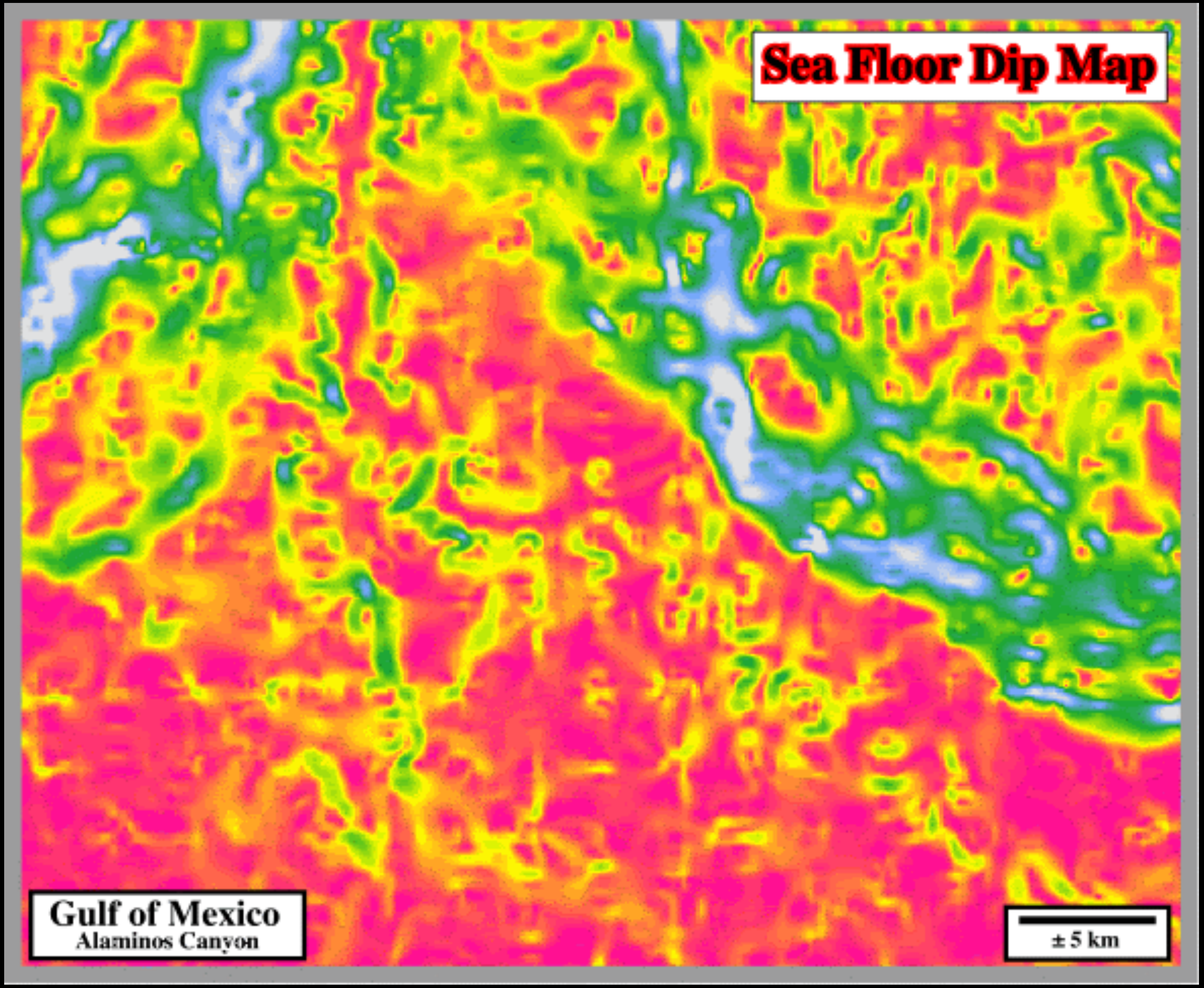
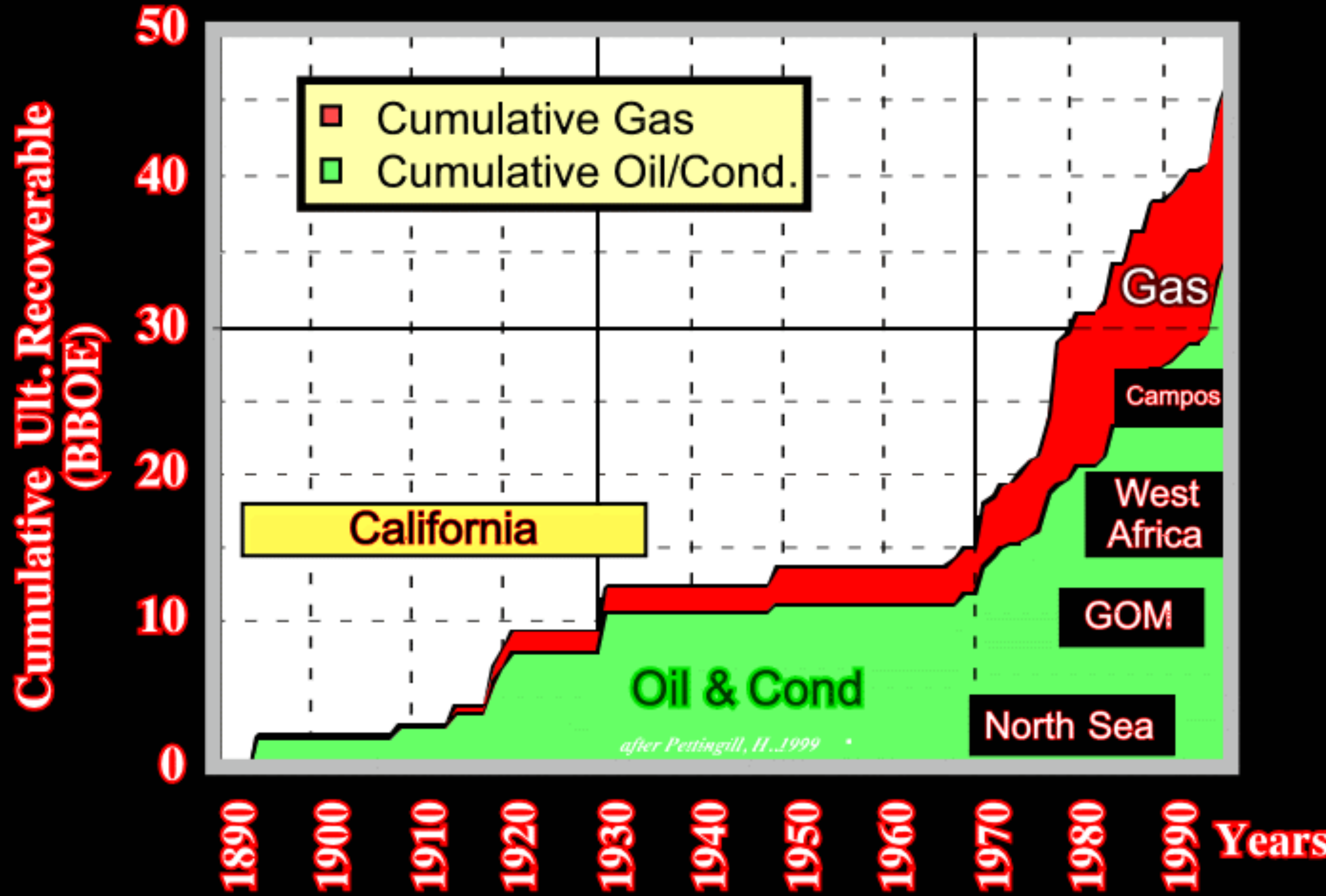
Turbidite Systems in Hydrocarbon Exploration



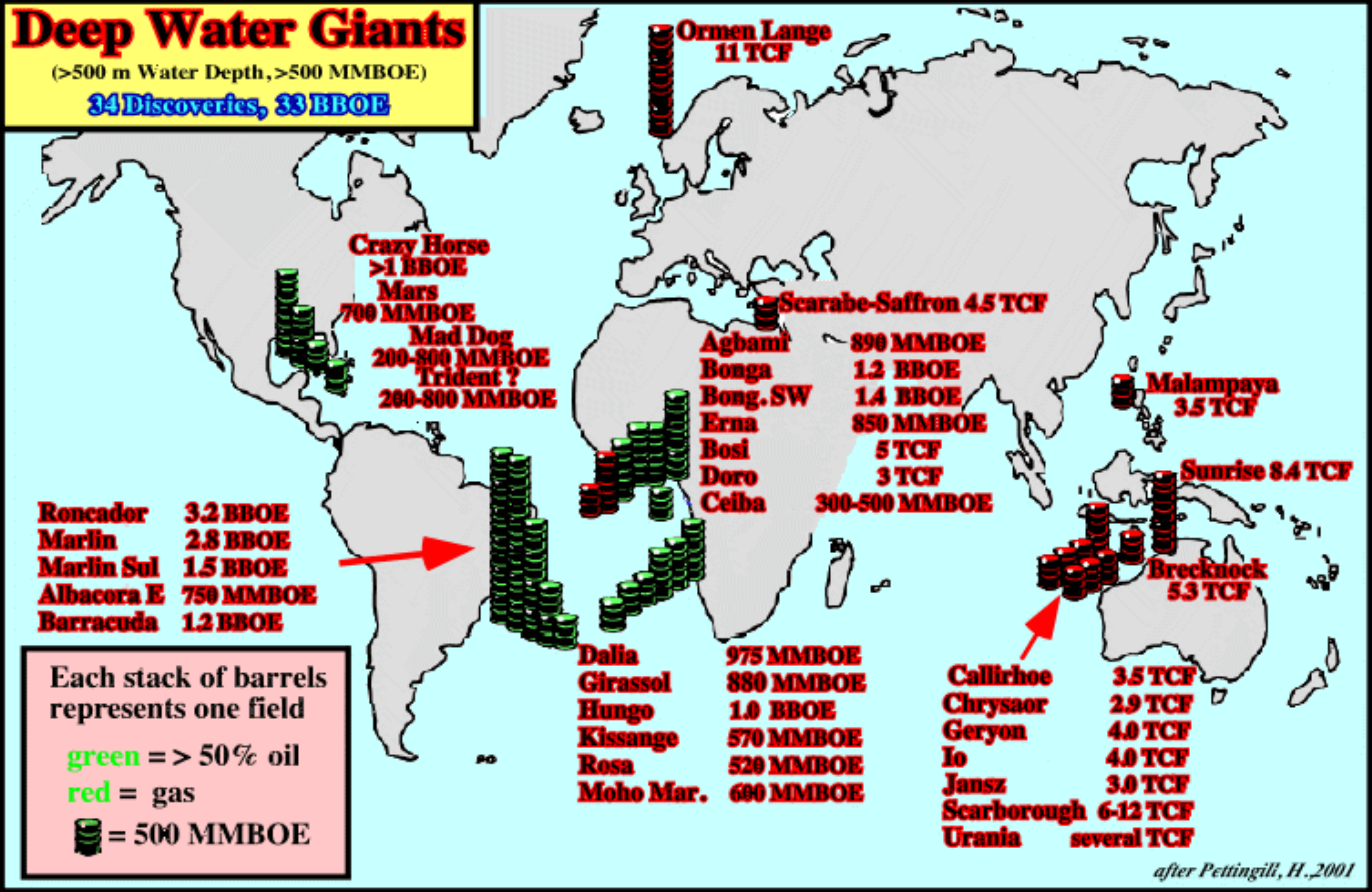
Aberdeen, April 2003

Turbidite Deposits & HC Exploration

Cumulative Turbidite Giant Reserves vs Time

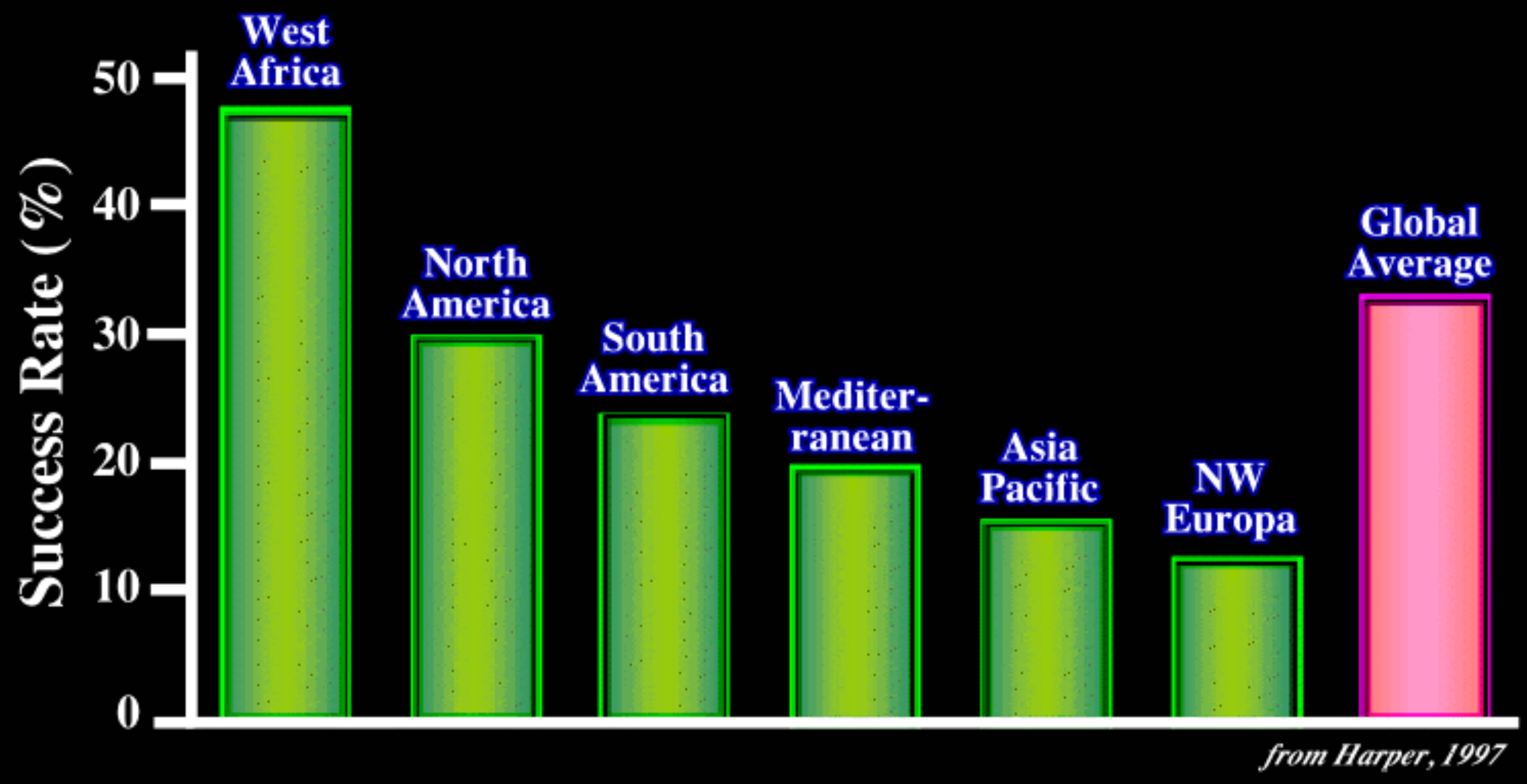


Deep Water Giants



Each stack of barrels represents deepwater HC discoveries under more of 500 m of water depth and exceeding 500 MMBOE. They (34 discoveries) have roughly 33 BBOE of reserves. Those made in South America and Gulf of Mexico are oil discoveries. In West Africa, they are either oil or gas. In Europe, Asia and Australia they are predominantly gas discoveries. For all barrel oil equivalents (BOE), the conversion factor employed is 6000 cu. ft. gas = 1 barrel oil or condensate.

Deep Water Success Rate



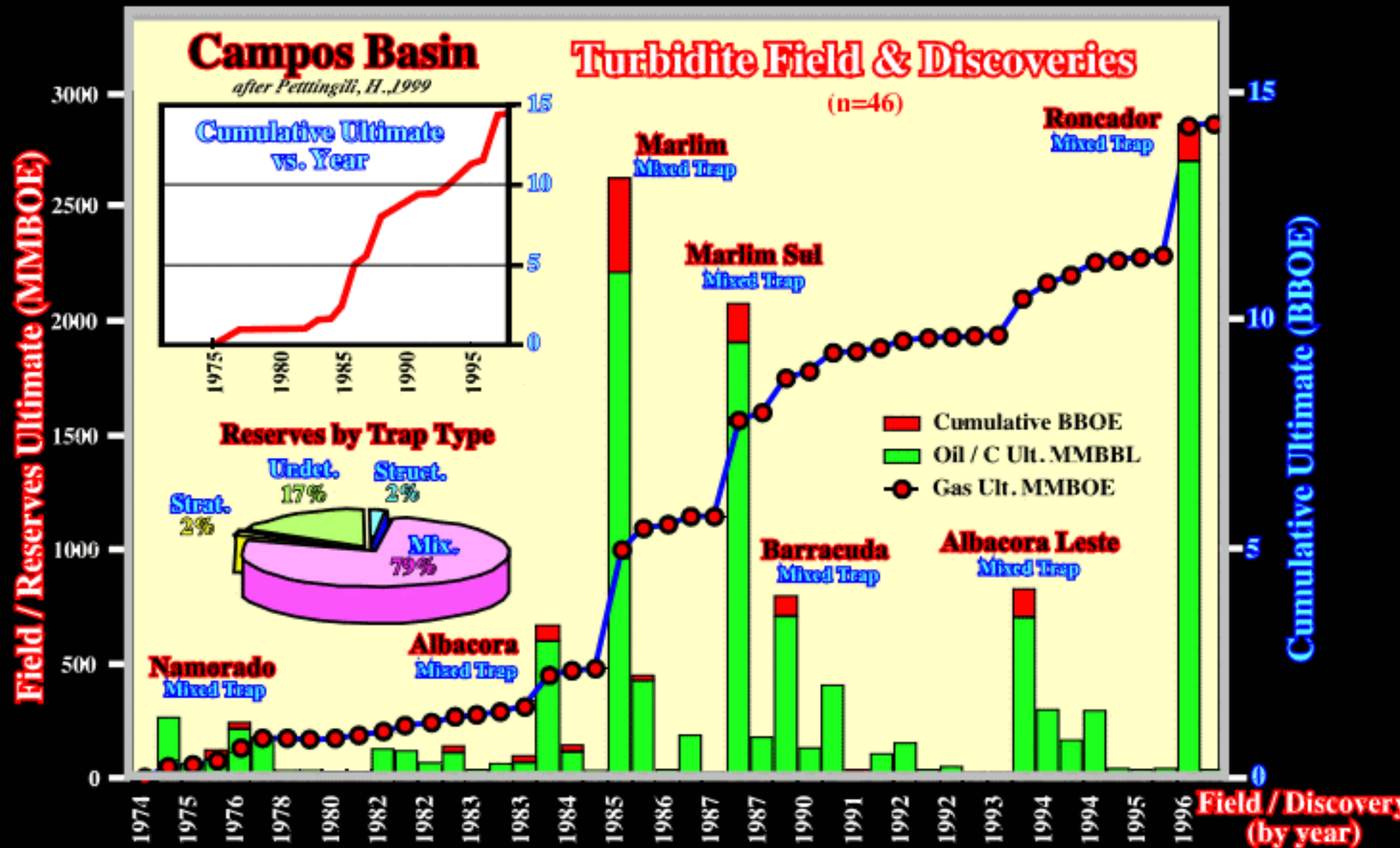
So far, in deep-water environment, exploration success rate is quite high, mainly in West Africa (40%). In Gulf of Mexico, it is around 30% and in Brazil roughly 25%. The global average exploration success rate is approximately 30 %, which, apparently, indicates that deep-water exploration is facile. However, not all discovered hydrocarbons have been proven to be economic. In addition, 200 MMBBOE discovered in West Africa will be classified as resources (may be non-economical), while in the GOM, they will be considered as reserves, i.e. economical.

Deep Water Cartesian Exploration

In spite of the large number of announced discoveries, the consequences of the Cartesian exploration deep water approach are already quite perceived. A lot of drilled amplitude anomalies (USA $30 to 50 M per well) are not associated with hydrocarbons but with:

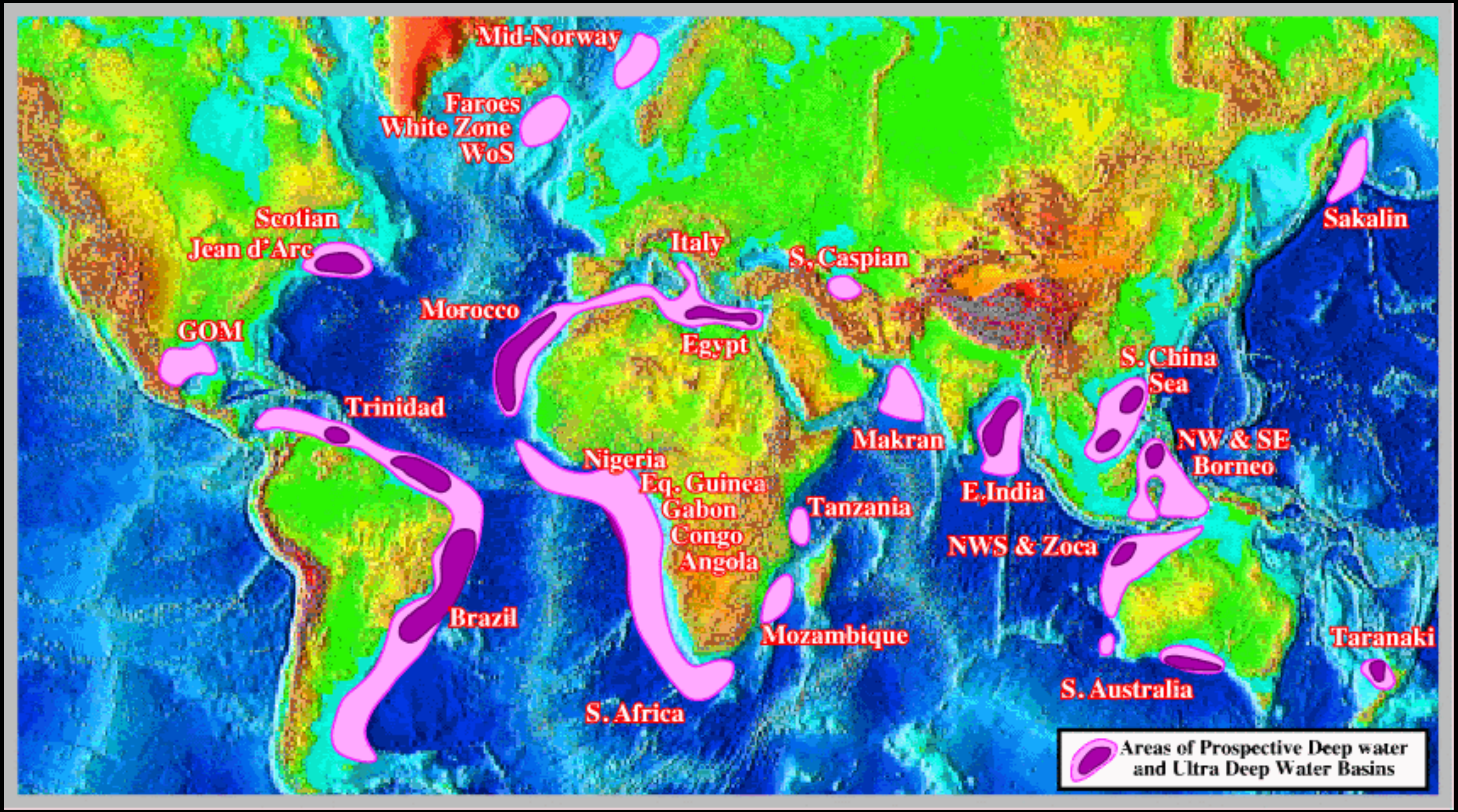
- Condensed stratigraphic sections
- Facies change
- Fault planes
- Volcanic glass
- Downlap surfaces
- Opal horizons
- Cherts
- Pelagic limestones
- BSR (Bottom Simulated Reflectors)
- Diagenic lines, etc.

Exploration Cycles



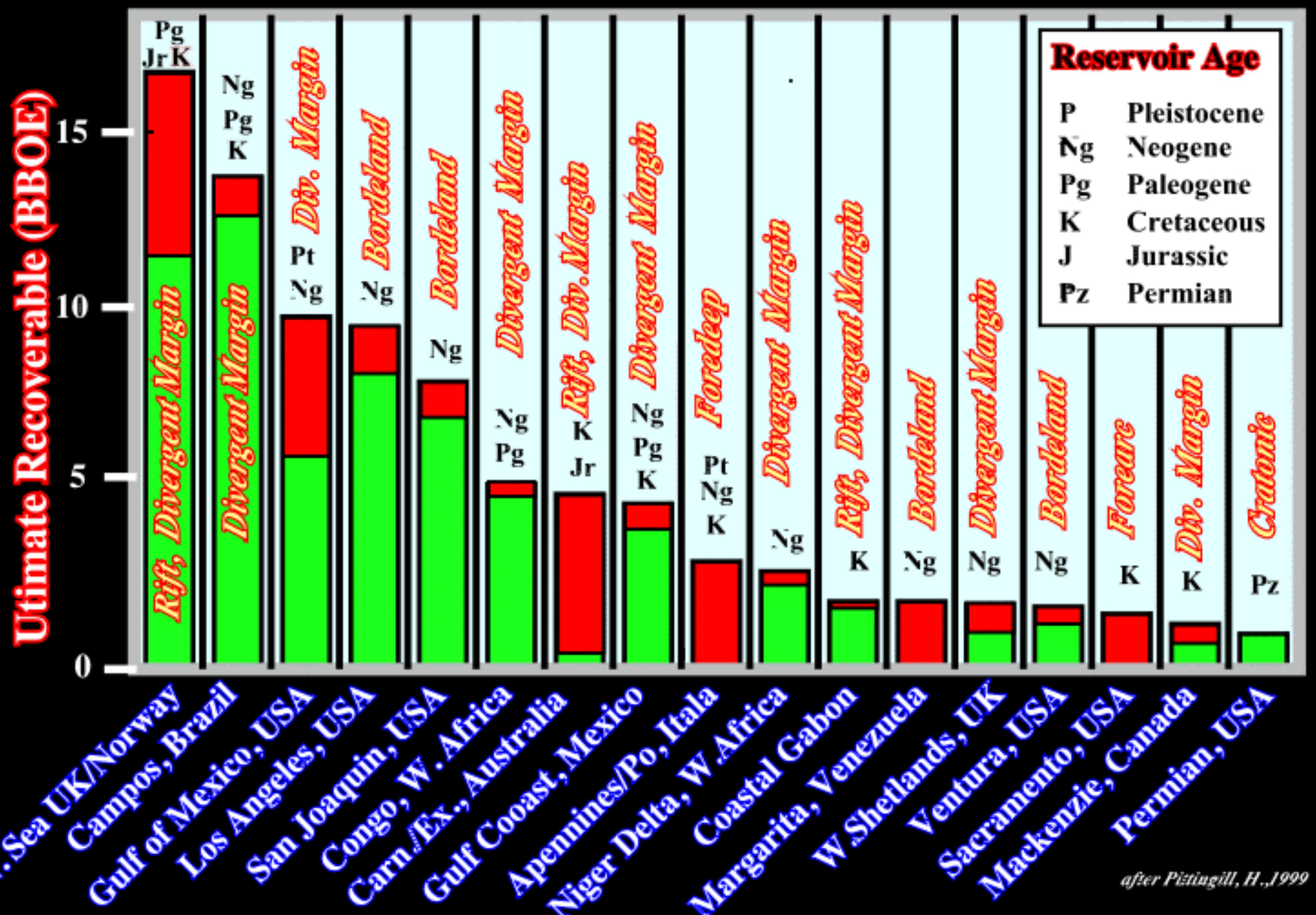
Cumulative reserves of 46 discovery from turbidite reservoirs in Campos basin. The main graphic shows individual fields and discoveries in chronological order (histogram bars, left y-axis) and cumulative ultimate recoverable reserves for the basin (right x-axis). The cumulative curve is re-scaled in time the upper left inset. The pie chart shows the percentage of the reserves for each trap type. Three exploration cycles can be recognized: (i) between 1974 and 1983, (ii) between 1983 and 1992, (iii) since 1993.

Major Deep Water Basins



In the deep water (>500 meters), the recoverable resources announced in Brazil, West Africa, GOM and NW Australia include producing reserves (those in development, and technically recoverable resources for which development has not been sanctioned). All these resources are in Atlantic-type divergent margins. The resources found in Mid-Norway (Ormen Lange) 11 TCF & 34 MMBC, Egypt (Scarab-Saffron) 4.5 TCF and Philippines (Malampaya) 3.5 TCF, strongly suggest that other type of basins can also be highly prospective. This seems particularly true for non Atlantic-type divergent margin. Other deep water basins as Jean d'Arc, Sakhalin, South Caspian, Taranaki, etc, and the ultra deep basins must also be taken into account.

Basin Ultimate Recoverable from Turbidites



Green = oil, red = gas.

Turbidite Models

This photograph of the Late Cretaceous Monte Cassio flysch (Northern Apennines), the parallel beds correspond to parallel bedded basin-plain deposits. They consist mainly of redeposited pelagic and hemipelagic biogenic oozoes. Subordinate, fine-grained sandstone form the darker and considerably thinner, however more resistant sedimentary units. These sediments, which are interpreted as trench-fill deposits, are thought to be a classic example of stacked megaturbidites deposited from gravity currents triggered by seismic activity (Mutti et al., 1984). The thin bedded sandstones and the dark mudstones represent the background sedimentation of the basin plain.

Turbidite Models

Several studies (side-scan sonography, narrow sea-beam bathymetry, high resolution seismic, sea bottom coring, etc.) of modern sedimentation of deep sea fans of Gulf of Guinea have been lanced in the last years. However:

- Despite the profuse efforts of modeling, the internal geometries, the facies distribution and the lateral variations of reservoirs associated to this type of deposits still are unforeseeable.
- Just in attempt to arrive to a better comprehension of these “modern” depositional systems, geologist return again to the study of the outcrops. A kind of “back to origins” in attempt of understand genesis, geometries and facies associations of the turbidite deposits that, in the scenery of stratigraphy and sedimentology, keep on to stay the more enigmatic.
- Systems with large variability, like turbidite systems, are complexes and cannot be understood just by a reductionist approach, i.e, in terms of the properties of simple building block.

Turbidite Models

- Turbidity currents, which create turbidite deposits, occur on time scales ranging from minutes to days.
- The time between successive depositional events is though to be on order of years to thousand years.
- When studying turbidites, we are dealing with intermittent, punctuated equilibrium events

So before going on, let's review the meaning and timing duration of a geological event.

Geological Events

Geological events

Discontinuous Geological Events

# of years need to have 95% of chances that a geological event take place at least once

Regular events...100

Common events..1.000

Recurrent events...1.000.000

Occasional events.....................................10.000.000

Rare events...1.000.000.000

after Gretener, 1967

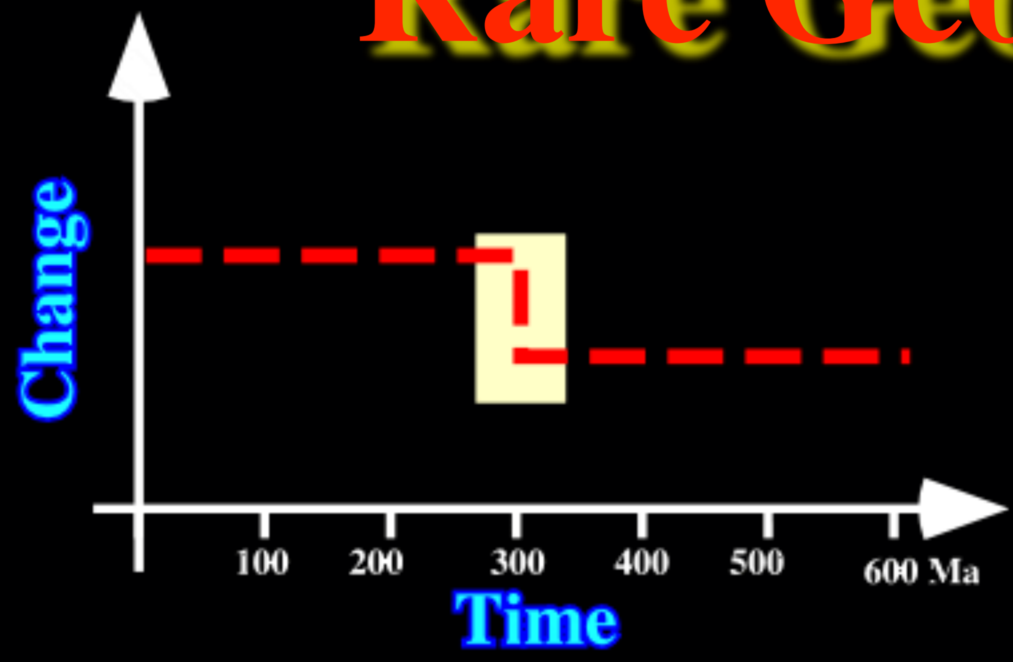
Geological Events

Taking into account Gretener's classification, in geological history, two families of geological events are often proposed:

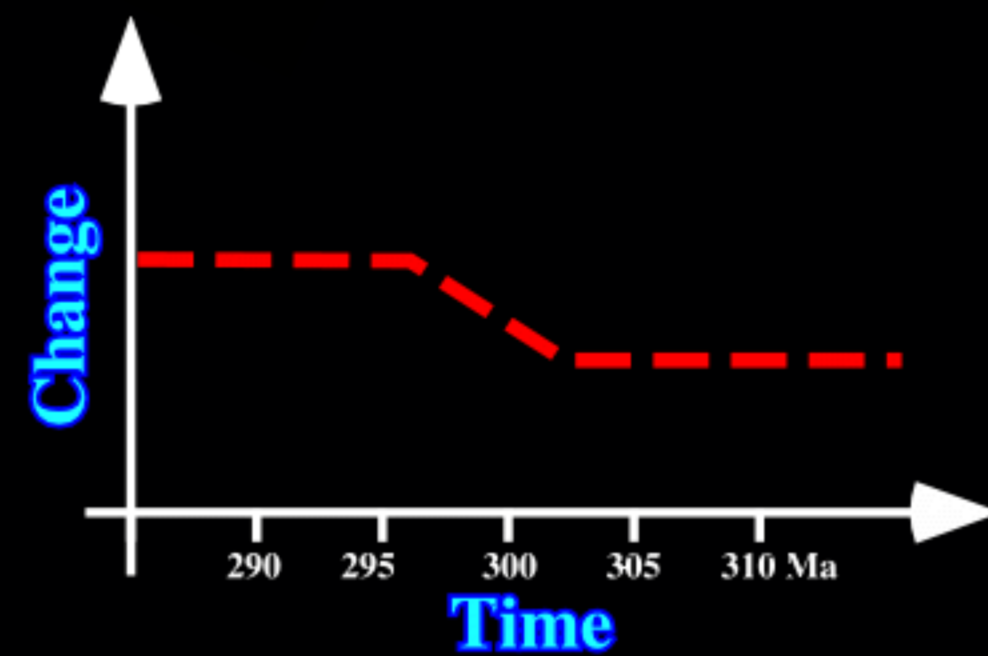
- **Frequent events**
  - They take place at least once all 100 My. Their time-duration is around 1 My, that is to say, roughly 1/100 of the total time (see next).
- **Rare events**
  - They take place at least once all 1.000 My. Their time-duration is around 10 My.

In this sense a turbidite-current (gravity current in a sensu lato) is a regular or common geological event. In a particular basin, its occurrence-time ranges between 1 and 5.000 years.

Rare Geological Event



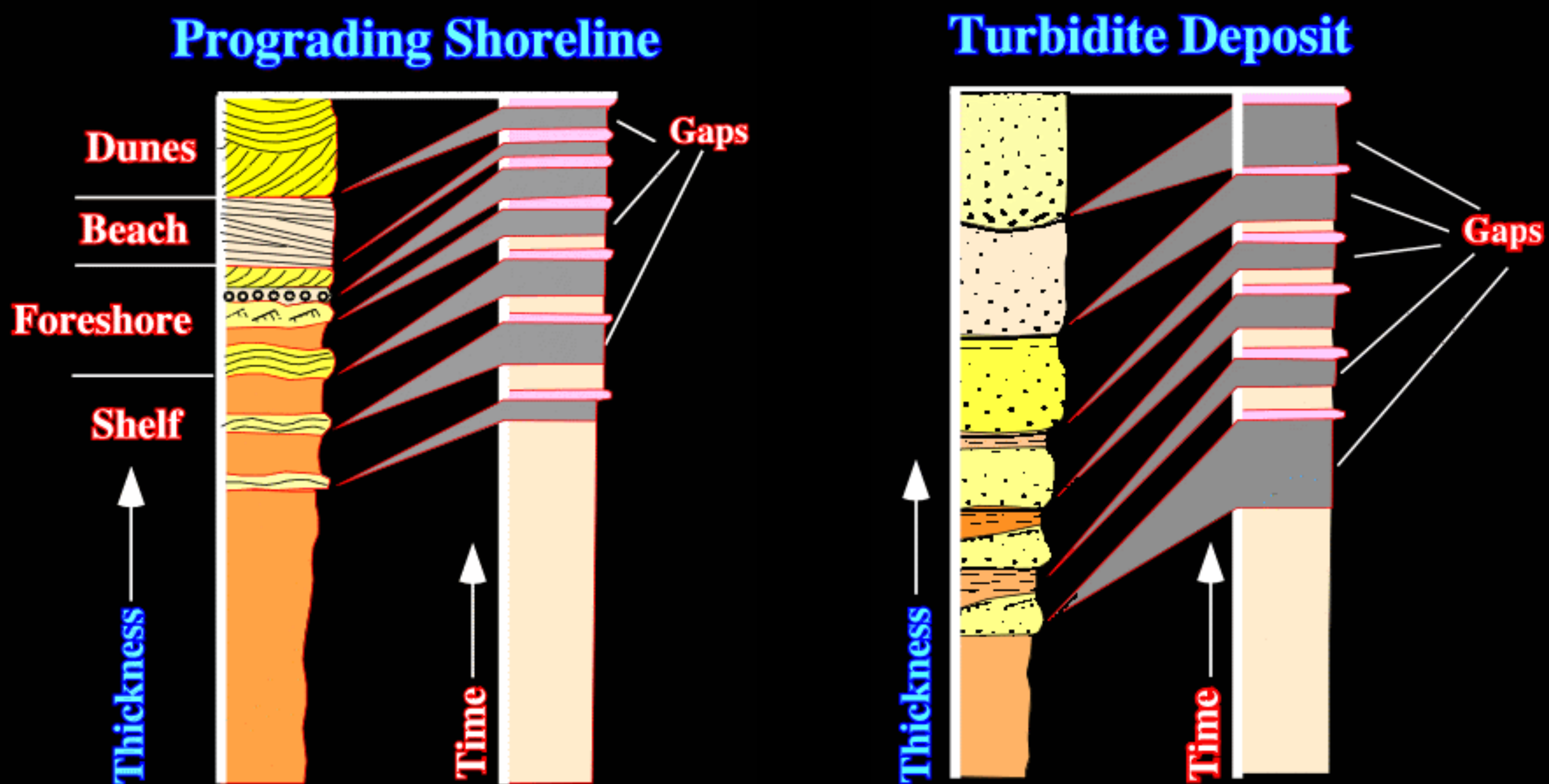
At geological scale, a Paleozoic geological event, such a sequence stratigraphic cycle, induced by a 3rd order eustatic cycle, which time duration ranges between 0.5-3 My, is an instantaneous geological event. Its time-duration (3 My) is approximately 1/100 of the total time of the Phanerozoic. However, in a dilated time-scale, it is not instantaneous, since it has a finite time-duration of 6 My.



Completness & Preservation

- The majority of geologists consider that sedimentary records are incomplete and separated by important periods of non-deposition during which nothing happens.
- The time-duration of hiatuses (by non-deposition or erosion) is generally much important than the deposition-time of the preserved sediments.
- Stratigraphic sections are just local archives of the geologic history.
- The records of these archives are the sedimentary layers.
- They are deposited in succession and, generally, numbered according to their thickness rather than their deposition-time.
- Stratigraphic sections contain numerous hiatuses induced whether by the erosion or non-deposition .

Completeness & Preservation



In these geological cross-sections, and particularly on their upper parts, the periods of non-deposition are much longer than the periods of deposition. In a prograding shoreline, a large number of geological events took place, but their associated deposits are not preserved. They have been eroded. They were replaced by significant erosional-hiatuses. In the turbidite, erosion is insignificant. The hiatuses are non-depositional. The sedimentary preservation is much higher than in the prograding shoreline cross-section, however, conversely the completeness is much lower.

Completness & Preservation

Sedimentary completness is the ratio between the total time of a stratigraphic section (span of time between the bounded unconformities) and the deposition-time of all its preserved beds.

- **Sadler (1982) suggested:**
  - ✓ **The deposition-time is conversely proportional to the rate of deposition.**
  - ✓ **Higher is the deposition rate shorter is the deposition time.**
  - ✓ **The majority of the periods of non-deposition escape us.**
- **The sedimentary records correspond to short periods of terror separated by long periods of tranquility where nothing happen (Ager, 1982).**

Turbidity Currents

A turbidite current is a bottom-flowing current laden with suspended sediment, moving swiftly (under the influence of gravity) down a sub-aqueous slope and spreading horizontally on the floor of the body water, having been set and / or maintained in motion by locally churned or stirred-up sediment that gives the water a density greater than that of the surrounding or overlying clear water (Bates R. L. & Jackson, J., 1980).

Turbidity currents occur on lakes and on sea.

They can produce sub-aqueous canyons by notching the slopes before deposing at their bottom the laden sediments as sub-aqueous fan or turbidite systems.

Turbidity Currents

Turbidity currents can be originate in various ways, such as:

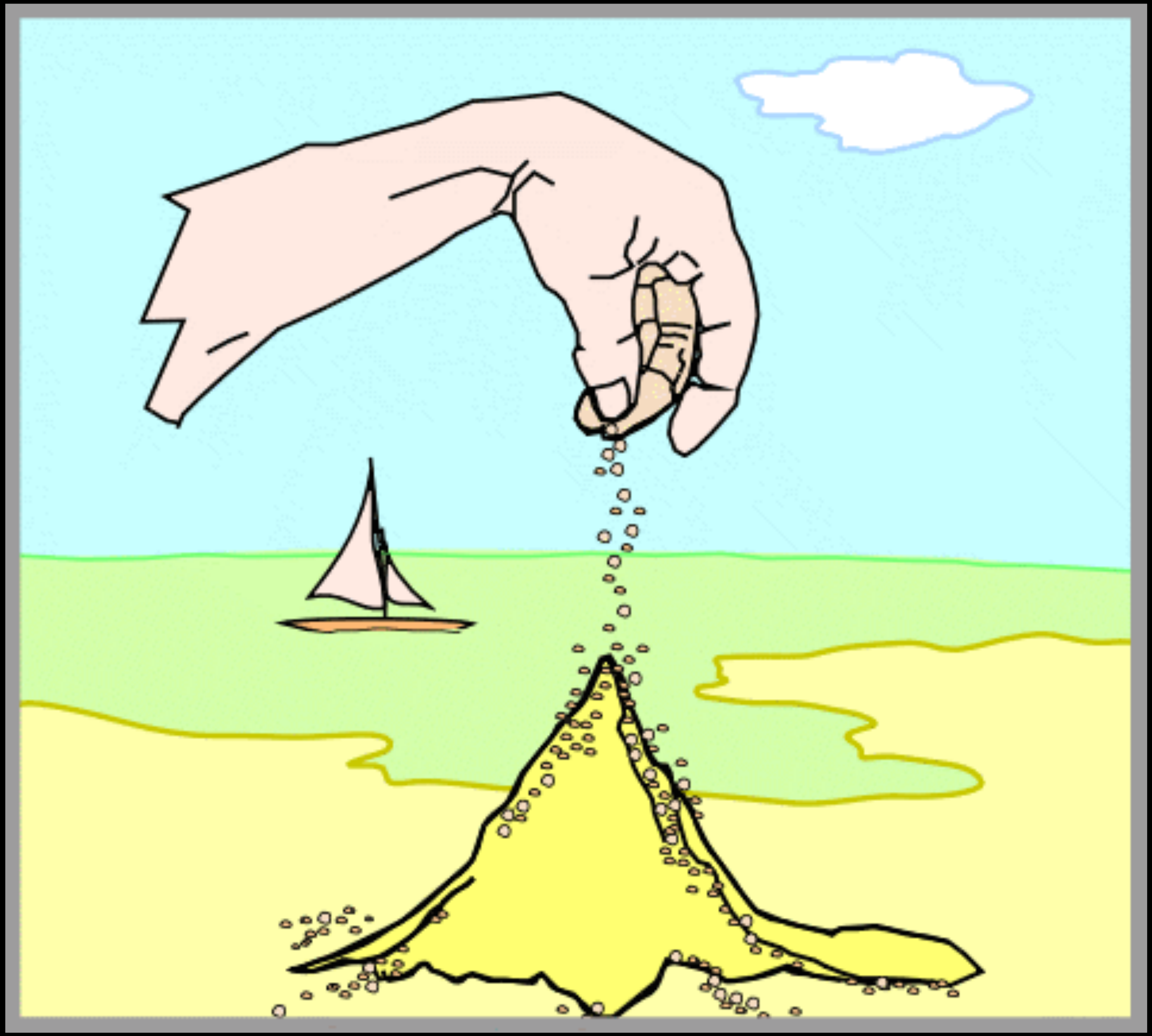
- Storm waves.
- Tsunamis.
- Earthquake-inducing sliding.
- Eustatic sea falls.
- Tectonic movements.
- Slope instabilities.
- Upwelling currents.
- Over-supply of sediments.Over-supply of sediments.
- Heavily charged rivers in spate with densities exceeding that of the sea

Turbidity Currents

The geological events inducing turbidite currents:

- ✓ Are catastrophic and discontinuous.
- ✓ They have a very different time-duration and all have a complex behavior, and the tendency to create large Self-Organized Critically systems or SOCs.
- ✓ Shelf-organized critically is the only known general mechanism able to generate complexity (Bak. P., 1996).
- ✓ Self-organized critically systems can be understood only from a holistic description of properties of the entire system.
- ✓ They cannot be understood from a reductionist description of the individual elements composing the system (as in the sandpile model of Bak, P., 1947).

Sandpile Model



The complex phenomena observed everywhere indicate that nature operates at the self-organized critical state. Thus, the behavior of the critical sandpile mimics several phenomena observed across many sciences, which are associated with complexity. This is particularly true for in geological sciences, where large catastrophic events such as turbidite systems that cannot be understood within the set of references developed within the conventional scientific domains. The theory of complexity is able to explain such a phenomena, at least partially.

Turbidite Facies

A turbidite facies tract (FT) was defined (Mutti, 1977, 1992) as the lateral association of genetic facies that can be observed within individual bed or a package of strictly time-equivalent beds. Although facies tracts develop both in crosscurrent and along-current directions, lateral facies tracts refer primarily to facies changes that are observed in a direction parallel to the flow.

The recognition of facies tracts suffers from two main limitations:

- The first is related to the fact that facies tracts can only be established within precise time-correlation patterns, i.e. within thin stratigraphic units that are physically traceable over significant areas.
- The second limitation is represented by the very low-gradient facies variations that most systems undergo over the available outcrop areas.

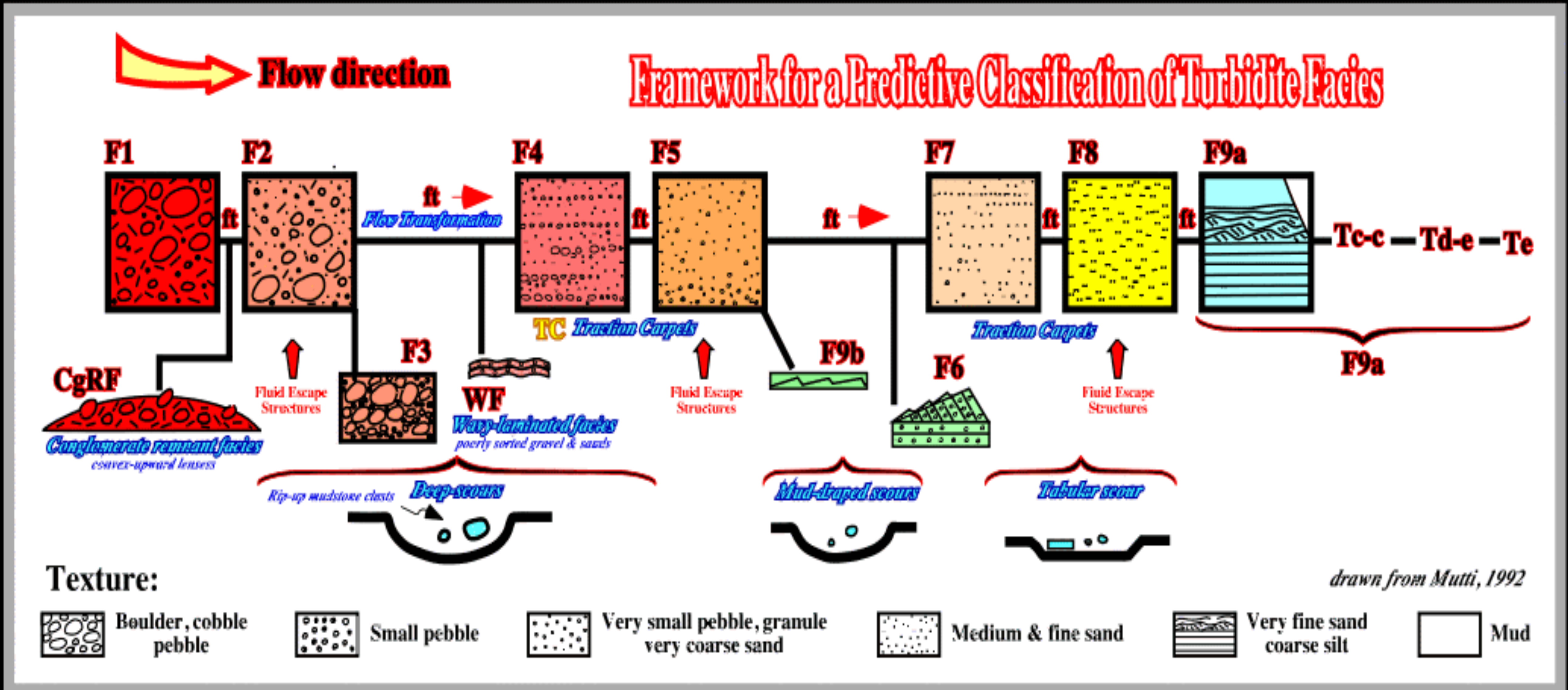
The main facies types can be subdivided into three principal groups:

A) Very Coarse Grained Facies.

B) Coarse Grained Facies.

C) Fine Grained Facies.

Turbidite Facies



Four kinds of flow transformations were recognized by Mutti in 1977 & 1992. (i) Body transformation occurs when the flow changes between laminar and turbulent within the body of a flow without significant addition or loss of interstitial fluid; (ii) Gravity transformation occurs when initially turbulent, particle-charged flows become gravitationally segregated and develop a high concentration, laminar underflow with an overriding more dilute turbulent flow; (iii) Surface transformation occurs when ambient fluid becomes mixed or lost at flow boundaries by drag over separation into laminar and turbulent flow; (iv) Elutriation transformation develops by elutriation of the particules by upward-moving fluids from a high-concentration flow to produce a turbulent dilute-phase above the base of the flow.

Very Coarse Grained Facies

Three main facies can often be distinguished:

F1, F2 and F3

- F1 deposits are the product of cohesive debris flows. They are characterized by:
  - The lack of significant basal scours.
  - The larger clasts floating in a matrix which – relatively to the F2 deposits of the same facies tract – is muddier and may show features related to plastic flow,
  - The tendency for the largest clasts to concentrate toward the top of the bed and project upward above the top of the bed.

Very Coarse Grained Facies

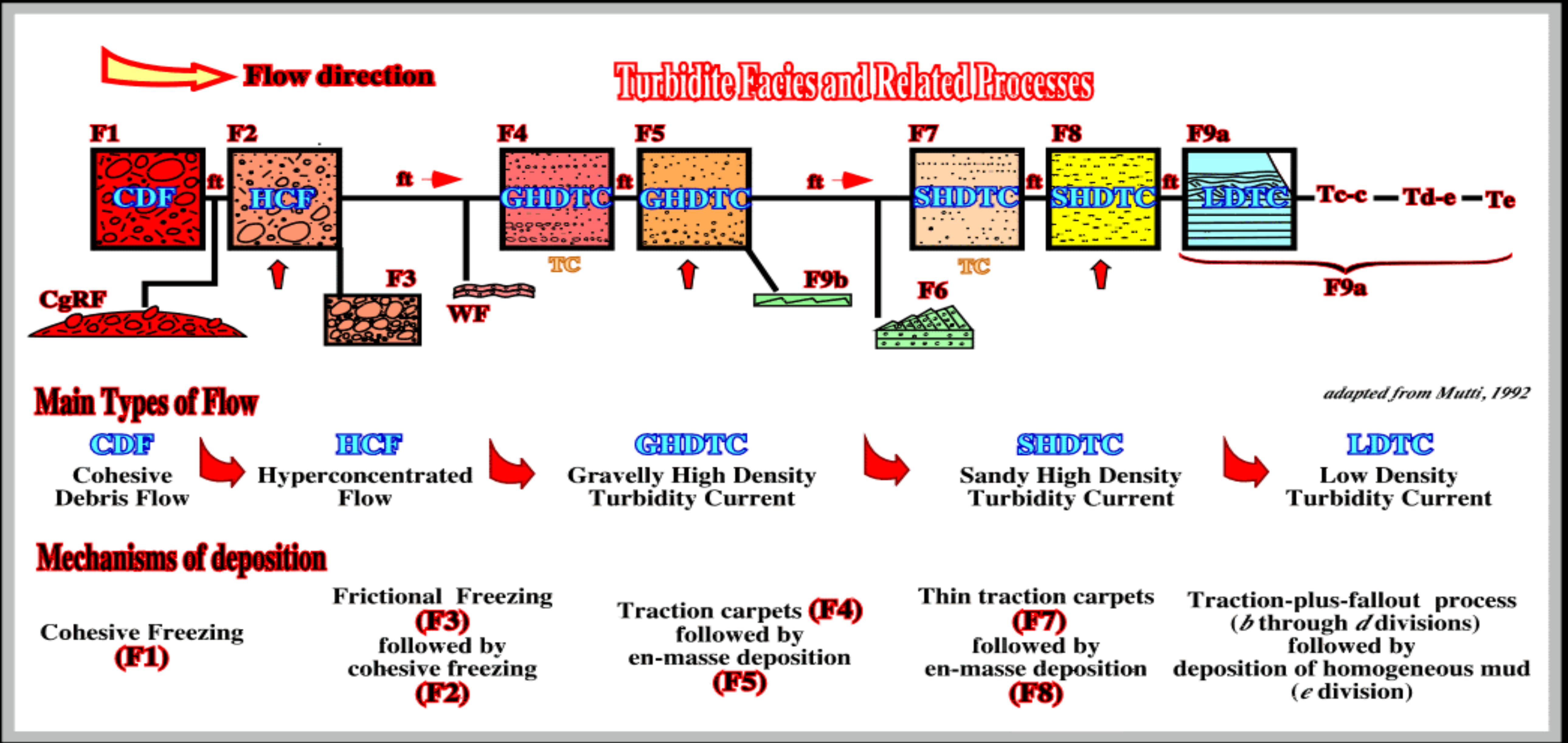
F2 and F3

- F2 deposits are considered as the product of hyperconcentrated flows resulting from the downslope transformation of cohesive flow through progressive mixing with ambient fluid. F2 deposits are extremely common in many coarse-grained turbidite systems. Relatively to the F1, the following features characterize them:

  - Occurrence of deep basal scours and large rip-up mudstone clasts.
  - The larger clasts float in a fully mixed and occasionally crudely graded matrix composed of mud, sand and gravel.
  - The largest clasts show a clear tendency to occur in the lower part of the bed.

- F3 deposits consist of clast-supported conglomerates forming beds and bedsets commonly bounded by basal erosional surfaces. The internal organization of this facies is variable and is most commonly represented y an unstratified and generally inversely graded deposit. This organization strictly depends on the shear stress imparted on these gravel layers from the overlying residual flow.

Turbidite Facies



Cohesive debris flows, clasts are supported by matrix strength and density, and deposition takes place when the applied shear can no longer overcome the flow strength. Sediments of this type, which result from cohesive freezing, are easily recognized since they consist of mud- supported clast. In high-density turbidity currents, either gravelly or sandy, clasts are supported within the flow by several mechanisms, which are inherent to sediment concentration and in which result in hindered settling of coarse particles. The sediments of these flows typically consist of thick-bedded and coarse-grained sandstone and pebbly sandstone facies. Low-density turbidity currents characteristically maintain their fine-grained sediment load within the flow through turbulence and deposit it through a very distinctive process of traction-plus-fallout. Beds in which thoroughly current-laminated fine-grained sandstone and coarse siltstone grade upward into a massive mudstone unit commonly represent these sediments.

Coarse Grained Facies

This group includes, in a downcurrent direction, WF, F4, F5, and F6 sediments, which are interpreted as product of gravelly, high-density turbidity currents and of the transformations which take place at the origin and the end of these flows:

- **WF sediments consist of relatively thin division, usually between 5-20 cm thick, of very poorly sorted very coarse sand and small gravel displaying a faint wavy lamination. Wavelength is generally less than 50 cm individual laminae have a thickness up to 1cm. These sediments have been tentatively interpreted as an upper flow regime, which forms at the transformation of a hyperconcentrated flow into a fluidal, high-density, and supercritical turbidity current.**
- **F4 and F5 deposits are the most common sediments found within this group of facies. Relatively thick and coarse-grained traction carpets characterize F4 deposits.**
- **F5 deposits are devoid of internal stratification fluid escape features can be very common. Unless the original parent flow already consisted of relatively well-sorted sediment, F5 beds are character-ristically poorly sorted compared with to F8 deposits.**
- **Coarse-grained and internally stratified deposits represent F6 sediments. These beds are generally relatively well sorted and characterized by the common lack of grading. These sediments are considered as product of a hydraulic jump that transforms a supercritical high-density turbidity current into a subcritical, low-density turbidity current.**

Fine Grained Facies

This group includes F7, F8 and F9 deposits, i.e., those sediments that are considered as the product of low-density, sub critical turbidite currents. These currents begin their deposits after either a hydraulic jump (F6) or a gravity transformation through which an F5 deposit is overlain or replaced in adown current direction by an F7 deposit. The end of the deposition is reached where the mud-size suspended load can settle through a quasi-static flow. This fine-grained facies are generally considered the best-known turbidite sediments since they include the classic Bouma sequence and the classic turbidite of Walker.

- F7 deposits are common in many turbidite systems and are characterized by thin and relatively coarse-grained, horizontal laminae that can be easily mistaken for the traction carpets of F4 deposits or the b Bouma division of F9 beds.

- F8 sediments are considered as the true *a* division of the Bouma sequence and consist of structureless, medium to fine sand. Grading may or may not be present. Within the same facies tract, an F8 division is always finer grained and considerably better sorted than an F5 deposit, thus permitting an easy distinction between the two facies types.

- F9 deposits are made up of thoroughly current-laminated divisions of very fine sand and coarse siltstone which are capped by a massive mudstone division, These sediments, which are commonly referred to in most literature as “base-missing” Bouma sequences (Tb-e, Tc-e, Td-e and Te sequences), constitute the volumetrically most important component of many ancient turbidite basin-fills. F9 strata can be simply defined as turbidite beds, which have been deposited by traction-plus-fallout processes, associated with the various stages of sedimentation of waning low-density turbidity currents.

Depositional Turbidite Systems

"a succession of layers deposited by gravity currents which take place between two depositional equilibrium phases of the margins of the basin, whether marine or lacustrine"

A depositional equilibrium phase is a period of time during which the profile of the external platform-upper slope is stable (no sliding or collapse phenomena), and the sediment supply is not big enough relatively to the size of the coastal area and/or the subsidence ratio. In other words, when any sediment is carried beyond the shelf break (deep water setting), or seaward the limit neritic-bathyal (ramp margin setting). The breakup of such equilibrium induces the formation of turbidity current and subsequently turbidite systems.

Turbidite Systems Classification

Assuming that the turbidity currents have a high degree of freedom, in other words in absence of effective obstacles along the slope, we will divide turbidite deposits into:

- ✓ Large Turbidite Systems.
- ✓ Middle Turbidite Systems.
- ✓ Small Turbidite Systems.

Such a classification takes into account the "efficiency" concepts of E, Mutti (1979), and it can looks like the classification that he proposed in1985, and in which, he divided turbidite systems into three "types":

A) Type I, mainly composed by tabular lobes.
B) Type II, mainly composed par transition channel-lobes.
C) Type III, composed mainly by channel-levees complexes.

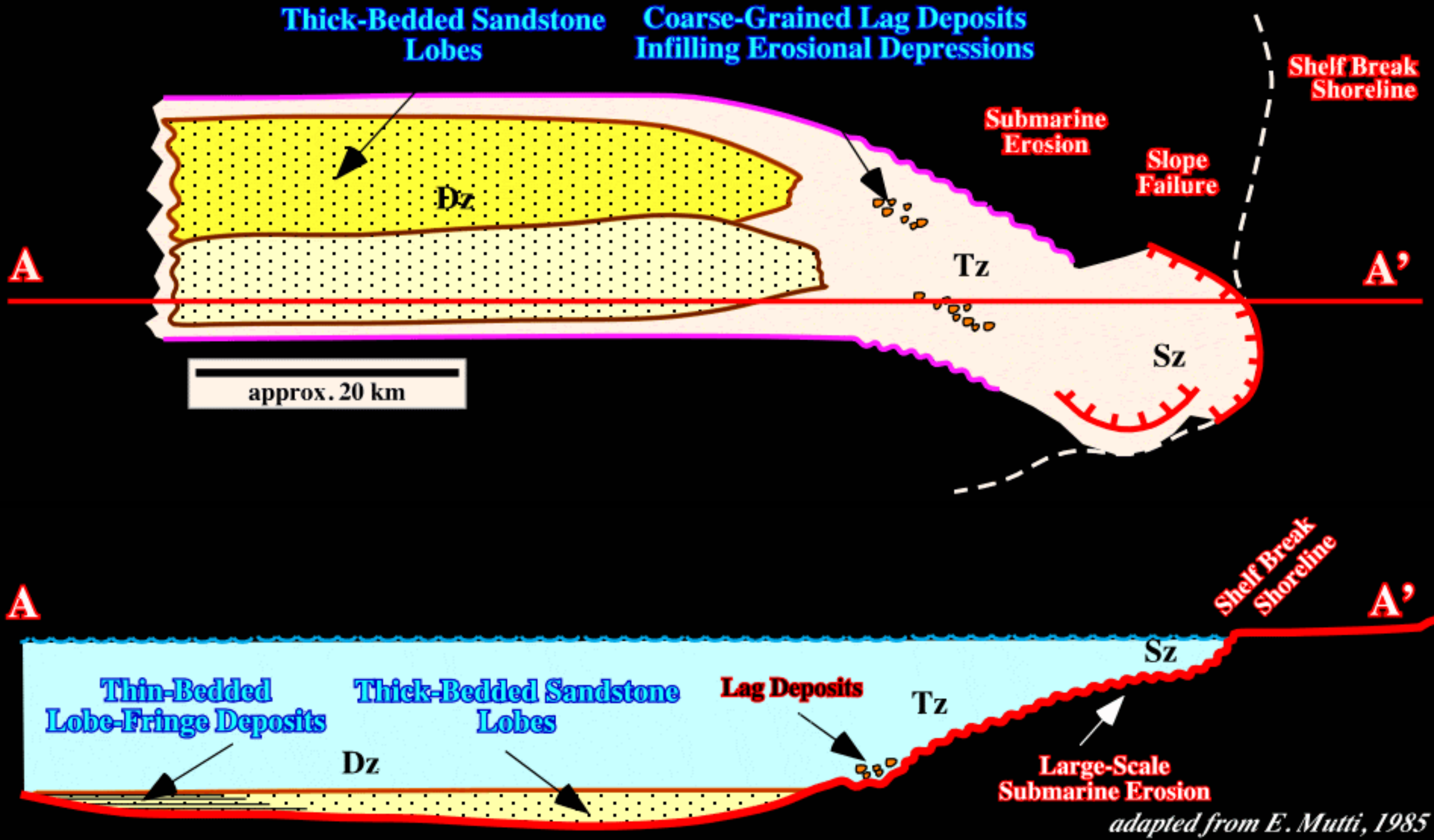
Nevertheless, our classification does not subdivide systems (or turbidite complexes within an eustatic cycle) in a lateral-vertical succession of stage of type I, II, III.

Large Turbidite Systems (LTS)

Geological Features:

- Slope failures.
- Large scale submarine erosions, i.e. erosion all along the continental slope.
- By-pass zone at the toe of the continental slope.
- Deposition of lobes on the abyssal plain.

Large Turbidite Systems (LTS)



In LTS, the bulk of the sandstone occurs in non-channelized and elongated bodies (lobes) in the outer region of the system. These potential reservoirs are characterized by a lateral continuity and a tabular geometry over distances up to several tens of kilometers parallel to the current direction. The thickness of each lobe, commonly range between 3-15 m thick; it is characteristically thick-bedded and grades in a down-current direction into thinner bedded and finer grained deposits.

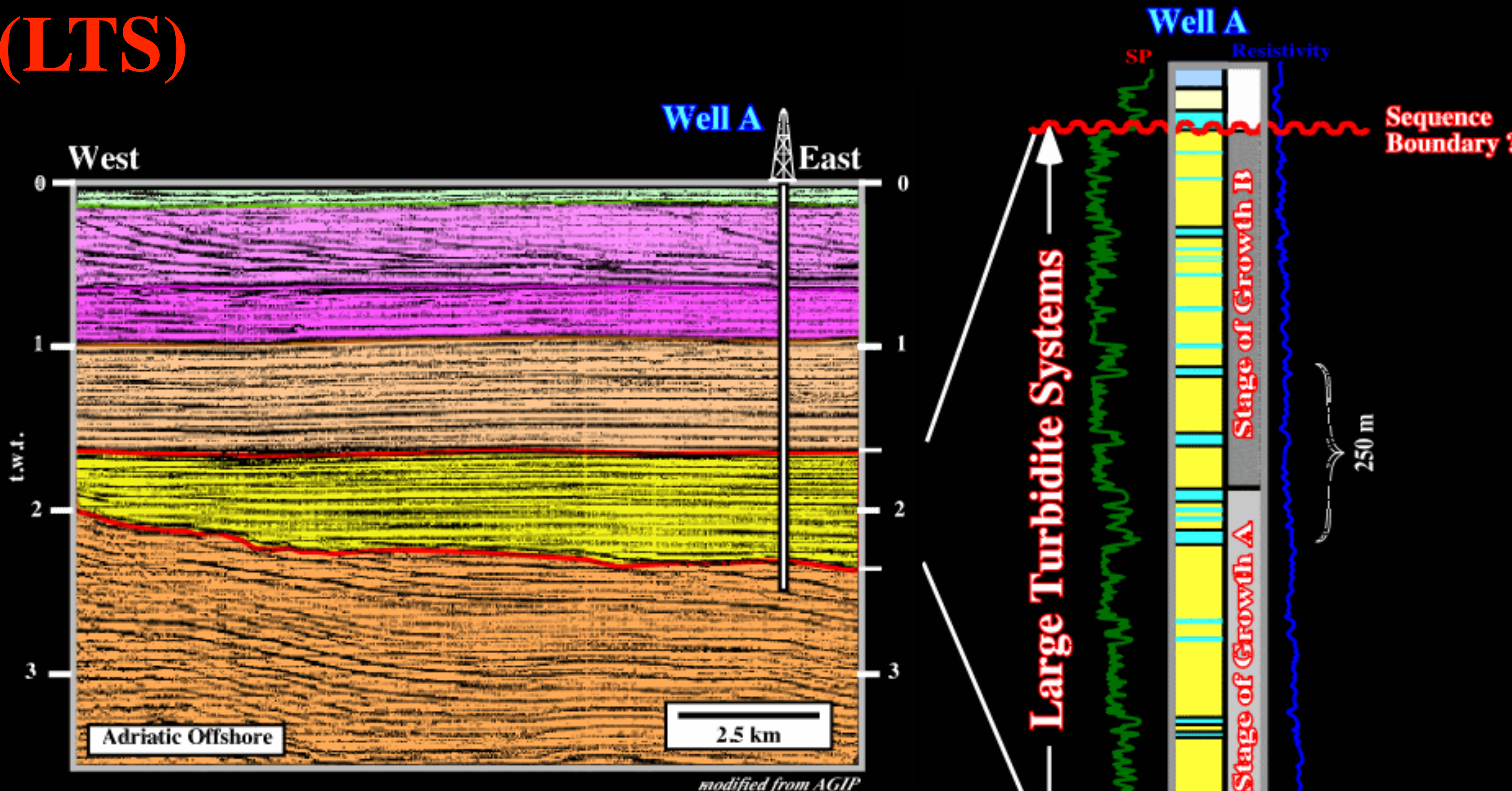
Large Turbidite Systems (LTS)

The major geological features are:

- ✓ The main depositional zone is located in the abyssal plain.
- ✓ The bulk of sandstones occur in non-channelized and elongated lobes in the outer area of the system.
- ✓ The potential sandprone reservoirs have a tabular geometry with 10 km extension.
- ✓ The individual strata thickness range between 0.5 and 2 meters.
- ✓ The thickness of each lobe, commonly range between 3-15 m thick.
- ✓ The total thickness of each system can reach 50-100 m with a sand/shale ratio (N/G around) 50%.
- ✓ Each lobe is thick-bedded and grades seaward into thinner bedded and finer grained deposits.
- ✓ They create huge morphologic traps with large four way dip closures.

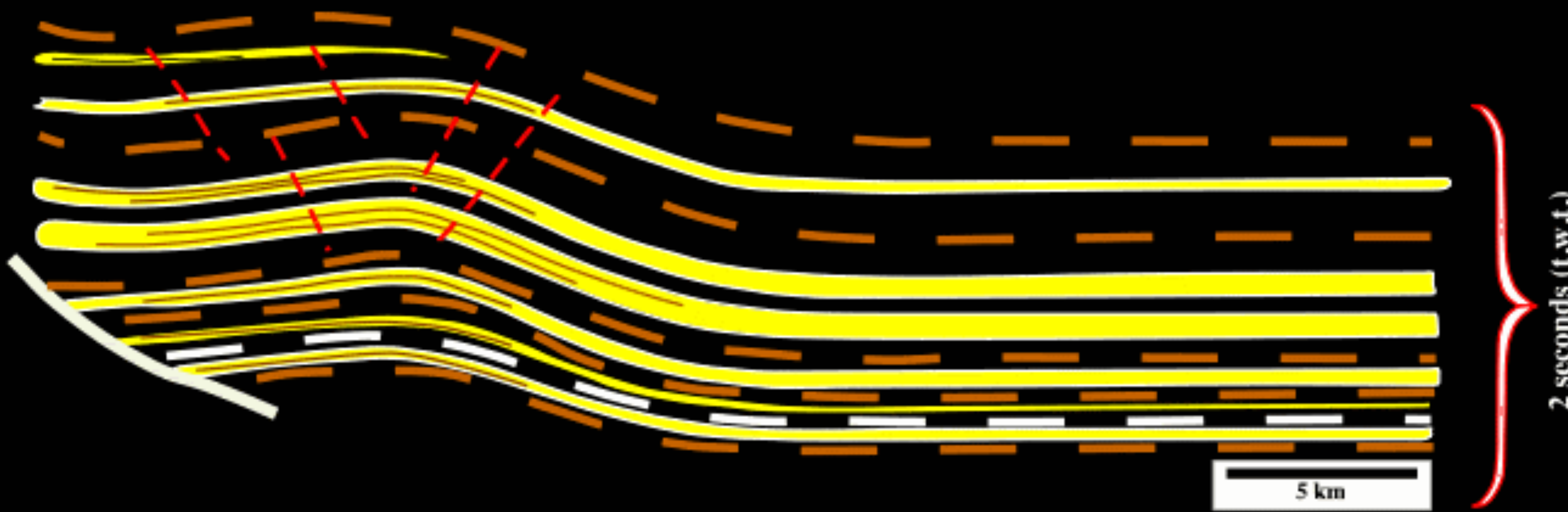
Large Turbidite Systems

(LTS)



This seismic line from Adriatic offshore illustrates a LTS (large turbidite system) overlying the Messianian unconformity (SB. 5.5 Ma). Six major seismic intervals are easily recognized. The lower one is limited at the top by a tectonically enhanced unconformity, which is fossilized by onlapping of the yellow interval, which has a parallel internal configuration. This interval corresponds to a LTS deposited at the toe of the slope of the SB. 5,5 Ma. In the well A, the wireline logs, and particularly the SP, have the typical signature of a stacking of the turbidite lobes. The total thickness of the systems is more than 1000 meters. However, without knowing the age of the upper unconformity of this interval, it is difficult to hypothesize whether it corresponds to a unique system or to the superposition of two systems.

Large Turbidite Systems (LTS)



In a LTS, from the abyssal plain to the upper-middle slope, three signatures are often recognized. In the deepest area, between the middle to distal abyssal plain, we find the distal lobes. They are well individualized with relatively thick shale intervals between them. Landward, between the bottom of slope and proximal basinal plain, the lobes are thicker and generally coalescent. They are overlain by middle or small turbidite systems. Between the upper and middle slope, lag deposits and channel levee complexes can be recognized.

Large Turbidite Systems (LTS)

A) Seismic lines located in the Upper to Middle Slope

On such a lines, very often it is possible to identify the canyon, or the submarine valleys (SUV) created or/and used by the currents to reach the abyssal plain. In many cases the geometry is similar to giant "gull wings" and it induced deposition of huge overbank shaly deposits. The central area corresponds to the bypass zone, where there is no deposition since the turbidity-currents are too competent. Later on, during the retrogradational infilling phase, the by pass area is filled by turbidite deposits generally belonging to middle or small turbidite systems.

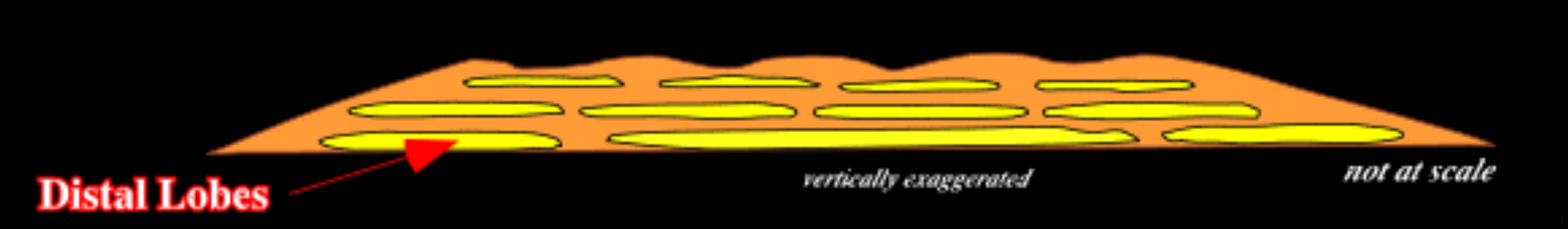
Large Turbidite Systems (LTS)

B) Seismic lines located between the base of Slope & Proximal Basin Plain

On such a lines, we recognize many times the proximal end of the lobes. Generally, they are quite thick and frequently they are coalescent forming huge potential hydrocarbon reservoirs. Such a large and thick reservoirs require well-defined structural traps (four way dips closures). The hydrocarbon parameter "retention" is critical. Overlying the major lobes, small lobes associated with rectilinear channel and channel-levee complexes are often recognized. They can be related with middle (MTS) or small turbidite systems (STS).

Large Turbidite Systems (LTS)

C) Seismic lines located between the Middle to Distal Plain



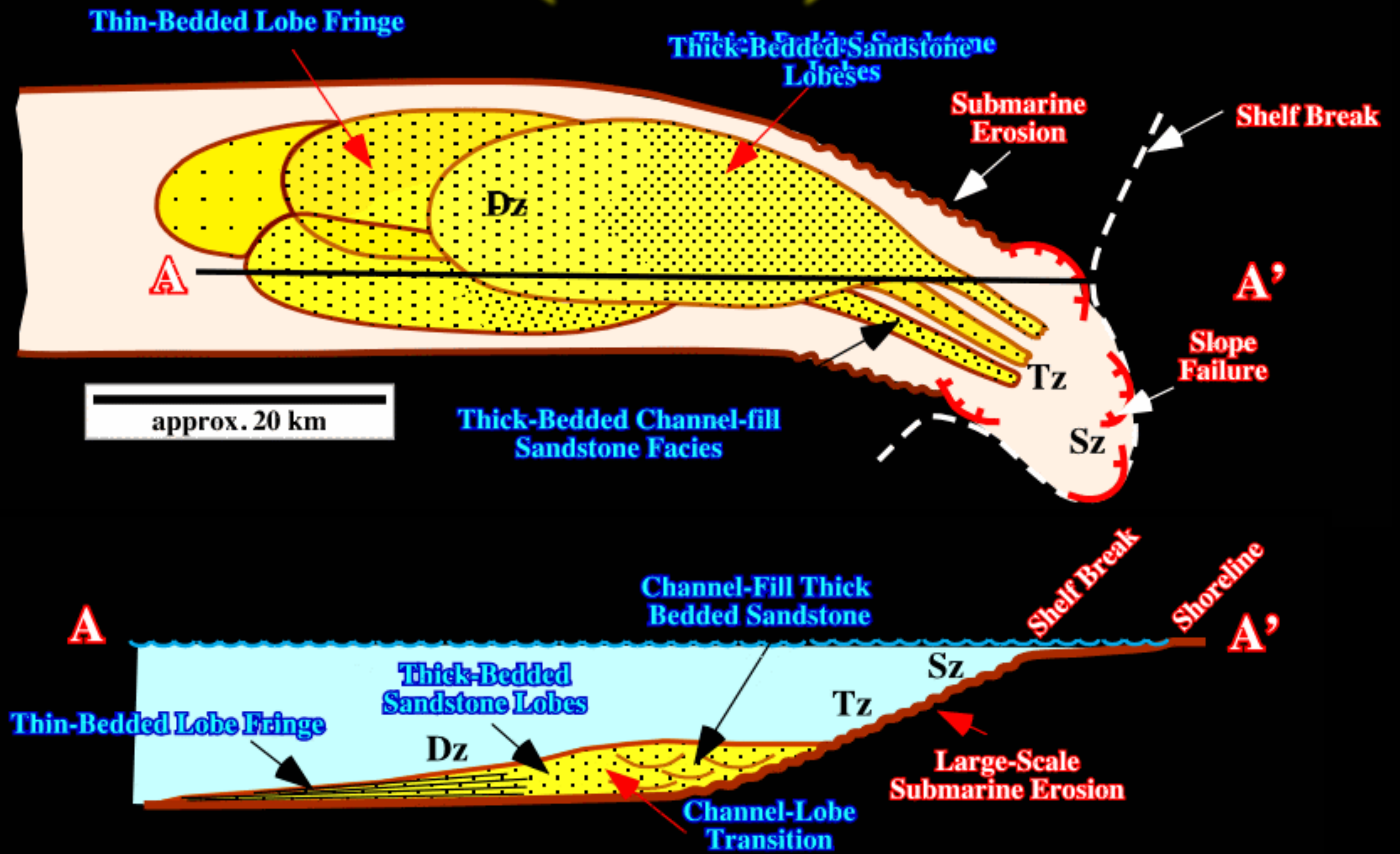
On such a lines, the distal proximal end of the lobes is generally easily recognized. Obvious, their thickness is smaller than previously and generally they are not coalescent. On contrary, they are well individualized and surround seaward by sealing shales. In such condition, they form good potential reservoirs, which can be tested not only by structural traps but in morphological and stratigraphic as well.

Middle Turbidite Systems (MTS)

Geological Features:

- Coastal depositional systems near the shelf break, i.e. depositional coastal break and shelf break are coincident (basin without platform).
- Erosion along the upper continental slope.
- Deposition takes place directly at the toe of the continental slope.
- There is an absence or a too small by-pass zone.

Middle Turbidite Systems (MTS)



Medium Turbidite Systems include all those depositional settings where sandstone facies are predominantly deposited in the lower reaches of channels and in the regions beyond channel mouths. These systems form extensively channelized bodies that grade down current into sandstone lobes. Very coarse-grained Type II systems are almost entirely composed of channelized deposits. Decrease of grain size tends to favor the development of associated lobes. However, the lobes are consistently less developed, in both volume and area extend, than those of large turbidite systems.

Middle Turbidite Systems (MTS)

The major geological features are:

- ✓ **Middle turbidite systems (MTS) are very sandy systems deposited at the bottom of the continental slope.**
- ✓ **They are deposited between the lower section of the continental slope and the proximal section of the abyssal plain.**
- ✓ **Their geometry is typically radial.**
- ✓ **The amount of the sand present in the alimentation zone controls their extension.**

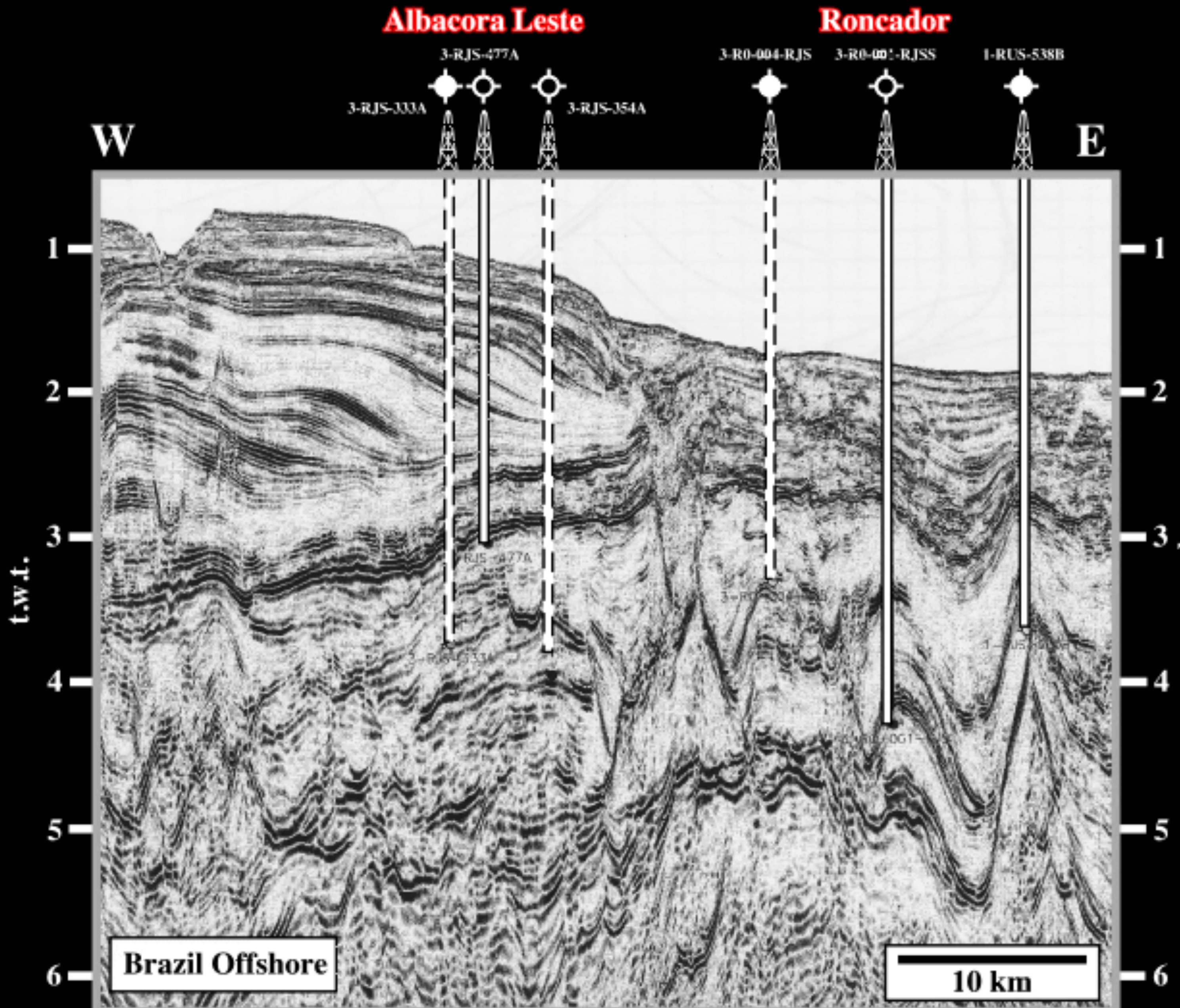
Middle Turbidite Systems

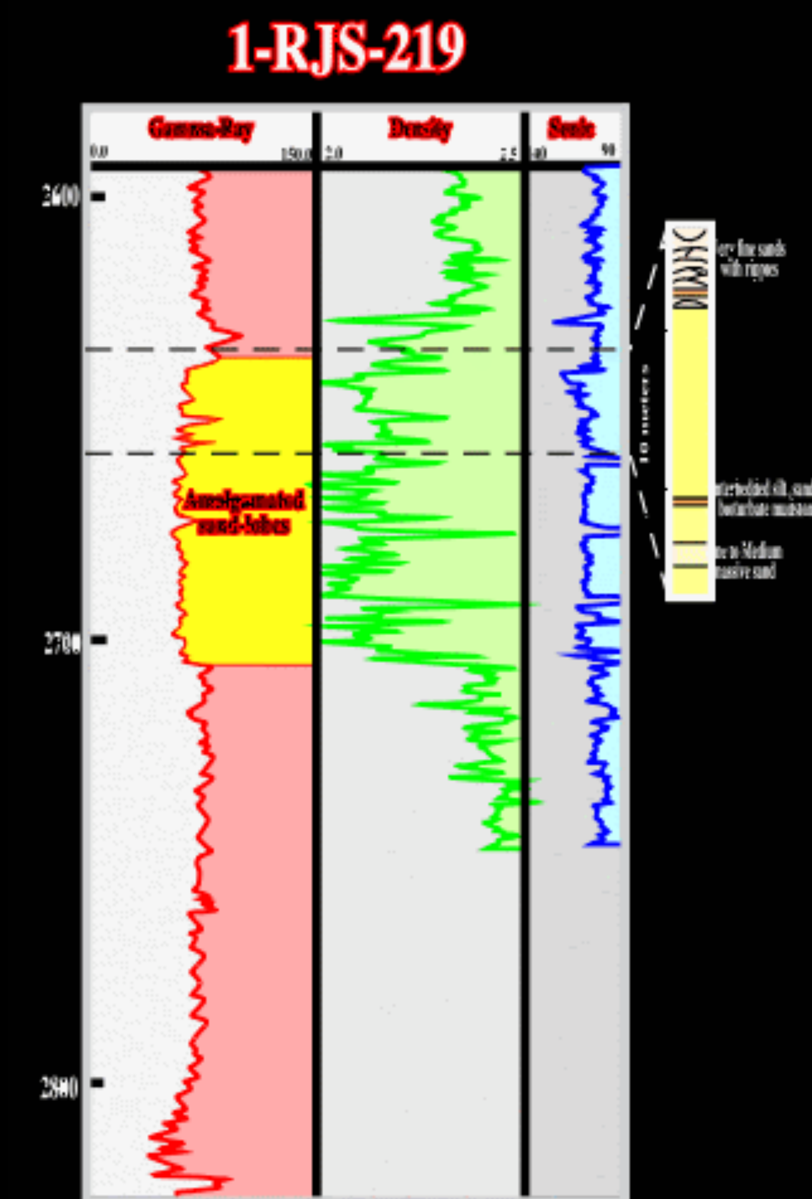
The major geological features are:

- **The more sandy systems (N/G>80) are deposited at the base of the slope:**
  - **Their extension is relatively small (around 10-15 km).**
  - **They change laterally into thin-bedded-turbidites (medium-small systems).**
- **The sand systems (N/G between 80-50%) are deposited mainly on the abyssal plain:**
  - **Their extension reaches several tens of kilometers (medium-large systems).**
  - **The thickness of individual strata ranges between 1-5 m and they are often amalgamated.**
- **The total thickness ranges between 100-200 meters.**
- **Potential reservoir associated with these systems are good target on hydrocarbon exploration. The trapping mechanism is mix (Ex; Roncador, Marlim, etc.).**

Middle Turbidite Systems

(MTS)





In Brazil offshore, as illustrated above, the main sandstone reservoirs are associated with amalgamated sandstone lobes located at the bottom of the continental slope. The reservoirs located in the lower reaches of the turbidite channels are secondary reservoirs. Their contribution for the total reserves is quite weak.

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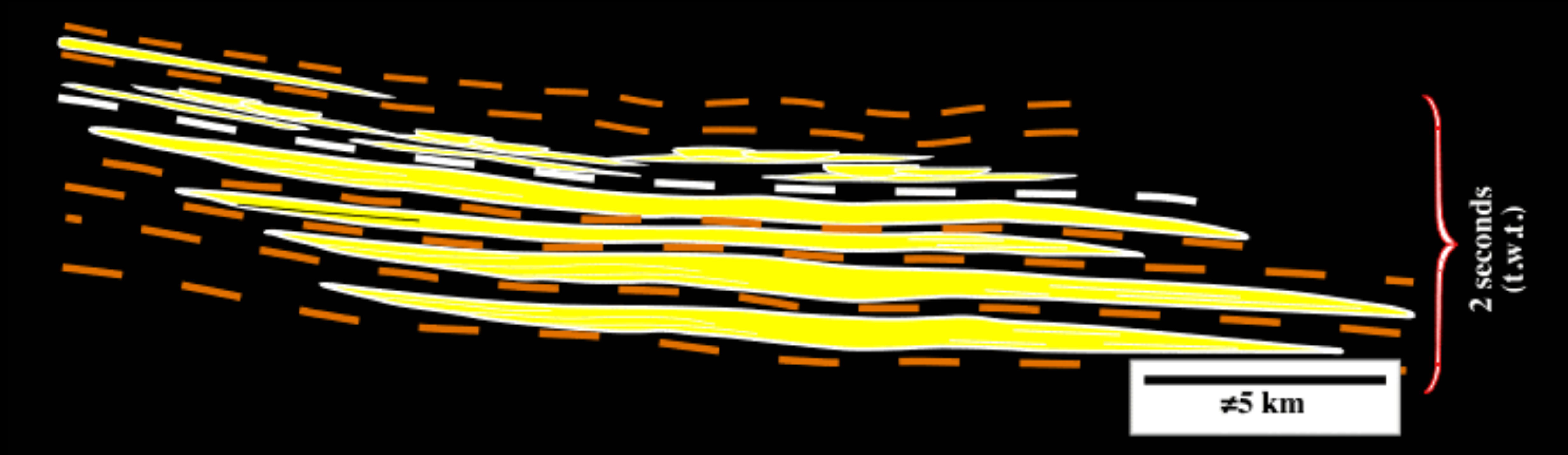
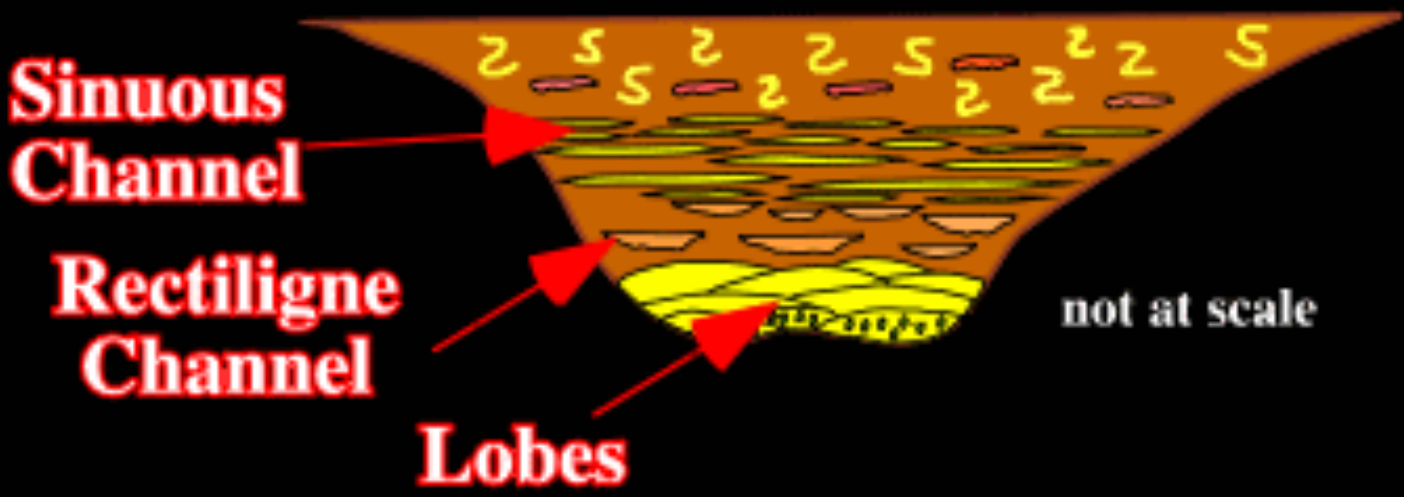


The geometry of middle turbidite systems (MTS) can be deducted using dip and at least three strike lines. In the deepest part of the basin, in the abyssal plain, the lobes are well individualized in spite of their thickness be relatively small. Landward, at the bottom of the slope, the lobes are generally coalescent. The individual thickness is maximum. Above the coalescent lobes, terminal lobes deposited at the mouth of rectilinear channel are often recognized. Landward, in the middle-upper slope, above the proximal end of the lobes, rectilinear and sinuous channel fill are easily recognized.

Middle Turbidite Systems (MTS)

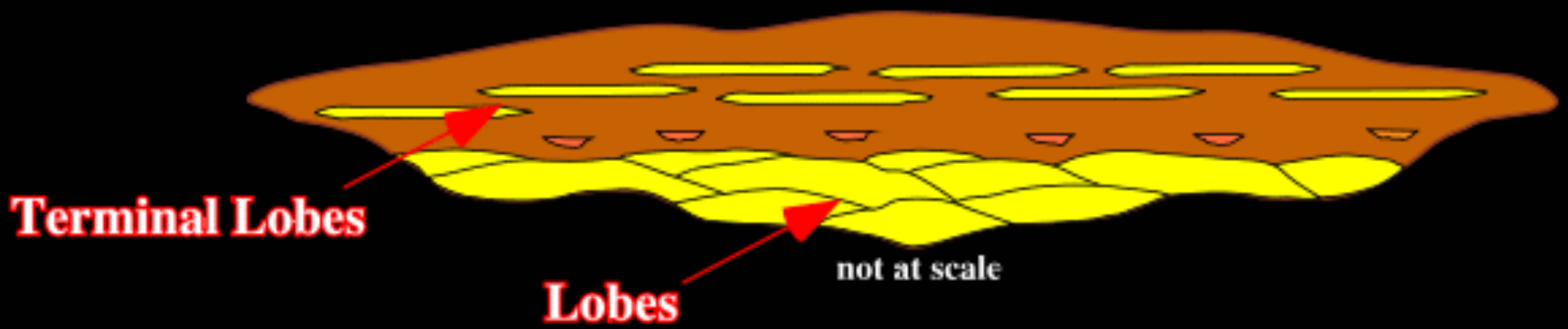
A) Seismic lines located in the Upper to Middle Slope



On proximal lines, located in the upper slope, generally, we can see the proximal end of the lobes, which are often overlain by sediments infilling rectilinear and sinuous channels. Small lobes located at the mouth of the rectilinear channel can be deposited. With exception of the lower lobes, the facies is mainly shaly, i.e. the absence of reservoirs is paramount.

Middle Turbidite Systems (MTS)

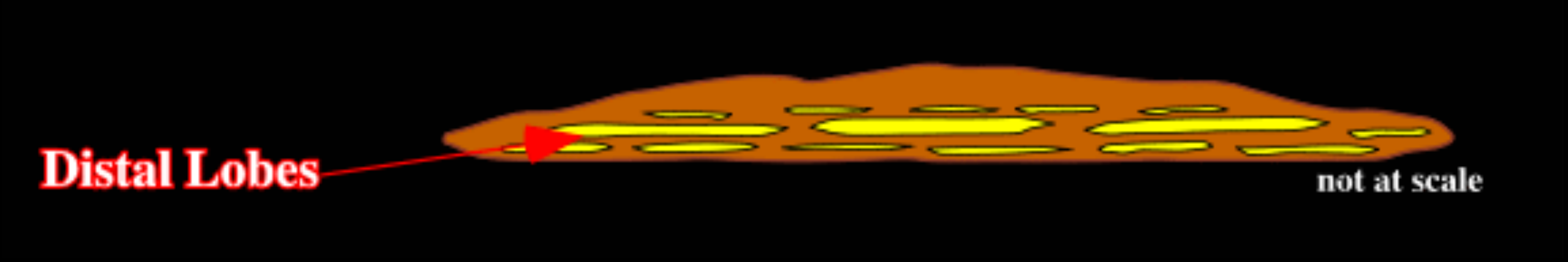
B) Seismic lines located between the base of Slope & Proximal Basin Plain



On distal lines, not far from the bottom on the continental slope, the geometry of MTS is elongate, with coalescent lobes and thicker lobes at the bottom and terminal lobes (mouth of rectilinear channel) at the top. The basal lobes are good potential reservoirs when deformed to create structural traps. The terminal lobes are often the target of mix or stratigraphic traps.

Middle Turbidite Systems (MTS)

C) Seismic lines located between the Middle to Distal Plain



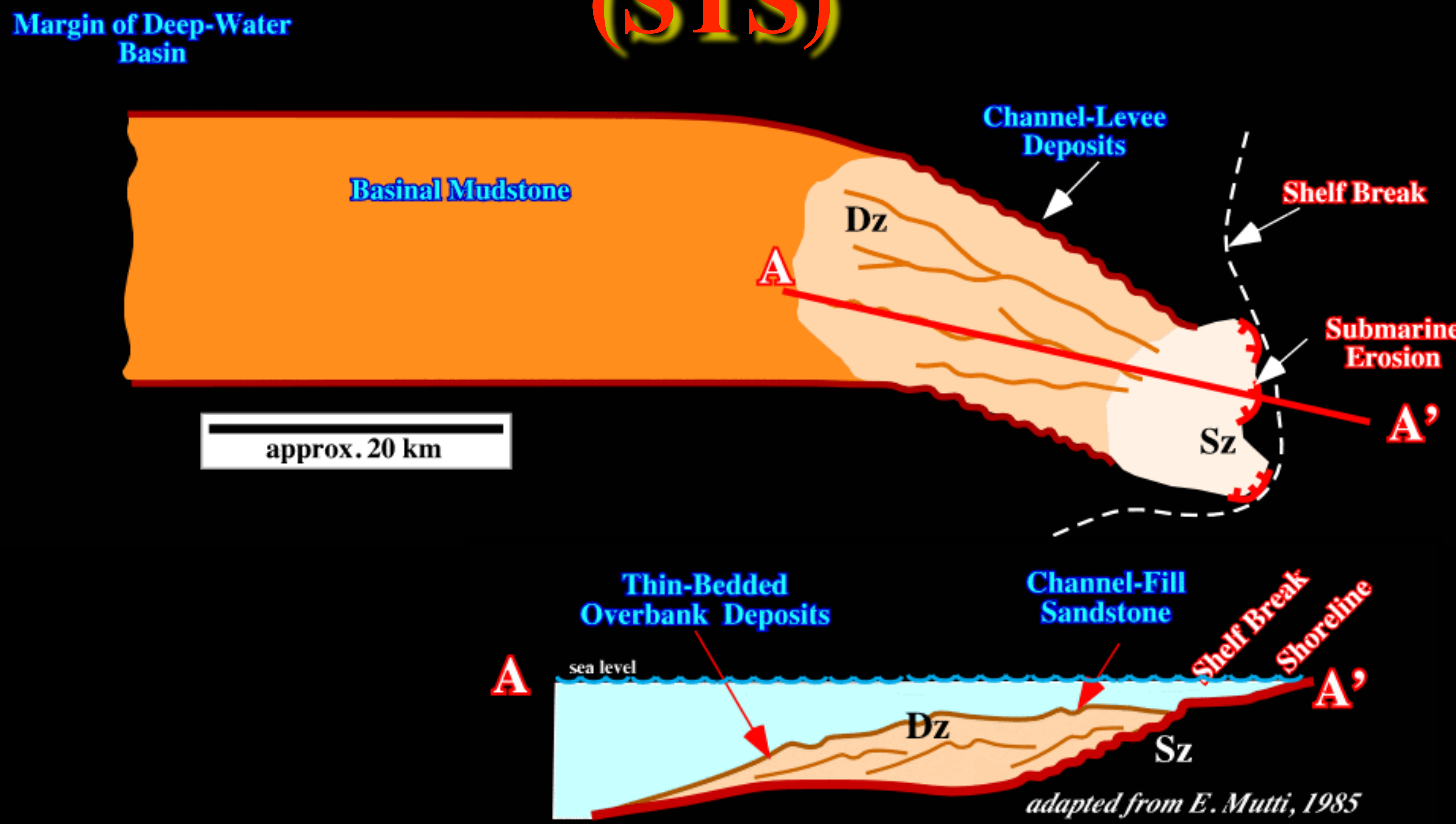
In the middle to basinal plain, the strike seismic lines generally show very elongate MTS, with small distal lobes surrounded by sealing shales. In favorable condition (landward dip and underlying source rocks), they can form interesting stratigraphic or mix trap, since seaward, the facies becoming too shaly can close the potential reservoirs.

Small Turbidite Systems (STS)

Geological Features:

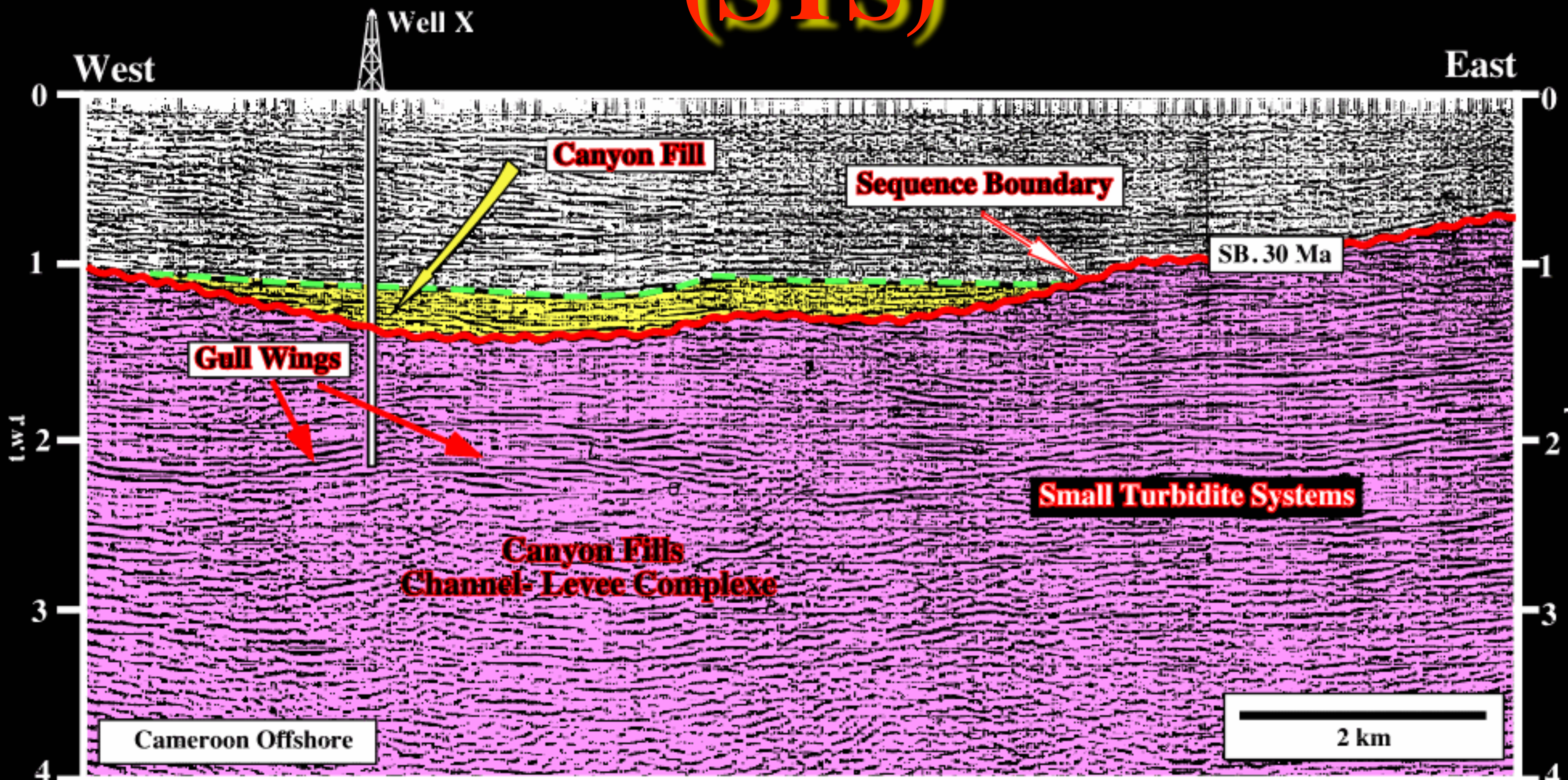
- They take place during the progradation of the shelf break. The continental slope has forestepping geometry.
- Rectilinear or sinuous channels along the continental slope.
- Sandstone terminal lobes at the end of the rectilinear channels.
- Siltstones terminal lobes at the end of the sinuous channels

Small Turbidite Systems (STS)



Small turbidite systems are generally developed during highstand geological conditions, i.e. when the self break and the depositional coastal break (roughly the shoreline) are not coincident (basin with platform). The bypass zone, if present, is very small and the slope failures quite insignificant.

Small Turbidite Systems (STS)



This seismic line shot in the conventional Cameroon offshore illustrates a canyon fill and channel-levee complexes associated with small turbidite systems. Underlying the Oligocene submarine erosion (SB 30 Ma) a thick channel-levee complex (small turbidite systems) has been recognized by all wells drilled in this offshore. Well results, such as Mutanda, Sulelaba, etc, have shown hydrocarbons on thin-bedded sandstones of over-bank deposits (levees). The reservoirs are too thin and too discontinuous to create conventional economical hydrocarbon accumulations.

Small Turbidite Systems (STS)

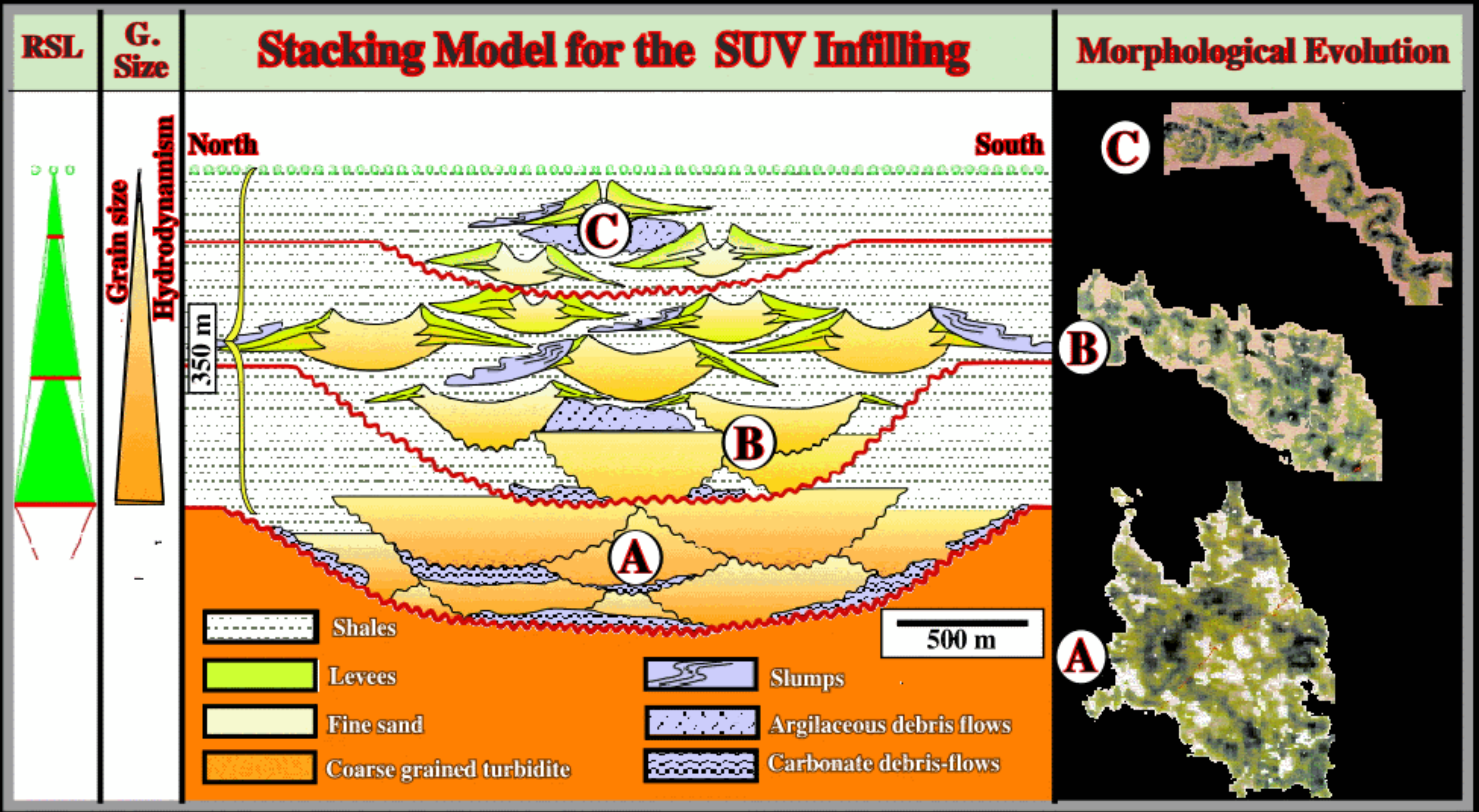
Confined Small Turbidite Systems are local, they are often the “proximal” expression of the retrogradation of Large or Medium Turbidite Systems. As a result, they often show a marked sequential character. The overall order of succession evolves from less evolved to more evolved resedimented deposits, in other words from debris flows to dilute turbidity currents.

Three successive packages were recognized:

- **Lower package:**
  - is dominated by depositional lobes deposited at the mouth of rectilinear or anastomosed channels.
- **Middle package:**
  - made up of rectilinear channel-fills.
- **Upper package:**
  - dominated by sinuous or meandering channels.

The filling of the Baudroie - Balliste submarine valley (SUV), illustrates, from bottom to top, the three different patterns turbidite patterns.

Small Turbidite Systems (STS)



This schematic diagram depict the fill of Baudroie-Baliste SUV (submarine valley), in Gabon offshore. From bottom to top three main patterns can be distinguished: (A) terminal lobes associated with rectilinear channels, (B) rectilinear channel fills and (C) Sinuous Channels.

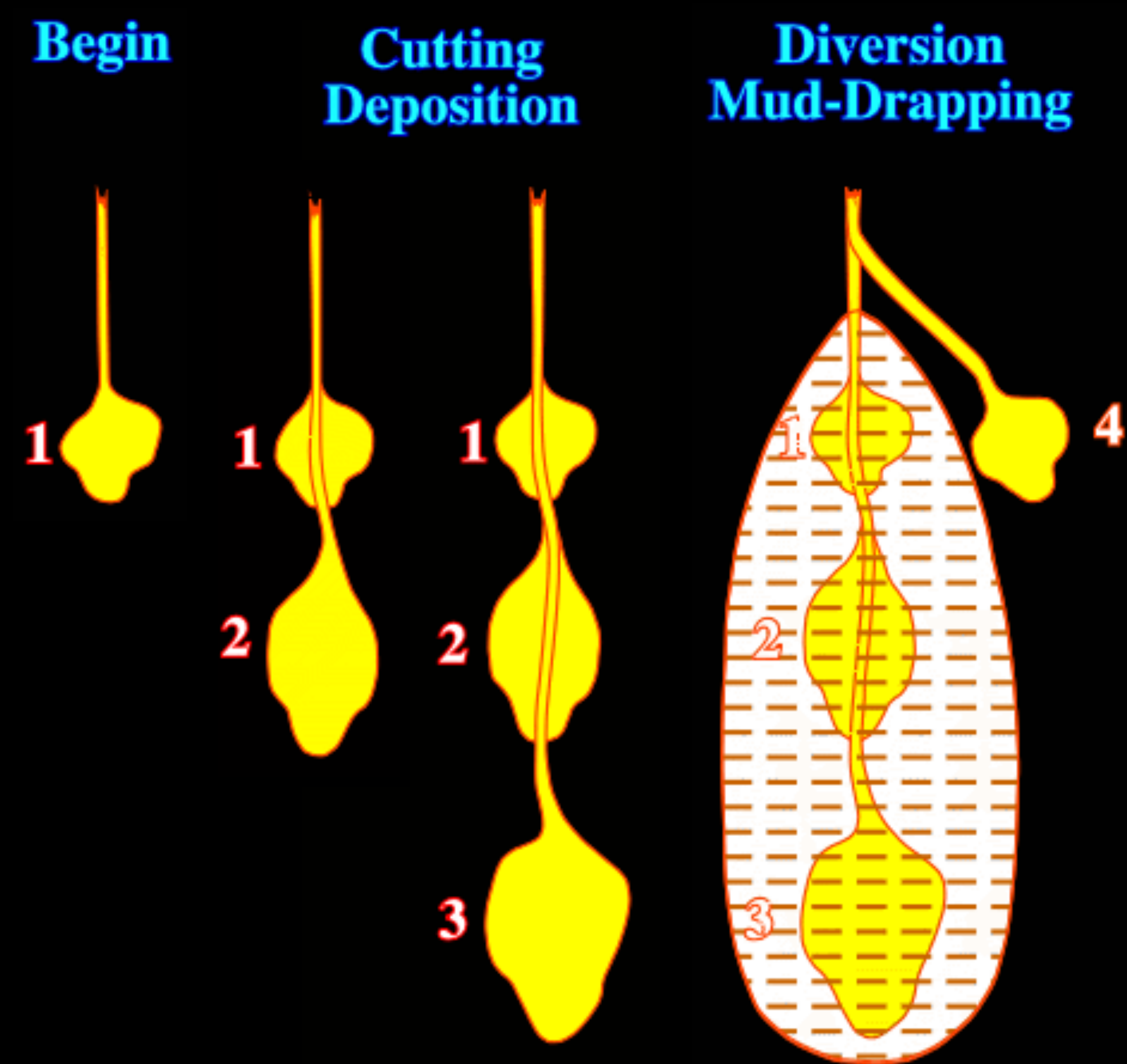
Rectilinear Turbidite Channels

A seismic pattern often observed during the evolution of unconfined continental slopes is a succession (in map view) of bright "pods" linked by rectilinear channels.

- **Minor changes in slope.**
  - ✓ Slope irregularities can result in the succession of local sand traps (decrease in slope) and bypass zones. This phenomenon is very similar to the "fill and spill" mechanism proposed by Prather et al. for minibasins, but does not imply the existence of proper lows dammed by sills, a slight decrease in a slope close to the depositional equilibrium is enough to slow down the flows, leading to sand deposition.
- **Changes in sand content of the flows.**
  - ✓ The same pattern can result from temporal changes in sand content of the flows. Minor variations in the sand / mud ratio of the flows modifies the energy of the flows and their ability to build levees constraining the next episodes.

Depending on the difference between the slope angle at the initiation of the system and the equilibrium slope angle (itself depending essentially on the volume and sand / mud content of the individual flows), sinuous / meandering channels can make minor isolated episodes being rapidly abandoned and replaced laterally by rectilinear channels and lobes, or pile up to reach a thickness of several hundreds of meters.

Rectilinear Turbidite Channels



Very often in rectilinear turbidite channels three major phases can be considered: (i) Begin phase, i.e., the initial phase, in which at the end of a terminal lobe is deposited. (ii) Cutting-Deposition phase, in which the last terminal lobe is partially eroded allowing a downward prolongment of the channel and finally, (iii) Diversion Mud-Drapping, when avulsion (change in turbidite current's course) allows a mud-drapping of the abandoned channel - lobe complex.

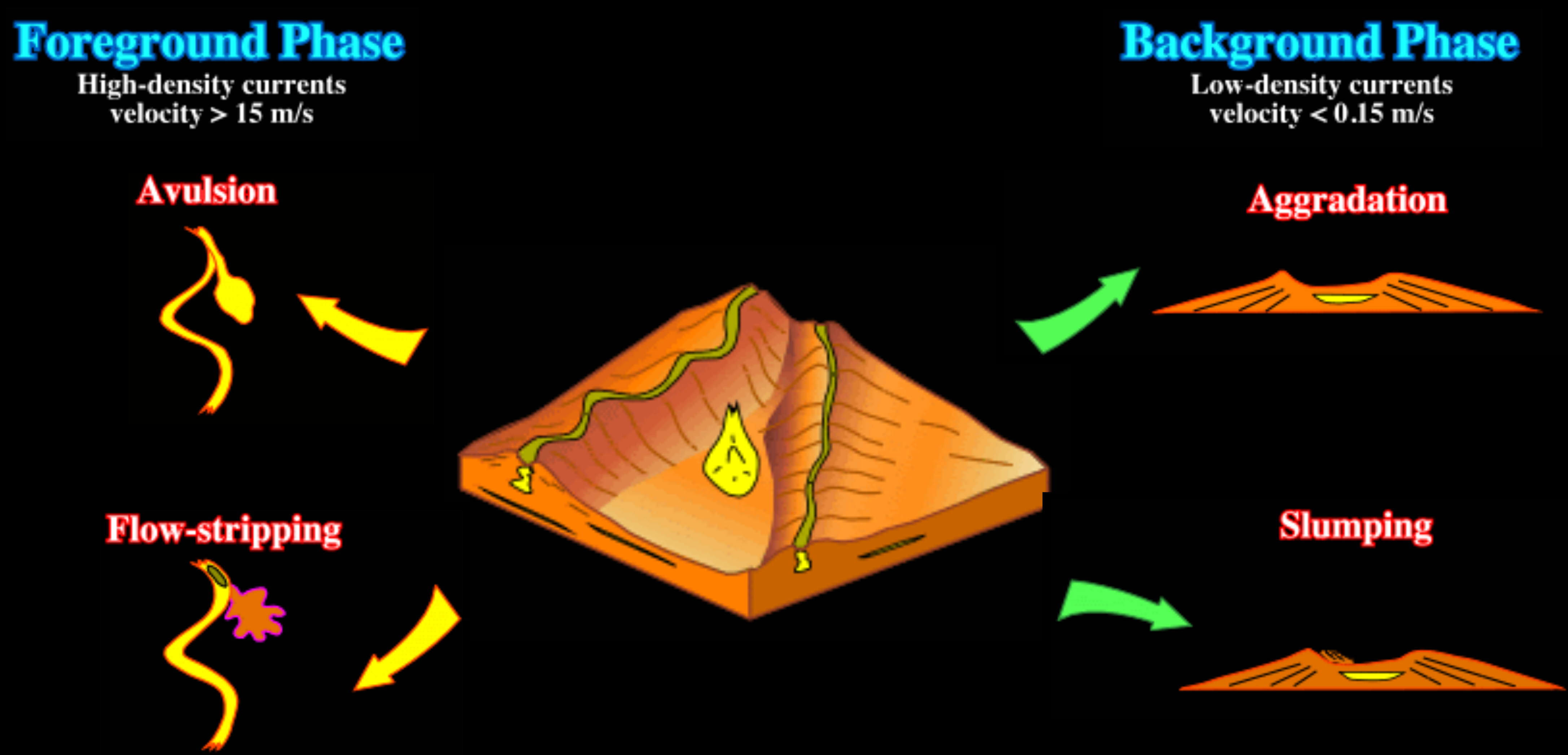
Sinuous Turbidite Channels

- Thick sinuous complexes can develop when re-establishing slope equilibrium in an area previously starved and oversteepened by tectonic activity during the period of starvation, or oversteepened simply as a result of hemipelagite deposition during the starvation period (oversteepening does not imply a precise angle, it corresponds to the contrast between the actual slope and the equilibrium slope of the system at issue).

- Seismic amplitude responses suggest that some sinuous channels can be filled by sand. These would result from more complex histories, where the sand infill is not associated with the process that built the meanders, but by the passive infill in a later stage of meanders created during episodes of low activity. Note that a flow is sinuous, when the ratio of sinuosity, (distance between two points following the flow versus the shortest distance between them), ranges between 1.5 and 2 and it is meandriform when it is higher than 2.

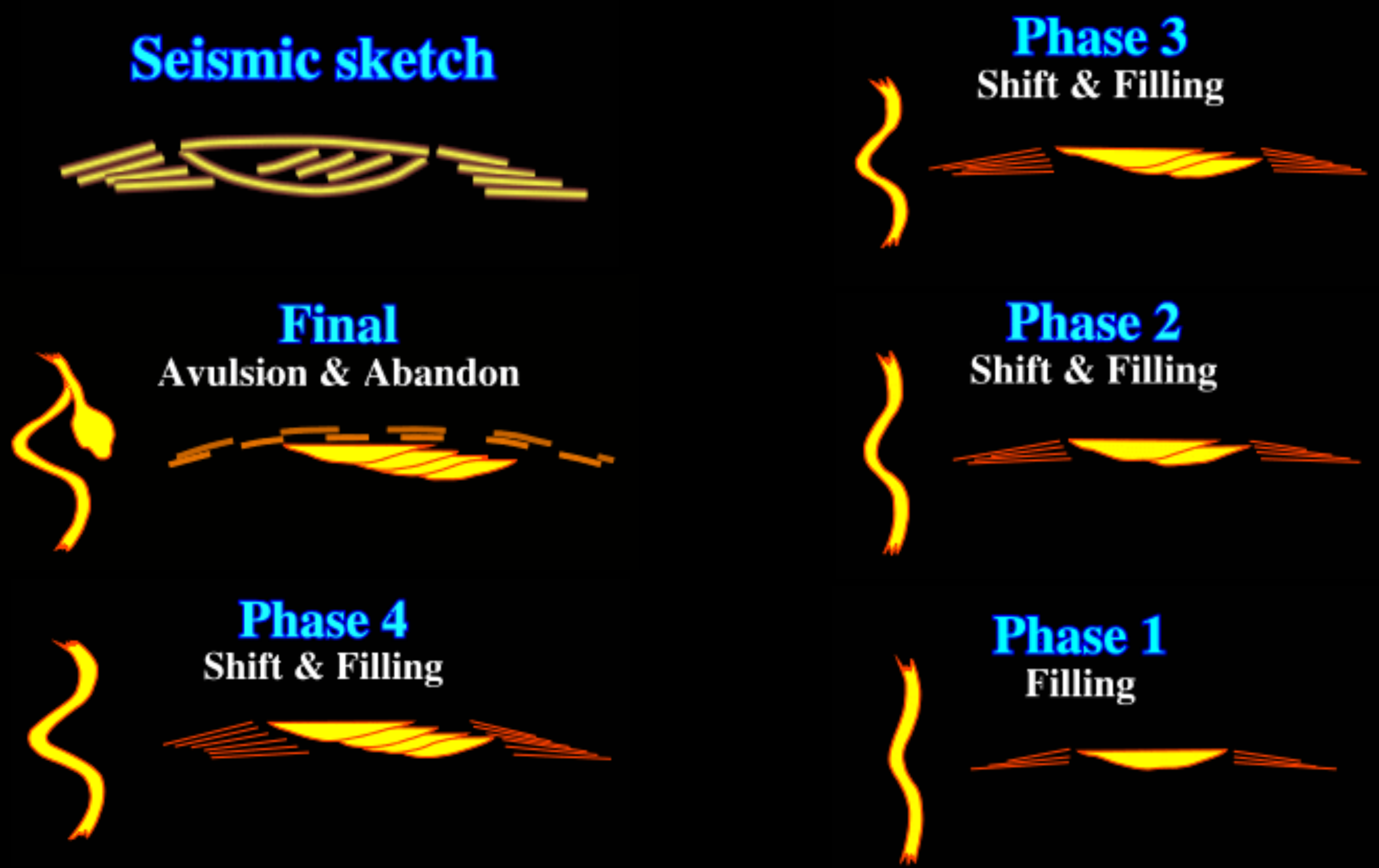
- Such complexes show the growth of a single channel over several hundred meters. The channel over that period of time usually shows a progressive increase from low sinuosity to meandering character. Most of the time, a maximum sinuosity is reached after a while and pure aggradation occurs afterwards with progressive migration downslope (sweep).

Sinuous Turbidite Channels



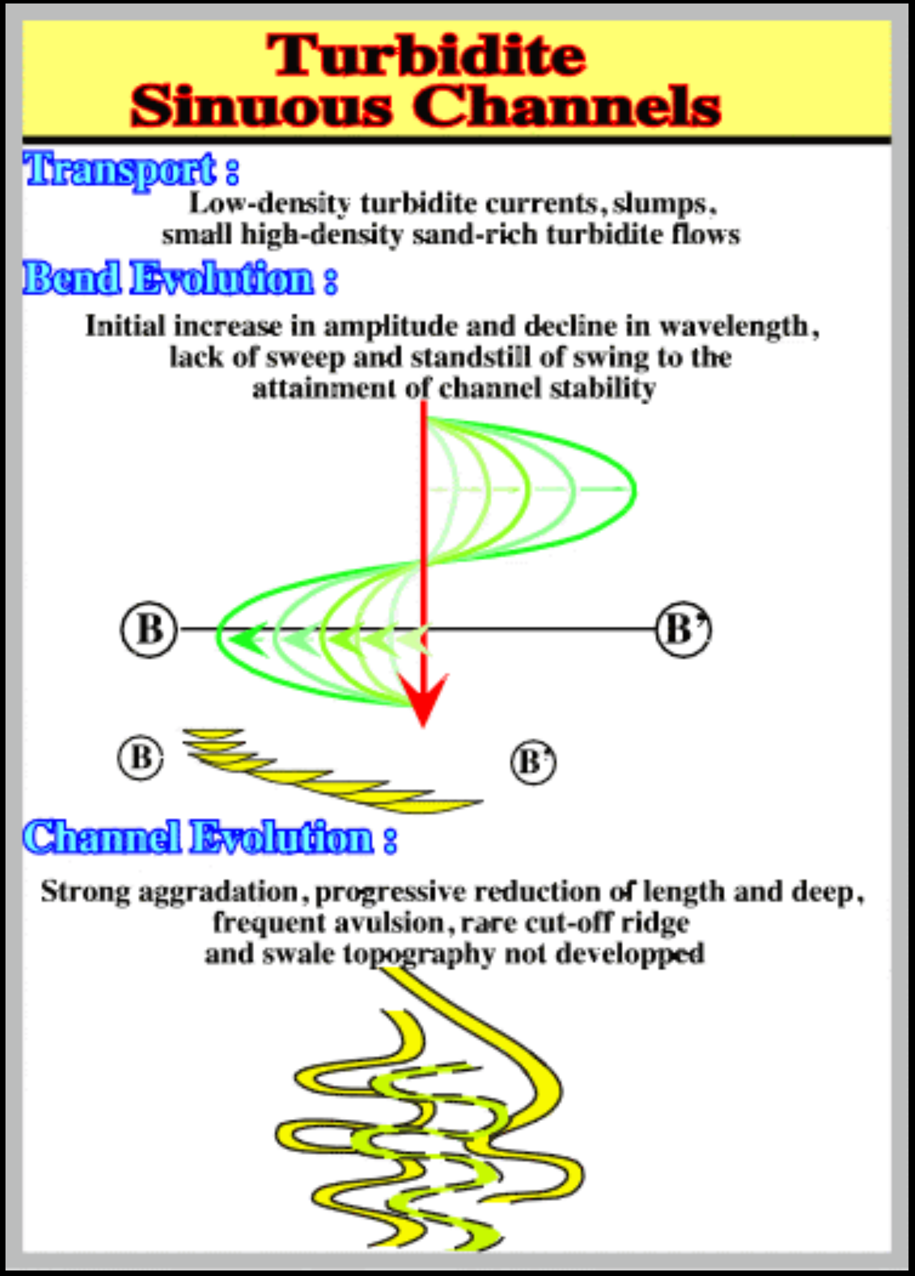
The avulsion mechanism in turbidite systems has treated by Flood et al. 1991. Avulsion typically leads to a steepening in slope, with the new channel less sinuous than the old, abandoned one. As the new channel progressively re-establishes equilibrium, its sinuosity increases to reach a maximum after which it essentially aggrades vertically.

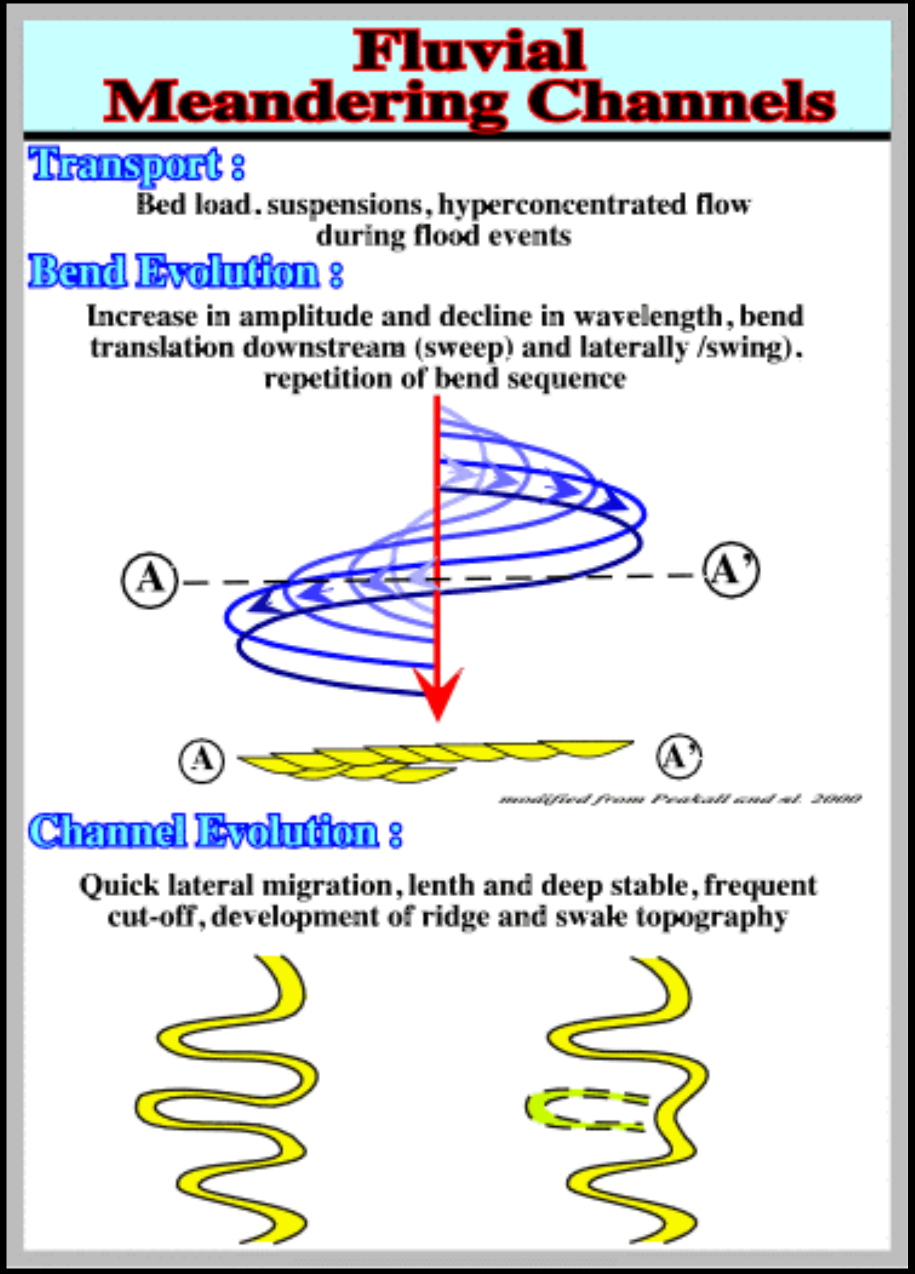
Sinuous Channels Fill



Contrary to fluvial meanders (progressive lateral accretion) turbidite sinuous channels get filled by successive episodes of cut and fill. Downcutting is interpreted to result from higher energy flows and produces sinuous lows, which are further filled up by retrogradational packages of turbidites. Successive episodes of cut and fill migrate laterally towards the concave bank due to the curvature of the channel (similarity with fluvial meanders at seismic scale).

Turbidite vs Fluvial Channels



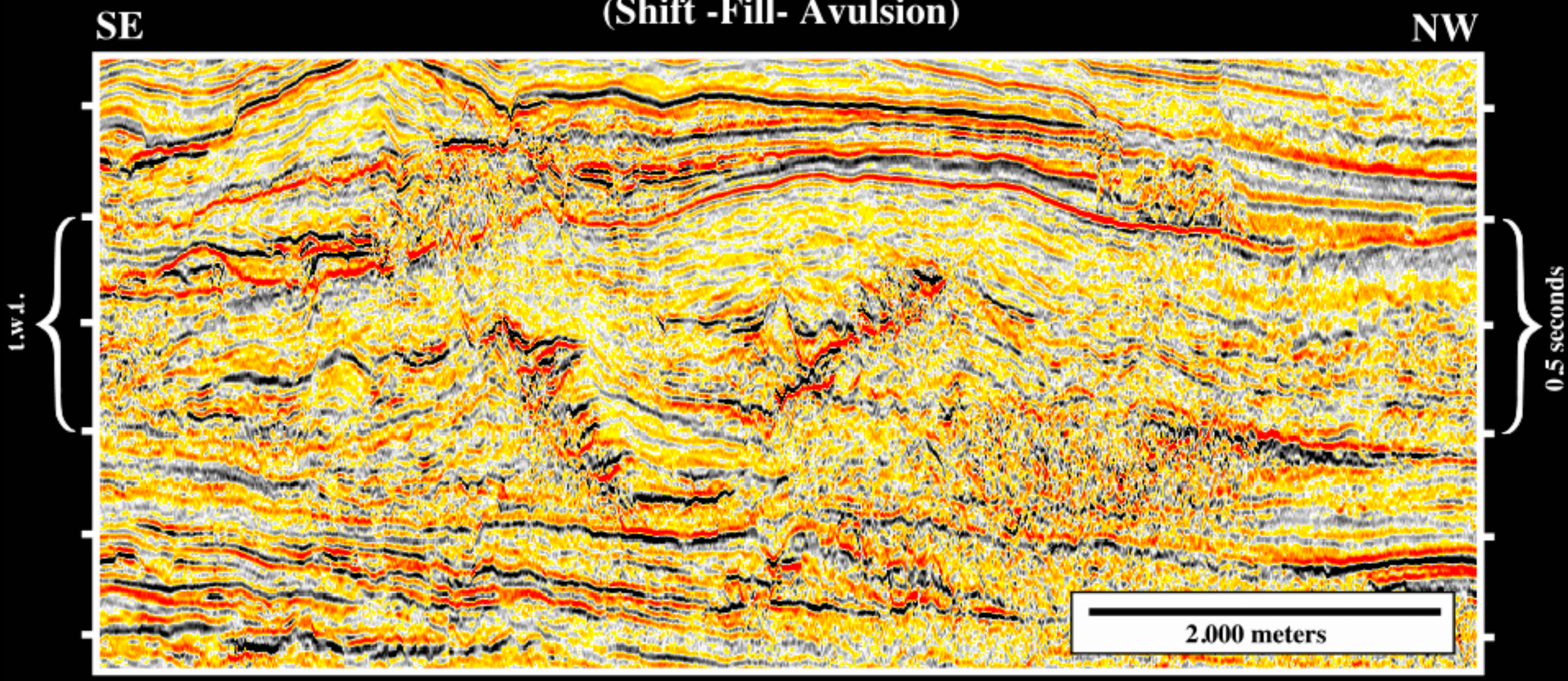


The main differences between fluvial and turbidite sinuous channels result from the difference in accommodation. Accommodation in fluvial systems is usually low, its rate of creation corresponding roughly to the subsidence of the area. Accommodation in turbidite systems is defined as the difference between the actual profile of the system and the "equilibrium profile" corresponding to the sediment supplied to the system (flow volume and sand / mud ratio). Accommodation for turbidite systems is very high, allowing a high aggradation, whereas fluvial systems essentially migrate laterally. The ratio between lateral migration and aggradation is high to very high in fluvial systems, lower in turbidite systems.

Small Turbidite Systems

Sinuous Channels

(Shift -Fill- Avulsion)



Two well-expressed successive channel-levee complexes in the deep Gulf of Mexico are illustrated. The lower channel displays very clearly the succession of downcutting events followed by rather aggradational fill. Both channels can easily be mapped, and are clearly highly sinuous in map view. Note that the migration is unidirectional for each channel complex, indicating that the lateral component of migration is predominant with respect to the downstream component.

The End