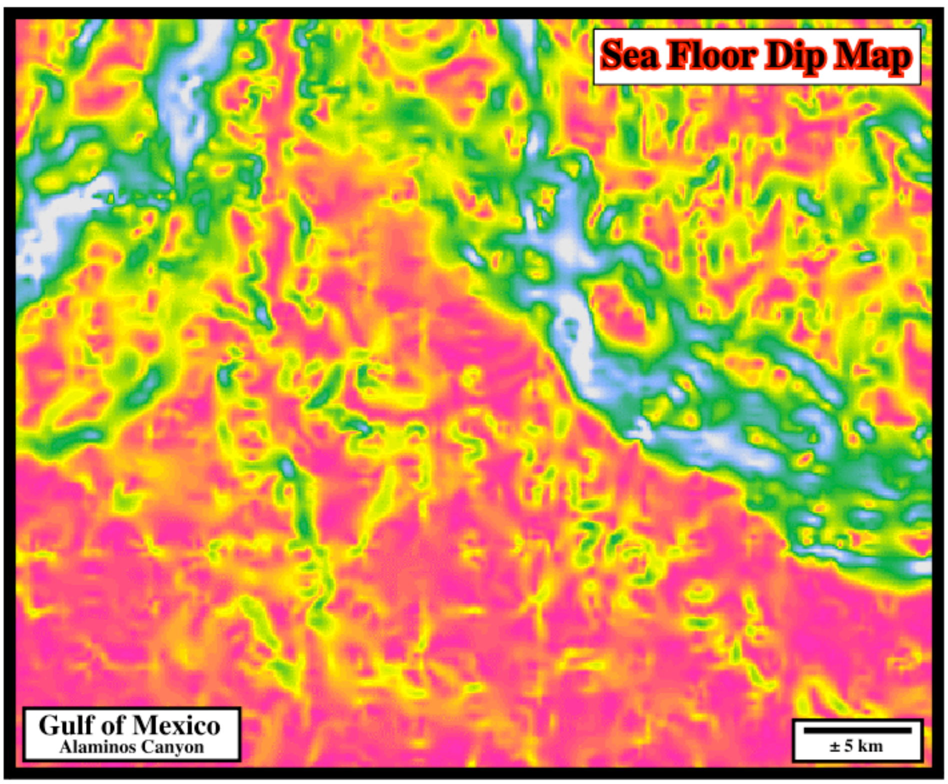
Turbidite Systems in HC Exploration



Carlos Cramez, 2003

These notes, made in collaboration with E. Mutti (Parma University), J. C. Navarre, P. Imbert and S. Mora (Total SA), claim to do no more than touch on some of the key issues, in order to give an overall perspective on what unconfined turbidite deposition is about.

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1) Turbidite Deposits & Hydrocarbon Exploration

In the past 25 years, in deep marine environments, reservoirs related to gravity flows have aroused an increasing interest in oil and gas exploration. Economical hydrocarbon accumulations associated with such reservoirs, generically, denominate turbidites, have been found in tens of sedimentary basins around the world (fig. 1).

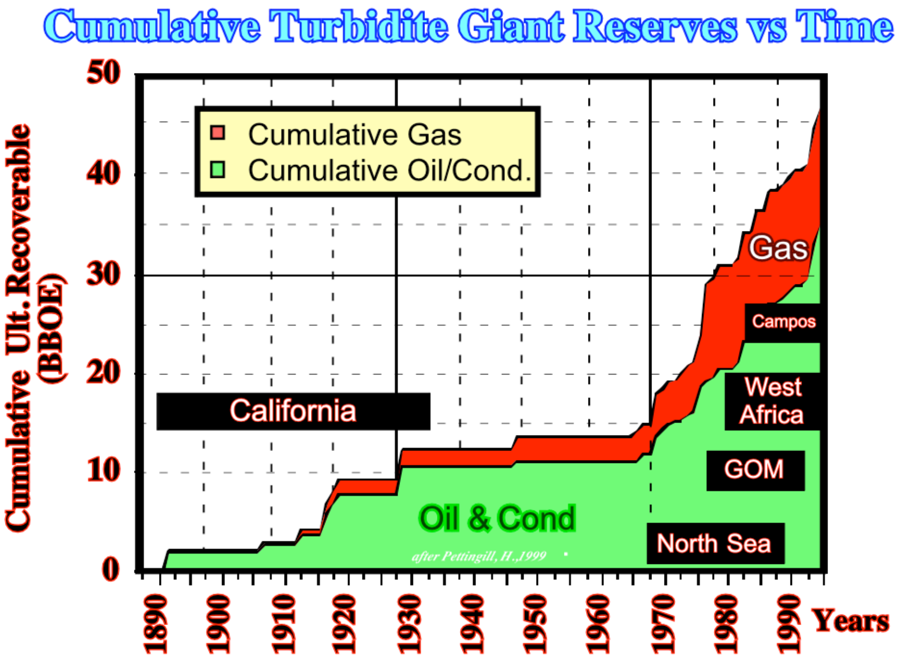

Fig. 1- Diagram illustrating the major hydrocarbon turbidite provinces related to time of giant field contribution.

During the first quarter of 20th century, hydrocarbon discoveries in turbidite sandstone reservoirs were circumscribed to California basins. With the advent of offshore exploration, large oil and gas fields were found in North Sea, between 1970 and 1990. Major discoveries in the deep-water of the Gulf of Mexico took place mainly between 1979-1996. Since 1990, offshore and particularly deep offshore exploration in West Africa (Congo, Angola, Gabon, and Nigeria) and Brazil (Campos) are the major supply of hydrocarbon reserves found in turbidite sandstone reservoirs (fig. 2).

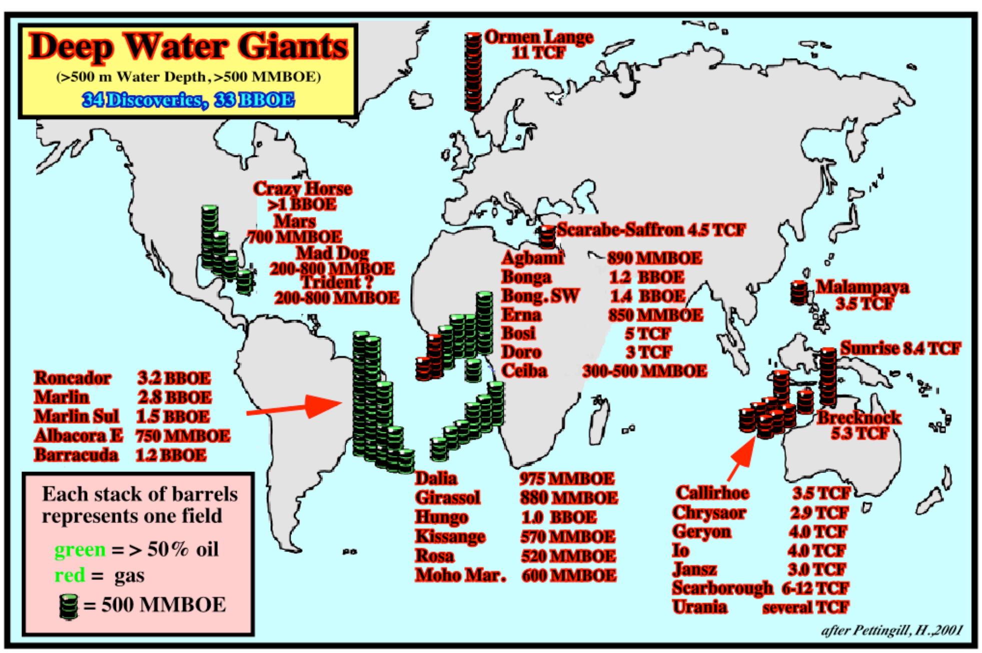

Fig. 2- Each stack of barrels represents deepwater hydrocarbon discoveries under more of 500 m of water depth and exceeding 500 MMBOE. They have roughly 33 BBOE of reserves (34 discoveries). Those made in South America, and Gulf of Mexico, are oil discoveries. In West Africa, they are either oil or gas. 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.

In other words, so far, the most active deep-water exploration frontiers and associated resources (not all of discovered hydrocarbons have been proven to be economic, and therefore can not be classified as reserves) are located along post-Pangaea Atlantic type continental divergent margins and very often down-dip from productive Tertiary delta systems, such as Niger, Congo, Mississippi).

The generating petroleum sub-system (potential source rocks) is located either in rift-type basin, either in the transgressive (backstepping) or regressive (forestepping) phase of the post-Pangaea continental encroachment stratigraphic cycle.

In West Africa, there are several potential generating petroleum-subsystems:

A) The organic-rich lacustrine shales (and limestones) deposited in rift-type basins. They are oil-prone source rocks with a type I organic matter.

B) The transgressive marine sediments associated with the maximum post-Pangaea flooding surface (Cenomanian-Turonian in age). Their organic matter is type II. They can generate oil or gas. Their burial is determinant.

C) Low TOC Tertiary deep-water sediments. Their organic matter is type III and dispersive. These source rocks are fundamental gas-prone, nevertheless, in favorable conditions condensate and small amounts of oil can be associated.

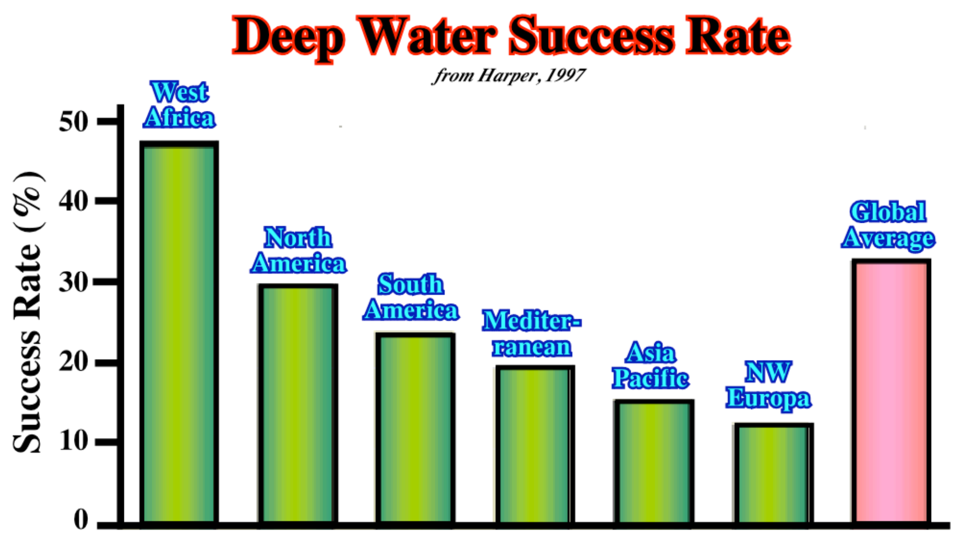

Fig. 3- So far, in deep-water environment, exploration success rate is quite high, mainly in West Africa (40%), In Gulf of Mexico, it is around 30% and in Brazil roughly 25%. The global average explorationsuccess rate is approximately 30 %, which, apparently, indicates that deep-water exploration is facile. However, not all discovered hydrocarbons have been proven to be economic. In addition, 200 MMBBOEdiscovered in West Africa will be classified as resources (may be non-economical), while in the GOM, theywill be considered as reserves, i.e. economical.

In the Gulf of Mexico, the predominant generating petroleum system is associated with the major downlap surface of the post-Pangaea continental encroachment stratigraphic cycle, i.e. with Cenomanian - Turonian sediments (La Luna equivalents):

- Their organic matter is marine and type II. The maturation of the organic matter determines the generation of oil or gas.

- Due to the presence of autochthonous and chiefly allochthonous salt, the knowledge of the burial and thermal flux are not sufficient to predict the maturation zones of the potential source rocks.

- The geometry of the salt, in related to the geometry of the source rocks, is also quite important. Actually, the salt being an excellent heat conductor can retard, or prevent the maturation, when it overlies the source rocks, or increase the maturation when it underlies them.

In NW Australia, the more likely potential generating petroleum subsystem is mainly gas prone:

- It is related either with the Kimmeridgian downlap surface or with the forestepping Tertiary sediments.

- The organic matter of Kimmeridgian shales is marine and type II. It can generate gas or oil depending of the burial. The organic matter of progradational Tertiary sediments is type III dispersive, i.e. gas-prone.
- Organic matter type III dispersive can generate economical gas accumulations only when the thickness of the source rock is quite important and the migration paths are vertical and convergent to a large trap.

So far, in deep-water exploration, the global exploration average success rate is around 30% (fig. 3). That is a quite high success rate, particularly knowing that, it reaches 45% for West Africa. Undeniably, the principal success factor has been seismic DHI's. Their identification allows explorationists to predict reservoirs and hydrocarbons almost without any knowledge of the geological and petroleum settings of the basin. Such a feature has strongly favored a reductionist (Cartesian) or fragmented approach in deep-water exploration. Unfortunately, when scientists reduce an integrated whole to its fundamental constituents -cells, genes, fundamental particles, reservoirs, anomaly amplitudes, etc., - and they try to explain all phenomena with regard to these elements, they are in the impossibility to understand the coordinating activities of system.

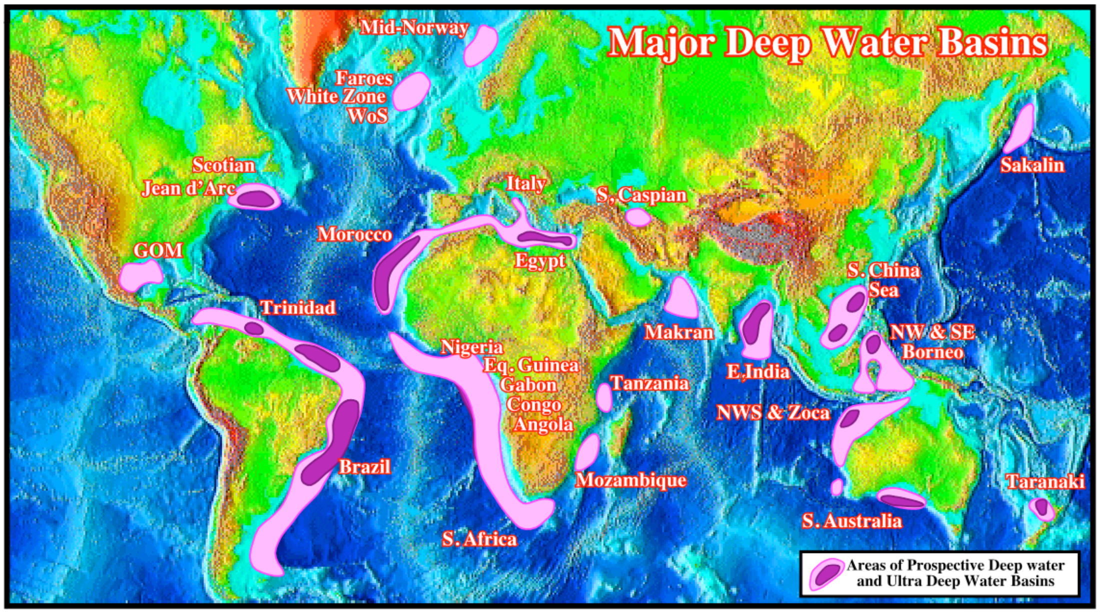

Fig. 4- In the deep water (>500 meters), the recoverable resources announced in Brazil, West Africa, GOM and NW Australia (fig. 1) include producing reserves, i.e. those in development, and technically recoverable resources for which development has not been sanctioned. All these resources are in Atlantic-type divergent margins. However, 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. In addition, as illustrated above, other deep water basins as Jean d'Arc, Sakhalin, South Caspian, Taranaki, etc, and the ultra deep basins must be taken into account.

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

a) Condensed stratigraphic sections,	b) Facies change,
c) Fault planes,	d) Volcanic glass,
d) Downlap surfaces,	f) Opal horizons
e) Cherts,	i) Pelagic limestones
j) BSR (Bottom Simulated Reflectors),	k) Diagenic line, etc.

In other words, in deep water, even above the inversion point, where the amplitude anomalies are normally located, a reductionist exploration is not appropriated. Amplitude anomalies are necessary but not fundamental. The identification of stratigraphic and morphological traps, the reservoirs architecture prediction, the cartography of the seals, the maturation zones and the migration paths, etc., are paramount.

So far, the reductionist approach in deep water exploration has been very successful and responsible of the exploration cycles that characterize almost all petroleum basins. Actually, in almost each petroleum basin, it is possible to recognize several exploration cycle associated with new technologies. For instance, in Campos basin (fig. 5), 3 exploration cycles ban be recognized:

(i) The first, between 1974 and 1983,
(ii) The second between 1983 and 1992, and
(iii) The third since 1993.

The first cycle emphasizes the conventional shallow water exploration. The second cycle marks the advent of the new drilling technologies, which allowed testing large deep-water turtleback structures such as Albcora, Marlin and Barracuda. The last cycle is mainly due to the new geophysical technology, particular the seismic DHI's.

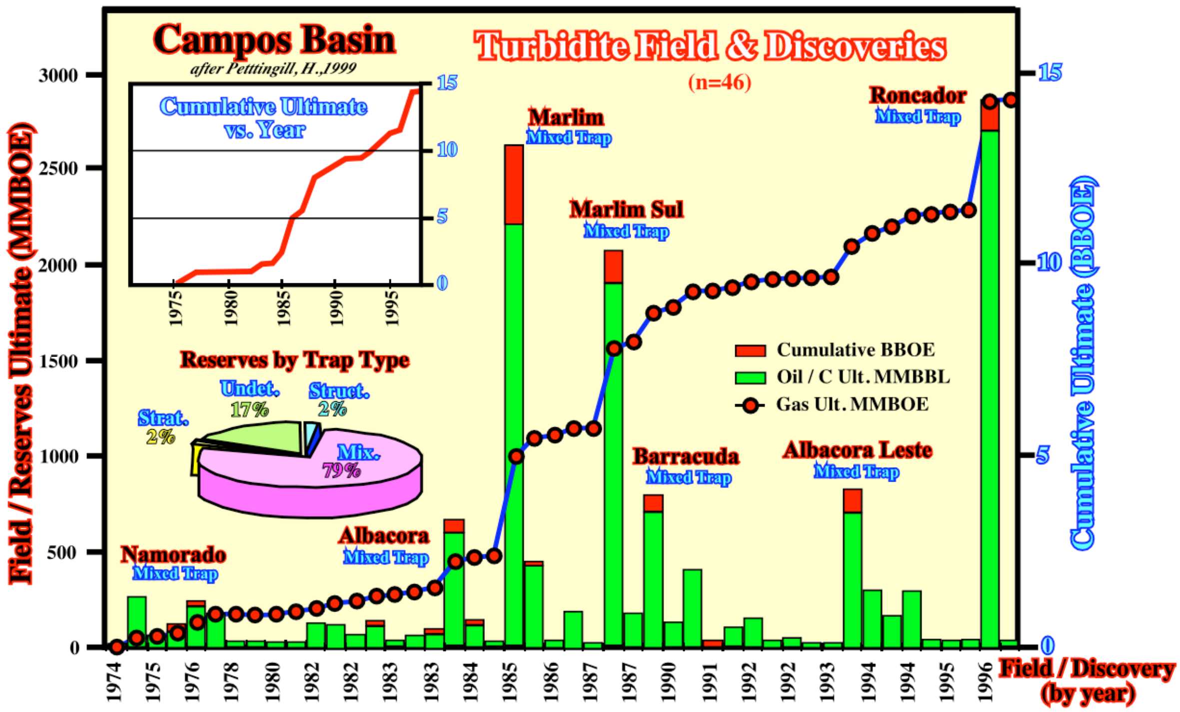

Fig. 5- Here are illustrated the cumulative reserves of 46 discovery from turbidite reservoirs in Campos basin. The main graphic shows individual fields and discoveries in chronological order (histogram bars, left y-axis) and cumulative ultimate recoverable reserves for the basin (right x-axis). The cumulative curve is re-scaled in time the upper left inset. The pie chart shows the percentage of the reserves for each trap type.

The tremendous progress realized by explorationists in deep-water exploration did not contribute to widen their basic philosophy. The Cartesian paradigm (reductionism or fragmentation of exploration) always dominates exploration and particularly deep-water exploration.

However, as amplitude anomalies and large structural or morphologic traps become more and more rare, to resolve future exploration's problems a new paradigm will be necessary with concepts transcending the Cartesian vision of the Geology. It is possible that a systemic or holistic vision furnish the conceptual setting of the new exploration. In such an exploration approach, the passage from the objects to the relations will have important implication. The relations should be used as base of all definition. Geological features, as a turbidite, for instance, should be defined not by what it is, in itself, but by the relations with other objects.

N.B.-The fragmentation or reduction of exploration should not be confused with the act of division of an area of knowledge into particular fields of specialization or with the abstraction of specific problems for study. These divisions may be perfectly legitimate, and in fact, they are essential features of exploration. Rather as the term indicates, to fragment means "to back up or to smash". Fragmentation in exploration arises when an attempt is made to impose divisions in an arbitrary fashion without any refer for wider context, even to the point of ignoring essential connections to the rest of the basin or adjacent basins.

The basin ultimate recoverable, exceeding 1 BBBOE from turbidites, for 17 sedimentary basins of different types are illustrated in fig. 6, as well as the age of the main reservoirs rocks. Cenozoic divergent margins (Atlantic and non-Atlantic type) are largely preponderant. However, Cenozoic perisutural and episutural basins are also quite prolific.

All hydrocarbon discoveries in turbidite reservoirs and particularly the discoveries of the giants oil fields in deep offshore of Atlantic margins in the last two decades, with the resultant large availability of seismic, wells and reservoir data, have occasioned a proliferation of geological turbidite models, as well as a sophisticated terminology, which very often contrast the models issued from the outcrops and the marine geological studies (fig, 7).

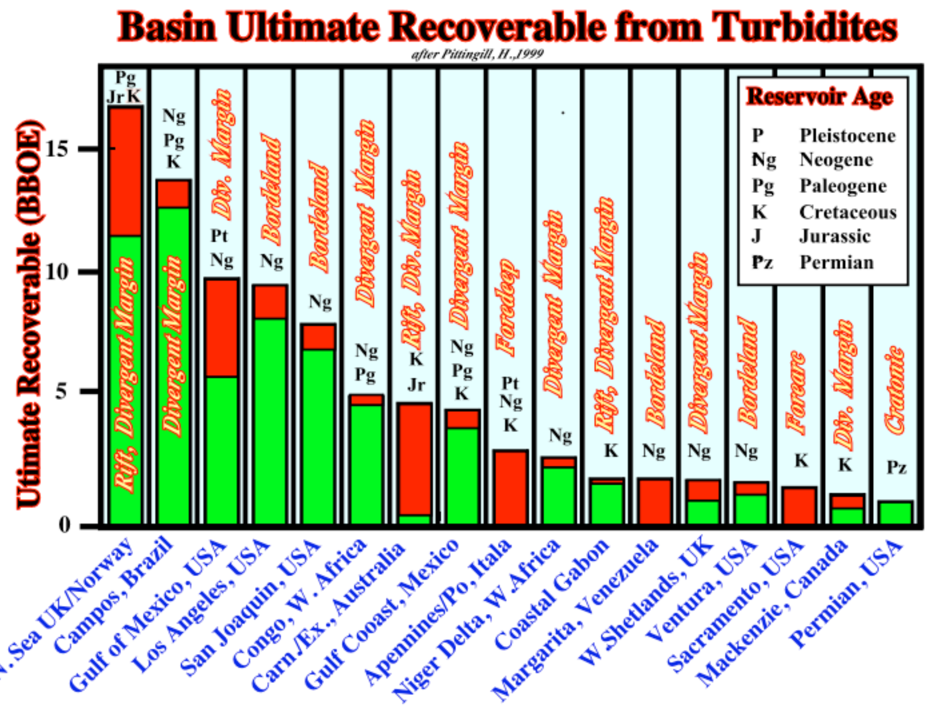

Fig. 6- Total Ultimate Reserves for 17 basins exceeding 1 BBOE ultimate recoverable. Basin types and reservoir ages are indicated. Green = oil, red = gas.

2) Turbidite Models

Several papers and books have been described, discussed, explained and proposed classifications of the turbidite systems concerning processes, facies, internal geometries (e.g. Bouma et al., 1985; Mutti & Normak, 1987; Pickering et al., 1989; Mutti & Normark, 1991; Weimer and Link, 1991; Mutti, 1992; Weimar et al., 1994, Mutti et al., 1994; Reading and Richard, 1994; Shanmugam, 1999; Mutti et al., 2000) and genetic signification of deep sea deposition systems (e.g. Mitchum et al., 1985; Stow et al., 1985; Mutti, 1985; Vail, 1987; Mutti et al., 1988, Posamentier et al., 1988; Pickering et al., 1989; Posamentier et al., 1991; Normark et al., 1993; Mulder and Syvitski, 1995; Mutti et al., 1996; Normark et al., 1998).

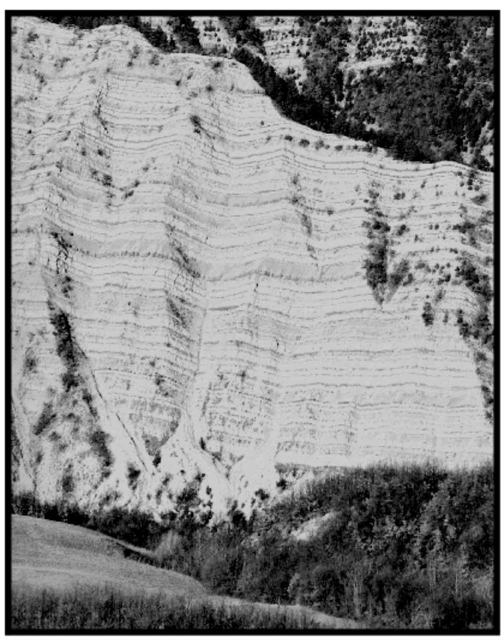

Fig.7 - In this outcrop from the Late Cretaceous Monte Cassio flysch (Northern Apennines), the parallel beds correspond to parallel bedded basin-plain deposits. They consist mainly of redeposited pelagic and hemi-pelagic biogenic oozoes. Subordinate, fine-grained sandstone form the darker and considerably thinner, however more resistant sedimentary units. These sediments, which are interpreted as trench-fill deposits are thought to be a classic example of stacked mega-turbidites deposited from gravity currents triggered by seismic activity (seismo-turbidites of Mutti et al., 1984), The thin bedded sandstones and the dark mudstones represent the background sedimentation of the basin plain.

Today, 50 years after that Kuenen and Migliorini interpreted the graded bedding observed in main ancient flysch deposits as a result of turbidity currents (see Kuenen and Migliorini, 1950), and 30 years after the first models of submarine fans (see Normark, 1970; Mutti and Ricci Lucchi, 1972), the number of models (frequently realized mixing subsurface and outcrops-derived data) approach the number of turbidite systems studied (situation already anticipated by Normark in 1993). For several authors (and for many geologist / geophysicist of oil companies) such a situation is firstly related to the fact that a great part of the present day knowledge on turbidites still coming from deep-marine succession deposed in ancient episutural and perisutural basins (fig. 7).

- If some "turbidite fans" still are active today (La Jolla, Magdalena, Crati, etc.), the Holocene sea level rise has deactivated most of them, which are now being veneered with mud rendering impossible comparisons between ancient and modern turbidite systems.

- In addition, it is impossible to directly reason in depositional contexts and their functioning. Depositional events are episodic at geological scale, but they surpass by several the times human time scale (see later).

In the last 5 years, following the discoveries in Tertiary turbidites of the Gulf of Guinea, the interest of the oil companies has been focused on the slope systems that have been considered, for long time, deprived of economic potential:

- These deposits are mainly associated with large deltaic systems developed in the central part of South Atlantic margin.

- Apparently, in terms of external geometry, they show strong similarity with the modern sedimentation.

- 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.

-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.

- Curiously, 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.

- It is evident that 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 blocks.

The discovery of giant oil fields in deep-offshore in offshore Brazil (Marlim, Albacora and more recently Roncador, fig. 5), characterized by sand deposits highly reworked or entirely deposited by bottom currents (Carminatti an Varela, 1987; Mutti, 1989; Mutti, 1992), again highlighted the apparent impossibility of comparison between the outcropping turbidite systems deposited in highly tectonically mobile basins (Pyrenees, Alps, Apennines, Neuquen, etc.), which are devoid of facies related to reworking by bottom currents, or turbidite systems recognized by drilling in cratonic basins (North Sea) and in divergent margins (West Africa, Gulf of Mexico, etc.).

- At the present-day and during the Tertiary time, the continent-basin profile through Campos' oil fields is strong different from the profiles across other margins (Gulf of Mexico, Congo, Pakistan, etc.).

- In contrast with these basins, characterized by large coastal plains and shelves with huge deltaic systems, in Campos basin only small deltaic systems are developed in a relatively short distance between the bay-line and the shelf-break.

- However, at Cretaceous time (mainly Upper Cretaceous), in Campos basin, the seismic lines and the exploration's results indicate very thick deep water wedge associated to a relatively thin platform sedimentary sequence.

- **Conversely, in the other basins mentioned above, the Upper Cretaceous stratigraphic deep sections are very condensed and their facies is shaly.**

3) Geological Events

Turbidity currents, which create turbidite deposits, occur on time scales ranging from minutes to days. In contrast, in any location, the time between successive depositional events is though to be on order of years to thousand years. Therefore, 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 (fig. 8).

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

Fig. 8- Gretener (1967) classified geological events can be classified in regular, common, recurrent, occasional and rare according to their frequency.

At the human scale, i.e. two or three generations, low probable geological events are considered as possible, even if there is any natural law forbidding them. In the same way, there is any law forbidding that if you throw eight dice you get eight six. It is just a question of scale. Geologists know that what at the human scale is considered impossible it is only improbable at geological scale (condition *sina qua non* to understand geological systems). Using a dice metaphor:

> **"If you consider that every six of a die represents a geological agent, such a storm, an hurricane, an earthquake, a turbidity current, etc., you can make the hypothesis that a result of 7 six (throwing eight dice) represents an event less dramatic that the one produced by a result of 8 six. Also, a result of 5 six will be even less dramatic and more frequent than a result of 7 sic, etc."**

It was using such reasoning that Gretener proposed a classification for discontinuous geological events (fig. 8). Taking into account such a classification, in geological history, two families of geological events can be proposed:

i) Frequent events

Which take place at least once all 100 My. Their time-duration is around 1 My (1/100 of total time).

ii) Rare events

Which take place at least once all 1.000 My. Their time-duration is about 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.

In other words, in any way, a turbidity current cannot be taken as a rare geological event, i.e. is a punctual geological episode with a low rate of renewal in the Earth's history (2-5 times). On the other hand, it must be notice that an instantaneous geological event, as turbidity current, is a relative concept. Actually, taking into account the deep-geological time, the time-duration of a geological event is always a relative concept, as illustrated on fig. 9.

Mathematically, an instantaneous event is characterized by a time-duration exceeding barely 1/100 of total time. Such a concept, when expressed diagrammatically in change versus time, as depicted on the fig. 9, the changing time corresponds just to the thickness of the pencil line.

Knowing the time-duration of the geological events and the directly or indirectly associated deposits, geologists always must take into account the completeness and the preservation of sedimentary records. On this subject the completeness and the preservation of the turbidite deposits is quite important to the understanding of turbidite systems.

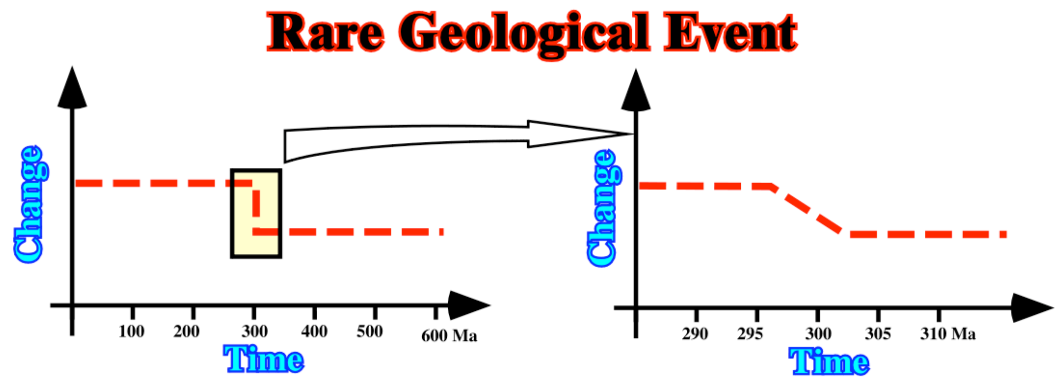

Fig. 9- At geological scale (on the left in the figure), a Paleozoic geological event, such a sequence stratigraphic cycle, induced by a 3rd order eustatic cycle, which time duration ranges between 0.5 and 3 My, is an instantaneous geological event. Its time-duration (3 My) is approximately 1/100 of the total time of the Phanerozoic. However, in a dilated time-scale (on the right), the same event has a finite time-duration of 6 My.

4) Completeness and Preservation

For a long time, geologists asked themselves the question of the continuity versus discontinuity of geologic events:

> **Are the sedimentary records the result of more or less continuous geologic processes, or are they associated to extraordinary processes, which take place in a spasmodic way?**

Since the 18th century, geologists have given very opposite answers. Presently, the majority of them consider that the sedimentary records are incomplete and separated by important periods of non-deposition during which nothing happens. In spite of that, it is surprising to see that some geologists continue to forget in their stratigraphic models the long periods of non-deposition during which nothing happens. In fact, in stratigraphic sections, the time-duration of hiatuses (by non-deposition or erosion) is generally much important than the deposition-time of the preserved sediments.

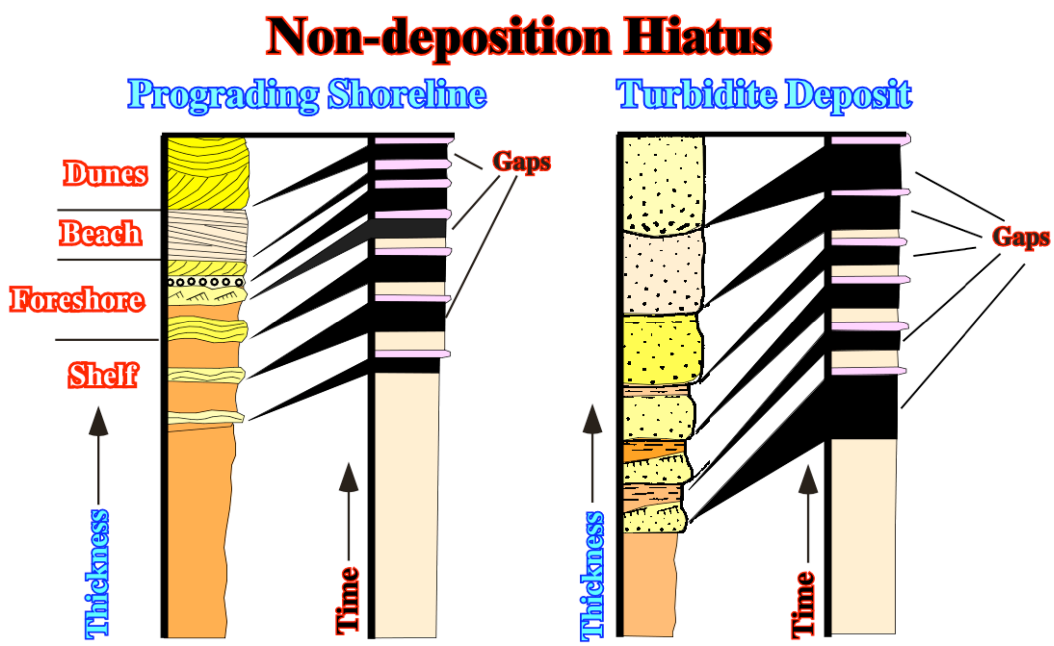

Fig. 10- In these geological cross-sections, and particularly on their upper parts, the periods of non-deposition aremuch longer than the periods of deposition. In the prograding shoreline cross-section, illustrated above, a largenumber of geological events took place, but the associated deposits are not preserved. They have been eroded. Theywere replaced by significant erosional-hiatuses. In the turbidite cross-section, 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 (see text below).

Stratigraphic sections are just local archives of the geologic history (Sadler, 1982). 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 (period during which there is deposition). Nevertheless, geologists know, since long time, that stratigraphic sections contain numerous hiatuses induced whether by the erosion or non-deposition (fig. 10).
On this particular subject, three important questions come always to the mind of geologists:

1) What is the deposition-time of a single sedimentary bed?
2) What is the total time of deposition of a stratigraphic section?
(span of time between the bounded unconformities)
3) What is the ratio between the total time of a section and the actual deposition-time of its beds?

The answers of the first two questions are relatively easy.

- Concerning the first question we one can say that:
 1.1) A lamination of a beach deposit is deposited in about one second,
 1.2) A HCS bed ("hummocky cross stratification"), characteristic of storm deposit, is deposited in few minutes.
 1.3) A turbidite layer is deposited in few hours.
 1.4) A flood deposits, such as the Scablands in Canada (deposits, and erosions, associated to the floods induced by the break-up of the lakes' retentions at the back of Plio-Pleistocene glaciers), can be deposited in few weeks,
 1.5) A glacial varve is deposited in a 1 year,
 1.6) A centimeter of a pelagic sediment is deposited during about 100 years.

- Concerning, the second question we can say that:

 2.1) A continental encroachment stratigraphic sub-cycle has a time-duration ranging between 10 and 20 millions years (Duval et al., 1993);
 2.2) A continental encroachment stratigraphic cycle has a time-duration ranging between 100 and 300 million years (Duval et al., 1993).

Sadler (1982) suggested that the deposition-time is conversely proportional to the rate of deposition. Higher is the rate shorter is the time. From such a hypothesis, it follows that 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).

The last question, i.e. what 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, is more difficult to answer. It put forward the problem of the completeness of stratigraphic section, i.e. the deposition-time and the preservation of the beds composing a section. The preservation of a stratigraphic section generally depends on:

(i) The amplitude.
(ii) The frequency of the stratigraphic events.
(iii) The depositional environment.

The stratigraphic events more represented in the stratigraphic records are those that have a normal or weak frequency, i.e. those that take place sporadically. In this sense, basin floor and slope fans strongly contrast with pelagic shaly intervals, which separate them. The pelagic intervals are stratigraphic events with normal frequency, whereas turbidite deposits are instantaneous low frequency events. Let's see an example:

a) Suppose an interval composed by 100 turbidite layers and 100 of pelagic clays.
 - Each turbidite-layer has a thickness of 10 cms,
 - Each pelagic-layer has a thickness of 5 cms,
b) The total thickness will be 1500 cms.
c) Assuming an average depositional rate of the pelagic clays clay of 5 cms / 1000 years, and
d) A depositional rate of the each turbidite-layer has instantaneous.

One can deduct:
(i) The total-deposition time is 100.000 years.
(ii) The frequency of turbidity currents is of 1000 years.
(iii) The completeness and the preservation of the pelagic clays is 1.
(iv) The completeness of the turbidite layers is almost zero (0), but its preservation is 1, i.e. almost total (Dott, 1983).

In this example we can conclude:

Two thirds of the sedimentary interval was deposited by instantaneous events with a low frequency (one event each thousand years). In 10 My, ten thousand (10.000) instantaneous turbidite-events have deposited a section of 1500 meters. In other words, what seems impossible at the human scale becomes, on a geological scale, is possible, and the improbable becomes inevitable (Simpson, G. G., 1952).

5) Turbidity Currents

Generally speaking, a turbidite is a sedimentary rock deposited from, or inferred to have been deposited from a turbidity current. The term turbidity current was introduced by Johnson, D. W. (1939) and applied to a current due to turbidity and not to one showing that property. Such a current can be defined as a density current in water (air or other fluid) caused by different amounts of matter in suspension. Specifically:

"it 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 can be originate in various ways, such as:

- **(i) Storm waves;**
- **(ii) Tsunamis;**
- **(iii) Earthquake-inducing sliding;**
- **(iv) Eustatic sea fall;**
- **(v) Tectonic movements;**
- **(vi) Slope instabilities;**
- **(vii) Upwelling currents;**
- **(viii) Over-supply of sediments;**
- **(ix) Heavily charged rivers in spate with densities exceeding that of the sea water, etc, etc.**

All these geological events 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. In fact, so far, shelf-organized critically is the only known general mechanism able to generate complexity (Bak. P., 1996). However, 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).

In other others, turbidite systems are deposited by turdidity-currents and are complex geological systems. Most of the changes take place through catastrophic events. They do not follow a smooth gradual path. Subsequently turbidite deposits cannot be understood just studying its different components, since the whole system is more than the simple the addition of its parts.

6) Turbidite Facies and Related Processes

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:

- **(i) 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.**
- **(ii) The second limitation is represented by the very low-gradient facies variations that most systems undergo over the available outcrop areas.**

Some large systems actually show no appreciable facies changes of individual beds or groups of beds even over distances of tens of kilometers. Facies tracts can only be significantly reconstructed within a framework for predictive facies classification scheme, which relates facies and processes, i.e., through the second, or genetic, level of facies analysis. Such a framework, proposed by Mutti (1977, 1992), is illustrated in fig. 11, cover a very broad spectrum of facies from cohesive debris flow deposits (F1), with boulder-, cobble-, and pebble-sized clasts, to graded mudstones (Te of F9a). Direct field evidence shows that cohesive debris flows; hypercontcentrated flows, and gravelly, high-density turbidity currents produce facies types, which are clearly genetically inter-related.

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

A) Very Coarse Grained Facies,
B) Coarse Grained Facies,
C) Fine Grained Facies

A) Very Coarse Grained Facies

Three main facies can often be distinguished:

F1 deposits (fig. 11) are the product of cohesive debris flows. The following features characterize them:

(i) The lack of significant basal scours,
(ii) 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,
(iii) The tendency for the largest clasts to concentrate toward the top of the bed and project upward above the top of the bed.

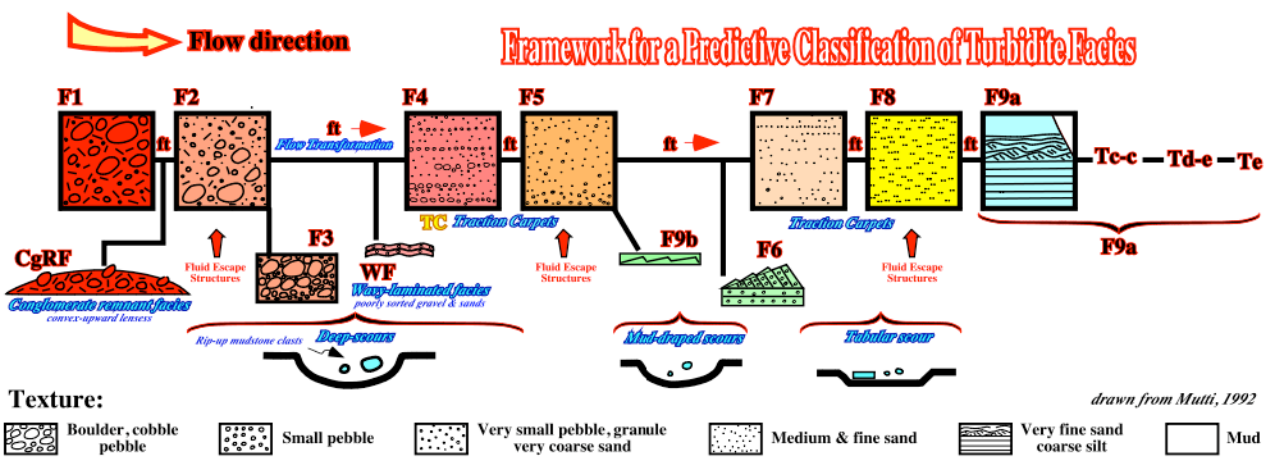

Fig. 11- Four kinds of flow transformations were recognized by Mutti in 1977 & 1992. (i) Body transformation occurs when the flow changes between laminar and turbulent within the body of a flow without significant addition or loss of interstitial fluid; (ii) Gravity transformation occurs when initially 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.

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:

(i) Occurrence of deep basal scours and large rip-up mudstone clasts.
(ii) The larger clasts float in a fully mixed and occasionally crudely graded matrix composed of mud, sand and gravel.
(iii) 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.

B) Coarse Grained Facies

This group includes, in a downcurrent direction, WF, F4, F5, and F6 (fig. 12) 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:

1) 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.

2) 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.

3) 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.

4) 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.

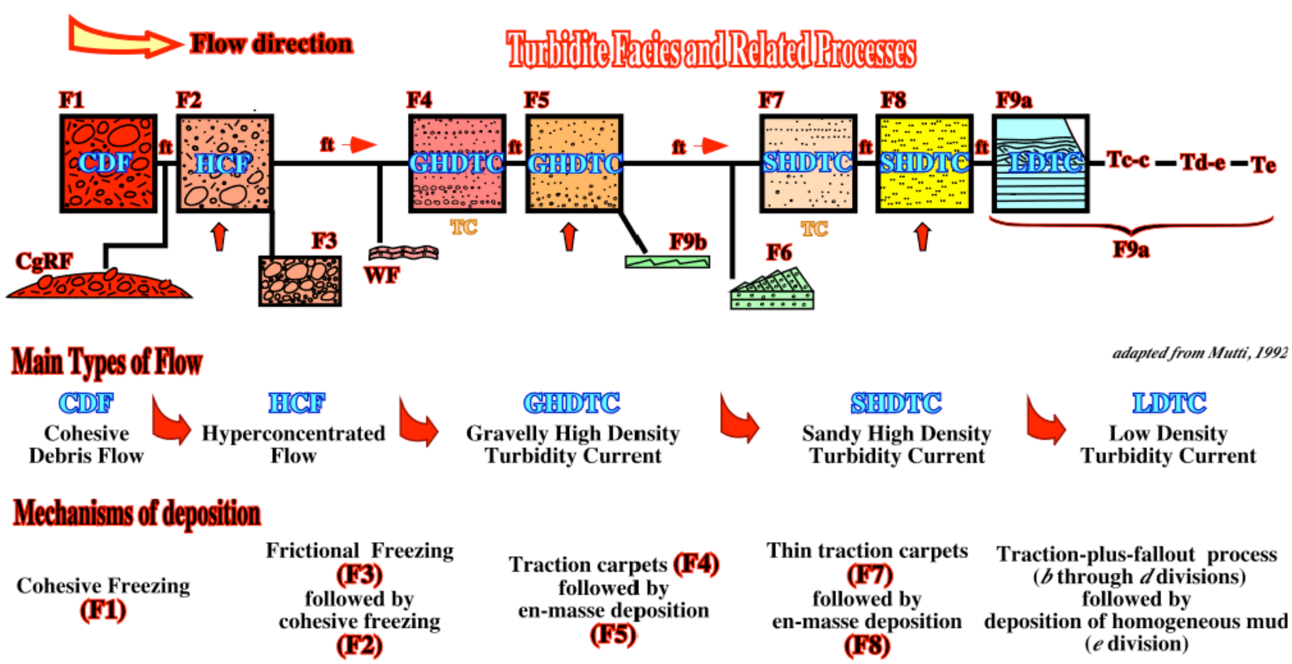

Fig. 12- Cohesive debris flows, clasts are supported by matrix strength and density, and deposition takes place when the applied shear can no longer overcome the flow strength. Sediments of this type, which result from cohesive freezing, are easily recognized since they consist of mud- supported clast. 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.

C) 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.

1) 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.

2) 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.

3) **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.**

7) Depositional Turbidite Systems

Depositional systems are defined as three-dimensional assemblages of lithofacies generally linked by active (modern) or inferred (ancient processes) and environments (Fisher and MGowen, 1967). The term lithofacies is redundant, since facies was defined, by Grossly (1835), as lithology with a characteristic fauna associated. In depositional systems, the facies are synchronous and genetically related. When a facies disappears, all others disappear too. In a deltaic system, there are three synchronous and genetically related facies: (i) the prodelta, (ii) the delta front and (iii) the delta plain. If the prodelta disappear, the other facies disappear too, i.e. the deltaic depositional system does not exist any more. In turbidite systems is quite similar, but not quit exactly.

By-pass zones can be developed and often the final facies are not coeval. This, in turbidite systems Type II of E. Mutti's (1985), from the shelf break basinward, three main non synchronous facies can be find:

(i) Channel-fill thick-bedded sandstone,
(ii) Thick-bedded sandstone lobes and
(iii) Thin-bedded lobe fringes,

Nevertheless, if the thick-bedded sandstone lobes are not present, the others facies are not present either, since they are more or less genetically related, and the turbidite systems disappear.

In the literature exist numerous definitions for turbidite systems (Mutti & Normark, 1987; Mutti, 1992, etc.). Presently, the most used are:

A) A genetic unit, which records a series of genetically related erosional and depositional events that occurred in virtual stratigraphic continuity and are expressed by erosional and depositional elements respectively.

B) Depositional systems denoting bodies of rock where channel-fill deposits are replaced by non-channelized sediments in a down-current direction.

These definitions are generic and valid for a large spectrum of depositional systems (alluvial, deltaic, turbiditic, etc.). They do not define the stratigraphic character and the genetic significance of the boundary surfaces. Tentatively, we will propose to state the meaning of turbidite systems as:

"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.

When the platform-upper slope profile is not stable, large slump-scars are created in the upper part of the slope. Then, they retrograde to the platform creating eventually canyons. At the same time, huge sandy turbidite fans (Large Turbidite Systems, see later) will be deposited in the deeper part of the basin. When terrigeneous influx is too big for the size of the shelf and the accommodation, sand-rich turbidite fans will be deposited at the toe of the slope (Medium Turbidite Systems, see later). Relative sea level falls create a similar geological situation. They decrease the size of the shelf and the accommodation.

As said previously, the onset of turbidity currents (gravity flow), which able to carry sediments into deep water. can be related to sliding phenomena induced by:

(i) Overloading of sediments,
(ii) Earthquakes,
(iii) Halokinesis (salt tectonics),
(iv) Shalokinesis /shale tectonics),
(v) Fusion of hydrate layers,
(vi) Hyperpycnal flows (*), etc.

(*) In certain geological settings, sediment flux to the sea can dramatically increase when climatic conditions provide sufficient amounts of water to produce catastrophic floods. These floods generate mixture of water and sediment that can enter sea water with sufficient velocity and sediment concentration to produce hyperpycnal flow ($\partial hf > \partial sw$) and related, shelf-sustained turbidite currents.

On the other hand, different geological factors control the geometry and the facies distribution of turbidite systems (Mutti & Normak, 1987 and 1991). They can be grouped in two major families:

(i) The physiography of the platform, slope and abyssal plain.

(ii) The initial texture and lithological composition of the turbidity current and its evolution.

The first family (width and dip of the platform, dip of the slope, presence or not of mini-basins and/or canyons in the slope, trench basin or flat abyssal plain) is related to geodynamic and tectonic evolution of the basin. The second family (gravel rich, sand rich, mud rich, siliciclastic or carbonate) is related to the depositional systems developed landward of the shelf break (carbonate platform, reefs, muddy estuary, braided-deltas, alluvial fans, etc.).

Theoretically, turbidite systems seem to correspond to large natural geological complex systems with many components to evolving into a poised, critical state, way out of balance, where minor disturbances may lead to catastrophic events. Turbidite systems can be taken as self-organized critically systems (SOC). In order to make this concept less abstract let's describe the Bak's sandpile model (fig. 13):

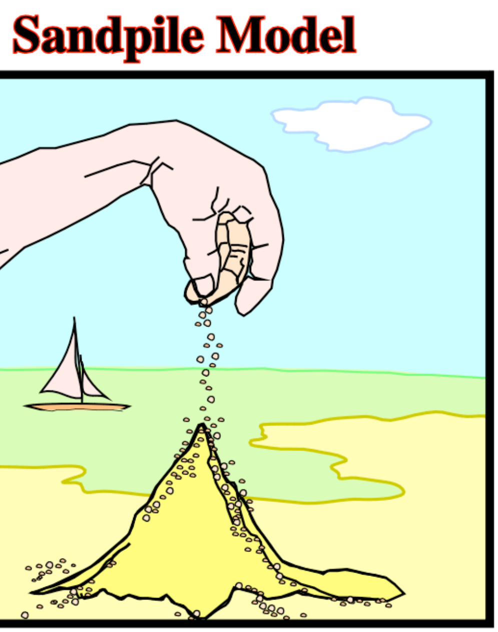

Fig. 13- The complex phenomena observed everywhere indicate that nature operates at the self-organized critical state. Thus, the behavior of the critical sandpile mimics several phenomena observed across many sciences, which are associated with complexity. This is particularly true for in geological 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.

"Consider the scenario of a child at the beach letting sand trickle down to form a pile (fig.13). In the beginning, the pile is flat, and the individual grains remain close to where they land. Their motion can be understood in terms of their physical properties. As the process continues steeper, and there will be little sand slides. As the process continues, the pile becomes steeper, and there will be little sand slides. As time goes on, the sand slides becomes bigger and bigger. Eventually, some of the sand slides may even span all most of the pile. At that point, the systems is far out of balance, and its behavior can no longer be understood in terms of the behavior of the individual grains. The avalanches form a dynamic of their own, which can be understood only from a

holistic description of the properties of the entire pile rather than from a reductionist description of individual grains: the sandpile is a complex system.“

The sandpile is the canonical example of a Self-Organized Critical system (SOC). It exhibits a punctuated equilibrium behavior, where periods of stasis are interrupted by intermittent sand slides (as in turbidite systems). It can be expressed as a straight line on a double logarithmic plot, which indicates that the number of events is given by a simple power law:

$$N(s) = s^{-\pi}$$

The exponent π is defined as the slope of the curve (*).

(*) Catastrophic events, fractals, 1/f noise (fractals in time), Zipf's law, etc., are examples of SOC, i.e. self-organized critical systems which evolved to complex critical state without interference from any outside agent.

Rothman et al., (1994) carried out a detailed study on the Precambrian turbidite deposits of Kingston Peak formation (Death Valley, California). For 1.235 turbidites observed, they counted how many layers (N) exceed a certain thickness (h) and made a log-log histogram, i.e. the number of turbidite layers thicker than "h" as function of the logarithm of the layer thickness "h". They found a power law distribution of layer thickness, as the theory of SOC predicts. The straight line with a slope of 1.39, indicates power law distribution of the thickness of the layers, and thus for the distribution of the turbidity currents which formed them. Before arguing that this is indeed the case for all turbidites, we are going to sharpen the classification of the turbidite systems, and then, we will return to this subject.

8) Turbidite Systems Classification

The more used classifications of turbidite systems are based either on the volume and texture of the gravity flow (sand-rich / mud-rich systems or type I, II and III of Mutti, 1985) or linked to the physiography of the margin and predominant sediment granulometry of coastal systems (Reading & Richard, 19??). However, as in petroleum exploration, the fundamental parameter in turbidite systems is the extension of potential sandstone reservoirs, we are going to use a classification based on this parameter. So, 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:

A) Large Turbidite Systems,
B) Middle Turbidite Systems, and
C) 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 3 "types":

- Type I, mainly composed by tabular lobes,
- Type II, mainly composed par transition channel-lobes,
- 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. In fact, at the scale of facies sequence (15-30m), very often, middle turbidite systems show, in the lower part, channel-lobe transition facies (F2-F5, characteristic of system type II of Mutti) and bypass facies (F6) associated to proximal lobes (F7), which characterize the type I of Mutti, in the middle and upper part (see later). Considering the 1985 Mutti's classification we will get stages of type II followed par type I, which is in total contradiction with the Mutti's model (1985). In these notes, we will adopt an operational classification in order to evaluate, on the basis of morphologic criteria (seismic data) and the facies sequence (the cores and field), the presence and extension of potential reservoirs. However, the terms large, middle and small do not make any reference to the size of the systems themselves but to the relative extension of the sandy facies, i.e. the potential reservoirs.

On the other hand, and in contrast with Mutti (1985), we consider a turbidite system at the scale of the stratigraphic cycle (sequence cycle, or continental encroachment sub-cycle (see Duval et al., 1993), and not at the scale of the depositional system *sensu strito* composed by different depositional elements such as bypass zone, with scours and residual lags, depositional zone with lobes, etc., which avoid us to introduce different hybrids depositional unities, i.e. the stages of growth proposed by Mutti. Roughly, we can say that Large (LTS), Middle (MTS) and Small Turbidite Systems (STS) are characterized by the following geological features:

Large Turbidite Systems (LTS):

- 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.

Middle Turbidite Systems (MTS):

- 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.

Small Turbidite Systems (STS):

- 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.

8a) Large Turbidite Systems

Large turbidite systems (LTS) are characterized by a large zone of non-deposition, or/and by residual deposits between the continental slope and the most proximal part of the abyssal plain (fig. 14). The other 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 tens of kilometers of 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.

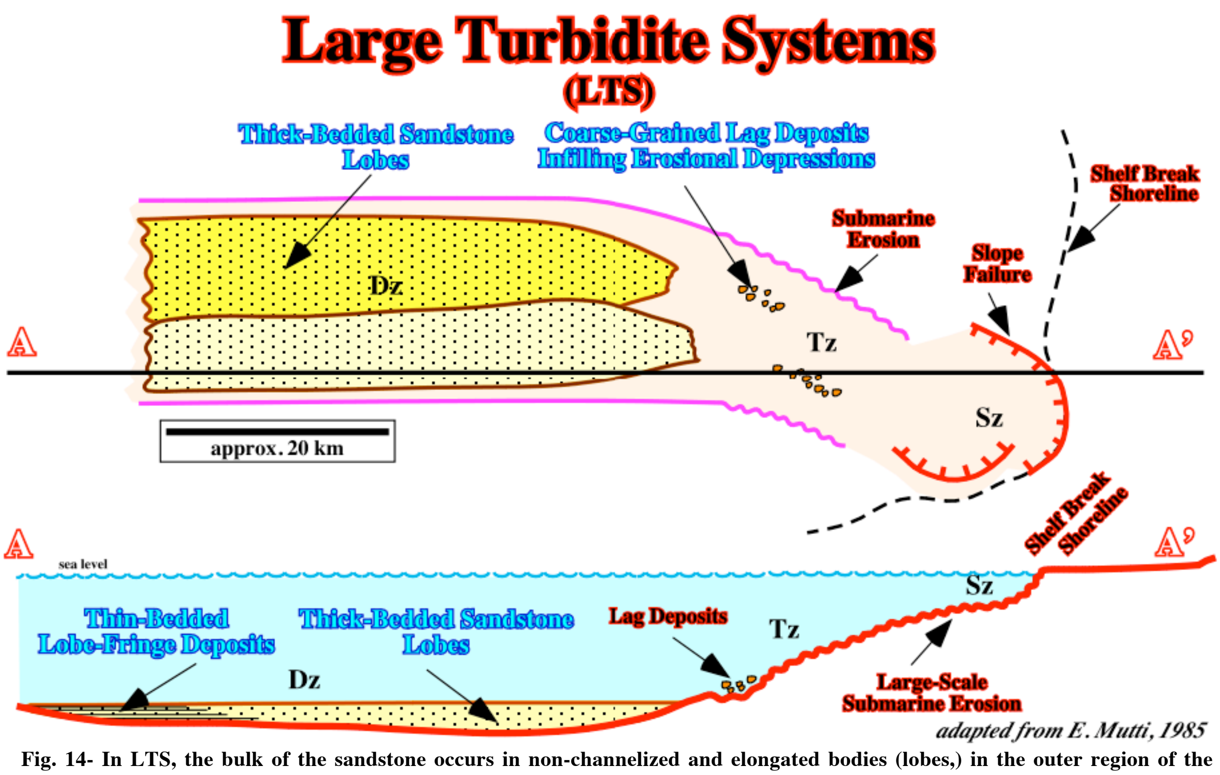

Fig. 14- In LTS, the bulk of the sandstone occurs in non-channelized and elongated bodies (lobes,) in the outer region of the system. These potential reservoirs are characterized by a lateral continuity and a tabular geometry over distances up to several tens of kilometers parallel to the current direction. 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.

As illustrated in fig. 14, in a LTS, there is an important zone of bypass between the shelf break and the proximal area of the abyssal plain. Locally, in the bypass zone, chaotic coarse-grained lag deposits fill deeper erosional features. In the uppermost part of the system, the shelf break, which corresponds to the shoreline (lowstand), underlines a slope failure induced by slump. The majority of the sediments are deposited in the abyssal plain forming non-channelized elongate lobes, which are mainly composed by sandstones, i.e. potential HC reservoirs.

During the retrogradational (backstepping) infilling phase, the lobes are progressively deposited landward in the direction of the bypass zone. They can be deposited directly in a canyon, if a canyon was developed. The final infilling phase is often culminated by small turbidite systems (STS), in which channel-levees complexes are predominant. Straight channels (sandprone) or sinuous channels (shale prone) are very often recognized.

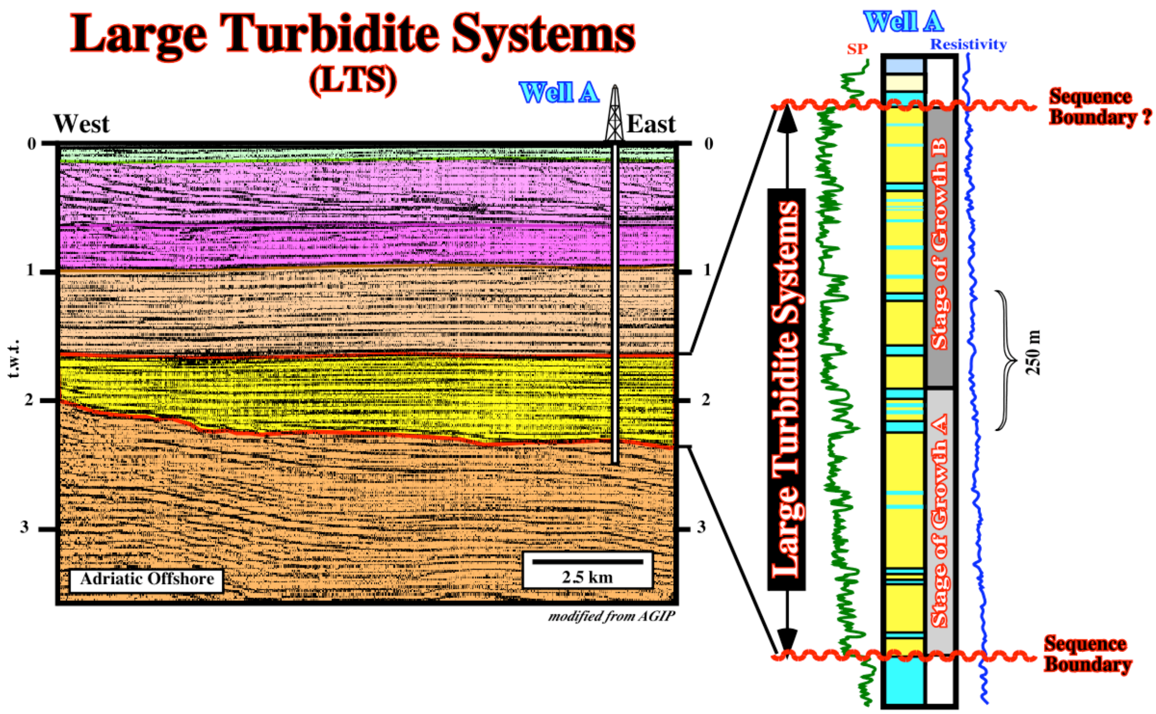

Fig. 15- This seismic line from Adriatic offshore illustrates a LTS (large turbidite system) overlying the Messianian unconformity (SB. 5.5 Ma). From bottom to top, six major seismic intervals are easily recognized. The lower one is limited at the top by a tectonically enhanced unconformity, which is fossilized by onlapping of the sediments of the yellow interval, which has a parallel internal configuration. This yellow interval corresponds to a LTS, which is deposited at the toe of the slope of the SB. 5,5 Ma. LTS was recognized in the well A. The electrical 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 if it corresponds to a unique system or to the superposing of two systems. We assume a unique LTS with two phases of infilling. The lower one is predominantly aggradational / forestepping and the upper one is mainly aggradtional / backstepping.

On this subject, it is interesting to notice that in the Congo (northern offshore Angola included) as well as in the Amazon offshore, seaward of the deltaic environments, the final STS infilling phase is extremely important not only in terms of thickness but in terms of surface as well. Nevertheless, one should not to forget that the lobes of the LTS are deposited hundred of kilometers seaward directly over the oceanic crust. This seems to be particularly true in northern offshore Angola (Congo basin), where the bathymetric map of the area suggests a large deep sea fan seaward of the present Congo Canyon.

On dip seismic lines (more or less perpendicular to the slope), seaward of the bypass zone, the geometry of LTS is the one recognized on the Adriatic line (fig. 15). It can be schematized as illustrated on top of fig. 16, where the seismic reflectors associated with the turbidite lobes can be easily followed in continuity during dozen of kilometers. In favorable cases, it can be recognized the lobes onlap landward on seismic surfaces correlative with an unconformity. The thickness of each lobe is difficult to determine. However, the total stacking thickness can reach thousands of meters, relying upon the efficiency of the systems. On strike seismic lines, the geometry depends how seaward the line is localized. To simplify, lets' considered the three cases illustrated in fig. 16:

A) 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.

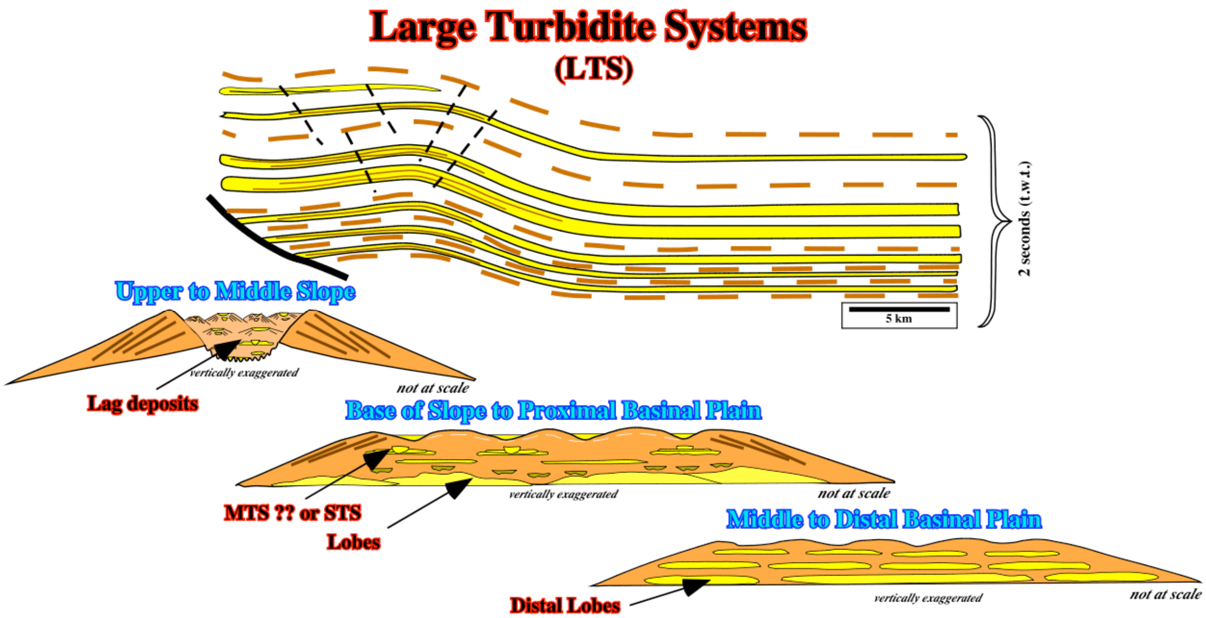

Fig. 16- In a LTS, from the abyssal plain to the upper-middle slope, three signatures are often recognized. In the deepest area, between the middle to distal abyssal plain, we find the distal lobes. They are well individualized with relatively thick shale intervals between them. Landward, between the 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.

B) Lines located between the base of Slope and 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).

C) 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.

8b) Medium Turbidite Systems

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.

A) 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).

B) 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 of medium turbidite systems (MTS) ranges between 100 and 200 meters. Potential reservoir associated with these systems are best target on hydrocarbon exploration, since, very often, the trapping mechanism is mix (Ex; Roncador, Marlim, etc.).

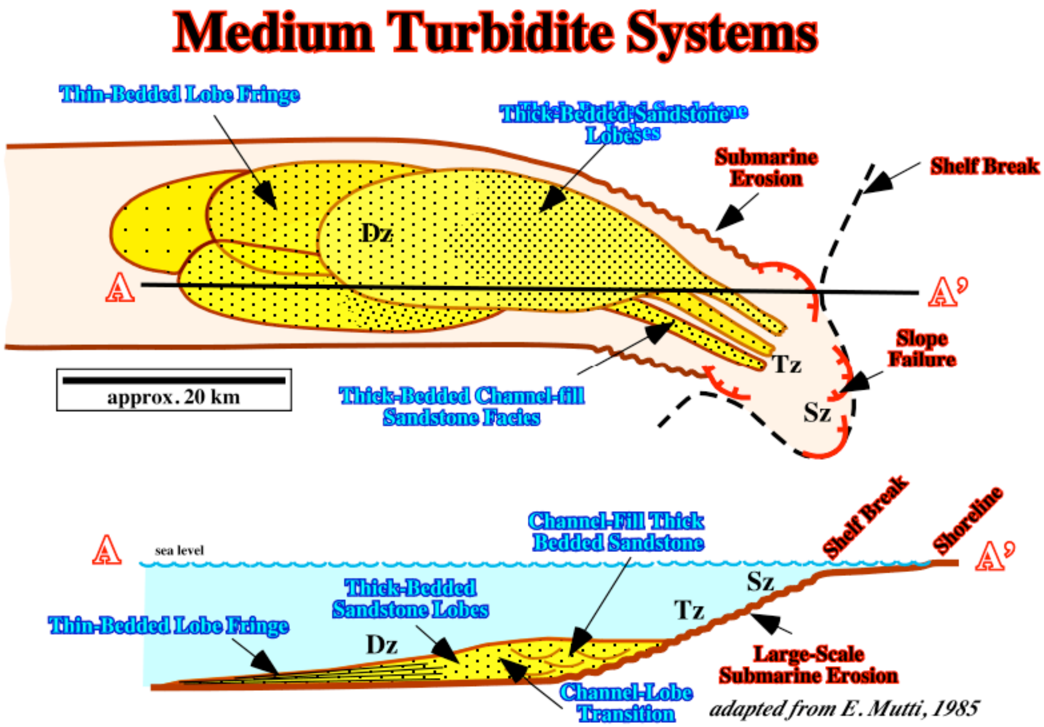

Fig. 17- Medium Turbidite Systems include all those depositional settings where sandstone facies are predominantly deposited in the lower reaches of channels and in the regions beyond channel mouths. These systems form extensively channelized bodies that grade down current into sandstone lobes. Very 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.

During the backstepping infilling phase, they depose sandstones in the associated canyon or SUV (submarine valleys, see later). During the desactivation phase, they change to small turbidite systems composed by rectilinear erosional channels with terminal lobes at their mouth (suprafans of Normark). At the end of their history, also, they are covered by small turbidite systems, but less developed than those covering LTS.

Middle turbidite systems (MTS) are found all along of the South Atlantic offshore. The majority of the oil discoveries in Brazil (fig. 16) and some of West Africa deep offshore were made in sandstones reservoirs belonging to middle turbidite systems. Nevertheless, the petroleum system is quite different.

A) Generating Petroleum Subsystem

- **In Brazil, margin hyper-saline lacustrine source rocks form the generating petroleum subsystem. They are located immediately below the autochthonous evaporites. Their organic matter is type I.**

- **In West Africa, the main source rocks are either the rift-type lacustrine source rocks (OM type I) or the marine transgressive sediments (OM type II) associated with the major downlap surface of the post-Pangaea continental encroachment cycle, i.e. Cenomanian-Turonian sediments.**

B) Reservoir / Entrapment Petroleum Subsystem

- **In Brazil, as illustrated in fig. 18, the main sandstone reservoirs are in the lobes located at the toe of the progradations.**

- **In West Africa, the main reservoirs are the sandstones infilling the rectilinear channels. The lobes beyond the channels mouths seem to be very distal under high water depth, probably in the ultra-deep areas.**

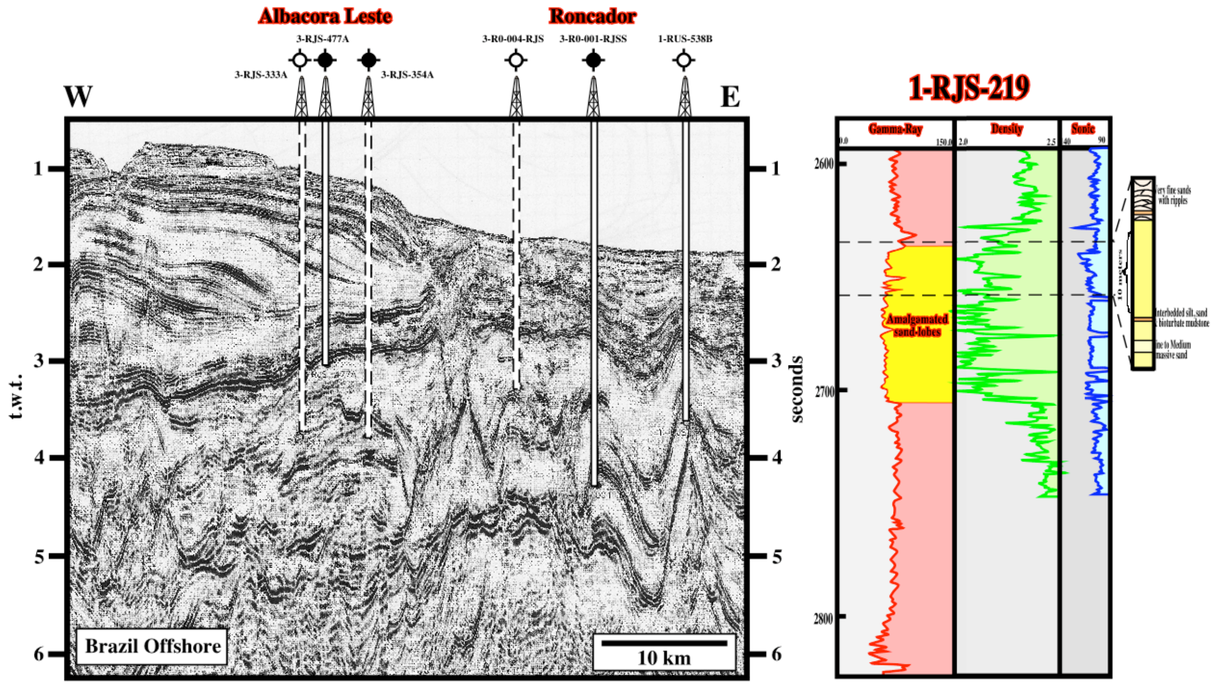

Fig.18- In Brazil offshore, as illustrated above, the main sandstone reservoirs are associated with amalgamated sandstone lobes located at the bottom of the continental slope. The reservoirs located in the lower reaches of the turbidite channels are secondary reservoirs. Their contribution for the total reserves is quite weak.

On dip seismic line, the geometry of the sand lobes is generally well recognized. If the line is long enough, as illustrated in the sketch below (fig. 18), it is possible to recognize the proximal and the distal onlap associated with the lobes. In favorable situations, the backstepping depositional geometry it is often recognized. Upward and landward of the more or less stacked lobes, very often, it is possible recognize channels fill (rectilinear or sinuous).

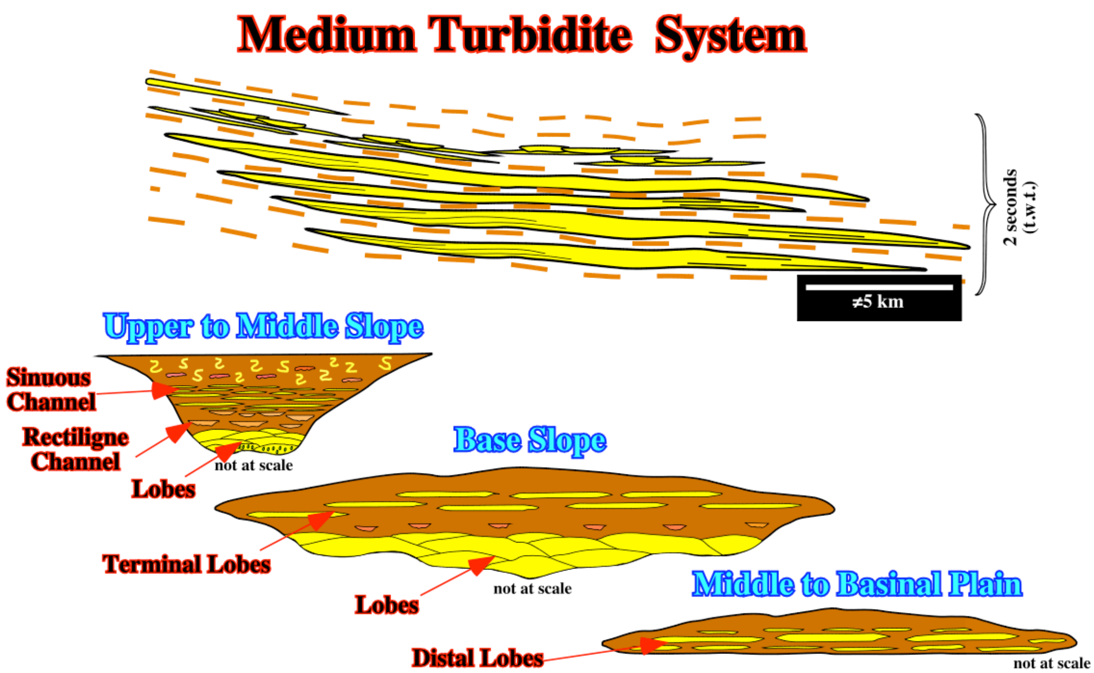

Fig. 19- The geometry of middle turbidite systems (MTS) can be deducted using dip and at least three strike lines. In the deepest part of the basin, in the abyssal plain, the lobes are well individualized in spite of their thickness be relatively small. Landward, at the bottom of the slope, the lobes 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.

As for MTS, on strike seismic lines, three conventional locations can be considered (fig. 19). The lines located in the upper to middle slope, the lines located at the base of the slope and the lines located in the middle to basinal plain:

a) 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.

b) 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.

c) 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.

8c) Small Turbidite Systems

Small turbidite systems (fig. 20) 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.

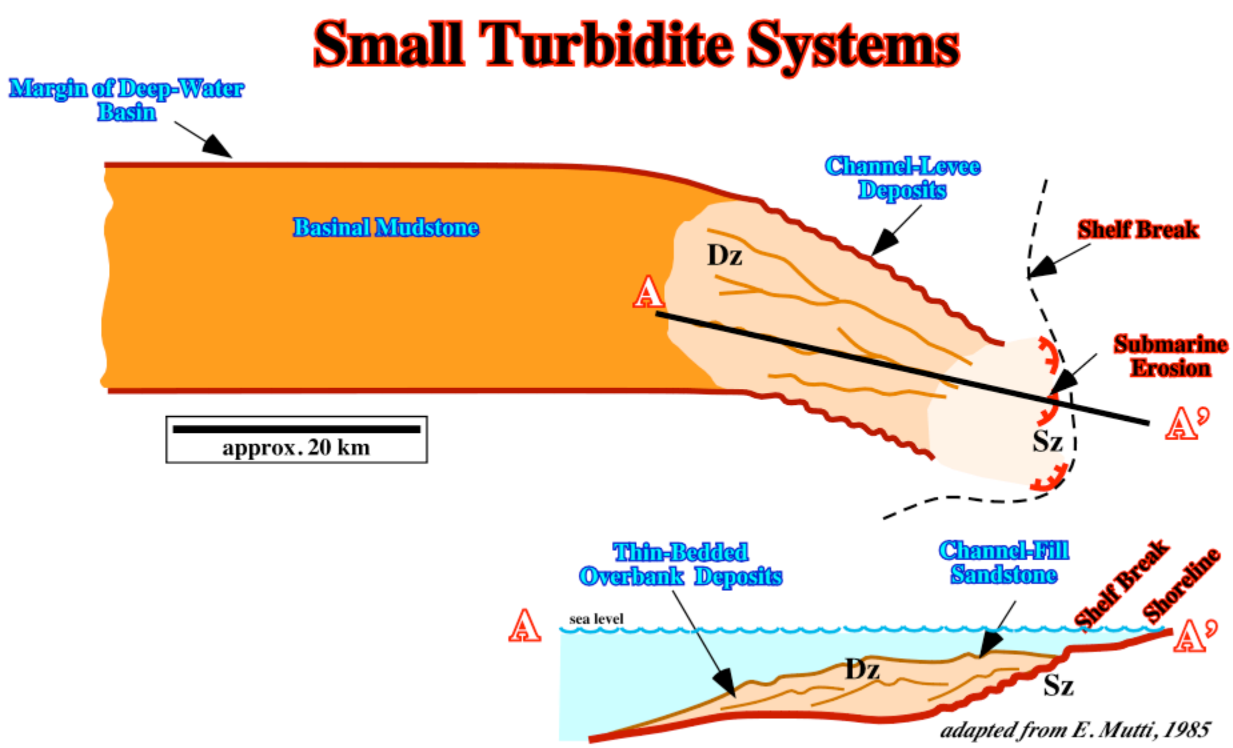

Fig. 20- Small Turbidite Systems (SMS) are characterized by small sandstone-filled channels that are enclosed by and grade down-current into predominantly muddy sequences. Channelized sandstone facies do not extend basinward and are therefore restricted to the inner portions of the systems. Channel-fill sequences are made up of fine to medium-grained sandstone in parallel-sided beds that characteristically thin and pinch-out toward both edges of the channel.

STSs develop in two main types of settings:

(i) In progradation phase of unconfined slopes.
(ii) In confined settings during the late, retrogradational phase of infill of the canyons or SUVs associated with large or medium systems.

In the first case, they often pile up to build the slope and they may not be associated with any Large or Medium system. In fact, in a forestepping context, particularly when the basin has no platform, i.e. when the depositional coastal break is coincident with the shelf break, small turbidite systems develop in upper and middle slope. The facies is predominantly shaly with piling up of channel-levees complexes. The resulting seismic patterns are dominantly hummocky. Depending on the sand content in the sediments source (coastal /deltaic deposits), sandstone reservoirs can be developed. In favorable conditions, when a deltaic system is present, channelized sandstones can be deposited in the upper-slope: they seldom extend basinward.

In West Africa offshore, and particularly in Cameroon offshore, small turbidite systems are quit well developed as illustrated in fig. 21. Actually, below the Oligocene unconformity (SB. 30 Ma), in Cretaceous sedimentary packages, it is easy to recognize the "gull-wing" or mounded geometry of the seismic markers.

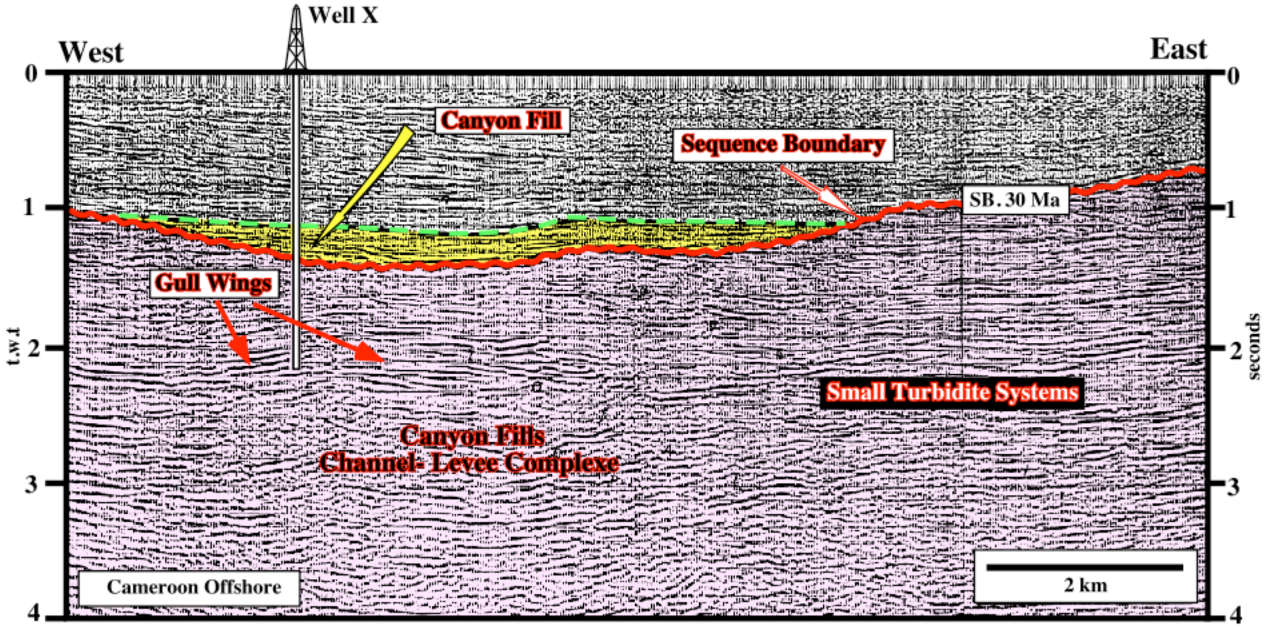

Fig. 21- This seismic line shot in the conventional Cameroon offshore illustrates a canyon fill and channel-levee complexes associated with small turbidite systems. Underlying the Oligocene submarine erosion (SB 30 Ma) a thick channel-leveecomplex (small turbidite systems) has been recognized by all 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 economical hydrocarbon accumulations.

In the 70's, such undulated geometry was interpreted as the result of a sedimentary shortening and the majority of the wells were drilled to test structural traps. However, the well results strongly refuted the assumed structural geological model. Subsequently, a turbidite conjecture was advanced and the geometry explained by channel levee complexes. In the 80's, the wells drilled corroborate the turbidite origin of the offshore deposits and a complex trapping mechanism (morphologic by juxtaposition / stratigraphic):

- **The reservoirs are mainly located in the overbank deposits (levees).**
- **They are too thin and too restricted.**
- **They hardly reach 1 km of extension.**
- **The turbidite channels are sinuous and filled by shales.**
- **Hydrocarbons were found in almost all wells, however any economical accumulation was discovered.**

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 (see later).

Three successive packages were recognized:

- Lower package,
which is dominated by depositional lobes deposited at the mouth of rectilinear or anastomosed channels.

- Middle package,
which made up of rectilinear channel-fills.

- Upper package,
which dominated by sinuous or meandering channels.

This kind of deposits can be illustrated be the filling of the Baudroie - Balliste submarine valley (SUV), in Gabon offshore (fig. 22), where, three different patterns can be recognized from the bottom to top:

A pattern,
which corresponds to a stacking of terminal lobes deposited at the mouth of rectilinear turbidite-channels.

B pattern,
which is interpreted as realm of sandstones filling rectilinear channels.

C pattern,
which marks the realm of sinuous and meandering turbidite channels.

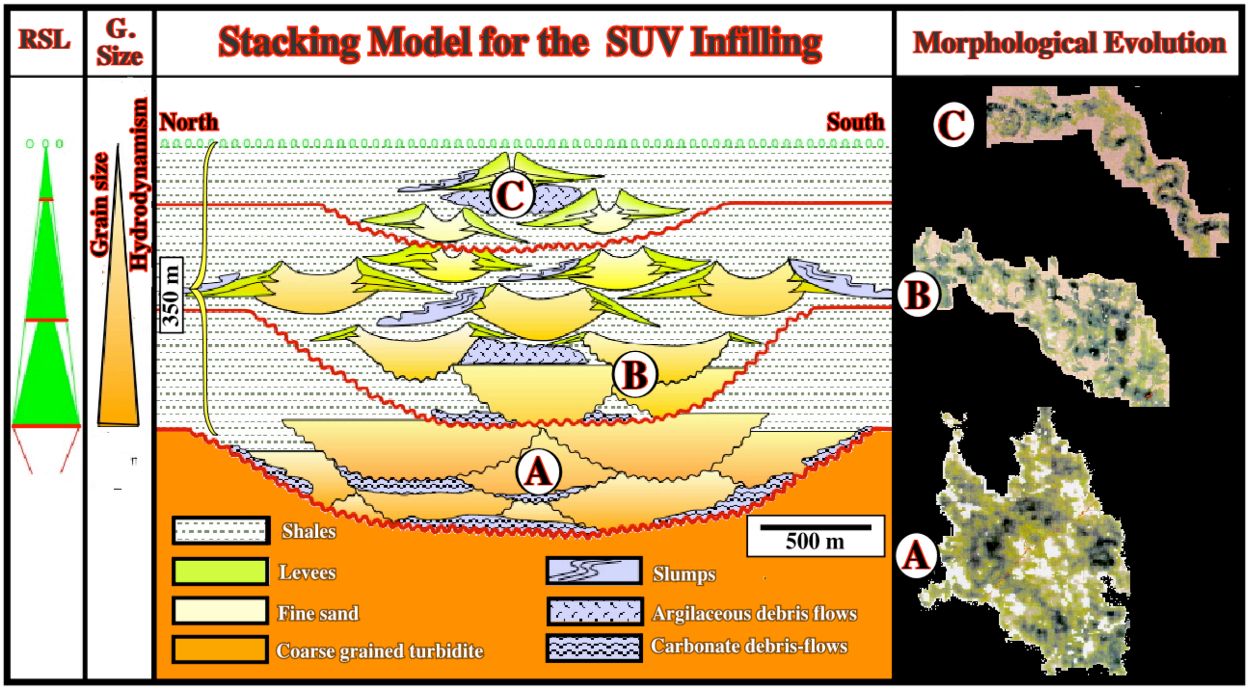

Fig. 22- This schematic diagram depict the fill of Baudroie-Baliste SUV (submarine valley), in Gabon offshore. From bottom to top threemain patterns can be distinguished: (A) terminal lobes associated with rectilinear channels, (B) rectilinear channel fills and (C) Sinuous Channels.

Such a vertical succession displays a retrogradational deposition, which is correlative with a decrease in and a decrease in sand/shale ratio thickness read on wireline logs. High amplitudes related to the infill of sinuous channels gradually develop up section. They are roughly correlative with a gradual decrease in channels width and sand/shale ratio.

8c1) 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. This pattern can develop in two ways:

(i) Minor changes in slope or

(ii) Changes in sand content of the flows.

(i) 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.

(ii) 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.

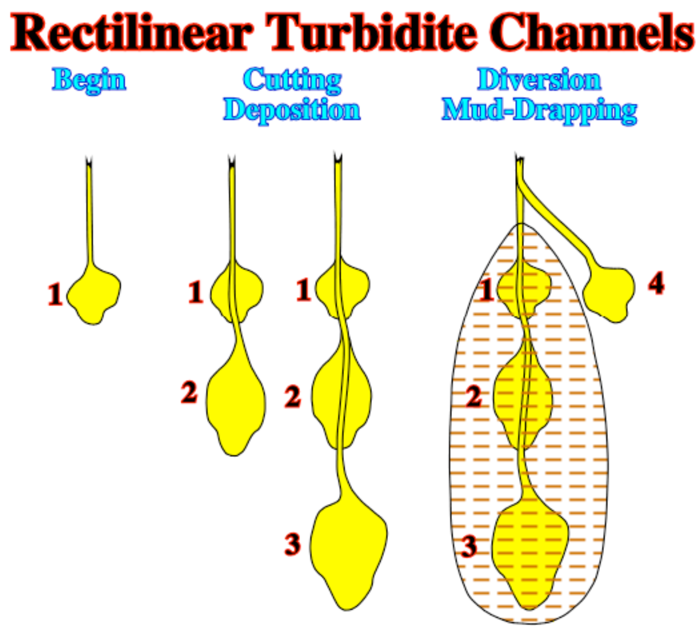

Fig. 23- Very often in rectilinear turbidite channels three major phases can beconsidered: (i) Begin phase, i.e., the initial phase, in which at the end of a terminal lobe isdeposited. (ii) Cutting-Deposition phase, in which the last terminal lobe is partiallyeroded allowing a downward prolongment of 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.

This association typically develops in continental slopes close to their equilibrium profile and devoid of a major sediment entry point (multiple source systems). The associated reservoirs are rather small and isolated, and their limited thickness does not allow easy recognition on 2D lines.

8c2) Sinuous Turbidite Channels

Isolated sinuous turbidite channels are usually identified by their characteristic pattern on amplitude slices of volumes of 3D seismic. In some cases, they are reasonably well imaged on 2D surveys, where one single line can cut three times the same channel across a loop.

Thick sinuous complexes appear to 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).

We use here the term "sinuous channel" for turbidite systems in order to avoid confusion with meandering fluvial channels. Sinuous channels develop in turbidite environments, when the density of turbidity currents is just slightly higher than the density of seawater, i.e. the currents carry a very small amount of sand. Sinuous* channel fill are predominantly shaly. Meandering (fluvial) channels typically develop in low-grade fluvial plains and high amounts of sand are deposited as point bars in the inner bends of the channels while the outer bank is excavated.

*** Notice that in classic sedimentology, 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.***

Seismic amplitude responses sometimes suggest that some sinuous (turbidite) 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. Notice that in classic sedimentology, 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.

Sinuous Turbidite Channels

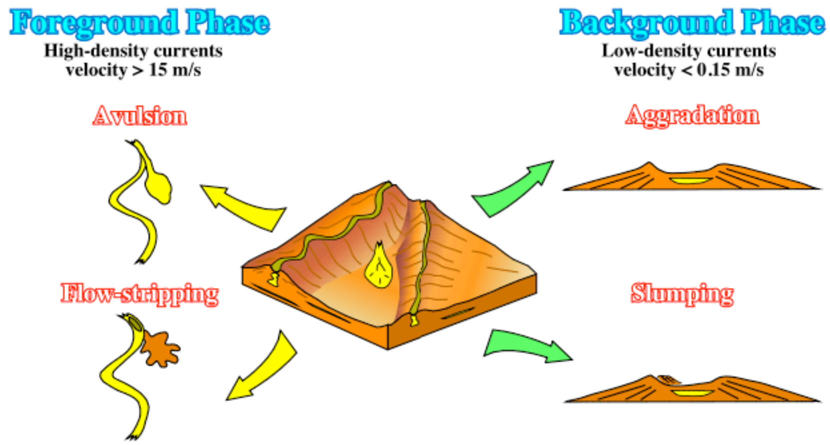

Fig. 24 – The avulsion mechanism in turbidite systems has treated by Flood et al. 1991. Avulsion typically leads to a steepening in slope, with the new channel less sinuous than the old, abandoned one. As the new channel progressively re-establishes equilibrium, its sinuosity increases to reach a maximum after which it essentially aggrades vertically.

Such complexes typically show the growth of a single channel over several hundreds of ms TWT (ca. 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 Channels Fill

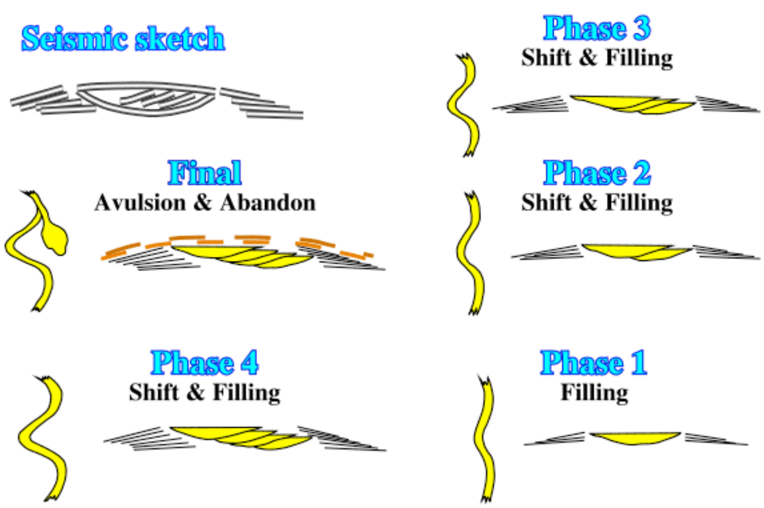

Fig. 25 – Contrary to fluvial meanders, which essentially get filled by progressive lateral accretion, turbidite sinuous channels typically get filled by successive episodes of cut and fill. Downcutting is interpreted to result from higher energy flows and produces sinuous lows, which are further filled up by retrogradational packages of turbidites. Like in fluvial meanders however, successive episodes of cut and fill migrate laterally towards the concave bank due to the curvature of the channel. Hence the similarity in the final geometry at seismic scale.

The main differences between fluvial and turbidite sinuous channels result from the difference in accommodation (fig. 25). Accommodation in fluvial systems is usually low, its rate of creation corresponding roughly to the subsidence of the area. On the other hand, accommodation in turbidite systems is best 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). In many cases, accommodation for turbidite systems is very high, allowing a high aggradation, whereas fluvial systems essentially migrate laterally. In other terms, the ratio between lateral migration and aggradation is high to very high in fluvial systems, lower in turbidite systems.

Equilibrium profile is probably the main quantitative difference between fluvial and turbiditic "meander belts": whereas the equilibrium slope of meandering rivers in on the order of 1:10,000, that of turbidite "meanders" more commonly ranges between 1:100 (Rhone) and 1:1000 (Indus) (see Clark and Pickering for a compete review).

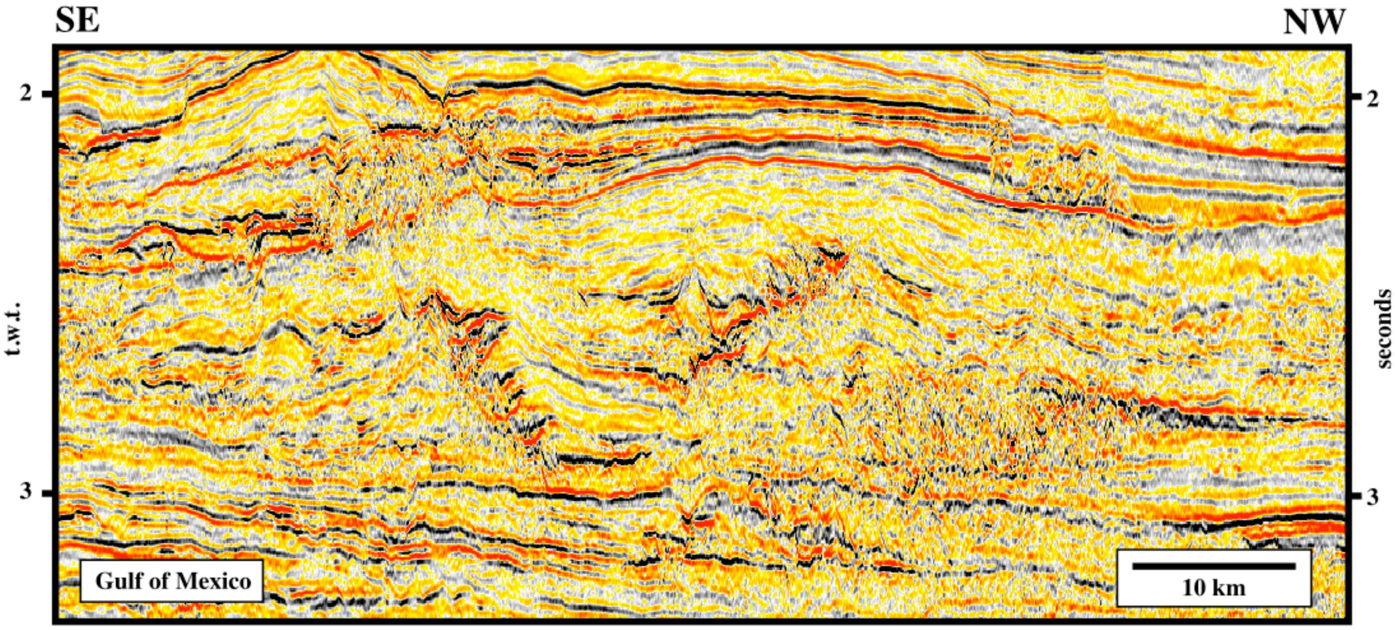

Fig. 26- Two well-expressed successive channel-levee complexes in the deep Gulf of Mexico. The lower channel displays very clearly the succession of downcutting events followed by rather aggradational fill. Both channels can easily be mapped, and are clearly highly sinuous in map view. Note that the migration is unidirectional for each channel complex, indicating that the lateral component of migration is predominant with respect to the downstream component.

The reservoirs of small turbidite systems include small lobes deposited at the termination of rectilinear channels, the proximal part of levees (proximal w/r to the channel with which they are associated), and the infill of channels, either rectilinear or meandering.