October 2022

CCE-04 Pre-Congres Continuous Education Course

Sedimentology for Depositional Environment Reconstruction

Prepared for

Dr. Emerson Marfisi Gonzalez

Senior Geoscientist

BeicipFranlab

Course Outline

Morning Session

9:30 am

- Introduction
- Sedimentology Principles

15 min Break

- Seismic Stratigraphy Principles
- Applying FSM to Reconstruct Sedimentary Environments

1h Lunch Break

Afternoon Session

1:30 pm

- Integration of G&G data
- Managing Uncertainties

15 min Break

- Results and Deliverables
- Conclusions and Take Away Messages

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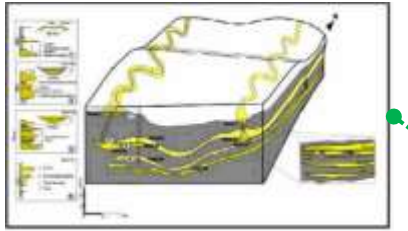
Sedimentary Environments Reconstruction

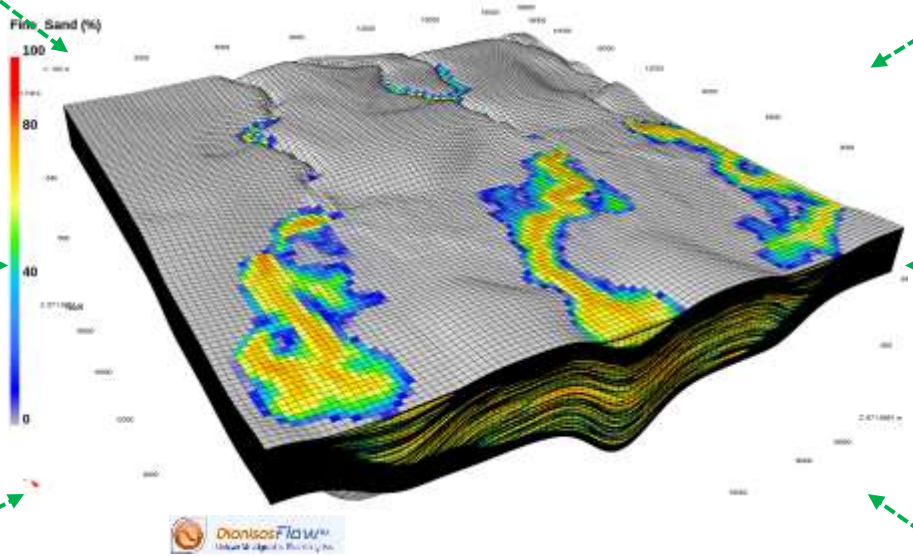
Integration of G&G Data to Reconstruct Sedimentary Environments.

Sedimentology



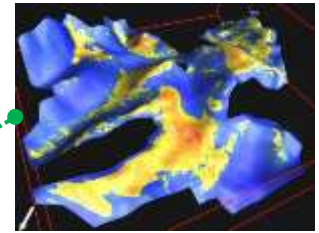
Biostratigraphy

GDE and NTG

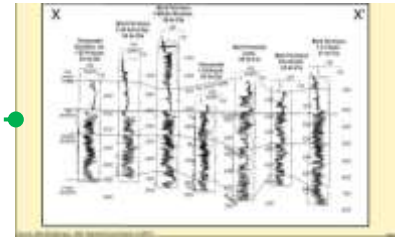


Forward Stratigraphic Model

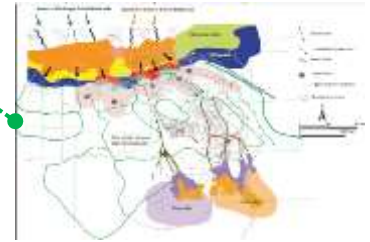
Seismic Data



Well Data



Basin Evolution Models



Combellas and Galloway 2006

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Sedimentology Principles

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Sedimentology

- "The scientific study of sedimentary rocks and of the processes by which they were formed; the description, classification, origin and interpretation of sediments" (Glossary of Geology, AGI, 1974)
  - Study of modern sediments such as sand, mud (silt),and clay.
  - Understanding the processes driving transport a sedimentation.
  - Studies of ancient sedimentary rocks.

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Two conceptions of Earth history:

Catastrophism

- Assumption: great effects require great causes
- Earth history dominated by violent events

Uniformitarianism

- Assumption: we can use cause and effect to determine causes of past events
- Finding: Earth history dominated by small-scale events typical of the present.
- Catastrophes do happen but are uncommon

Sir Charles Lyell

Baron Georges Cuvier

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Uniformitarianism

Continuity of Cause and Effect

- Uniformitarianism, states that sediments within ancient sedimentary rocks were deposited in the same way as sediments which are being deposited today.

Recent Ripple Marks

Fossil Ripple Marks

Recent Mud Cracks

Fossil Mud Cracks

The present as the key to the past

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Catastrophism

- "…Geological history could be likened to the life of a soldier: "Long periods of boredom and short periods of terror." Gradualistic processes occurred, but were punctuated by the unusual…*
- Series of large, violent, quick, worldwide upheavals changed the earth greatly and produced mountains, valleys, and various other large-scale features.

Indonesian Earthquake/Tsunami

A large mudflow in Washington State, USA

https://blogs.agu.org/landslideblog/2013/09/09/stehekin-mudflow/

*Simmons, Mike. (2018). Catastrophism and the Deep Historical Roots of Sequence Stratigraphy.

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Other Principles

- **Principle of superposition** *Sedimentary layers are deposited in a time sequence, with the oldest on the bottom and the youngest on the top.*
- **Principle of original horizontality** sediments are deposited at their angle of repose which, for most types of sediment, is essentially horizontal.
- **Principle of lateral continuity** states that layers of sediment initially extend laterally in all directions unless obstructed by a physical object or topography.
- **Principle of cross-cutting relationships** states that whatever cuts across or intrudes into the layers of strata is younger than the layers of strata.

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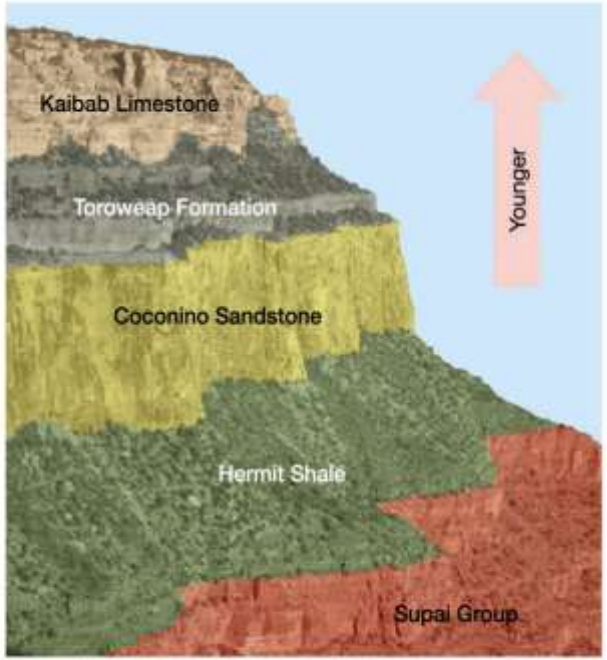
Principles of Sedimentology

Principle of Superposition: Sedimentary layers are deposited in a time sequence, with the oldest on the bottom and the youngest on the top.

A.



B.

Modified from Phil Murphy, University of Leeds

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Principles of Sedimentology

- **Principle of original horizontality:** sediments are deposited at their angle of repose which, for most types of sediment, is essentially horizontal.
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Principles of Sedimentology

- **Principle of cross-cutting relationships:** states that whatever cuts across or intrudes into the layers of strata is younger than the layers of strata. A geologic object can not be altered until it exists.

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Sedimentary Particles

- **Sediment:** loose, solid particles originating from**:**
  - Weathering and erosion of pre-existing rocks
  - Chemical precipitation from solution, including secretion by organisms in water.

- Produced from weathering products of pre-existing rocks or accumulated biological matter
  - **Detrital (clastic)** rocks produced from rock fragments
  - **Chemical** rocks produced by precipitation of dissolved ions in water
  - **Organic rocks** produced by accumulation of biological debris, such as in swamps or bogs.

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Sedimentary Particles

- **Sedimentary rock types and sedimentary structures** within the rocks give clues to past environments.
- **Fossils in sedimentary rocks** give clues to the history of life and help to place rocks in a chronostratigraphic context.
- **Important resources** (coal, oil, water and minerals) are found in sedimentary rocks.

Source USGS

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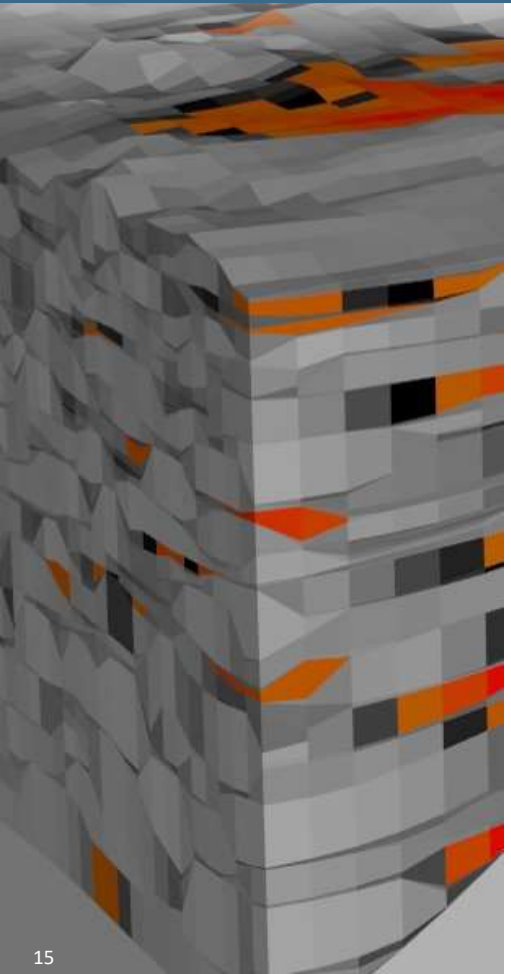
Sedimentary Particles



GRAIN SIZE

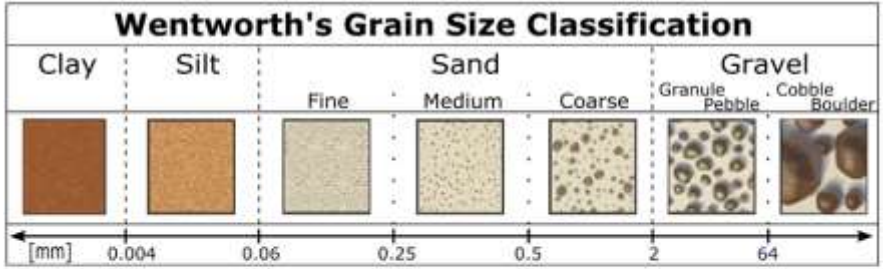
Gravel	Sand	Silt	Clay
>256-2 mm	2- 0.062 mm	0.062-0.004 mm	**<0.004 mm**

Boulder: >256mm

Cobble: 64-256 mm

Pebble: 4-64 mm

Granule: 2-4mm
Fine gravel



Density of Minerals

From Sharma (1997) and Mineralogy Database

Terrigenous		Clays		Carbonates		Evaporites	
Quartz	= 2630 kg/m³	Illite	= 2750 kg/m³	Calcite	= 2710 kg/m³	Halite	= 2710 kg/m³
K-feldspar	= 2560 kg/m³	Kaolinite	= 2600 kg/m³	Aragonite	= 2930 kg/m³	Anhydrite	= 2970 kg/m³
Plagioclase	= 2690 kg/m³	Smectite	= 2300 kg/m³	Dolomite	= 2850 kg/m³	Gypsum	= 2300 kg/m³

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Sedimentary Particles

- **Rounded clasts:** long distance transport.
- **Angular clasts:** short distance transport from the source.
- **Degree of roundness helps in knowing the distance of transportation.**

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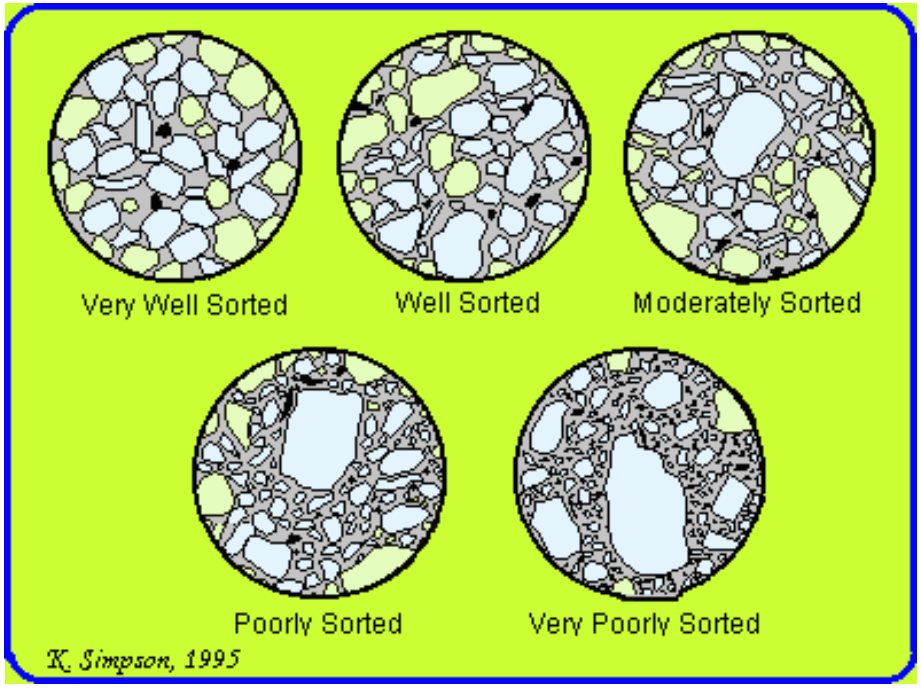
Sedimentary Particles

- Sorting of the sediments provides information on the mode of deposition, nature of the sedimentary sources and transportation mechanism.



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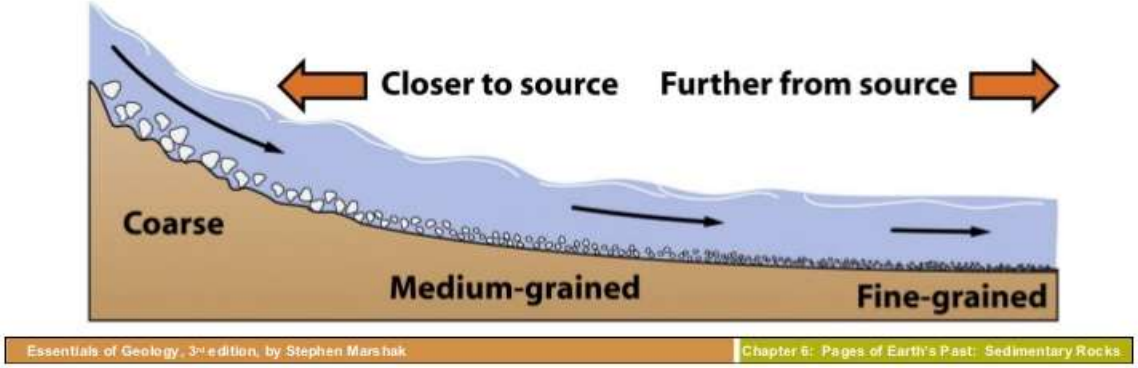
From Sediment to Sedimentary Rocks

Sedimentary Transport

- Movement of sediment away from its source, typically by water, wind, gravity or ice.
- Rounding of particles occurs due to abrasion during transport.
- Sorting occurs as sediment is separated according to grain size by transport capacity of agents, especially running water.
- Sediment size decreases with increased transport distance



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From Sediment to Sedimentary Rocks

Deposition or Sedimentation

- Settling and coming to rest of transported material.
- Accumulation of chemical or organic sediments, typically in water.

Environment of deposition is the location in which deposition occurs:

- Deep sea floor
- Beach
- Desert dunes
- River channel
- Lake bottom

Loire River – Orleans France

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From Sediment to Sedimentary Rocks

Preservation

- Sediment must be preserved, as by burial with additional sediments, in order to become a sedimentary rock

Lithification

- General term for processes converting loose sediment into sedimentary rock.
- Combination of compaction and cementation.

Types of Sedimentary Rocks

- Detrital (clastic) sedimentary rocks
- Chemical sedimentary rocks
- Organic sedimentary rocks

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Sedimentary Rocks

Breccia and Conglomerate

- Coarse-grained clastic sedimentary rocks
- Sedimentary breccia composed of coarse, angular rock fragments cemented together
- Conglomerate composed of rounded gravel cemented together

Sandstone

- Medium-grained clastic sedimentary rock
- Types determined by composition
- Quartz sandstone - >90% quartz grains
- Arkose - mostly feldspar and quartz grains
- Graywacke - sand grains surrounded by dark, fine-grained matrix, often clay-rich

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Sedimentary Rocks

Shale

- Fine-grained clastic sedimentary rock
- Splits into thin layers (fissile)
- Sediment deposited in lake bottoms, river deltas, floodplains, and on deep ocean floor

Siltstone

- Slightly coarser-grained than shales
- Lacks fissility

Mudstone

- Silt- and clay-sized grains; massive/blocky
- Contain CO3 as part of their chemical composition

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Sedimentary Rocks

Carbonates

- Contain CO3 as part of their chemical composition
- Limestone is composed mainly of calcite
- Most are biochemical, but can be inorganic
- Often contain easily recognizable fossils
- Chemical alteration of limestone in Mg-rich water solutions can produce dolomite

Chert

- Hard, compact, fine-grained, formed almost entirely of silica
- Can occur as layers or as lumpy nodules within other sedimentary rocks, especially limestones

Evaporites

- Form from evaporating saline waters (lake, ocean)
- Common examples are rock gypsum, rock salt

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Sedimentary Rocks

Coal

- Sedimentary rock forming from compaction of partially decayed plant material
- Organic material deposited in water with low oxygen content (i.e., stagnant)

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Sedimentary Structures

Bedding

- Series of visible layers within a rock
- Most common sedimentary structure

Sedimentary structures

- Features within sedimentary rocks produced during or just after sediment deposition
- Provide clues to how and where deposition of sediments occurred

Cross-bedding

- Series of thin, inclined layers within a horizontal bed of rock
- Common in sandstones
- Indicative of deposition in ripples, bars, dunes, deltas

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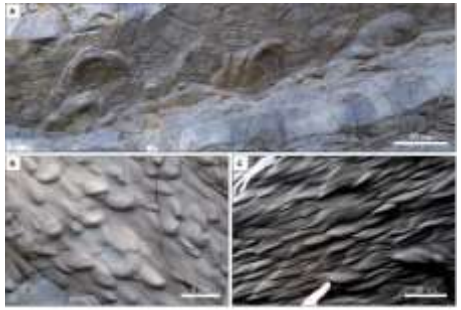
Sedimentary Structures

Ripple marks

- Small ridges formed on surface of sediment layer by moving wind or water
- Graded bedding
- Progressive change in grain size from bottom to top of a bed



https://www.researchgate.net/publication/339779093_An_integrated_process-based_model_of_flutes_and_tool_marks_in_deep-water_environments_Implications_for_palaeohydraulics_the_Bouma_sequence_and_hybrid_event_beds

Mud cracks

- Polygonal cracks formed in drying mud

Fossils

- Traces of plants or animals preserved in rock
- Hard parts (shells, bones) more easily preserved as fossils

Bottom Structures

- Occur at the base of beds
- Loading: grooves formed after passage of turbidity currents
- Fluting: grooves forming during passage of turbidity currents

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Depositional Environments and Sedimentary Facies

- **Sedimentary Facies:** distinctive kind of sedimentary deposit, which was deposited in a distinctive setting.
  - Can be also defined as: the total textural, compositional and structural characteristics of a sedimentary deposit resulting from accumulation and modification in a particular setting.
    - grain size, sorting, rounding
    - lithology
    - sedimentary structures
    - bedding type
    - fossil assemblages

- **Sedimentary facies** often get reduced to **lithofacies** which detail grain-size, composition, and dominant sedimentary structures only: planar cross-stratified gravel, inversely graded massive sandstone

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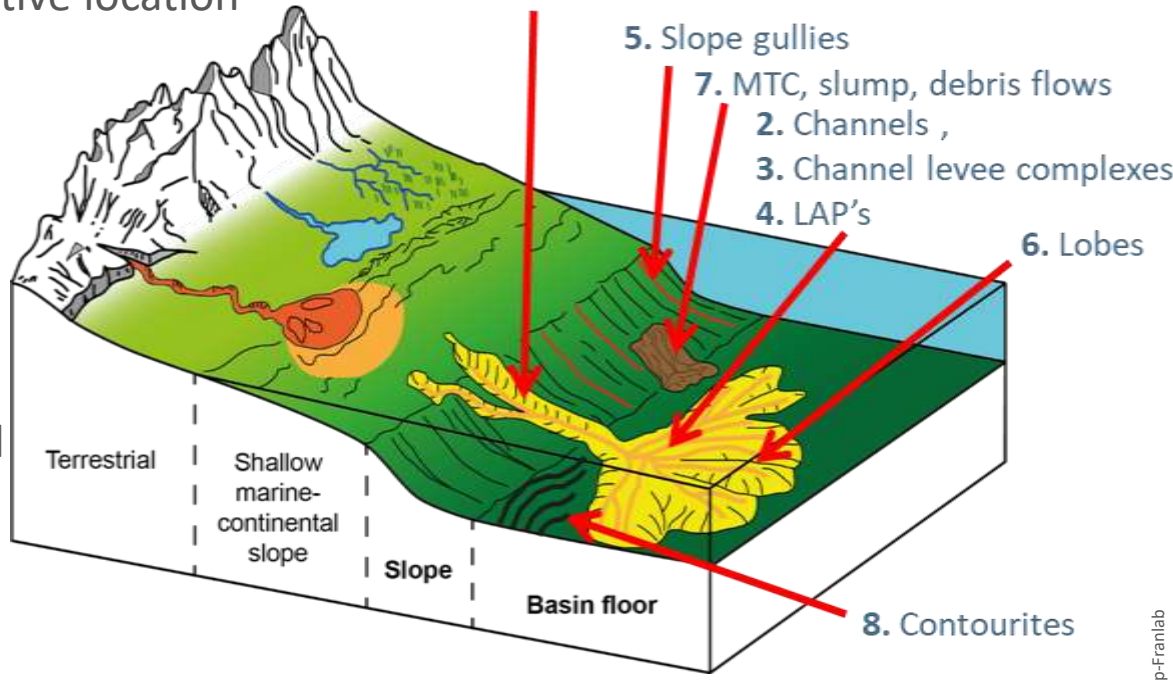
Depositional Environments and Sedimentary Facies

Source Area

- Locality that eroded and provided sediment
- Distinctive composition, shape, size and sorting are indicators of source and relative location

Depositional Environments

- Location where sediment came to rest
- Sediment characteristics and sedimentary structures (including fossils) are indicators
- Examples: glacial valleys, alluvial fans, river channels and floodplains, lakes, deltas, beaches, dunes, shallow marine, reefs, deep marine



Oxford University Press

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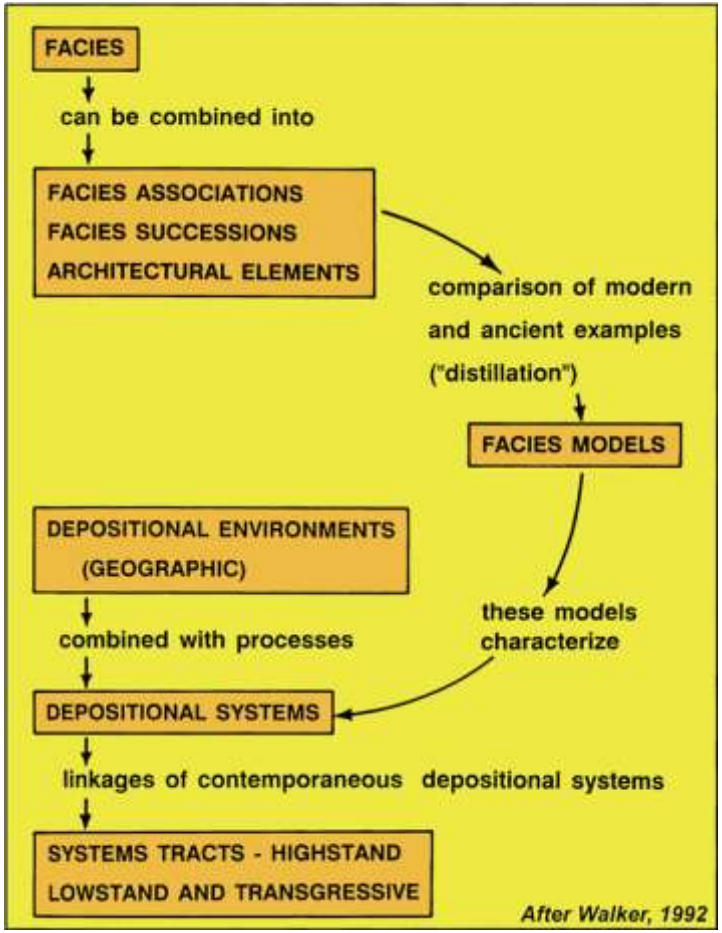
Depositional Environments

Relationship between:

- Facies
- Architectural elements
- Depositional settings
- Systems
- Systems tracts

Scheme used to characterize each depositional system from: “Sequence Stratigraphy – Facies, Elements, Architecture” C. G. St. C. Kendall & D. Barbeau



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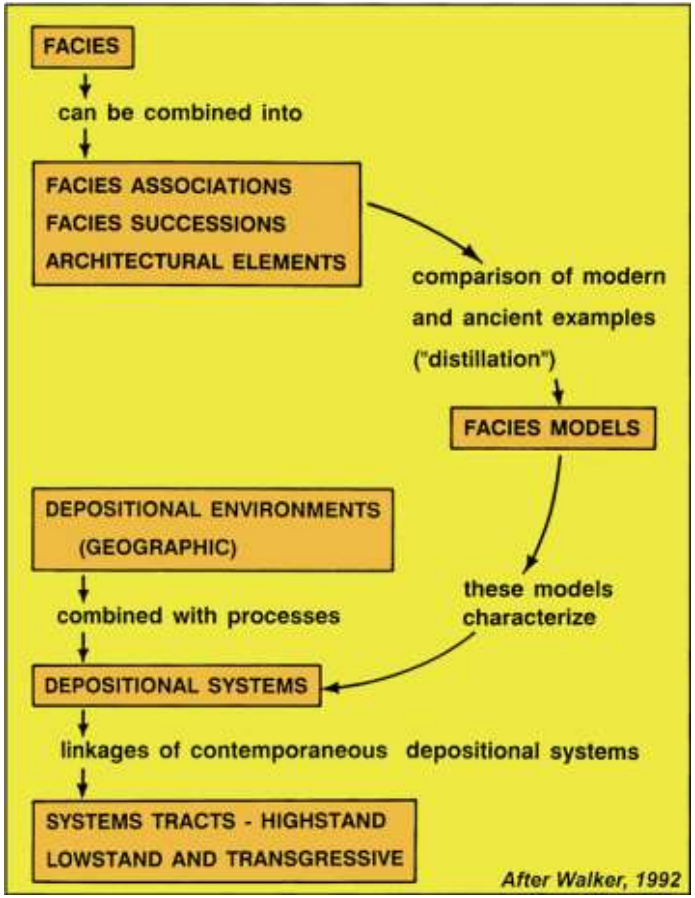
Depositional Environments

A Framework for Systematic Description and Comparison of Setting's Deposits

- Based on physical relationships (geometry) of strata and their bounding surfaces
- Based on recognition of genetically-related stratigraphic elements
- Applicable at all scales and to all styles

What are the benefits?

- Analysis and comparison of sedimentary elements,
- Net to-gross, geometry and connectivity
- Lithofacies type and reservoir quality



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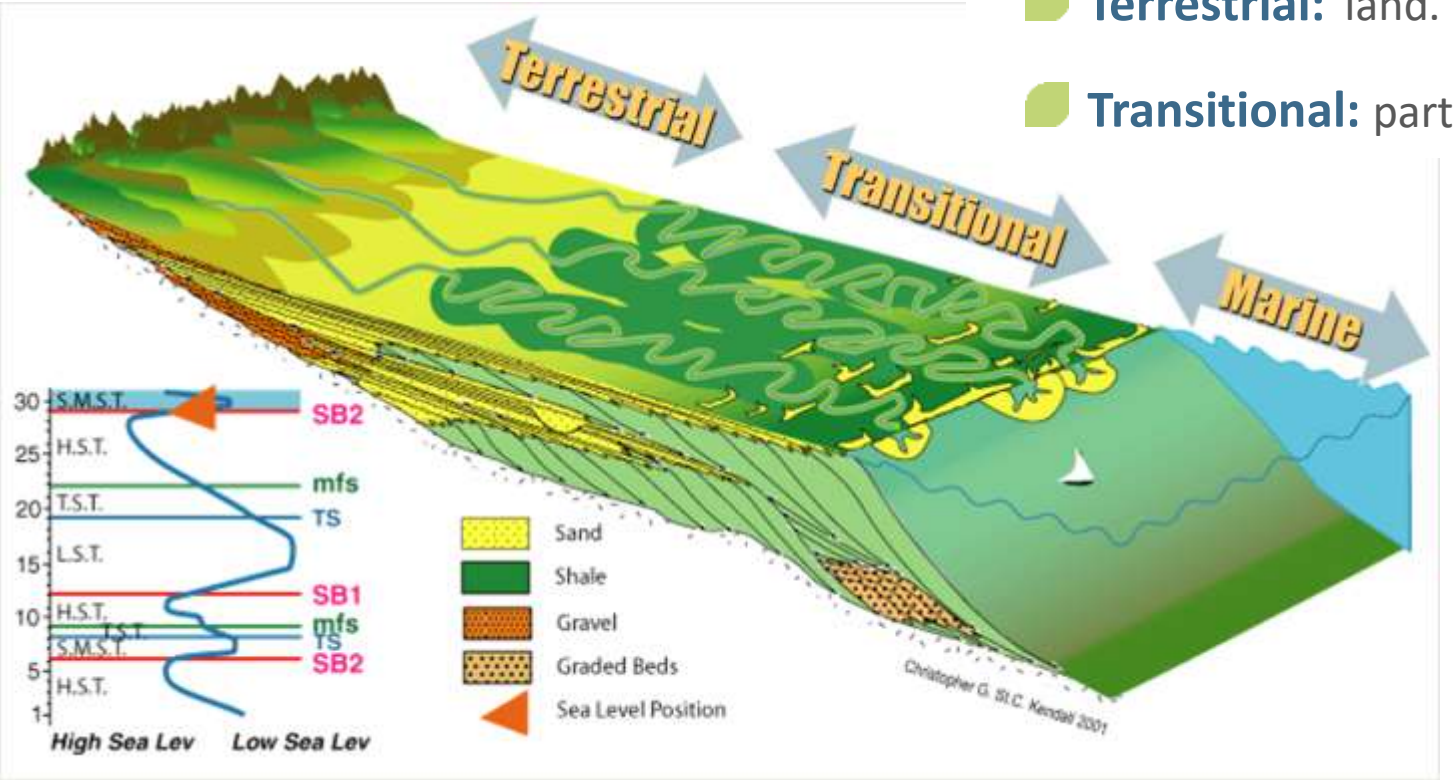
Types of Depositional Systems

- **Marine:** ocean, sea.
- **Terrestrial:** land.
- **Transitional:** part land, part ocean.



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Terrestrial Depositional Systems

- Fluvial-alluvial fan
- Glacial
- Eolian
- Lacustrine
- Playa

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Fluvial System Characteristics

- **Dominant conduit from regions of sediment production (mountains) to sediment storage (oceans, basins)**

- **Characterized by channel pattern**
  - Meandering
  - Braided
  - Anastomozing

- **Characterized by sediment load**
  - Bedload
  - Suspended load
  - Mixed load

- **Unidirectional sediment dispersal**

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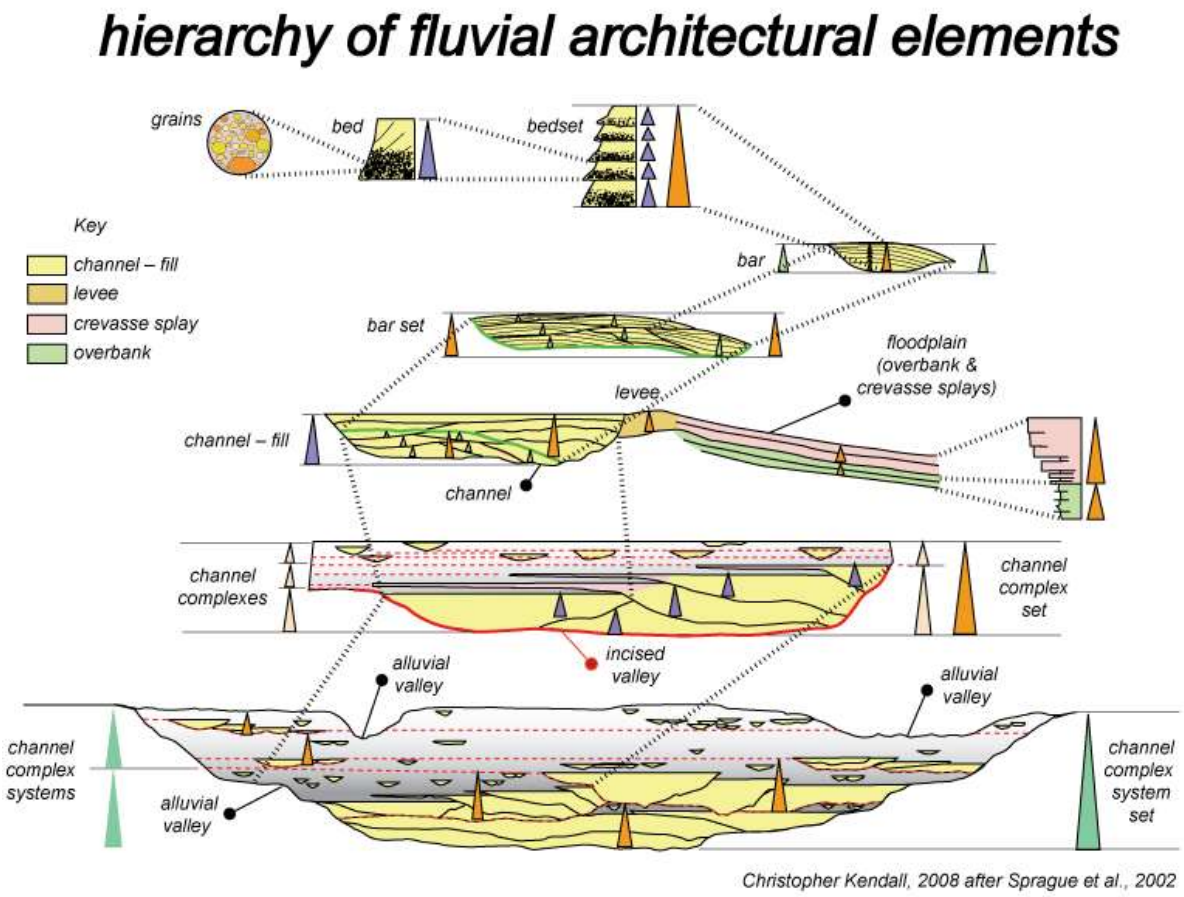
Fluvial - Architectural Elements



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Marine Depositional Systems

Shallow/nearshore

- Tide-dominated
- Wave-dominated
- Reef

Shelf/platform

- Carbonate
- Clastic

Deep marine

- Deep sea fans
- Pelagic

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Coastal Depositional Systems

- **Form proximal to shorelines**
- **Geographically narrow, geologically important**
- **Fluid flow transport and deposition**
  - Surface waves
  - Tidal waves (not tsunami!)
  - Fluvial input
- **Grain-size decreases with deeper water**
- **Onshore, offshore & longshore sediment transport important**
- **Net sediment input (often from rivers) often leads to progradational geometries**
- **Important for tracking sea-level changes**

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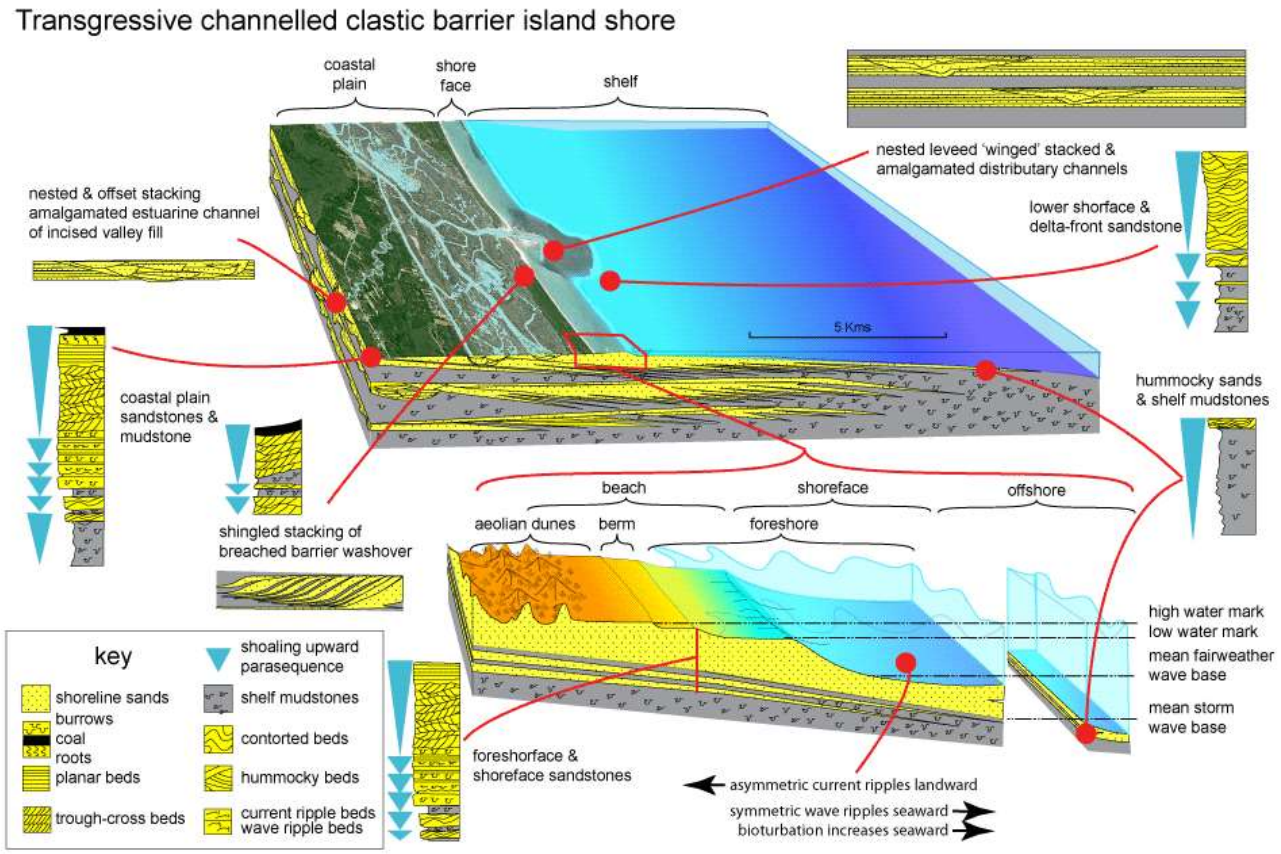
Coastal Elements



Depositional settings of transgressive channelled barrier island shore change lateral position, as sedimentary facies of adjacent settings succeed one another as vertical parasequences (concept from Middleton, 1973 after Johannes Walther).

Christopher G. St.C. Kendall, 2013

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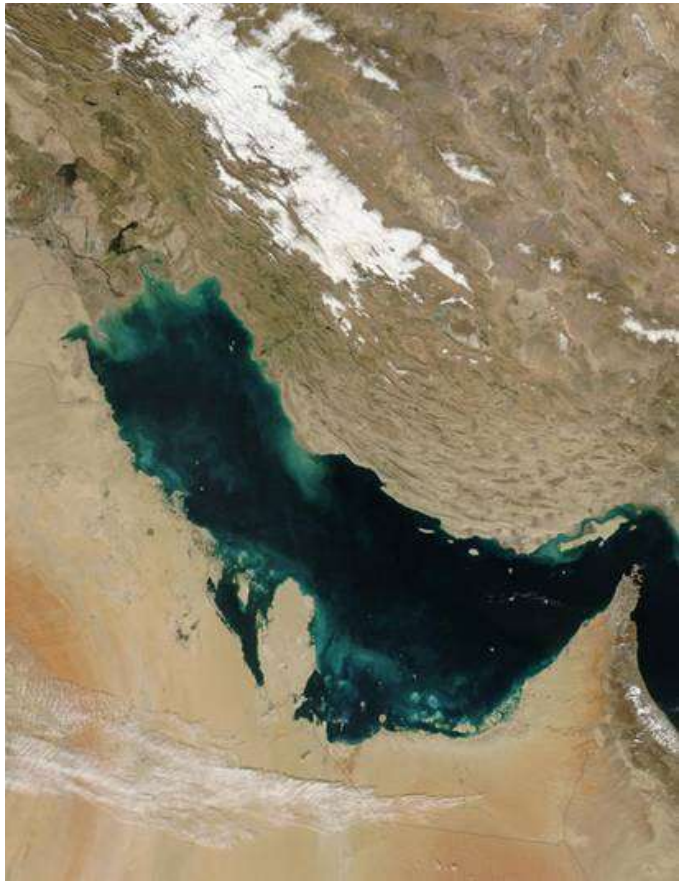
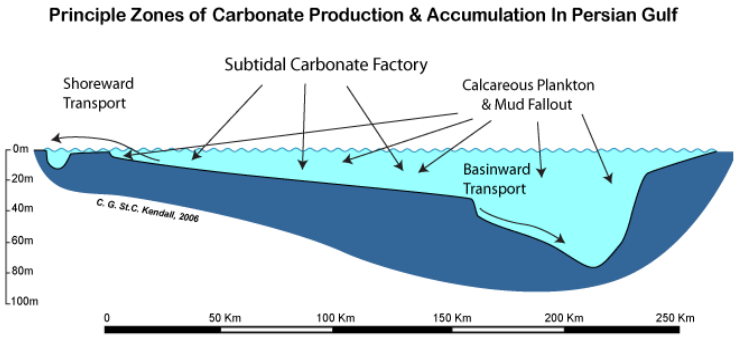
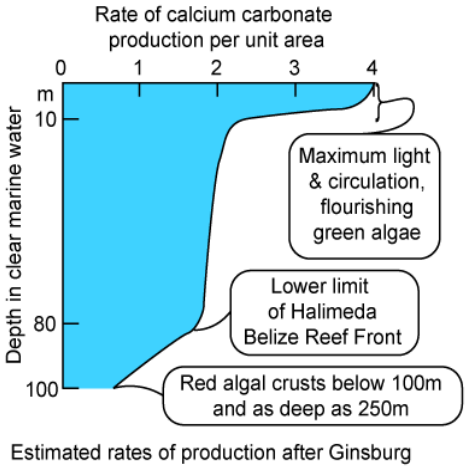
Carbonate Platform Environment







Estimated rates of production after Ginsburg

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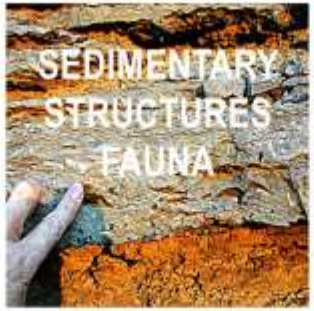
Carbonate Platform Architectural Elements

ALLOCHEMS
CEMENTATION
& DIAGENESIS



MARGIN
COMPLEX

SHELF
MARGIN
COMPLEX

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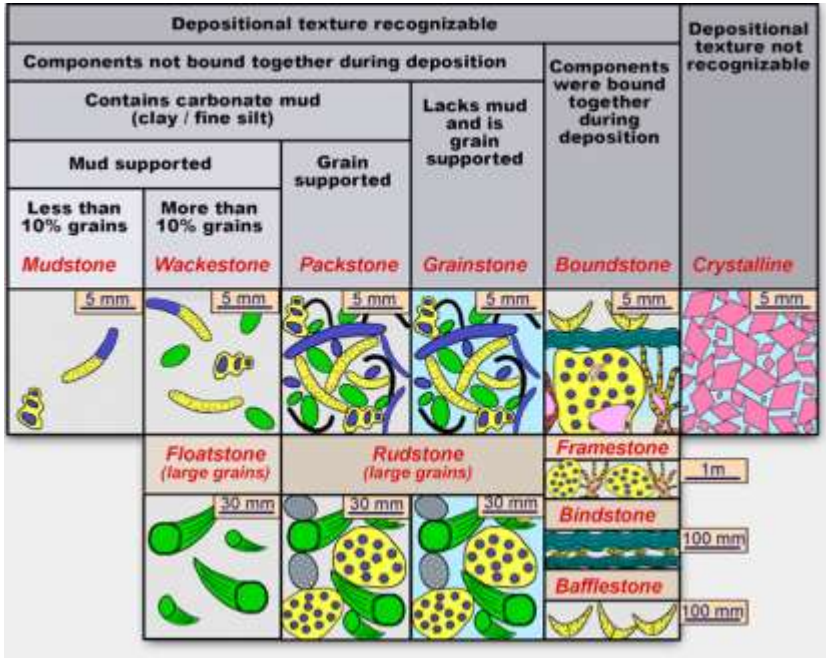
Carbonate Platform Environment

- **Interpretation of depositional setting of carbonates is based on**
  - Grain types
  - Grain packing or fabric
  - Sedimentary structures
  - Early diagenetic changes

- Identification of grain types commonly used in subsurface studies of depositional setting because, unlike particles in siliciclastic rocks, carbonate grains generally formed within basin of deposition



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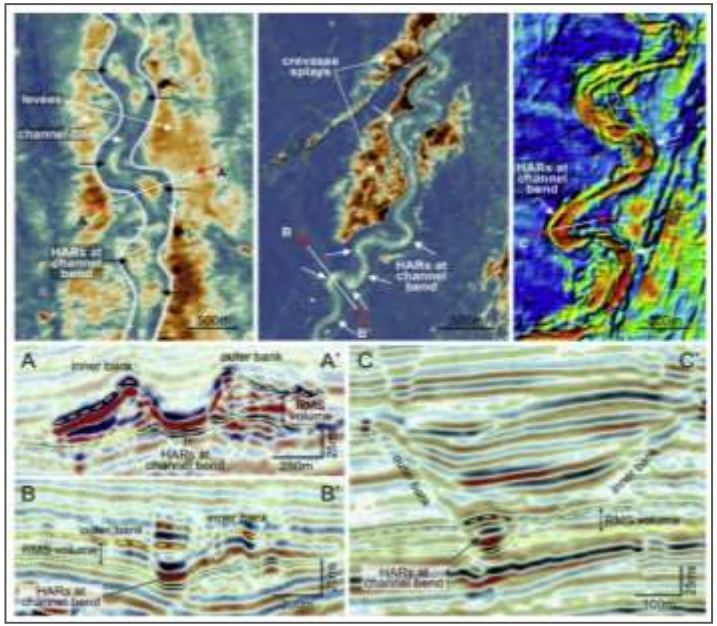
Deepmarine Systems

- Form in the moderate to deep ocean, down-dip of submarine canyons and often deltas
- Large sediment flux, high sedimentation rate, large area
- Gravity flow transport and deposition
  - turbidity currents
  - subaqueous debris flows
  - suspension fall-out
- Lobes and lobe-switching important
- Both coarse and fine grained sediment
- Often well-sorted and normally graded



Janocko et al. (2012)

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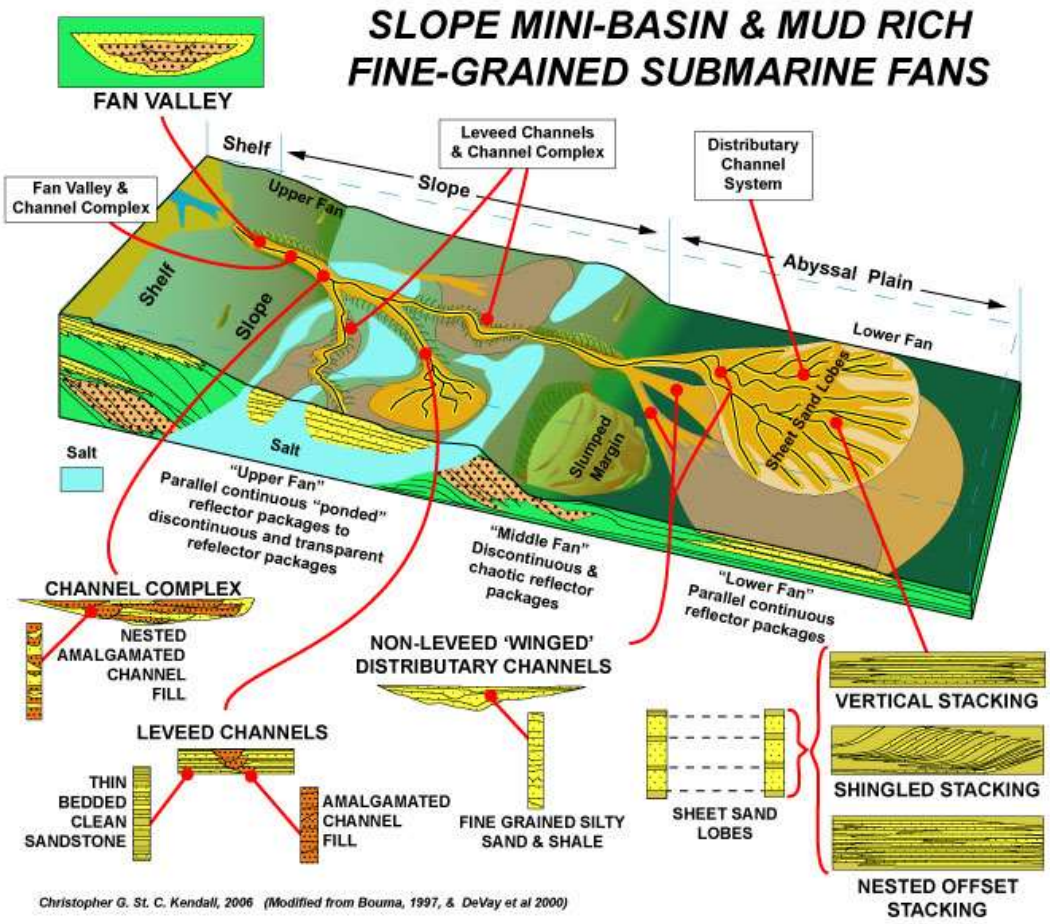
Deepmarine - Architectural Elements



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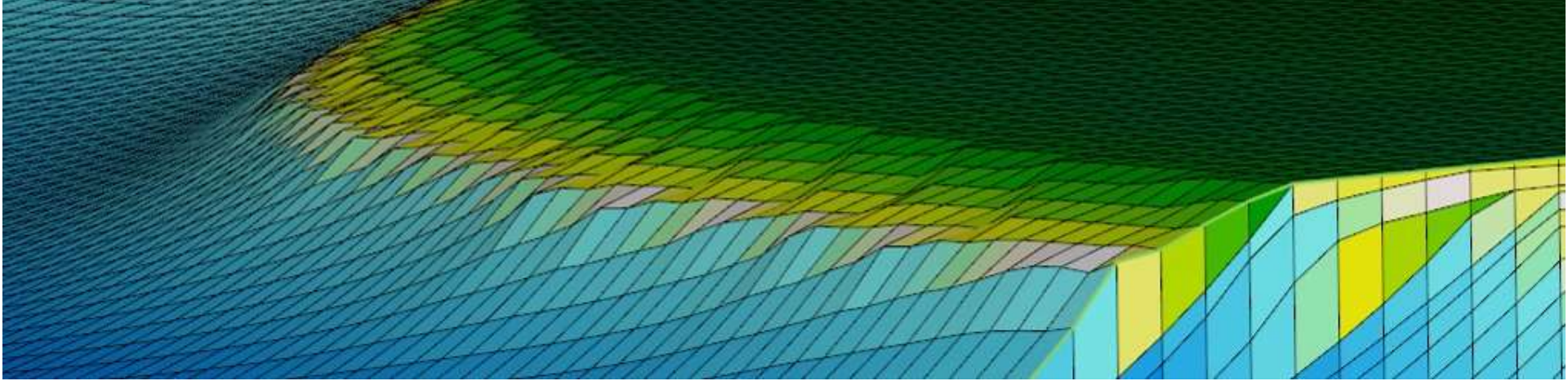

Fondamentals of Sequence Stratigraphy

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Fondamentals of Sequence Stratigraphy

- **Three Northwestern graduates join the stratigraphic research team of Exxon and begin to use sequence stratigraphic concepts to interpret seismic data:**
  - Recognition and definition of unconformity-bounded units
  - The time-transgressive nature of facies

Peter Vail:
PhD Northwestern 1956

Bob Mitchum:
PhD Northwestern 1954

John Sangree:
PhD Northwestern 1959

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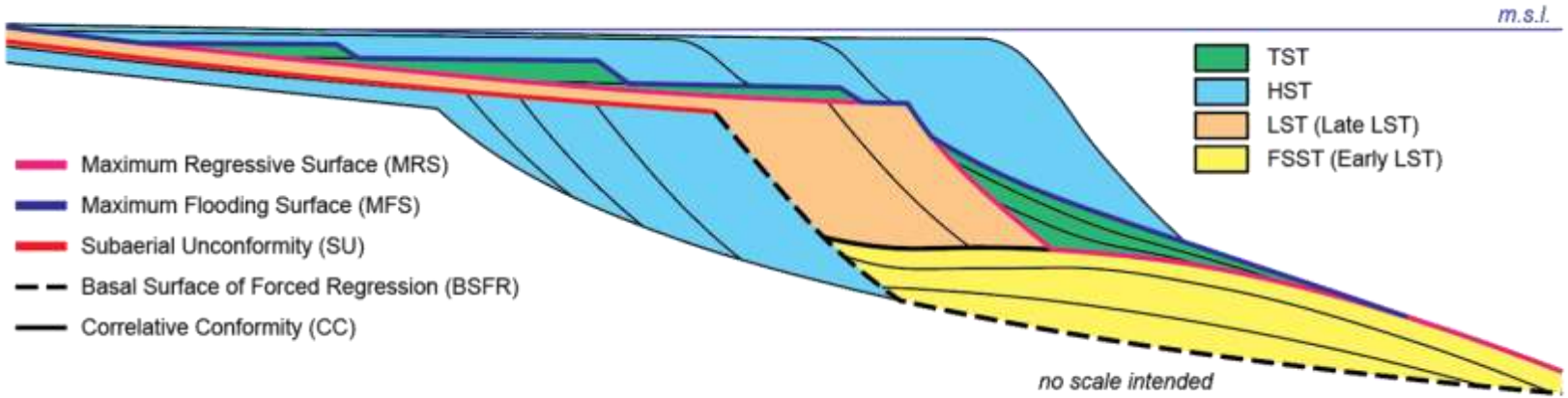
Introduction

- The conceptual framework of the controlling mechanisms for the deposition of sequences and systems tracks has been presented by Mitchum et al. (1972, 1977), Vail et al. (1977), Pitman (1979), Jervey (1982), Posamentier (1983, 1985), Posamentier and Vail (1988), and Posamentier et al. (1988).



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Definition of Key Terms

- **DEPOSITIONAL SYSTEM:** A three-dimensional assemblage of lithofacies, genetically linked by active (modern) or inferred (ancient) processes and environments (delta, river, barrier island, etc.) (Brown and Fisher, 1977)

- **SEQUENCE:** A relatively conformable succession of genetically related strata bounded at its top and base by unconformities or their correlative conformities (Vail et al., 1977). It is composed of a succession of systems tracts and is deposited between eustatic fall inflection points.

- **SYSTEMS TRACT:** A linkage of contemporaneous depositional systems (Brown and Fisher, 1977). Each is associated with a specific segment of the eustatic curve leustatic lowstand -lowstand wedge; eustatic rise-transgressive; rapid eustatic fall - lowstand fan, etc.)

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Definition of Key Terms

- **Unconformity:** A surface representing a significant time gap which is characterized by subaerial land sometimes subaqueous) erosional truncation (Vail, Hardenbol, And Todd, 1977).
- **Condensed Section:** A thin marine stratigraphic interval characterized by very slow depositional rates (less than 1-10 mm/1 000 yr) (Vail, Hardenbol, and Todd, 1977).
- **Accommodation:** The space made available for potential sediment accumulation (Jervey, 1982).
- **Equilibrium Point:** The point along a profile where the rate of eustatic change equals the rate of subsidence. It separates zones of rising and falling sea level.

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Assumptions

- **In order to develop depositional models that would be broadly applicable, certain assumptions were made:**

- The rate of **seafloor subsidence** at any single location on a profile was assumed to be constant. Seafloor subsidence is primarily a function of lithospheric cooling and sediment loading (total subsidence). Geohistory analyses from a variety of sedimentary basins suggest that eustatic variations occur more frequently than subsidence variations. Thus, over a limited interval the assumption of constant subsidence rate seems acceptable. Nonetheless, when the general model is modified to account for local conditions, nonuniform subsidence can be accommodated.

- **Total subsidence increases in a basinward direction**. This seems to characterize most divergent basin margins.

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Assumptions

- Deposition was occurring along a divergent continental margin composed of a shelf, slope, and basin, where **sediment supply is assumed to remain constant**.

- In the real world, differing rates of sediment supply affect primarily the seaward extent of deposition. In the landward direction, stratal patterns will usually show onlap and aggradation as the space between seafloor and base level is filled, whereas the basinward limit of progradation is a function of sediment supply.

- In the landward direction, where base level (sea level or graded stream profile) is the controlling factor, the stratal patterns on the landward side of identical basins will be the same regardless of the sediment supply. When local sediment supply parameters are incorporated into the model, the effect will be observed primarily at the seaward limit of deposition.

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Accommodation

- The way a basin fills with sediment and the stratal patterns that result depend upon how much space is available for the sediment to fill and how rapidly new space is added.
- Sediment is deposited in the space between the seafloor and base level (sea level or graded stream profile).
- When space is made available, we refer to the term «accommodation» .. "Accommodation" refers to all the space available for sediment to fill.

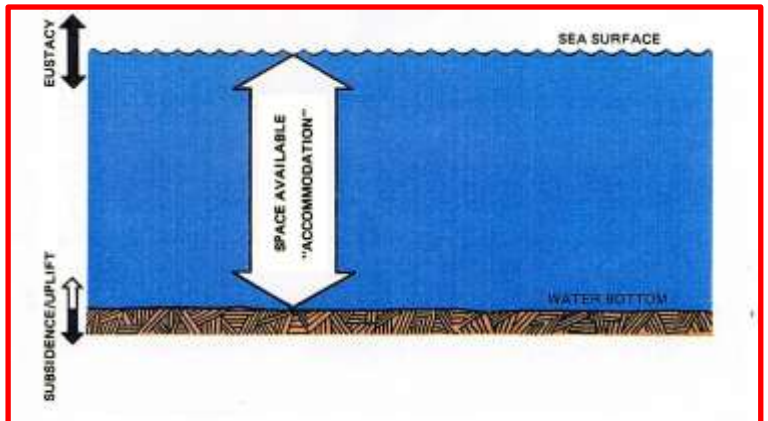

Figure 1. Accommodation envelope as a function of eustacy and subsidence

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Accommodation

- Relative sea-level change rather than eustatic change is an indicator of accommodation change.
- Relative sea level incorporates local subsidence by referring to the position of the sea surface with respect to a datum at or near the seafloor.
- Thus, even during an eustatic stillstand or slow eustatic fall, relative sea level may still be rising and making new space as a result of local subsidence.

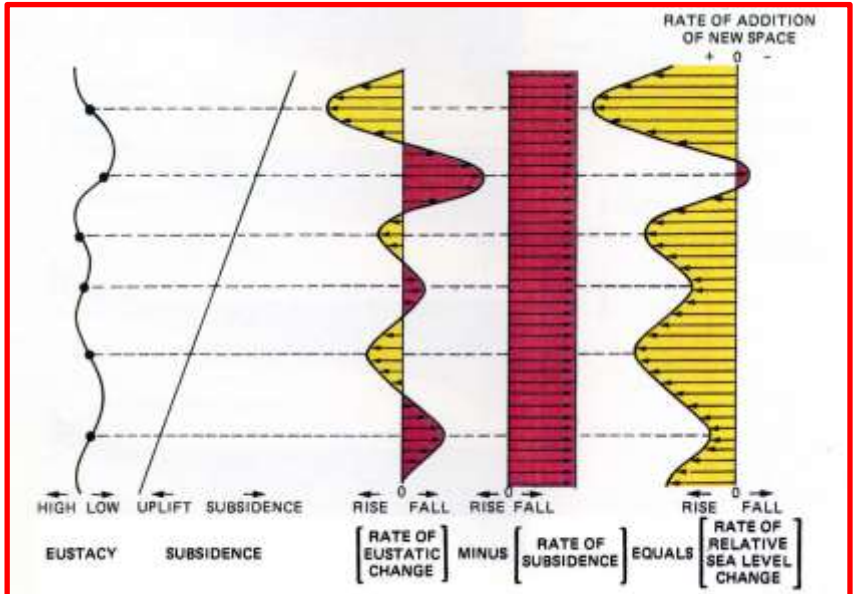

Figure 2. Relative sea level as a function of eustacy and subsidence

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Principles of Sequence Stratigraphy

Sequence stratigraphy definition :

A “4D“ study of spatial and temporal relationships recorded by rocks

SEQUENCE STRATIGRAPHY

=

Localization,
Quantification
Prediction

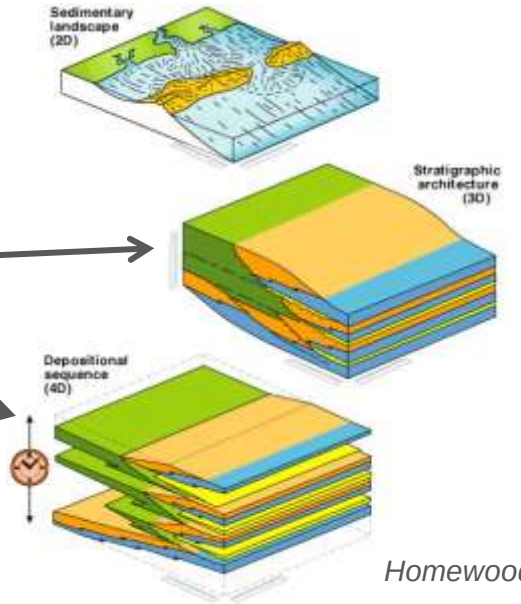
of sedimentary bodies (3D)…
… through time (4D)

=

spatialization (location +volume) of sedimentary bodies

+

history (time) of sedimentation



Homewood, 2000

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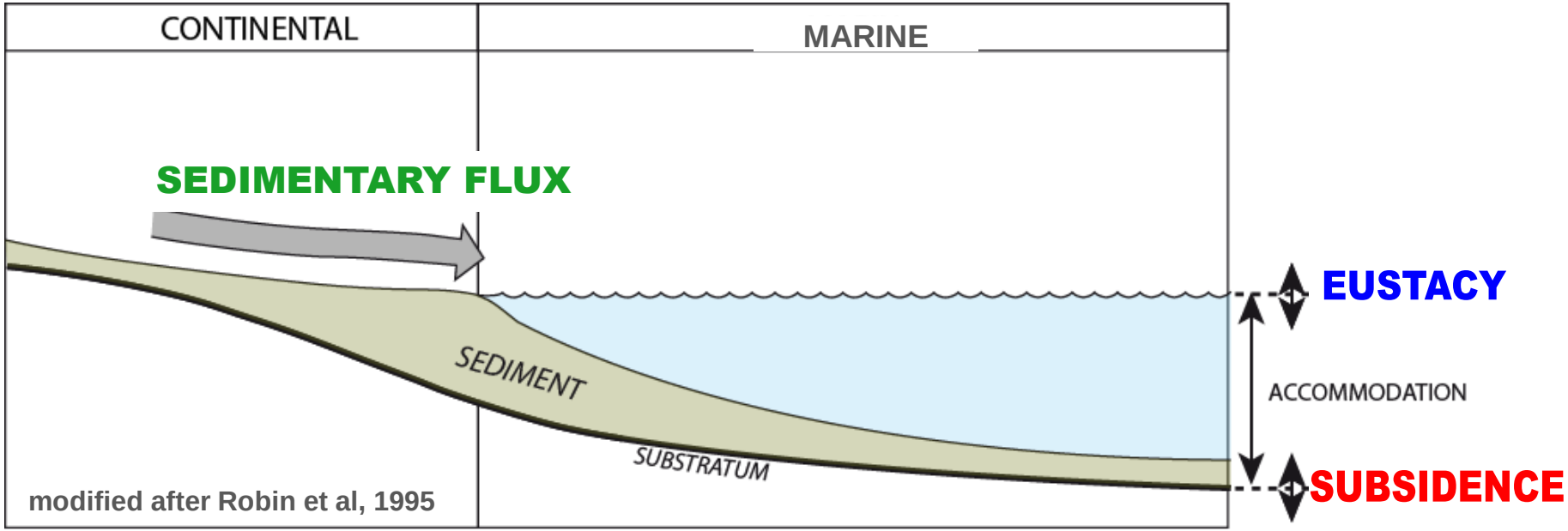
Principles of Sequence Stratigraphy

- Sequence stratigraphy reflects the influence of environmental parameters



control of sedimentary architecture along a margin = 3 main environmental parameters:

- VARIATION OF SEDIMENT SUPPLY
- EUSTACY,
- SUBSIDENCE

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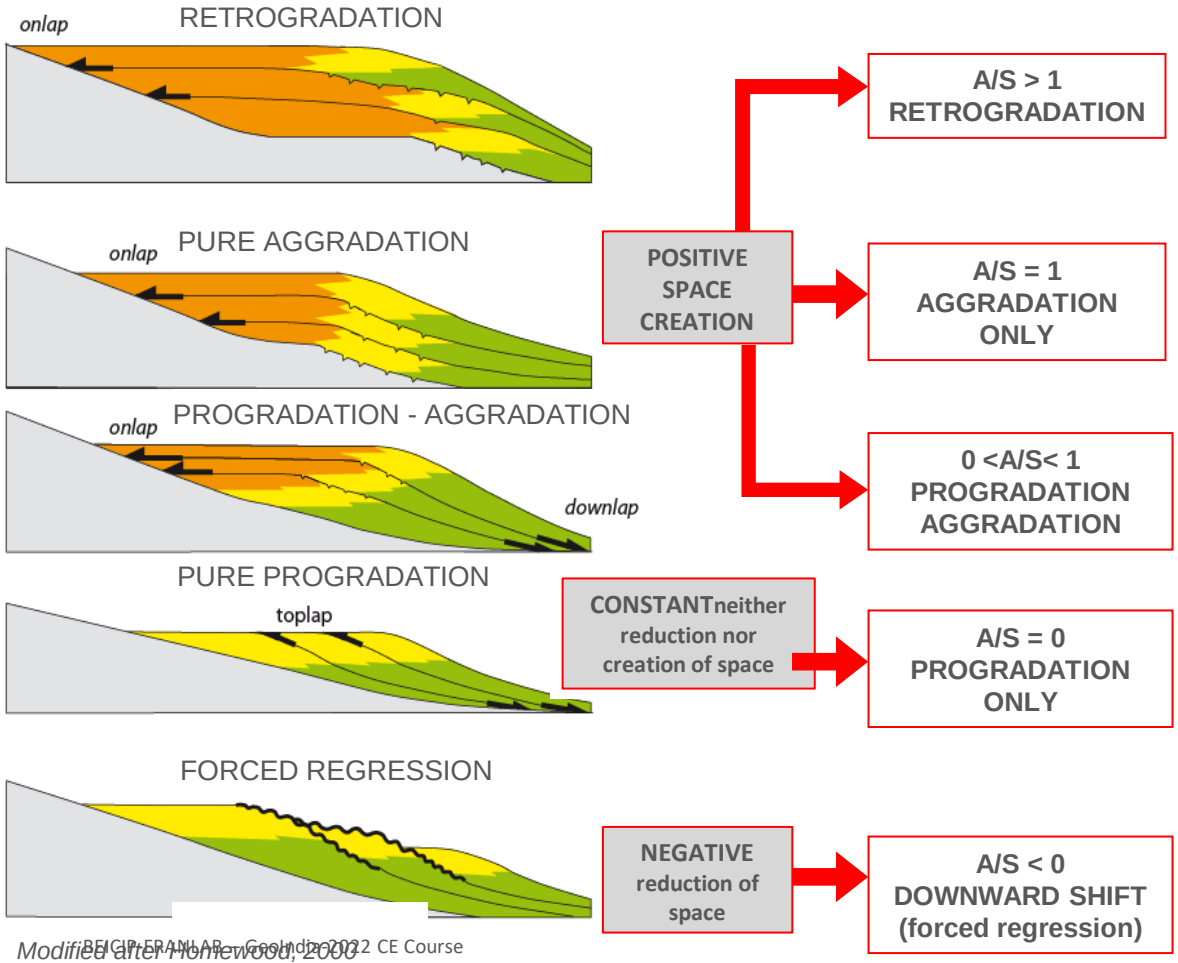
Principles of Sequence Stratigraphy

- Stratal geometries are connected to the balance between Accommodation and Supply.
- 5 main stratigraphic architectures can be defined according to the geometry of the staked sequences.



Modified after Homewood, 2000

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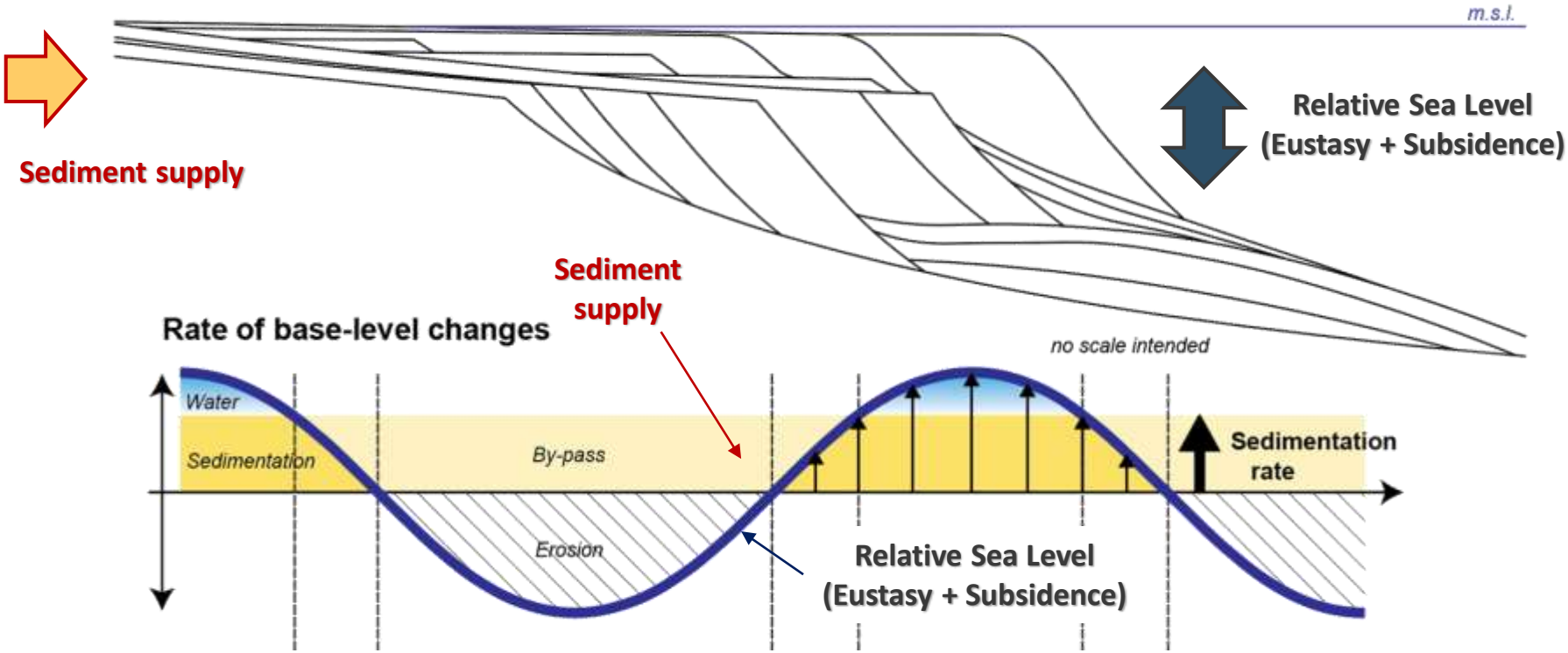
Principles of Sequence Stratigraphy

- Two problem-solving approaches



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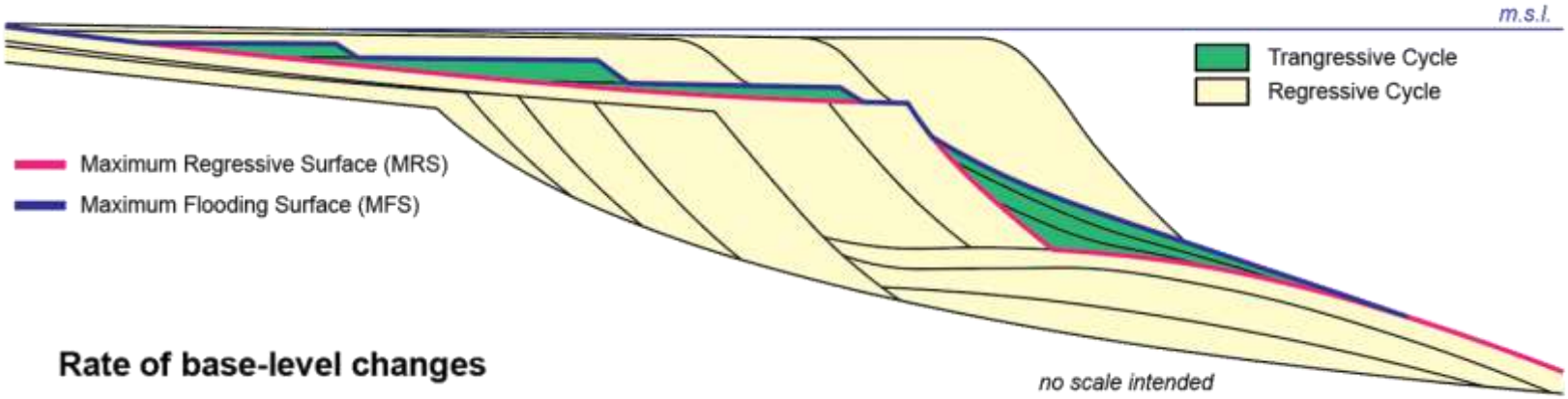
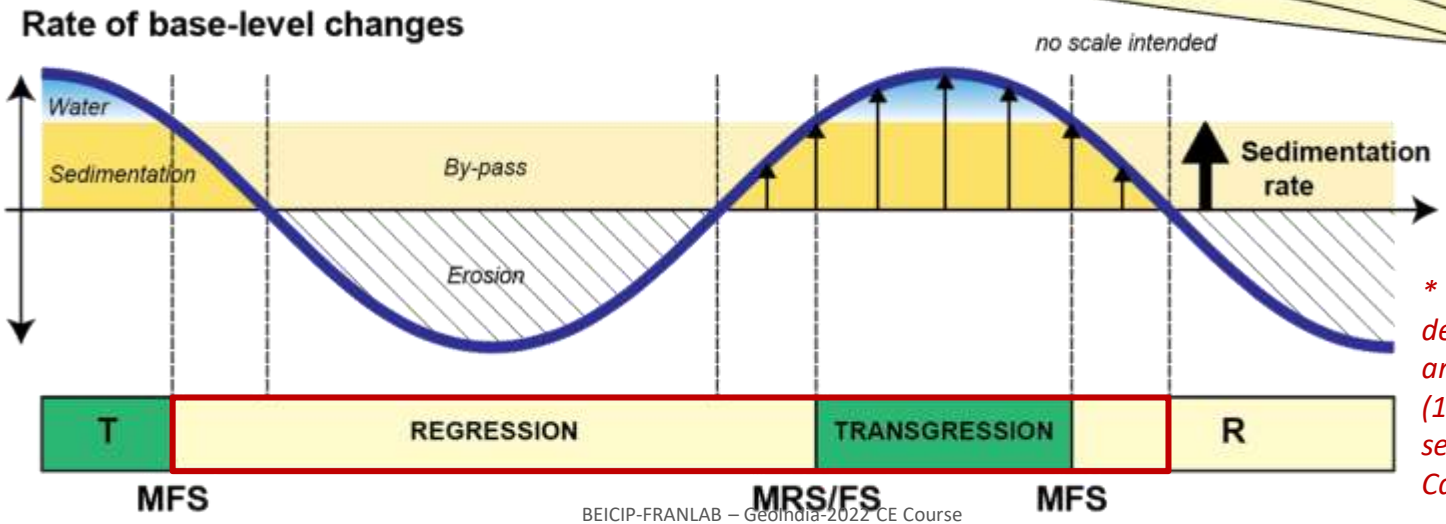
Principles of Sequence Stratigraphy

Discriminating Regressive and Transgressive cycles: T-R Cycles method





** T-R Cycles were defined by Embry and Johannessen (1992). Here their sense is after Catuneanu (2006).*

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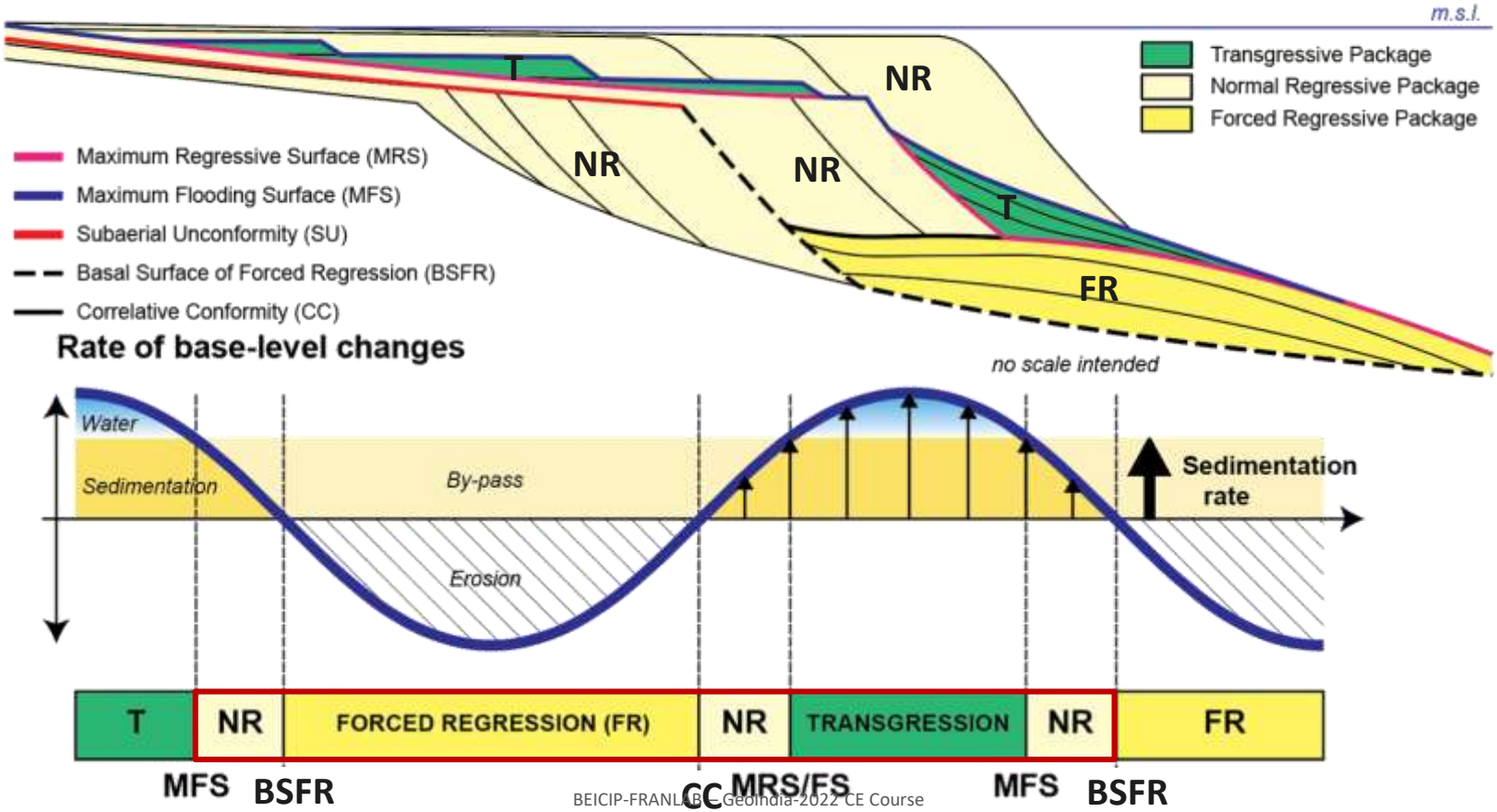
Principles of Sequence Stratigraphy

Subdivision of Cycles into Packages



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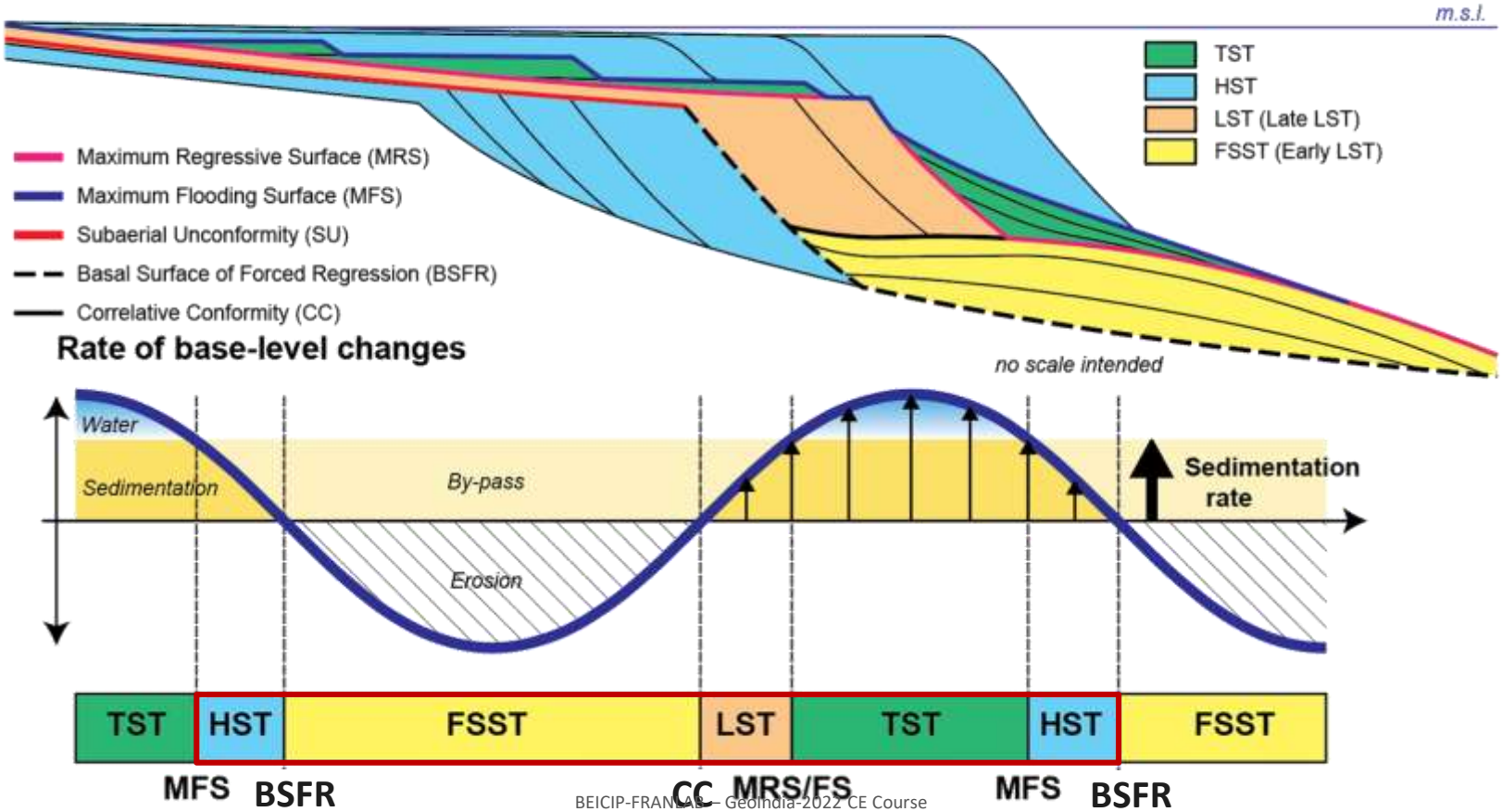
Subdivision of Packages into Systems Tracts



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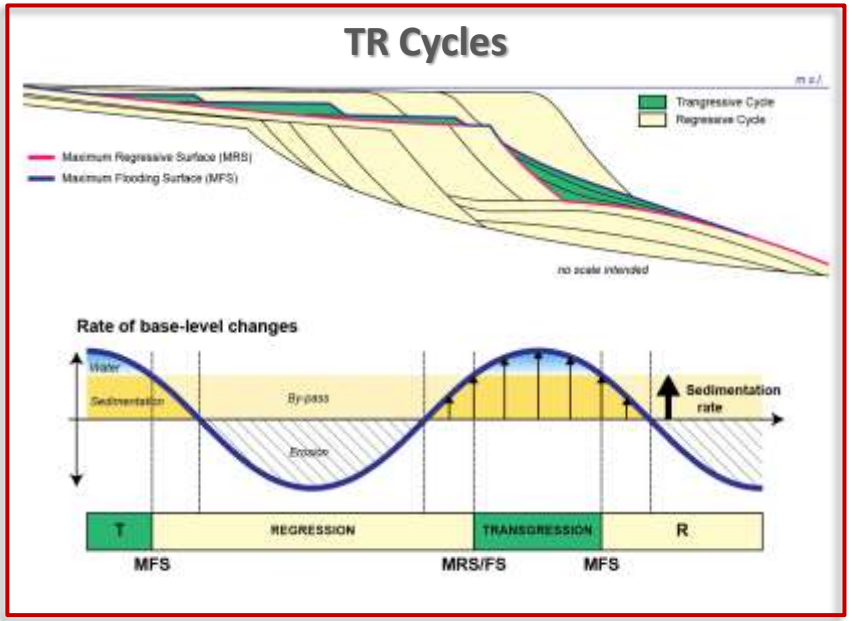
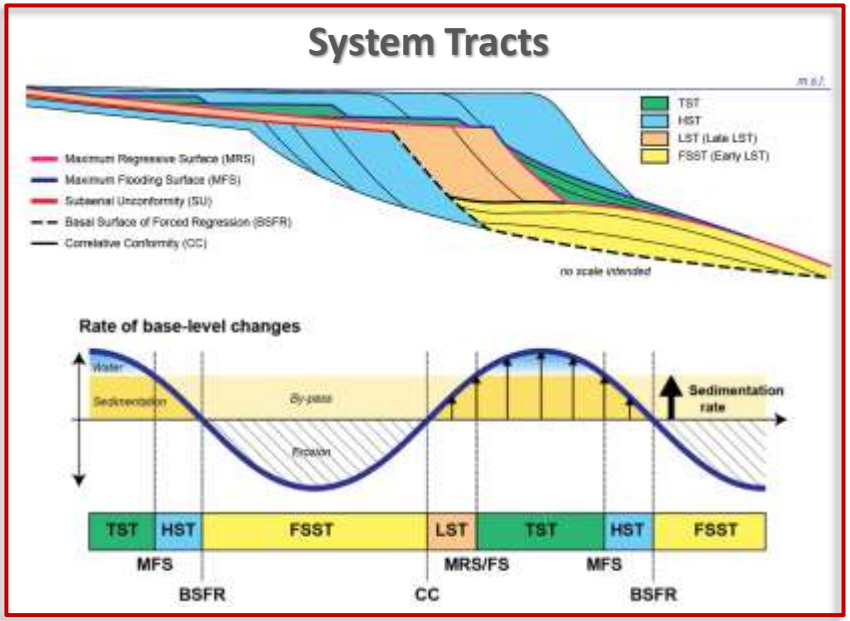
Principles of Sequence Stratigraphy

Two SCALES of sequence stratigraphic investigations





- Broad or Quick Look approach (2nd order).
- Used in exploration studies or low-quality datasets.
- Provide the gross envelop of potential reservoir stacks (R cycles) and correlation rails (T Cycles).

- Refined approach (3rd to 4th order).
- Used in reservoir studies, involving good-quality datasets.
- Provide a precise correlation scheme, allowing individual reservoir units to be deciphered within stacks.

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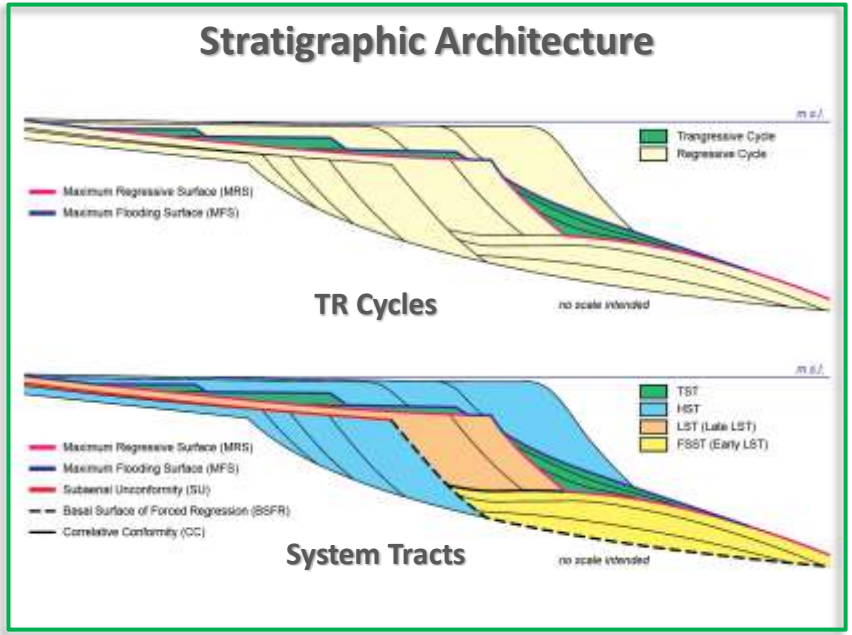
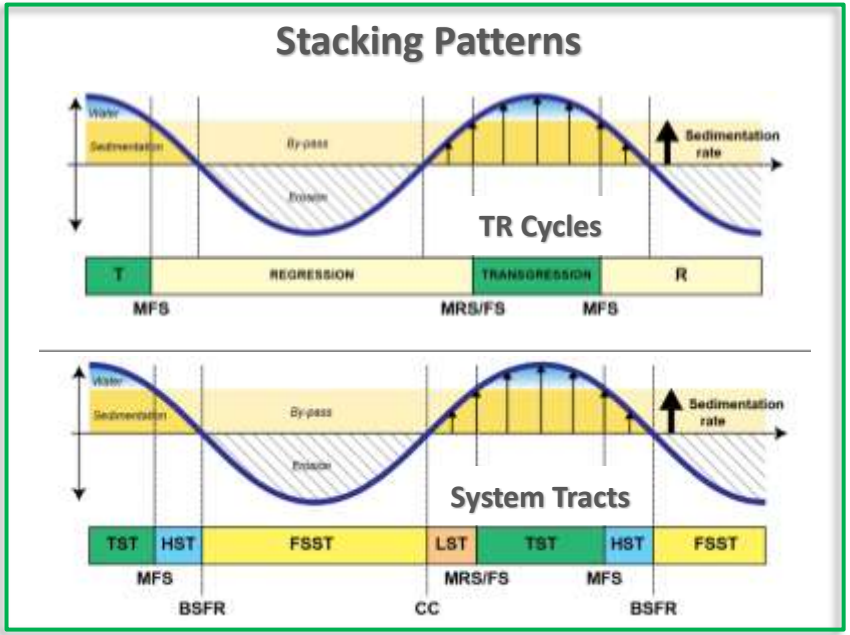
Principles of Sequence Stratigraphy

Two METHODS of sequence stratigraphic investigations





- Stratigraphic units are associated with specific geometries
- Stratal terminations
- Seismic stratigraphy concept

- Stratigraphic units are associated with specific A-S ratio
- Sedimentary surfaces & patterns
- Sequence stratigraphy concept

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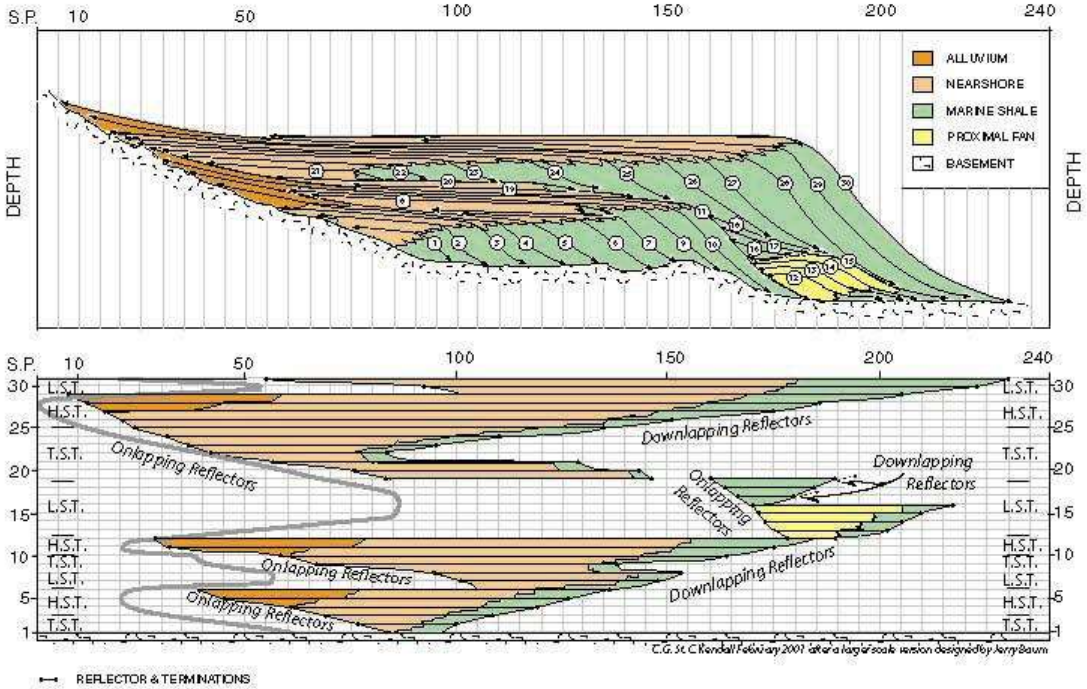
Chronostratigraphic Chart

EXERCISE: *CHRONOSTRATIGRAPHIC CHART CONSTRUCTION*

Chronostratigraphic Chart and the Relative Sea Level Curve from the Pseudo Seismic Line identifying:- Lithology, Reflection Terminations including "Onlap", "Offlap", and "Downlap", Sequence Boundaries (type 1 or 2), Systems Tracts, Ravinement Surfaces, Transgressive Layers, Maximum Flooding Surfaces, and Condensed Sections.



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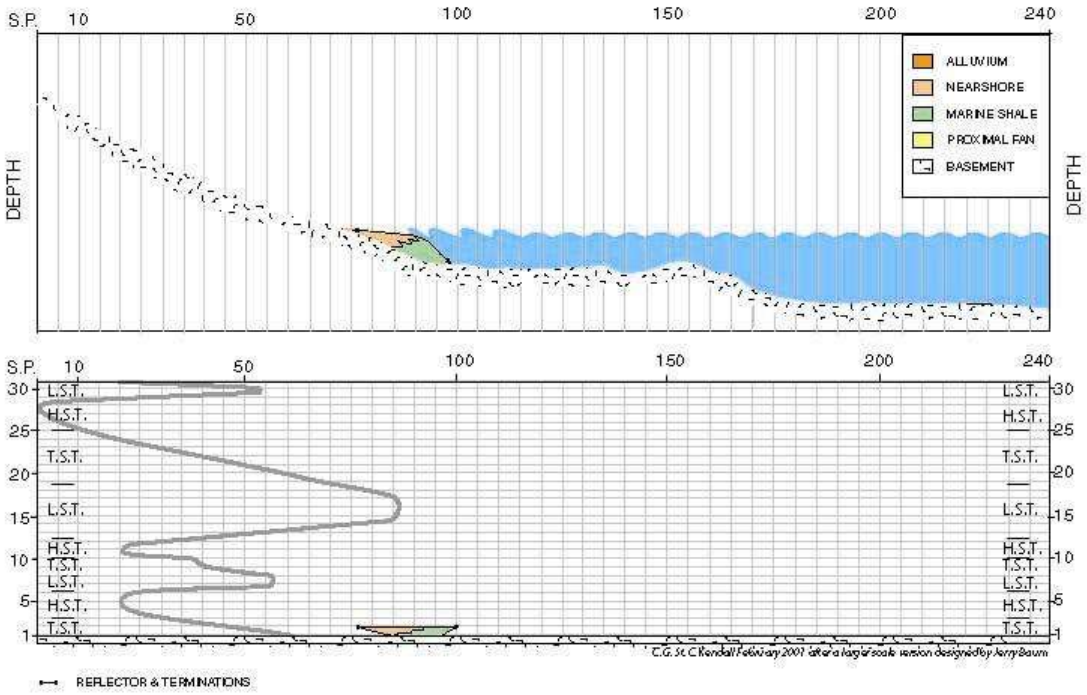
Chronostratigraphic Chart



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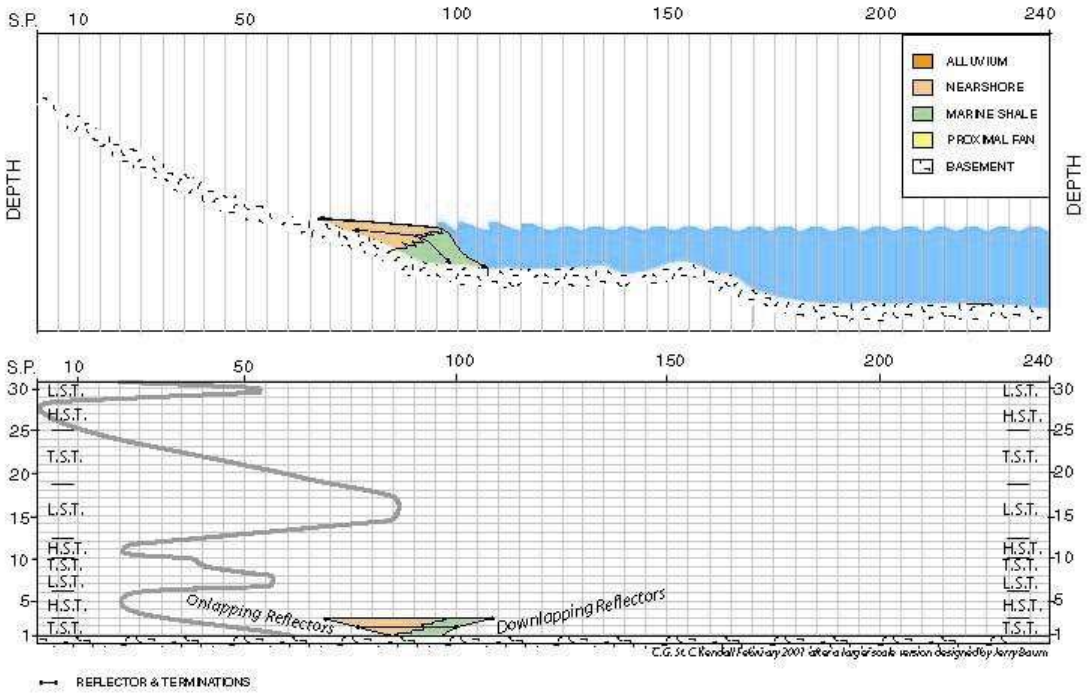

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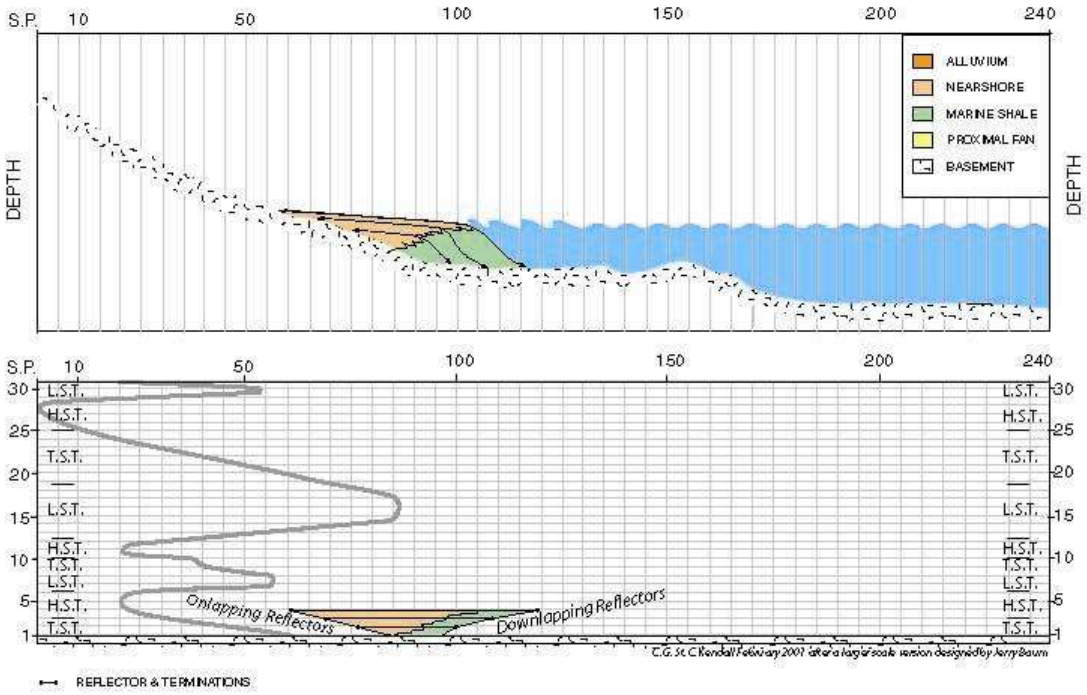

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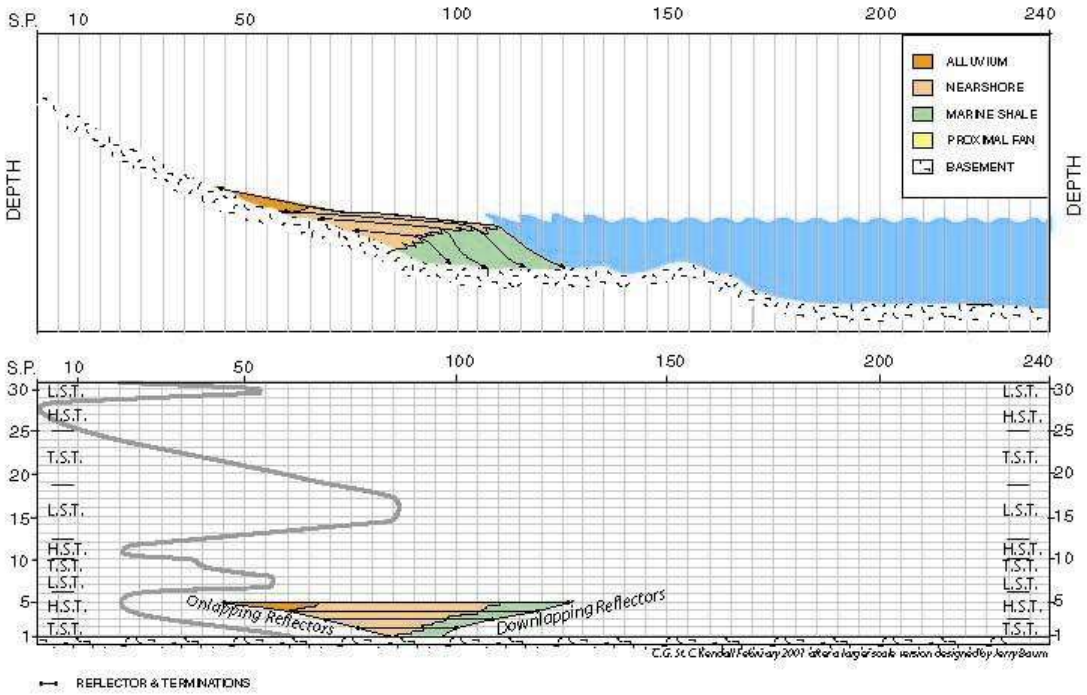

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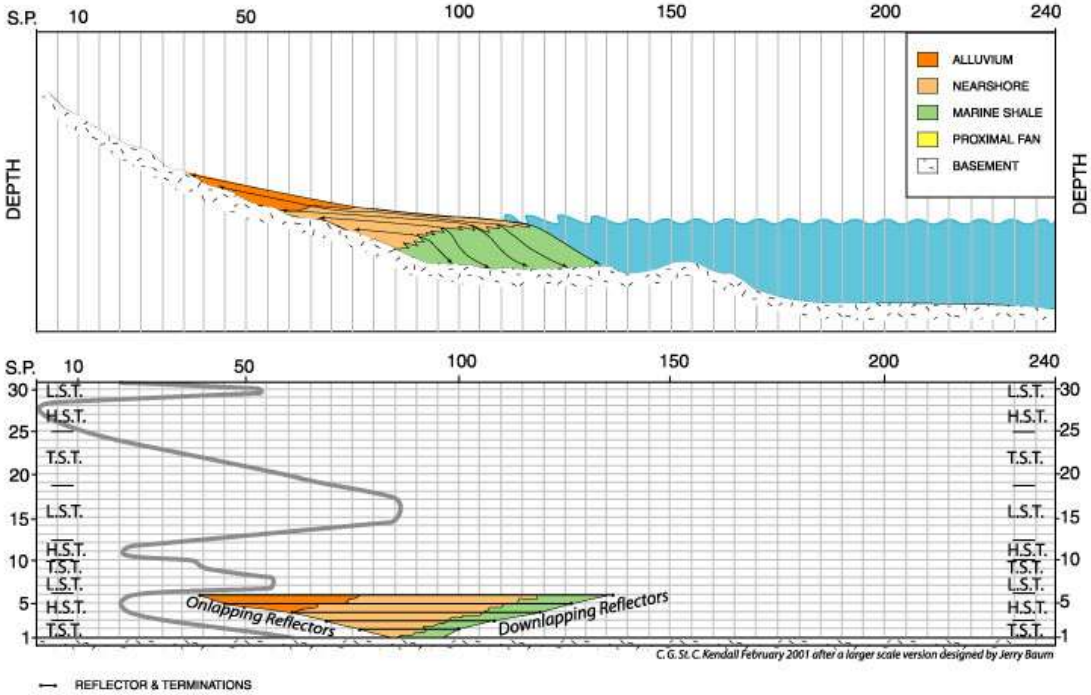

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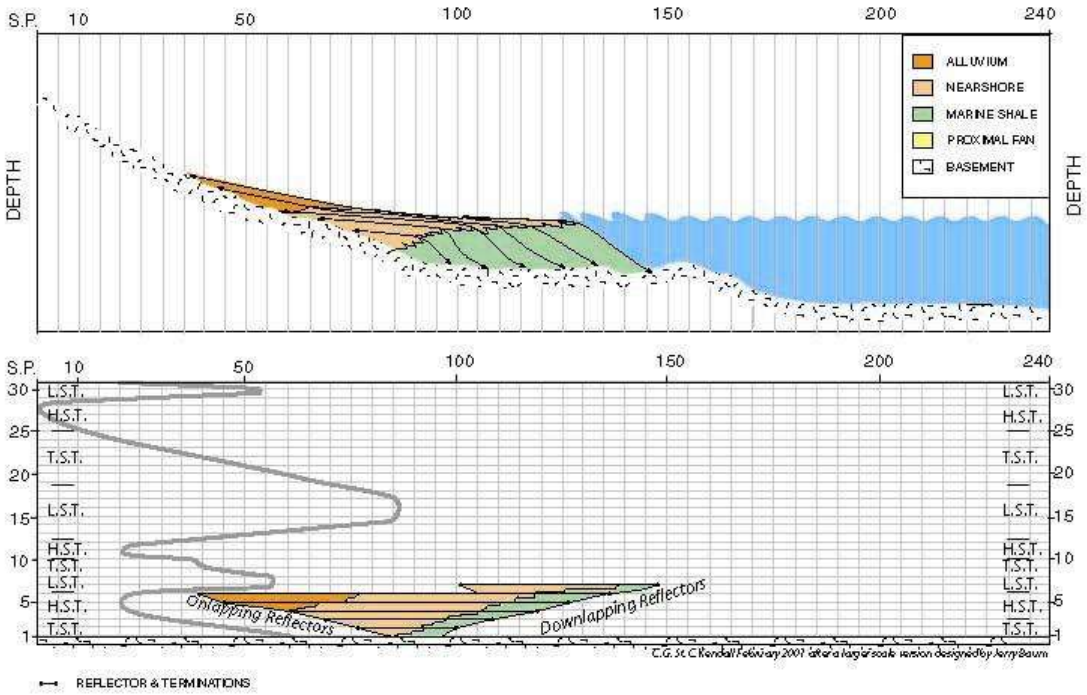

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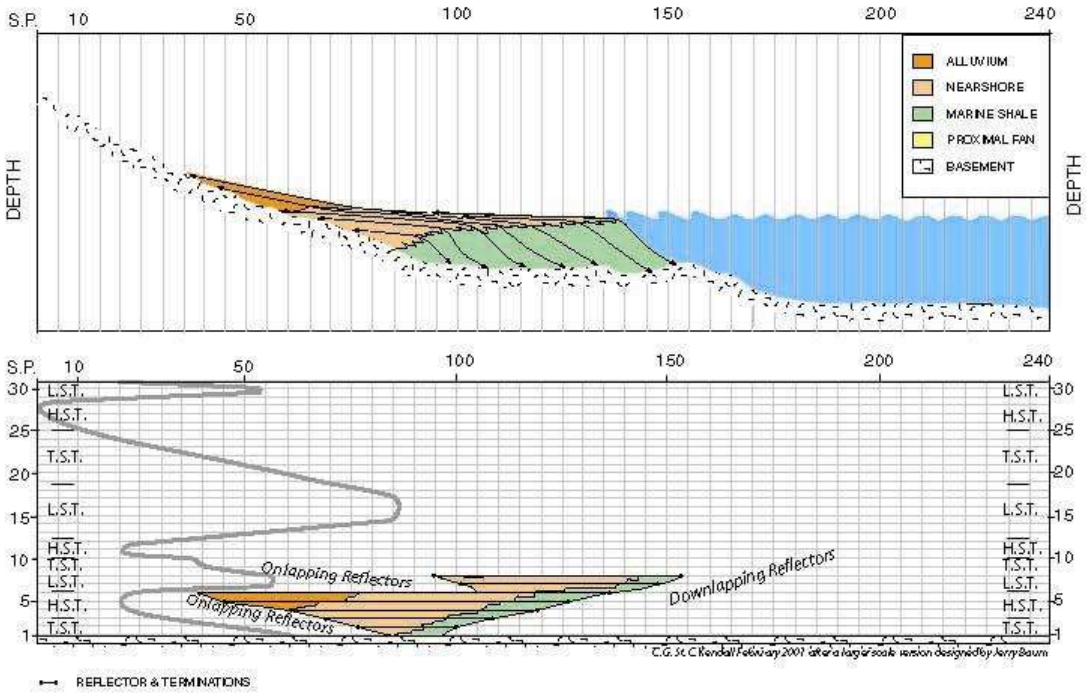

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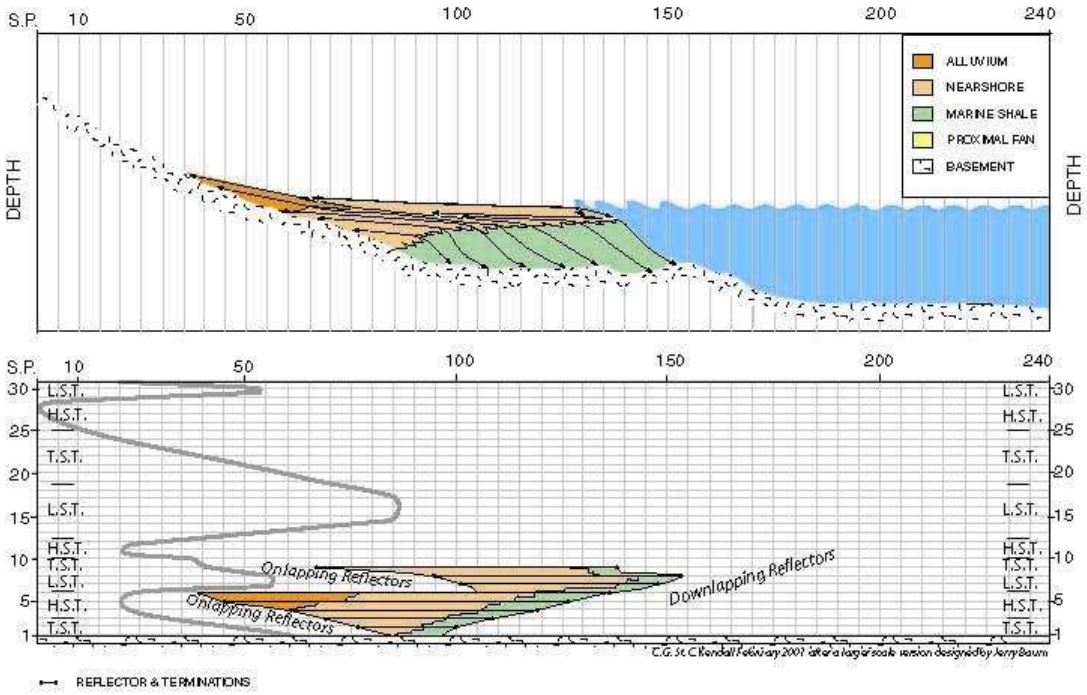

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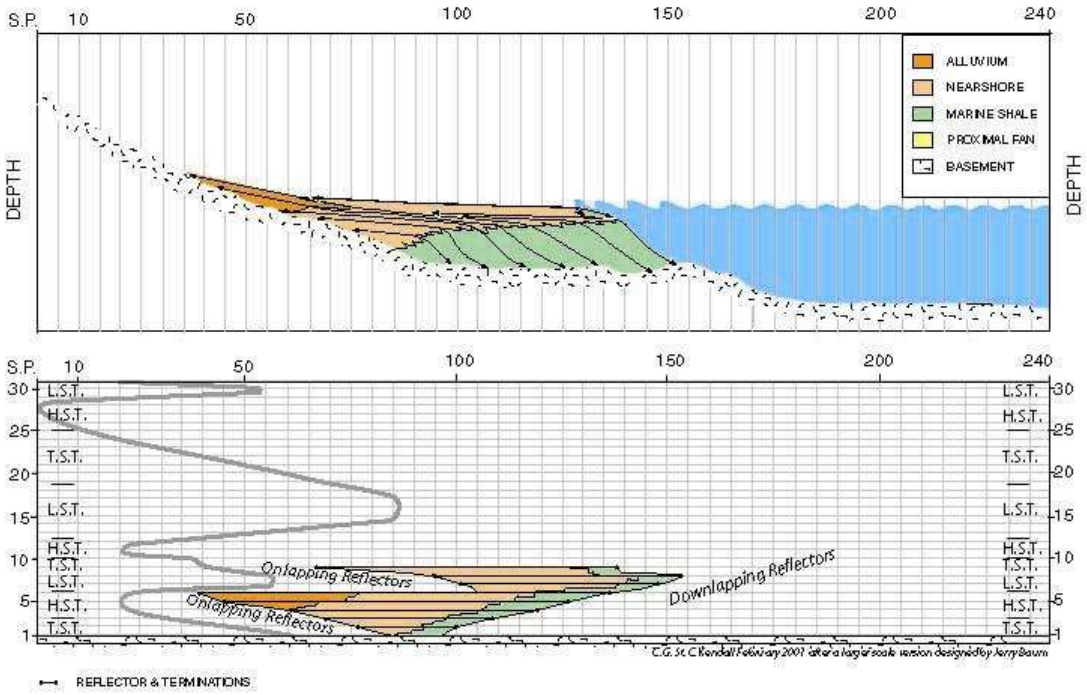

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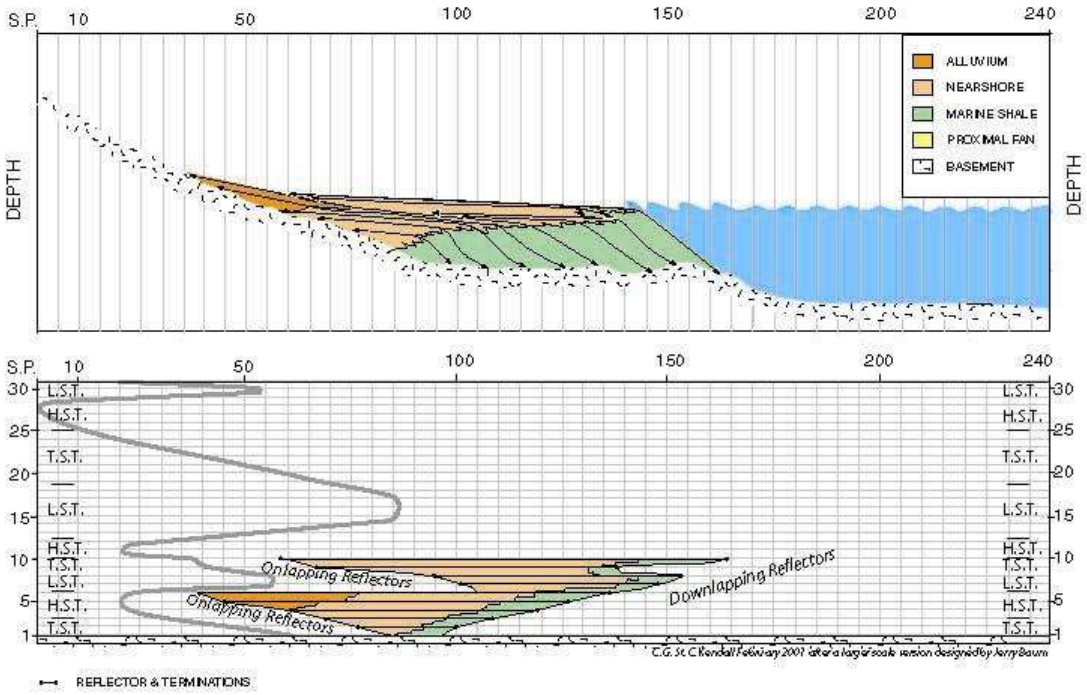

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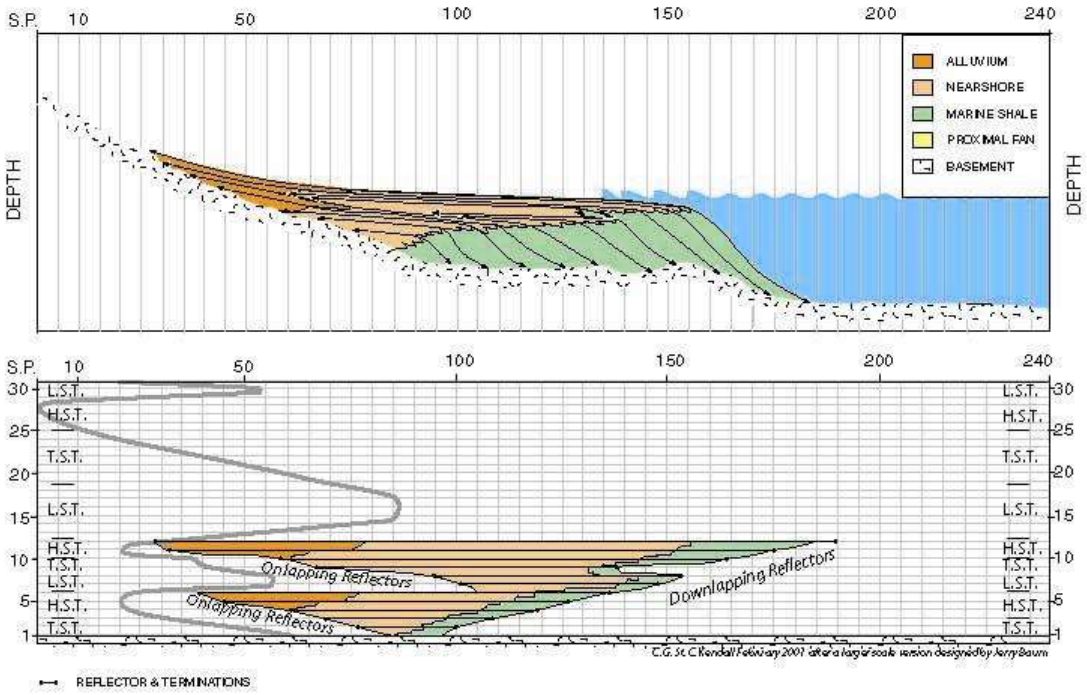

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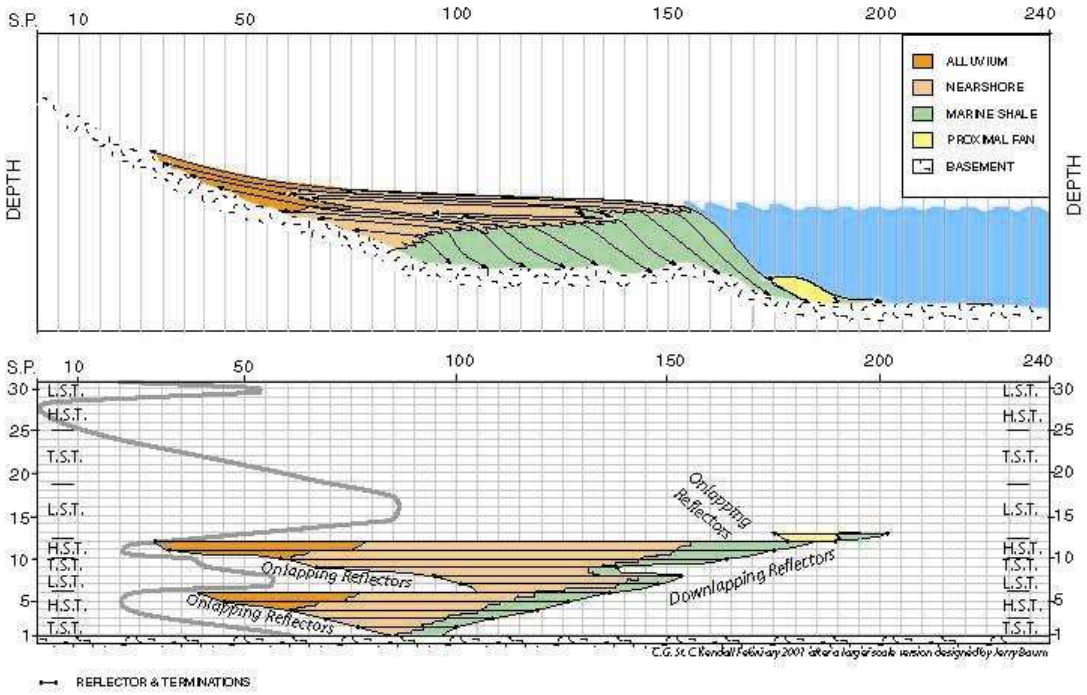

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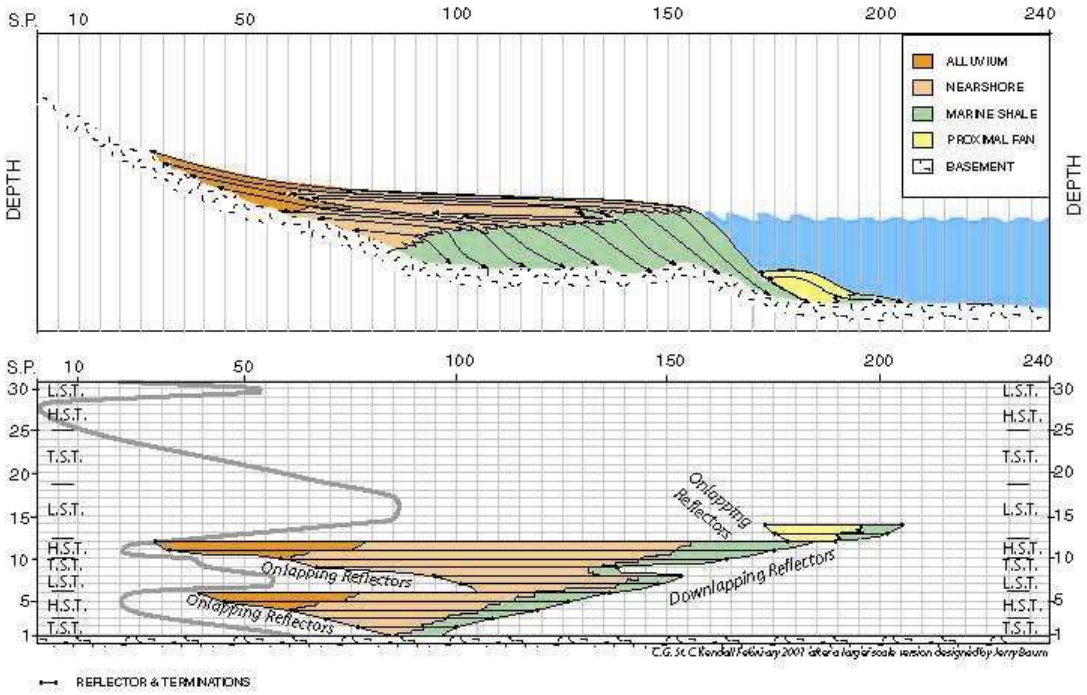

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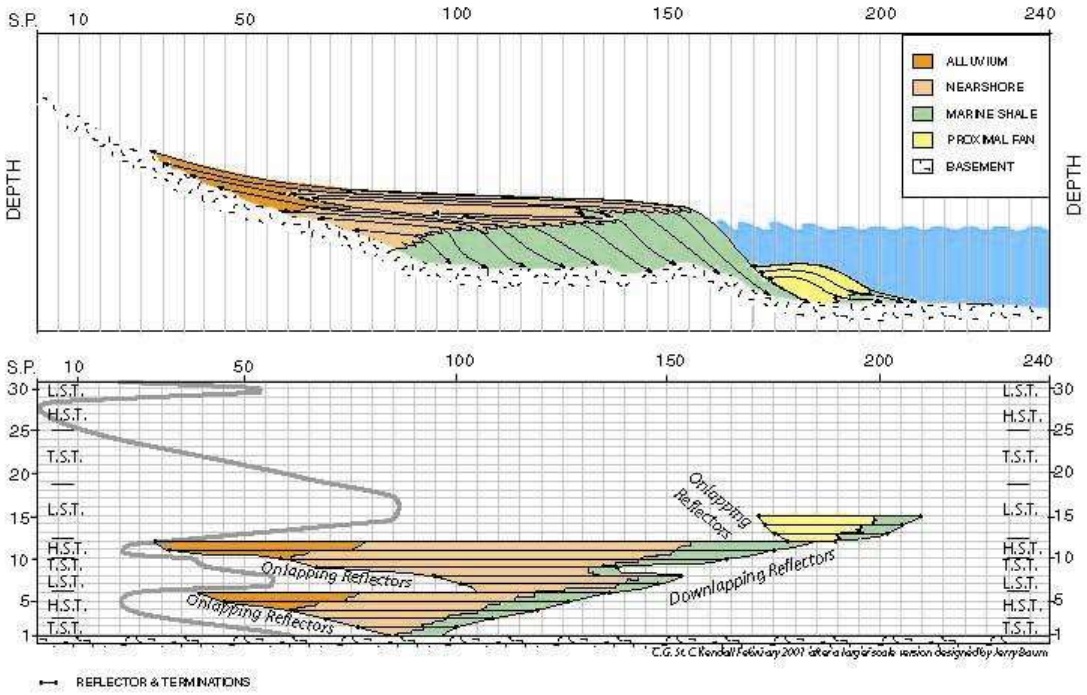

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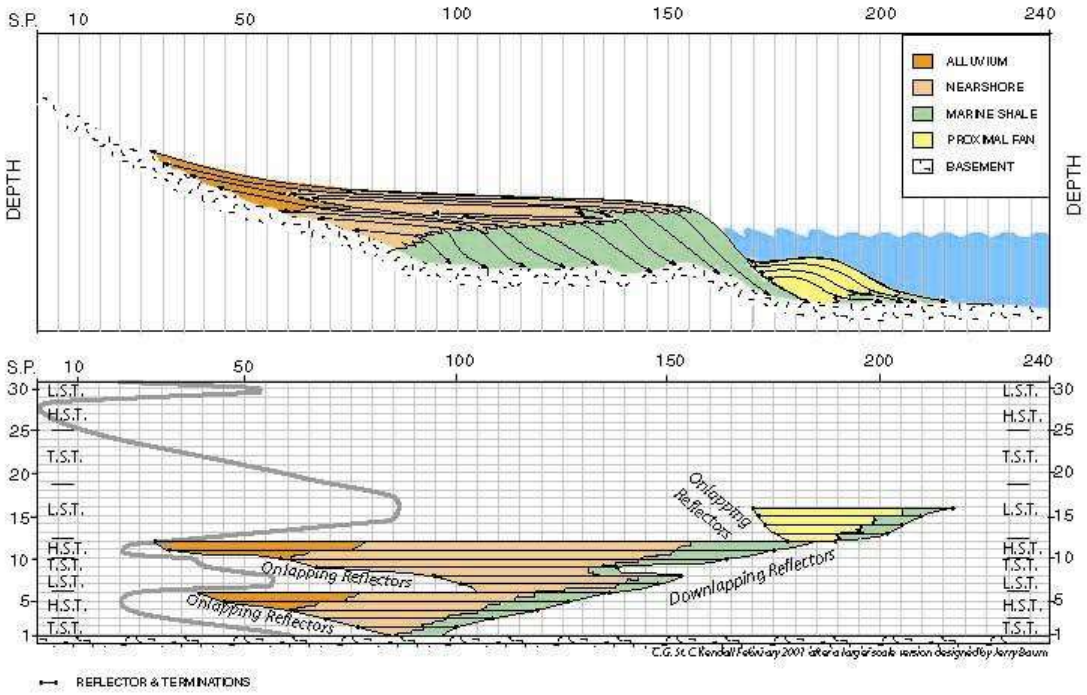

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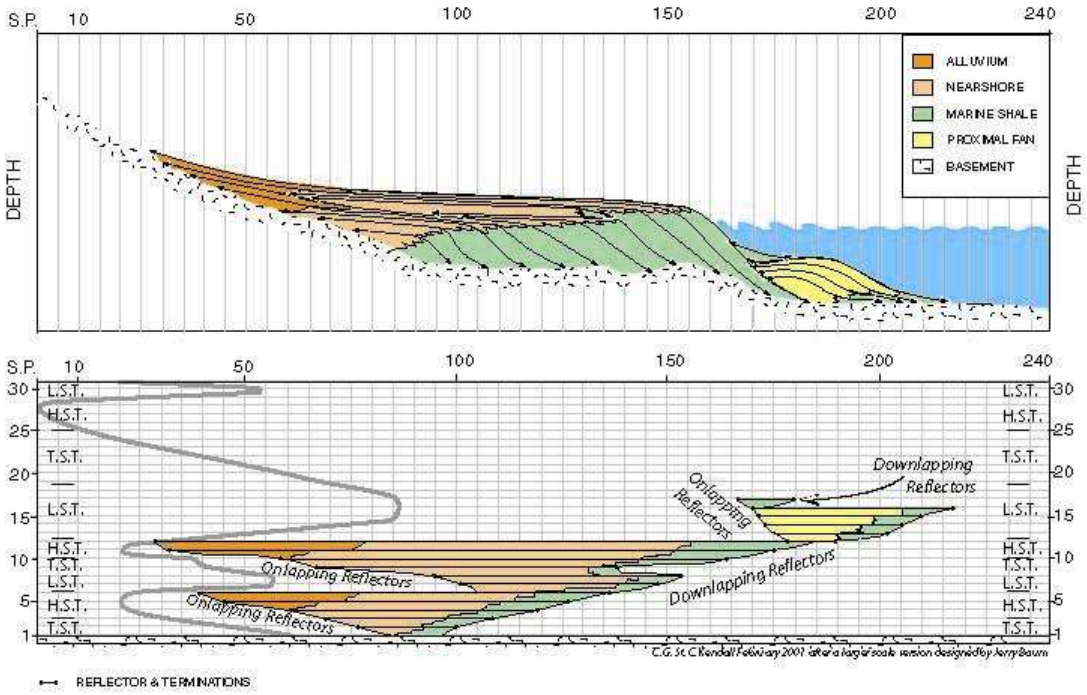

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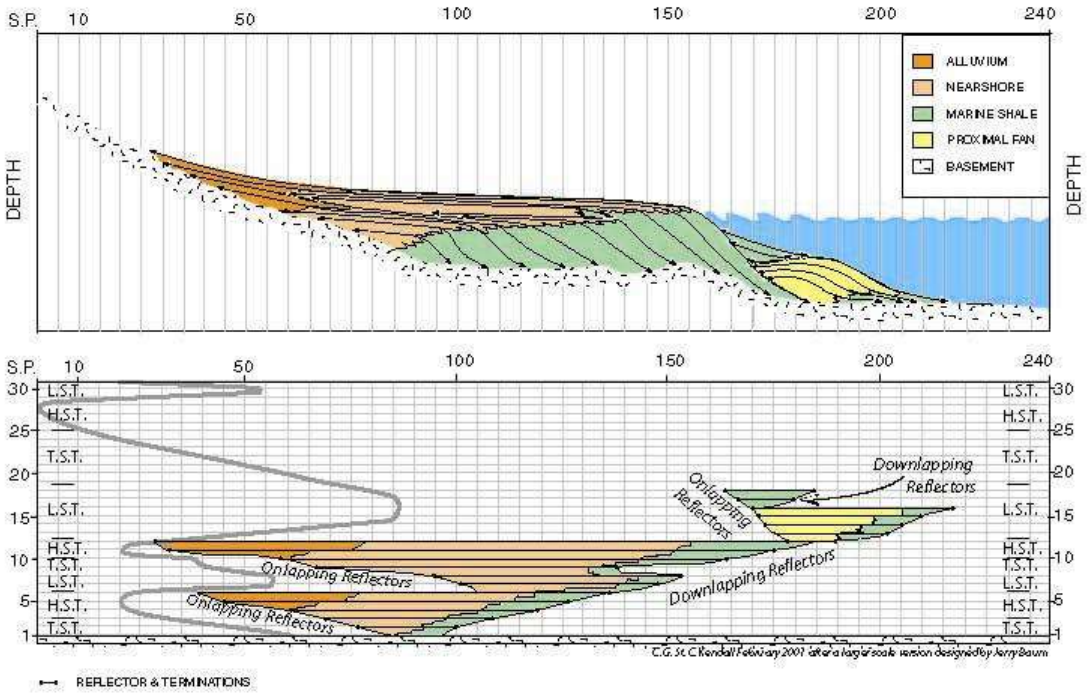

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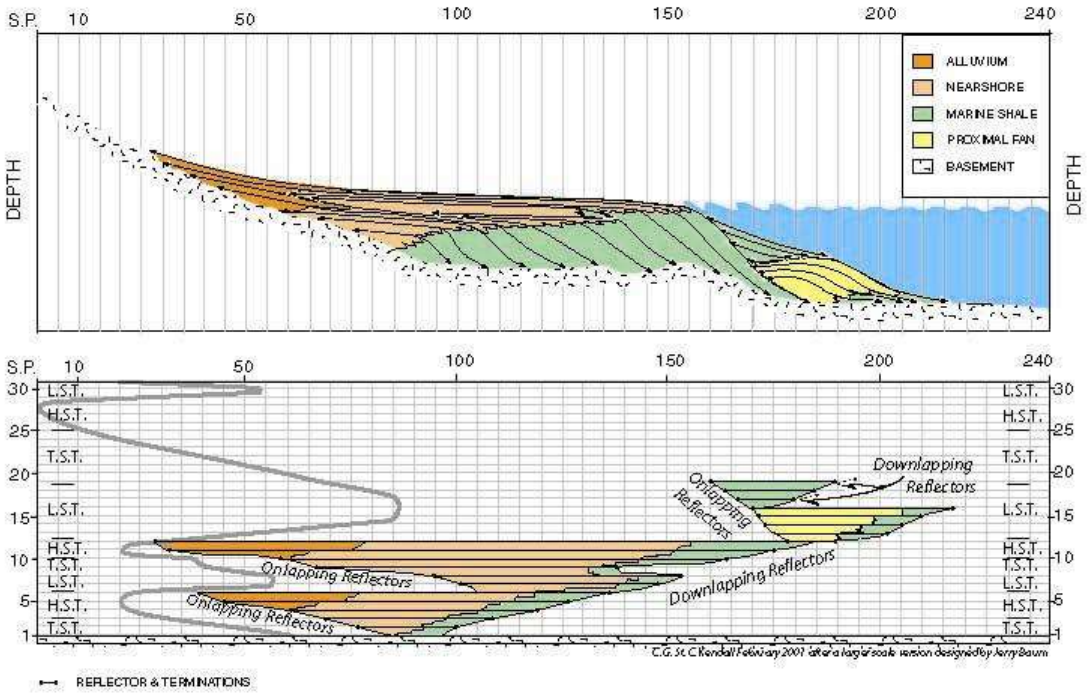

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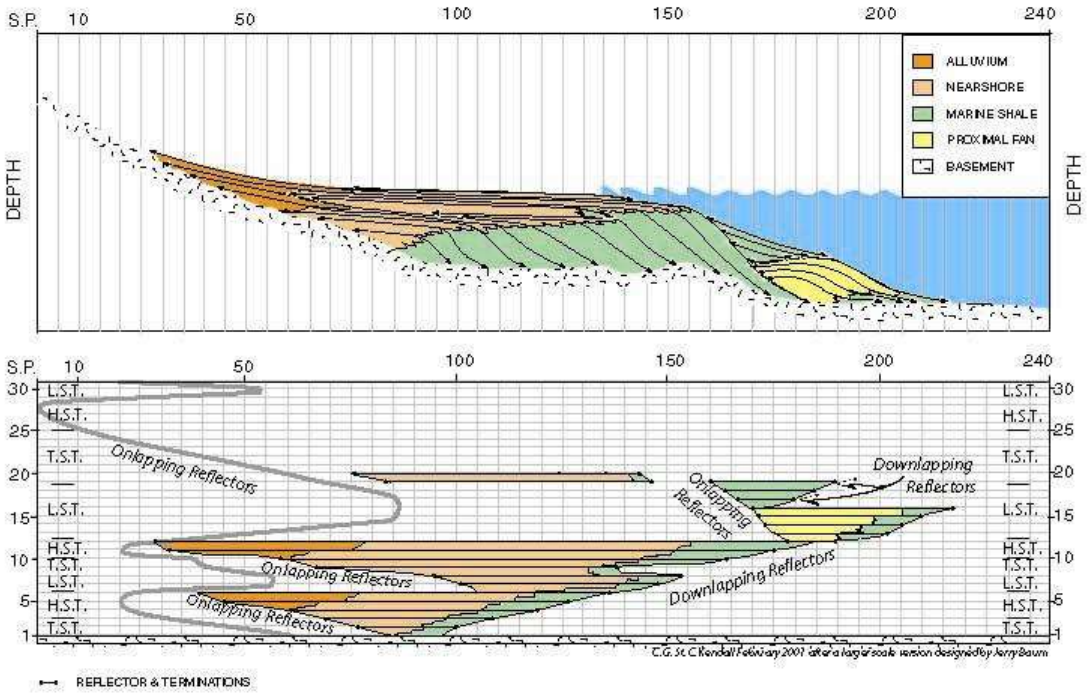

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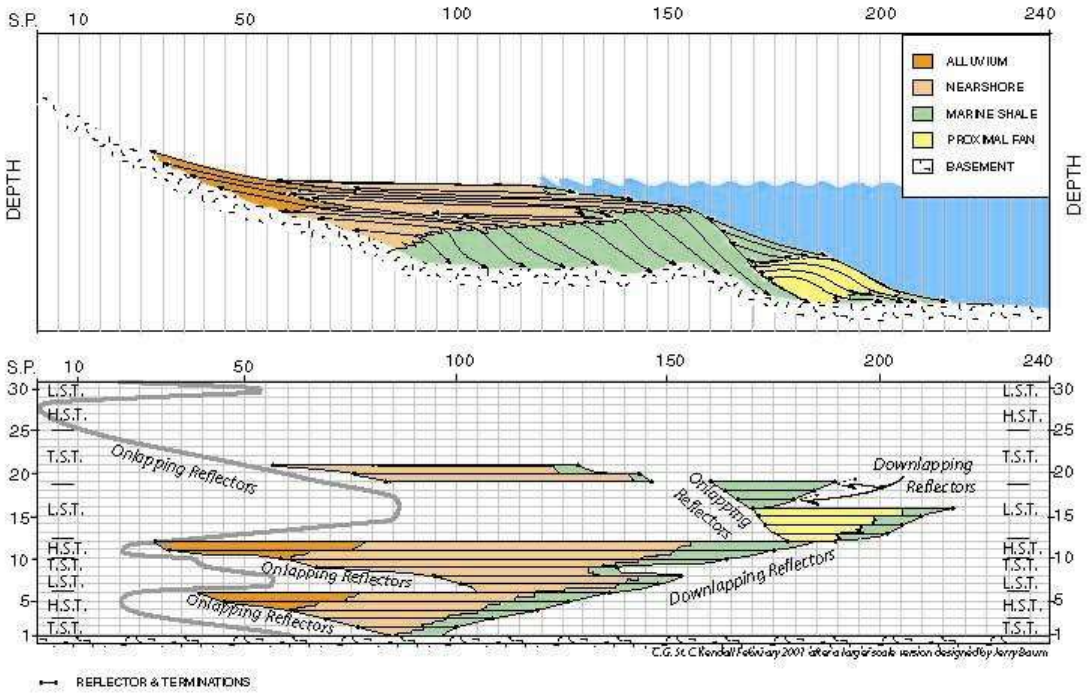

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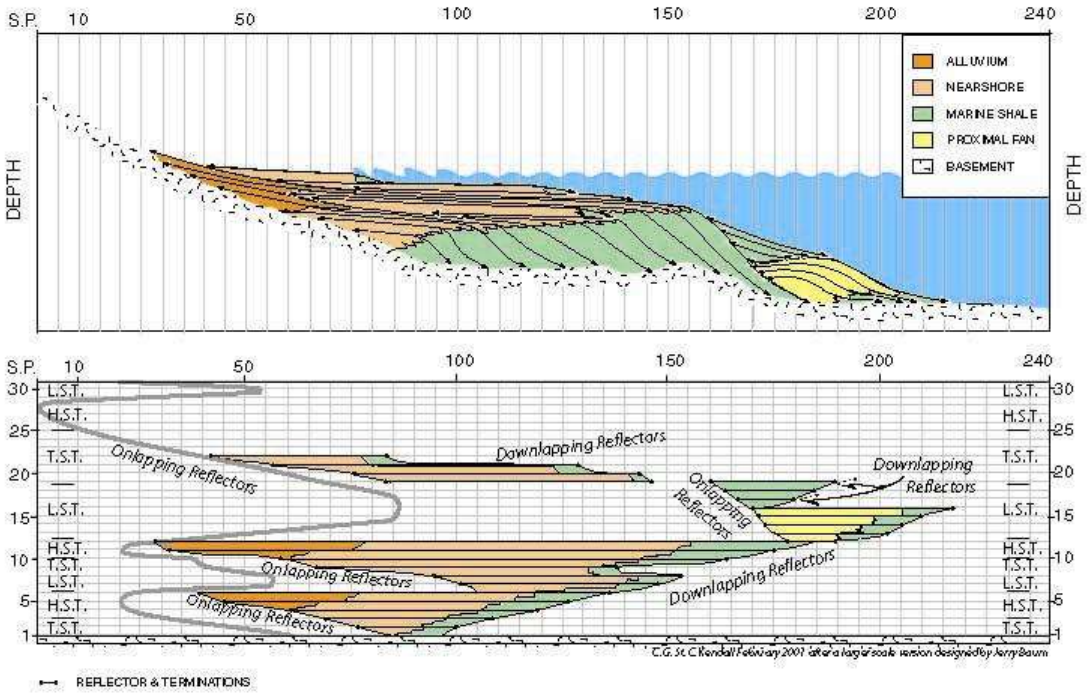

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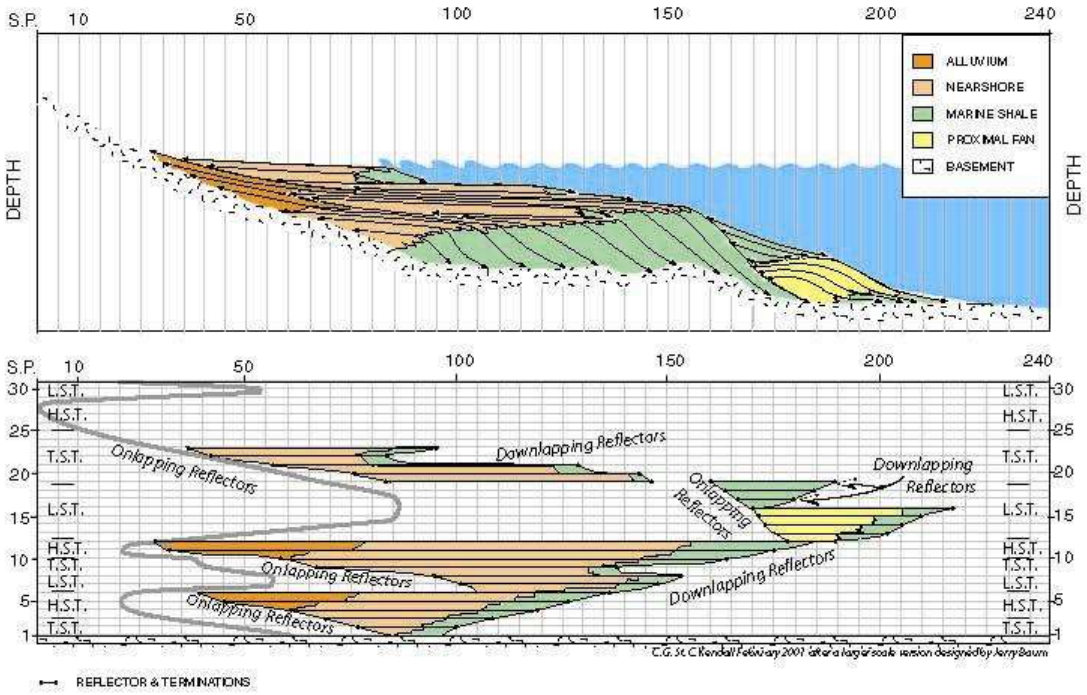

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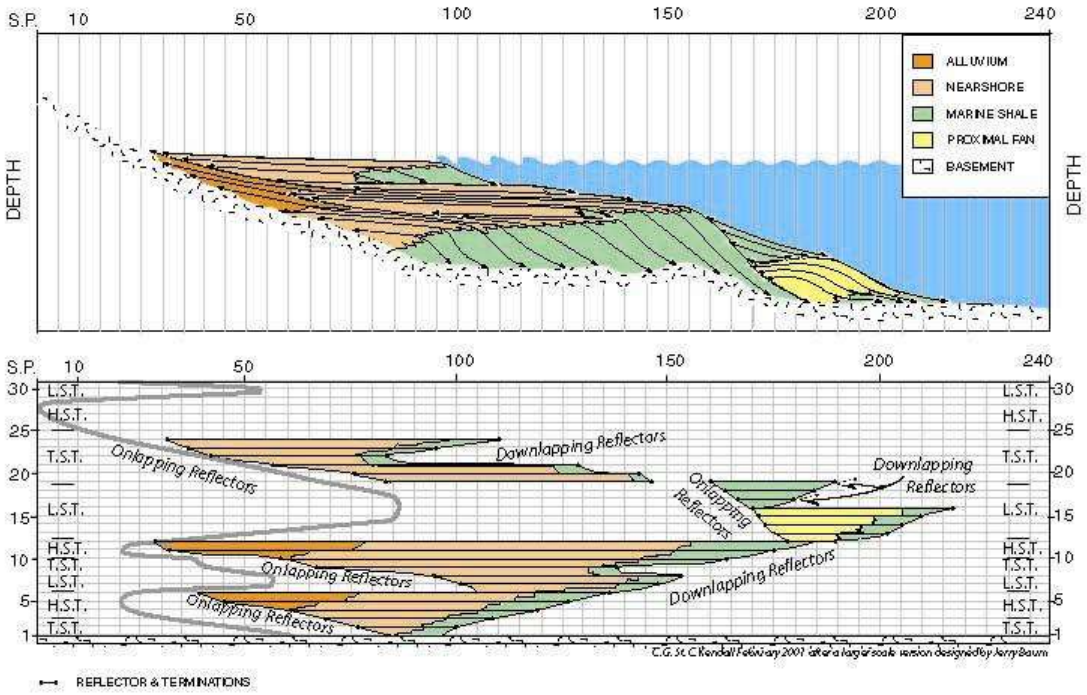

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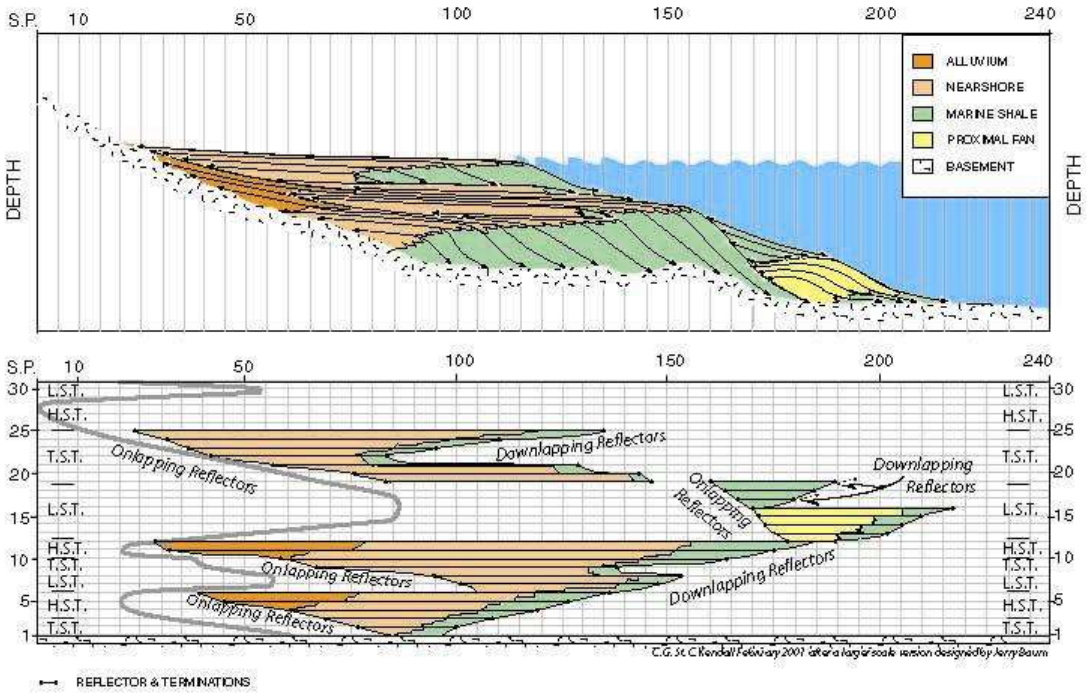

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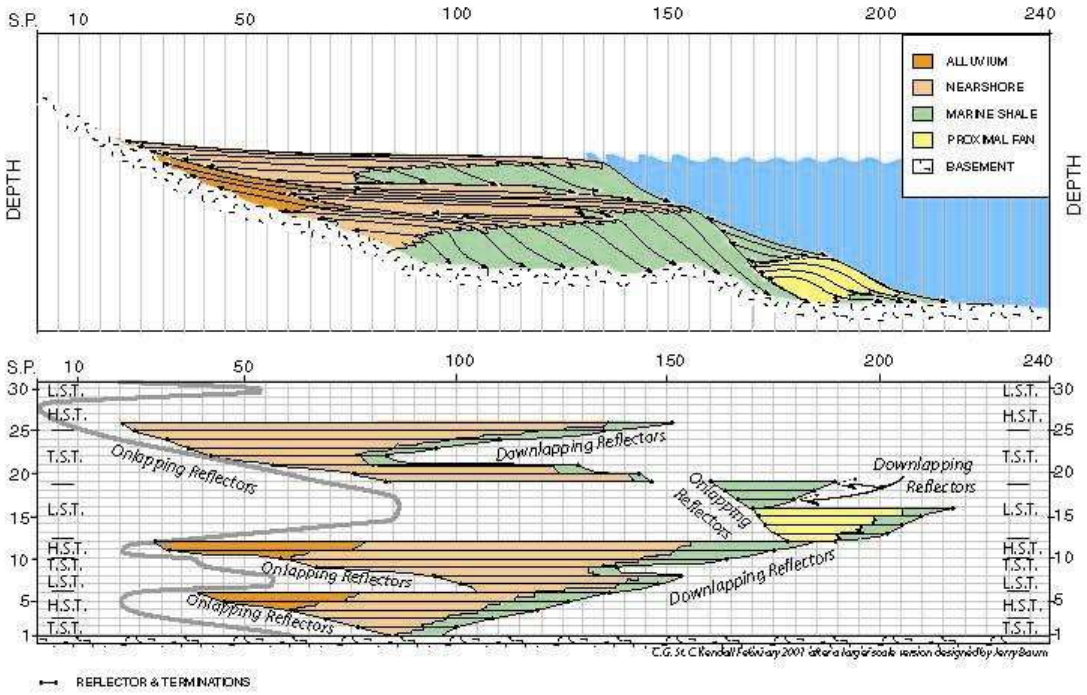

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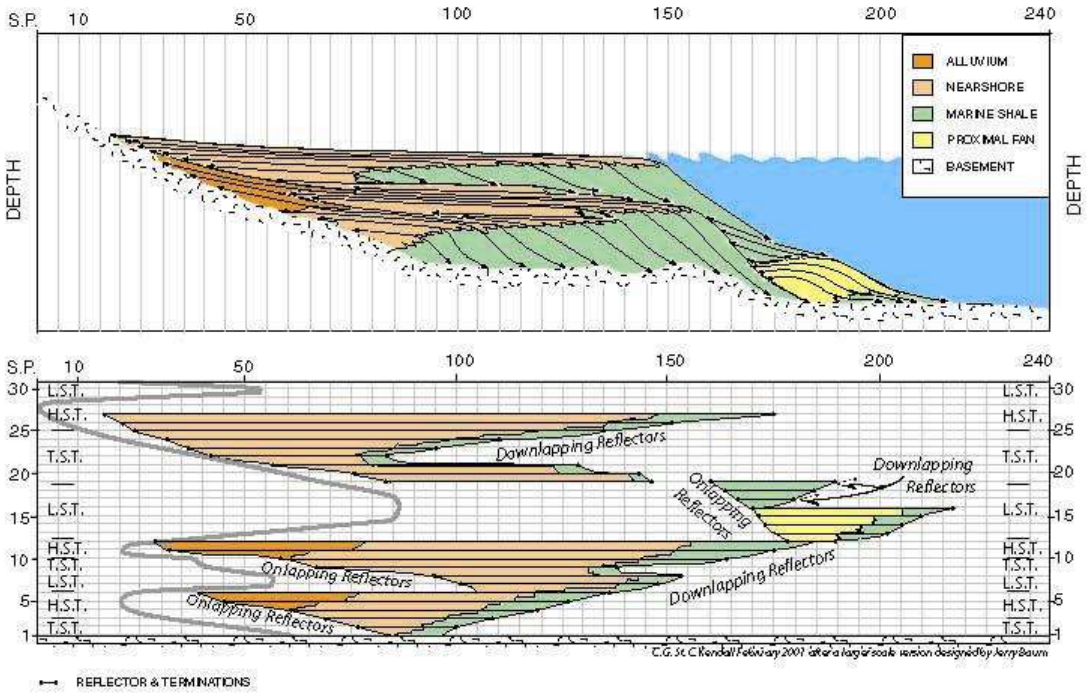

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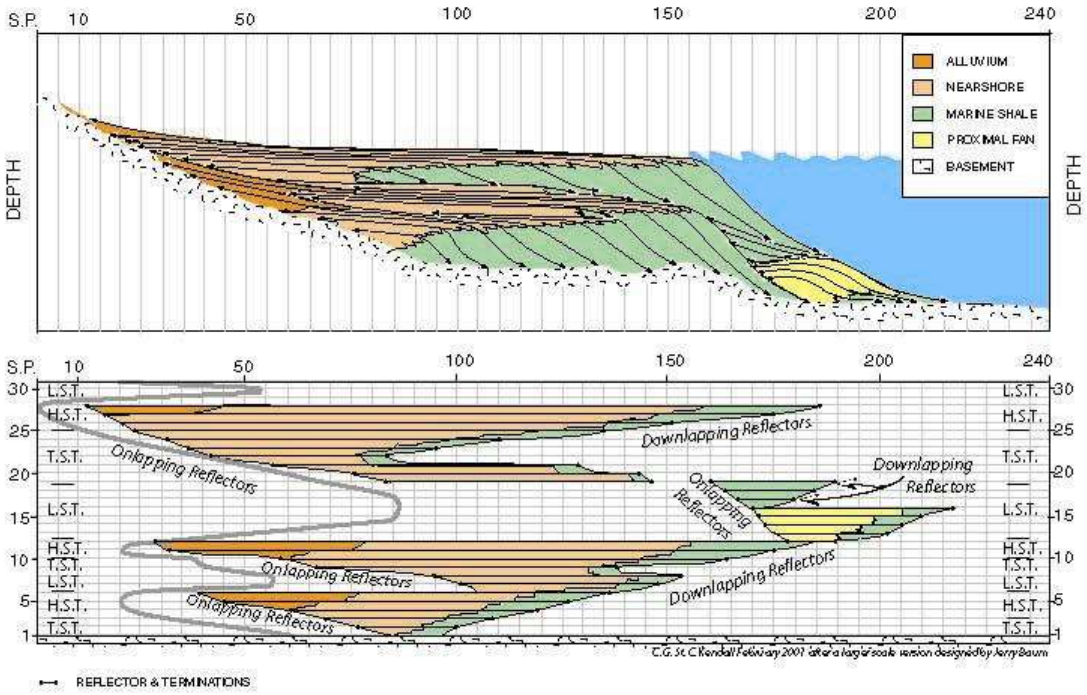
Chronostratigraphic Chart



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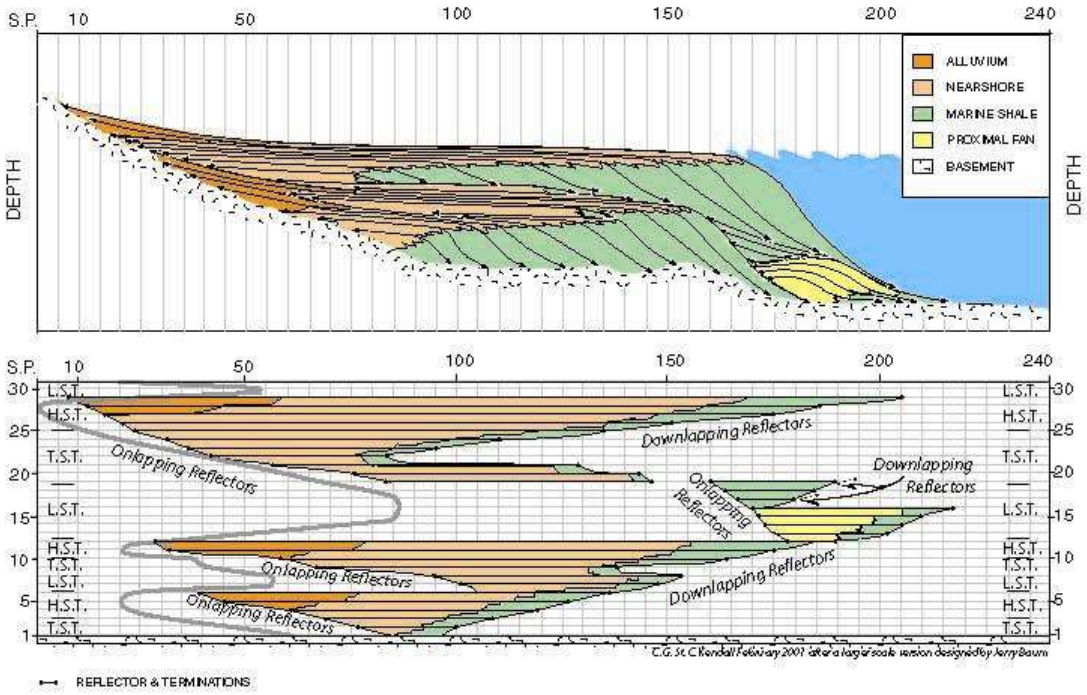
Chronostratigraphic Chart



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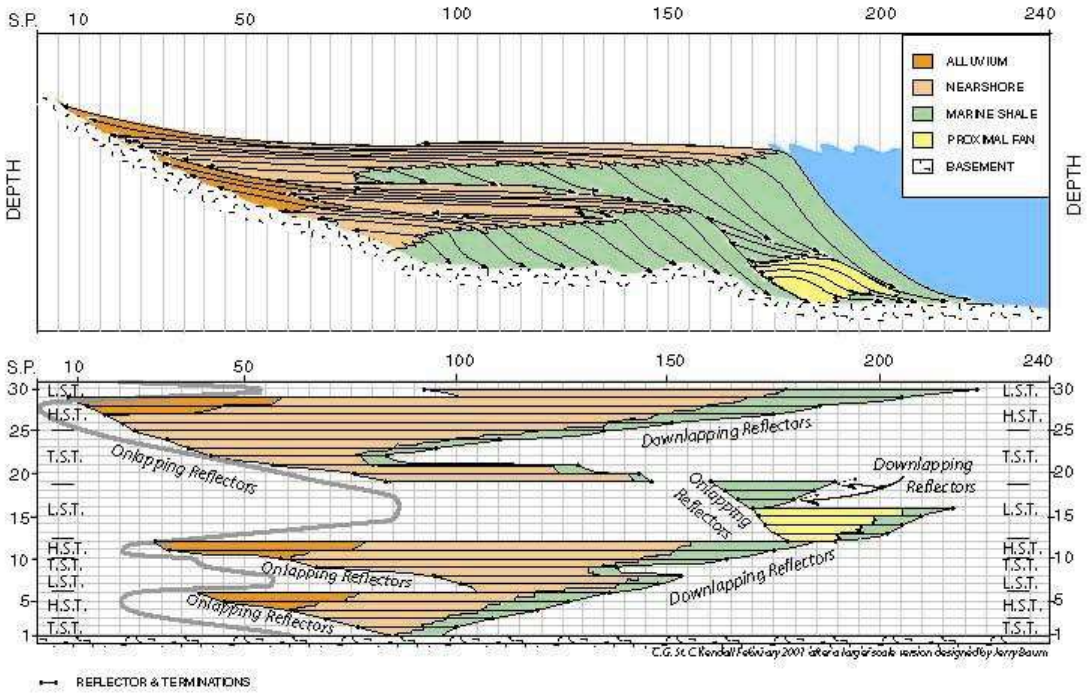
Chronostratigraphic Chart



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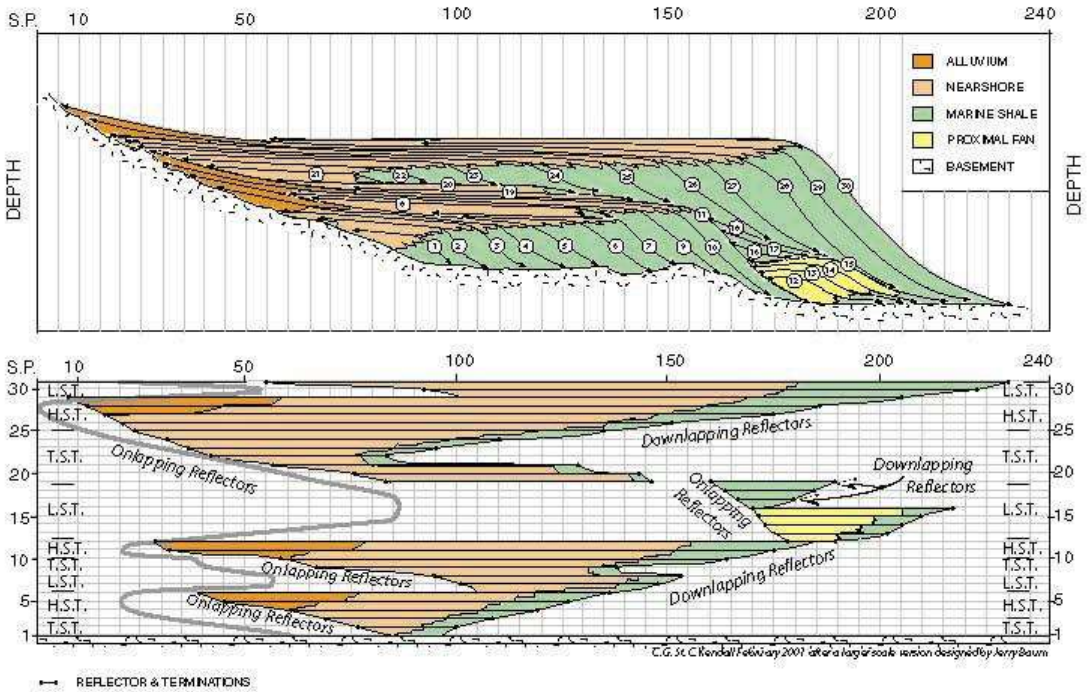
Chronostratigraphic Chart

EXERCISE: *CHRONOSTRATIGRAPHIC CHART CONSTRUCTION*

Chronostratigraphic Chart and the Relative Sea Level Curve from the Pseudo Seismic Line identifying:- Lithology, Reflection Terminations including "Onlap", "Offlap", and "Downlap", Sequence Boundaries (type 1 or 2), Systems Tracts, Ravinement Surfaces, Transgressive Layers, Maximum Flooding Surfaces, and Condensed Sections.



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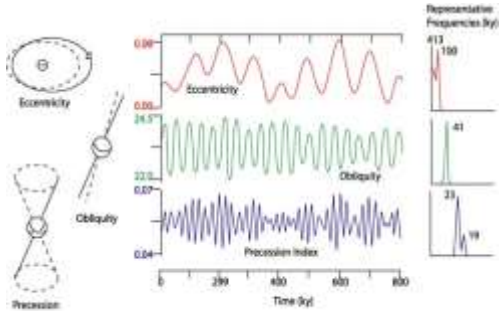
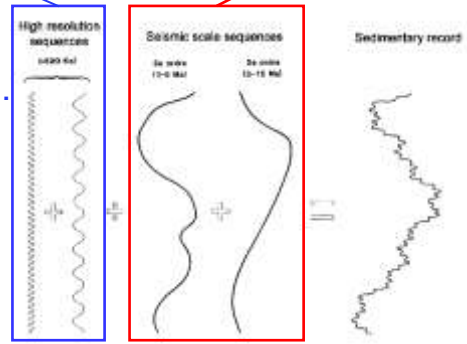
Controls of the sedimentary record

Controls driving the sedimentary record

Astronomic cycles

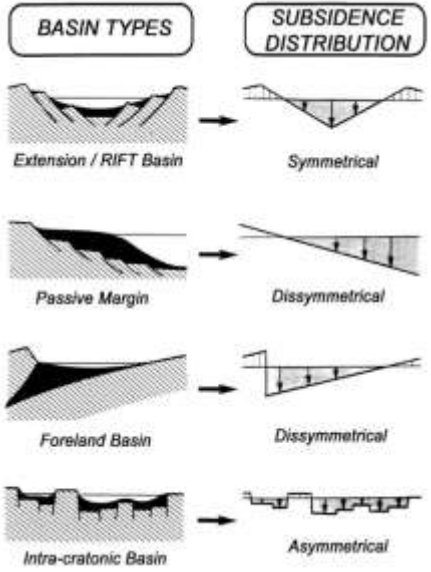


- Glacio-eustatism
- Climate
- Paleogeography…



Relative sea level variations

Tectonic regimes



- Tectono-eustatism
- Paleogeography
- Sediment supply…

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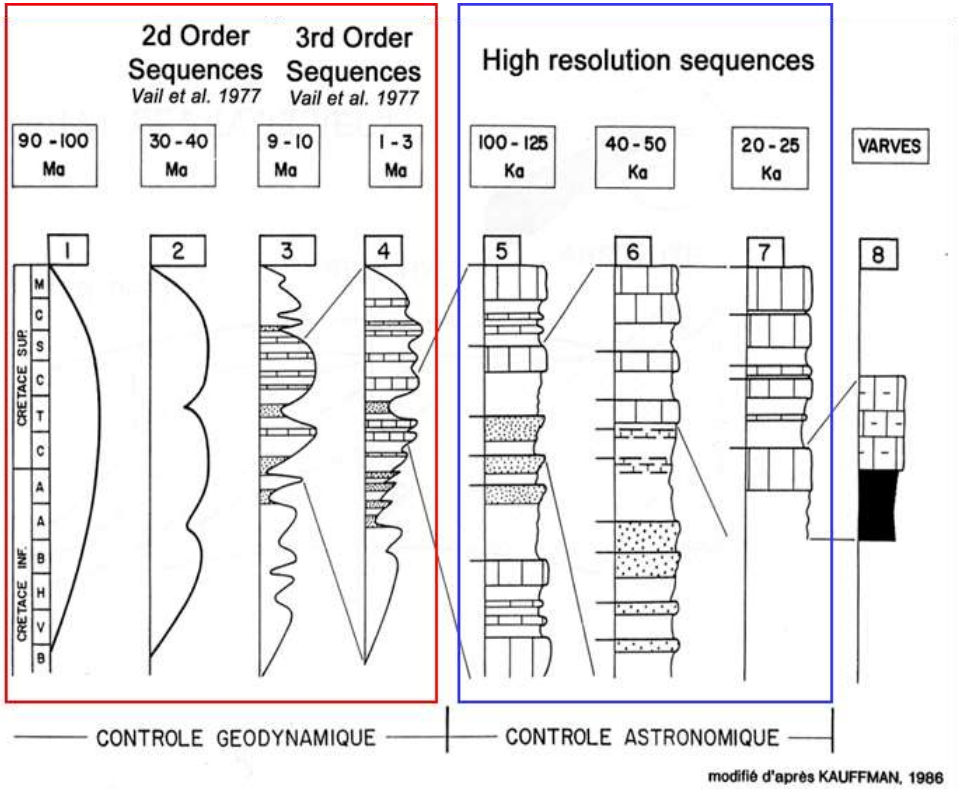
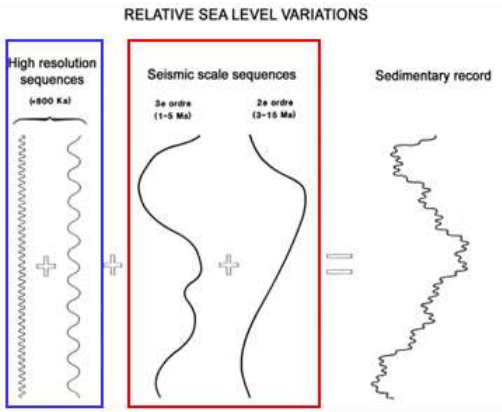
Scale and Orders in Sequence Stratigraphy

Nature of the sedimentary record





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Seismic Stratigraphic Background

Seismic stratigraphy:

- To identify **Time Lines** ideally by combining well and seismic reflection data.
- To interpret seismic reflectors with a stratigraphic significance (SB, MFS)
- To predict the Distribution in Time and Depth of potential reservoirs based on their stratigraphic position along the profile.

Seismic geomorphology:

- To recognize Depositional Elements (geobodies) based on their seismic response (facies, size) within a regional geological context (depositional environments).

Usually Seismic geomorphology and Seismic stratigraphy have to be combined to predict the presence of petroleum system elements

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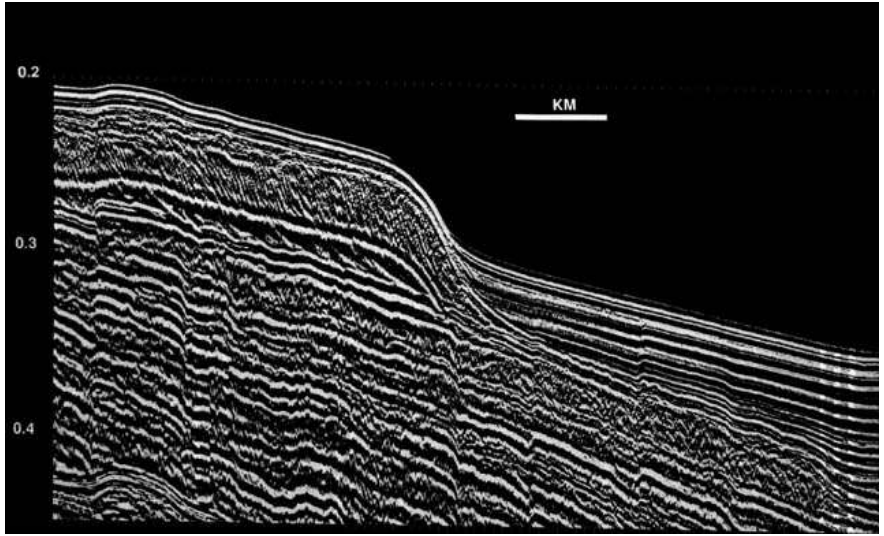
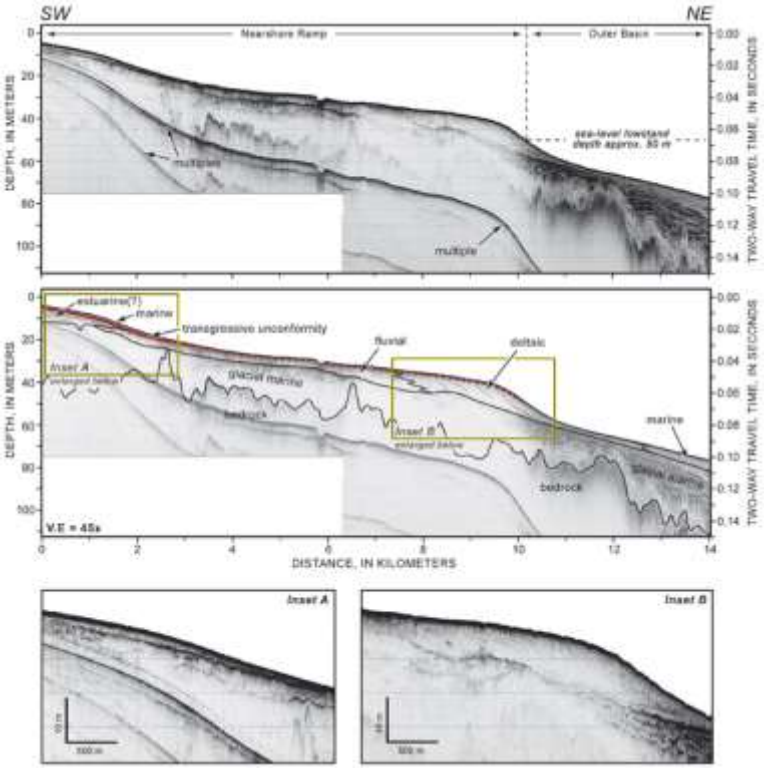
Deltas – Seismic morphology

*Small airgun seismic profile off of a **flexural margin delta (Dwangwa Delta) in Lake Malawi**. Note steeply-dipping (~6°) clinoform reflections which probably represents a major lowstand delta lobe dating to the late-Pleistocene. These clinoform reflections are onlapped by continuous, high amplitude reflections which represent hemipelagic, organic-rich facies.*





***Seismic-reflection profile across the inner continental shelf of the Gulf of Maine - USA**. Seaward-dipping clinoforms (inset B) indicate progradation of the delta offshore into a deep, muddy basin.*

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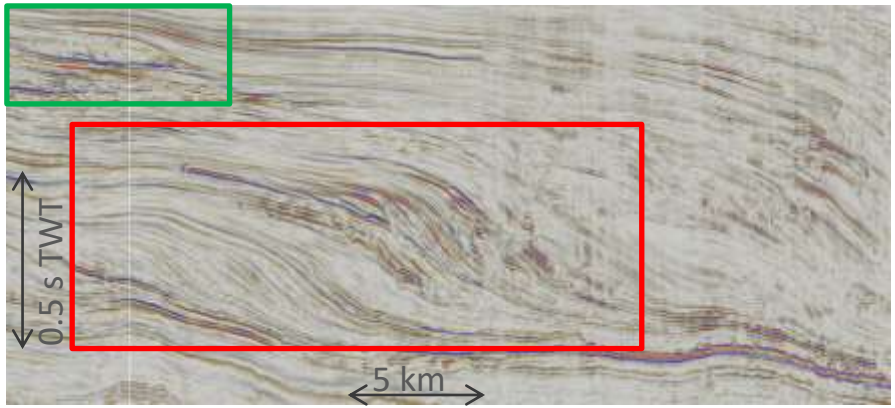
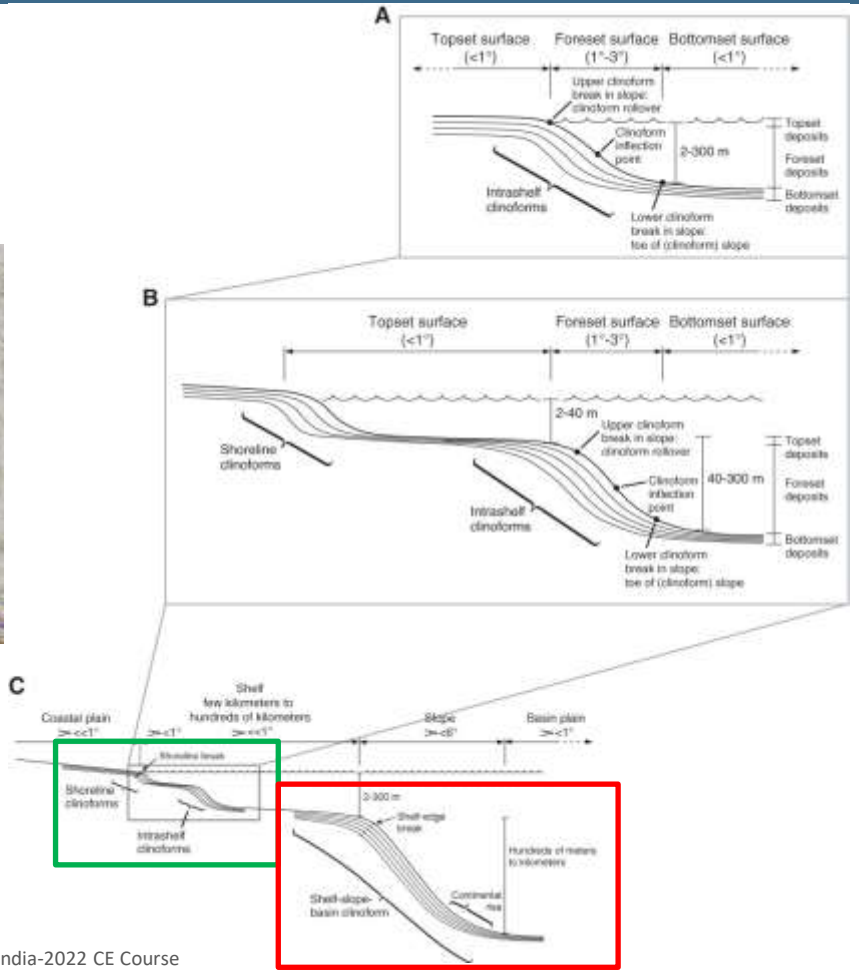
Deltas – Seismic morphology

Always look at the scale of clinoforms as they are not always deltas!





Most of clinoforms observed at seismic scale are Shelf edge deltas developping during lowstands

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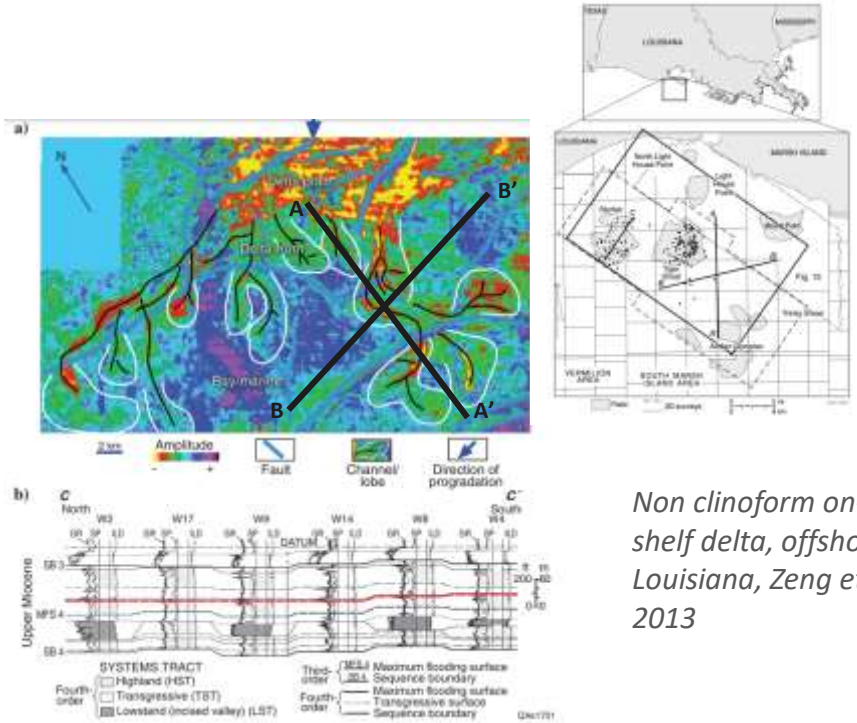
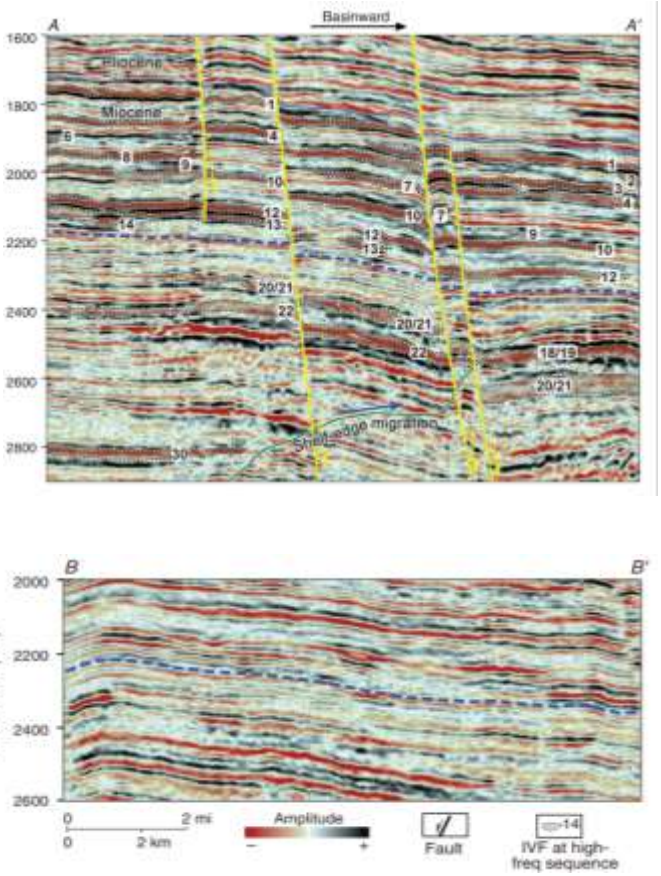
Deltas – often sub-seismic clinoforms

Not all prograding deltas are necessarily represented by tall seismic clinoforms (>100m height)





Non clinoform on-shelf delta, offshore Louisiana, Zeng et al, 2013

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Deltas – often sub-seismic clinoforms

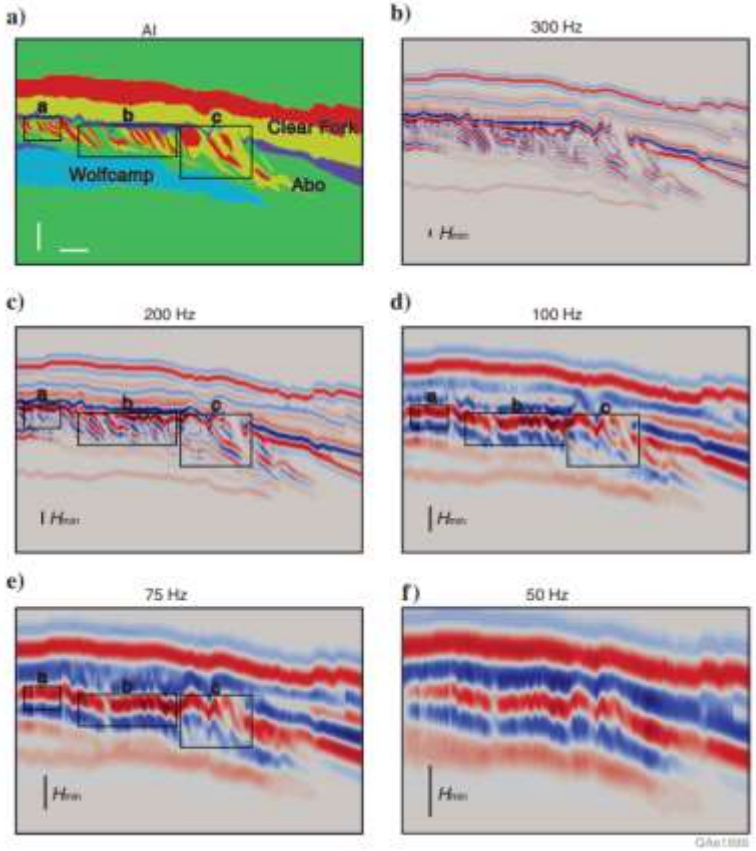

Figure 17. An AI model of the Abo carbonate clinoform complex at Apache Canyon, Sierra Diablo, west Texas (Courme, 1999), and its synthetic seismic responses with Ricker wavelets of various frequencies. For better comparison with field data, the predominant frequency is used in modeling, which is equal to 1.3 times the peak frequency for Ricker wavelet. Clinoform detection limits are calculated from equation 1. Boxes a, b, and c denote relatively thin, moderate, and thick clinoform complexes in the model, respectively.

VHR Seismic

Conventional seismic

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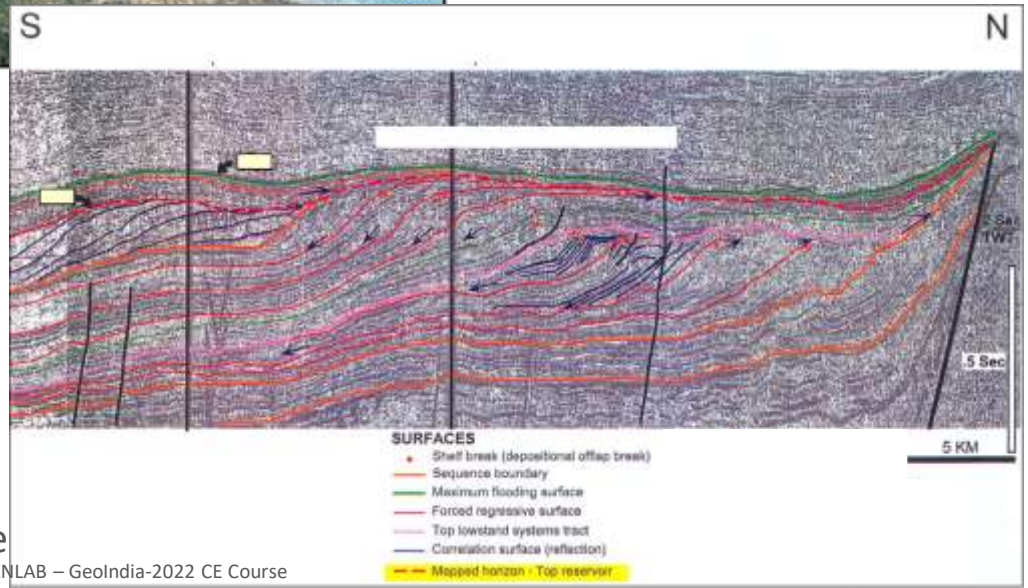
Delta associated with syn-rift context

- examples of syn-rift deltaic system = Gilbert type delta

Pleistocene Gilbert delta - Greece



Seismic example

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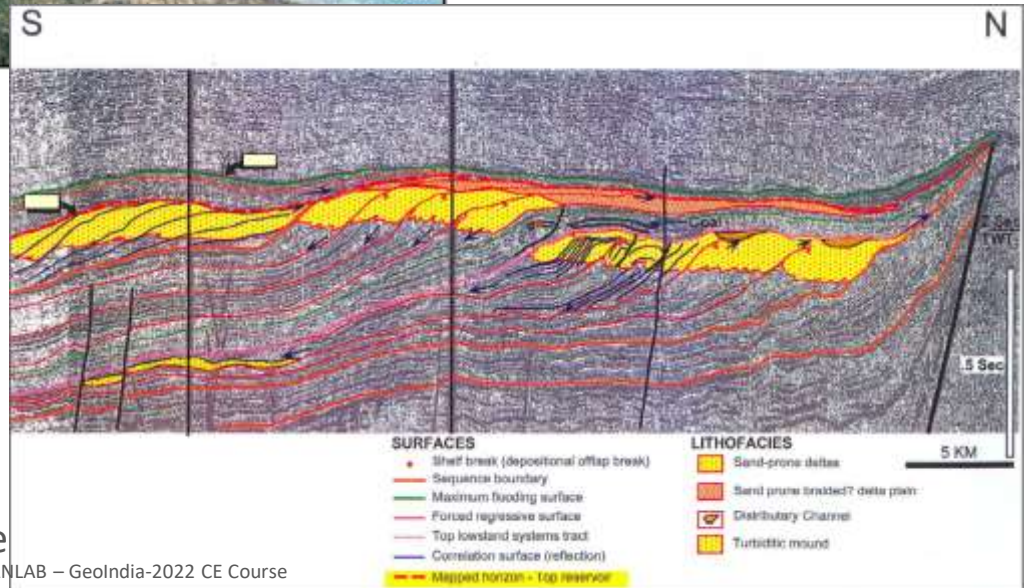
Delta associated with syn-rift context

- examples of syn-rift deltaic system = Gilbert type delta

Pleistocene Gilbert delta - Greece



Seismic example

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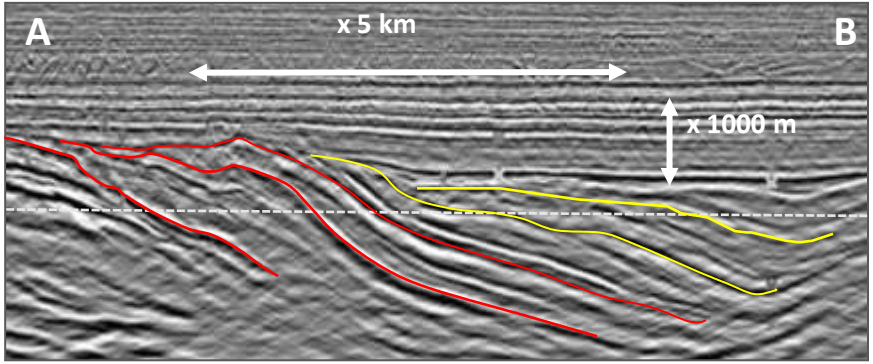
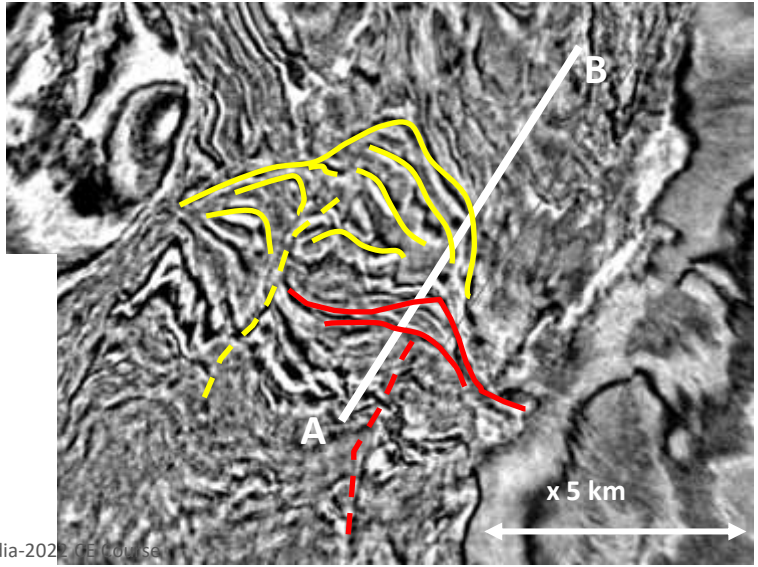
Deltaic/fans deltas –syn-rift complex

Deltaic objects are small
But clinoform height is huge (>400m)



South Orphan Basin
SynRift opening

SynRift Gilbert type delta



Lowstand delta

Highstand delta

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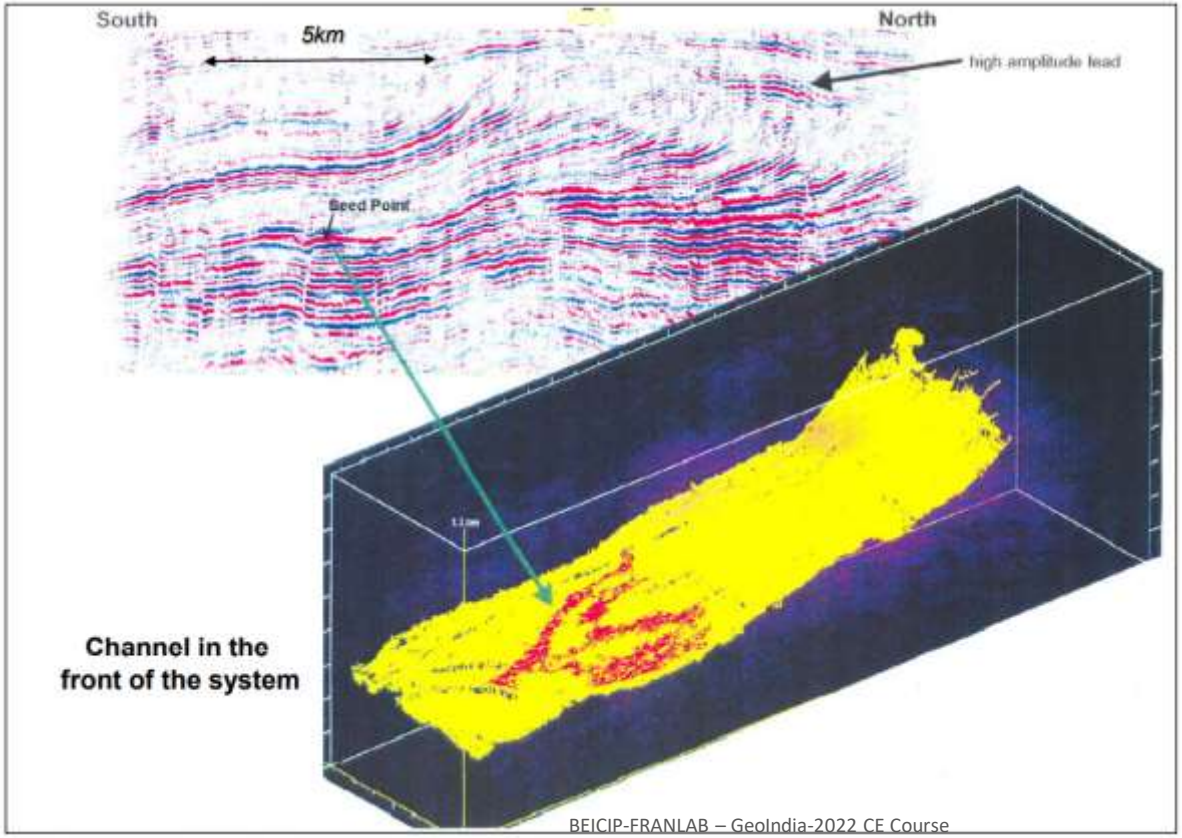
Shelf edge deltas & slope apron

- examples of deltaic clinoform developing during lowstand at slope edge



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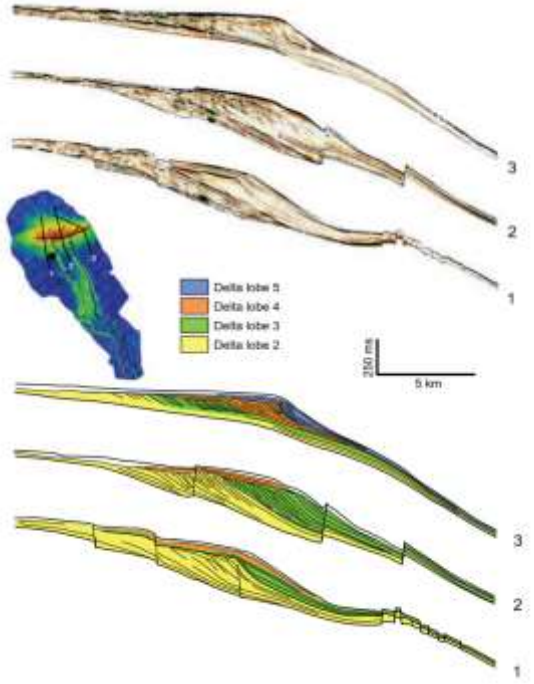
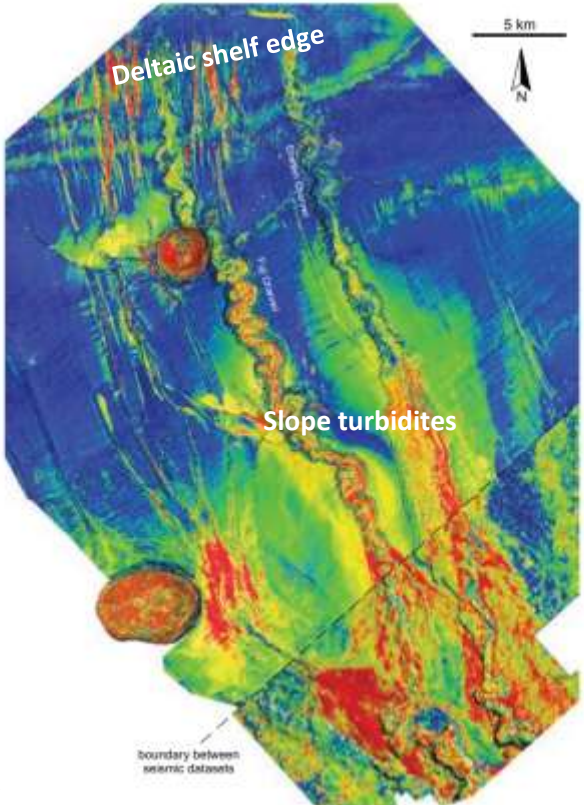
Shelf edge deltas & slope apron

- examples of Slope edge delta in the Offshore Mexico



Dip oriented views and map view showing the successive clinoforms associated with successive shelf edge deltas

Fuji Einstein delta, Sylvester et al., 2012



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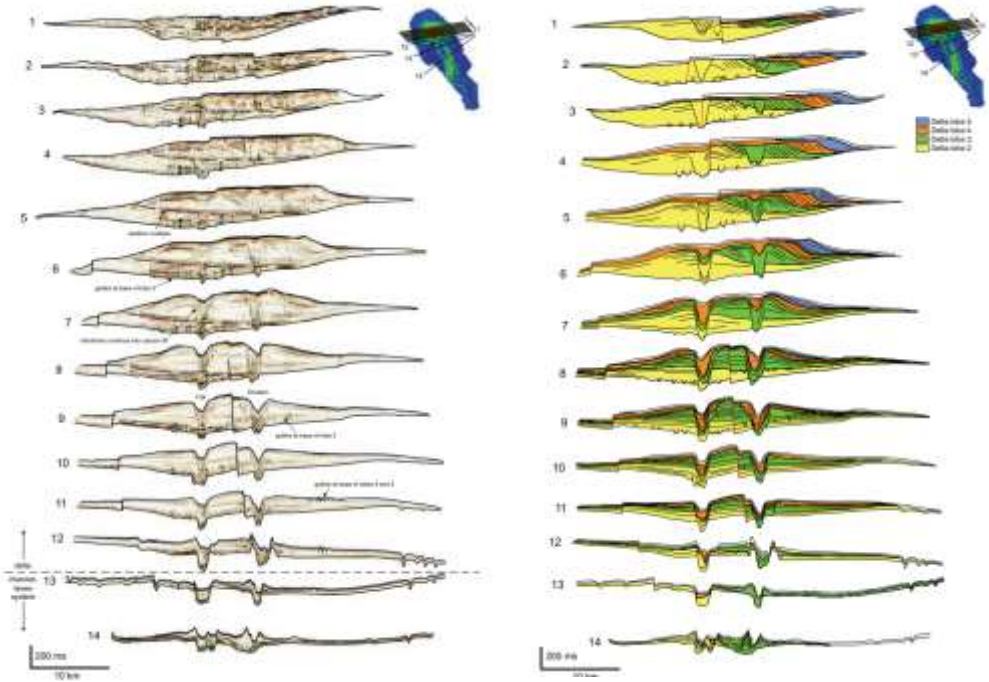
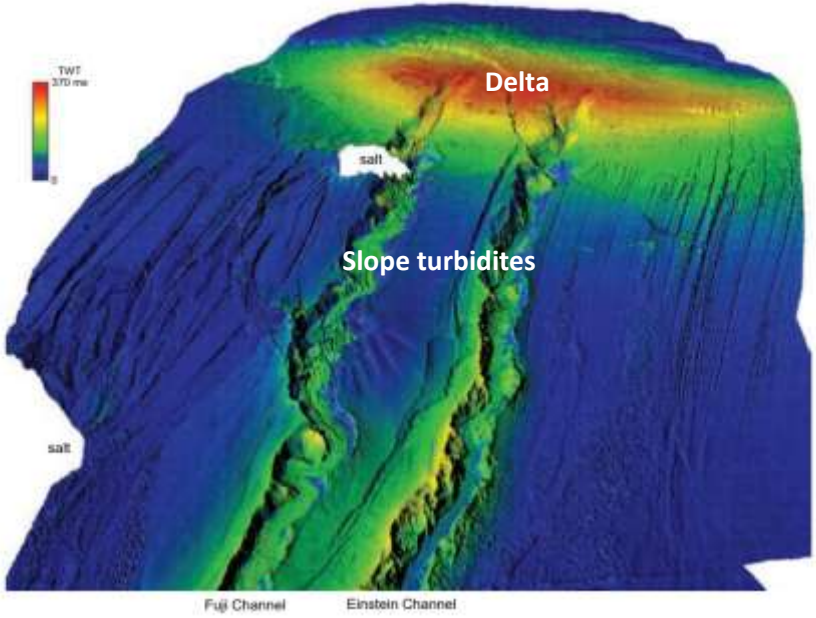
Shelf edge deltas & slope apron

- examples of Slope edge delta in the Offshore Mexico

Fuji Einstein delta, Sylvester et al., 2012





Strike views and 3D view showing that slope turbiditic channels are coeval with the delta lobes

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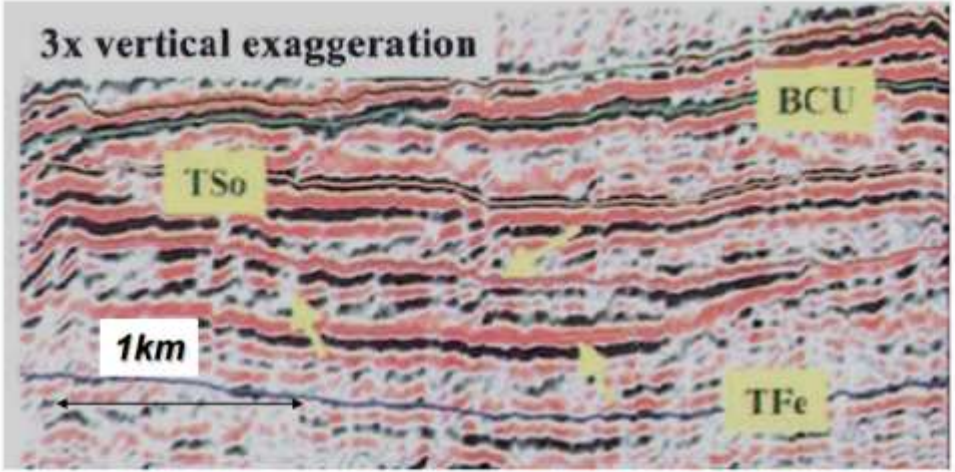
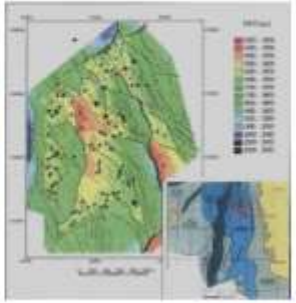
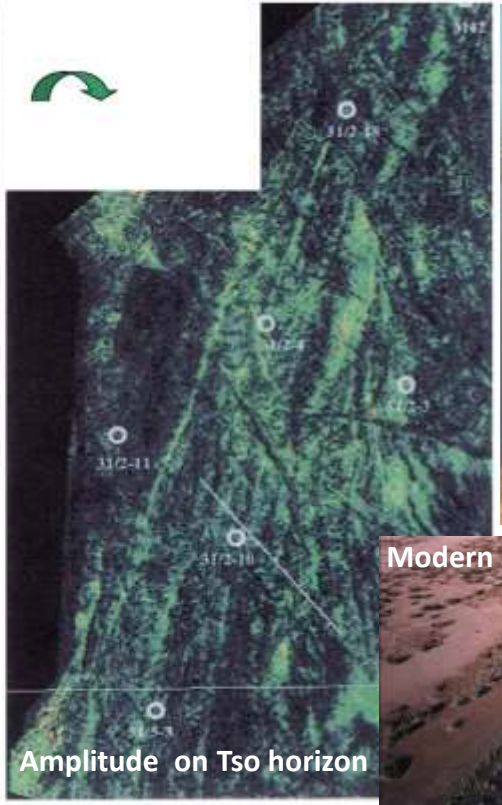
Coastal deposits – wave dominated beach ridges

- examples of Beach ridges (North Sea) – pure laterally extensive wave dominated coastlines



From Dryer & al. 2005



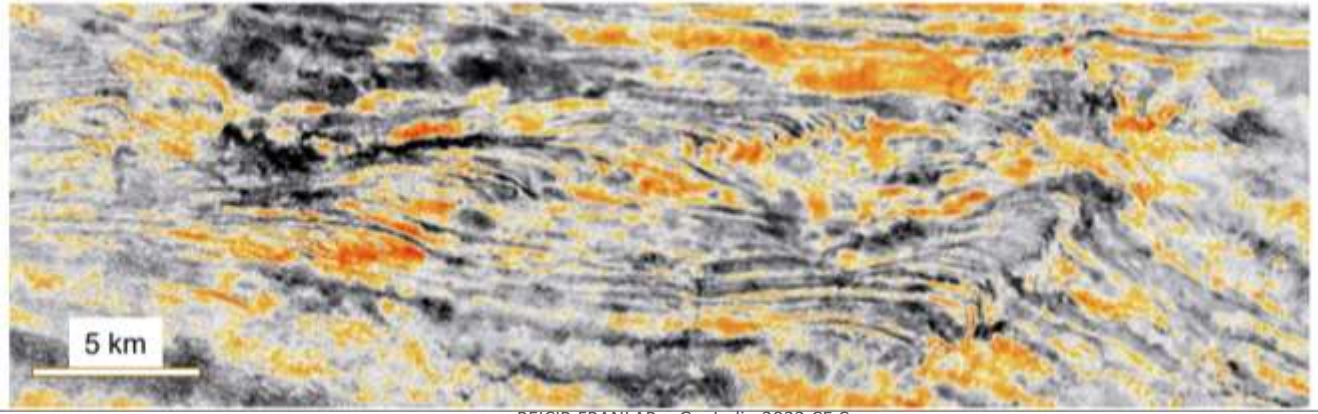


Coastal deposits – wave dominated

- examples of Migrating spit bars = satellite image vs 3D slice

Wave indicators: linear succession of coastlines with littoral spits

Wave 4



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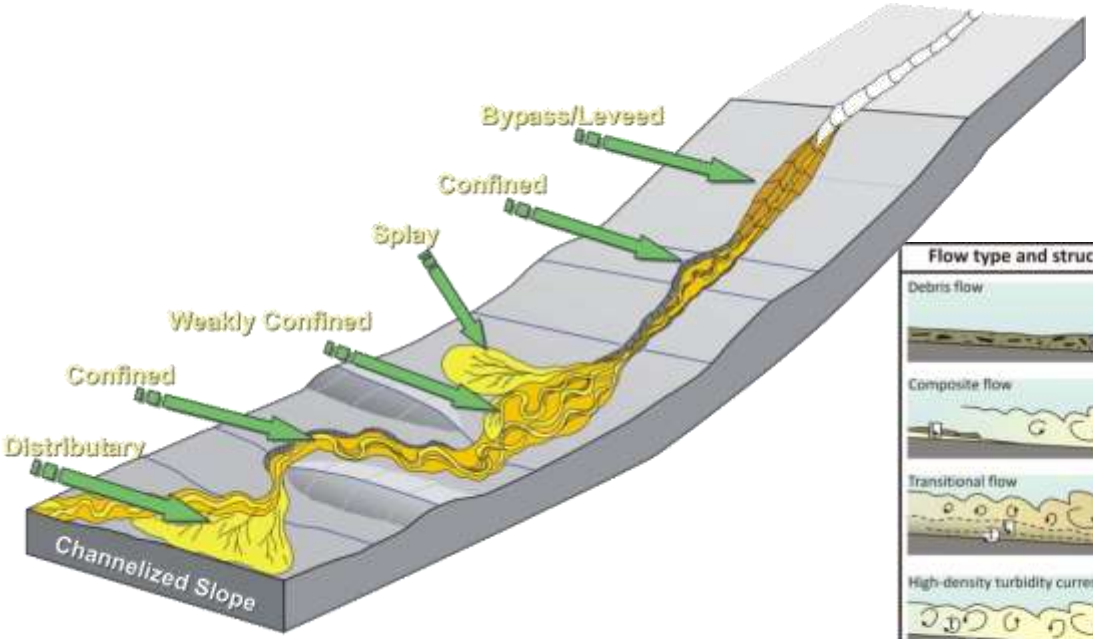
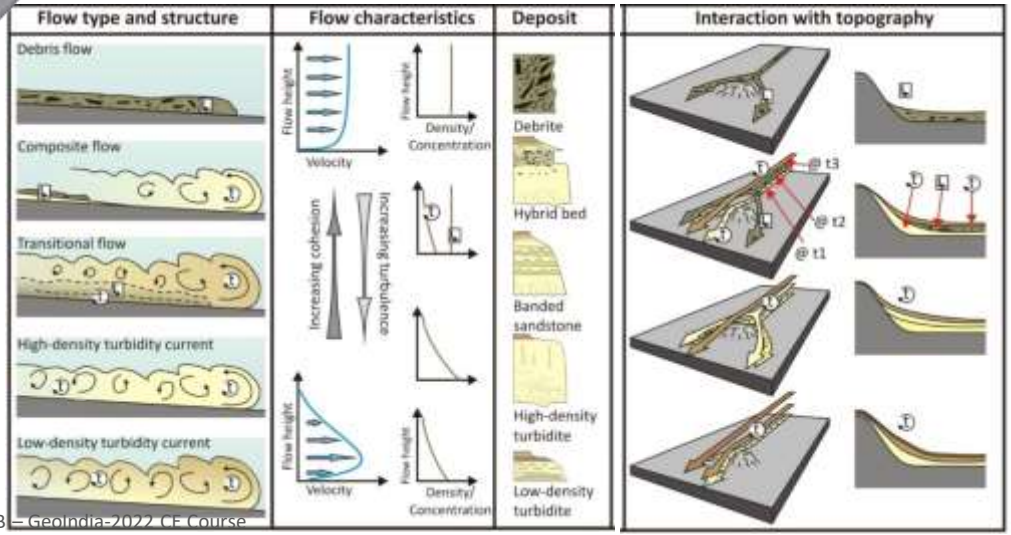
Turbidite

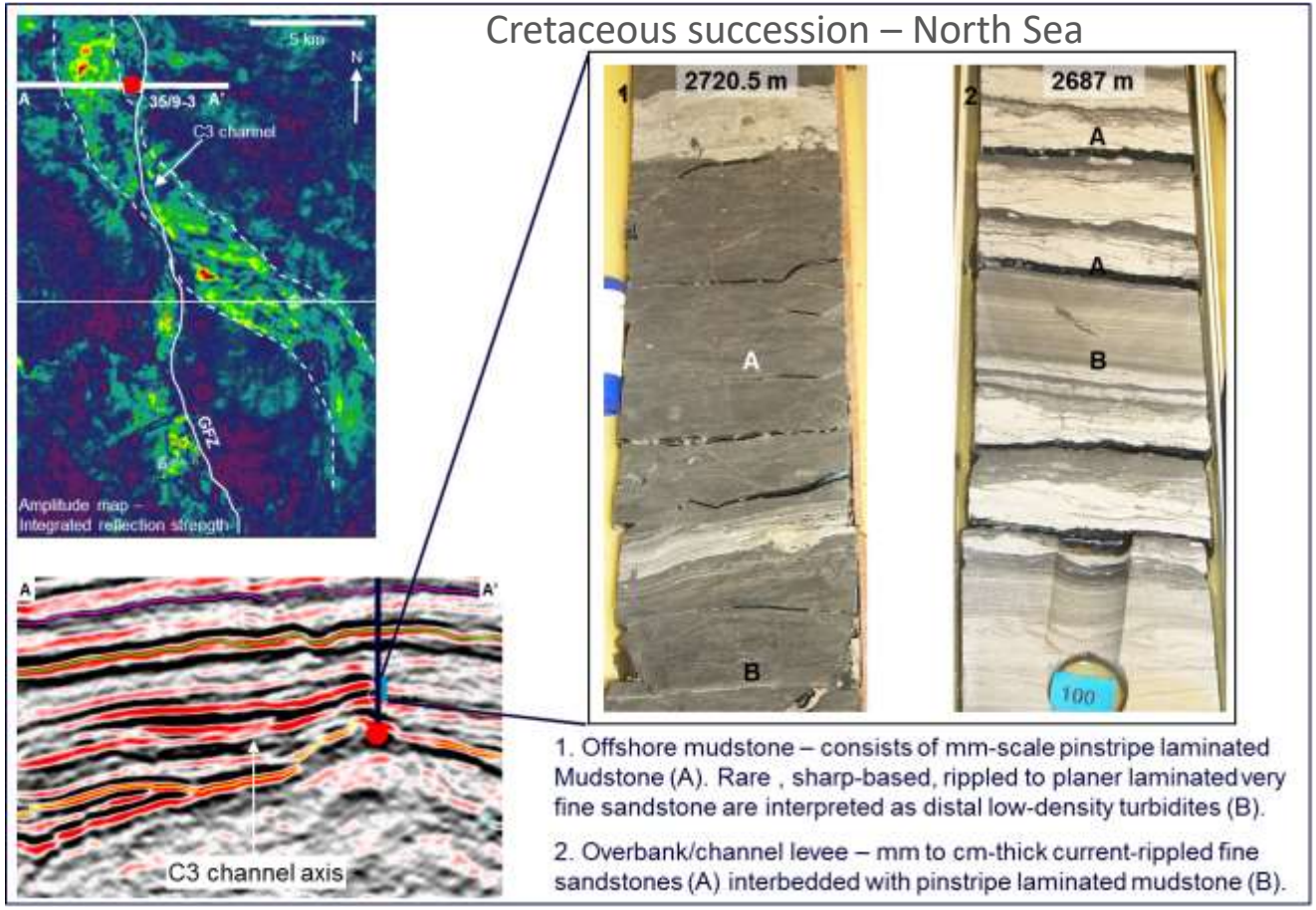
- Just sediments flowing down slope? → NO… because Submarine slopes and sediment gravity flows are both complicated and composite:





Turbidite

Cretaceous succession – North Sea



1. Offshore mudstone – consists of mm-scale pinstripe laminated Mudstone (A). Rare , sharp-based, rippled to planer laminated very fine sandstone are interpreted as distal low-density turbidites (B).

2. Overbank/channel levee – mm to cm-thick current-rippled fine sandstones (A) interbedded with pinstripe laminated mudstone (B).

Turbidites DO NOT have a specific seismic facies → the object does

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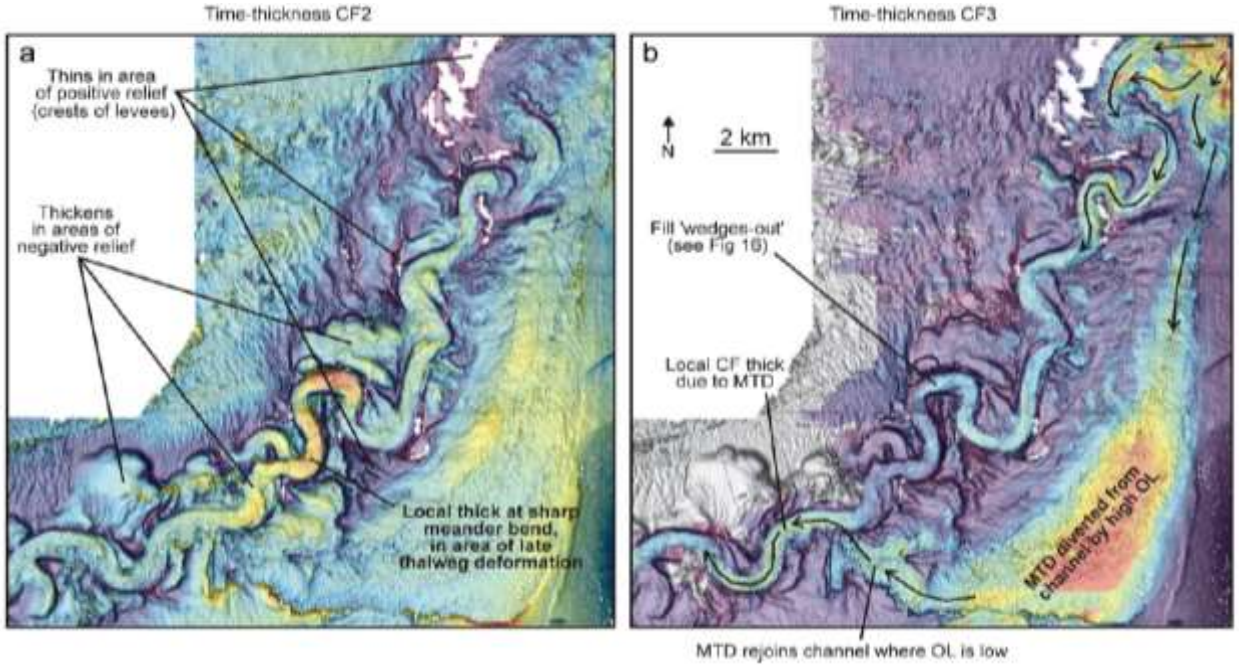
Slope canyon/Valleys



- Isopach mapping can help constrain the morphology and fill style of strongly-erosional slope valleys or channels
- In example (a) marked thickening in the channel axis and thinning over the levee crests is observed
- In (b) infilling of the channel axis is still observed, but a large MTC was deflected to the SE of the channel levee and then rejoined the channel further downslope
- **These images are produced by co-blending dip and amplitude maps**

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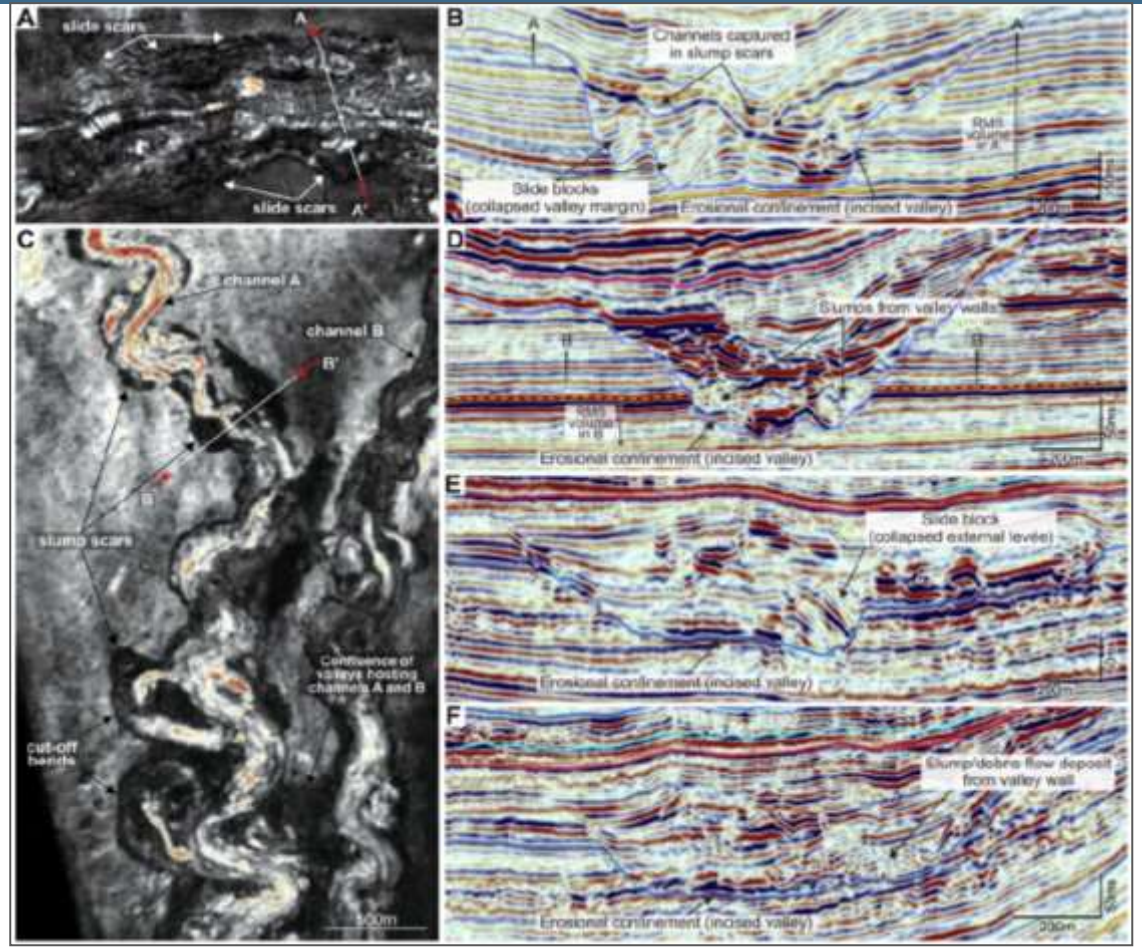
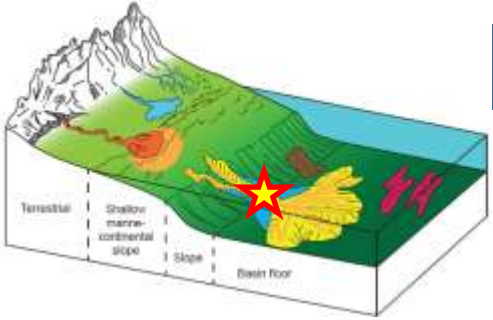
Slope canyon/Valleys





- These examples come from offshore West Africa and suggest that MTC deposition and failure of the slope valley margins can contribute a substantial amount of sediment to the conduit fill
- These deposits are likely to have poor reservoir properties, poor lateral and vertical connectivity and result in compartmentalisation of turbidite sandstone reservoirs
- However, the majority of the slope valleys appear to be filled by channel-levee complexes<<<

Janocko et al. (2012)

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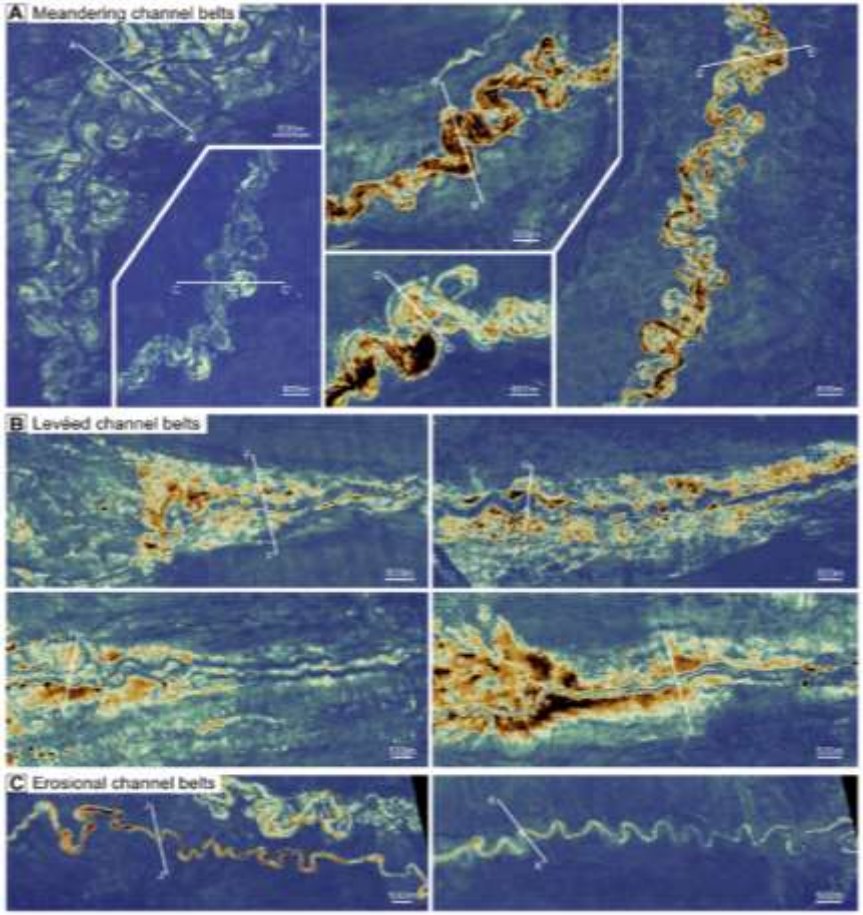
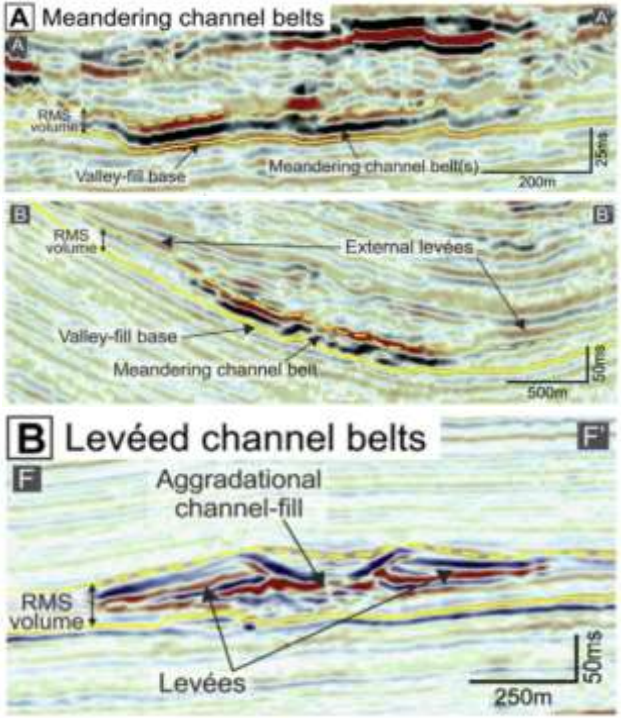
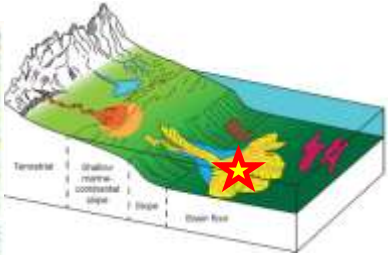
Channels







Janocko et al. (2012)

- Seismic examples of channels from offshore West Africa
- **Note the variability in map-view and section expression and seismic facies**
- Note also the very subtle expression of lateral accretion surfaces associated with the meandering channel in seismic section (B)

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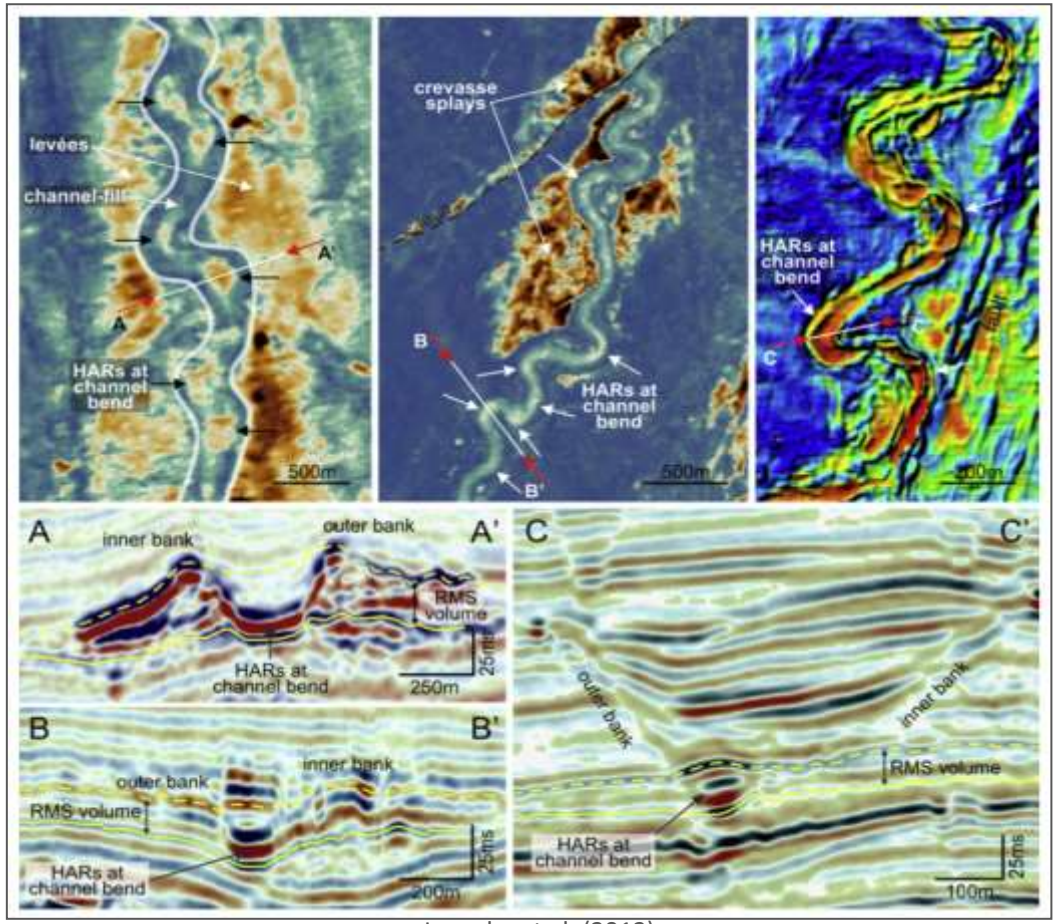
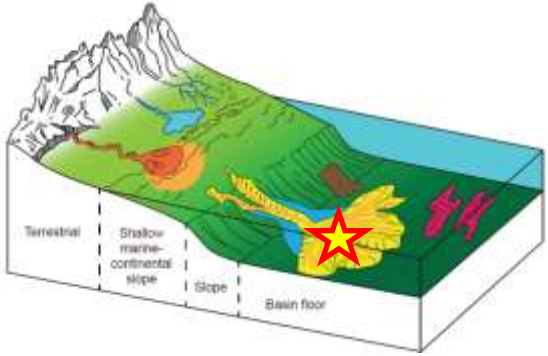
Channel-levee complex



Janocko et al. (2012)



- **Left** – aggradational channel-levee systems; **middle** – erosional channel belt; **right** - non-aggradational meandering channel belt
- **Note the restriction of high-amplitude reflections (HARs) to channel bends**
- These high-amplitude features are interpreted as sandstone-rich, channel bend mounds or bars
- Note also the variability in the presence and amplitude expression of levee deposits

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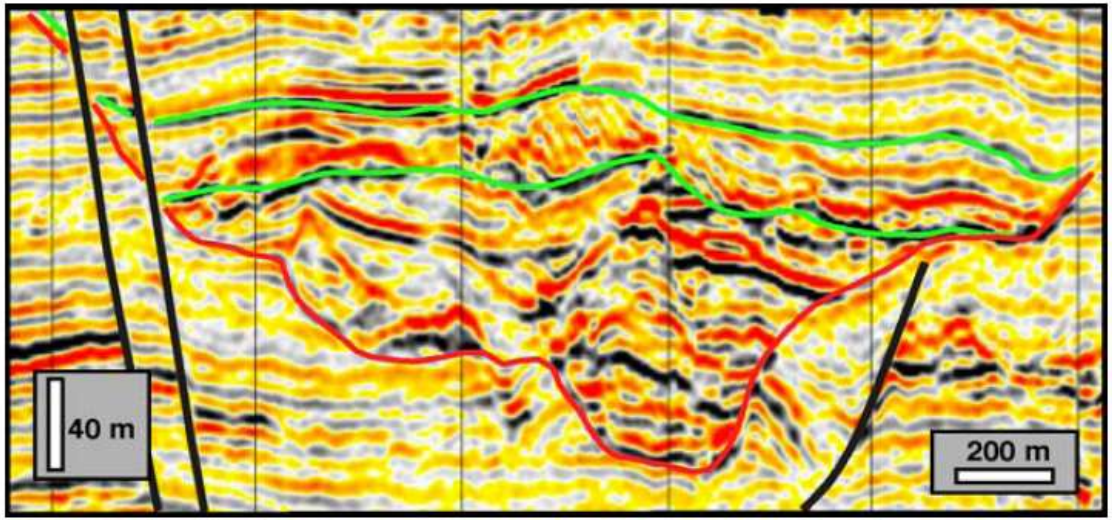
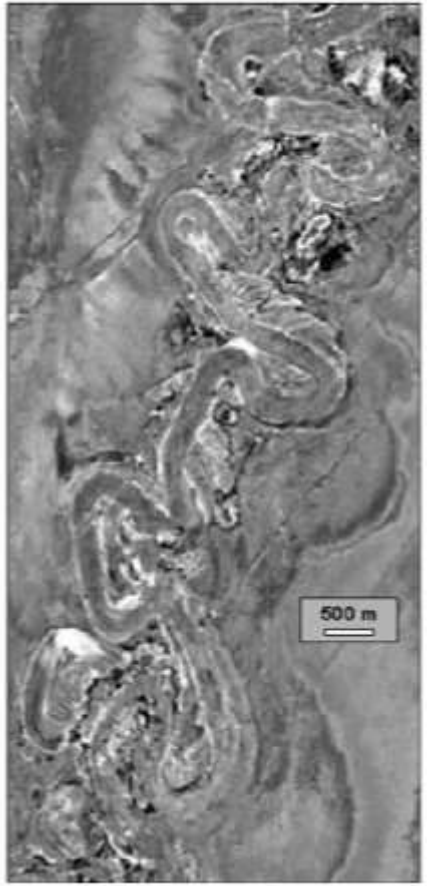
Lateral Accretion Packages (LAPs)

Abreu et al. (2003)





- Seismic profile from the Dalia M9 Upper Channel System (above)
- The 'channel system' is constructed of numerous 'channel complexes', which are confined at the base and more weakly-confined at the top
- Lateral Accretion Packages or 'LAPs' are developed in the youngest, uppermost, meandering channel complex (see horizon slice), which is bound above and below by green horizons

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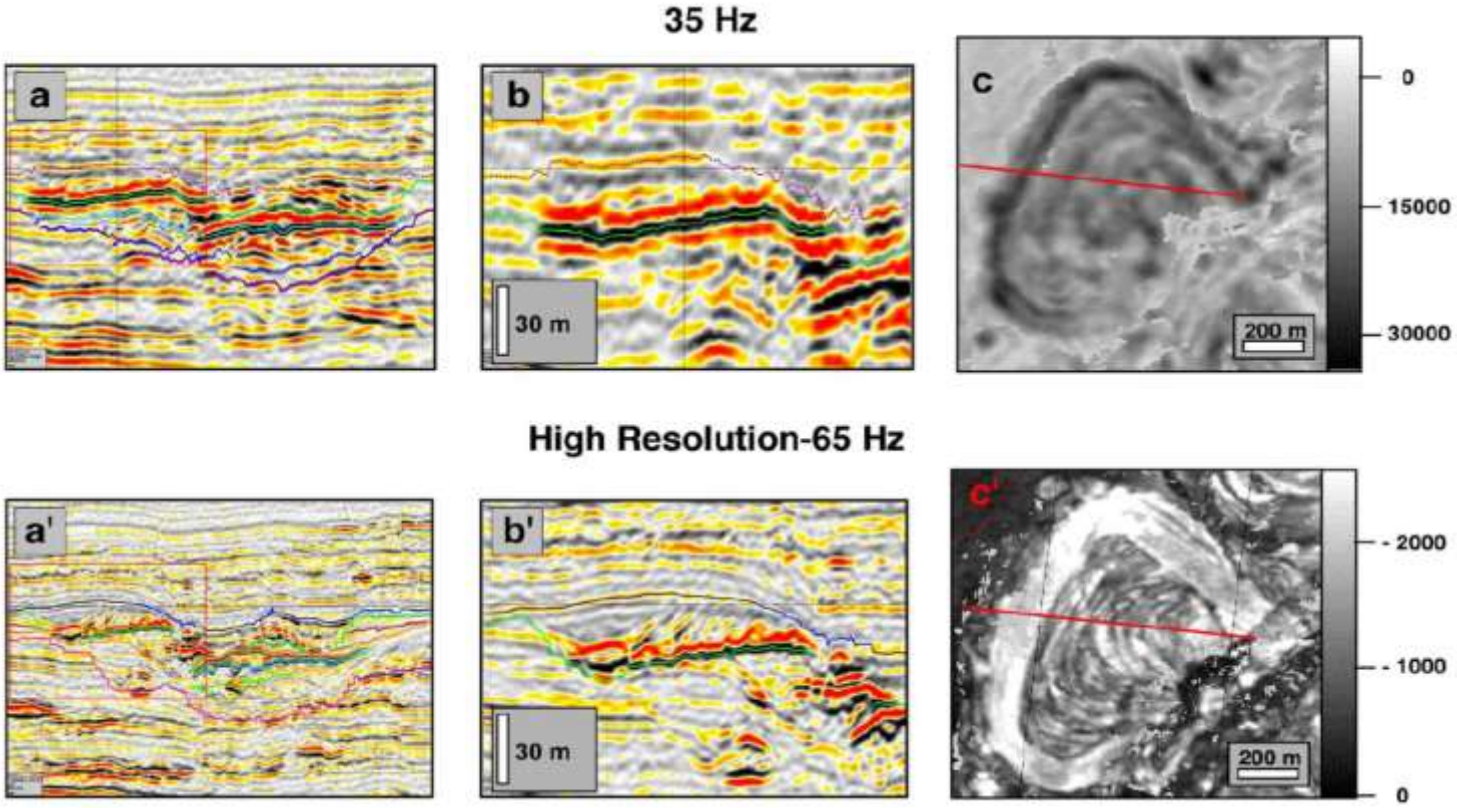
Lateral Accretion Packages (LAPs)

- Comparison of the stratigraphic detail imaged using conventional, 35 Hz seismic data (above) and high-resolution, 65 Hz seismic data (below)

- Note the enhanced imaging of the channel system in general and LAPs in particular



Abreu et al. (2003)

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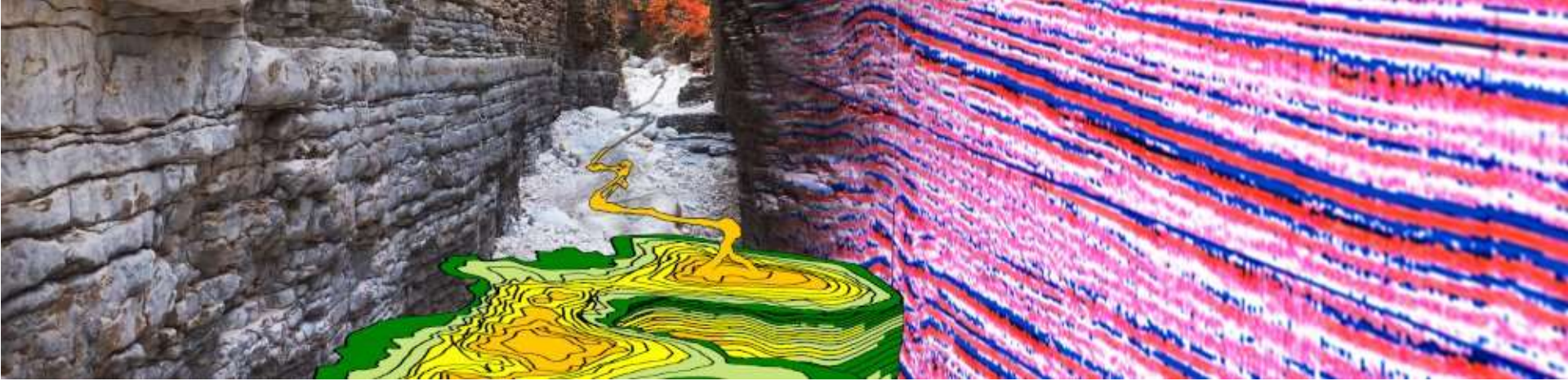

Applying FSM to Reconstruct Sedimentary Environments

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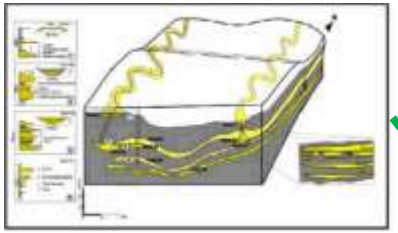
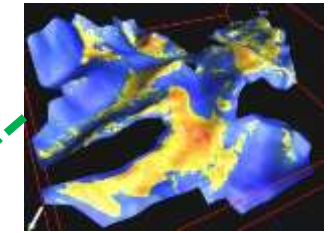
Data Integration for forward modeling

- *Integrates in a single platform all your stratigraphic database.*
- *A coherency test for your depositional models.*

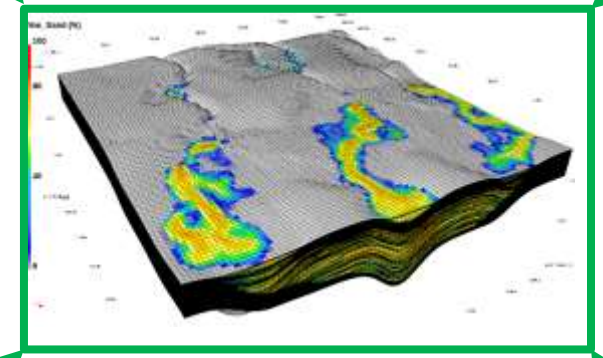
Depositional Models



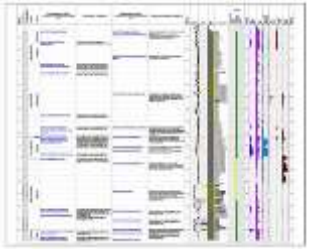
Seismic Data



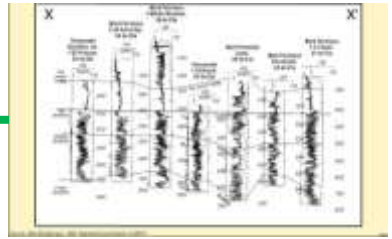
Forward Stratigraphic Modeling



Biostratigraphy

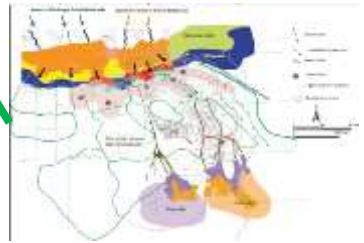


Well Correlations



GDE and NTG

Basin Evolution Models



Combellas and Galloway 2006

- *Full 3D facies grids exportable to PETREL or into a basin modeling software*

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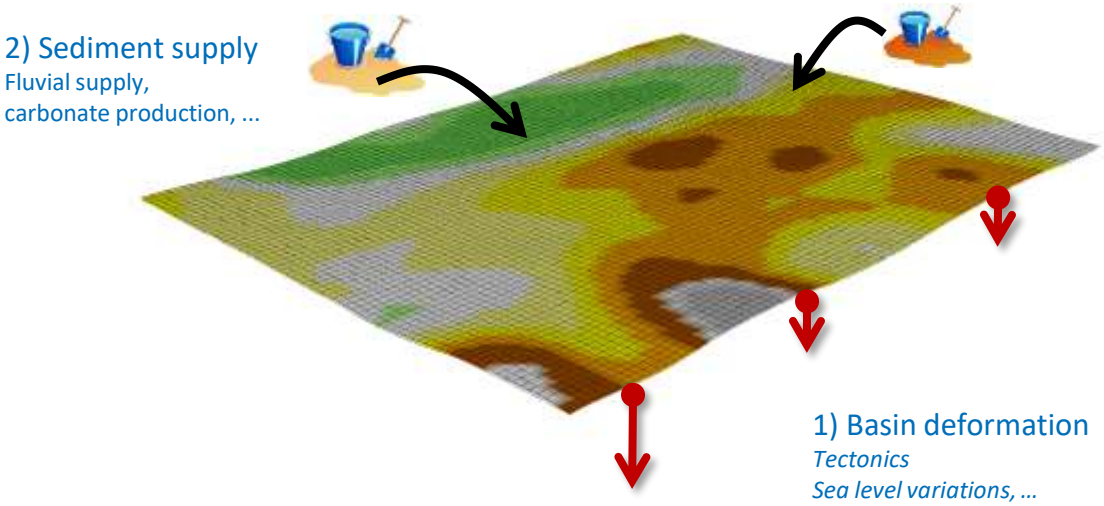
SFM at a Glance

DionisosFlow: forward simulation of sedimentary processes



The Miocene Fm., Pannonian Basin (Hungary)
[L= 140 km x 185 km; T=10 My] (Csato et al., 2013)

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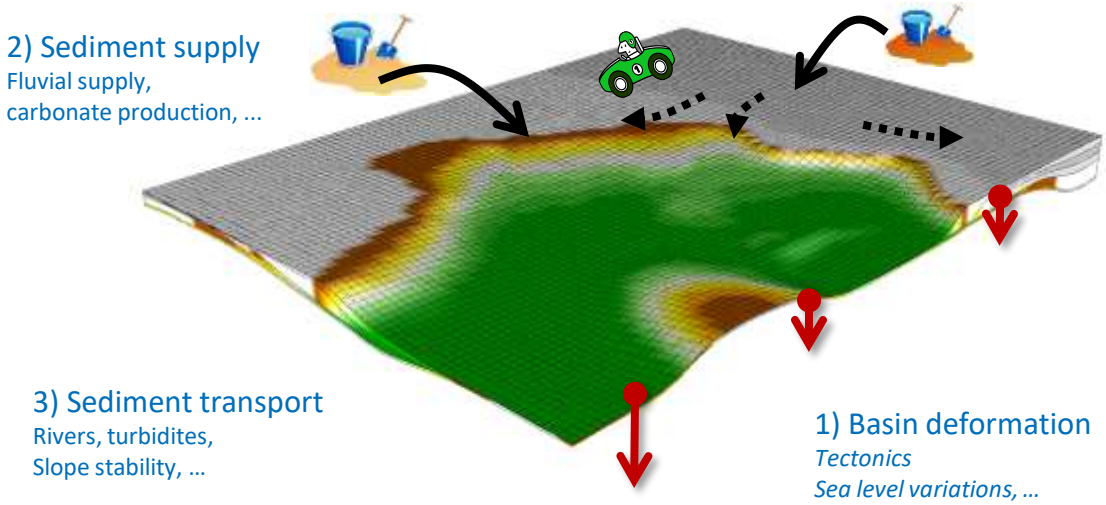
SFM at a Glance

- DionisosFlow: forward simulation of sedimentary processes



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SFM at a Glance

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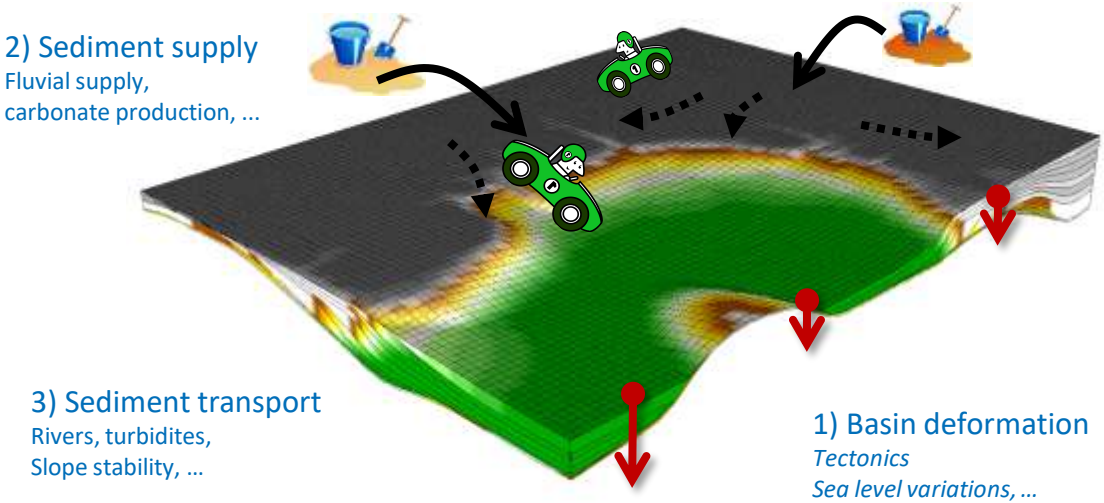

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SFM at a Glance

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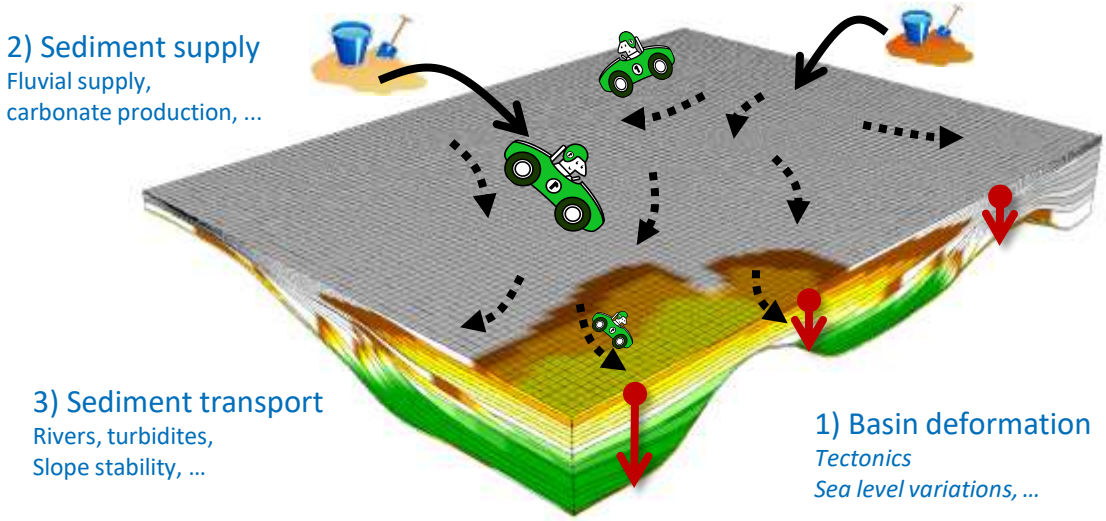

The Miocene Fm., Pannonian Basin (Hungary)
[L= 140 km x 185 km; T=10 My] (Csato et al., 2013)

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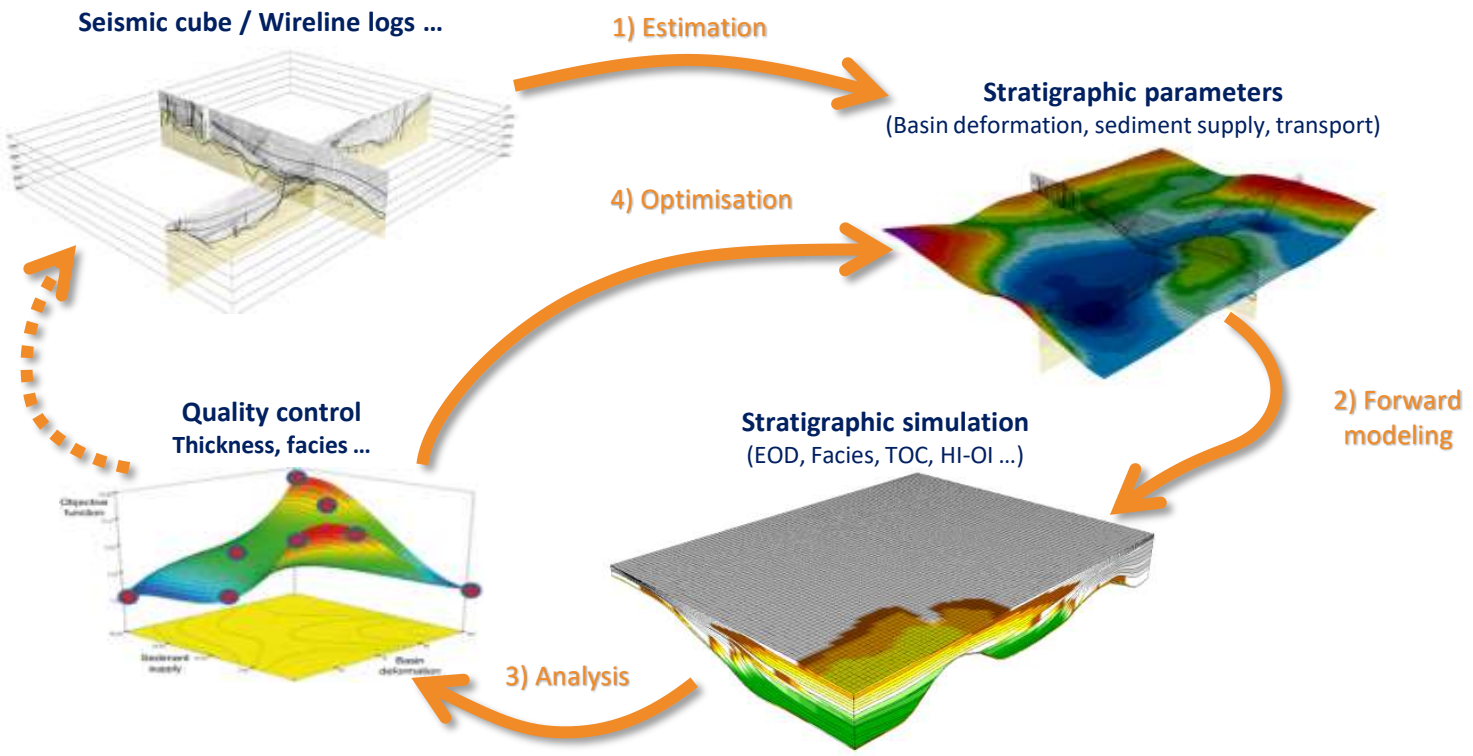
SFM at a Glance



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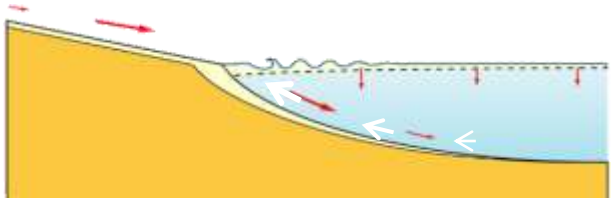
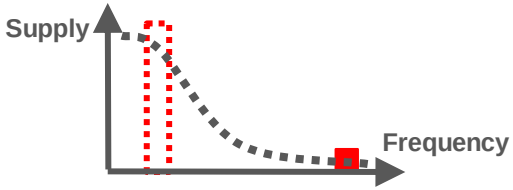
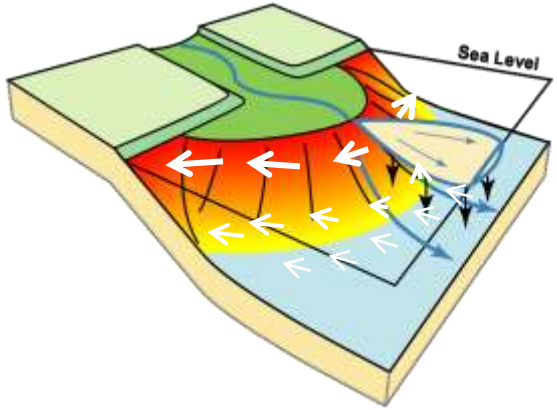
Advanced Transport Processes

Low Energy Long Term: slow gravity permanent fluvial transport







Low-Energy Bed-load

Transport rate proportional to basin slope and water discharge.

Sediment flux → $Q_s = K_i * Q_w * S$

Diffusion Coefficient, Fluvial Discharge, Slope

Nearshore Processes

Advection due to wave current.

Sediment flux → $Q_s = K_i * Q_w * W_e * S$

Diffusion Coefficient, Fluvial Discharge, Wave Energy, Slope

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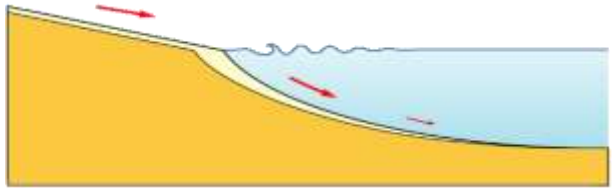
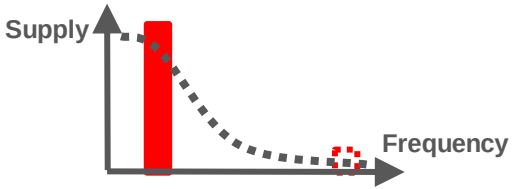
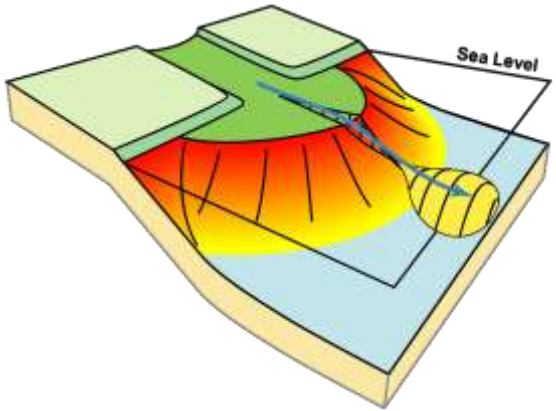
Advanced Transport Processes

High Energy Short Term: hyperpycnites, fine turbidites







High-Energy Bed-load

Transport rate proportional to basin slope and water discharge and inertia.

Sediment flux → $Q_s = K * m(u) * Q_w * S$

Diffusion Coefficient, HEST Coefficient, Fluvial Discharge, Slope

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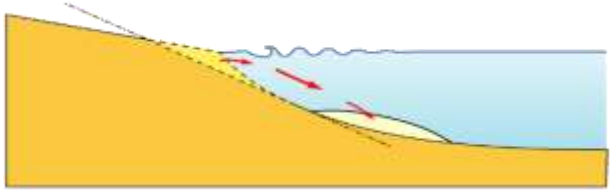
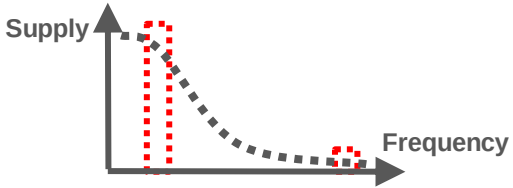
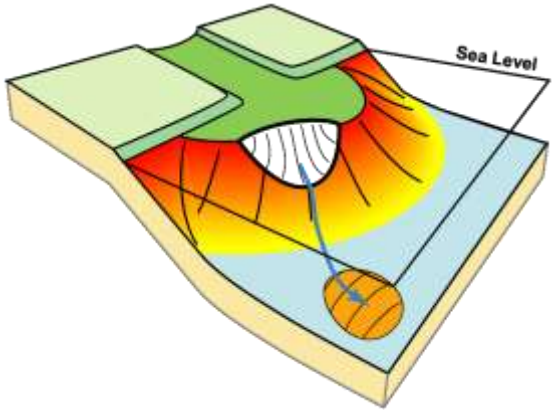
Catastrophic Events







Slope Instability

Triggers slumps and debris-flows. If Slope > Critical Slope, sediments are unstable and turbidites appears.

Newton's Principle

$$\text{Acceleration} = \text{Gravity} - \text{Friction}$$

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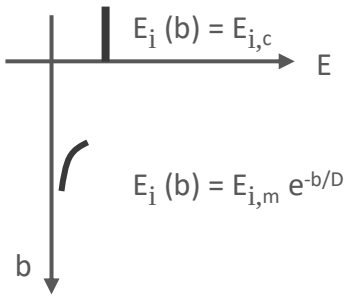
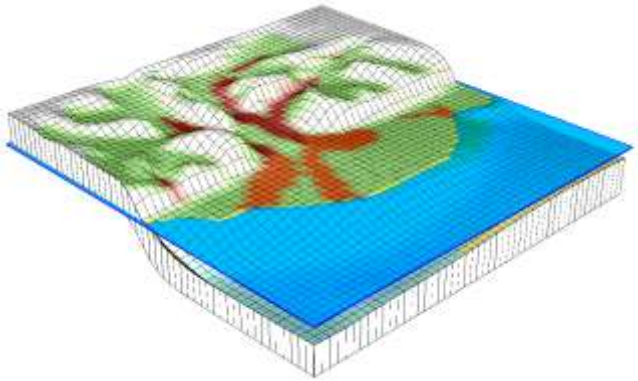
Erosion Modeling

- Erosion is taken into account through various type of laws:
  - **Uniform** erosion law for **continental environment**,
  - **Lithology-dependent** erosion law for both **continental and marine environments**,
  - **Advanced erosion law** integrating uniform or water **weathering** (erosion is a function of water discharge).





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Advanced Carbonate Production Options

Advanced Ecology Parameters

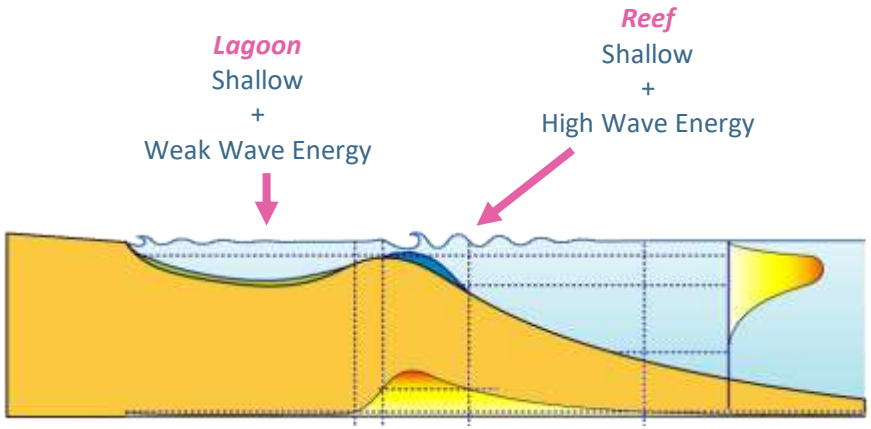
- Production Constrained by : $P_{i\,(m/My)} = P_{ref\,(t)} \cdot P_{bathy.i} \cdot P_{wave.i} \cdot P_{ecology.i}$
  - Production rate by lithology
  - Water Turbidity
  - Seafloor Sediment Content
- Carbonate Dissolution
- Transformation into Bioclasts

Production of reference

Bathymetric factor

Wave Influence

Ecology Influence



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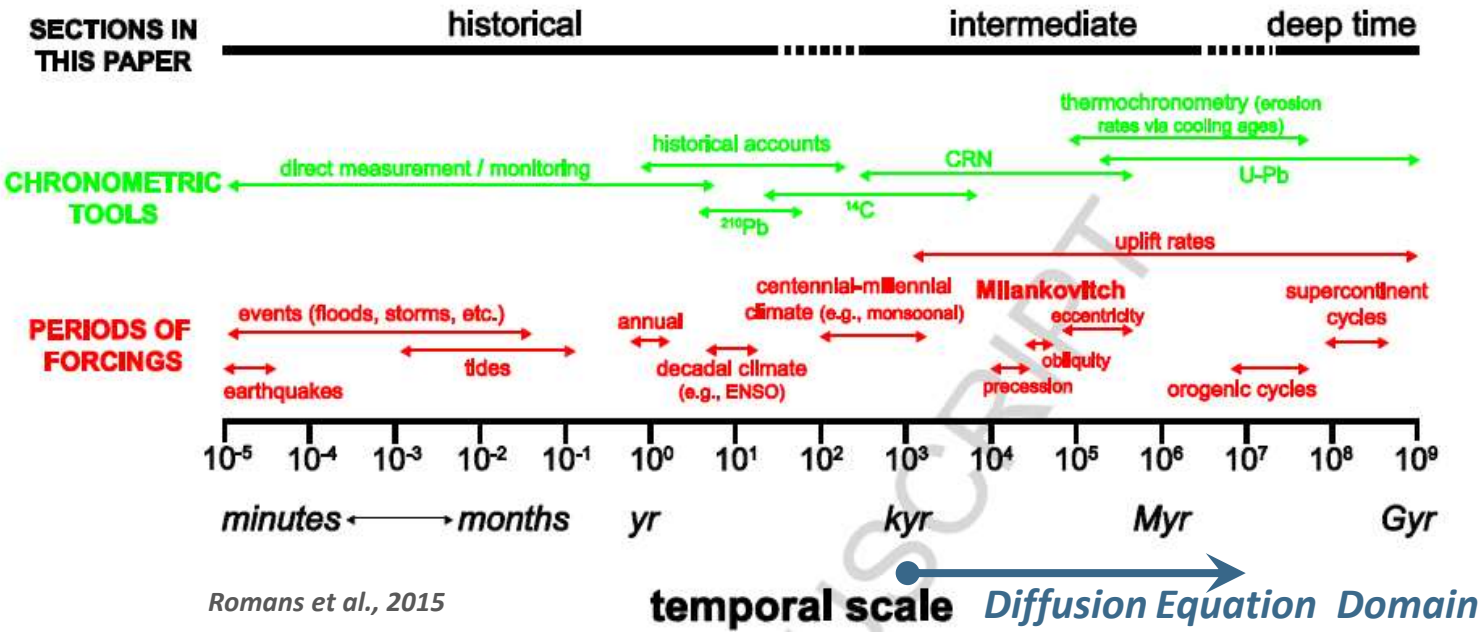
Principle of Transport by Diffusion



Romans et al., 2015

Romans, Brian W., Castelltort, S´ebastien, Covault, Jacob A., Fildani, Andrea, Walsh, J.P., Environmental Signal Propagation In Sedimentary Systems Across Timescales, *Earth Science Reviews* (2015), doi: 10.1016/j.earscirev.2015.07.012

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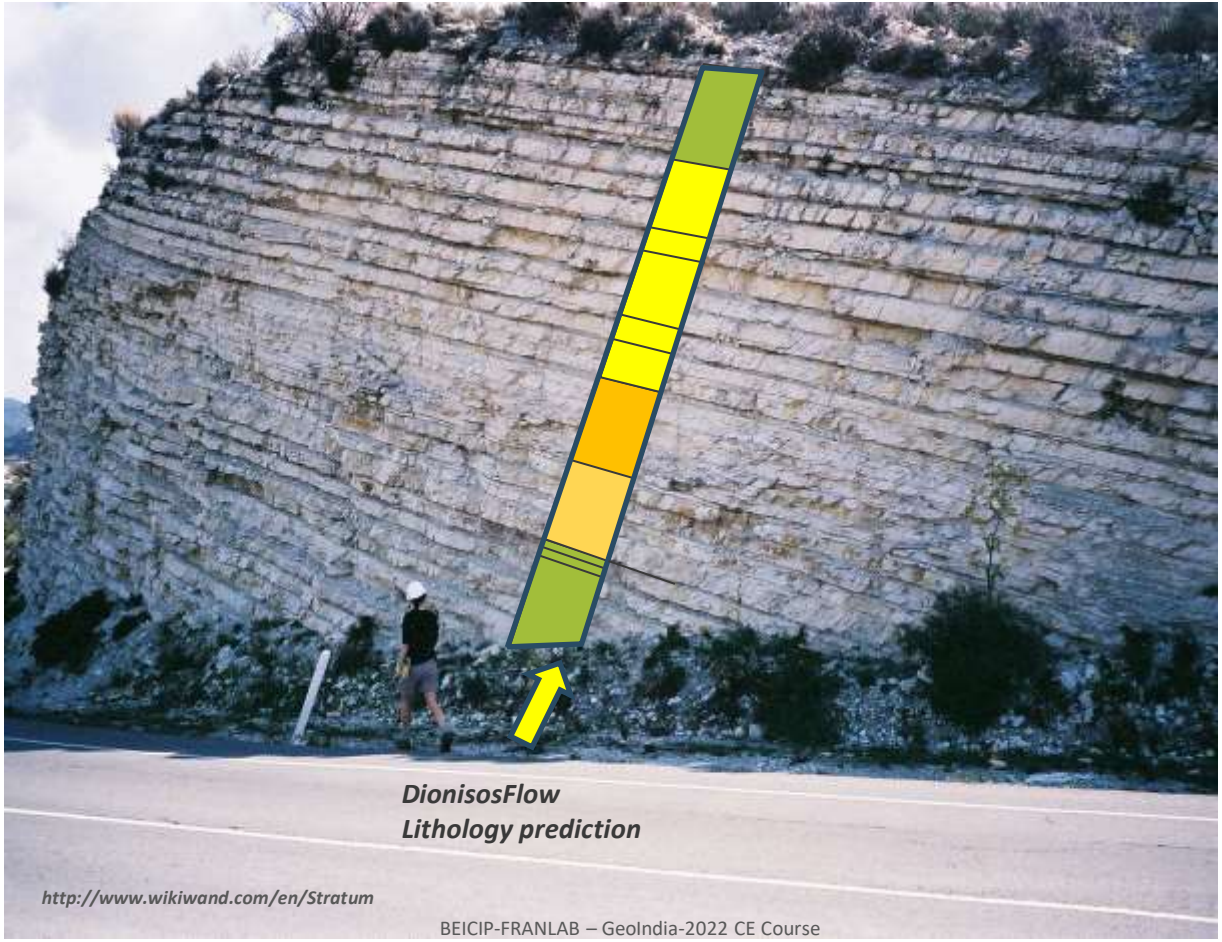
Model Vs Outcrop



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Live Demo on FSM

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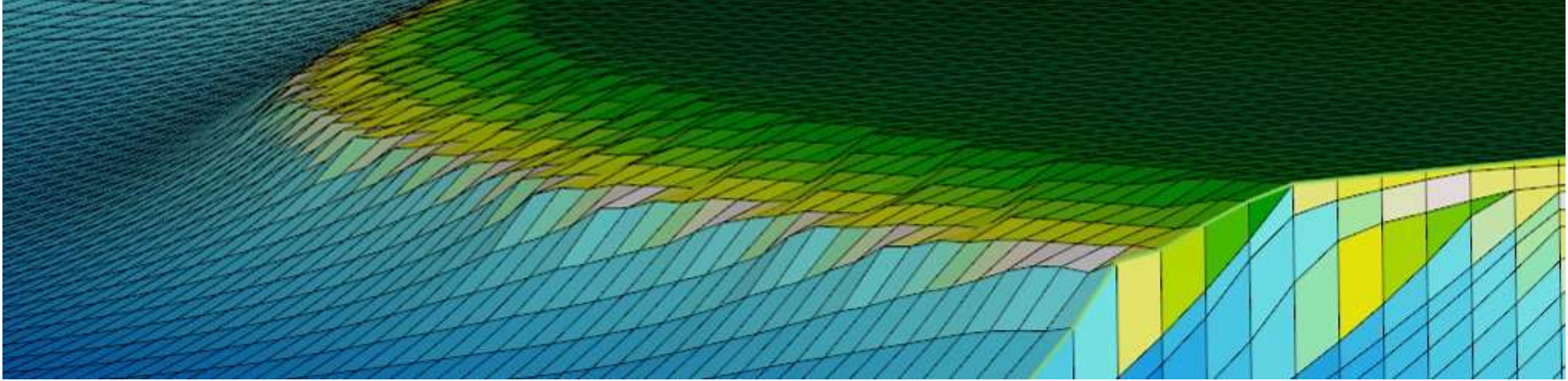

Managing Uncertainties

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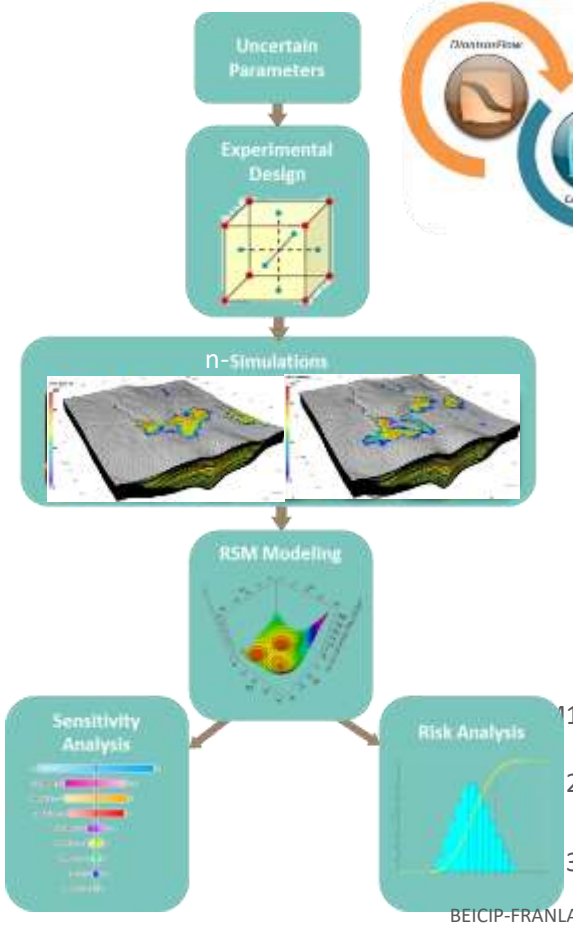
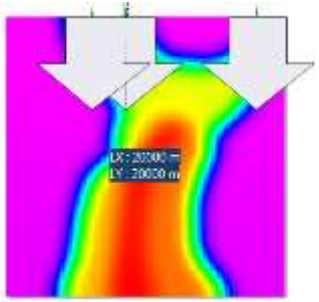
Managing Uncertainties



Sensitivity and Uncertainty Analysis

- Coupling DionisosFlow – CougarFlow.
- Evaluate the impact of uncertainties in:
  - Sources position and width.
  - Supply volume and proportion
  - Diffusion Coefficients and many others

- N-simulation allowing a statistical analysis of modelling results.



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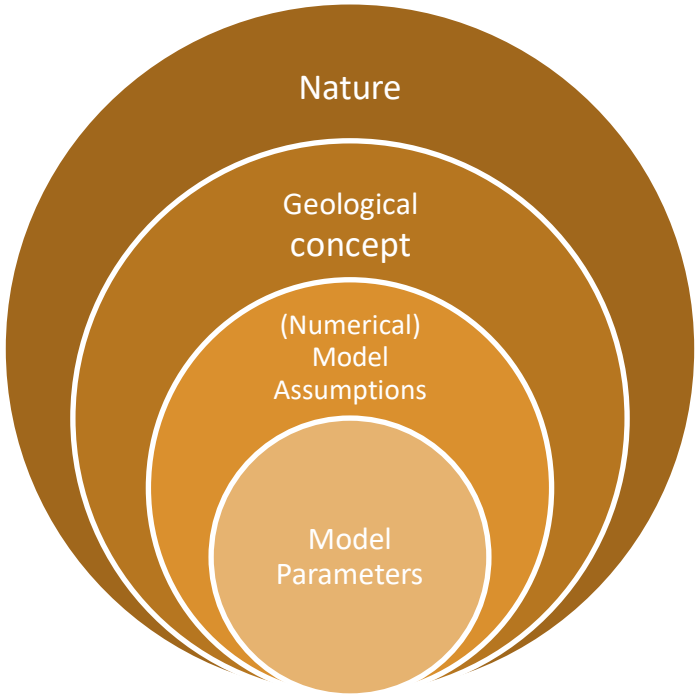
Uncertainties in Stratigraphic Modeling

- Making choices, increase uncertainties at each step of the modeling.



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CougarFlow Principles

Coupling FSM **DionisosFlow and CougarFlow** allows users to:

- Launch many simulations at once to test the effect of some parameters' variation
  - **Multi-realization**
- Determine the contribution of some uncertain parameters on an output property
  - **Sensitivity** Analysis
- Determine the range of possible values for a property given some uncertain inputs
  - **Risk** Analysis

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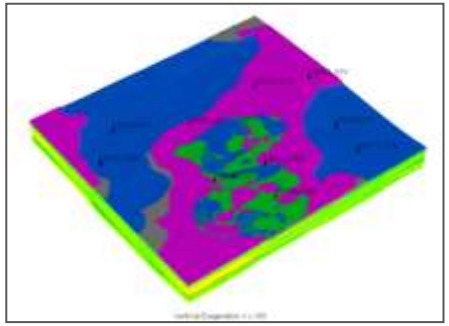
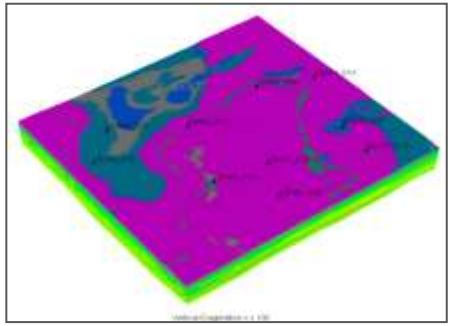
Multi-Realizations

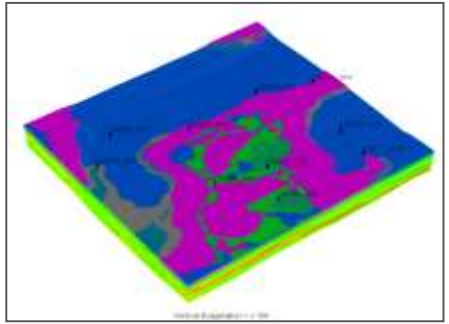
- Texture on several validated multi-realizations



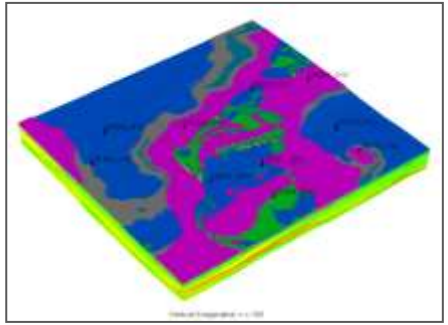
Realization n°1



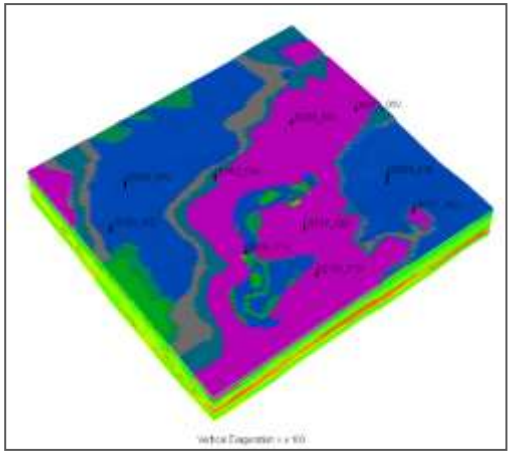
Realization n°2



Realization n°3



Realization n°4



Reference Model

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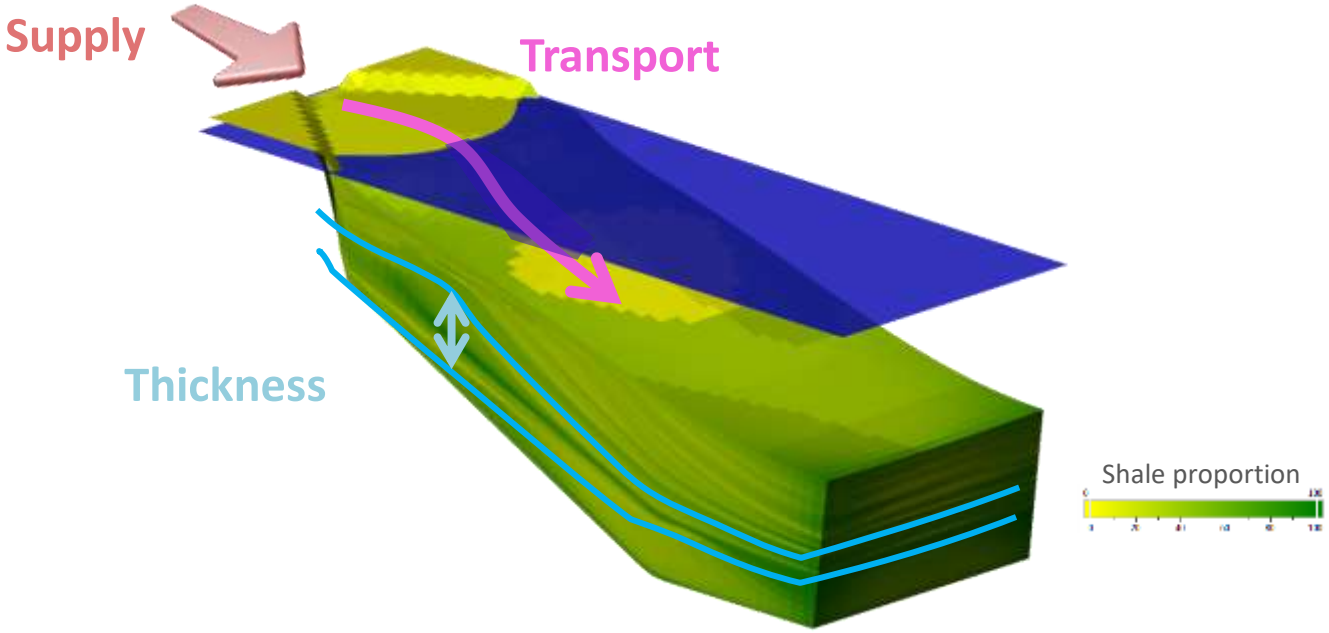
Sensitivity Analysis

- Which parameter (Supply or Transport Coefficient here) is the **most influential** on the sequence thickness?



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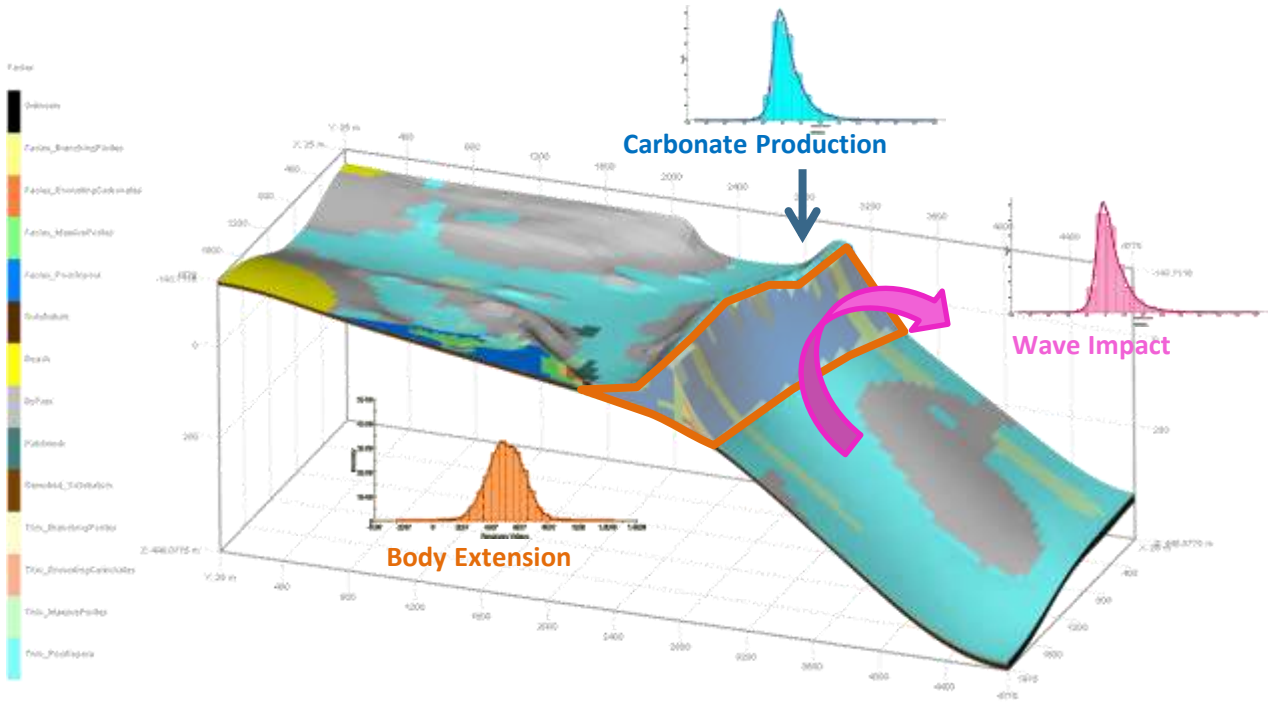
Risk Analysis

- How does the **uncertainty on input parameters** (carbonate production and wave impact) impact the **output variables** (body extension)?



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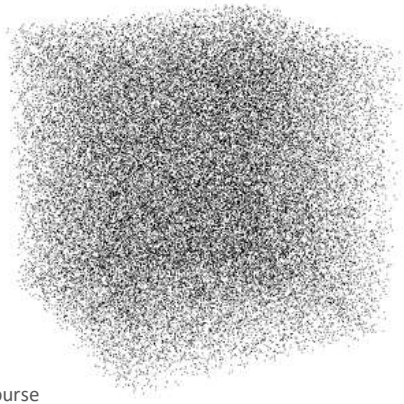
Monte Carlo vs RSM Based Tool

- Traditionally in stratigraphic modeling, risk assessment is done performing **multi-realizations** with a **Monte-Carlo sampling**:
  - **Several 100s** of simulations to launch (or more!)
  - Simulation time: **1-10h**

- This workflow can take up to **several weeks** (or **months** on more complex simulations), unaligned with the industry requirements.

- **Response Surface Model based tools** can offer a **satisfactory** solution:
  - **Response surface** built from a **limited number** of simulations (**10** to **100** depending on the number of uncertain parameters)
  - **Mimics** the calculator behavior and allows saving time



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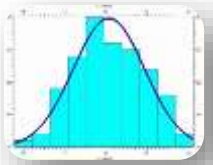
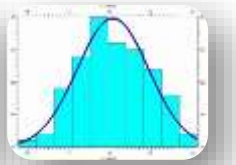
RSM Based Tool: Principles

Uncertain parameters



Supply



Transport

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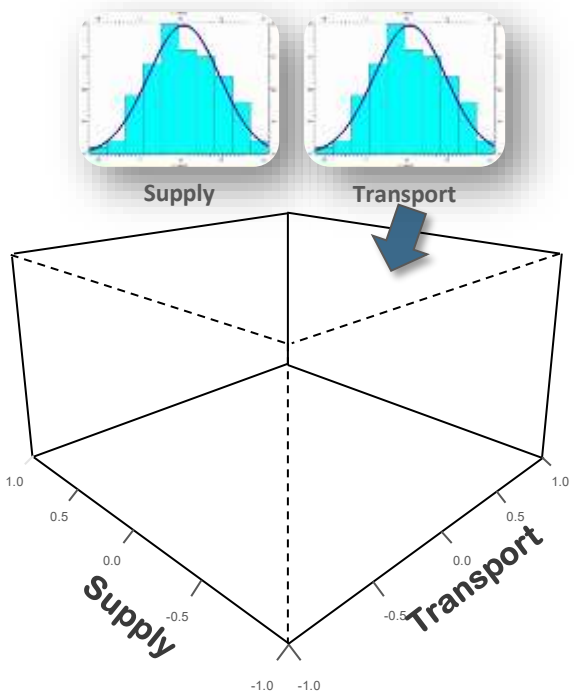
RSM Based Tool: Principles

- Uncertain parameters
- Experimental design



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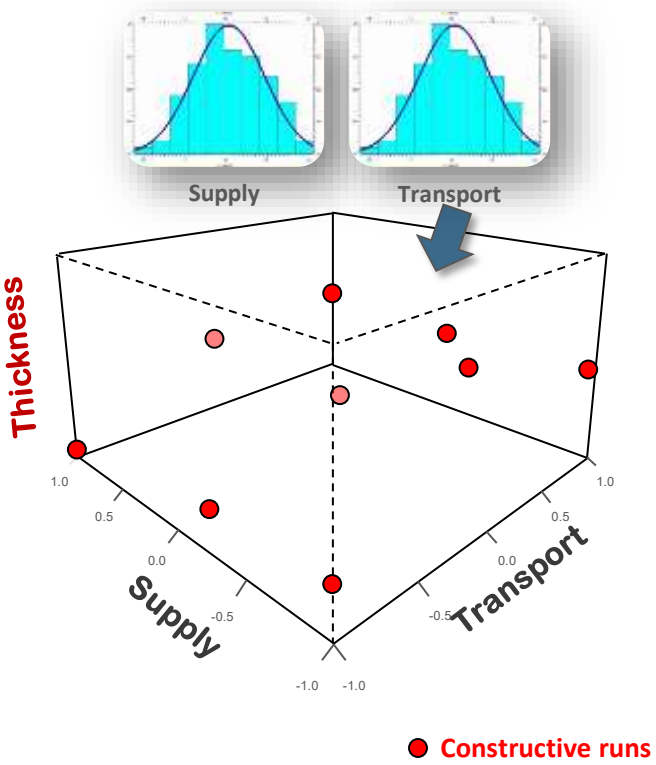
RSM Based Tool: Principles

- Uncertain parameters
- Experimental design



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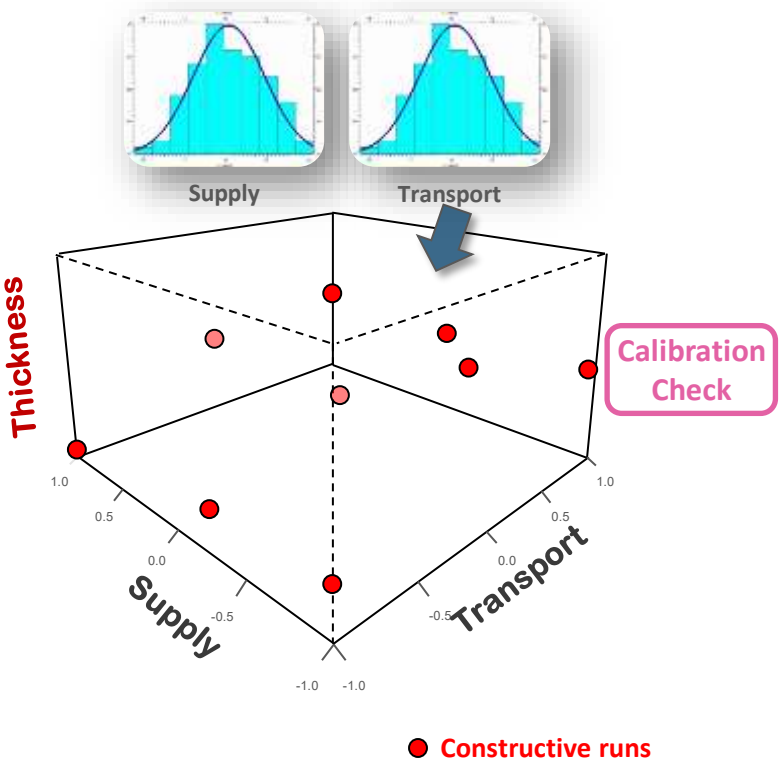
RSM Based Tool: Principles

- Uncertain parameters
- Experimental design



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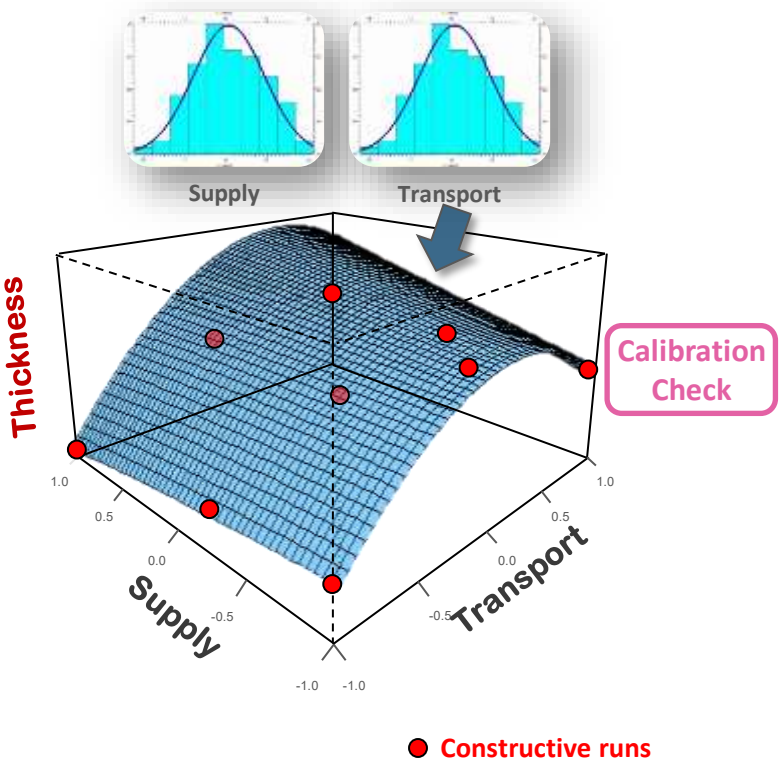
RSM Based Tool: Principles

- **Uncertain parameters**
- **Experimental design**
- **Response surface**
  - Parametric or Krigging



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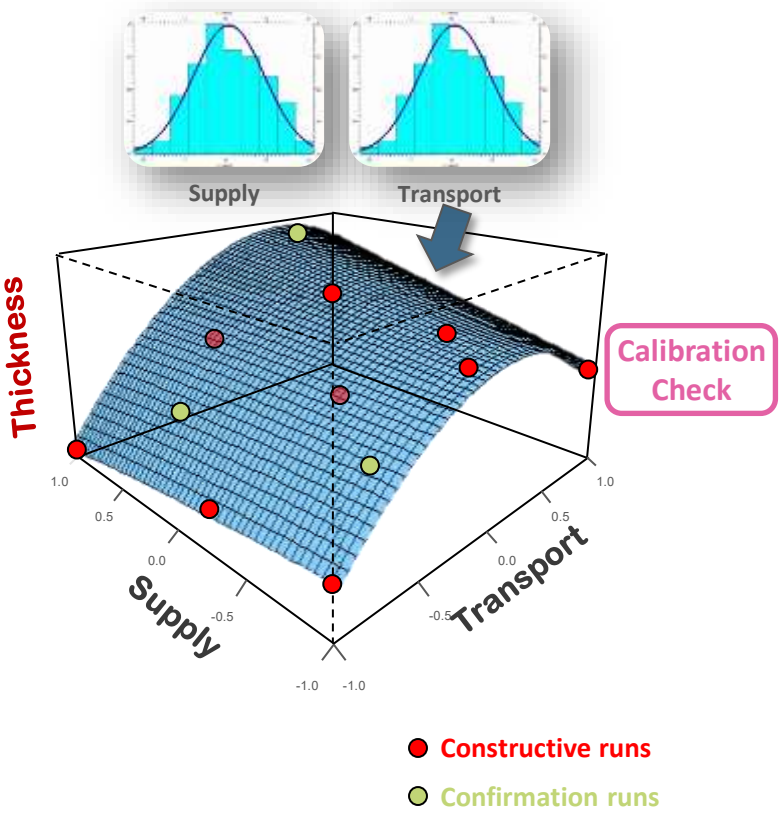
RSM Based Tool: Principles

- **Uncertain parameters**
- **Experimental design**
- **Response surface**
  - Parametric or Krigging



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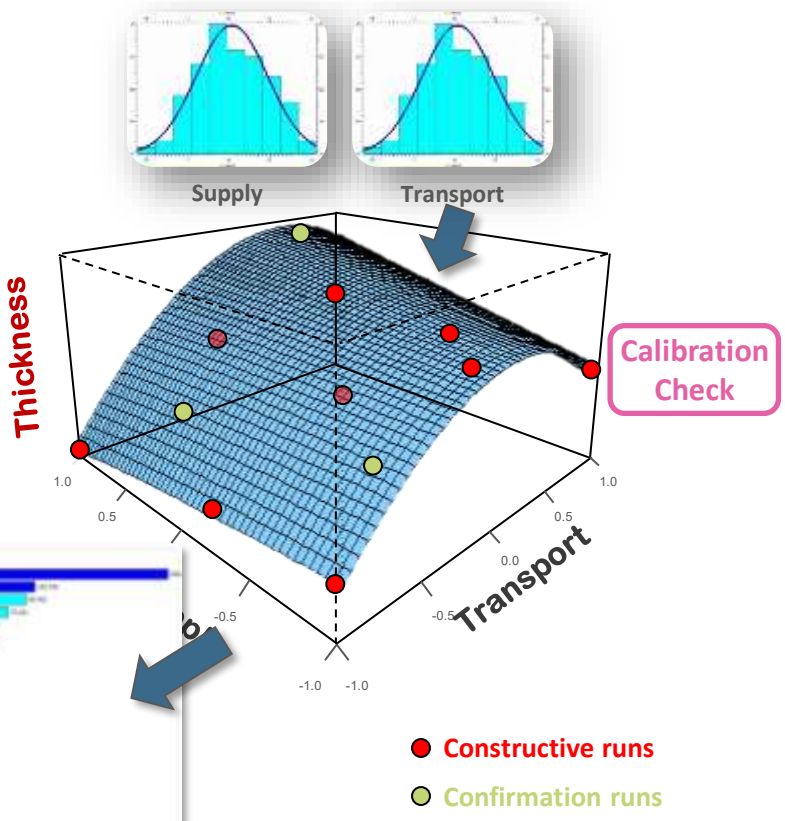
RSM Based Tool: Principles

- **Uncertain parameters**
- **Experimental design**
- **Response surface**
  - Parametric or Krigging
- **Monte-Carlo** simulation
  - On the response surface



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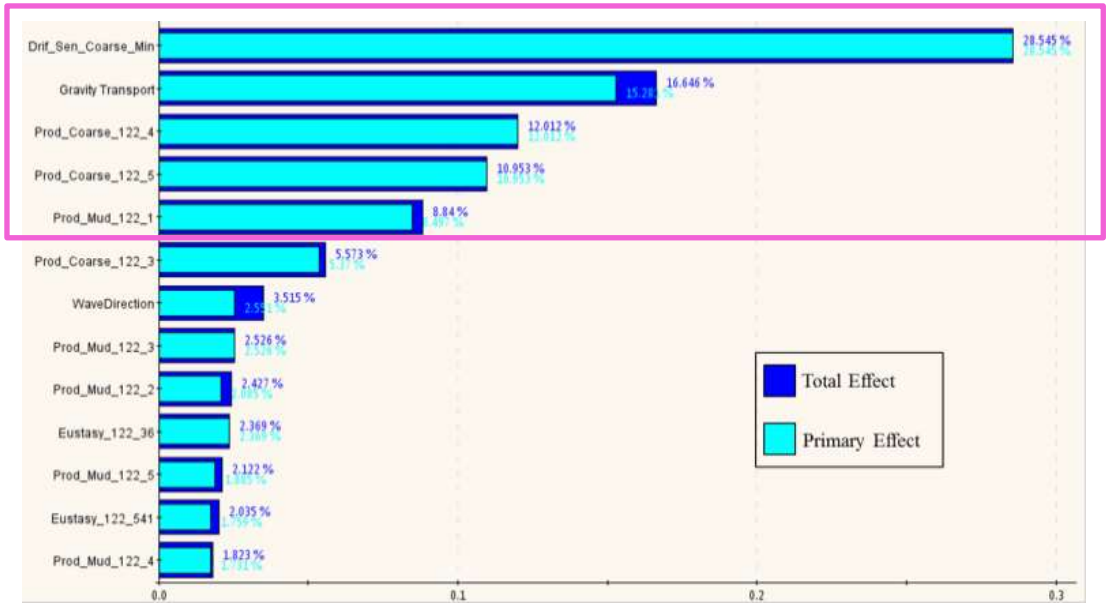
Sensitivity Analysis Results

Most influent parameters



Primary Effect: impact of a parameter if only this parameter varies
Total Effect: impact of a parameter with the other parameters varying as well

- Other parameters can be removed for the Risk analysis.

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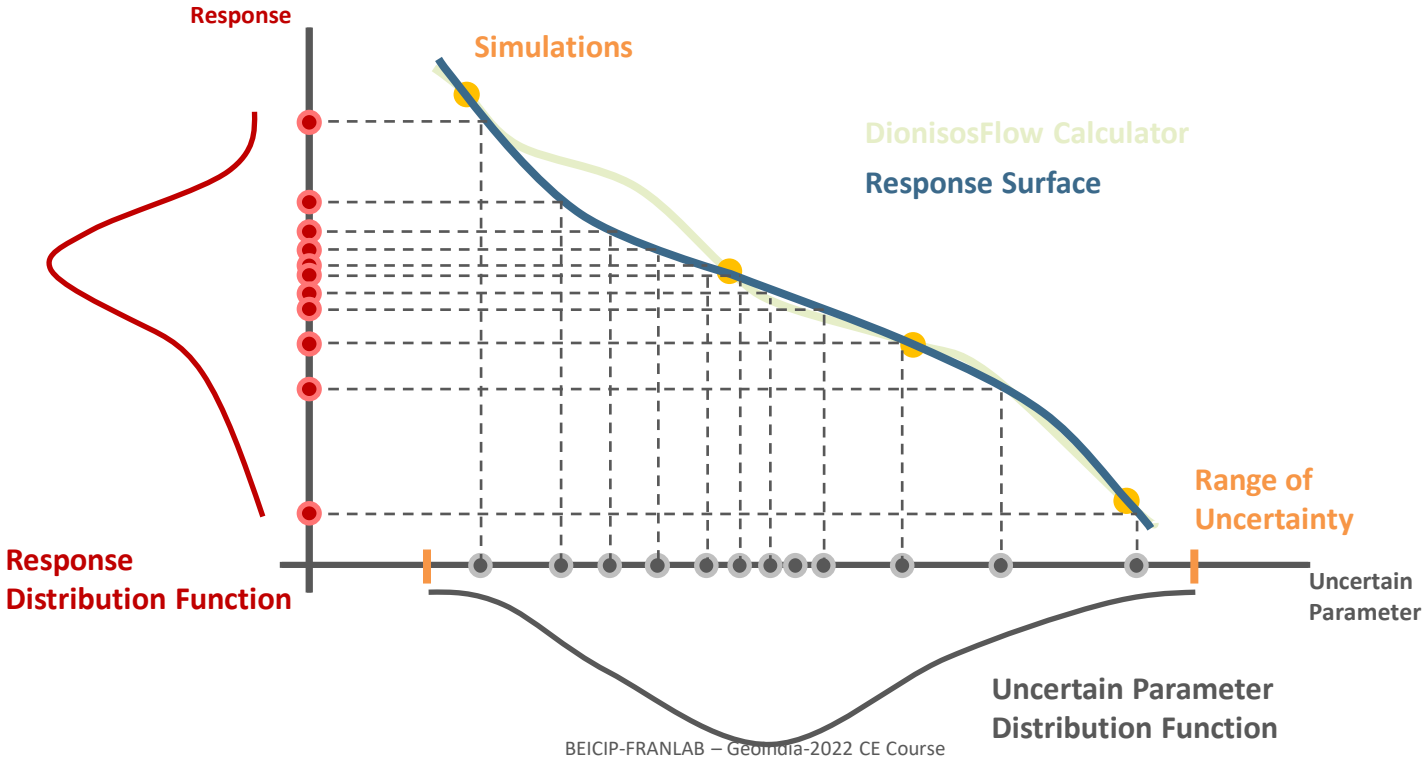
Risk Analysis Principles

Monte Carlo method on the response surface



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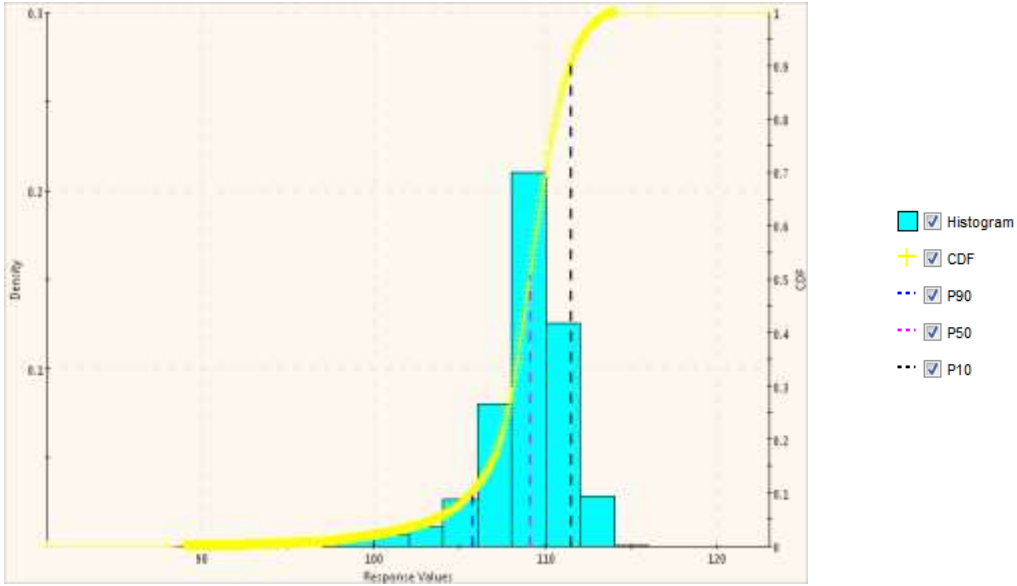
Risk Analysis Results



Sequence Thickness

- Determination of the **P10/P50/P90** for the response.

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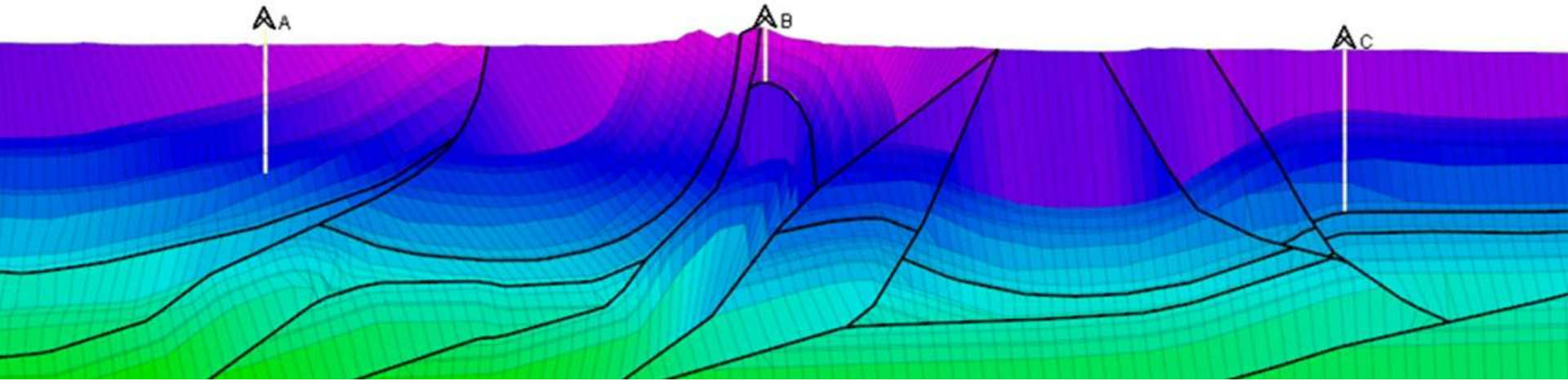

Results and Deliverables

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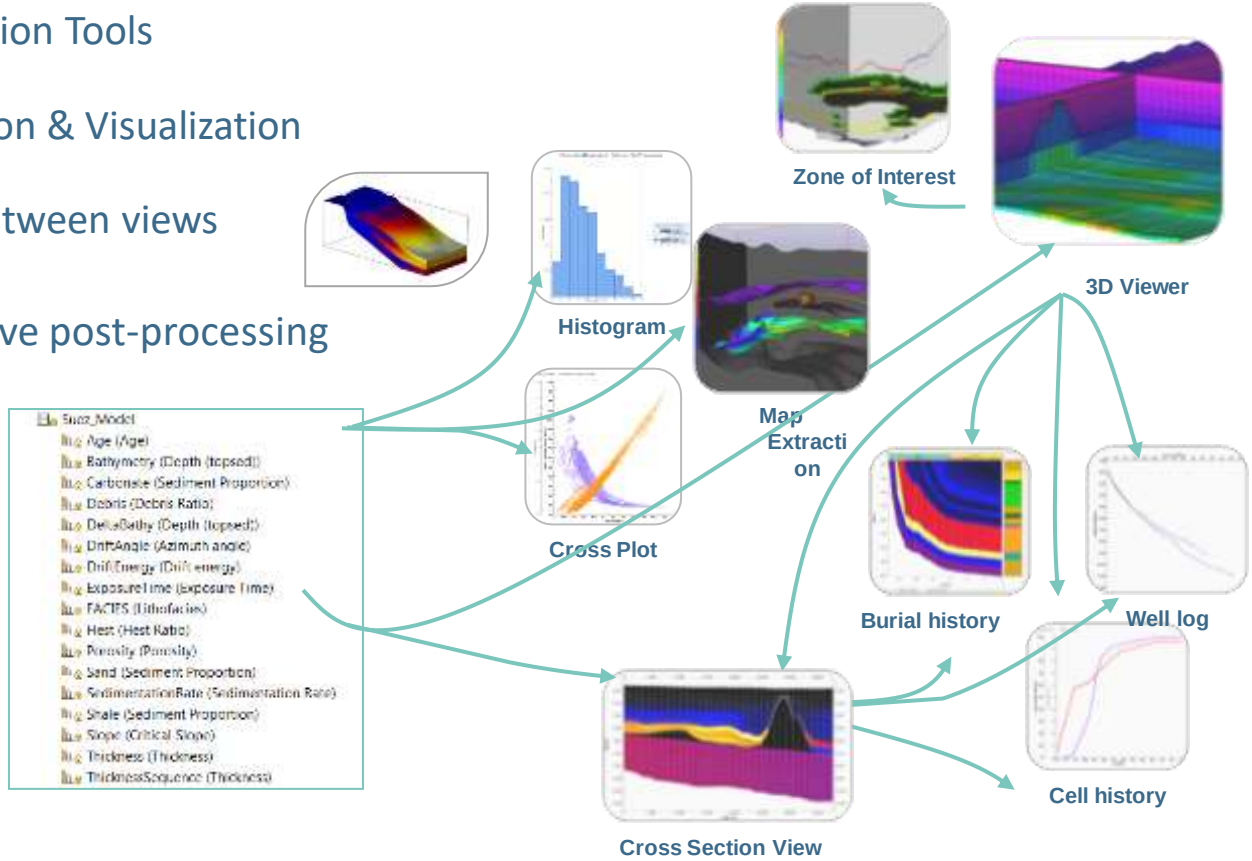
Multiple kind of results to be delivered

- Bunch of Visualization Tools
- Region Based Edition & Visualization
- Synchronization between views

Advanced & innovative post-processing



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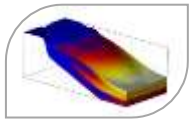
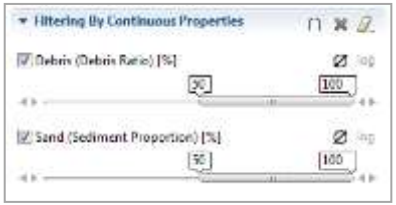
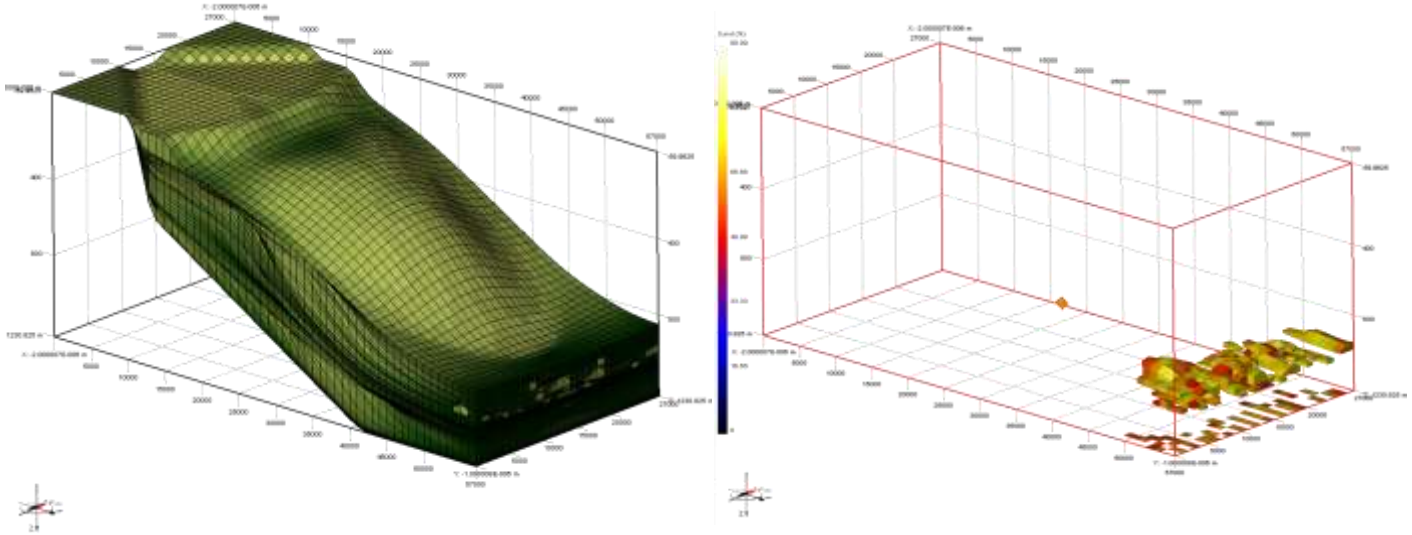
A Smooth User Experience

- Filters by Discrete or Continuous Properties and Objects of Interest
  Filtering on Areas of Interest







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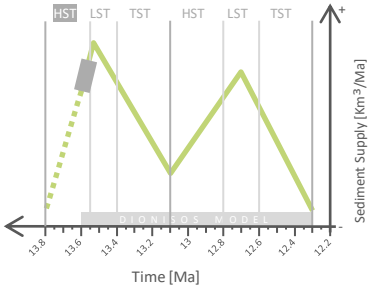
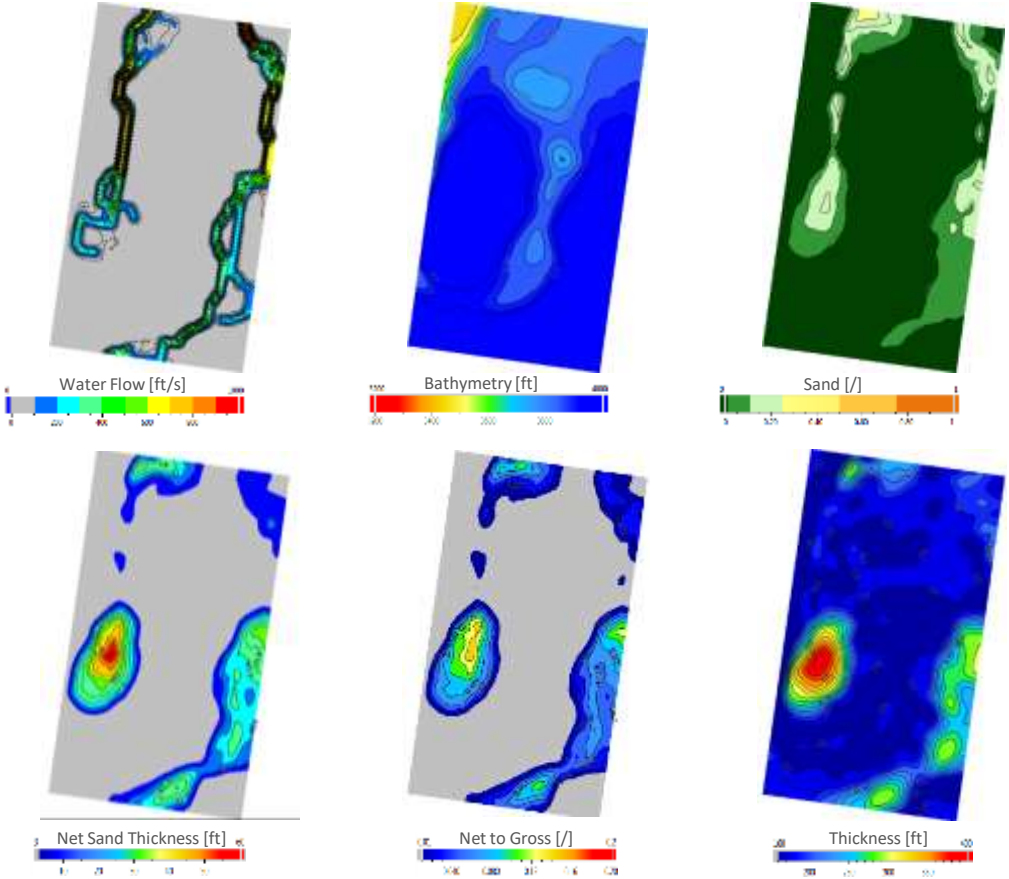
Example of Model Result Extractions





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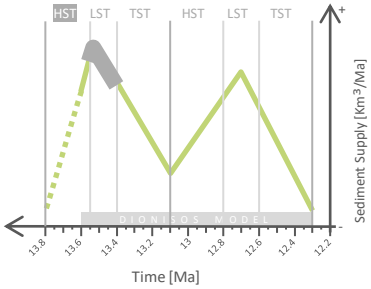
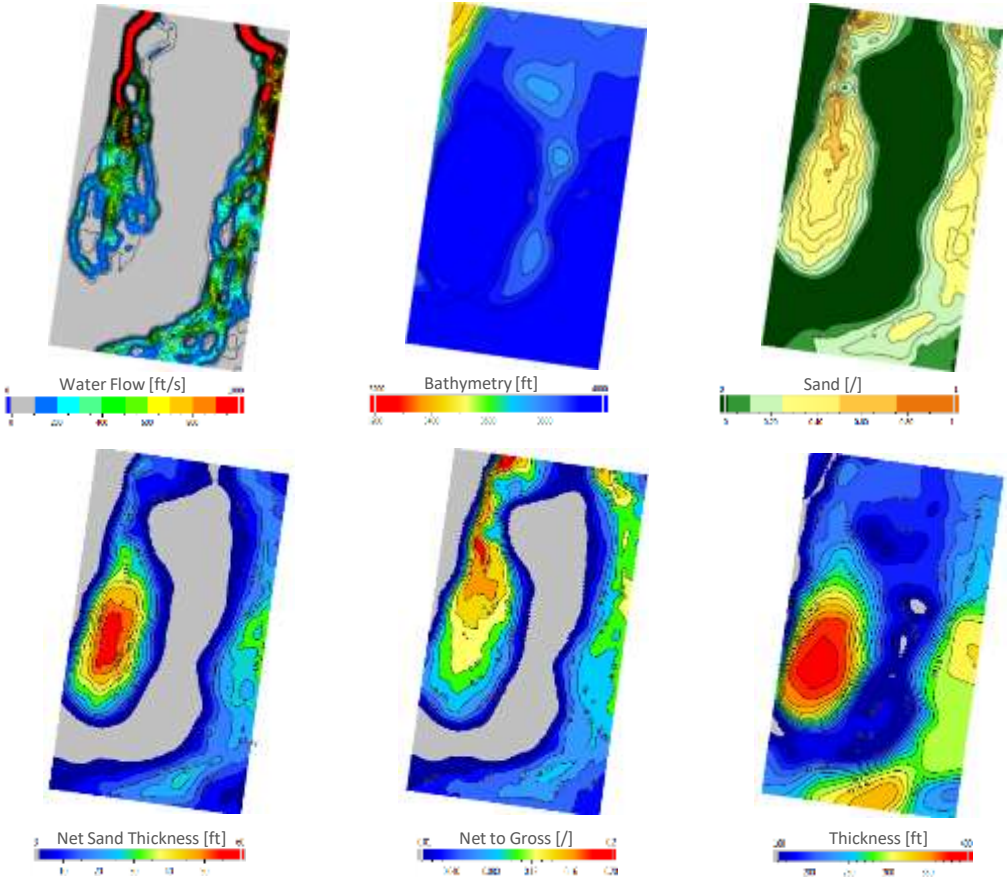
Example of Model Result Extractions





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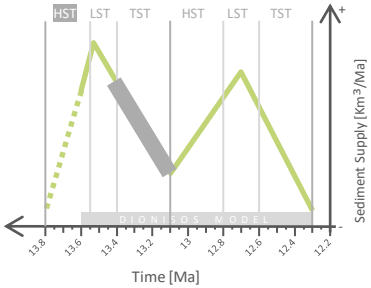
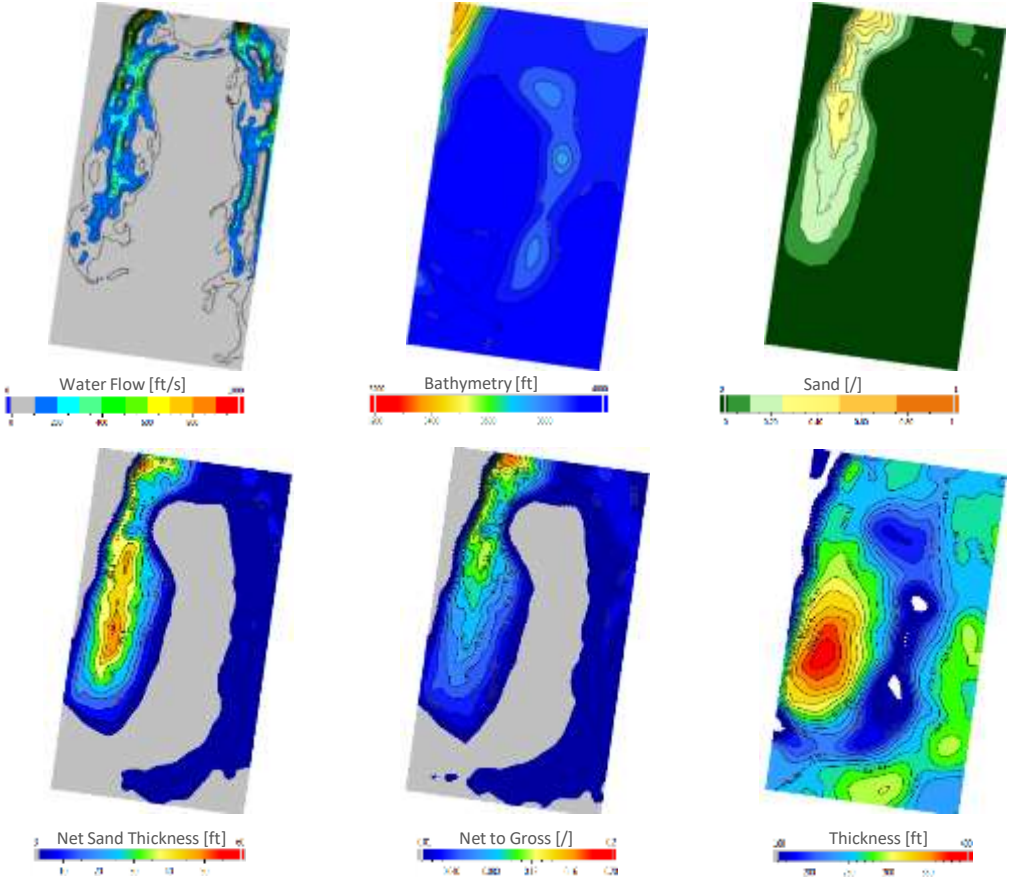
Example of Model Result Extractions





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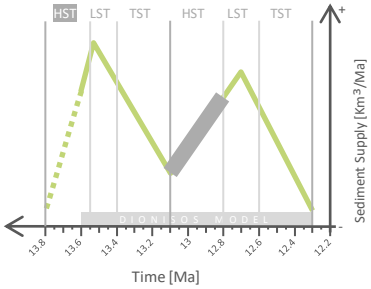
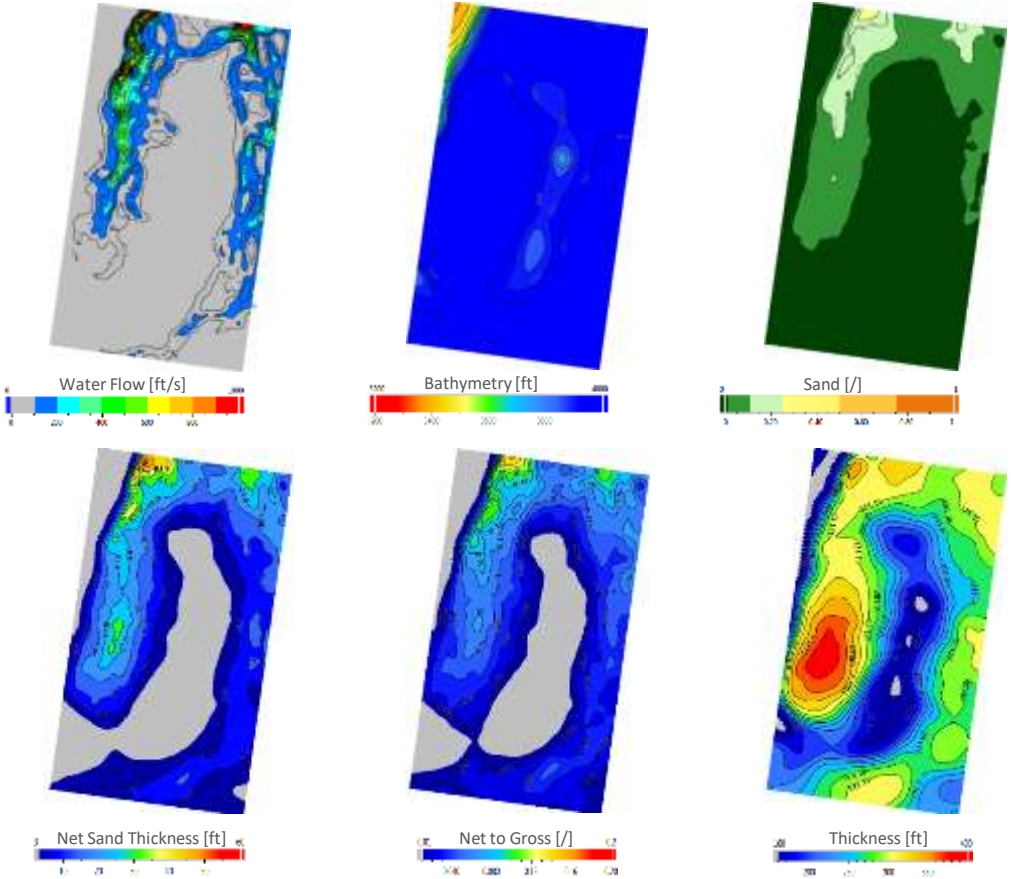
Example of Model Result Extractions





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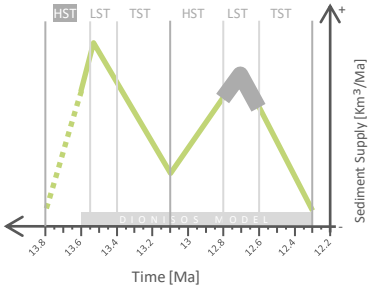
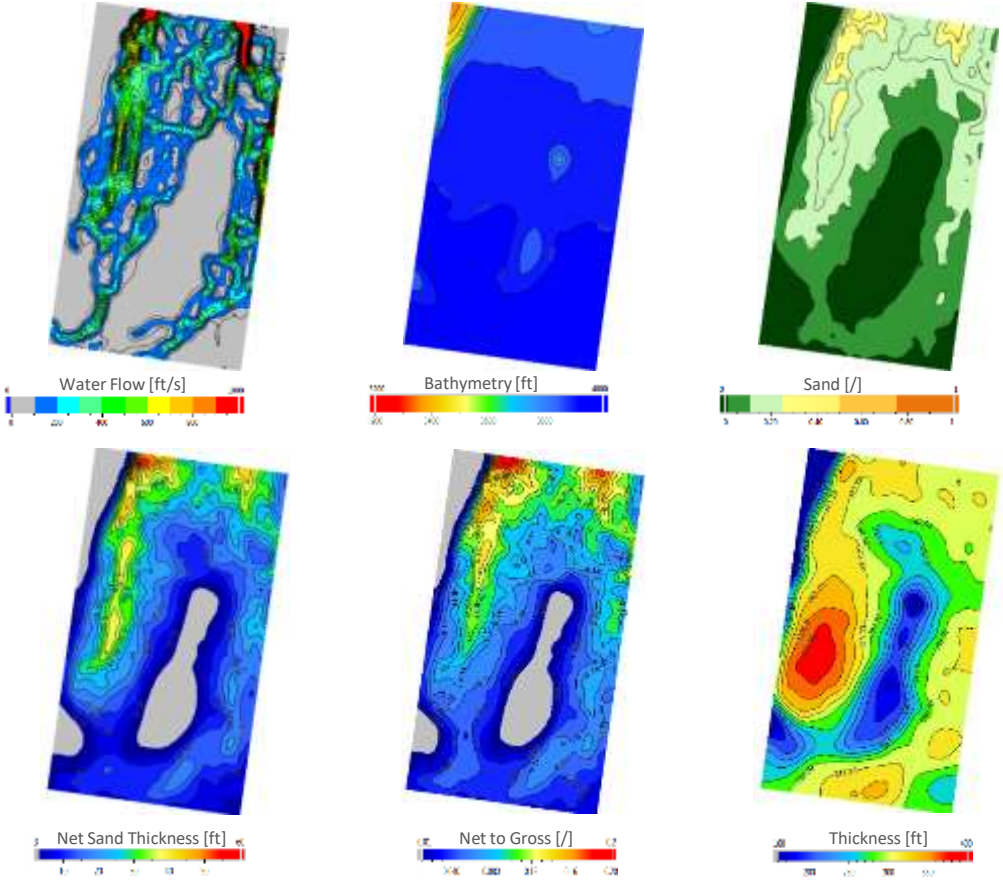
Local Model Result





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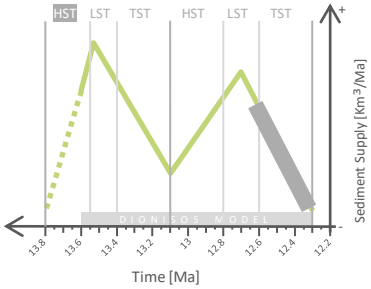
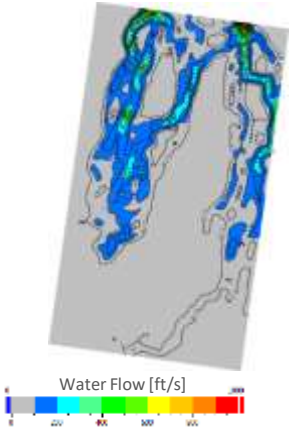
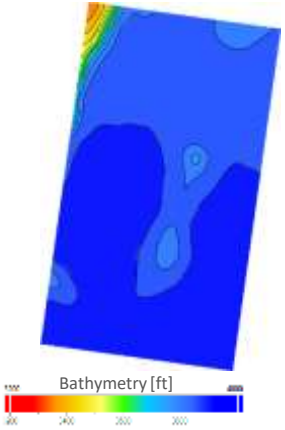
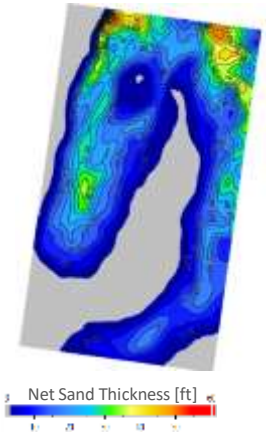
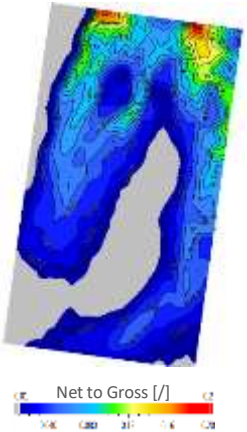
Example of Model Result Extractions

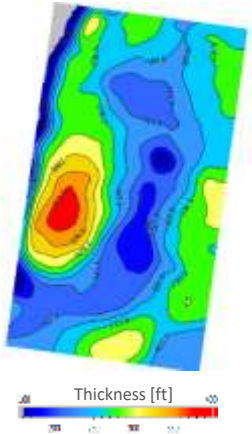












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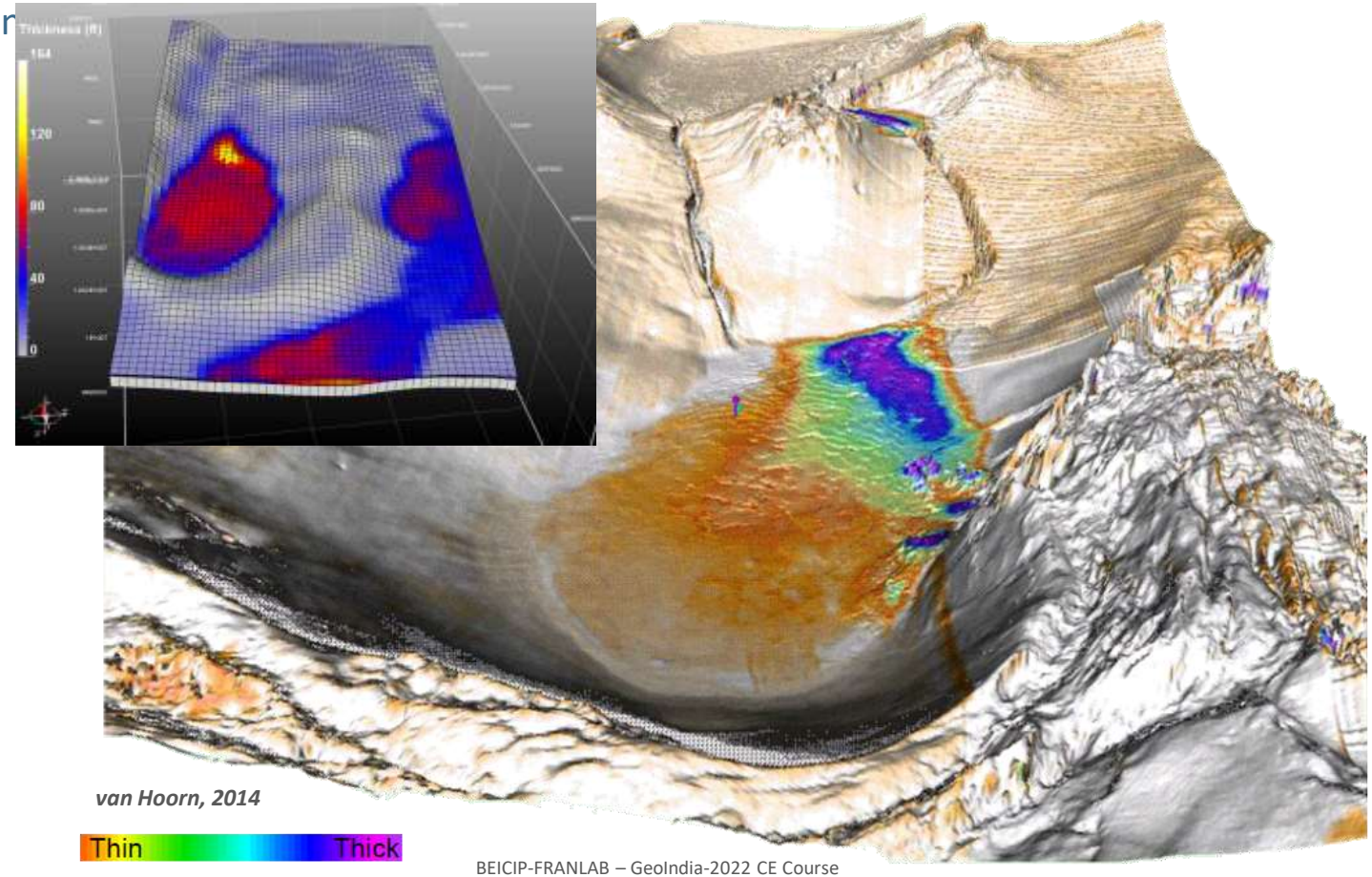
Comparison with Present Day Features

- GoM mir



van Hoorn, 2014

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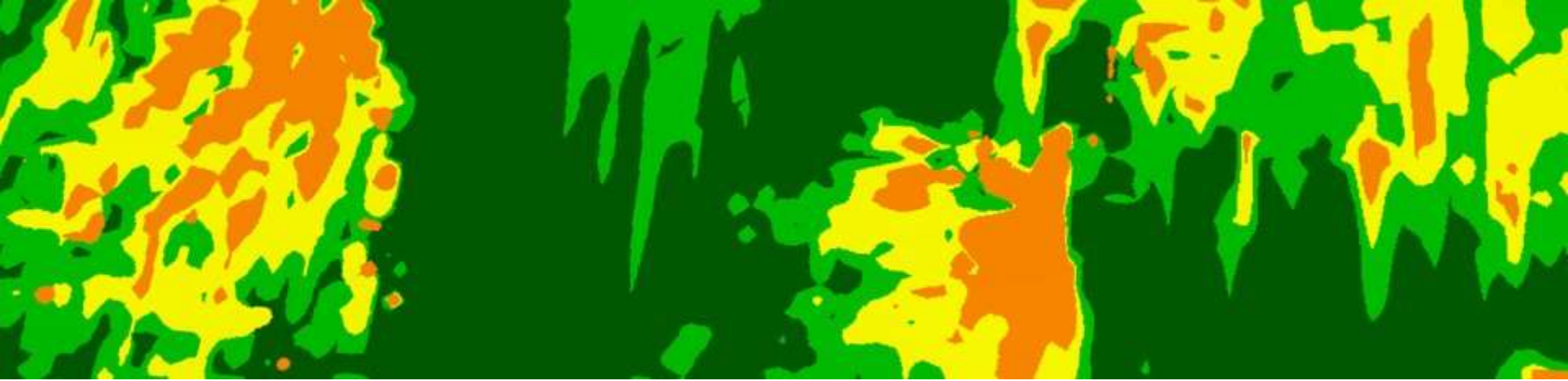

Submarine Fan Prediction

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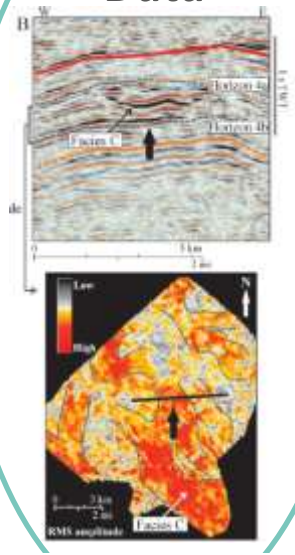
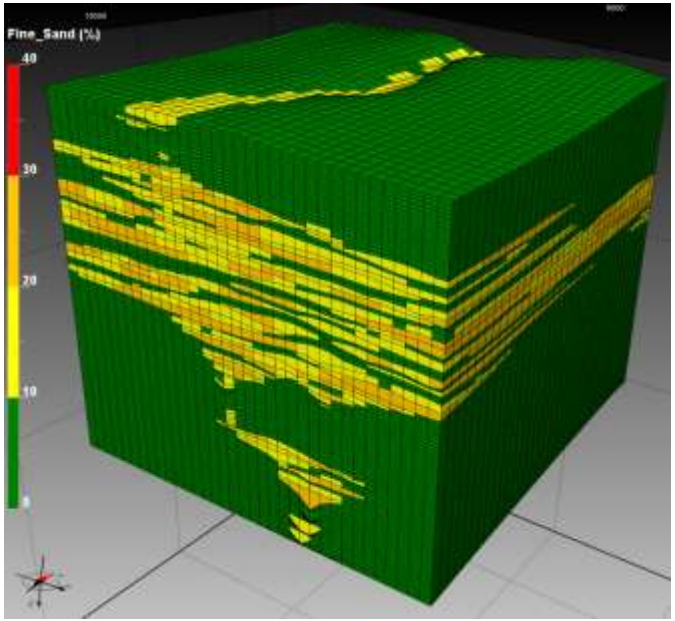
Objective

Seismic Data



McDonnell et al., 2008

Forward Stratigraphic Modelling



Outcrop Description

G. Gordon, 2014

Providing a time scaled reproduction of the geometry and distribution of sedimentary bodies in deep sea marine environments

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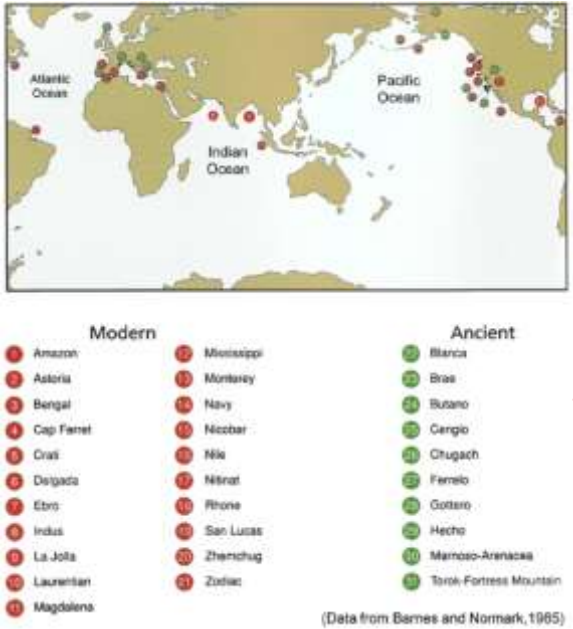
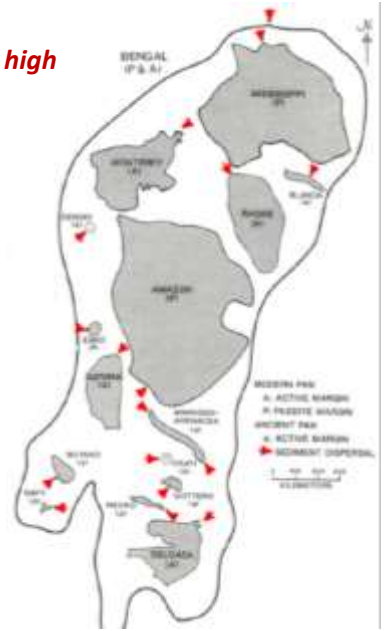
Submarine Fan's Distribution



Distributed worldwide with a very high variability in forms and sizes

Many examples preserved in the stratigraphic record

Commonly present on the submarine slope and basin floor zone



Shanmugam, 2016

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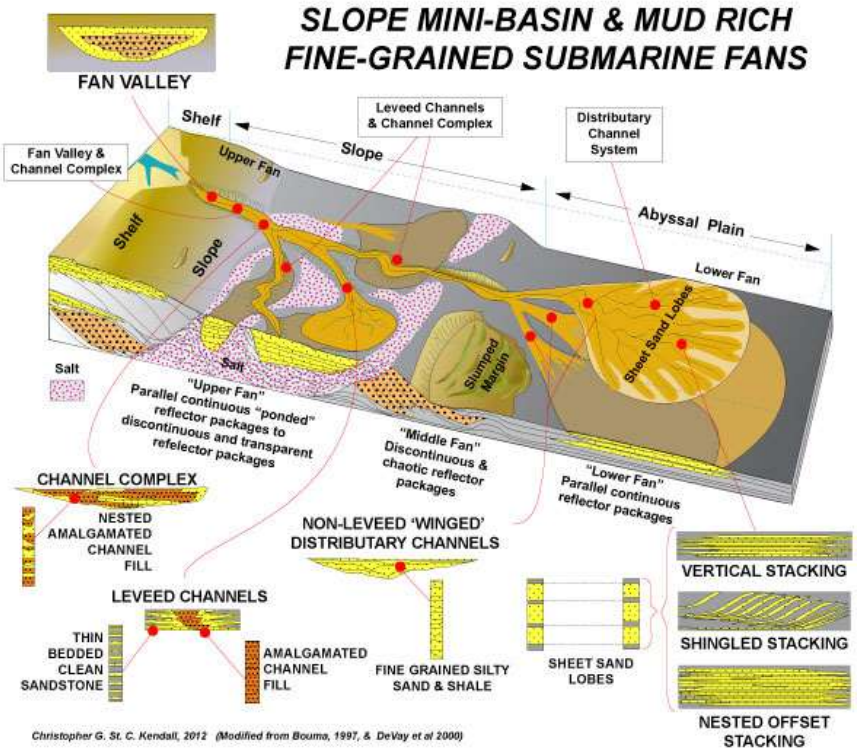
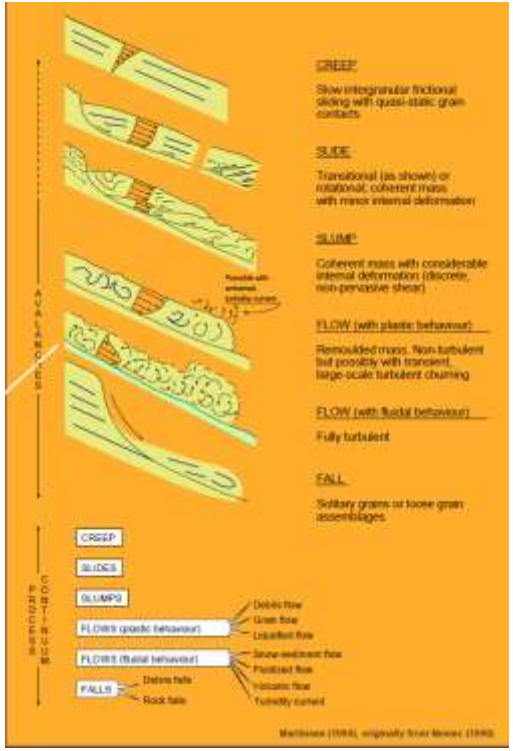
Sedimentary Processes in Deep Settings

A variety of sedimentary Processes



Kendall, 2012



Martinsen, 2010

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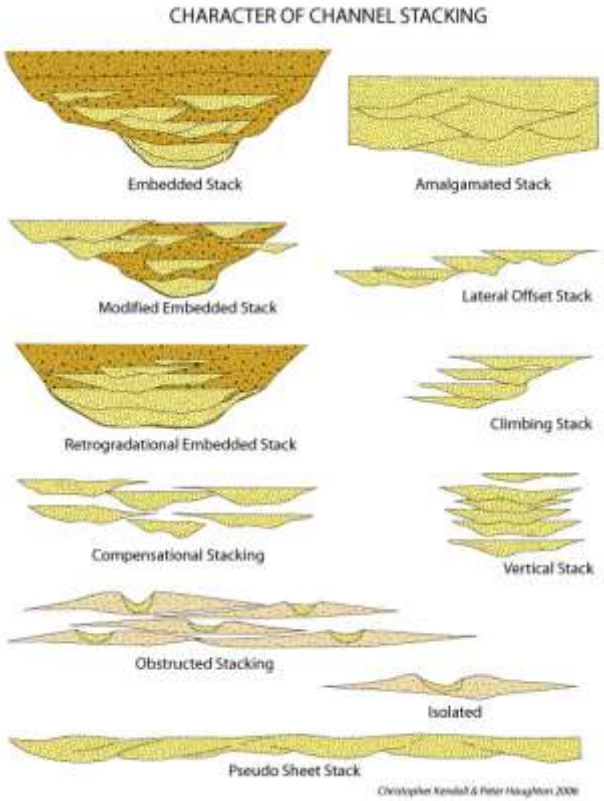
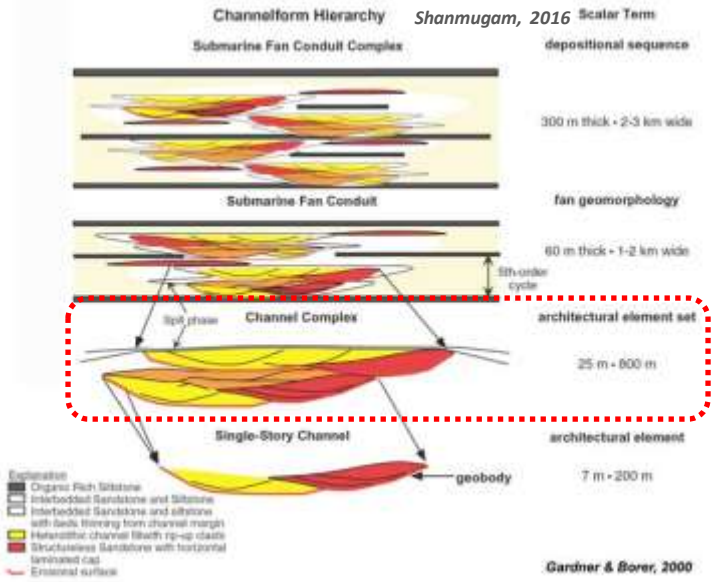
Detailed Geometries





Shanmugam, 2016

Gardner & Borer, 2000

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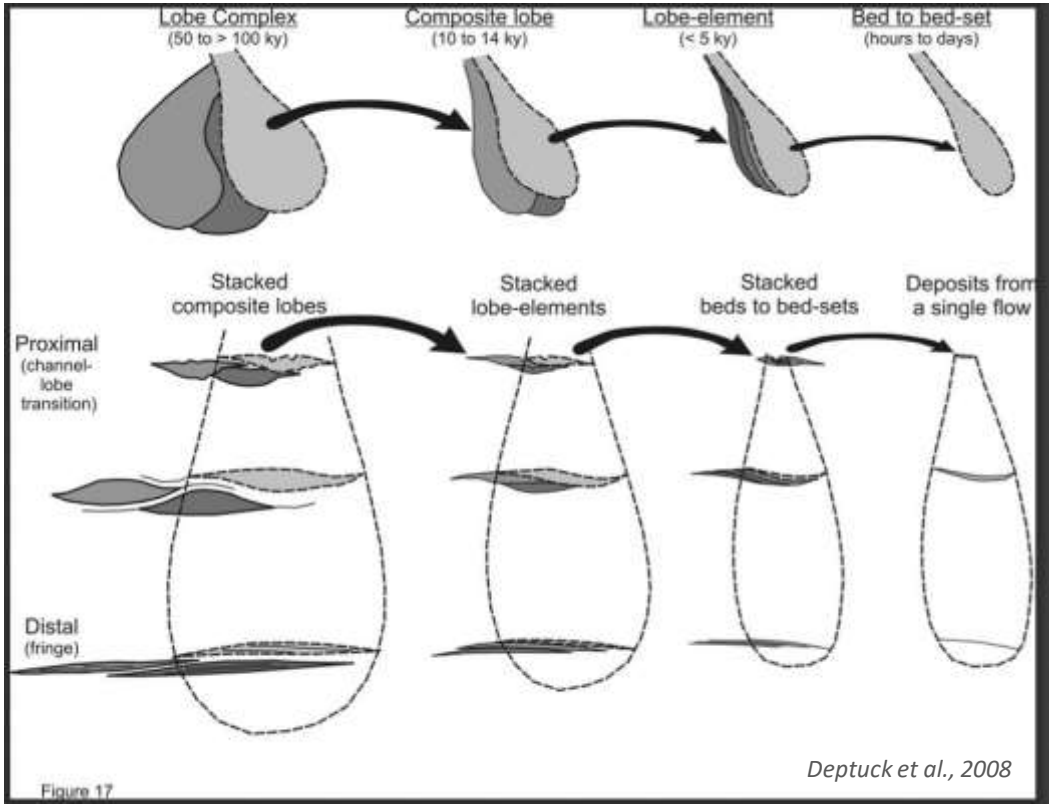
Timing & Hierarchy



Deptuck et al., 2008

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Model Building (1/2)

Model Specifications:

- 20km*20km extension
- 200m*200m cell size
- Simulation time steps: 20kyrs and 50 kyrs
- Time span simulated: 5Ma, from 35 to 30Ma

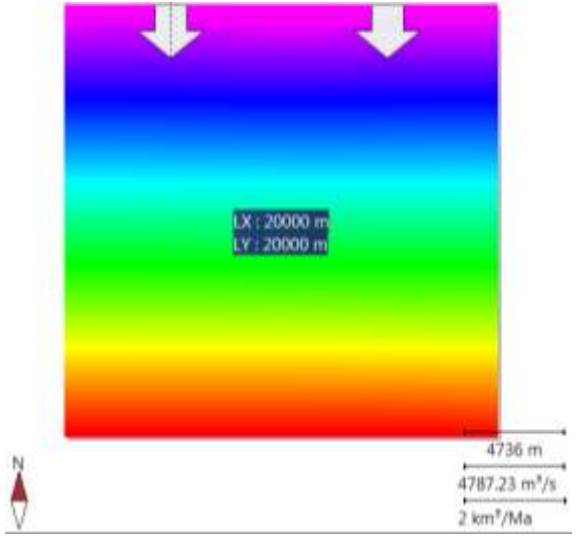
Two sources of sediments, located North

- 5 classes of sediments:
  - Shale
  - Fine Sand
  - Medium Sand
  - Quarzitic Medium Sand
  - Coarse Sand

Sediment Input

From 35 to 33Ma

From 33 to 30Ma



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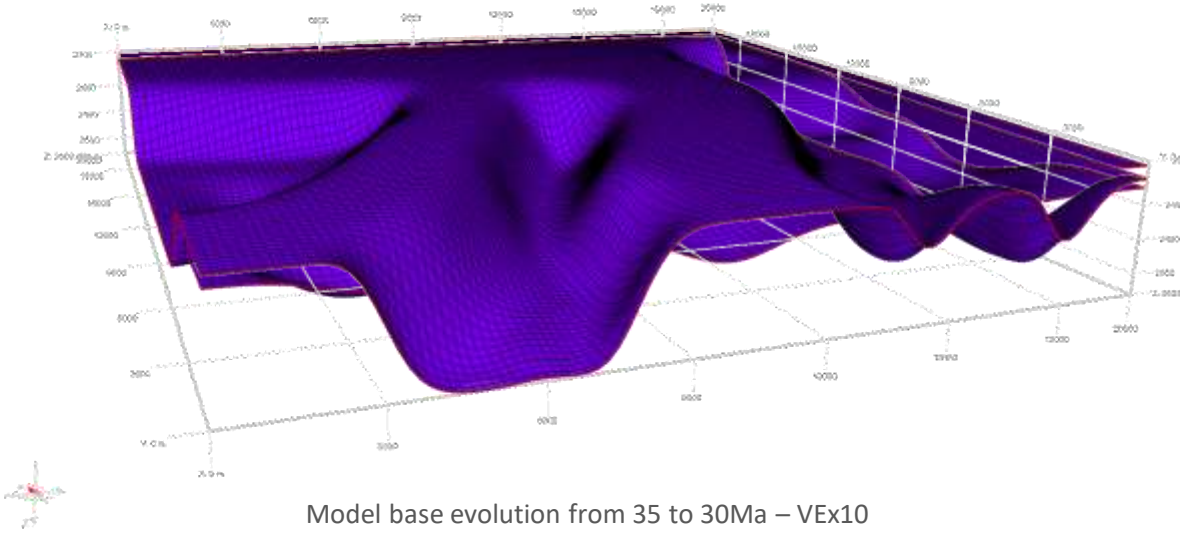
Model Building (2/2)

- Long-term flow + short term events (climatic cycles)
- **Salt deformation** and its impact on sedimentation was simulated



Model base evolution from 35 to 30Ma – VEx10

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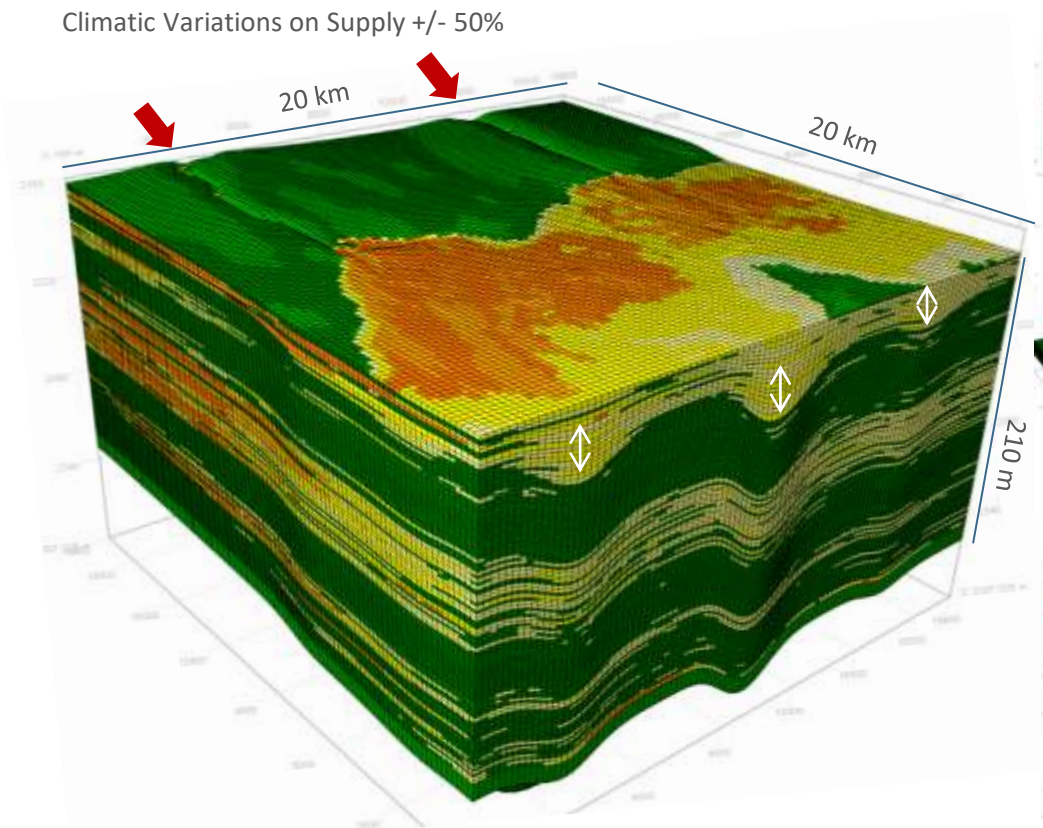
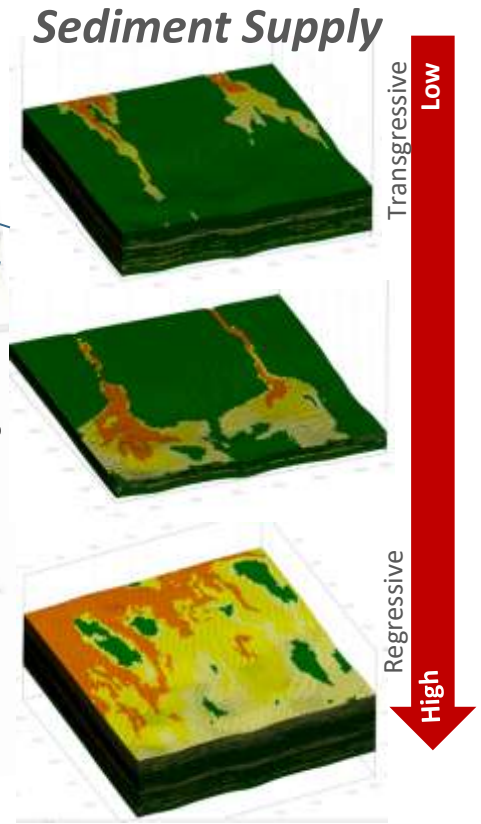
Overall Facies Model



Example from 35-32,6 Ma VEx50



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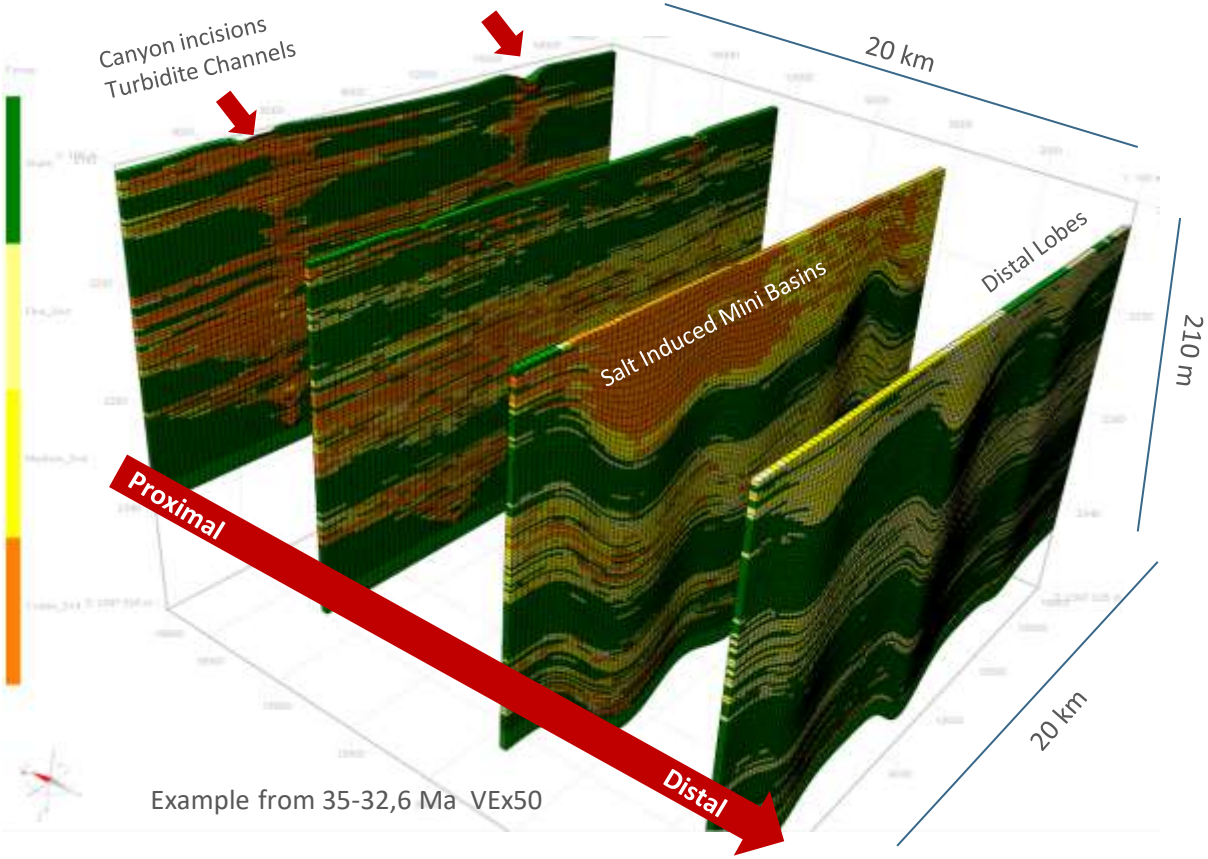
Overall Facies Model & Geometries



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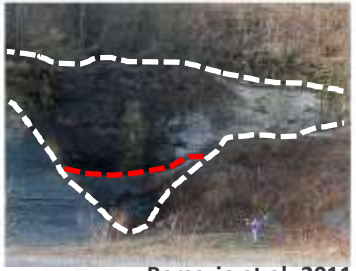
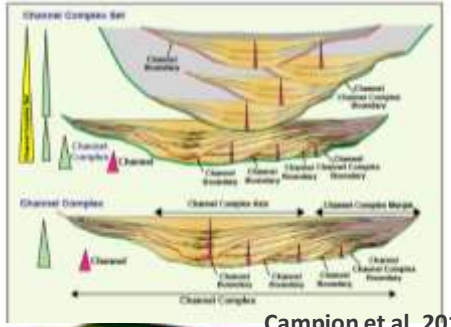
Channel Stacking Patterns

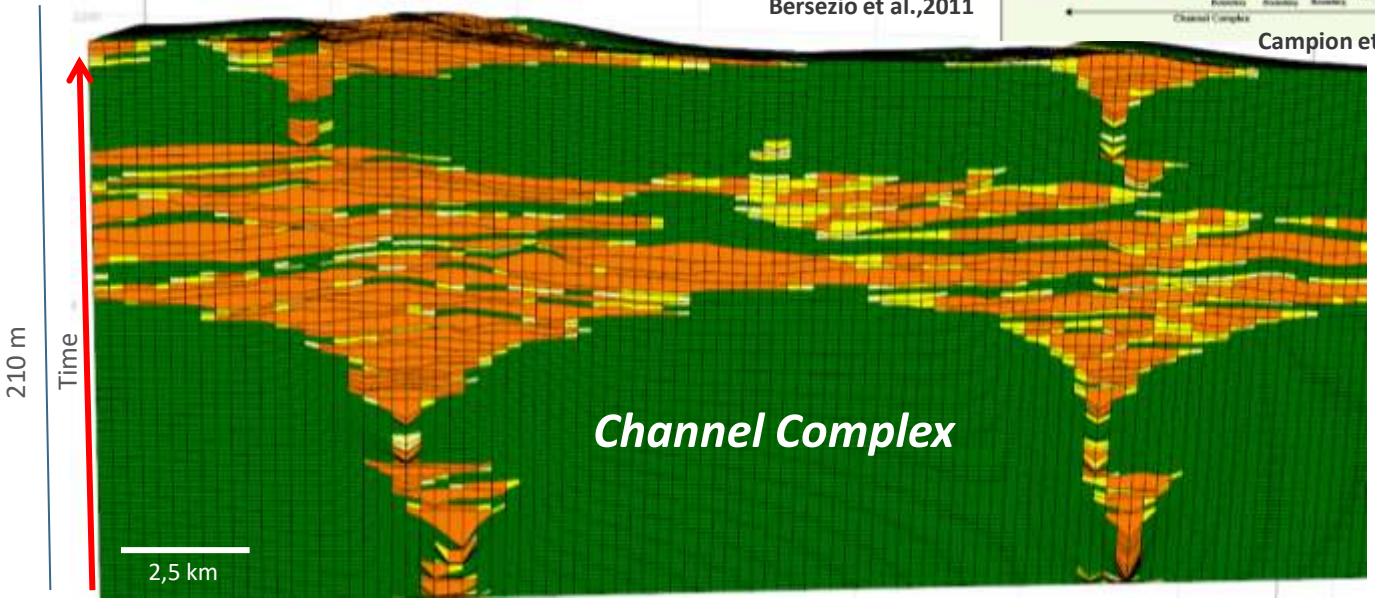


Bersezio et al.,2011



Campion et al. 2011,

Example from 35-32,6 Ma VEx50



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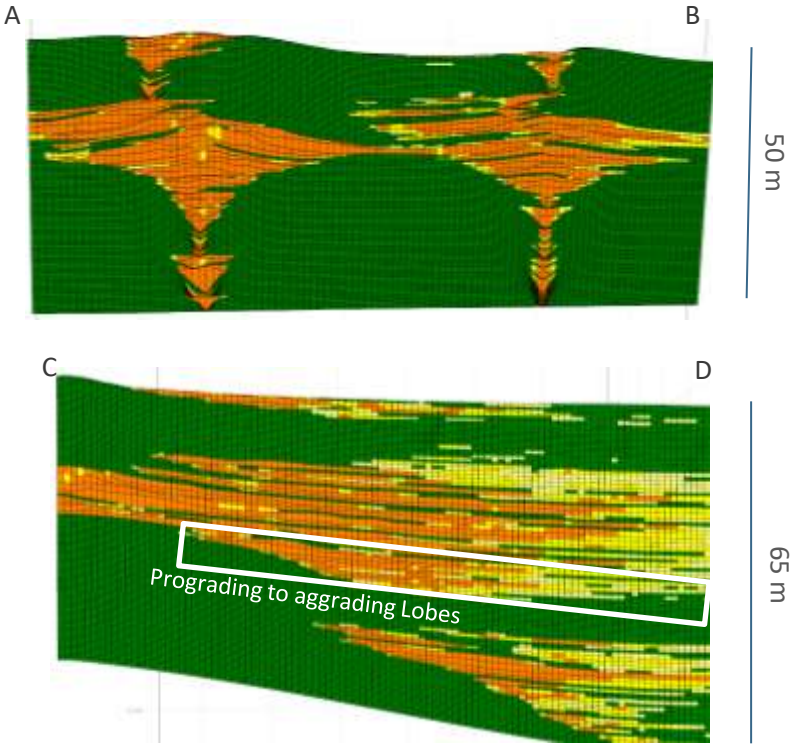
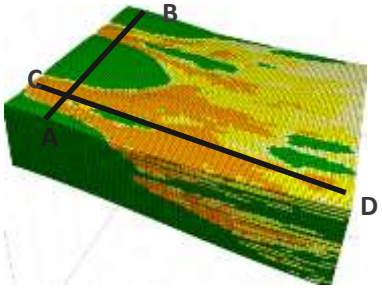
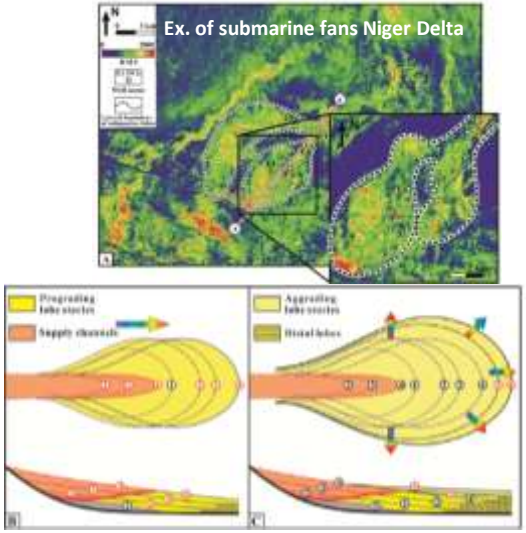
Channel & Lobe Architecture



Zoom on Channel- Lobe complex VEx50





Zhang et al. 2016,

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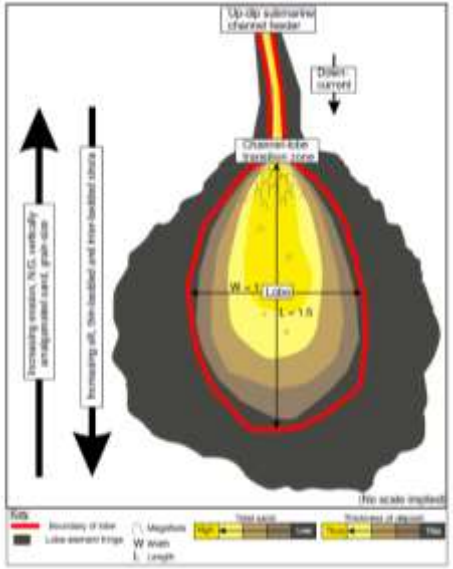
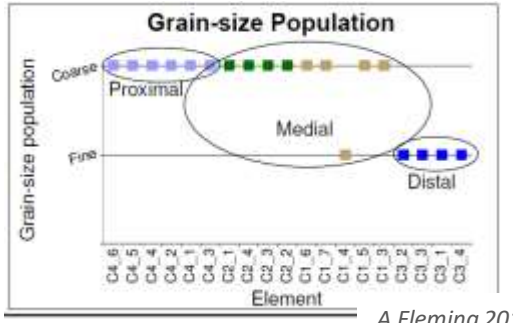
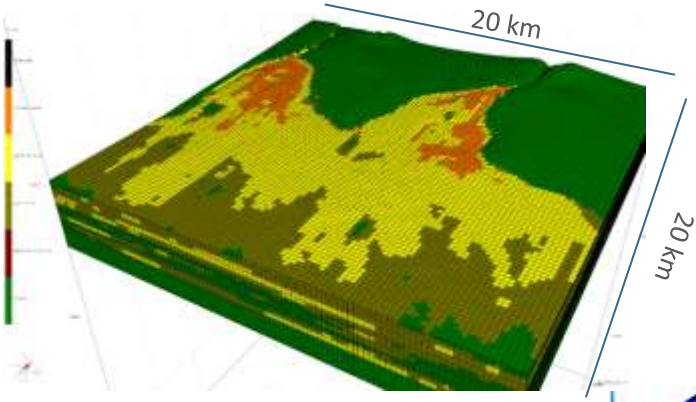
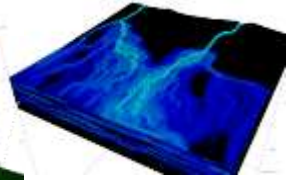
Channel & Lobe Granulometry



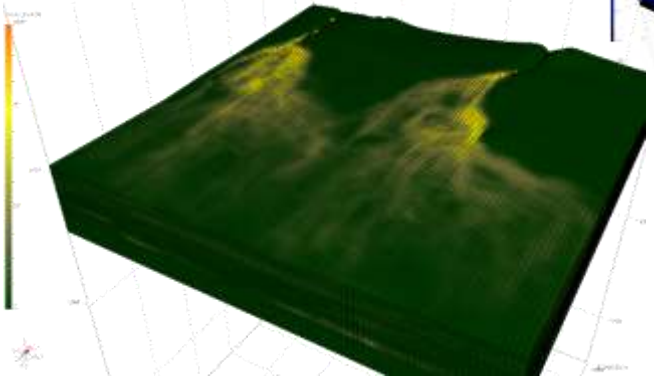




Facies distribution



Water flow



VEx100

Coarse sand distribution

A Fleming 2013

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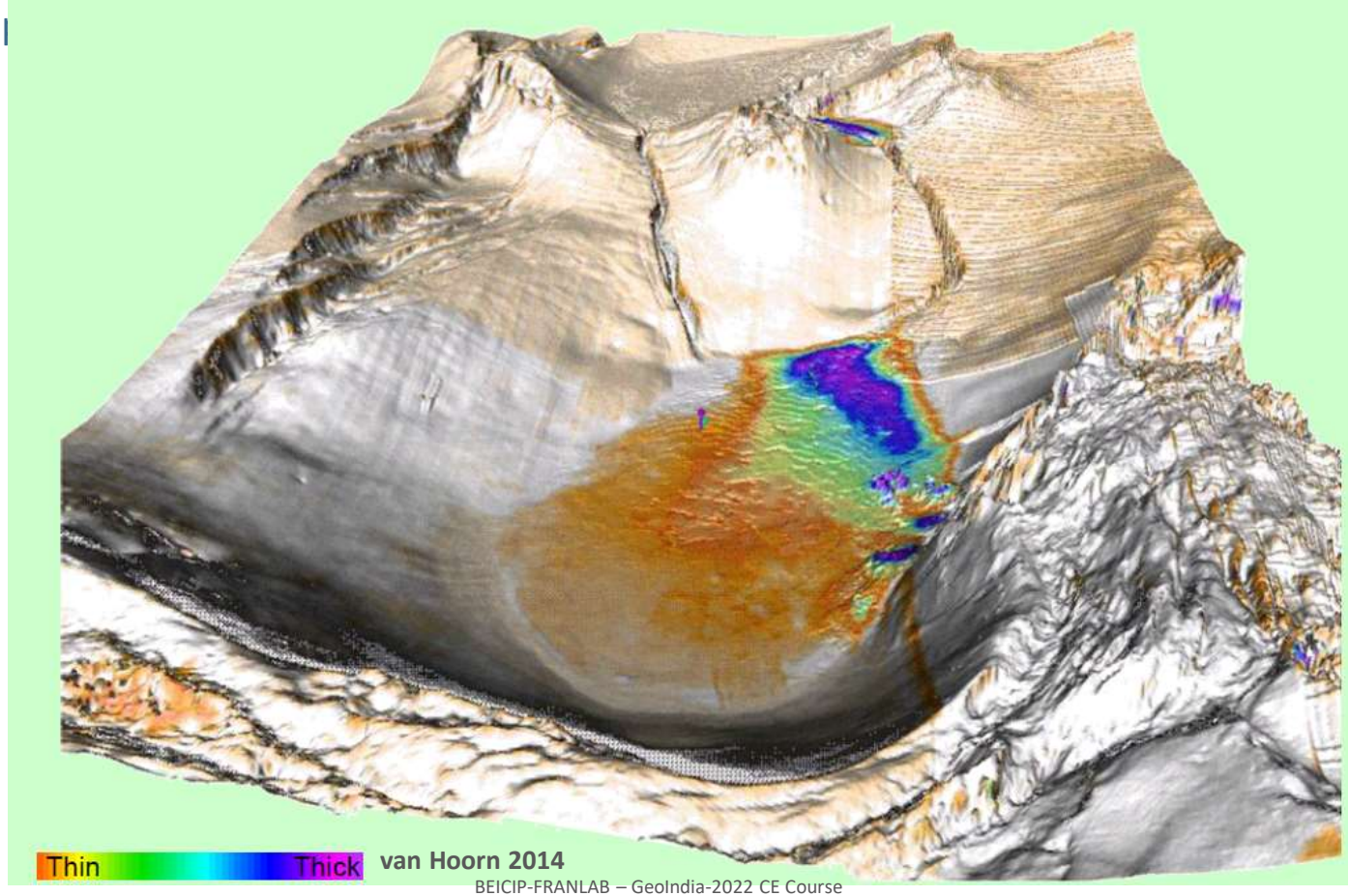
Impact of Salt Deformation

- Time step



van Hoorn 2014

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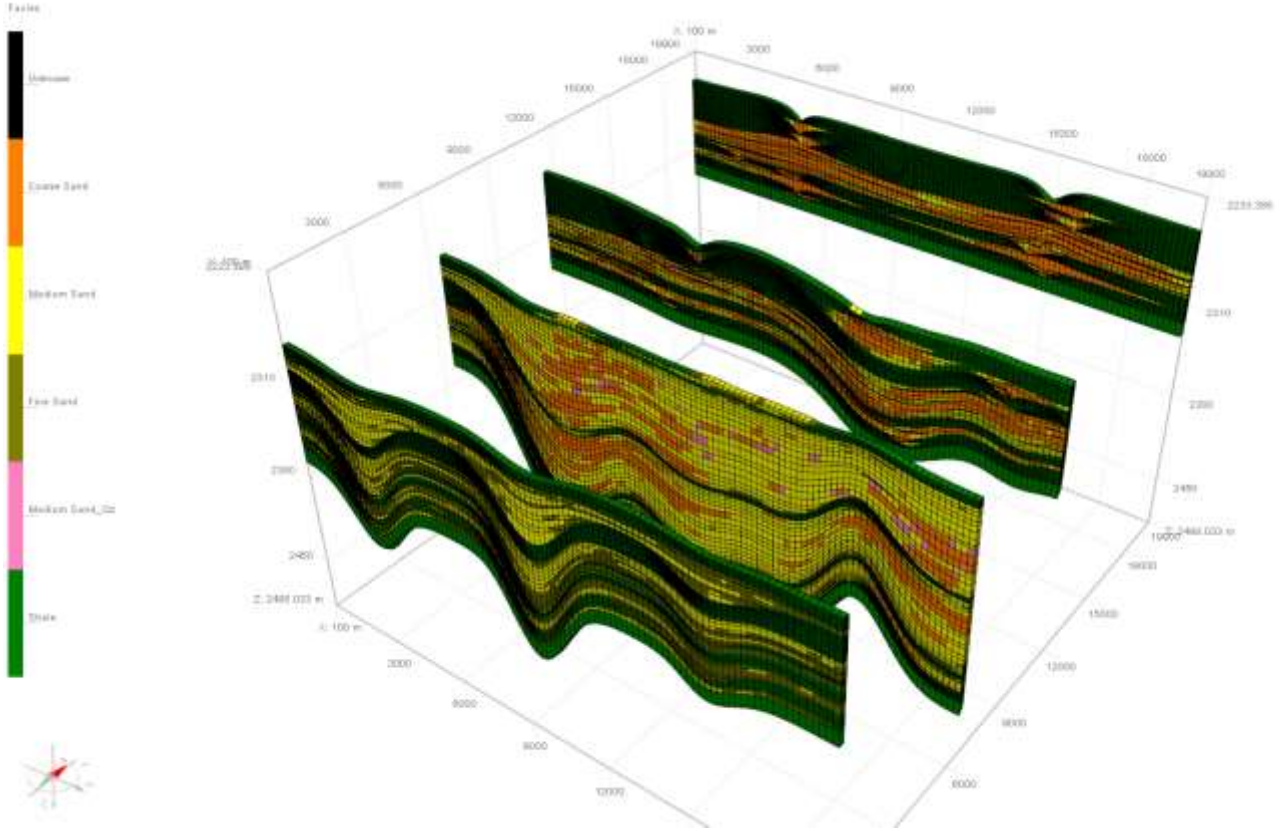
Impact of Salt Deformation

- Time



VEx50

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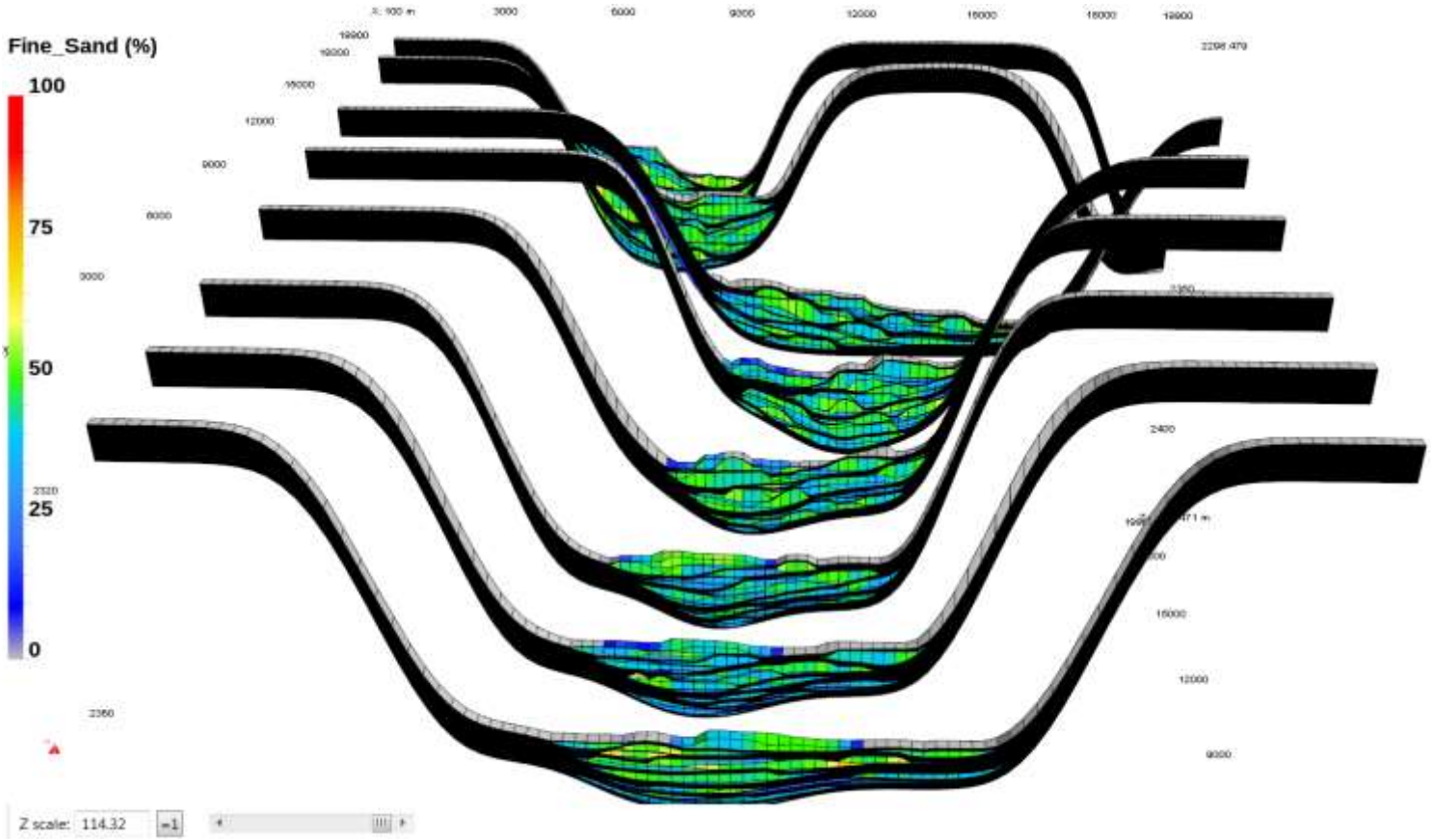
Internal Architecture



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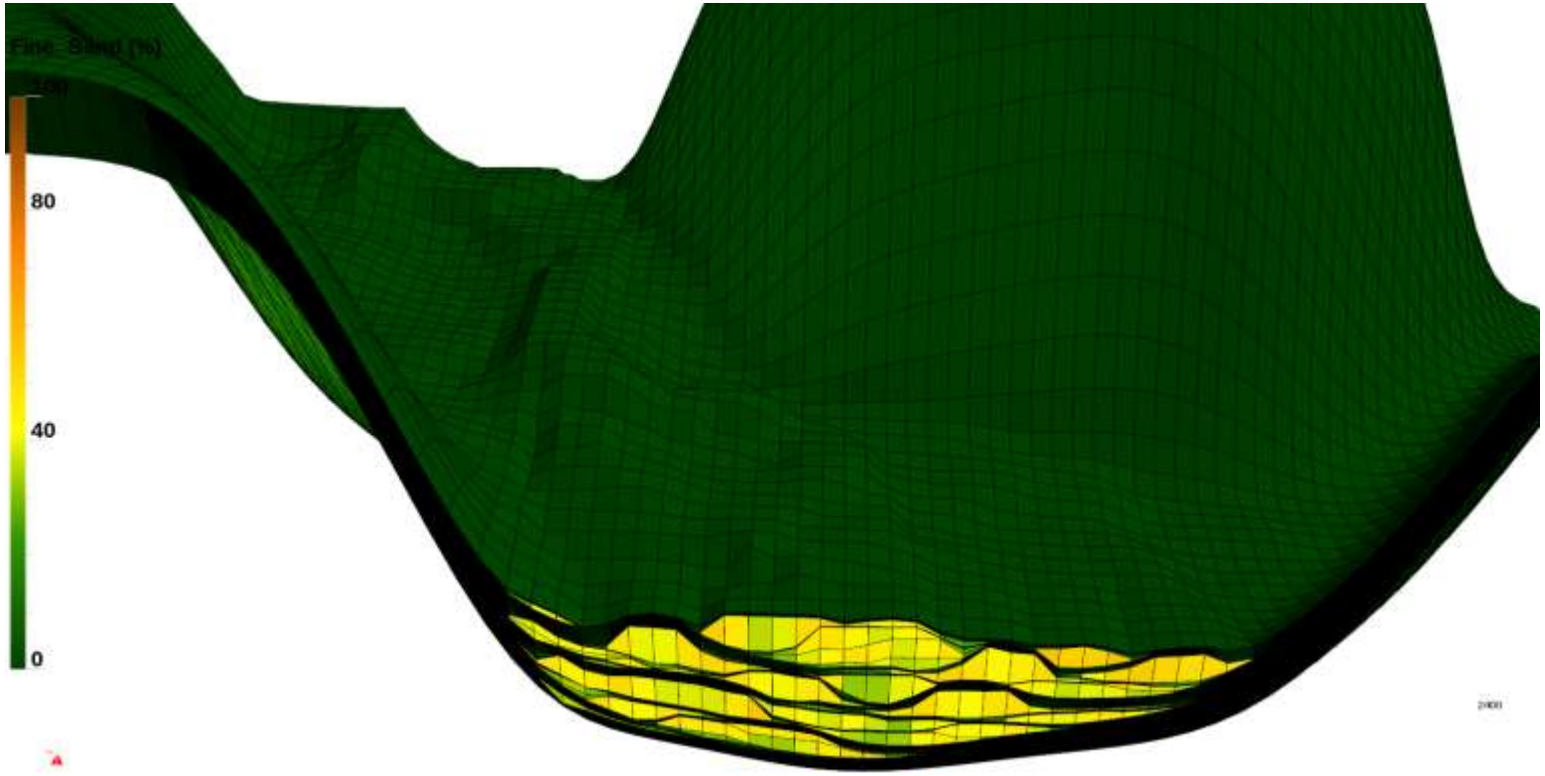
Internal Architecture



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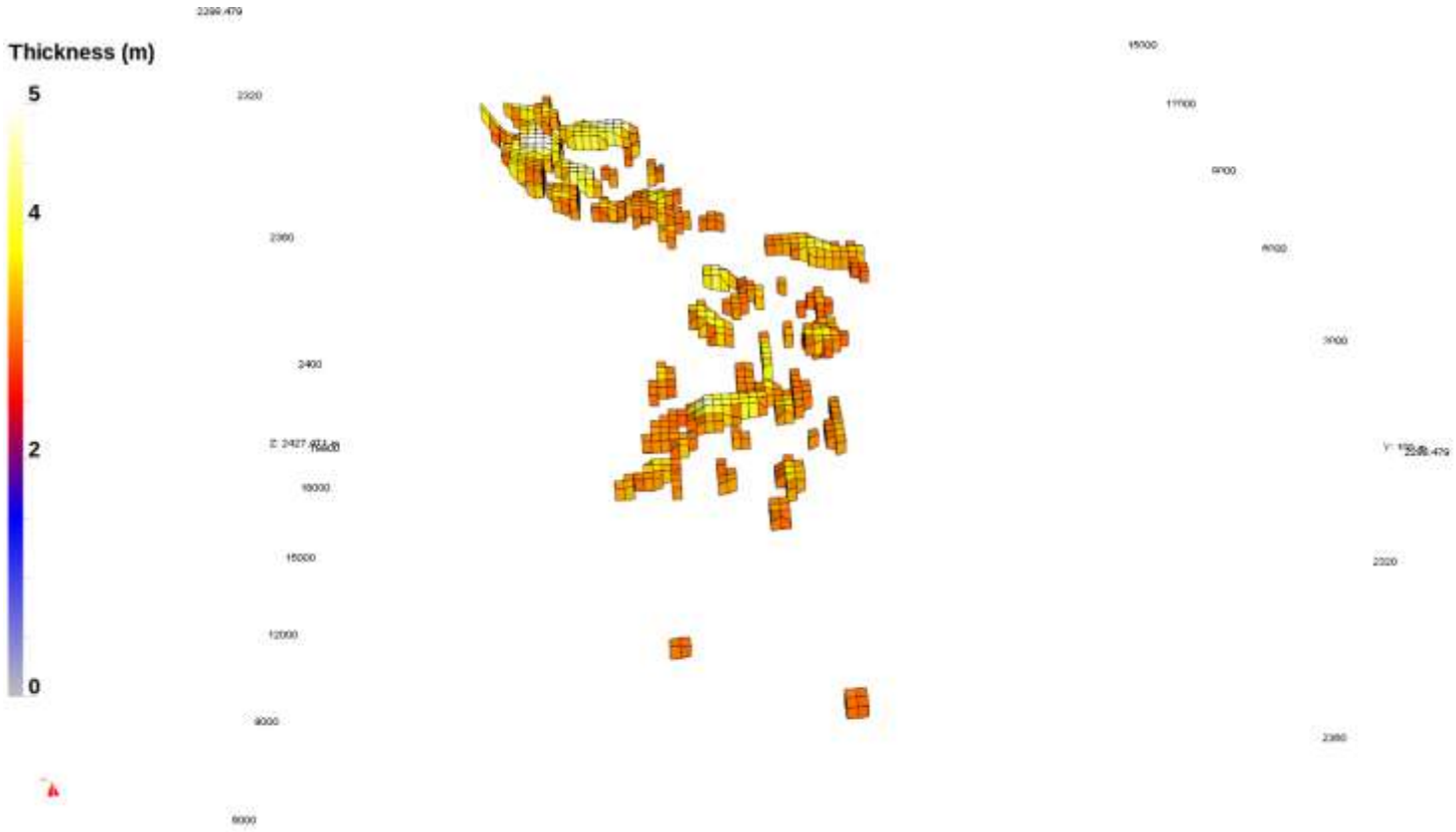
Filters



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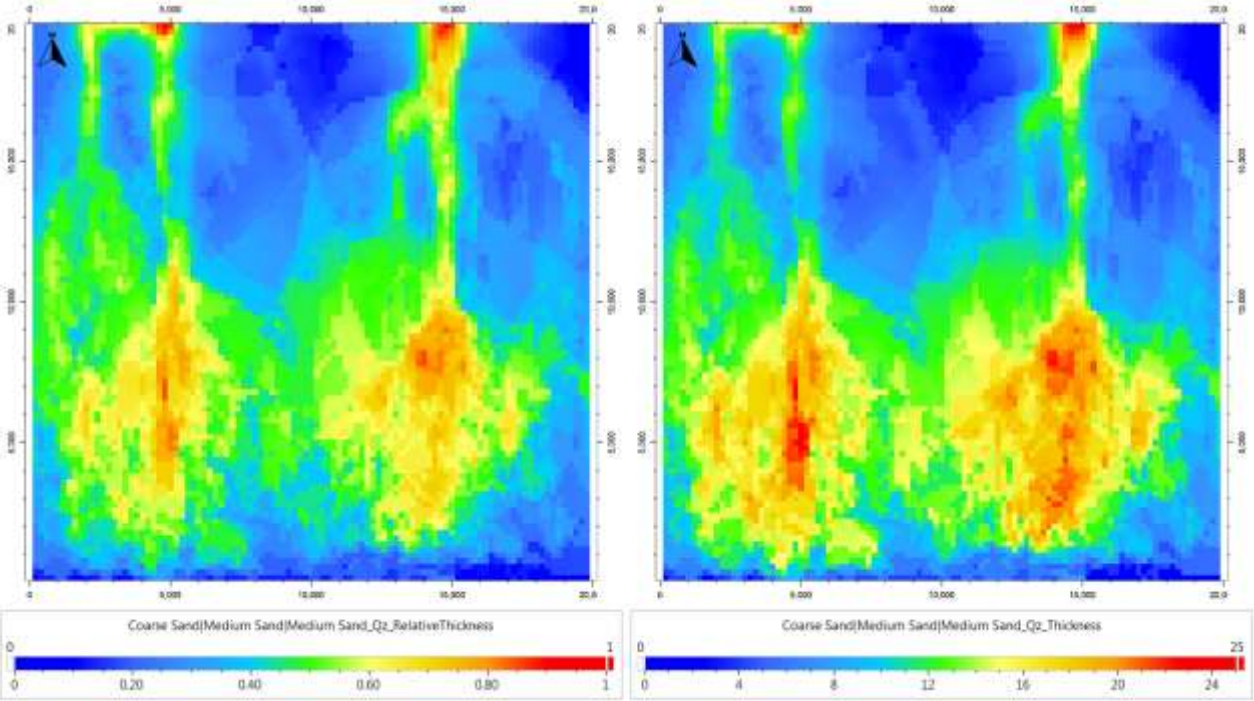
Thickness & NTG Maps (1/2)

- Pre-Salt (35 to 34Ma): {medium + coarse sand}



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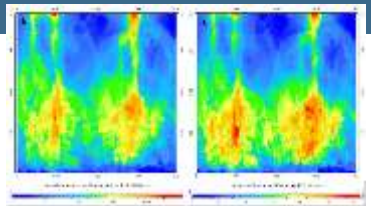
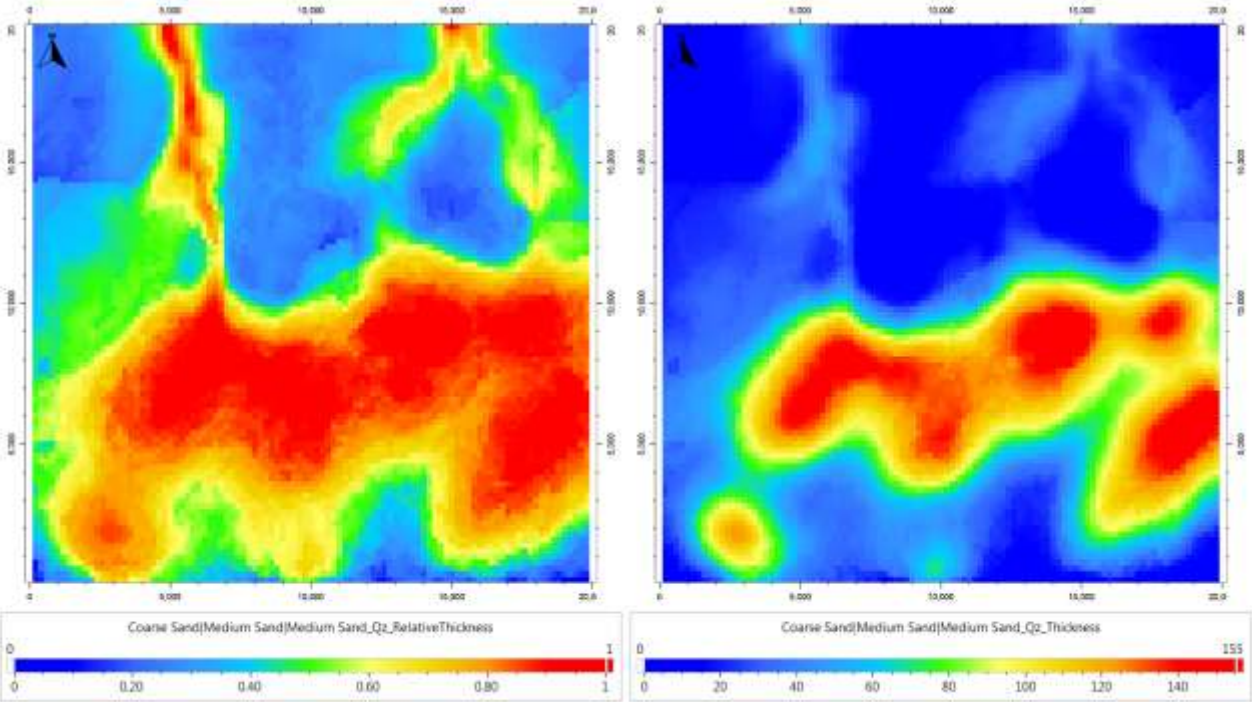
Thickness & NTG Maps (2/2)

- Post-Salt (34 to 32Ma): {medium + coarse sand}





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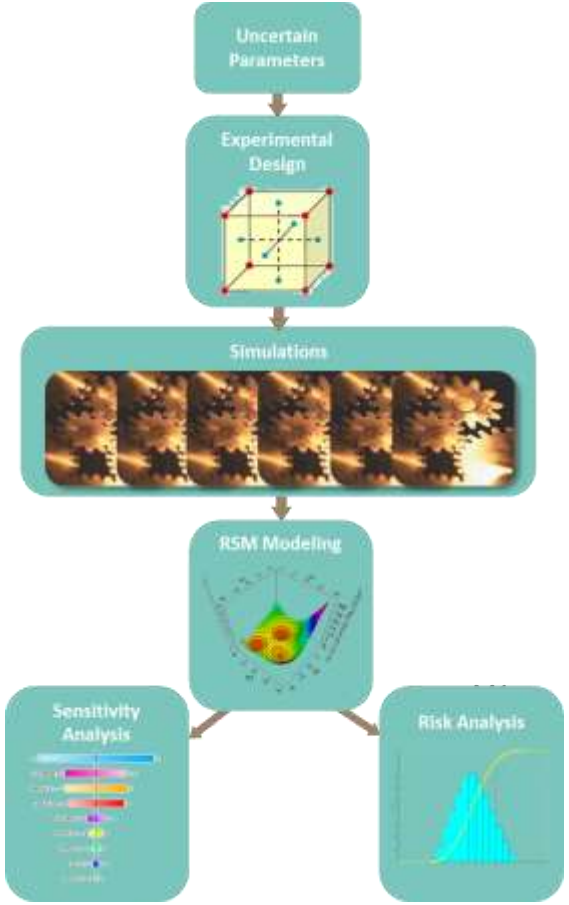
Automated Multi-Realization

CougarFlow coupling allows:

- Generating of alternative scenarios by varying some input parameters according to an Experimental Design.
- To assess the impact of main influential parameters on thickness and texture calibration.
- **Sensitivity Analysis**

➔ It allows the analysis of uncertainties on input parameters and their influence on simulation results



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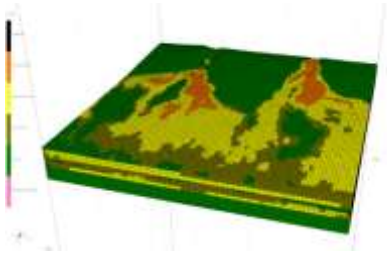
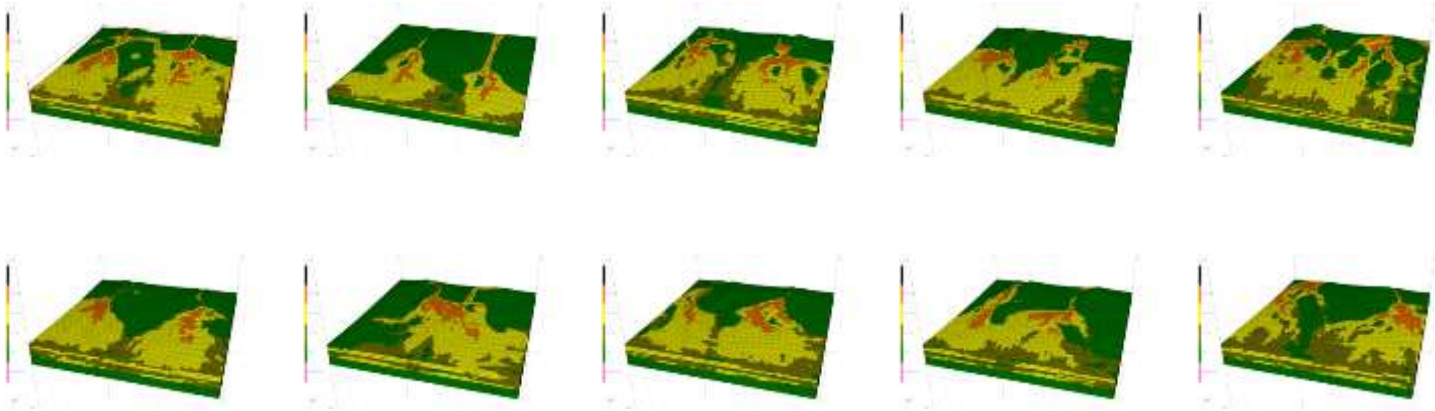
Uncertainties & Experimental Design

- 3 uncertain parameters
  - Fluvial discharge through time (+/- 20%)
  - Sediment supply for both sources (+/- 20%)
  - Proportion of qz sand in both sources from 33Ma (+/- 20%)



- Total of 11 simulations to cover the entire uncertain domain



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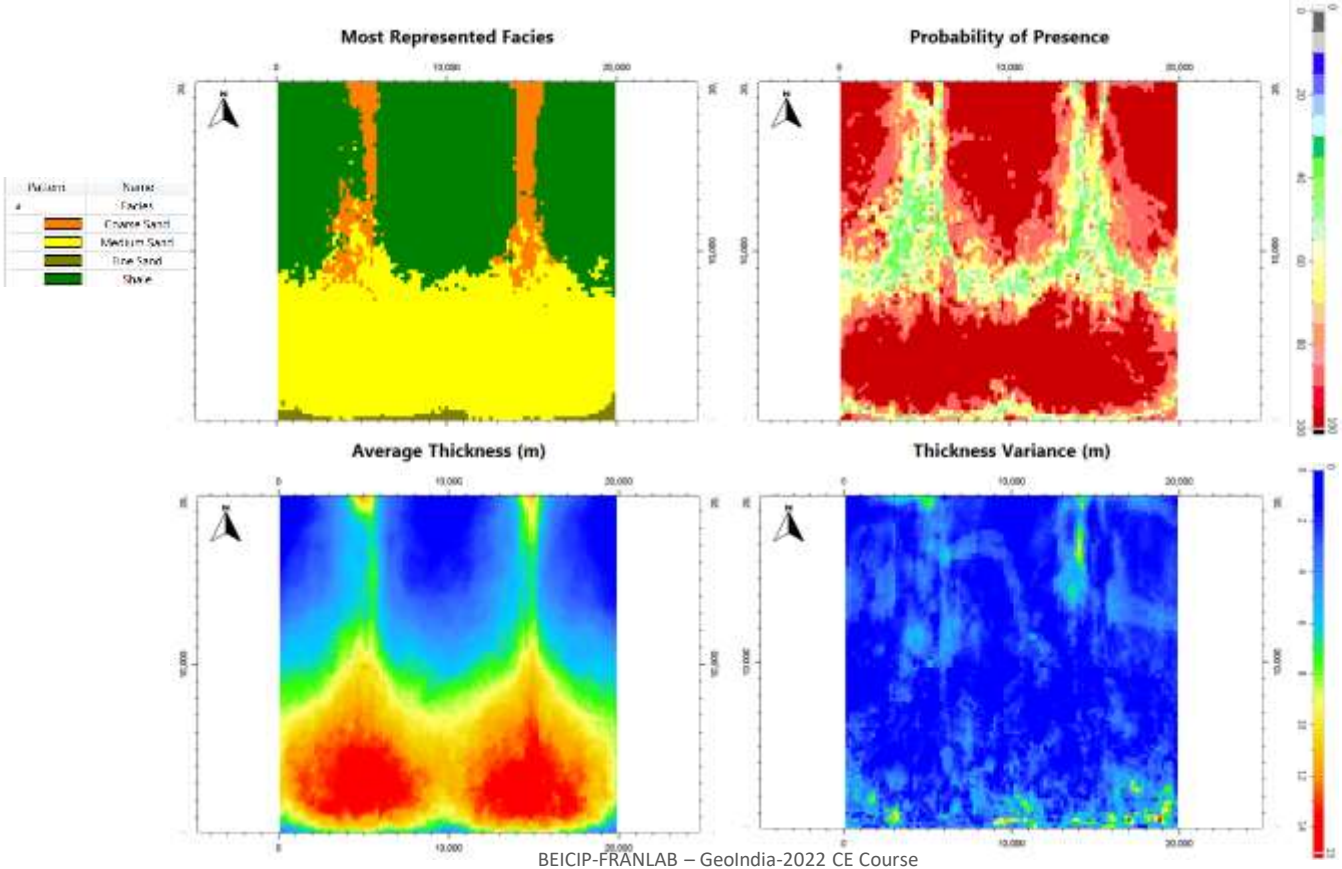
Sensitivity Maps

- Example for the pre-salt deformation sequence:



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Conclusions

- Deformation history and sediment supply are the main controls on the sand facies distribution in deep-sea environments.
- Well defined laterally constrained channel complexes are related to periods of decreasing sediment load (ie. Transgressive?)
- High sediment load periods lead to sand rich and laterally extended channel and lobes complexes (ie. Lowstand – highstand?)
- Multi-realizations generated using ranges of values for the input parameters allow to have alternative models to test sensitivity and reducing uncertainties on results.

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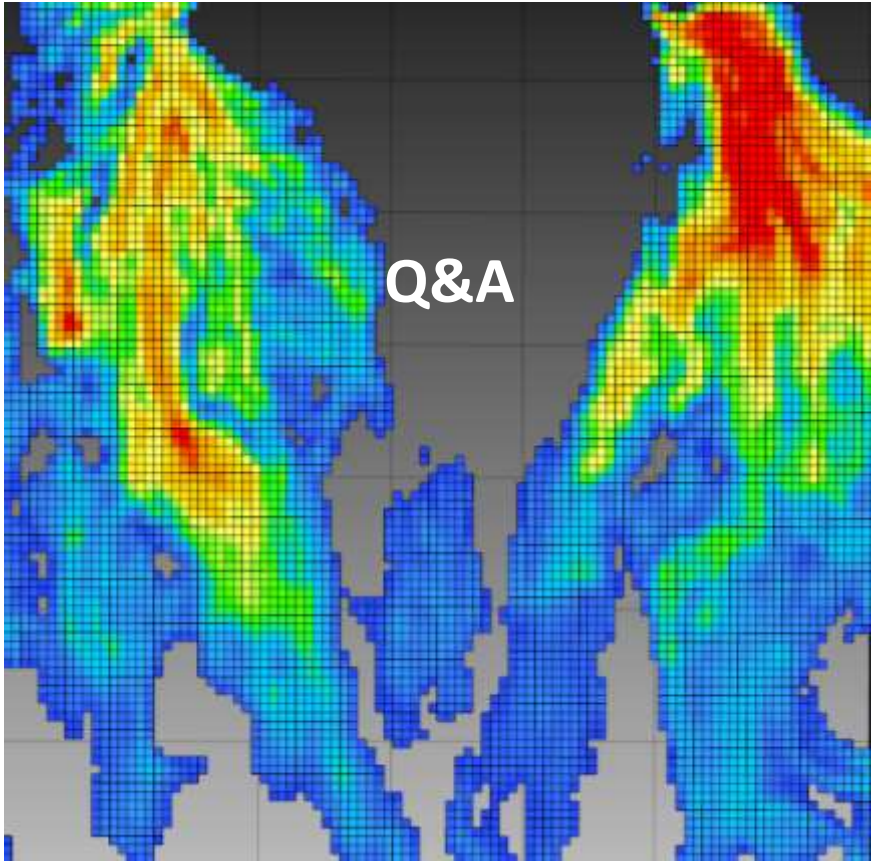

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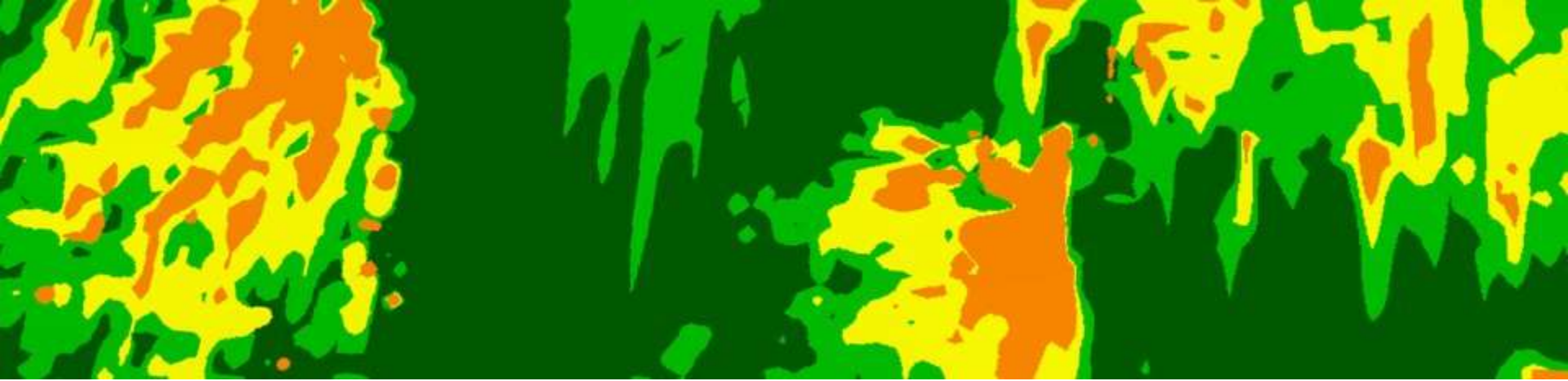

Case Study1:
Offshore Trinidad

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Case Study: Trinidad

Marine and Petroleum Geology 91 (2018) 576–588

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Research paper

Slope-fan depositional architecture from high-resolution forward stratigraphic models

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Deep-water
Channel
Lobe
Compensational stacking

ABSTRACT

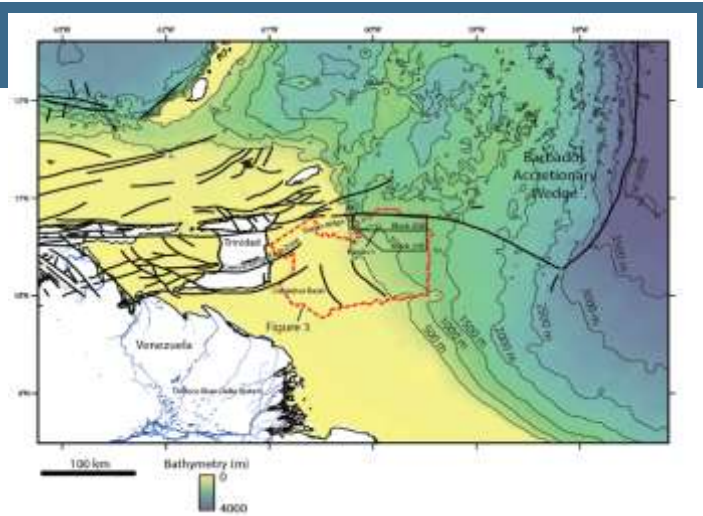
Submarine fans in tectonically active continental-slope basins are targets of petroleum exploration and production. These slope fans commonly comprise compensationally stacked sandy and muddy architectural elements, including mass-transport deposits, weakly confined to distributary channel-and-lobe deposits, and leveed-channel deposits. The lateral continuity and vertical connectivity of these architectural elements are important uncertainties in reservoir characterization that influence fluid-flow behavior during hydrocarbon production. Here, we use a simple forward stratigraphic model to simulate the stratigraphic patterns and illuminate the likely distribution of fine-scale, sub-seismic heterogeneity in a slope fan. We used published seismic-reflection horizons

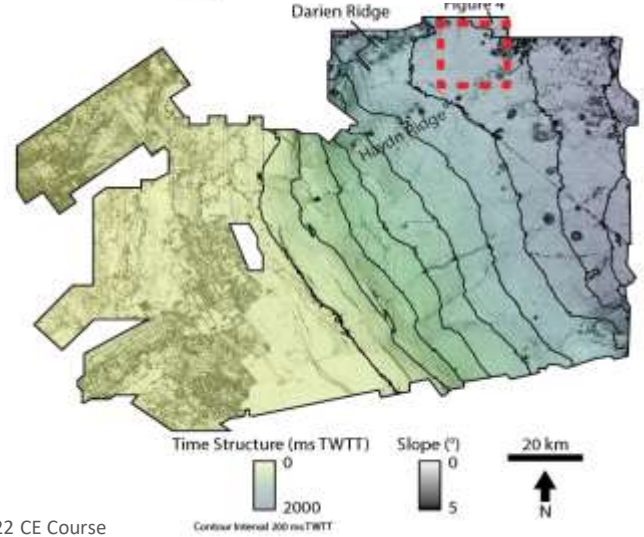
Trinidad Intra-Slope Fan

- Oblique subduction of S.American plate beneath the eastward migrating Caribbean plate since the Miocene

- Development of the Columbus foreland-basin in the present-day shelf offshore E. Trinidad (500 MMBL of oil, >20 TCF gas)

- The Orinoco river-delta system has delivered terrigenous sediment to the Columbus basin and continental margin offshore of Trinidad since the Miocene (>12 km of Pliocene-Pleistocene)





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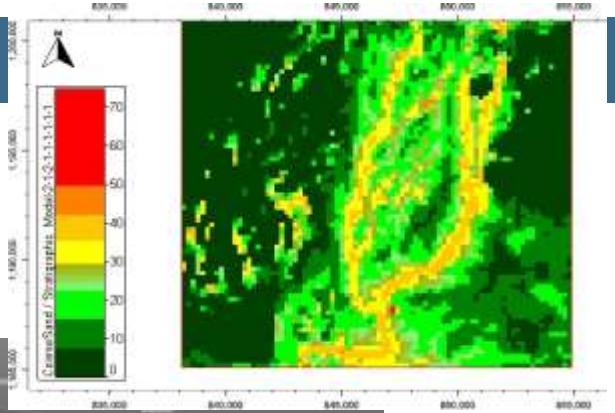
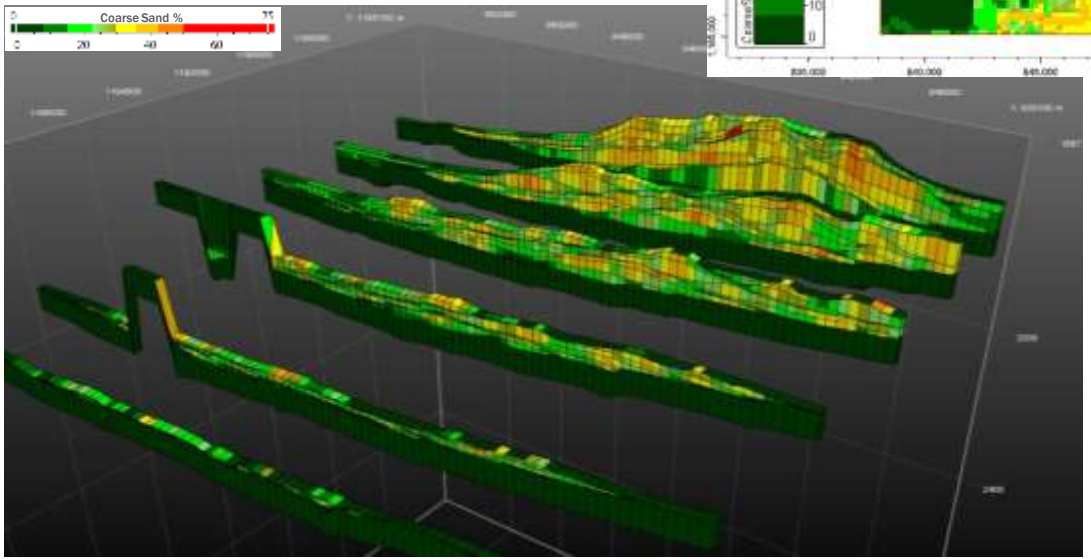
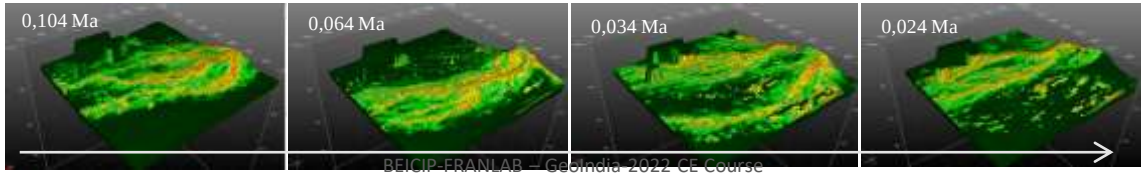
Reference Case Model

Model Specifications:

- 17km*17km
- 200m*200m cell size
- Simulation time steps: 10kyrs







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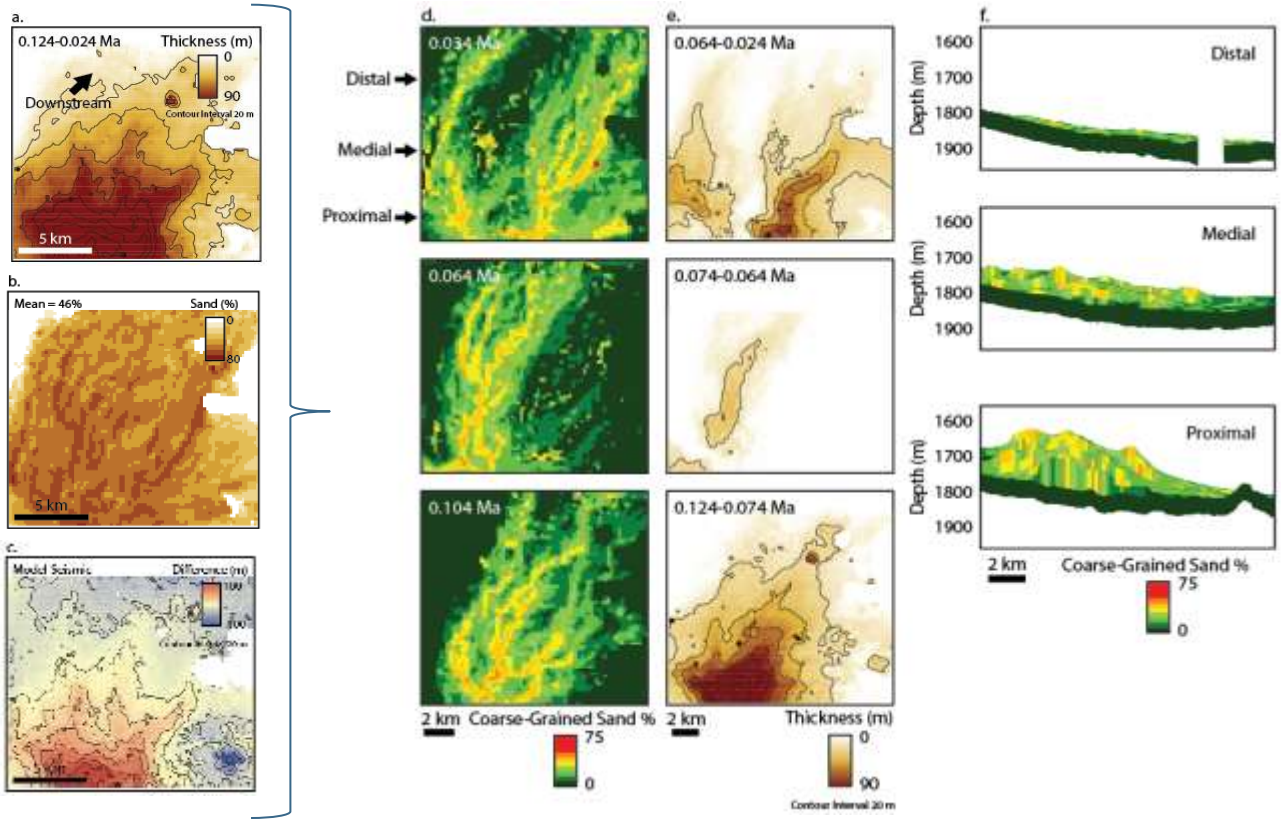
Reference Case Model

Total Model thickness

Overall Sand Proportions

Overall Sand Proportions



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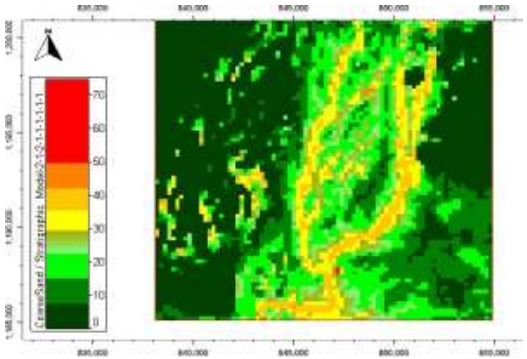
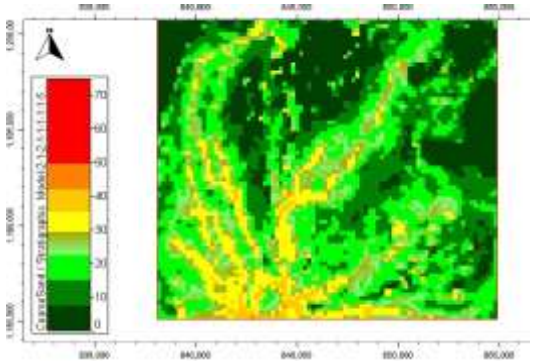
Scaling (1kyrs, 5kyrs, 10 kyrs, 20kyrs time steps)

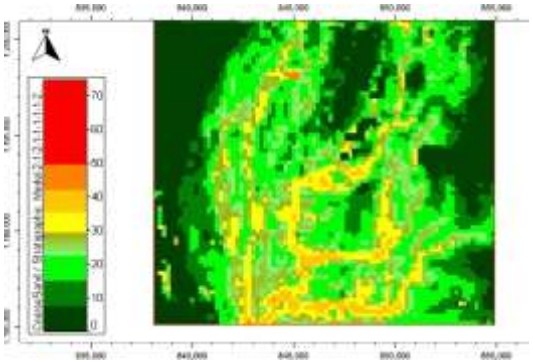
Ref.Case 10 kyr- Time steps



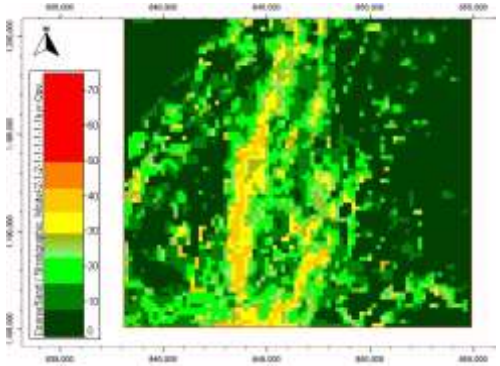
5kyr- Time steps



20 kyr- Time steps



1kyr- Time steps



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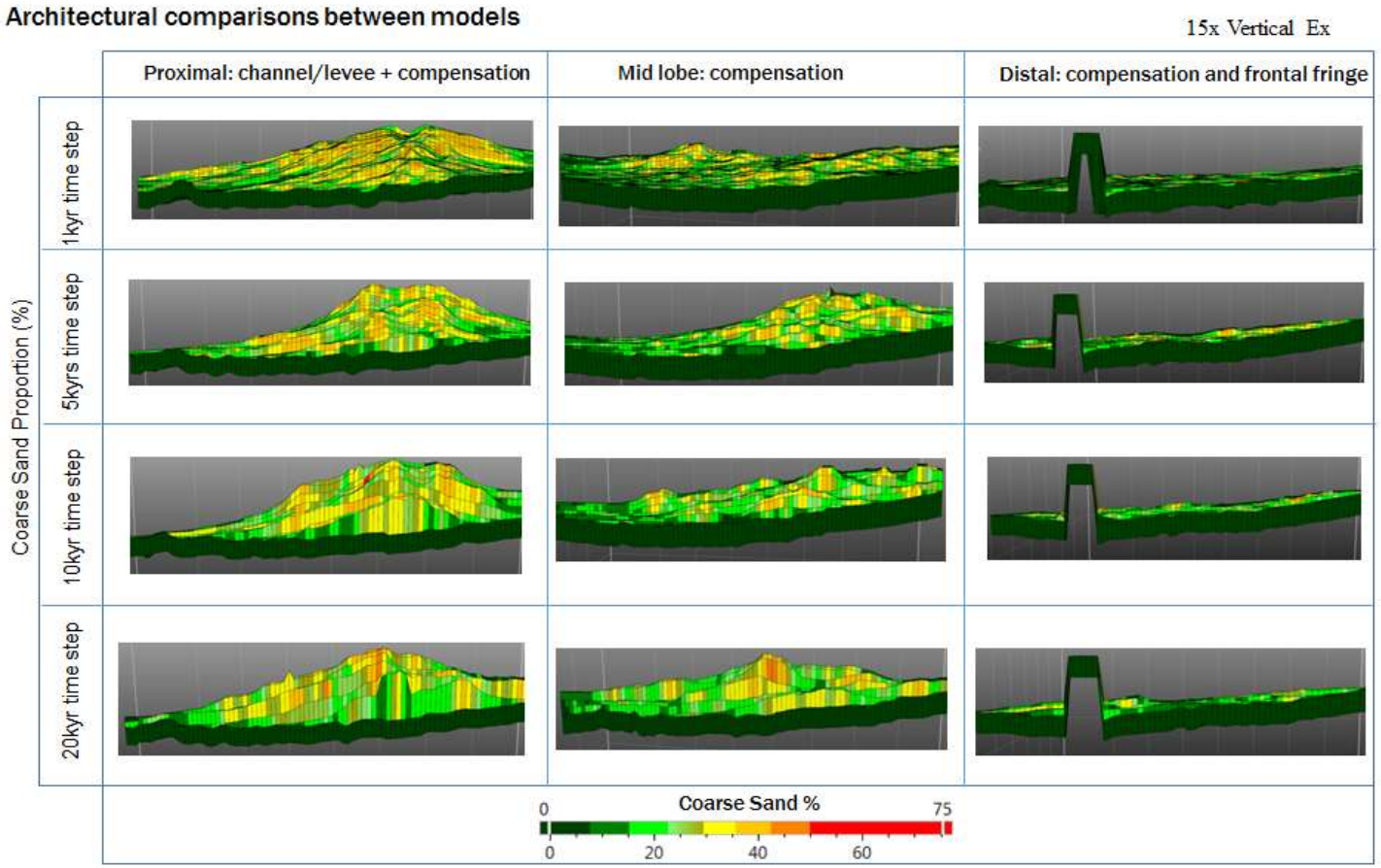
Scaling (1kyrs, 5kyrs, 10 kyrs, 20kyrs time steps)



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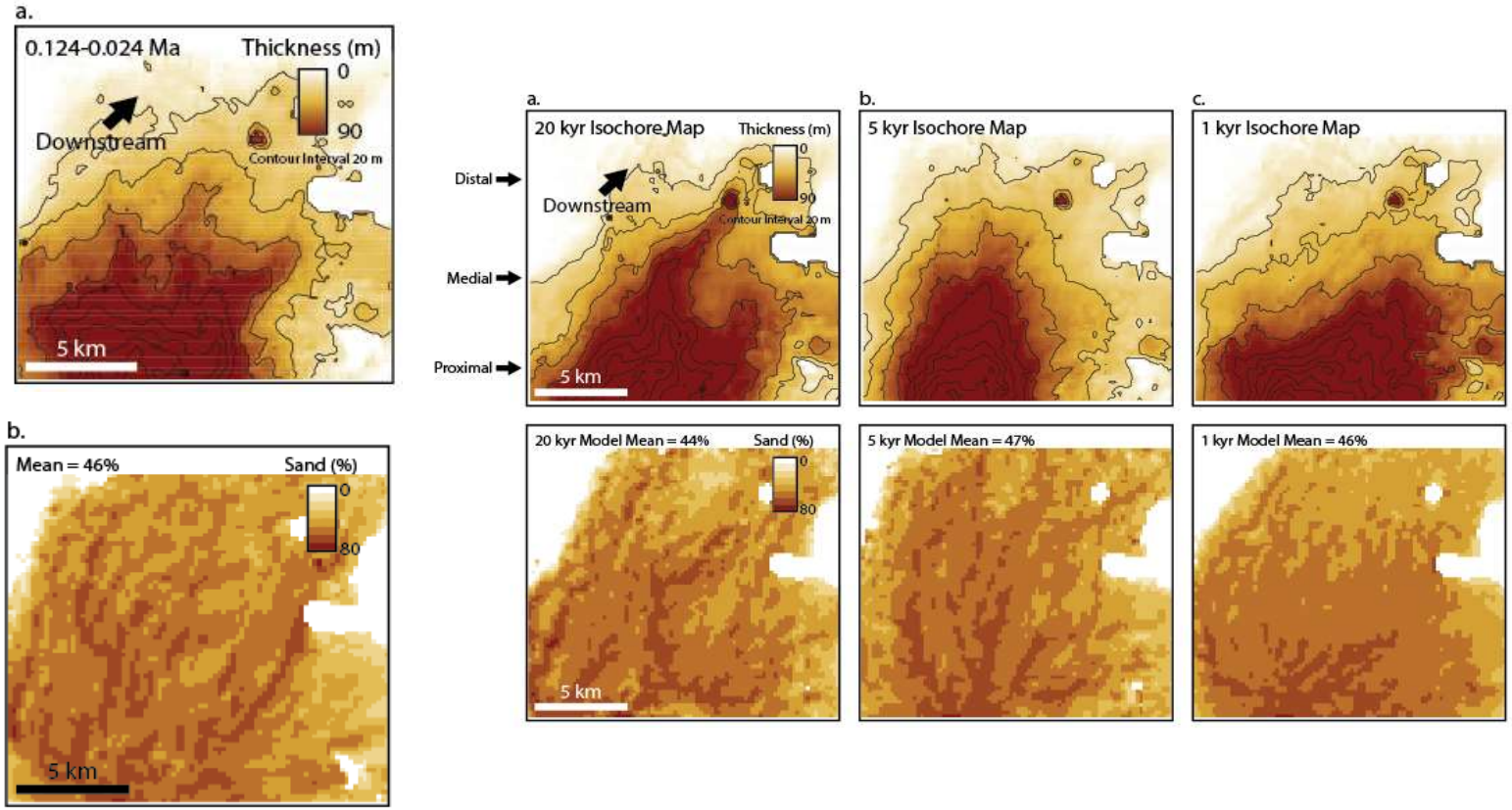
Ref. Case Model versus Multi-Simulations



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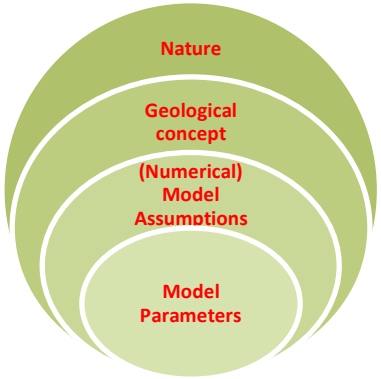
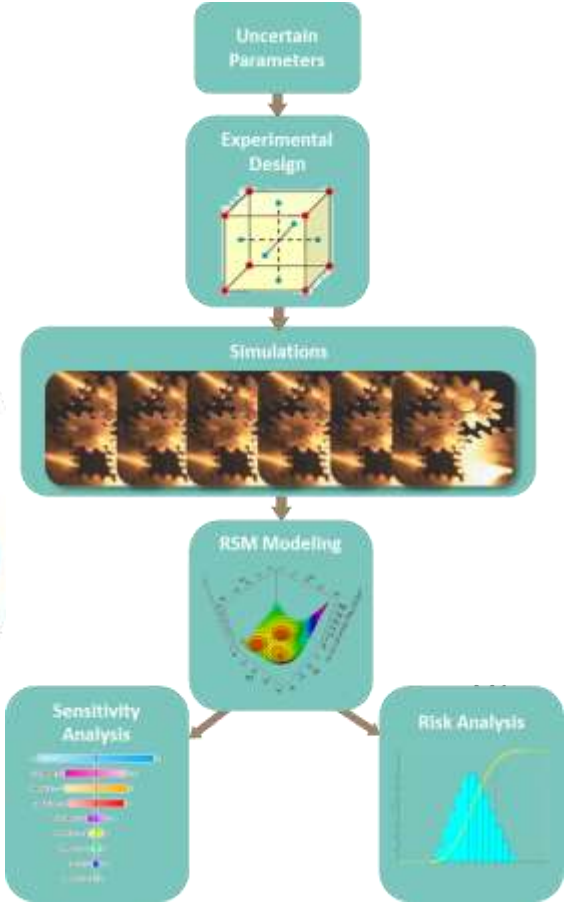
Perspectives: Exploring other Geological Models

CougarFlow coupling allows:

- Alternative scenarios by varying input parameters according to an Experimental Design.
- To assess the impact of main influential parameters on thickness and texture calibration.
- Sensitivity Analysis





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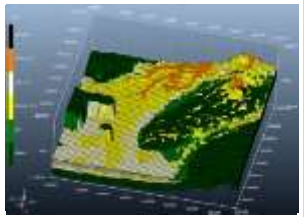
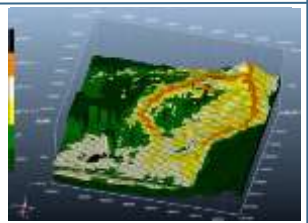
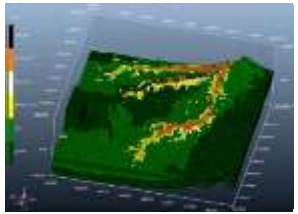
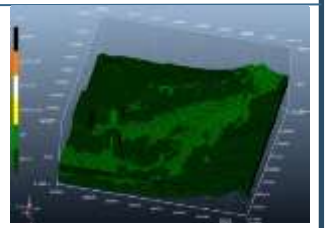
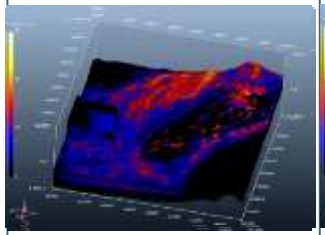
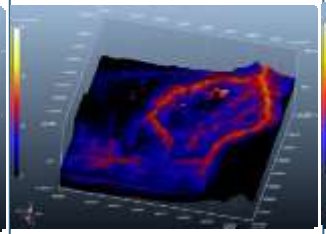
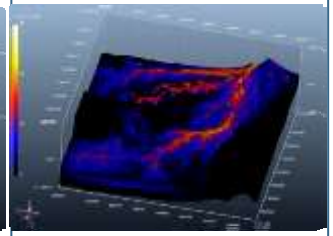
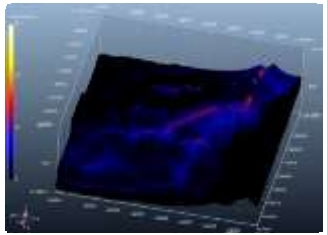
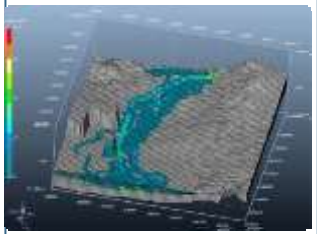
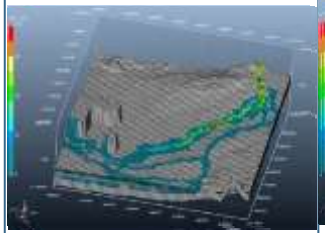
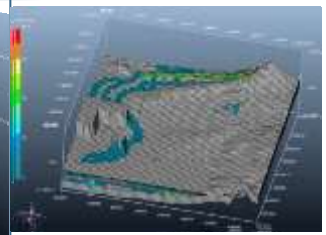
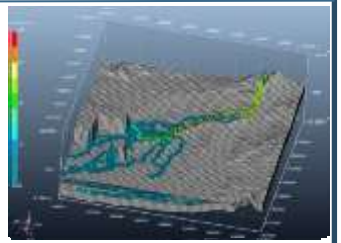
Experimental Design 1 (Shale Content)

Shale Content →	Very Low	Low	Medium	High
Facies				
Coarse Sand				
Water Discharge				

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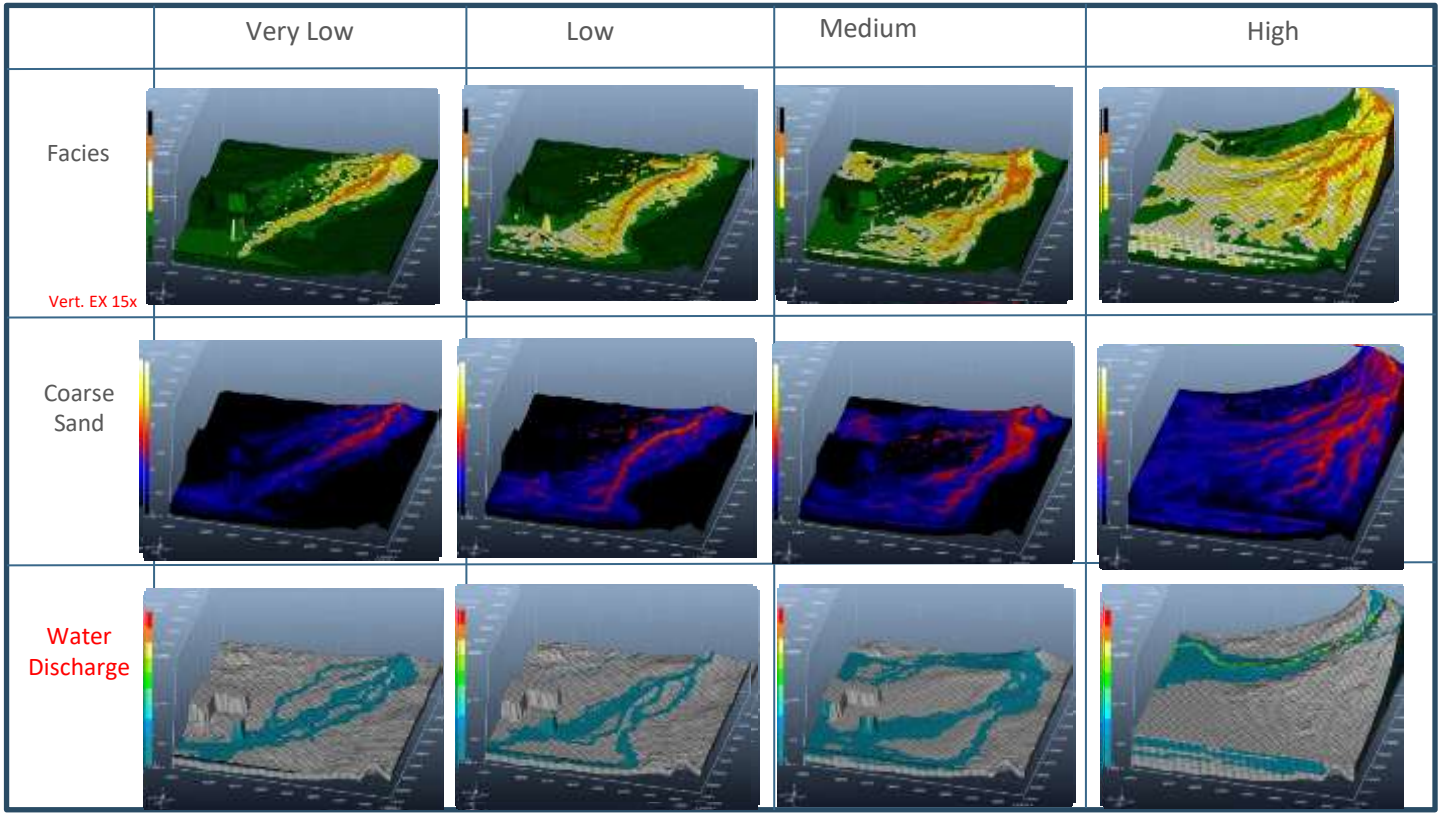
Experimental Design 2 (QW,QS)



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