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 2022 - 2023

Analisi di Bacino e Stratigrafia Sequenziale (426SM)

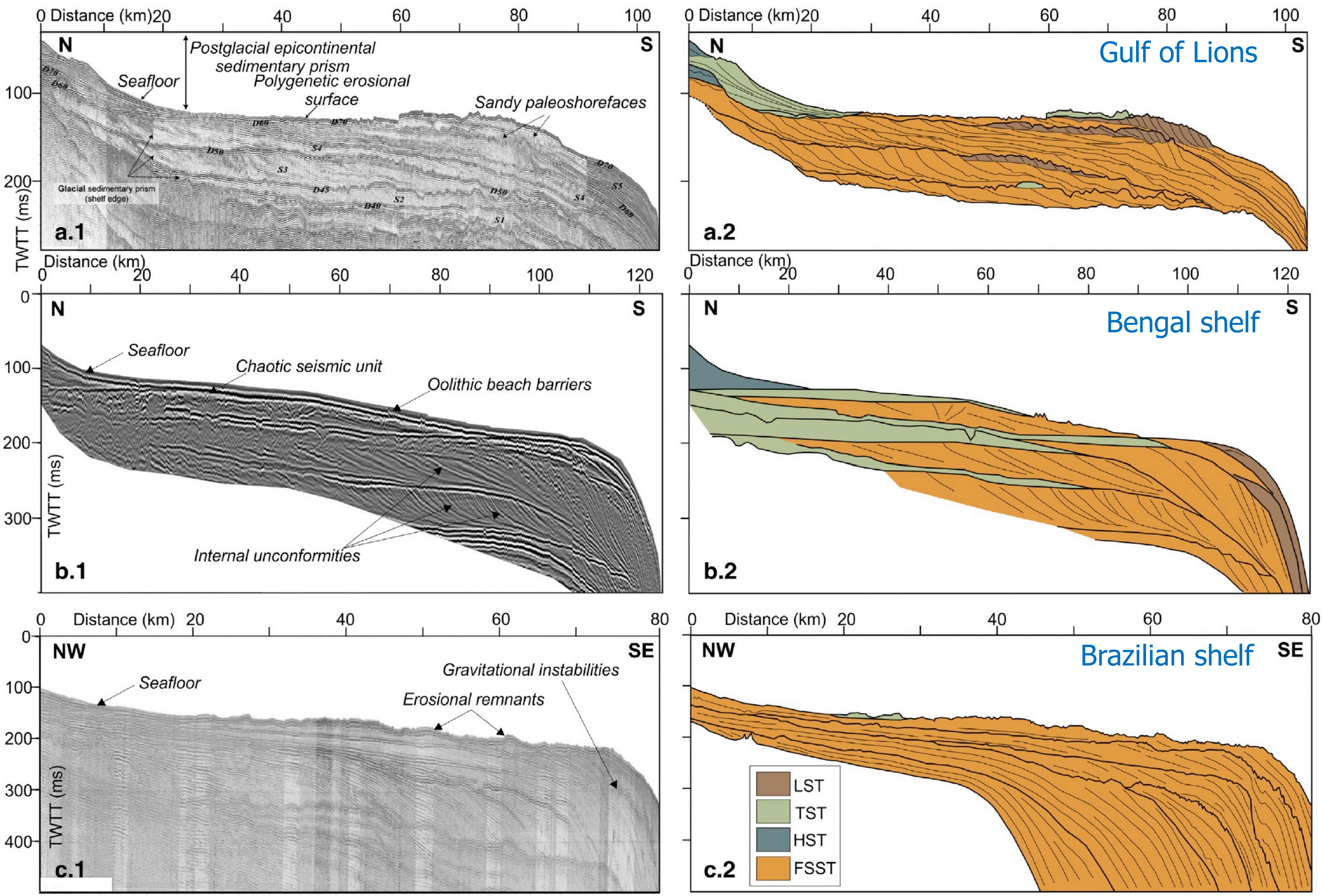
Docente: **Michele Rebesco**

Modulo 4.3
Sequence stratigraphy – closer view

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

Upper Pleistocene shelf

From Lobo & Ridente (2013)

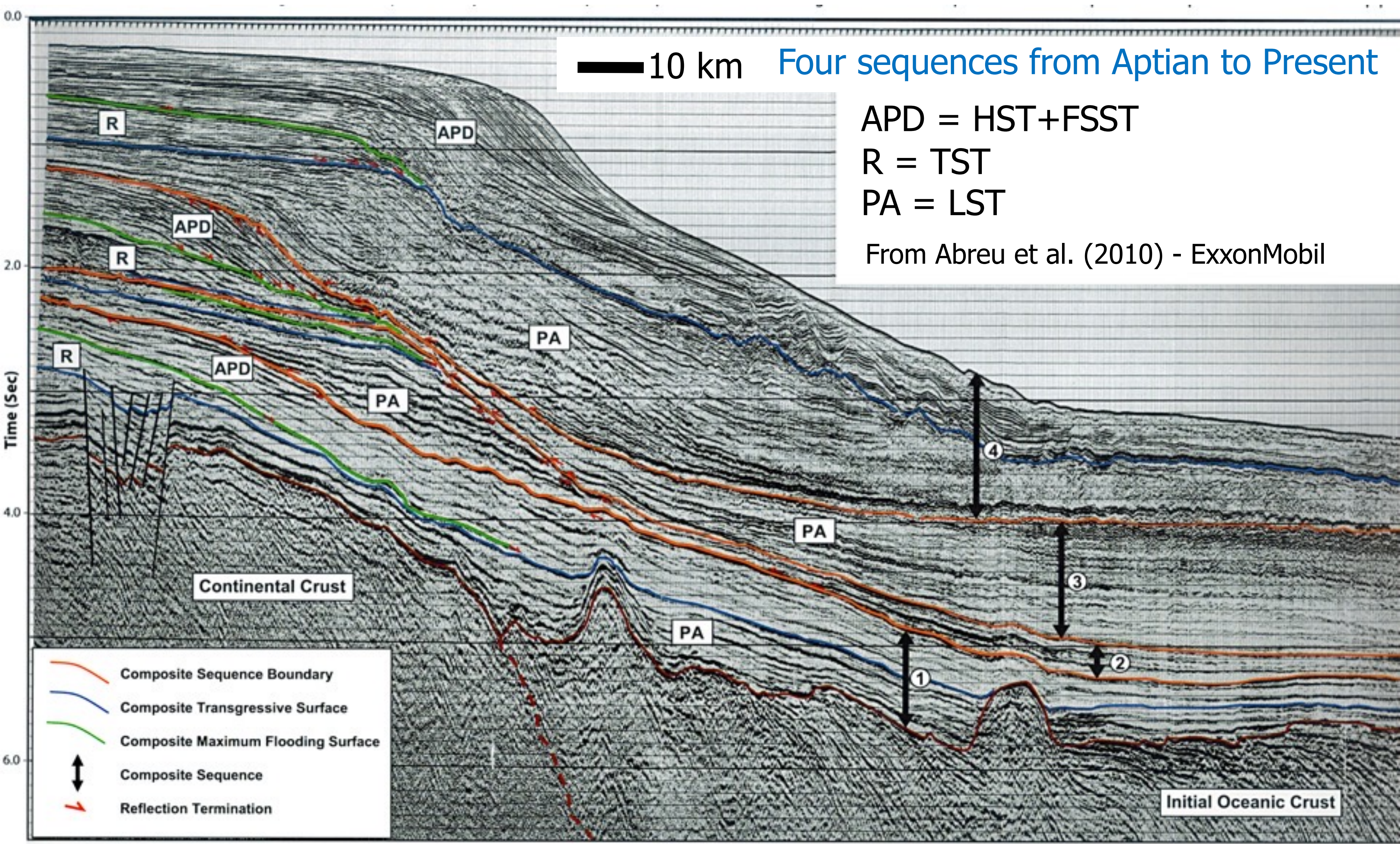


Pelotas Basin (southern Brazil)

Four sequences from Aptian to Present

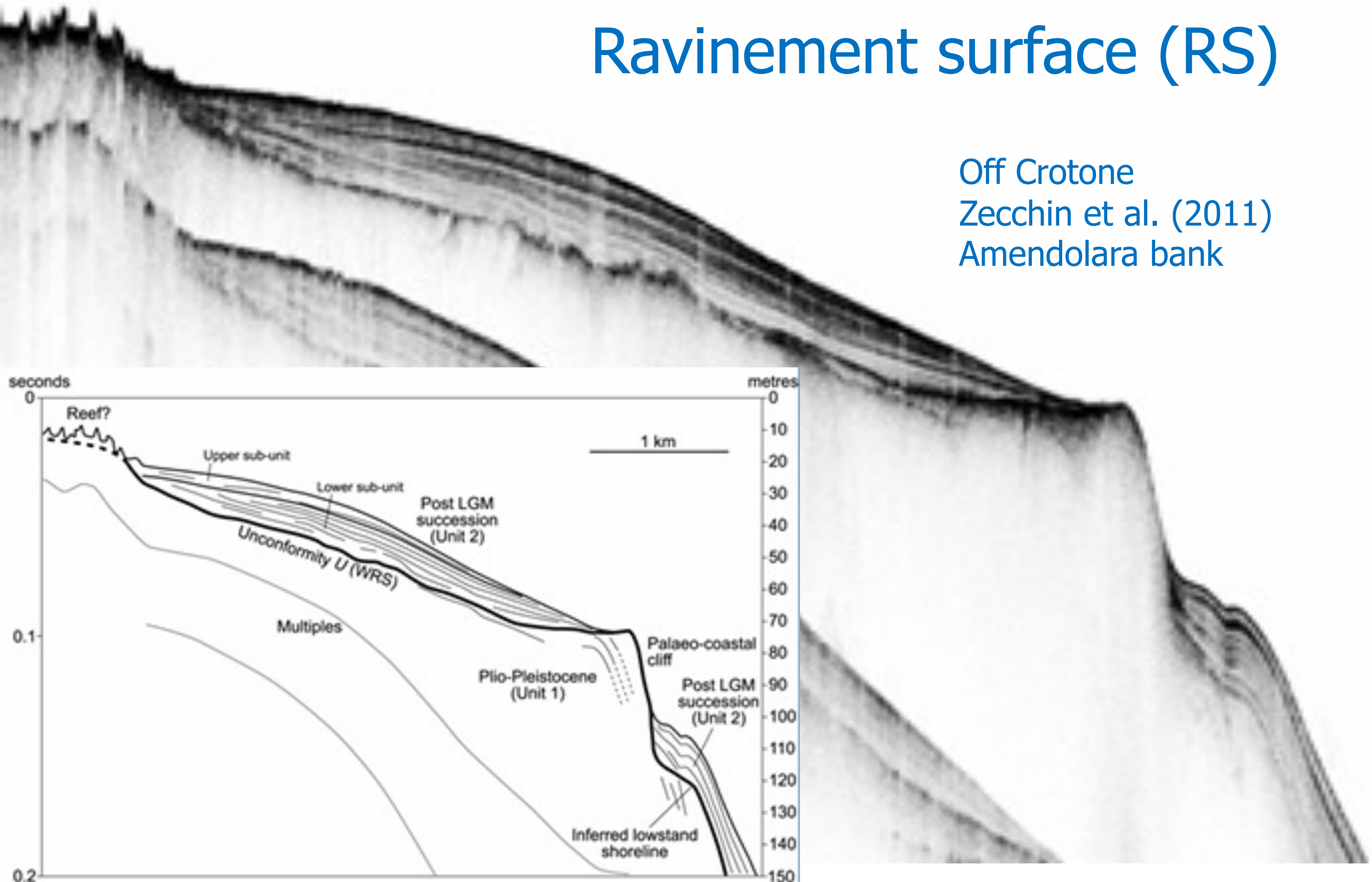
APD = HST+FSST
R = TST
PA = LST

From Abreu et al. (2010) - ExxonMobil



Ravinement surface (RS)

Off Crotone
Zecchin et al. (2011)
Amendolara bank

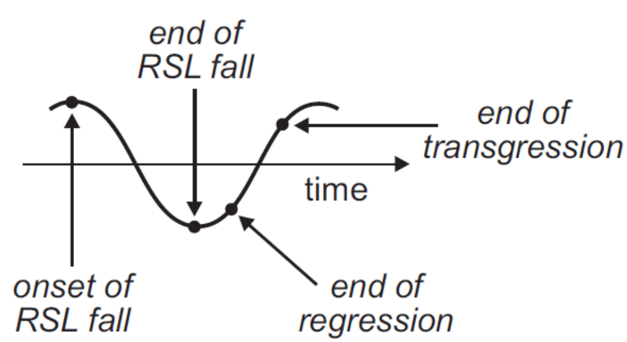


Models

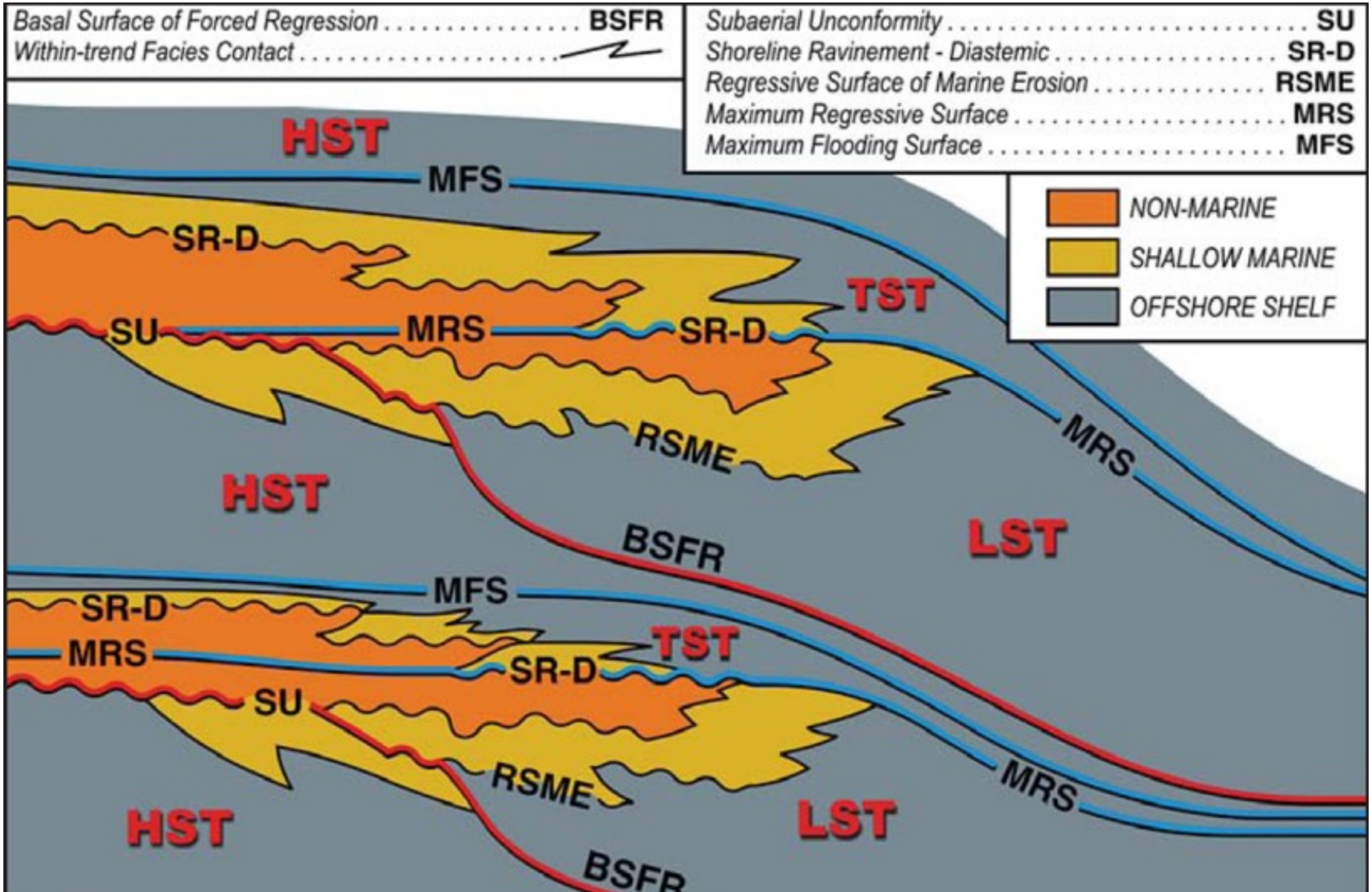
Events and stages \ Sequence model	Mitchum et al. (1977) Depositional Sequence I	Posamentier et al. (1988) Depositional Sequence II	Van Wagoner et al. (1988) Depositional Sequence III	Hunt & Tucker (1992) Depositional Sequence IV	Galloway (1989) Genetic Sequence	Johnson & Murphy (1984) T-R Sequence
HNR		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

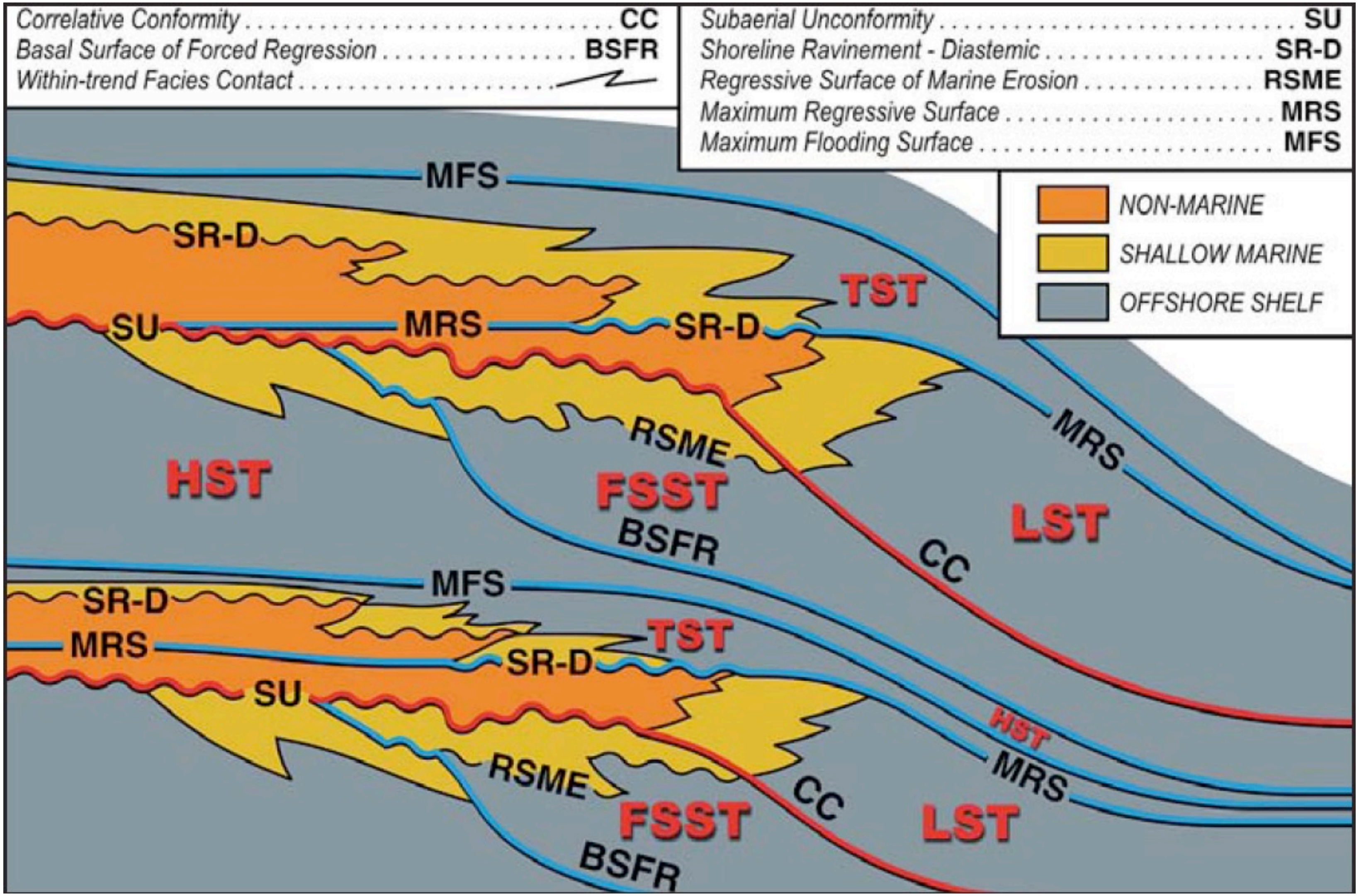
sequence boundary
systems tract boundary
within-sequence surface
within-systems tract surface



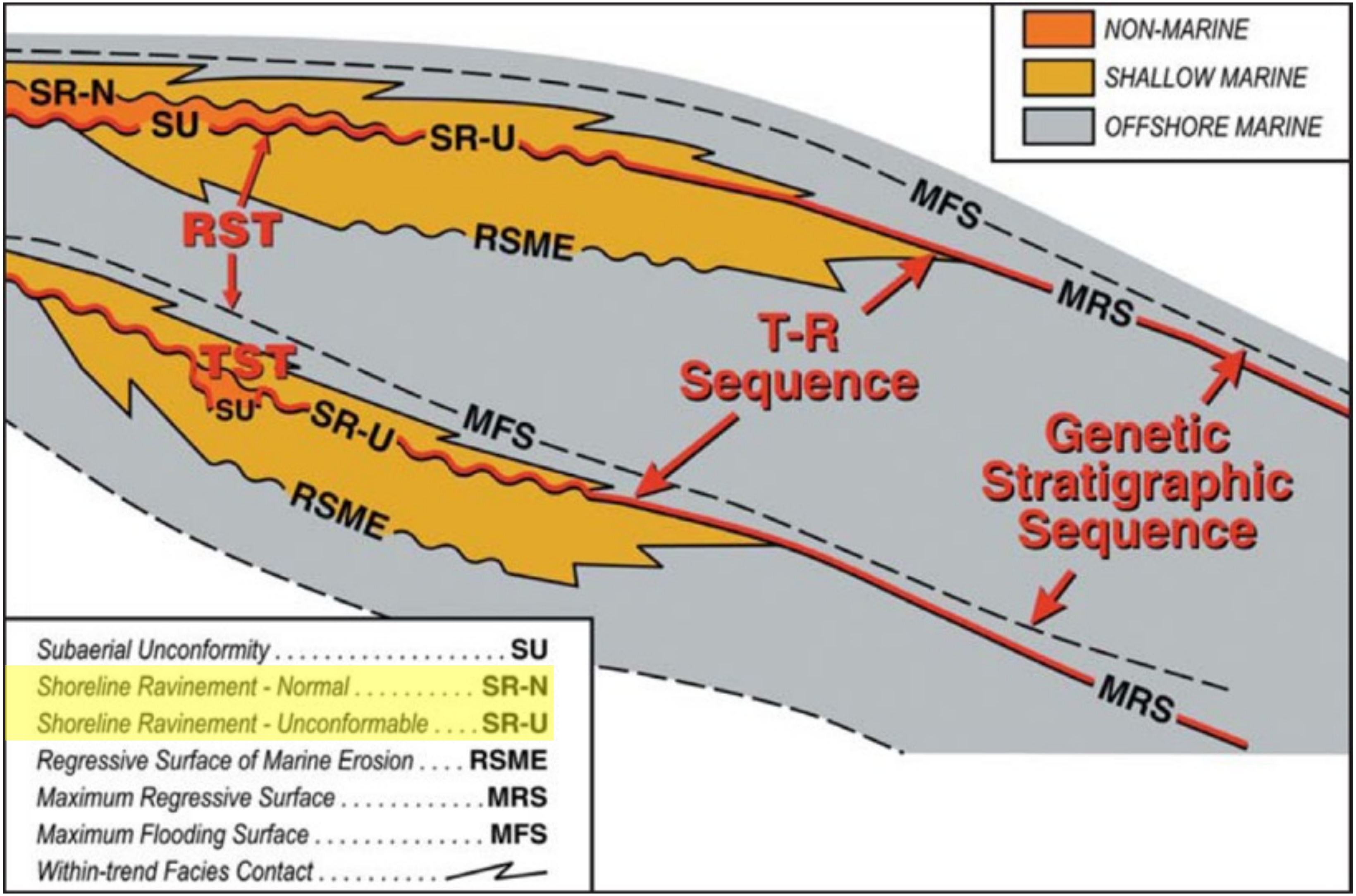
Depositional sequence of Posamentier & Allen, 1999



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

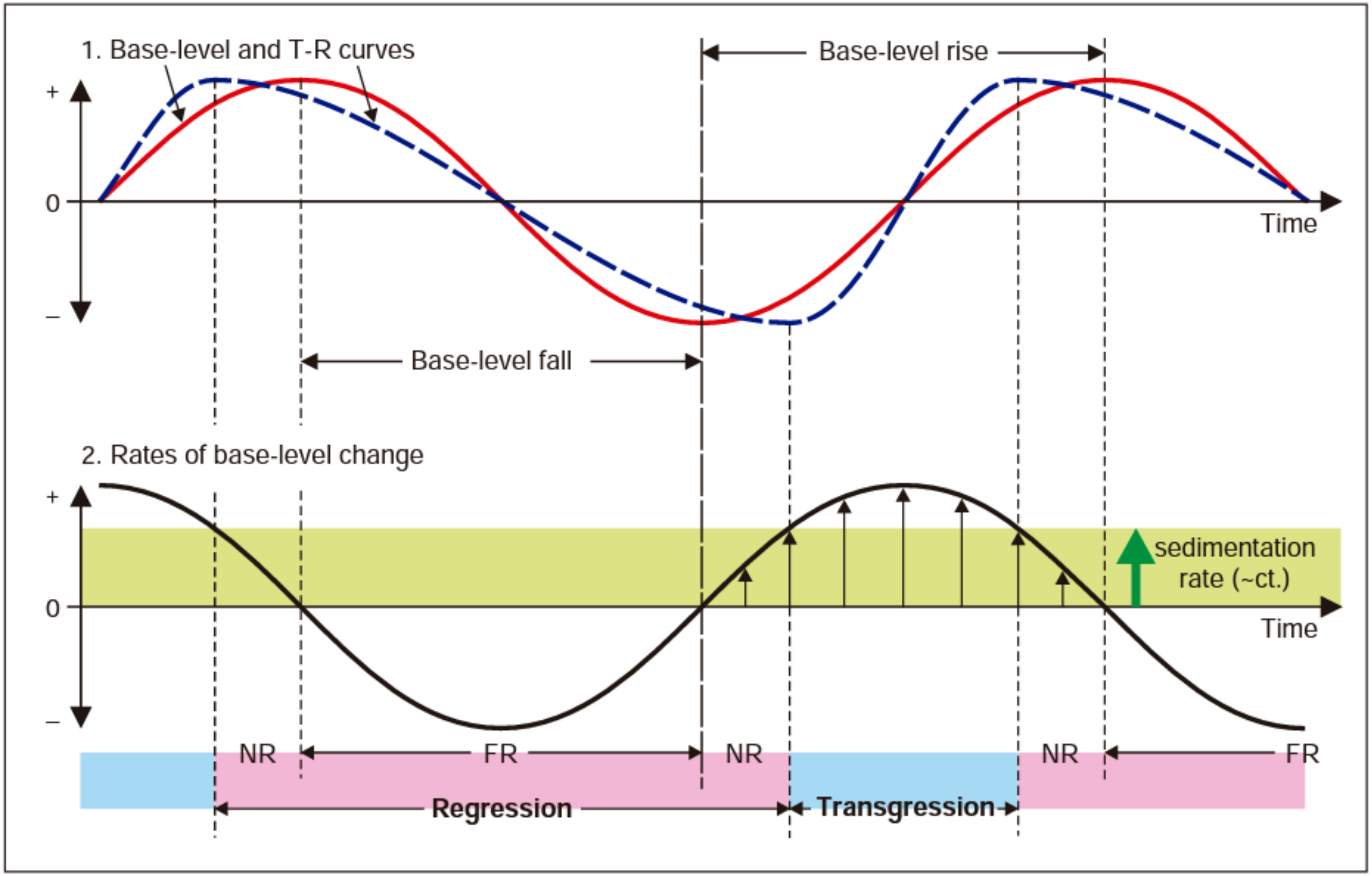


T-R and genetic sequences



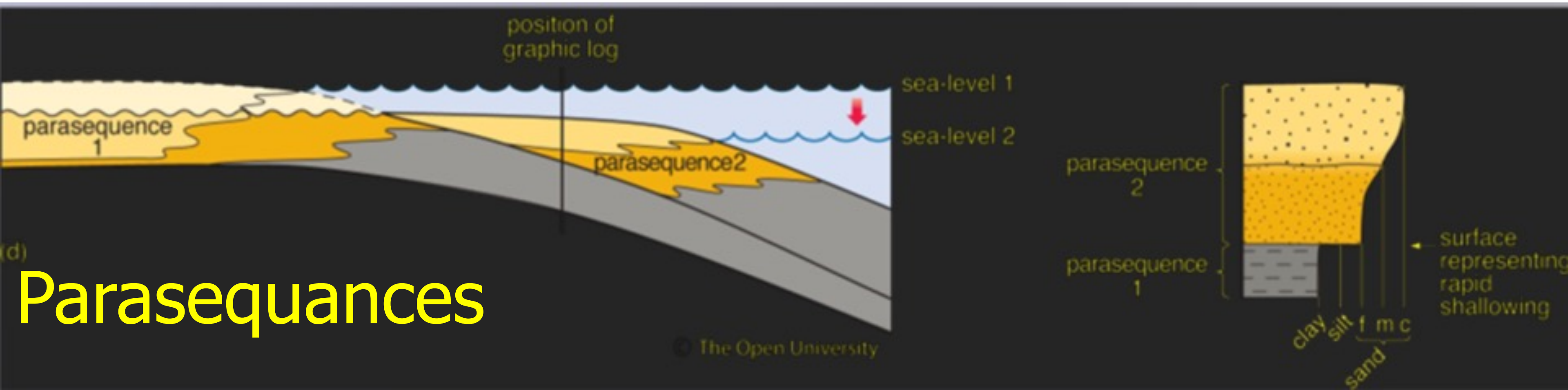
Base-level and transgressive–regressive (T–R) curves.

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.



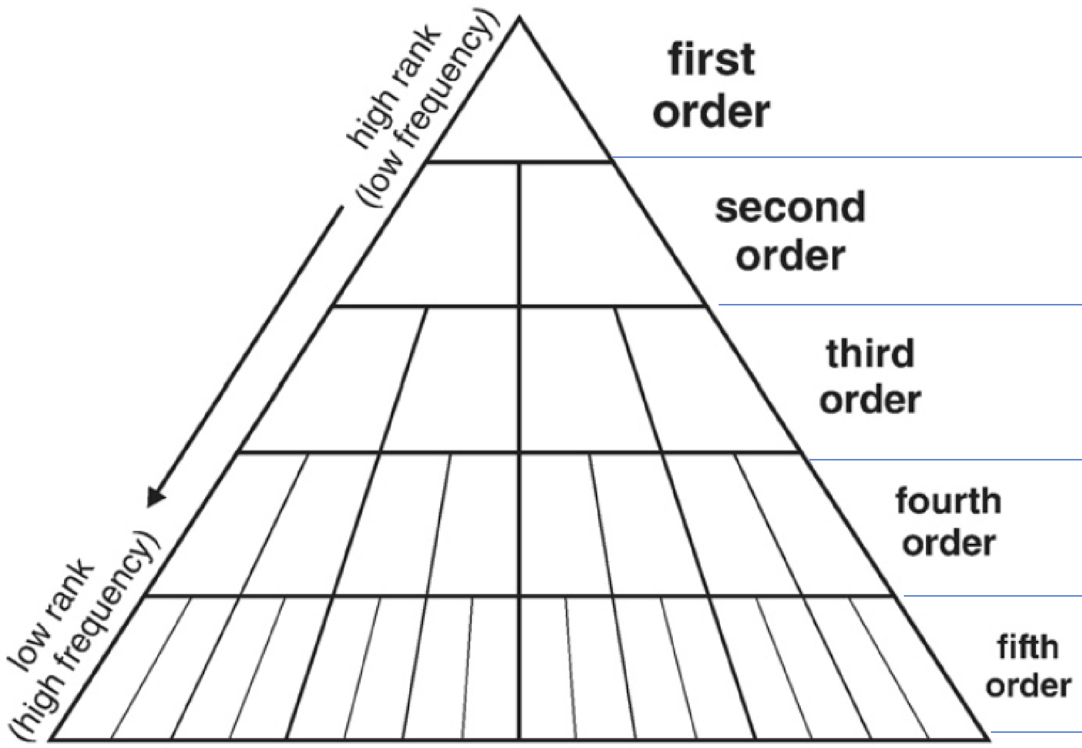
Sedimentation rates during a cycle of base-level change are considered constant and the reference baselevel curve is shown as a symmetrical sine curve, only for simplicity.

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

Sequence hierarchy

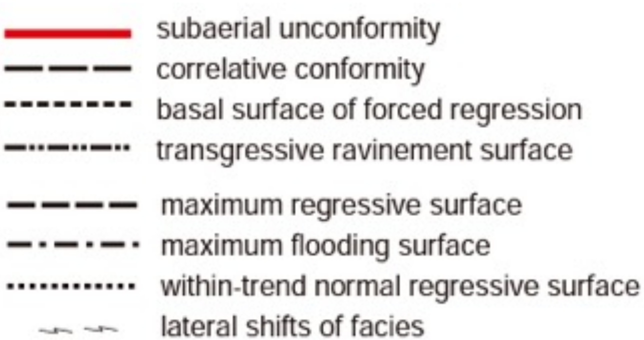


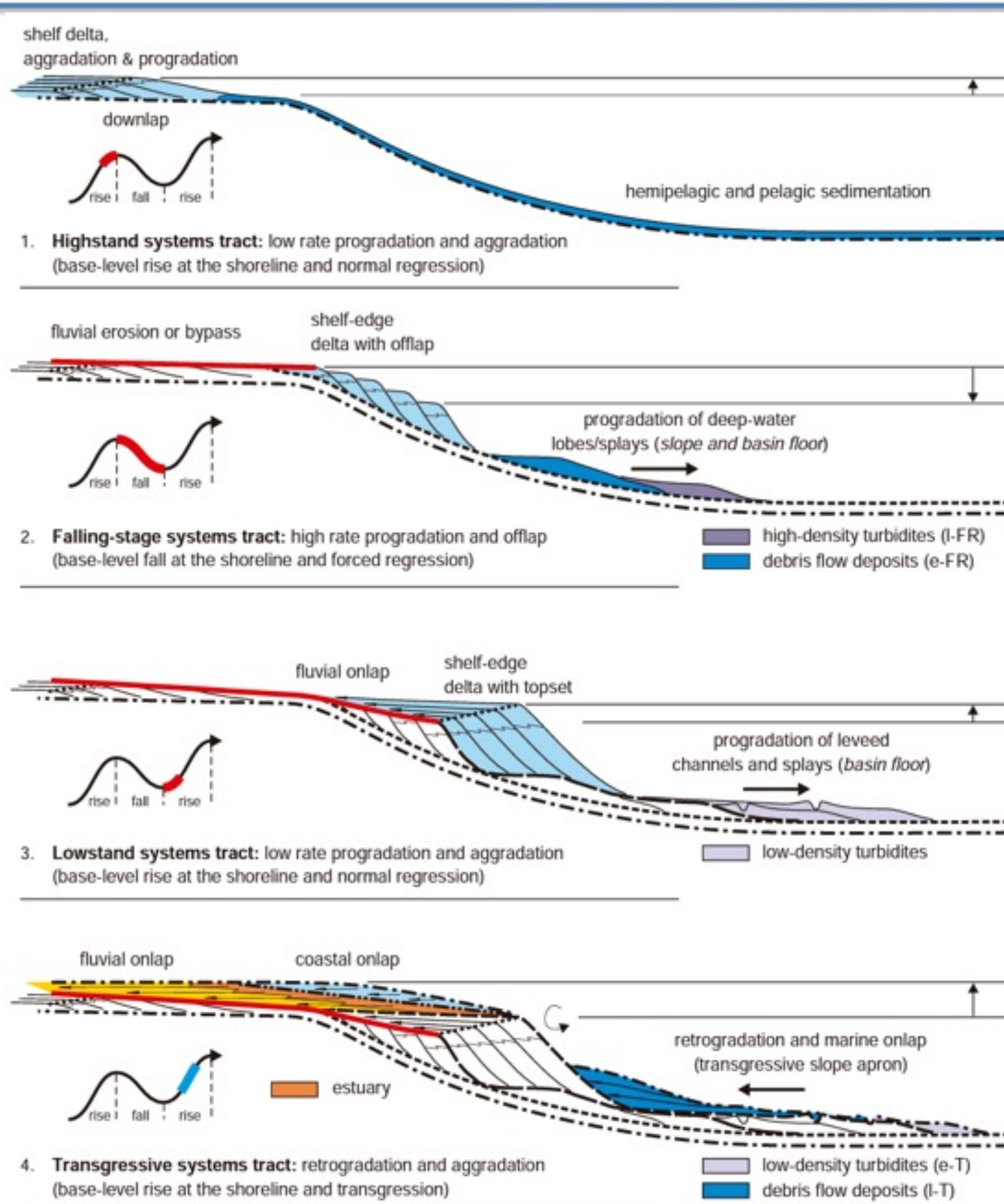
Order	Time (Ma)
First order	50+
Second order	3-50
Third order	0.5-3
Fourth order	0.08-0.5
Fifth order	0.03-0.08
Sixth order	0.01-0.03

From Vail et al. (1991)

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



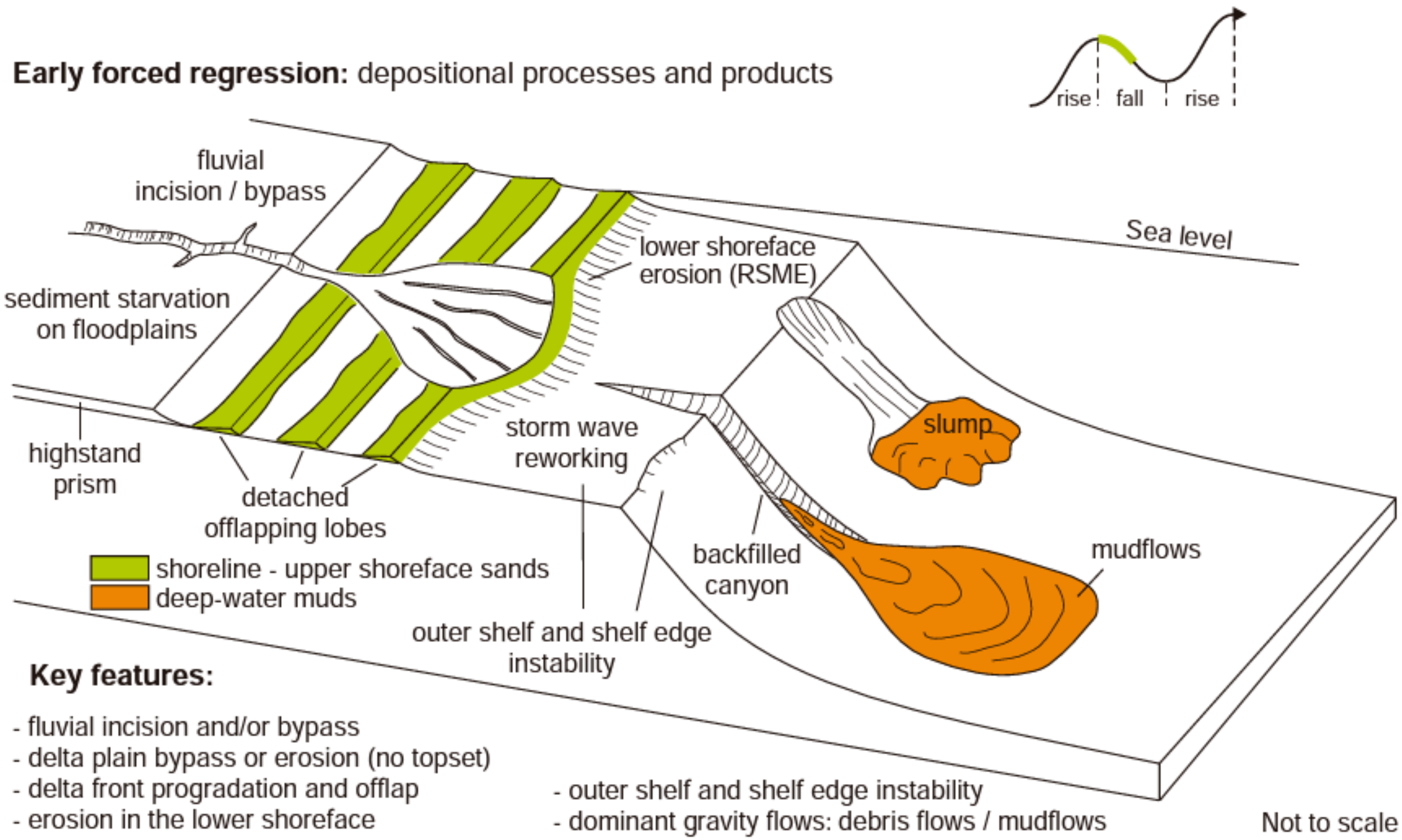


Grading trends along vertical profiles through the fluvial, shallow- and deep-water parts of the various systems tracts.

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)	

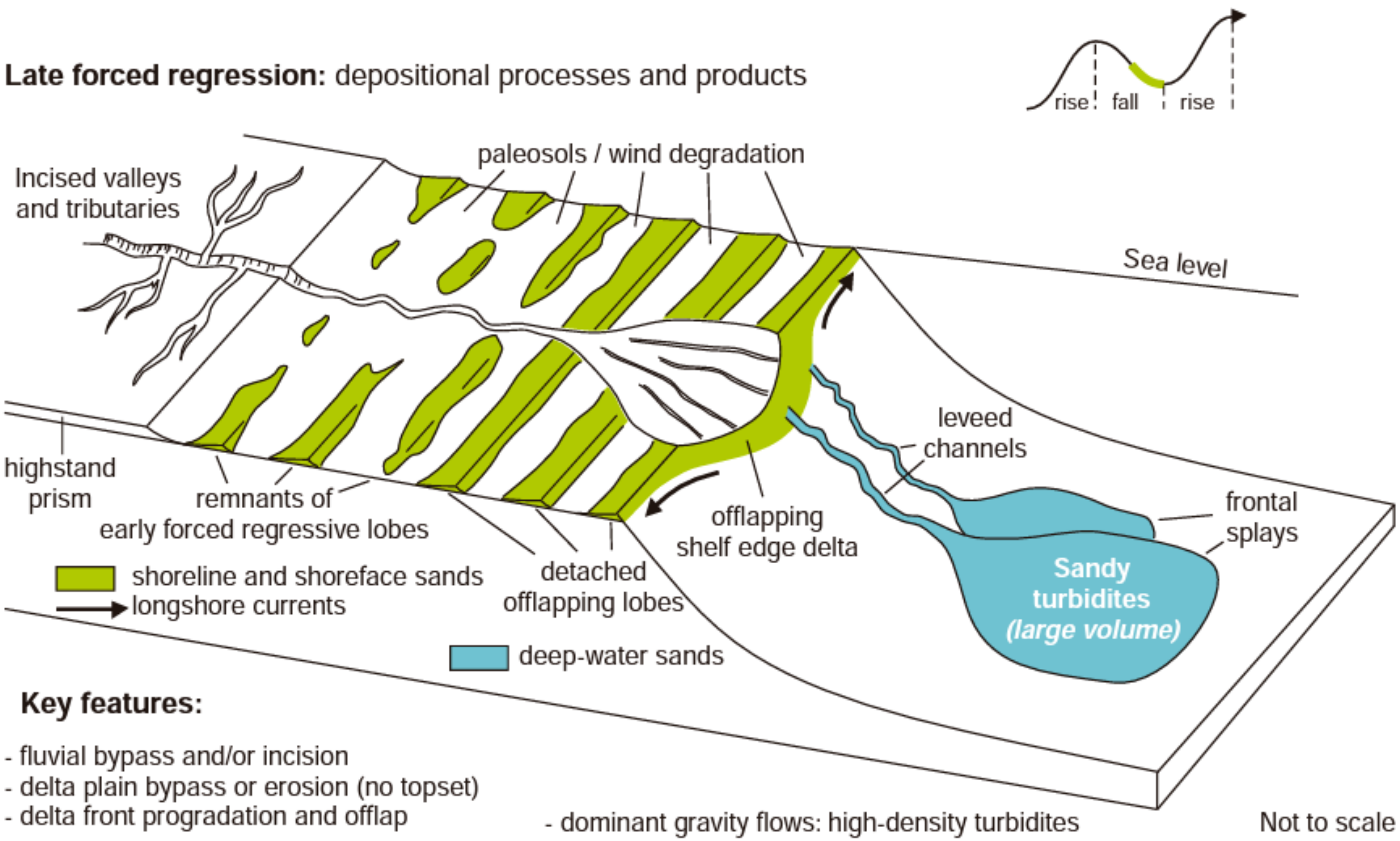
The trends of change in maximum grain size and sand/mud ratio correlate in general, with the exception of the highstand fluvial systems (shaded area).

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)

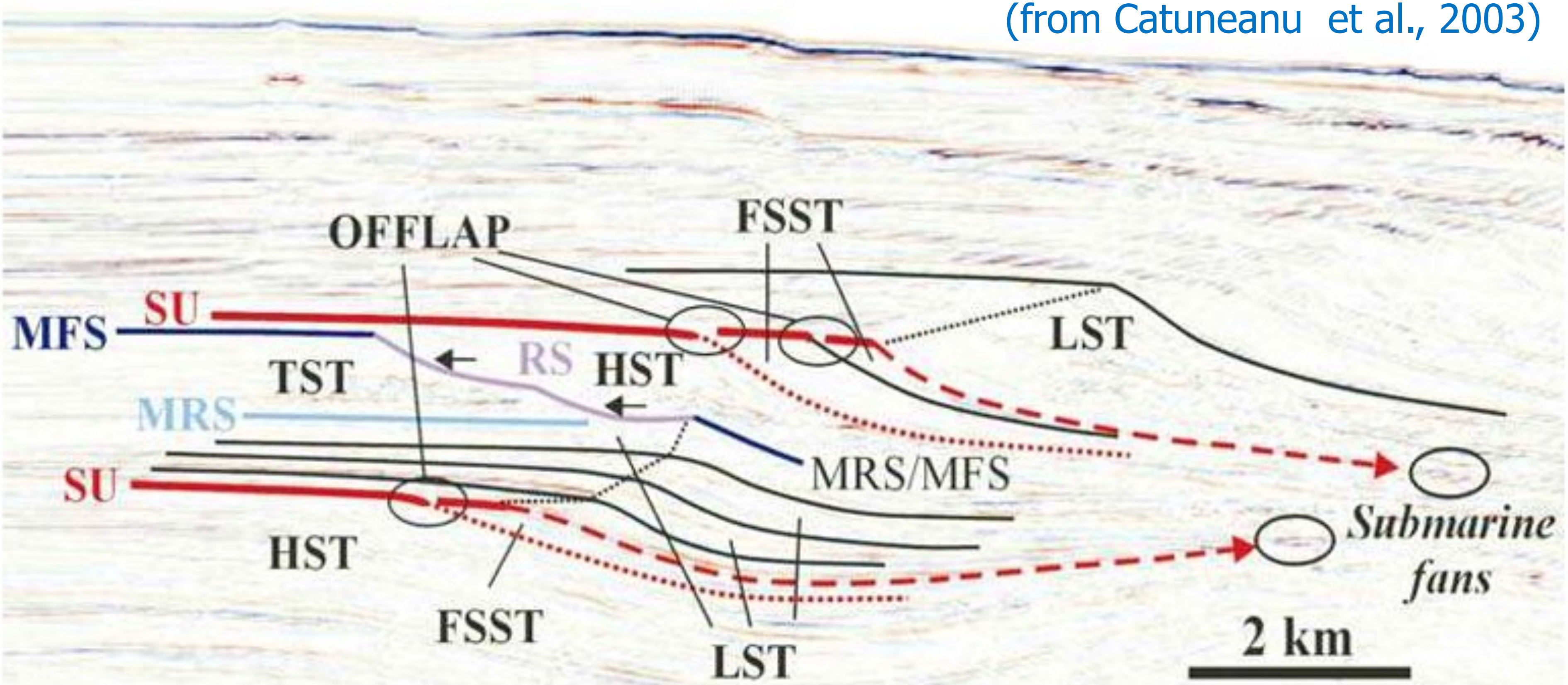


The sediment mass balance changes in the favor of the deep-sea submarine fans, which capture most of the sand. The subaerial unconformity keeps forming and expanding basinward until the end of base-level fall. Note that fluvial systems are likely to incise into the highstand prism but may only bypass 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)

Interpreted seismic line showing the location of the best deep-water reservoirs in a sequence stratigraphic framework

(from Catuneanu et al., 2003)



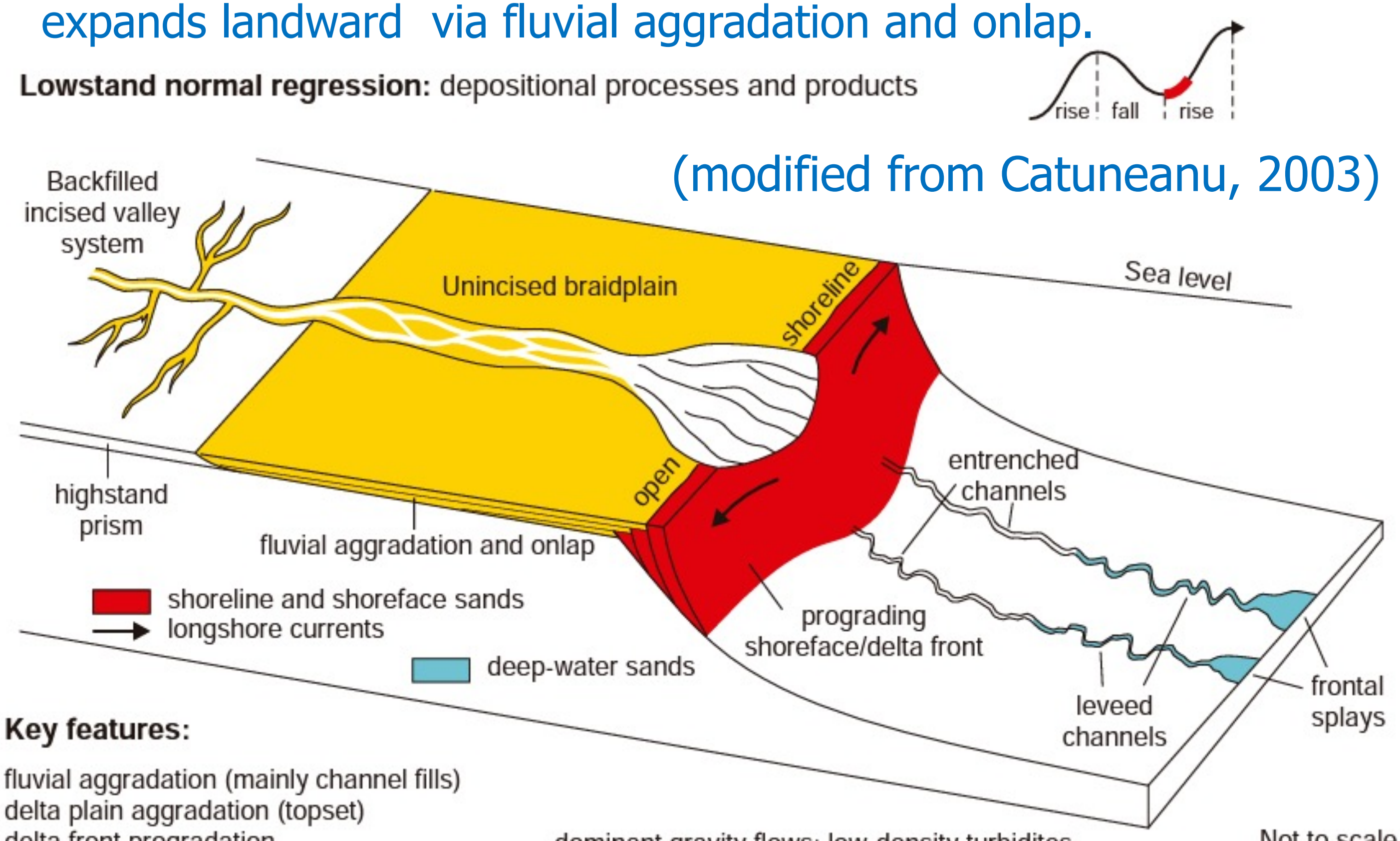
The offlap type of stratal termination is highly significant for deep-water exploration because the youngest clinoform associated with offlap leads to the top of the coarsest deep-water facies.

Depositional processes and products of the lowstand systems tract

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.

Lowstand normal regression: depositional processes and products



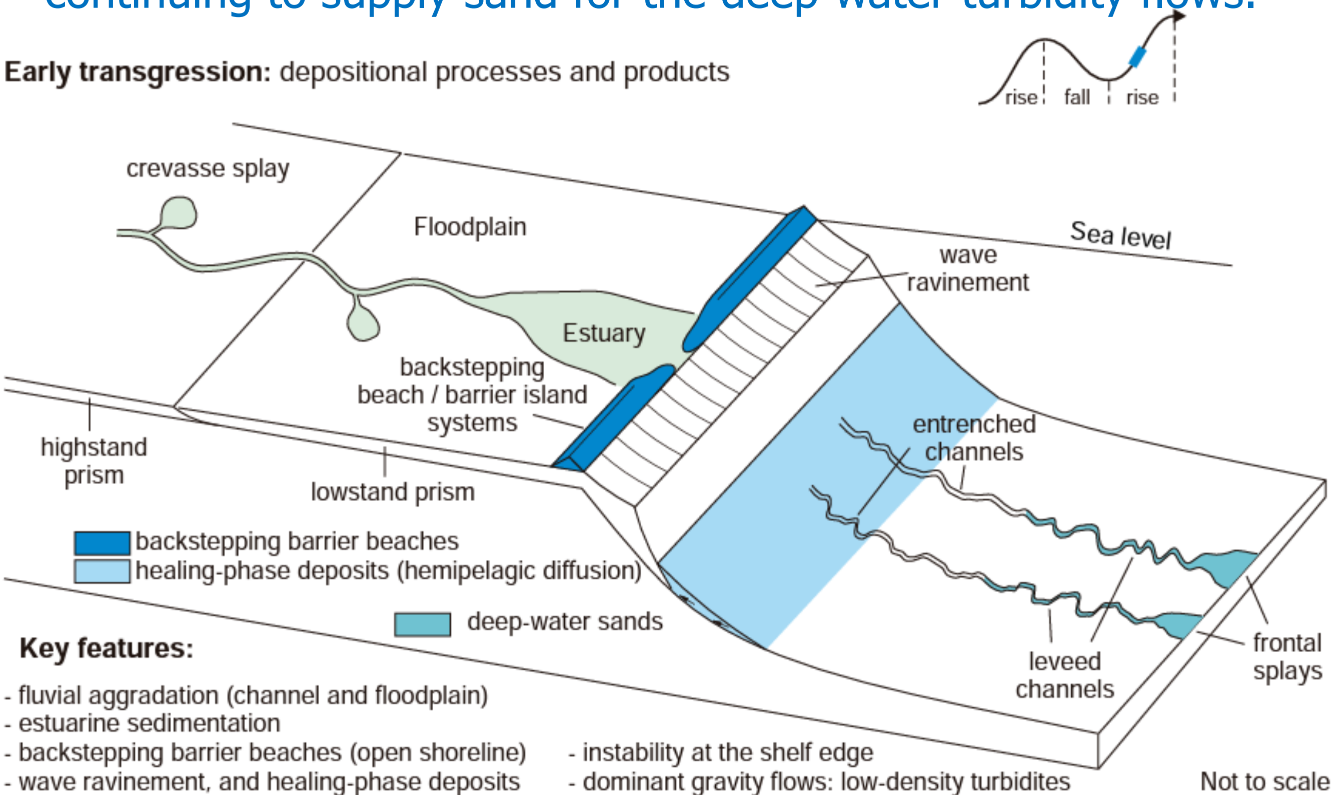
(modified from Catuneanu, 2003)

Key features:

- fluvial aggradation (mainly channel fills)
- delta plain aggradation (topset)
- delta front progradation
- dominant gravity flows: low-density turbidites

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

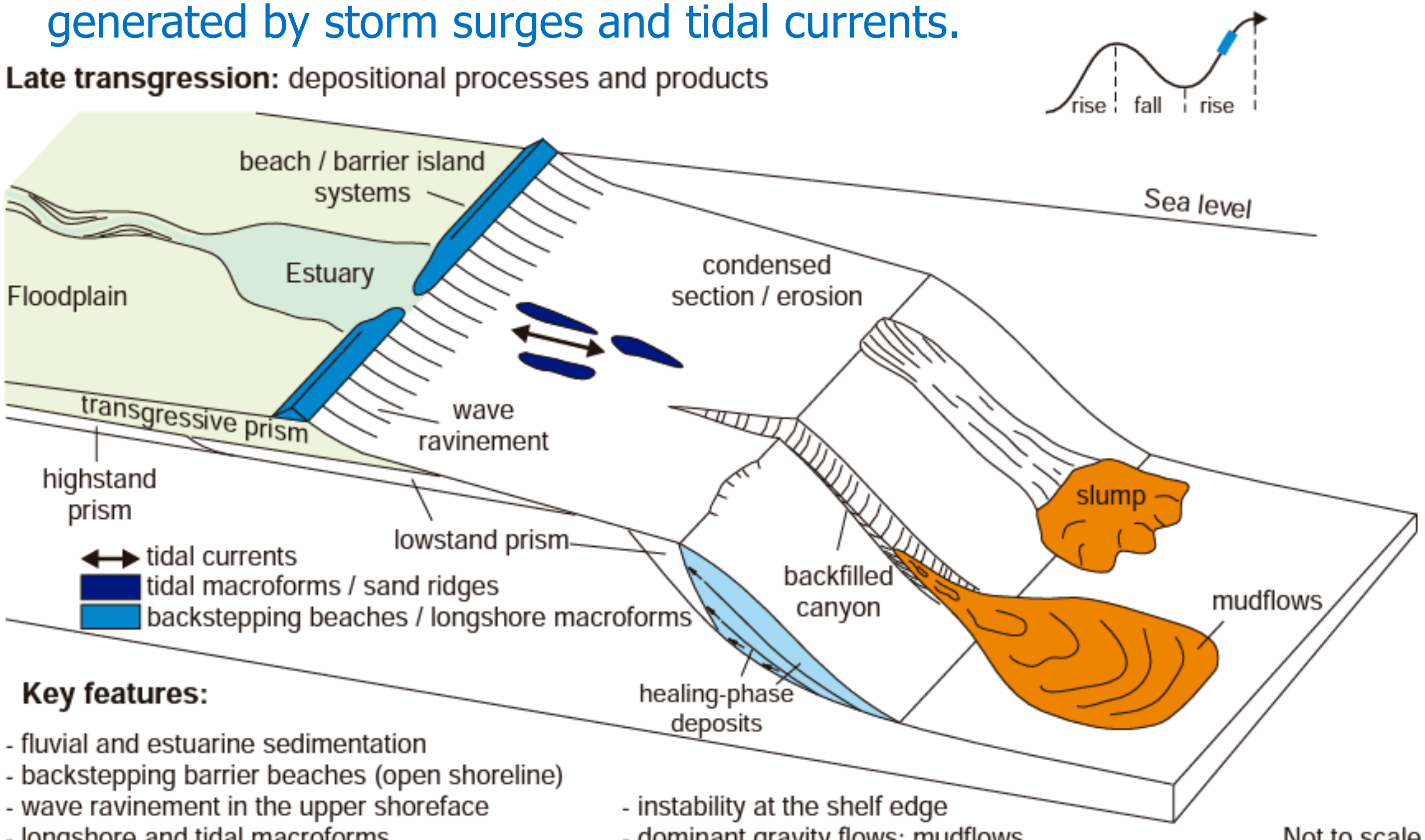
Rapid rates of base-level rise trigger a retrogradational shift of facies on the continental shelf, where most of the riverborn sediment is now trapped in fluvial, coastal and shallow-marine systems. Wave-ravinement processes erode the underlying normal regressive shelf-edge deltas and open shoreline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

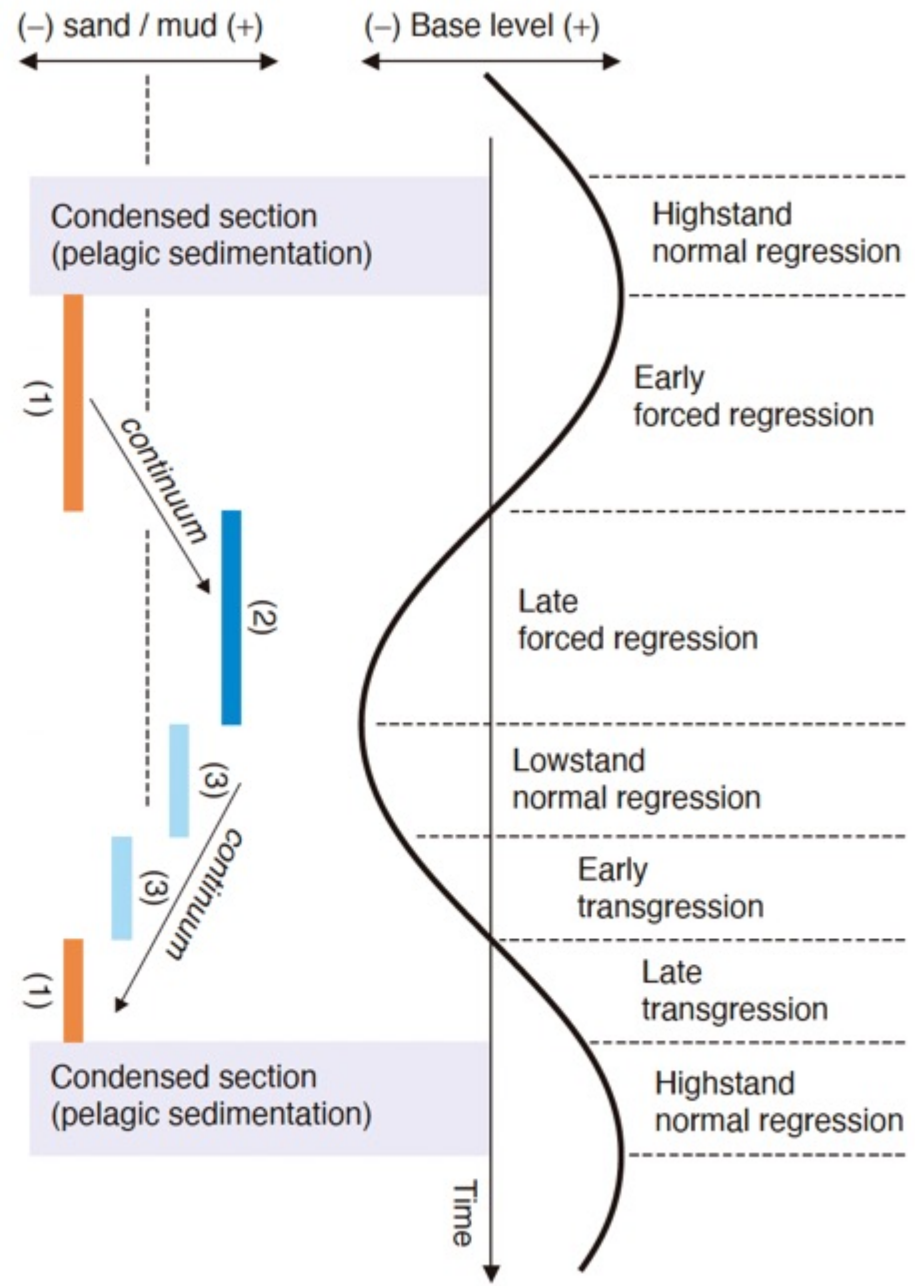
Depositional processes and products of the late TST (modified from Catuneanu, 2003)

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.

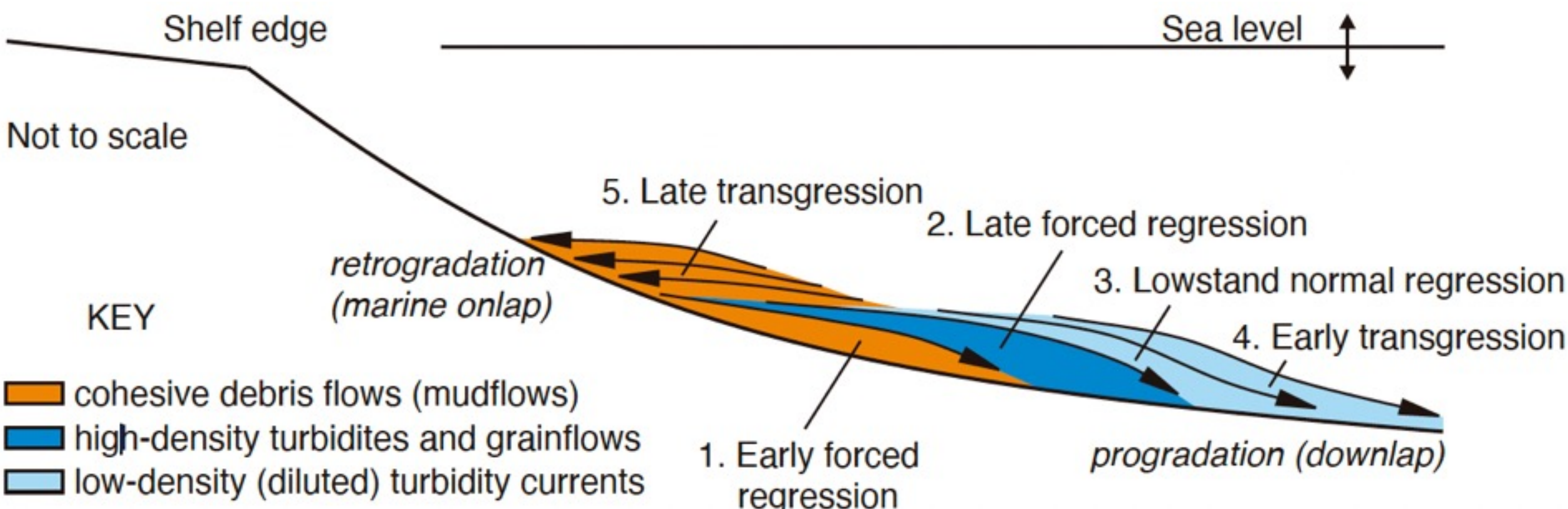
Dominant types of gravity flows that supply sediment to the deep-water environment, in relation to specific stages of shoreline shift



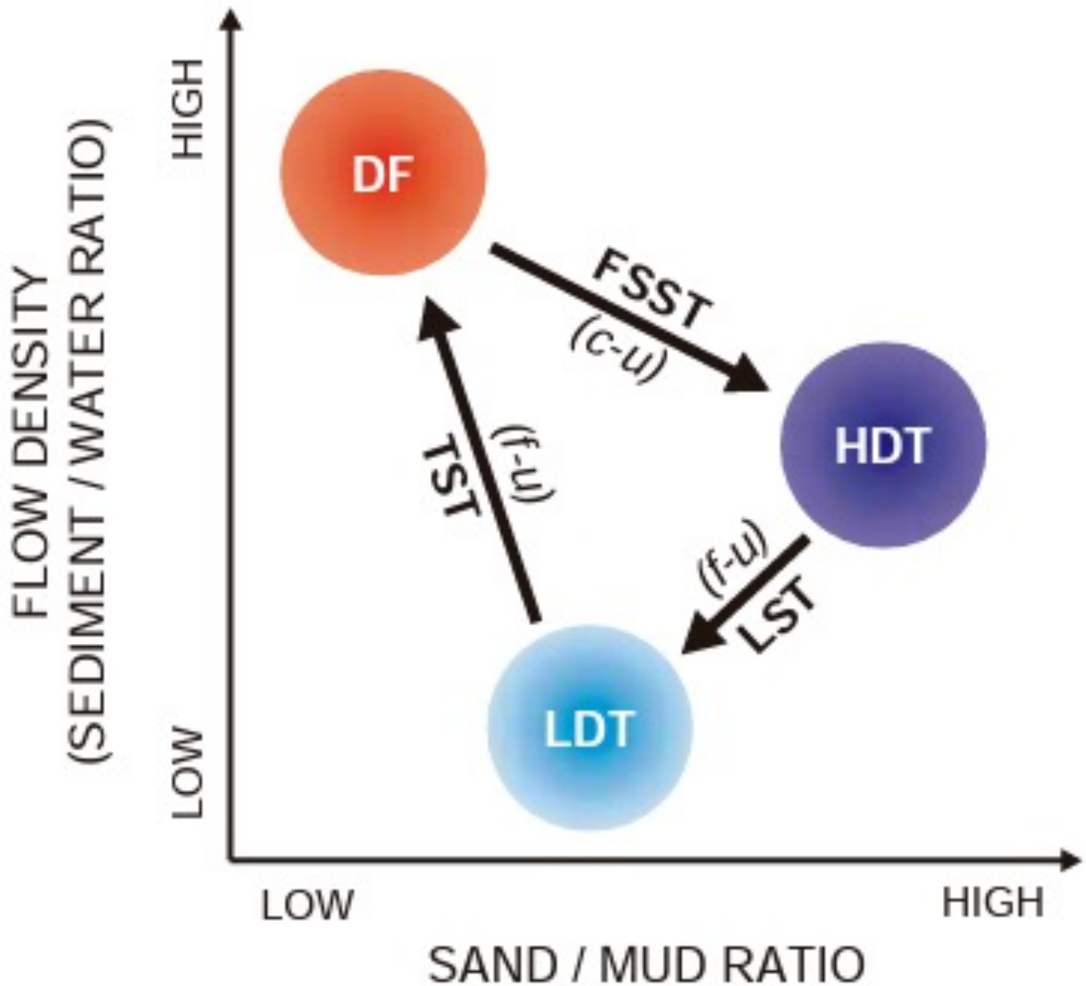
Note that there is a continuum between the end-member types of gravity flows as changes in sediment supply are gradational through time.
Key: (1) cohesive debris flows (mudflows); (2) high-density turbidity currents and grainflows, forming proximal frontal splays; (3) lower-density turbidity currents,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

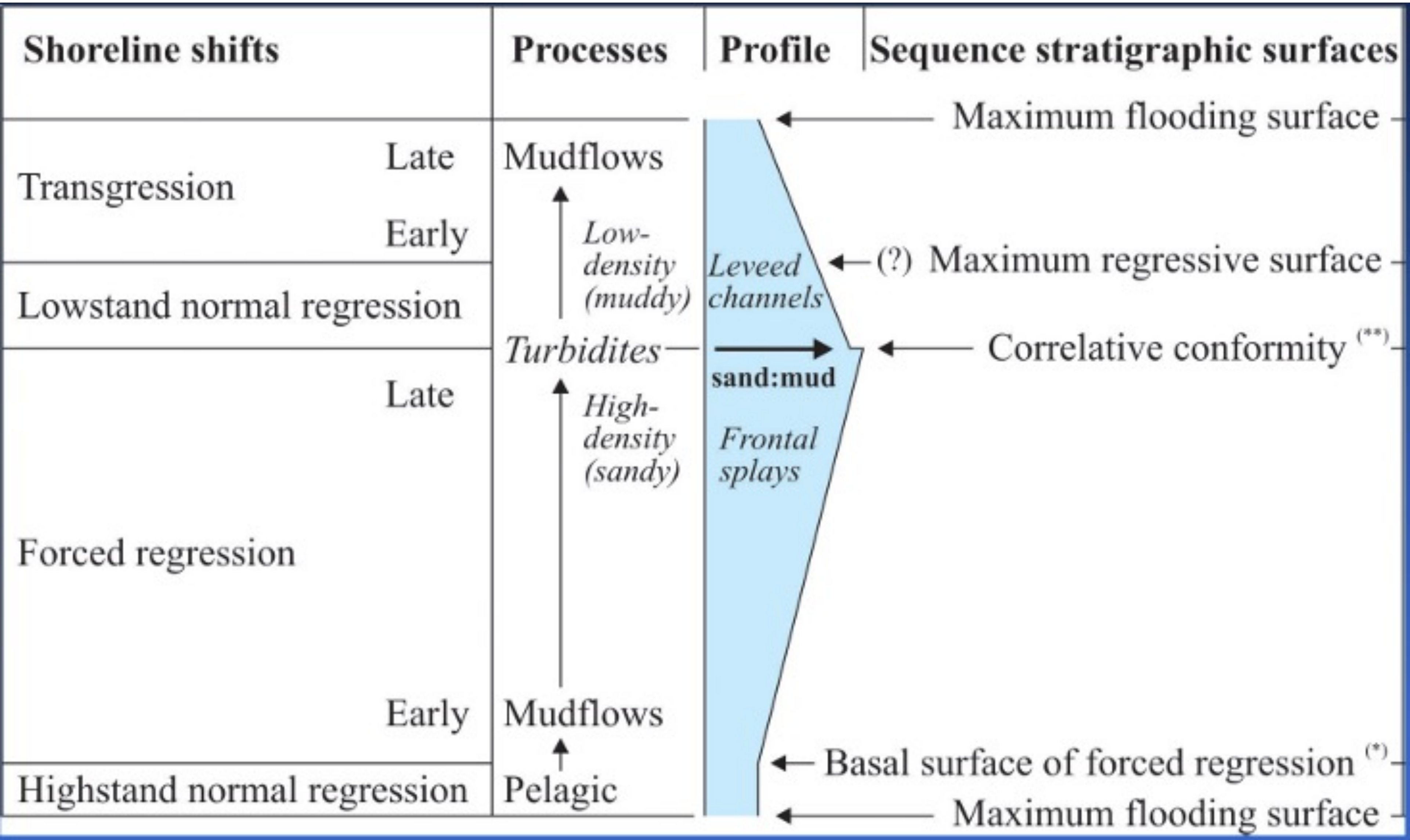


Trends of change in the main types of gravity flows that operate in the deep-water environment during the formation of systems tracts



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*

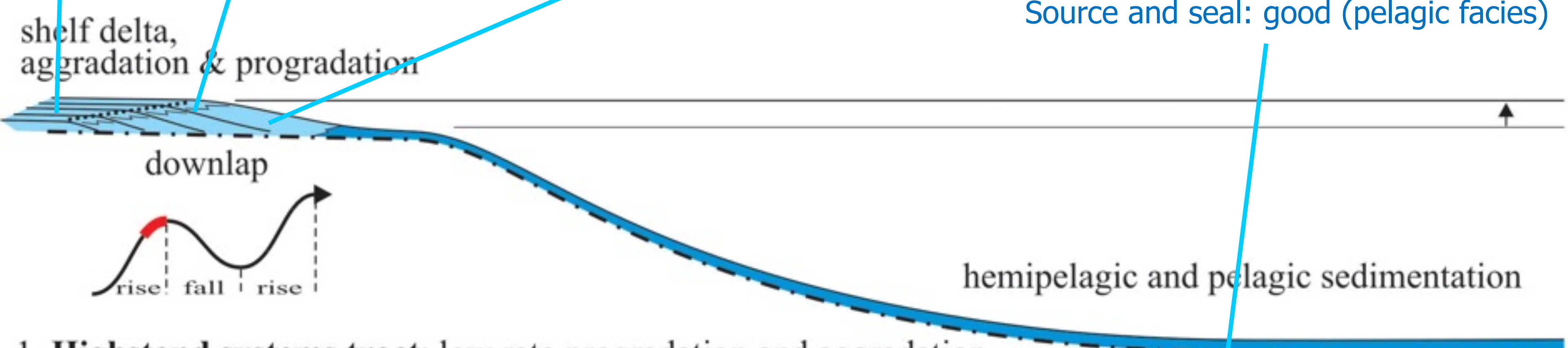
Application to reservoir geology: HST

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 (shorefaceì 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)

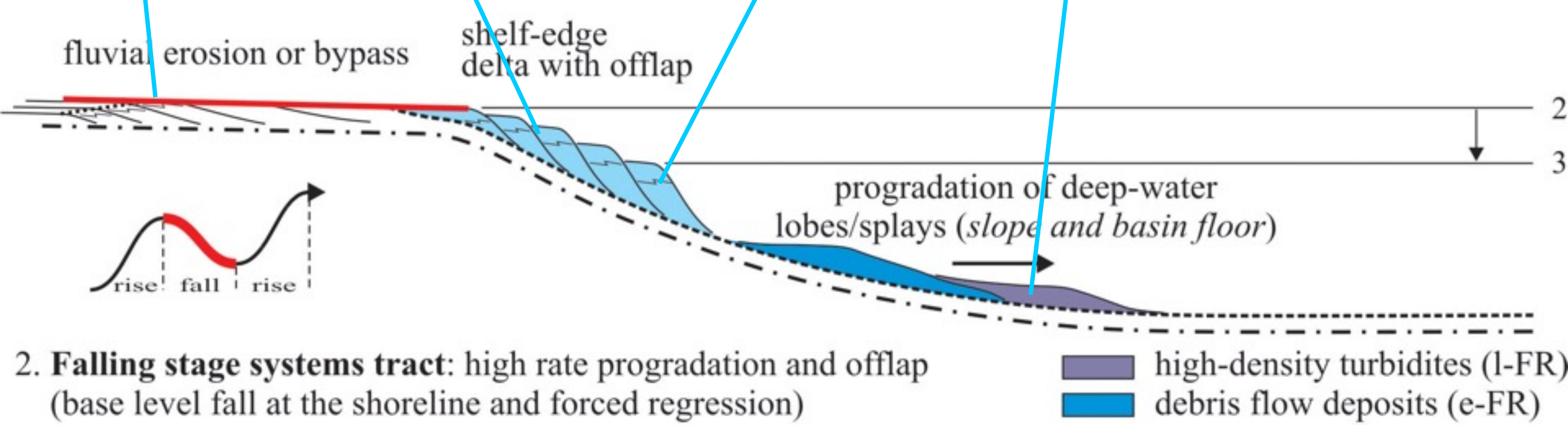
Application to reservoir geology: FSST

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

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

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

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)

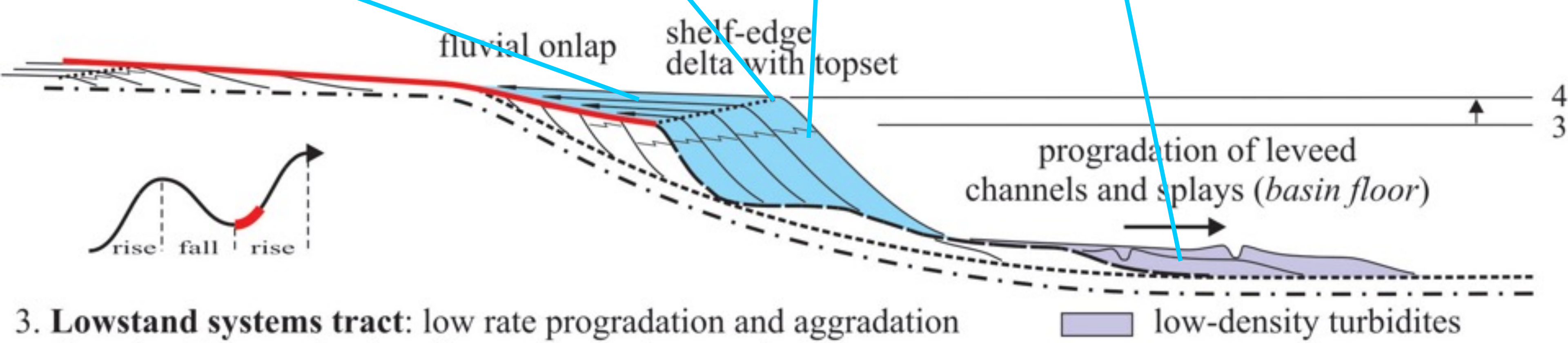
Application to reservoir geology: LST

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)

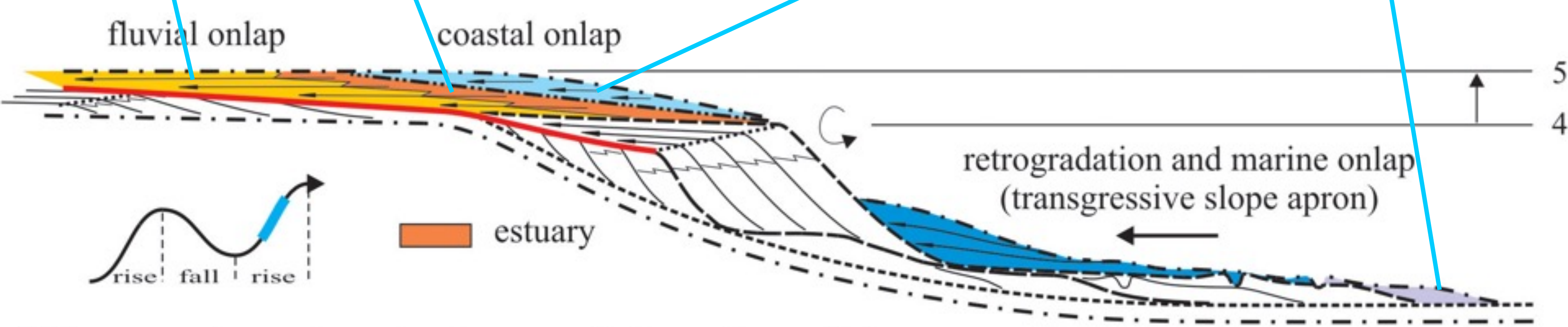
Application to reservoir geology: TST

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

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

Continuity of reservoirs in continental settings

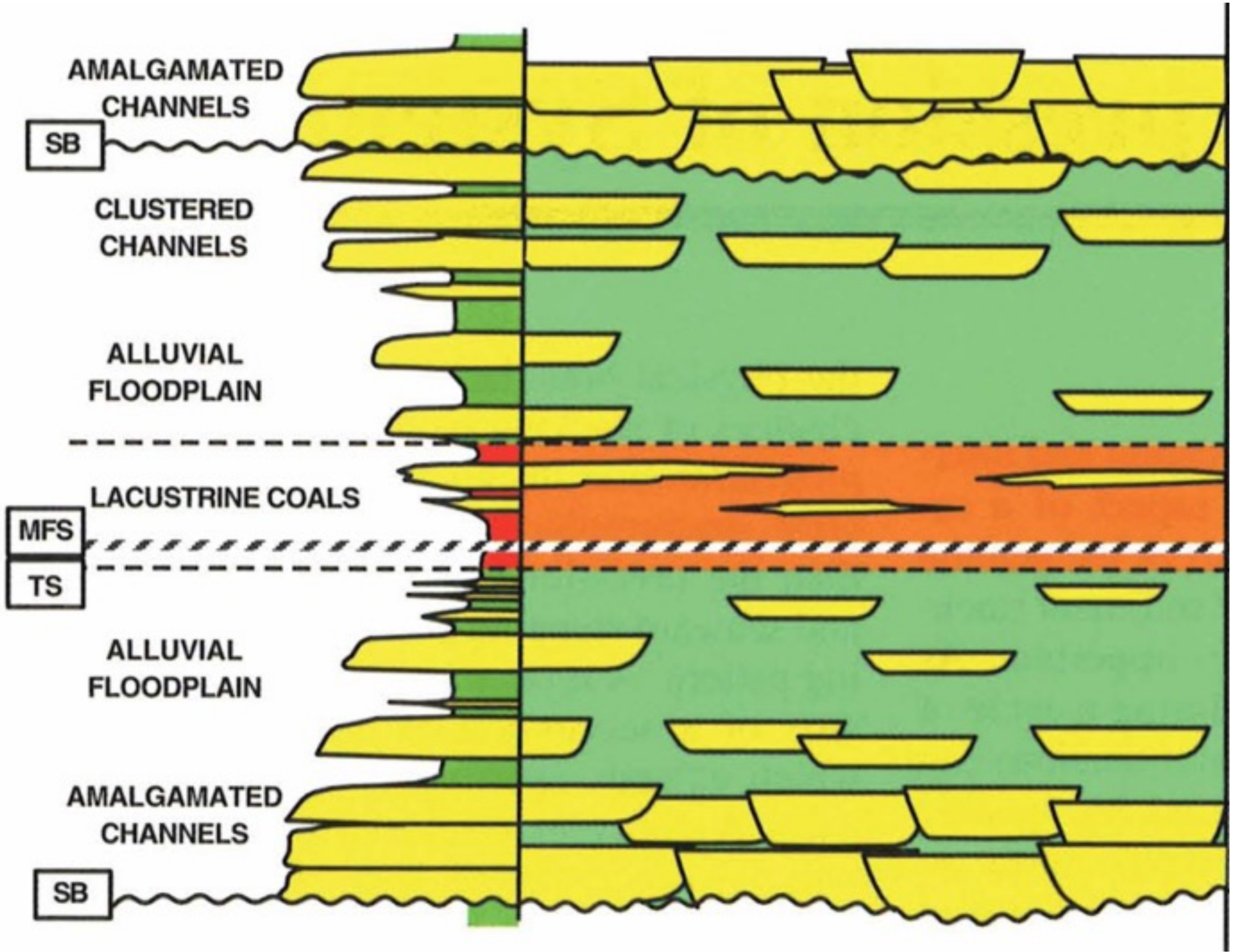
Good reservoir continuity

Isolated reservoirs

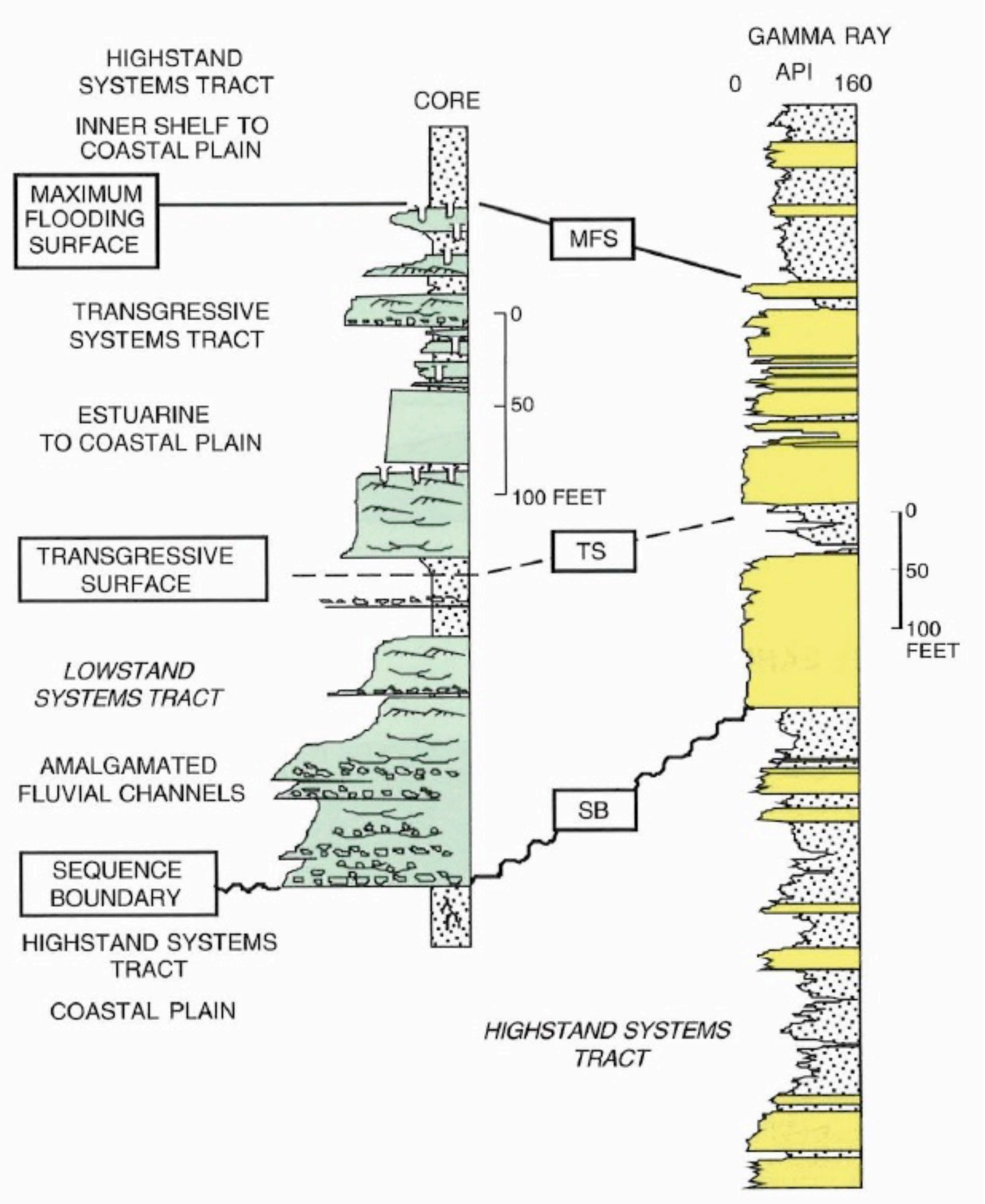
Potential source rock

Isolated reservoirs

Good reservoir continuity



Potential continental to coastal reservoirs

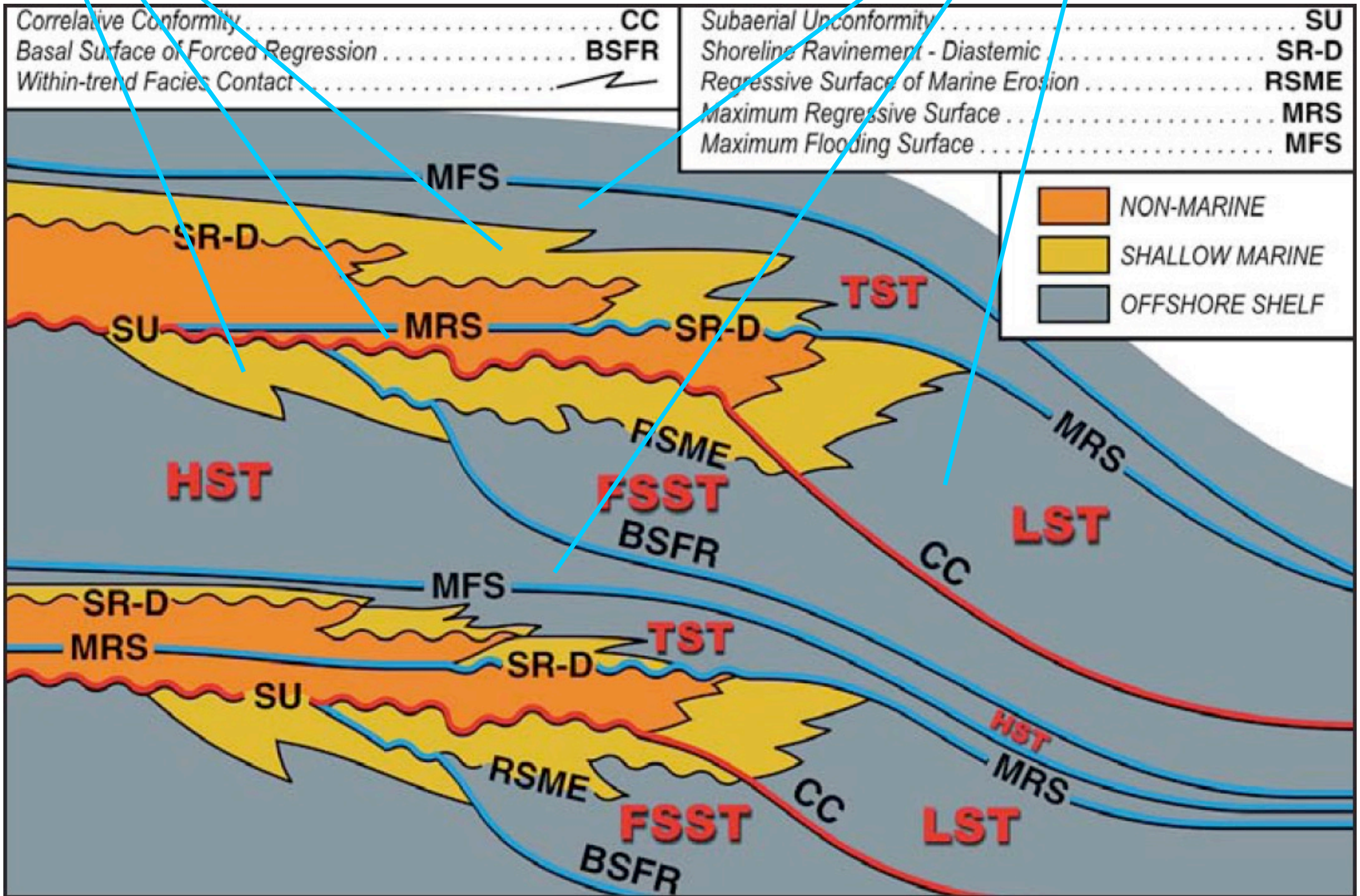


Paleocene of Colombia

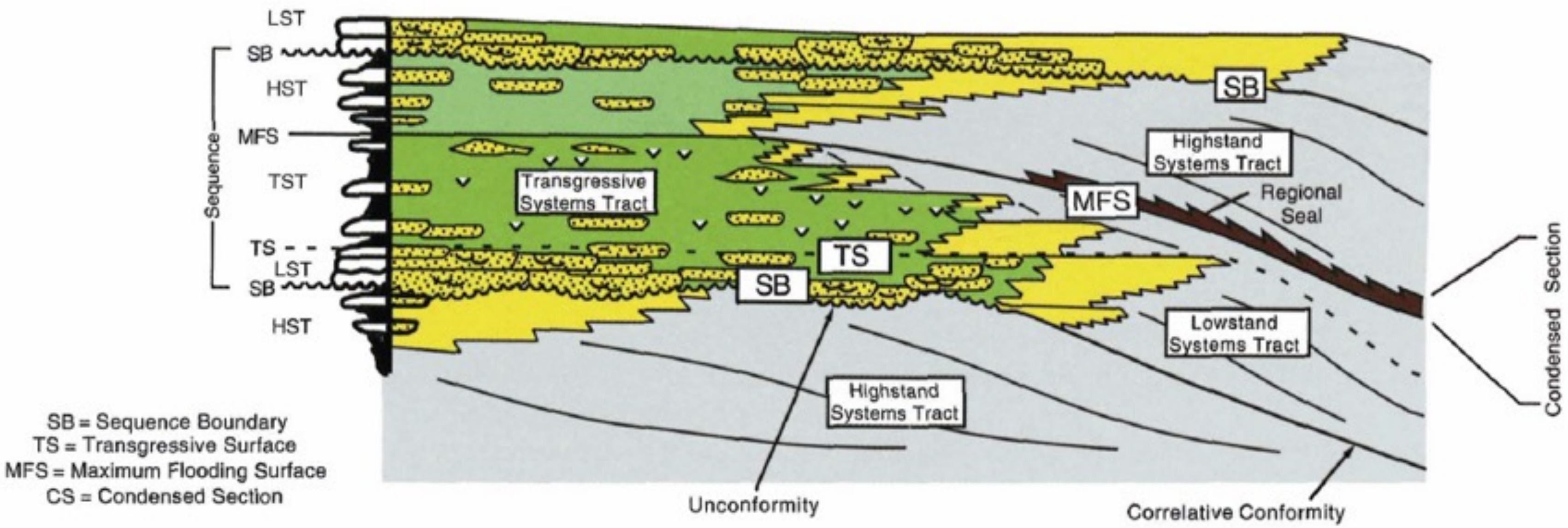
Continental to shallow-marine reservoirs

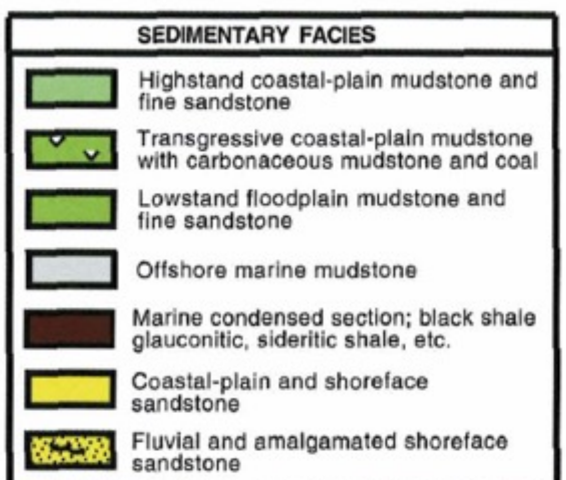
Potential reservoirs

Sealing deposits



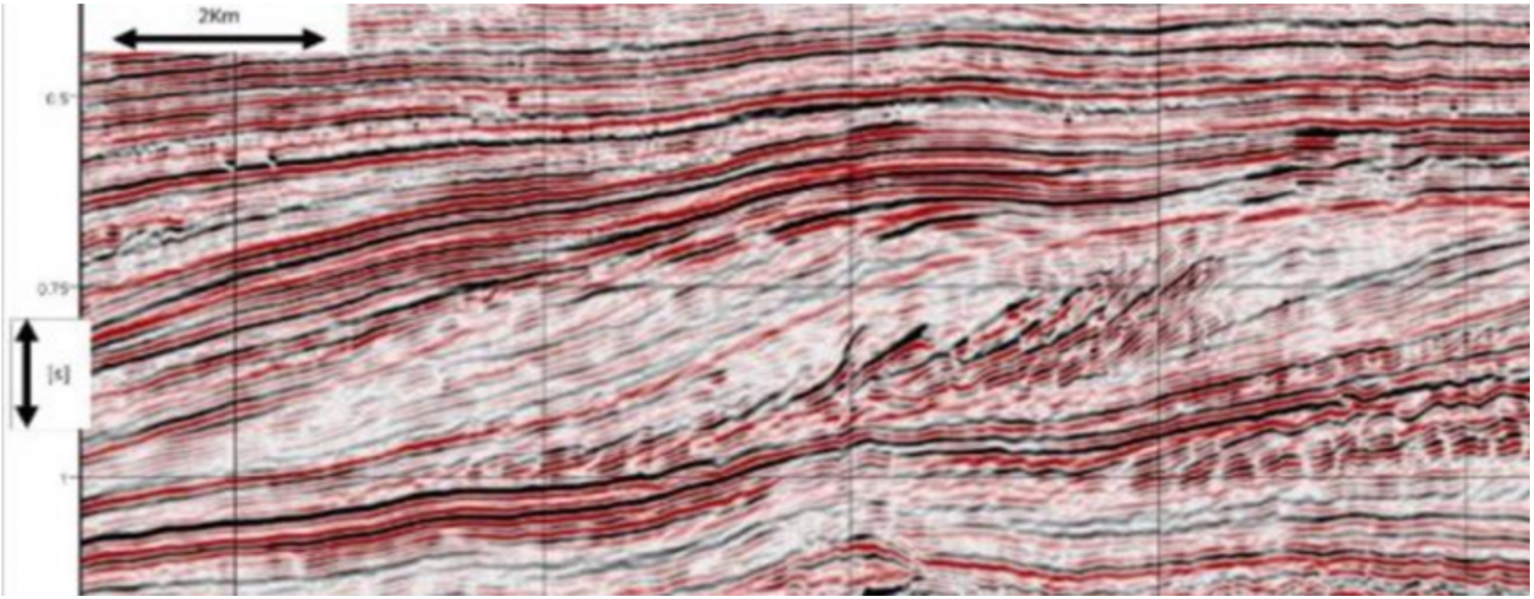
Continental to shallow-marine reservoirs

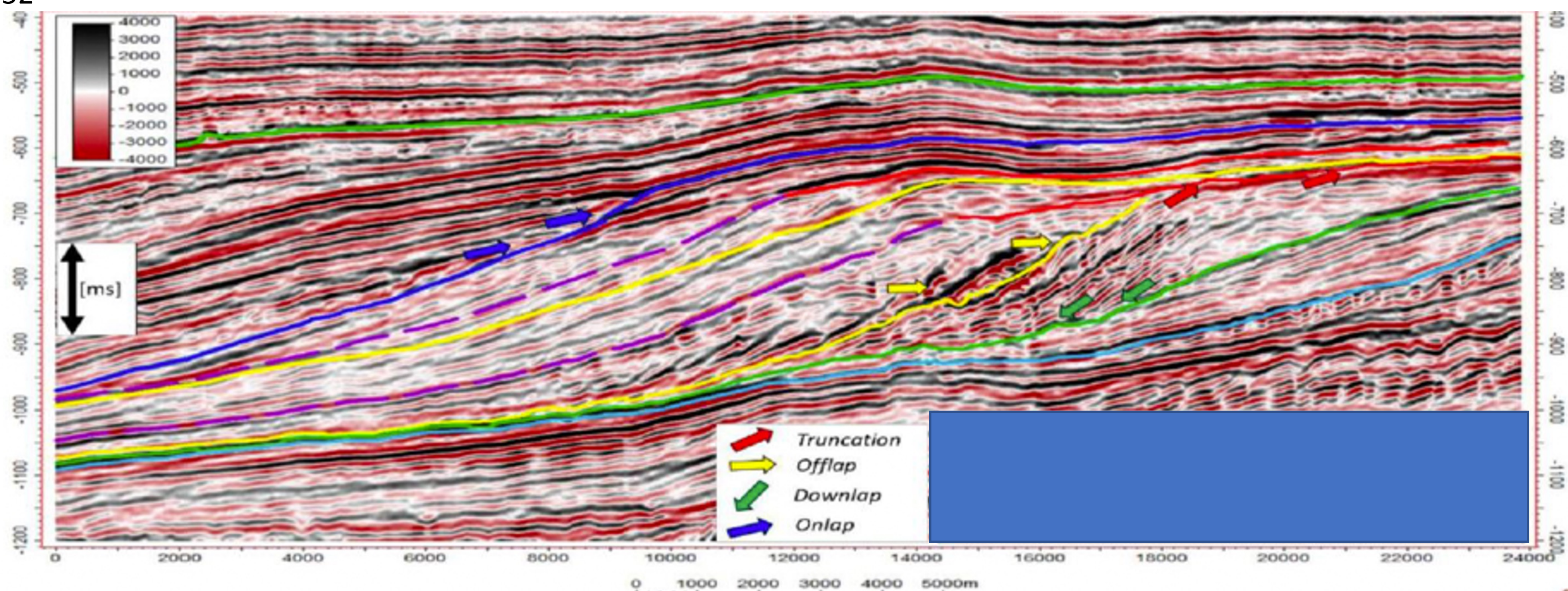


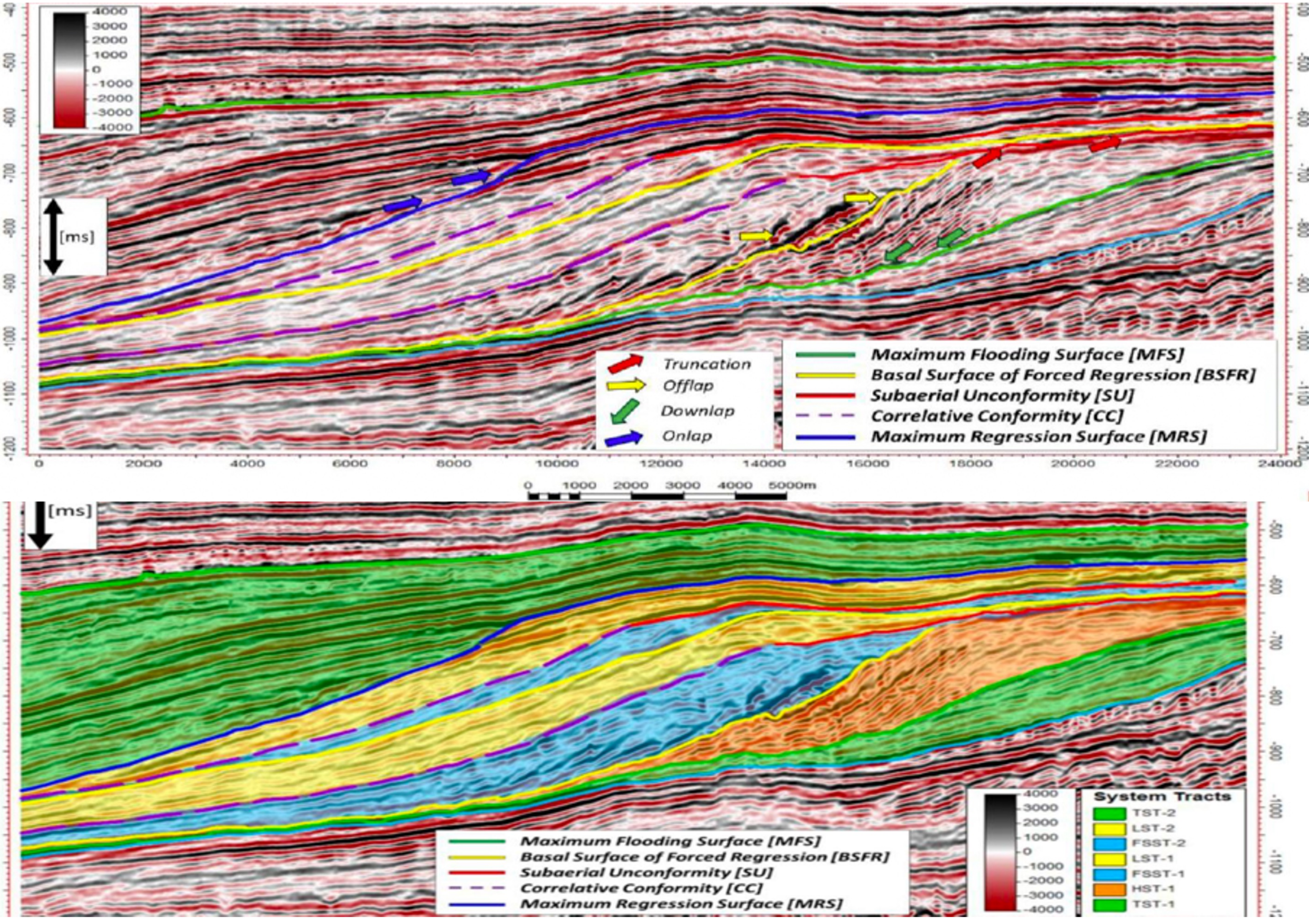


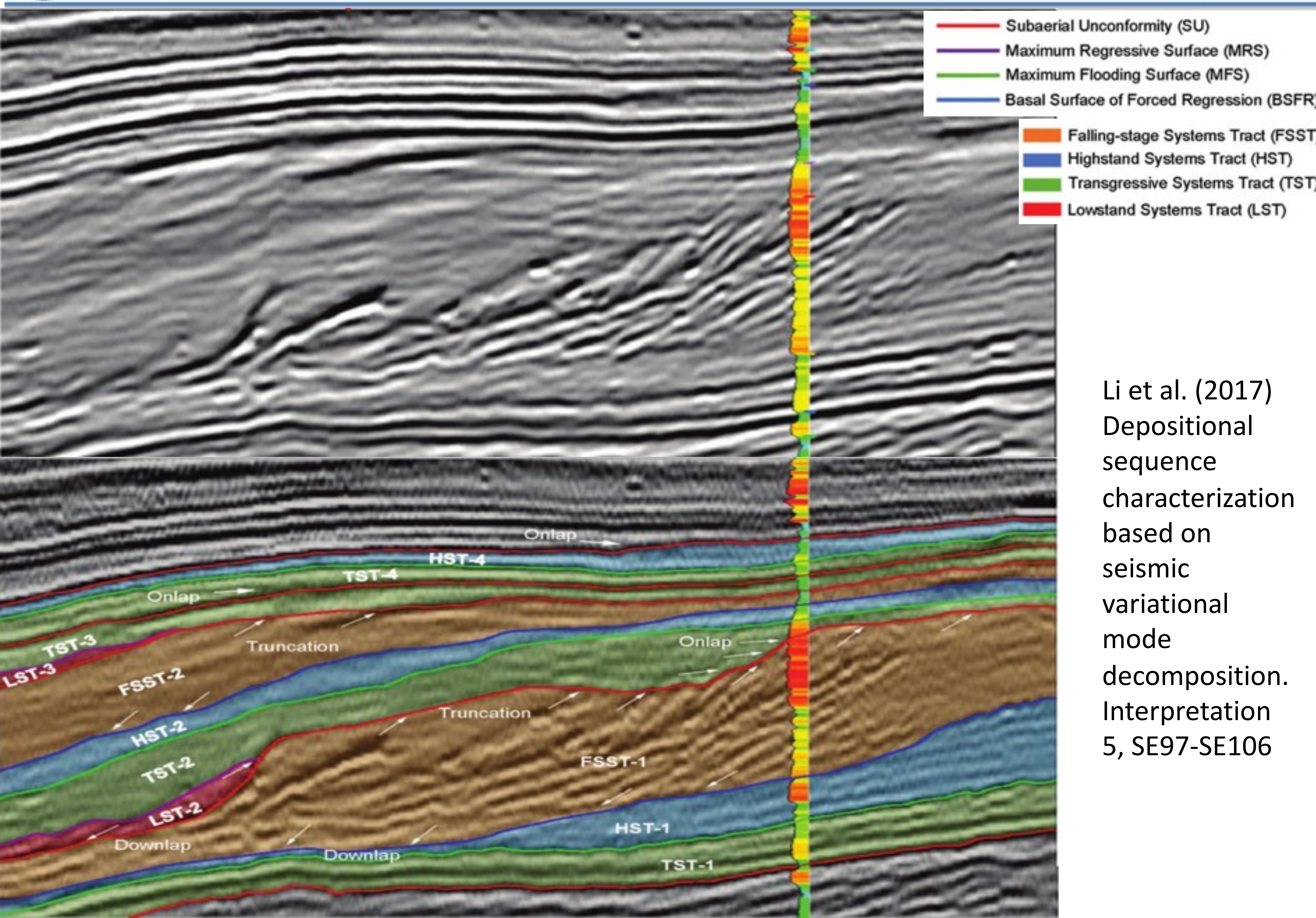
Systems Tract	Play Significance	Risk	Facies Examples
Lowstand	Reservoir	Source,Charge	***Reservoir:*** Shelf-edge deltas, incised-valley fill fluvial deposits, forced-regression shoreface/deltaic deposits deep-waterturbidite and bottom-current reworked deposits
Transgressive	Source, Seal, Reservoir	Reservoir	***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

Illidge E., Camargo J., Pinto J. (2016) Turbidites Characterization from Seismic Stratigraphy Analysis: Application to the Netherlands Offshore F3 Block. Search and Discovery Article 41952






[ms]
Truncation
Offlap
Downlap
Onlap
Maximum Flooding Surface [MFS]
Basal Surface of Forced Regression [BSFR]
Subaerial Unconformity [SU]
Correlative Conformity [CC]
Maximum Regression Surface [MRS]
0 1000 2000 3000 4000 5000m
[ms]
Maximum Flooding Surface [MFS]
Basal Surface of Forced Regression [BSFR]
Subaerial Unconformity [SU]
Correlative Conformity [CC]
Maximum Regression Surface [MRS]
System Tracts
TST-2
LST-2
FSST-2
LST-1
FSST-1
HST-1
TST-1



Li et al. (2017) Depositional sequence characterization based on seismic variational mode decomposition. Interpretation 5, SE97-SE106