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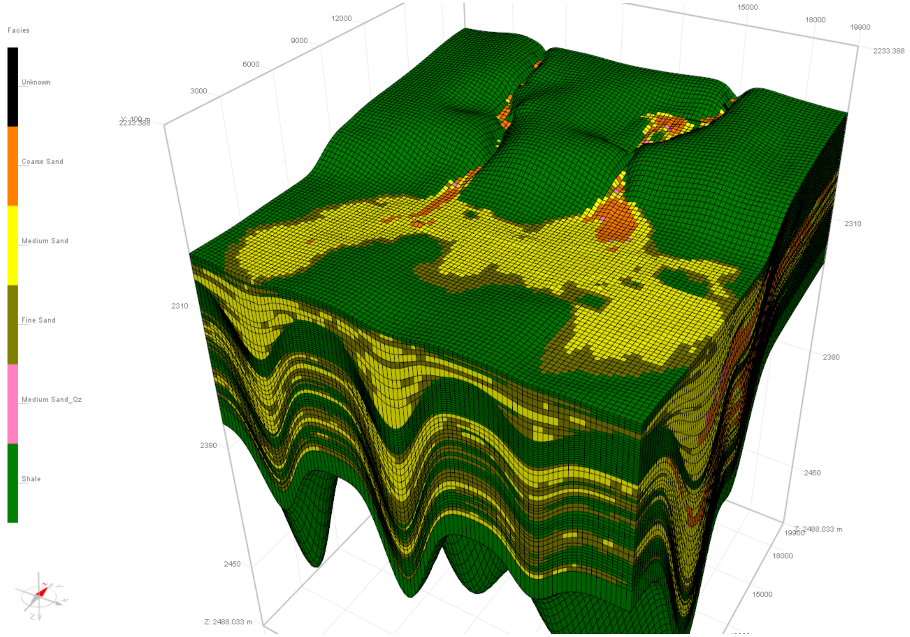
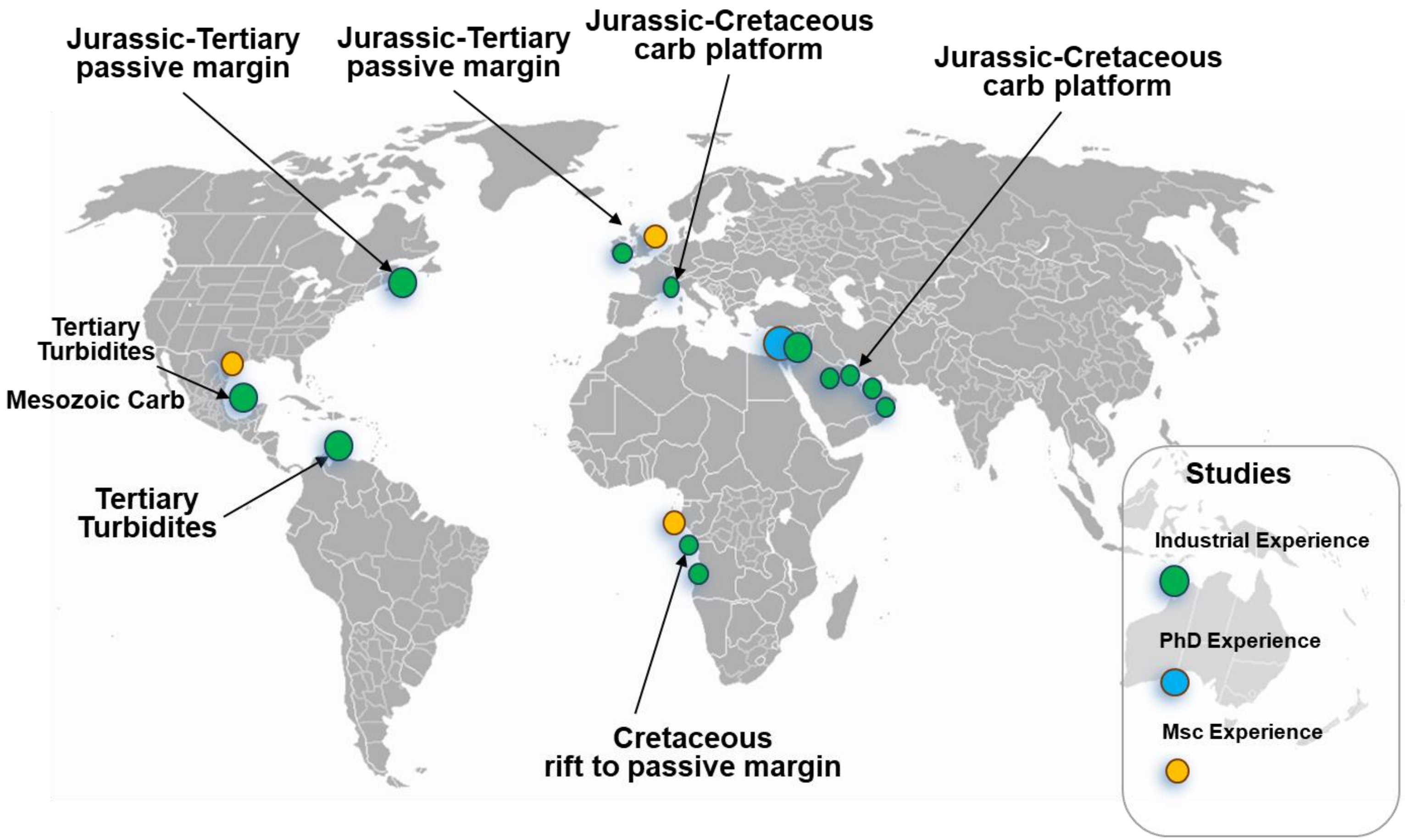
GEO India 2022

Assessing Deep-Water Systems Using Integrated Source to Sink Shared Earth Approach

Nicolas Hawie (PhD)



Experience Overview in Deep Water Systems



International Experience	NOCs, IOCs, Consultants	University Collaborations

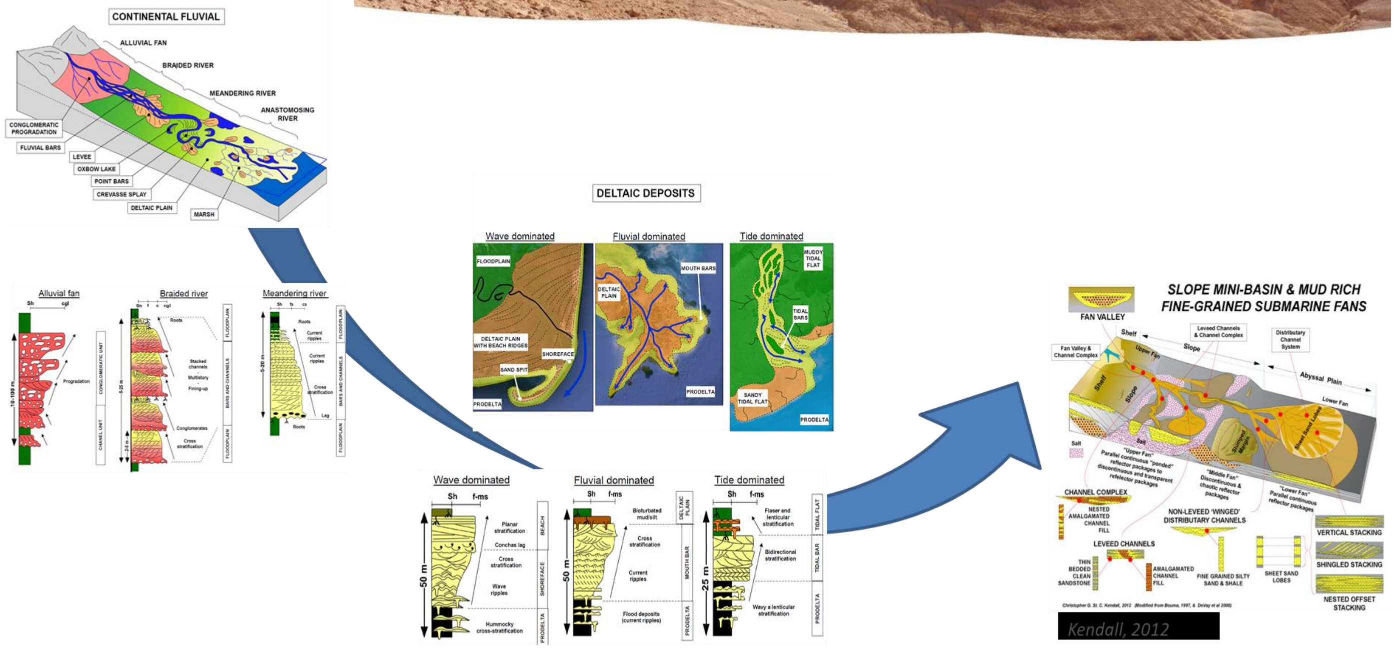
Euro-MENA region

Americas

International Peer-Reviewed Publications

Agenda

- Introduction
  - Petroleum systems
  - Putting things into Perspective
  - Integrated Shared Earth Approach
- Source to Sink Approaches
  - Integrated G&G approach
  - Landscape Evolution
  - Numerical Modelling
- Conceptual Models for Deep Water Systems
  - Siliciclastic Systems
  - Carbonate Systems
- Sequence Stratigraphic Assessment
  - Controlling Parameters
  - Sedimentological log assessment
  - Forward Stratigraphic Modelling
- Integrated Case Studies
  - The Levant Basin, The Canadian Offshore, GoM
- Open Discussions around Indian Exploration Perspective

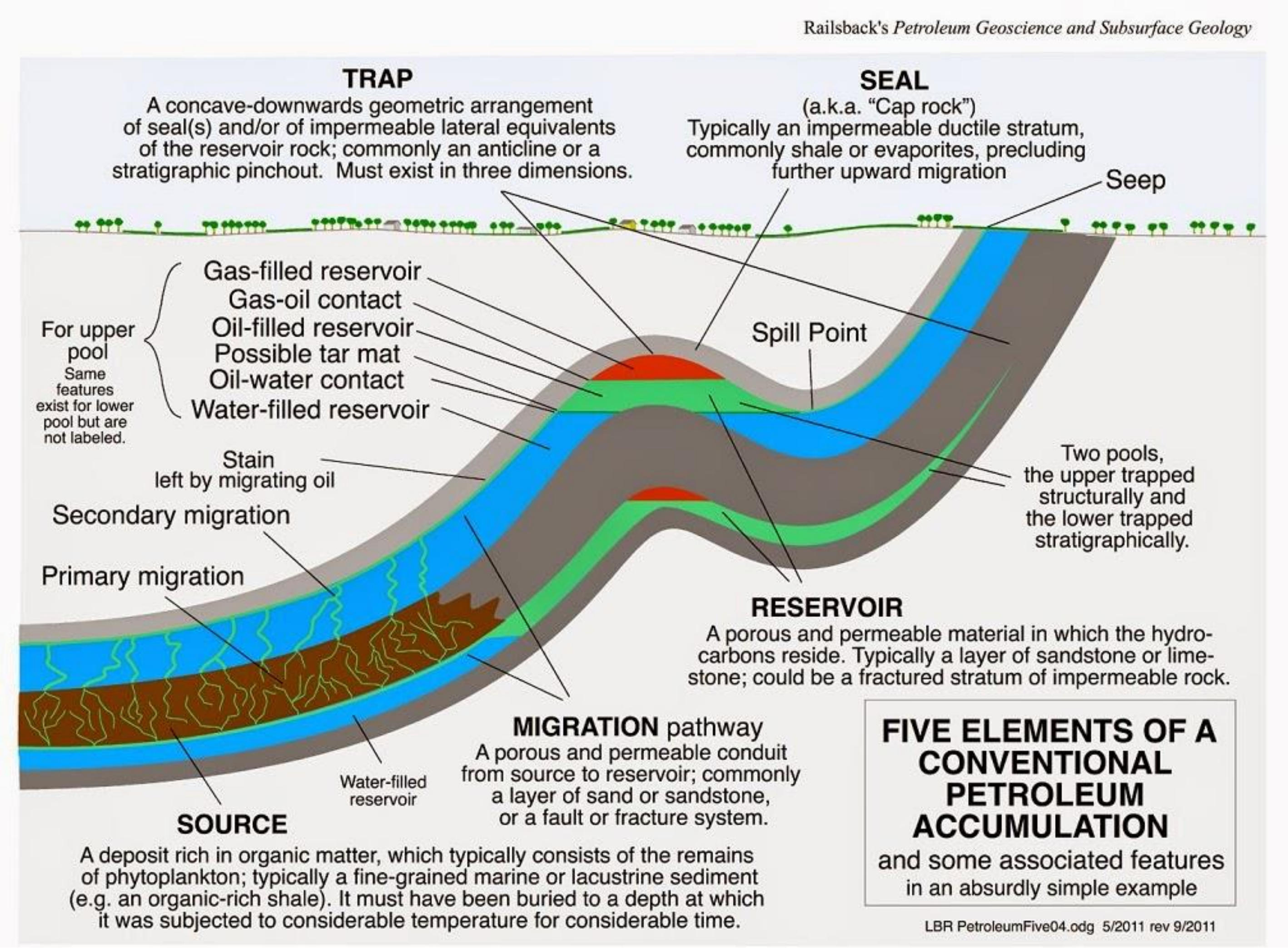


Petroleum Systems: An Overview

- A Petroleum System includes all the geologic elements and processes that are essential to generate a hydrocarbon accumulation

- The essential elements of a Petroleum System include:
    - Source rock,
    - Reservoir rock ,
    - Seal rock,
    - Trap and
    - Migration

- These elements and processes must be correctly placed in time and space so that organic matter included in a Source Rock can be converted into a petroleum accumulation.



Petroleum Systems: An Overview

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- The essential elements of a petroleum system include:
    - » Source rock
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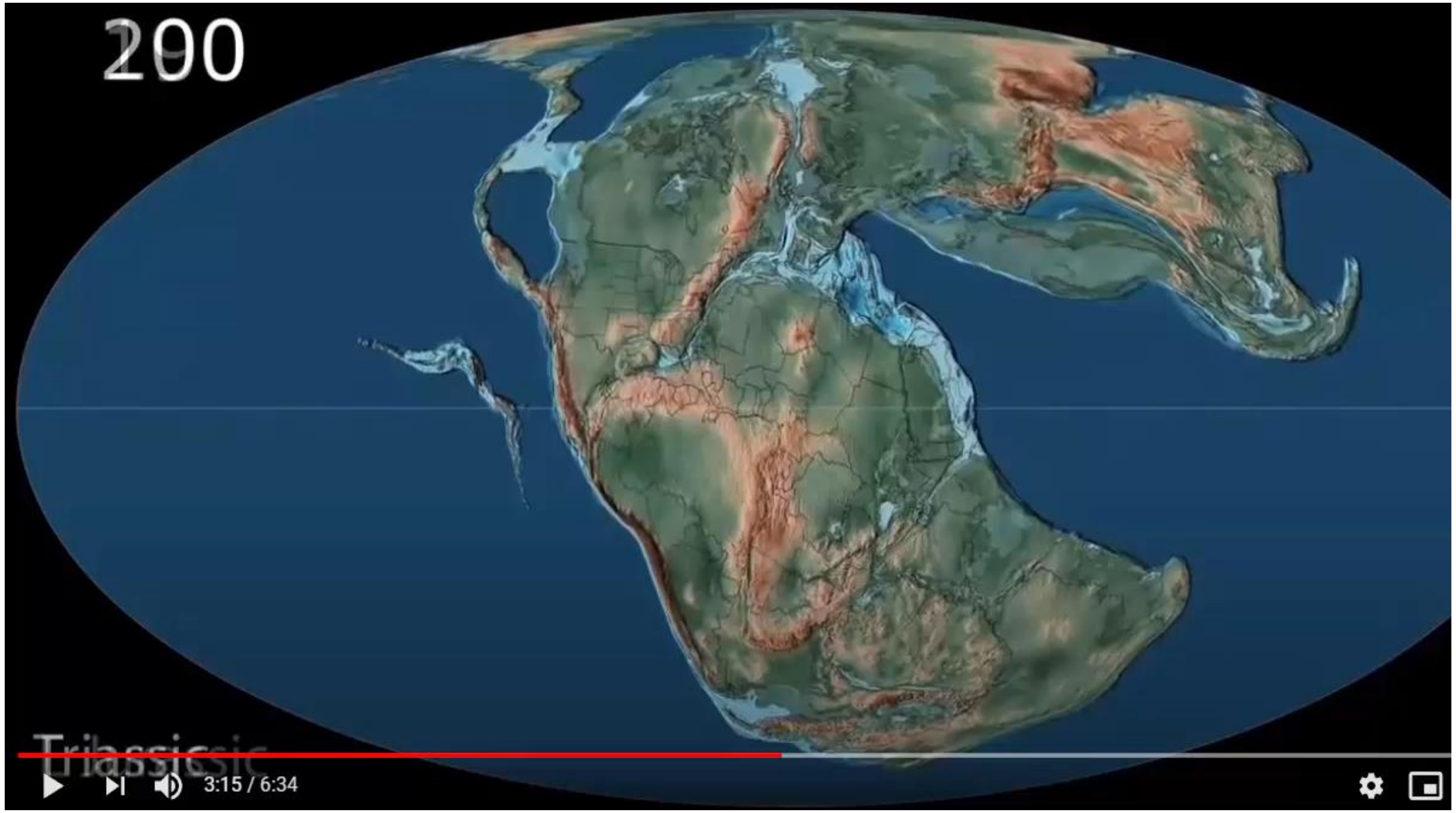
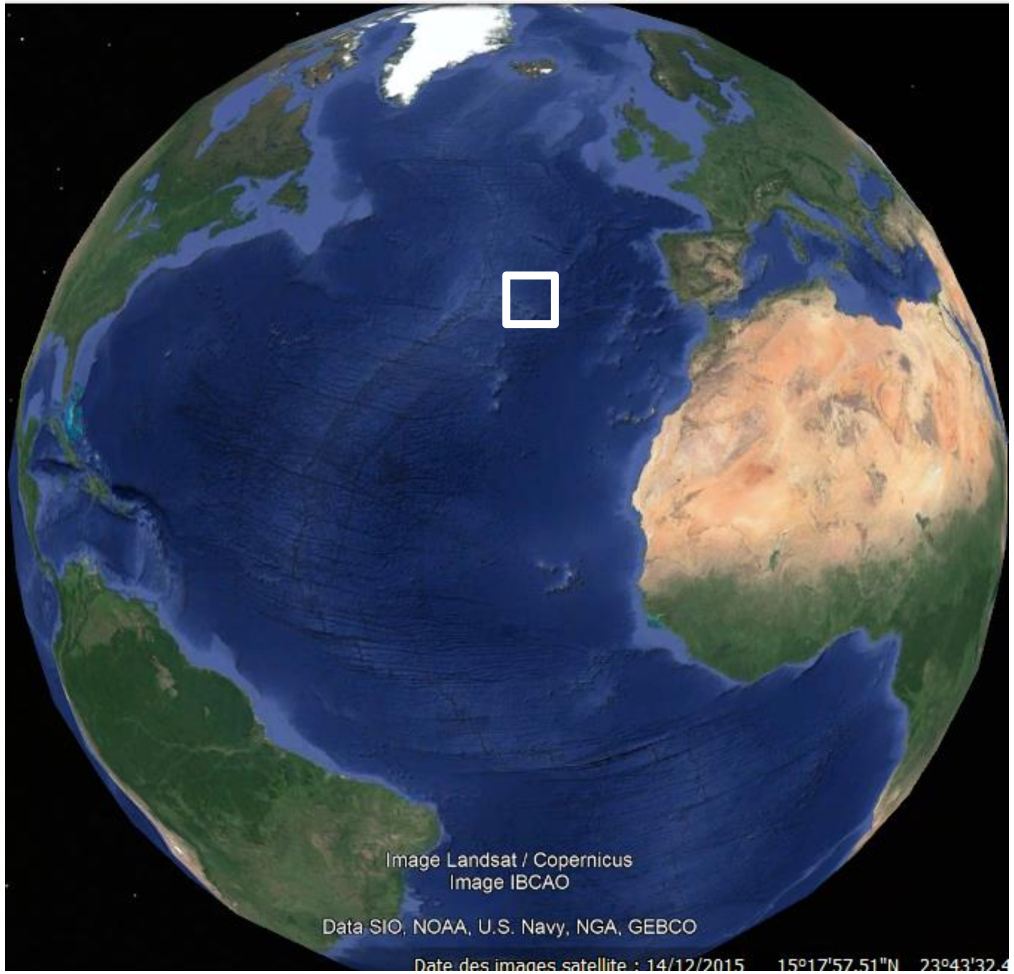
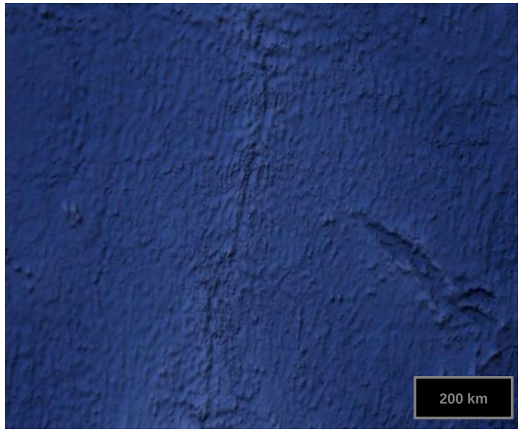
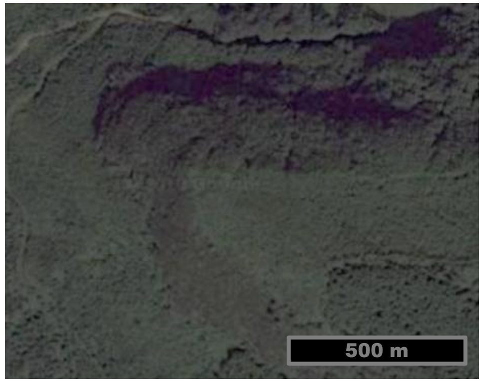


Putting things into Perspective







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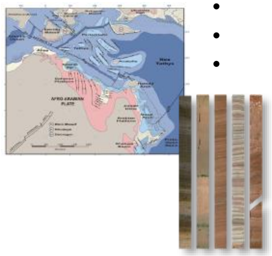
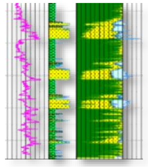
Integrated Shared Earth Approach

Sedimentological and Stratigraphic Assessment

- Sedimentological Core Descriptions
- Well Correlations
- High Resolution Sequence Stratigraphy



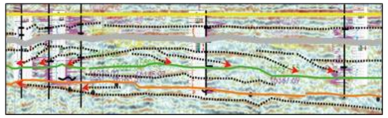
Petrophysical Assessment



- Log correlation
- Lithologies and facies prediction
- Potential Fluid Assessment

2D- 3D Seismic Stratigraphic Interpretation

- Reflector termination
- Reflector Stacking Patterns
- Reflection configuration



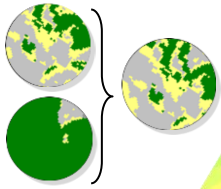
3D Seismic Attribute Assessment

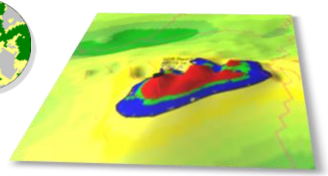
- RMS Amplitude (lithology/porosity)
- Spectral Decomposition (good, sedimentology + fluids)
- Waveform Classification/PCA (Facies + reservoir parameters)
- Sweetness (lithology-fluids?)
- Coherency (sharp stratigraphic boundaries, faults)

Pre-Drill & Geomechanics

Prospect Ranking

- De-risking
- Well Location Planning



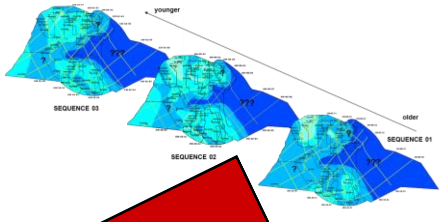


Prospect Delineation

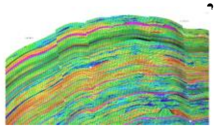
- Structural and Stratigraphic
- Volumetric Assessment

3D Mapping of Geobodies:

- Lateral+ Vertical Extension
- Porosities and Potential Fluid Fill
- Overlay of Structural Component
- Off-structure Assessment



3D Seismic Reservoir Characterization



- Pre-stack
  - VP/VS (lithology)
  - LR (fluid filled)
  - MR (lithology)
  - Porosity
- AI-GI (lithology + potential Fluid)
- High Resolution Neural Network

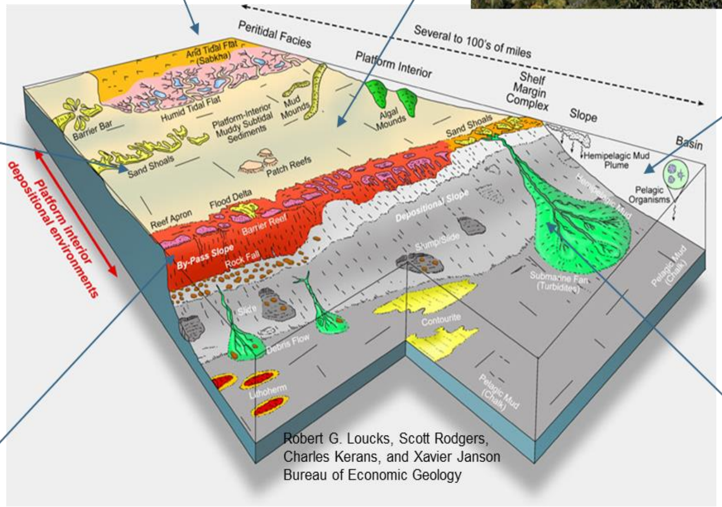
The Geological Model Uncertainties

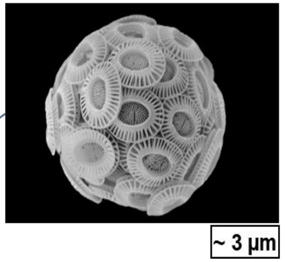
- **Data** uncertainties:
  - Volume of data available
  - Spatial extent covered (poor versus wide coverage)
  - Type of data (single set versus multi-scale & multi-disciplinary)
  - Quality and consistency of datasets

- **Interpretation** uncertainties:
  - But what is in between well data?
  - How can we extrapolate in regions not covered by any dataset?
  - Complexity of multi-scale & multi-disciplinary data integration
  - Non-uniqueness of interpretations!

Sandy/Oolitic Shoals

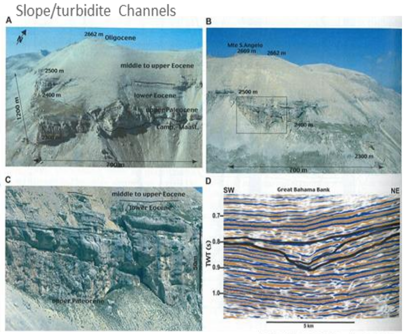
AAPG Methods in exploration N°11, 1994



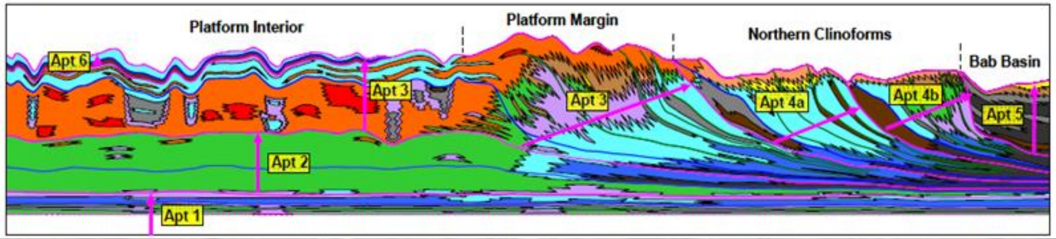


Great Barrier Reef

Slope/turbidite Channels

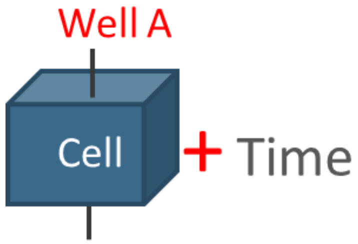


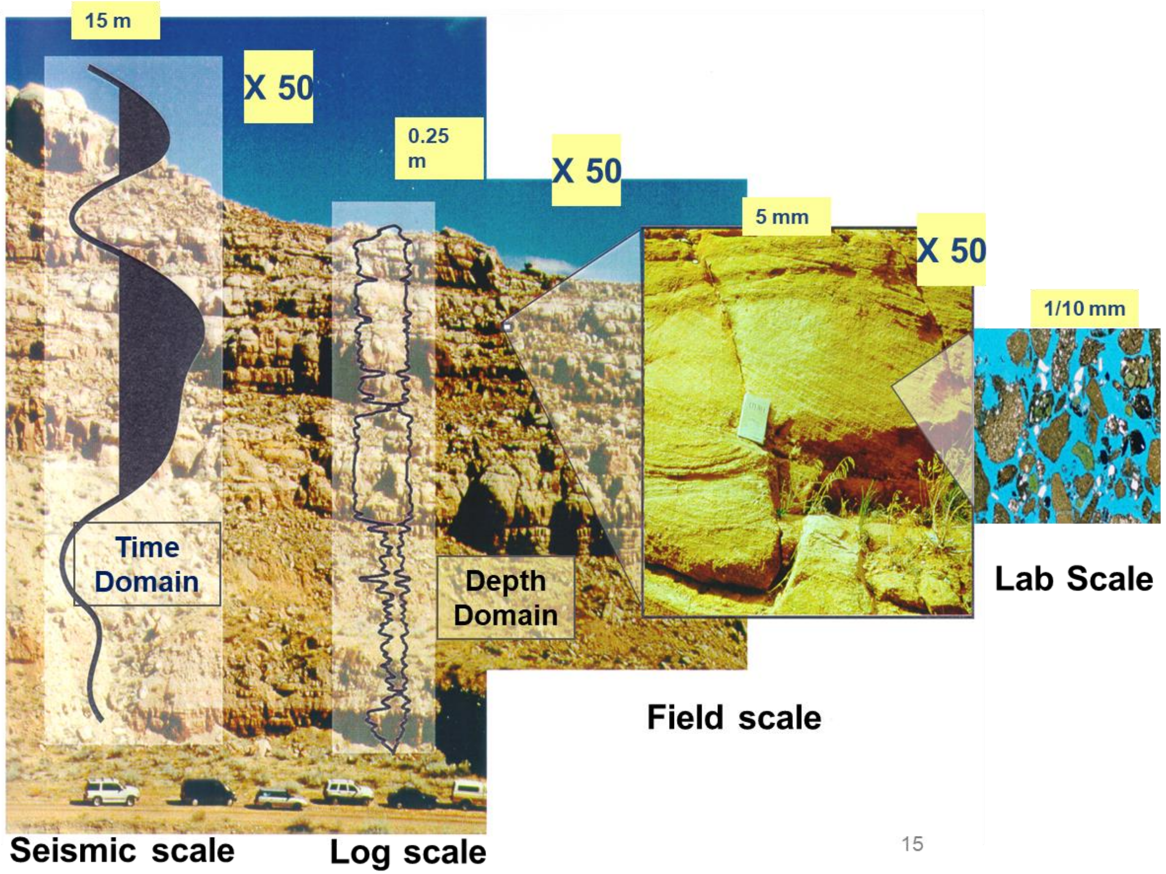
Eberli in AAPG Memoir 81, 2004



Bridging the Scale Gap

Space + Time!!





HIERARCHY OF DEPOSITIONAL SEQUENCES AND RELATED PROCESSES

ORDER	1st	2nd	3rd	4th/5th
DURATION	> 50 My	3–50 My	3–0.5 My	400,000 } (Eccentricity) 100,000 } 40,000 (Obliquity) 20,000 (Precession)
MAIN PROCESS	Long-term global tectonics	Medium-term global tectonics	Local tectonics	Orbital control
EFFECTS	• Atmospheric CO_2 (Ice / Greenhouse) • Volume of mid-ocean ridges (sea level)	• Amplification / damping of 1st order effects • Orogenies	• Sea level / base level • Sediment supply • Long-term climatic change	• Short-term climatic changes: -Rainfall / runoff -Zonal T° gradient -Zonal wind stress -Sea level

Source to Sink Approaches

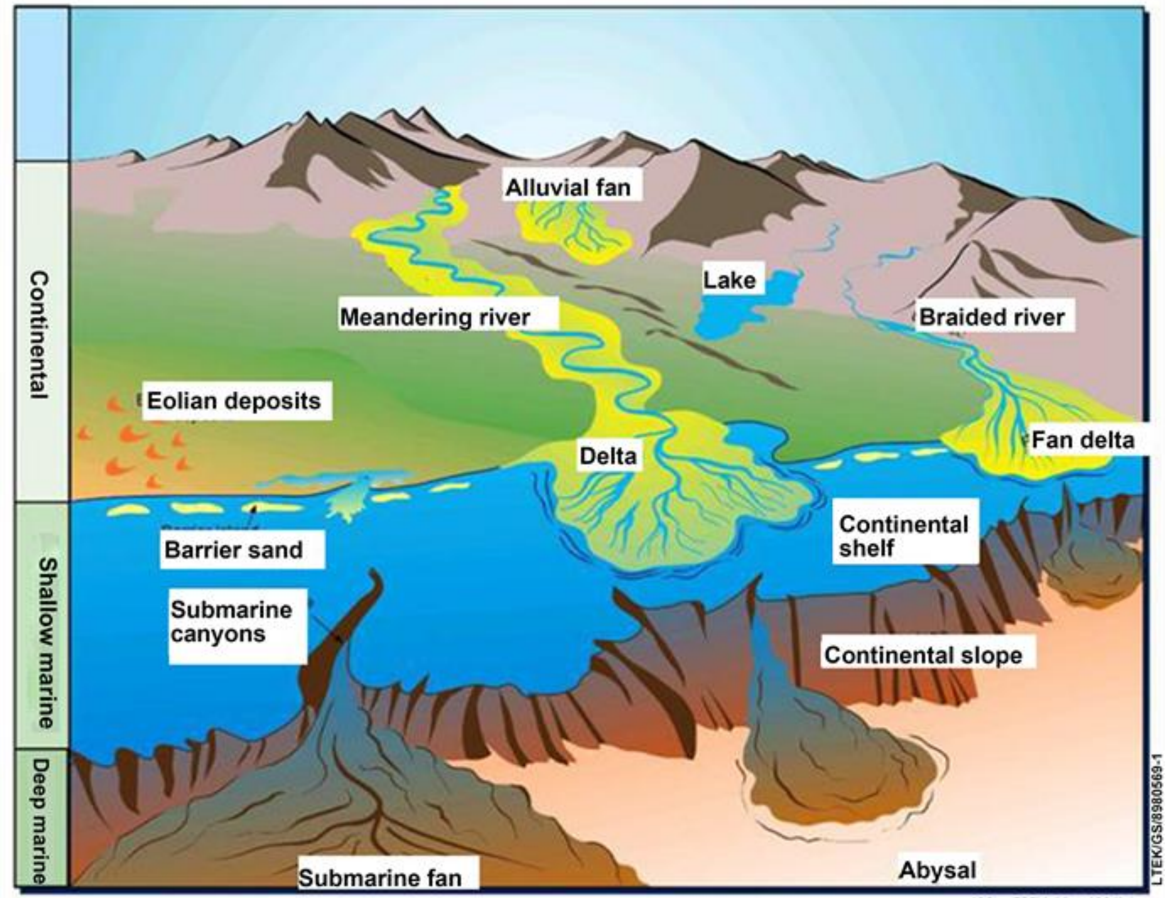
Source To Sink Approaches in Mixed Sedimentary Systems

- A Siliciclastic System is composed of silica-rich sedimentary rocks generated dominantly though mechanical erosion, transport and deposition and successive burial

- A Depositional System represents various related processes that drives sediments from a ‘source’ to a ‘sink’.

- Multiple Depositional Systems are studied:
  - Continental Depositional systems (inc. Glacial)
  - Transitional Depositional systems
  - Marine Depositional systems

- The associated sedimentary architecture and lateral and vertical facies associations are dependent of the various depositional setting

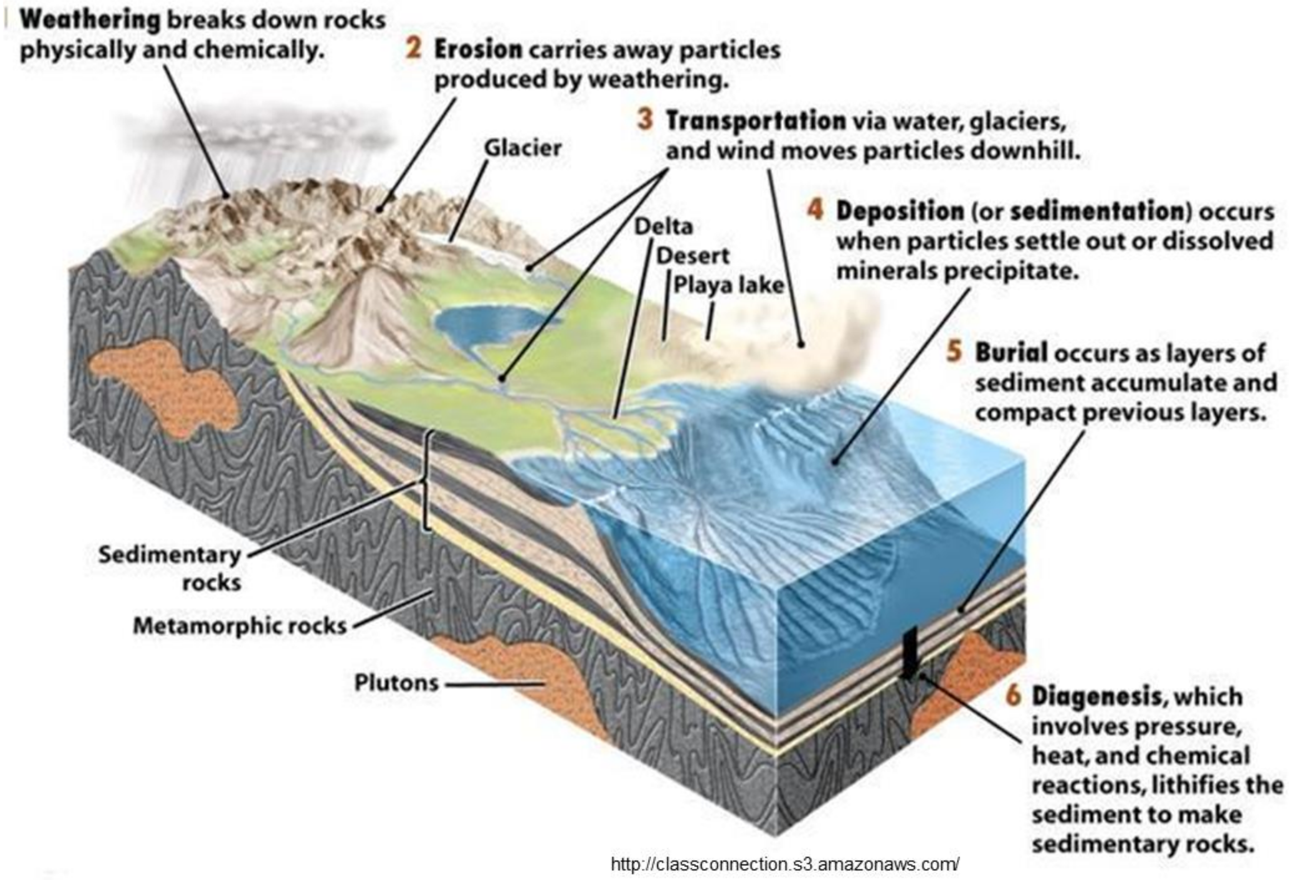


(After BjØrlykke, 1984)

Source To Sink Approaches in Mixed Sedimentary Systems

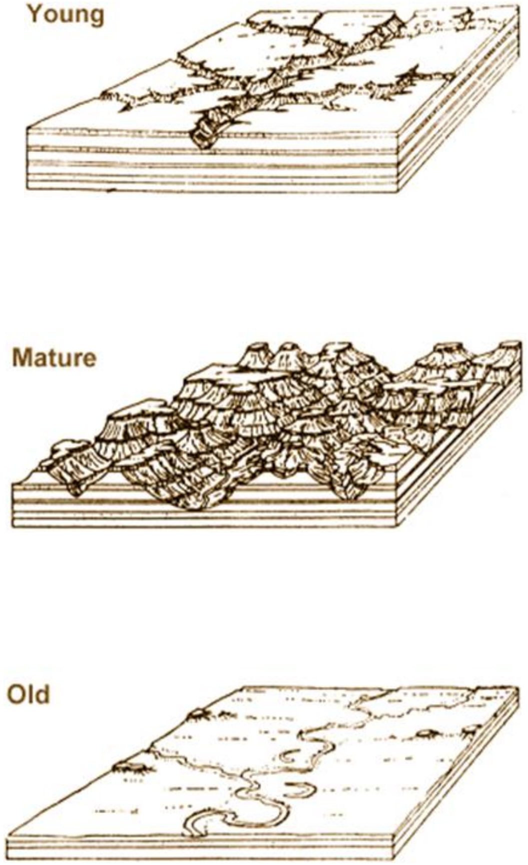
- Various processes need to be closely assessed in order to be able to depict the depositional pattern of sedimentary systems
  - Weathering
  - Erosion
  - Transport (via water, wind, gravity)
  - Deposition
  - Burial
  - Diagenesis

- Depositional systems represent modern processes and associated features which are used to interpret ancient sedimentary systems through observations and comparisons



Landscape Evolution

- Geographic cycle (Davis,1912): following its creation by an initial rapid tectonic uplift, landforms evolved in a sequence of young, mature and old stages. **This evolution is driven by rivers and streams** which progressively reduce the land surface to a peneplain, a low-relief plain close to the sea level.



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Landscape evolution

- Landscape studies have demonstrated that rivers and streams are the most important landscape carving tool and sediment transport agent (Walling and Webb, 1996; Syvitski, 2003; Orme, 2007). Rivers provide around 15 to 50 Gt each year which correspond to 95 % of sediment entering the ocean (Syvitski, 2003).

	Sediment supply (Gt/y)	Sediment supply (10^6 km^3/My)	Yield (t/km^2.y)	Denudation rate (m/My)
Lopatin, 1952	12.7	5.1	91	36
Fournier, 1960	51.1	20.4	365	146
Schumm, 1963	20.5	8.2	146	59
Milliman and Meade, 1983	13.5	5.4	96	39
Milliman and Syvitski, 1992	20	8	143	57
Ludwig and Probst, 1998	16	6.4	114	46
Deadkov and Mozzherin, 2000	15.5	6.2	111	44

Sediment delivery to the oceans by rivers (after Walling and Webb, 1996)

Importance of a **source-to-sink** approach to understand a full sedimentary basin, or just the deep-water systems.
A source-to-sink model is not required, but an analysis of sources is useful.

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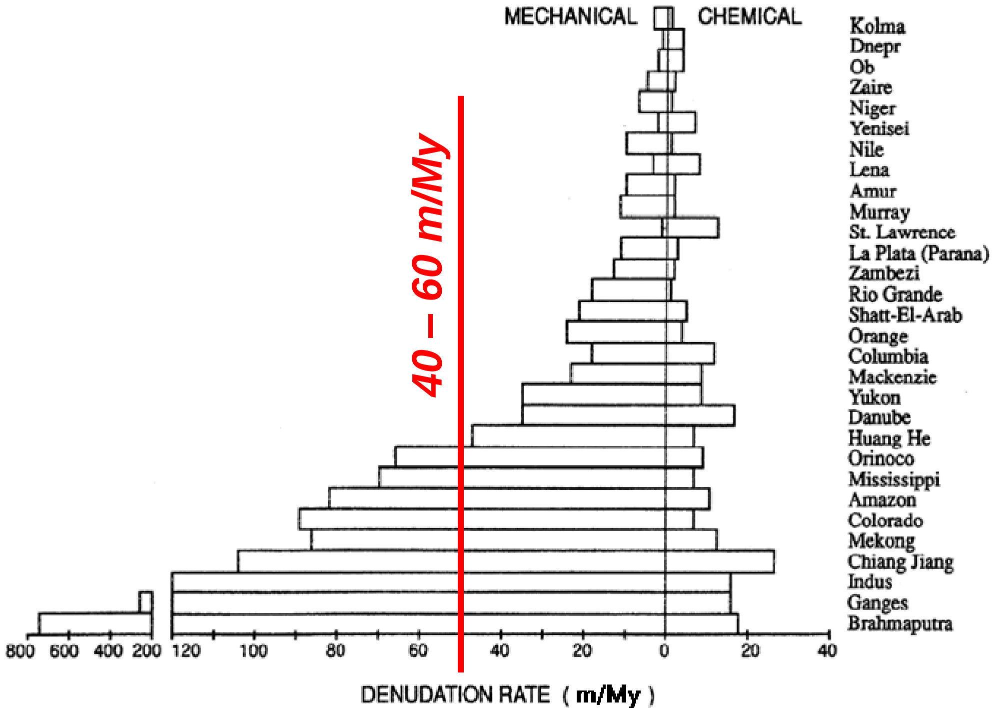
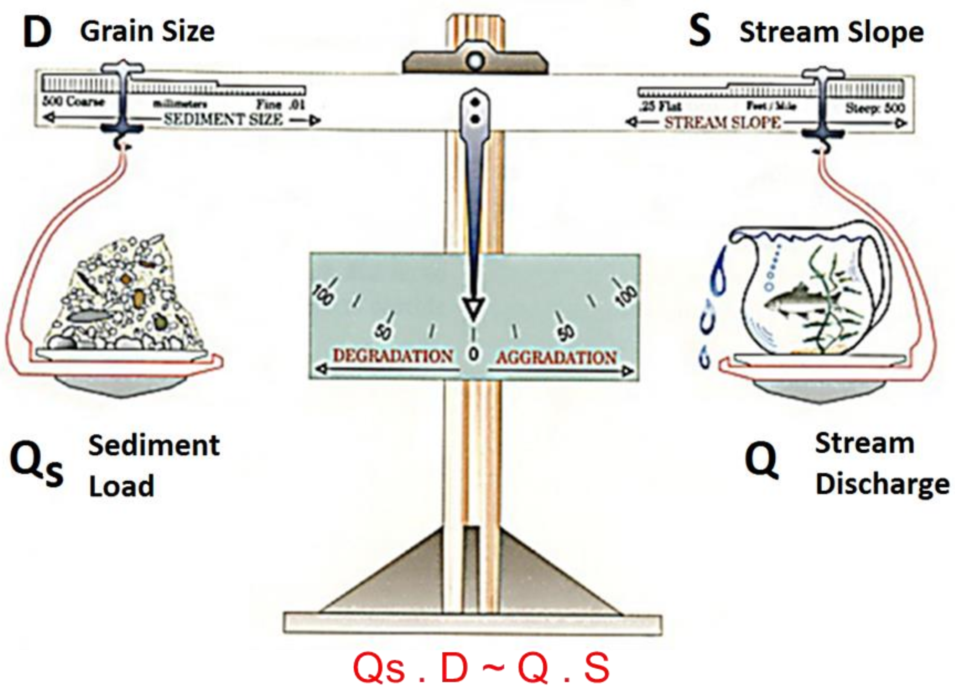
Landscape evolution

- Observations of sediment yield: The worldly-average denudation rate is about 40 to 60 m/Ma. Summerfield and Hulton (1994) demonstrated that the key factors controlling denudation rates are variables expressing basin relief characteristics and runoff.

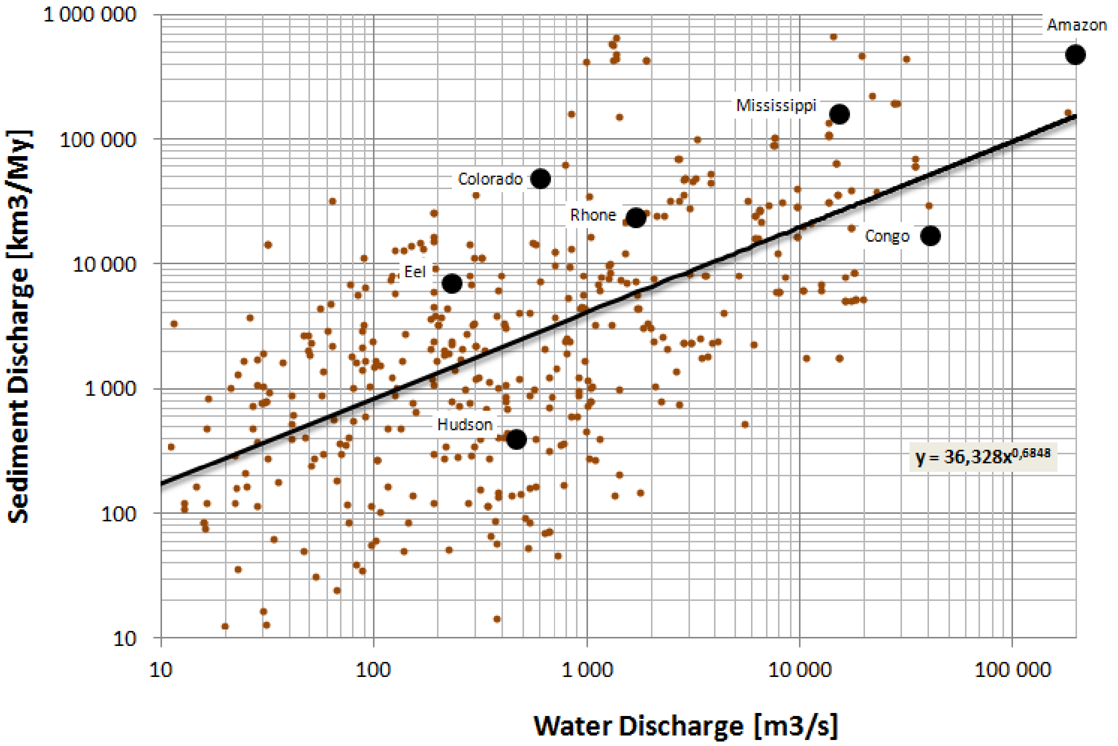


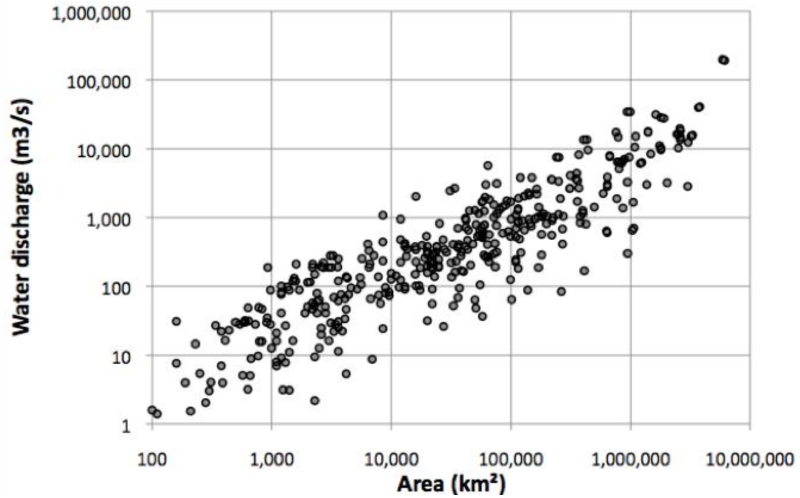
- From observation to physics: a river system is in equilibrium if its transport capacity is equal to its load (Lane, 1957).
- If the transport capacity is greater than the load, then erosion occurs to satisfy this excess transport energy.
- On the contrary, if the transport capacity is less than the load, deposition occurs in the channel.

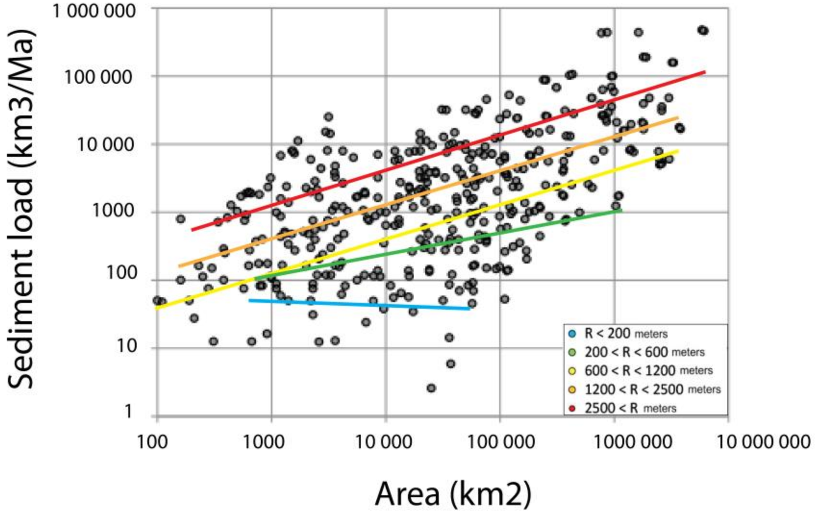


Yearly average Water Discharge QW and Sediment Load QS

- Since the early work of Holeman (1968), and Milliman and Meade (1983), and thanks to the increasing numbers of gauging stations, huge data bases are available and allow us to study long-term behavior of rivers.







from Dai and Trentberth, 2002, Syvitski and Milliman, 2007

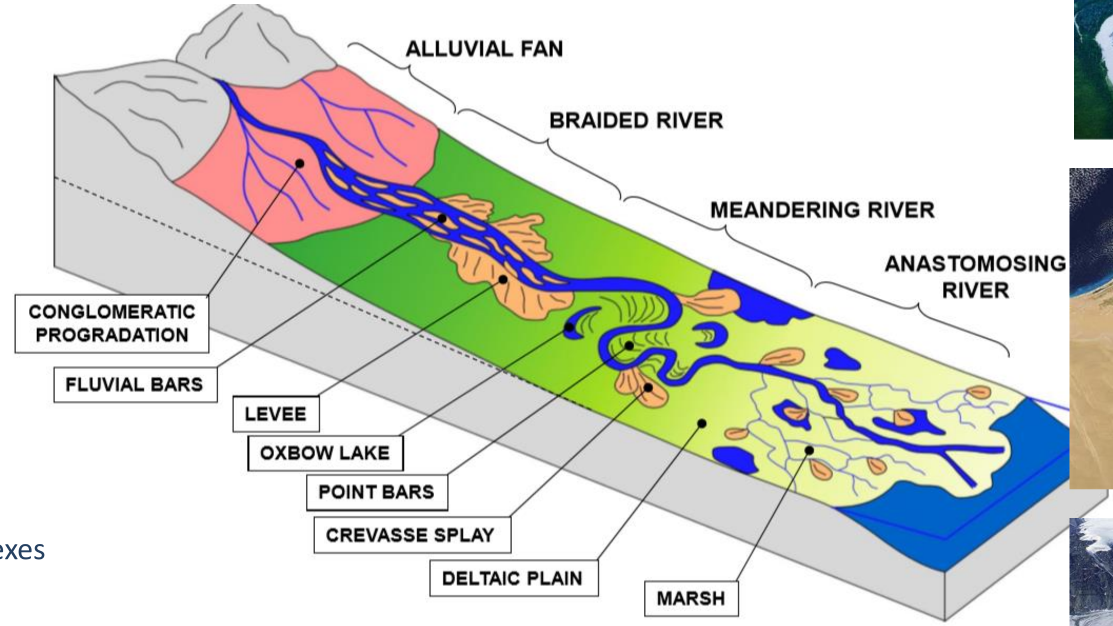
From Source To Sink (From Continental to Transitional)

- Continental Fluvial Systems:
  - Alluvial Fans
  - Braided Rivers
  - Meandering Rivers
  - Anastomosing Rivers/ Deltaic Plains

- Deltaic and Coastal Systems:
  - Wave Dominated Deltas
  - Fluvial Dominated Deltas
  - Time Dominated Deltas
  - Costal Deposits/ non deltaic

- Marine/Deep Marine systems
  - Canyons
  - Turbidites and Mass Transport Complexes

- Glacial Systems

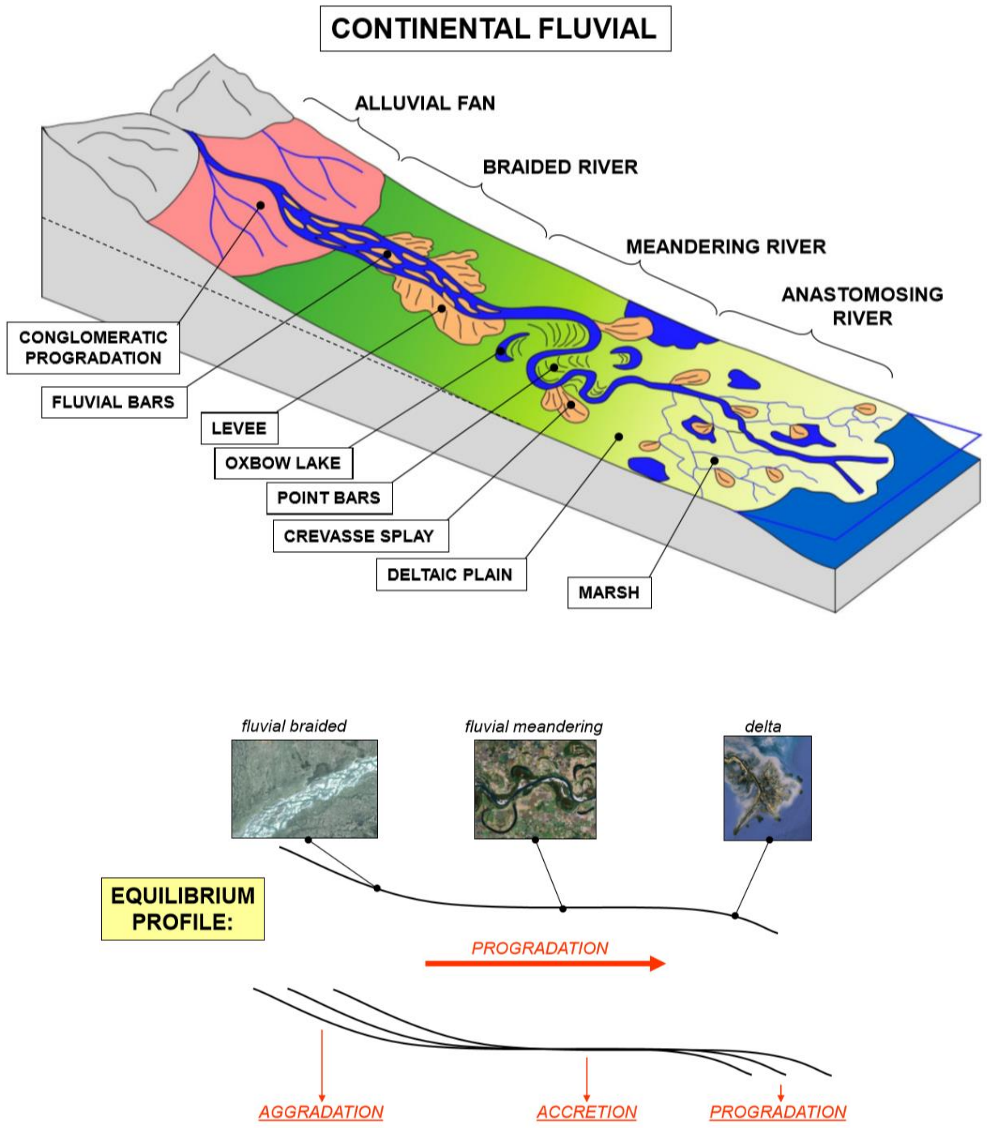


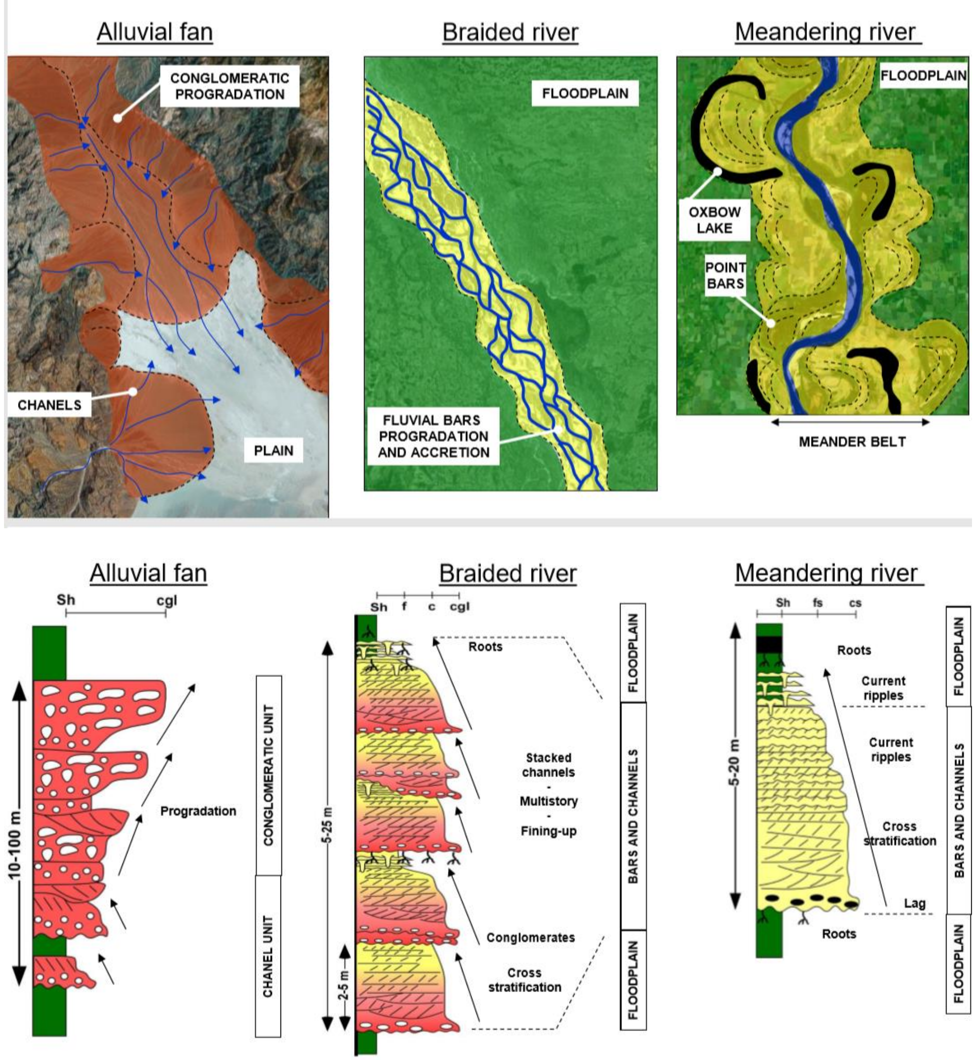




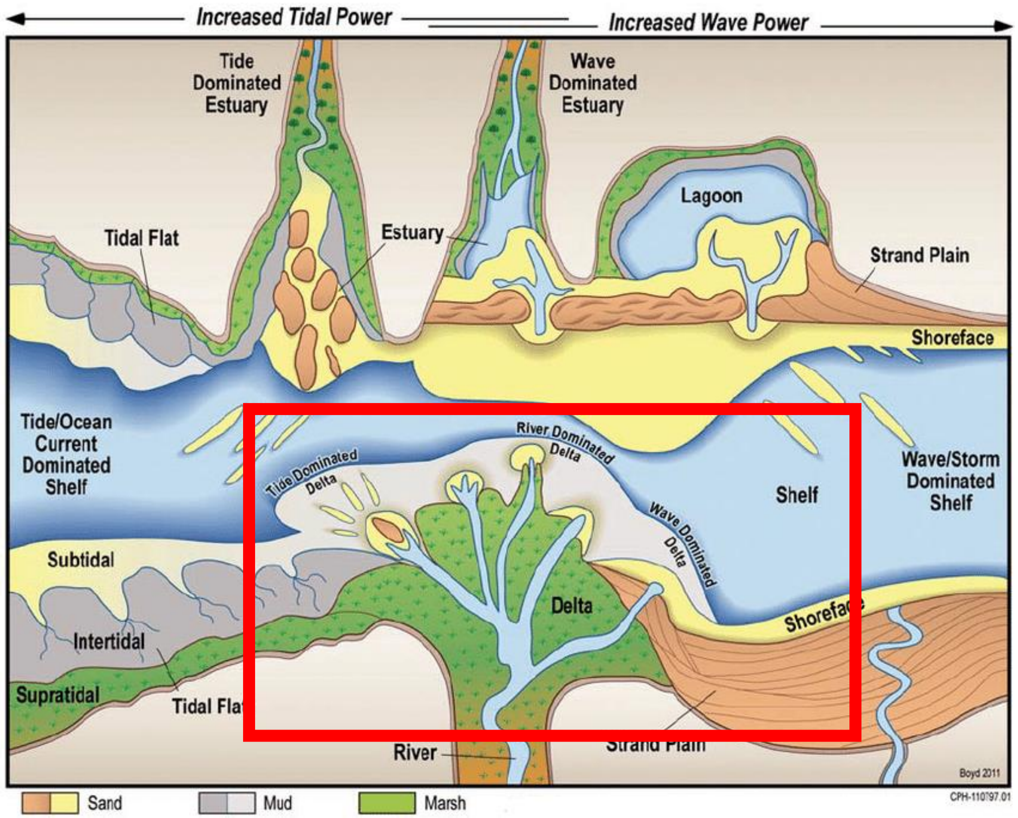

Curtesy of J. Musial

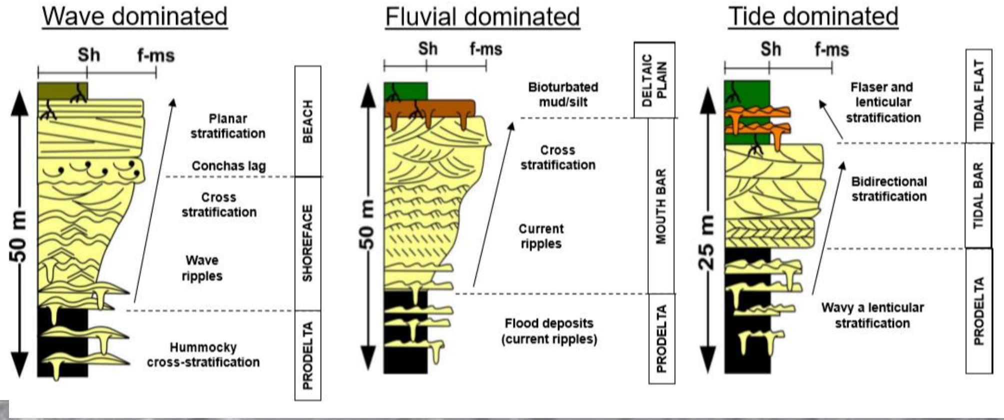
Continental Fluvial System

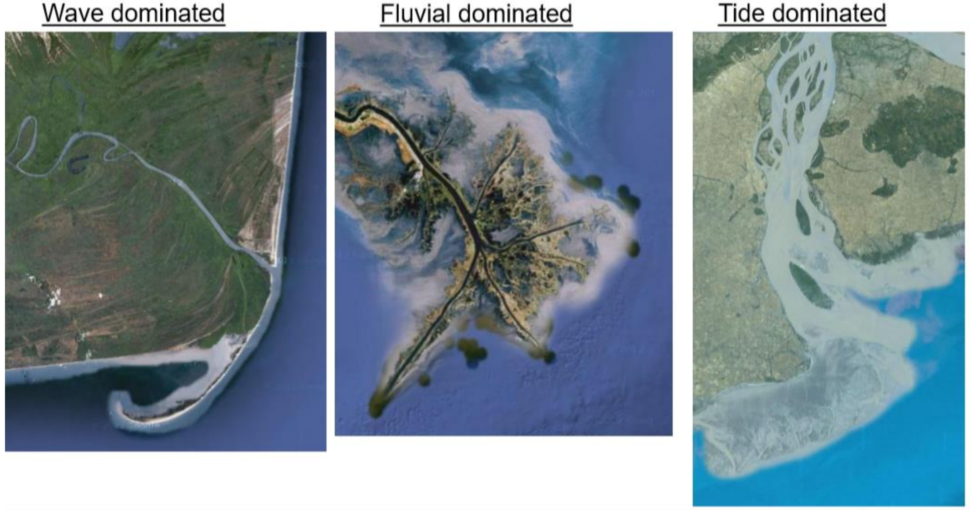


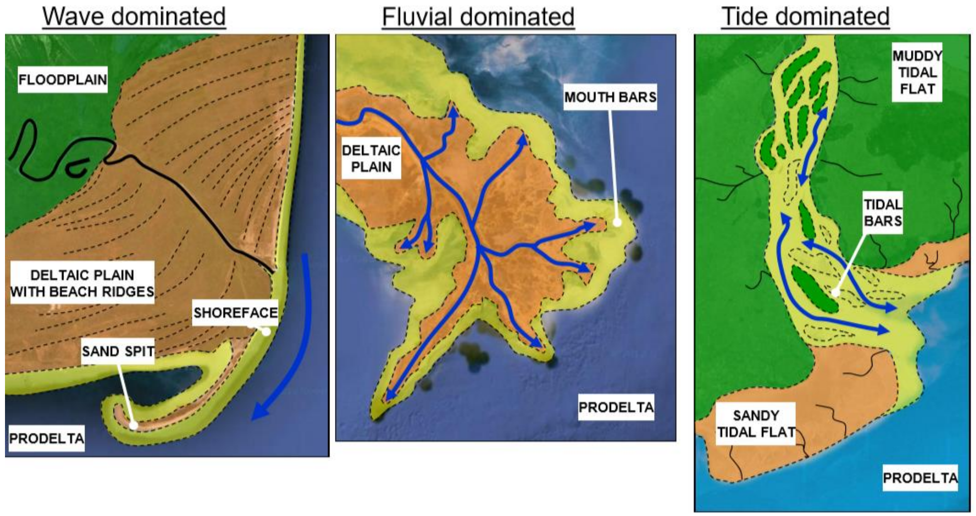


Deltaic Systems







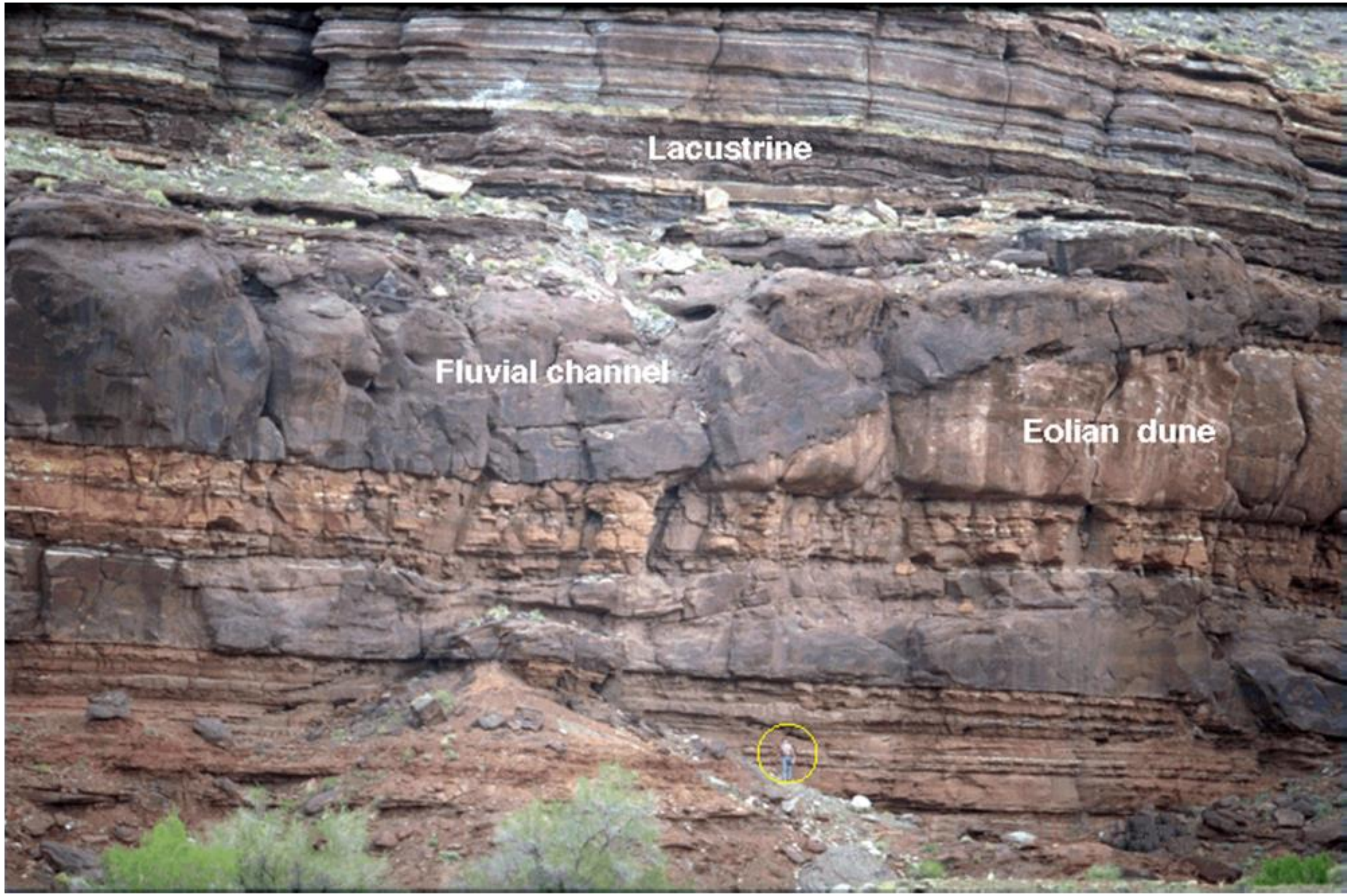


Continental Fluvial System

Fluvial channel and point-bar, Cretaceous Dunvegan Fm, Peace River, Alberta

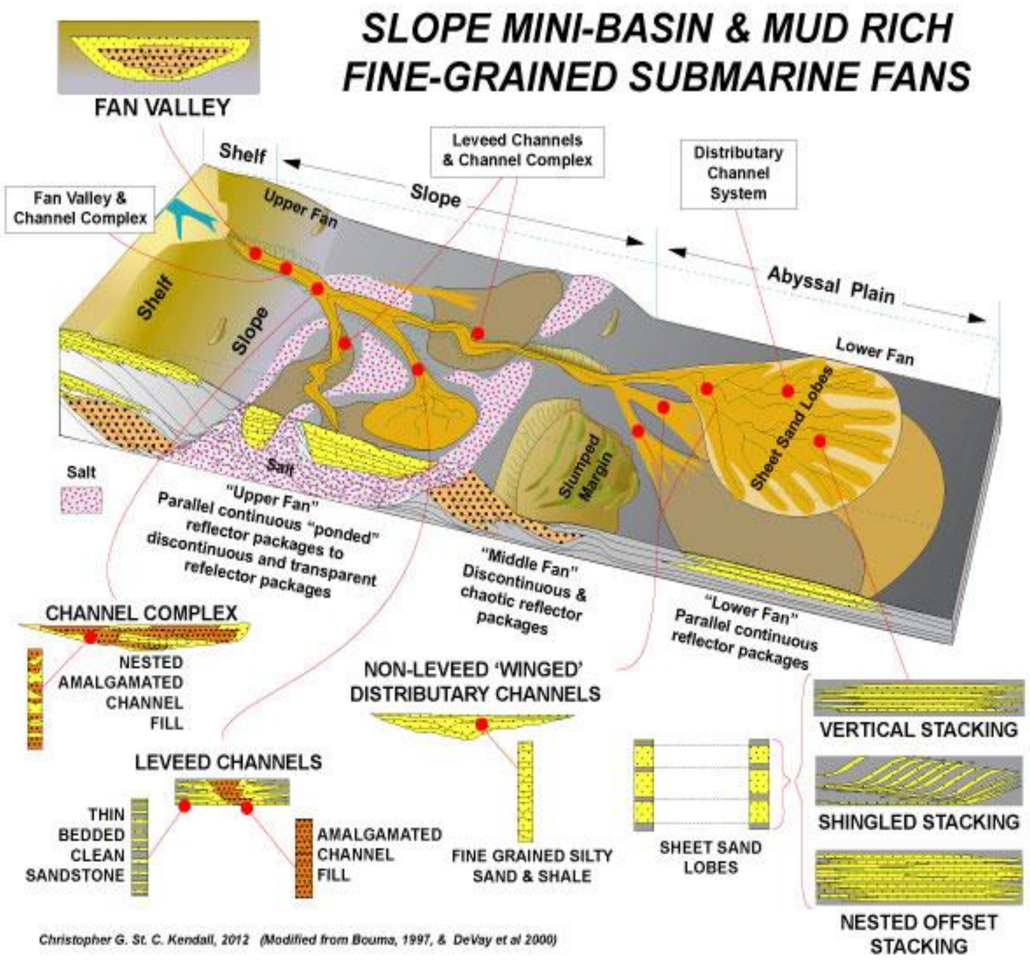
Can you determine the direction of channel flow here? This is a 2D exposure, so all we can say is flow was into or out of the image, and at a high angle to the direction of point-bar accretion. Summary stratigraphic column on right.

Continental Fluvial System



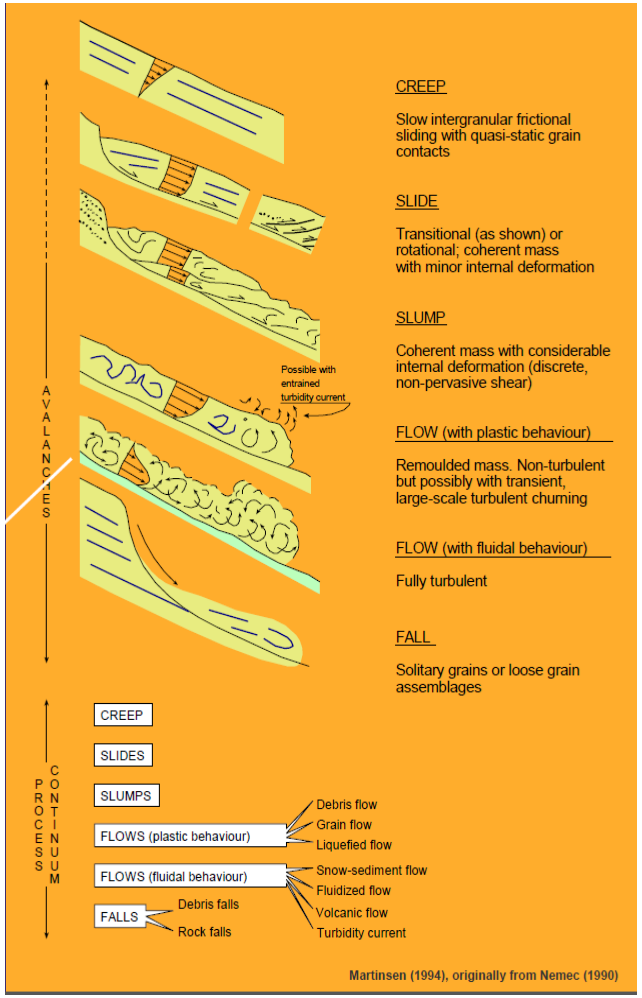
http://www.epgeology.com/

From Source To Sink (Towards Deep Water)



Kendall, 2012

Sedimentary Processes



Martinsen, 2010

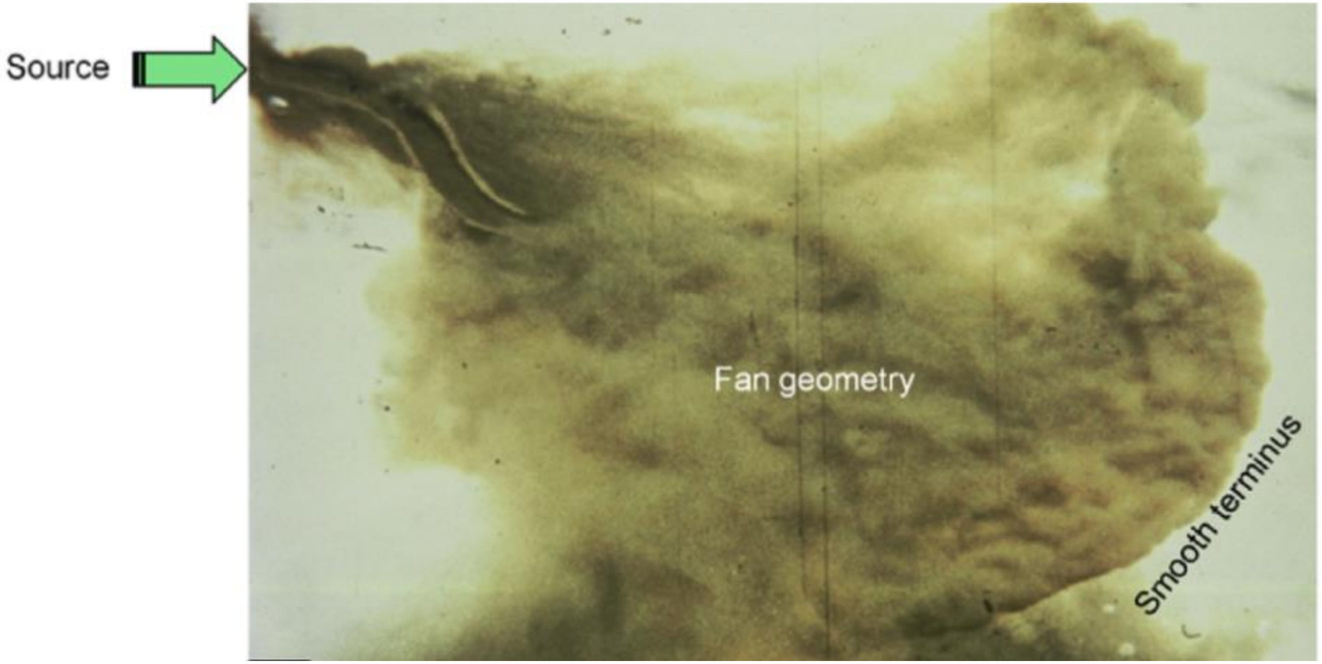
Conceptual Models for Deep Water Systems:

Siliciclastic Systems

The Complexity of Submarine Fans

Types of Submarine Fan Lobes: Models and Implications[1]

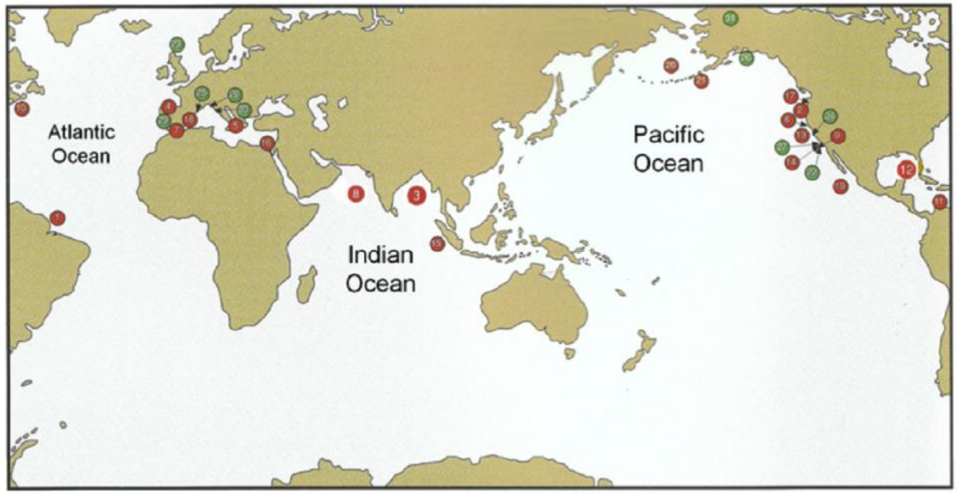
G. Shanmugam and R. J. Moiola[2] 1991



ABSTRACT

Different lobe models imply significantly different reservoir geometries; thus, one must apply the proper lobe model to ancient fan sequences. Braided suprafan lobes are characterized by stacked channel sand bodies with good lateral and vertical communication, and they constitute excellent reservoir facies. Depositional lobes, composed of sheet-like sand bodies with good lateral and moderate vertical communication, exhibit properties of good reservoir facies. Fanlobes, which refer to meandering channels and associated levee facies of large mud-rich submarine fans such as the Mississippi fan, are characterized by offset stacked sand bodies with poor lateral and vertical communication. These lenticular sands have the potential to be moderately good reservoir facies. Ponded lobes, which represent mud-rich slump facies of slope environments, comprise poor reservoir facies because of low sand content and poor sand-body connectivity. Furthermore, the presence of contorted mud layers in ponded lobes is expected to hinder fluid flow. External mounded reflections in seismic profiles often are interpreted as lobes; however, there are no definite seismic criteria to delineate mud-rich lobes from sand-rich lobes.

Submarine Fans In the Recent and Ancient Record



Modern

1 Amazon
2 Astoria
3 Bengal
4 Cap Ferret
5 Crati
6 Delgada
7 Ebro
8 Indus
9 La Jolla
10 Laurentian
11 Magdalena
12 Mississippi
13 Monterey
14 Navy
15 Nicobar
16 Nile
17 Nitinat
18 Rhone
19 San Lucas
20 Zhemchug
21 Zodiac

Ancient

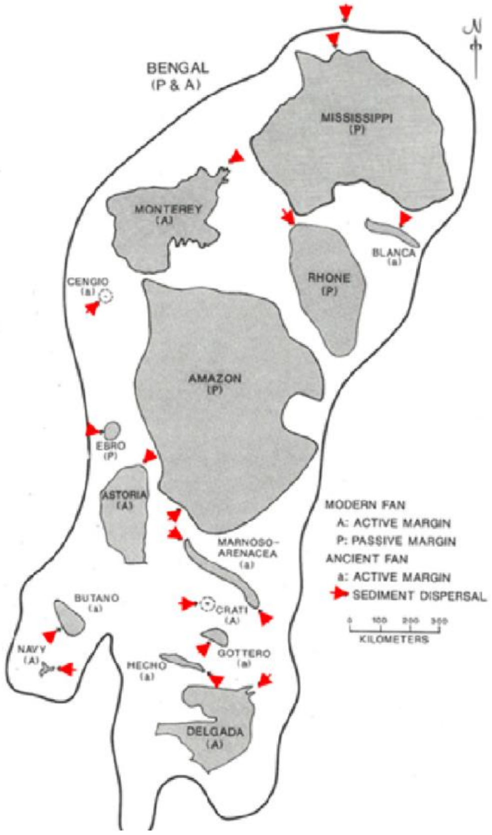
22 Blanca
23 Brae
24 Butano
25 Cengio
26 Chugach
27 Ferrelo
28 Gottero
29 Hecho
30 Marnoso-Arenacea
31 Torok-Fortress Mountain

(Data from Barnes and Normark, 1985)

Distributed worldwide with a very high variability in forms and sizes

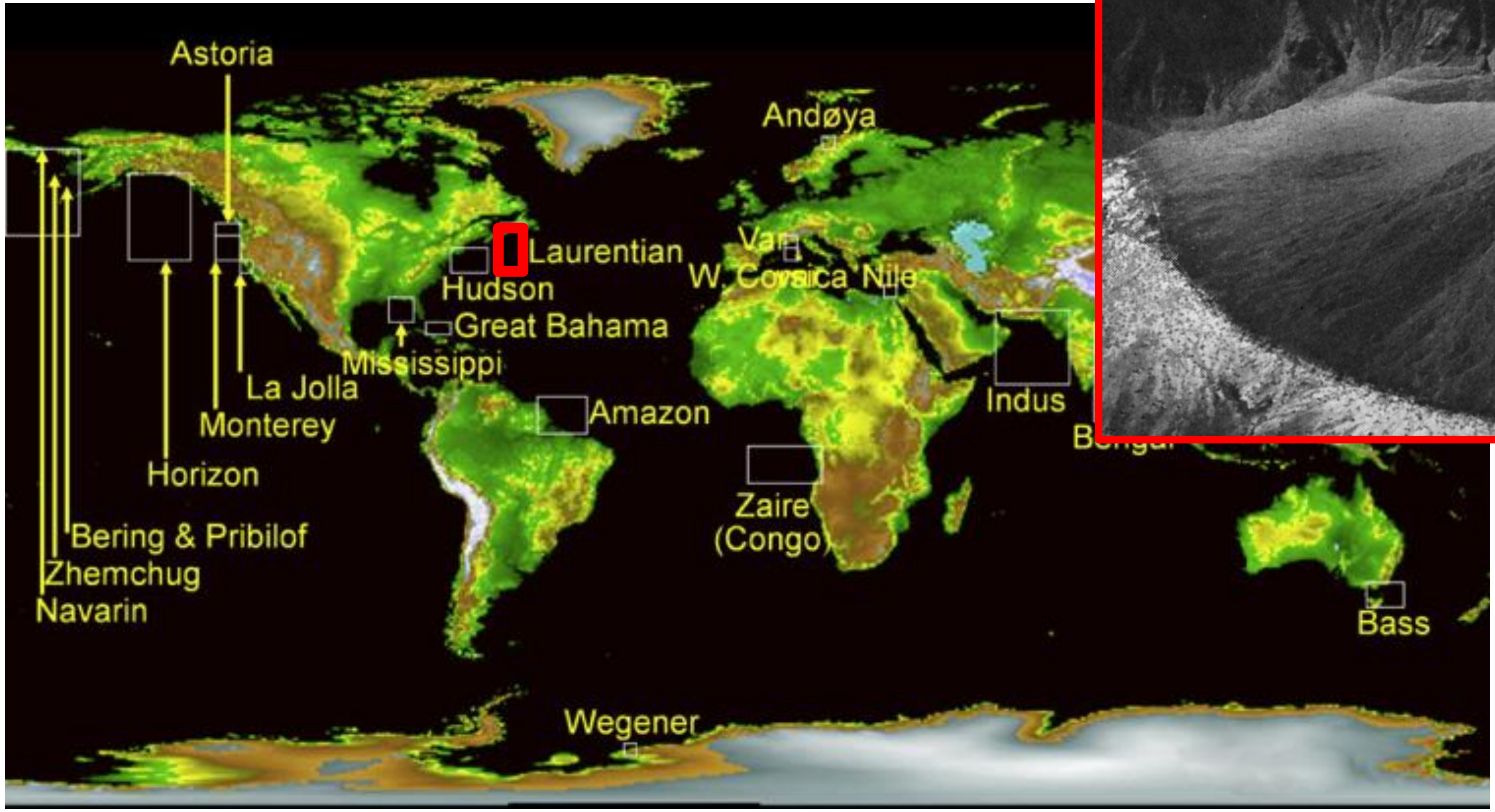
Many examples preserved in the stratigraphic record

Commonly present on the submarine slope and basin floor zone

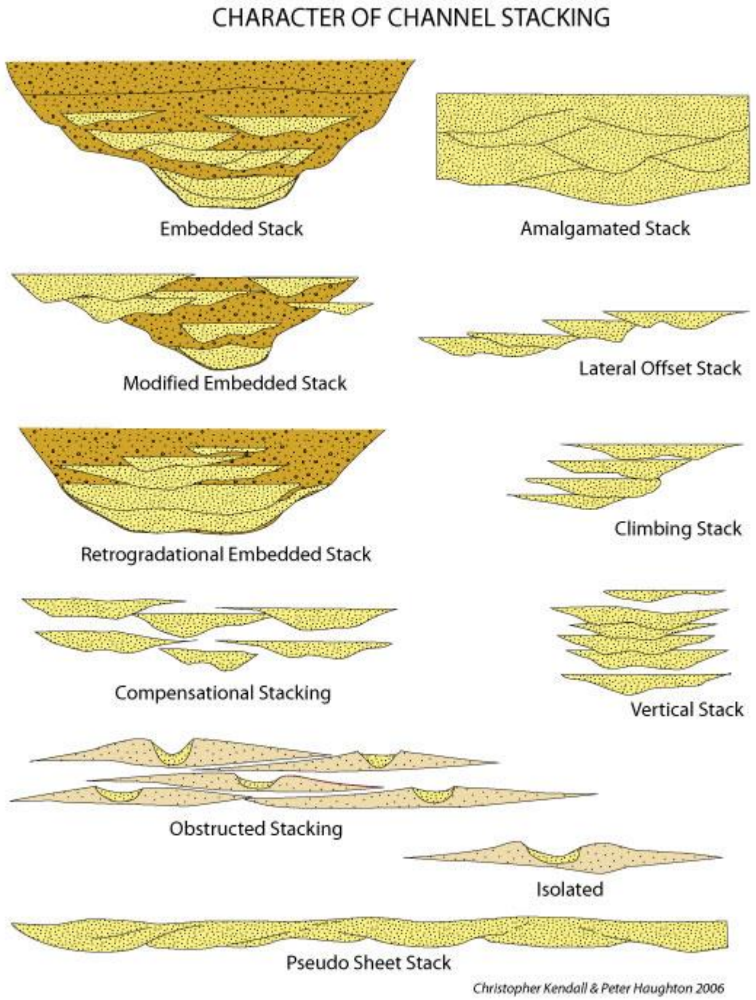


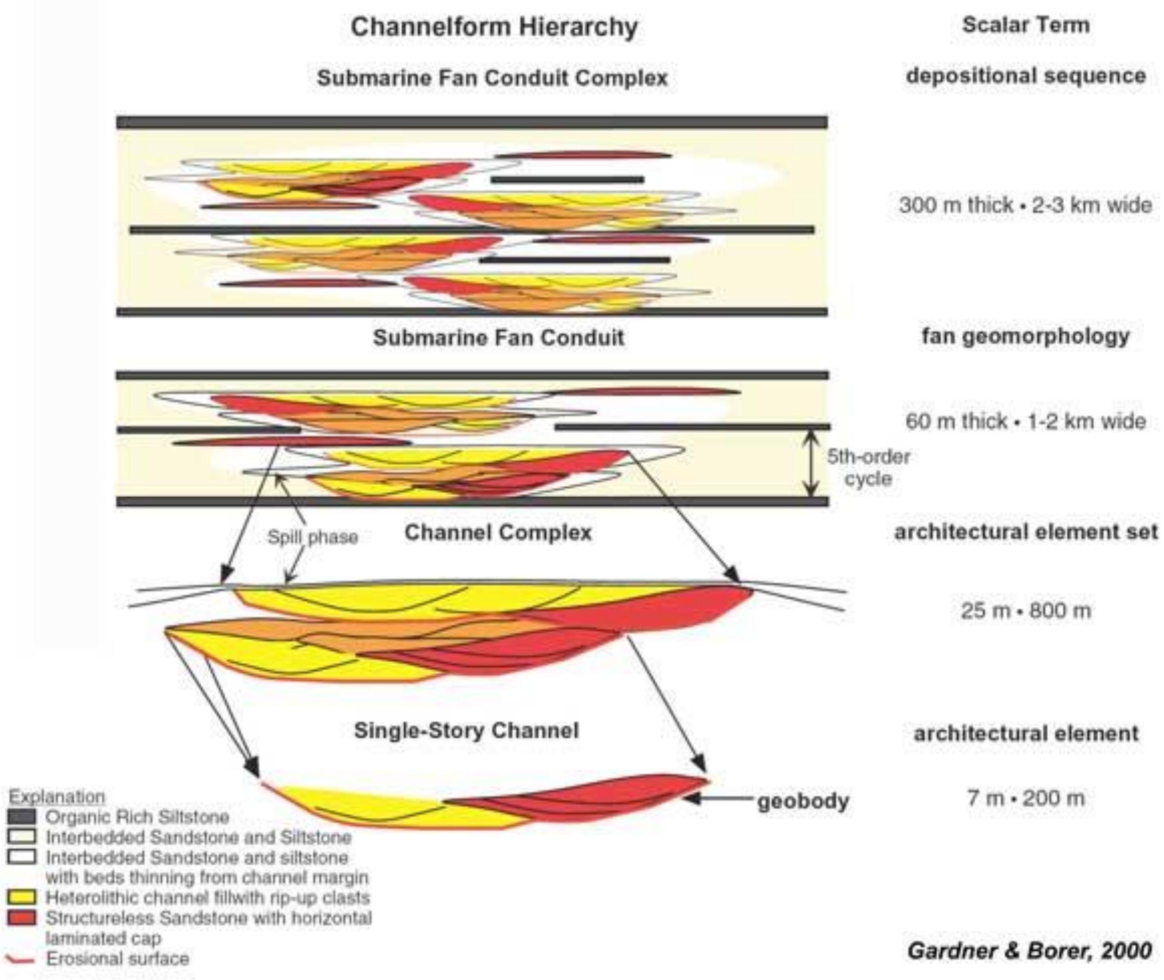
Shanmugam, 2016

Modern Submarine Fans



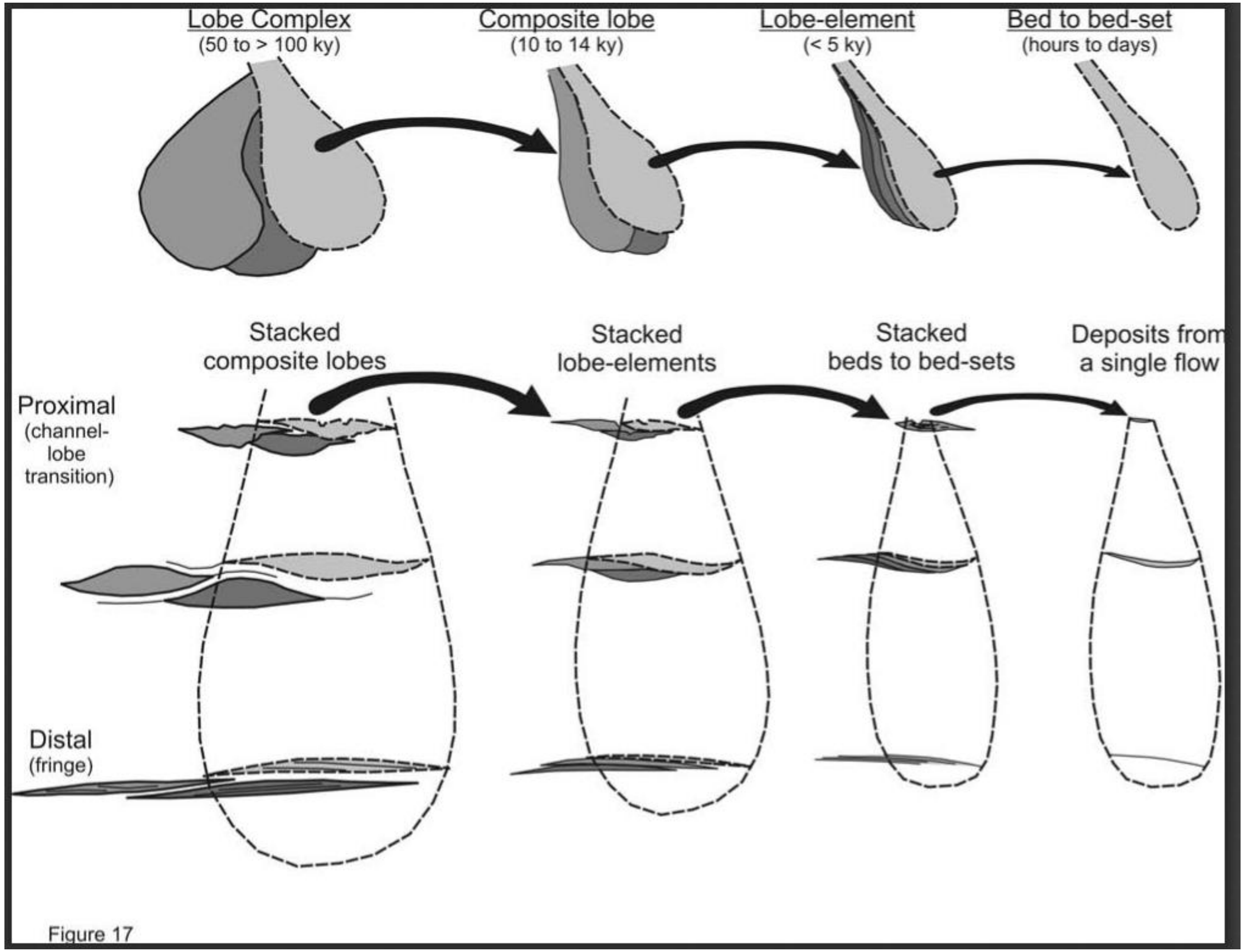
Submarine Fans Stacking Geometries and Architectural Patterns

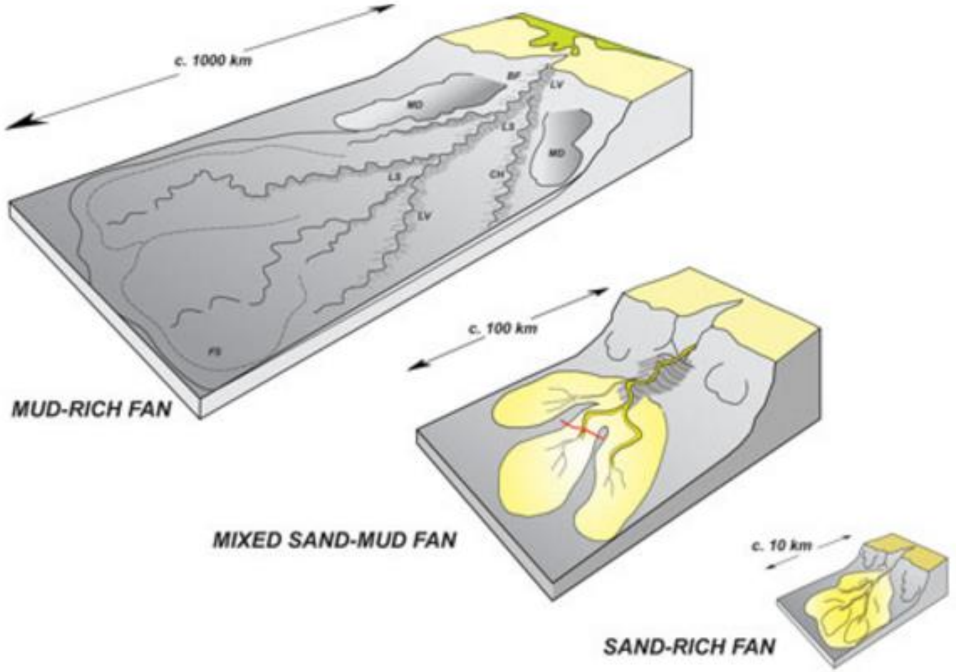




Shanmugam,et al., 2016 2016

Submarine Fans: Apprehending Temporal and Spatial Scales!





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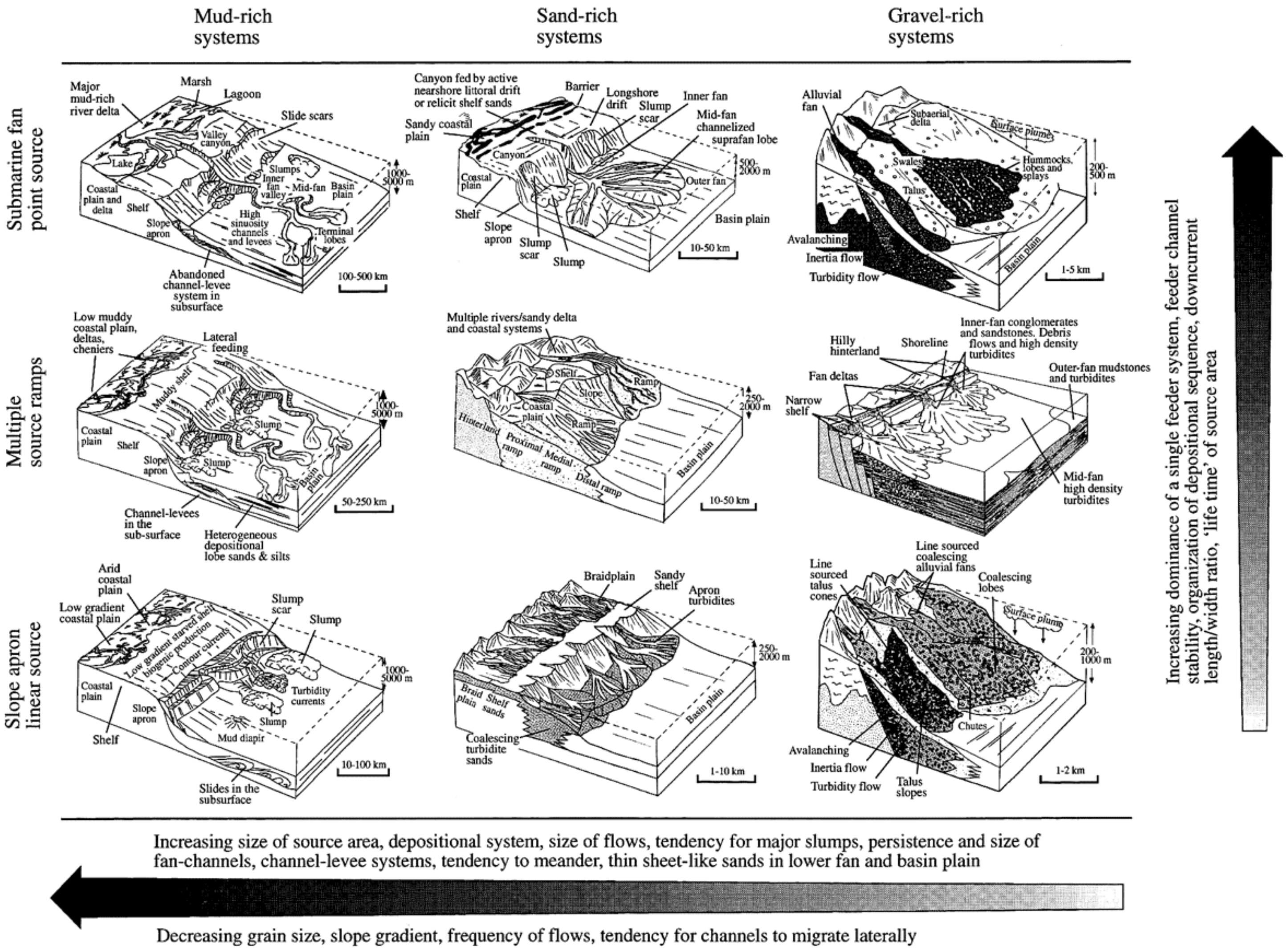
From Source To Sink (Towards Deep Water)

- These collective sedimentary building blocks are categorized on the basis of:
- Their often uniform and cyclic vertical composition
- Contact Boundaries
- Amalgamation
- Stacking
- Variations in lateral thickness of their geometries

- Whether these bodies are:
  - Confined within eroded or constructed depressions
  - Unconfined sheet



After Stow & Mayall 2000 (based on Reading & Richards 1994 & Stow et al 1996)

29

General Fan Conceptual Models

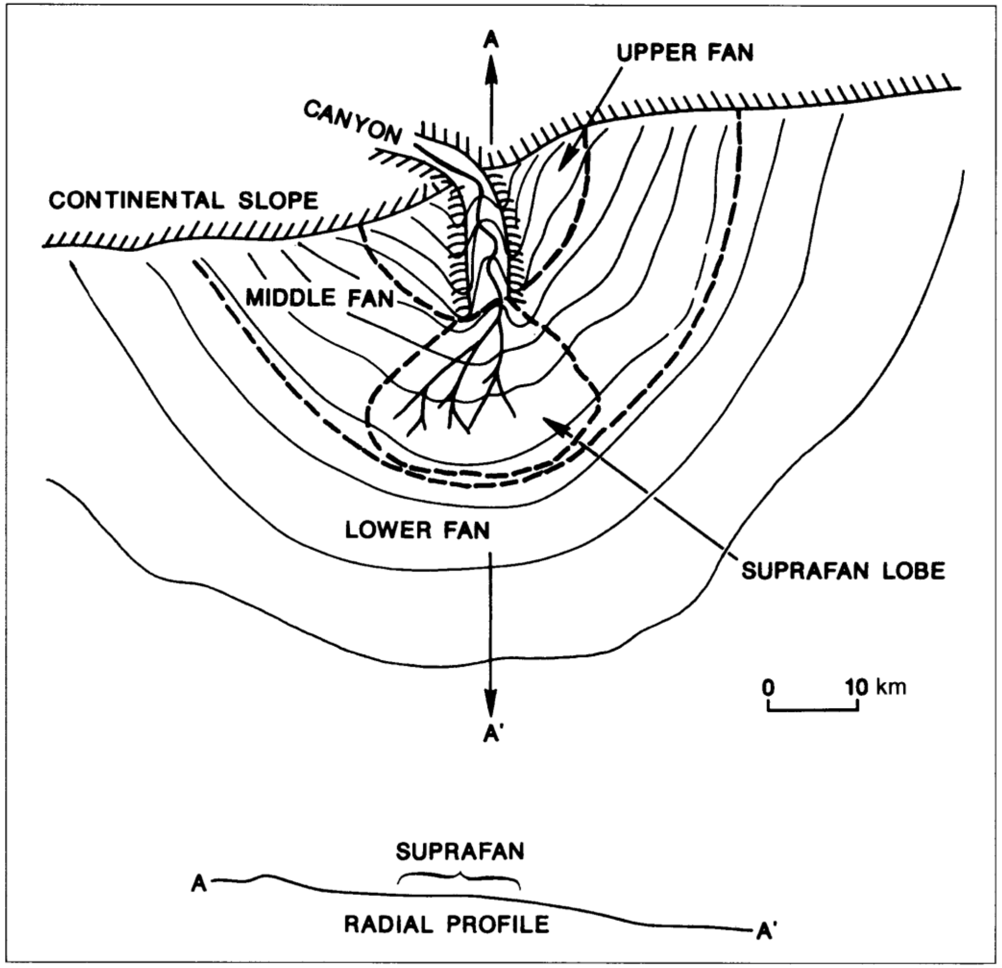


Figure 1—Suprafan lobe model of sand-rich modern fans showing a depositional bulge in radial profile. Simplified after Normark (1970, 1978).

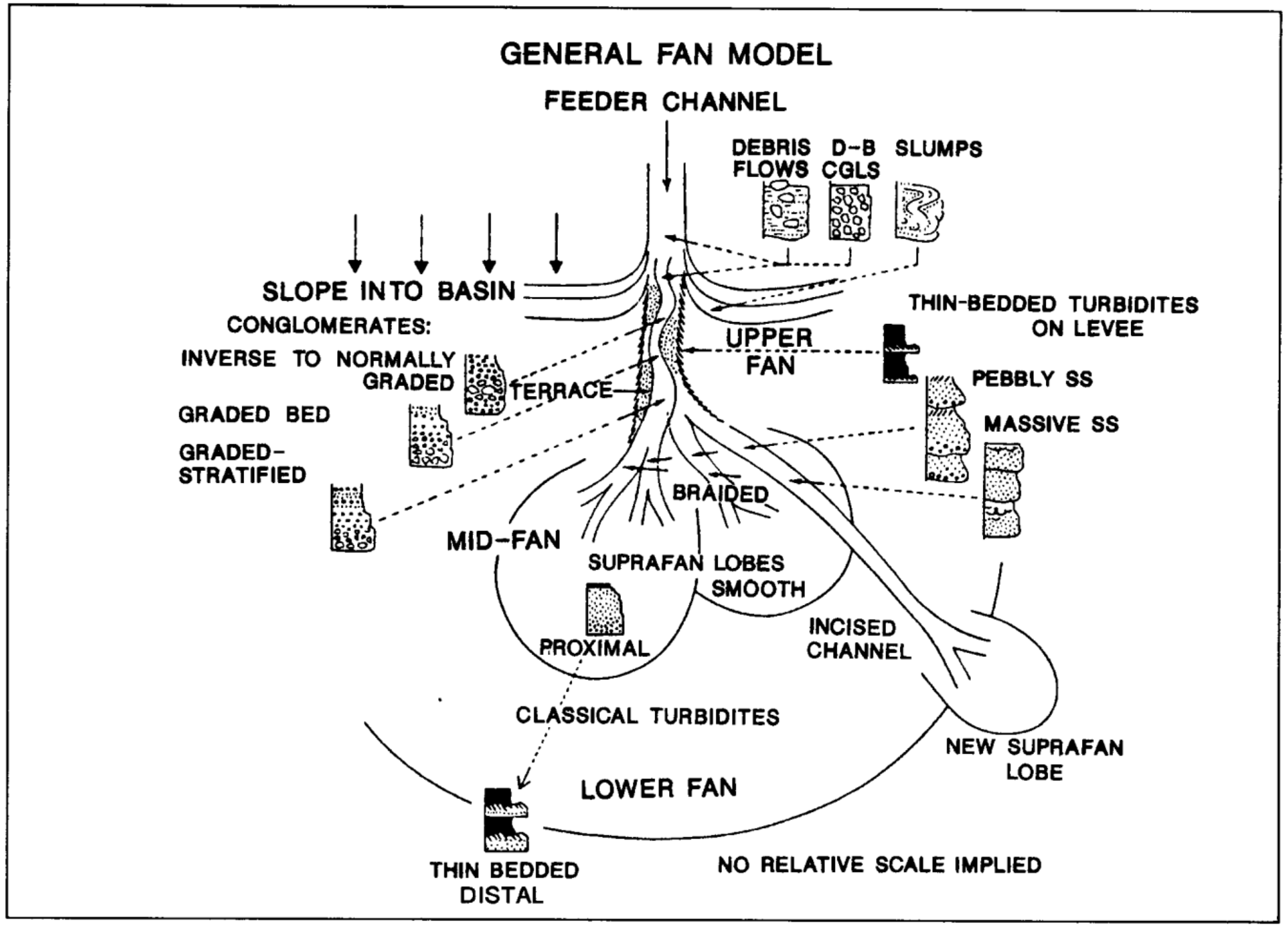
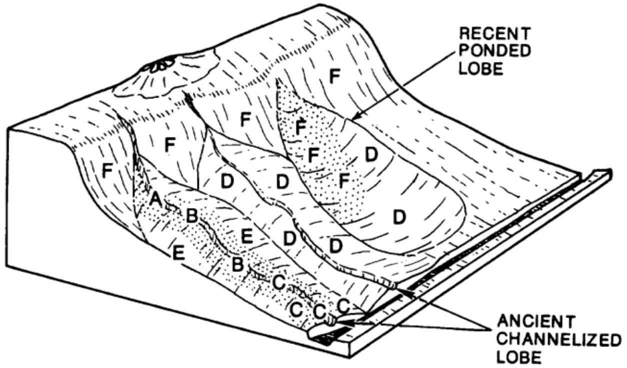


Figure 2—A general ancient-fan model with suprafan lobes. Note the presence of braided channels in the inner part of suprafan lobes. From Walker (1978). D-B CGLS = disorganized-bed conglomerates, SS = sandstones.

General Fan Conceptual Models from Wells and Seismic Patterns



A–F: FACIES SCHEME OF MUTTI AND RICCI LUCCHI (1972)

Facies	Lithology	Bedding	Features
A	Conglomerate, Coarse Sandstone	Thick, Irregular, Amalgamated	Channel Fill, Shale Clasts, Poor Sorting
B	Coarse To Medium Sandstone	Thick, Lenticular	Channel Fill, Shale Clasts, Dish Structures
C	Medium To Fine Sandstone, Minor Shale	Medium, Continuous	Complete Bouma Sequence
D	Fine To Very Fine Sandstone, Siltstone, Shale	Thin, Remarkably Continuous, Parallel	Bouma Sequence With Base Missing
E	Sandstone, Siltstone	Thin To Medium, Irregular, Discontinuous	Beds With Sharp Upper Contacts
F	Complex	Chaotic	Slumps
G	Shale, Marl	Laminated, Remarkably Continuous, Parallel	Homogeneous Texture

Figure 10—Channelized and ponded lobes, and distribution of turbidite facies associations (see Table 1 for explanation of each facies according to Mutti and Ricci Lucchi, 1972) in the modern Ebro fan. From Nelson et al. (1985).

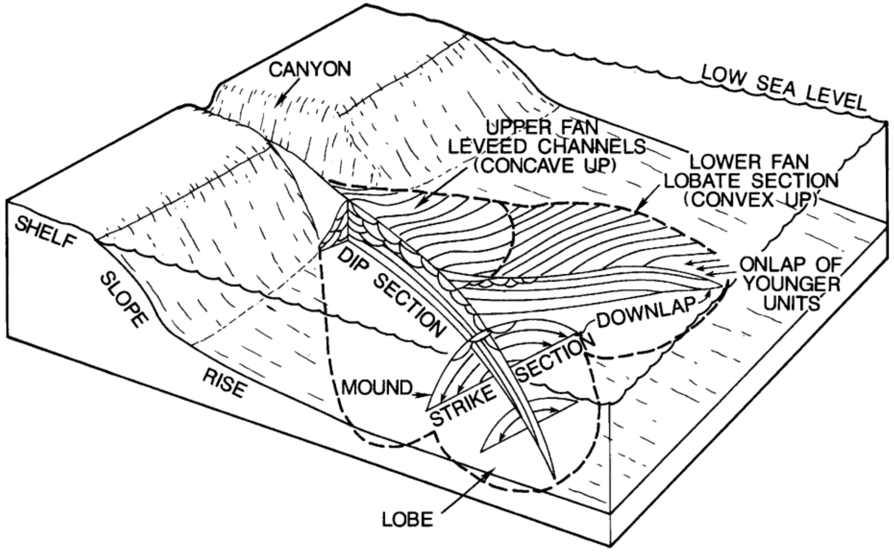


Figure 12—A model of seismic expression of ancient submarine fans. Modified after Mitchum (1985).

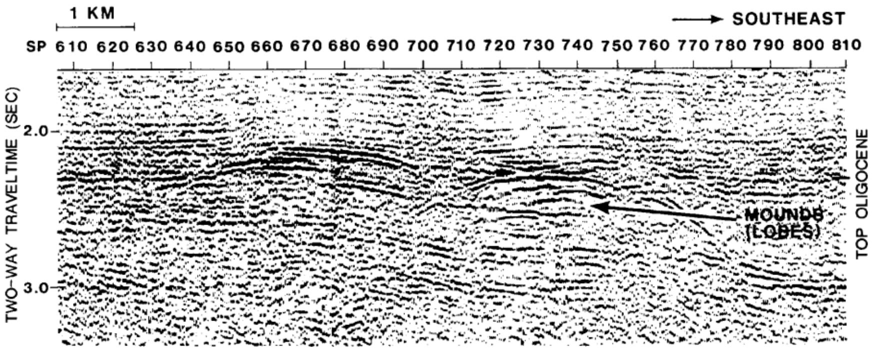
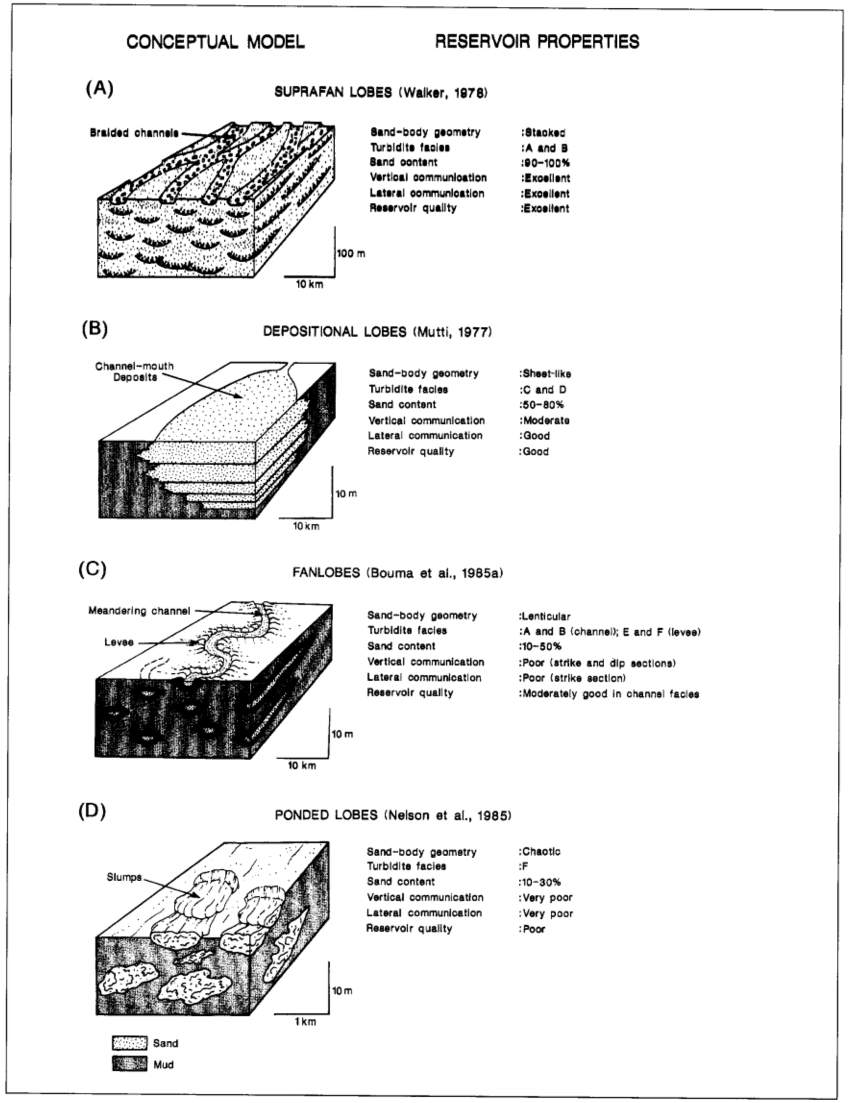


Figure 13—Seismic reflection profile (unmigrated) showing mounded patterns interpreted as submarine fan lobes, Oligocene, onshore, Colombia, South America. See text discussion for problems in interpreting seismic mounds as lobes. From Shanmugam and Moiola (1988). SP = shot point.

Submarine Fans with Idealized electric Log Patterns



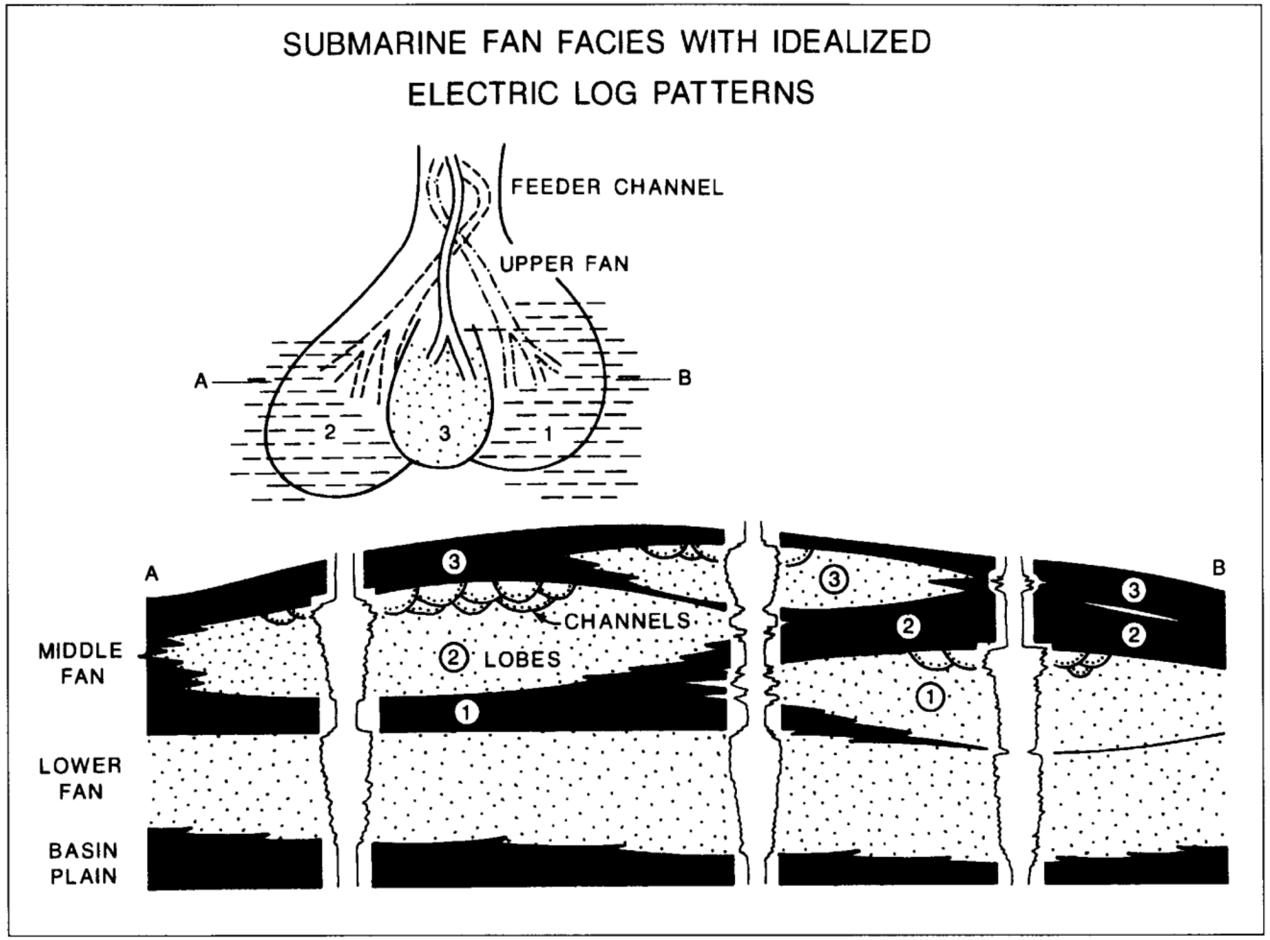
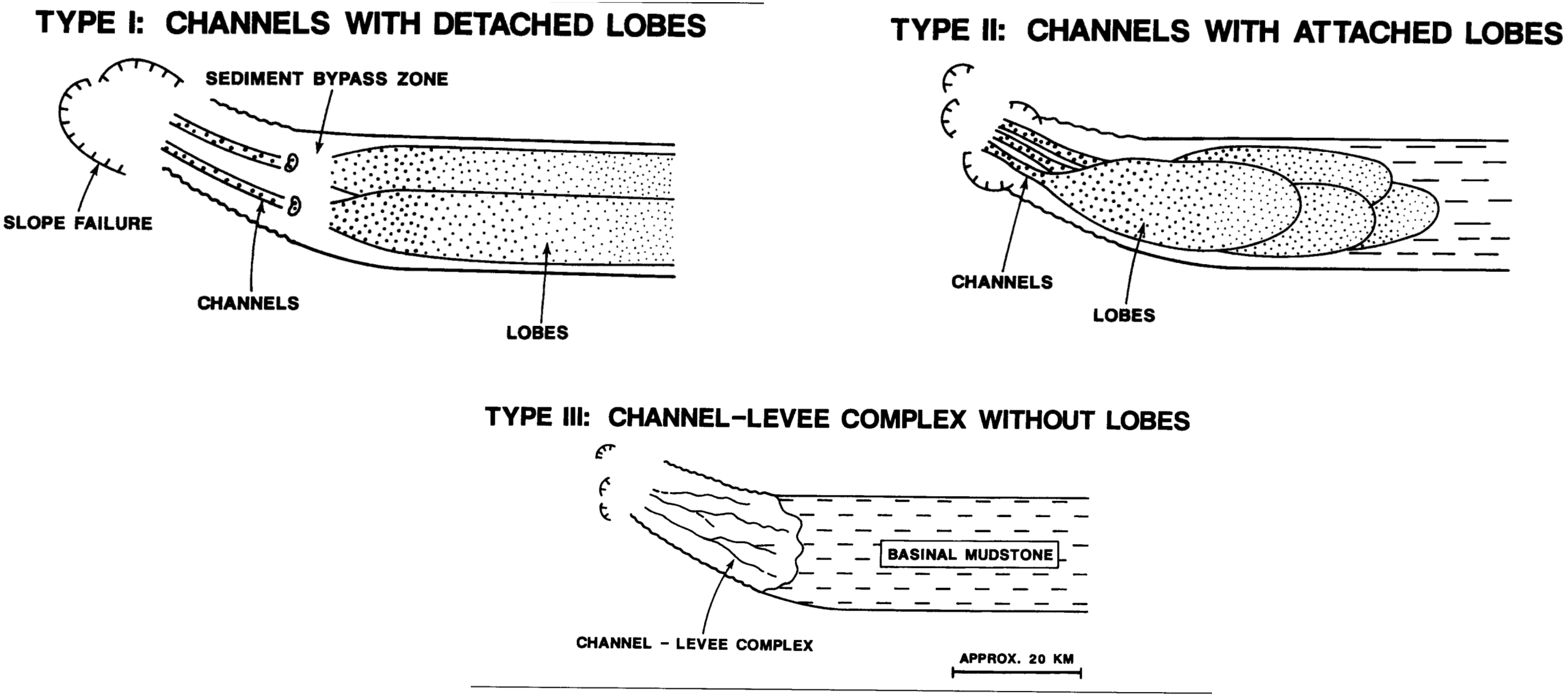


Figure 18—Hypothetical model showing lateral switching of suprafan lobes (1–3) in plan view (upper diagram) and facies distribution in cross section (lower diagram). Stippled area denotes sandstone and black area represents mudstone in the cross section. Logs show expected SP or GR (left) and resistivity (right) responses. The offset stacked suprafan lobes with mudstone blankets would develop excellent stratigraphic traps. From Walker (1978).

Types of Channel Lobes Complexes



igure 19—Map views of three types of turbidite systems. Simplified after Mutti (1985).

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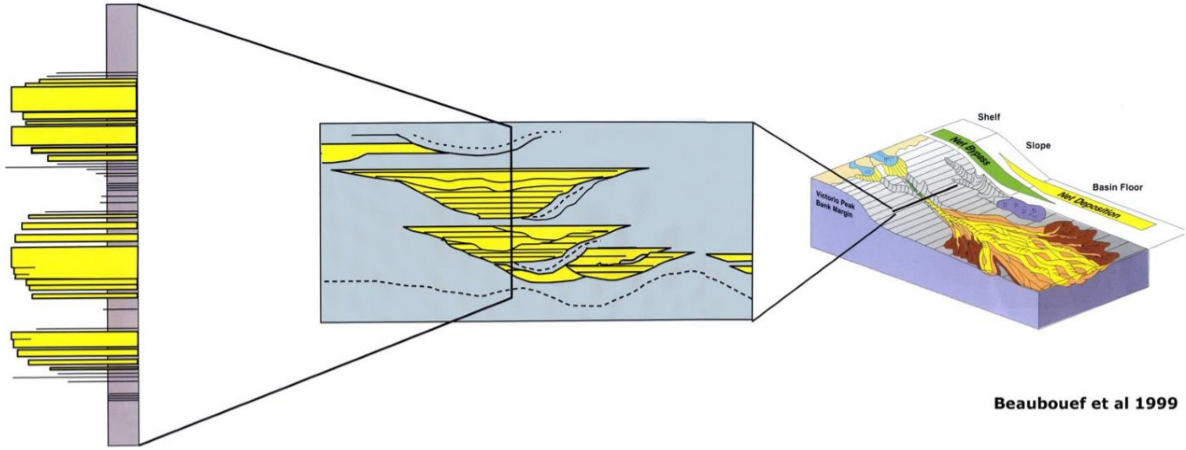
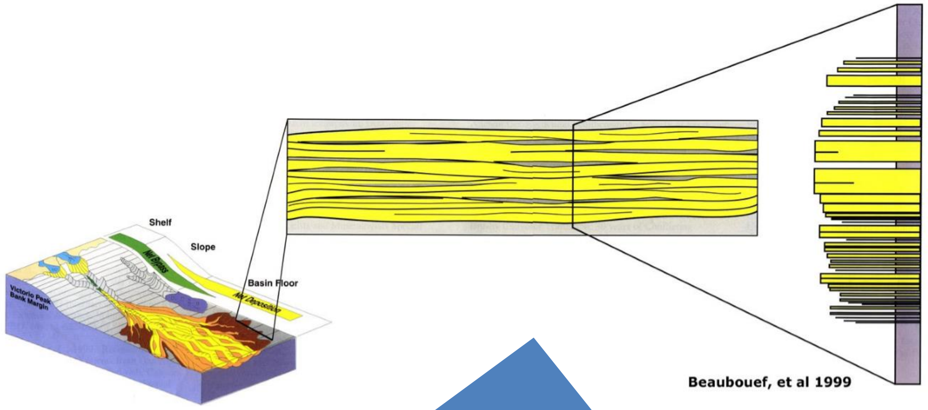
Architectures of deep Marine Systems

Middle Slope Channel Summary



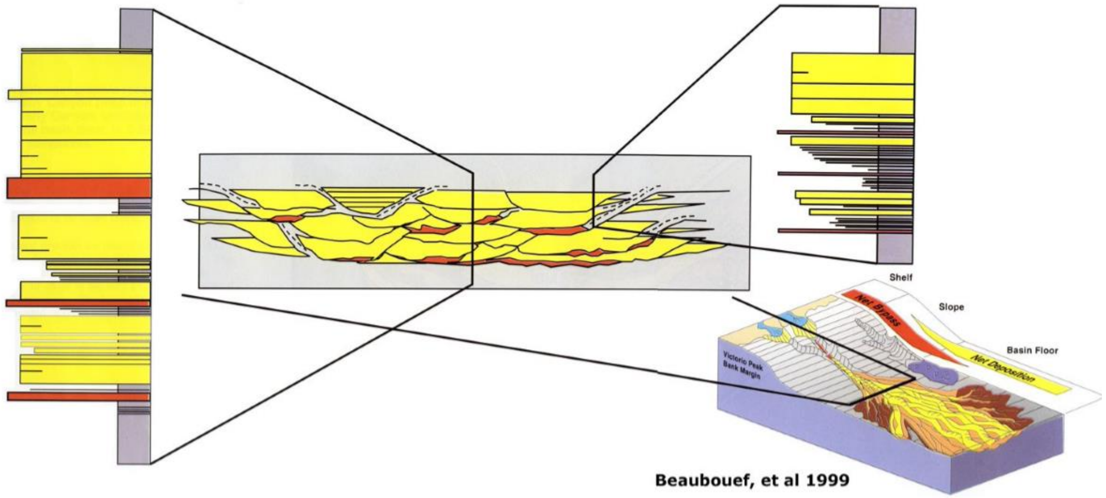
Beaubouef et al 1999

Outer Basin Floor Fan



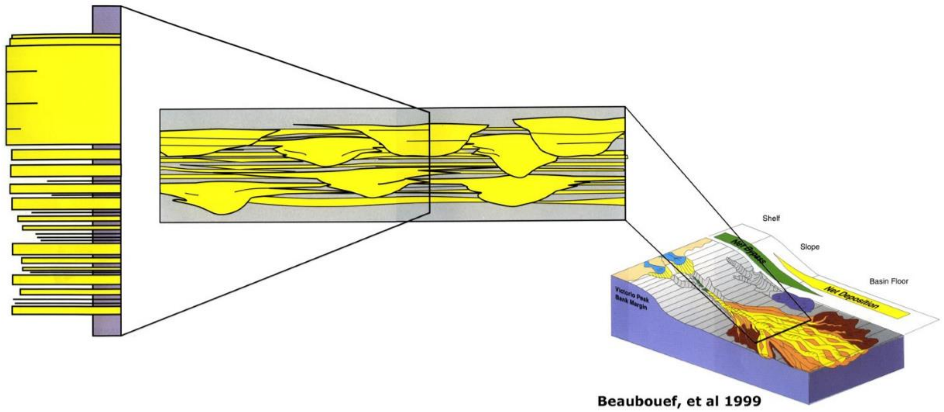
Beaubouef, et al 1999

Toe-of-Slope Channel Complexes



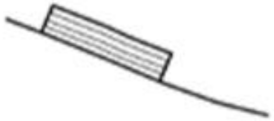
Beaubouef, et al 1999

Proximal Basin Floor Channel Complexes



Beaubouef, et al 1999

Gravity vs Turbidity Transport Classification

GRAVITY INDUCED DEPOSITS			Genetic Classification Transport Mechanism	Descriptive Classification Sedimentary Structures	Seismically Recognizable Features (Moscardelli et al., 2006; this work)
Mass Transport Complex	Slide		Shear failure along discrete shear planes with little or no internal deformation or rotation	Essentially undeformed, continuous bedding	Continuous blocks without apparent internal deformation. High-amplitude, continuous reflections.
	Slump		Shear failure accompanied by rotation along discrete shear surfaces with various degrees of internal deformation	Plastic deformation particularly at the toe or base. Plow structures, folds, tension faults, joints, slickensides, grooves, rotational blocks	Compressional ridges, imbricate slides, irregular upper bedding contacts, duplex structures, contorted layers. Low- and high-amplitude reflections geometrically arranged as though deformed through compressive stresses.
	Debris Flow		Shear distributed throughout the sediment mass. Strength is principally from cohesion due to clay content. Additional matrix support may come from buoyancy. Plastic rheology and laminar state.	Matrix supported, random fabric, clast size variable, matrix variable. Rip ups, rafts, inverse grading and flow structures possible.	Mega rafted and/or detached blocks, irregular upper bedding contacts, lateral pinch-out geometries, oriented ridges and scours. Low-amplitude, semitransparent chaotic reflections.
Turbidity Current	Turbidite		Supported by fluid turbulence (newtonian rheology)	Normal size grading, sharp basal contacts, gradational upper contacts.	Lobate features Laterally continuous

(Moscardelli and and Wood, 2007).

Mass Transport Deposits

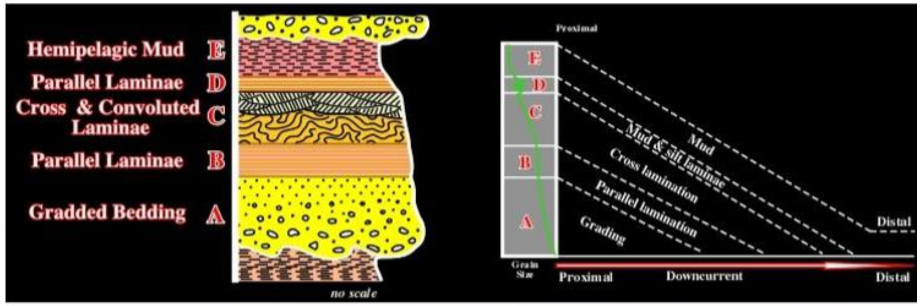
(BSRG - British Sedimentological Research Group photo archive).

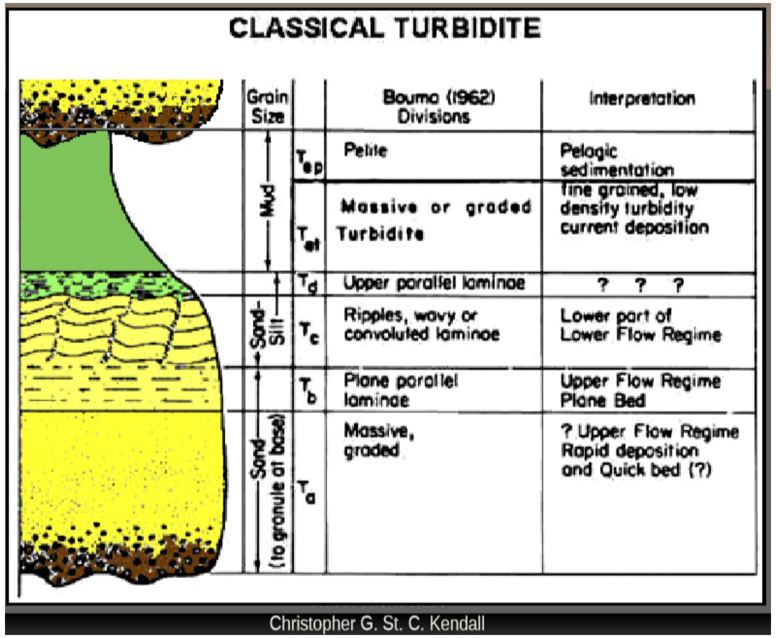
Classification of Turbidite by Bouma

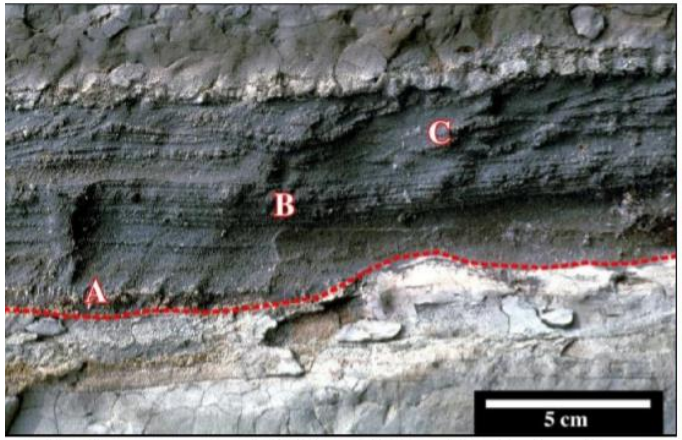
BOUMA SEQUENCE:

(http://homepage.ufp.pt/biblioteca/WEBTurdiDepSystems.htm).

TURBIDITIC PROCESS

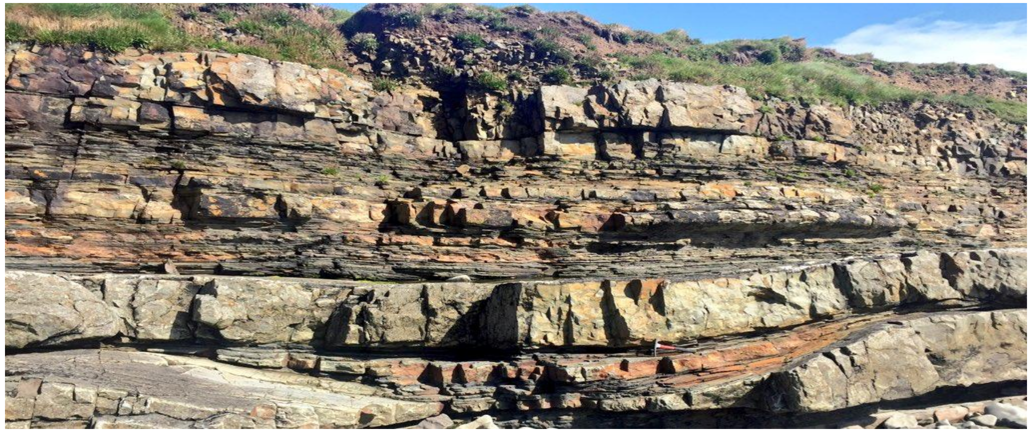




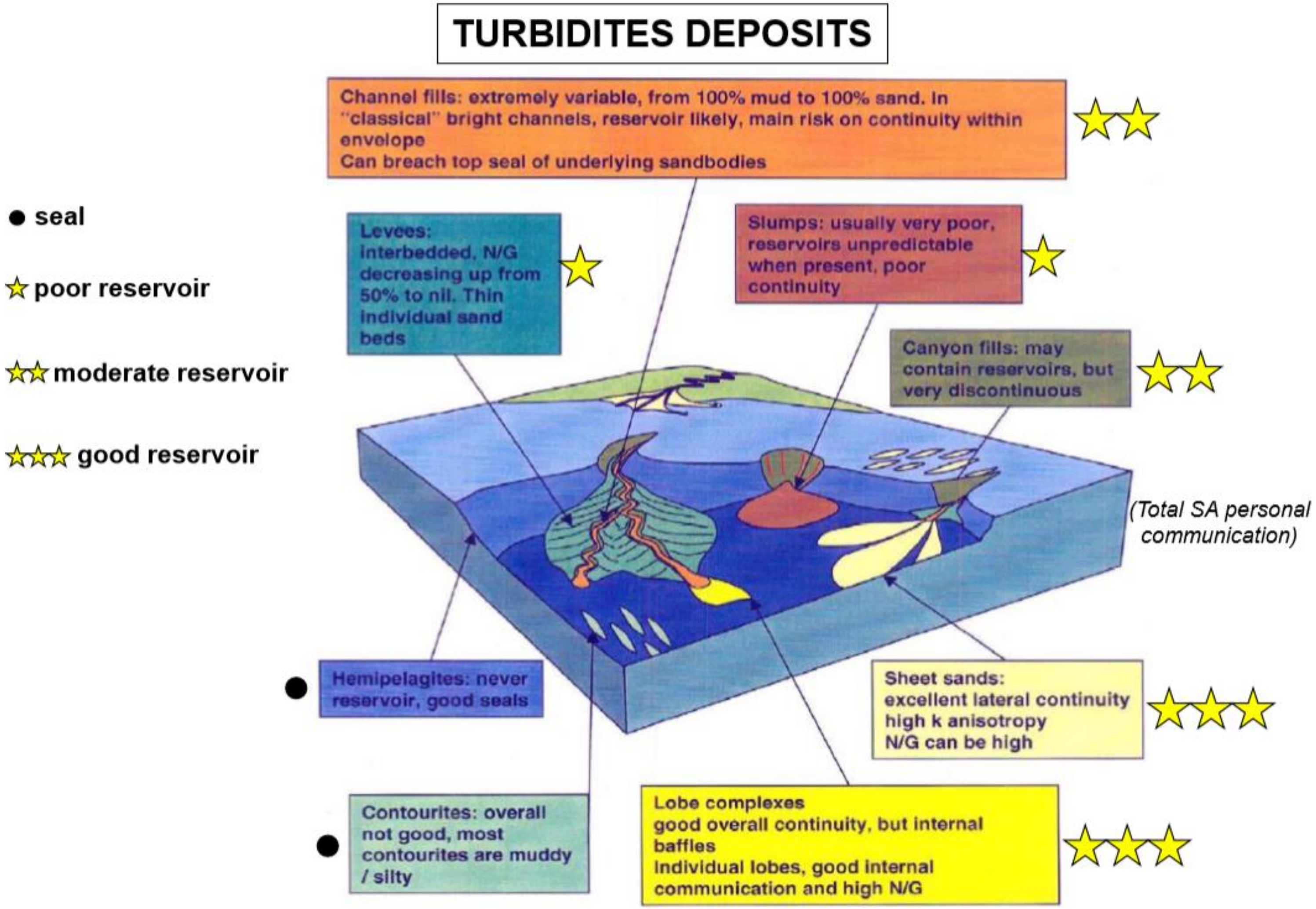


(http://homepage.ufp.pt/biblioteca/WEBTurdiDepSystems/Pages/Page4.htm).

F9 Mutti facies: thin bedded turbidites (Roquebrun, France).

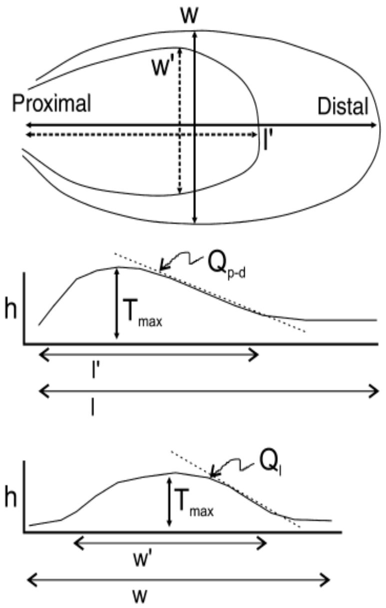


Turbidite deposits Petroleum Systems Elements



Quantification of Lobe Sizes

- Quantification of channel and lobe sizes (plots)
- Thickness and lithology standard deviation maps per experimental design
- Lobe measurement analysis Test other parameters
- Initiation of article



w - Width including fringe
w' - Width of acoustic facies VII
l - Length including fringe
l' - Length of acoustic facies VII
h - Thickness of lobe
T_{max} - Maximum thickness of lobe
Q_{p-d} - Max. proximal to distal thinning rate
Q_l - Max. lateral thinning rate

Fig. 7. Cartoon illustrating the types of measurements made from lobes in the study area.

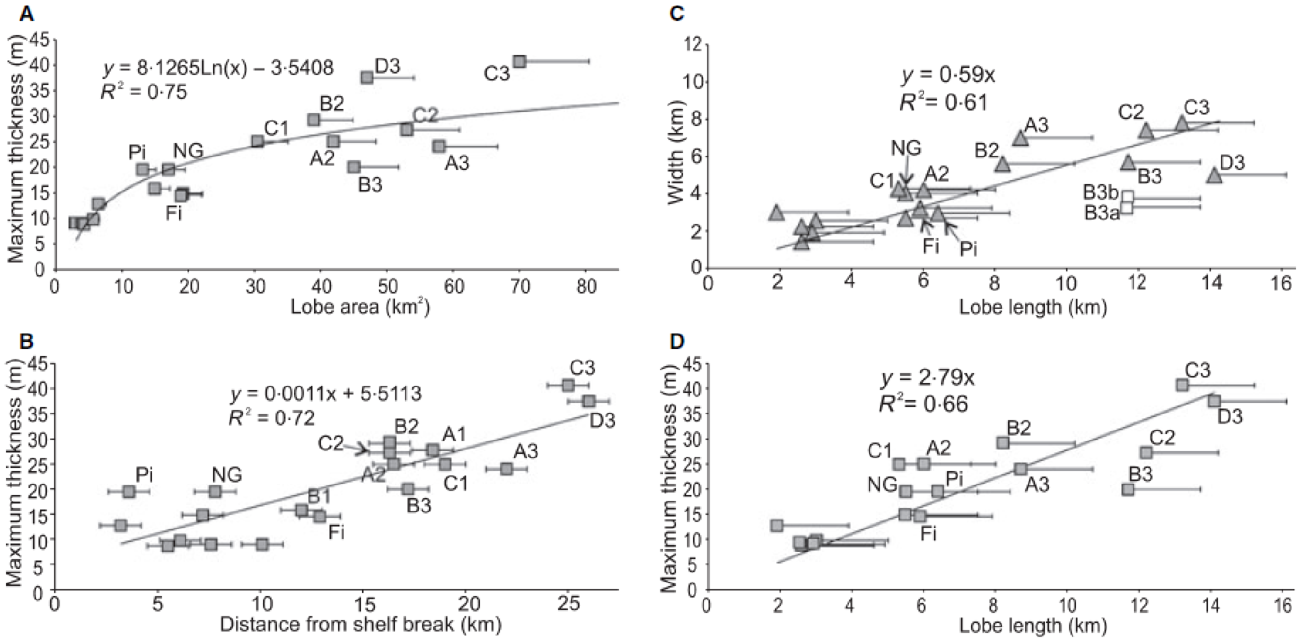
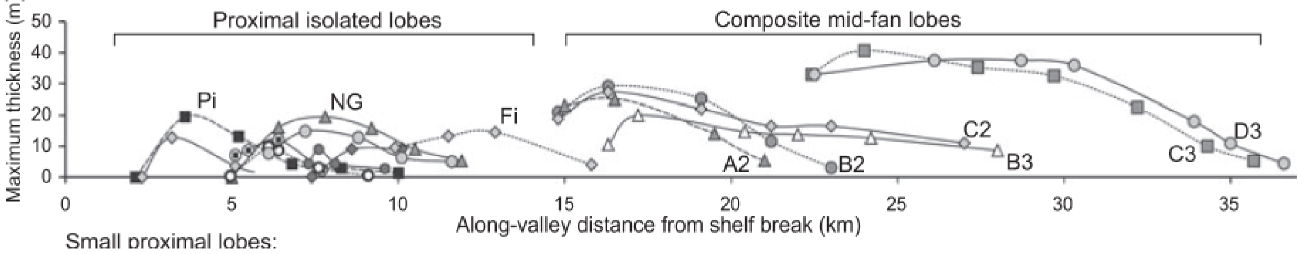


Fig. 8. Cross-plots of: (A) Maximum lobe thickness versus lobe area. Note that thicker lobes tend to cover a larger area. (B) Maximum lobe thickness versus distance from the shelf-break (measured along the feeder channel and the length axis of the lobe-form). Note that lobes show peak thicknesses that vary from 2 to >25 km from the shelf-break. (C) Lobe width versus lobe length. (D) Maximum lobe thickness versus lobe length.



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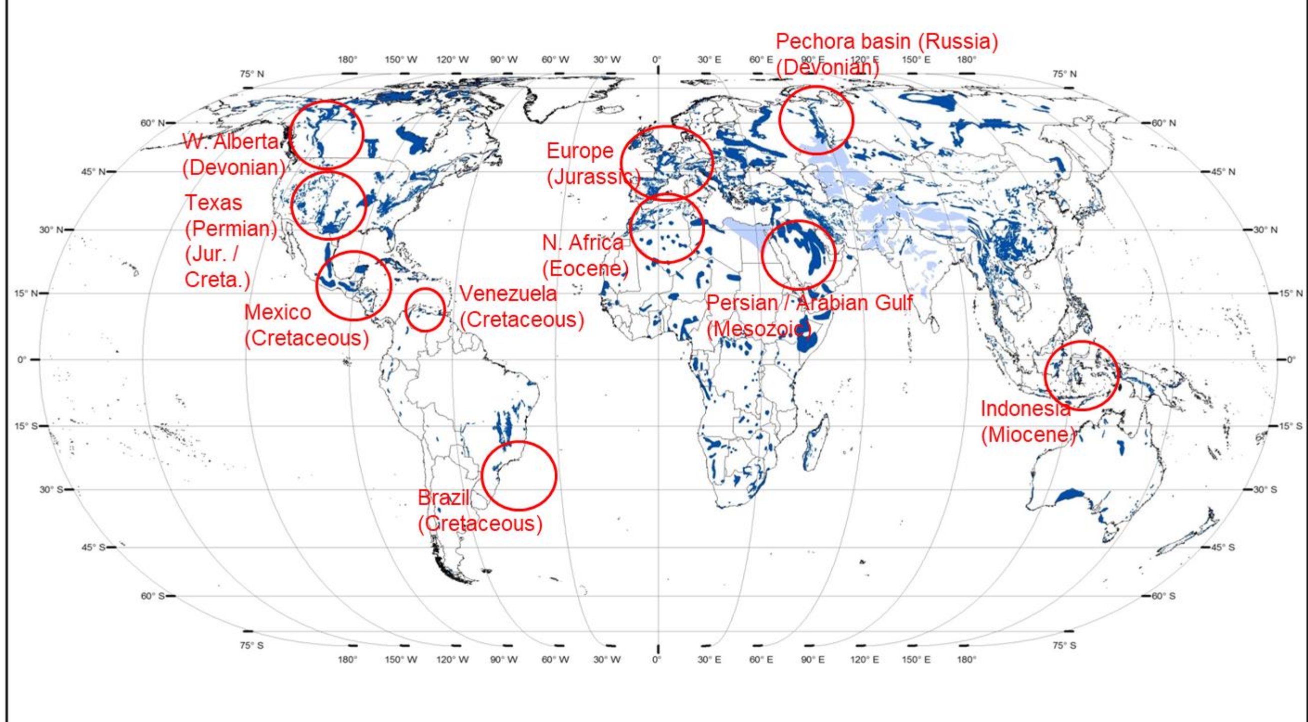
Conceptual Models for Deep Water Systems:

Carbonate Systems

Main Carbonate Reservoirs Location

Carbonates	Siliciclastics
Most sediments occur in shallow, tropical environments	Climate is not a constraint; sediments occur worldwide and at all depths
Most sediments are from marine environments.	Sediments are from marine and terrestrial environments.
Sediment grain size depends on the size of organisms' skeletons and calcified hard parts.	Sediment grain size depends on the hydraulic energy of the environment.
Lime mud indicates presence and growth of organisms whose calcified parts are mud-sized crystalites.	Mud indicates settling out from suspension.
Shallow water lime sand bodies result from localized chemical reactions (ie. physiochemical reactions or biological fixation of carbonate).	Shallow water sand bodies result from ocean current and wave action.
Sedimentary environments may change without a change in general hydraulic regime. (Local build-ups of sediments can alter properties of surrounding sediments)	Changes in the sedimentary environments correspond to changes in the general hydraulic regime
Sediments are cemented on the sea floor. Strong diagenetic control on petrophysical characteristics	Sediments remain unconsolidated in the environment of deposition and on the sea floor
Periodic exposure of sediments during deposition will cause diagenesis (ie. intensive cementation and recrystalization)	Periodic exposure of sediments during deposition does not affect the deposits.

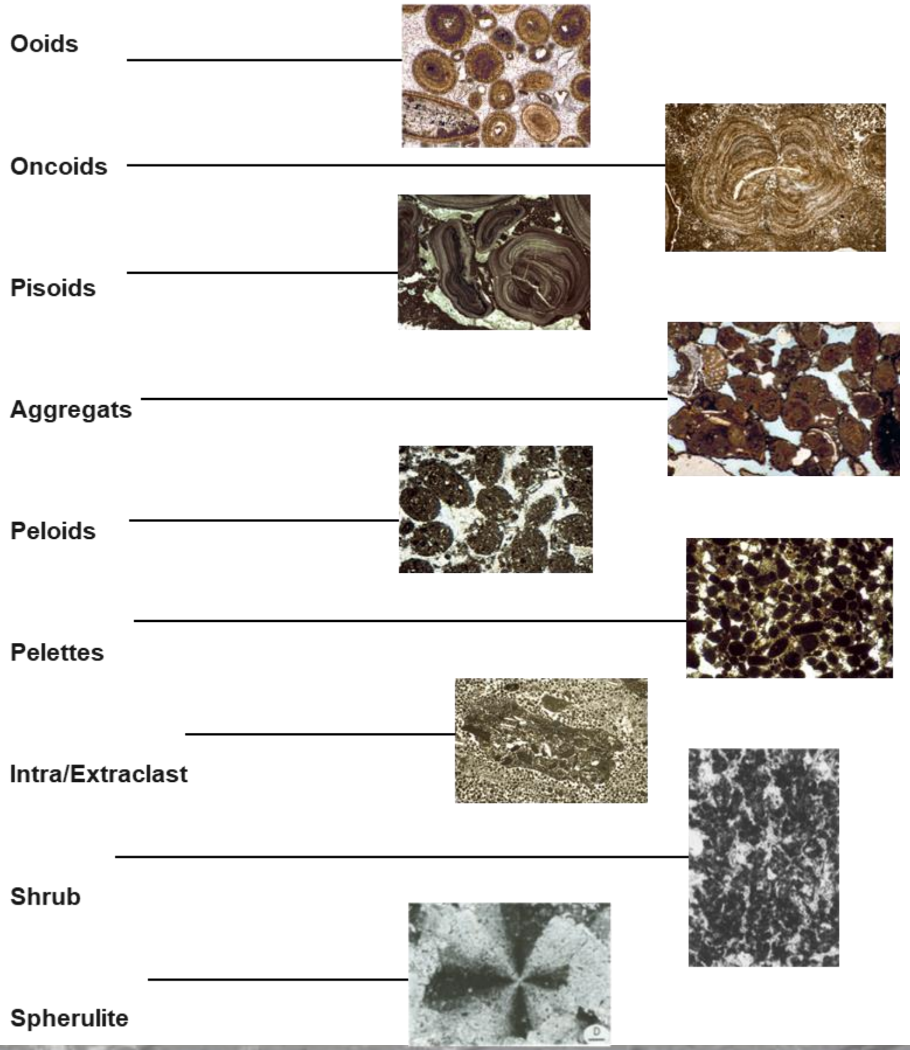
Carbonates represent > 40% of Oil and Gas resources of the Planet



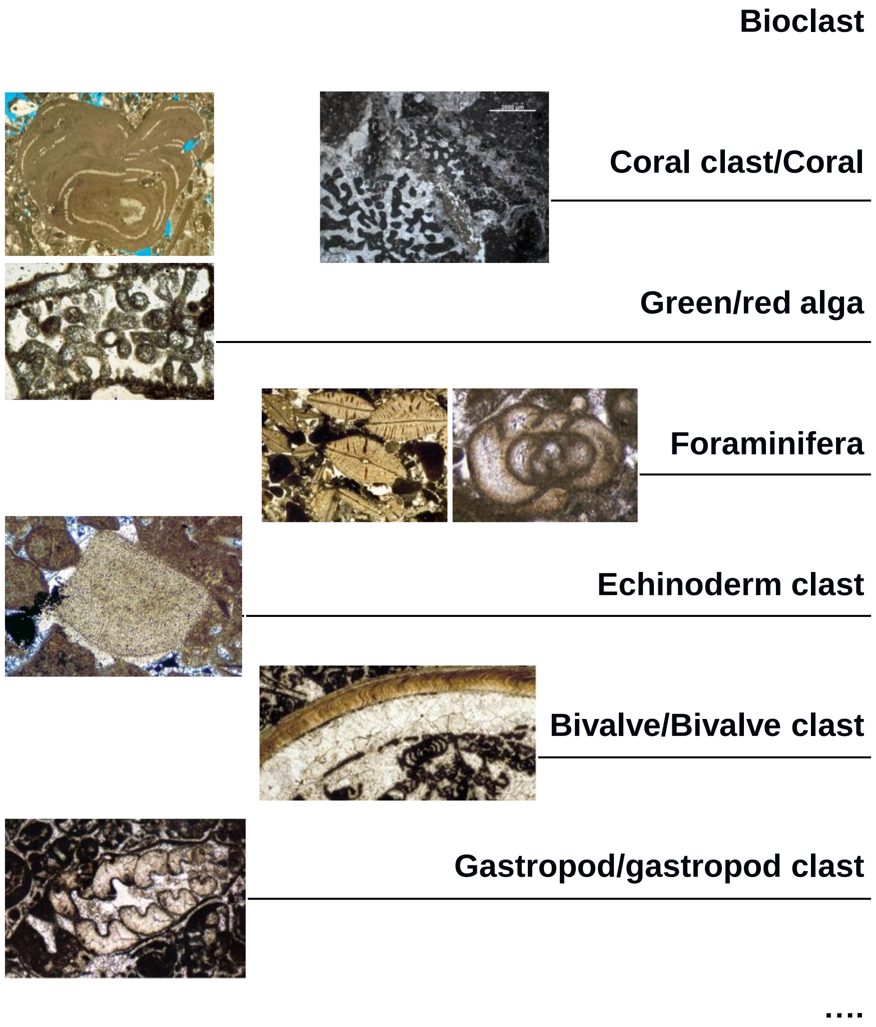
Williams & Ford (2006), modified

Carbonate Structure

Non-skeletal



Skeletal

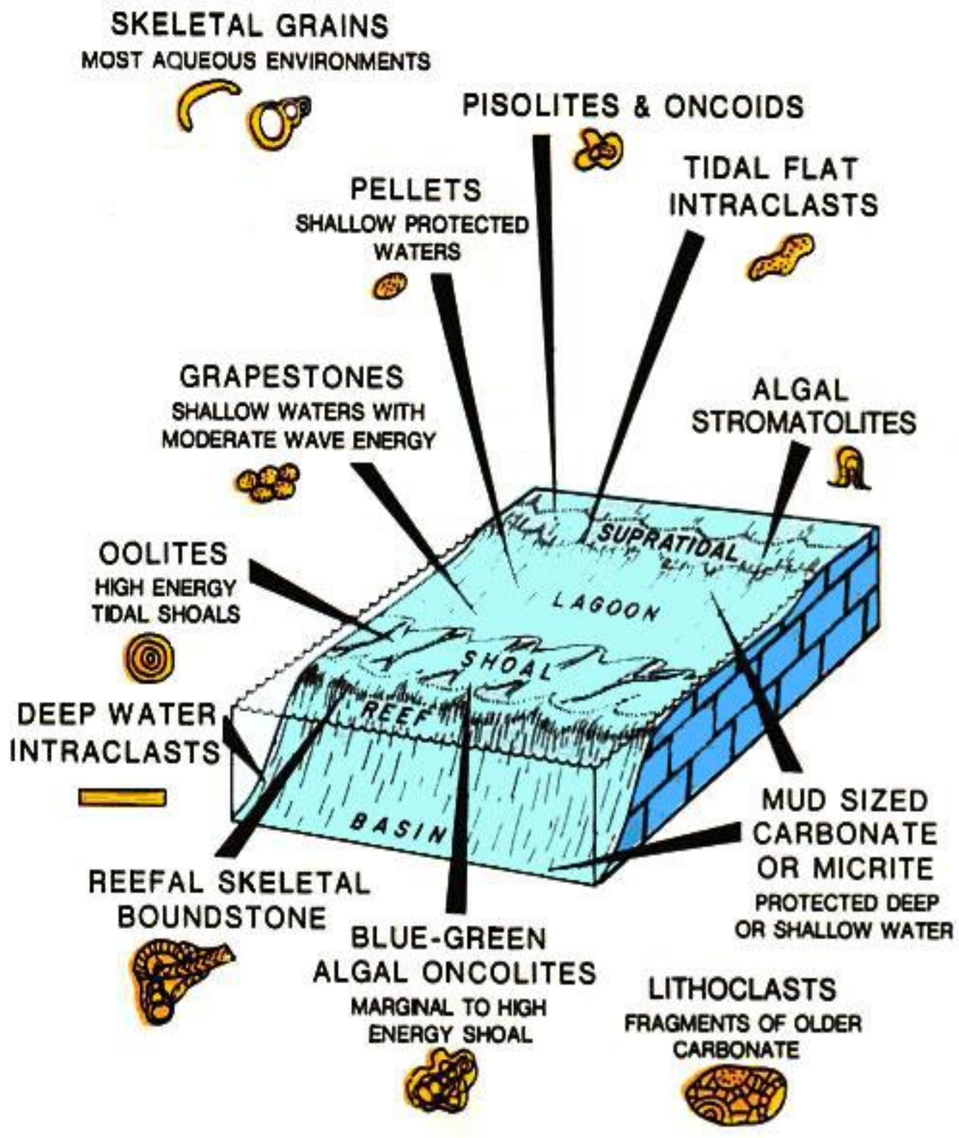


Non-Skeletal grain occurrence

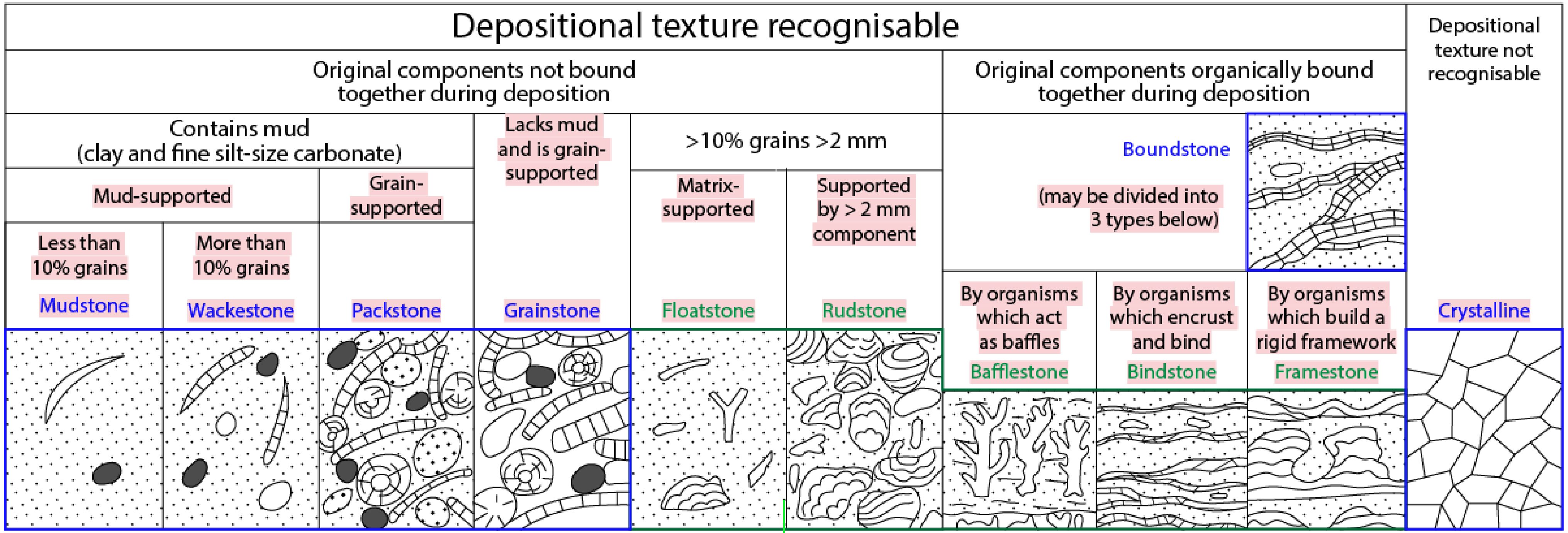
- Different approach to classification by focusing upon depositional limestone textures rather than upon the identity of specific kinds of carbonate grains.

- Two aspects of texture:
  - (1) grain packing and the relative abundance of grains and micrite
  - (2) depositional binding of grains.

- Embry and Klovan (1971) modified Dunham's classification by subdividing limestones composed of originally unbound constituents into two groups on the basis of carbonate grain size.
  - They introduced the terms floatstone and rudstone to describe conglomeratic texture.
  - They also subdivided boundstone into three subcategories on the basis of the presumed kind of organisms that built the limestones: bafflestone, framestone and bindstone.



Dunham’s Classification (1962)

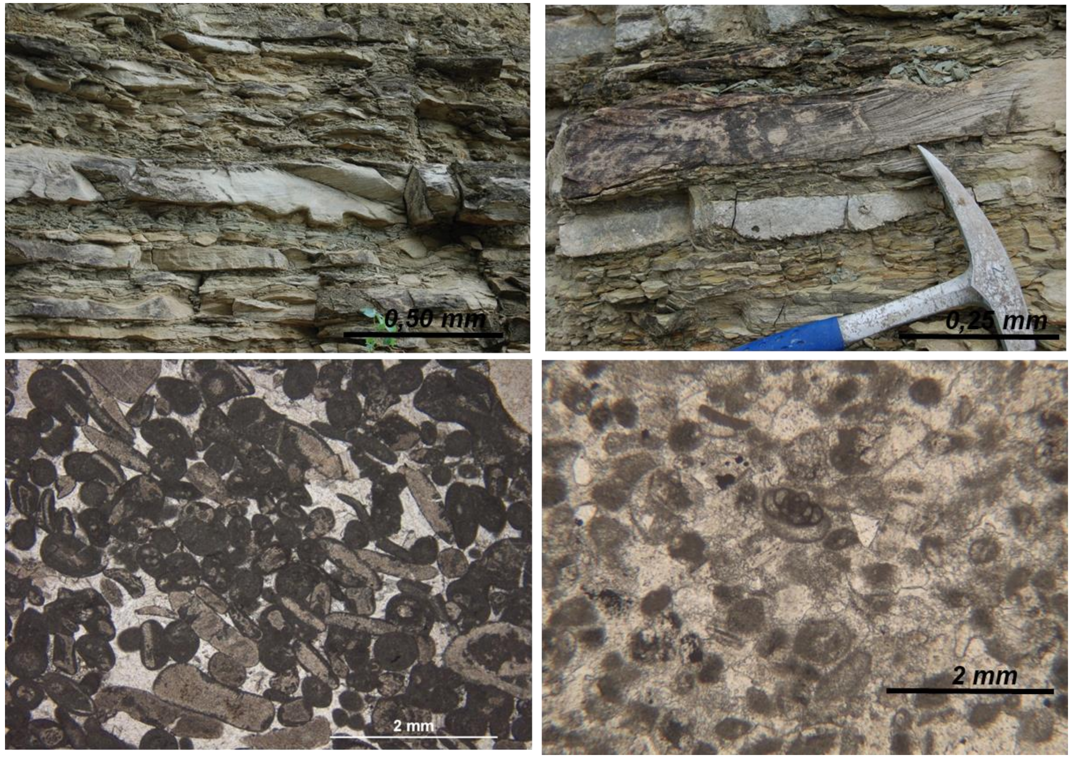


Dunham’s (1962) textural classification modified by Embry and Klovan (1971). Original Dunham’s subdivisions (blue) and modification by Embry and Kovan (green).

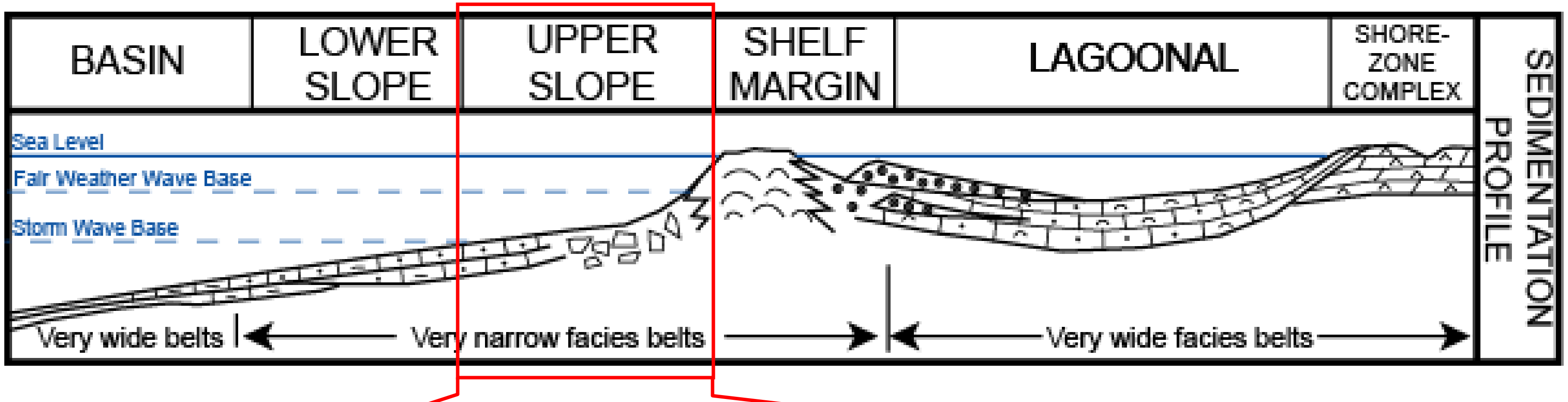
Outer Platform and Upper Slope

- We are going deeper and deeper. So now let's see the outer-platform and the upper slope, corresponding to the transition at the shallow-water platform margin to a transitional slope facies in which the bulk of sediment has been re-sedimented

- Carbonate platform slopes can range between 1 to 90 °.
- Granular and coarse grained sediment (non cohesive) as conglomerates or calcarenites are able to construct steeper slopes than the muddy ones.
- The early cementation of carbonate mud can also help build much steeper slopes than in siliciclastic environments
- Storm structures as (HCS) could also be identified in such settings.



Outer Platform and Upper Slope



<u>General assumptions</u>

- Transitional facies between shallow platform margin and deep platform facies
- Storm structures are frequent in the upper part
- Grainy and muddy facies can coexist in these environments
- Crinoids, echinoids, brachiopods, annelids tubes, planktonic forams are the main organisms

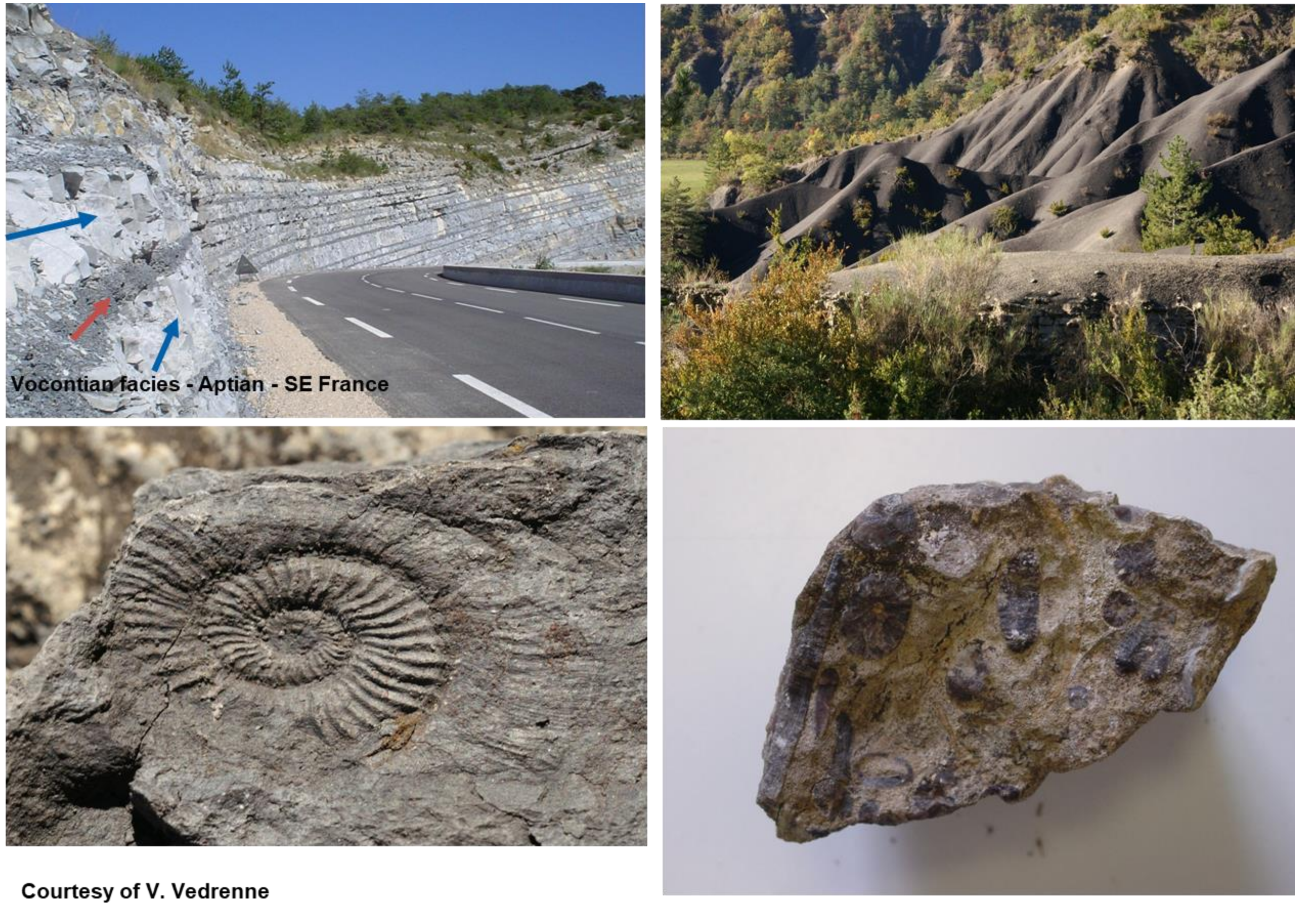
Lower Slope & Deeper Basin

- Such deep environments are below the Fair weather wave base and are thus calm and characterized by detritic components (quartz…) and by a muddy texture (mudstone to wackstone as well as by several specific organisms

- Gravity driven deposits are also expected

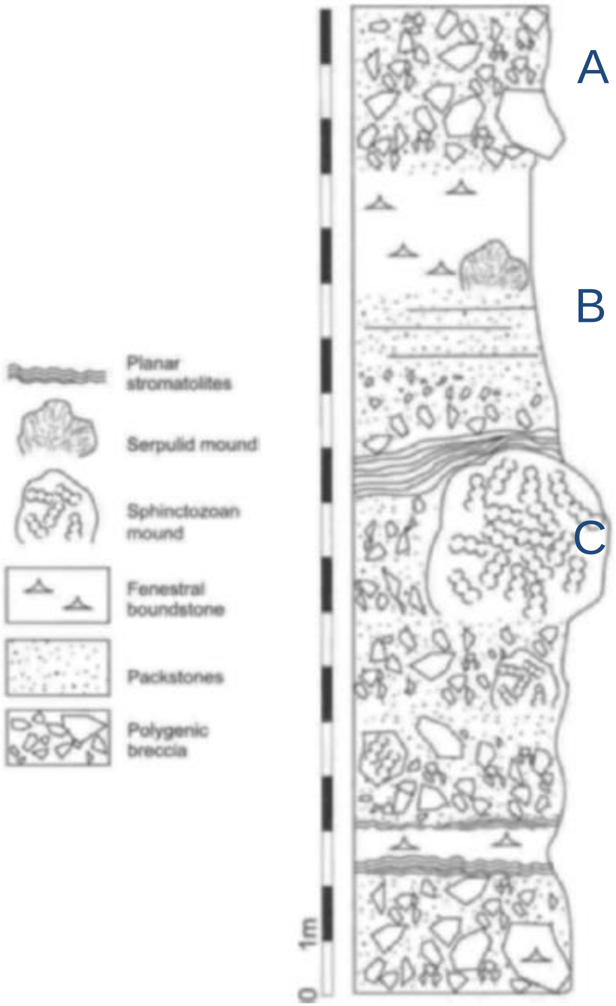
- In such type of environment the sedimentation is mainly represented by a marked stratification between shale and carbonates

- Storm events produce a large variability of stratigfication architectures that impacts sediment deposits in ramp settings



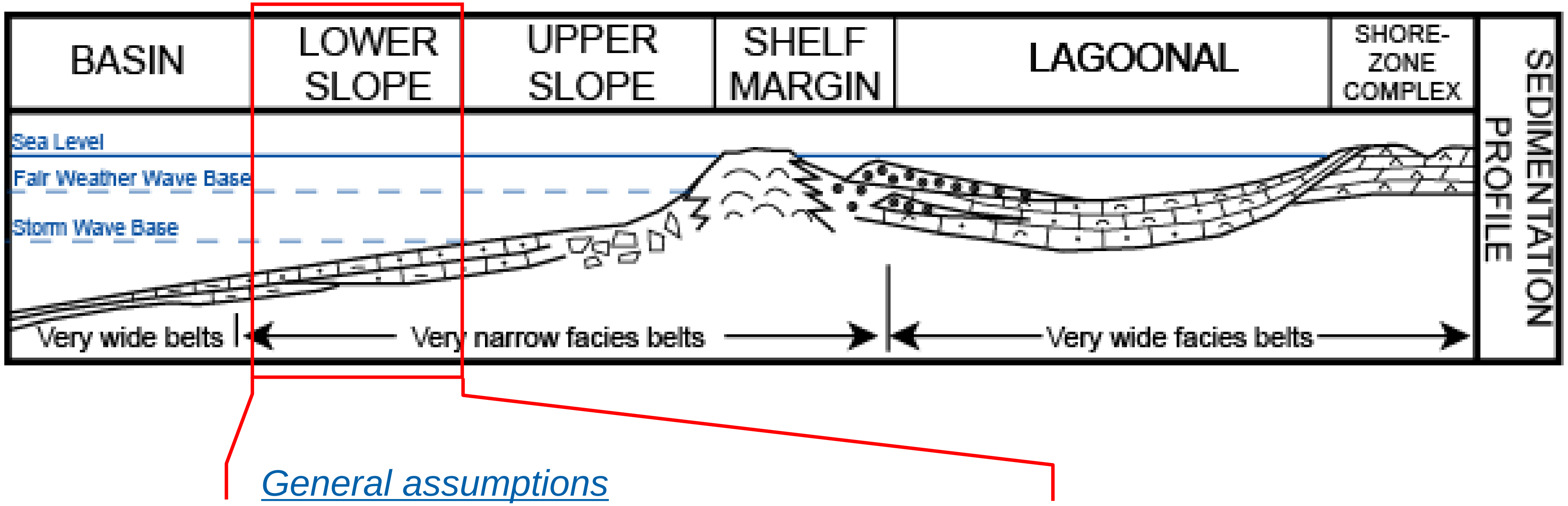
Courtesy of V. Vedrenne

Deeper Environments



Carbonate turbidites and ***slump***
(Slope deposits – Norian of Calabria,
Southern Italy)

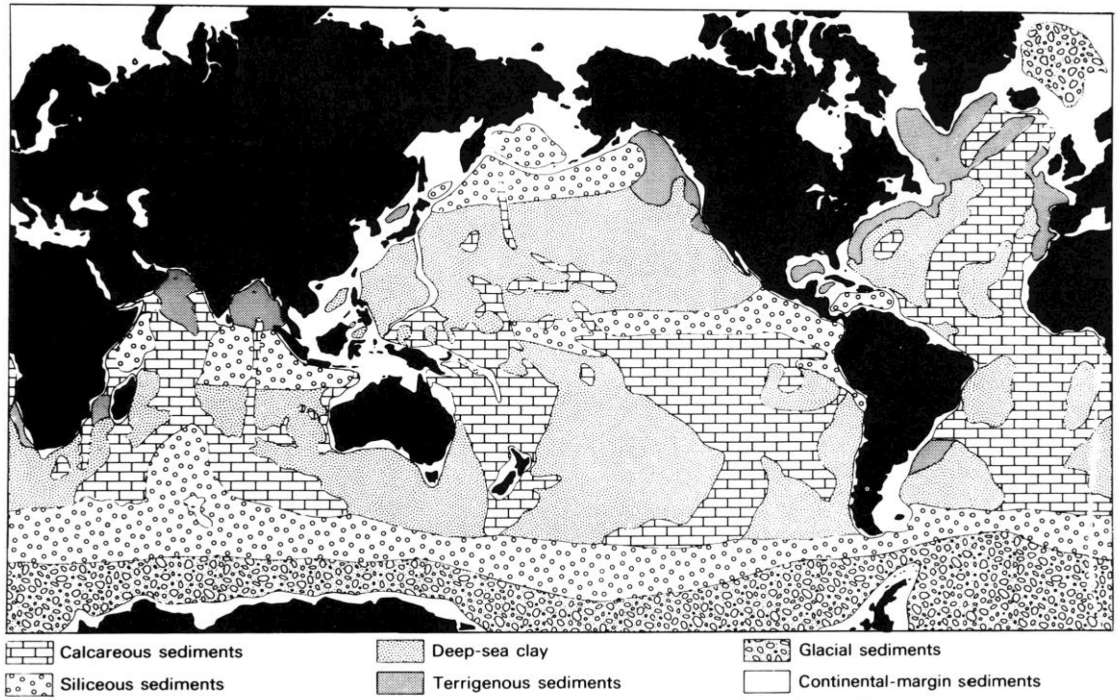
Lower Slope & Deeper Basin: Summary



General assumptions
- Presence of a detrital fraction
- Muddy texture (mudstone and wackestone)
- Slumps, turbidites
- Cephalopods (ammonites, belemnites), irregular echinoids, sponge spicules, Calpionella
- Radiolarites

Deep Basin: Pelagic Deposits

- At first deep marine sediments were thought to be mainly composed of pelagic mud and ooze deposited in a calm setting.
- However calcarenites have been observed and are expected to be linked to turbidite currents in deep settings and are expected to contribute to the deep marine deposits
- Pelagic carbonates are debris of skeletal planktonic organisms deposited in open marine systems in the Mesozoic and Cenozoic
- Non lithified carbonates (ooze) cover almost half of the deep marine settings. They are mainly present above 4500m of water depth.
- These carbonates desolve deeper than 4500m (Carbonate Compensation Depth CCD-acuumulation rates equal to dissolution of carbonates)



Global distribution of principal types of pelagic and other sediments on the ocean floors. After Jenkyns (1986).

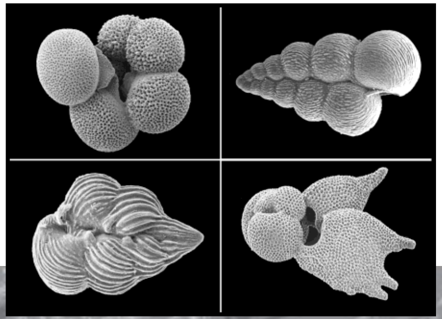
in Tucker et Wright, 1990

Different depositional locations for carbonate ooze

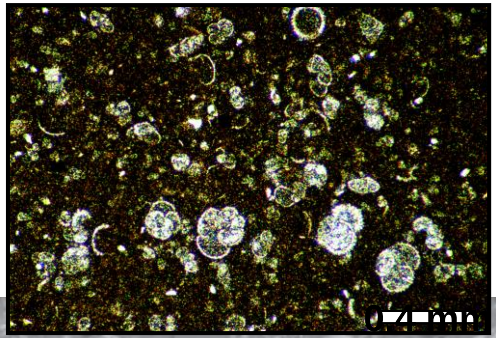
on highs: spreading ridges (2.5 to 3 kms deep), volcanic highs

small ocean basins (Red Sea, Mediterranean): high T° and salinities

continental margins : pelagic sediments with no terrigenous input (Bahamas, Yucatan)



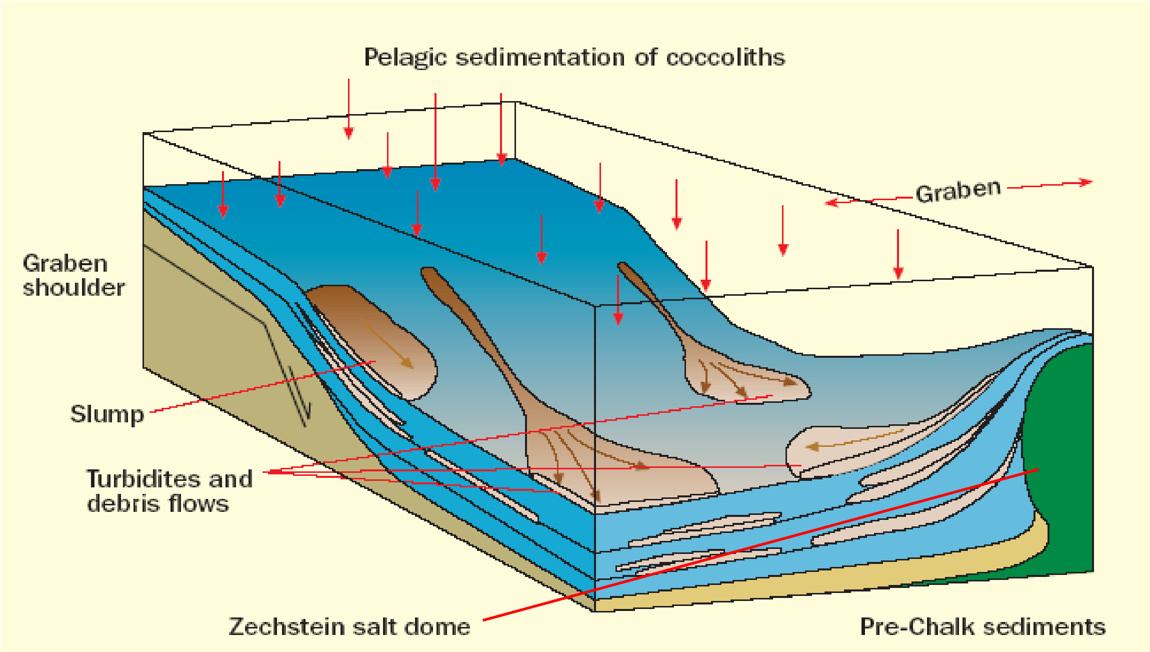
globigenirids



AAPG Memoir 77, 2003

North Sea example

- Many lithofacies due to different depositional processes, and diagenesis
- 2 main facies:
  - pelagic chalk: accumulation of coccoliths, 15-25 cm/1000 yr
  - resedimented units (allochtonous): thin turbidite beds, slumps, slides
- Diagenesis:
  - chalk mostly made of low Mg Calcite (96-99%)
  - main process: compaction (chemical and physical): but limited due to several reasons!



- Porosity:
- wide range: 0-52 %, high porosity (50%) can occur at great depths (3 kms)

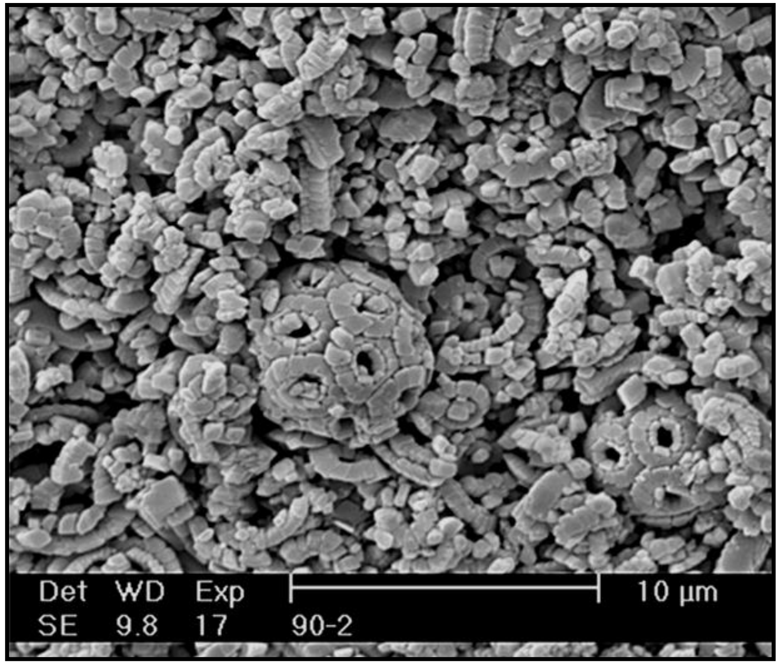
- Overpressuring due to:
  - rapid subsidence after deposition, low total permeability & lateral confinement by graben margins

  - Lithostatic pressure supported by pore fluid pressure -> reduced compaction -> porosity is preserved

Ancient Pelagic Carbonates

Upper Cret. is a period of high sea-level: 200 m of chalk deposited in Western Europe, thickening to 1200 m in the North Sea - important HC reservoir

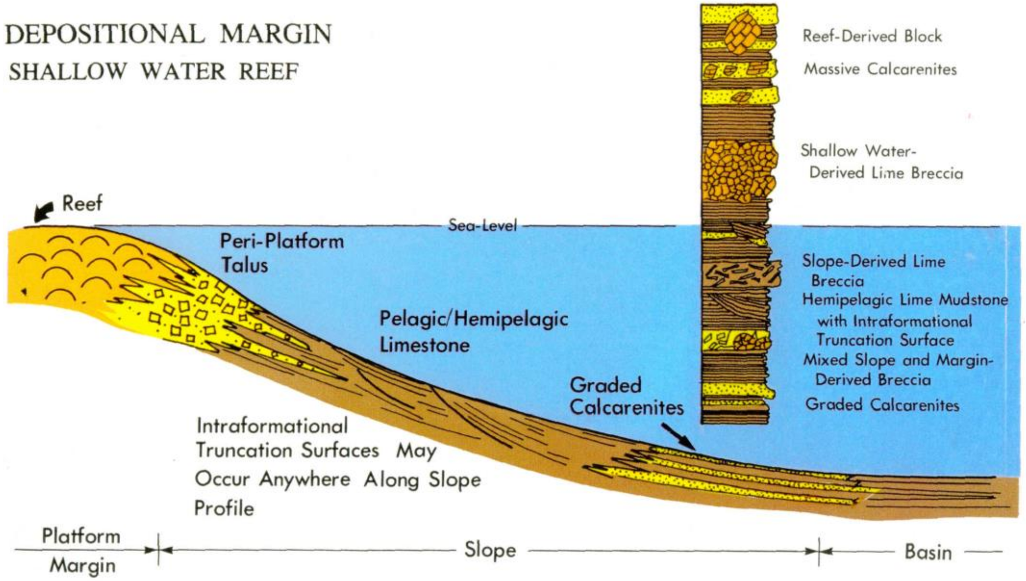
Chalk – Etretat, France,
(Cretaceous and Tertiary)



Resedimented carbonates

Shallow-water carbonates in deep-water settings are common in the geological record !

- Resedimented carbonates (reef debris, carbonate megabreccias, limestone turbidites) are important Hc reservoirs (Permian of Texas, Mexico, North sea chalks)
- Different processes are involved: rock falls, slides, slumps, gravity flows, turbidity currents



Source material: pelagic ooze in most cases

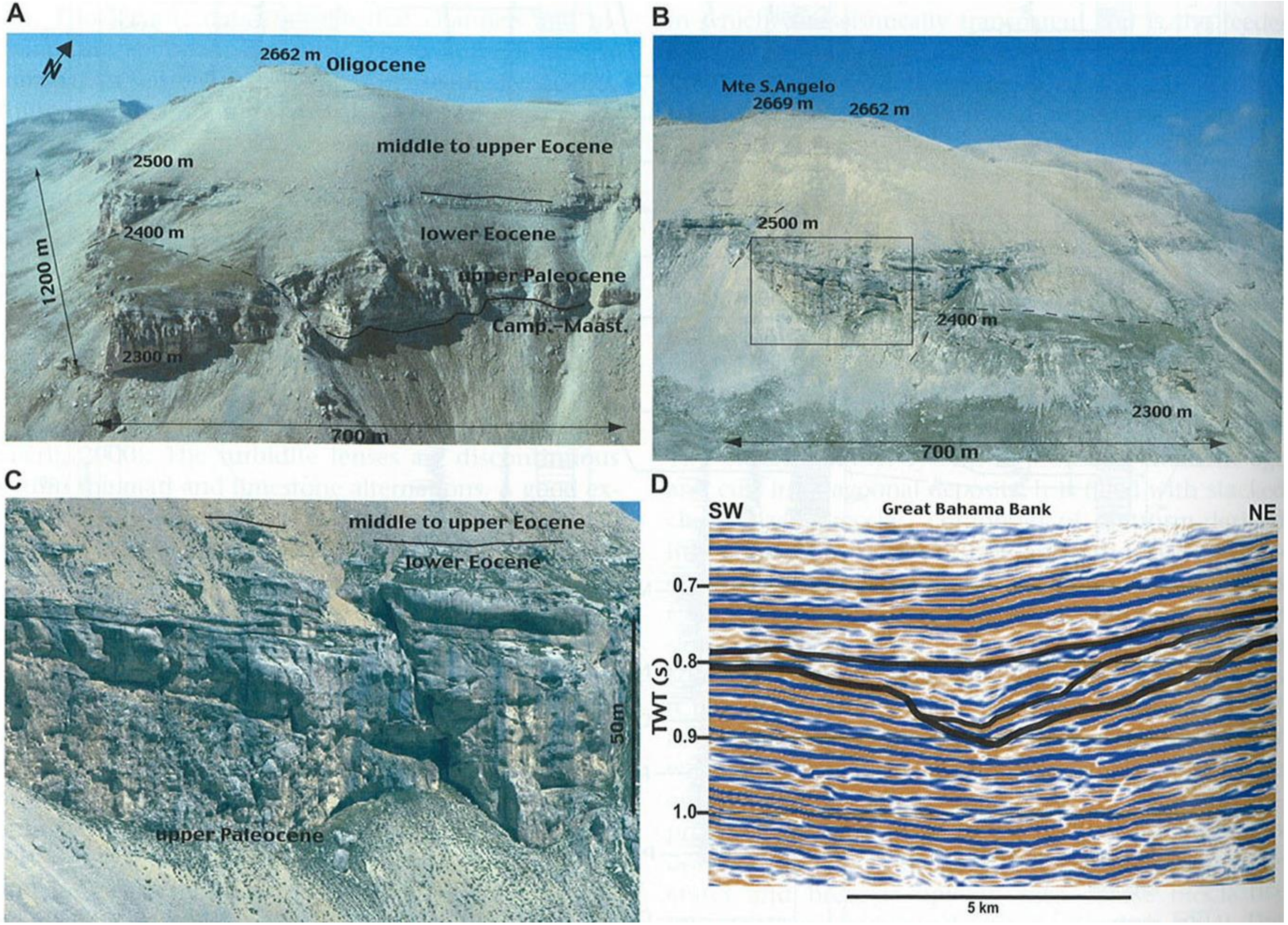
Mobilization: by seismic events or sea-level variations

Processes:

- Rockfalls: along steep slopes (common along PF margin limited by a fault, or near reefs)
- Slides and slumps: sediment movement on carbonate slopes, along detachment surfaces, with more or less internal deformation
- Sediment gravity flow: turbidity currents, limestone turbidites

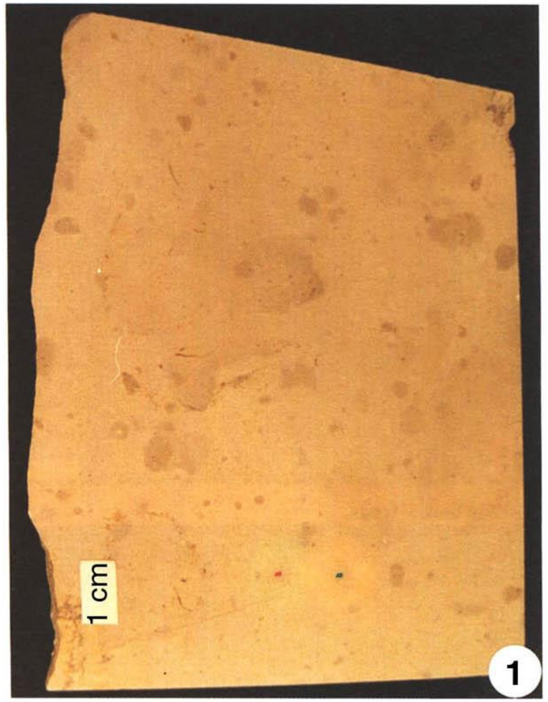
Forereef Breccia

Slope Channels/ Turbidite channels

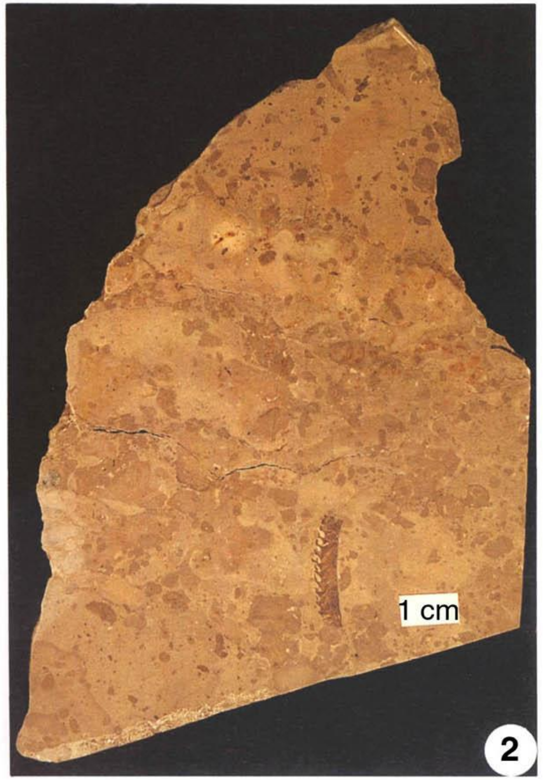


Eberli in AAPG Memoir 81, 2004

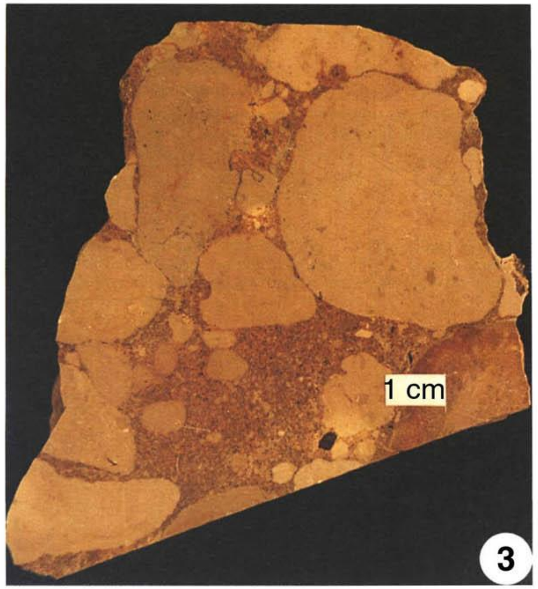
Gravity driven processes



Mud flow deposit



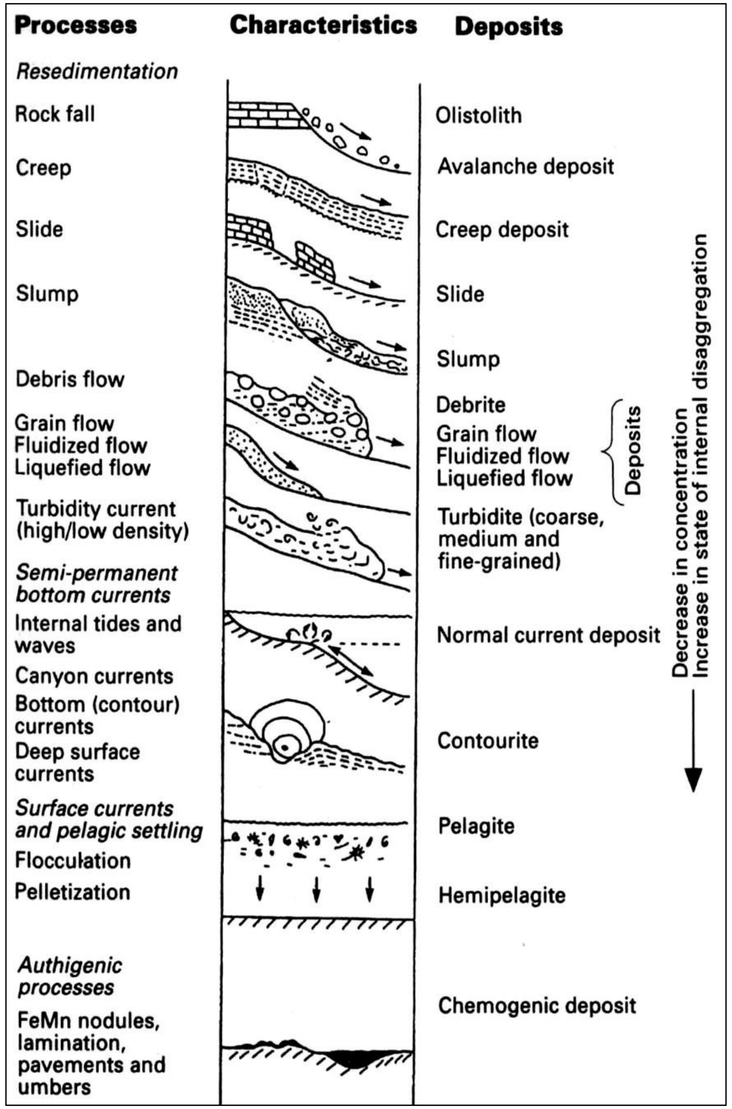
Debris fow deposit



Grain flow deposit with limestone clasts

Polished slabs from Broyon section

Strohmenger et al., BCREDP 17 (1993)

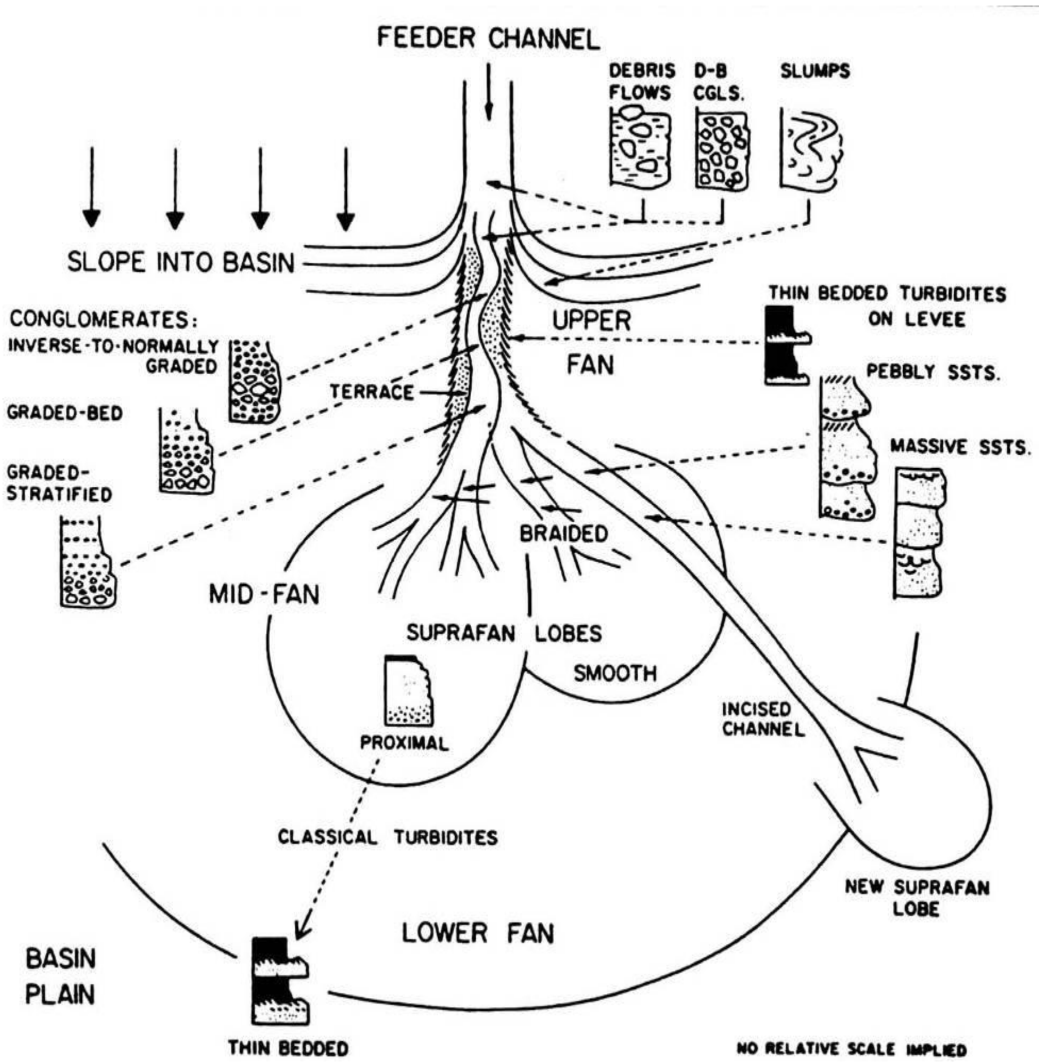


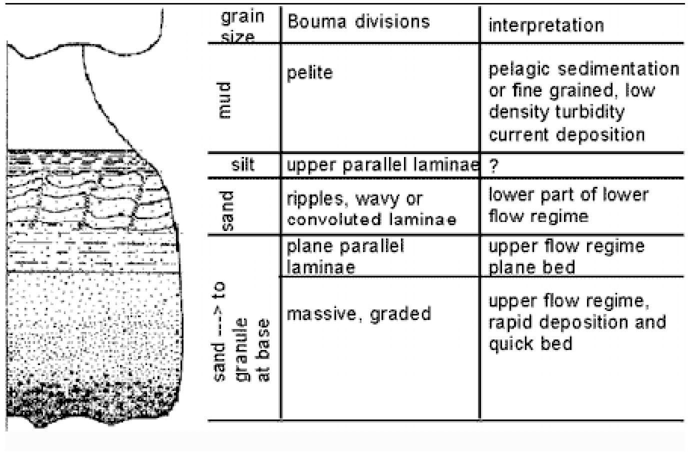
Carbonate Slope Deposits

A sequence illustrating two different types of carbonate slope deposits; debris flows with large limestone clasts (right) and thin-bedded, graded calcarenites (the thin, gray limestone beds), interbedded with black fissile shale. This overturned sequence (top at lower left) of Middle Ordovician age occurs at Cape Cormorant, Port-au-Port Peninsula, Western Newfoundland (from McIlreath and James, 1978; courtesy of N. P. James).

H.E. Cook & H.T. Mullins, in AAPG mem. 33, 1983

Resedimented carbonates





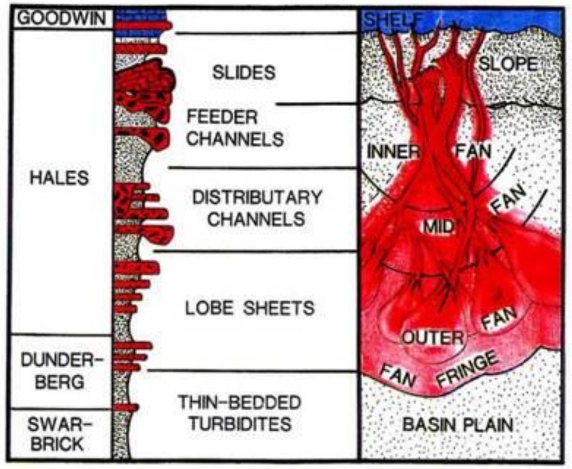
grain size	Bouma divisions	interpretation
mud	pelite	pelagic sedimentation or fine grained, low density turbidity current deposition
silt	upper parallel laminae	?
sand	ripples, wavy or convoluted laminae	lower part of lower flow regime
sand ---> to granule at base	plane parallel laminae	upper flow regime plane bed
	massive, graded	upper flow regime, rapid deposition and quick bed

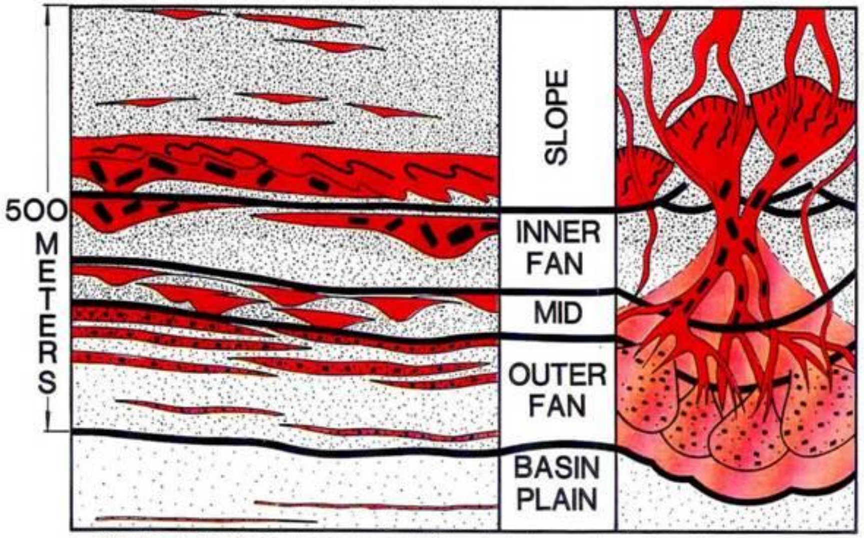
Bouma sequence

Schematic model of submarine fan sequence

Resedimented carbonates

Preliminary local carbonate submarine-fan model showing that fan sediment is derived from both shoal-water shelf areas and by the remolding of deeper water slides and slumps into mass-flows, large slides and channelized conglomerates that occur in outer fan sites, calcarenites in non-channelized sheets in mid-fan sites, and thin-bedded silt to fine sand-sized carbonate turbidites in fan fringe and basin plain. Slope and fan facies about 500 m thick, basin plain facies about 1000 m thick. Model based on studies in Cambrian and Ordovician strata in Nevada (modified from Cook and Egbert, 1981b, c).

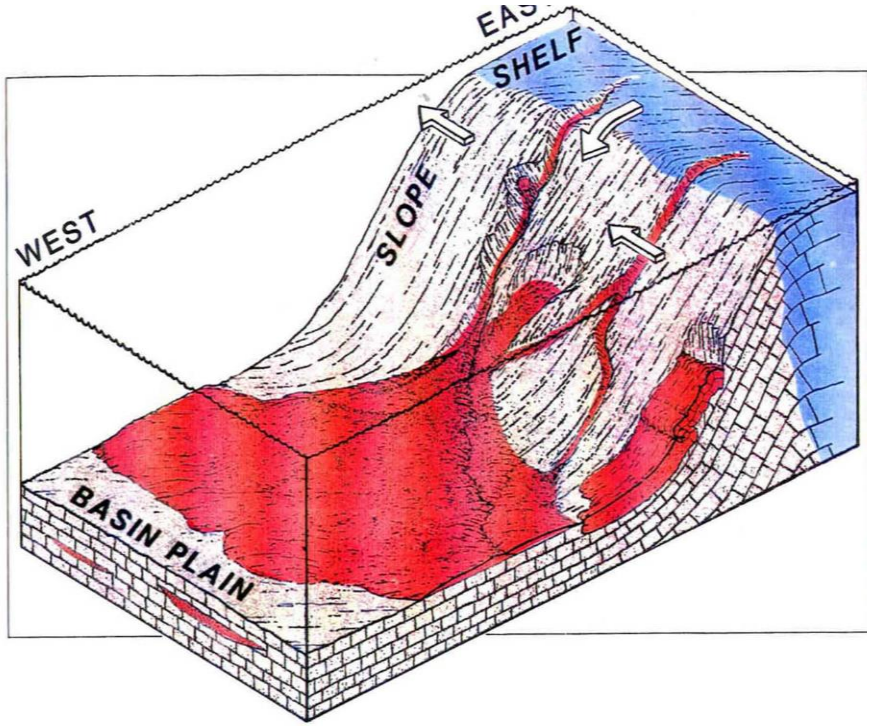




Preliminary local carbonate submarine fan model. Schematically shows vertical and lateral facies sequences that occur in prograding continental margin section illustrated in Figure 117b. Model based on studies in Cambrian and Ordovician strata in Nevada (from Cook and Egbert, 1981a).

Carbonate submarine fan model

Cook and Edberg, 1981



Model of shelf-slope-basin transition in the Late Cambrian and Early Ordovician of Nevada

The Importance of Sequence Stratigraphy

Definition & Application

Sequence stratigraphy (Posamentier et al., 1988; Van Wagoner, 1995): the study of rock relationships within a time-stratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or nondeposition, or their correlative conformities.

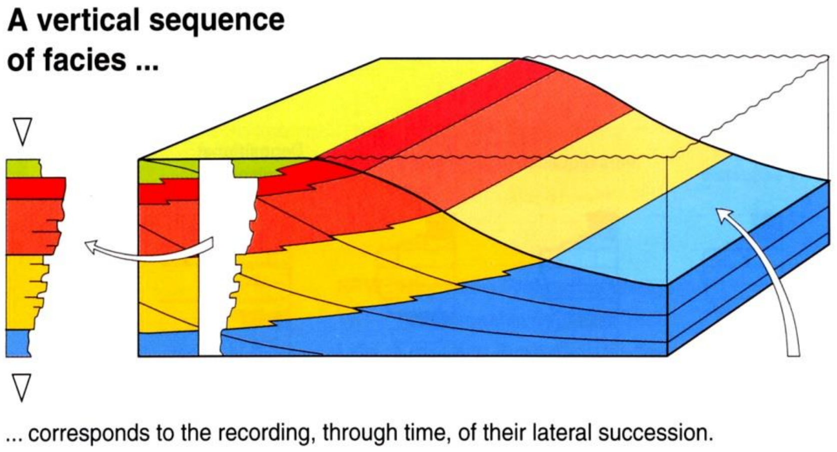
Sequence stratigraphy (Galloway, 1989): the analysis of repetitive genetically related depositional units bounded in part by surfaces of nondeposition or erosion.

Sequence stratigraphy (Posamentier and Allen, 1999): the analysis of cyclic sedimentation patterns that are present in stratigraphic successions, as they develop in response to variations in sediment supply and space available for sediment to accumulate.

Sequence stratigraphy (Catuneanu, 2006): the analysis of the sedimentary response to changes in base level, and the depositional trends that emerge from the interplay of accommodation (space available for sediments to fill) and sedimentation.

Historical Background: 1880-1900, Walter’s law

Johannes Walther enunciated (1893-94) the principle that



- *to a vertical progression of facies can be found corresponding lateral facies changes*. Or,
- *lithologies that conformably overlie one another must have accumulated in adjacent depositional environments.*

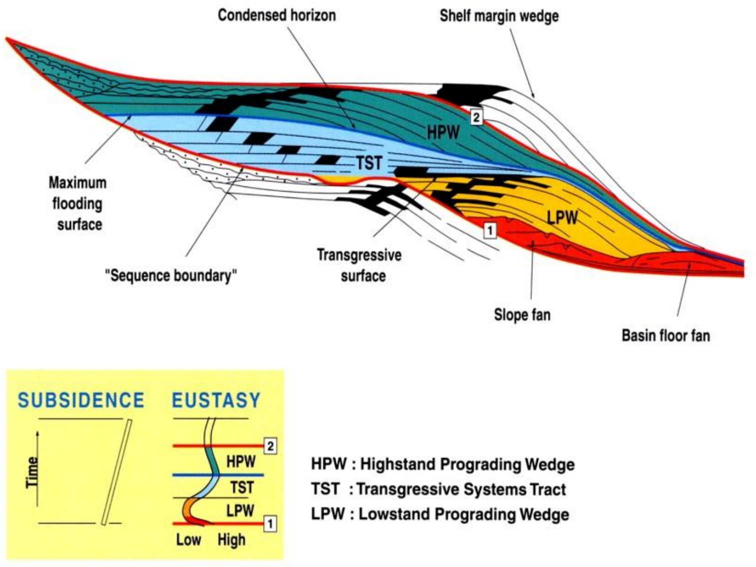
- Sedimentary rock types also record the environment of their deposition.
- Depositional environments can shift laterally as conditions change.
- When so, laterally related environments become superimposed.
- Time transgressive sedimentary formations, are the result.
- The succession vertically and laterally will be the same.

Historical Background: 1950-1980, Seismic Stratigraphy

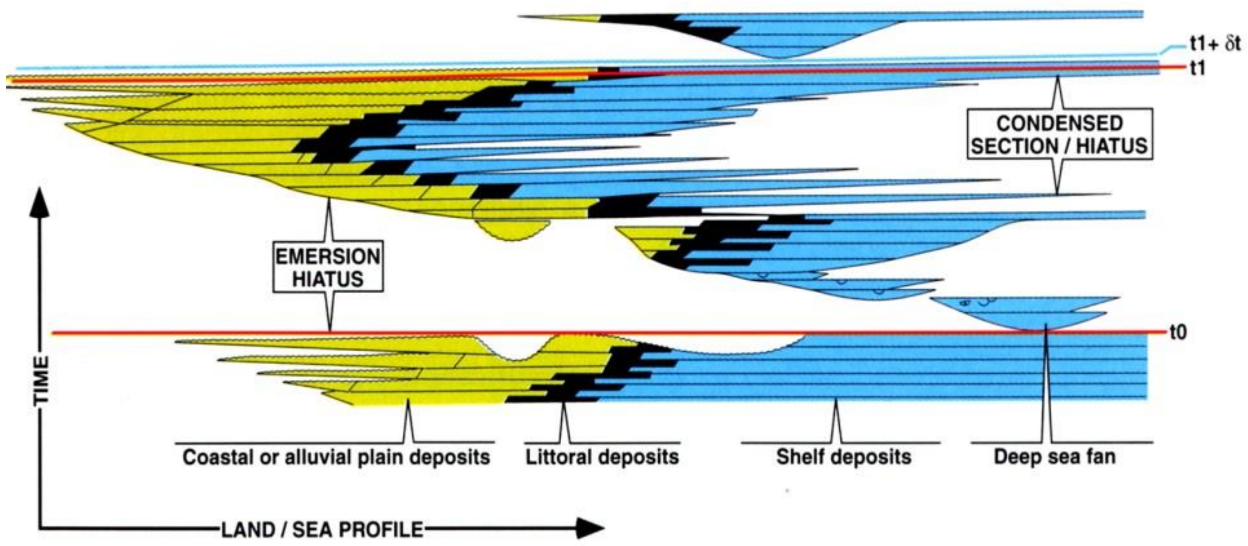
Seismic stratigraphy: study of the stratigraphic relationships on seismic data

- Originated during the 1960s with the study of the stratigraphy of the continental USA, where numerous unconformities could be correlated widely, and led to the proposal that major unconformities might mark synchronous global-scale events.

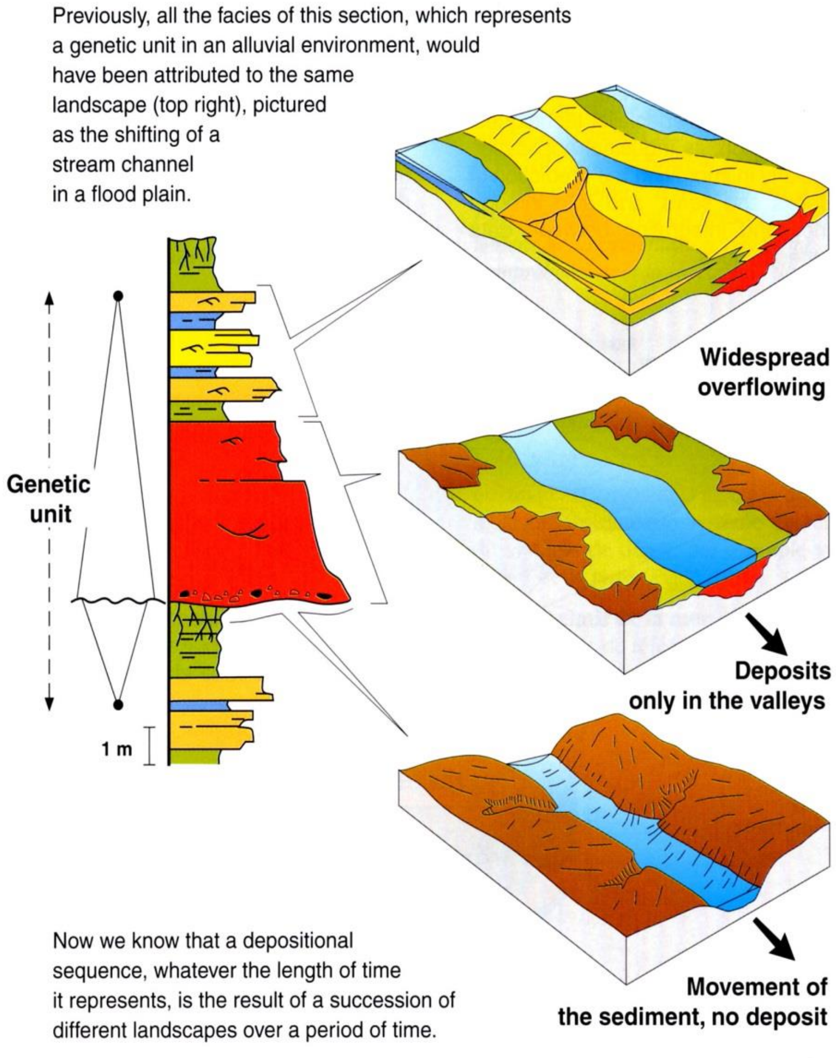
- Studies of outcrops and seismic lines bore out these concepts, which initially were called "Seismic Stratigraphy" and first published widely in 1977.



Vail's famous "slug" model at the continental margin scale. This has become the symbol of sequence stratigraphy.

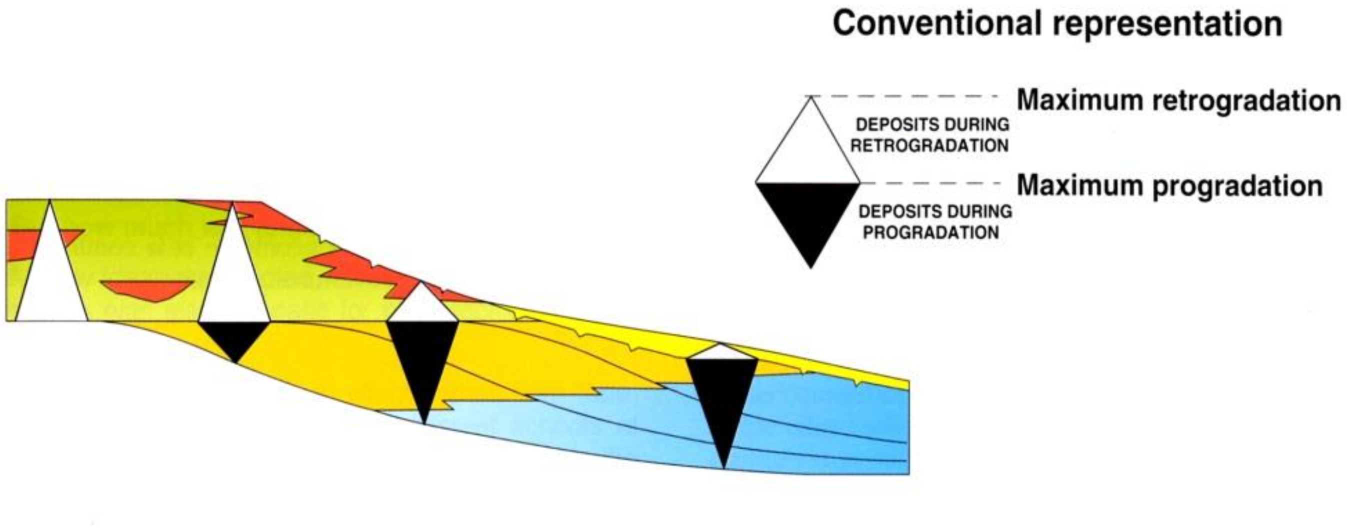


Historical Background: 1950-1980, Genetic Stratigraphy



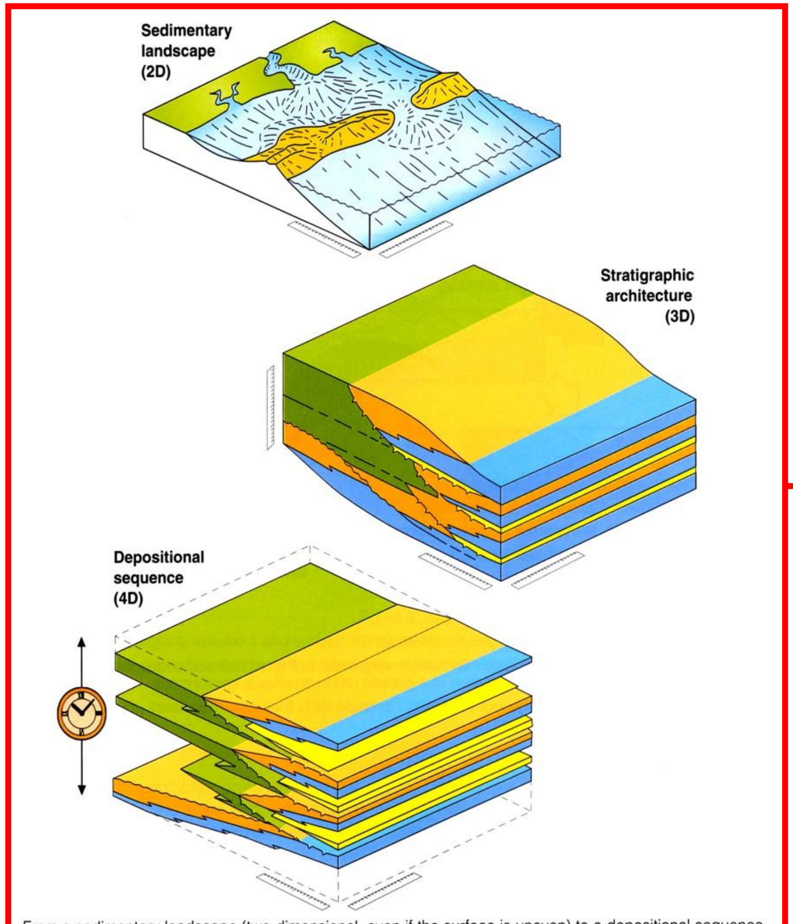
From the geomorphological "landscape sequence" to the depositional sequence: for example, the formation of a genetic unit in an alluvial environment.

Genetic stratigraphy: sequence stratigraphy building up from smaller units such as from cores and logs, integrating facies models.

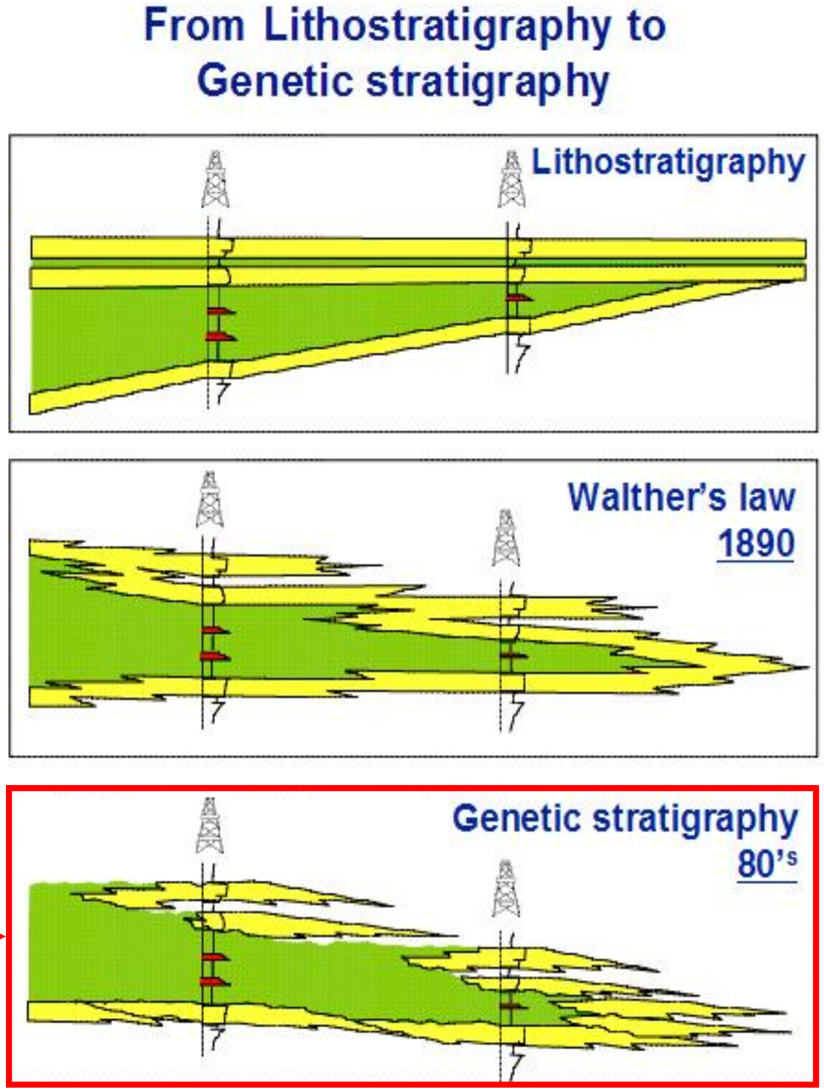


The sedimentary pattern of an accommodation cycle is almost never symmetrical.

Historical Background: Summary



From a sedimentary landscape (two-dimensional, even if the surface is uneven) to a depositional sequence (four-dimensional: three dimensions in space and one in time).



Definition & Application

- Sequence stratigraphy is uniquely focused on analyzing changes in facies and geometric character of strata and identification of key surfaces to determine the chronological order of basin filling and erosional events.

- Applications of sequence stratigraphy cover a wide range, from deciphering the Earth's geological record of local to global changes in paleogeography and the controls governing sedimentary processes, to improving the success of Petroleum Exploration and Production

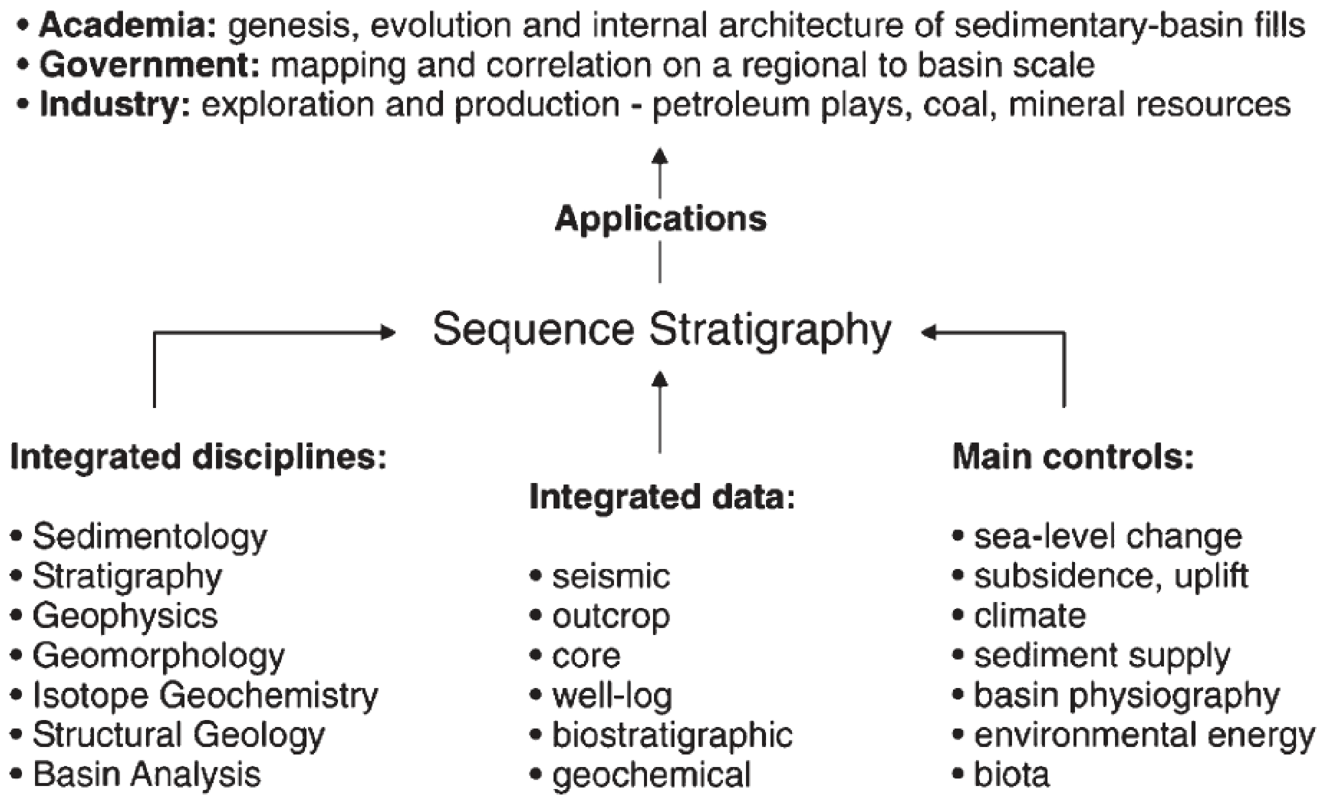


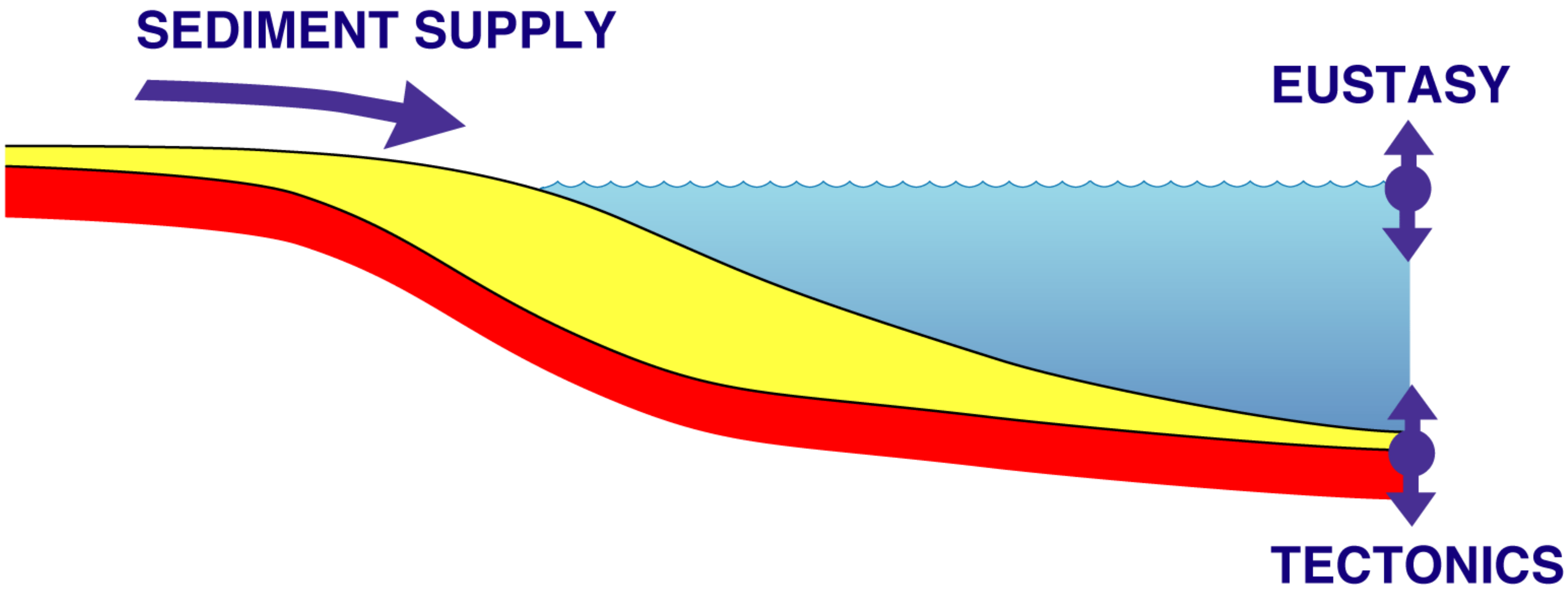
Figure 1. Sequence stratigraphy in the context of interdisciplinary research.

Cataneanu et al., 2009

Influencing Factors

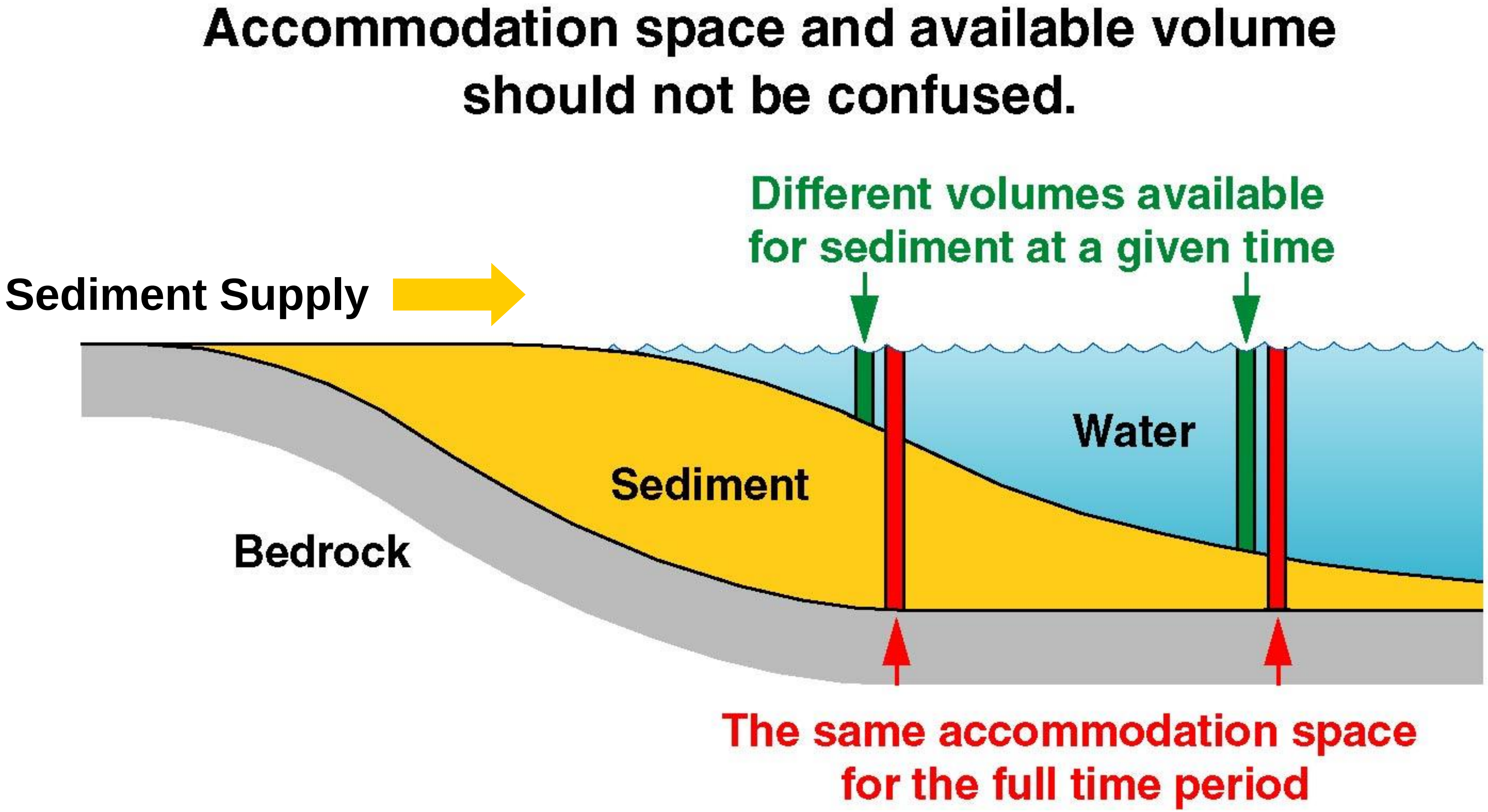
Sedimentation is controlled by 3 main factors

Principle of accommodation space



Homewood *et al.* (2000)

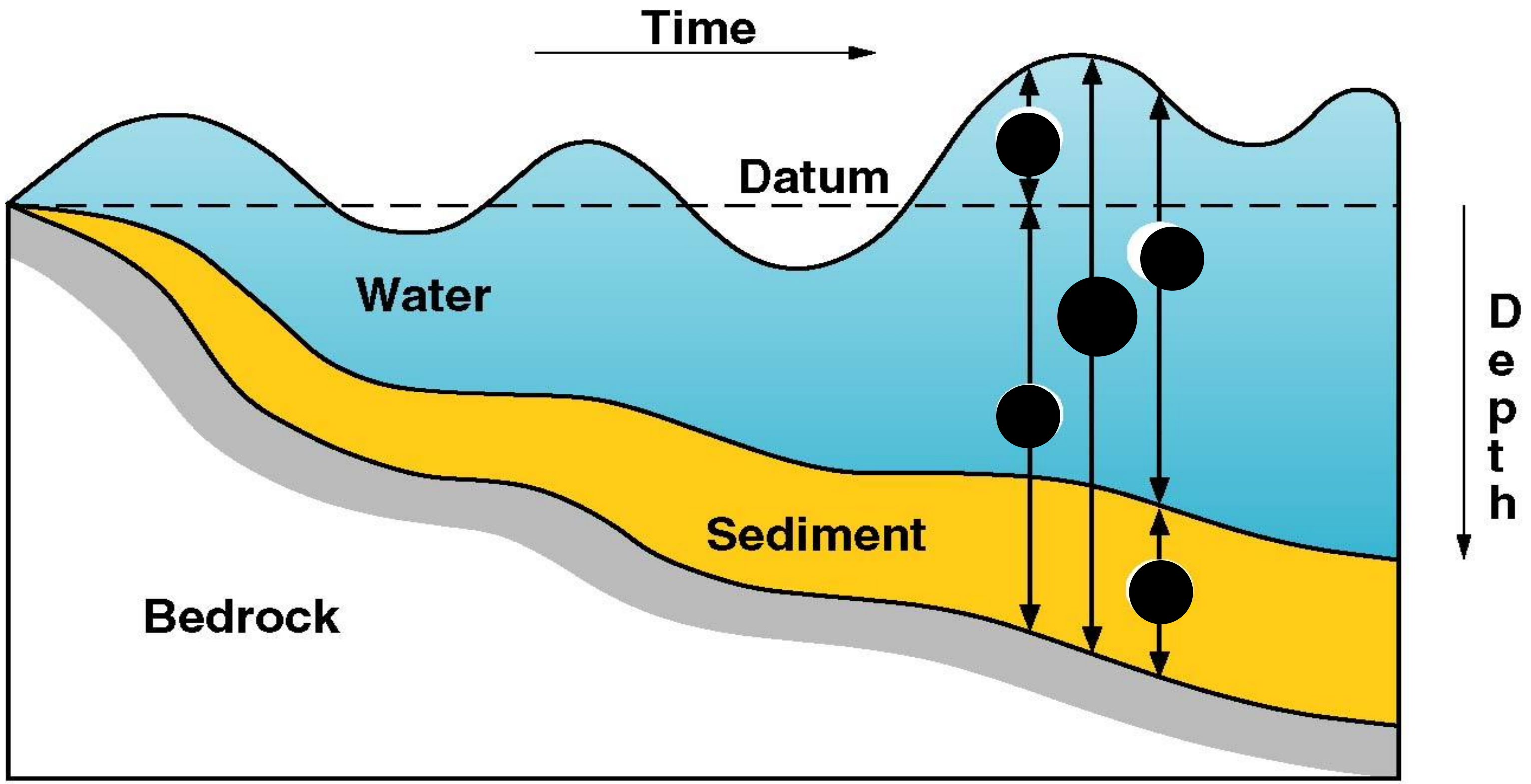
Influencing Factors



Homewood *et al.* (2000)

Influencing Factors

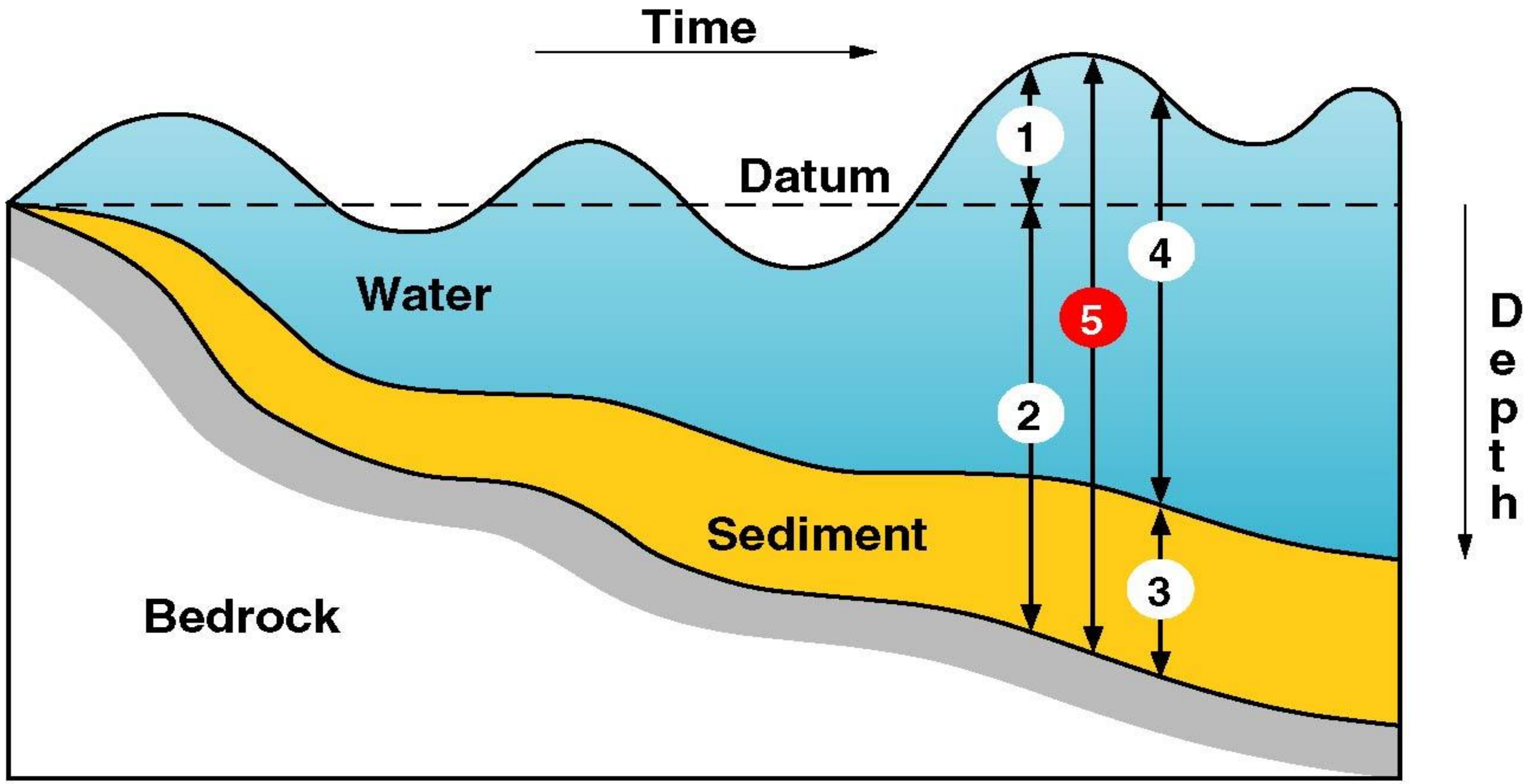
Exercise



1 : Eustatic level
2 : Subsidence
3 : Thickness of sediment (effective accommodation)
4 : Depth (unfilled accommodation)
5 : Relative sea level or TOTAL ACCOMMODATION

Influencing Factors

Exercise



1 : Eustatic level
2 : Subsidence
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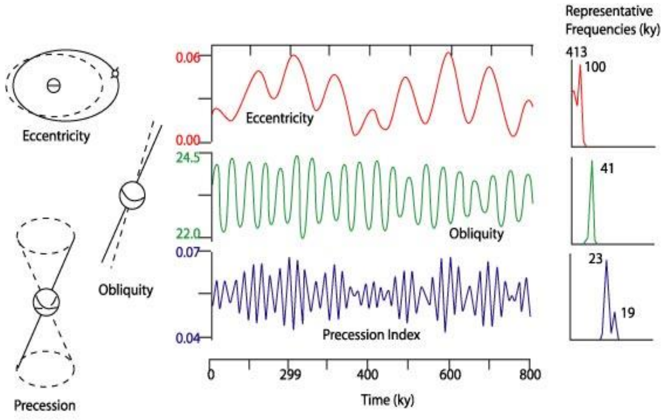
DEFINITIONS & CONCEPTS in sequential stratigraphy

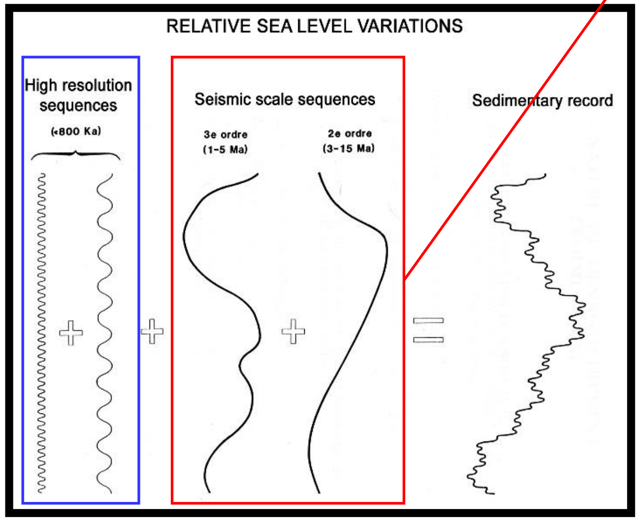
Controls on the sedimentary record

Astronomic cycles

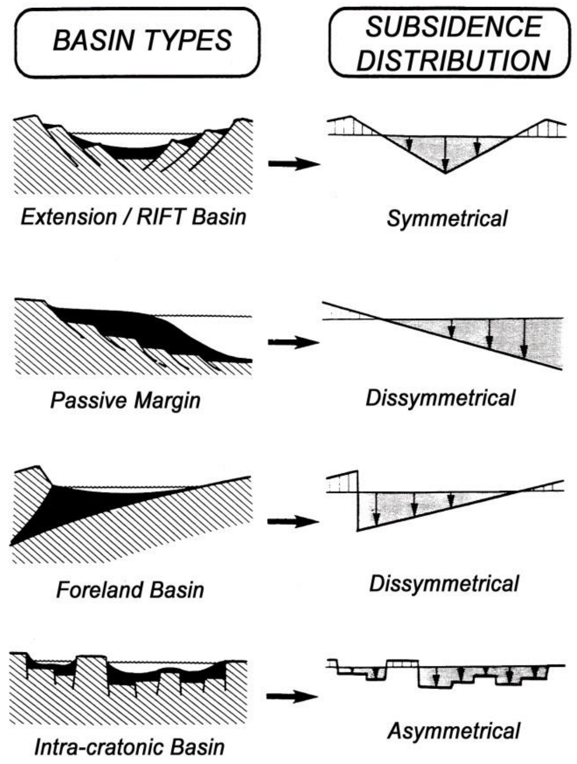


Milankovitch Frequencies (from SEPM # 40)

- Glacio-eustatism
- Climate
- Paleogeography…



Tectonic regimes



- Tectono-eustatism
- Paleogeography
- Sediment supply…

Hierarchical Depositional Sequences

HIERARCHY OF DEPOSITIONAL SEQUENCES AND RELATED PROCESSES

ORDER	1st	2nd	3rd	4th/5th
DURATION	> 50 My	3–50 My	3–0.5 My	400,000 } (Eccentricity) 100,000 } 40,000 (Obliquity) 20,000 (Precession)
MAIN PROCESS	Long-term global tectonics	Medium-term global tectonics	Local tectonics	Orbital control
EFFECTS	• Atmospheric CO_2 (Ice / Greenhouse) • Volume of mid-ocean ridges (sea level)	• Amplification / damping of 1st order effects • Orogenies	• Sea level / base level • Sediment supply • Long-term climatic change	• Short-term climatic changes: -Rainfall / runoff -Zonal T° gradient -Zonal wind stress -Sea level

Vail *et al.* (1991)

Genetic types of Deposits

- Stratal stacking patterns respond to the interplay of changes in rates of sedimentation and base level, and reflect combinations of depositional trends that include progradation, retrogradation, aggradation and downcutting.

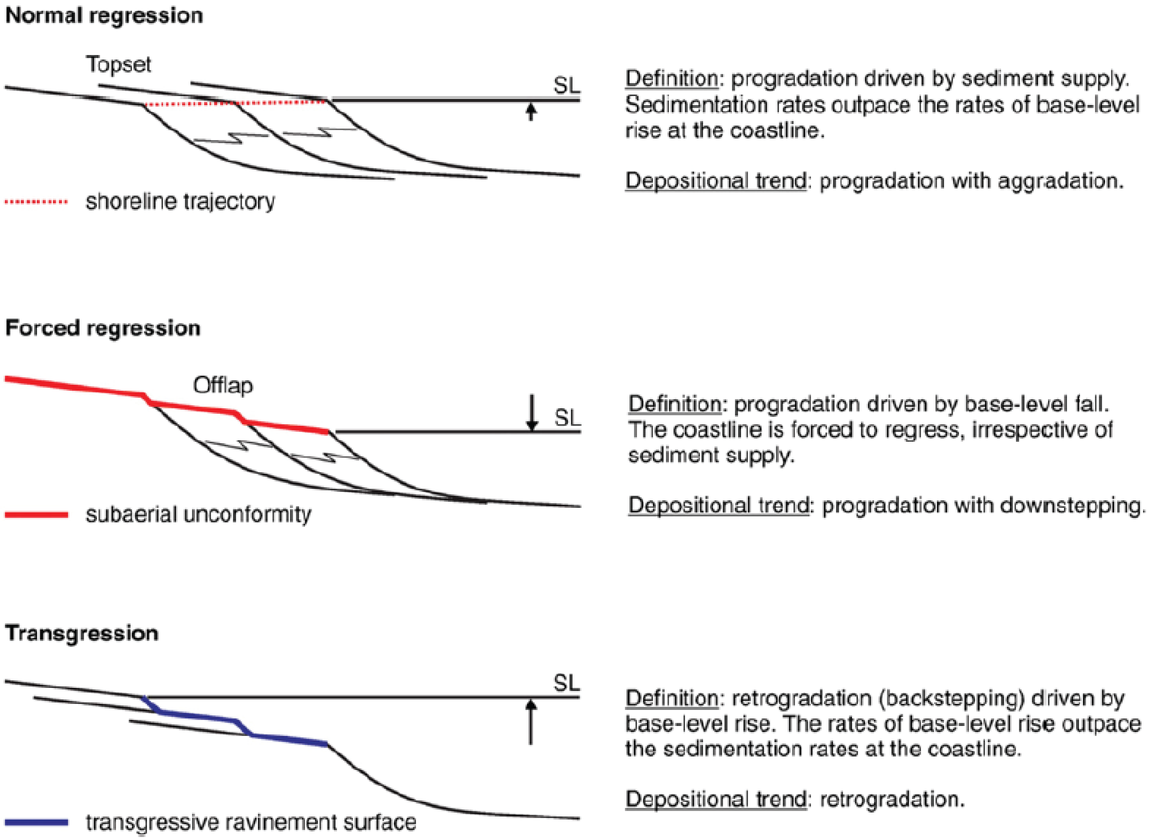


Figure 2. Genetic types of deposits: normal regressive, forced regressive, transgressive. Zigzag lines indicate lateral changes of facies within the same sedimentary bodies (e.g., individual prograding lobes). The diagram shows the possible types of shoreline trajectory during *changes* (rise or fall) in base level. During a *stillstand* of base level (not shown), the shoreline may undergo sediment-driven progradation (normal regression, where the topset is replaced by toplap), erosional transgression, or no movement at all. However, due to the complexity of independent variables that interplay to control base-level changes, it is unlikely to maintain stillstand conditions for any extended period of time.

Geometries of stacking patterns

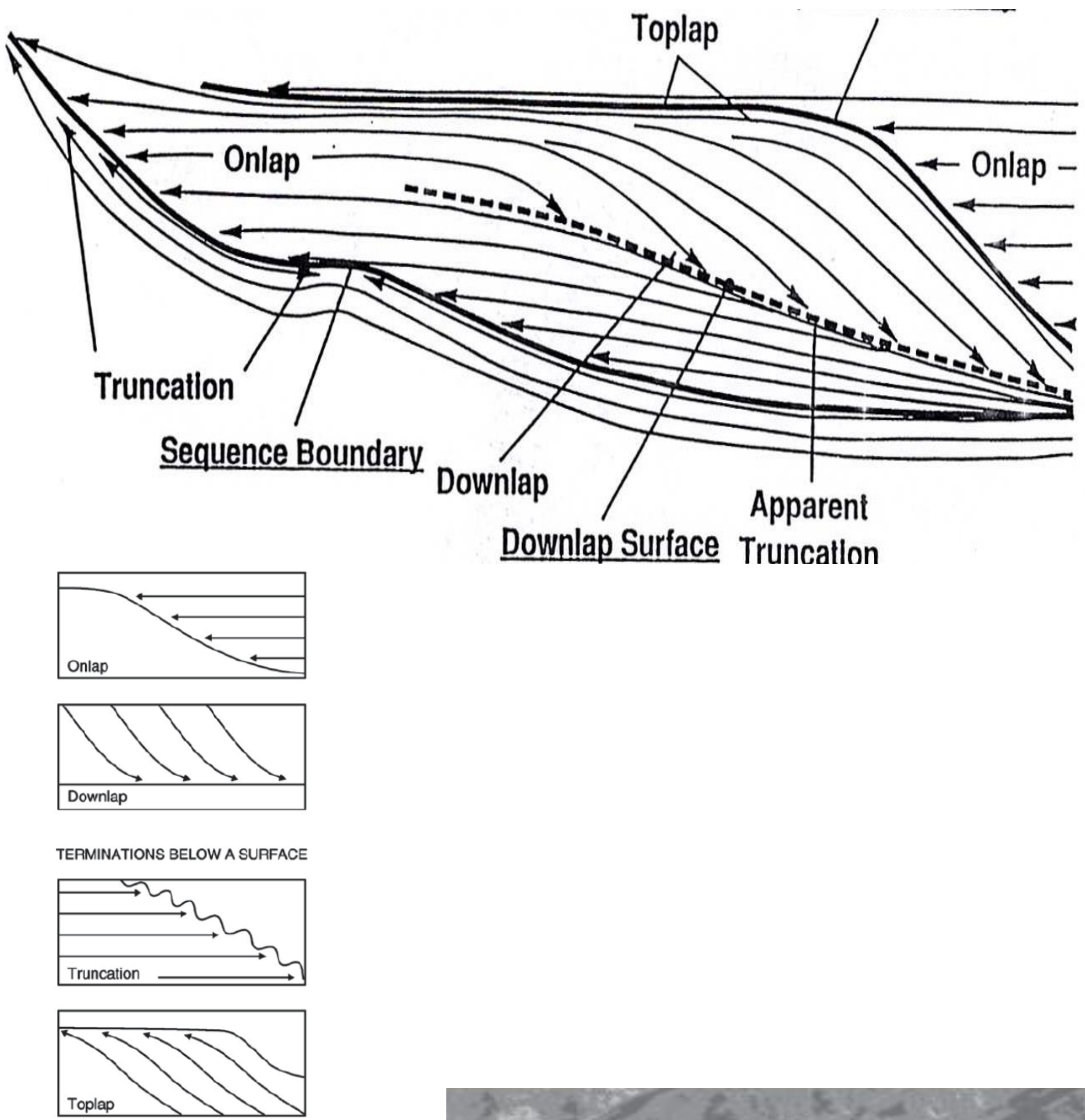
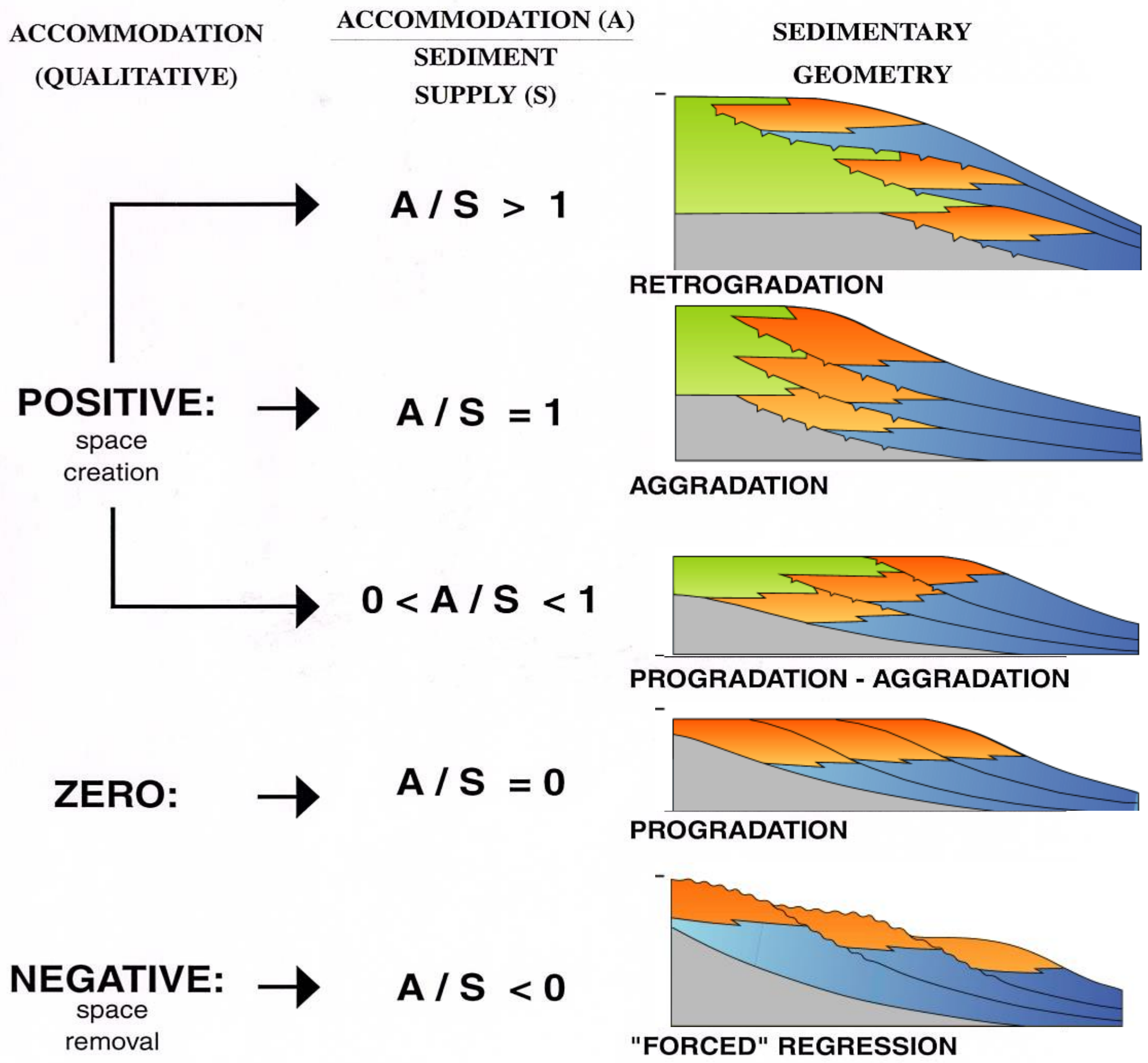
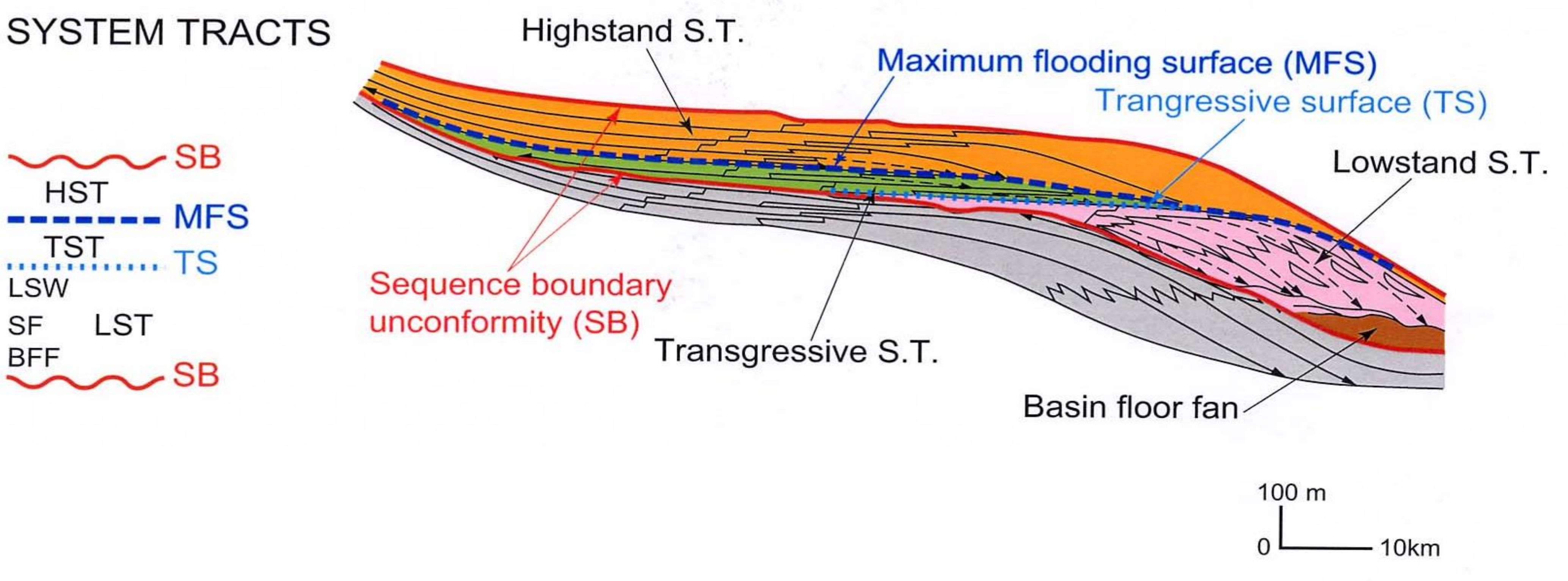


Figure 13. Stratal terminations that can be observed above or below a stratigraphic surface in seismic profiles and larger scale outcrops (from Mitchum and Vail, 1977).



Homewood *et al.* (2000)

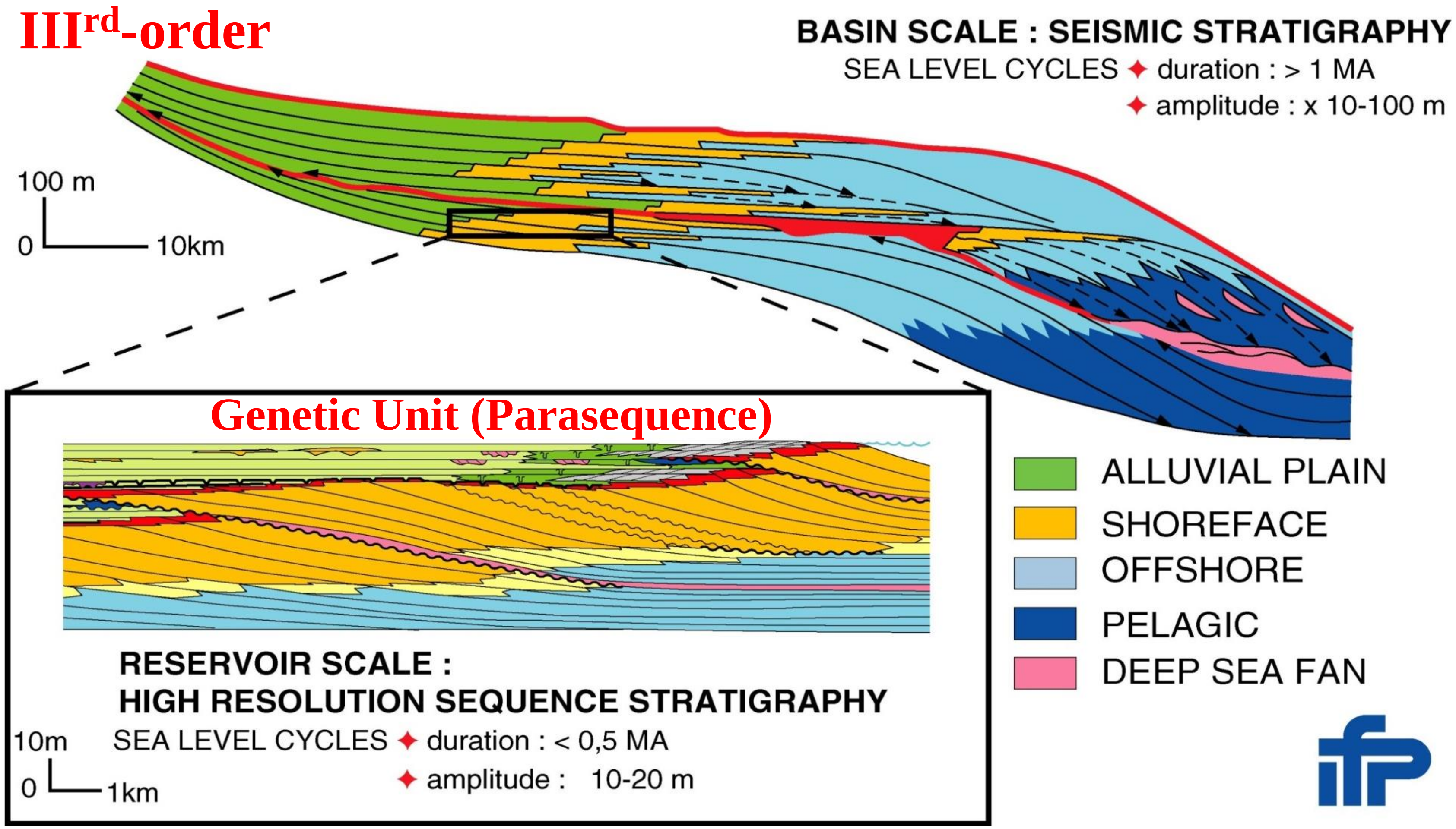
System Tracts



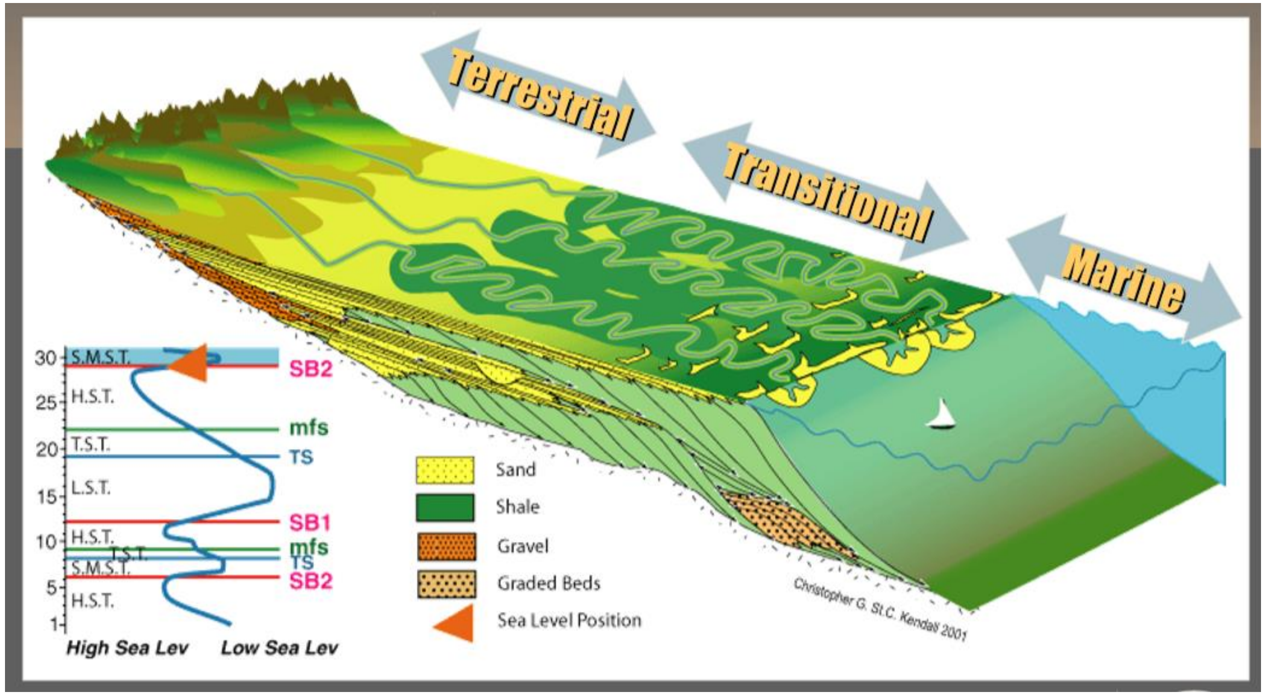
Van Wagoner et al., 1988

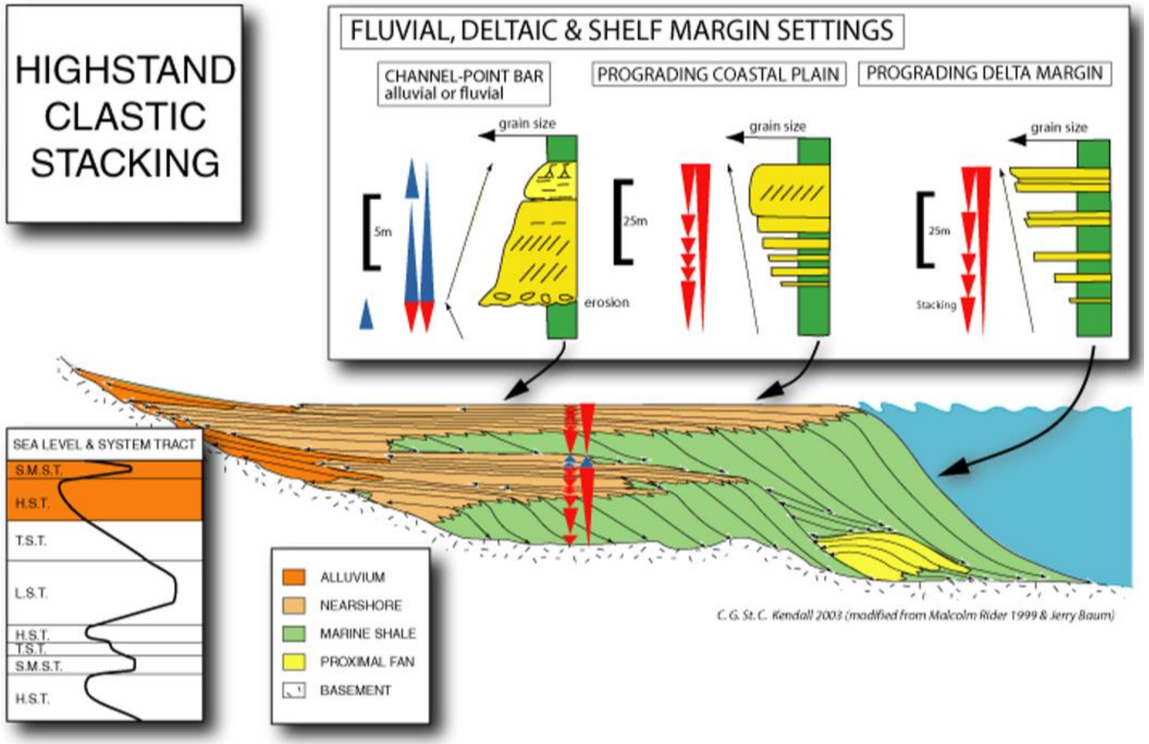
Sequences Orders

Different orders of sequences

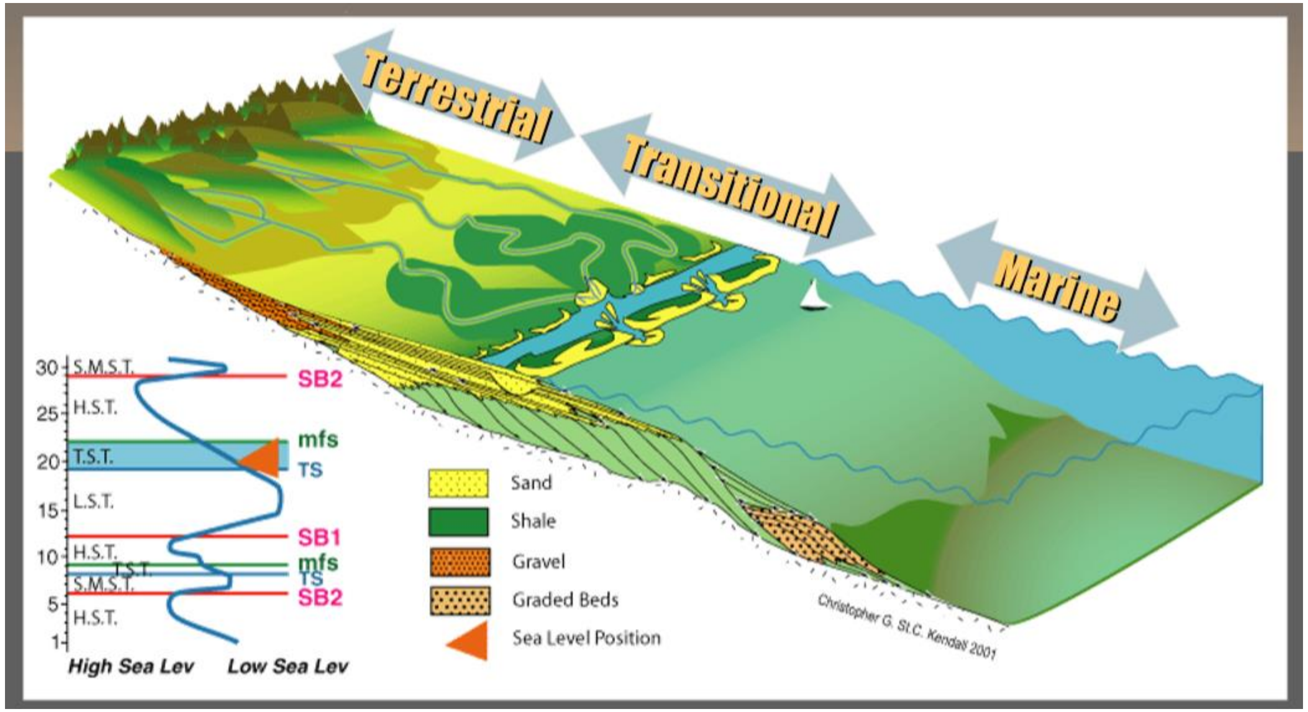


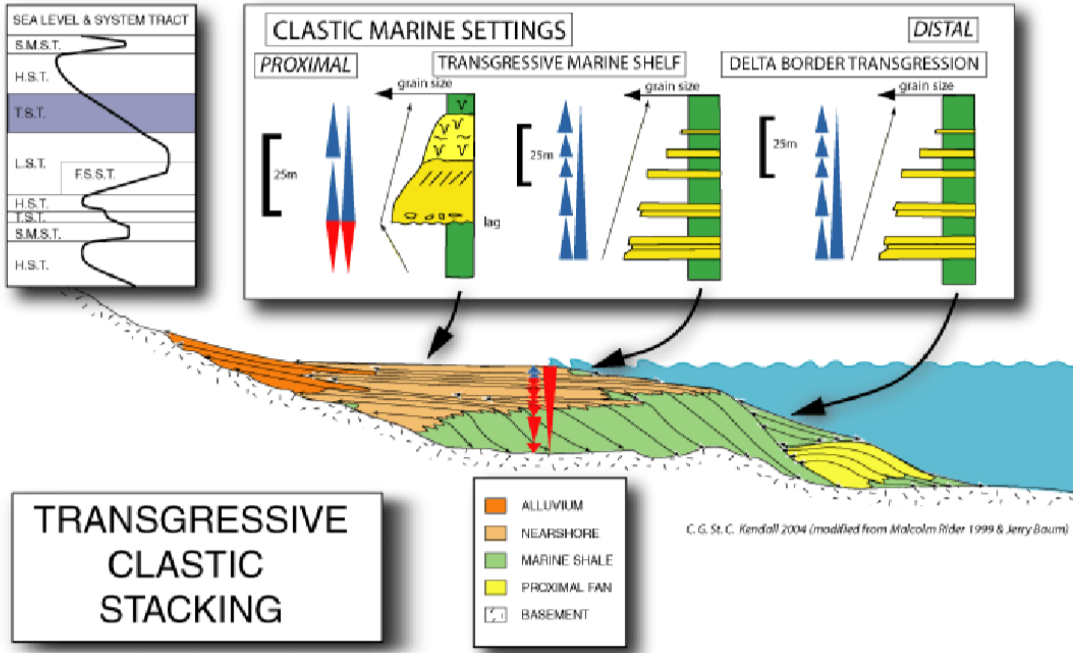
Highstand Systems Tract



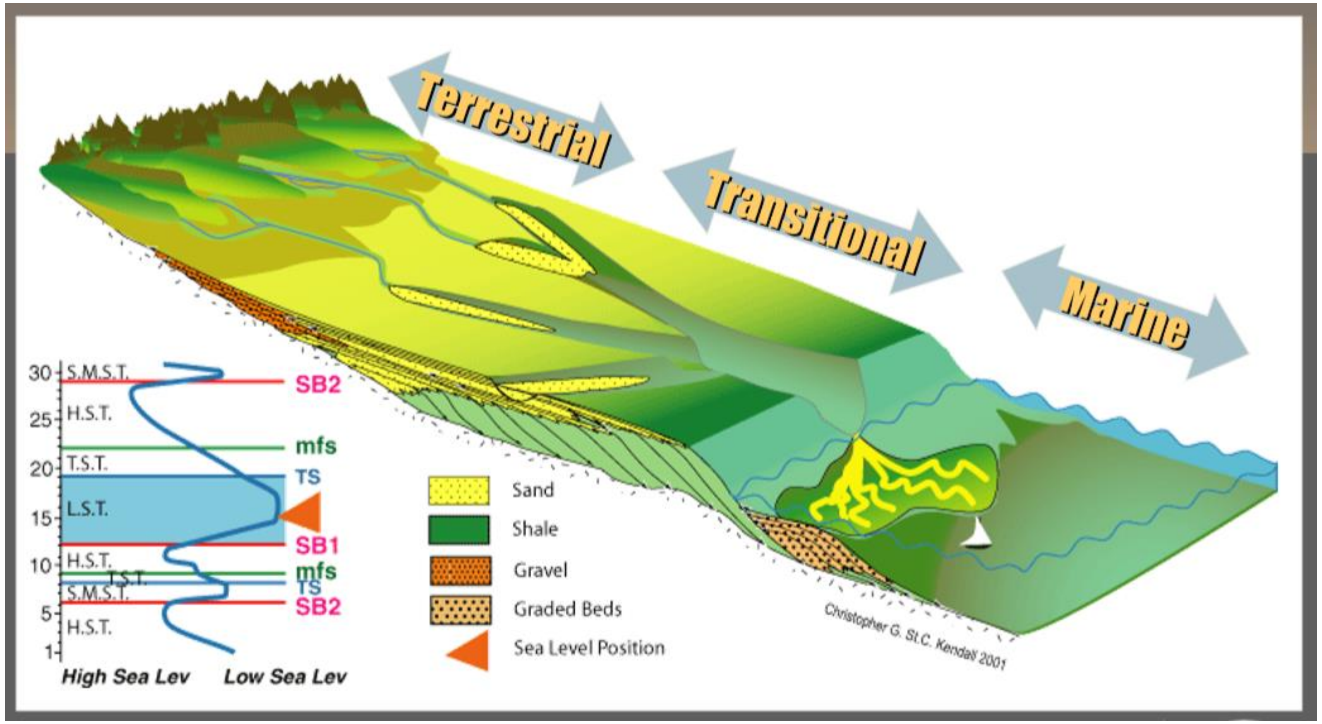


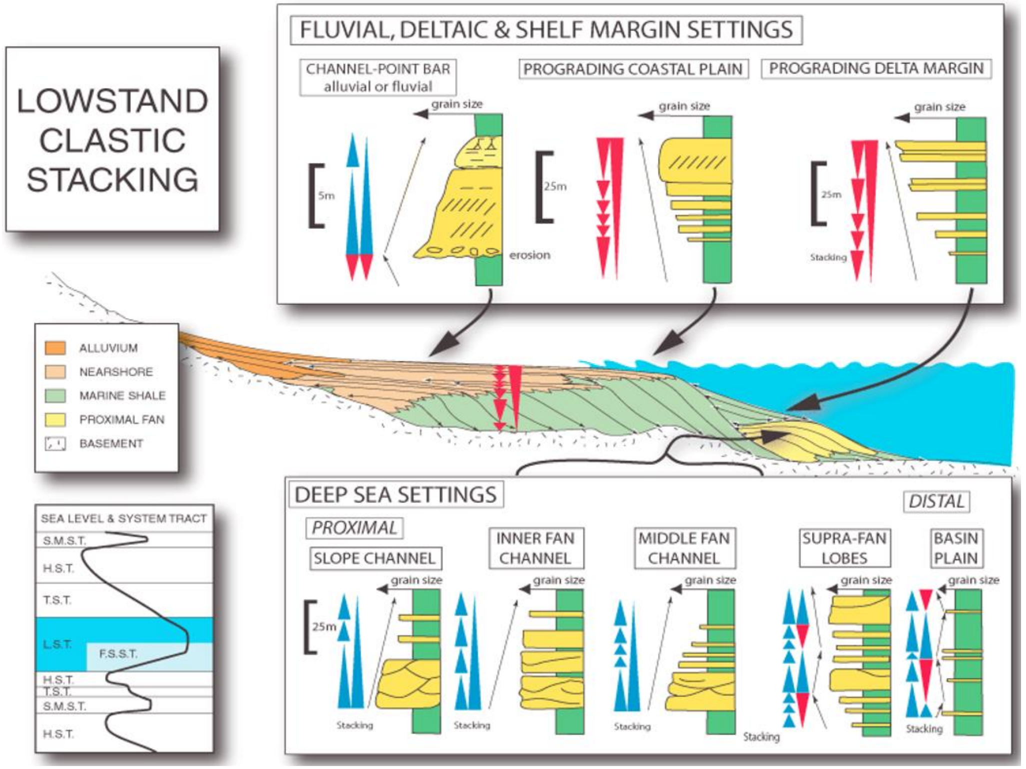
Transgressive Systems Tract





Lowstand Systems Tract





Q&A

Influencing Factors

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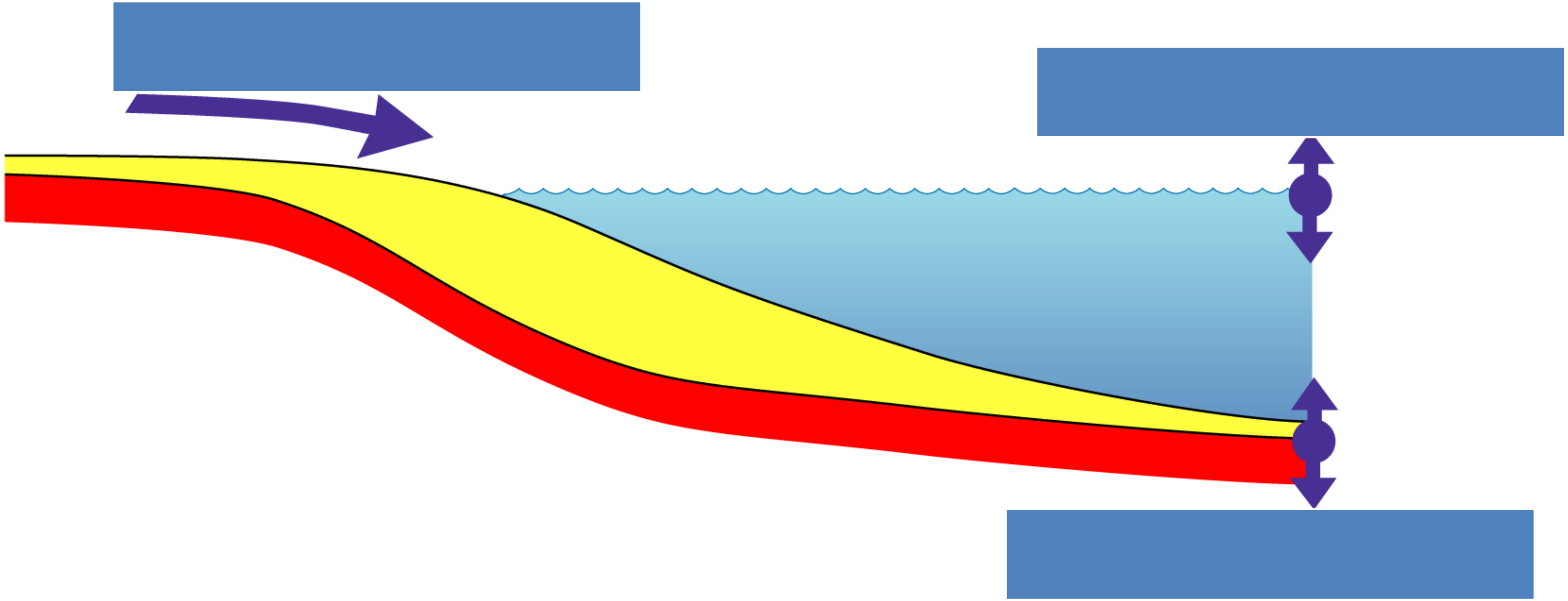
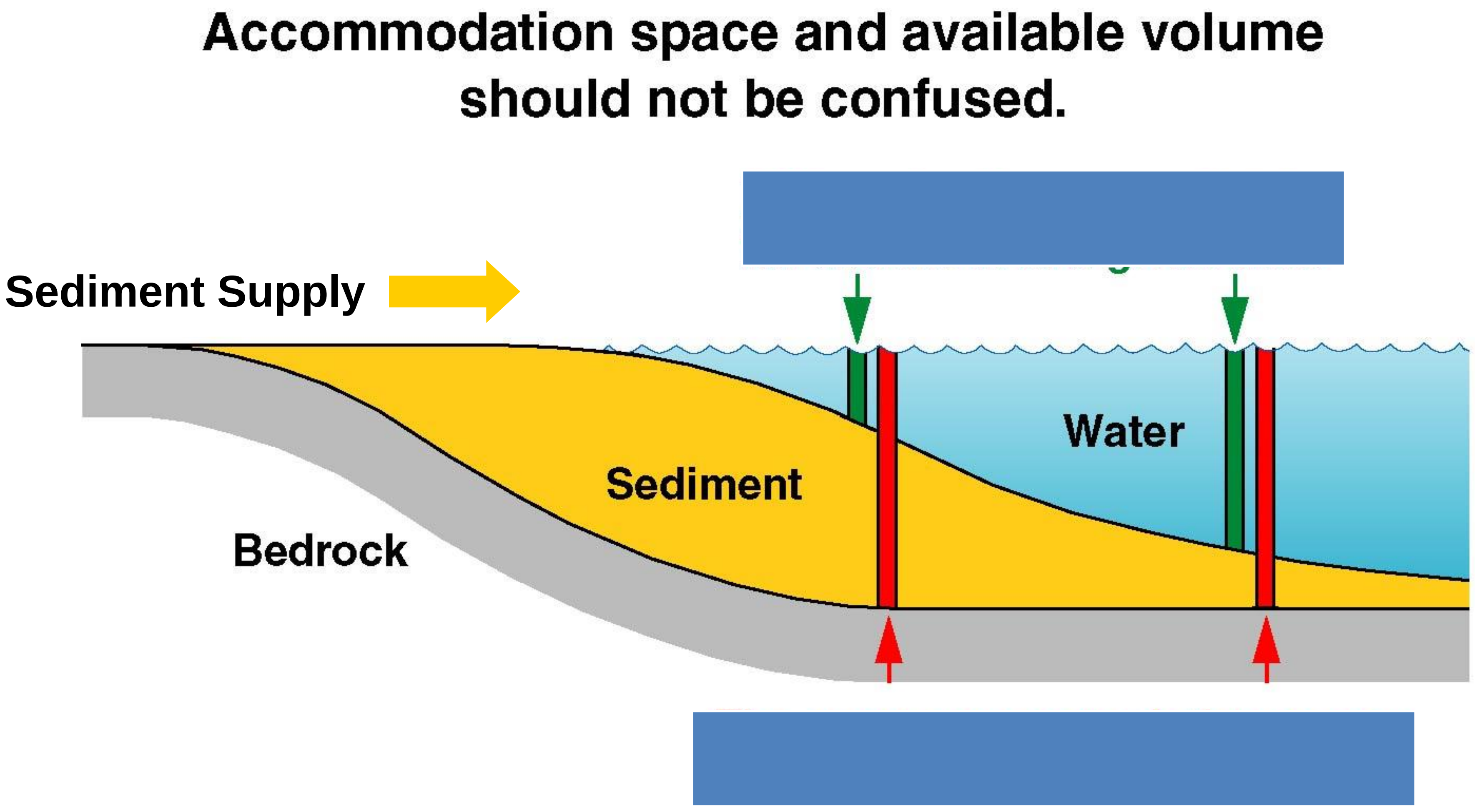


Homewood *et al.* (2000)

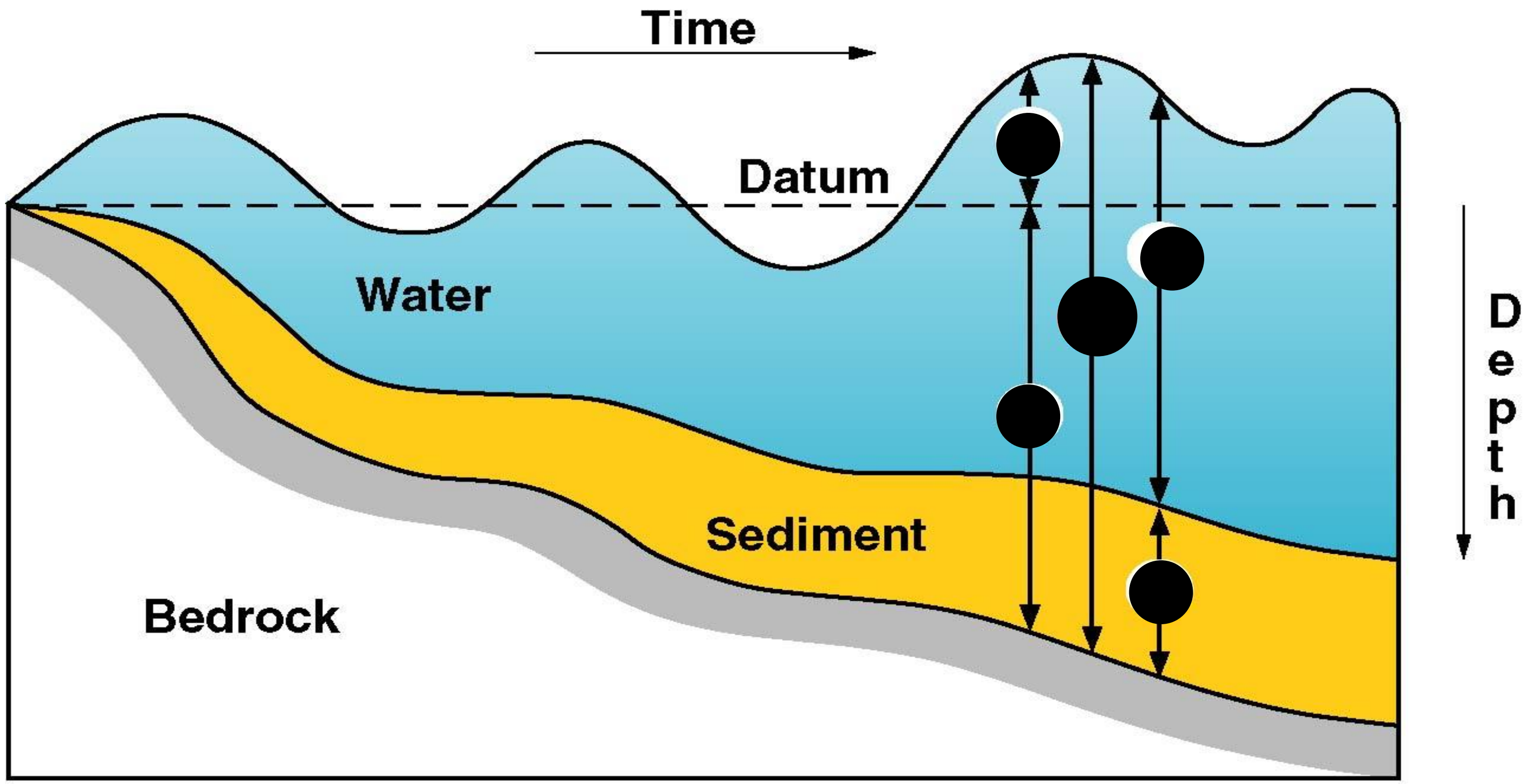
Influencing Factors



Homewood *et al.* (2000)

Influencing Factors

Exercise



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EFFECTS	• Atmospheric CO_2 (Ice / Greenhouse) • Volume of mid-ocean ridges (sea level)	• Amplification / damping of 1st order effects • Orogenies	• Sea level / base level • Sediment supply • Long-term climatic change	• Short-term climatic changes: -Rainfall / runoff -Zonal T° gradient -Zonal wind stress -Sea level

Vail *et al.* (1991)

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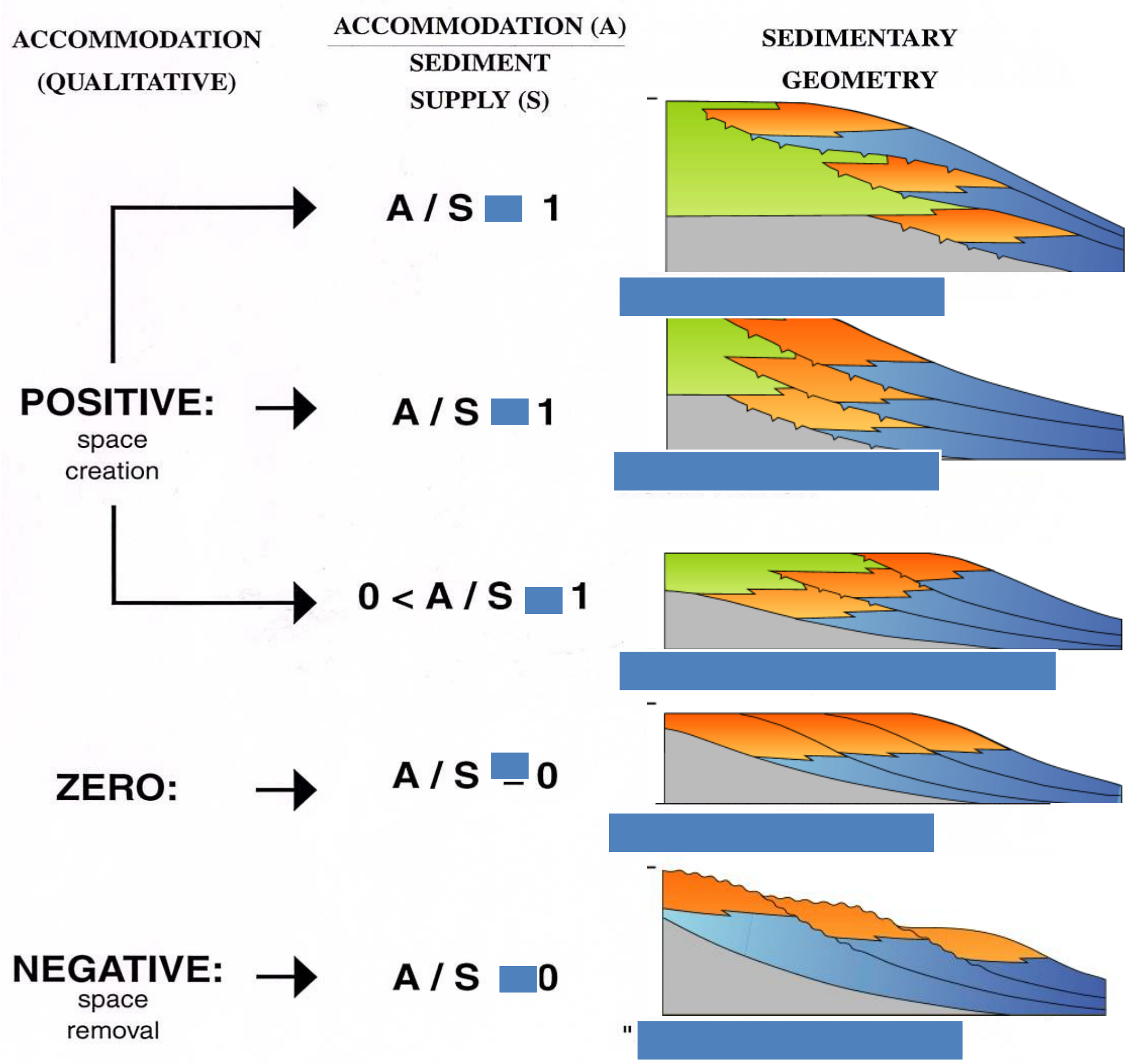
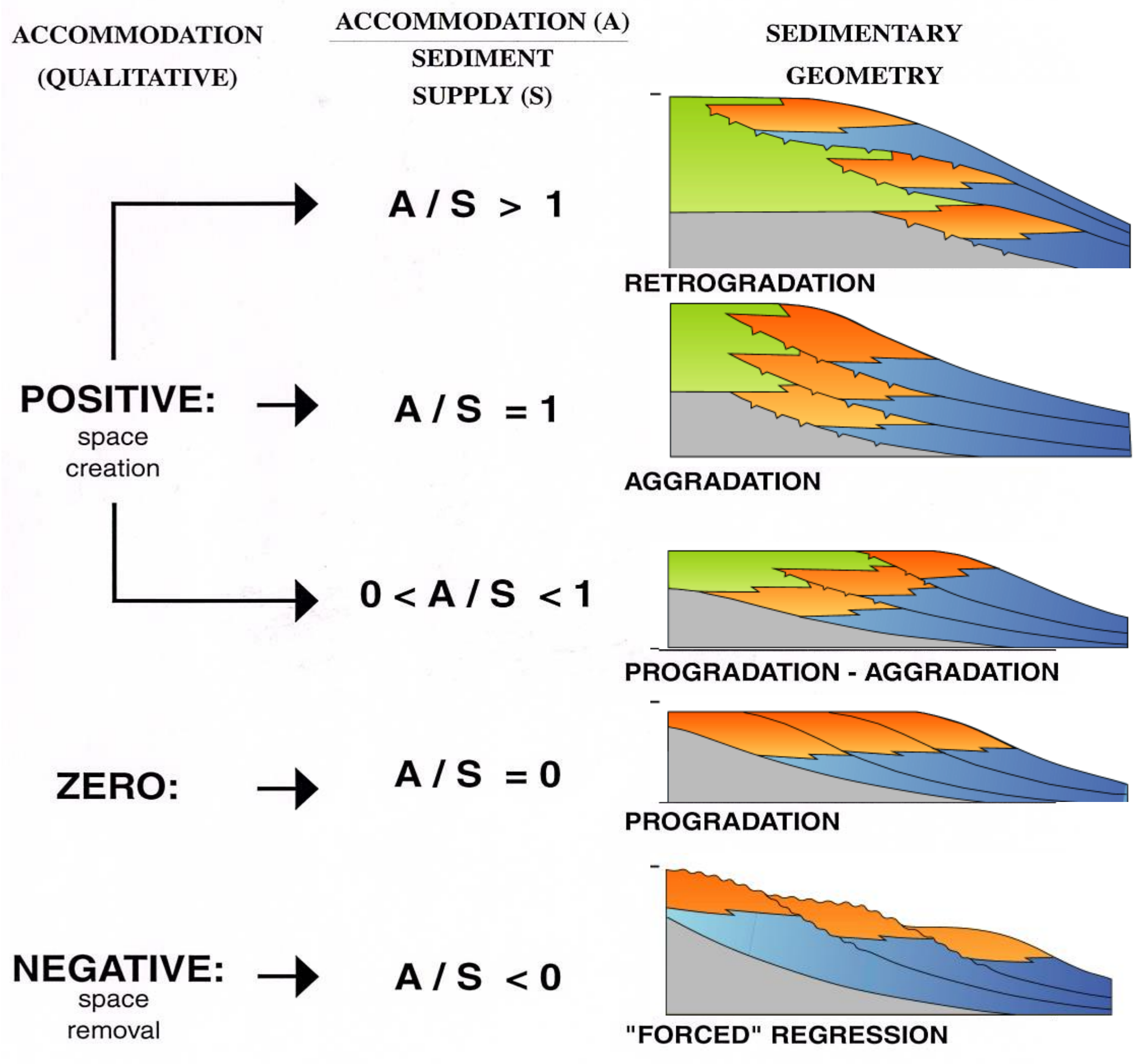
Vail *et al.* (1991)

Geometries of stacking patterns



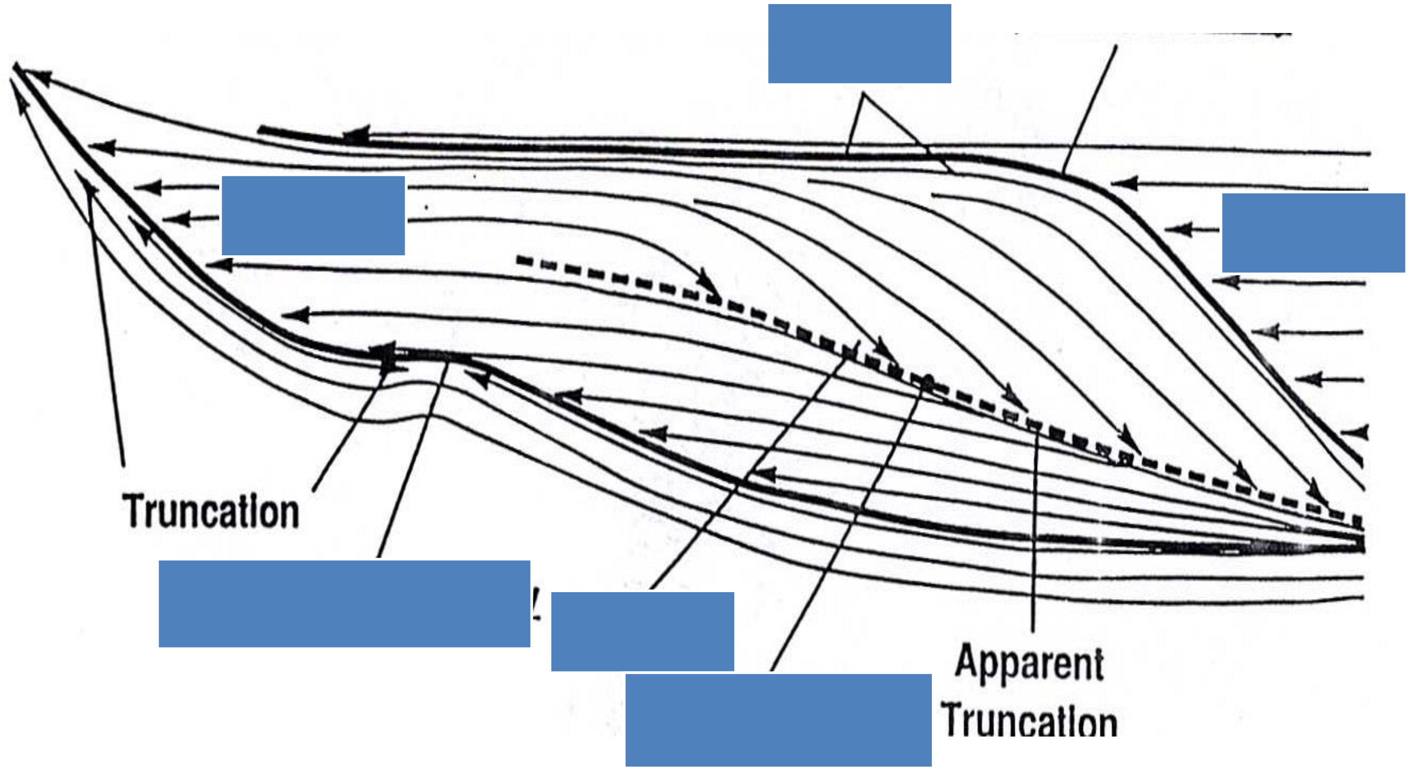
Homewood *et al.* (2000)

Geometries of stacking patterns



Homewood *et al.* (2000)

Termination Geometries



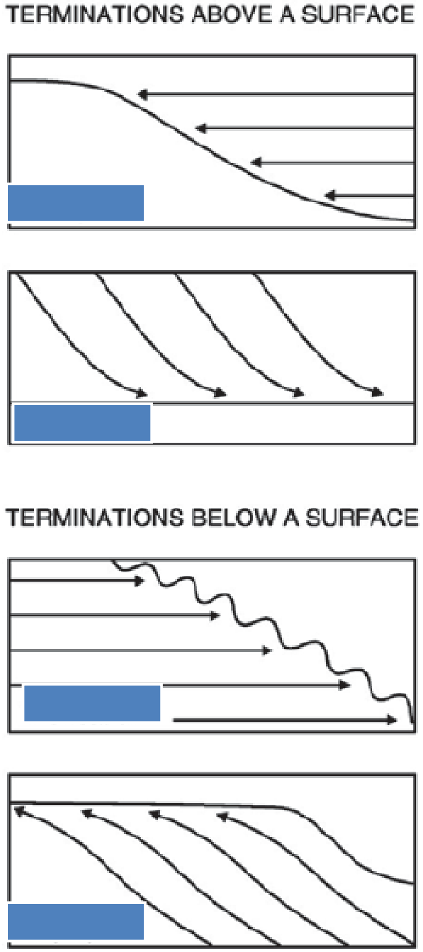
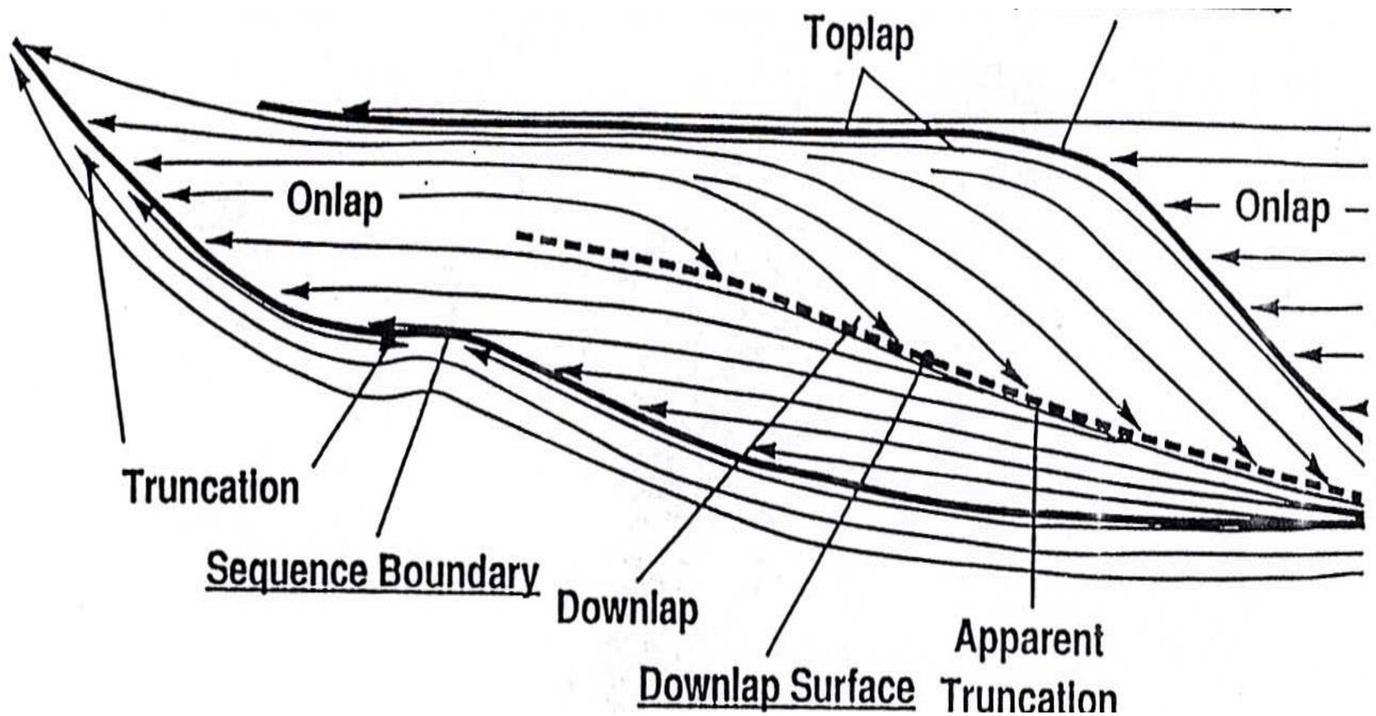


Figure 13. Stratal terminations that can be observed above or below a stratigraphic surface in seismic profiles and larger scale outcrops (from Mitchum and Vail, 1977).

Termination Geometries



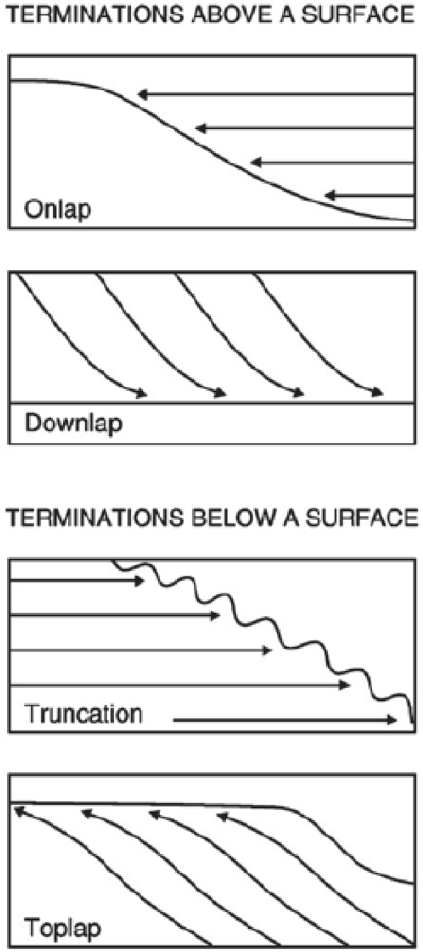
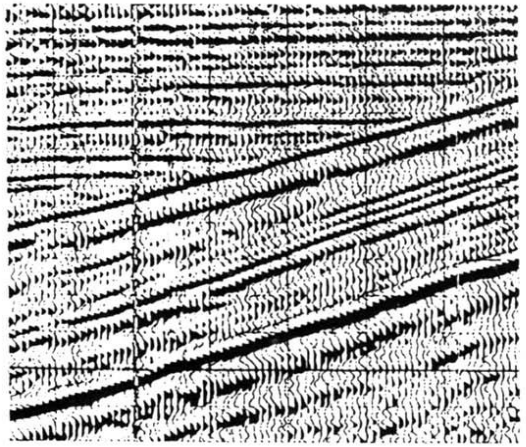
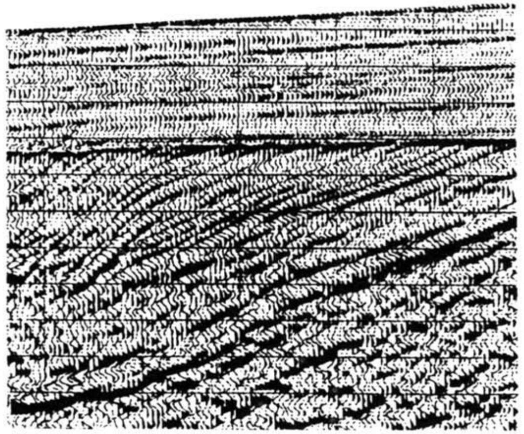


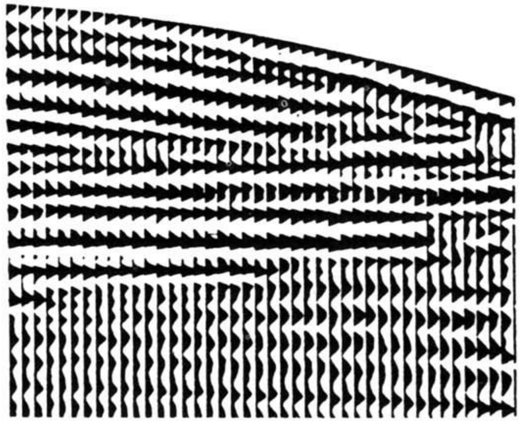
Figure 13. Stratal terminations that can be observed above or below a stratigraphic surface in seismic profiles and larger scale outcrops (from Mitchum and Vail, 1977).

Termination Geometries on Seismics

Exercise

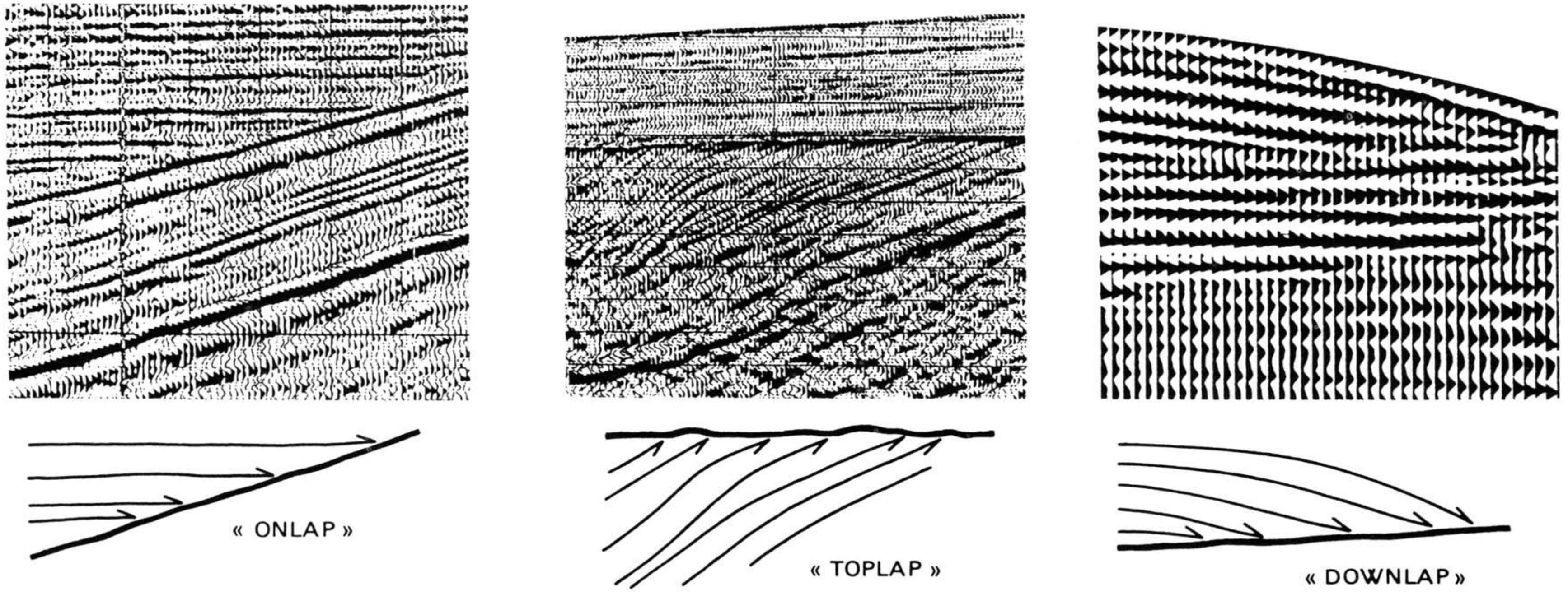






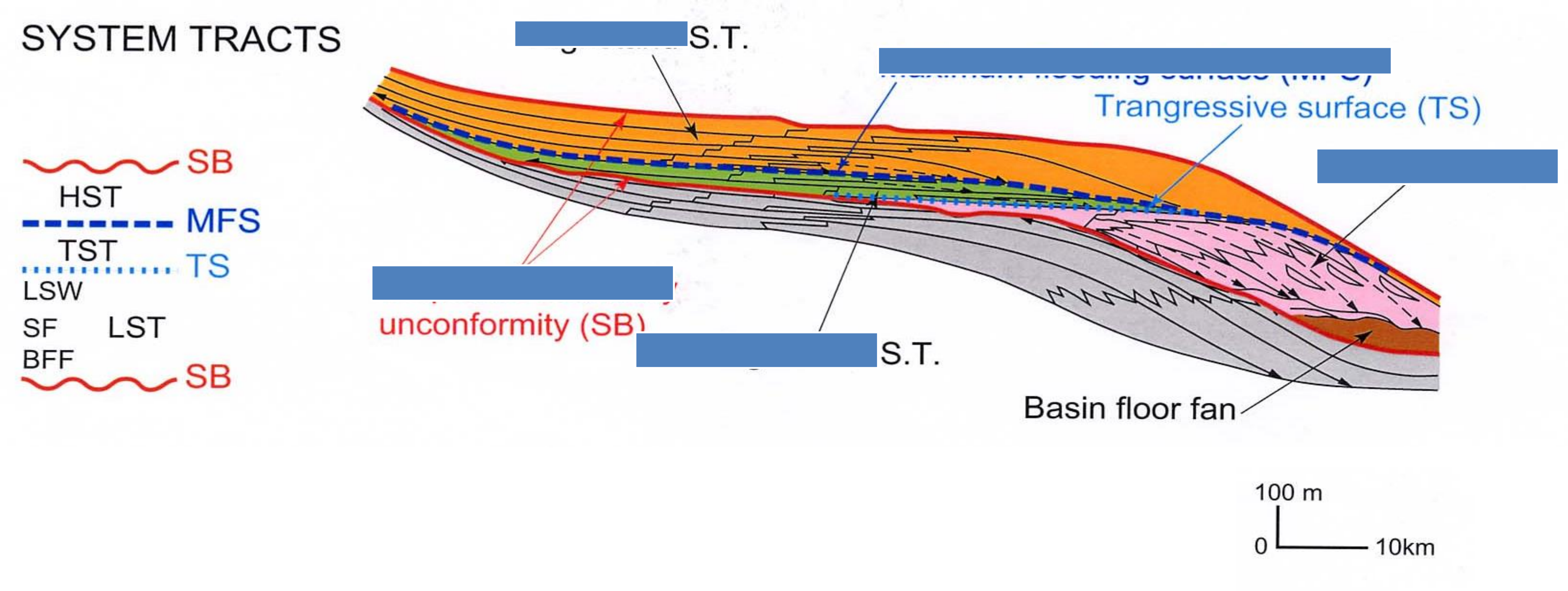
Termination Geometries on Seismics

Exercise



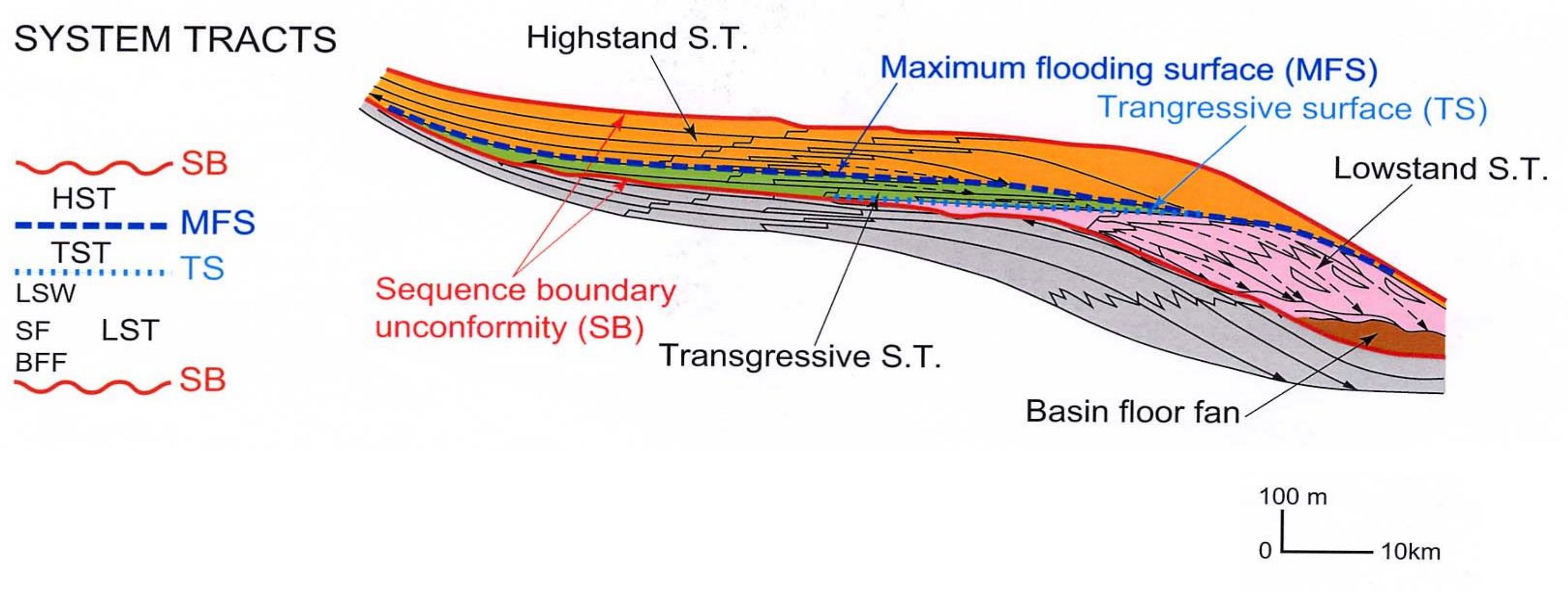
After Nely, 1989

System Tracts



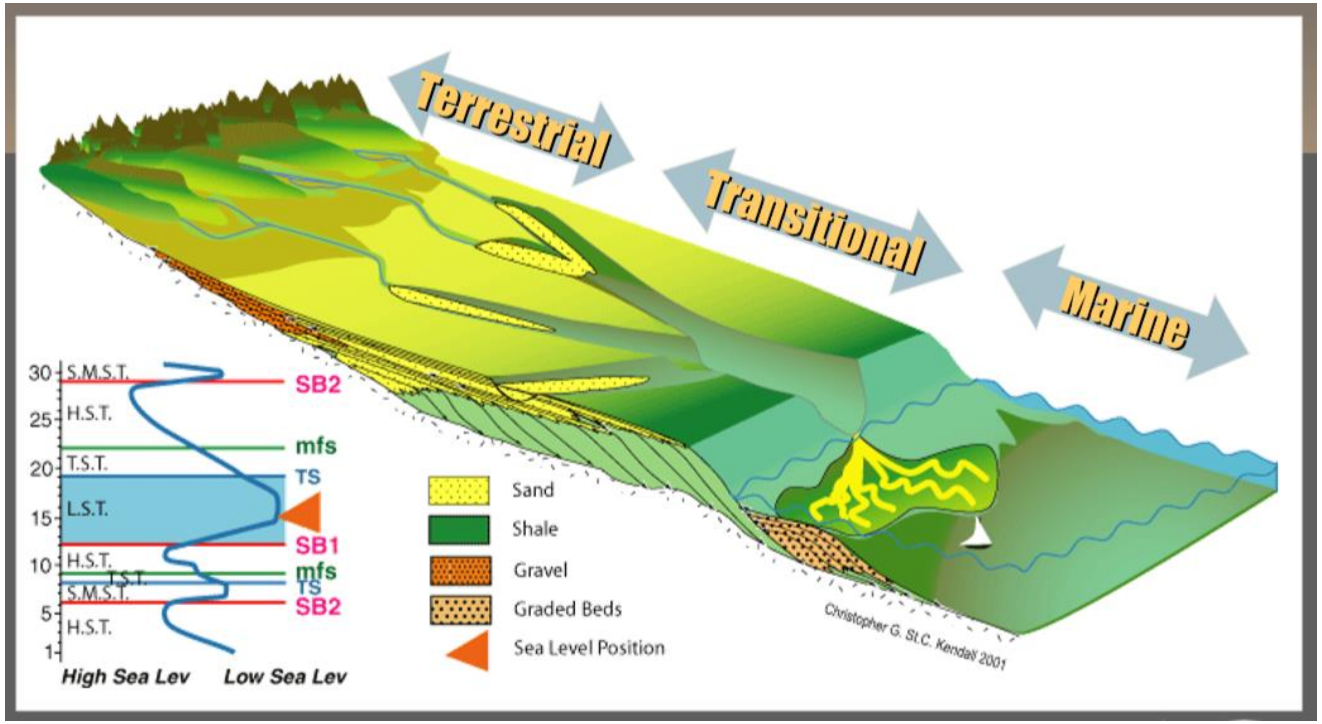
Van Wagoner et al., 1988

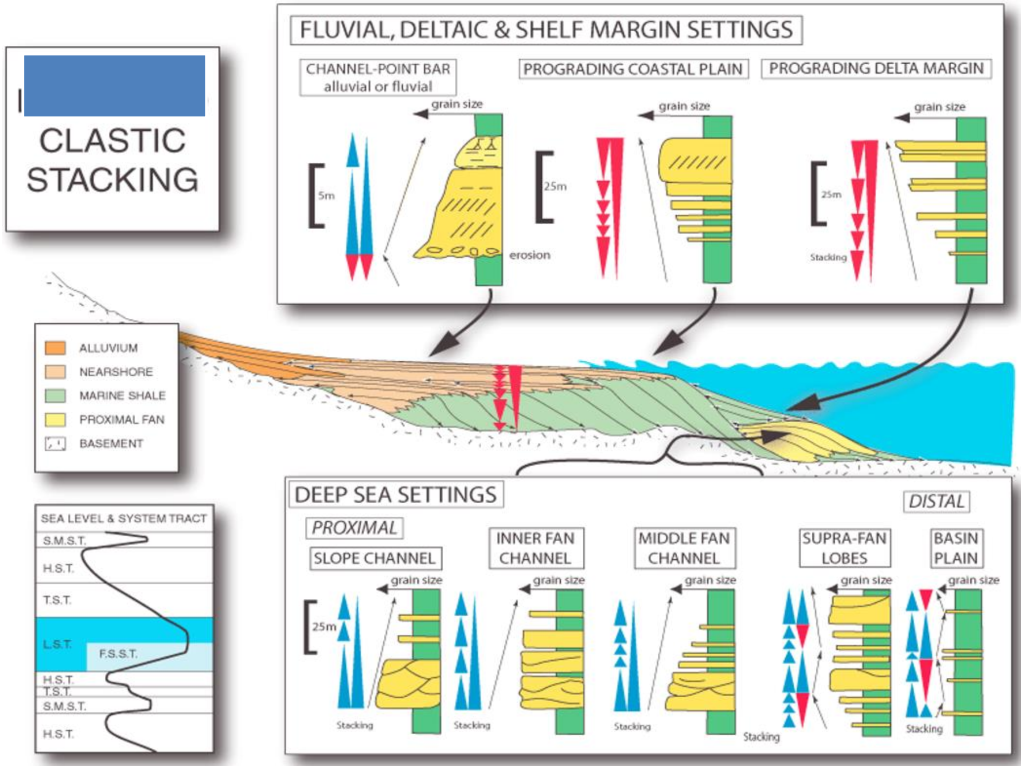
System Tracts



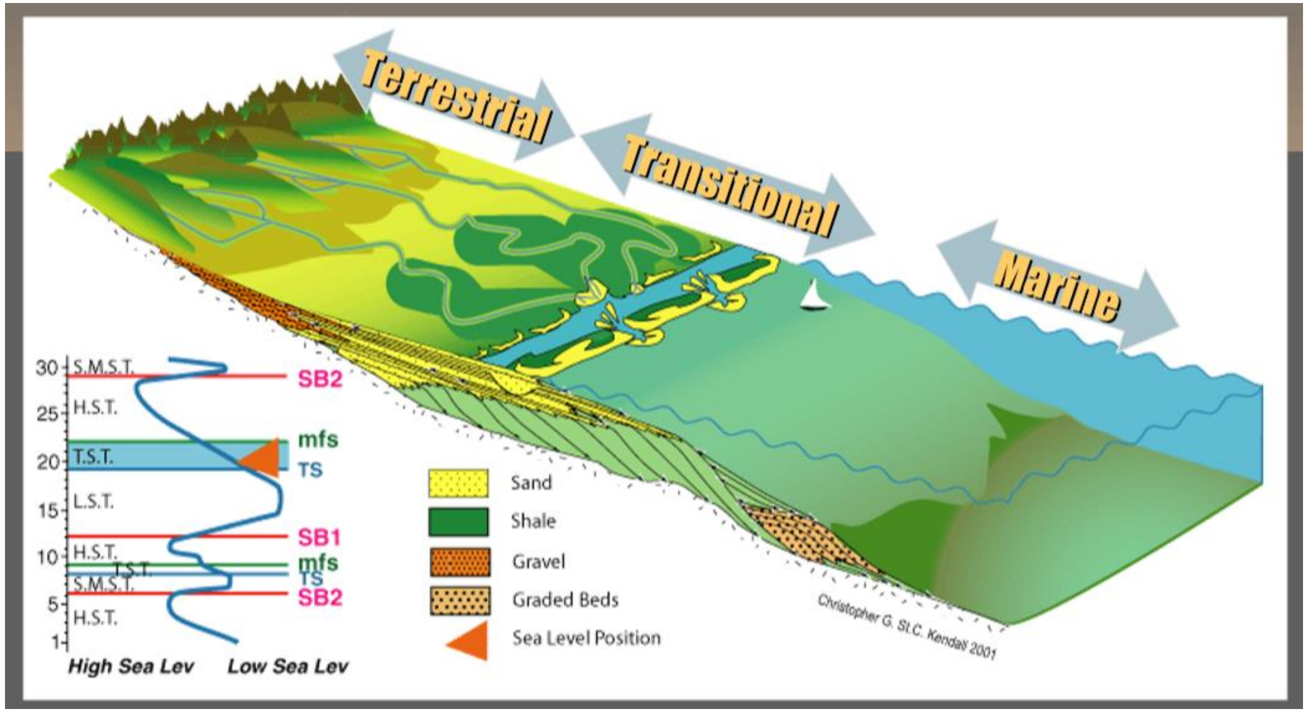
Van Wagoner et al., 1988

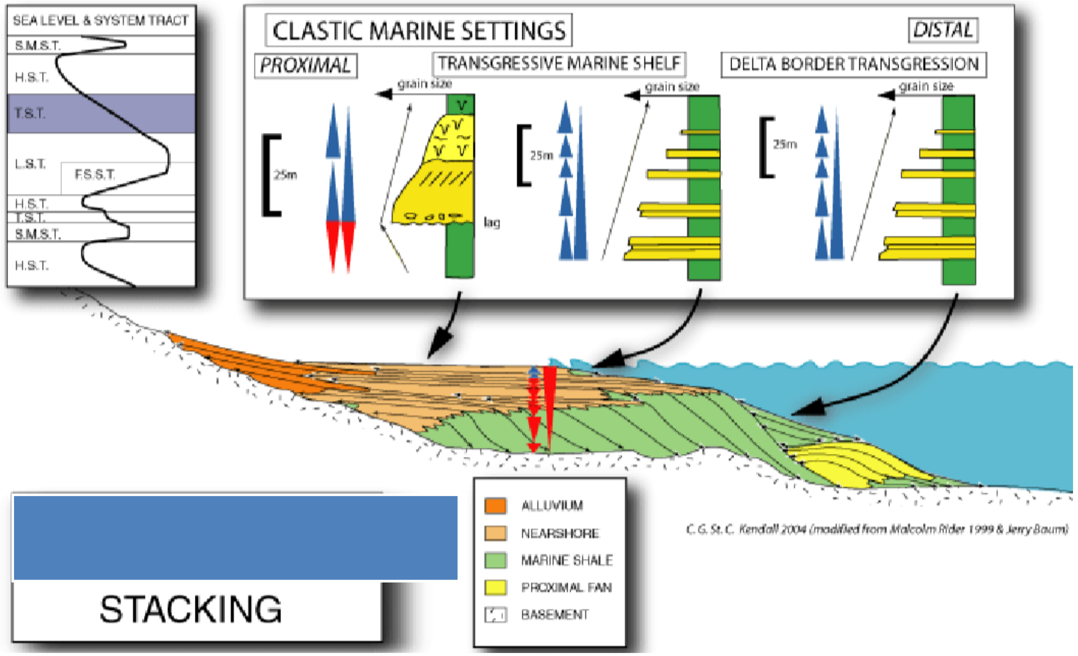
Systems Tract



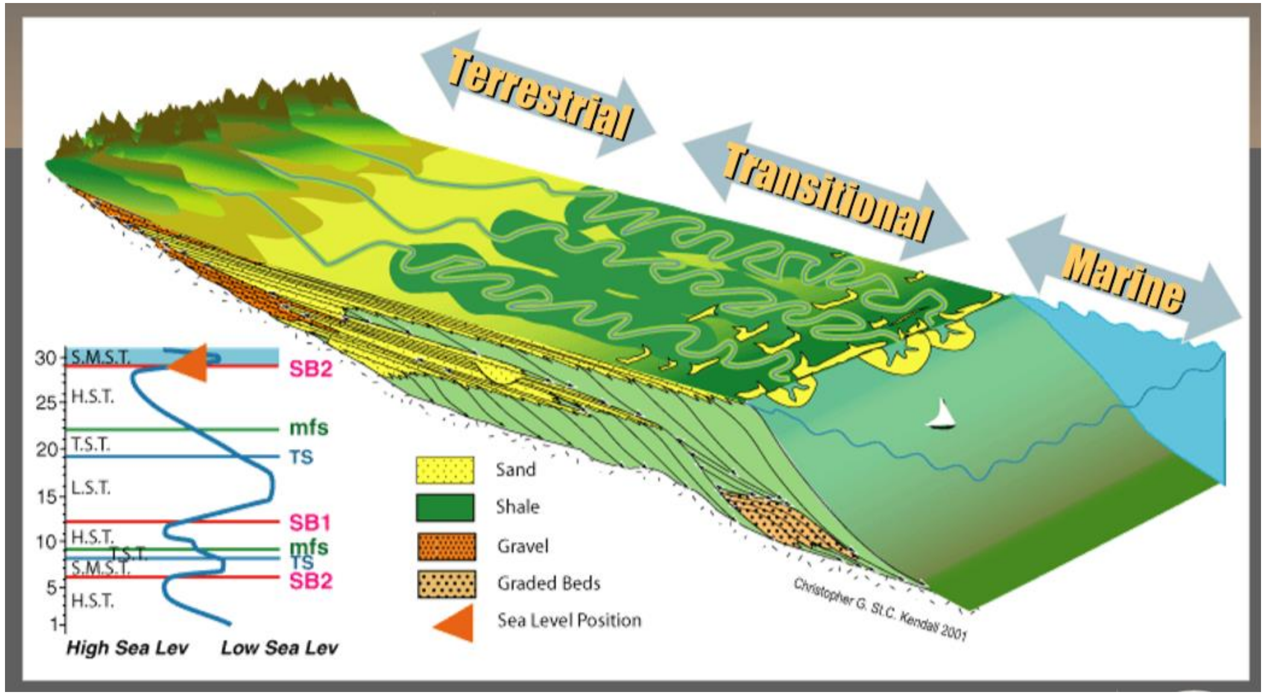


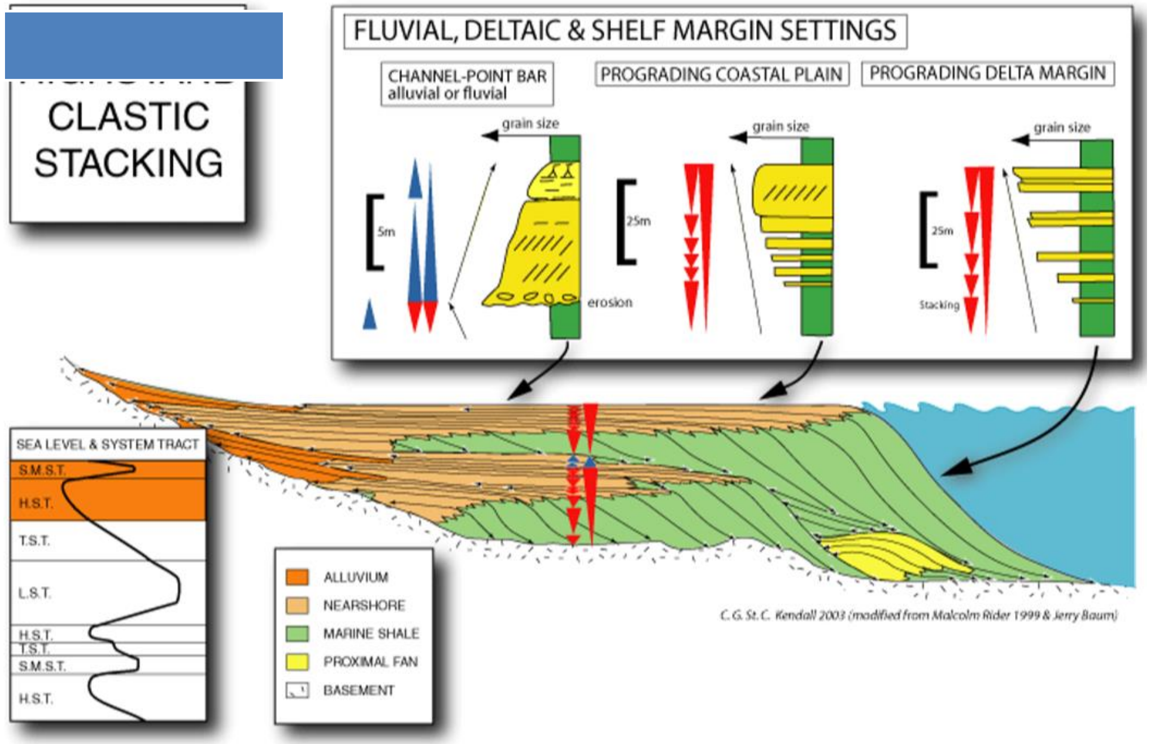
Systems Tract





[redacted] Systems Tract





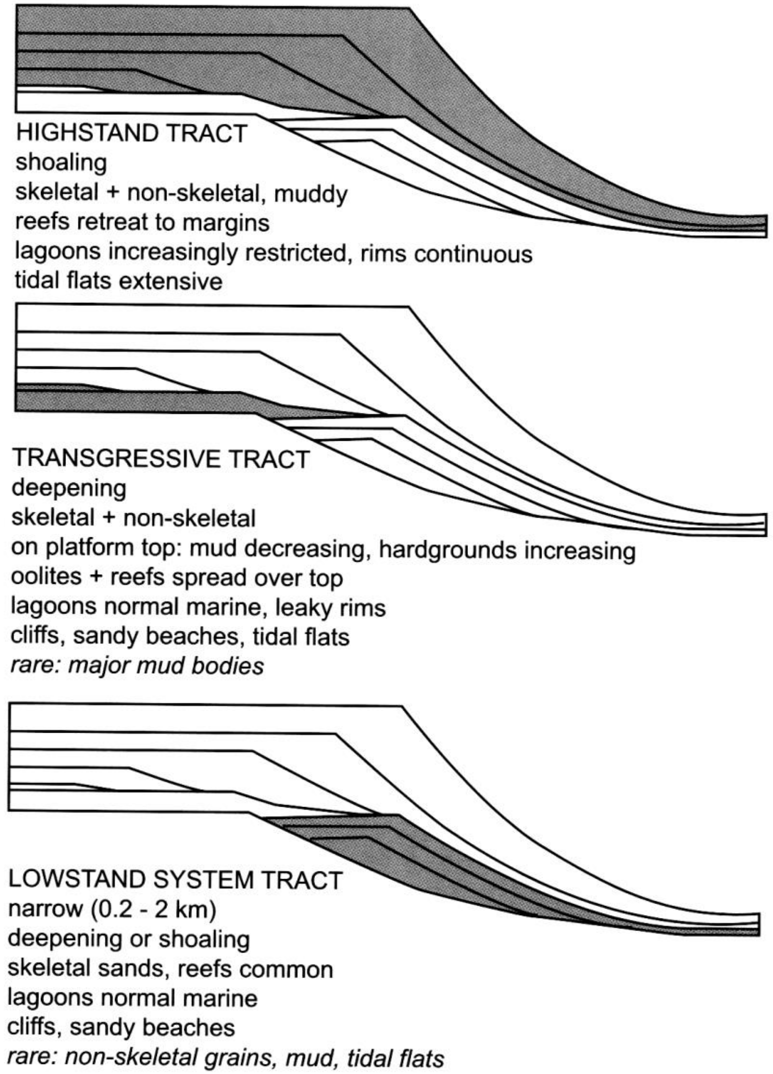
Carbonate Sequence Stratigraphy

Characteristics of depositional patterns

- Stationary sea-level : vertical accretion only, increase of relief between shelf and basin

- Sea-level rise : shelfwards migration of facies belts, backstepping - onlaps
- Rapid sea-level rise (much higher than carb. sedi. rate): drowning, deposition of deep water sediments

- Sea-level fall (or overproduction of carbonate): basinward progradation - offlaps, development of clinoforms
  - if sea-level below the shelf break, subaerial exposure of the shelf



Schlager, 2006

Characteristics of Rimmed Shelves

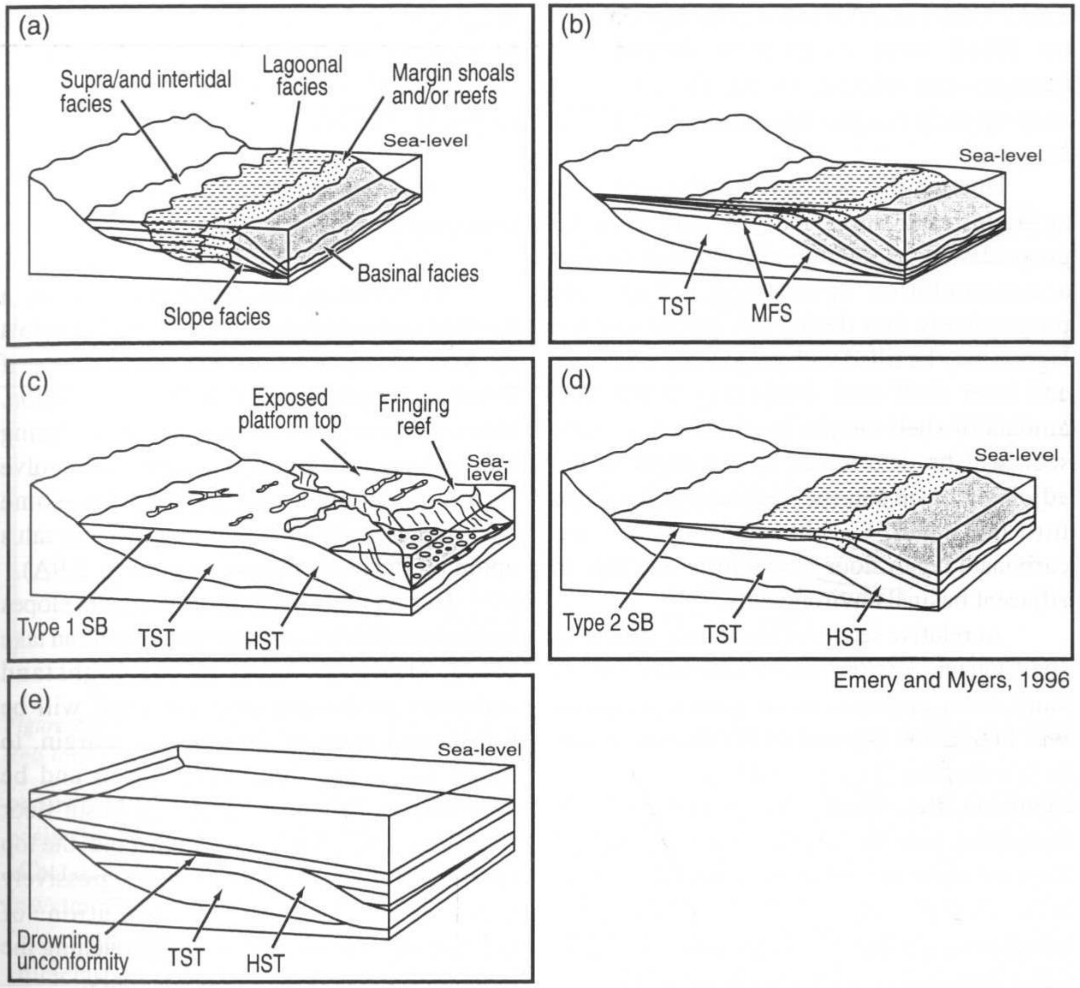


Figure 2.8. Sequence stratigraphic models for rimmed shelves. A) Transgressive systems tract B) Highstand systems tract C) Lowstand systems tract D) Type 2 unconformity and development of a shelf margin wedge E) Drowning unconformity. Used with permission of Blackwell Science.

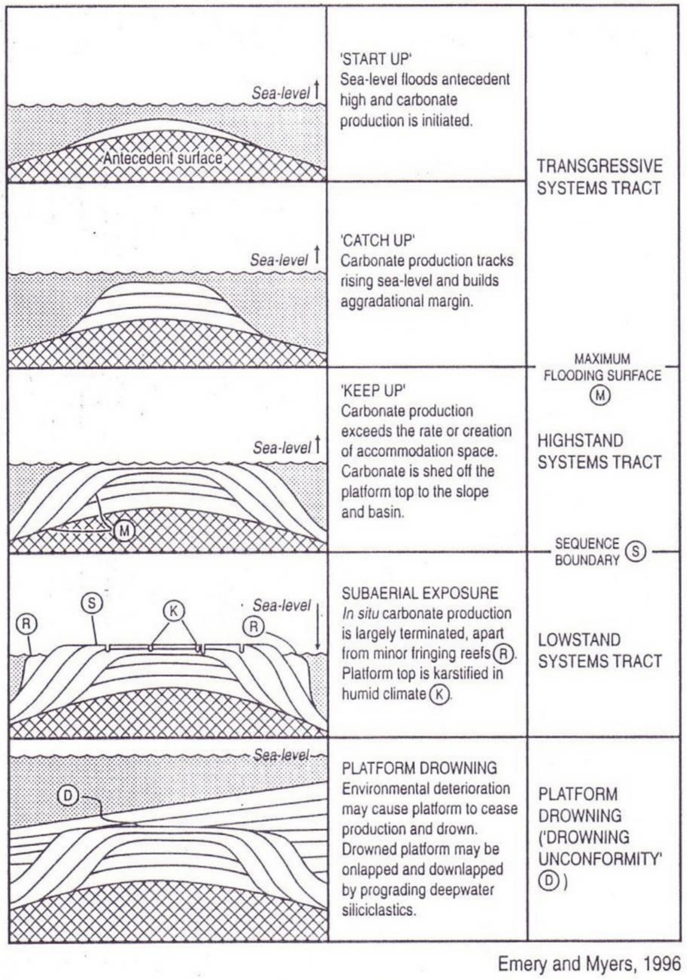
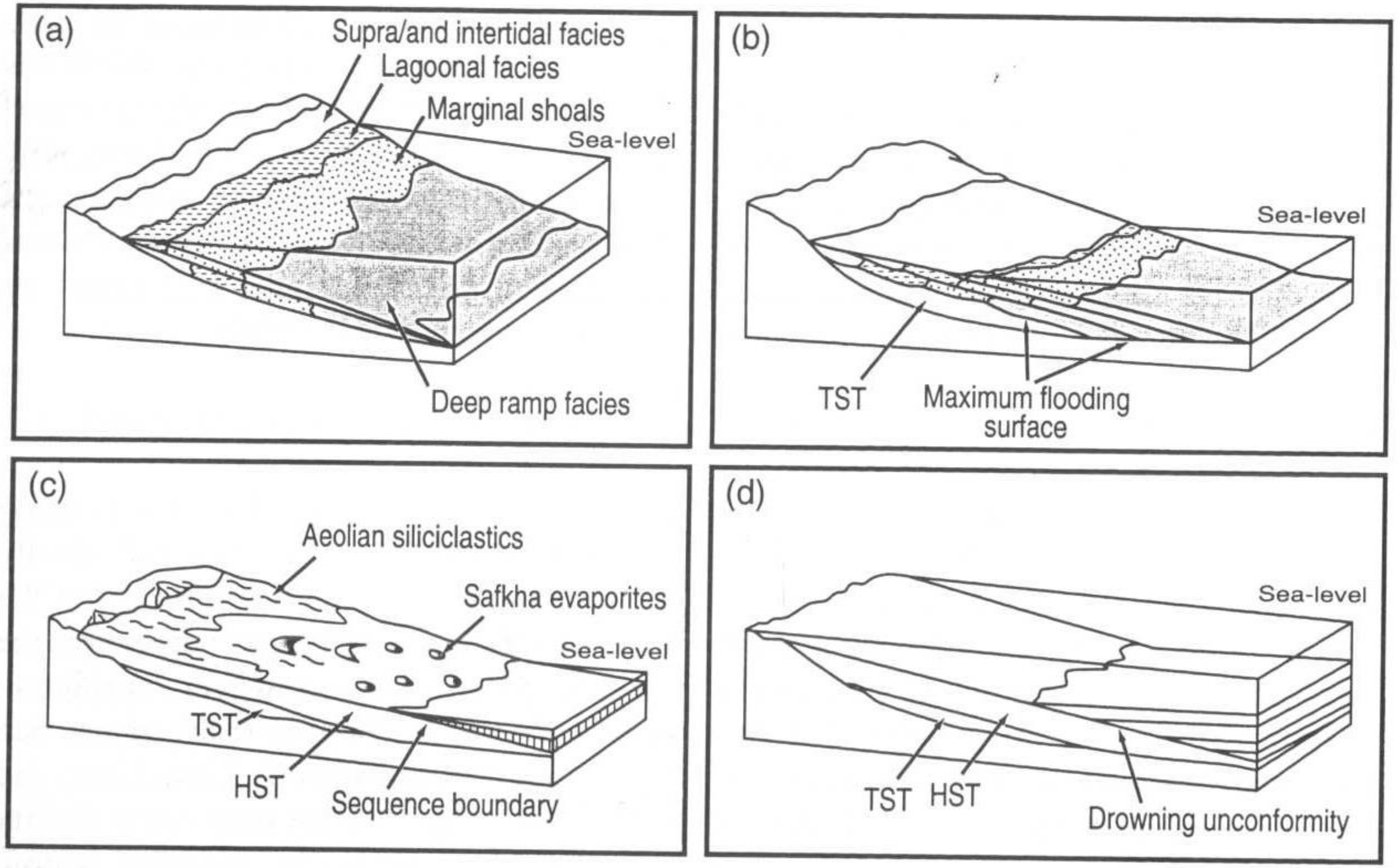


Figure 1.11. Schematic model for an isolated carbonate platform, showing idealized systems tract geometries and platform drowning. Used with permission of Blackwell Science.

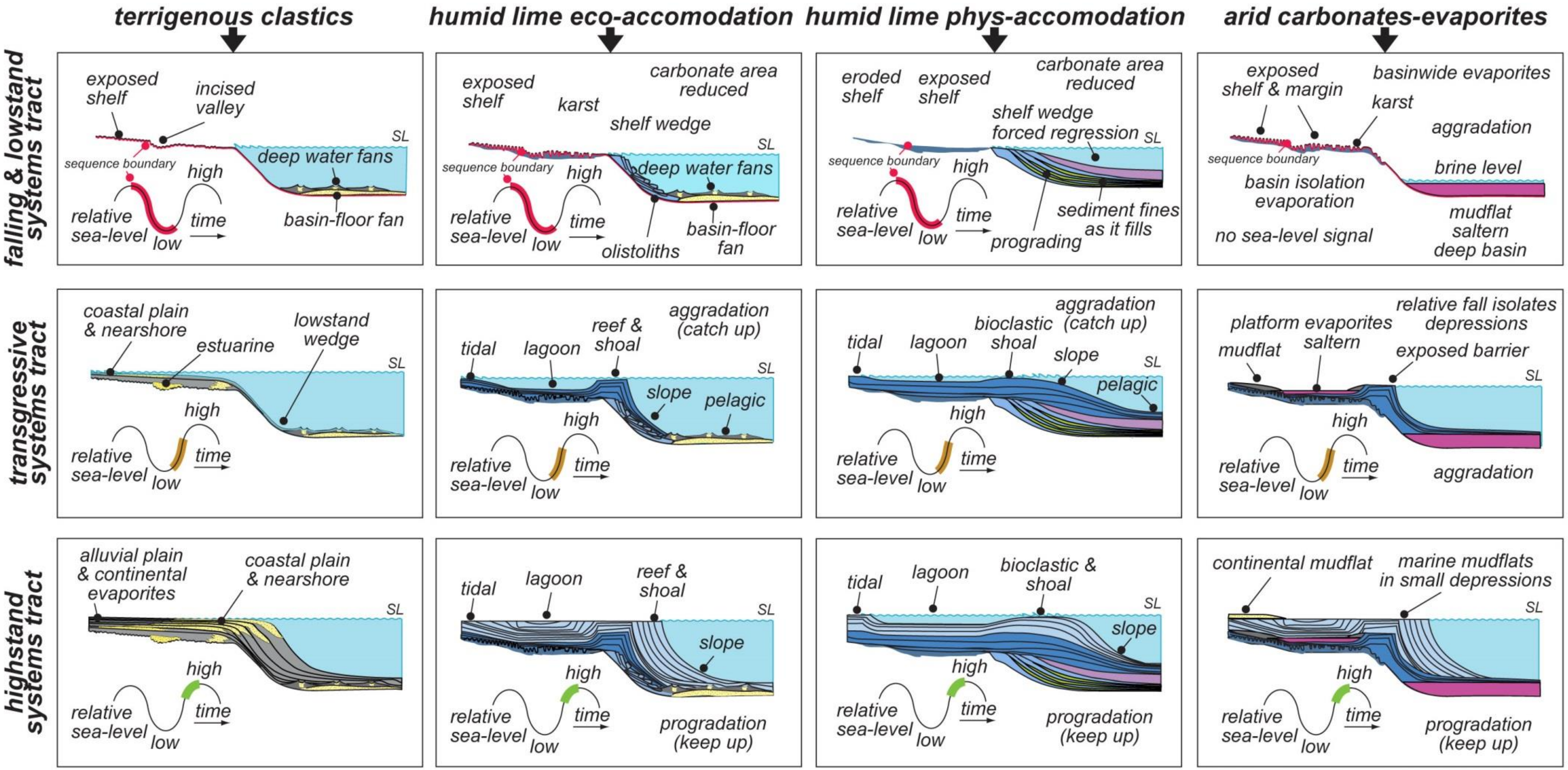
Characteristics of Ramp Settings



Emery and Myers, 1996

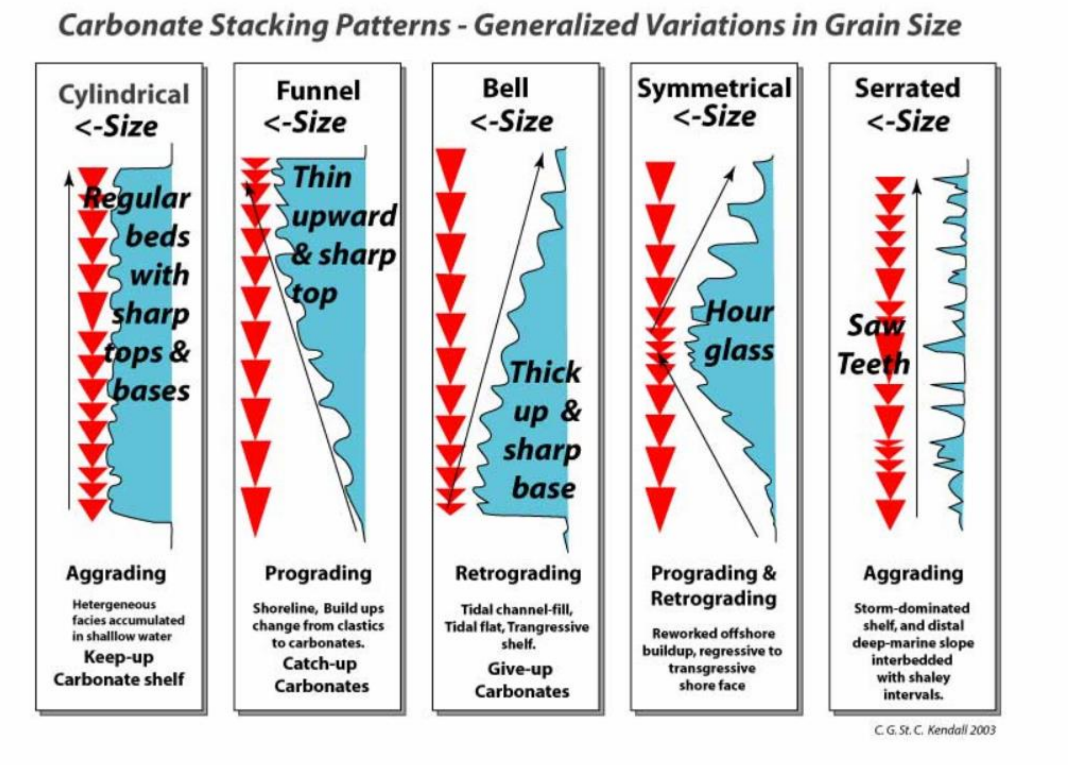
Figure 2.7. Sequence stratigraphic models for ramp systems. A) Transgressive systems tract B) High stand systems tract C) Low stand systems tract D) Drowning unconformity. Used with permission of Blackwell Science.

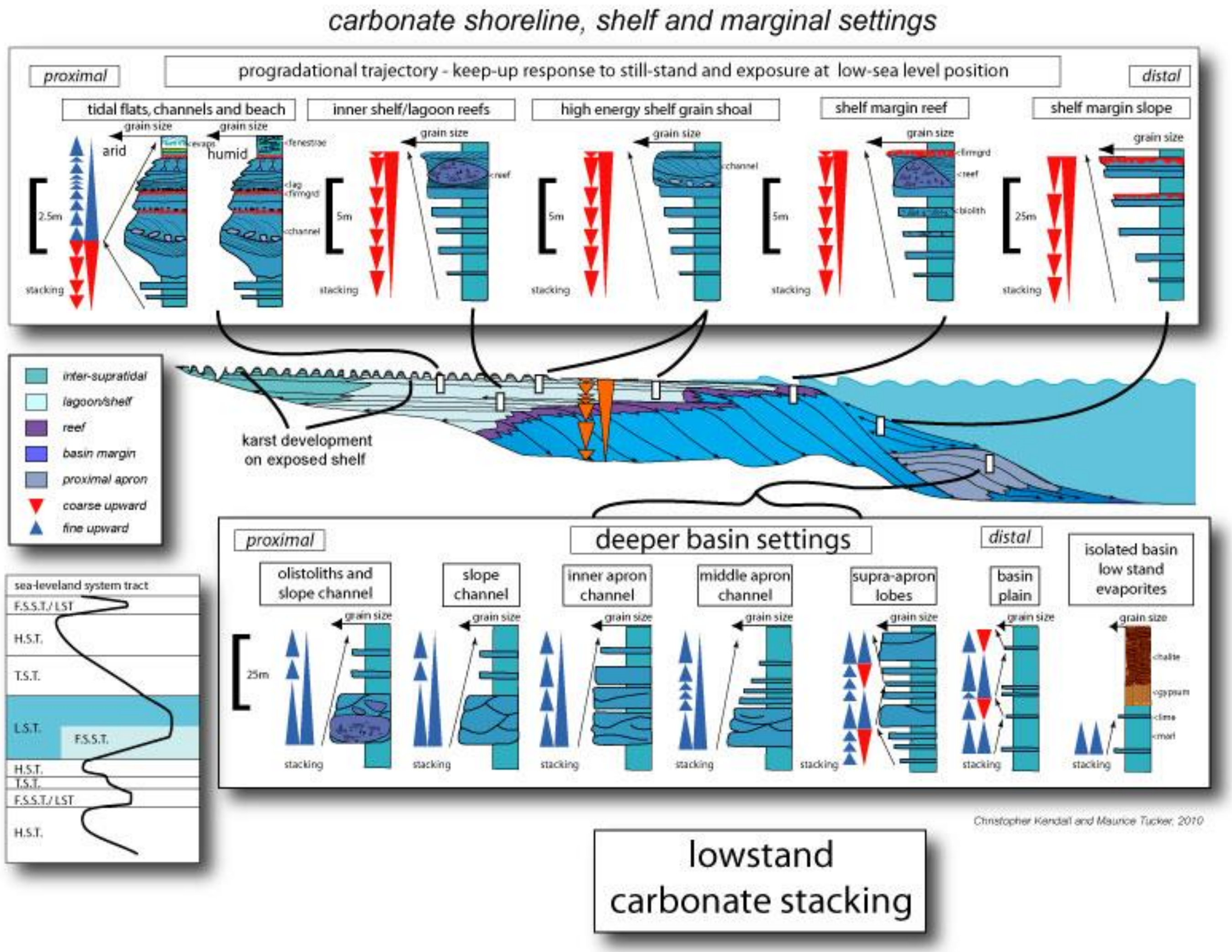
Summary



Christopher Kendall, Thomas De Keyser & Sarah Arawi, 2010 (After Warren 2001)

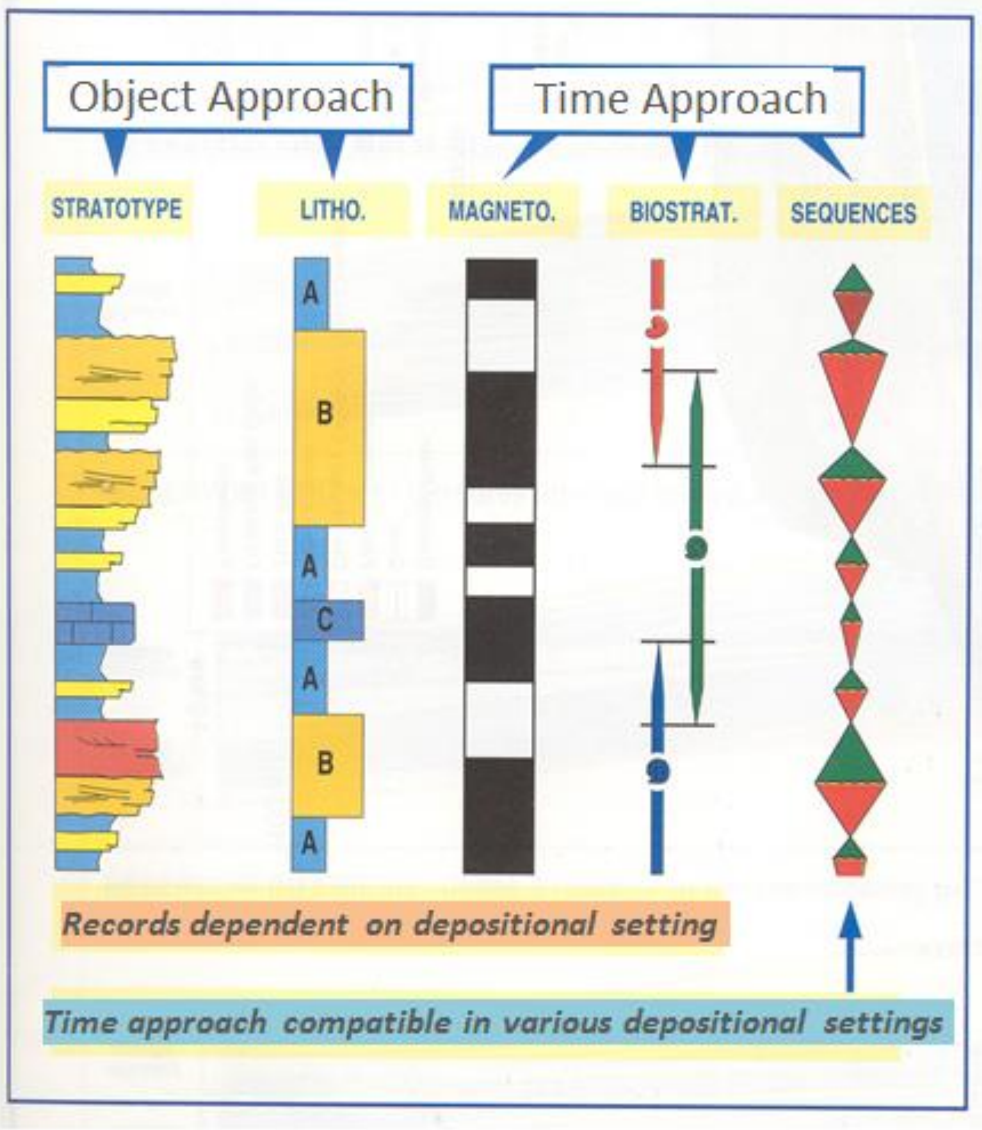
Carbonate Stacking Patterns





Conclusions

- The optimal approach to the application of sequence stratigraphy relies on the integration of outcrop, core, well-log and seismic data sets (1D, 2D and 3D).
- Each provides different insights into the identification of stratal stacking patterns and sequence stratigraphic surfaces, and mutual corroboration is important to reduce the uncertainty of the interpretations.
- Not all data sets may be available in every case study, a factor which may limit the "resolution" of the sequence stratigraphic interpretation.

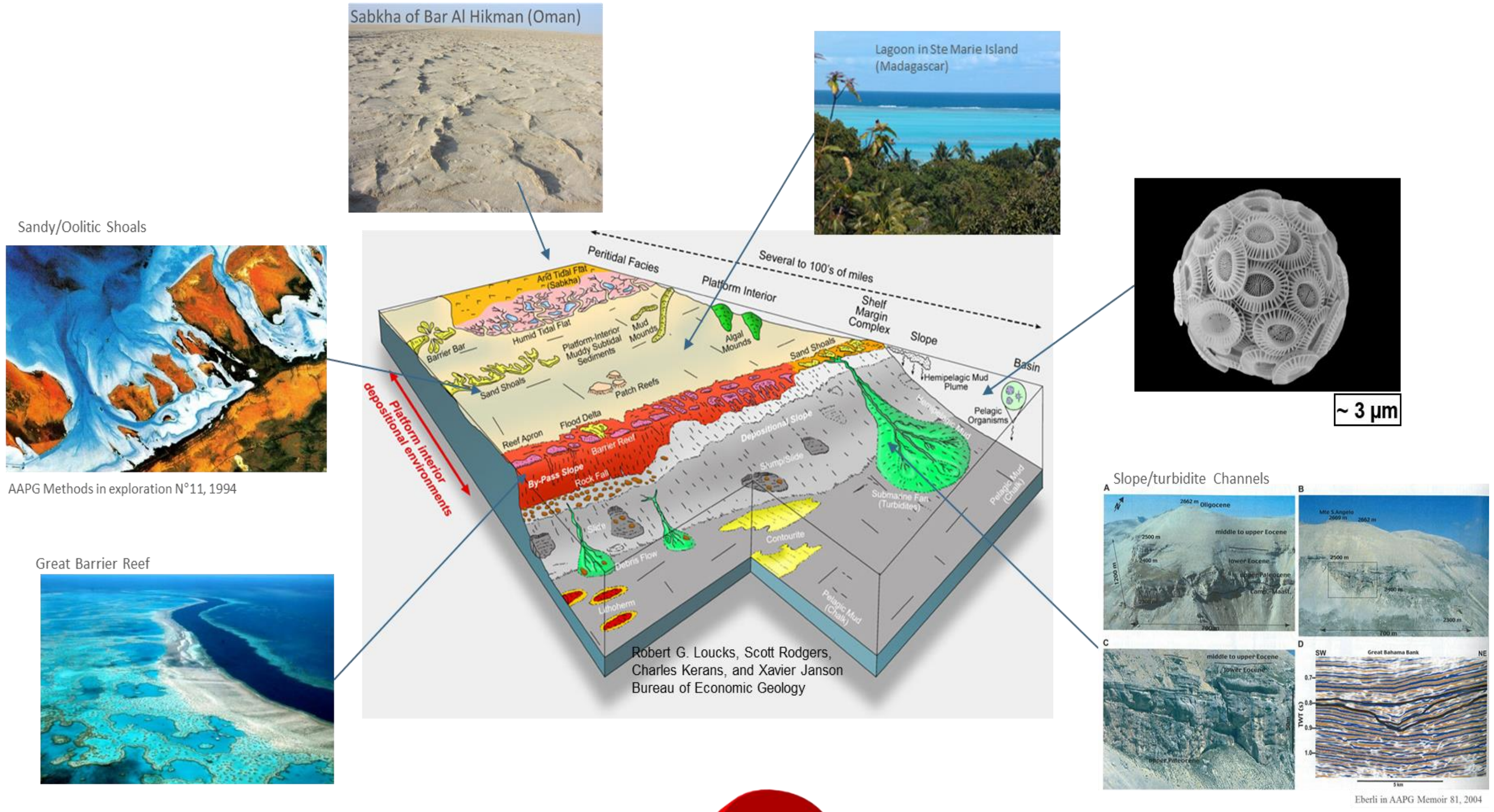


Forward Stratigraphic Modelling

How far can we Define and Quantify Uncertainties?

- Data uncertainties:
  - Volume of data available
  - Spatial extent covered (poor versus wide coverage)
  - Type of data (single set versus multi-scale & multi-disciplinary)
  - Quality and consistency of datasets

- Interpretation uncertainties:
  - But what is in between well data?
  - How can we extrapolate in regions not covered by any dataset?
  - Complexity of multi-scale & multi-disciplinary data integration
  - Non-uniqueness of interpretations!



Locks et al., Eberli 2004

Towards Numerical Modelling Approaches

Conceptual Model

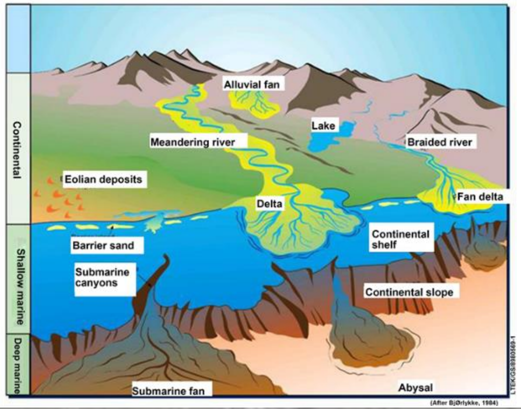
- Representation of a **"System",** based on concepts which are used to allow people better assess, understand and simulate it.
- **Conceptual models** are often <u>abstractions</u> of the real world whether physical or social or...

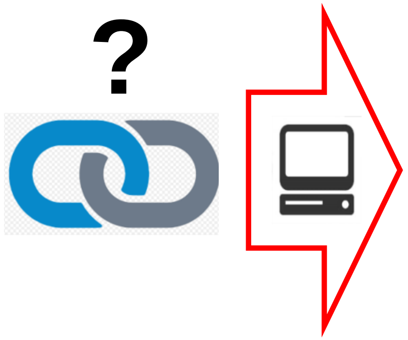
VS

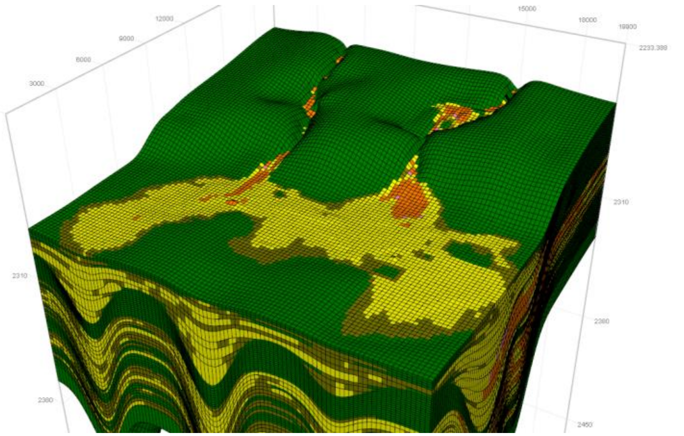
Numerical Model

- **Numerical models** are mathematical models that are designed to simulate and reproduce the mechanisms and behavior of a particular physical system.
- **A numerical simulation** is a calculation that is run on a computer following a program that implements a mathematical model for a physical system. (Nature journal)

<u>A need to understand the link between concepts and numbers is of utmost importance</u>

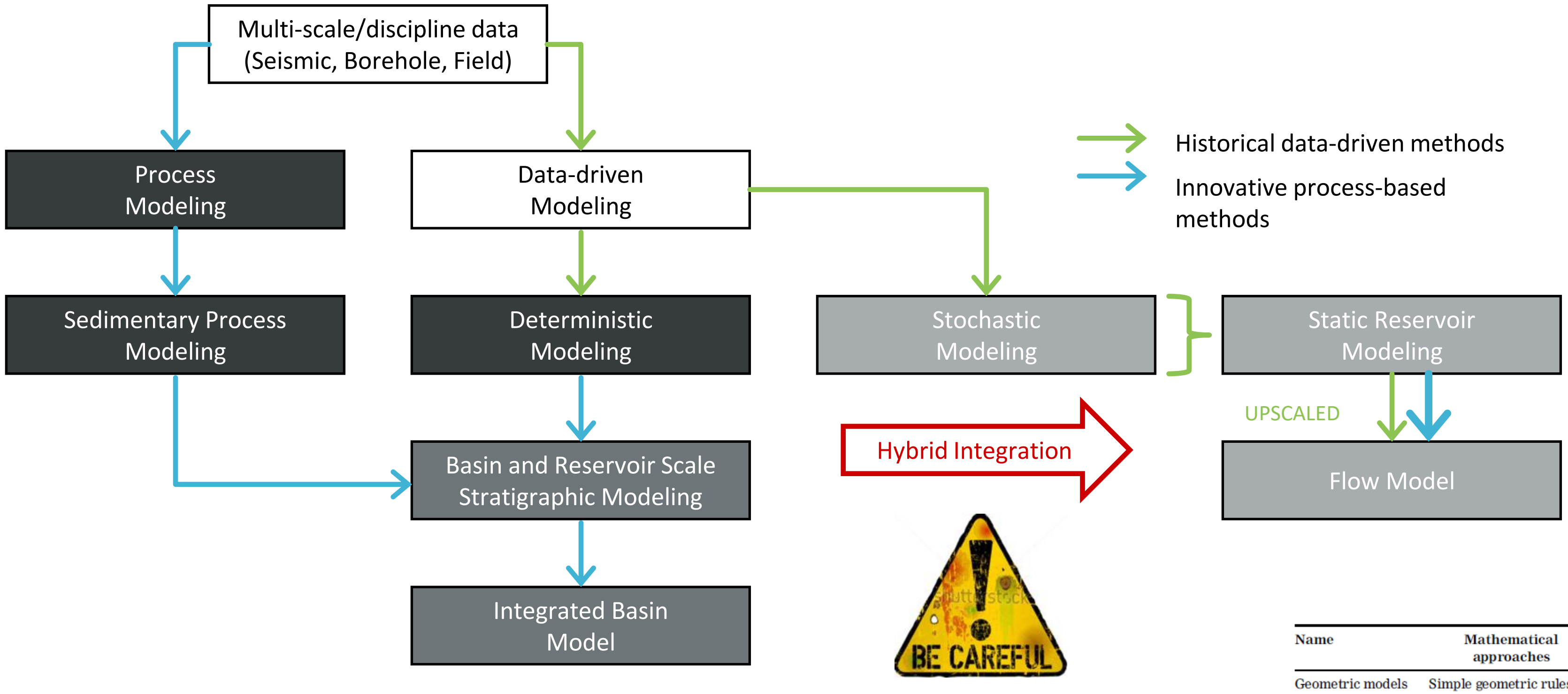






Marfisi & Hawie 2016

Shift from Data-Driven to Process-Based Hybrid Approaches



Scale and Methodology Challenges

Name	Mathematical approaches	Advantages	Disadvantages	References
Geometric models	Simple geometric rules	Quick 2D illustration of sequences and systems tract concepts in relation to accommodation change and sediment supply	Only two-dimensional and consequently unable to effectively model the 3D distribution of stratal packages. Models the consequences of processes rather than the processes themselves.	Strobel *et al.* (1989), Kendall *et al.* (1991a, b)
Diffusion models	Fick's laws of diffusion	Simplicity and wide applicability to different depositional systems	The appropriateness of the diffusion process to represent sediment transport is questionable owing to its non-uniqueness and some inherent assumptions	Rivænes (1992), Flemings & Grotzinger (1996), Granjeon (1997), Granjeon & Joseph (1999), Quiquerez *et al.* (2000), Hutton & Syvitski (2008)
Fuzzy logic models	Fuzzy logic/fuzzy-set theory	Quick and computationally efficient means of simulating 3D ecological niches over time in carbonates and vegetation (source rocks). Can be readily integrated with hydraulic models for mixed carbonate/siliciclastic systems.	Not as predictive as hydraulic simulation in siliciclastics.	Nordlund & Silfversparre (1994), Nordlund (1996, 1999)
Hydraulic models	Approximations to Navier–Stokes equations	Excellent capability to deal with flow in a very natural way, allows the realistic patterns of sediments and topography to be well developed	Very computationally intensive and some inherent assumptions need to be pre-determined relating to the appropriateness of approximations and simplifications to fluid flow equations.	Gratacós (2004), Tetzlaff & Harbaugh, (1989), Hutton & Syvitski (2008)

Hawie et al., 2015-2020, Huang 2015

Process Based FSM Workflows

- Use of deterministic process-based tools that reproduces the interaction between the main mechanisms driving sedimentation (i.e., subsidence, bathymetry, sediment transport/in situ production, erosion, eustasy) to generate geologically sound numerical models.

Workflow

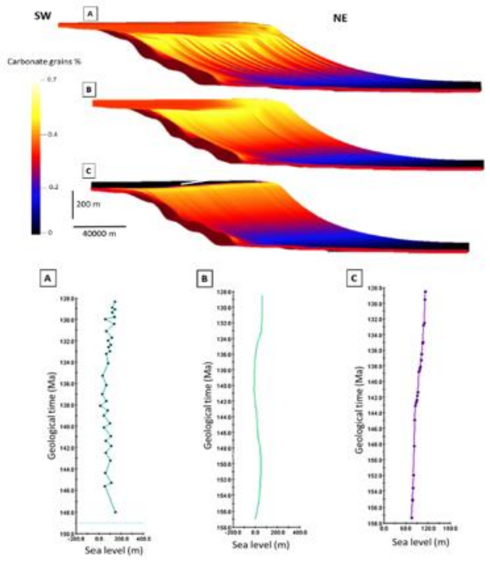
1. Initial Paleo-bathymetry
2. Subsidence History
3. Eustasy
4. Supply and Production
5. Transport processes
6. Calibration
7. Facies Definition

Input

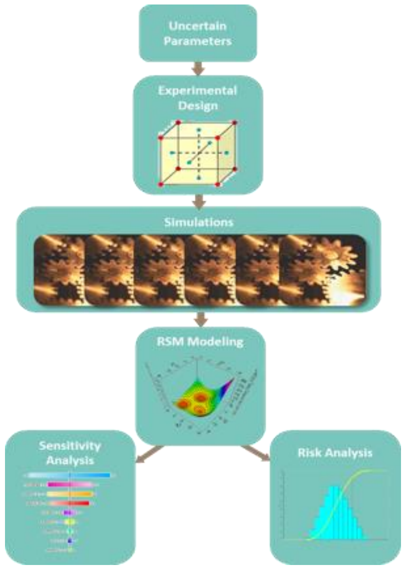
Variable parameters:

+/- Initial Bathymetry
+/- Sediment Supply,
+/- Fluvial Discharge,
+/- Content (sediment ratio),
+/- Sea Level
+/- Wave Energy,
+/- Long Term transport,
+/- Short term transport,
+/- Slope failure,
+/- Precipitation

Scenarios



Sensitivity Analysis



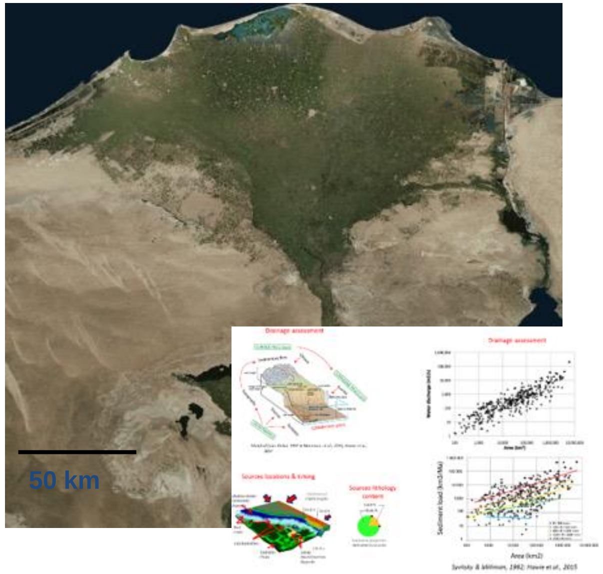
Hawie et al., 2014, 2015, 2016,, 2019, Salmi et al., 2019

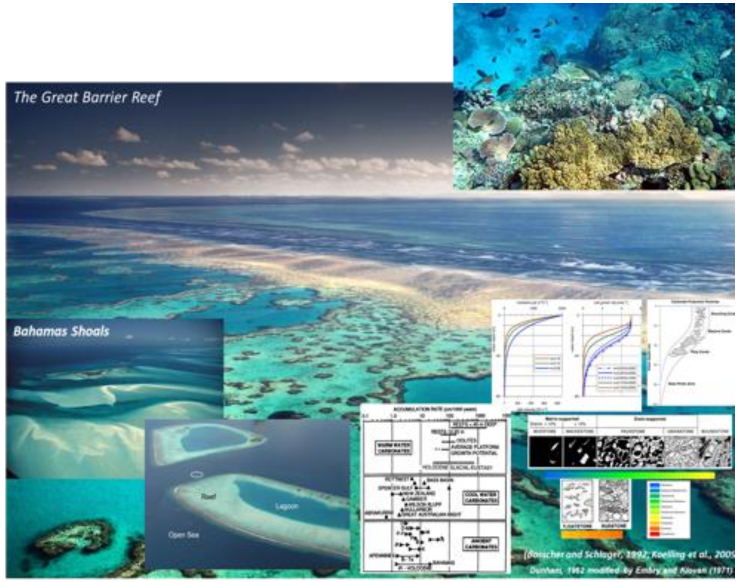
Complex Ecological Interaction in Mixed Sedimentary Systems

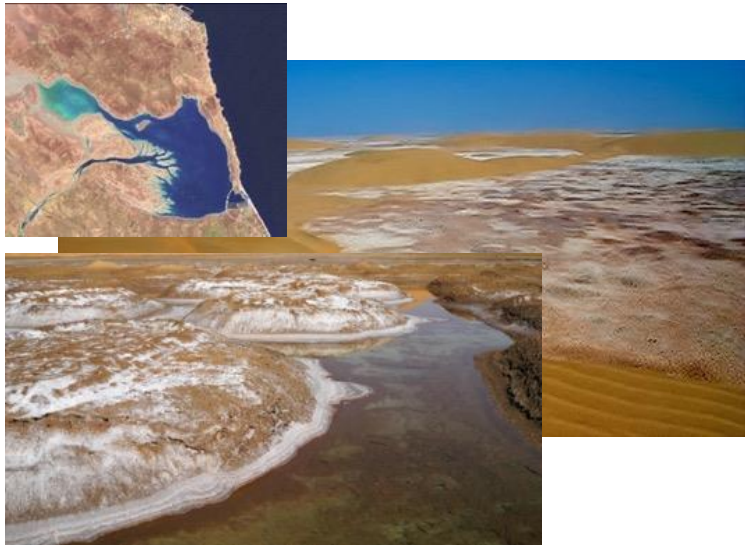
- **Siliciclastic Continental and Marine Environments**
  - Source location and direction
  - Water discharge characteristics
  - Transported lithologies
  - Erosion
  - Source activation….

- **Carbonate Marine Environment**
  - Wave characteristics
  - Carbonate production laws
  - Temperature, lighting
  - Ecology + carbonate factory
  - Transport….

- **Sabkha/Hypersaline Environment**
  - Precipitation versus evaporation
  - Water salinity index
  - Salt ecological system (wave energy, siliciclastic influx)
  - Salt production and dissolution rates…







Data Science and AI can play a major role in screening rapidly these input parameters

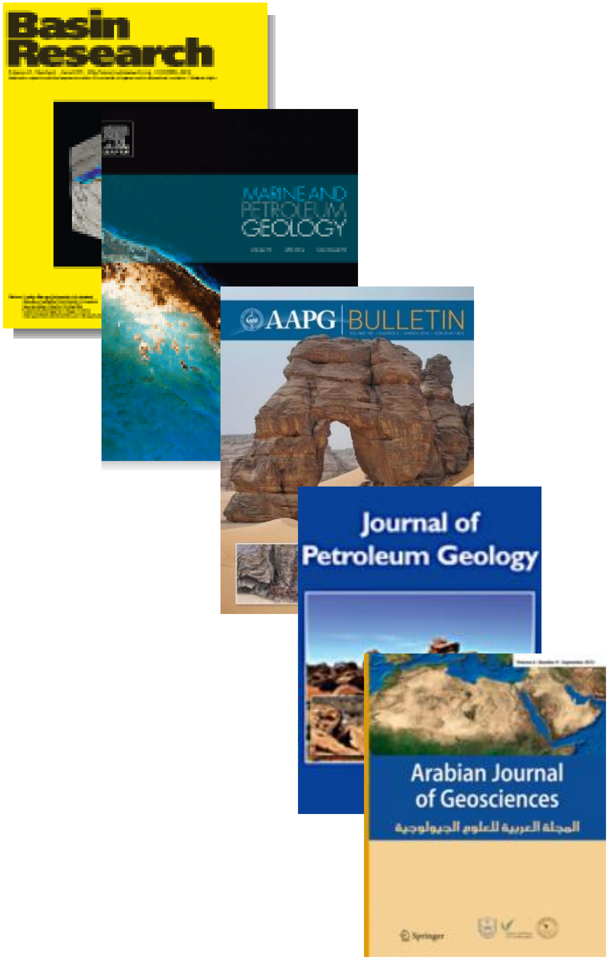
Using Integrated Database to Constrain Numerical Models

- Various integrated platforms/databases that combine models of plate tectonics, sea level change, paleoclimate and geological structure

- Integrated databases plays an important role in quantitively assessing input parameters ranges of values as well as allows a much faster model calibration approach and a better de-risking of petroleum systems elements

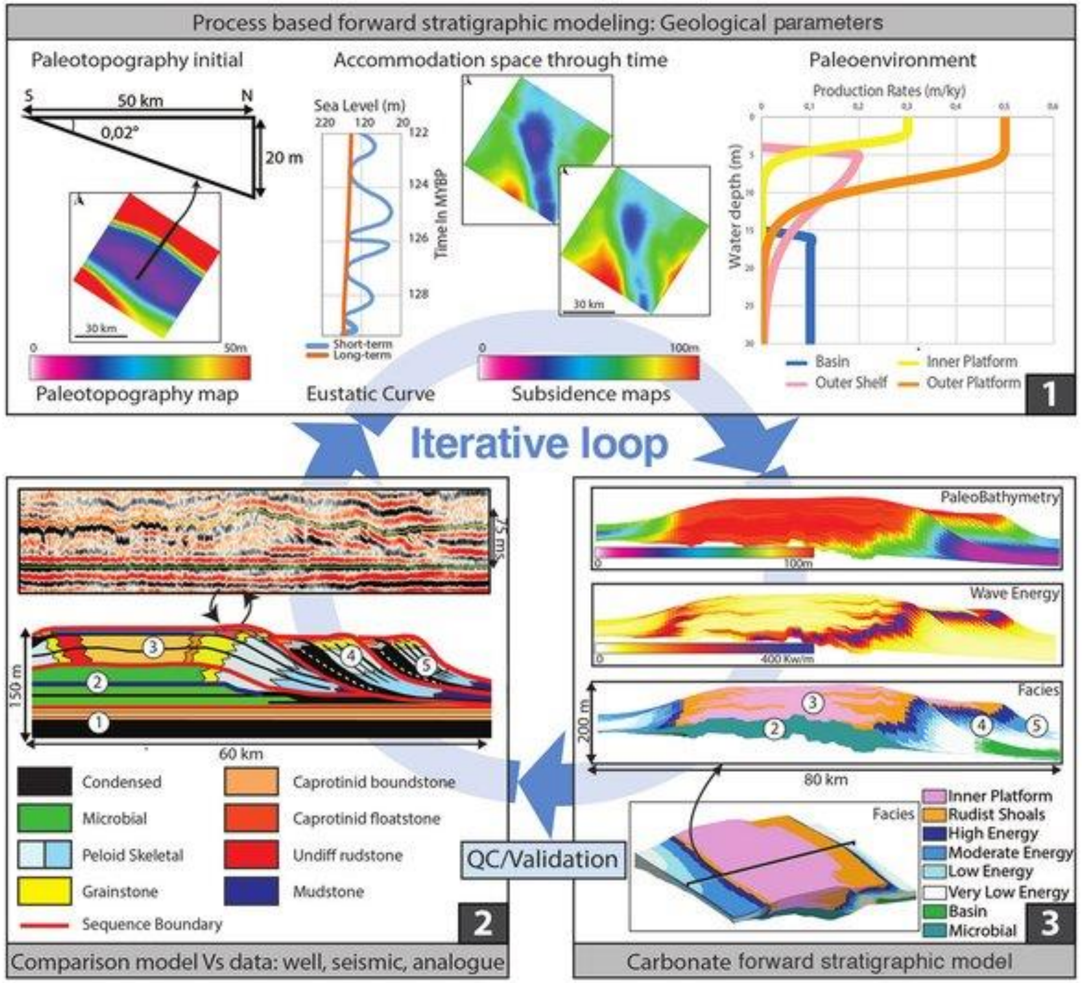
- Training models through Artificial intelligence (e.g., Neural Network approaches) is currently being used in G&G to overcome various mapping and properties prediction challenges

International Peer-Reviewed Publications



1D, 2D and 3D Calibration of Stratigraphic Models

- Calibration of Forward Stratigraphic Models is conducted in 1D, 2D and 3D
- Qualitative versus Quantitative Calibration
- 1D-3D Calibration Indicator Factors are developed to assess various simulated properties:
  - Lithology/Facies Calibration
  - Thickness Calibration
  - Rock Properties Calibration
  - Ecological factors
  - Geometry/Architecture Calibration
- Sensitivity Analysis is conducted to predict simulation/model behavior in areas lacking enough constraints



Lanteaume et al., 2018

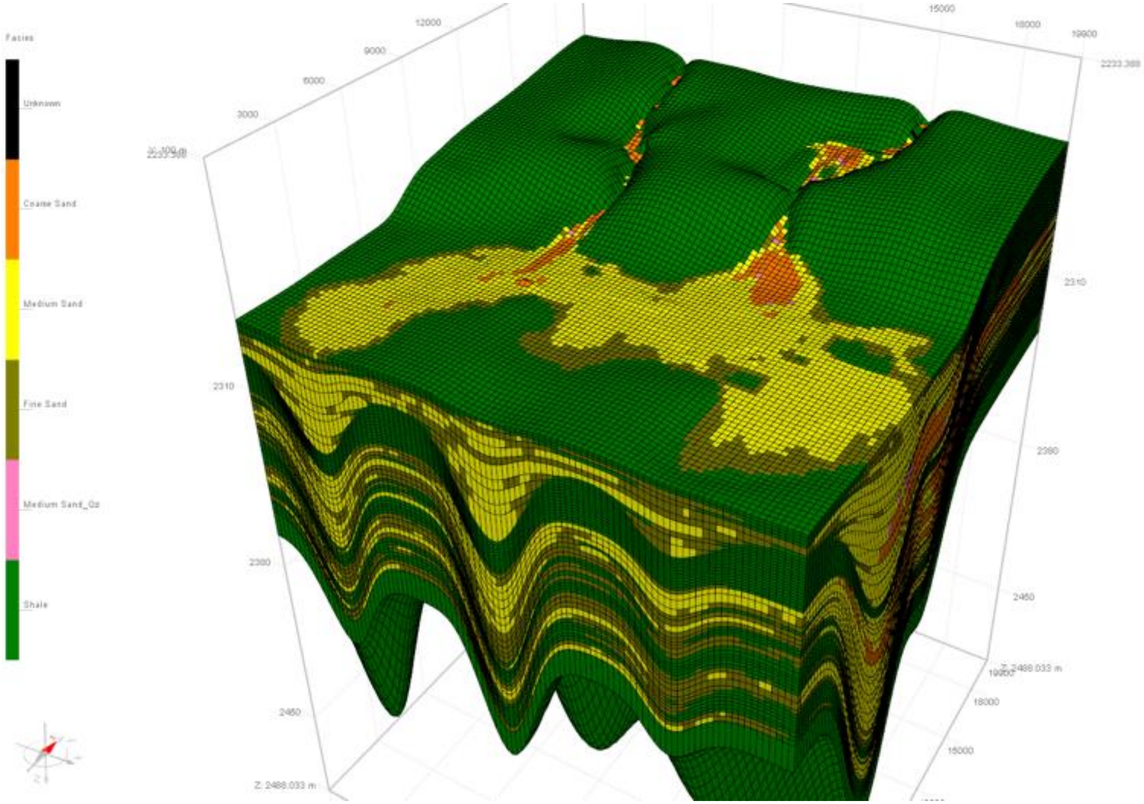
- Well data
- Seismic Reservoir Characterization
- Multi-Seismic Attributes
- ….

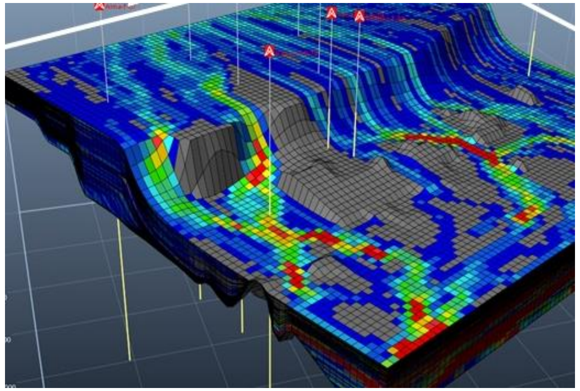
Process Based FSM Models

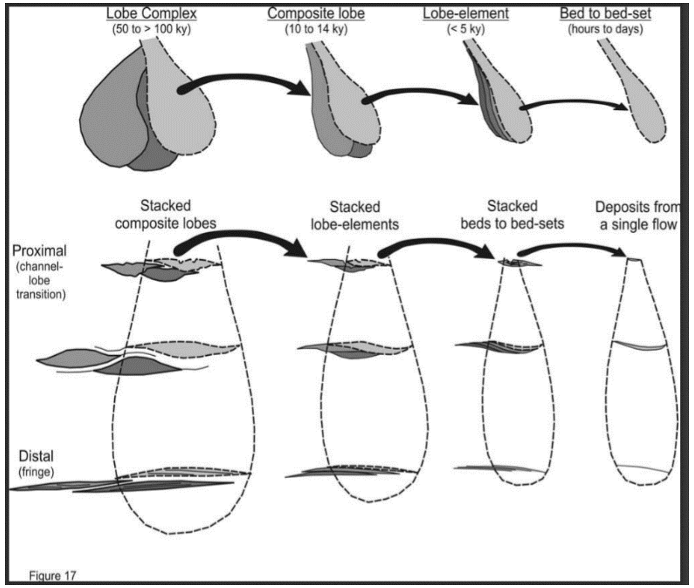
Canyon to Basin floor Fan

Siliciclastic Systems

- Model Specifications:



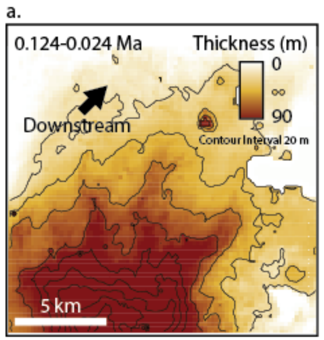




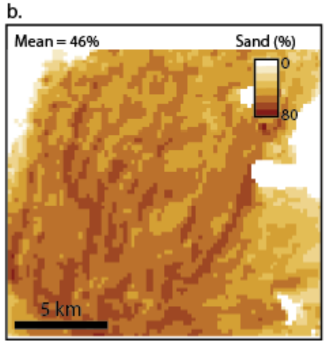
Process Based FSM Models

Siliciclastic Systems

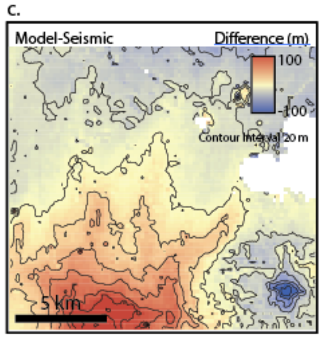
Total Model thickness



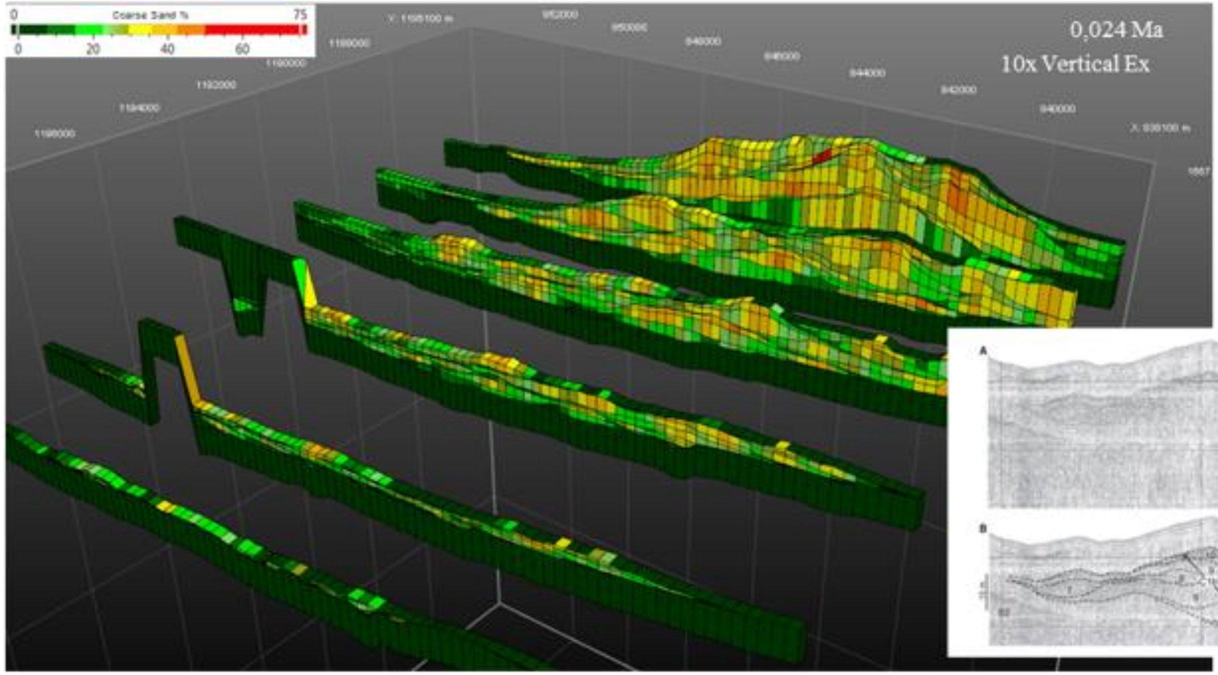
Overall Sand Proportions



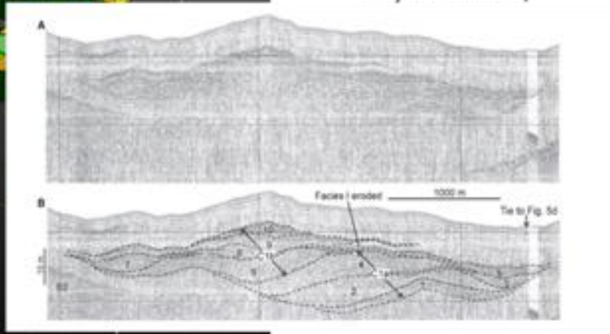
Overall Sand Proportions

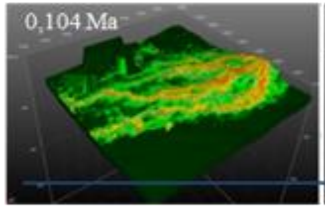


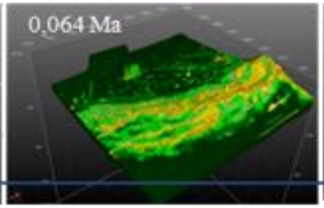
Intra-slope Fan: Trinidad

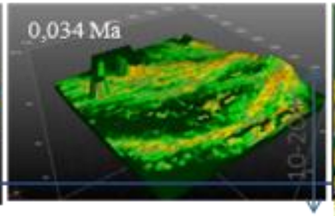


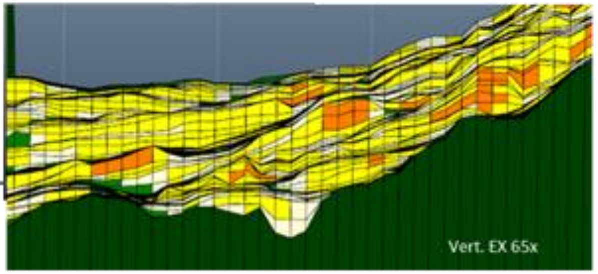
Deptuck et al.,





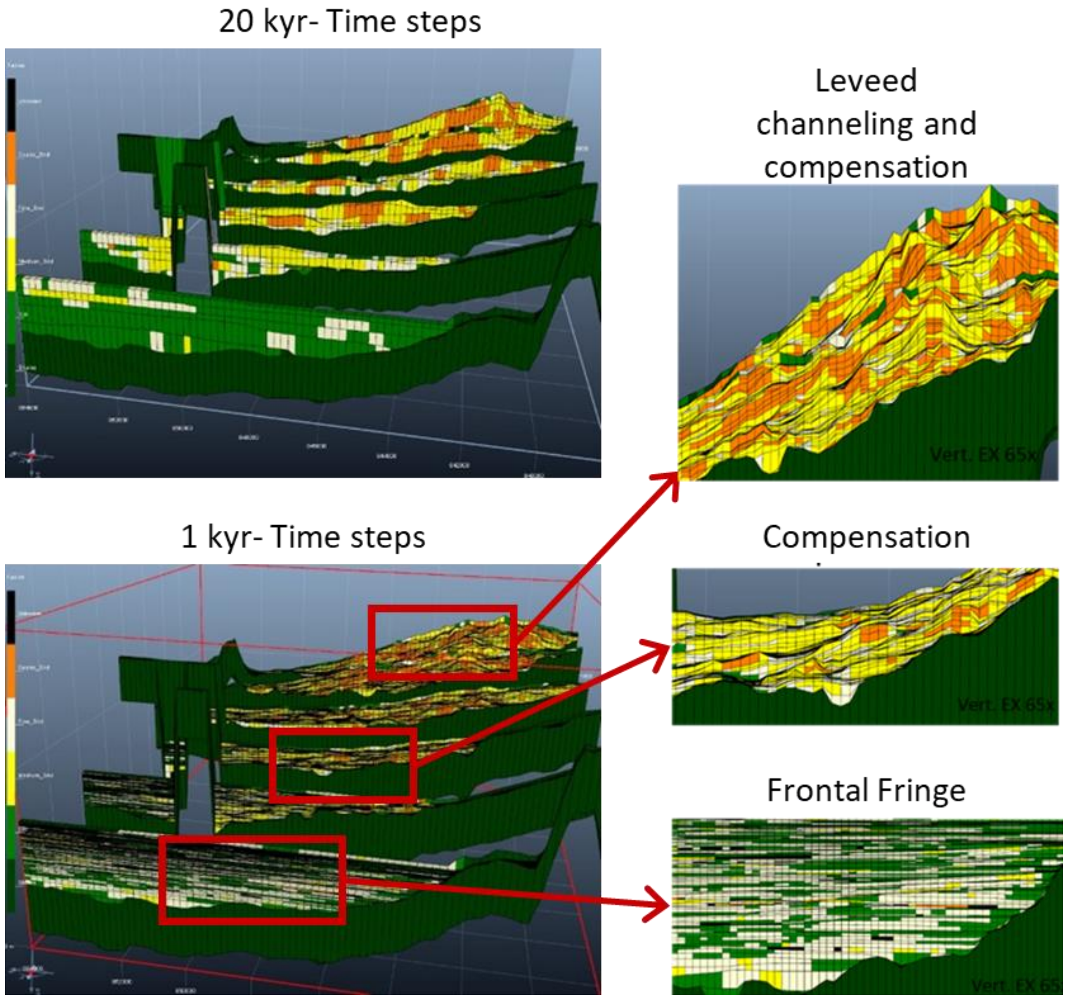


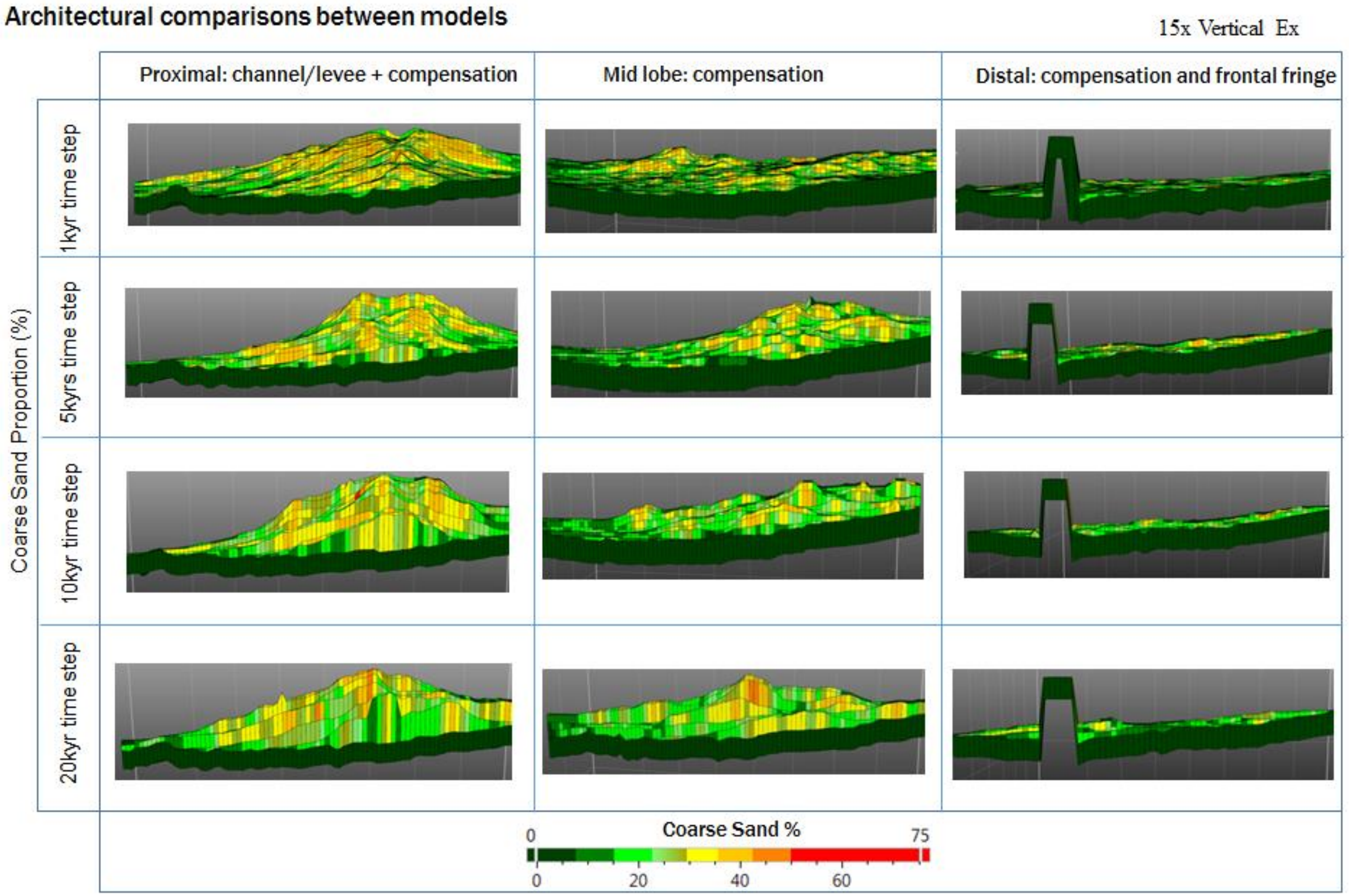




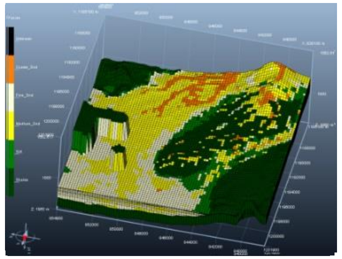
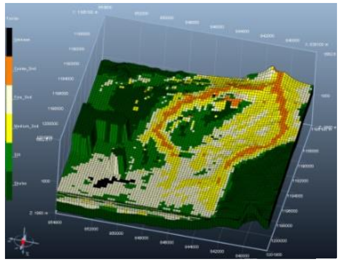
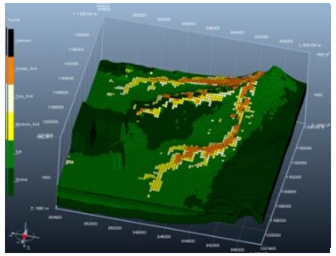
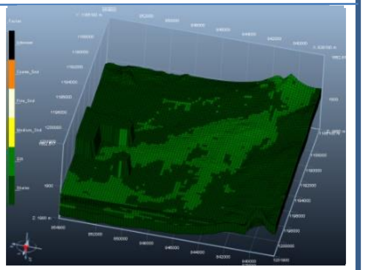
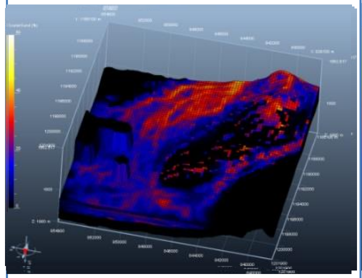
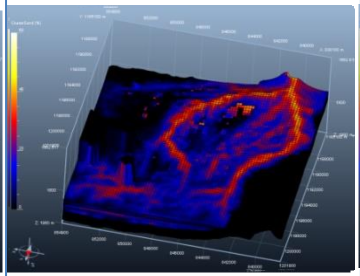
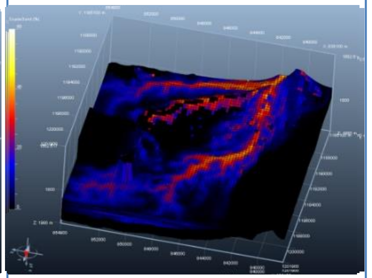
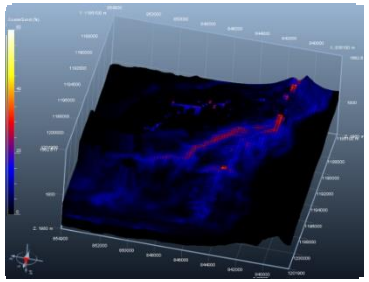
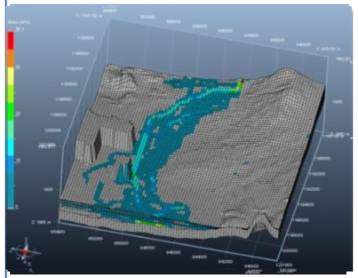
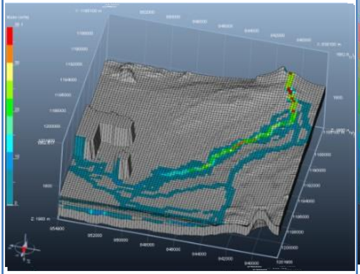
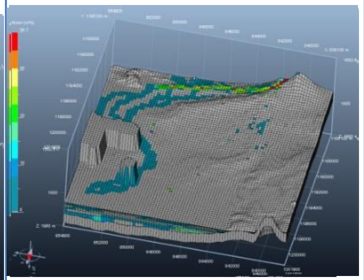
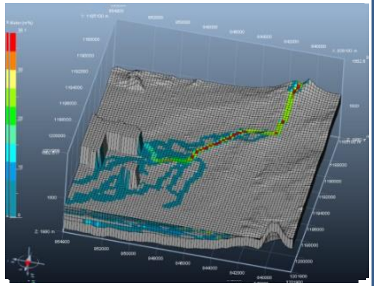
Hawie et al., 2018-2019

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





Sensitivity Analysis (Shale vs Sand Content ex)

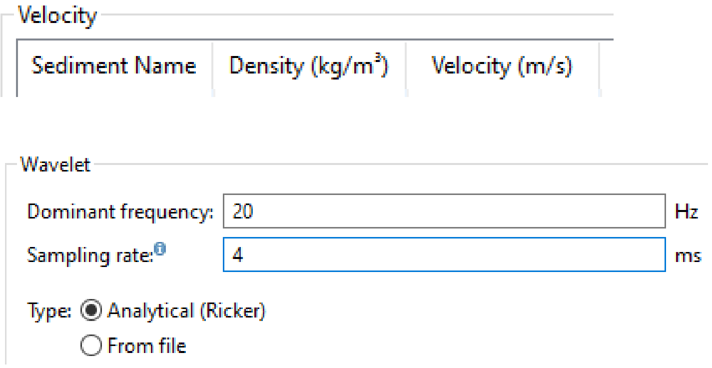
Shale Content	Very Low	Low	Medium	High
Facies				
Coarse Sand				
Water Discharge				

Generating Sensitivity Maps on:

- Lithology N/G
- Thickness STD
- Reservoir Thickness STD
- Seal Thickness STD
- Amongst others

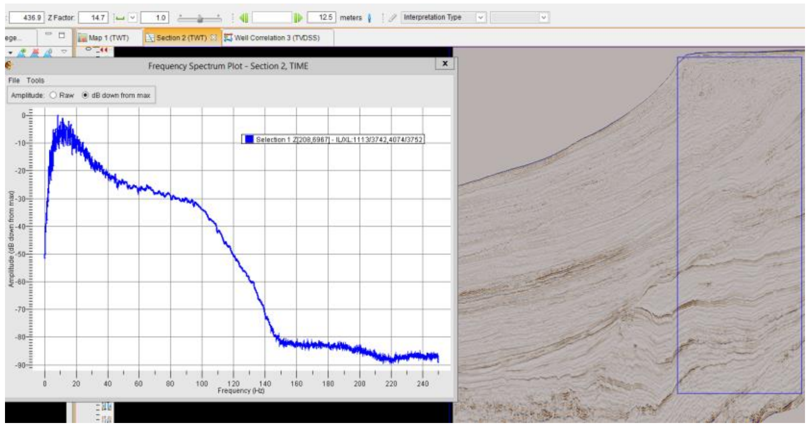
Generating a Seismic Synthetic out of the FSM

Recent advances have been made to use FSM as a backbone to generating seismic synthetic



This approach allows to:

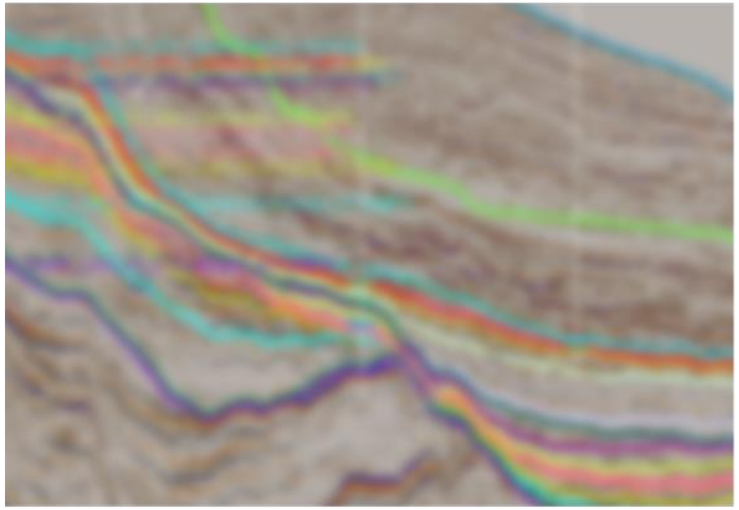
- Compare FSM synthetic to gathered seismic response
- Focus on geometrical, architectural and stratigraphic patterns
- Identify regions with potential amplitude/geophysical anomalies for further investigation
- Predict lithology response on the resultant



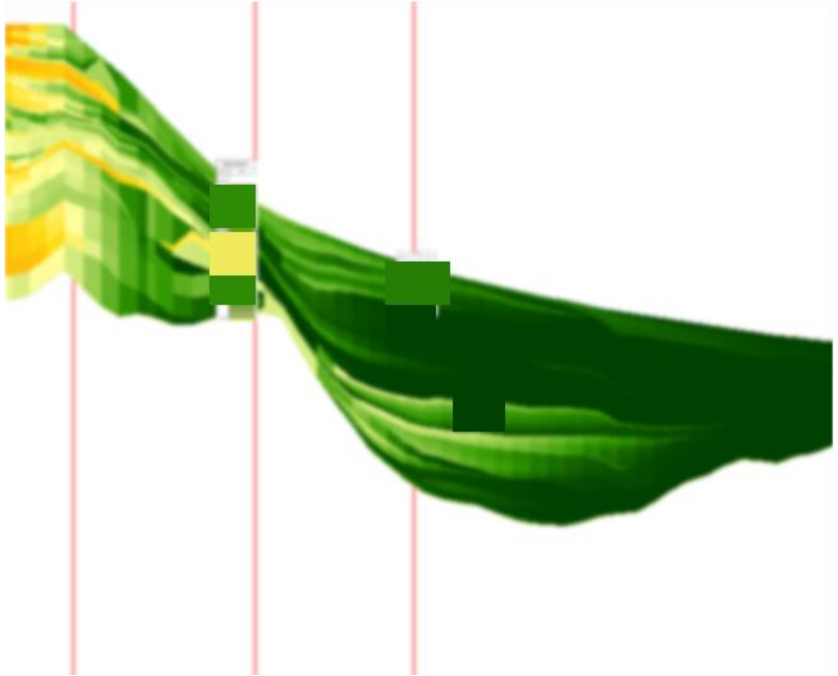
Note that: The generating seismic synthetic in the FSM is representative of the signal response of PRIMARY LITHOLOGY and DEPOSITION and does not account to any fluid presence in the rocks neither to post deposition DIAGENESIS or ALTERATION OF FACIES. So care should be taken while comparing real to FSM synthetic!

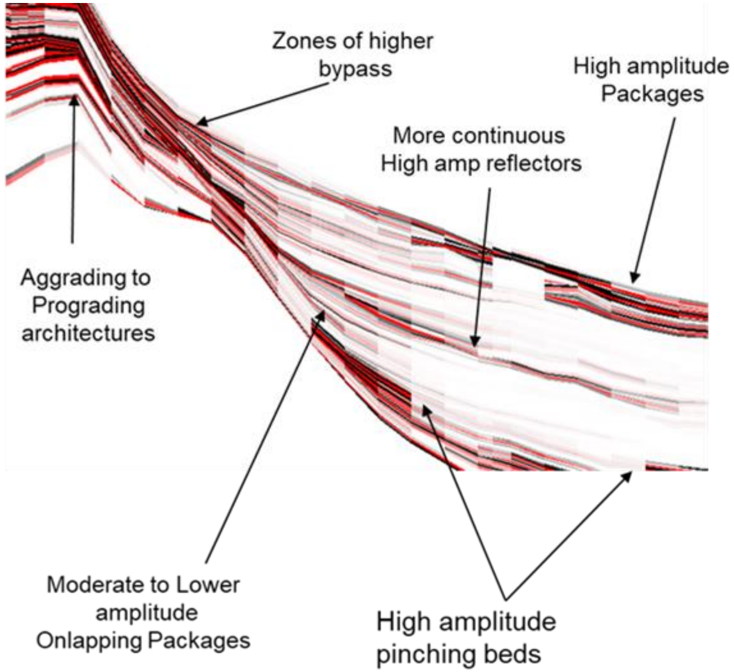
Generating a Seismic Synthetic out of the FSM

Seismic Data → High Resolution FSM → Seismic Synthetic FSM



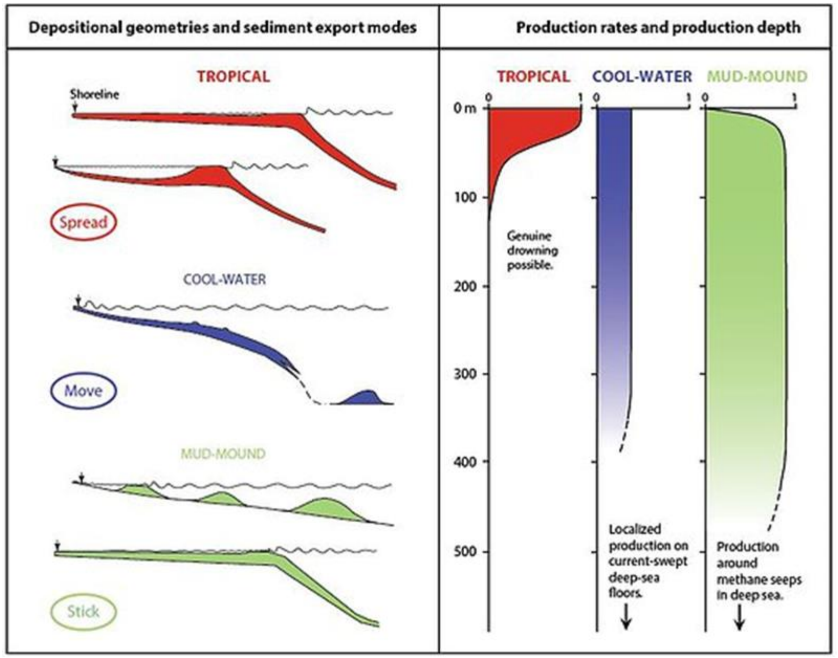
Figures not to scale/ distorted





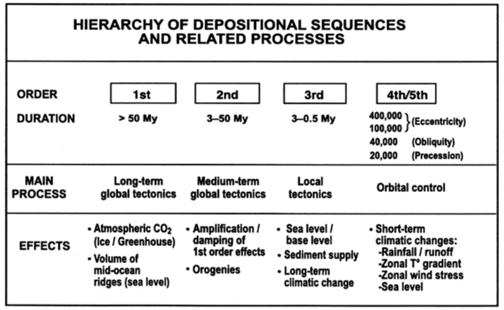
Controls on Carbonate + Evaporite Deposition

Carbonate Factories



Schlager et al., 2005

Stratigraphic Hierarchy

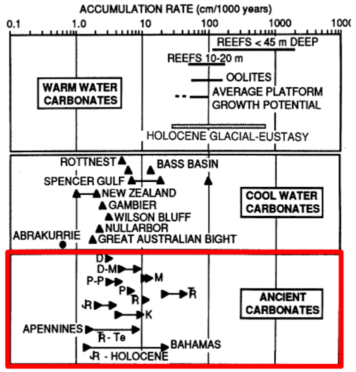


HIERARCHY OF DEPOSITIONAL SEQUENCES AND RELATED PROCESSES

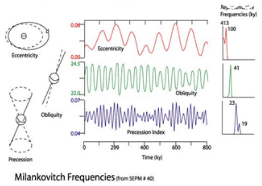
ORDER	1st	2nd	3rd	4th/5th
DURATION	> 50 My	3–50 My	3–0.5 My	400,000 100,000 (Eccentricity) 40,000 (Obliquity) 20,000 (Precession)
MAIN PROCESS	Long-term global tectonics	Medium-term global tectonics	Local tectonics	Orbital control
EFFECTS	• Atmospheric CO_2 (Ice / Greenhouse) • Volume of mid-ocean ridges (sea level)	• Amplification / damping of 1st order effects • Orogenies	• Sea level / base level • Sediment supply • Long-term climatic change	• Short-term climatic changes: -Rainfall / runoff -Zonal T° gradient -Zonal wind stress -Sea level

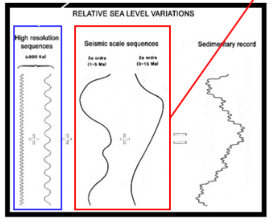
Schlager et al., 2005

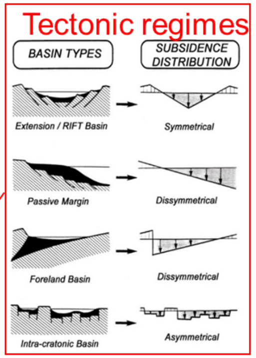
Production Rates



Controls on the sedimentary record

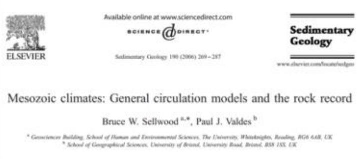






- Tectono-eustatism
- Paleogeography
- Sediment supply…

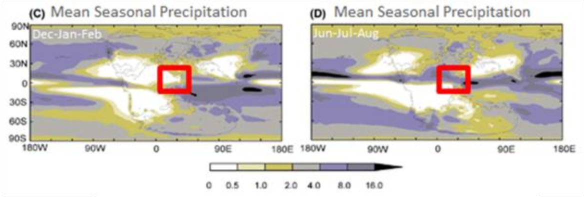
Climatic and Oceanographic conditions

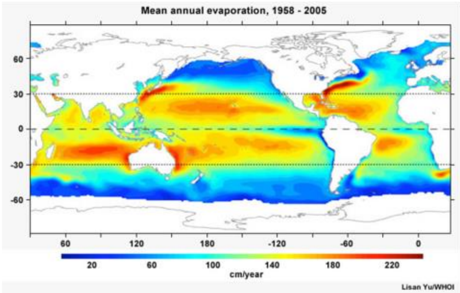


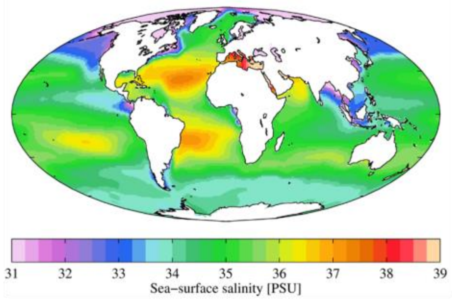
Sedimentary Geology

Mesozoic climates: General circulation models and the rock record

Bruce W. Sellwood, Paul J. Valdes

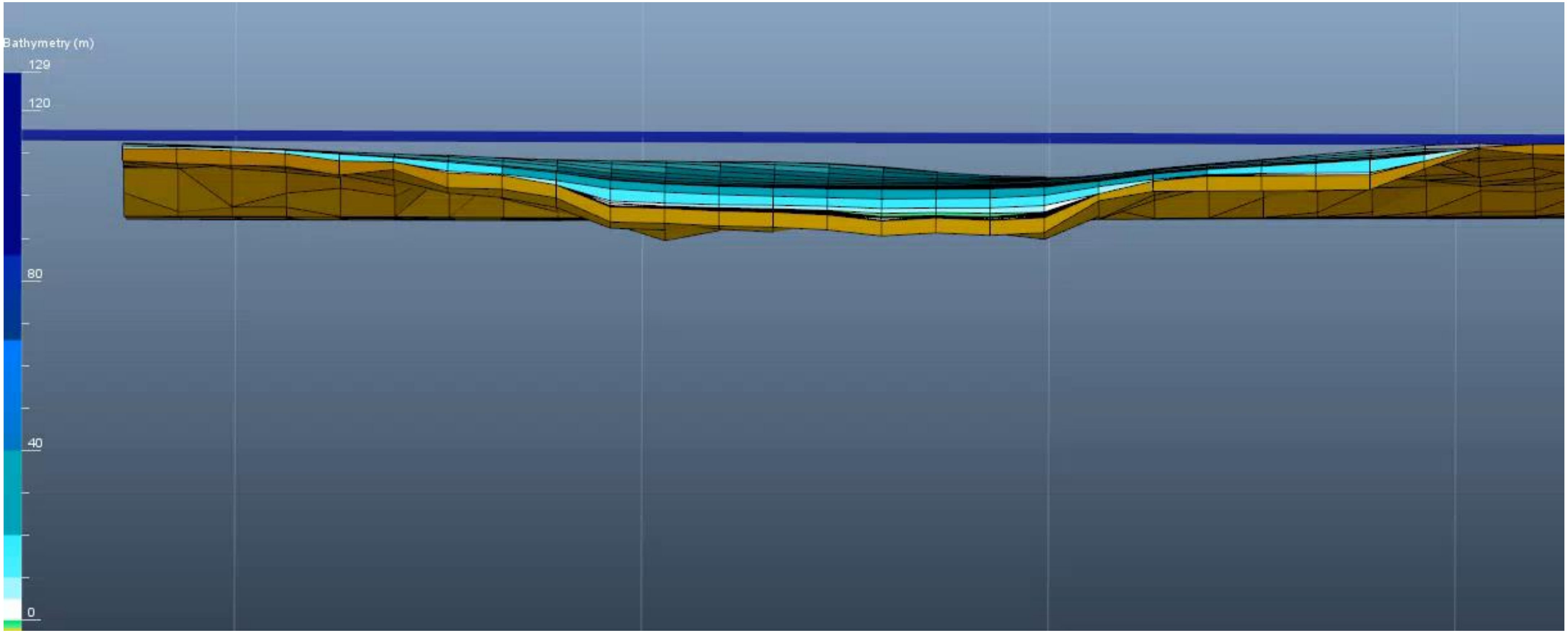




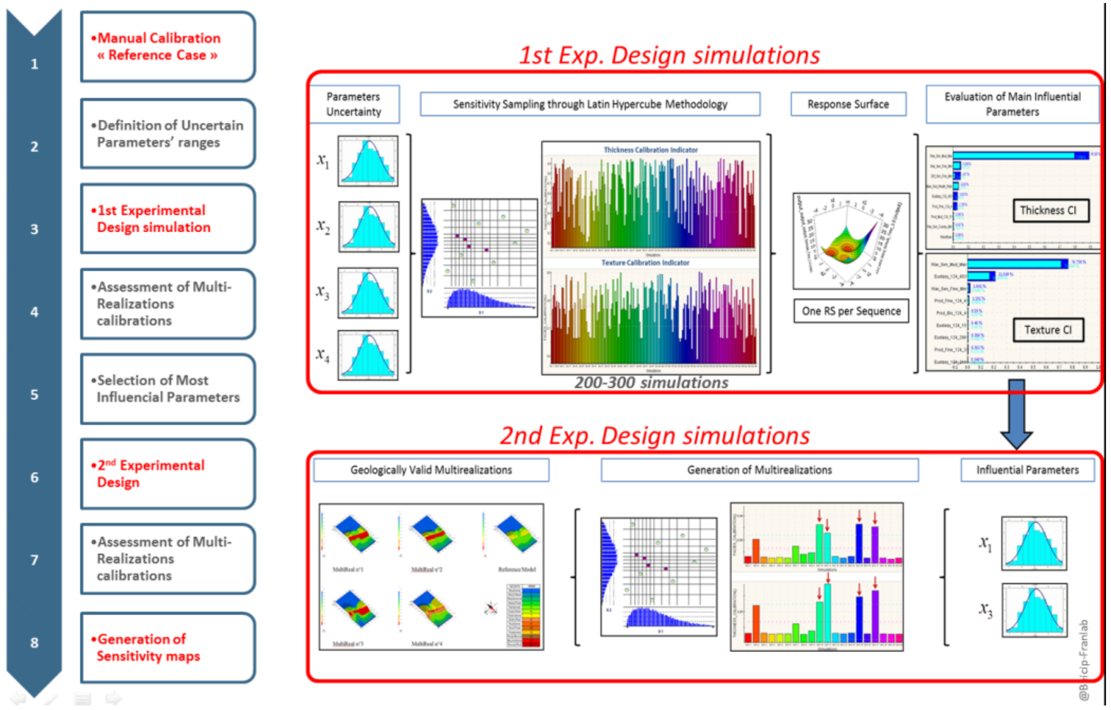


Process Based FSM Models

Carbonate Systems



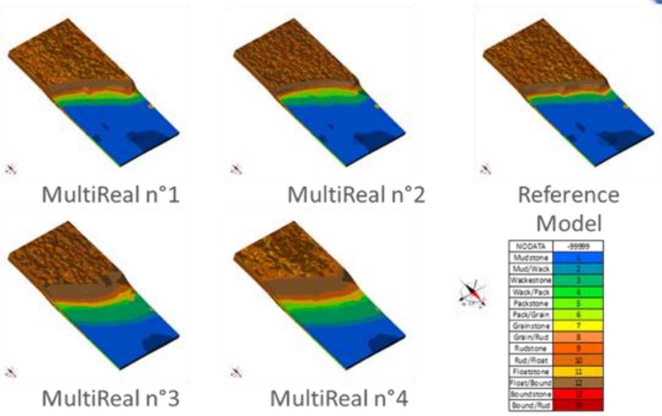
Automated Multi-simulations



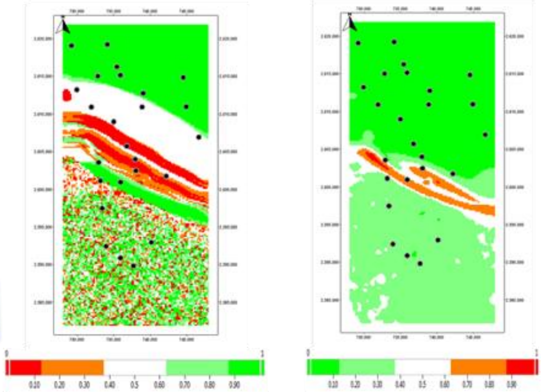
Sensitivity Analysis

Most Sensitive Parameter is Eustasy at Tx

Multi-Realizations example



Sensitivity Analysis



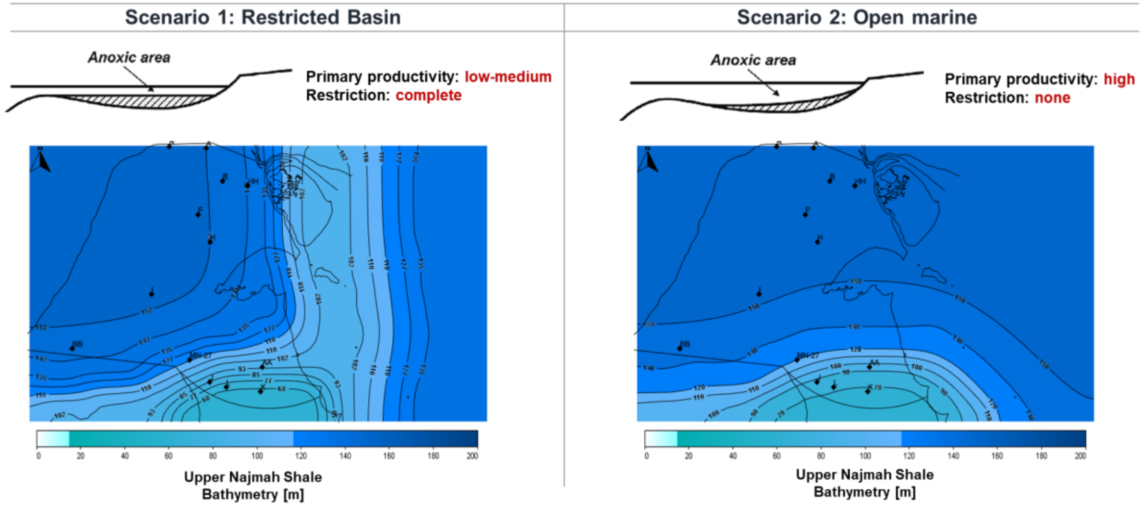
Texture Sensitivity Map

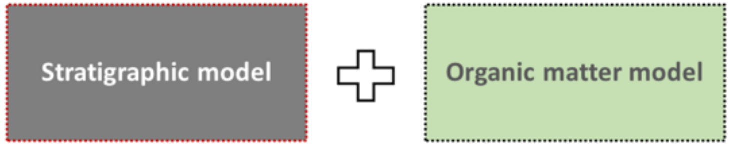
Normalized Thickness Standard Deviation Map

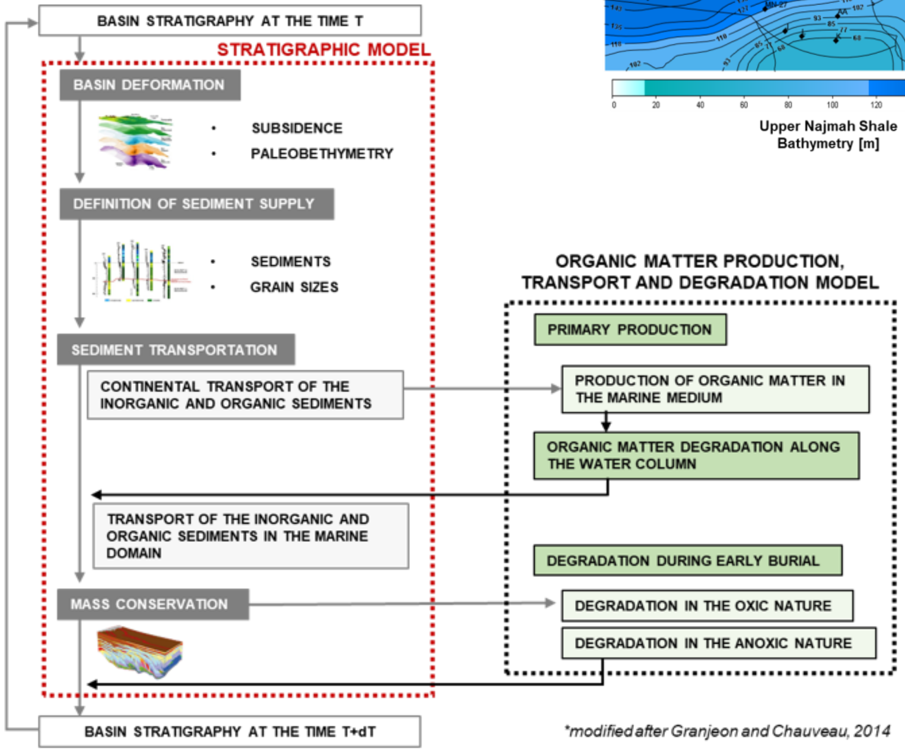
Red	More Change
Green	Less Change

Organic Matter Prediction + Basin Modelling coupling

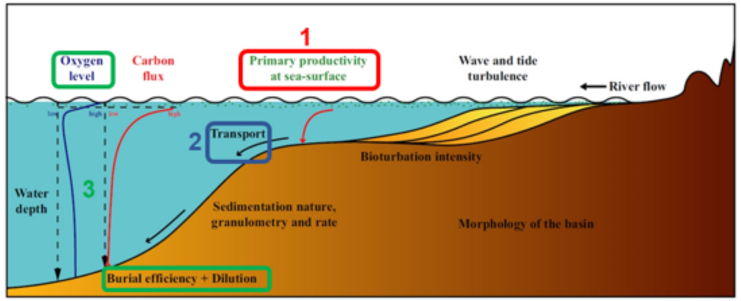
- Stratigraphic model takes into account:
  - Primary productivity of organic matter
  - Degradation along water column
  - Substratum content oxygenation
  - Preservation by burial efficiency







*modified after Granjeon and Chauveau, 2014

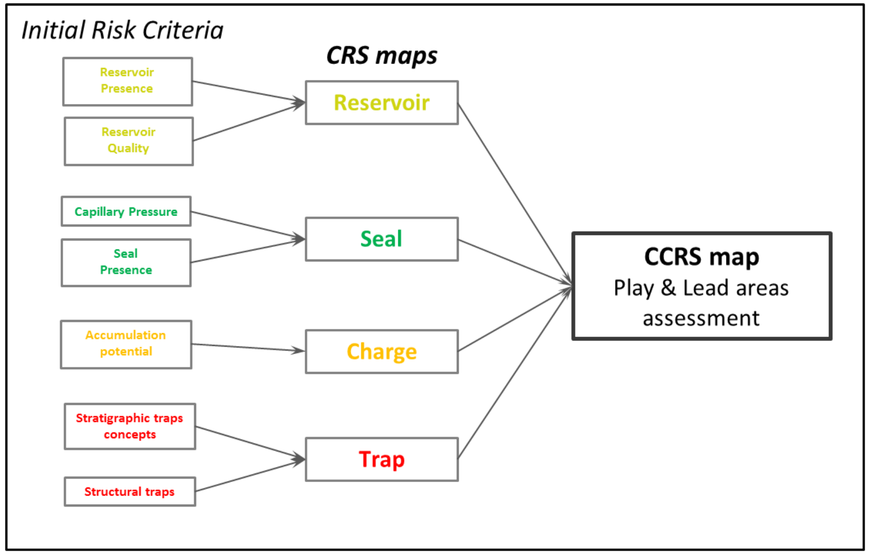


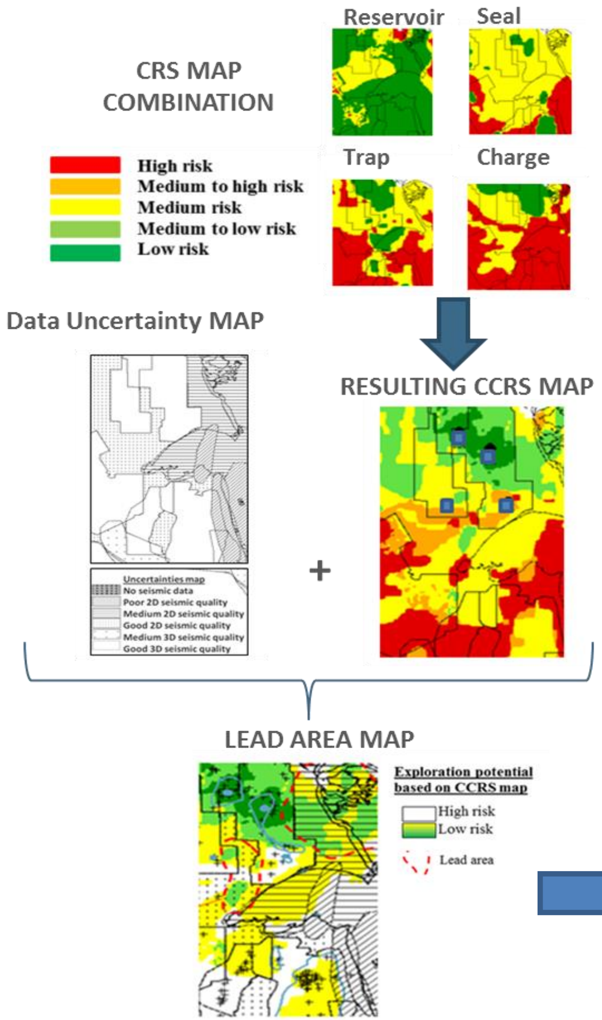
* Bruneau et al., 2016; modified after Tyson, 1995

It is also used in Unconventional Systems while coupled with Basin models to predict primary SR characteristics and present day yet to find

From Final Integrated De-Risking of Plays to Prospect Evaluation

- G & G interpretation and integration
- Stratigraphic and Basin Modeling for Petroleum systems element prediction
- Play Assessment and Risking





High Resolution Prospect de-risking

4D Field Development Support

Hawie et al., 2016, 2019

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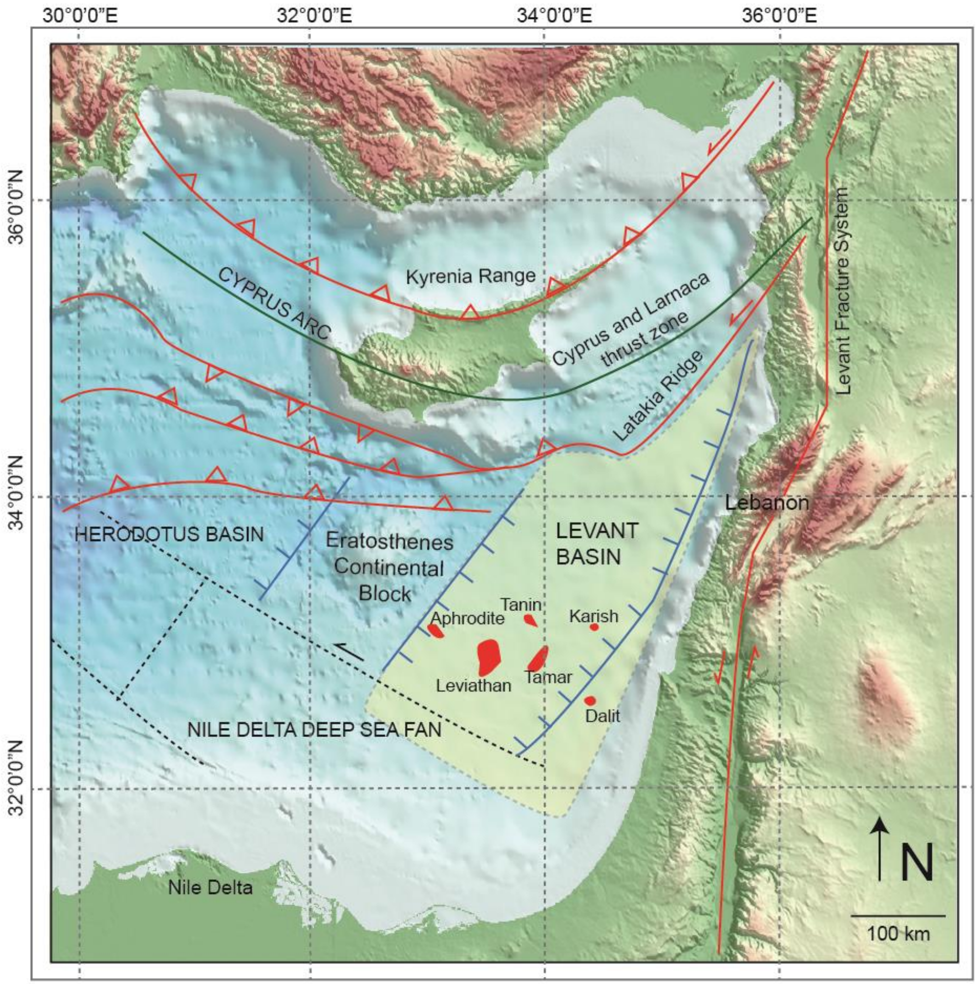
Case Studies:

1. The Levant Basin
2. Canadian Offshore
3. Golf of Mexico/ Trinidad

The Levant Basin

The Eastern Mediterranean domain

- How can sedimentary record help in deciphering the geodynamic evolution of a frontier basin?
- What are the impacts of successive deformation events on the subsidence and architectural evolution of the Levant Basin and its margin?
- How can sediment sources contribute to the filling of a continuously deforming margin and basin?



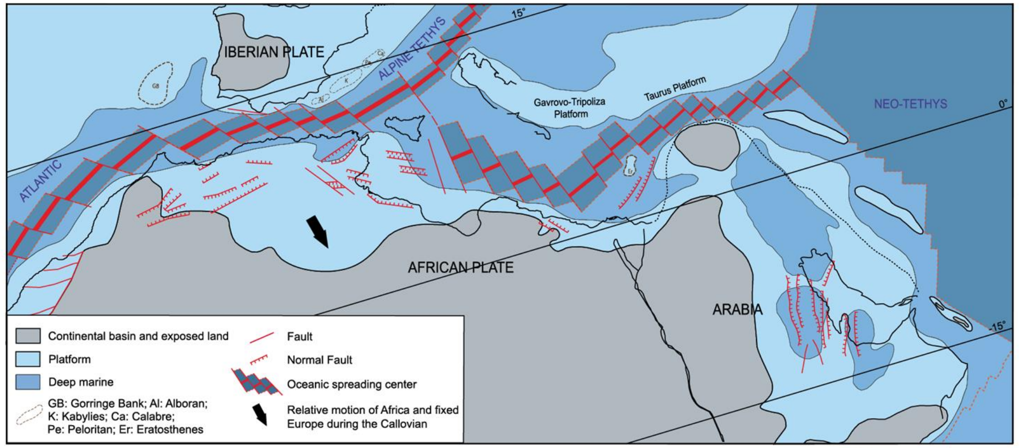
Modified from *Le Pichon & Kreemer (2010)*

Outline

1. Geodynamic and tectono-stratigraphic framework of the Levant region
2. Methodology
3. Results
    1. Seismic interpretation
    2. Fieldwork results
    3. Forward stratigraphic modeling of the Miocene source to sink system
4. Concluding remarks

Mesozoic extension in the Tethyan domain

Middle Jurassic



Modified from Frizon et al., 2011

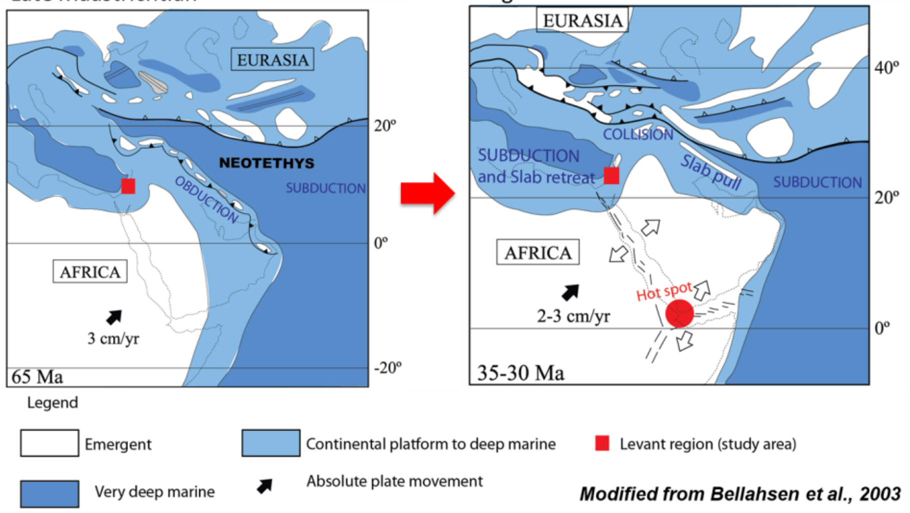
Frizon et al., 2011

Late Cretaceous to Cenozoic convergence of Afro-Arabia towards Eurasia

Middle Jurassic

Late Maastrichtian

Oligocene

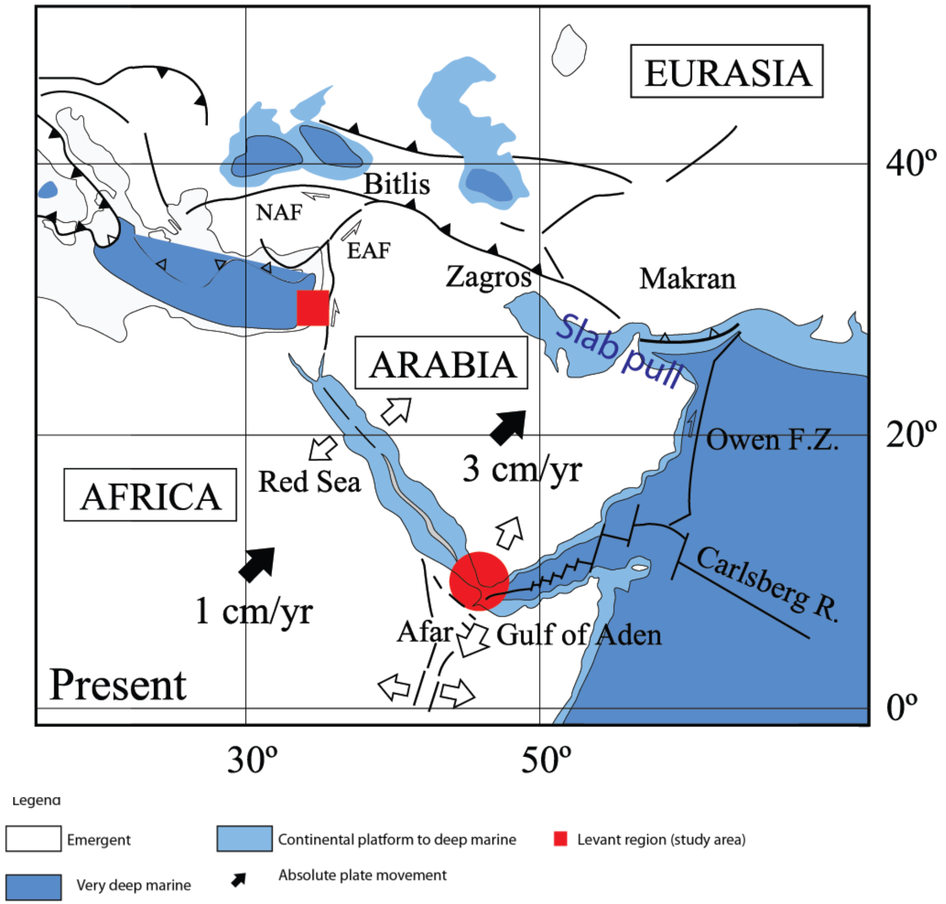


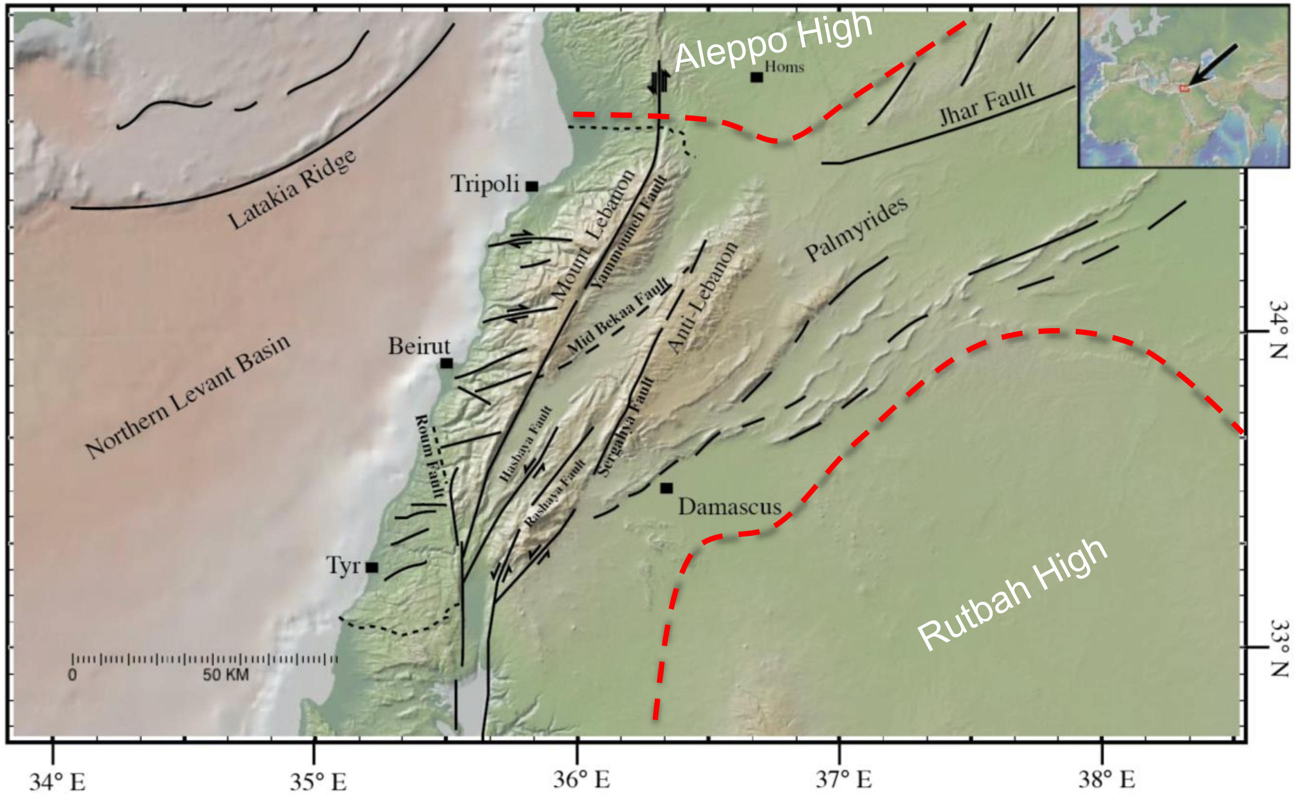
Modified from Bellahsen et al., 2003

Geodynamics

Middle Miocene to present collision and strike slip deformation

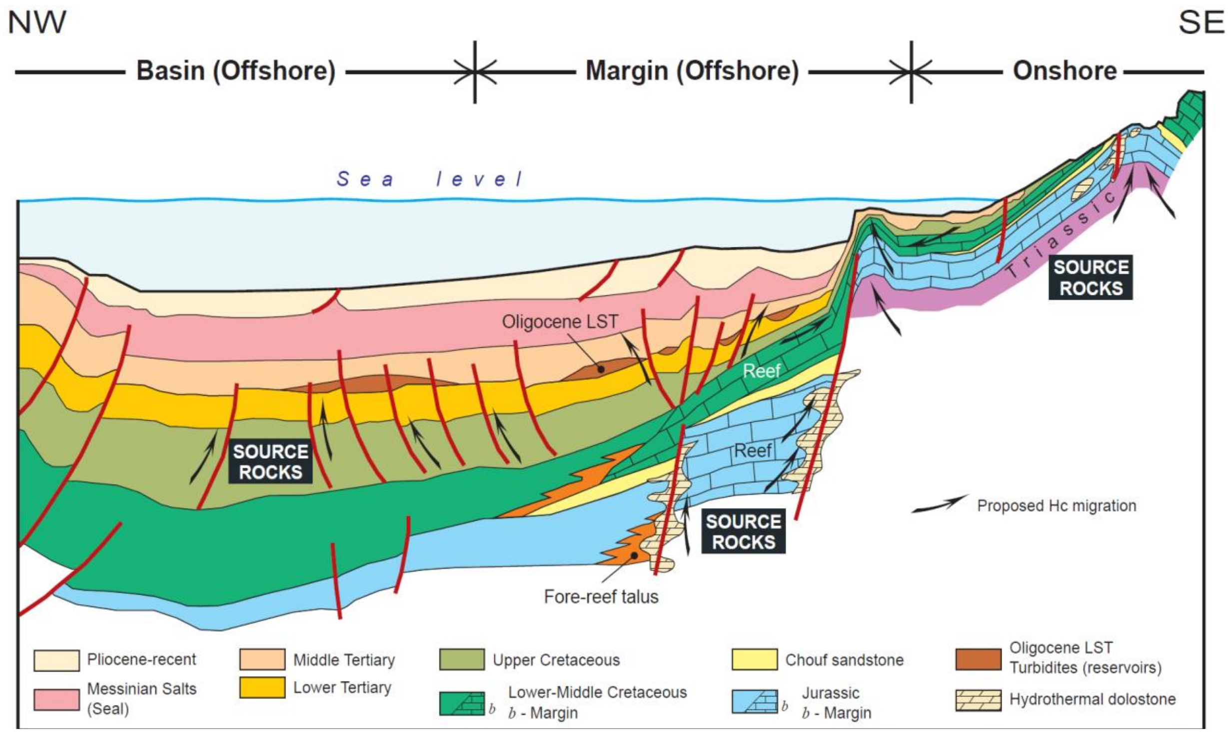
Middle Miocene to Present

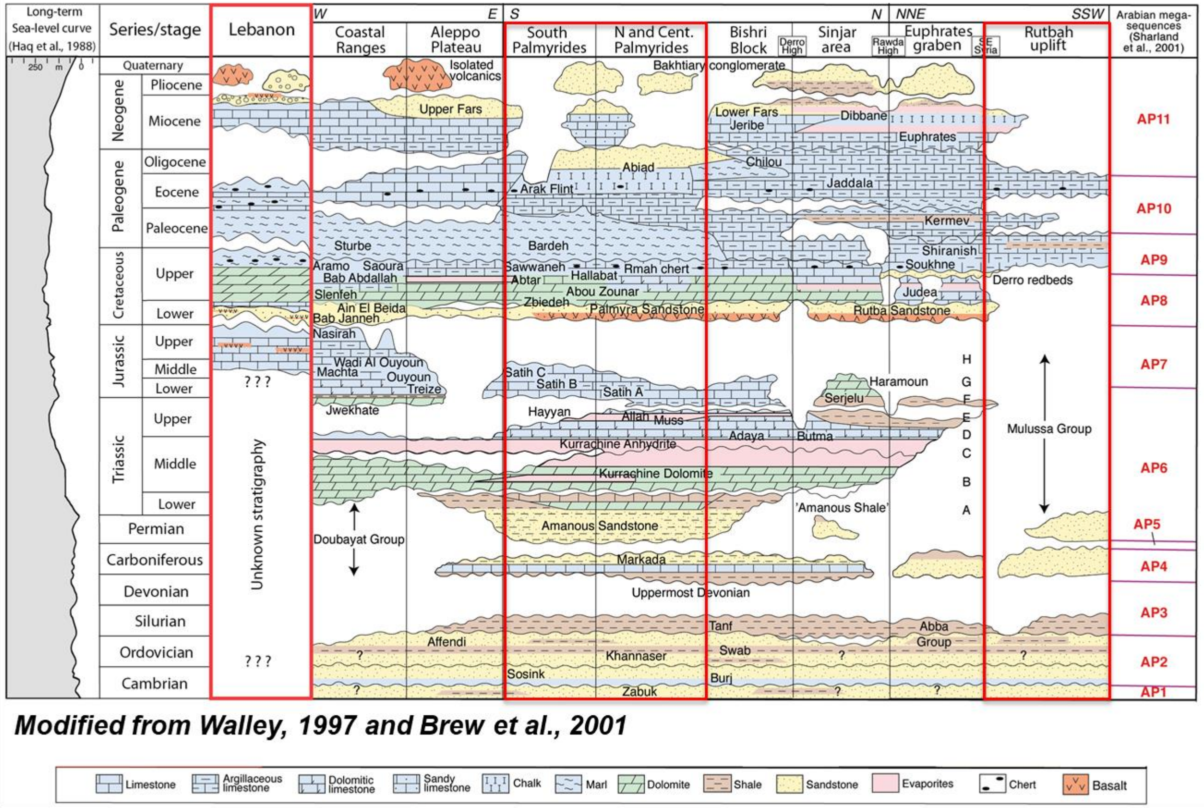




Modified from Bellahsen et al., 2003; Hawie et al., 2013, 2014

Levant Onshore Offsore Conceptual Model

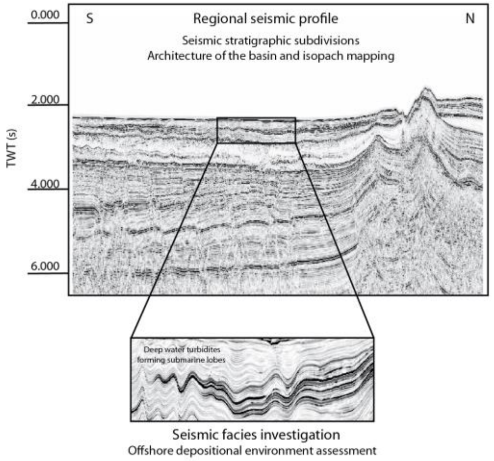




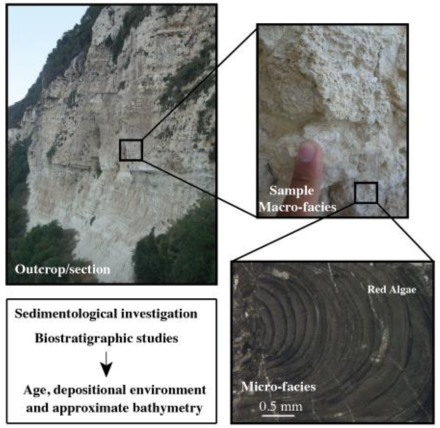
Modified from Walley, 1997 and Brew et al., 2001

Methodology

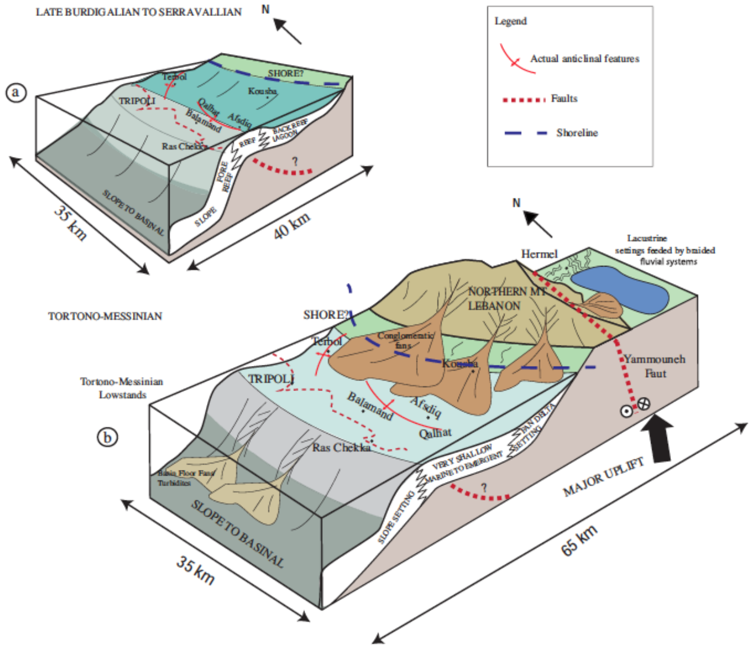
1. Seismic interpretation



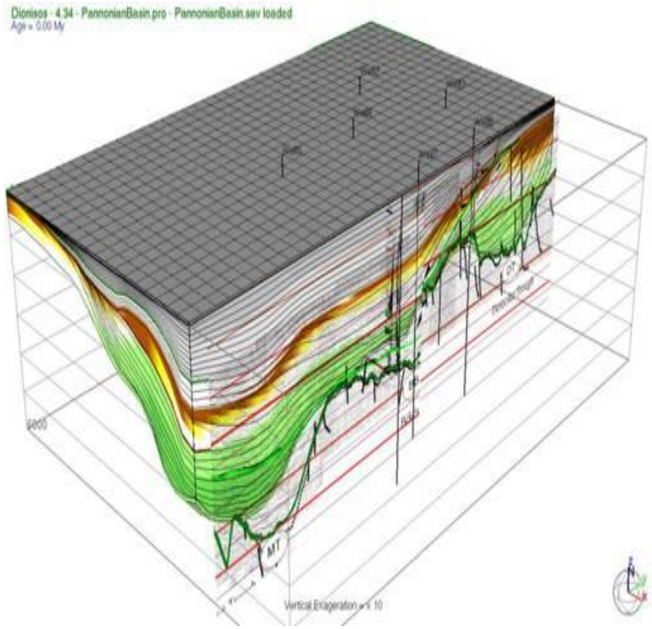
2. Fieldwork



3. Conceptual geological model



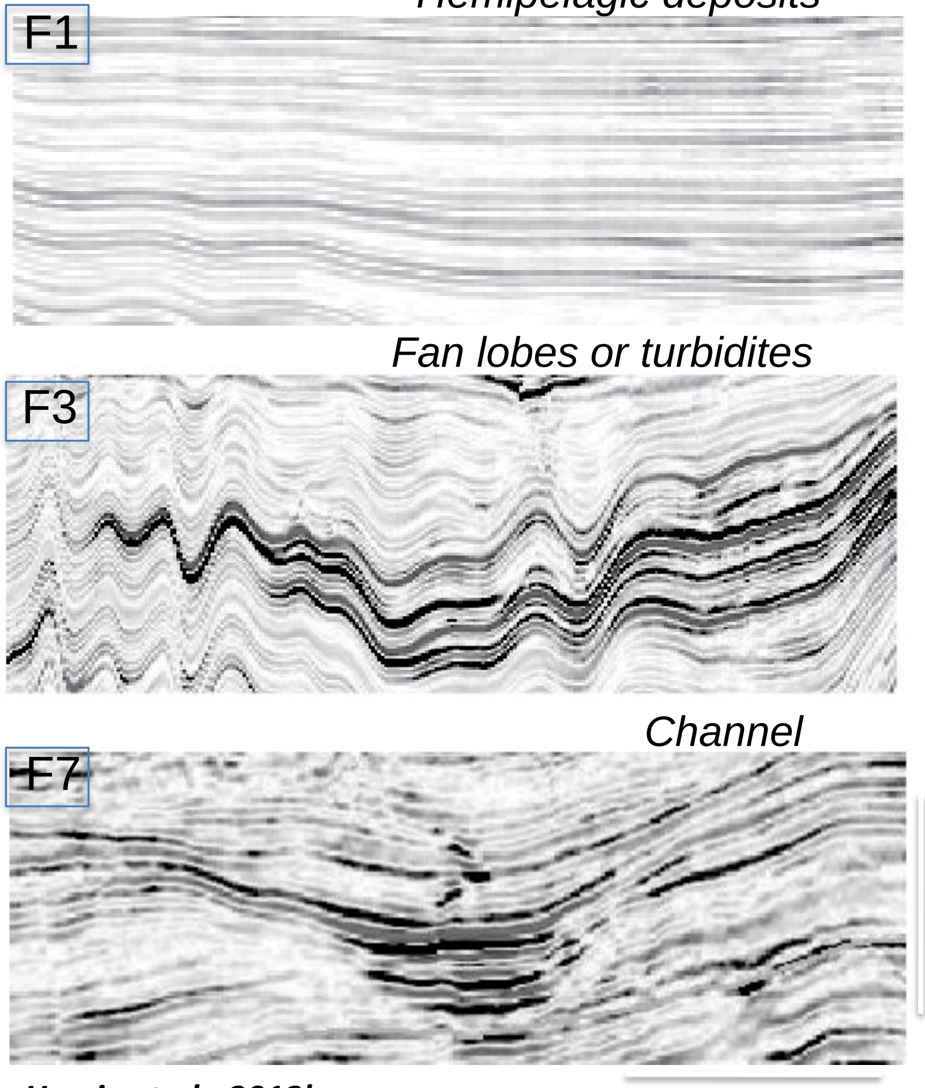
4. Forward Stratigraphic Modeling



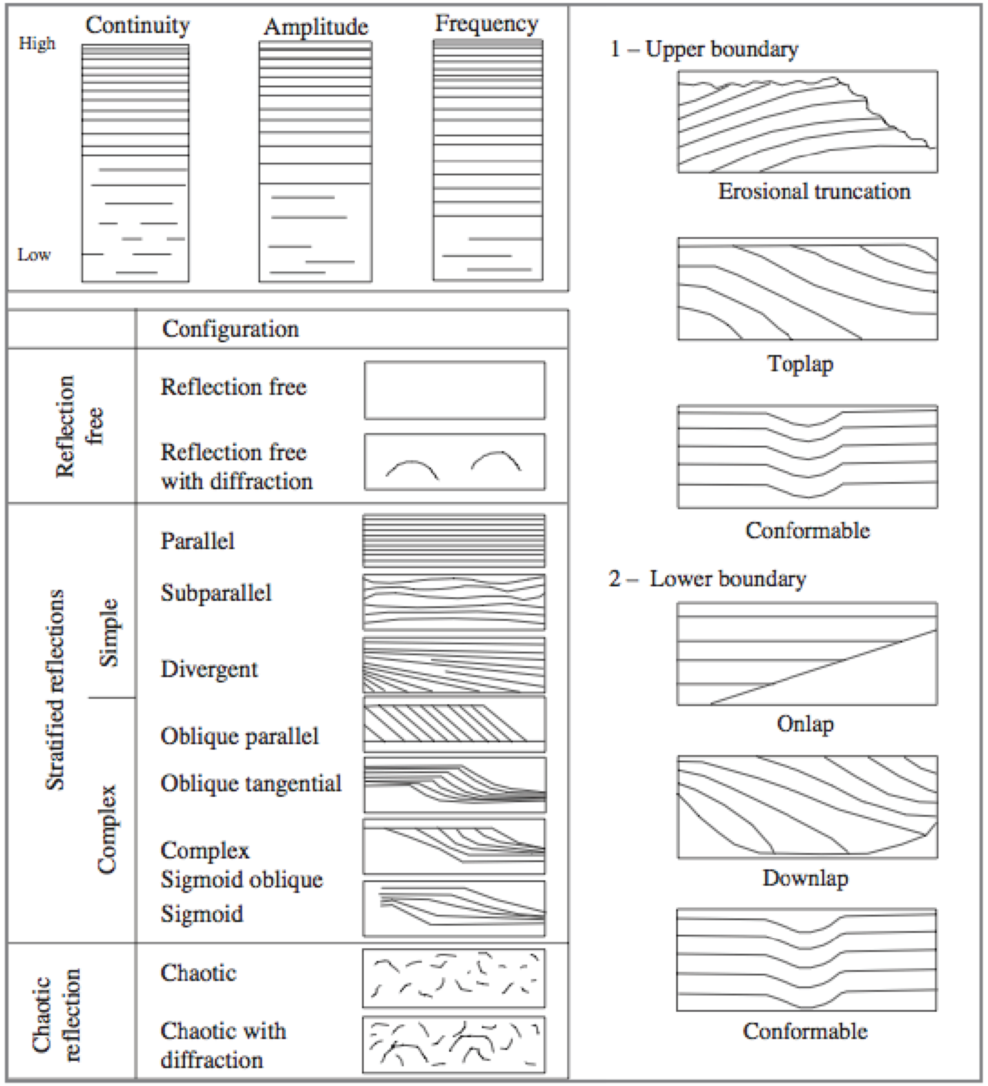
Modified from Csato et al., 2010

Hawie et al., 2013a, b; 2014, 2015

Seismic facies analysis



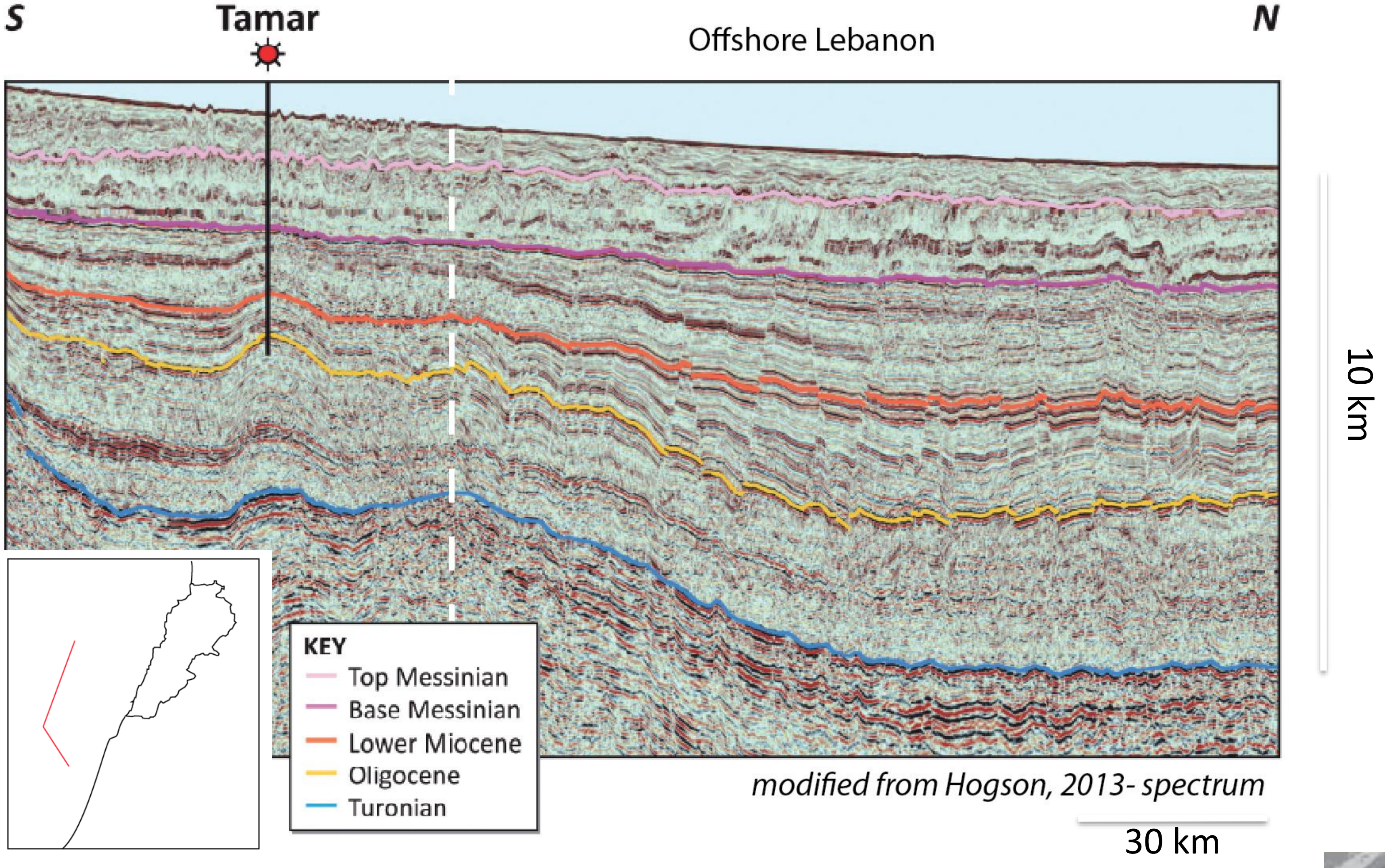
Hawie et al., 2013b



Mitchum et al., 1977; Catuneanu et al., 2009

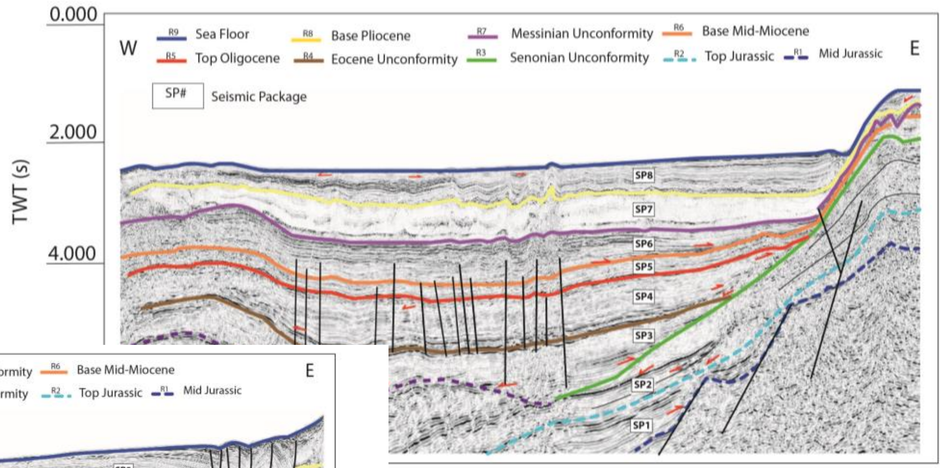
15 seismic facies described for the northern Levant Basin

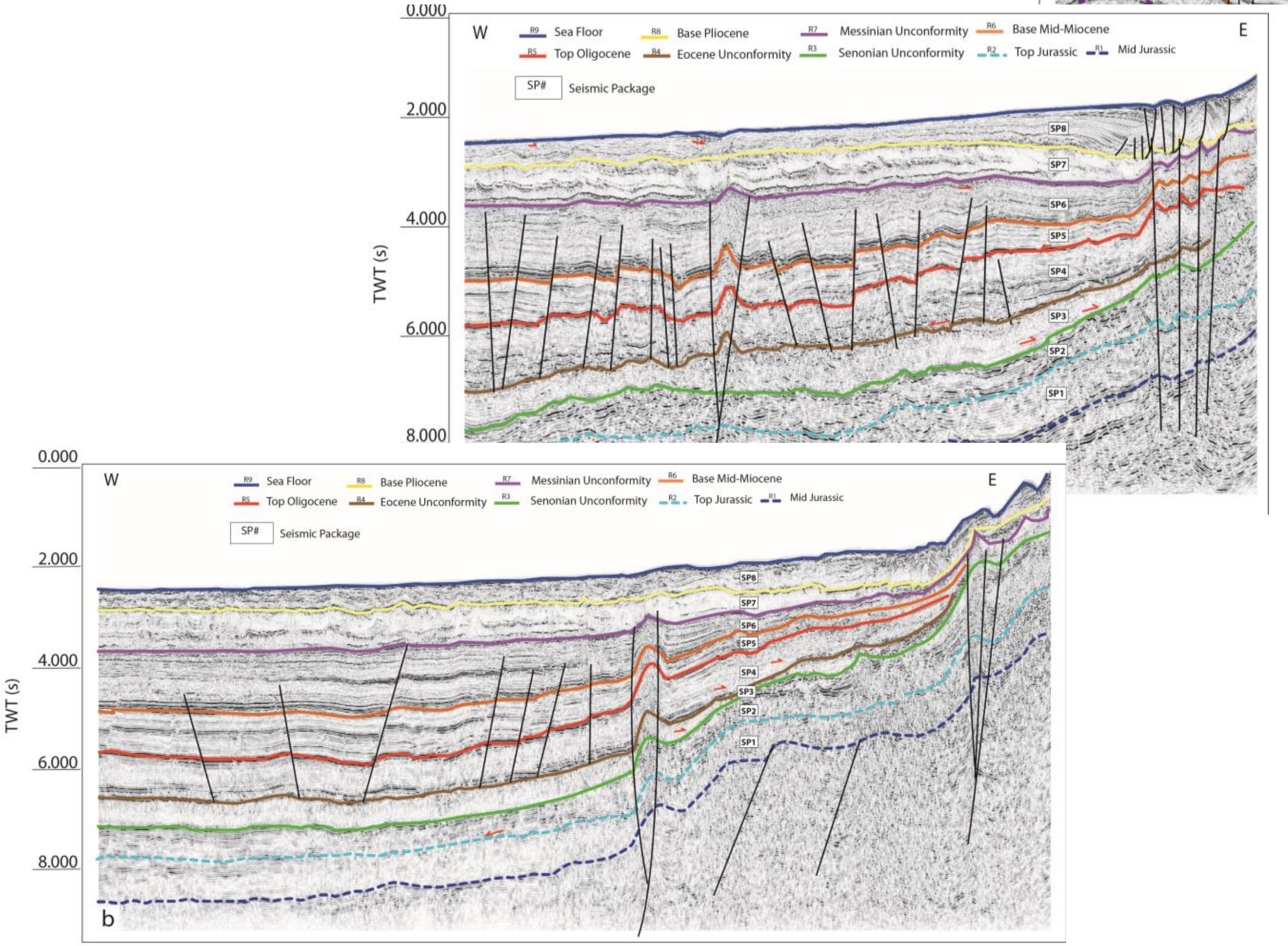
Levant Basin correlation and age constraints



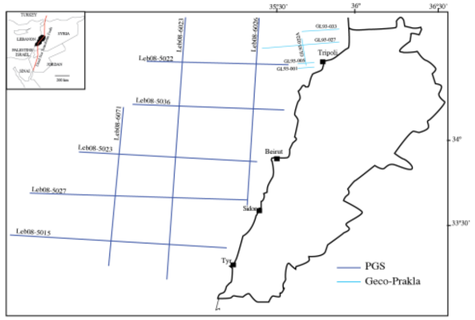
modified from Hogson, 2013- spectrum

Levant Basin architecture





25km

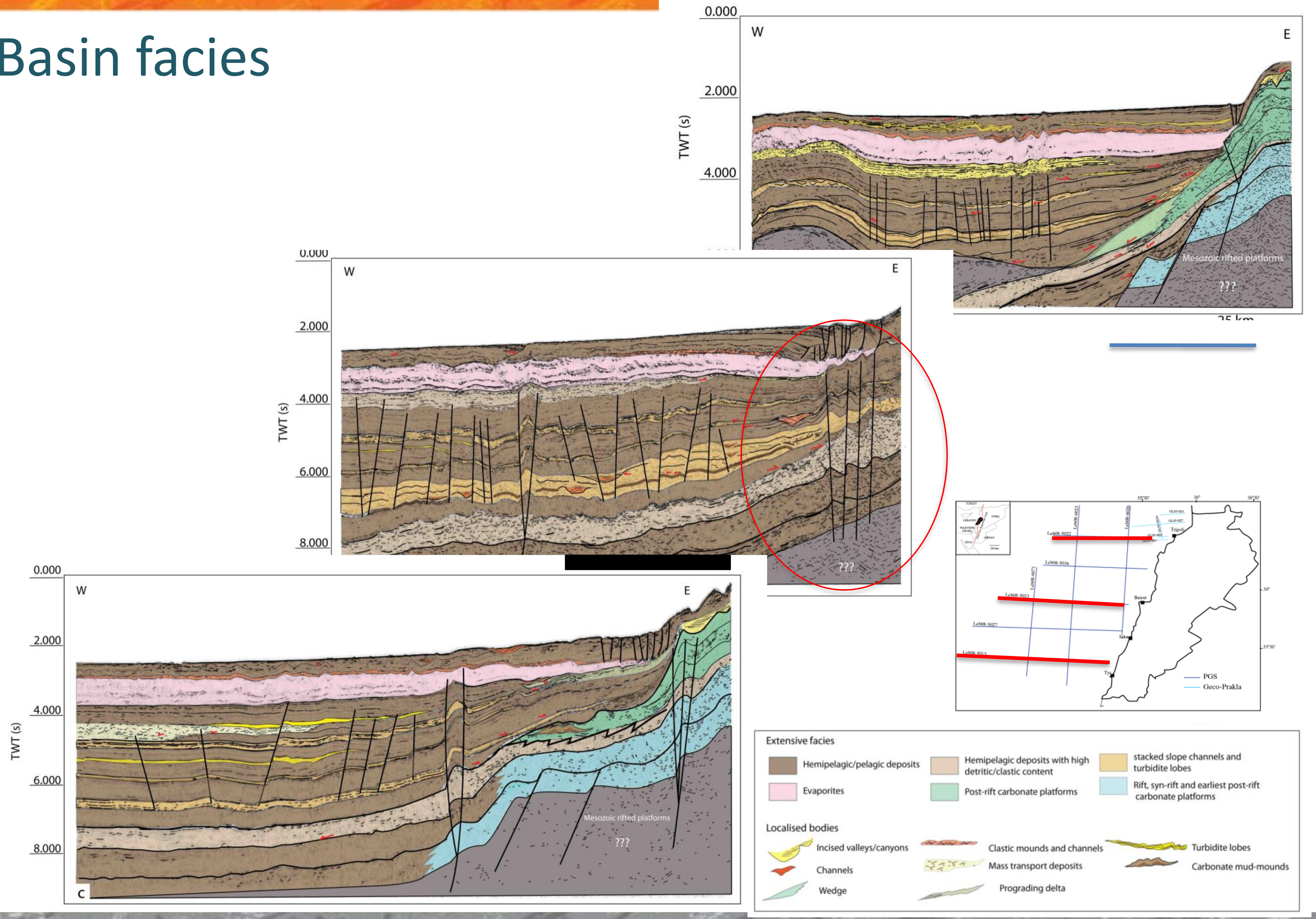


Hawie et al., 2013b

R9 Sea Floor | R8 Base Pliocene | R7 Messinian Unconformity | R6 Base Mid-Miocene

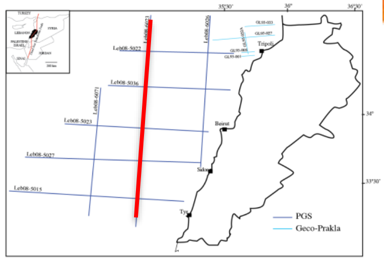
R5 Top Oligocene | R4 Eocene Unconformity | R3 Senonian Unconformity | R2 Top Jurassic | R1 Mid Jurassic

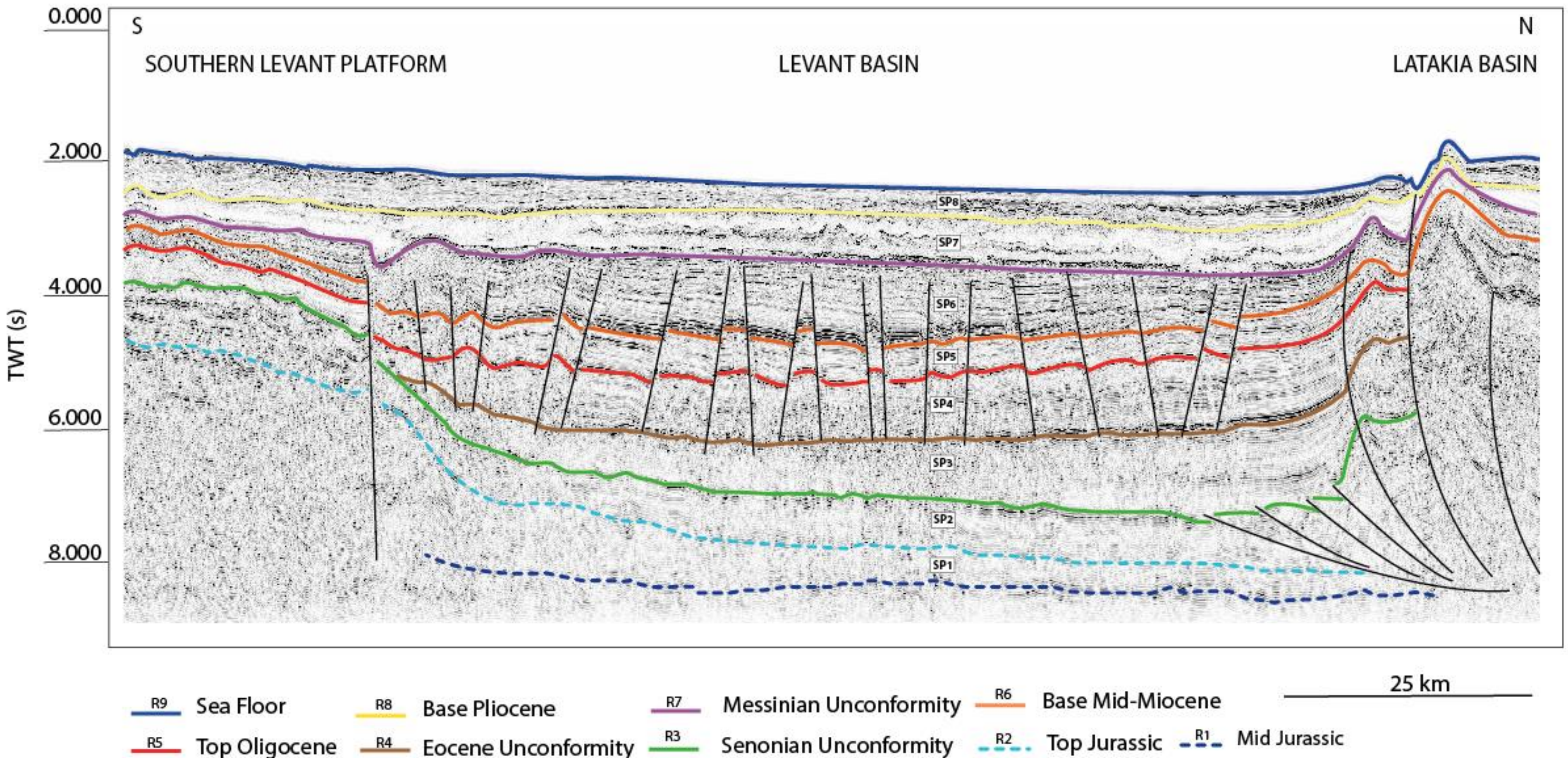
Levant Basin facies



Hawie et al., 2013b

Levant Basin offshore Lebanon





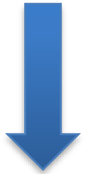
Hawie et al., 2013b

Why focus on the Middle to Late Miocene rock unit ?

- Major change in the geodynamic setting from collision into strike slip

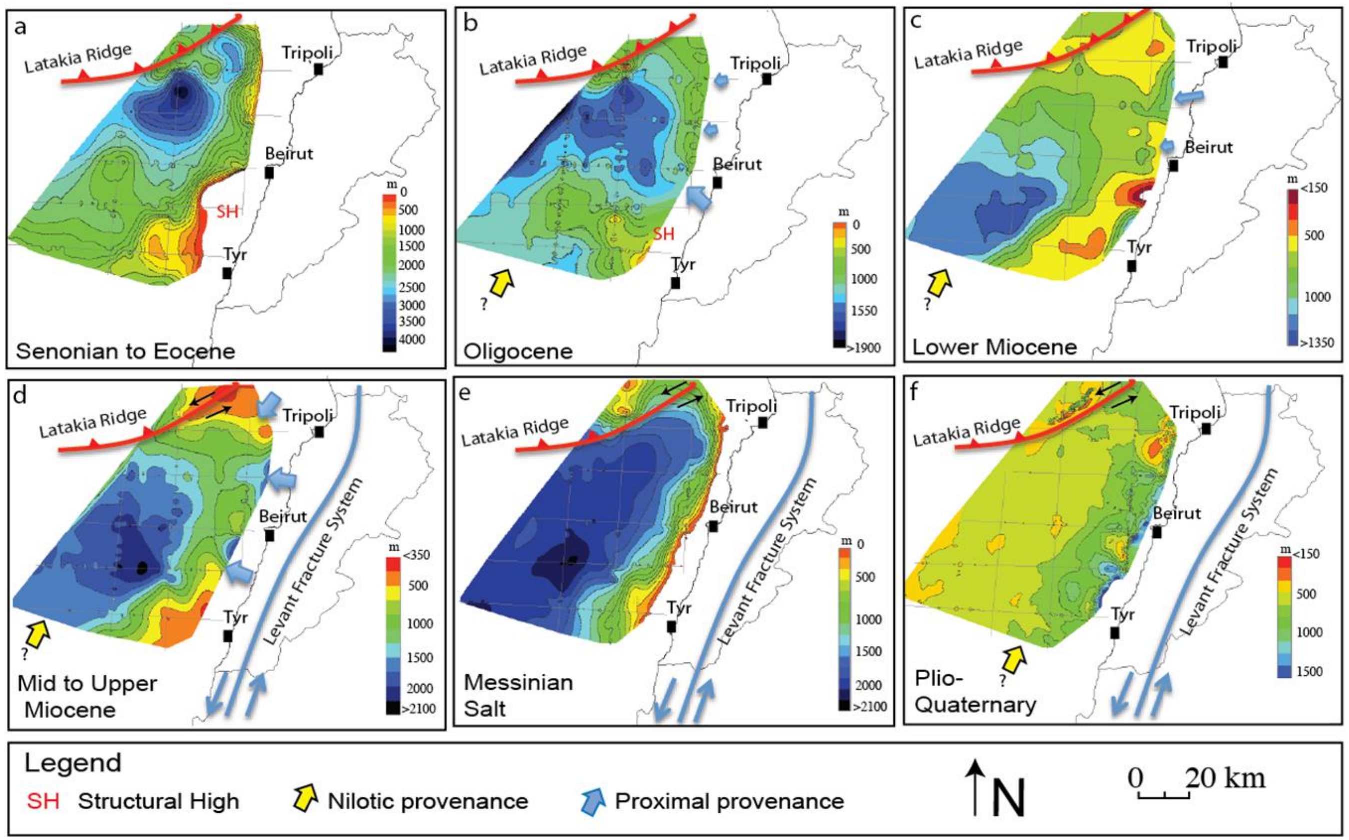
- Northward propagation of the Levant Fracture System and rapid evolution of Mount Lebanon

- Escape tectonism attested along the Anatolian Micro-plate and the Latakia Ridge



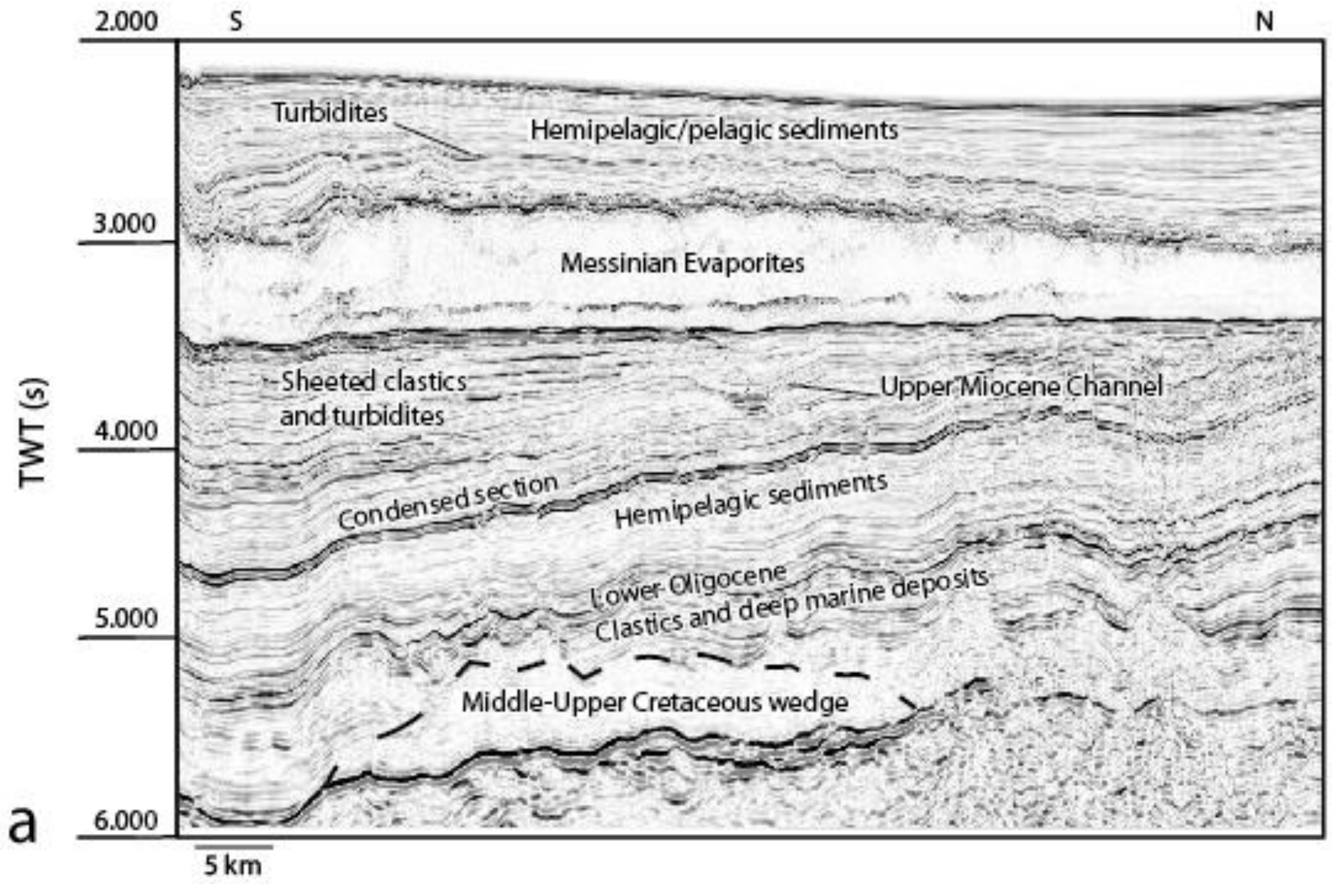
Impact on sediment erosion transport and deposition from the rapidly deforming margin into the continuously subsiding Levant Basin

Isopach Mapping

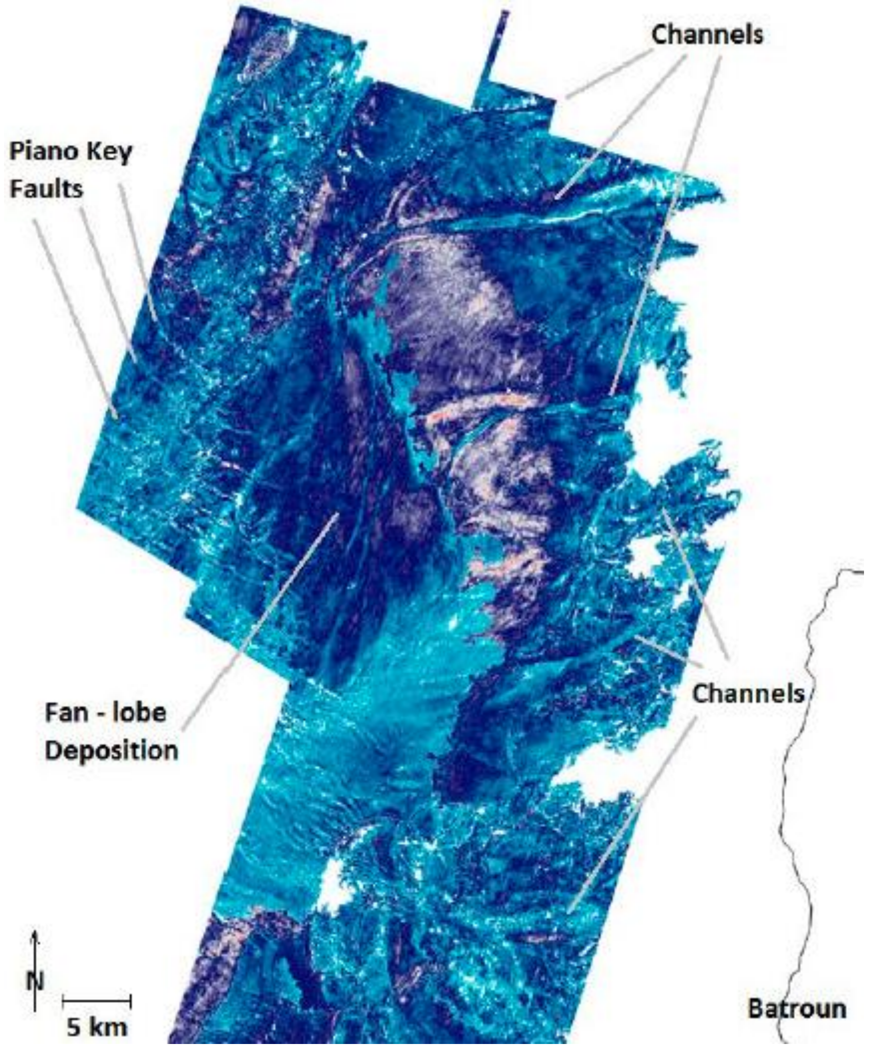


Hawie et al., 2013b

Mid to Late Miocene Model
Northern Lebanon (facing Tripoli)



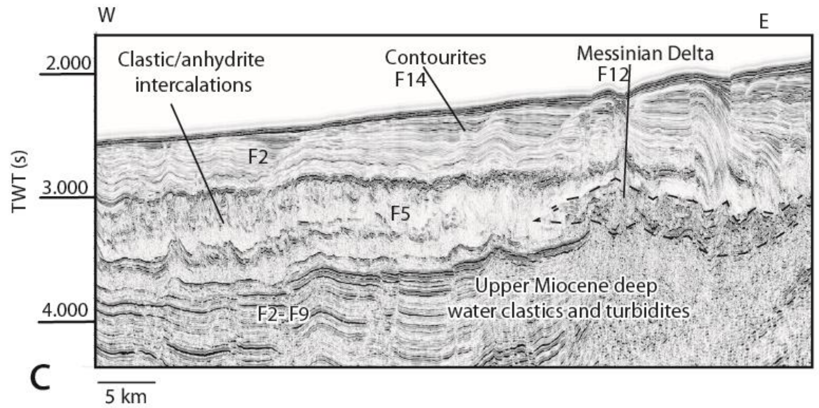
Hawie et al. 2013b

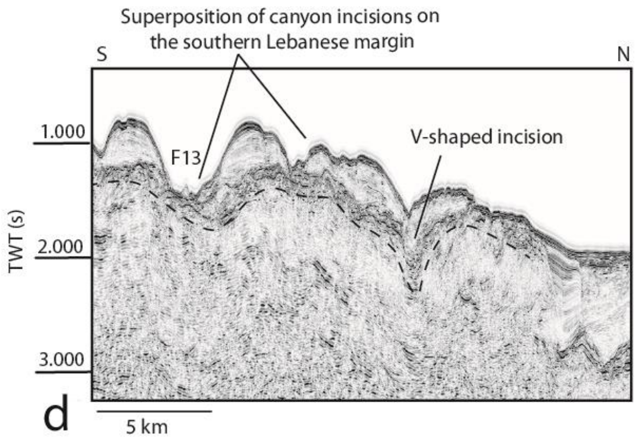


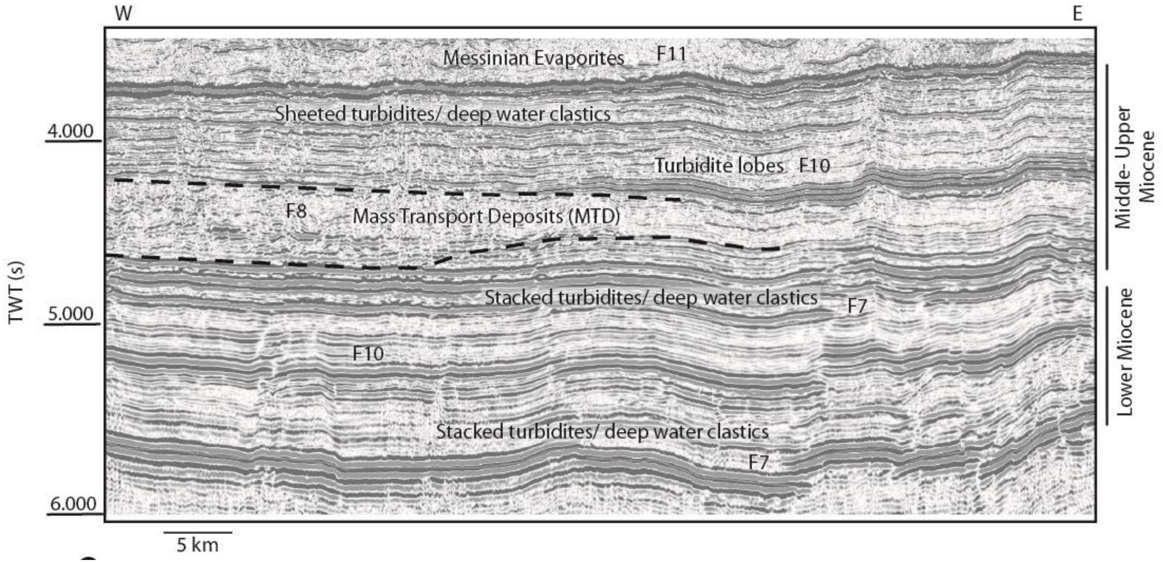
Furstenau et al., 2013

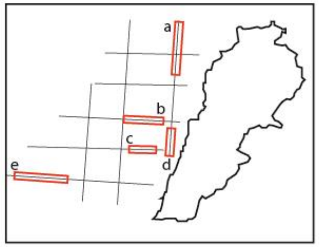
Amplitude map (low-blue, high-light blue; highest-red)

Mid to Late Miocene Model
Southern Lebanon (facing Saida & Tyr)

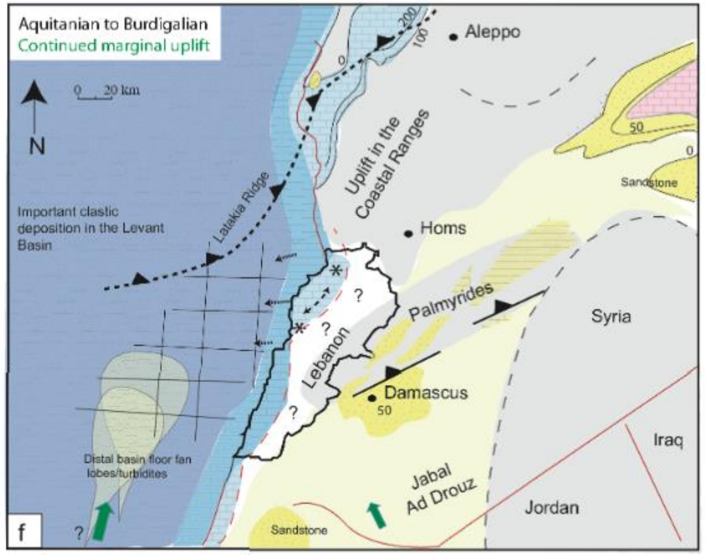


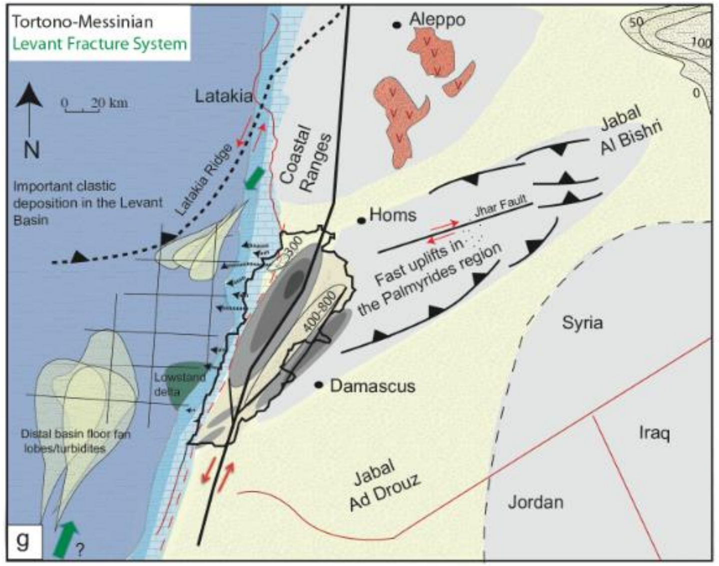


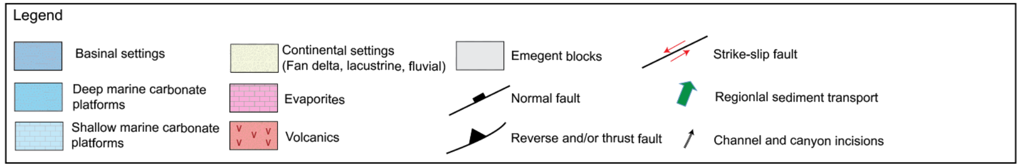




Hawie et al., 2013b







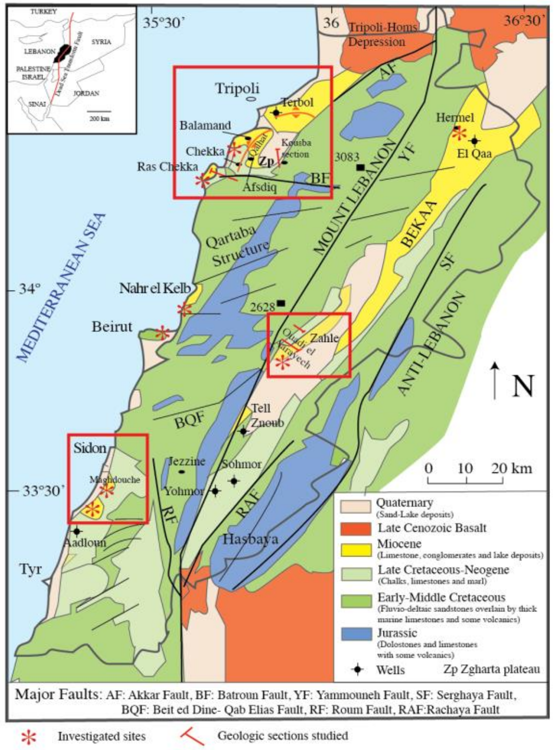
Fieldwork

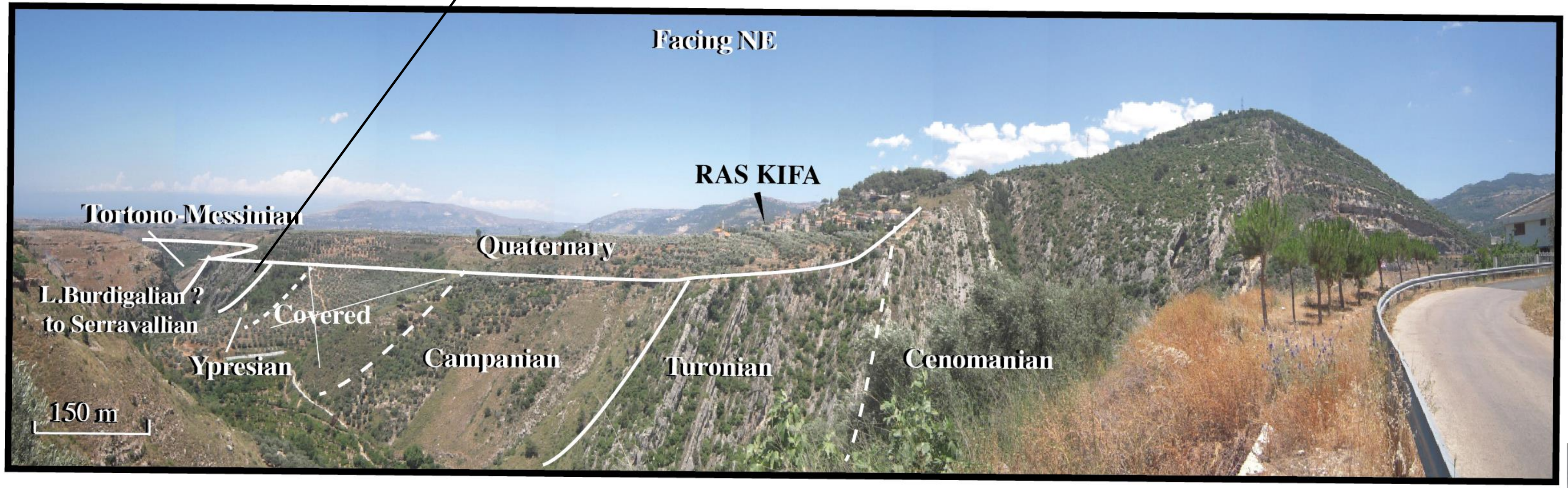
- Focus on the sedimentological and stratigraphic evolution of northern, central and southern Lebanon from the Upper Jurassic to the Late Miocene

- 6 field trips have been conducted

  Total of about 6000 m of sedimentary logs supported by nannofossil and foraminifer biostratigraphy

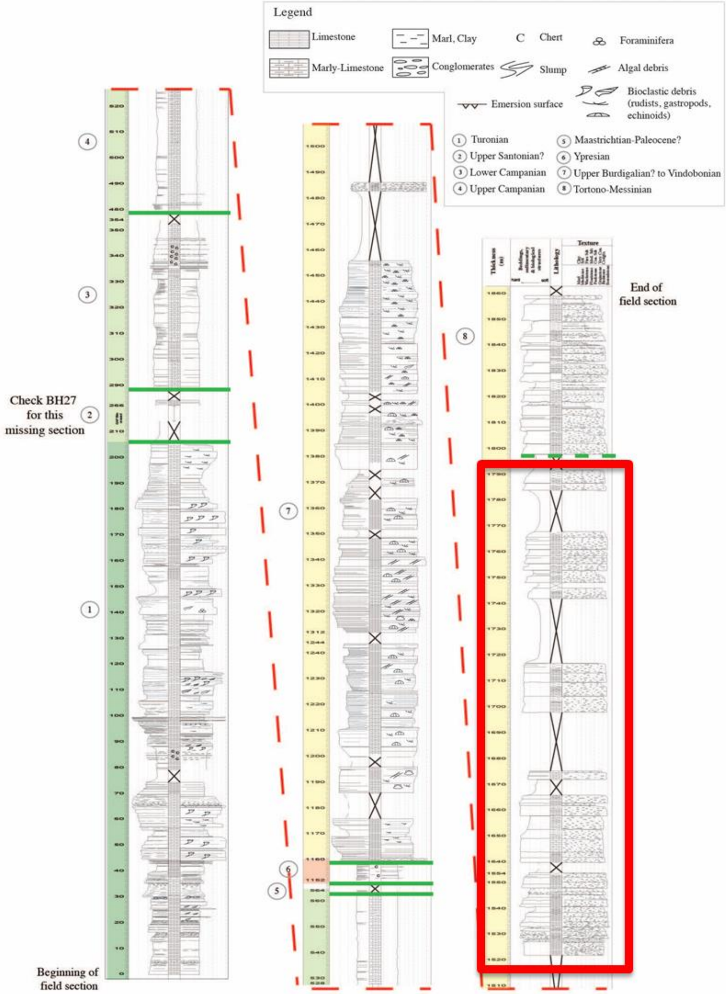
-Lower Eocene (outer-shelf)
-Middle Miocene (lagoonal-back reefal)





Hawie et al., 2013a

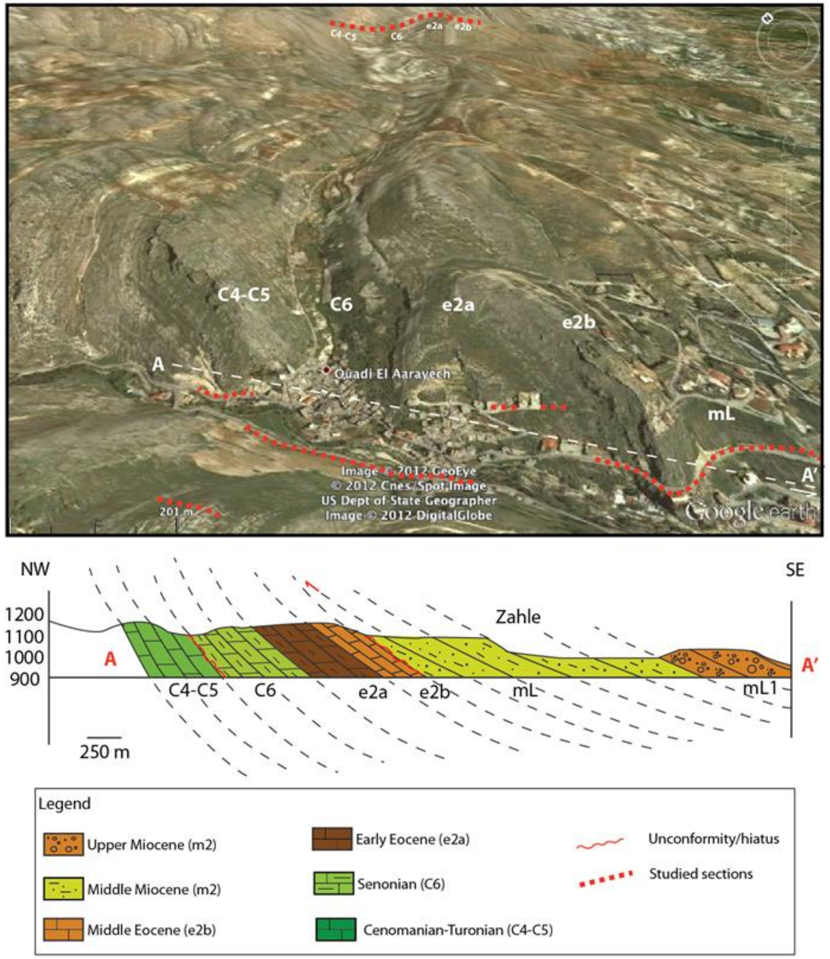
North Lebanon

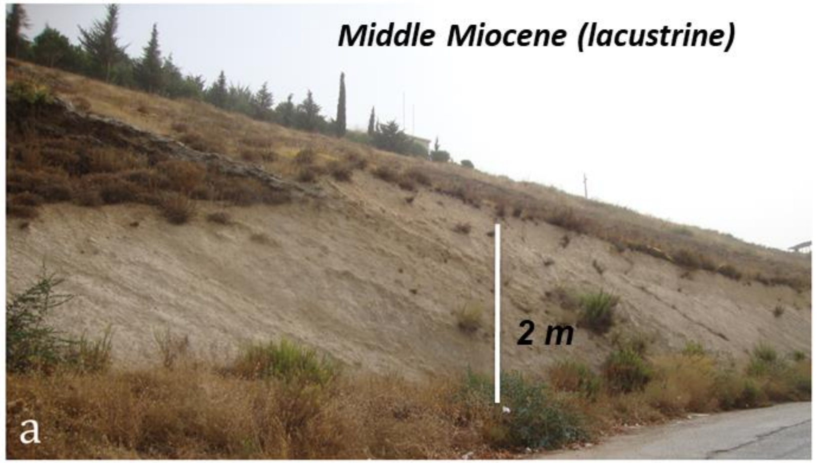


Hawie et al., 2013a

Lebanese Hinterland: Bekaa Valley

Central Lebanon (1720 m log)

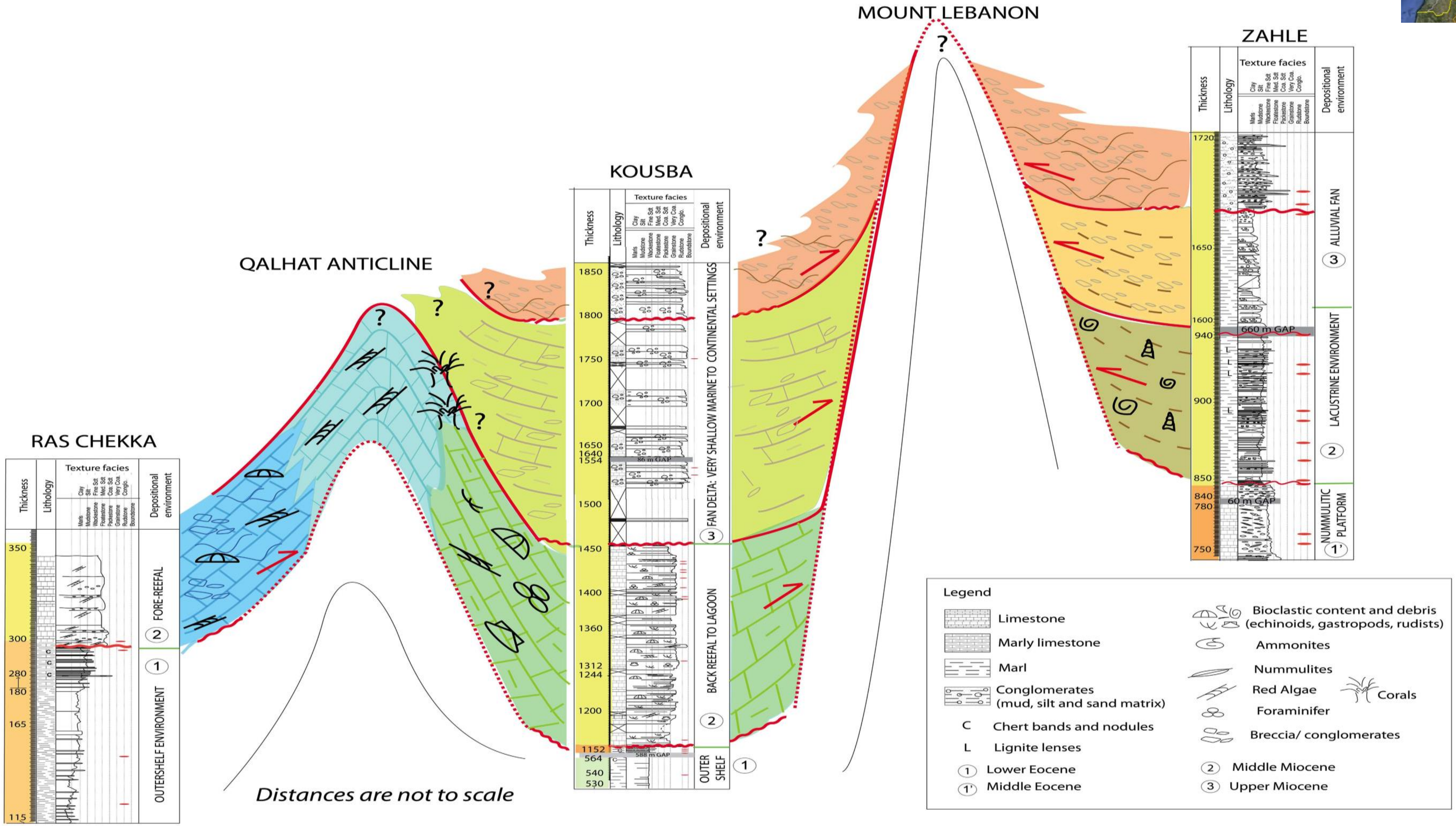




[redacted]

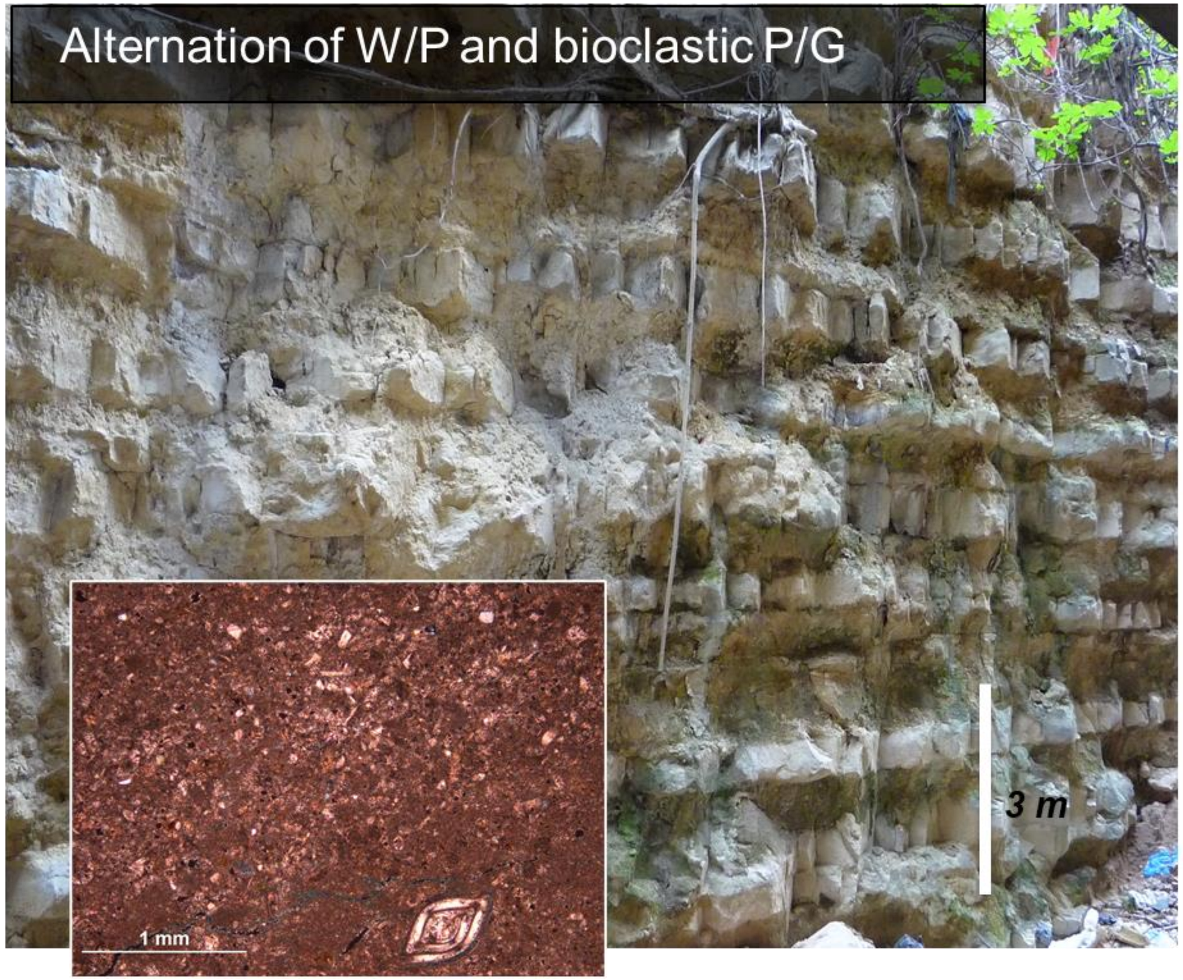
Hawie et al.,2015

Miocene correlation

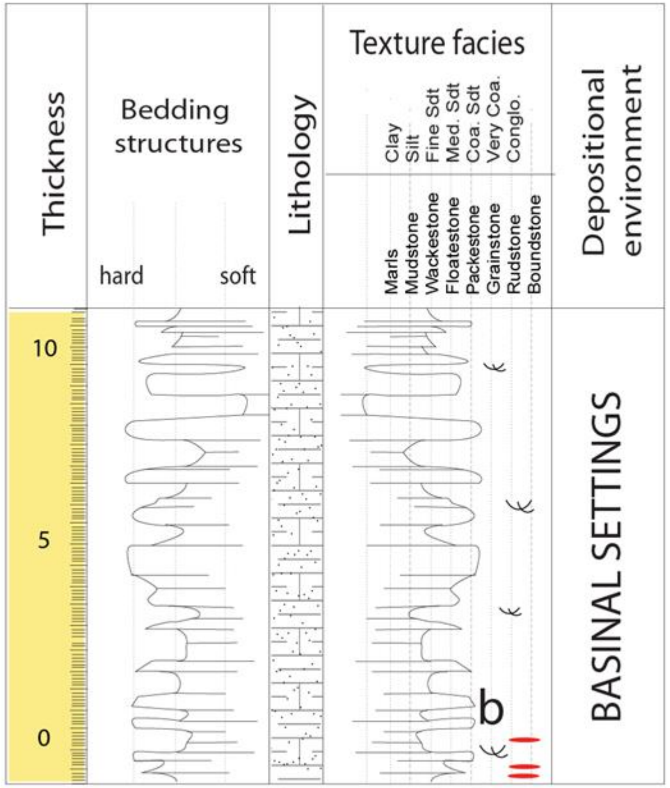


Hawie et al., in prep 2015

Miocene (central coastal Lebanon)

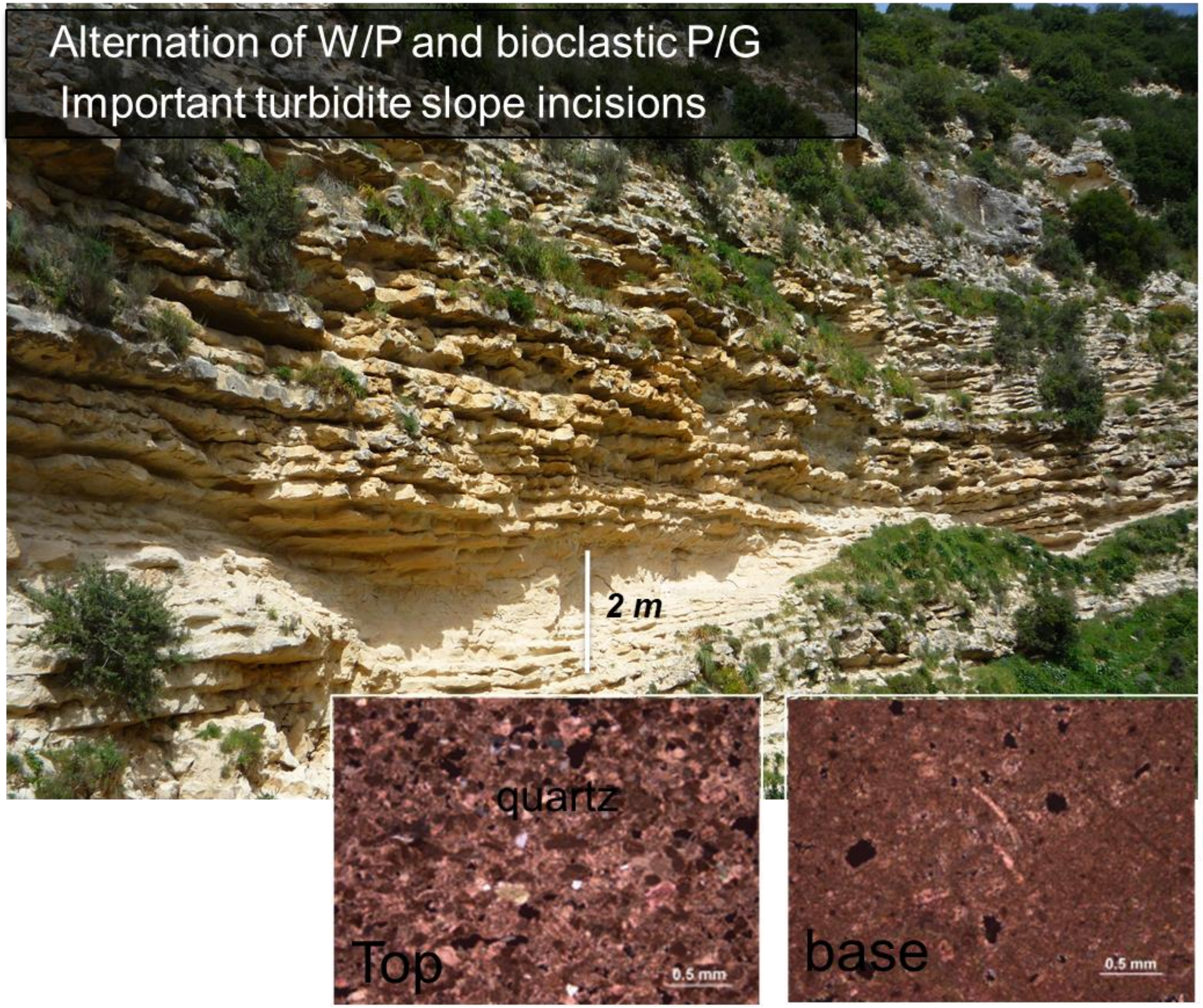


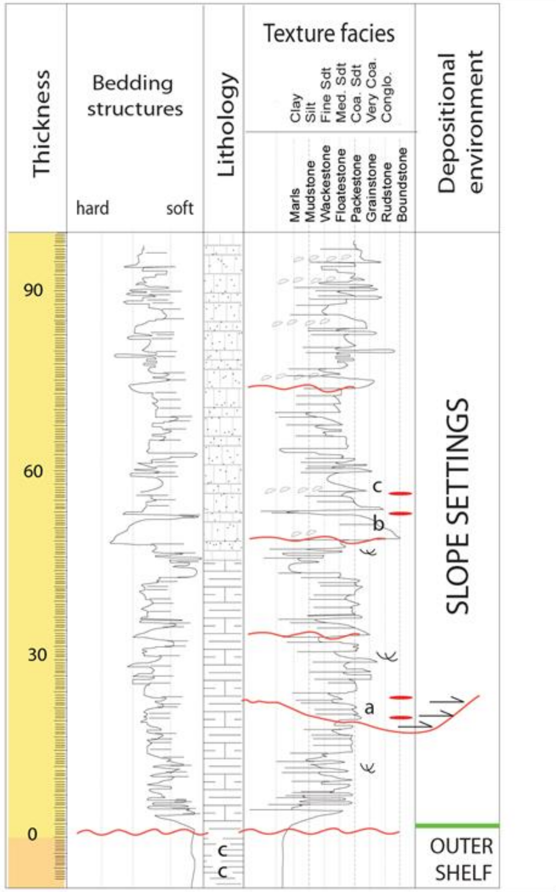
Distal setting-turbidites



Hawie et al., 2015

Miocene (southern coastal Lebanon)

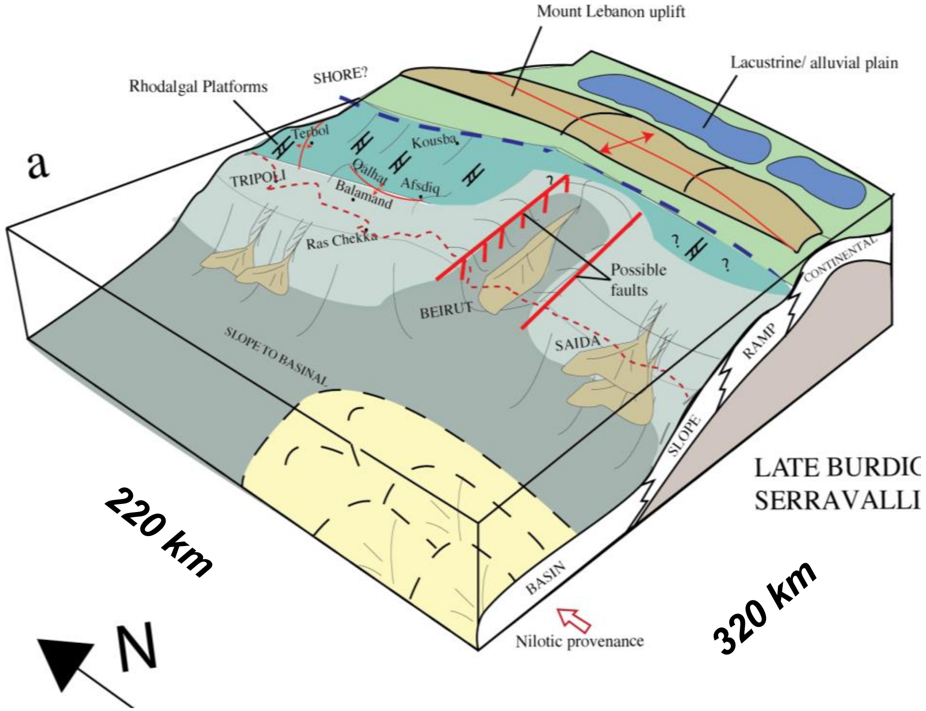




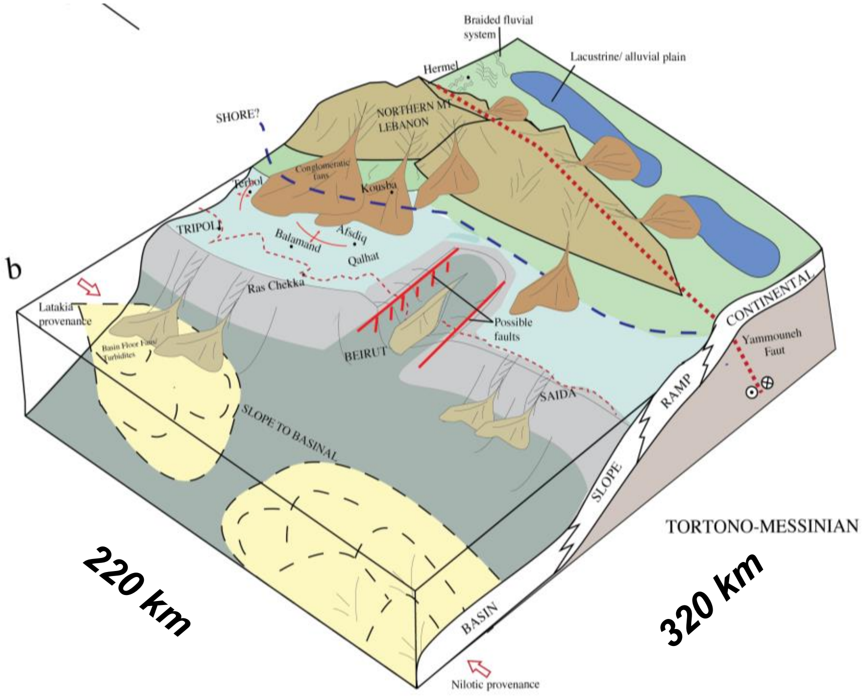
Hawie et al., 2014, 2015

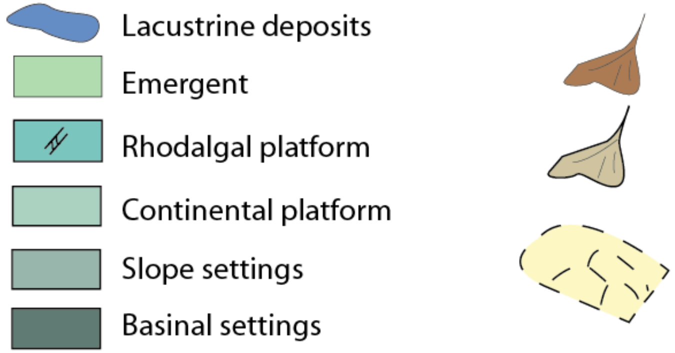
Miocene conceptual model

Middle Miocene



Upper Miocene





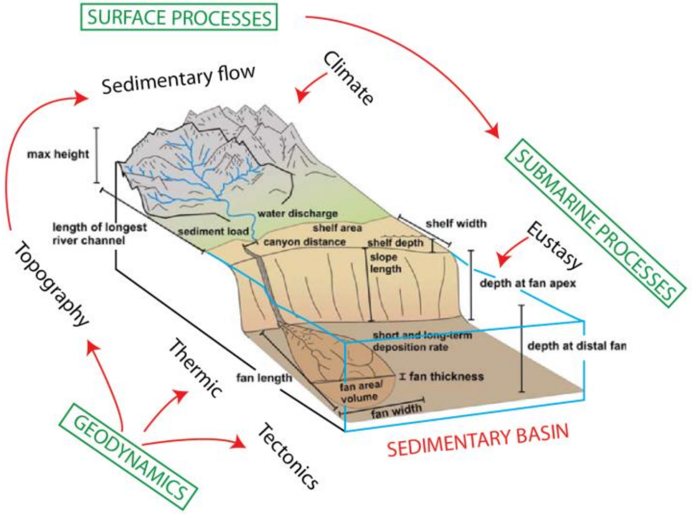
Lacustrine deposits
Emergent
Rhodalgal platform
Continental platform
Slope settings
Basinal settings
Alluvial Fans
Turbidite lobes facing canyons
Basin floor fans/ or distal turbidites

Hawie et al., in prep. (a)

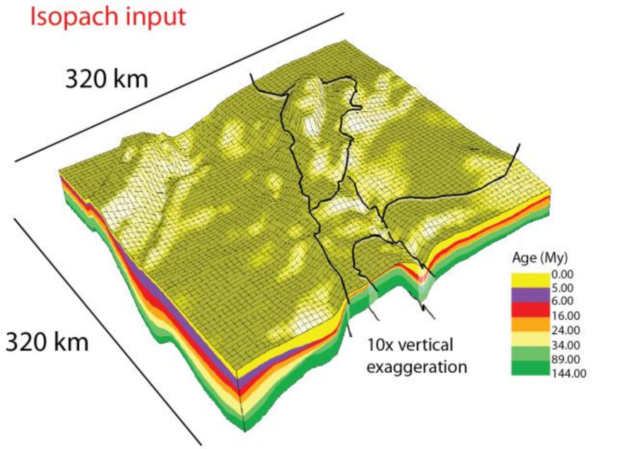
Source to Sink approach

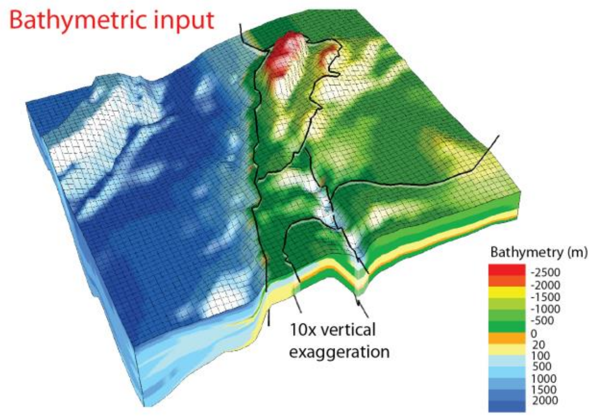
•Multi-disciplinary approach permitting the assessment of

- (1) sedimentary basins a architecture
- (2) sedimentary erosion, transport and deposition
- (3) sedimentary volumes and facies



Modified from Robin, 1997 & Martinsen et al., 2010

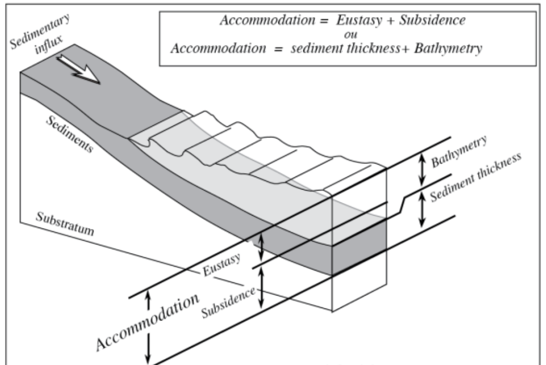




FSM is a deterministic "process-based modeling tool that accounts for accommodation, supply and transport" ***(Granjeon, 2009)***.

Diffusion equation: Qs= K. Qw.S

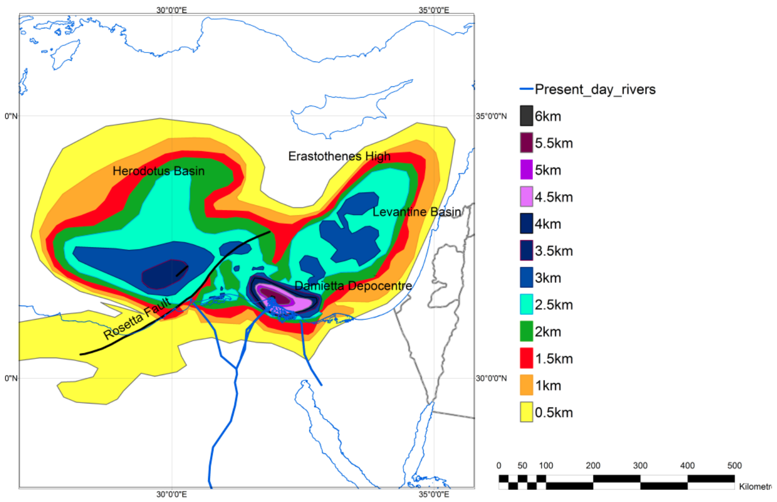
Qs: sediment flux (m2/s) K (km2/ky): diffusion coefficient
Qw: water flux S: Slope



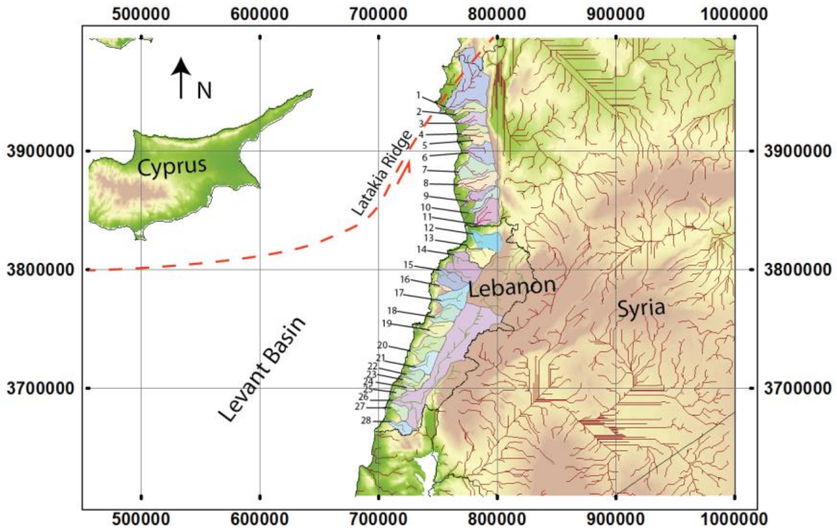
modified from Granjeon, 1994

Volume calculations and uncertainties

- Volume estimations based on Literature and ArcGIS workflow and 3D simplified polygon calculations



Modified from Macgregor, 2012



Hawie et al., 2013, 2014, 2015

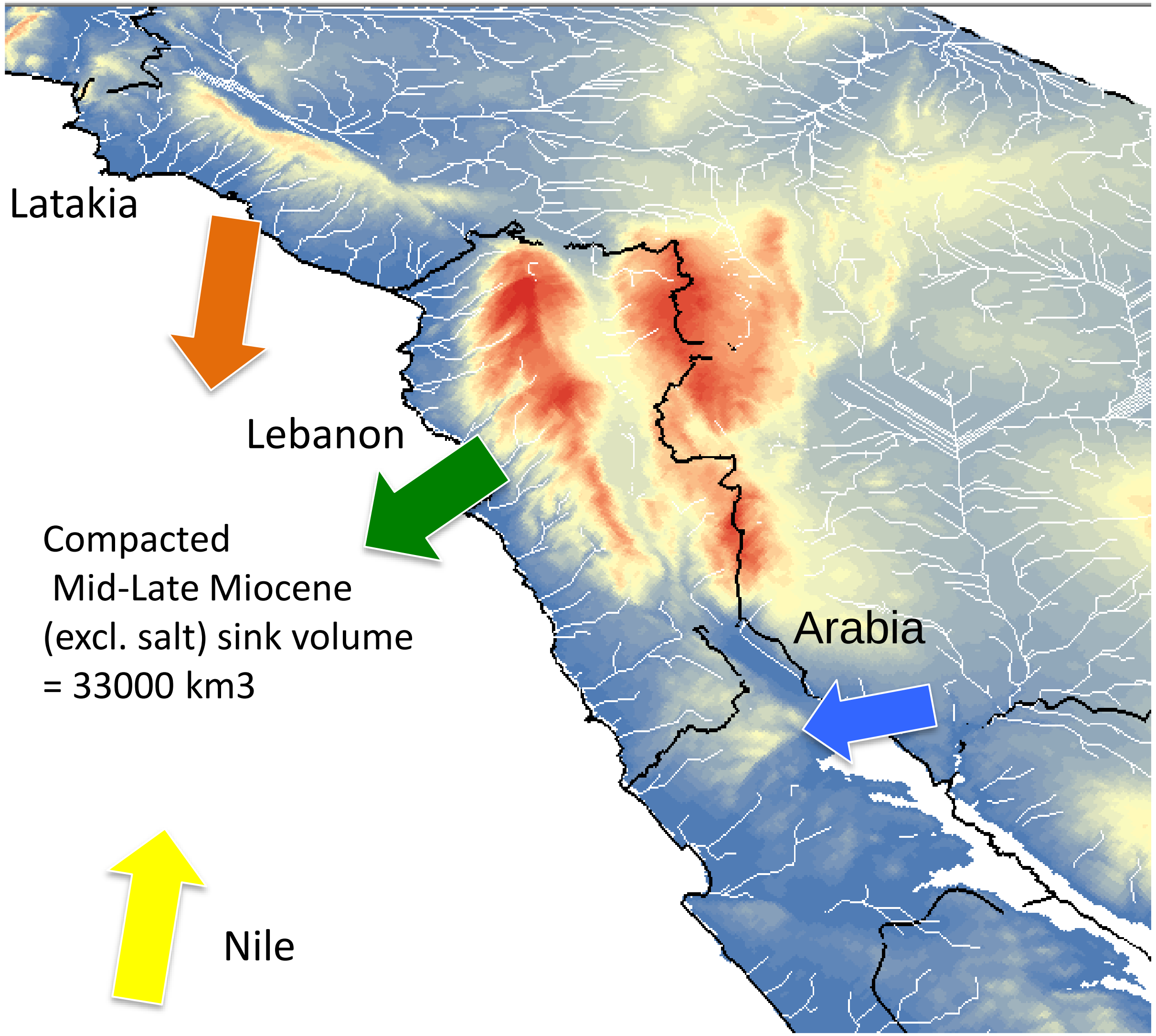
LOCATION	#	CATCHMENT AREA (km2)		MAJOR RIVERS
COASTAL SYRIA	1	1106	2D total drained area = 3540	Nahr el Kabir el Shimali
	2	170		No names assigned
	3	217		
	4	146		
	5	151		
	6	319		
	7	384		
	8	339		
	9	161		
	10	194		
	11	353		Nahr el Kabir el Jounoubi
LEBANON	12	343	2D total drained area = 5593	Nahr Ostouane (+sur.)
	13	274		Nahr el Bared
	14	494		Nahr Abou Ali
	15	291		Nahr el Jaouzi (+sur.)
	16	53		
	17	346		Nahr Ibrahim
	18	244		Nahr el Kalb
	19	240		Nahr Beirut
	20	329		Nahr el Damour
	21	226		Nahr Bisri
	22	118		Nahr Saitanik
	23	120		Nahr el Zahrani
	24	51		Rivers passing by Merwaniyeh (+sur.)
	25	65		Nahr Abou Aswad
	26	2117		Nahr el Litani
	27	134		Nahr abou Zeble (+sur.)
	28	148		River passing between the Azziye and Henniye villages

Best fit model

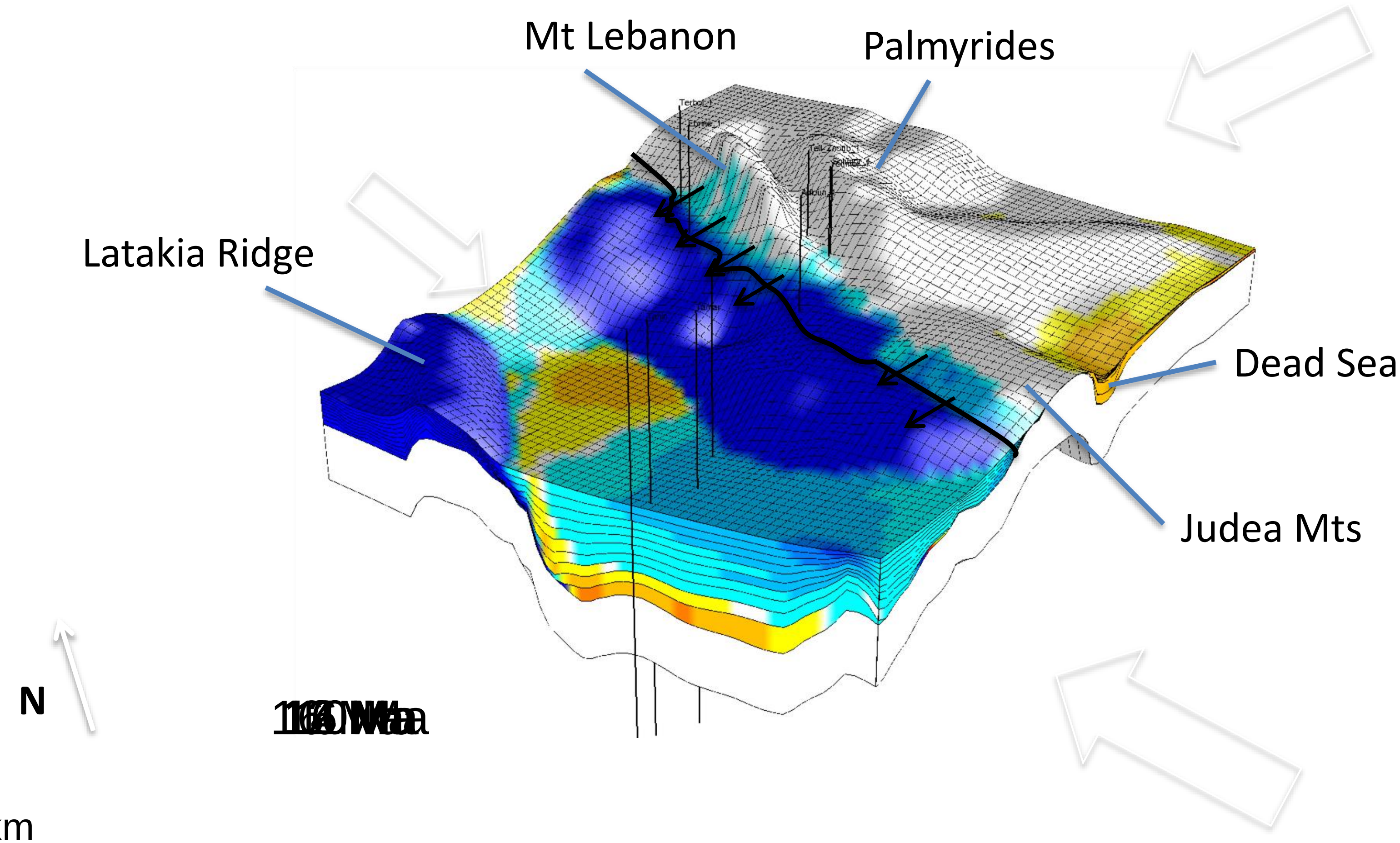
•Honors the thicknesses and facies spatial extent

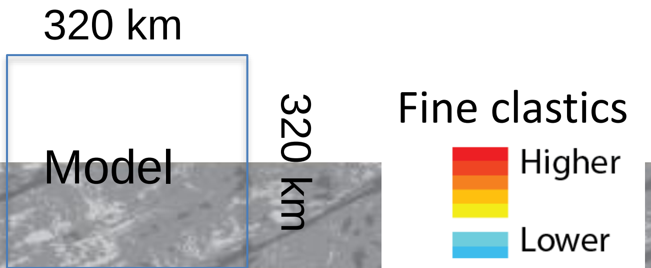
•Volumes order of magnitude are split into:

- •Southern source
  - •50% nilotic provenance
- •Northern & Eastern
  - •30% from the Levant margin (Lebanon/Arabia, Latakia)
- •Basin in situ sources
  - •20% of carbonate and hemipelagic deposits



Best fit model

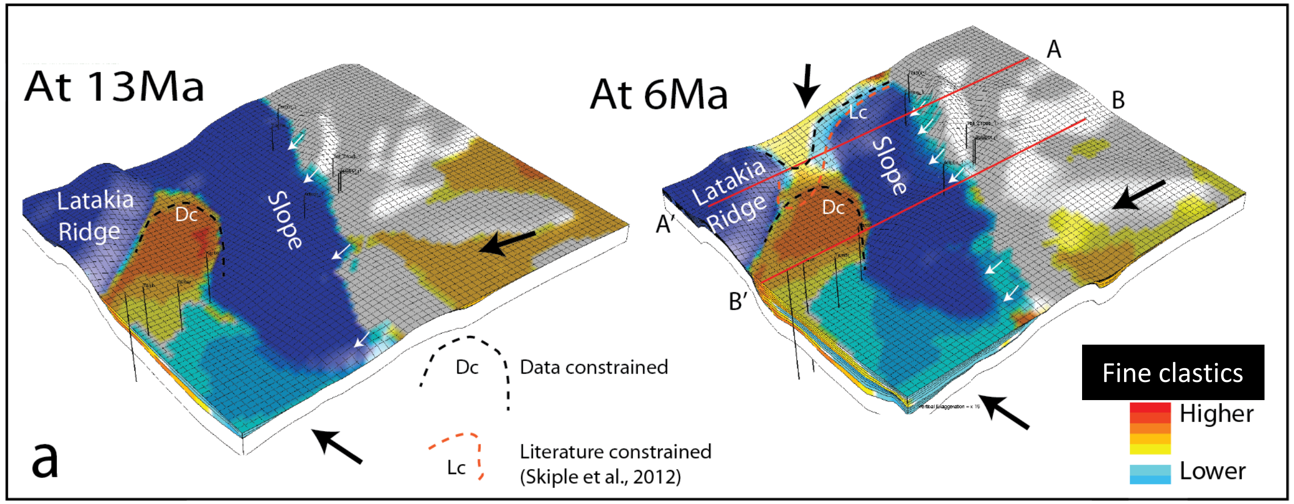




Best fit model

Hawie et al., 2015

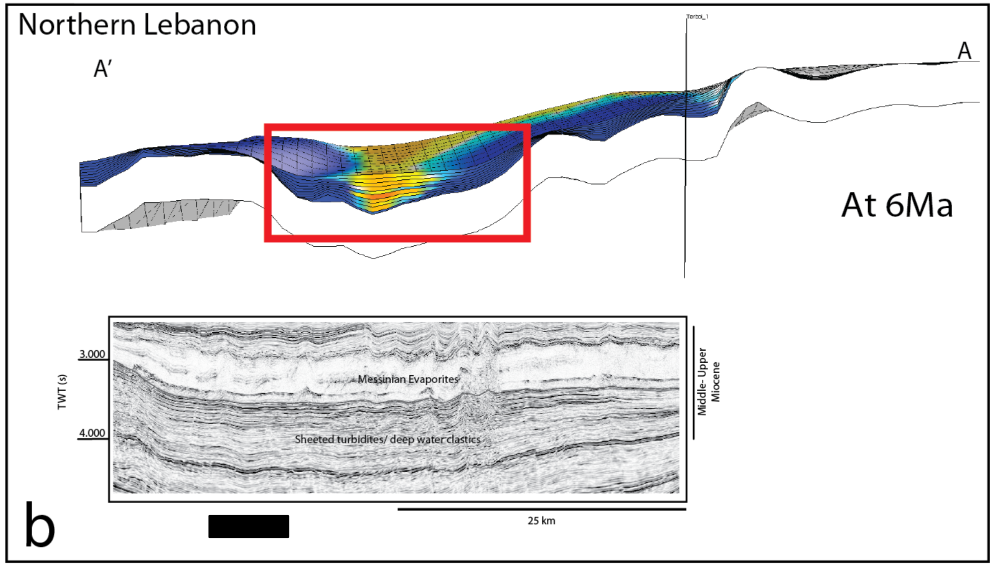
K=3-5 km2/Ka



Qw Nile: 2830 m3/s
Qw Arabia: 800 m3/s
Qw Latakia: 80 m3/s

K coarse> 5km2/ka

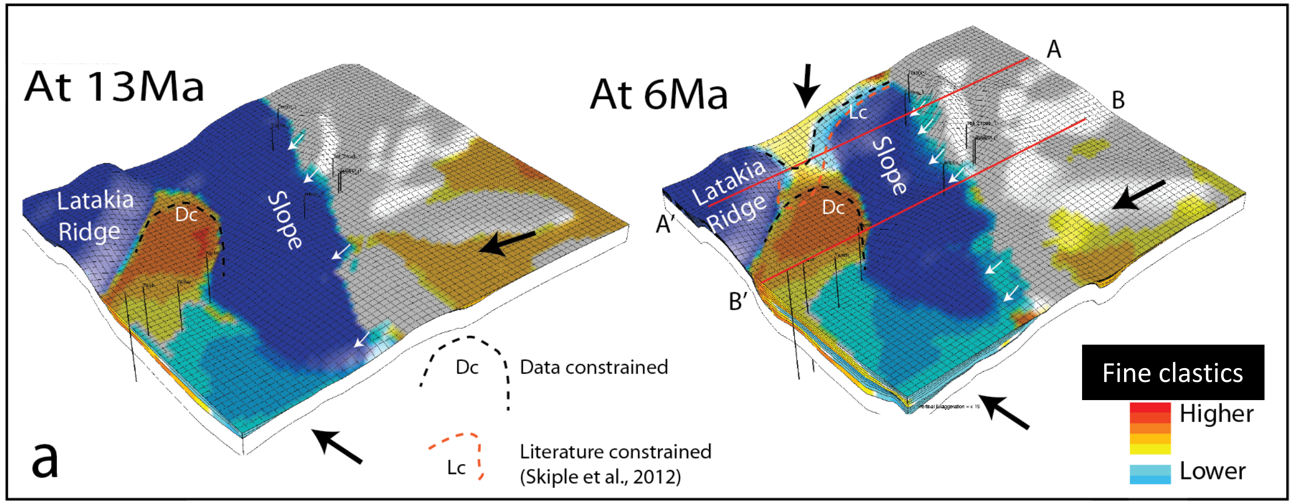
K fine= 5X K coarse



Best fit model

Hawie et al., 2015

K=3-5 km2/Ka



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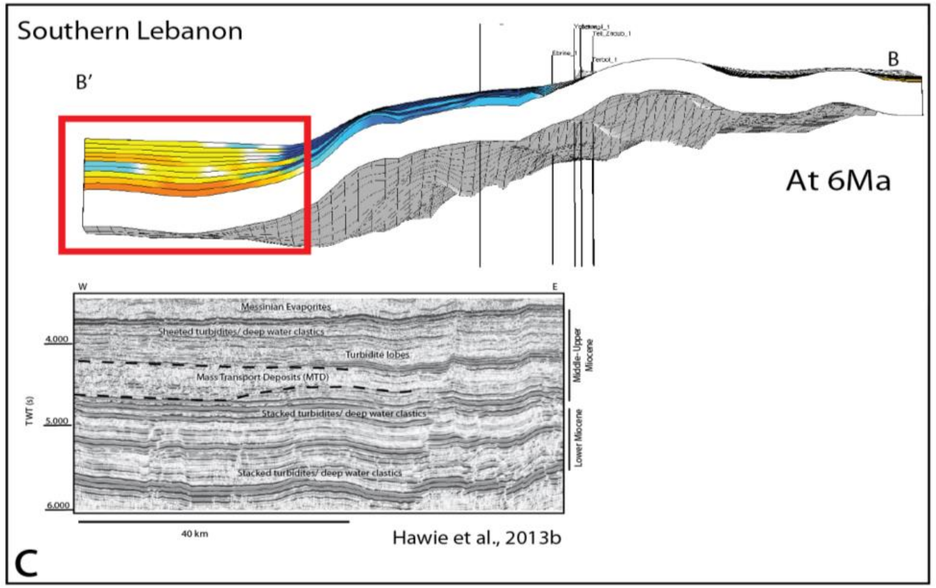
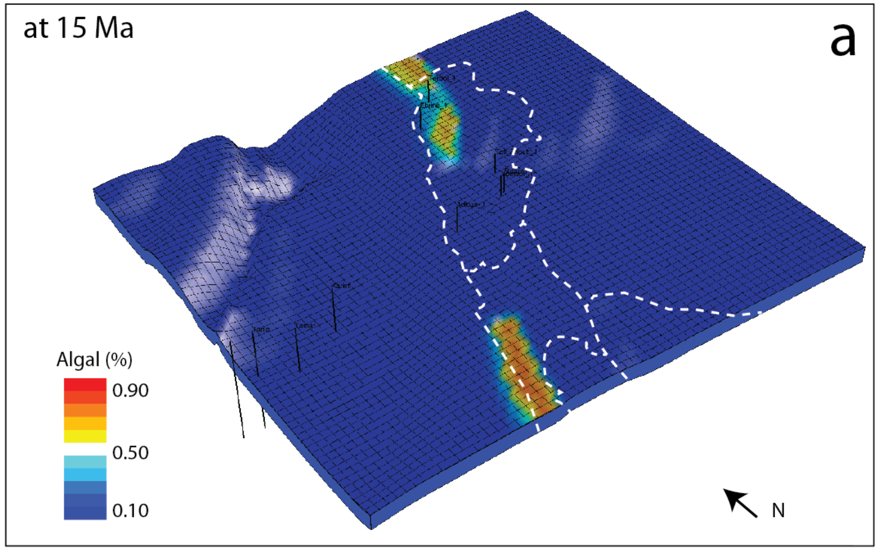


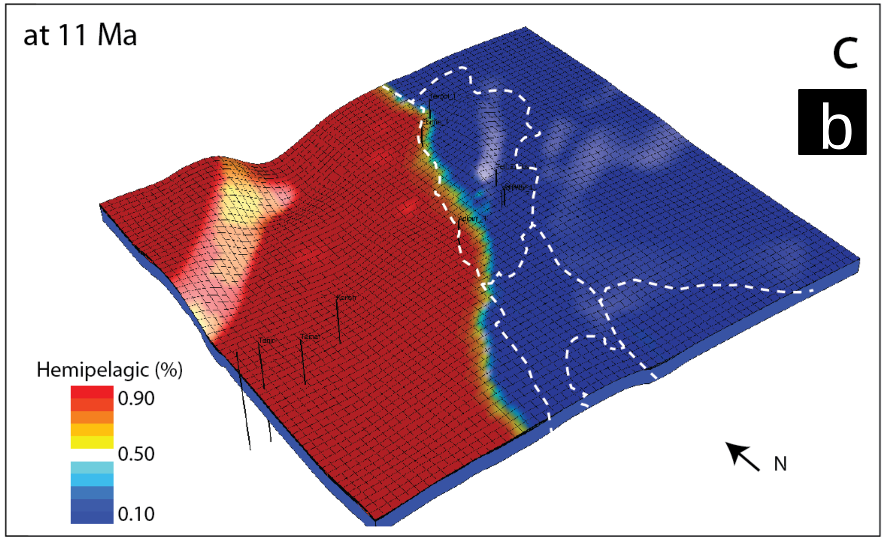
Best fit model

Rhodalgal deposition



Hawie et al., in prep (b)

Hemipelagic deposition



Rhodalgal realm: 0-100 m depth
Production: 60 m/Ma

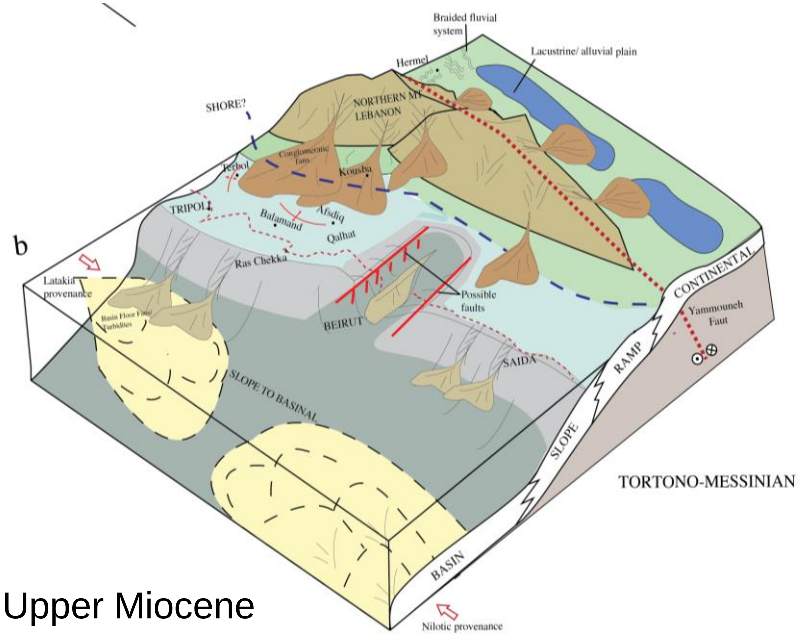
Hemipelagic realm: >200 m depth
Production: 30-40 m/Ma

Good fit with the field work results

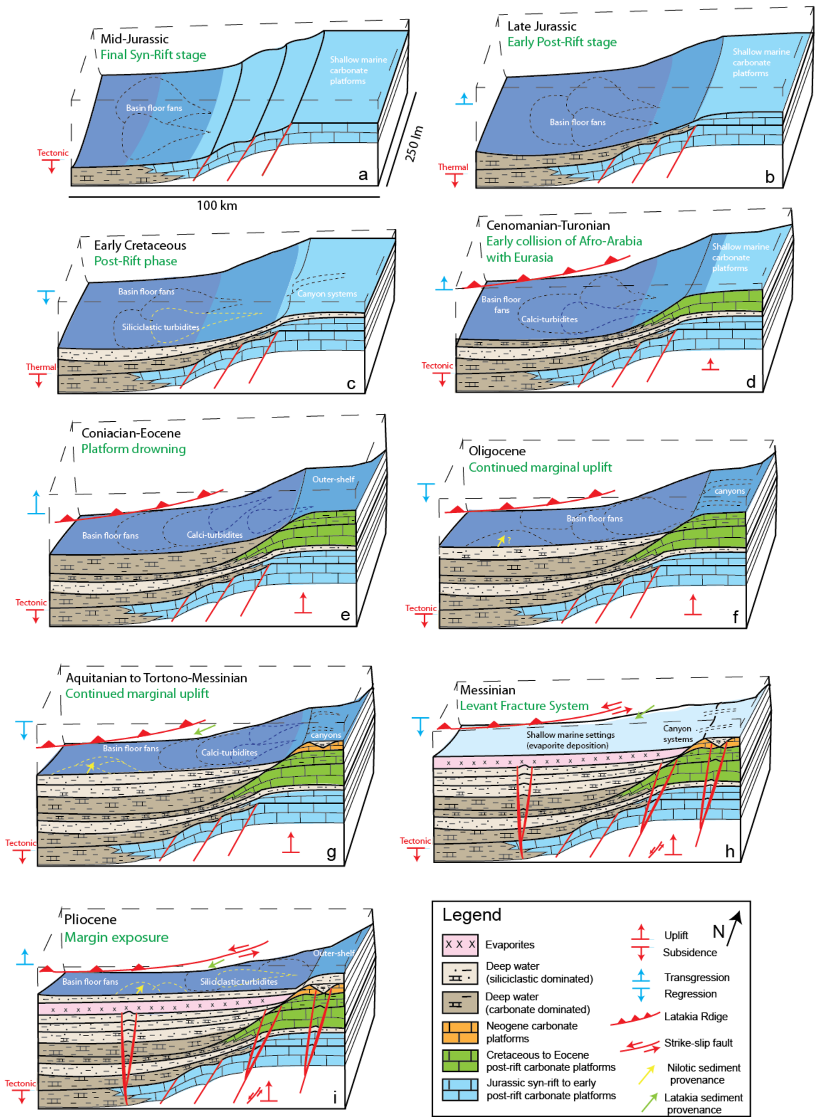
Conclusions

•Facies models for the Middle Jurassic to recent have been proposed

•Miocene source to sink system tested by Forward Stratigaphic Modeling



Upper Miocene



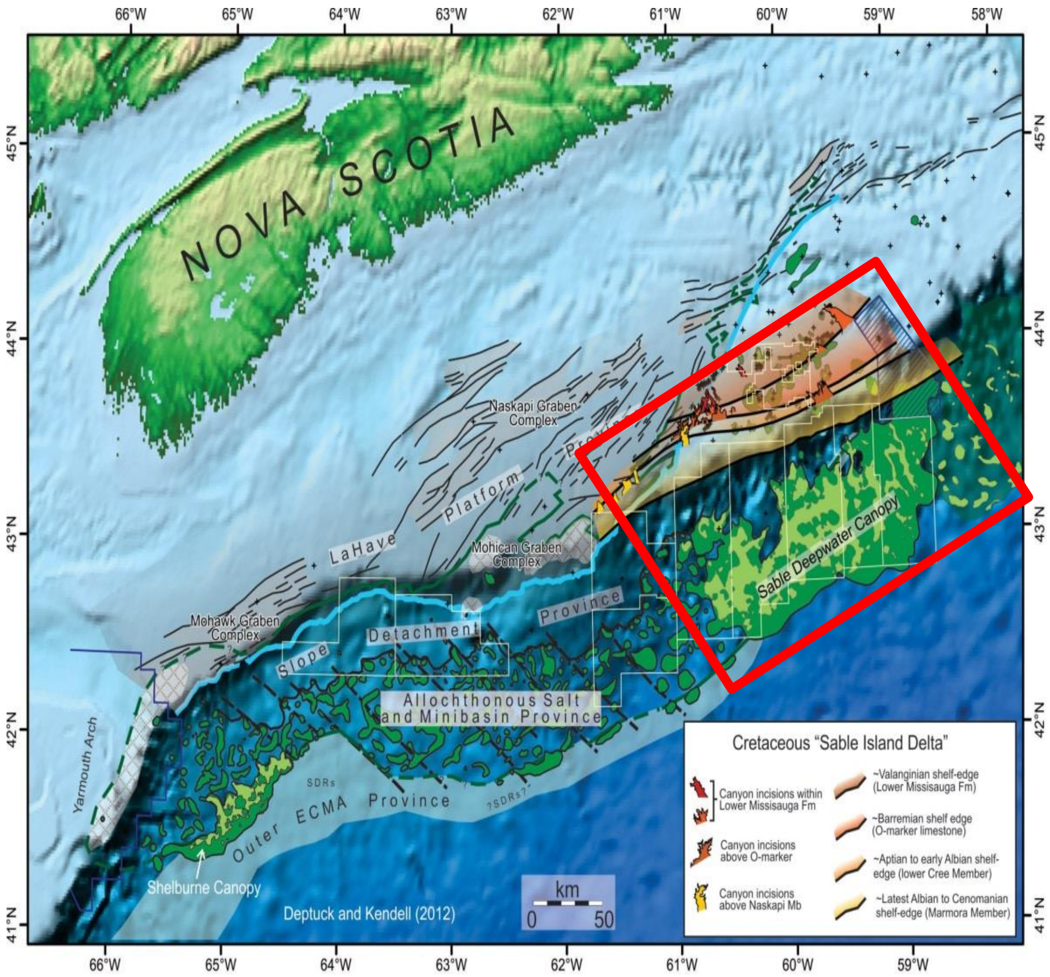
Hawie et al., 2013b

The Canadian Offshore

Study Framework and Objectives

- Study area located around the SE flank of Nova Scotia along the Central Scottian Basin (Sable Sub basin).

- The main objectives are to:
  - Assess the source to sink systems contributing to the Upper Jurassic and Lower Cretaceous sedimentary infill
  - Evaluate the deposition of reservoir facies along the shelf, slope and basin through integrated multi-disciplinary and multi-scale approaches
  - De-risk petroleum systems elements (reservoir, seal, stratigraphic trapping)



From Kendell and Deptuck, 2012

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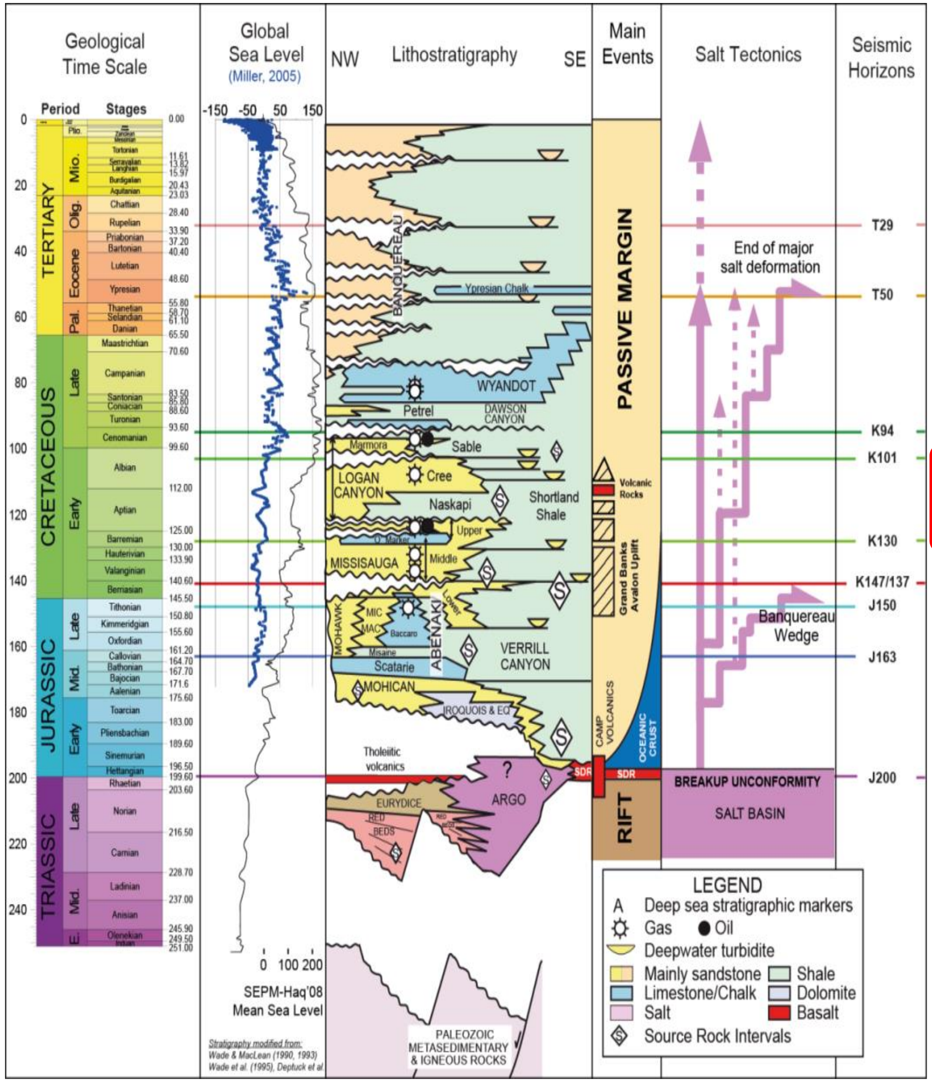
Regional Geology

- Rifting in the Late Triassic followed by Salt deposition and the onset of a passive margin along the Scotian Basin

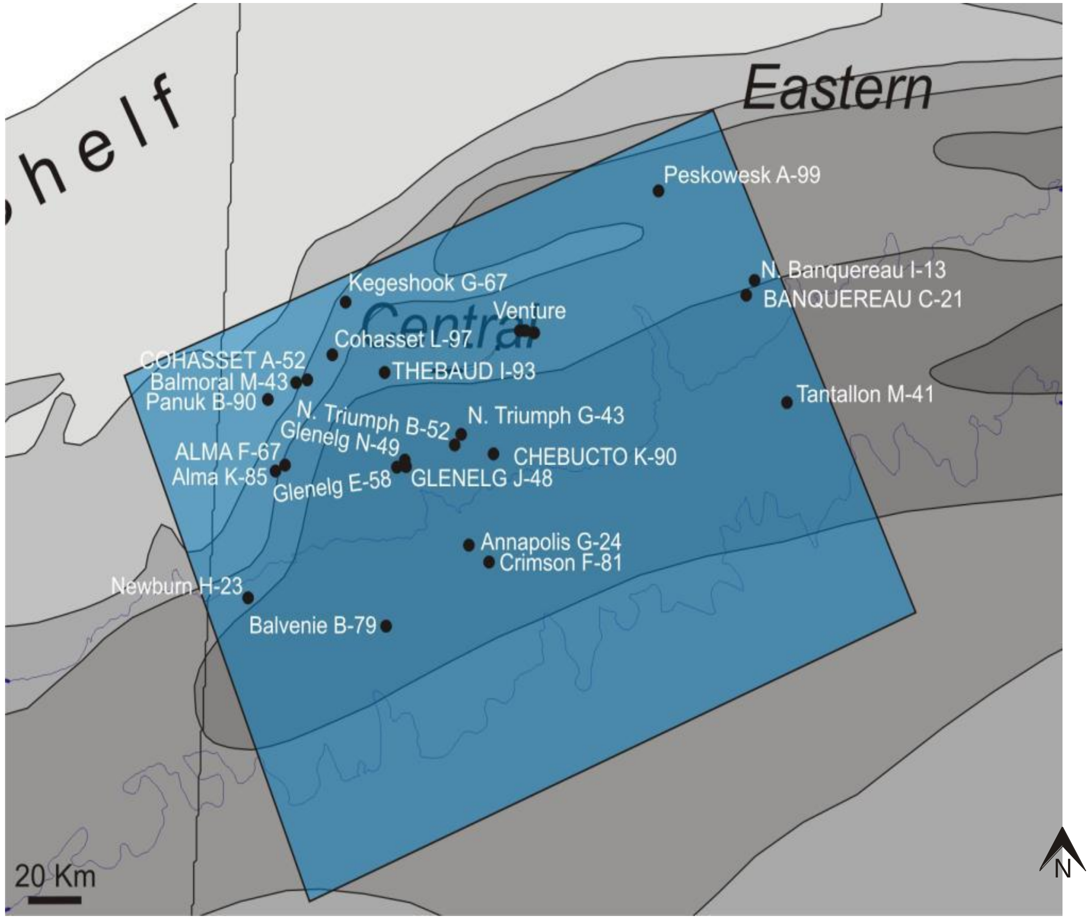
- Fluvio-deltaic setting developing in the Lower Cretaceous along the shelf while deeper basinal settings are identified offshore (Cummings and Arnott, 2005; Piper et al., 2010)

- Loading of salt induced deformation controlling the onset of growth listric faults and mini-basins depocenter (Shimeld, 2004; Ings and Shimeld, 2006)



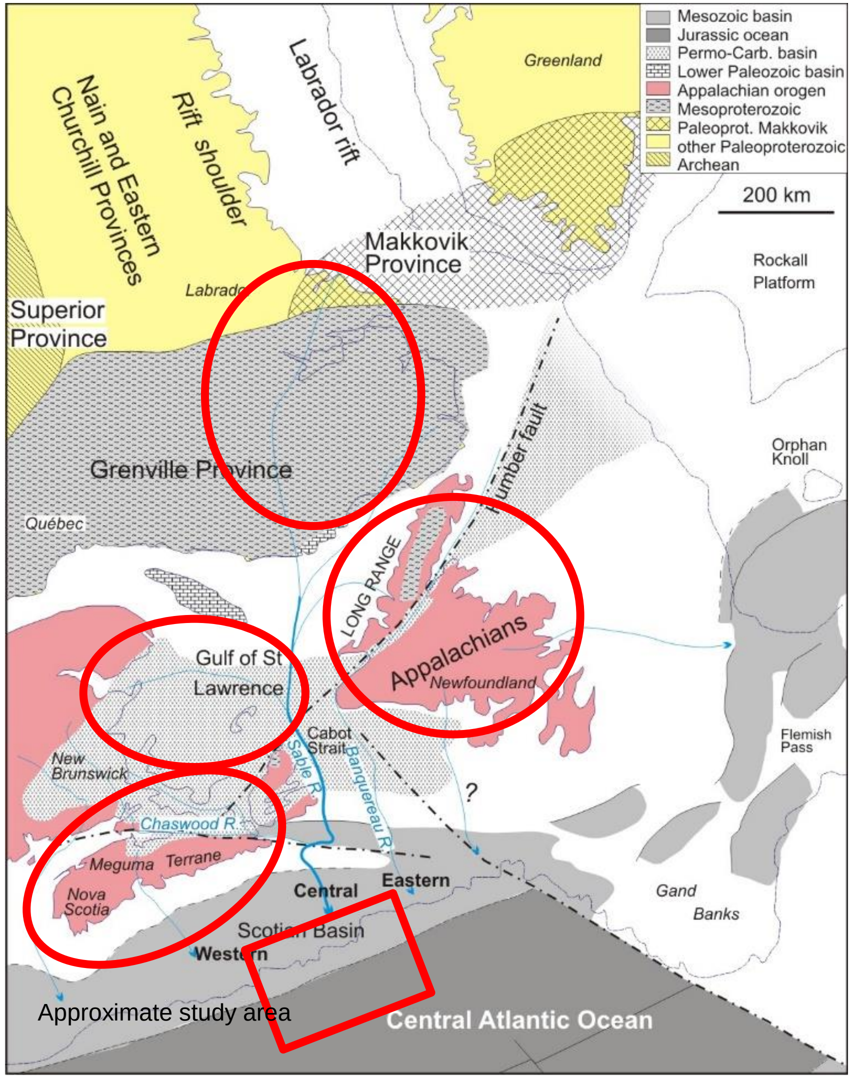
Sedimentological and Stratigraphic Datasets

- Provenance
  - Age dating
  - Chemical Data
- Paleoclimate
- Biostratigraphy
- Lithofacies classification
- Shelf edge interpretations
- Point Counting
- Grainsize
- Lithology from cores



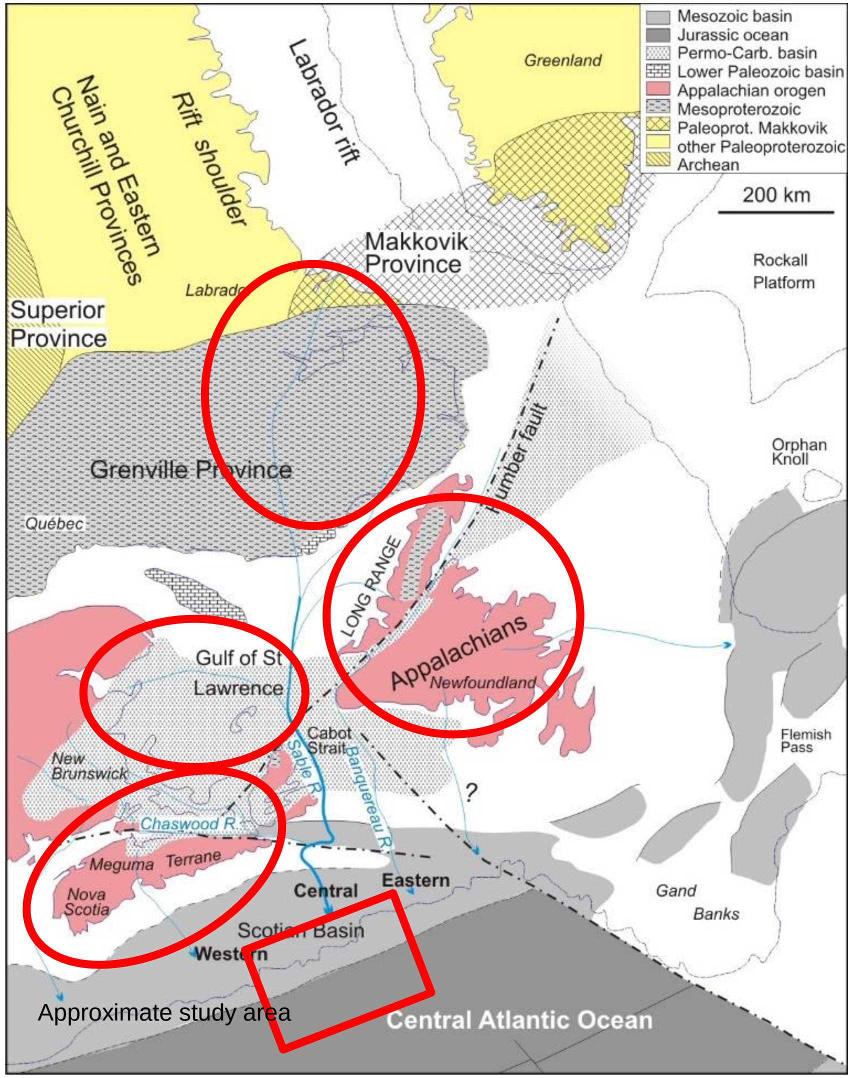
Sources Locations

- **Determined from provenance studies**
- **Age dating**
  - Muscovite (Reynolds et al., 2012)
  - Monazite (Pe-Piper et al., 2014)
  - Zircon (Pe-Piper et al., 2012)
- **Chemical Data**
  - Bulk rock geochemistry (Zhang et al., 2015)
  - Geochemical fingerprinting (Tsikouras et al., 2011)



Sources Locations

- **3 Main sources:**
  - The Meguma terrane
    - Mainland Nova Scotia
  - The Sable River
    - Southern Labrador, the long range inlier of Western Newfoundland, and the Maritimes Basin
  - The Banquereau River
    - Humber Valley of Western Newfoundland, and Southern Newfoundland



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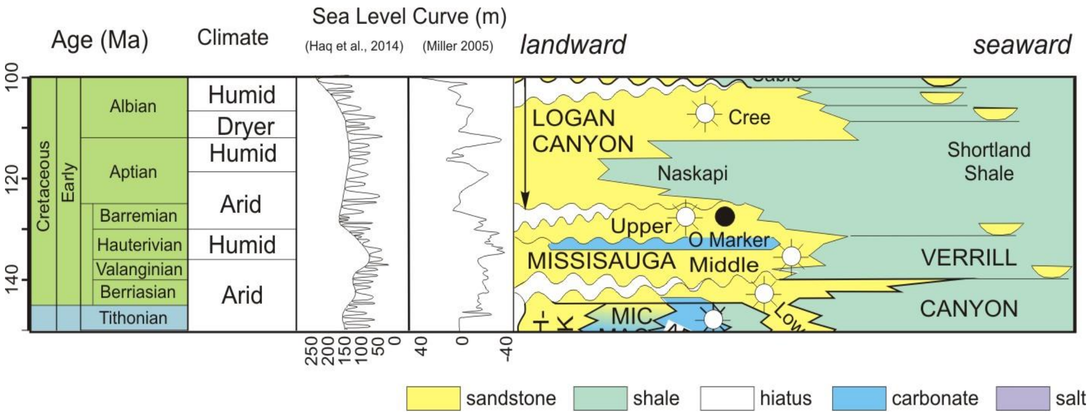
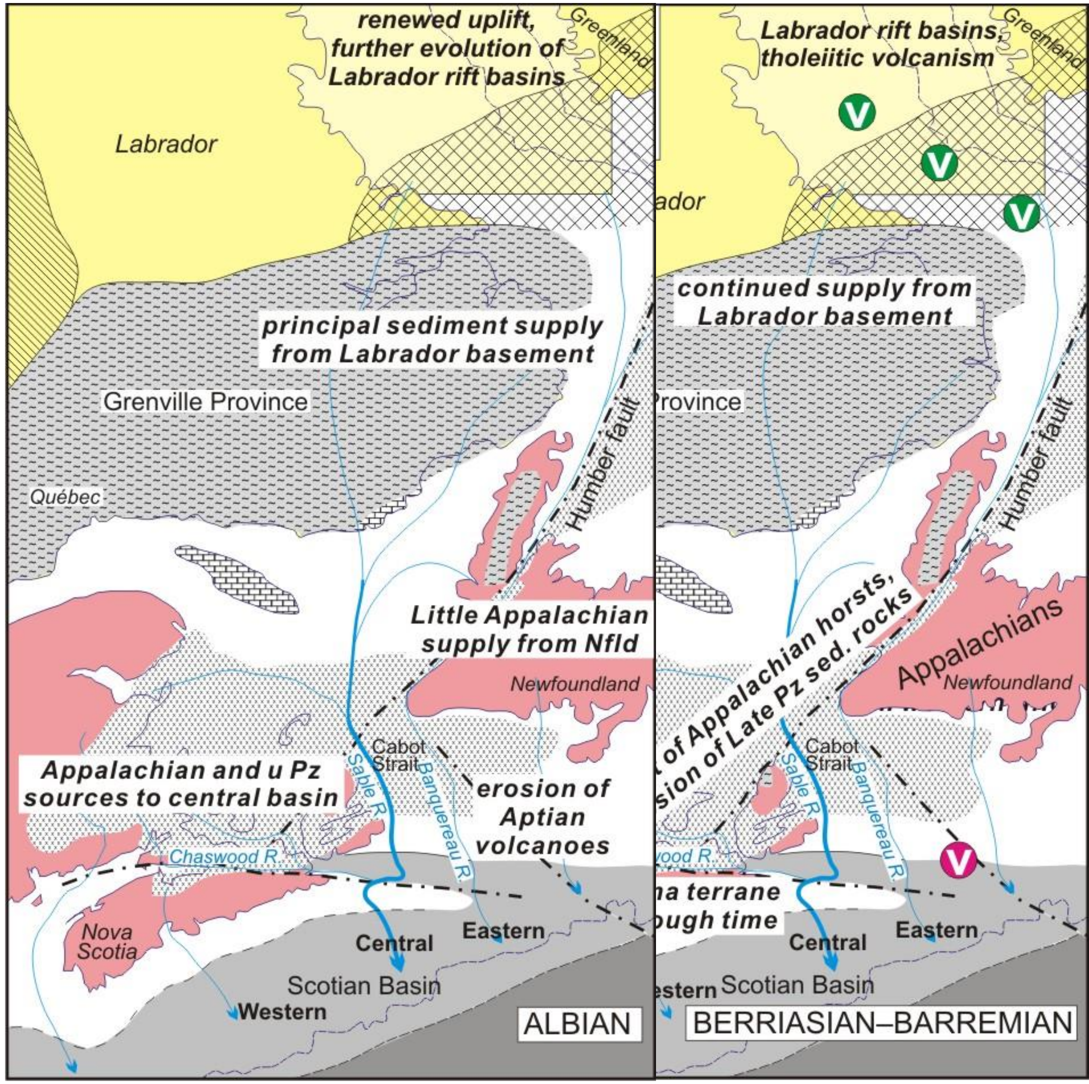
Sources Activation in the E.Cretaceous

- Upper Missisauga Formation (130-125Ma)
  - Sable, Meguma, and Banquereau
- Naskapi Member (125-112Ma)
  - Meguma
- Cree Member (112-101Ma)
  - Sable, Meguma, and Banquereau



Haywood et al., 2005



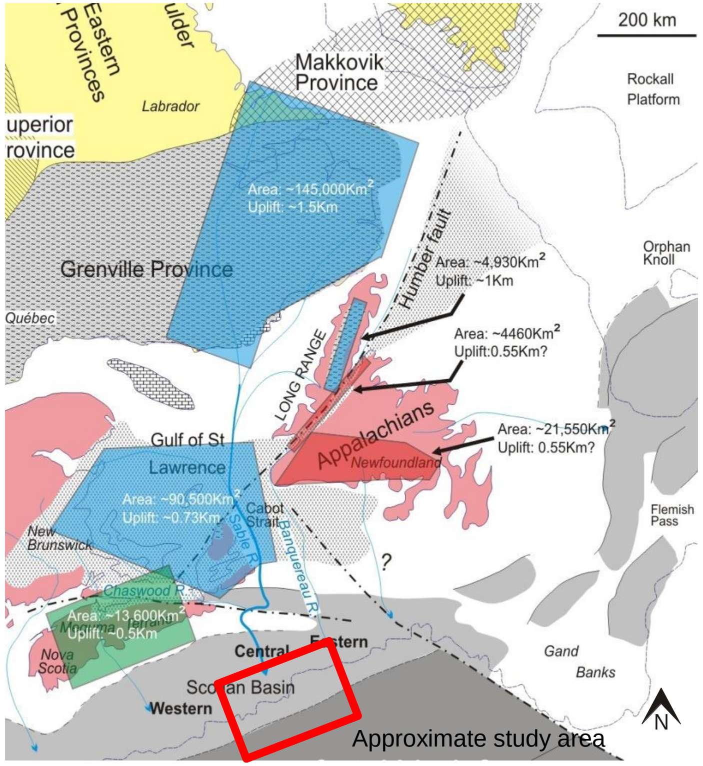
Catchment Areas

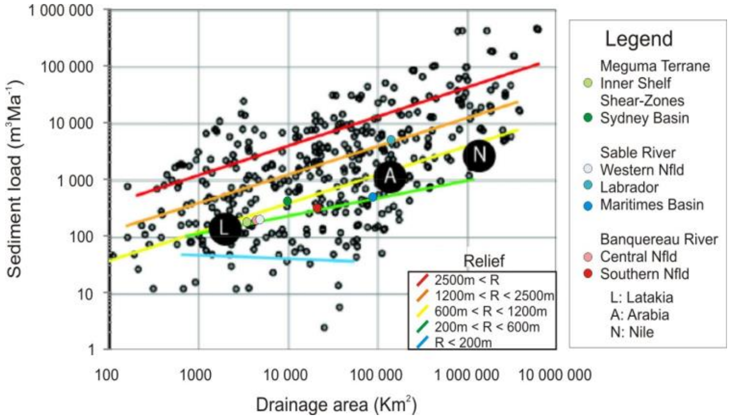
- Apatite fission track models
  - Grist and Zentilli 2003
  - Hendriks et al., 1993

- Comparison to the East African Rift
  - Chorowicz, 2005

- Mass balance calculations
  - Reynolds et al., 2009

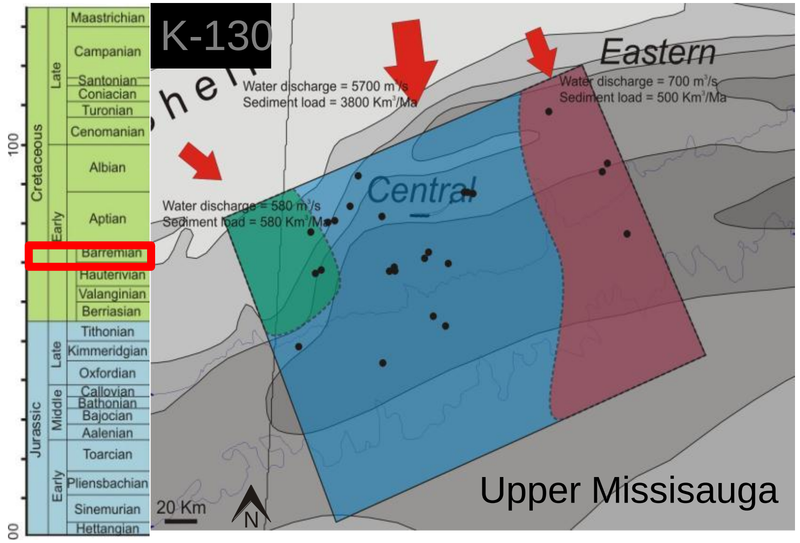
Source River	Input*	K-130 - K-125	K-125 - K-112	K-112 - K - 101
Meguma	Water Discharge (m^3/s)	580	580	580
	Sediment Load (Km^3/Ma)	580	580	580
Sable River	Water Discharge (m^3/s)	5700	0	5700
	Sediment Load (Km^3/Ma)	3800	0	3800
Banquereau River	Water Discharge (m^3/s)	700	0	700
	Sediment Load (Km^3/Ma)	500	0	500

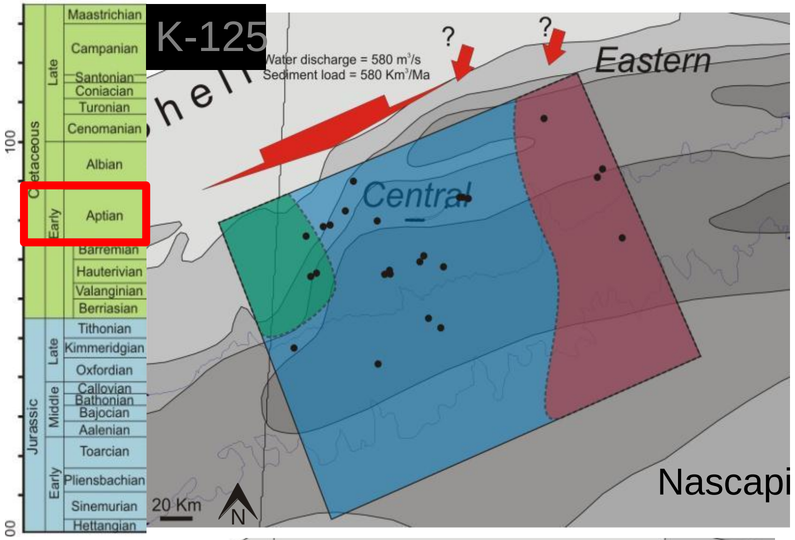


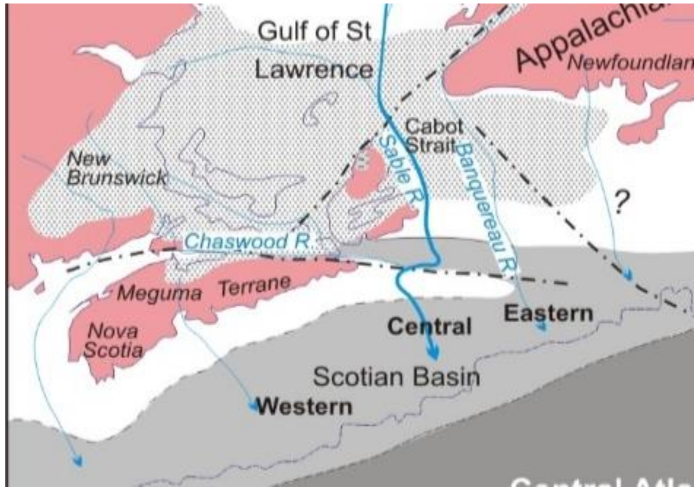


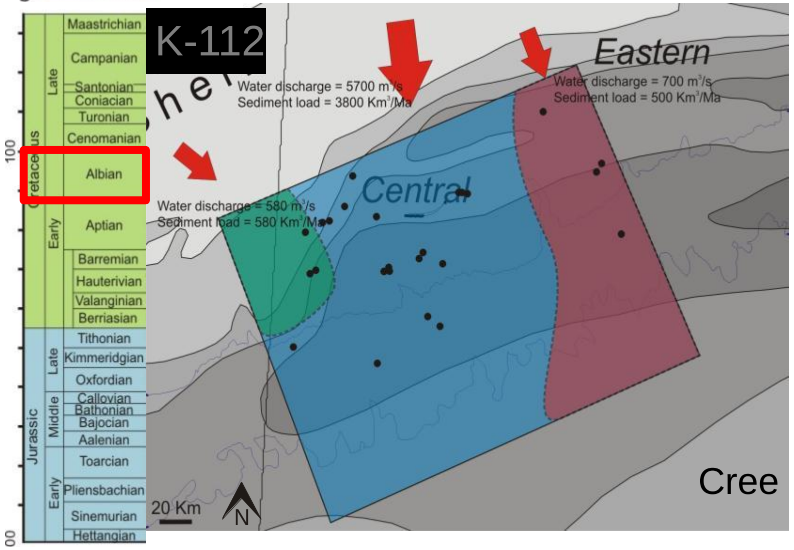
*Inputs are maximum values, they assume 100% transport from all catchment areas to the study area.

System Inputs (Flow Paths)





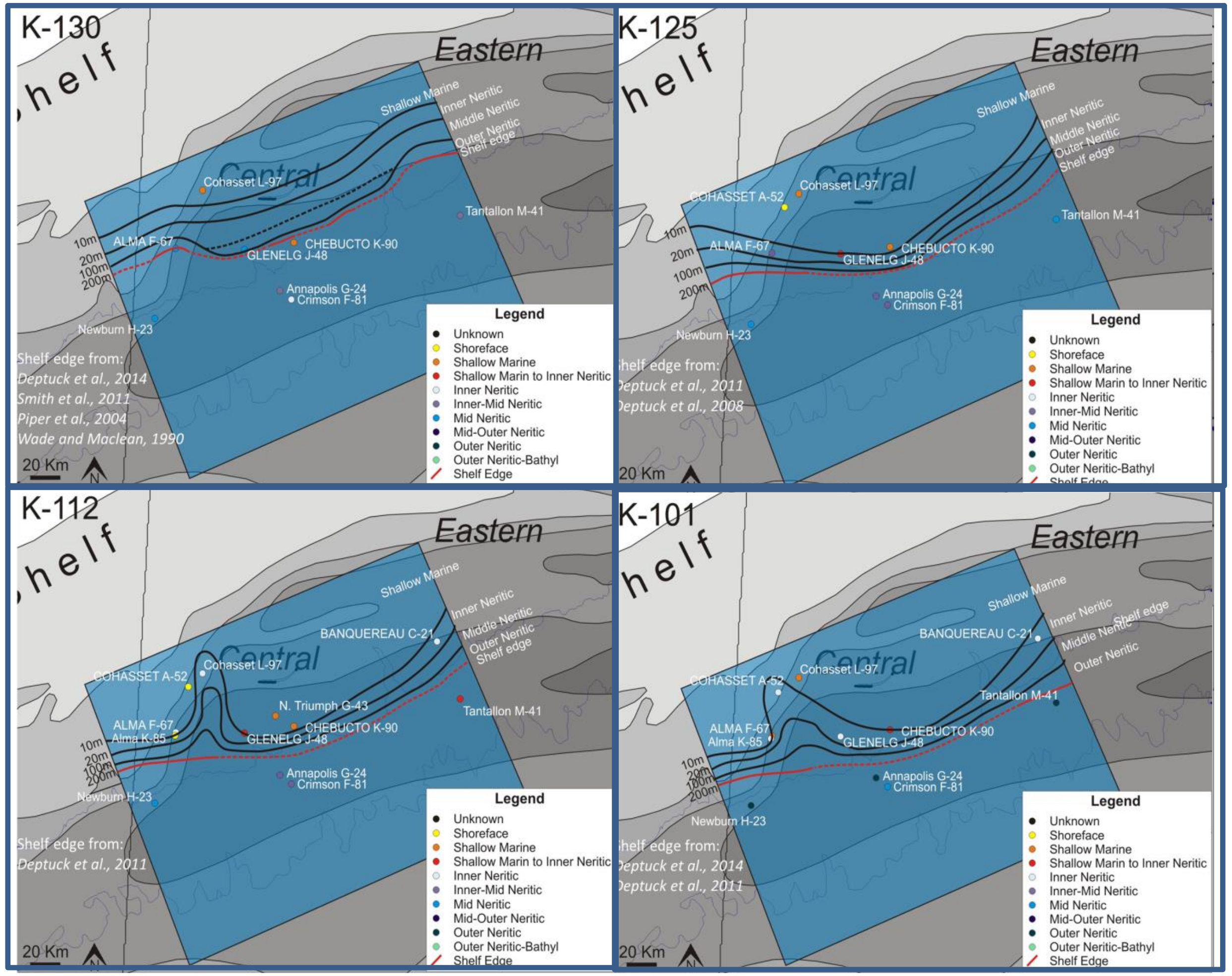




Hawie et al., 2017
Sangster et al., 2019

Bathymetry

- **Based on a compilation of data sets**
- **Biostratigraphy**
  - Weston et al., 2012
  - Ascoli, 2011
  - Ascoli, 2010
  - Robertson Res.Inter. Ltd., 2004
  - Robertson Res. Inter. Ltd., 2000
  - Petro Canada Exploration Inc., 1982



- **Lithofacies classification**
  - Gould et al., 2012
- **Shelf edge interpretations**
  - Deptuck et al., 2014
  - Deptuck et al., 2011
  - Smith et al., 2011
  - Deptuck et al., 2008
  - Piper et al., 2004
  - Wade and Maclean, 1990

Hawie et al., 2017
Sangster et al., 2019

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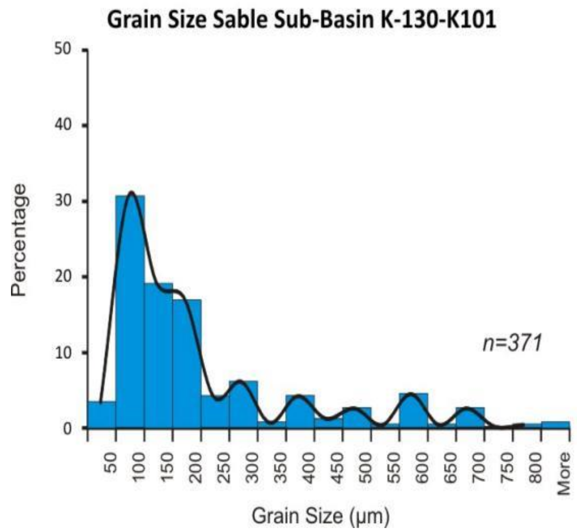
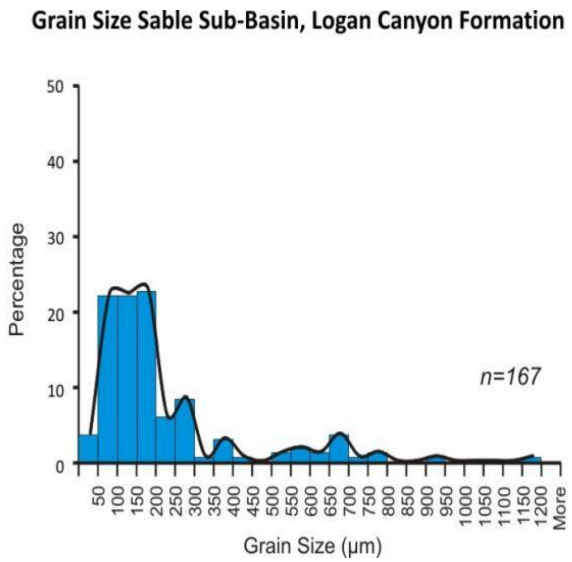
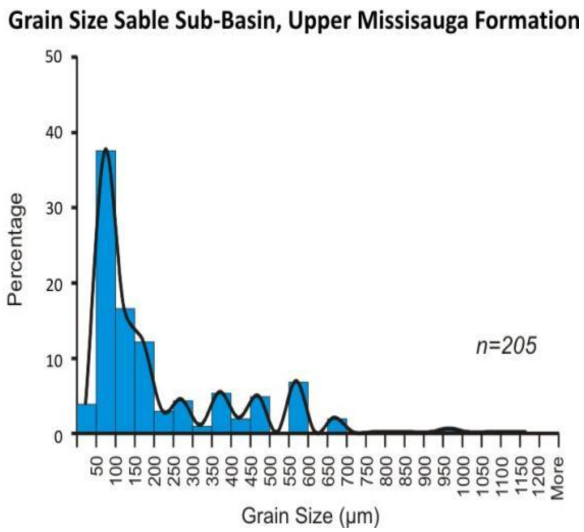
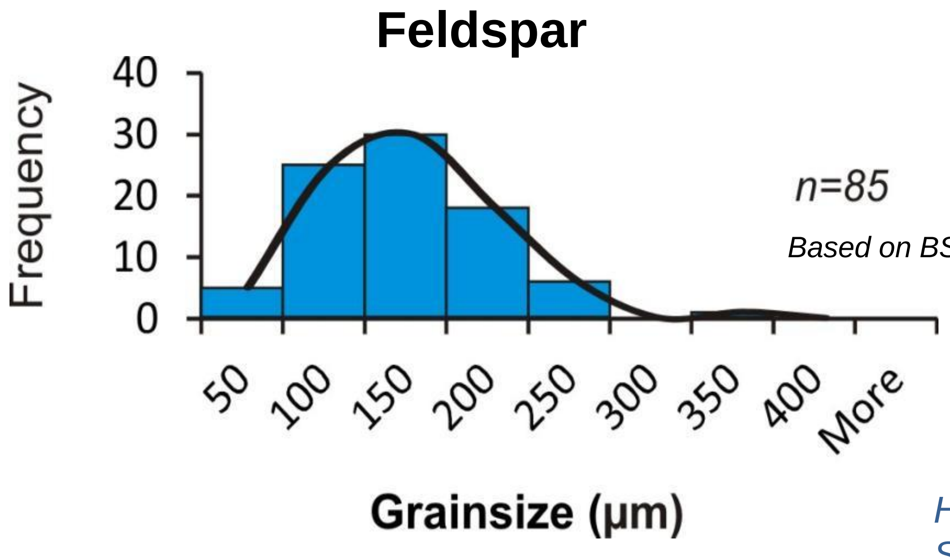
Grain size (Average)







Based on compiled point counting data



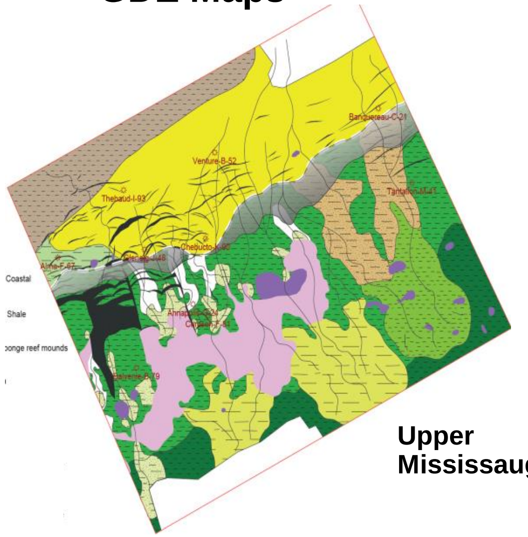
Based on BSE images from Pe-Piper and Yang, 2014

Hawie et al., 2017
Sangster et al., 2019

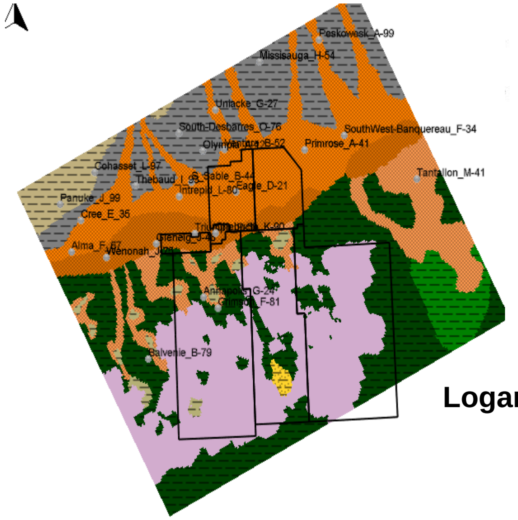
Proposed Geological Model

- **Wide dataset to be explored:**
  - Well data (margin and slope)
  - 2D and 3D seismic data
  - Seismic Stratigraphy
  - Sedimentological interpretation
- **Shelf, slope to deepwater domain**
- **Complex Salt deformation**
- **Reservoir Assessment**

GDE Maps

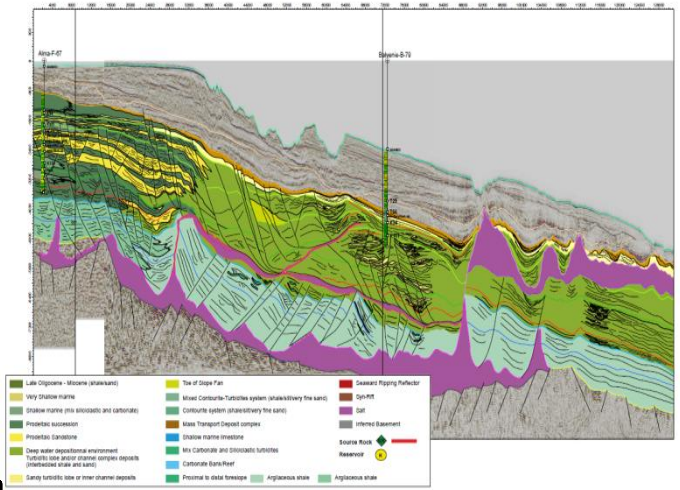


Upper Mississauga

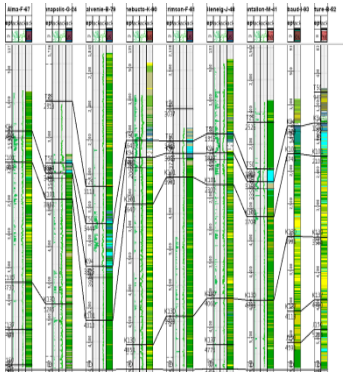


Logan Canyon

Seismic Stratigraphic and facies analysis



Well Correlations



Hawie et al., 2017
Sangster et al., 2019

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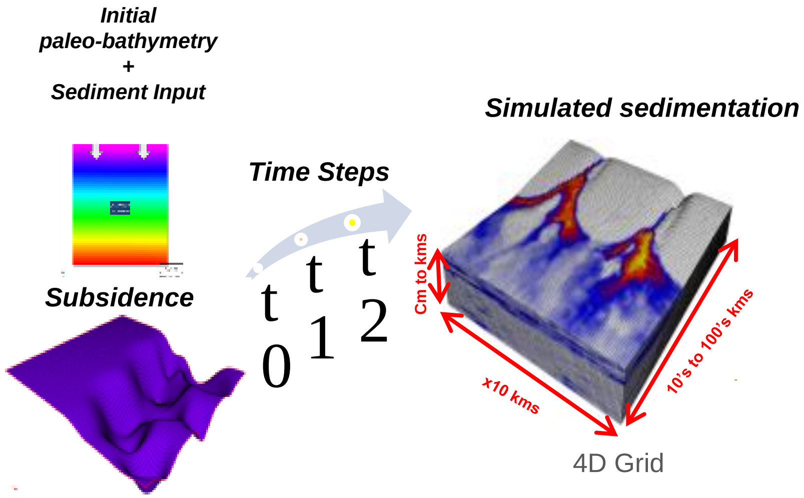
Forward Stratigraphic Modelling

- FSM is a deterministic process based tool that reproduces sedimentary transport and deposition of **siliciclastic and carbonates**.

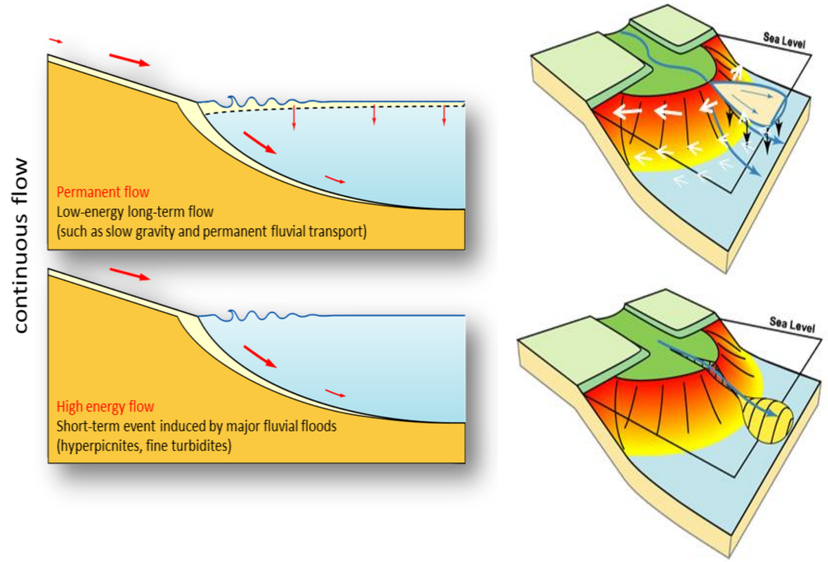
The transport rate proportional to basin slope and water discharge:

$$Q_s = K\,Q_w\,S$$

- Qs = Sediment Load
- Qw= Water Discharge
- S = Depositional Slope
- K = Diffusive Coefficient



- **Low Energy Long Term (LELT)**: slow gravity permanent fluvial transport
  - Gravity Driven
  - Water Driven
  - Wave Driven
- **High Energy Short Term (HEST)**: induced by major fluvial floods (hyperpycnites, fine turbidites)



Hawie et al., 2017
Sangster et al., 2019

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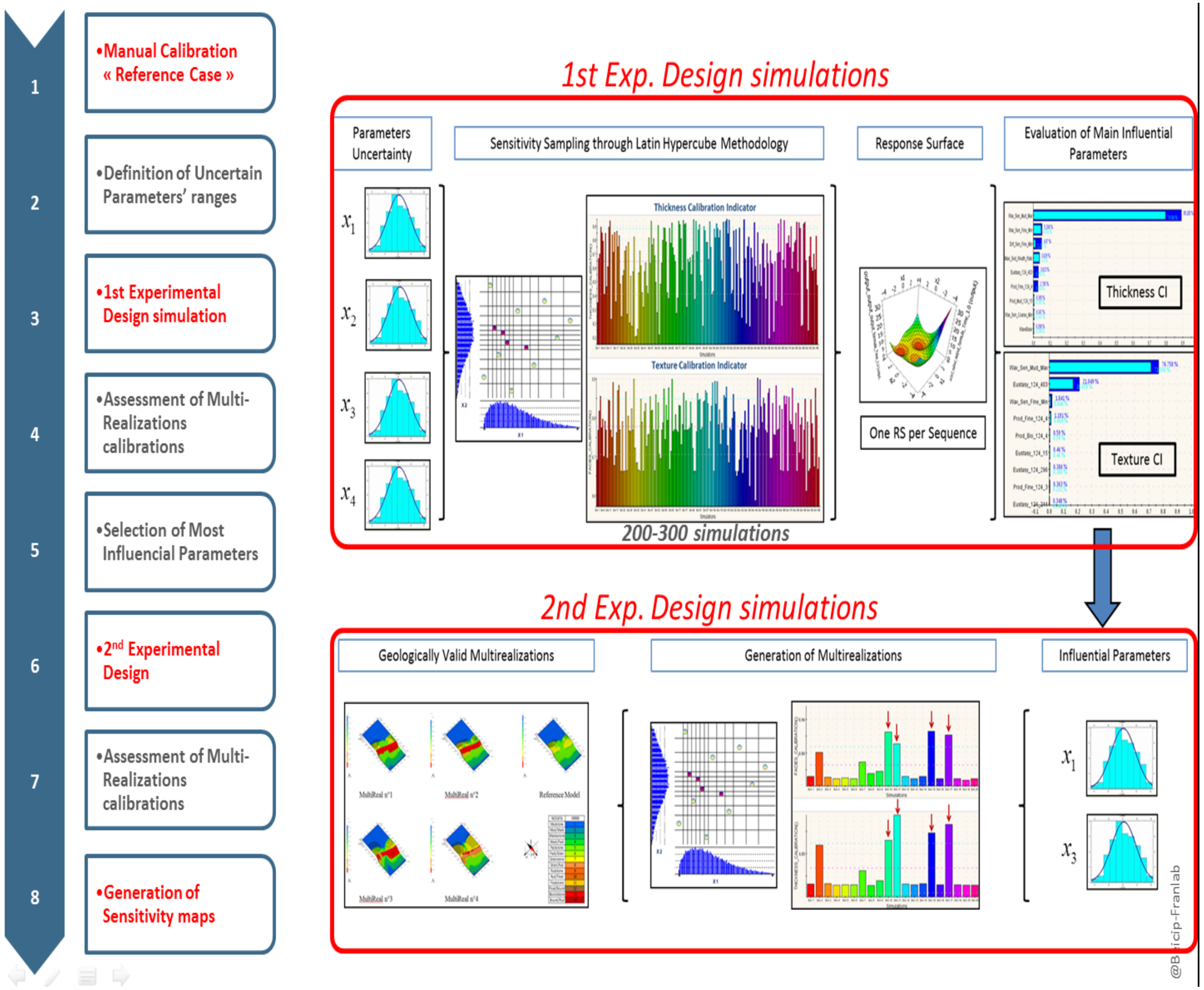
Multi-Realization and Sensitivity Analysis

- Integrated link to **CougarFlow:**
  - Understand **uncertainties**
  - Understand the **risk** associated to the model

- **RSM based** (Response Surface Model): drastic **reduction** the number of simulations **without compromising** results quality.

Main parameters types to be tested: Sediment lithology proportions, Water discharge and sediment load, sources location and width



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Model Framework

Simulation Parameters

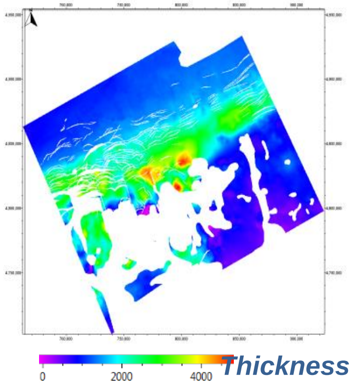
- Block X length
  – 185 Km
- Block Y length
  – 215 Km
- Block Azimuth (orientation)
  – 63.9°
- Cell size
  – 5 km x 5 km
- Initial age of simulation
  – 130 Ma
- Final age of simulation
  – 101 Ma
- Size of time steps
  – 0.5 Ma
  – 0.2 Ma
- Miller et al., 2005 Eustatic curve
- 3 Main lithologies:: Sand, Silt, Shale

Available Geophysical input data

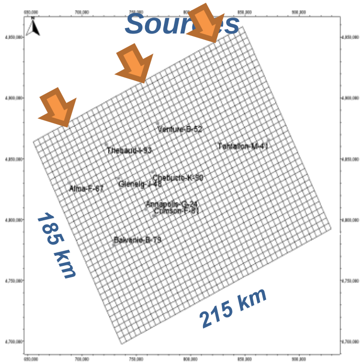
- K-130 and K101 interpreted surfaces
- Salt depth map
- Need to acquire intermediate surfaces for the next phase of the project

Unit	Avg. thickness (m) (PFA 2011)	Percent Thickness
Cree	685	43
Naskapi	200	20
Upper Missisauga	368	37

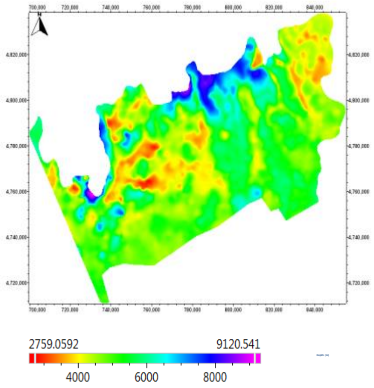
Thickness maps



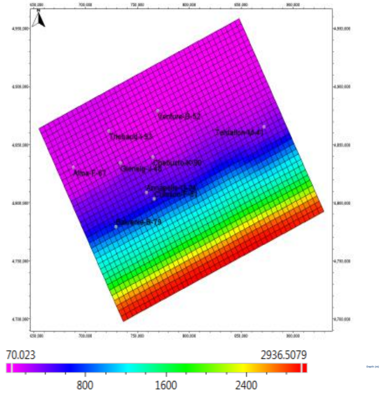
Sediment Sources



Salt depth map



Initial paleo-bathymetry



Hawie et al., 2017
Sangster et al., 2019

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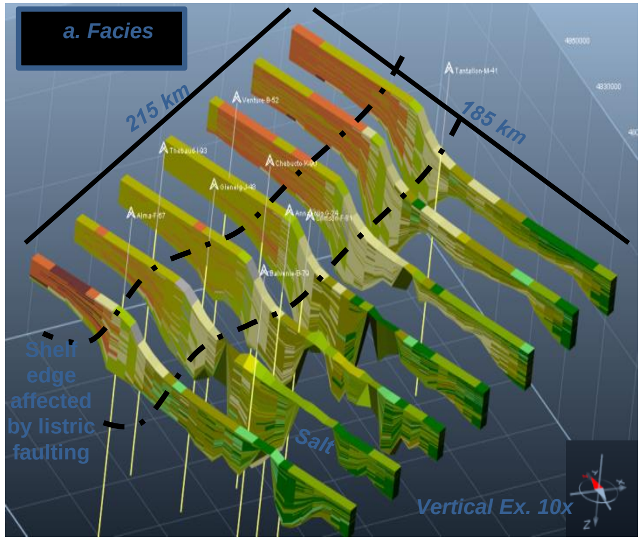
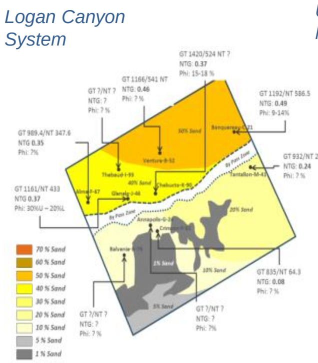
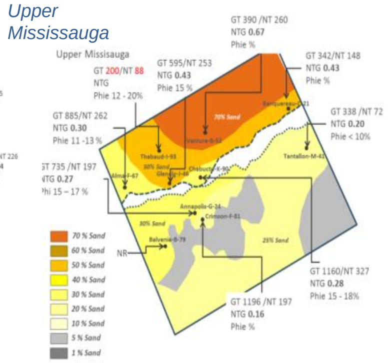
Reference Case Model

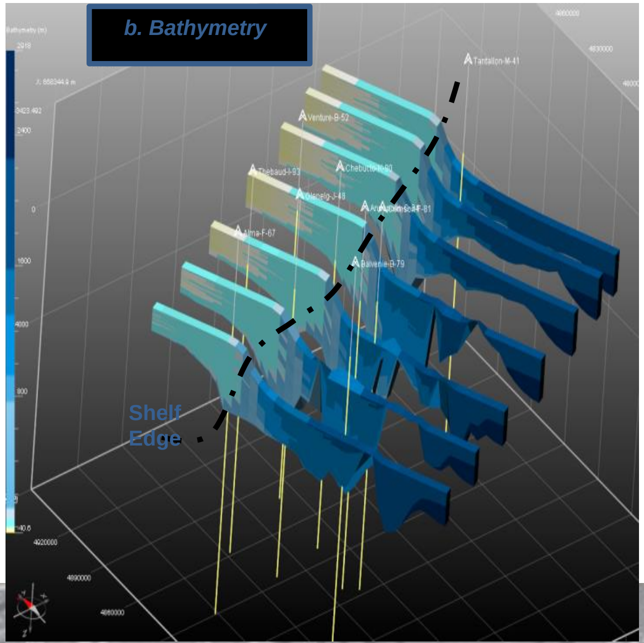


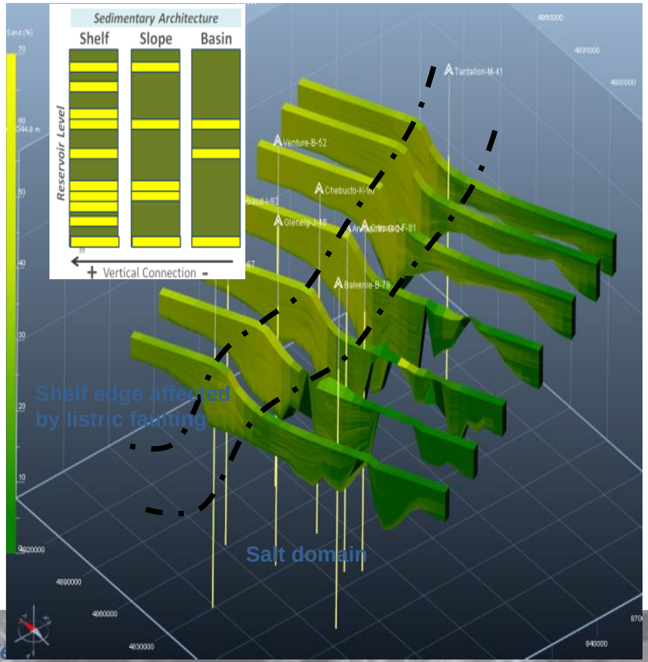
Sedimentary Facies

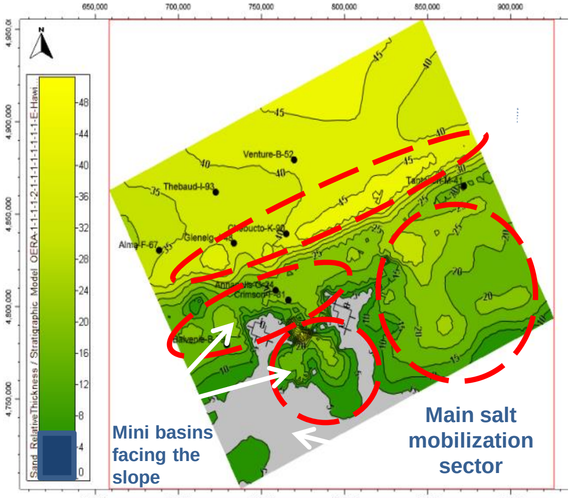
- *Fluvio-Deltaic/ Estuarine (sand >30%)*
- *Fluvio-Deltaic/ Estuarine (sand<30%)*
- *Fluvio-deltaic channels*
- *Inner neritic sand*
- *Middle outer neritic sand*
- *Sandy turbidites*
- *Fine turbidites*
- *Mixed turbidites (shale & silt dominated)*
- *Mixed lobes (sand>20%)*
- *Mixed lobes (sand<20%)*
- *Basinal Shale*











Hawie et al., 2017
Sangster et al., 2019

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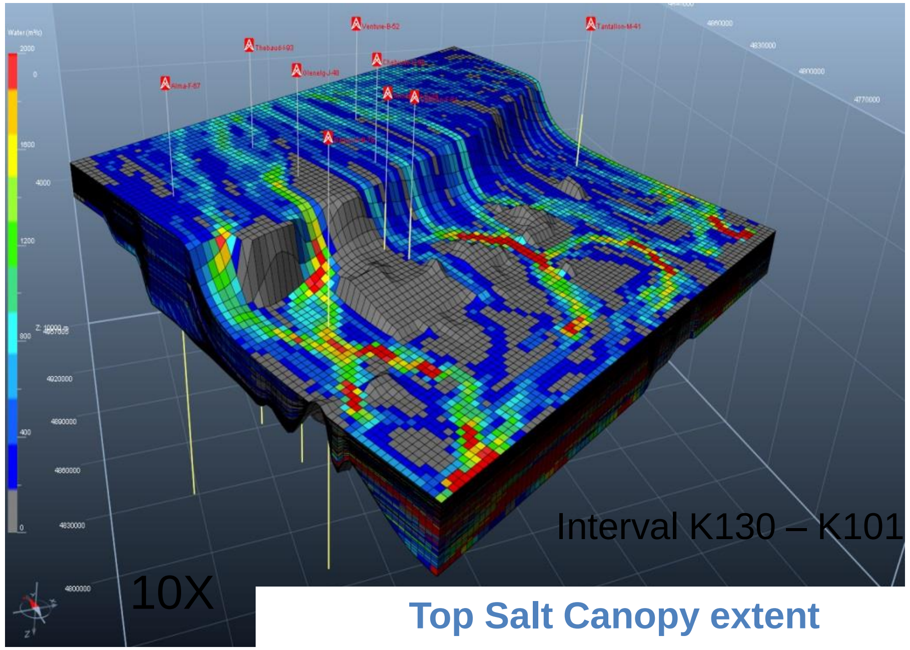
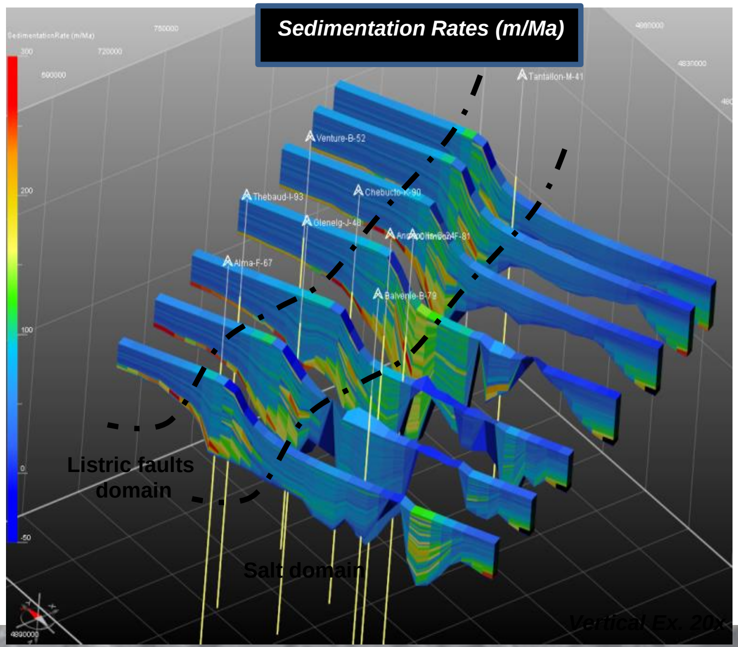
Sedimentary Pathways

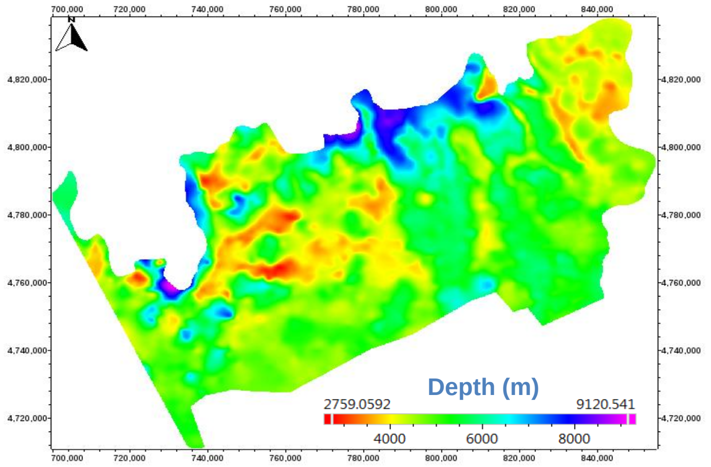
- Main **sedimentary pathways** driving sediments from the shelf towards the basin are **diverted around salt domes and canopies**

- Large sediment entrapment is occurring around **the shelf** following syn-sedimentary **listric faulting** development as well as in **mini-basins** formed as a consequence of continuous **salt deformation**





Top Salt Canopy extent



Hawie et al., 2017
Sangster et al., 2019

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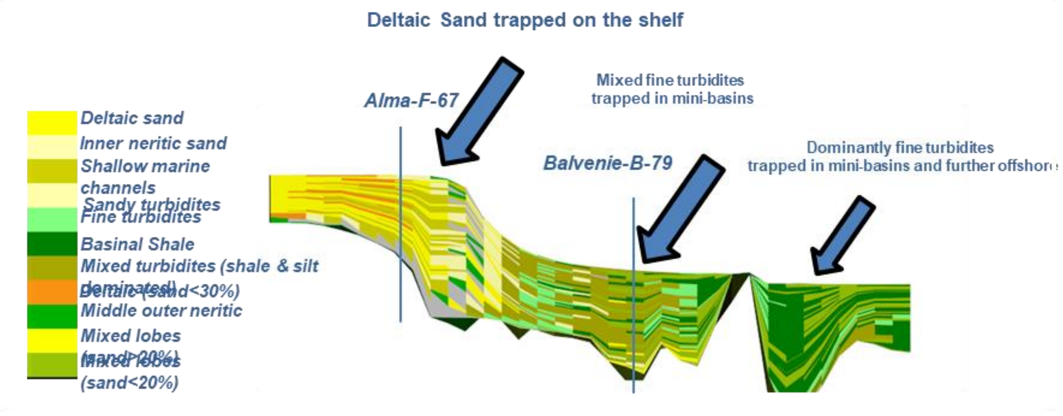
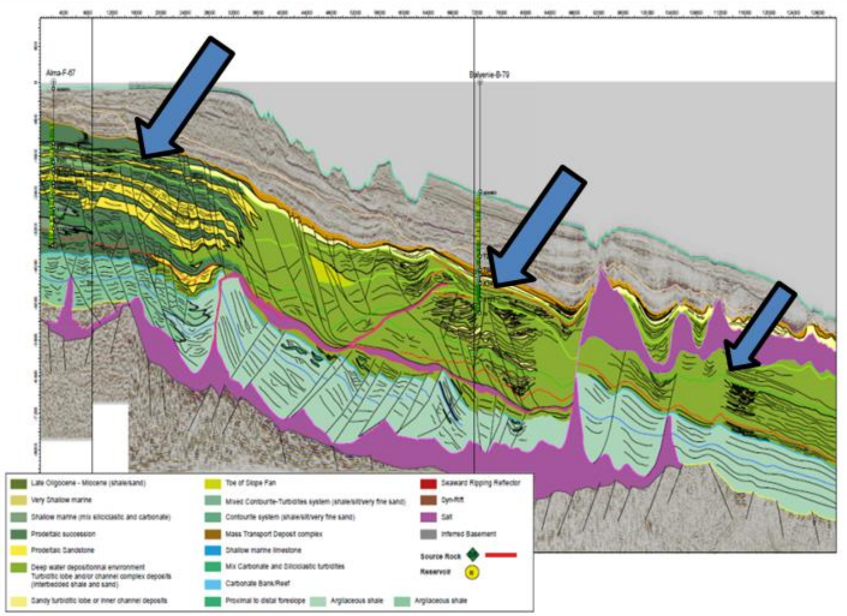
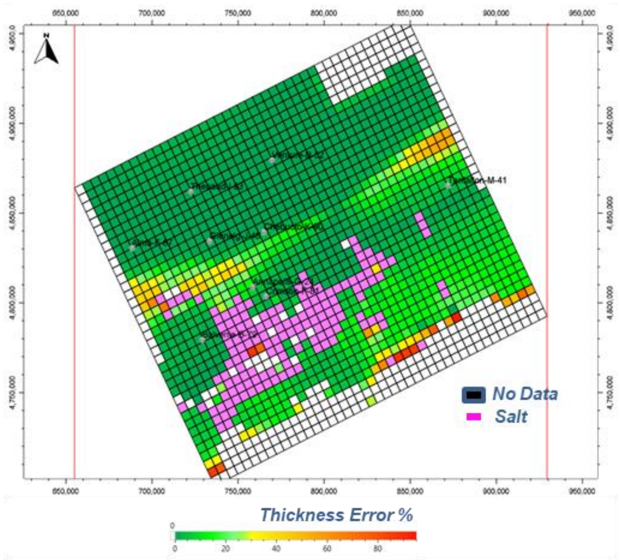
The Alma-Balvenie Sector







Hawie et al., 2017
Sangster et al., 2019

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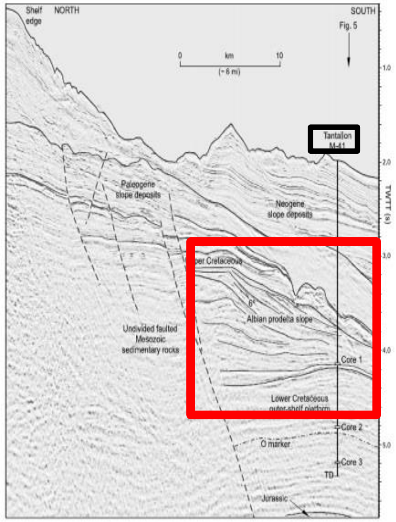
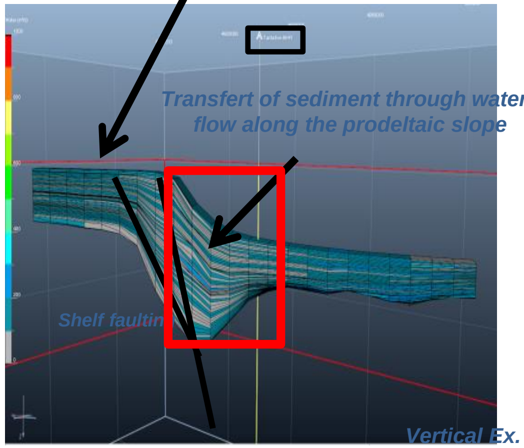
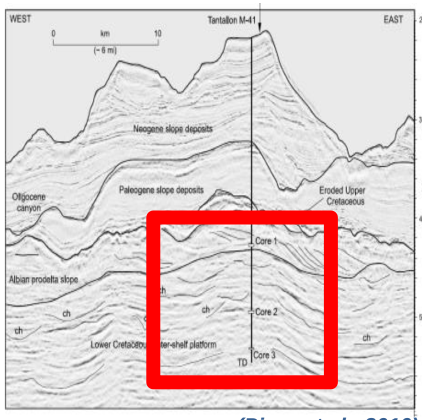
The Tantallon Sector

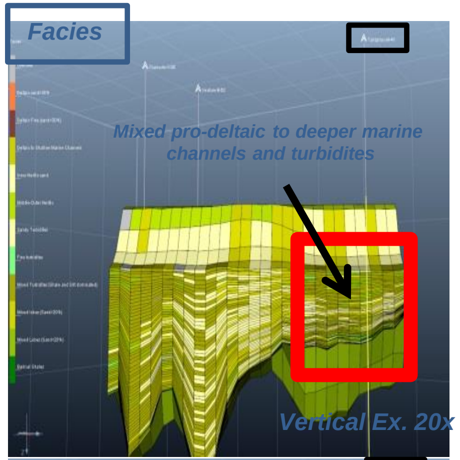


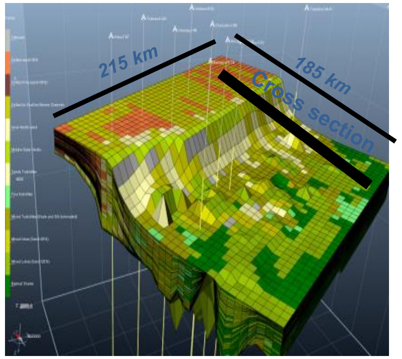
(Piper et al., 2010)

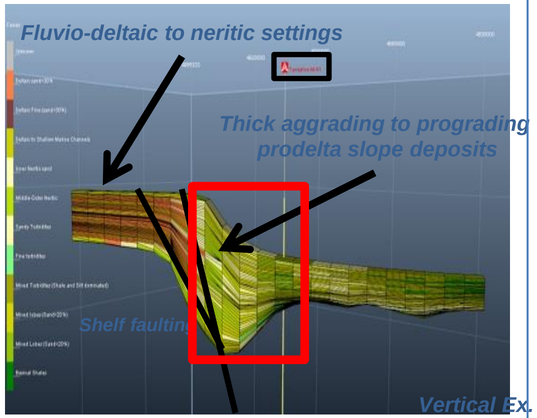


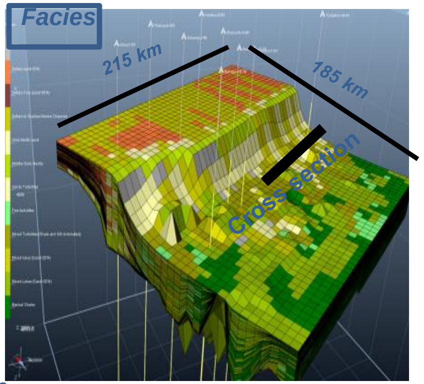


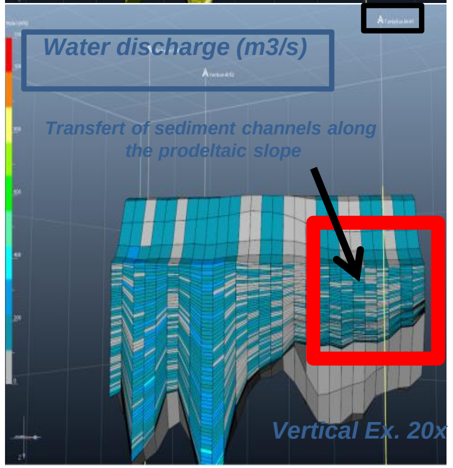
(Piper et al., 2010)





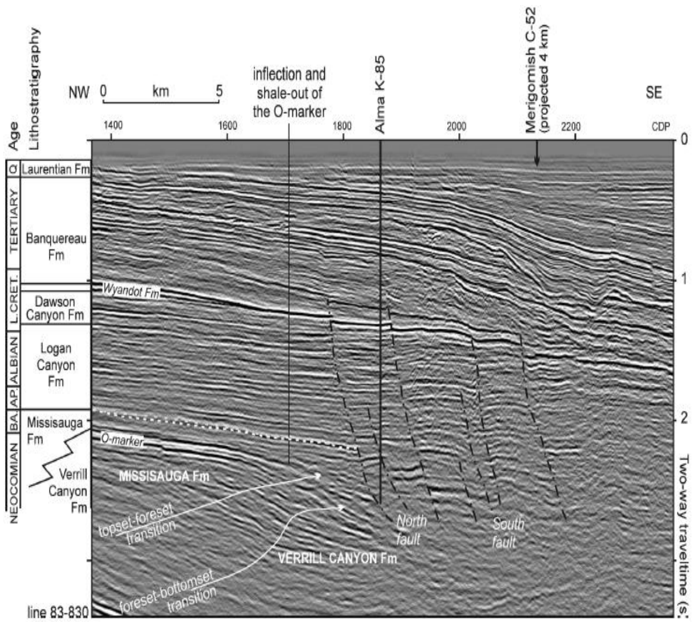


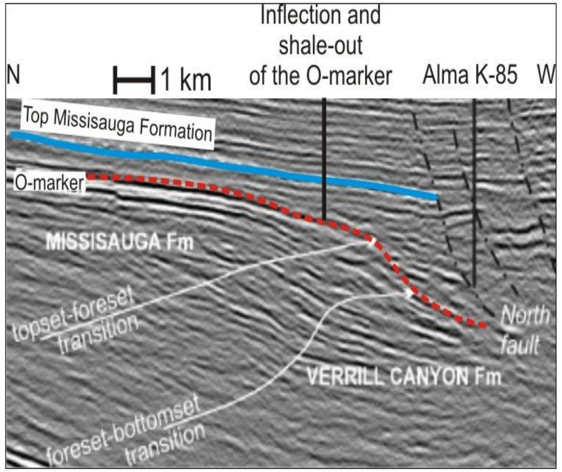




Hawie et al., 2017
Sangster et al., 2019

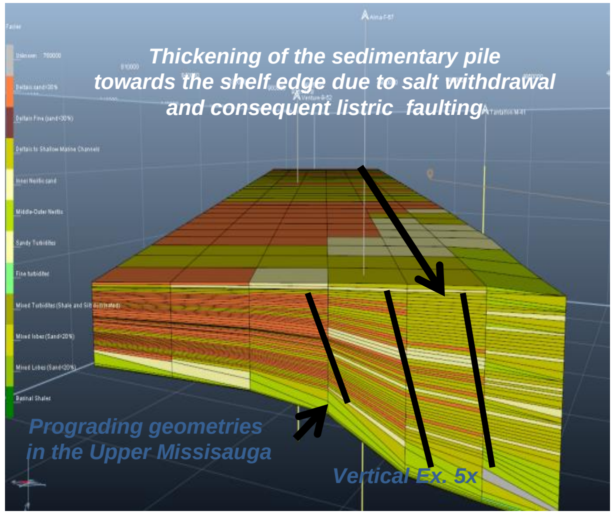
The Alma Marginal Sector



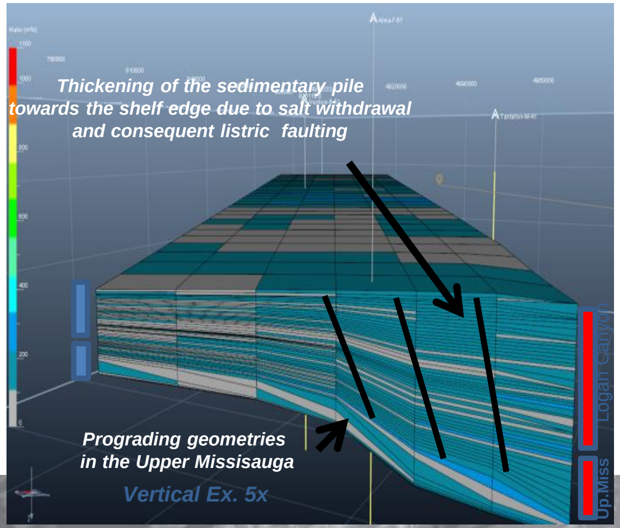


(Modified from Piper et al., 2004)

Facies



Water discharge (m3/s)



Sedimentary Facies

- *Fluvio-Deltaic/ Estuarine (sand >30%)*
- *Fluvio-Deltaic/ Estuarine (sand<30%)*
- *Fluvio-deltaic channels*
- *Inner neritic sand*
- *Middle outer neritic sand*
- *Sandy turbidites*
- *Fine turbidites*
- *Mixed turbidites (shale & silt dominated)*
- *Mixed lobes (sand>20%)*
- *Mixed lobes (sand<20%)*
- *Basinal Shale*

Hawie et al., 2017
Sangster et al., 2019

Model Sensitivity (QS,QW)

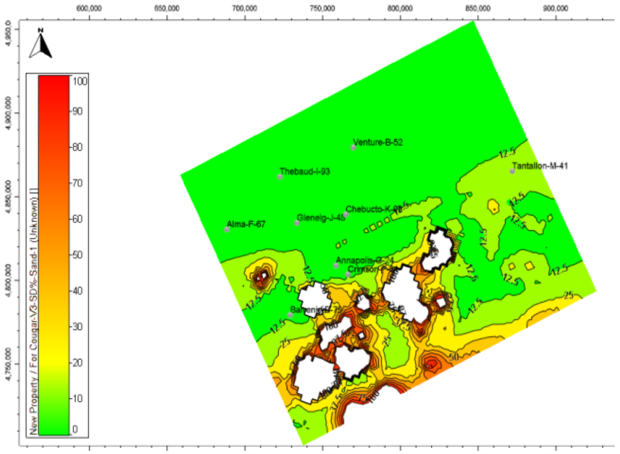
- Overall average sand content results of the 1st experimental design (+/-20% on Qw & Qs)

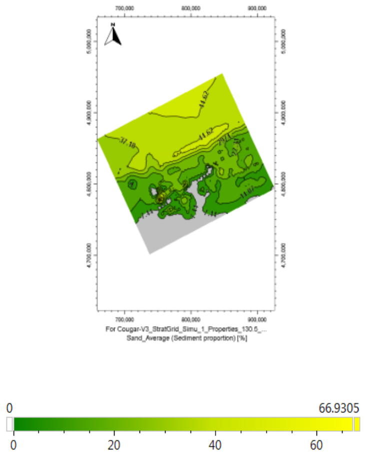
- The related standard deviation (top-right).

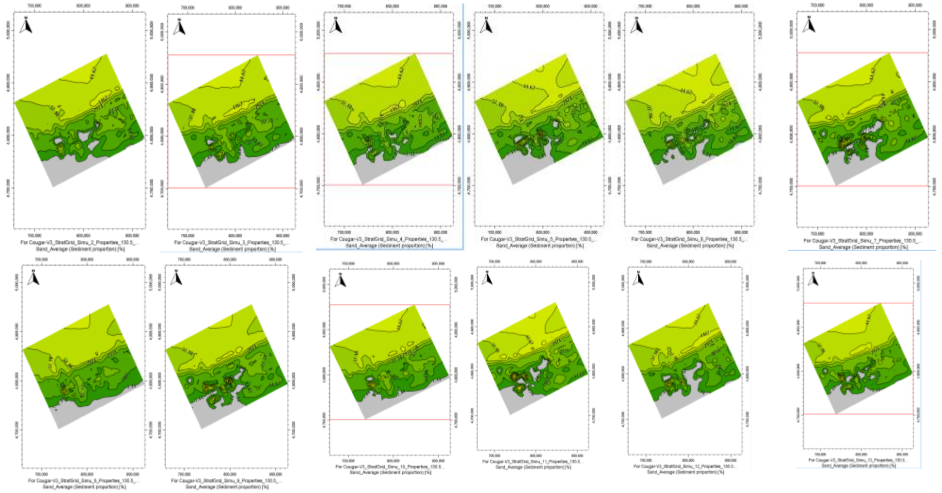
Experimental Design 1

Name	Identifier	Initial	Min	Max	Unit	Law
Source S1,fluvDischarge	Source S1,fluvDischarge	3000	2400	3600	m^3/s	Uniform
Source S1,supply	Source S1,supply	850	680	1020	km^3/Ma	Uniform
Source S2,fluvDischarge	Source S2,fluvDischarge	2000	1600	2400	m^3/s	Uniform
Source S2,supply	Source S2,supply	750	600	900	km^3/Ma	Uniform
Source S3,fluvDischarge	Source S3,fluvDischarge	200	160	240	m^3/s	Uniform
Source S3,supply	Source S3,supply	200	160	240	km^3/Ma	Uniform

Simulation	Source S1,fluvDischarge	Source S1,supply	Source S2,fluvDischarge	Source S2,supply	Source S3,fluvDischarge	Source S3,supply
1	3000	850	2000	750	200	200
2	2640	1020	2000	660	224	176
3	3360	850	2400	870	200	208
4	2520	816	1600	840	184	224
5	2400	884	2320	630	176	216
6	3240	952	1920	600	240	240
7	3600	714	1680	750	216	192
8	3000	918	1840	900	160	184
9	2760	748	1760	780	168	160
10	3480	986	2080	810	232	200
11	3120	680	2160	690	208	232
12	3600	1020	2400	600	240	160
13	2400	680	1600	900	160	240







Hawie et al., 2017
Sangster et al., 2019

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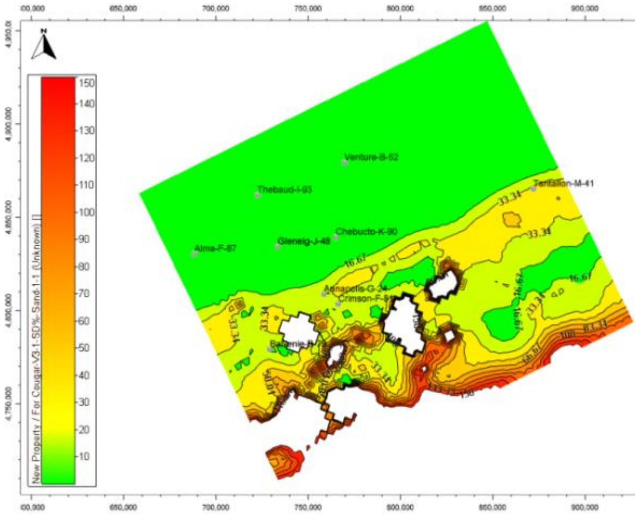
Model Sensitivity (Ksand)

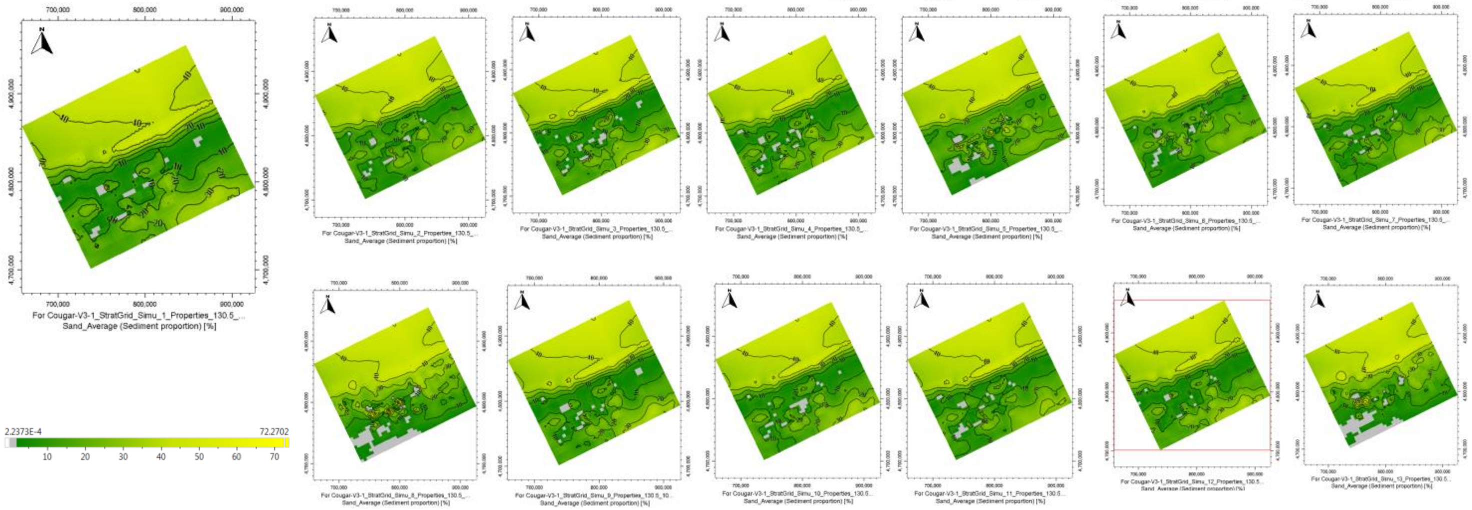
- Overall average sand content results of the 2nd experimental design (Ksand variation)
- the related standard deviation (top).

Experimental Design 2

Name	Identifier	Initial	Min	Max	Unit	Law
Sand,Marine water driven	Sand,Marine water driven	0,013	0,0065	0,026	km²/kyr	Uniform
Sand,Marine high energy	Sand,Marine high energy	0,1	0,05	2	km²/kyr	Uniform

Simulation	Sand,Marine water driven	Sand,Marine high energy
1	0,0182	2
2	0,02405	0,635
3	0,0065	1,805
4	0,026	1,415
5	0,00845	0,245
6	0,0143	0,44
7	0,02015	1,025
8	0,0221	0,05
9	0,01235	1,61
10	0,01625	1,22
11	0,0104	0,83
12	0,026	2
13	0,0065	0,05





Hawie et al., 2017
Sangster et al., 2019

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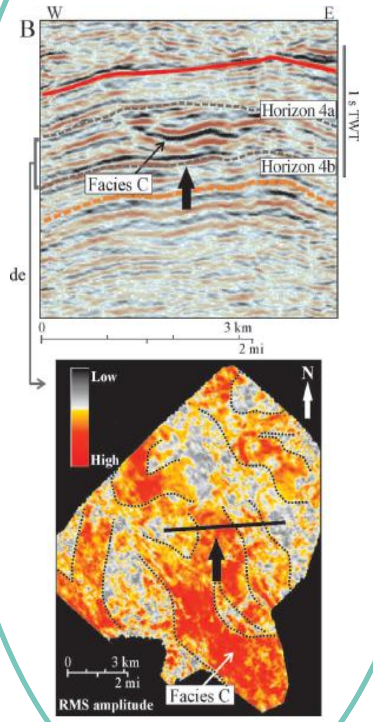
The Golf of Mexico and Trinidad

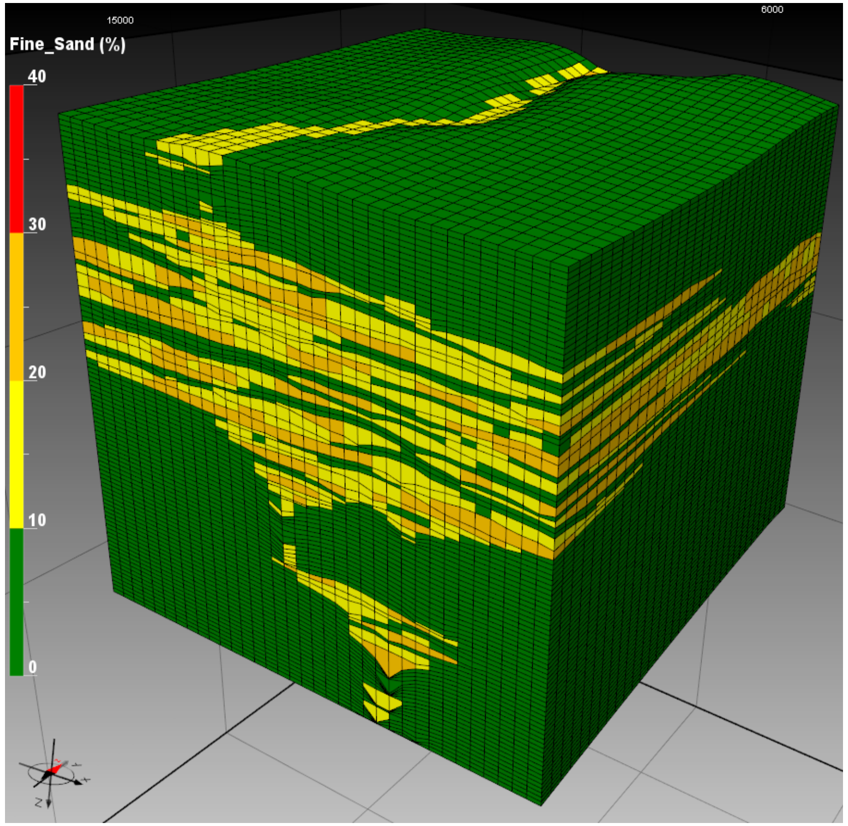
Objective

Forward Stratigraphic Modelling

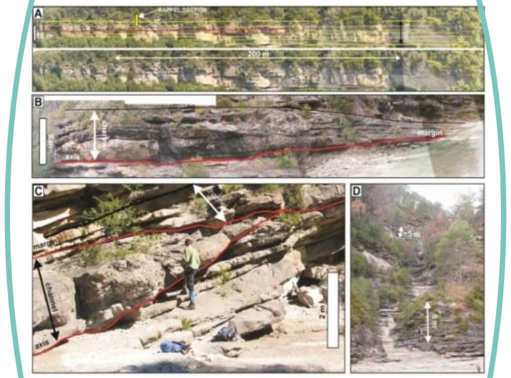
Seismic Data



McDonnell et al., 2008



Outcrop Description



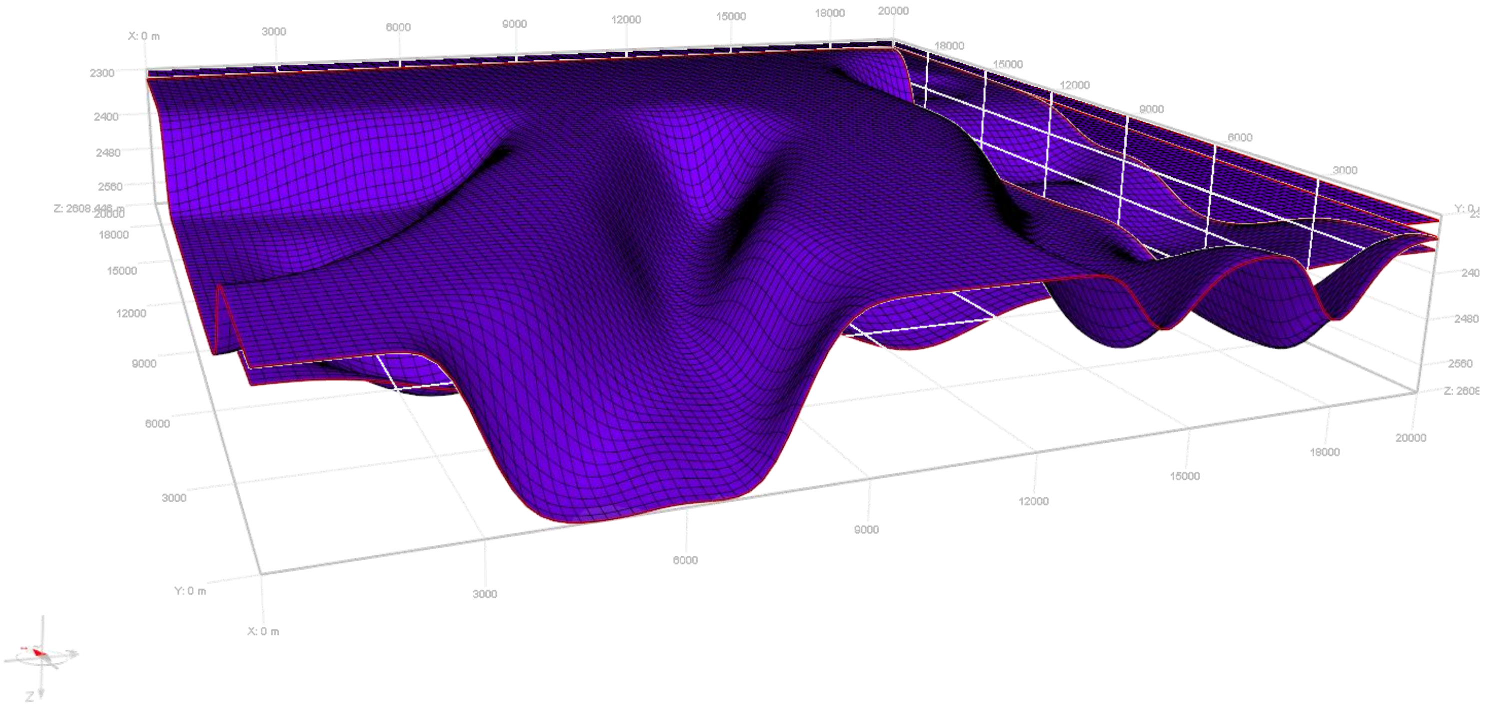
G. Gordon, 2014

Hawie & Marfisi 2017

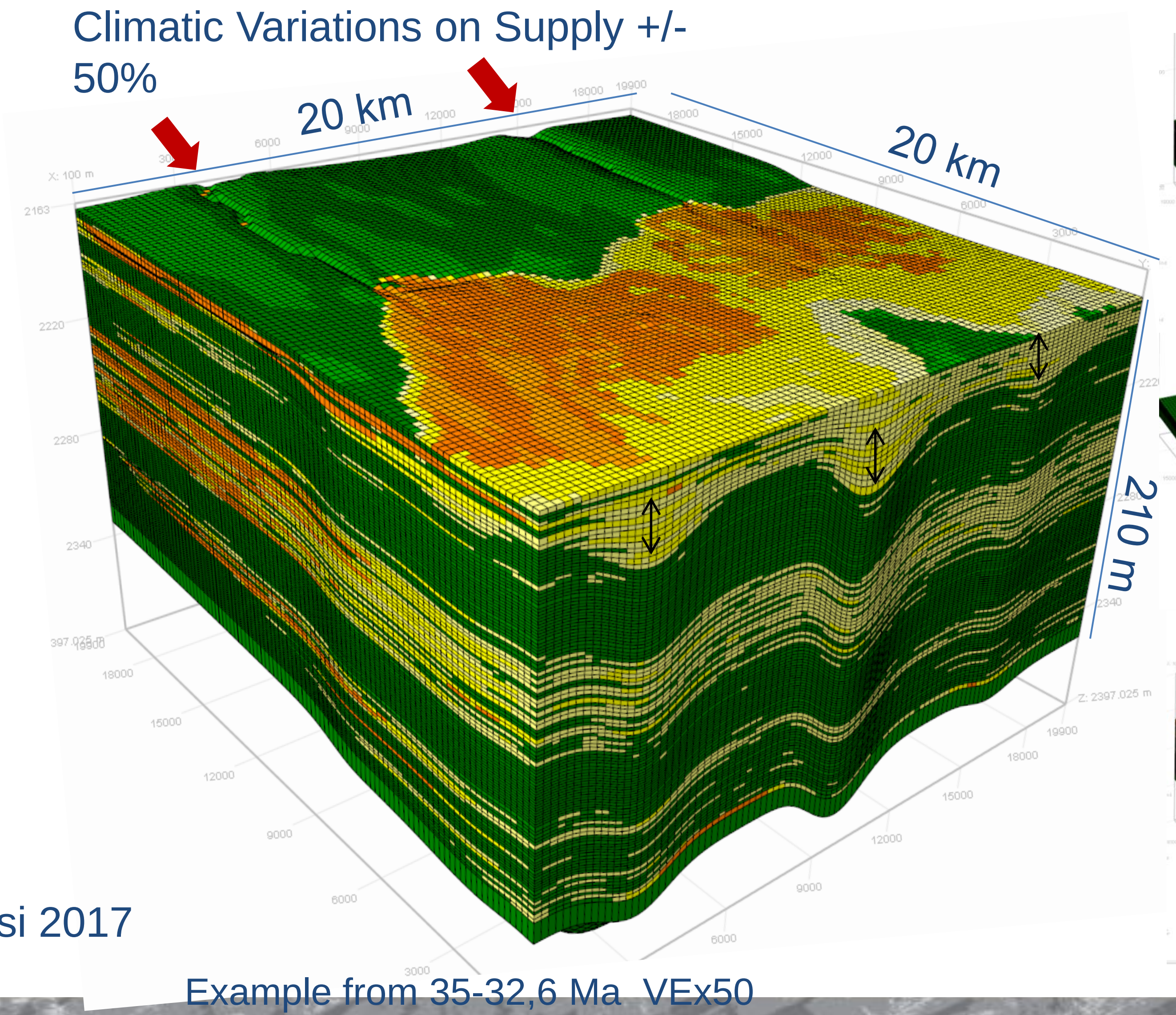
Providing a time scaled reproduction of the geometry and distribution of sedimentary bodies in deep sea marine environments

Model Building (2/2)

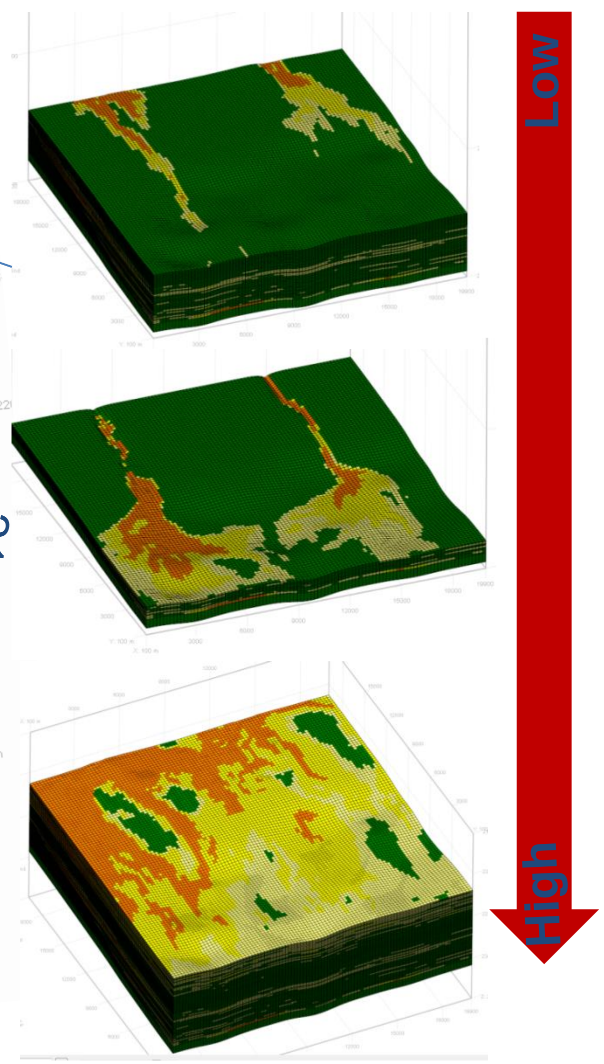
- Long-term flow + short term events (climatic cycles)
- **Salt deformation** and its impact on sedimentation was simulated



Overall Facies Model

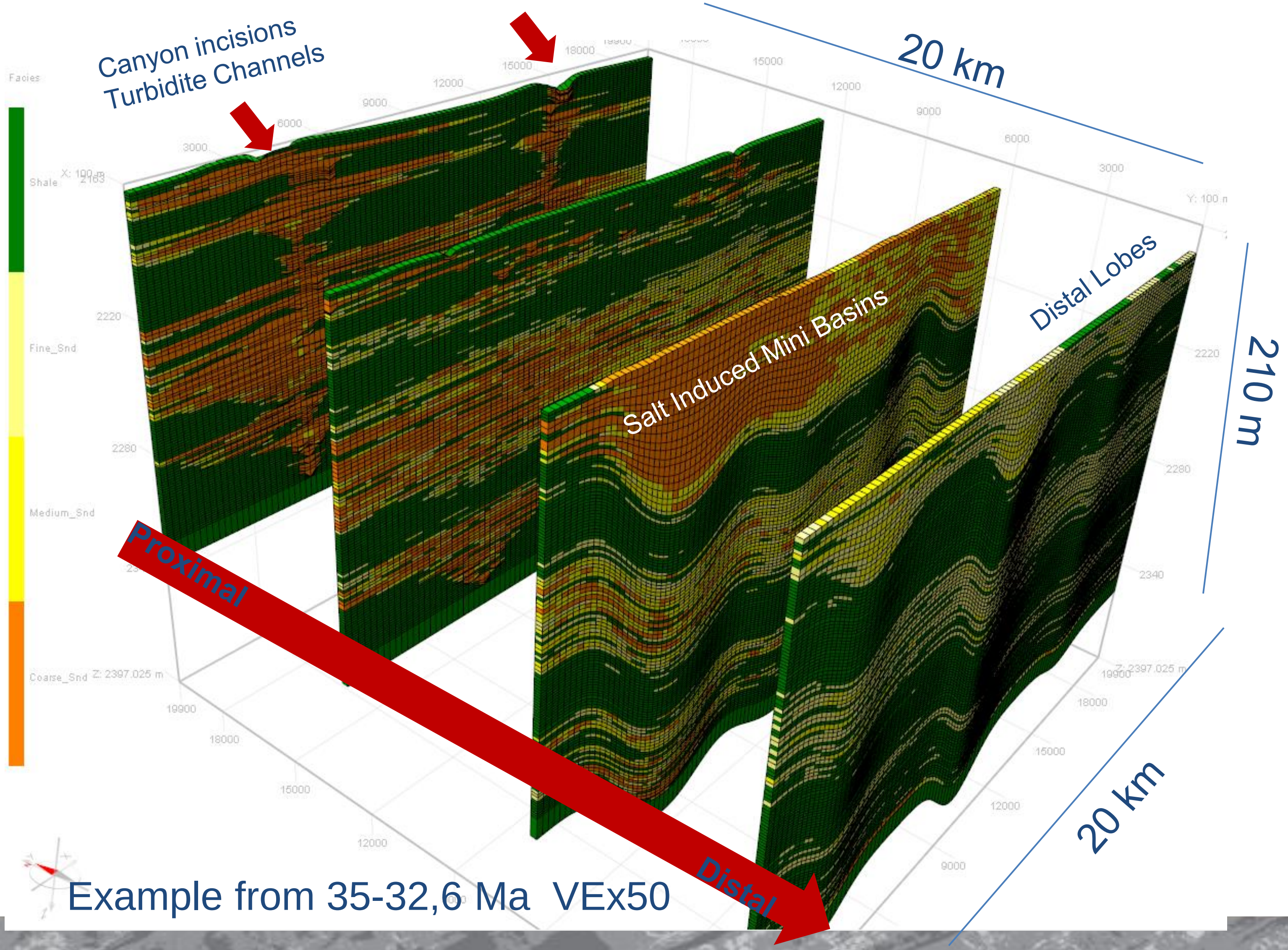


Sediment Supply



Hawie & Marfisi 2017

Overall Facies Model & Geometries

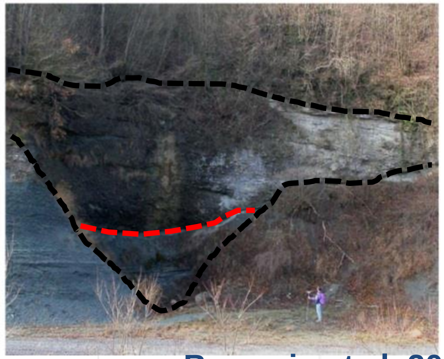


Example from 35-32,6 Ma VEx50

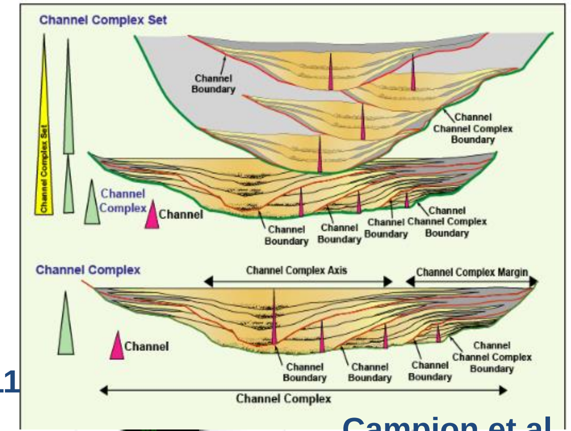
Hawie & Marfisi 2017

Channel Stacking Patterns

Hawie & Marfisi 2017

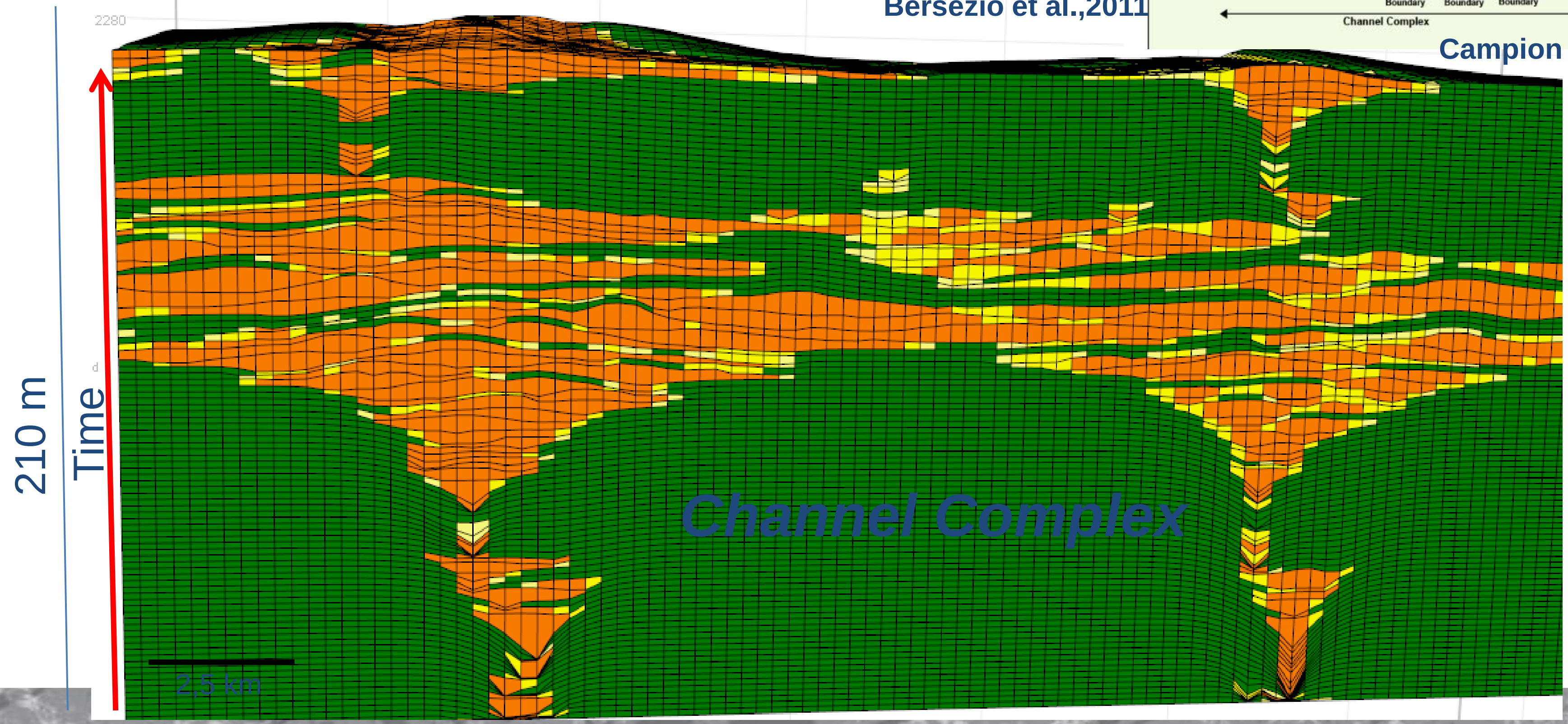


Bersezio et al.,2011

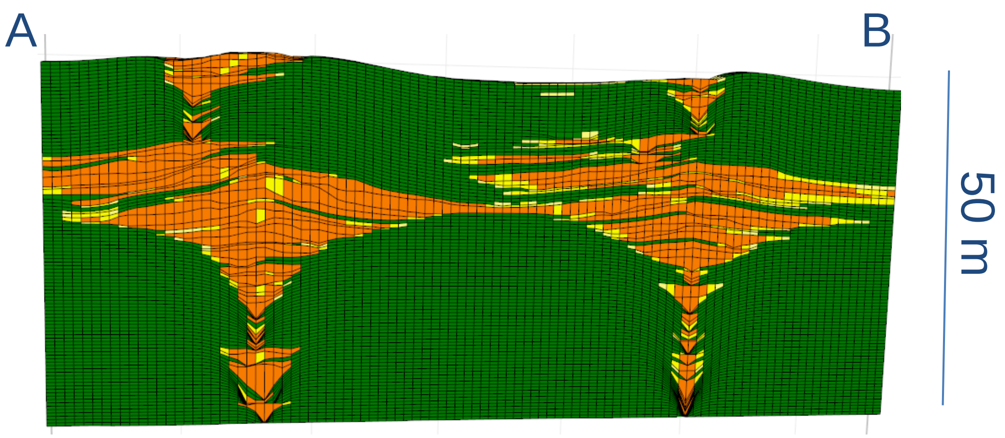


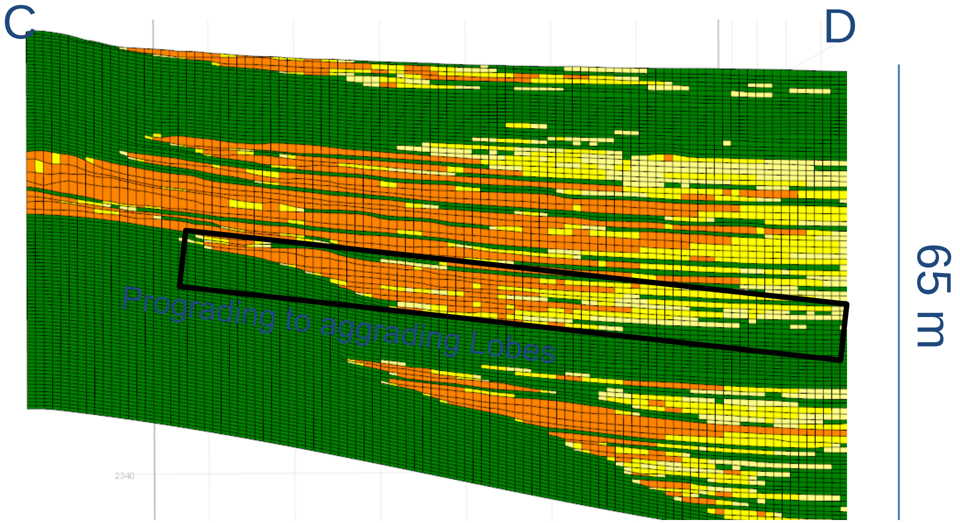
Campion et al. 2011,

Example from 35-32,6 Ma VEx50

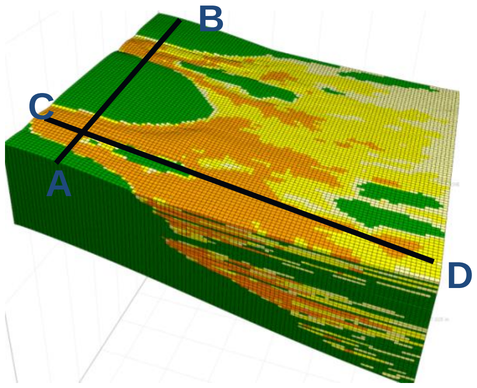


Channel Stacking Patterns & Lobe Architecture

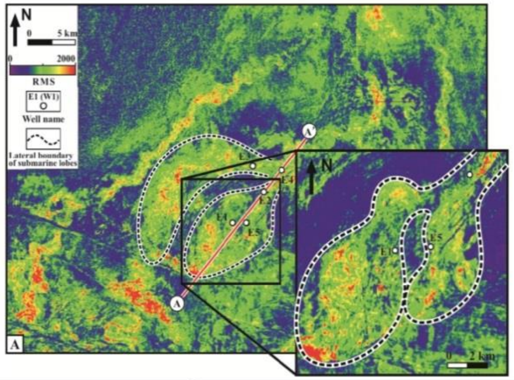


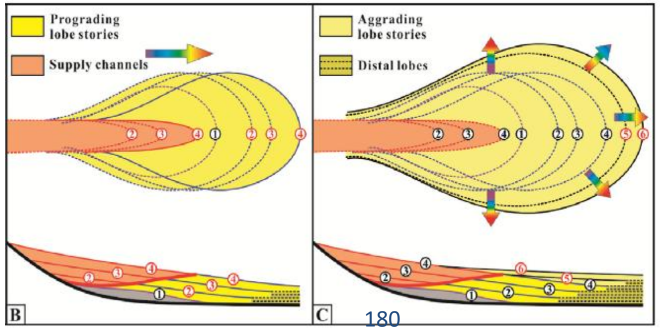


Zoom on Channel- Lobe complex VEx50



Ex. of submarine fans Niger Delta

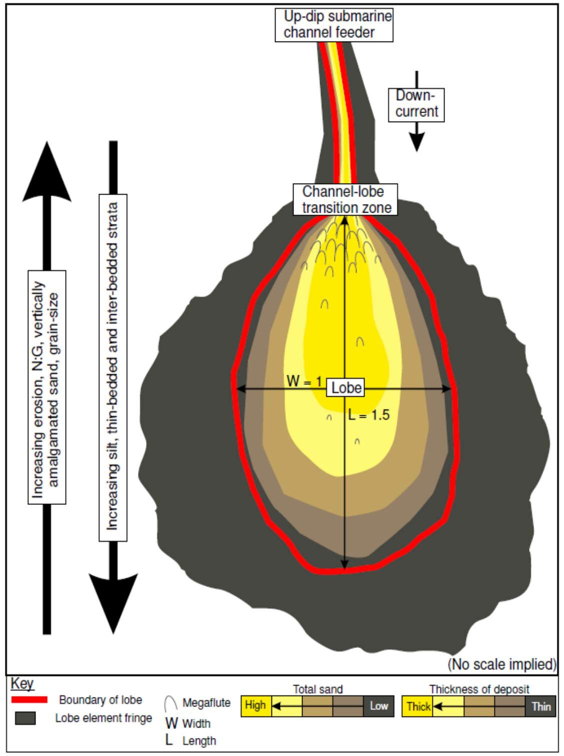


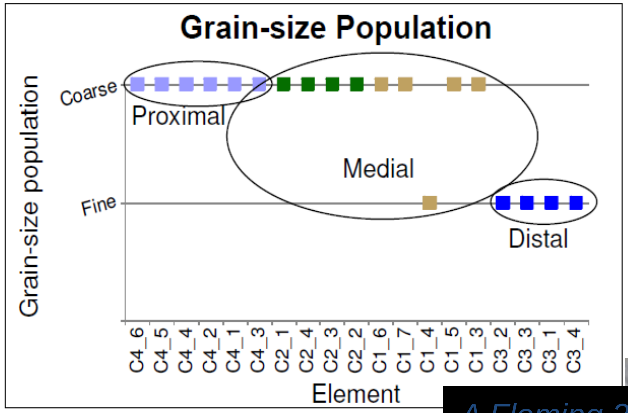


Zhang et al. 2016,

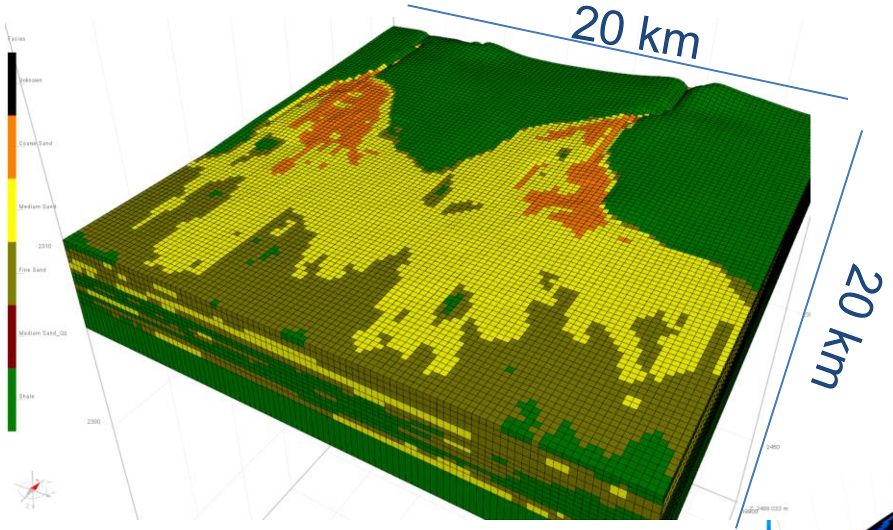
Hawie & Marfisi 2017

Channel & Lobe Granulometry

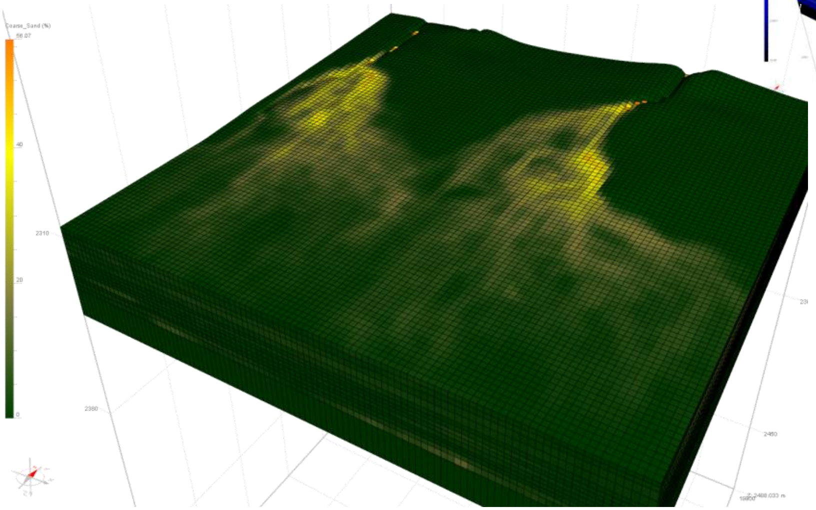




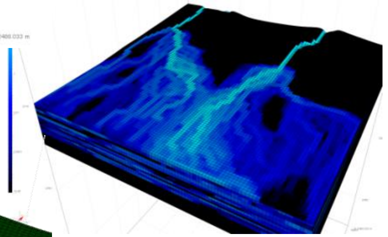
A Fleming 2013



Facies distribution



Coarse sand distribution



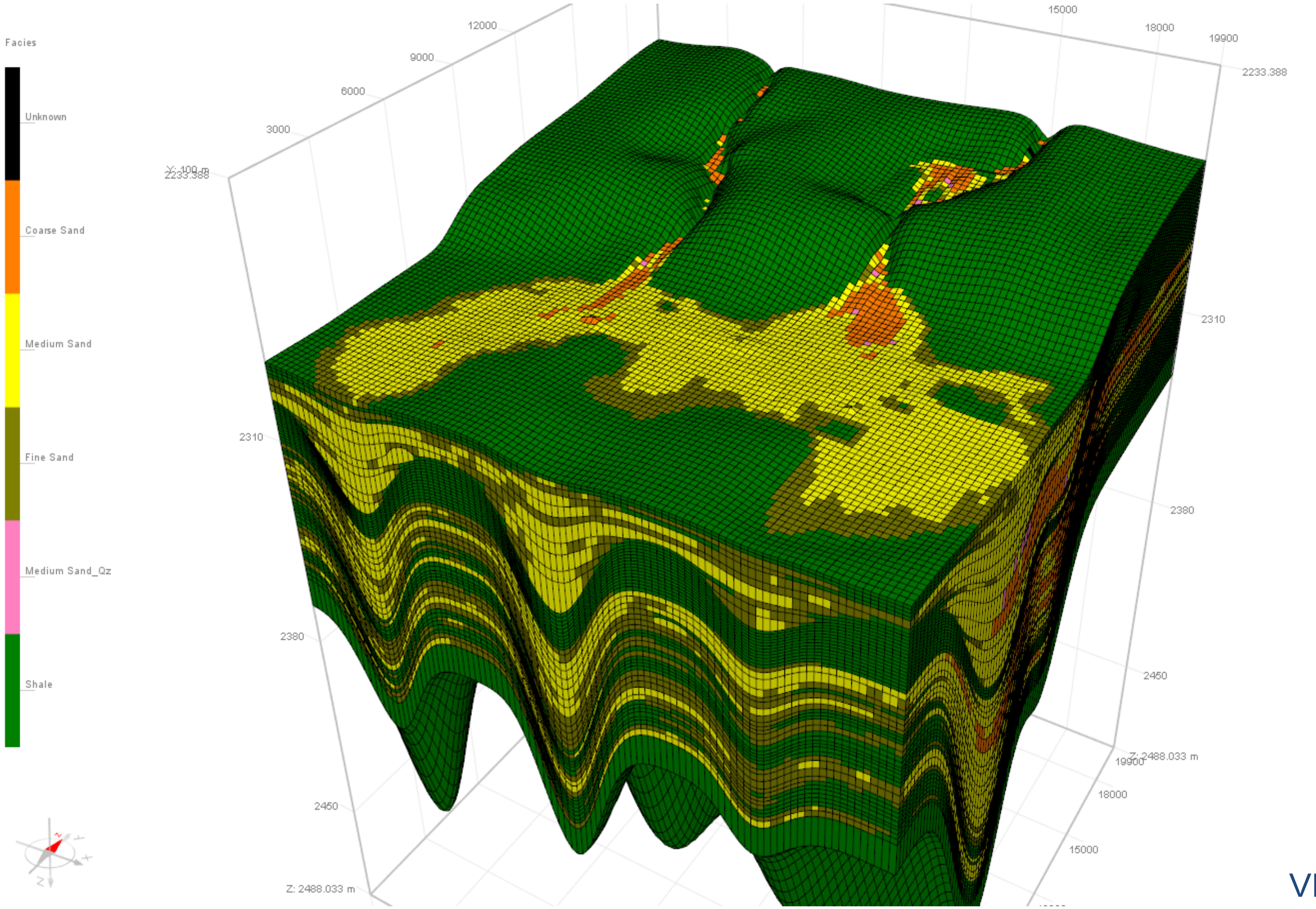
Water flow

VEx100

Hawie & Marfisi 2017

Impact of Salt Deformation

- Time step of 50kyrs

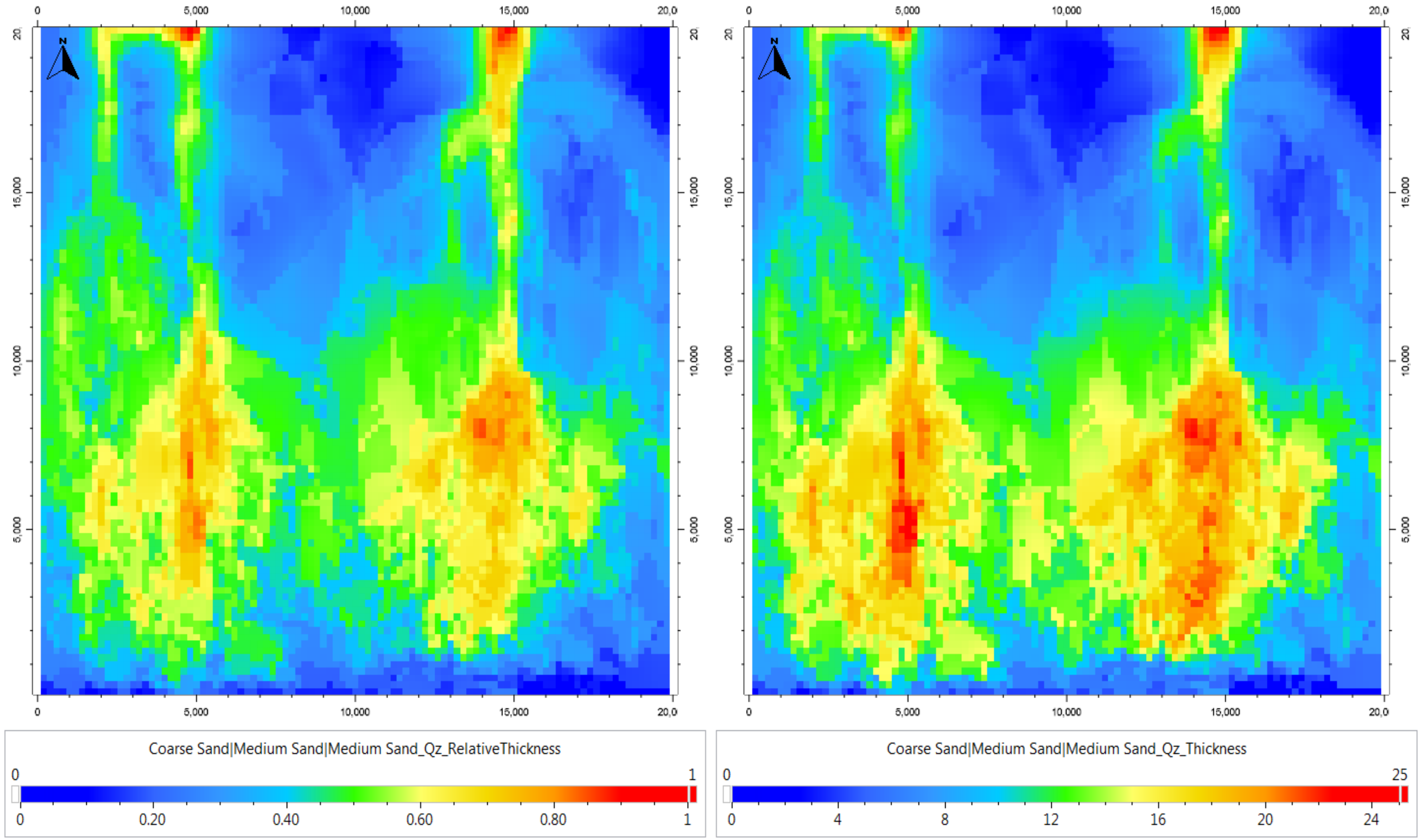


VEx100

Hawie & Marfisi 2017

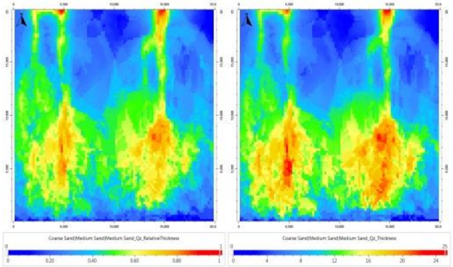
Thickness & NTG Maps (1/2)

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

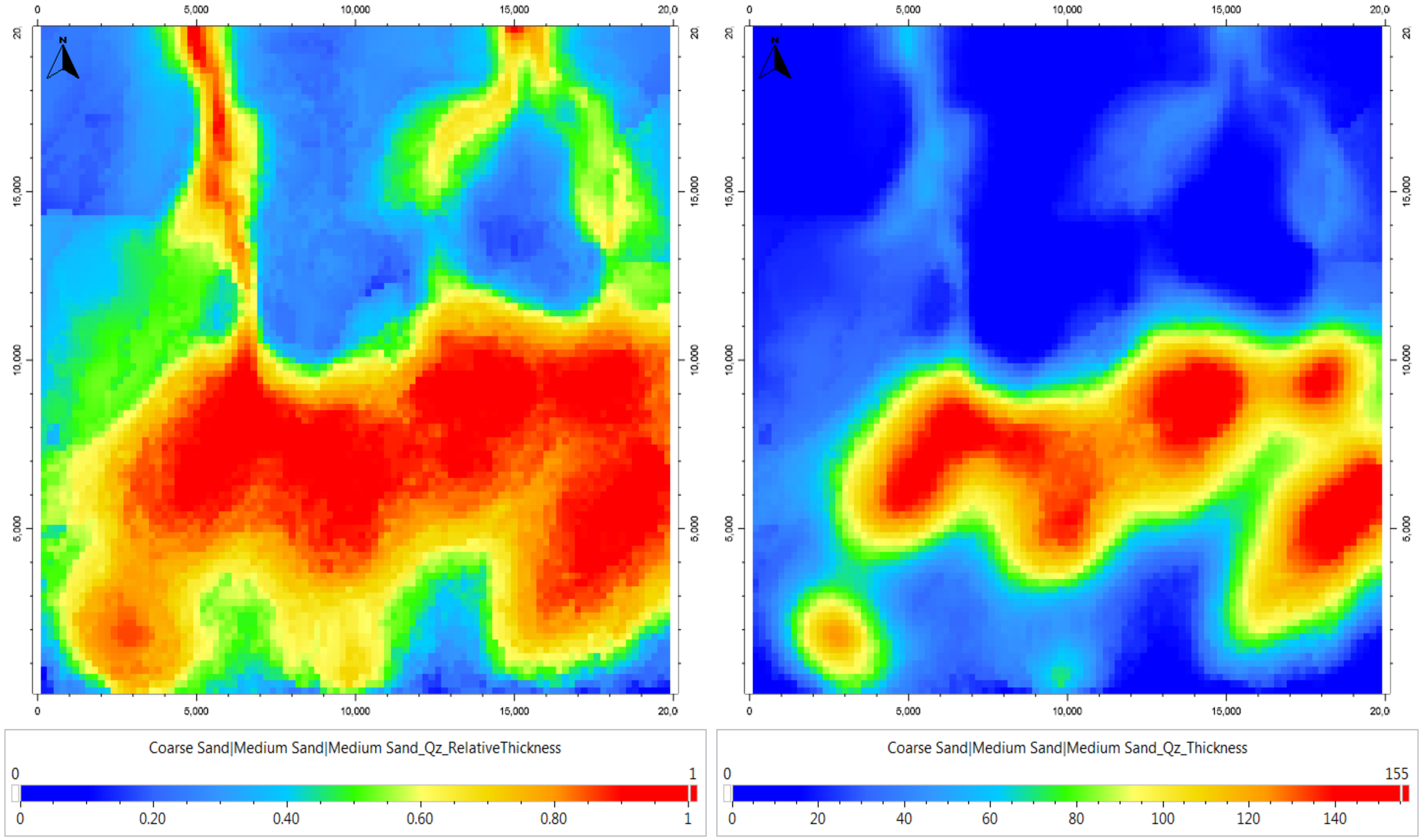


Hawie & Marfisi 2017

Thickness & NTG Maps (2/2)



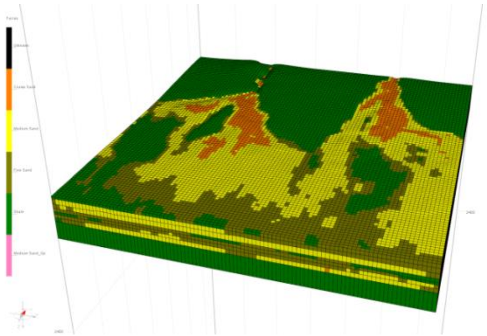
- Post-Salt (34 to 32Ma): {medium + coarse sand}



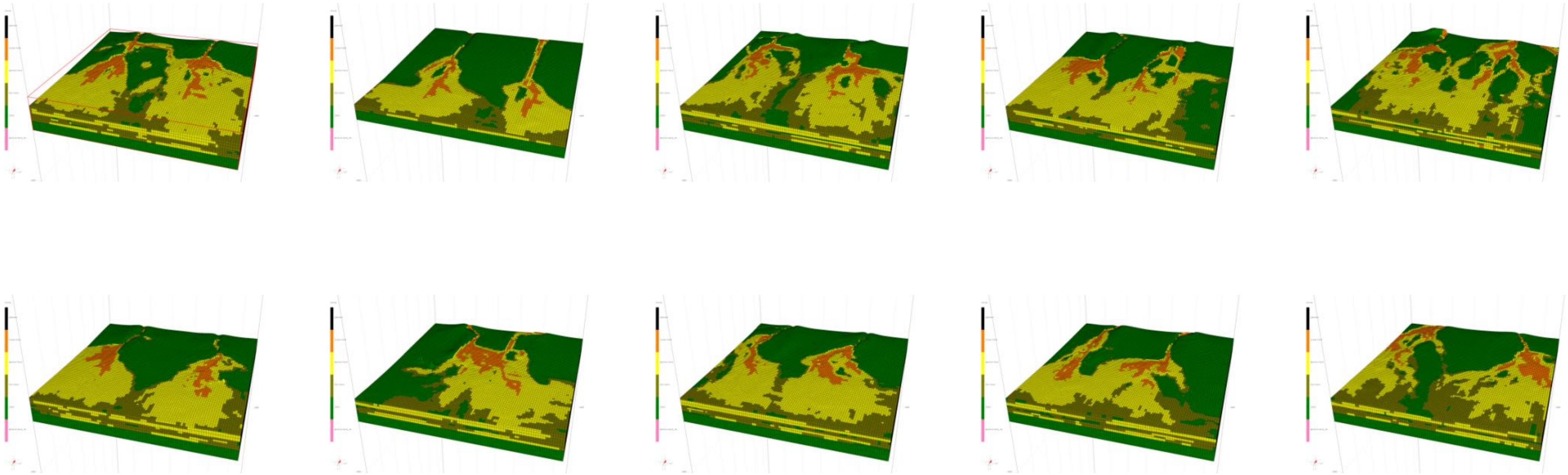
Hawie & Marfisi 2017

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%)



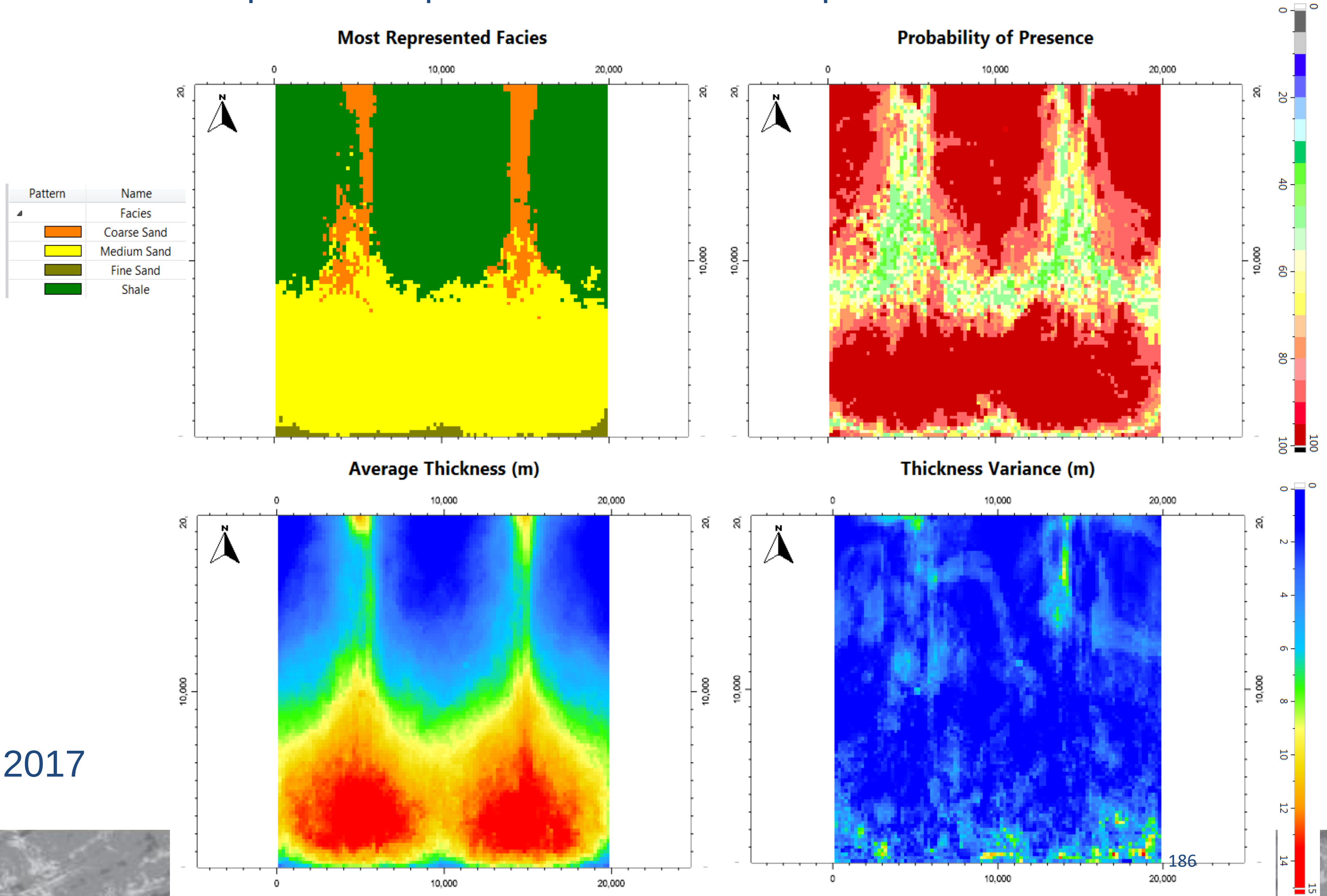
- Total of 11 simulations to cover the entire uncertain domain



Hawie & Marfisi 2017

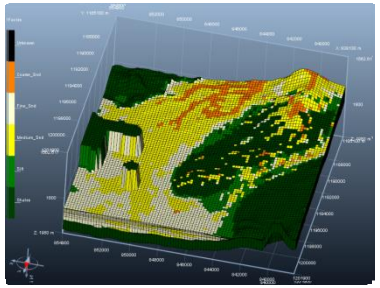
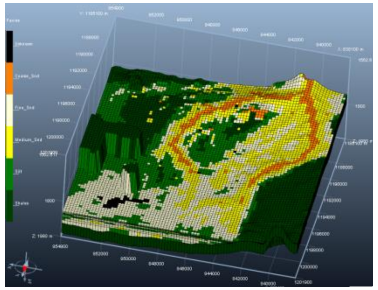
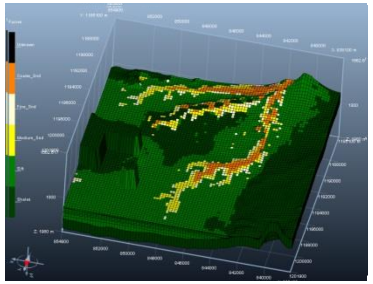
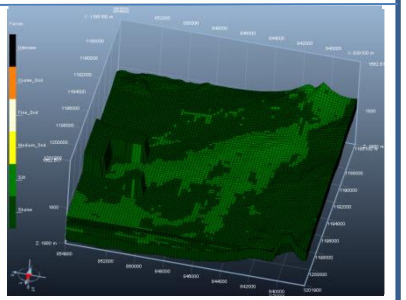
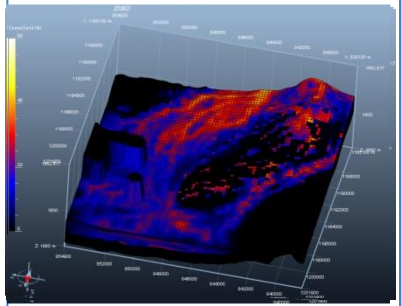
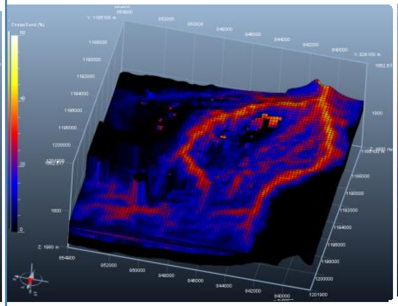
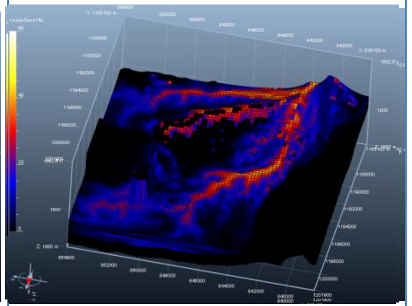
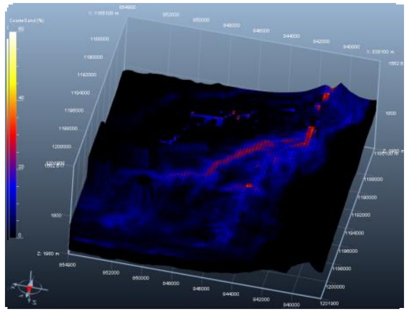
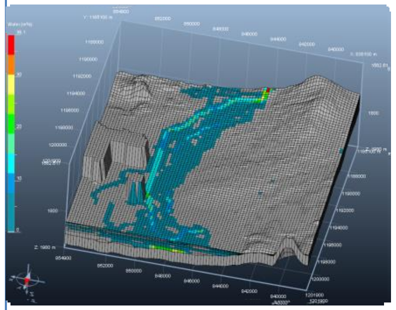
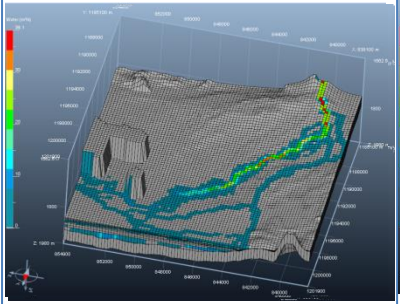
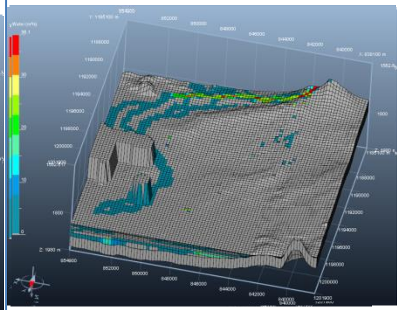
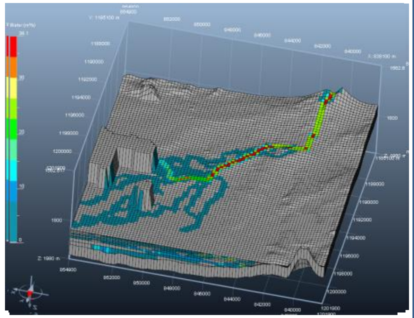
Sensitivity Maps

- Example for the pre-salt deformation sequence:



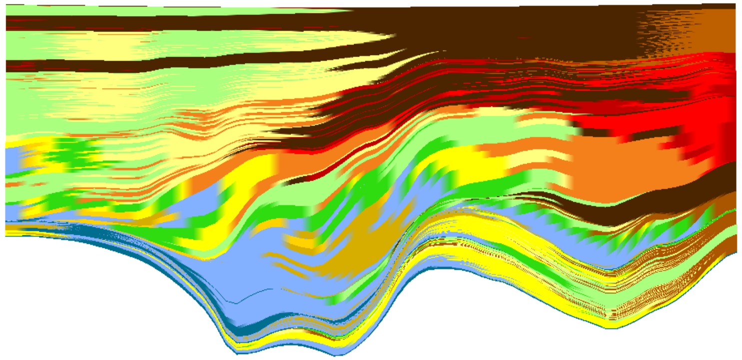
Hawie & Marfisi 2017

Experimental Design 1 (Shale Content)

				
				
Water Discharge				

Hawie et al., 2017,2018, 2019

Added-Value of Integrated FSM for E & P



Geological & Facies Model Validation

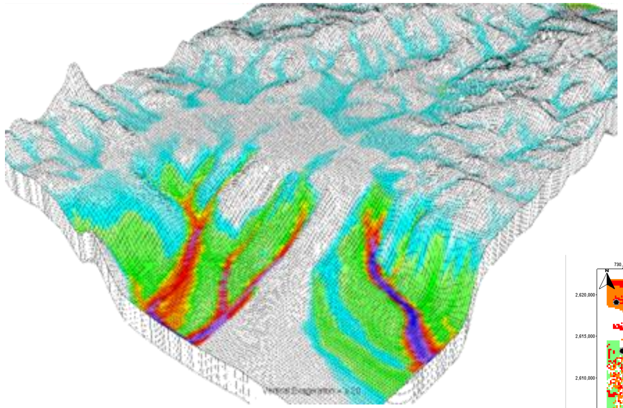
- Evaluate all compiled data consistency
- Regional sedimentary concepts

Study of Sedimentary processes

- Depositional environment and environmental parameters for clastics and carbonate

Reservoirs, Seals & Source Rock Delineation

- Geometries and facies : extension, thicknesses, connectivity
- Extension and thicknesses of seals
- Distribution, thicknesses and nature of source rocks

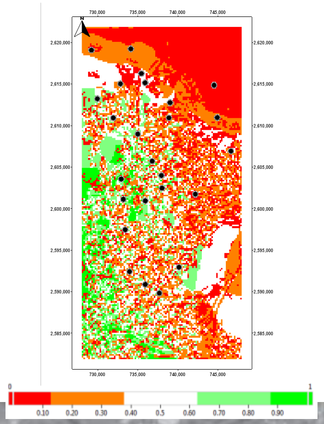


Water Flow

Enhance basin petroleum models (pressure, temperature and migration simulations)

- Generation of detailed facies maps for basin modeling

Enhance Reservoir Models



Texture Sensitivity Map

Multi-realizations & sensitivity analysis

- Better assessment of geological uncertainty and risk

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Final Open Discussion:
Interesting Exploration in India

Interesting Exploration Frontiers in India

Mumbai Offshore Basin

- Age of the Basin & Sediment-thickness
  Late Cretaceous to Holocene with thick sedimentary fill ranging from 1100-5000 m. possibility of occurrence of Mesozoic synrift sequences in the deep-water basin have been indicated by the recently acquired seismic data by GXT, it needs to be further ascertained by future studies.

- Exploration history
  The first oil discovery in this basin was made in the Miocene limestone reservoir of Mumbai High field in February 1974. Several significant discoveries including oil and gas fields like Heera,Panna, Bassein, Neelam,Mukta, Ratna,Soth tapti, Mid Tapti etc.In addition number of marginal fields like B-55, B-173A, B-119/121, D-1 and D-18 have been put on production in the last decade.

- Different Tectonic Zones within the Basin
  Five distinct structural provinces with different tectonic and stratigraphic events can be identified within the basin viz. Surat Depression (Tapti-Daman Block) in the north, Panna-Bassein-Heera Block in the east central part, Ratnagiri in the southern part, Mumbai High-/Platform-Deep Continental Shelf (DCS) in the mid western side and Shelf Margin adjoing DCS and the Ratnagiri Shelf.

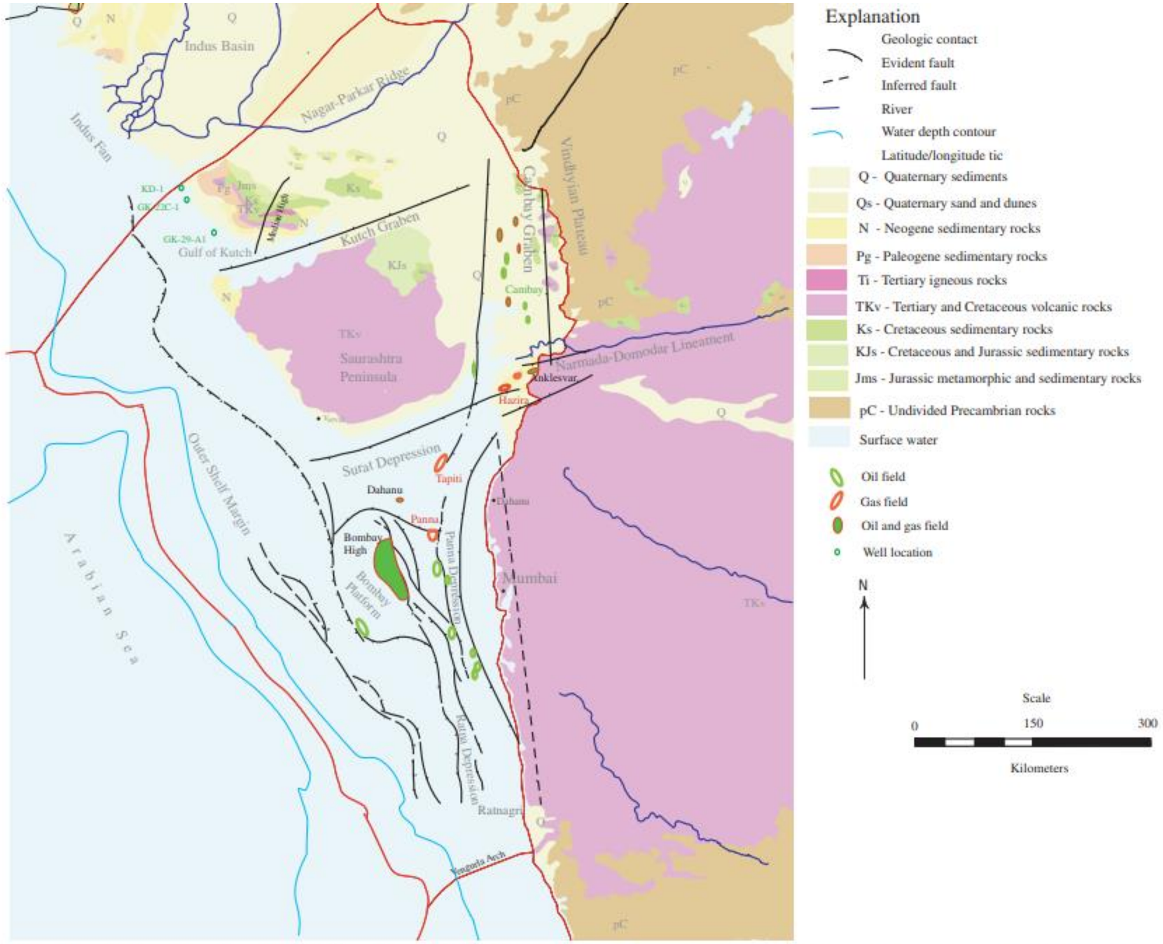


Figure 15. Regional structure and selected oil and gas fields (modified from Rao and Talukdar, 1980; Biswas and Deshpande, 1983; Mitra and others 1983; Wandrey and Law, 1999).

[Mumbai Offshore Basin | NDR (National Data Repository)-Directorate General of Hydrocarbons(DGH) | Ministry of Petroleum and Natural Gas, Government of India (ndrdgh.gov.in)]

Interesting Exploration Frontiers in India

Mumbai Offshore Basin

Reservoir		
Age	**Lithology/Location**	**Comments**
Middle Miocene	Carbonate sections at Ratnagiri, Mumbai high & Diu (Ratnagiri & Bandra formations)	The uppermost part has been found to be hydrocarbon bearing at a few places A sheet like sand deposited over Mumbai High (S1) is also proved to be gas bearing in commercial quantity in Mumbai High
Lower Miocene	Represented by a thick pile of carbonates hosting huge quantity of oil and gas over Mumbai High (Bombay, Ratnagiri)	Deposited under cyclic sedimentation with each cycle represented by lagoonal, algal mound, foraminiferal mound and coastal marsh facies The porosity is mainly intergranular, intragranular, moldic, vuggy and micro-fissures and the solution cavities interconnected by micro-fissures provided excellent permeability.
Oligo– Early Miocene	Sands in the central and mid-eastern part of Surat depression i.e. Tapti- Daman area, Daman formation. Carbonates adjoining Mumbai High(Panvel formation)	Deposited under prograding delta conditionsProved to be excellent reservoirs
Eocene and Early Oligocene	E.Oligocene clastics of Surat depression(Mahuva Formation) Deposition of thicker carbonate facies over the horst blocks in Panna- Basein-Heera and Ratnagiri blocks (Bassein, Mukta & Heera formations).	Proven hydrocarbon bearing reservoirs in Tapti area. Gradual increase of sea level, shielding from the clastic onslaught from the northern part of the basin. The intervening regressive phases have aided in developing good porosity in these rocks making them excellent reservoir levels in the basin.
Paleocene	Coarser clastic facies developed within the upper marine shale sequence in areas of Mumbai High, Panna and Ratnagiri (Panna Formation)	The clastics of Panna formation are proved to be excellent reservoirs in the Sw flank of Panna –Basin platform.

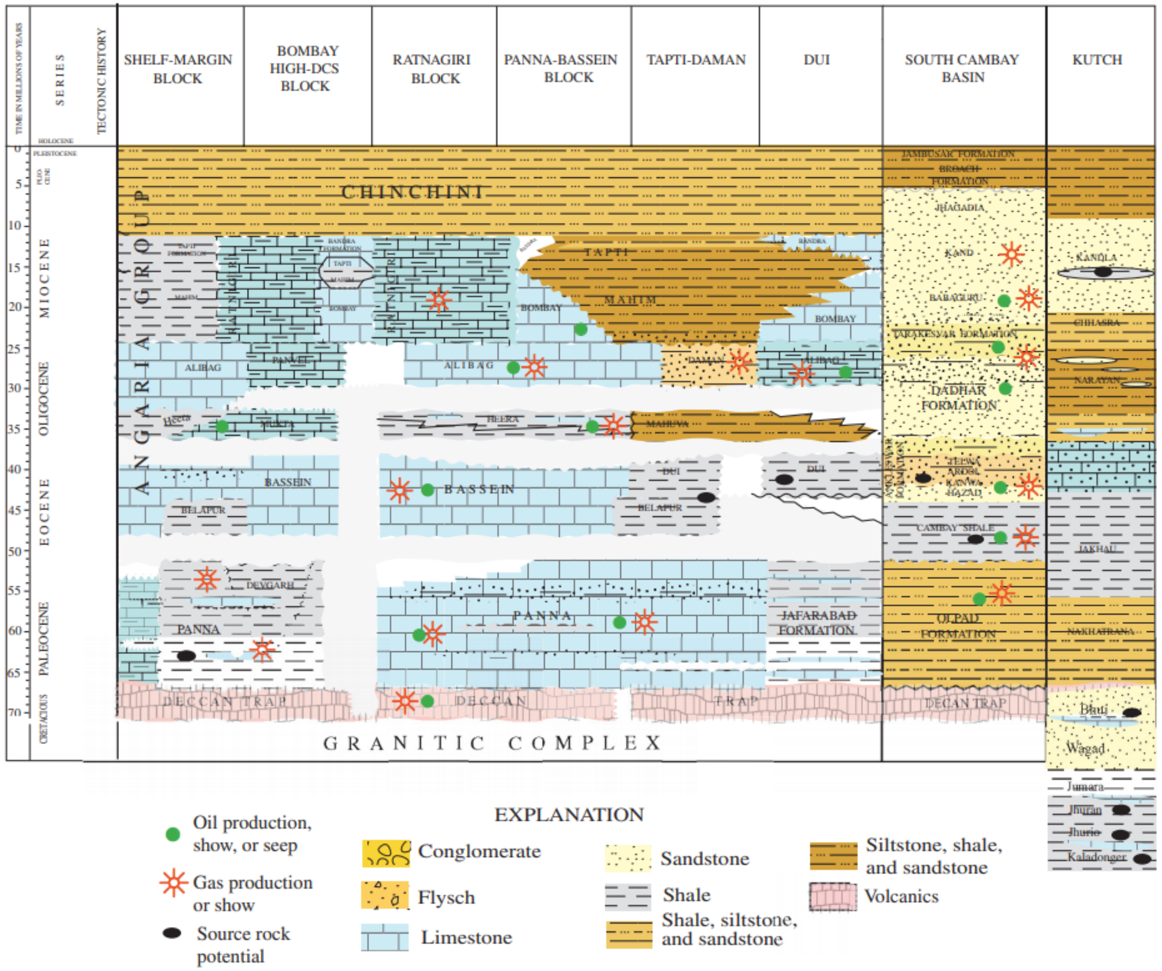


Figure 4. Generalized stratigraphy of the Bombay-Cambay-Kutch area (modified from Mishra and others, 1997; ONGC, 1983; Biswas and others, 1982)

Interesting Exploration Frontiers in India

Mumbai Offshore Basin

- **Major Identified play types**
  - Paleogene Synrift clastics(Paleocene-Lr. Eocene, Panna Fm)
  - Eocene Carbonate Platform (Bassein formation)
  - Lr.Oligocene Carbonate plays (Mukta and Heera formations)
  - Oligocene-Lr. Miocene deltaic Play (Mahuva &Daman formations)
  - Up. Oligocene carbonates (Panvel and Ratna formations)
  - Lr. Miocene carbonate (L-III and L-IV reservoirs, Bombay / Ratnagiri formation)
  - Lr-Mid. Miocene clastics(S1 sands),
  - Mid. Miocene carbonate (L-I and L-II reservoirs, Bandra Formation)

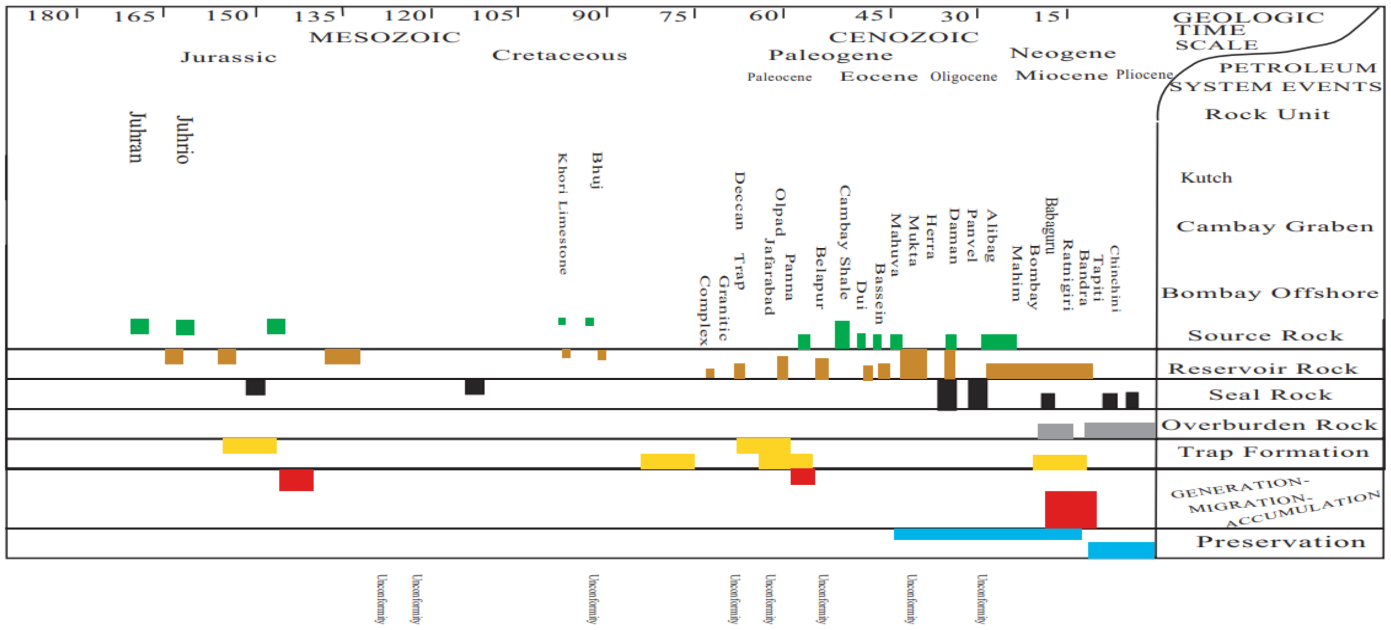


Figure 25. Events chart summarizing stratigraphy, source rocks, reservoirs, seals, traps, and petroleum information for the Bombay Geologic Province Eocene-Miocene Composite Total Petroleum System.

Interesting Exploration Frontiers in India

Vindhyana Proterozoic intracontinental Basin

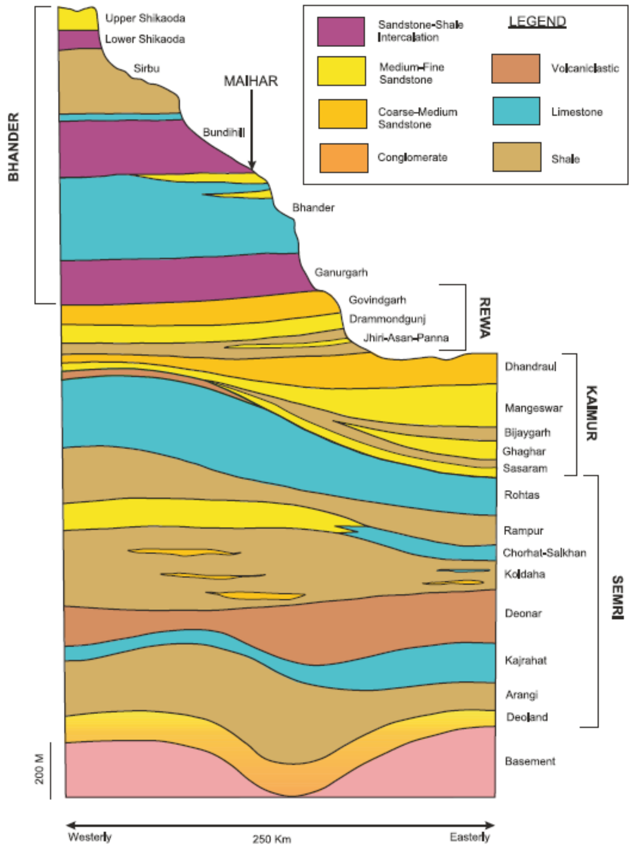


Figure 2. Strike-wise stratigraphic column of the Vindhyan Supergroup in the Son valley prepared by combining several discrete logs constructed at different locations along the structural strike. The upper boundary of the column represents the present-day topography. Maihar town has been shown as a reference location on the topographic profile.

- Succession of siliciclastic, carbonate and mixed systems
- Carbonate systems are dominated by oolites and stromatolites
- Karst features may play a role at the top of Rohtas fm.

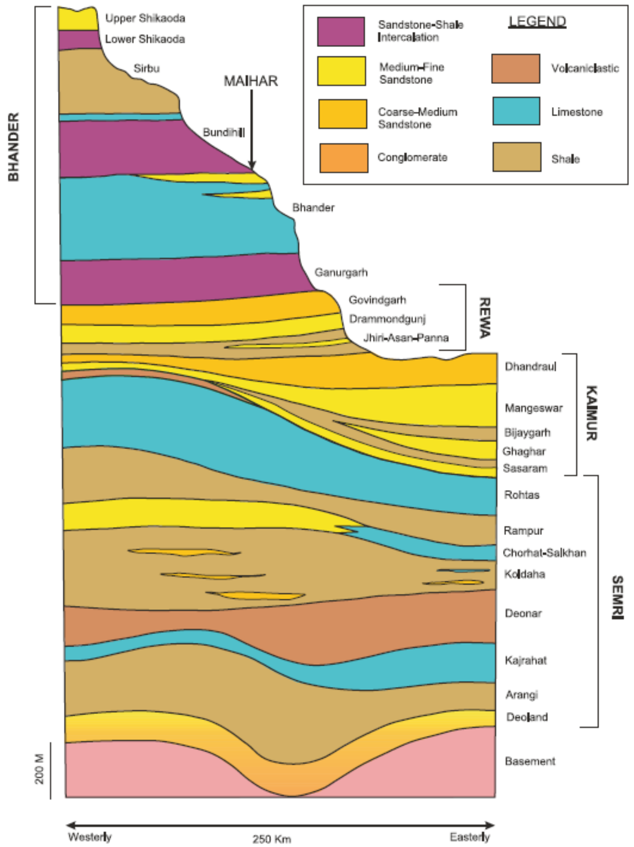
- Analogue proterozoic systems:
  - Vuggy carbonate from Eastern Siberia
  - Carbonate and siliciclastic from Taoudeni basin

- Analogues experience:
  - Mesozoic of Middle East (carbonate and mixed systems)
  - Cretaceous margin of Angola
  - Miocene of Southern Spain (outcrop)

- Numerous modern analogues could be found (Bahamas, inner Great Barrier Reef, Central Eastern margin of Australia, Belize)

Interesting Exploration Frontiers in India

Vindhyana Proterozoic intracontinental Basin



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SQ.	FORMATION		DESCRIPTION	PALEO-GEOGRAPHY
4500 (m) UPPER VINDHYAN	BHANDER	Upper Bhander Sandstone	Well sorted Sst with wave features below and cross-strata translatent, and adhesion laminae above (CU)	Fluvio-eolian and marginally marine
		Sirbu Shale	Sst-Sh interbed with wave and quadripolar sole features. Carbonate patches in Sh with emergence features below (CU)	Shelf Lagoon
		Lower Bhander Sandstone	Sst-mudstone interbed with wave and emergence features (NT)	Coastal playa
		Bhander Limestone	Micritic, oolitic and stromatolitic LSt (NT)	Shallow marine
		Ganurgarh Shale	Mudstone-Sst interbed with wave and emergence features (NT)	Chenier
	REWA	Rewa Sandstone	Well sorted Sst, bimodal x-strata below and assorted Sst unimodal x-strata and emergence features above (CU)	Tidal to fluvio-eolian
		Rewa Shale	Sh-Sst interbeds with wave and sole features (CU)	Shelf
	KAIMUR	Upper Kaimur	Well sorted Sst with thin mudstone below and large x-stratified coarser Sst with emergence features above (CU)	Shelf in fluvio-eolian
		Lower Kaimur	Sst-Sh interbeds with waves and sole features sand-free black Sh above (FU)	Intertidal to shelf
LOWER VINDHYAN	ROHTAS	Rohtas Limestone	Lst, Locally intraclastic, wave rippled (NT)	Shelf
		Rampur Shale	Gray Sh with sand-filled gutters (FU)	Shelf
	KHEINJUA	Chorhat Sandstone	Well sorted, wave featured Sst often amalgamated (CU)	Shallow marine
		Koldaha Shale	Sh-Sst interbed with waves and sole features. Local coarser poorly sorted Sst intervals with emergence features (CU)	Dominantly shelf, deltaic fluvial
	PORCELLANITE		Volcanic ash, pyroclastic flow/surge deposits, locally bearing large bombs (NT)	Shallow marine
	KAJRAHAT	Kajhrahat Limestone	Dolomitized Lst with stromatolitic and desiccation features towards top (NT)	Subtidal to peritidal
		Arangi Shale	Scarcely exposed grey Sh	Shelf
0	DEOLAND		Well sorted Sst, bimodal–bipolar cross-stratified. Localized basal diamictite (FU)	Shallow shelf

Bose et al. 2001

Thank you