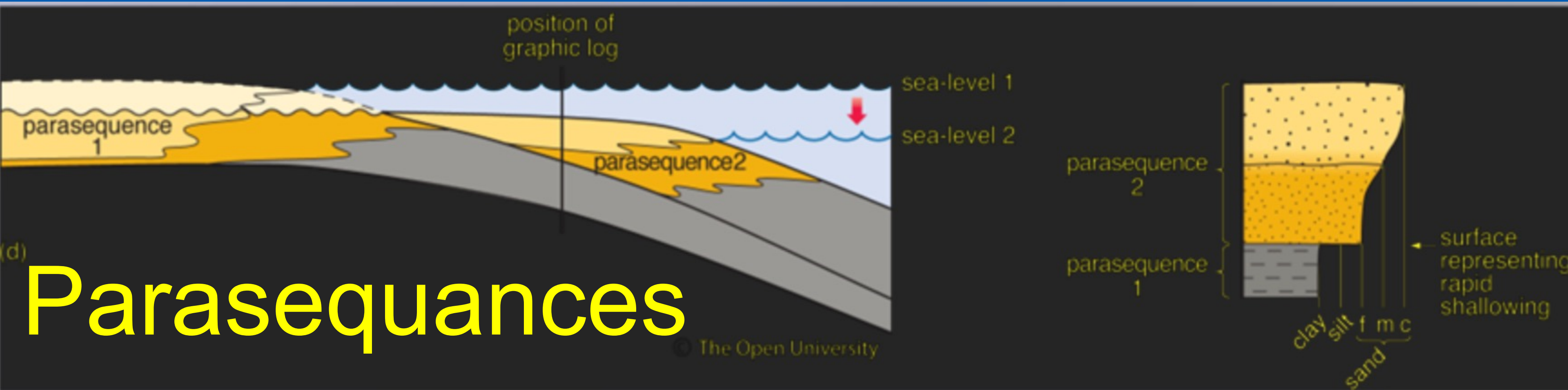



| | Ma |
|---|---|
| First order | 50+ |
| Second order | 3-50 |
| Third order | 0.5-3 |
| Fourth order | 0.08-0.5 |
| Fifth order | 0.03-0.08 |
| Sixth order | 0.01-0.03 |

From Vail et al. (1991)

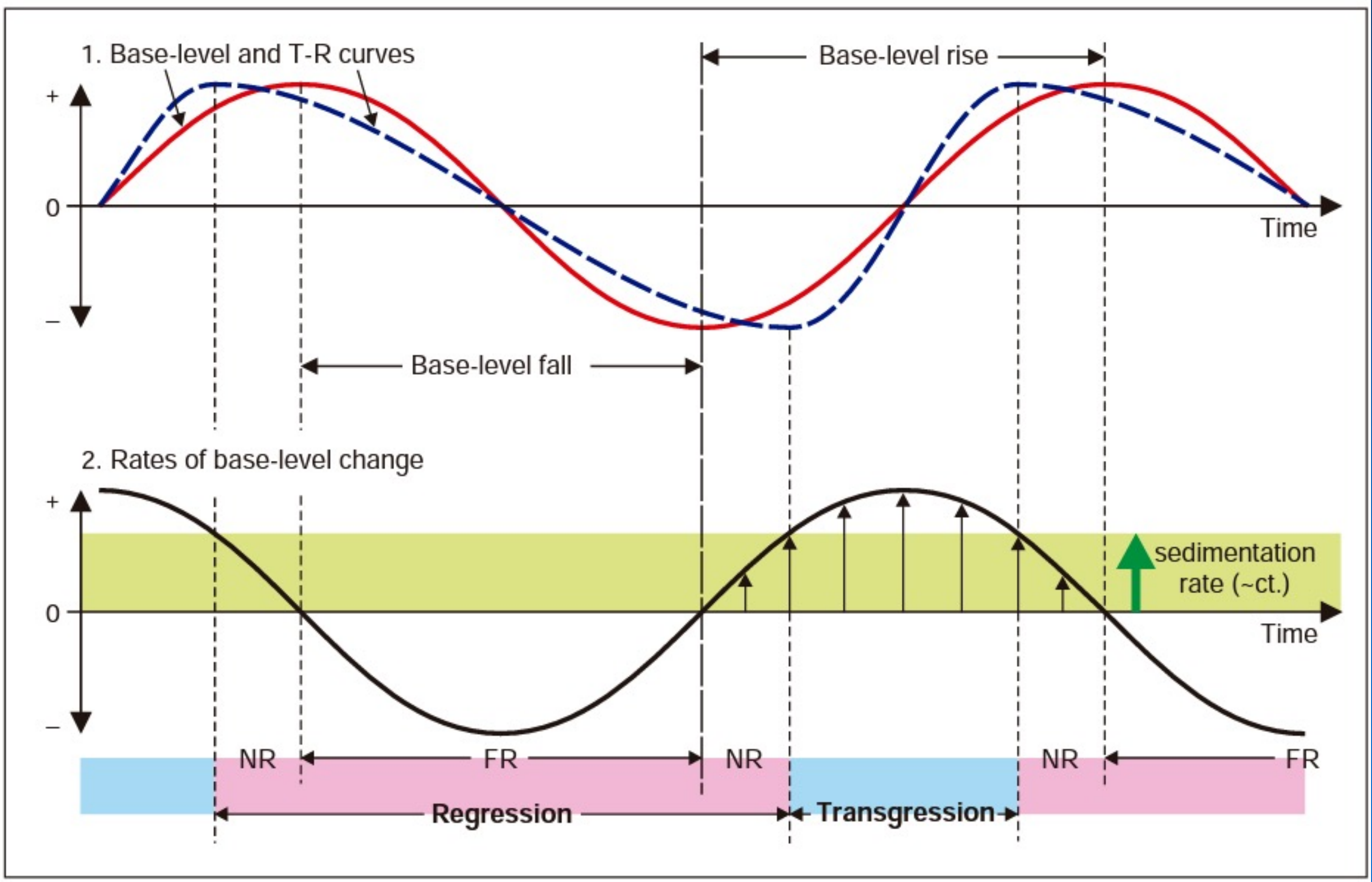
The ‘parasequence’ is a stratigraphic unit defined as ‘a relatively conformable succession of genetically related beds or bedsets bounded by flooding surfaces’. Parasequences are commonly identified with the coarsening-upward prograding lobes in coastal to shallow-marine settings. Such parasequences are usually the higher frequency building blocks of successions associated with overall trends of coastal progradation or retrogradation, so they may be part of larger-scale systems tracts. Depending on the scale of observation, parasequences could be placed within the context of larger-scale systems tracts, or they could be studied in relation to discrete cycles of changing depositional trends. Overall, there has been more confusion than advantage associated with the usage of the parasequence concept.

# Parasequances



# Base-level and transgressive–regressive (T–R) curves.

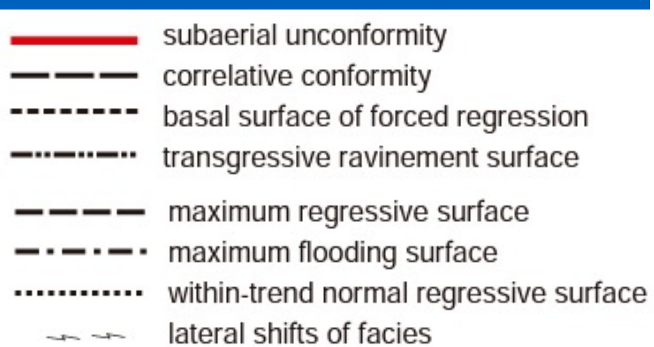
Sequence stratigraphic surfaces, and systems tracts, are all defined relative to these curves. The T–R curve, describing the shoreline shifts, is the result of the interplay between sedimentation and base-level changes at the shoreline.

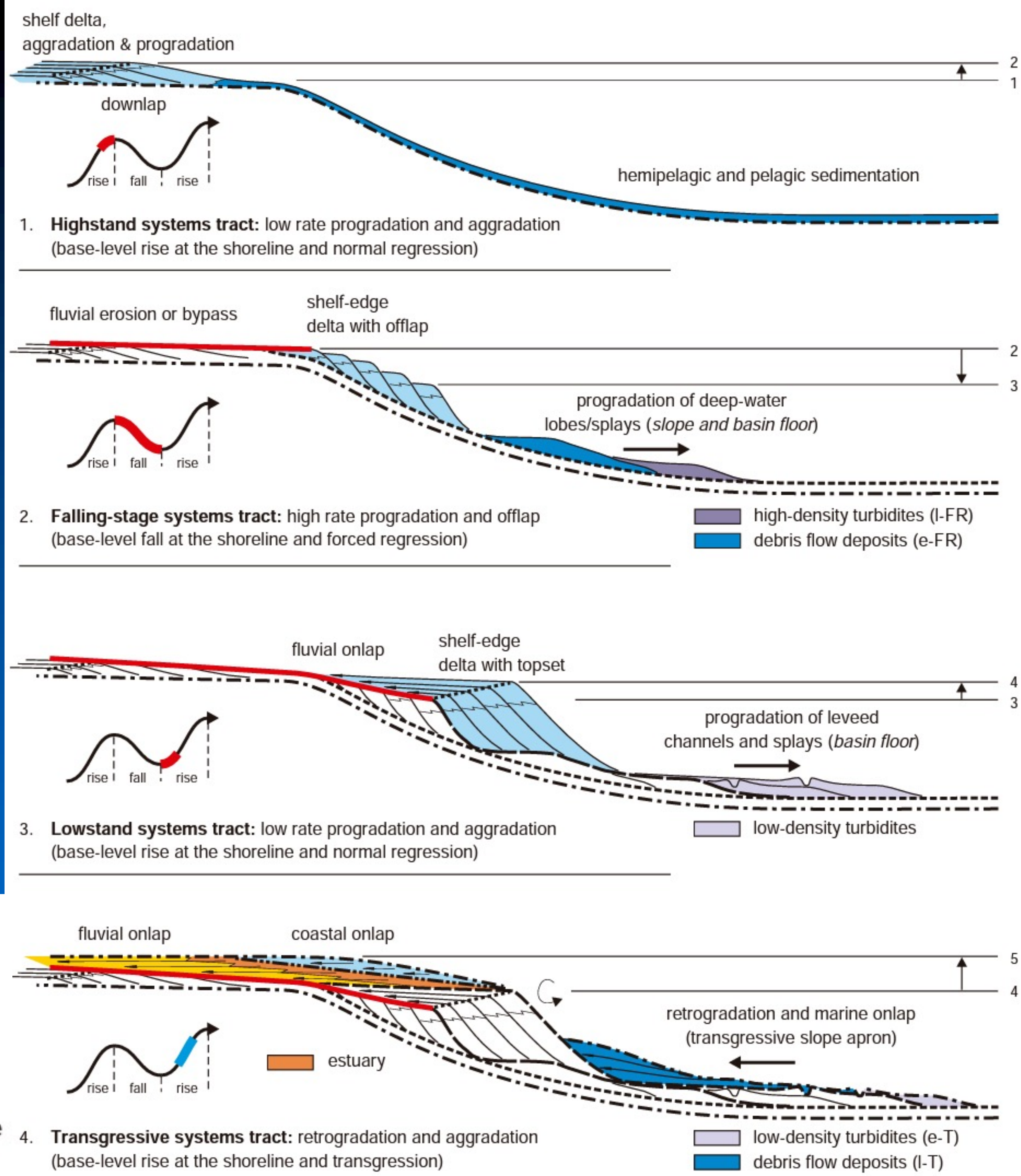



Sedimentation rates during a cycle of base-level change are considered constant and the reference baselevel curve is shown as a symmetrical sine curve, only for simplicity.

# Regional architecture of depositional systems (modified from Catuneanu, 2002)

downlapping clinoforms are concave-up, whereas transgressive ‘healing phase’ strata associated with coastal and marine onlap tend to be convex-up



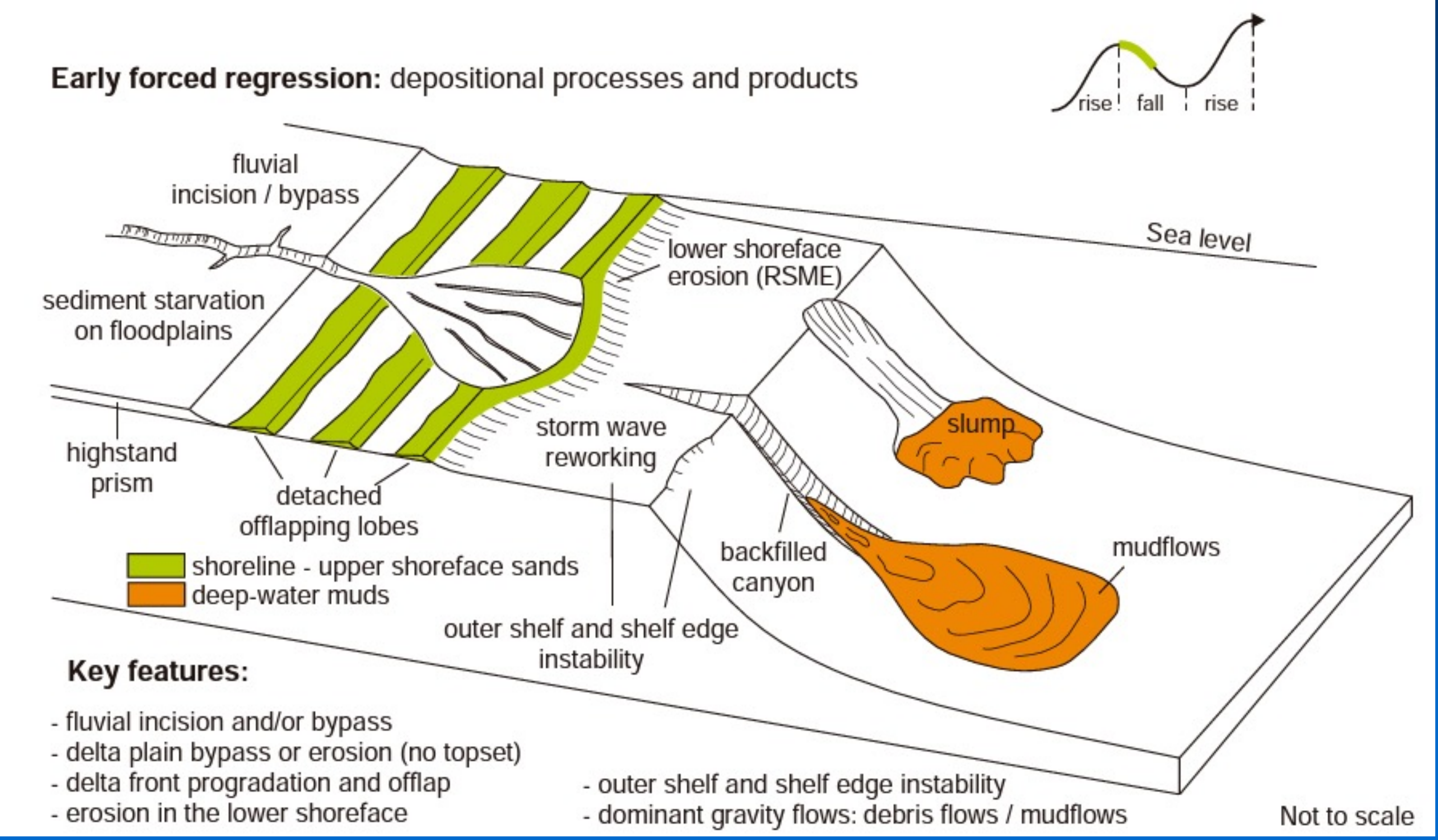



# Grading trends along vertical profiles through the fluvial, shallow- and deep-water portions of the various systems tracts.

| Systems tract / Environment | HST | | FSST | | LST | | TST | |
|---|---|---|---|---|---|---|---|---|
| | maximum grain size | sand-mud ratio | maximum grain size | sand-mud ratio | maximum grain size | sand-mud ratio | maximum grain size | sand-mud ratio |
| **Fluvial** | Upward decrease(1) | Upward increase(2) | N/A(3) | | Upward decrease(4) | | Upward decrease(4) | |
| **Shallow water** | Upward increase(5) | | Upward increase(5) | | Upward increase(5) | | Upward decrease(6) | |
| **Deep water** | N/A(7) | | Upward increase(8) | | Upward decrease(9) | | Upward decrease(10) | |

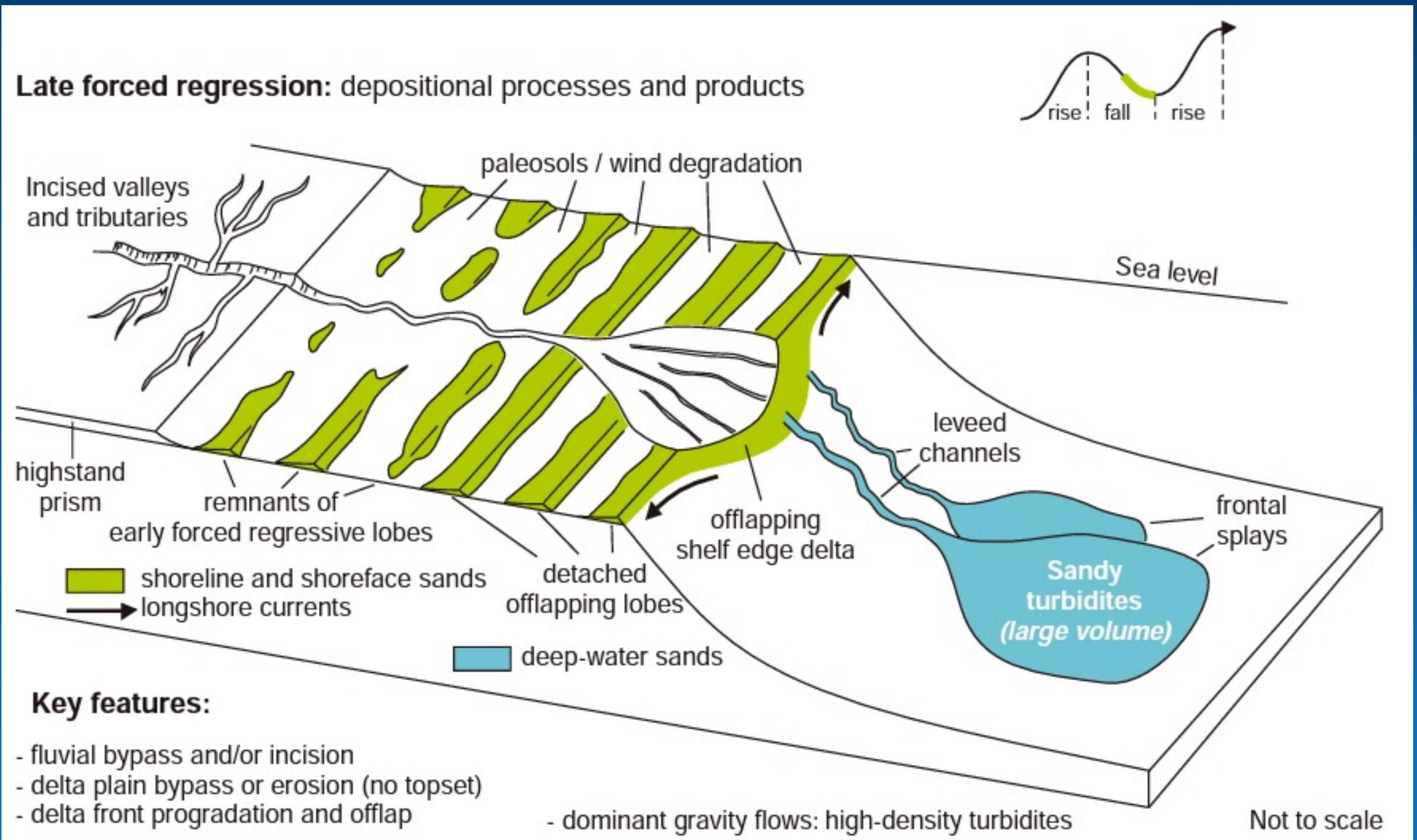
The trends of change in maximum grain size and sand/mud ratio correlate in general, with the exception of the highstand fluvial systems (shaded area).

# Depositional processes and products of the early falling-stage systems tract (modified from Catuneanu, 2003).




Most of the sand that accumulates during this stage is captured within detached and offlapping shoreline to upper shoreface systems. A significant amount of finer-grained sediment starts to accumulate in the deep-water environment as mudflow deposits.

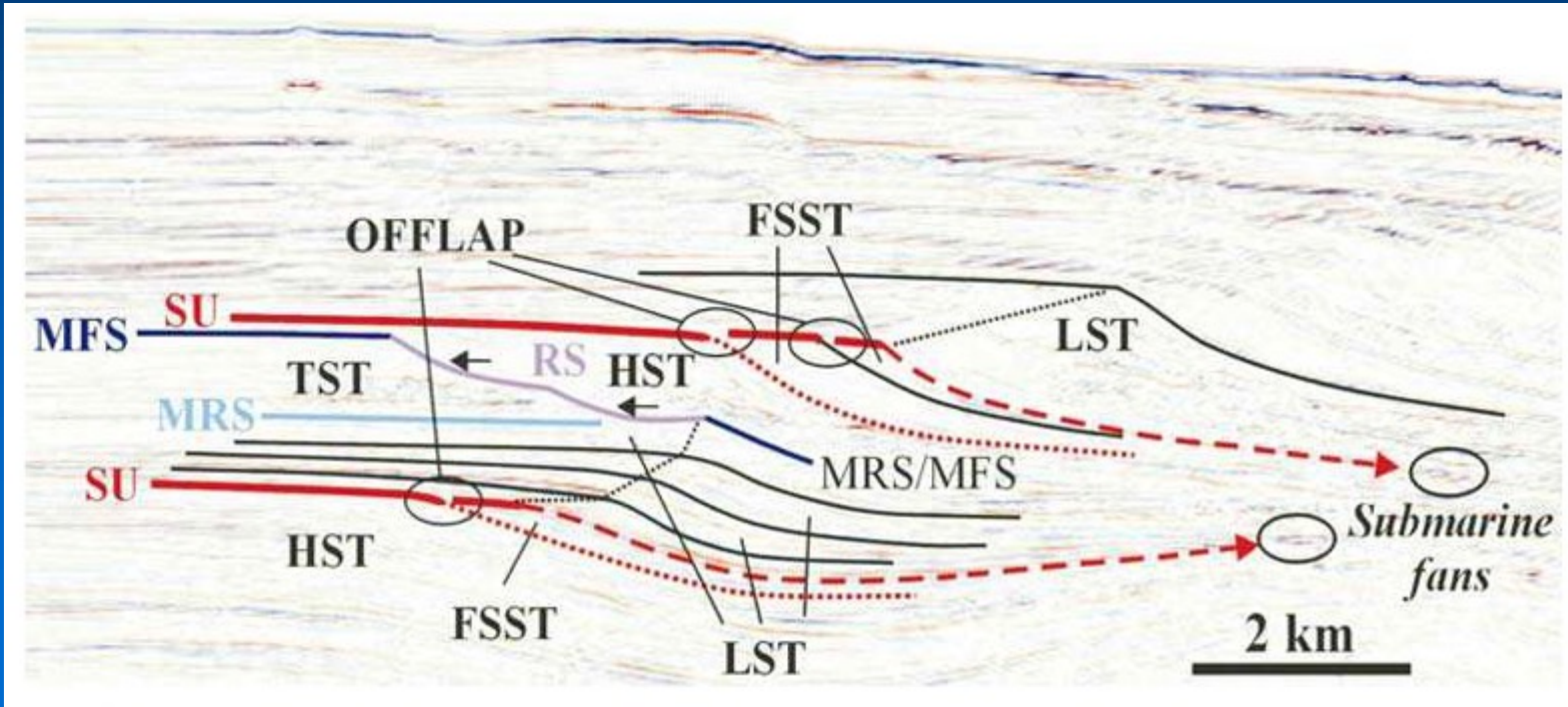
# Depositional processes and products of the late falling-stage systems tract (modified from Catuneanu, 2003).




The sediment mass balance changes in the favor of the deep-sea submarine fans, which capture most of the sand. The subaerial unconformity keeps forming and expanding basinward until the end of base-level fall. Once the shoreline falls below the shelf edge, the regressive surface of marine erosion stops forming as the seafloor gradient of the continental slope is steeper than what is required by the shoreface profile to be in equilibrium with the wave energy. Note that fluvial systems are likely to incise into the highstand prism but may only bypass the rest of the subaerially exposed shelf, unless the base level falls below the elevation of the shelf edge. The turbidity currents of the deep basin are dominantly of high-density type, due to the massive amount of sediment supply, and hence they tend to be overloaded and aggradational (sediment load > energy of the flow) along their entire course.

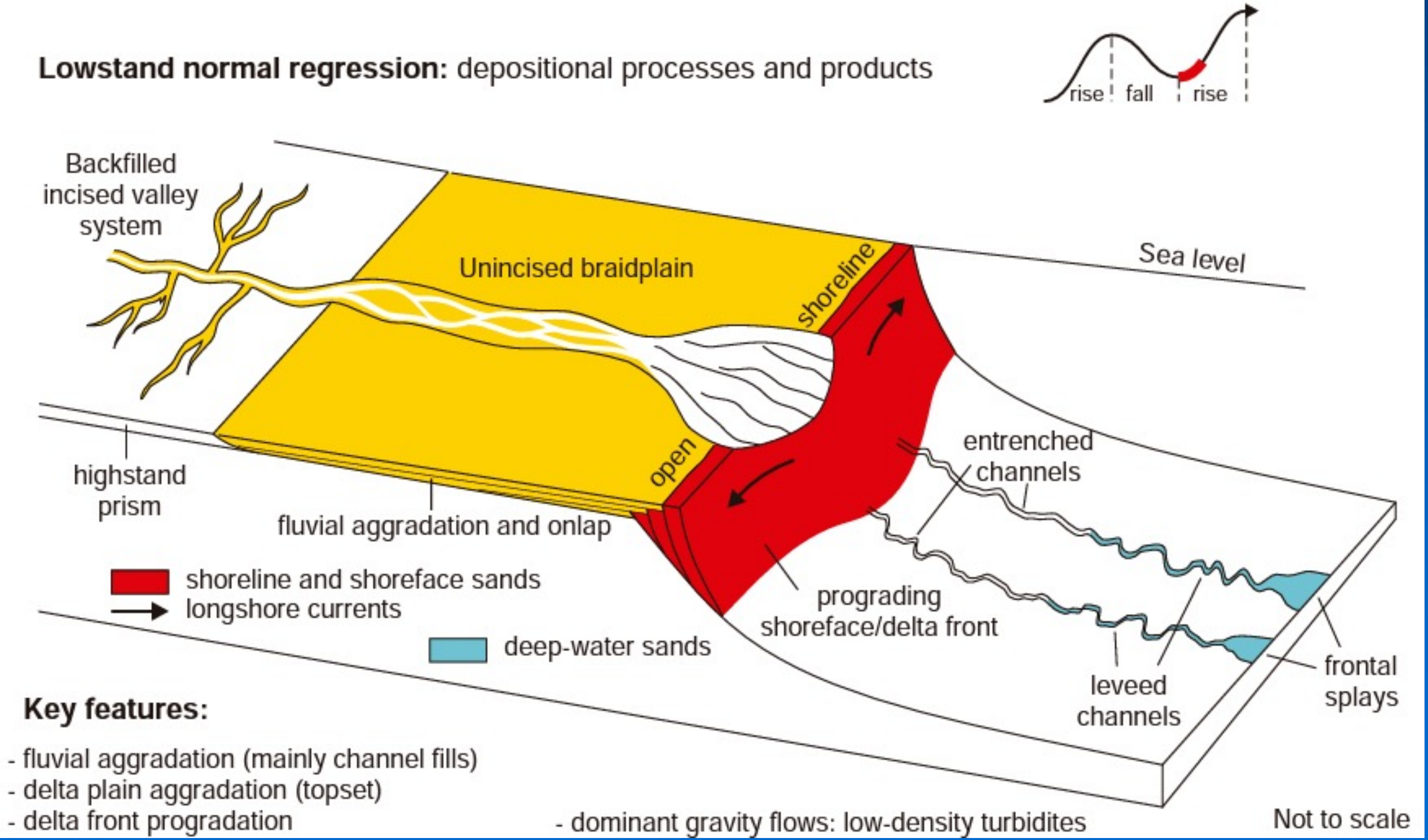
# Interpreted seismic line showing the location of the best deep-water reservoirs in a sequence stratigraphic framework (from Catuneanu et al., 2003)

The offlap type of stratal termination is highly significant for deep-water exploration because the youngest clinoform associated with offlap leads to the top of the coarsest deep-water facies.



# Depositional processes and products of the lowstand systems tract (modified from Catuneanu, 2003).

In contrast to the FSST, the sediment of this stage of early-rise normal regression is more evenly distributed. Sand is present in amalgamated fluvial channel fills, beach, and delta front systems, as well as in submarine fans. The ‘lowstand prism’ gradually expands landward  via fluvial aggradation and onlap.

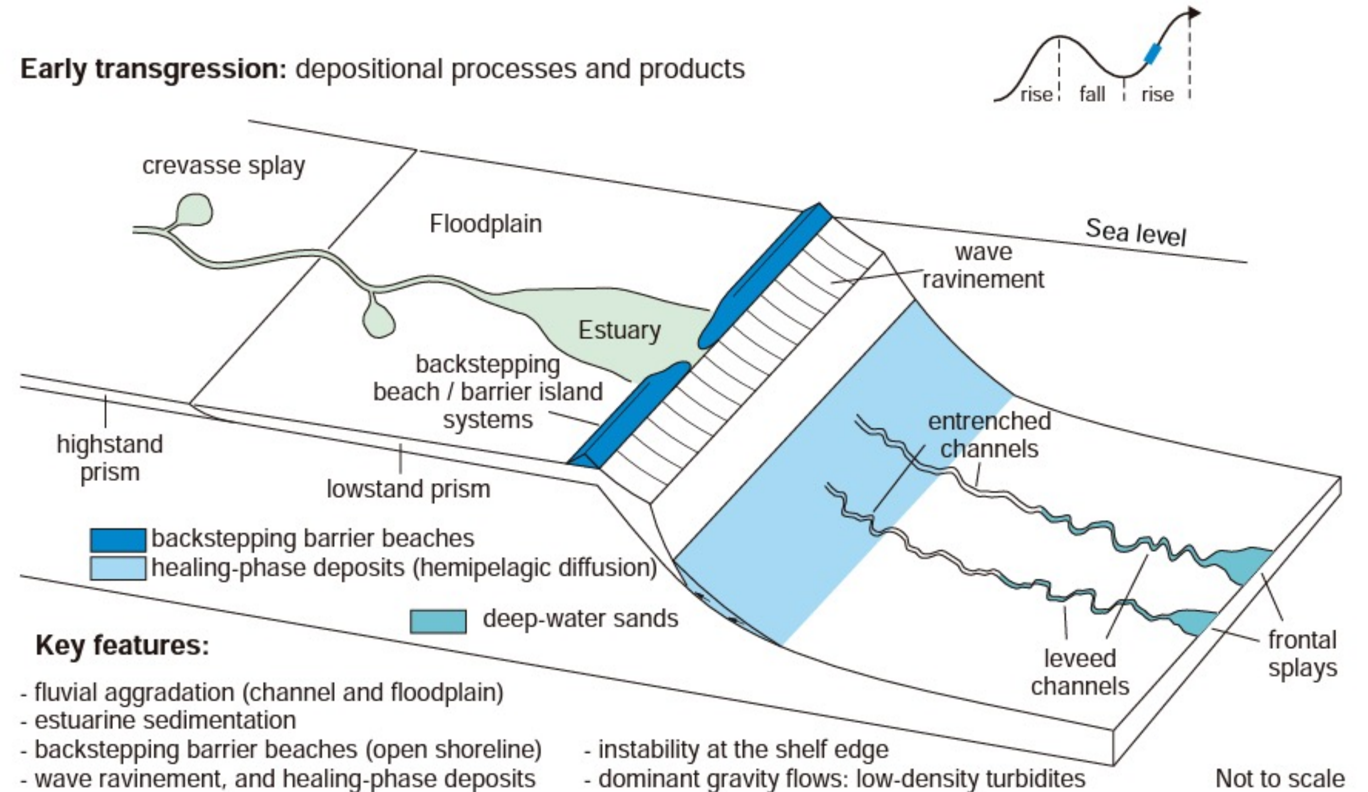



Aggradation on the continental shelf in fluvial to shallow-marine environments reduces the amount of sediment supply to the deep basin, and hence the turbidity currents of this stage are dominantly of low-density type, being underloaded (entrenched) on the continental slope and aggradational only on the low-gradient basin floor where the energy of the flow drops below the threshold of balance with the sediment load.

# Depositional processes and products of the early TST (modified from Catuneanu, 2003)

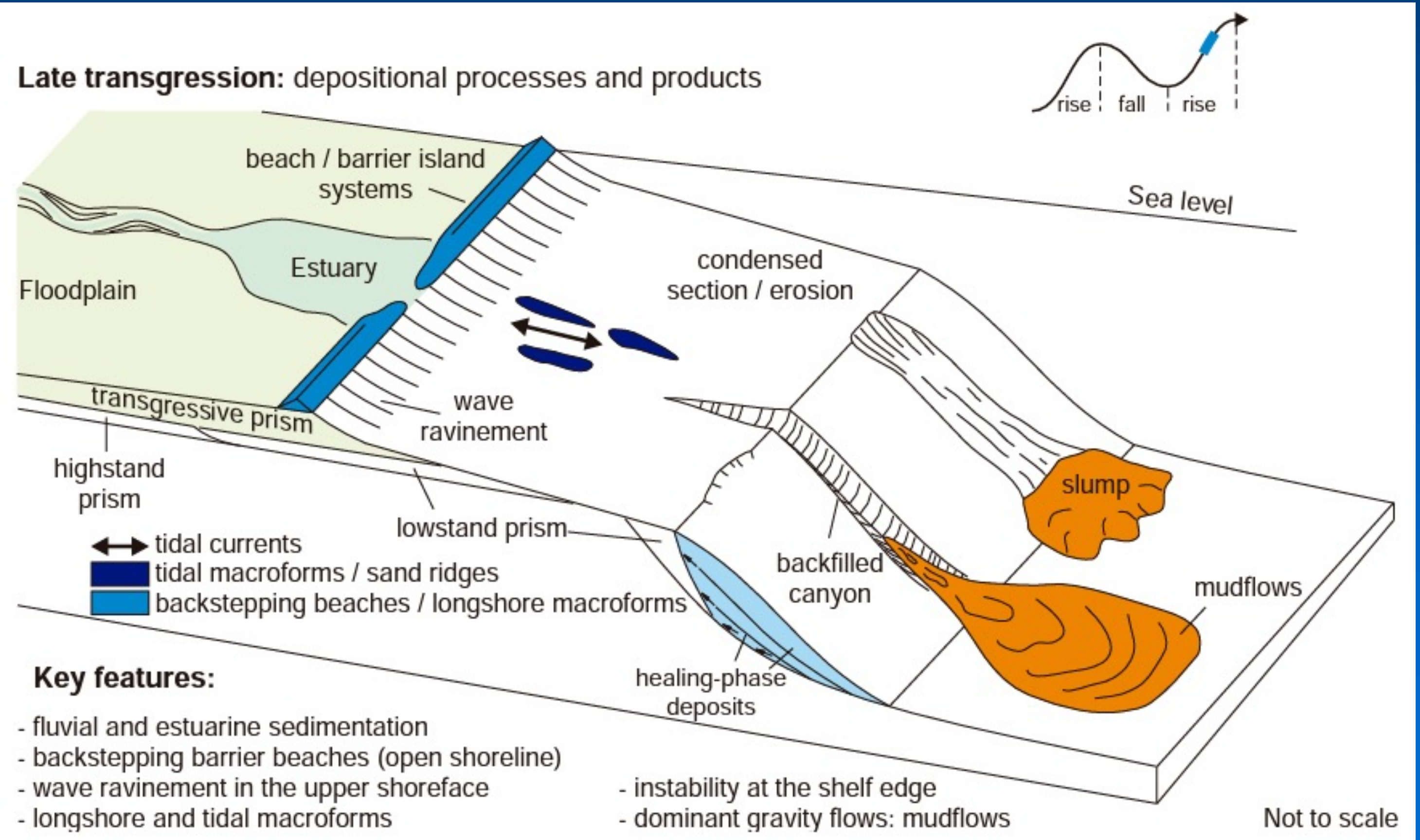
Rapid rates of base-level rise trigger a retrogradational shift of facies on the continental shelf, where most of the riverborn sediment is now trapped in fluvial, coastal and shallow-marine systems. Wave-ravinement processes erode the underlying normal regressive shelf-edge deltas and open shoreline systems, continuing to supply sand for the deep-water turbidity flows.

Similarly to the lowstand systems tract, the turbidity flows tend to be of low-density type, underloaded on the steep continental slope (flow energy > sediment load, which causes entrenchment), but become overloaded/aggradational on the low-gradient basin floor (sediment load > flow energy). They travel farther into the basin relative to the high-density late falling-stage flows because the higher proportion of mud sustains the construction of levees over larger distances.



# Depositional processes and products of the late TST (modified from Catuneanu, 2003)

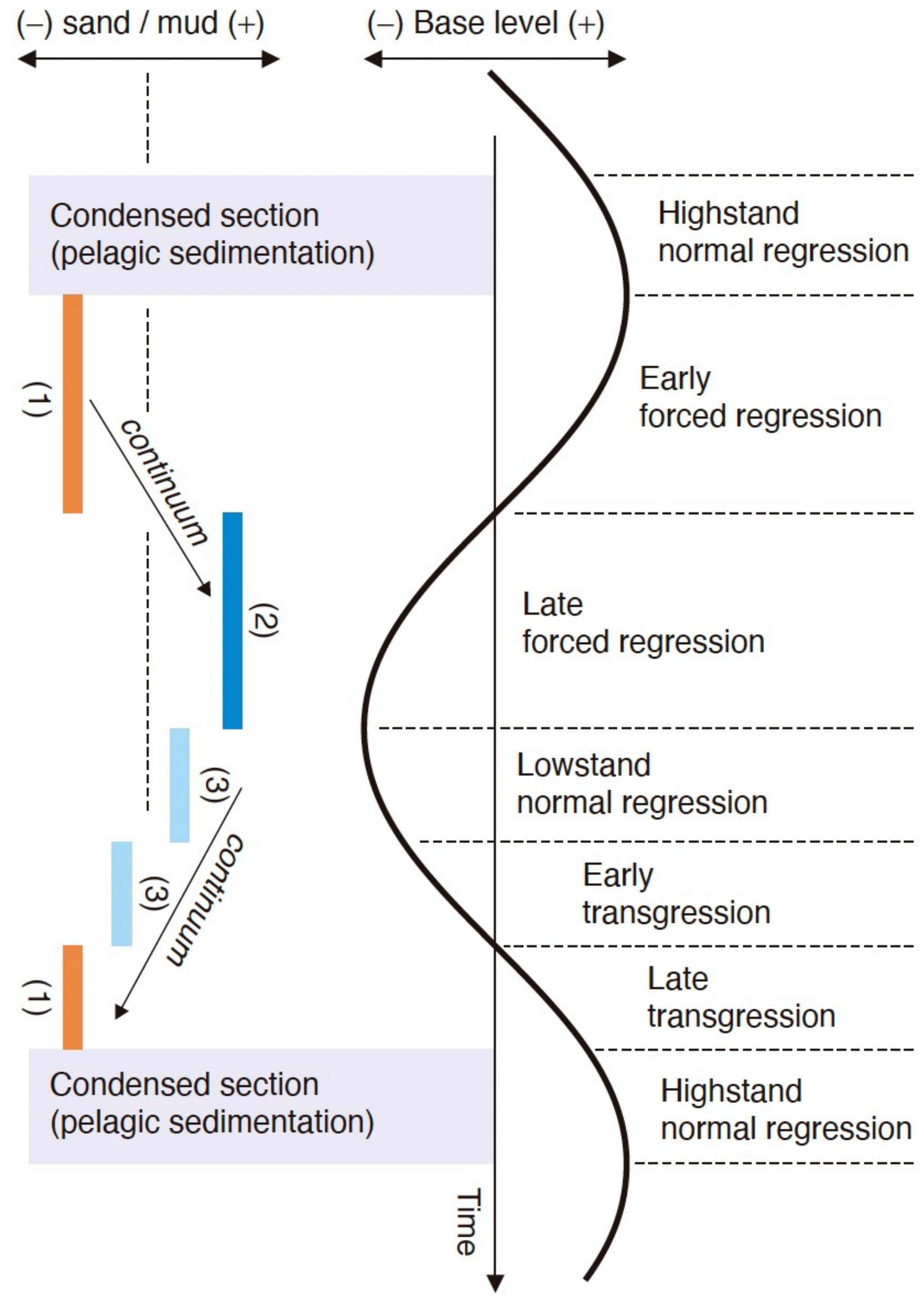
Most of the terrigenous sediment is trapped in the fluvial to shallow-marine transgressive prism, which includes fluvial, estuarine, deltaic, open shoreline, and lower shoreface deposits. Additional sand is incorporated within shelf macroforms (sheets, ridges, ribbons) generated by storm surges and tidal currents.




Such shelf-sand deposits are generally associated with the transgressive systems tract, as the best conditions to accumulate and the highest preservation potential are offered to shelf macroforms that form during shoreline transgression. As base level rises rapidly during transgression, hydraulic instability at the shelf edge generates mudflows in the deep-water environment.

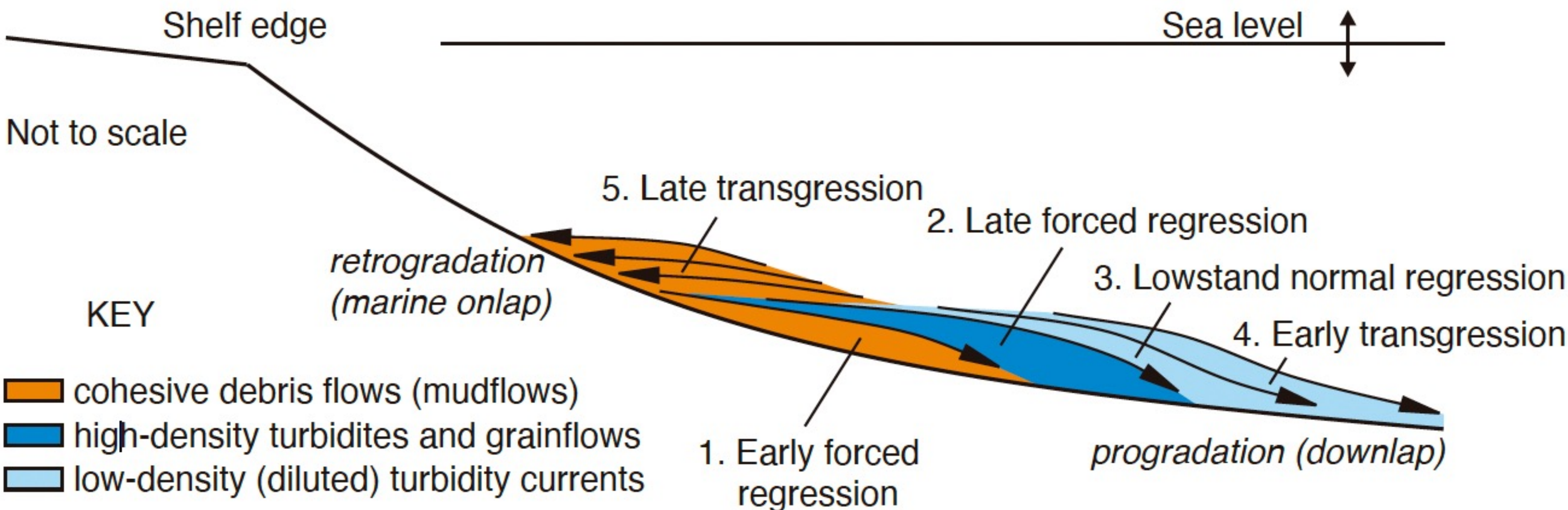
# Dominant types of gravity flows that supply sediment to the deep-water environment, in relation to specific stages of shoreline shift

Note that there is a continuum between the end-member types of gravity flows as changes in sediment supply are gradational through time.
Key: (1) cohesive debris flows (mudflows); (2) high-density turbidity currents and grainflows, forming proximal frontal splays; (3) lower-density turbidity currents, forming leveed channels and distal frontal splays.

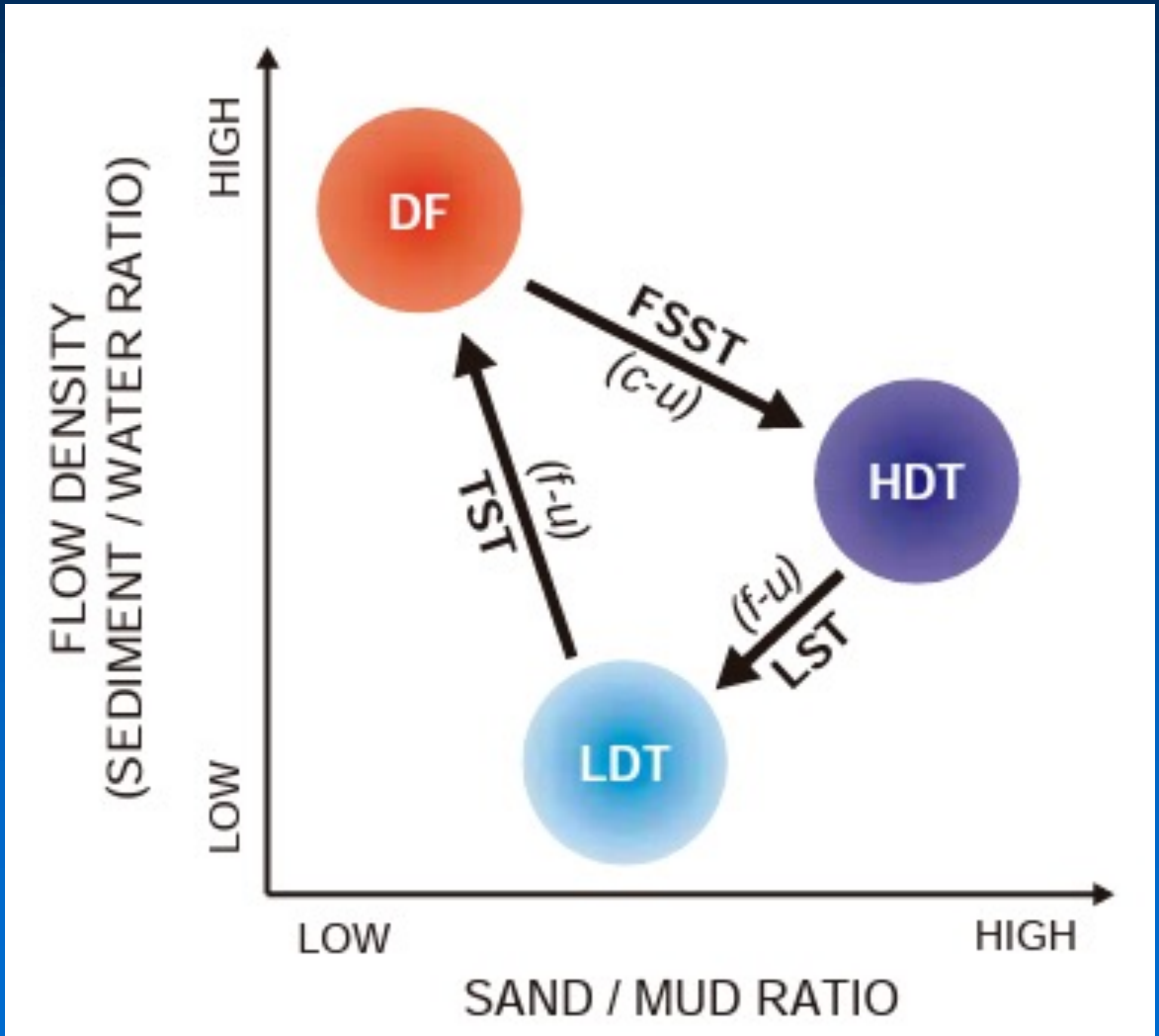


# Idealized architecture of a submarine fan complex that may form during the base-level cycle

The fan progrades during the first four time in response to the change in the type of gravity flow, based on the assumption that the travel distance of the flow depends on its rheological behavior: mudflows travel the shortest distance, due to their discrete shear strength; turbidites travel farther, due to their fluidal behavior, to a distance that is inversely proportional to the flow density. The fan retrogrades during transgression, as a result of the gradual change from fluidal to plastic behavior (turbidites to mudflows, respectively) which accompanies the decrease with time in the sand/mud ratio. According to this general scenario, submarine fans are more likely to onlap the continental slope during transgressions.

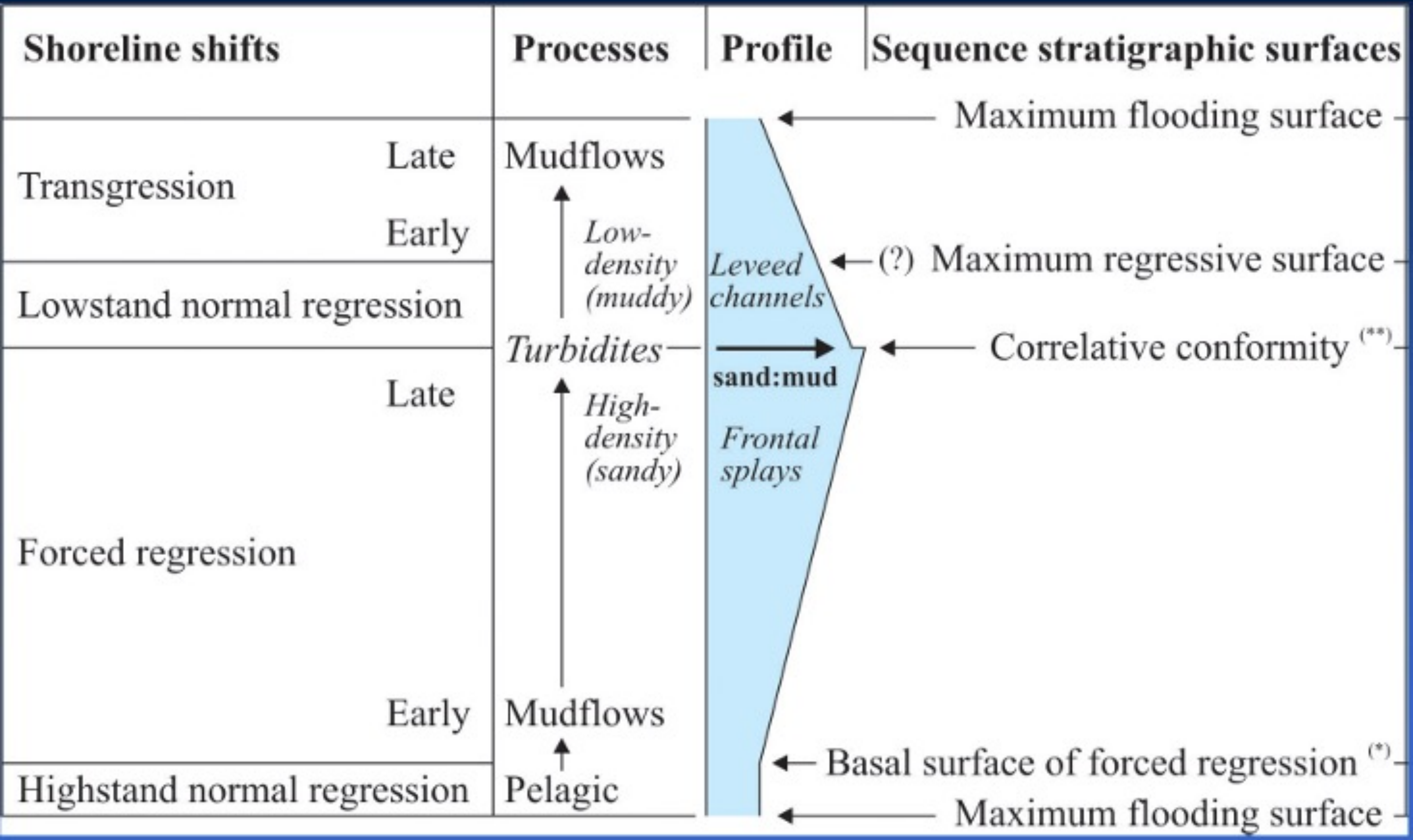


# Trends of change in the main types of gravity flows that operate in the deep-water environment during the formation of systems tracts




**Abbreviations:**
DF—cohesive debris flows (mudflows);
HDT—high-density turbidites;
LDT—low-density turbidites;
FSST— falling-stage systems tract;
LST—lowstand systems tract;
TST—transgressive systems tract;
c-u—coarsening-upward;
f-u—fining-upward.

# Deep-water sequence



# Sediment budget and the petroleum play significance of systems tracts.

| Systems tract | Significance | Fluvial | Coastal | Shallow-water | Deep-water |
|---|---|---|---|---|---|
| Highstand Systems Tract | Sediment budget | Good: *aggrading systems* | Good: *deltas and strandplains (coastal prisms)* | Good: *gradationally based shoreface and shelf facies* | Poor |
| | Reservoir | Fair: *channel fills, crevasse splays* | Good: *shoreline sands* | Good: *shoreface sands* | Poor |
| | Source and Seal | Poor source, fair seal: *overbank facies* | Poor | Fair: *shelf fines* | Good: *pelagic facies* |
| Transgressive Systems Tract | Sediment budget | Good: *rapidly aggrading systems, incised and unincised* | Good: *estuaries, deltas, backstepping beaches* | Fair: *onlapping shoreface and shelf facies* | Fair: *low-density turbidity flows and debris flows* |
| | Reservoir | Fair: *channel fills, crevasse splays* | Good: *estuarine, deltaic, and beach sands* | Fair: *shelf-sand deposits, basal healing-phase wedges* | Fair: *turbidites (basin floor)* |
| | Source and Seal | Poor source, fair seal: *overbank fines* | Poor source, fair seal: *central estuary facies* | Good: *shelf fines (shelf facies may be missing distally)* | Good: *pelagic facies* |
| Lowstand Systems Tract | Sediment budget | Good: *amalgamated channel fills, incised and unincised* | Good: *shelf/shelf-edge deltas, strandplains* | Good: *gradationally based shoreface and shelf facies* | Fair: *low-density turbidity flows* |
| | Reservoir | Good: *channel fills* | Good: *shoreline sands* | Good: *shoreface sands* | Good: *turbidites (basin floor)* |
| | Source and Seal | Poor | Poor | Fair: *shelf fines* | Fair: *"overbank" pelagics* |
| Falling-stage Systems Tract | Sediment budget | Poor | Fair: *offlapping deltas, downstepping beaches* | Fair: *sharp-based shoreface, and shelf facies* | Good: *debris flows and high-density turbidity flows* |
| | Reservoir | Poor | Fair: *detached shoreline sands* | Fair: *shoreface sands* | Good: *turbidites (slope and basin floor)* |
| | Source and Seal | Poor | Poor | Fair: *shelf fines* | Fair: *"overbank" pelagics* |

# Application to reservoir geology: HST

## Fluvial

Sediment budget: good (aggrading systems)
Reservoir: fair (channel fill, crevasse splays)
Poor source, fair seal (overbank fines)

## Shallow-water

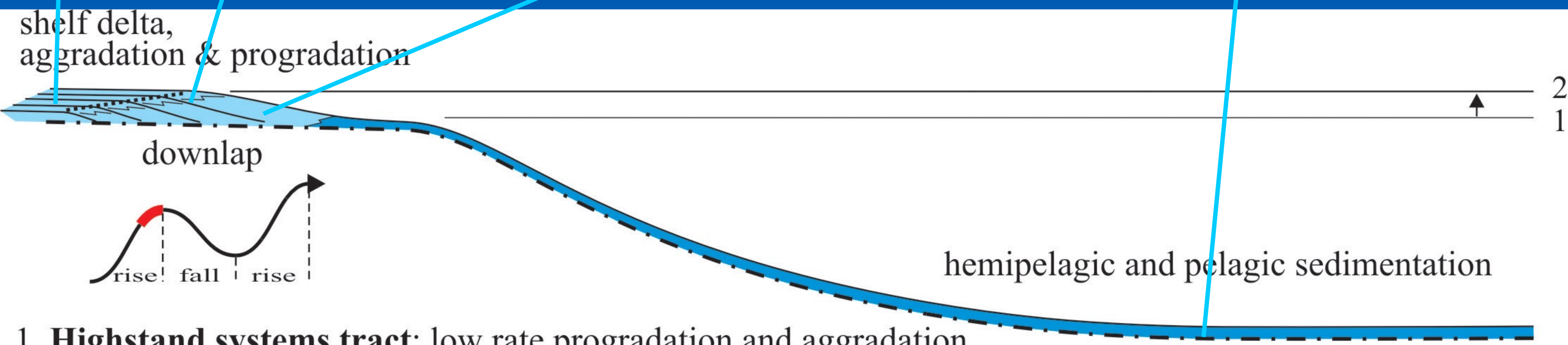
Sediment budget: good (shoreface and shelf facies)
Reservoir: good (shoreface sands)
Source and seal: fair (shelf fines)

## Coastal

Sediment budget: good (deltas and strandplains)
Reservoir: good (shoreline sands)
Source and seal: poor

## Deep-water

Sediment budget: poor
Reservoir: poor
Source and seal: good (pelagic facies)




1. **Highstand systems tract**: low rate progradation and aggradation (base level rise at the shoreline and normal regression)

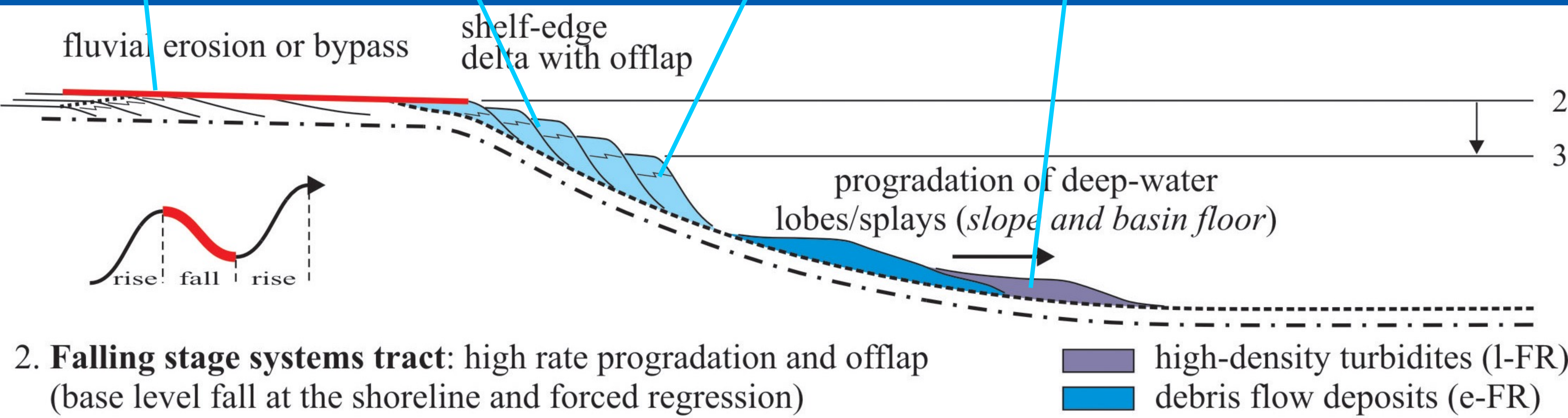
# Application to reservoir geology: FSST

## Fluvial
Sediment budget: poor
Reservoir: poor
Source and seal: poor

## Coastal
Sediment budget: fair (offlapping deltas, downstepping beaches)
Reservoir: fair (detached shoreline sands)
Source and seal: poor

## Shallow-water
Sediment budget: fair (shoreface and shelf facies)
Reservoir: fair (shoreface sands)
Source and seal: fair (shelf fines)

## Deep-water
Sediment budget: good (debris flows and high-density turbidity flows)
Reservoir: good (turbidites)
Source and seal: fair ("overbank" pelagics)




2. **Falling stage systems tract**: high rate progradation and offlap (base level fall at the shoreline and forced regression)

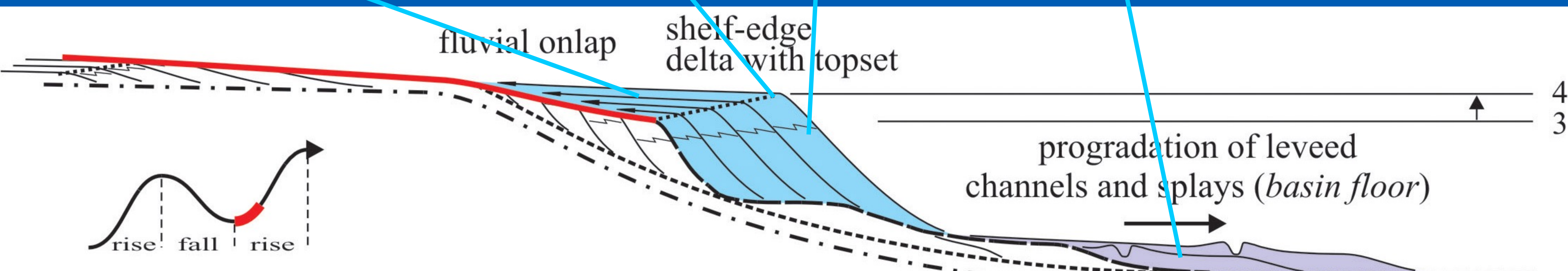
# Application to reservoir geology: LST

## Fluvial
Sediment budget: good (amalgamated channel fills)
Reservoir: good (channel fills)
Source and seal: poor

## Shallow-water
Sediment budget: good (shoreface and shelf facies)
Reservoir: good (shoreface sands)
Source and seal: fair (shelf fines)

## Coastal
Sediment budget: good (shelf/shelf-edge deltas, strandplains)
Reservoir: good (shoreline sands)
Source and seal: poor

## Deep-water
Sediment budget: fair (low-density turbidity flows)
Reservoir: good (turbidites)
Source and seal: fair ("overbank" pelagics)




3. **Lowstand systems tract**: low rate progradation and aggradation (base level rise at the shoreline and normal regression)

low-density turbidites

# Application to reservoir geology: TST

## Shallow-water

Sediment budget: fair (onlapping shoreface and shelf facies)
Reservoir: fair (shelf sands, basal healing-phase wedges)
Source and seal: good (shelf fines)

## Fluvial

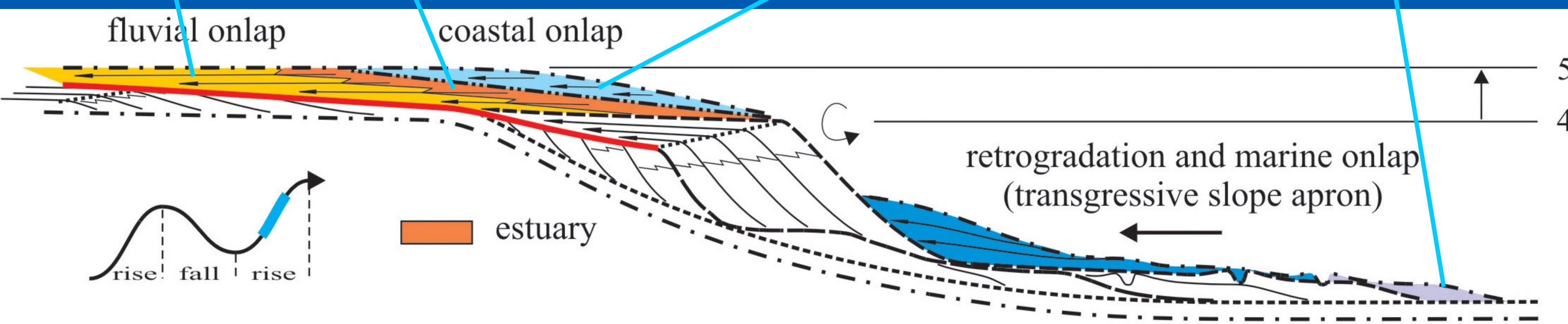
Sediment budget: good (aggrading systems)
Reservoir: fair (channel fills, crevasse splays)
Poor source, fair seal (overbank fines)

## Coastal

Sediment budget: good (estuaries, deltas, backstepping beaches)
Reservoir: good (estuarine, deltaic and beach sands)
Poor source, fair seal (central estuary facies)

## Deep-water

Sediment budget: fair (low-density turbidity flows and debris flows)
Reservoir: fair (turbidites)
Source and seal: good (pelagic facies)




4. **Transgressive systems tract**: retrogradation and aggradation (base level rise at the shoreline and transgression)

low-density turbidites (e-T)
debris flow deposits (l-T)

# Continuity of reservoirs in continental settings

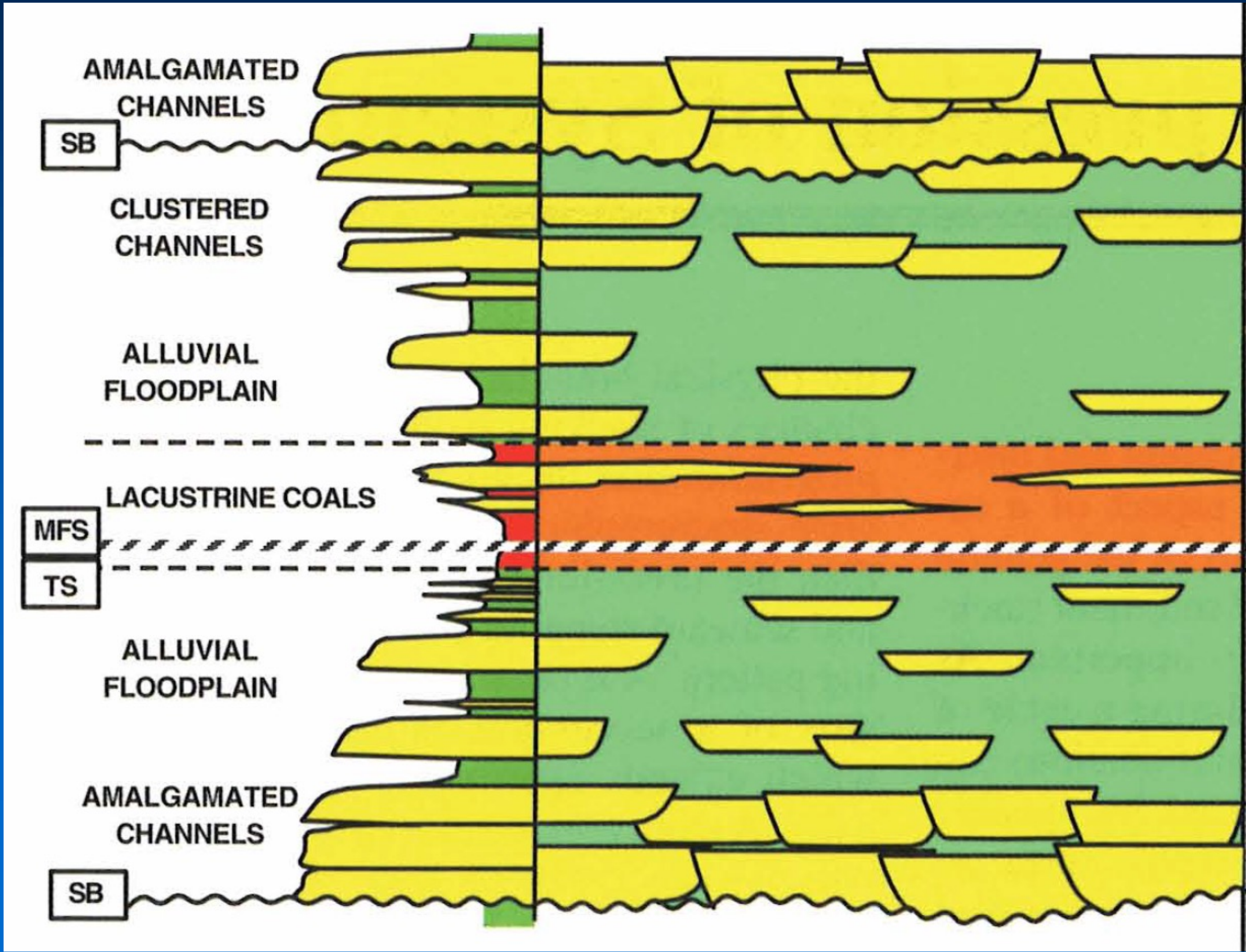
Good reservoir continuity

Isolated reservoirs

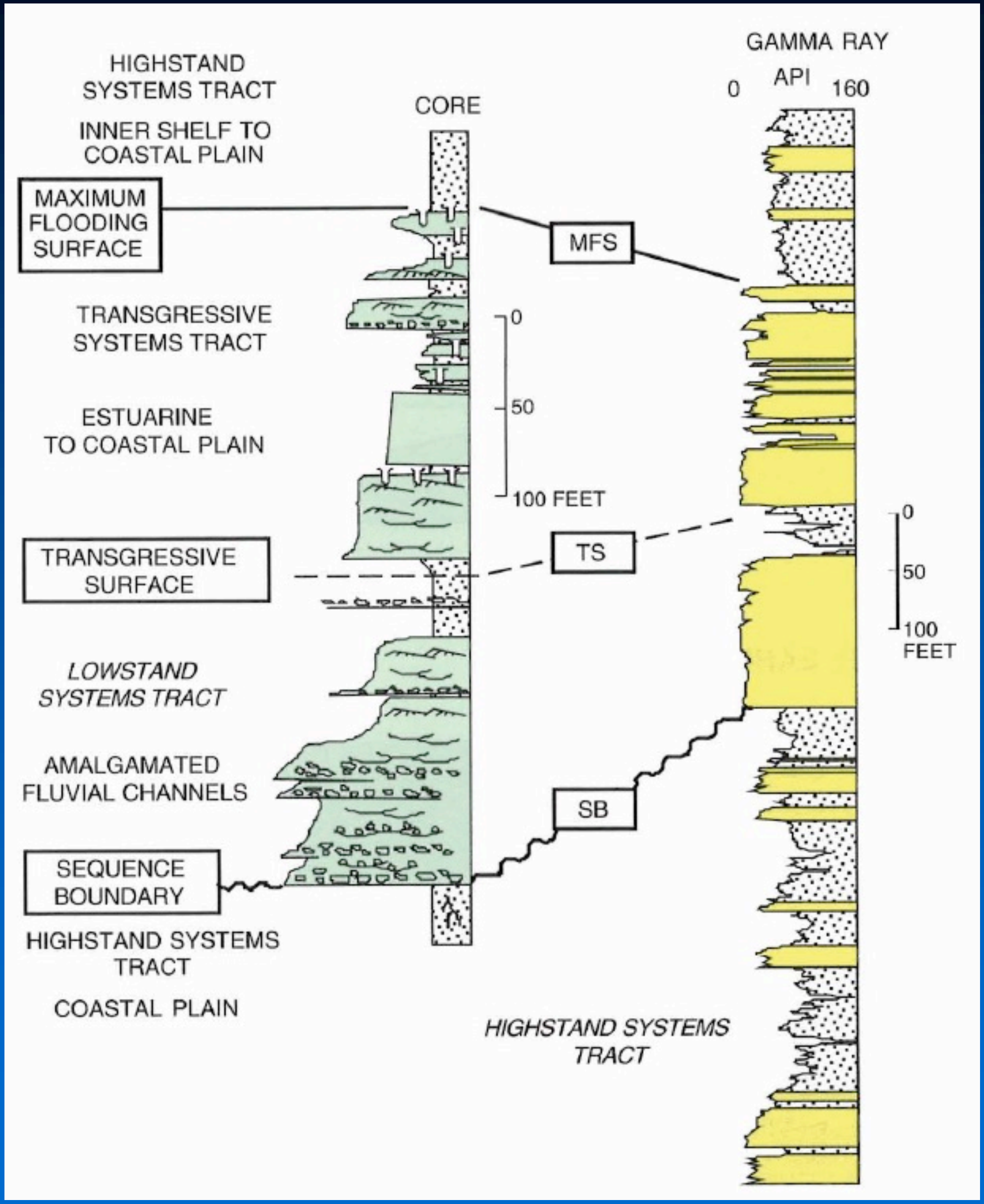
Potential source rock

Isolated reservoirs

Good reservoir continuity

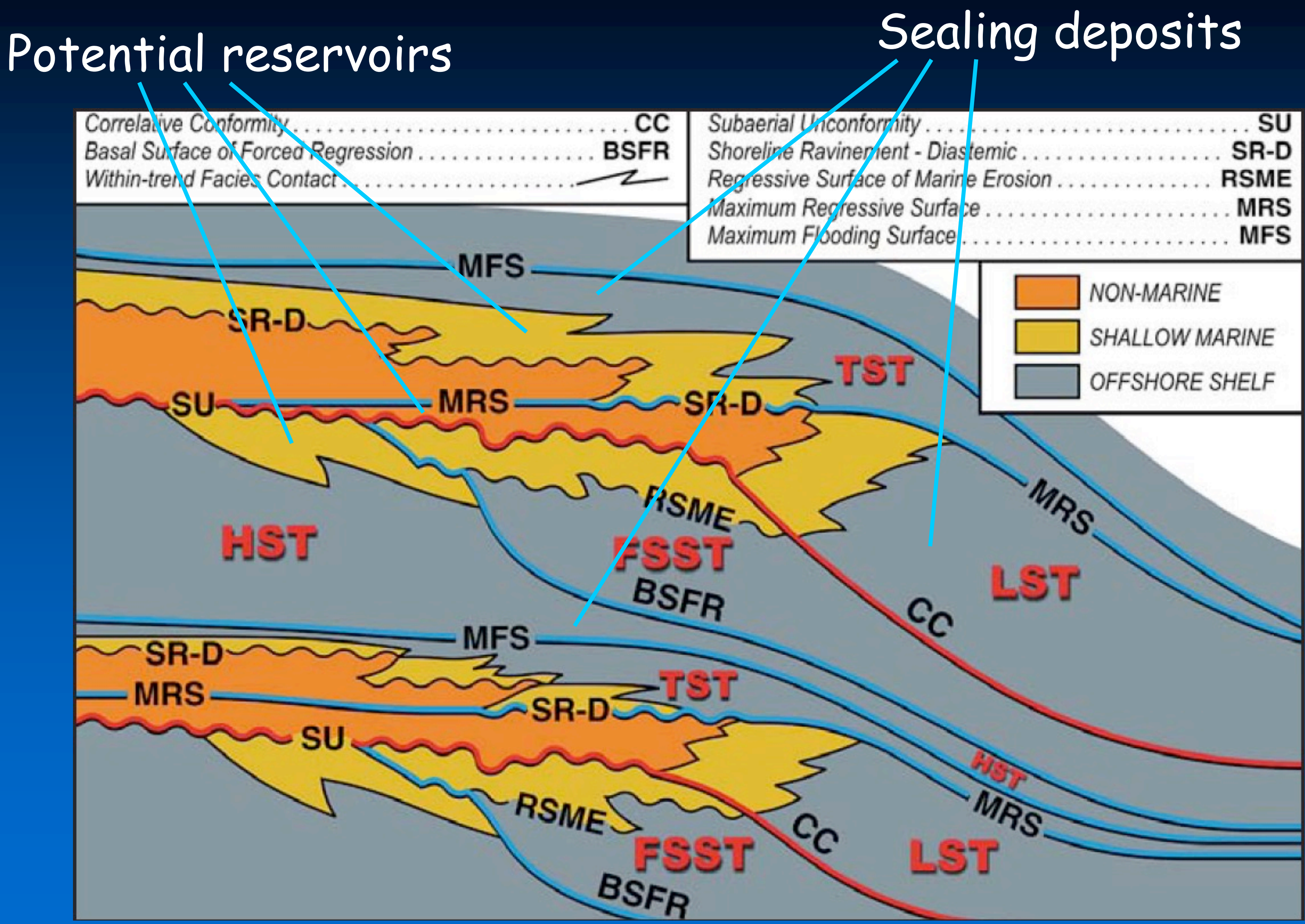


# Potential continental to coastal reservoirs

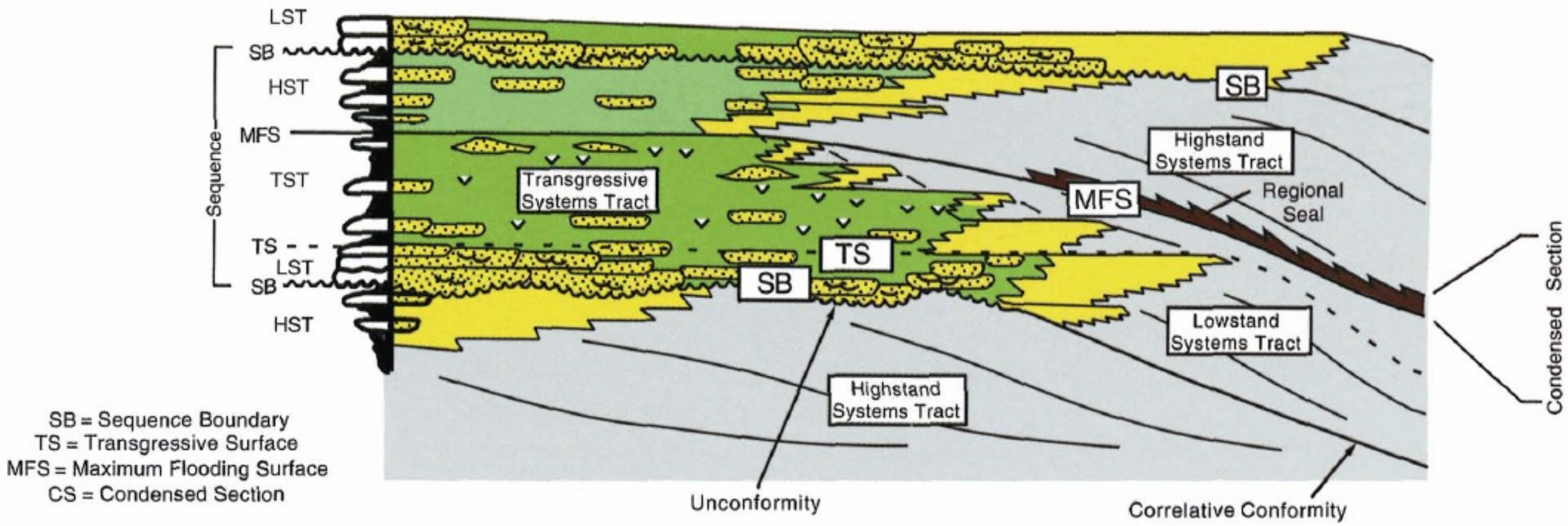


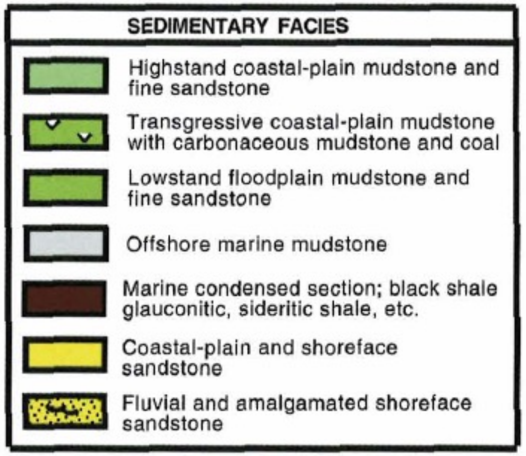

Paleocene of Colombia

# Continental to shallow-marine reservoirs



# Continental to shallow-marine reservoirs




| Systems Tract | Play Significance | Risk | Facies Examples |
|---|---|---|---|
| Lowstand | Reservoir | Source,Charge | ***Reservoir:*** Shelf-edge deltas, incised-valley fill fluvial deposits, forced-regression shoreface/deltaic deposits deep-waterturbidite and bottom-current reworked deposits |
| Transgressive | Source, Seal, Reservoir | Reservoir | ***Source:*** Marine shale (mid- to outer-shelf/slope/basin floor (condensed section), bay and lagoon deposits, coal ***Seal:*** Condensed-section shale ***Reservoir:*** Transgressive lag, incised-valley fill estuarine deposits, basal healing-phase-wedge deposits, backstepped shoreface deposits |
| Highstand | Reservoir; Source and Seal (Distally) | Seal (Proximally) | ***Source:*** Marine shale (slope/basin-floor condensed section) ***Seal:*** Condensed-section shale (slope and basin floor), alluvial-floodplain shale ***Reservoir:*** Shelf deltas; bayhead (estuary-head) deltas, coastal/alluvial-plain deposits |

# Final remarks

- Sequence stratigraphy represents a powerful tool for the study of sedimentary successions, allowing the recognition of the relationship between stratal architecture and changes of base level and sediment supply.

- The linkage between sequence stratigraphy and eustasy is an outdated concept. Modern sequence stratigraphy refers to relative sea-level changes of various frequency and amplitude, which depend on the interplay of eustasy and tectonics, and sediment supply changes.

- Sequence stratigraphic analysis should be conducted on the basis of descriptive, model independent criteria, by the recognition of *genetic units* and surfaces typified by diagnostic physical attributes. The application of the preferred or the most appropriate model may follow.

- The application of sequence stratigraphy ranges from research in academia to hydrocarbon industry. The sequence-stratigraphic method is the modern sedimentologic and stratigraphic approach for the identification of stratigraphic traps by predicting facies distribution and stratal architecture within the basin fill.

# Pathways for Geoscientists in a Net-Zero Future Forum (19 - 20 May 2022, London, UK)

AAPG | PESGB energy transition

Geoscientists can be proud of the enormous contributions they have made to the progress of society over time. Today, geoscientists have an exciting and challenging role in the ongoing energy transition. The contribution of petroleum energy is set to remain for several decades while renewable resources are forecast to increase. This setting creates a new and ever-changing energy portfolio that geoscientists have the privilege to effect…

"Pathways for Geoscientists in a Net-Zero Future," the tagline for this year's forum, focuses on how we as geoscientists can play an active role in this transition with a focus on sustainability, digitalization, skills, and capabilities…

During the four months prior to the Forum, AAPG Will be hosting dedicated 1hour webinars focused on each one of the sessions, bringing together high level speakers that will introduce each of the topics and start shaping the discussion. The webinars are free and open to everyone from everywhere.


*Thursday, 13 January 2022, 2:00 p.m.–3:00 p.m.*

## Maximizing Future Impact of Geoscientists

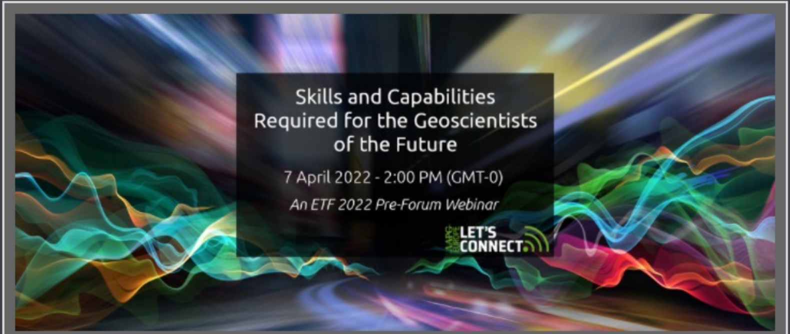

*Thursday, 10 February 2022, 2:00 p.m.–3:00 p.m.*

## Sustainability & Emerging Geoscience Sectors

**https://energytransition.aapg.org/2022/Forum-Agenda/Pre-Forum-Webinars**


*Thursday, 10 March 2022, 2:00 p.m.–3:00 p.m.*

## Digitalization Impacting Geoscience




*Thursday, 7 April 2022, 2:00 p.m.–3:00 p.m.*

## Skills and Capabilies Required for the Geoscientists of the Future