International degree on

Geosciences and Georesources

Course of
Applied Stratigraphy and Sedimentology

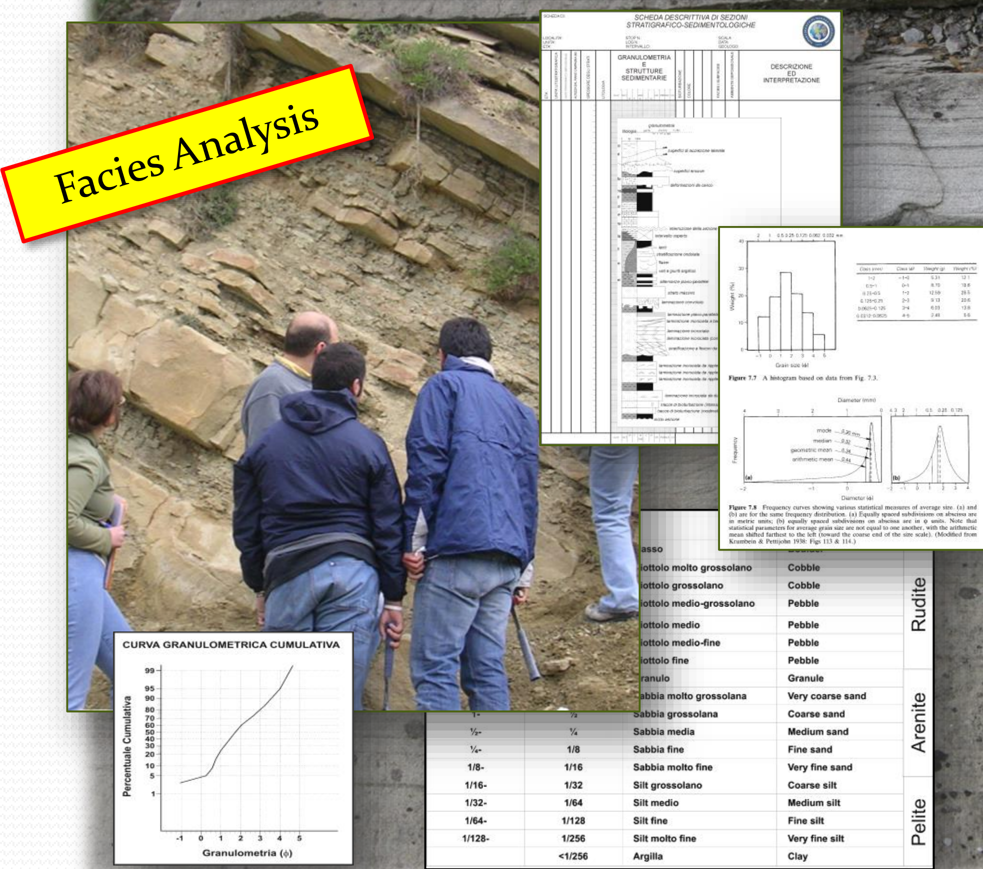
3. Sedimentology

3a. Origin of sediments; **3b.** Clastic and non-clastic sediments; **3c.** Main processes of erosion, transport and sedimentation; **3d.** Main sedimentary processes (tractive, mass, etc …); **3e.** Facies, facies associations, depositional environments and systems. **3f**. Georisources of sedimentary origin.

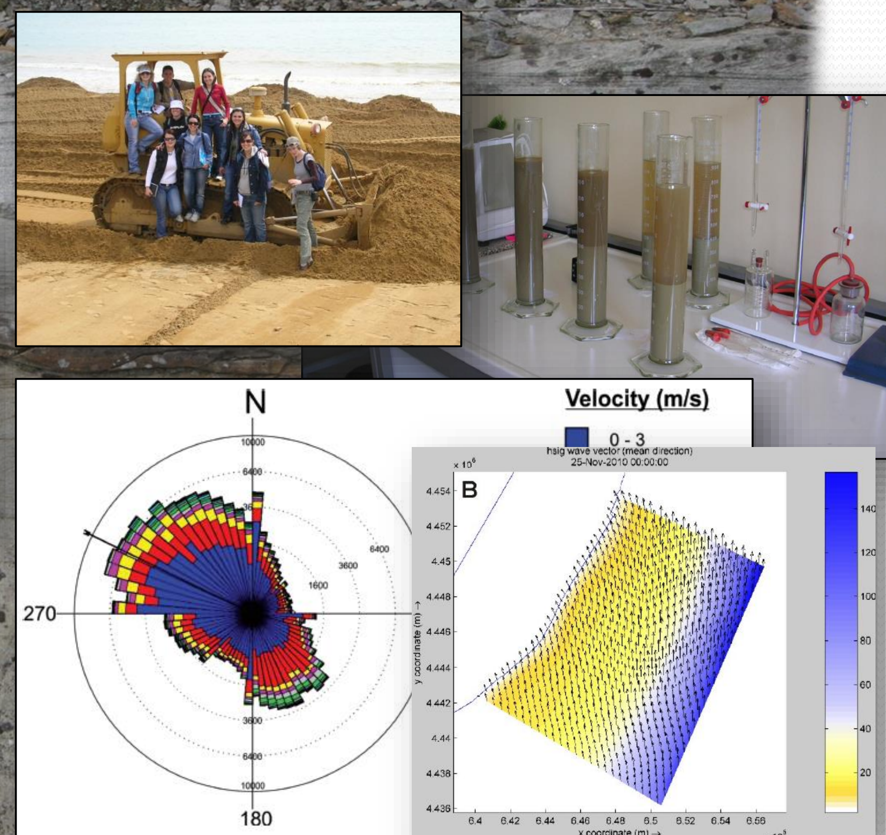
SEDIMENTOLOGY

It includes the observation, description and interpretation of the sedimentary rocks and deposits (facies), in order to understand their genetic processes, the depositional environments and the depositional systems, boh from surface and subsurface data.

CLASSIC SEDIMENTOLOGY



MODERN SEDIMENTOLOGY



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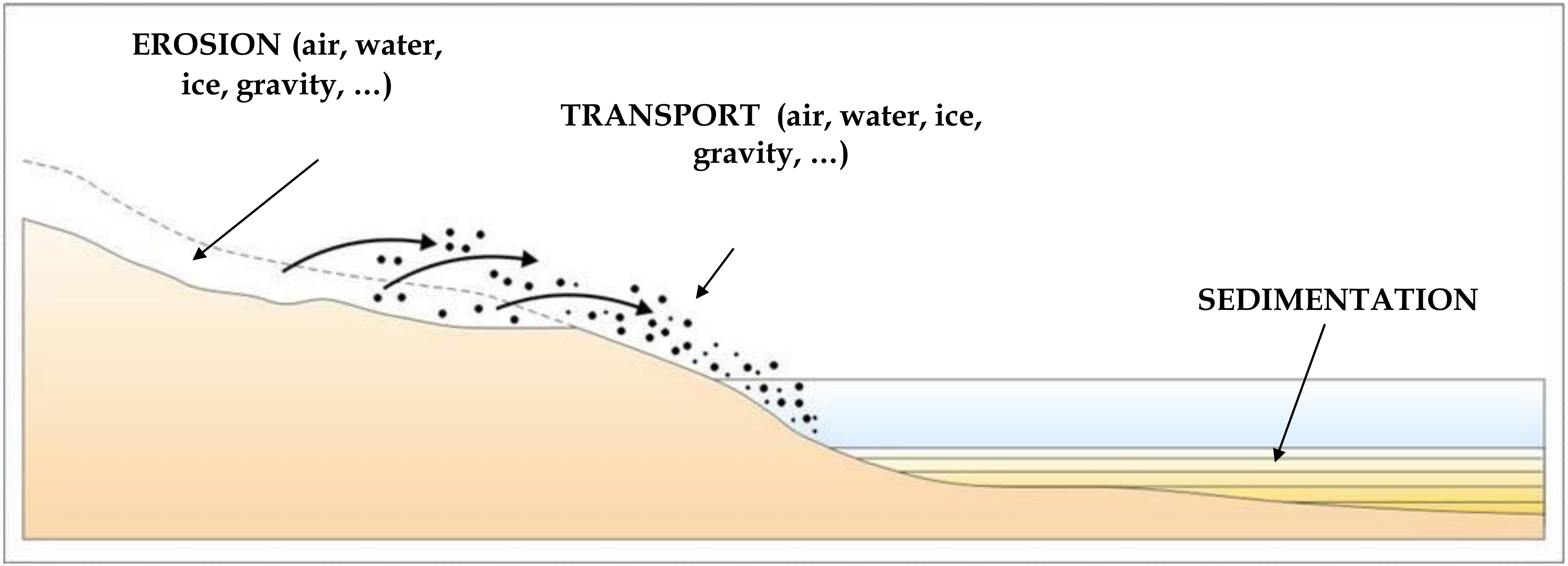
Clastic sediments originate due to the fragmentation of pre-existent rocks (EROSION).

Sediments can undergo a TRANSPORT, whose time duration indicates SELECTION.

Sediments can be accumulated or deposited (SEDIMENTATION).



EROSION, TRANSPORTO and SEDIMENTATION represent the three phases of a SEDIMENTARY CYCLE

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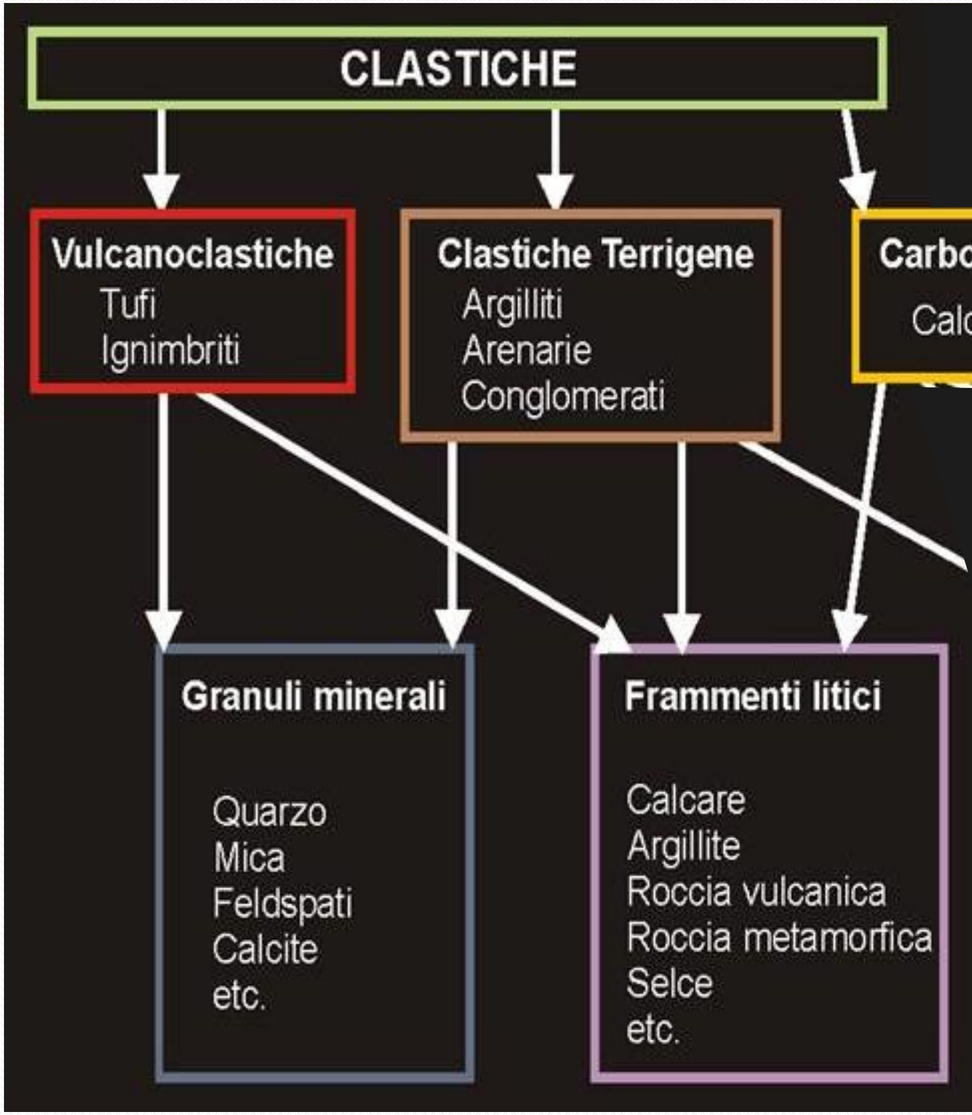
SEDIMENTS and SEDIMENTARY ROCKS can be divided into CLASTIC and NON-CLASTIC



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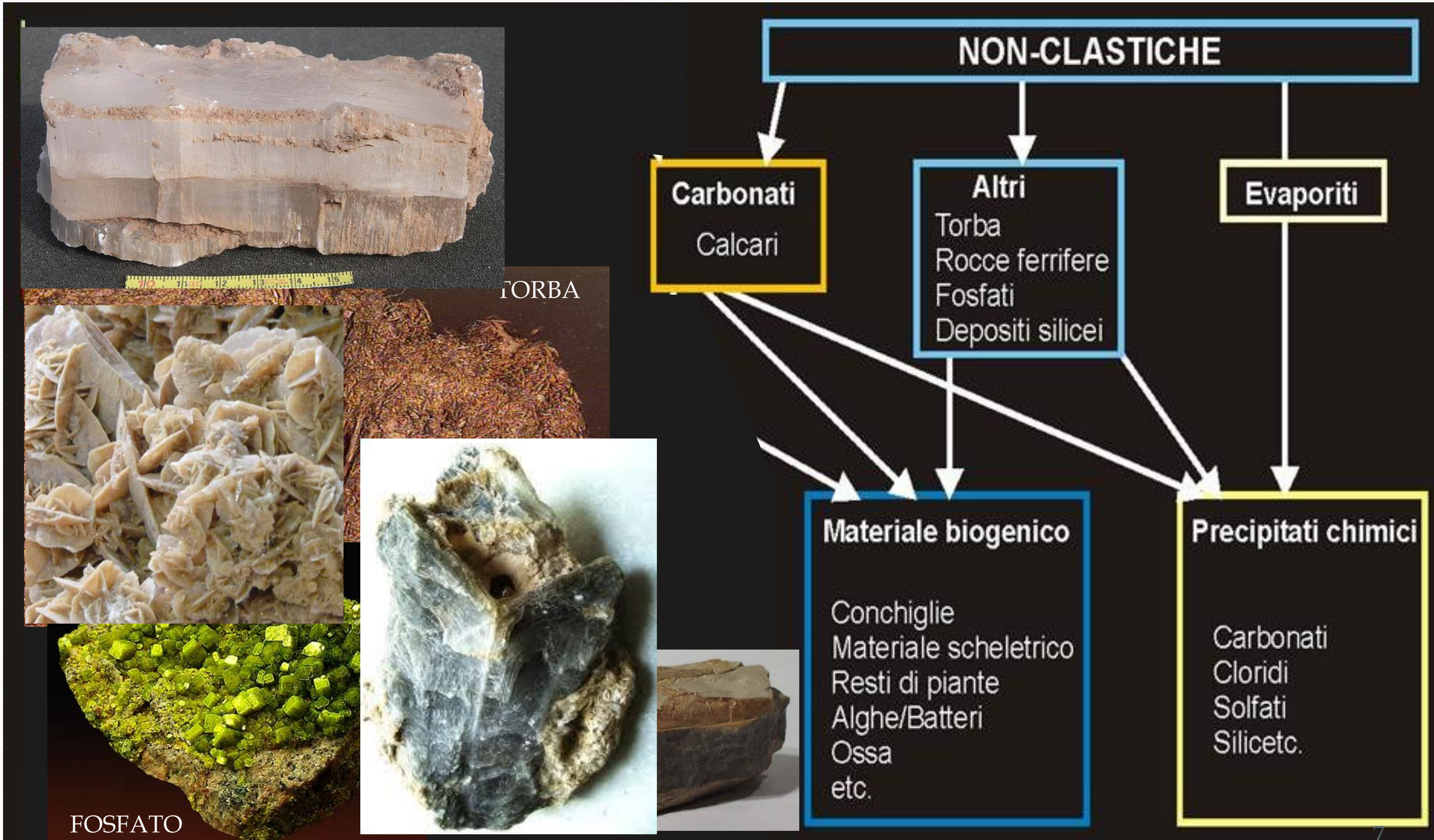


CLASTIC SEDIMENTS and SEDIMENTARY ROCKS can be distinguished based on the dominant composition of the composing elements.

Therefore, we can identify:

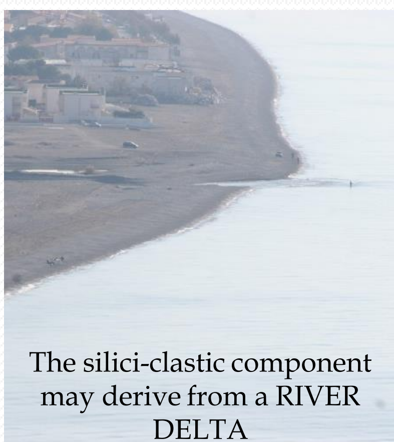
1) **terrigenous** (siliciclastic or calcilcastic),
2) **carbonatic** (or bioclastic)
3) **mixed** (siliciclastic/bioclastic).

A TERRIGENOUS ROCK contains more than the 80% of clastic components deriving from fragments of pre-existing rocks.

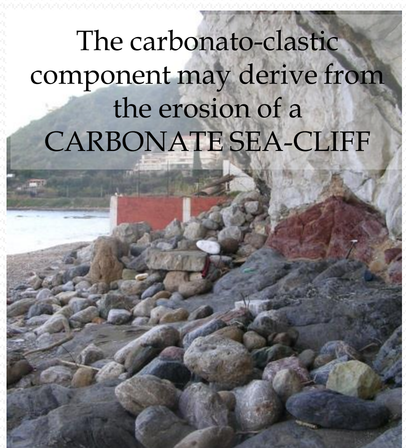
These components can be dominantly Quartz-rich (silici-clastics) or carbonatic (carbonato-clastics).

siliciclastic rock (conglomerate)

carbonato-clastic rock (micro-conglomerate)



The silici-clastic component may derive from a RIVER DELTA



The carbonato-clastic component may derive from the erosion of a CARBONATE SEA-CLIFF

CLASTIC SEDIMENTS and SEDIMENTARY ROCKS can be distinguished based on the dominant composition of the composing elements.

Therefore, we can identify:

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2) **carbonatic** (or bioclastic),
3) **mixed** (siliciclastic/bioclastic).

Bioclastic rock (*grainstone* o *biosparite*)

Bioclastic rock (*grainstone* o *biosparite*)

A CARBONATE ROCK contains more than the 80% of bio-clastic components, deriving from carbonate or aragonitic shells or skeletal parts of living orgnisms.

These components can be **oligotypic** (consisting of rests of one type of organism) or **multitypic**, formed by different species occurring together in the same fossil assemblage).

CLASTIC SEDIMENTS and SEDIMENTARY ROCKS can be distinguished based on the dominant composition of the composing elements.

Therefore, we can identify:

1) **terrigenous (siliciclastic or calcilcastic),**
2) **carbonatic (or bioclastic),**
3) **mixed** (siliciclastic/bioclastic).

A mixed rock (silici-clastic/bio-clastic)

A MIXED ROCK contains more than the 20% both of bio-clastic and silici-clastic components.

The silico-clastic component may derive from pre-existent volcanic, metamorphic or sedimentary rocks.

The bio-clastic component may derive from the consumption of calcareous shells of different phaunal associations.

A mixed sediment (silici-clastic/bio-clastic)

TERRIGENOUS
SEDIMENTS and ROCKS

(SILICICLASTIC and CALCICLASTIC)

The **TEXTURE** of a sediment or a sedimentary rock is the ensemble of physical features that can be observed both in a macro- and a microscopic view.
The TEXTURE includes:

- The **GRAIN SIZE**
- The **MORPHOMETRY** (roundness, elongation & sphericity)
- The **SORTING**

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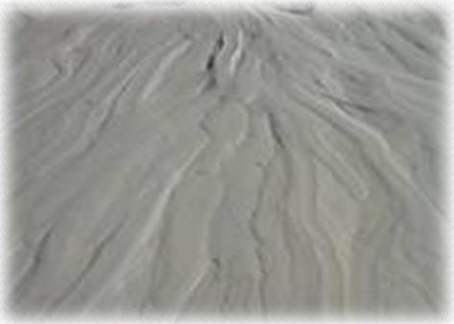
- The **SORTING**

The GRAIN SIZE (*GRANULOMETRIA in Italian*) is the quantitative estimation of the average size of the clasts composing a sediment or a sedimentary rock.



Generally, it can be referred to the energy, modality and amount of sedimentary transport that a sediment undergoes (e.g.,: high-energy transport can move coarse-grained sediments).

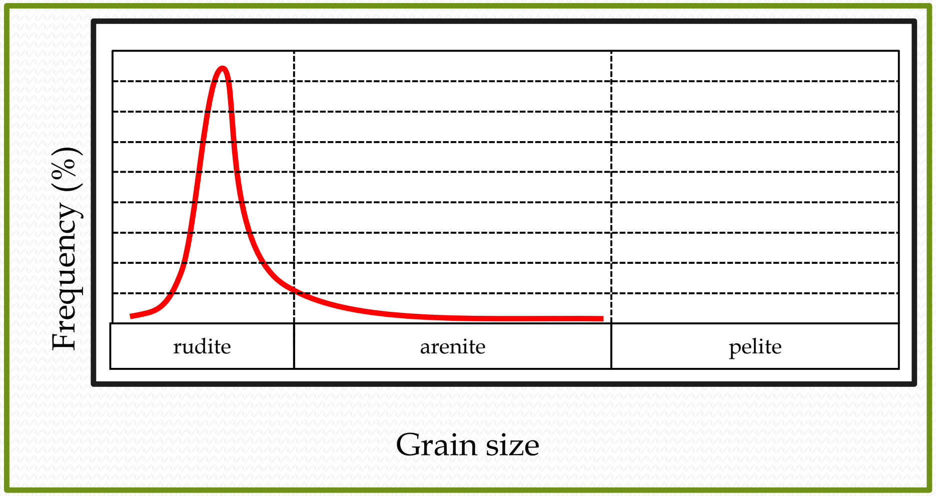
HOW TO MEASURE SEDIMENT GRAIN SIZE?

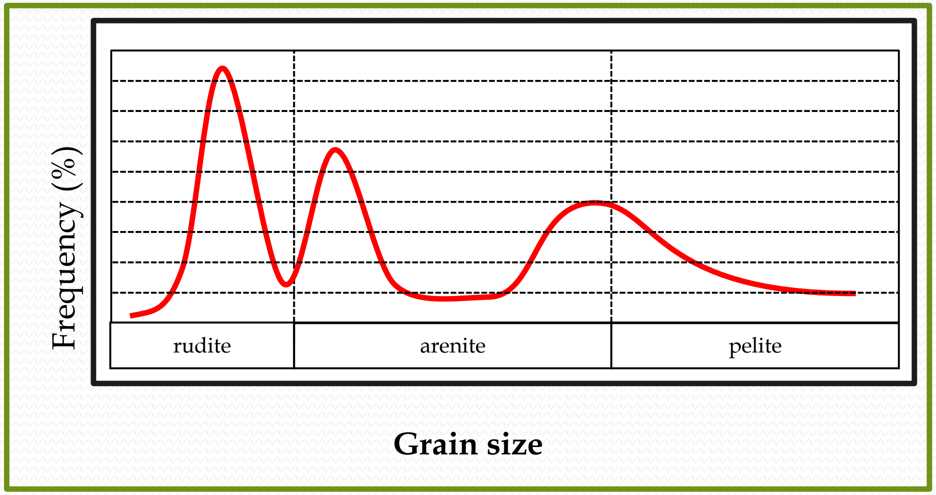
The Udden-Wentworth scale

Diameter of the particles in ϕ	Diameter of the particles in mm	Definition		
	> 256	Masso	Boulder	Rudite
256-	128	Ciottolo molto grossolano	Cobble	Rudite
128-	64	Ciottolo grossolano	Cobble	Rudite
64-	32	Ciottolo medio-grossolano	Pebble	Rudite
32-	16	Ciottolo medio	Pebble	Rudite
16-	8	Ciottolo medio-fine	Pebble	Rudite
8-	4	Ciottolo fine	Pebble	Rudite
4-	2	Granulo	Granule	Arenite
2-	1	Sabbia molto grossolana	Very coarse sand	Arenite
1-	½	Sabbia grossolana	Coarse sand	Arenite
½-	¼	Sabbia media	Medium sand	Arenite
¼-	1/8	Sabbia fine	Fine sand	Arenite
1/8-	1/16	Sabbia molto fine	Very fine sand	Arenite
1/16-	1/32	Silt grossolano	Coarse silt	Pelite
1/32-	1/64	Silt medio	Medium silt	Pelite
1/64-	1/128	Silt fine	Fine silt	Pelite
1/128-	1/256	Silt molto fine	Very fine silt	Pelite
	<1/256	Argilla	Clay	Pelite

HOW TO MEASURE SEDIMENT GRAIN SIZE?

Frequency plots





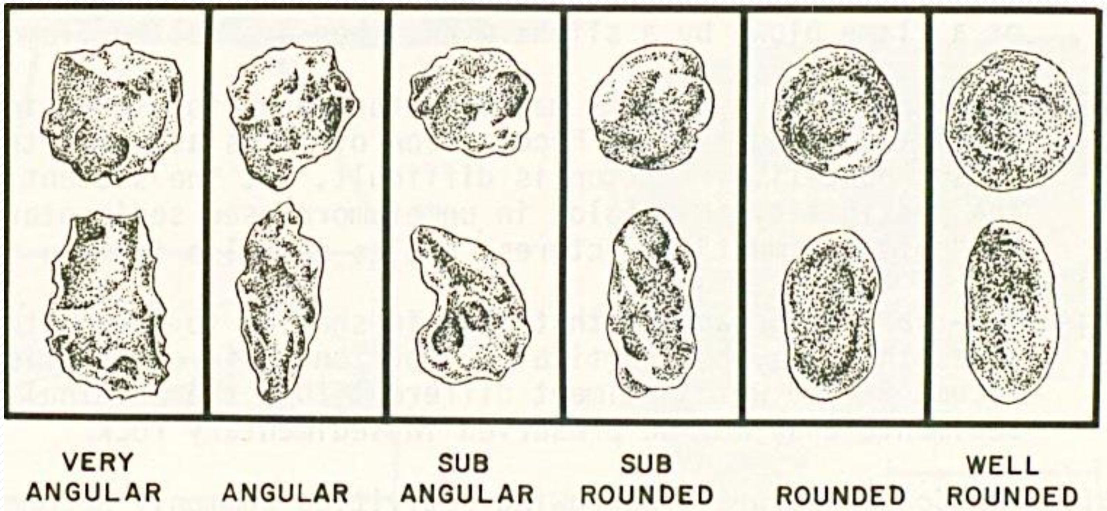
The **TEXTURE** of a sediment or a sedimentary rock is the ensemble of physical features that can be observed both in a macro- and a microscopic view.
The TEXTURE includes:

- The **GRAIN SIZE**
- The **MORPHOMETRY** (roundness, elongation & sphericity)
- The **SORTING**

La MORPHOMETRY is the estimation of the shape of the clasts contained in a sediment or a sedimentary rock

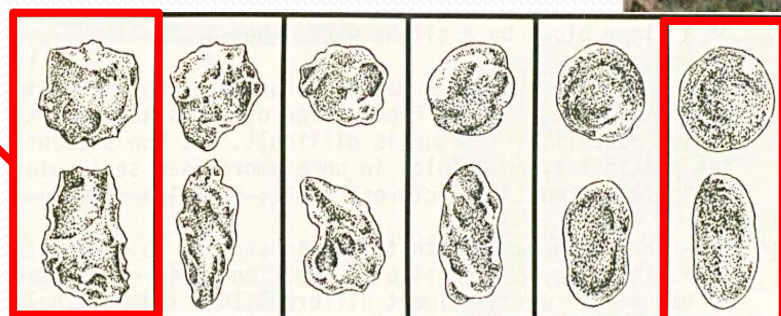
i. Degree of roundness degree: it defines the degree of consumption or angulosity of a group of clasts

Generally, it correlates with the amount of transportof a sediment (e.g., the more longer the transport, the better rounded the clasts).



MONOMICTIC BRECCIA

POLYMICTIC CONGLOMERATE



COLLUVIAL FAN

ALLUVIAL FAN

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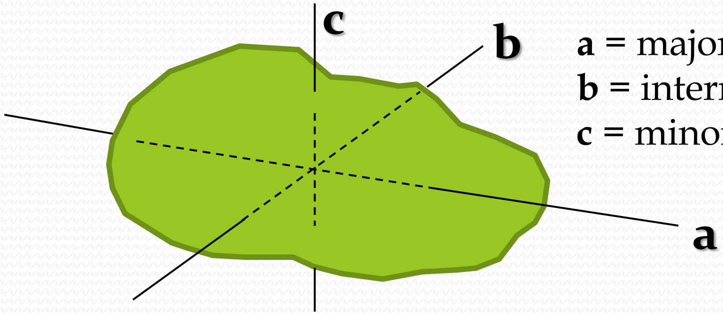
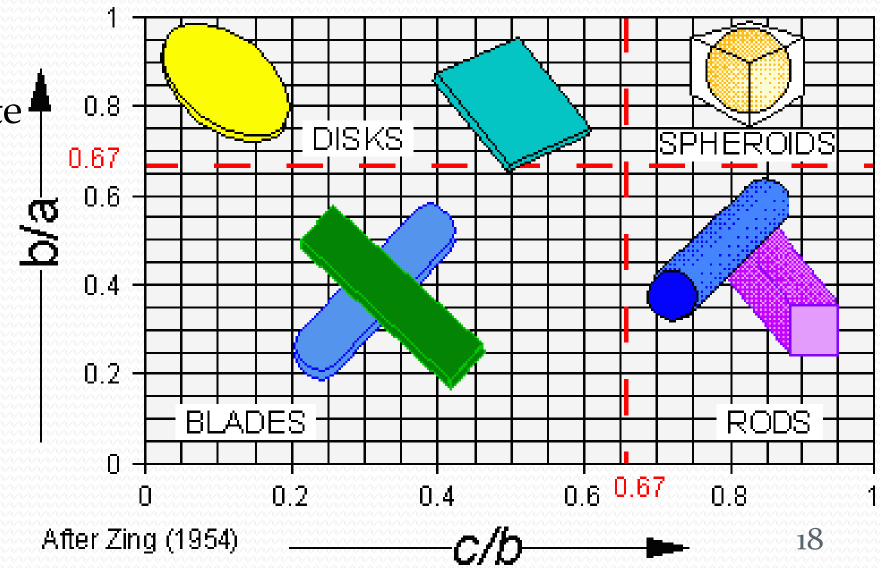
La MORPHOMETRY is the estimation of the shape of the clasts contained in a sediment or a sedimentary rock

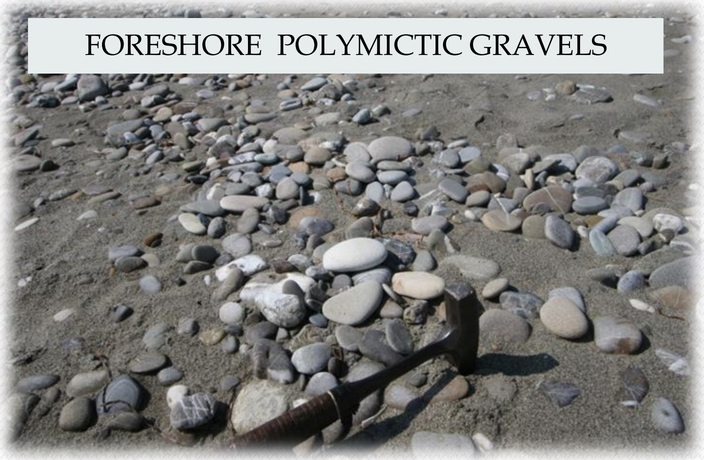
ii. Degree of Elongation: it defines the reciprocal dimensions of the three main axes which individuate each single clast



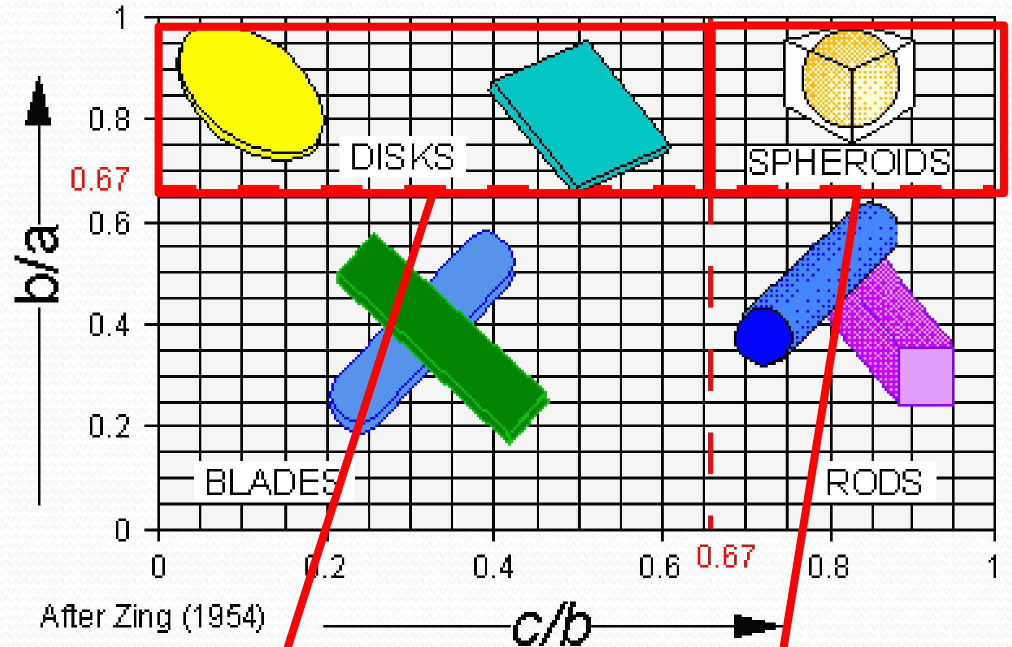
a = major axis;
b = intermediate axis;
c = minor axis.



After Zing (1954)


FORESHORE POLYMICTIC GRAVELS


ALLUVIAL POLYMICTIC CONGLOMERATES


b/a
1
0.8
0.67
0.6
0.4
0.2
0
DISKS
SPHEROIDS
BLADES
RODS
0
0.2
0.4
0.6
0.67
0.8
1
c/b
After Zing (1954)

The **TEXTURE** of a sediment or a sedimentary rock is the ensemble of physical features that can be observed both in a macro- and a microscopic view.
The TEXTURE includes:

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- The **SORTING**

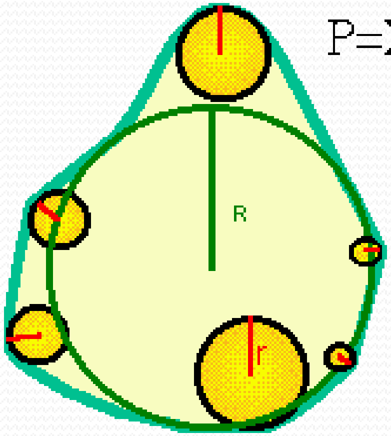
La MORPHOMETRY is the estimation of the shape of the clasts contained in a sediment or a sedimentary rock

iii. Degree of Sphericity: defines the degree of approximation of the clast profile to a spheric contour

$$P = \frac{\Sigma\left(\frac{r_i}{R}\right)}{N}$$

Es.: also in this case, the more spherical, the longer the transport.

Well-rounded clasts indicate a better degree of textural maturity, compared to angular clasts.



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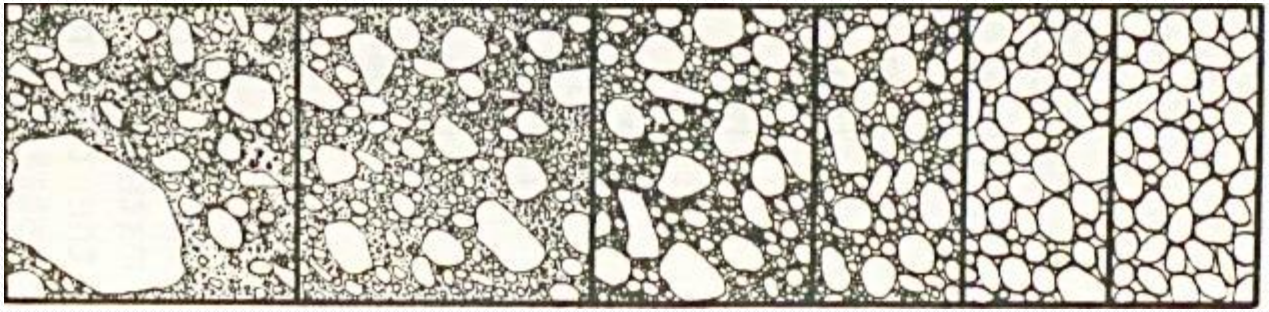
- The **SORTING**

The SORTING (*cernita, in Italian*) **is the degree of variability in the average grain size of the clasts.**

e.g., a scarce sorting indicates a very rapd deposition. On the contrary, a good sorting indicates a longer transport and a consequent selection. In order of effectiveness: wind > waves > rivers > glaciers.
A well-sorted sediment is texturally more mature than a poorly-sorted sediment.



UNSORTED | POORLY SORTED | MODERAT. SORTED | SORTED | WELL SORTED

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Main type of sediments and sedimentary rocks

Terrigenous sediments and sedimentary rocks can be classified based on their dominant grain size. Therefore, we can distinguish:

	SEDIMENT	ROCK
• GRAVEL or CONGLOMERATE		
• SAND or SANDSTONE		
• CLAY or CLAYSTONE		

i. GRAVELS and CONGLOMERATES

Gravels and conglomerates are sediments and rocks dominantly formed by ruditic clasts. They can be divided into:

- MONOMICTIC
  with one dominant lithology

POLYMICTIC
with more lithologies

- CLAST-SUPPORTED
  Clasts are self-sustained as they are at direct contact each other (matrix is scarce or absent)

MATRIX-SUPPORTED
Clasts float into a finer matrix

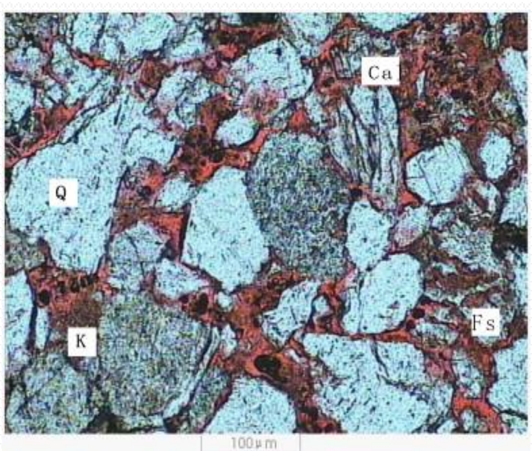
ii. SANDS and SANDSTONES

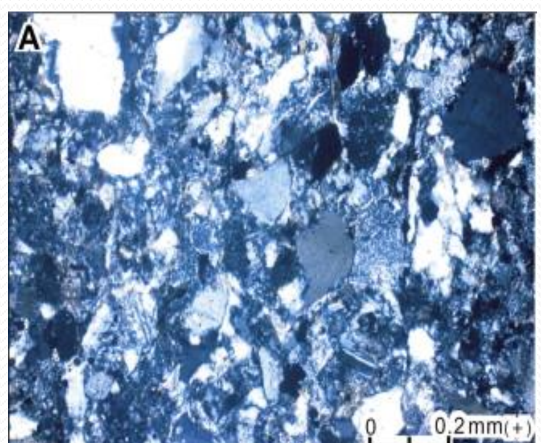
SANDSTONES are sedimentary rocks dominantly consisting of arenitic clasts. Based on their mineralogic composition e.g., % of Quartz, Feldspar (Sodium, Potassium, Calcium allumosilicates: Ortoclasium, Albite, Anortite, Celsian) and lithic fragments, sandstones can assume different names.

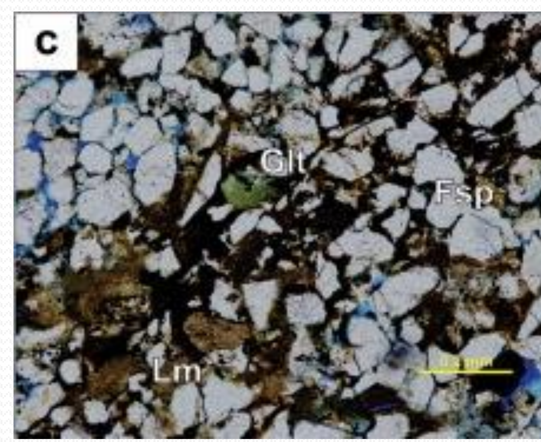
	QUARTZ (*Q*)	**FELDSPAR (*F*)**	**LITHIC FRAGMENTS (*R*)**

Macroscopic aspect

Microscopic aspect







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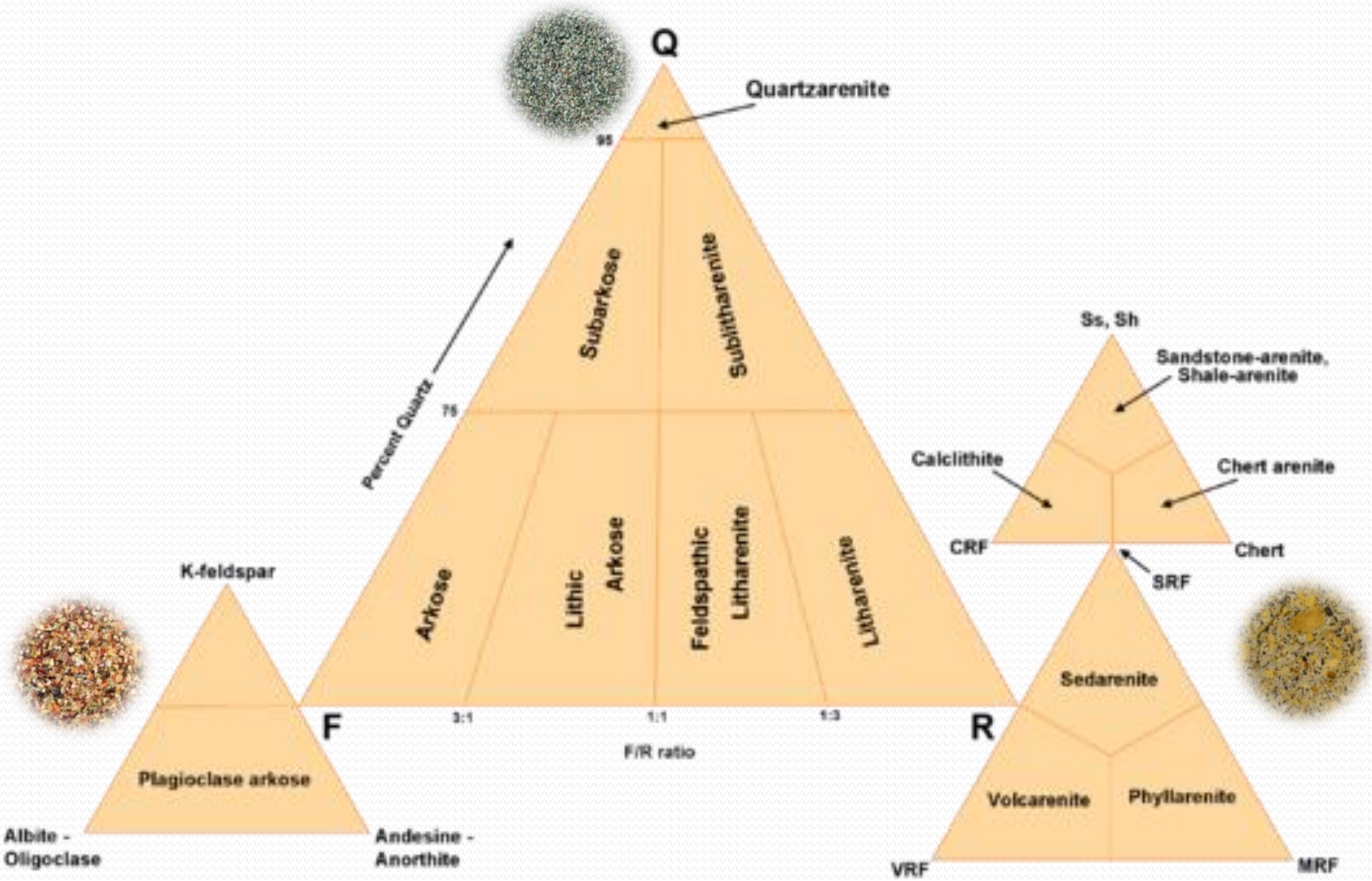
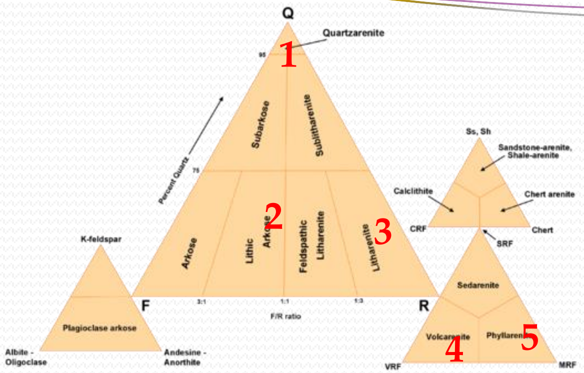
CLASSIFICATION OF SANDSTONES



ii. SANDS and SANDSTONES



Some common example …

QUARZARENITE

LITHIC ARCOSE

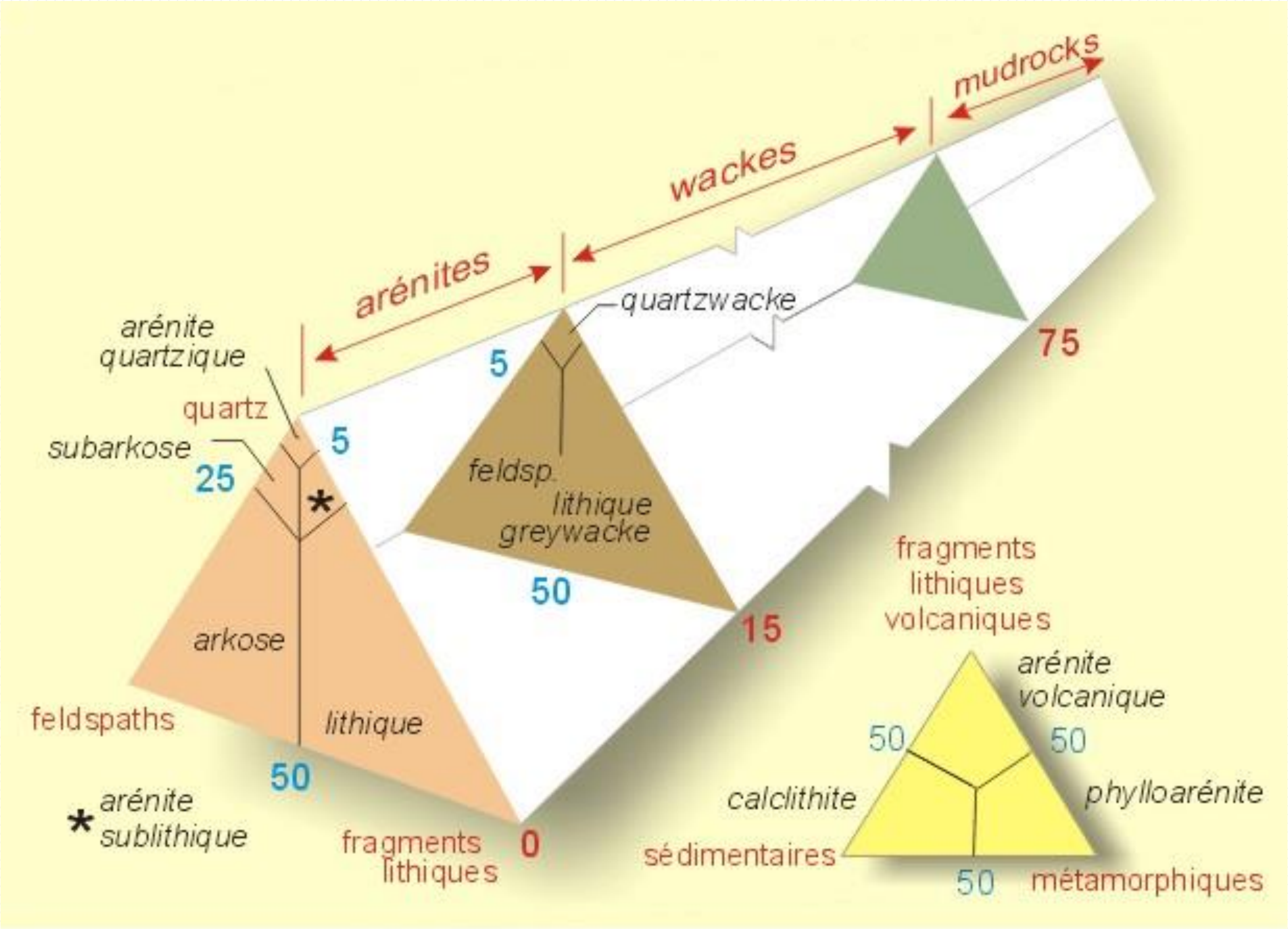
LITHARENITE

VOLCANIC SANDSTONE

FILLARENITE

ii. SANDS and SANDSTONES

SANDSTONES are sedimentary rocks dominantly consisting of arenitic clasts. Based on their mineralogic composition e.g., % of Quartz, Feldspar (Sodium, Potassium, Calcium allumosilicates: Ortoclasium, Albite, Anortite, Celsian) and lithic fragments, sandstones can assume different names.



iii. CLAYS and CLAYSTONES

CLAYS are fine-grained sediments consisting of particles with grain size less than 2 μm (pelite) . Once lithified, and depending on their mineralogic composition (e.g., % di fillosilicates), CLAYSTONES can assue different names. Amog the most common, we can list the fillosilicate-based ones:

Kaolinite

$[Si_4]Al_4O_{10}(OH)_8.nH_2O$

Illite

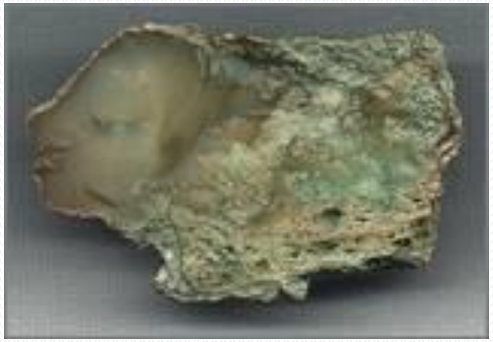
$[Si_{6.8}Al_{1.2}]Al_3Fe.025Mg_{0.7}5O20(OH)_4$

Vermiculite

$[Si_7Al]AlFe.05Mg0.5O_20(OH)_4$

Smectite

$[Si_8]Al_{3.2}Fe_{0.2}Mg_{0.6}O_20(OH)_4)$



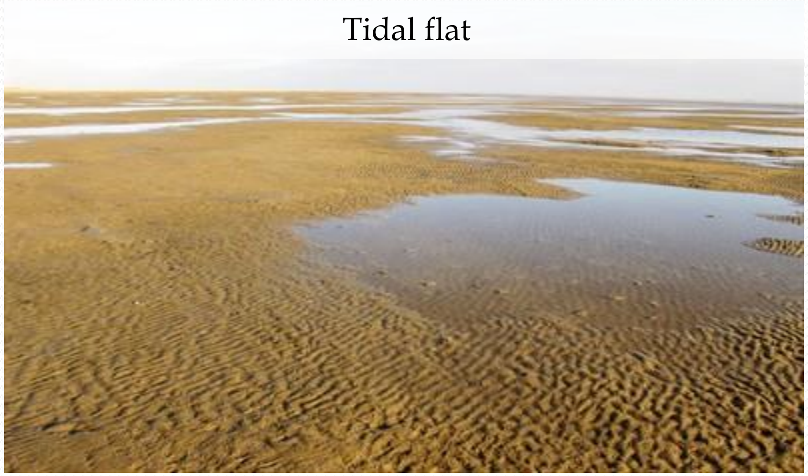
Clorite

$(Al(OH)_{2.55})4[Si_{6.8}Al0_{1.2}\}Al_{3.4}Mg_{0.6})20(OH)_4$

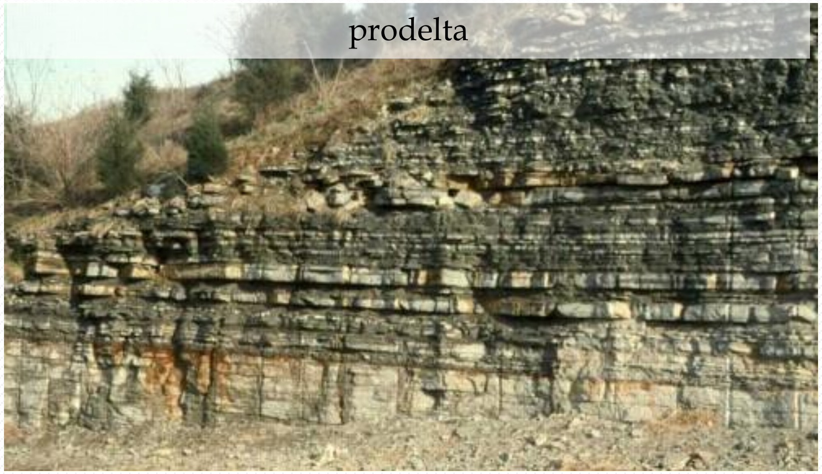
iii. CLAYS and CLAYSTONES

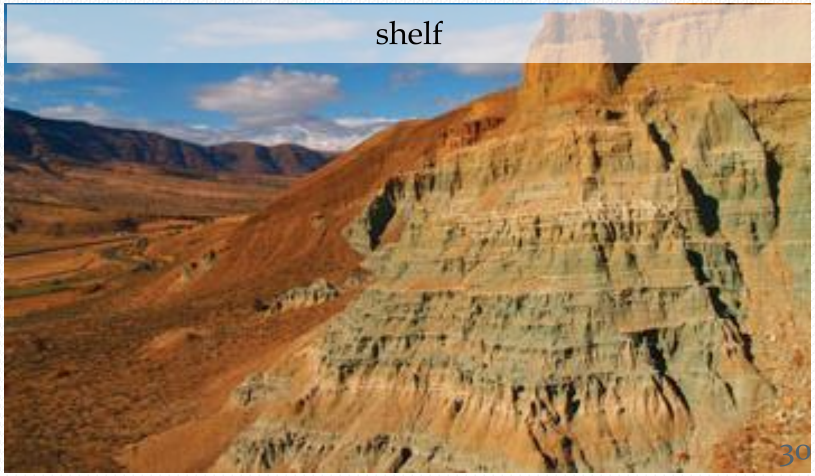
Depositional systems (consisting of a numbero of environments) that can provide clays:

MODERN



ANCIENT





CARBONATE SEDIMENTS and ROCKS

CARBONATE ROCKS

CARBONATES are CaCo3-rich rocks, mostly generated by biological and chemical processes.
Carbonates record a number of relevant information on the primary sedimentary environment, including:

1. Temperature of the waters during the sedimentation.
2. Salinity of the waters.
3. Depth.

These three factors change the nature of carbonate rocks. This is due to organisms living within the sediment and to the Carbonate Compensation Depth (CCD).

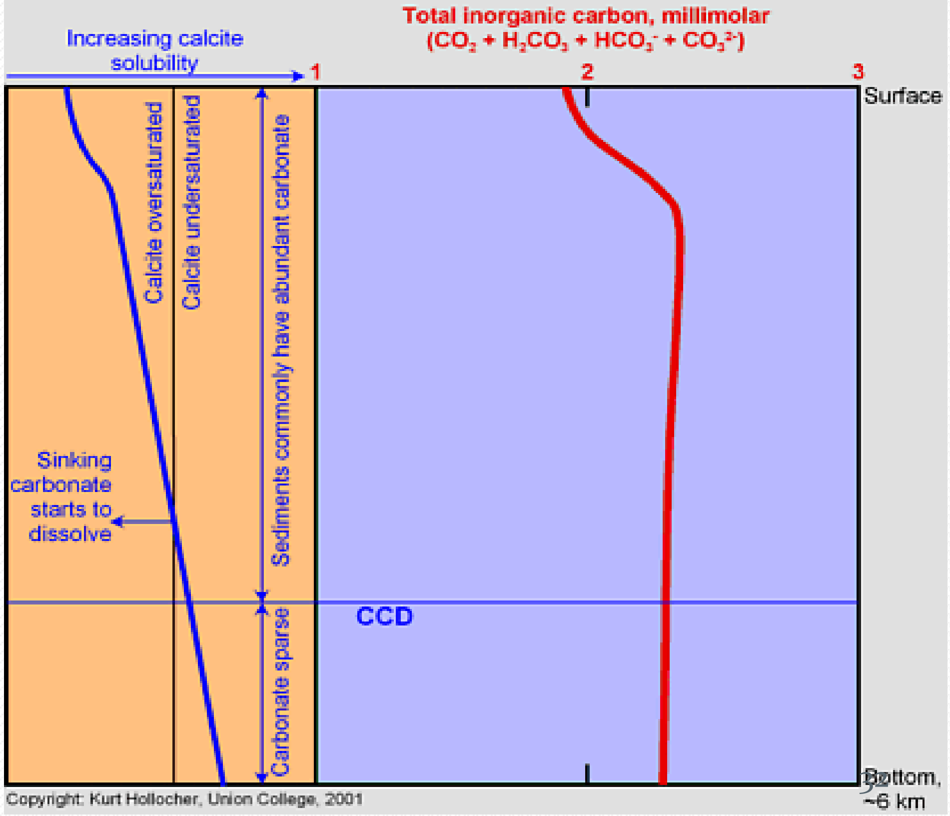
Som shell remains (after the deth of the organisms) fall out from the surface of the water downwards;

Shells reach a depth where waters are significantly sub-sature of $CaCO_3$

At that depth, shells begin to dissolve.

In modern environments (e.g., oceans) there is a depth beneath which $CaCO_3$ is chemically unstable.

Such a depth is known as CARBONATE COMPENSATION DEPTH (CCD).

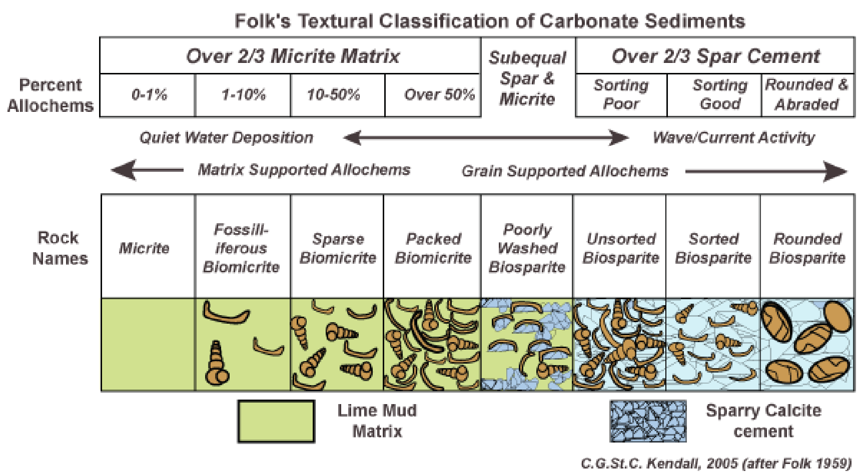


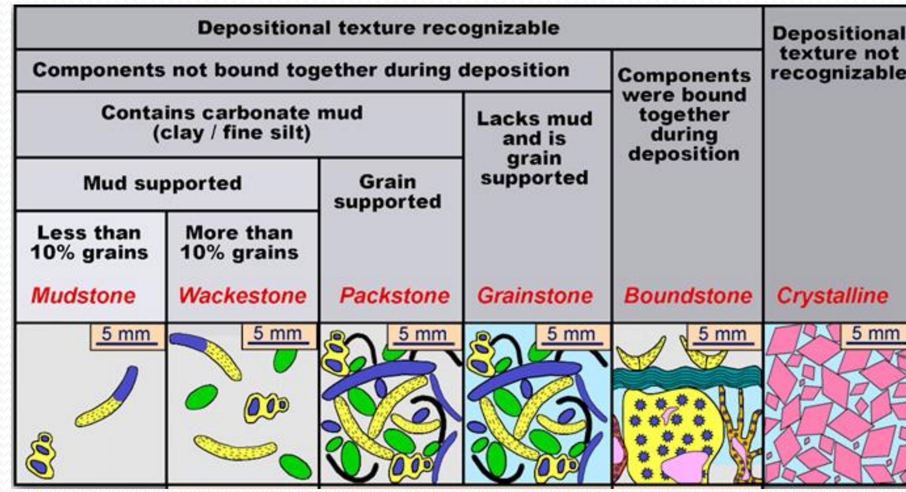
CARBONATE ROCKS

There are two main classifications for carbonate rocks:

The most common and widely used classification is after **Folk** (1962), which is based on the carbonate rock textures.

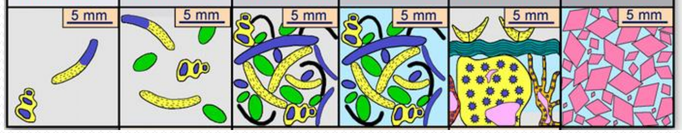
A second, more used approach is after **Dunham** (1962), which is based on the composition of carbonate rocks and their average grain size.





CARBONATE ROCKS

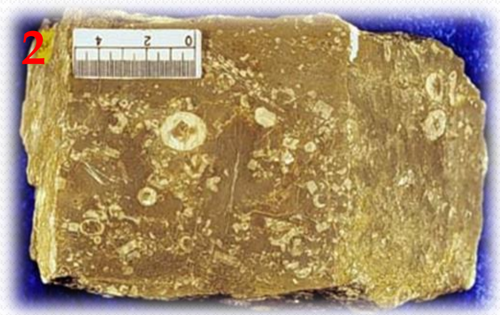
Depositional texture recognizable					Depositional texture not recognizable
Components not bound together during deposition				Components were bound together during deposition	
Contains carbonate mud (clay / fine silt)			Lacks mud and is grain supported		
Mud supported		Grain supported			
Less than 10% grains	More than 10% grains				
Mudstone	*Wackestone*	*Packstone*	*Grainstone*	*Boundstone*	*Crystalline*



1 2 3 4 5 6

MUDSTONE

WACKESTONE



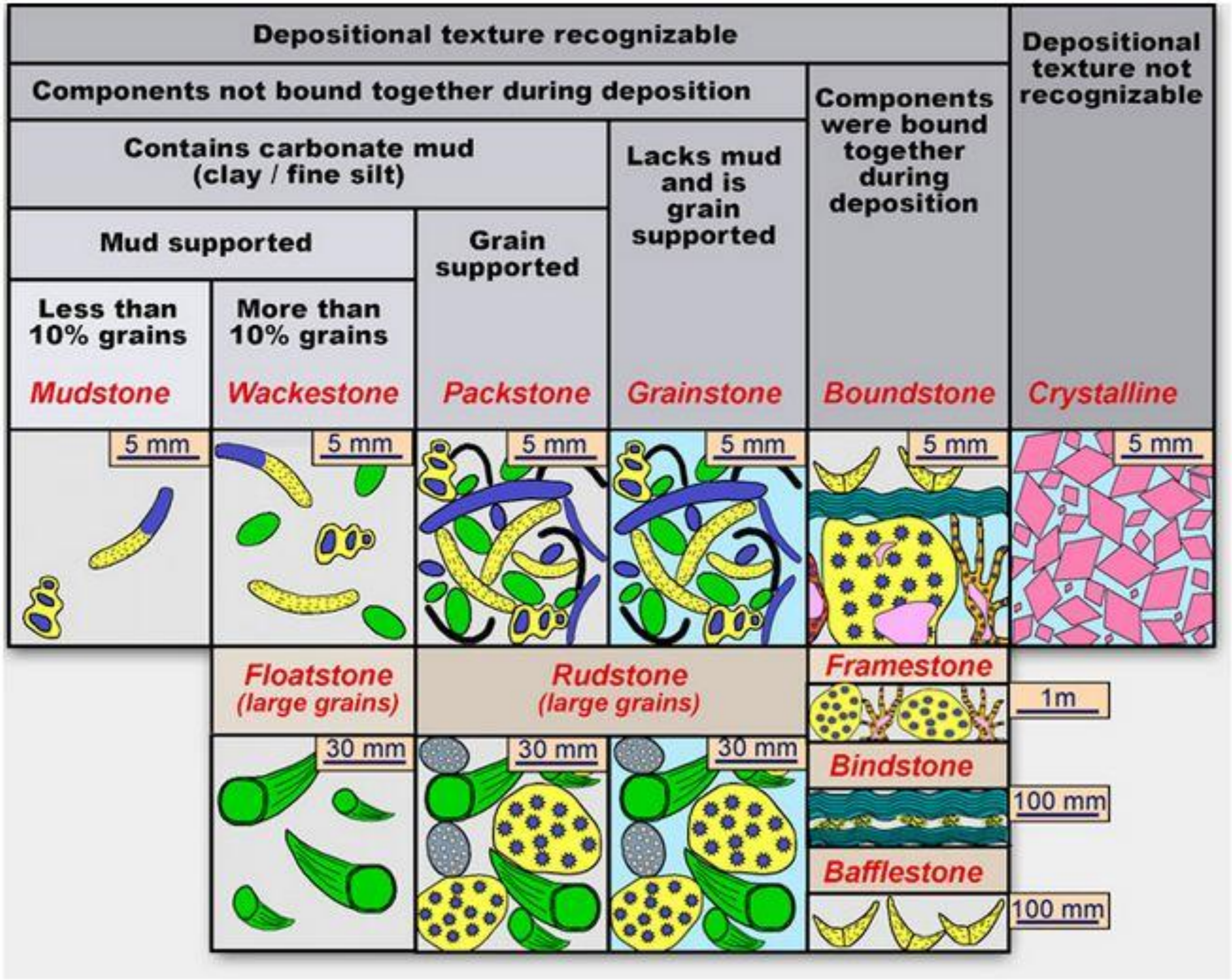
PACKSTONE

GRAINSTONE

BOUNDSTONE

CRYSTALLINE CARBONATE

CARBONATE ROCKS



MIXED
SEDIMENTS and ROCKS

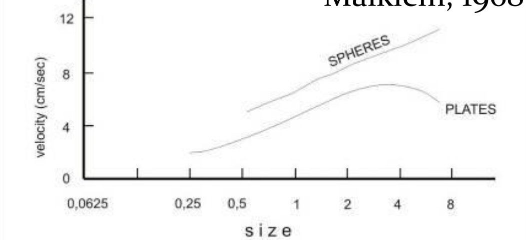
Often in nature, it is possible recognize rocks in which the **carbonate** and **siliciclastic** fractions occur together, although with different proportions or percentages.

When we are able to estimate such percentages with precision (e.g., with mineralogical quantitative analysis) an indicative nomenclature can be adopted on these rocks which are of MIXED COMPOSITION.

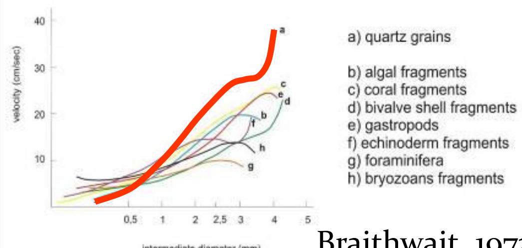
A MIXED SEDIMENT or ROCK consists of:

1) an EXTRA-BACINAL fraction, and

2) An INTRA-BACINAL fraction (Mount, 1984).

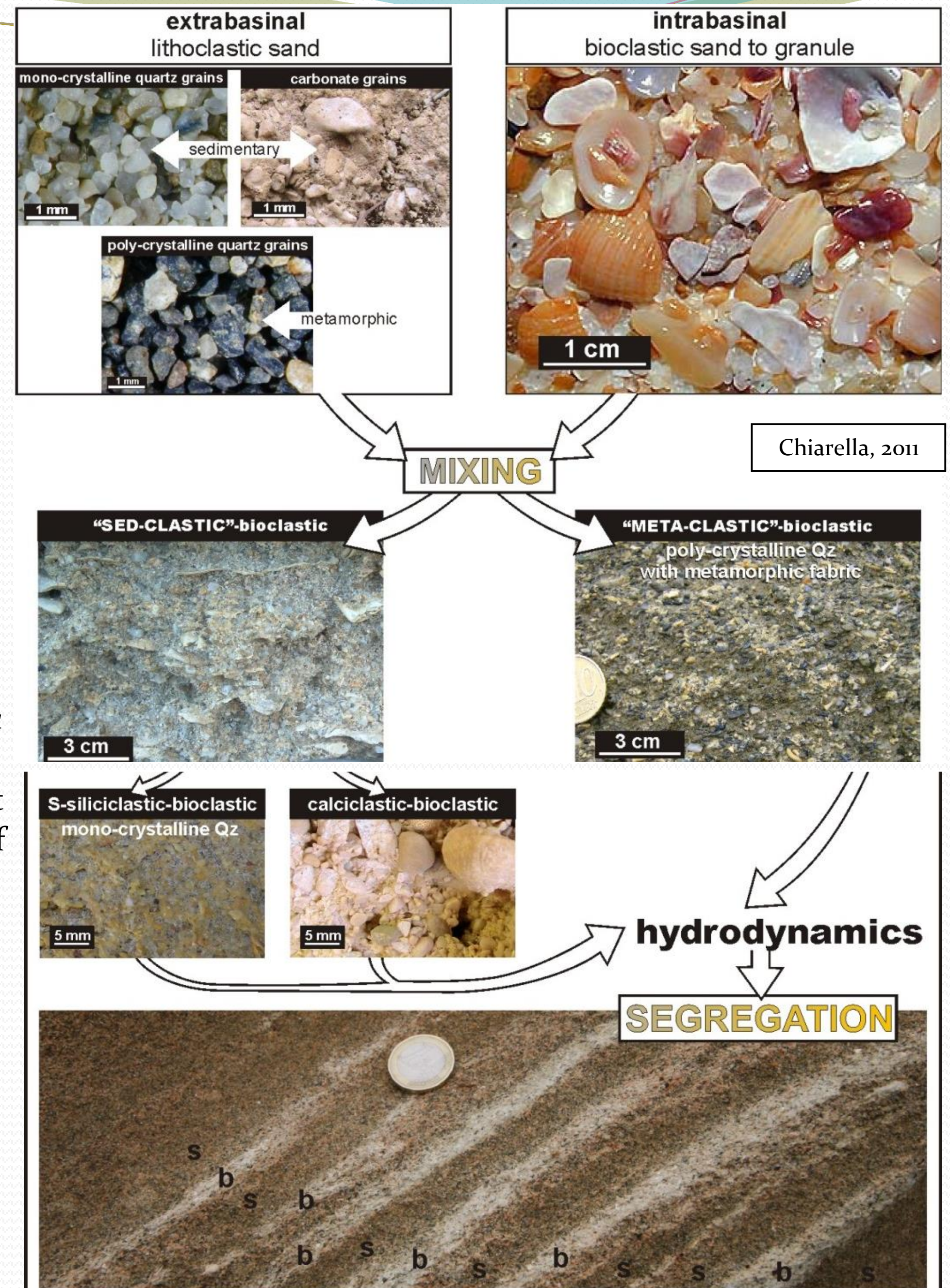


Maiklem, 1968



Braithwait, 1973

The two heterolithic components can be subject to a different hydraulic behavior if incepted in a moving (e.g., waves, currents, ...). Consequently, they can be organized into different ways or structures, allowing to a HETEROLITHIC SEGREGATION.

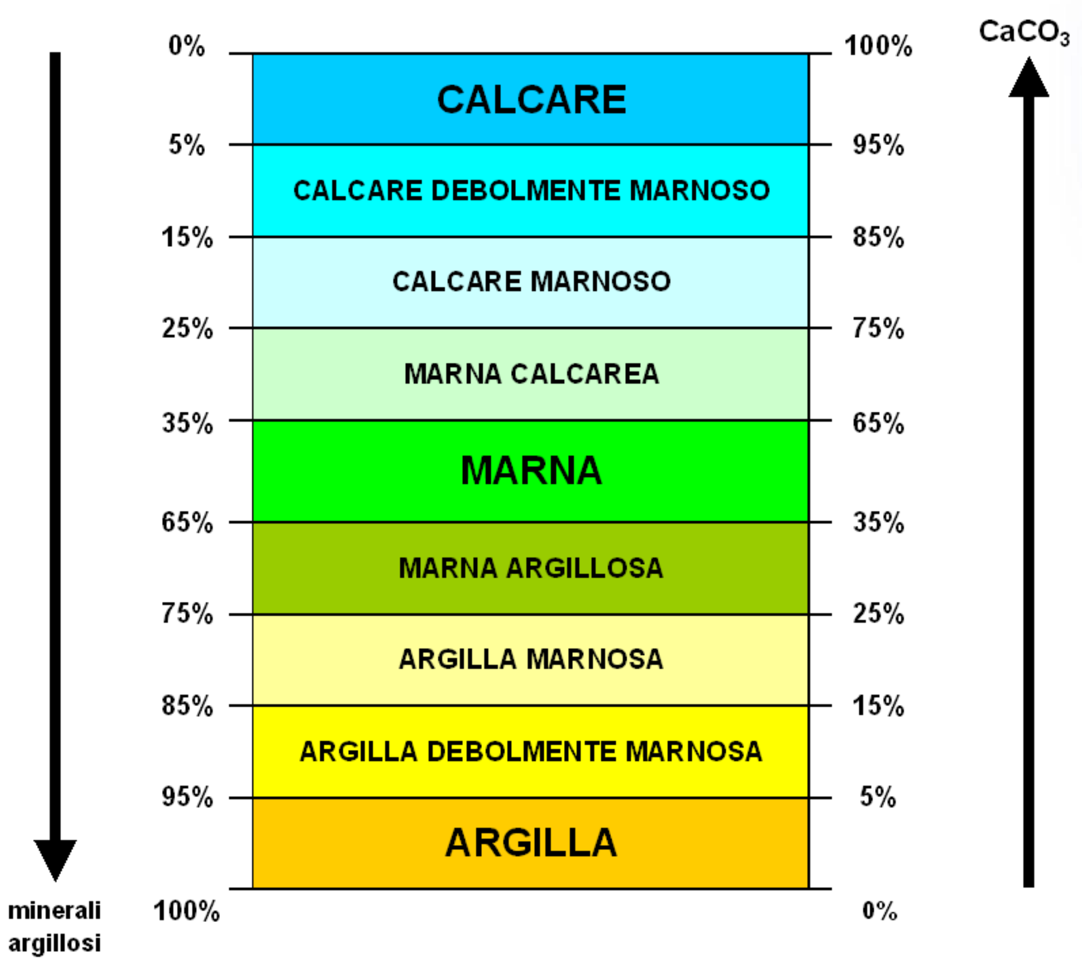


Chiarella, 2011

Often in nature, it is possible recognize rocks in which the **carbonate** and **siliciclastic** fractions occur together, although with different proportions or percentages.

When we are able to estimate such percentages with precision (e.g., with mineralogical quantitative analysis) an indicative nomenclature can be adopted on these rocks which are of MIXED COMPOSITION.

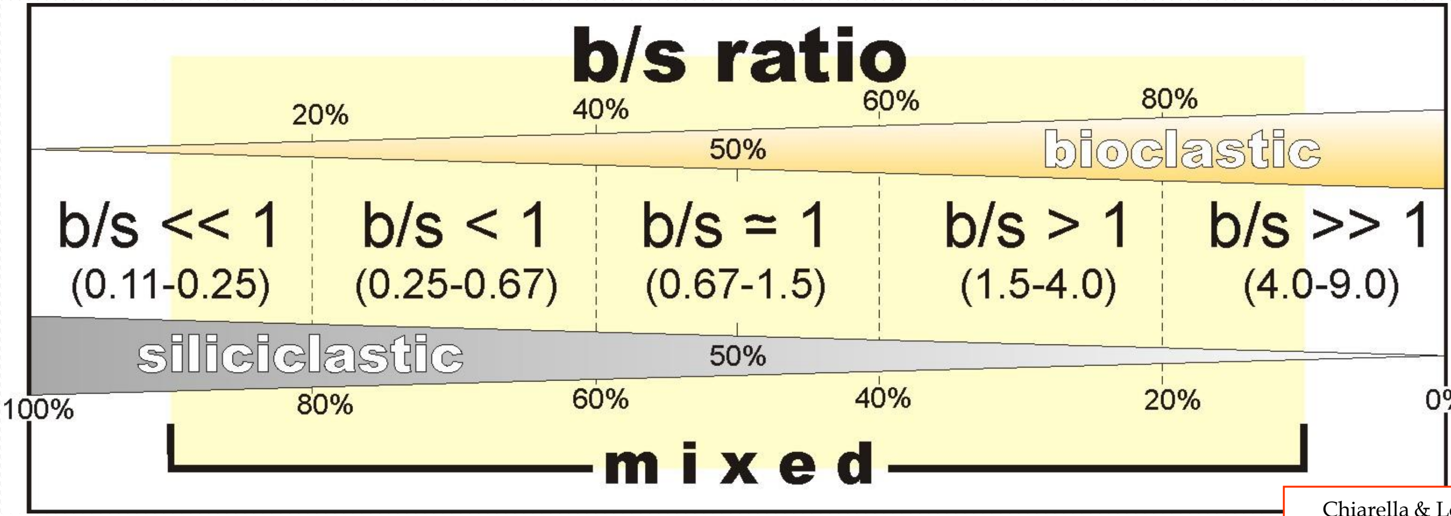
FINE-GRAINED MIXED ROCKS



MIXED ROCKS. A method to classify them [*bioclastic/siliciclastic ratio* (*b/s*)]

The *bioclastic/siliciclastic ratio* (*b/s*) misures the quantitative proportion of the two heterolithic components of a mixed sediment or rock (Chiarella & Longhitano, 2012)

Such feature is a pre-condition to consider or define a sediment as MIXED: «a mixed sediment can be considered as such, when both of their component are more than the 10%» (Mount, 1985).



Chiarella & Longhitano, JSR (2012)

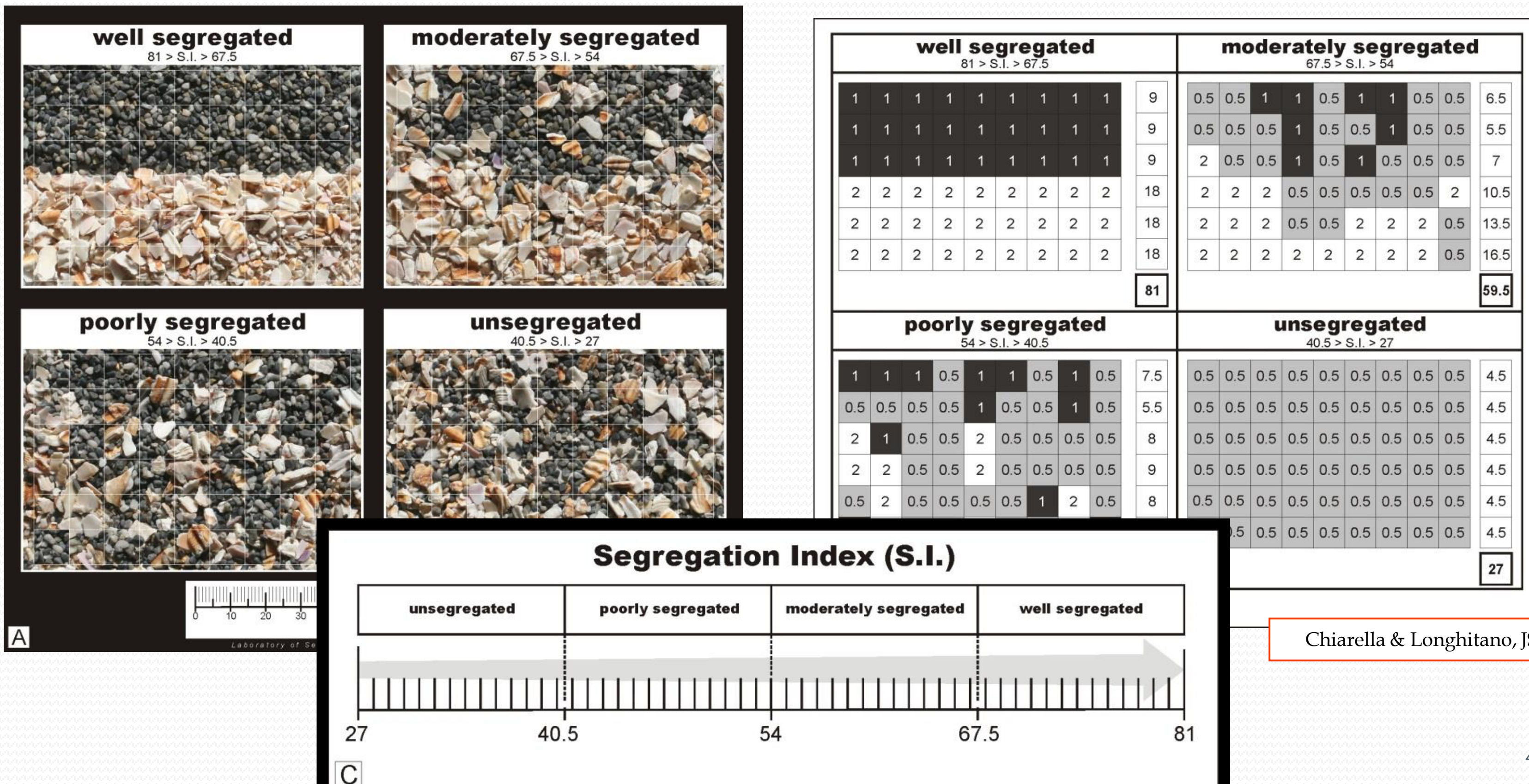
The *b/s* ratio includes 5 classes, in which the numerical interval corresponds to the reciprocal relationship between the two components, according to a progression of the 20%.

MIXED ROCKS. A method to classify them [*segregation index* (*S.I.*)]

The *Segregation Index* (*S.I.*) represents an adimensional parameter whch quantifies the degree of heterolithic segregation in a mixed sediment or rock.

For HETEROLITHIC SEGREGATION we intend the spatial distribution that clastic particles assume within a rock.

The numerical estimation of such feature can be applied through the use of a visual comparator.



Chiarella & Longhitano, JSR (2012)

Evaluation of the *Segregation Index* (*S.I.*). Use of a matrix (9 x 6) and arithmetic sum of the indexes.

EXAMPLE # 1

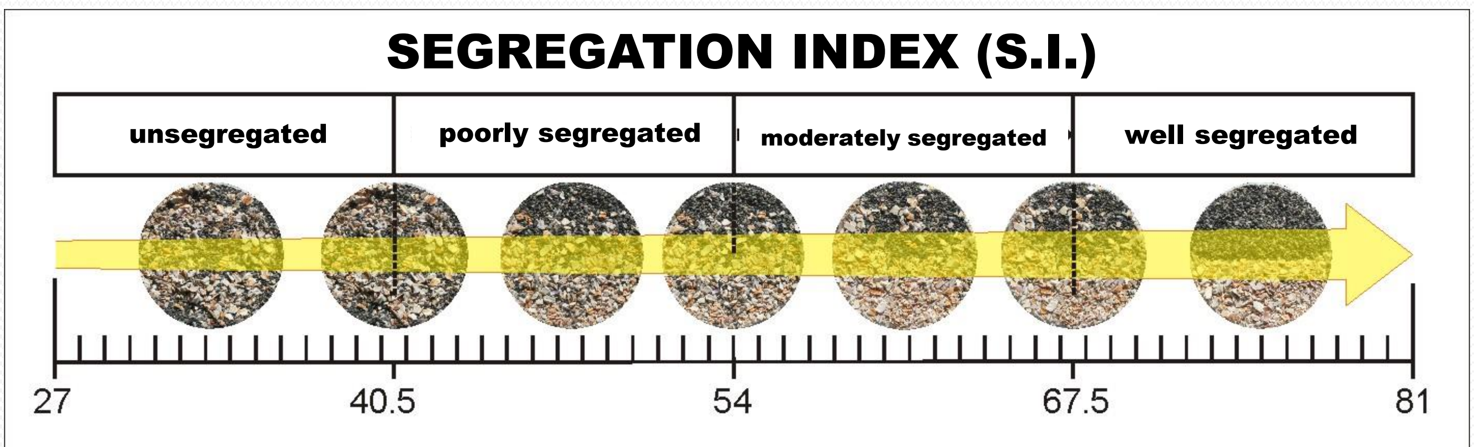
USED INDEXES:

SiliclClastic = 1

Bioclastic = 2

Mixed = 0,5

1	1	1	1	2	2	0.5	2	2	⇨ 12.5
1	1	1	0.5	2	2	2	2	2	⇨ 13.5
2	2	2	1	1	1	1	1	2	⇨ 13
1	1	1	1	1	0.5	0.5	2	2	⇨ 10
1	2	2	2	2	2	2	2	2	⇨ 17
0.5	2	2	2	2	2	2	2	2	⇨ 16.5



82.5

Evaluation of the *Segregation Index* (S.I.). Use of a matrix (9 x 6) and arithmetic sum of the indexes.

EXAMPLE # 2

USED INDEXES:

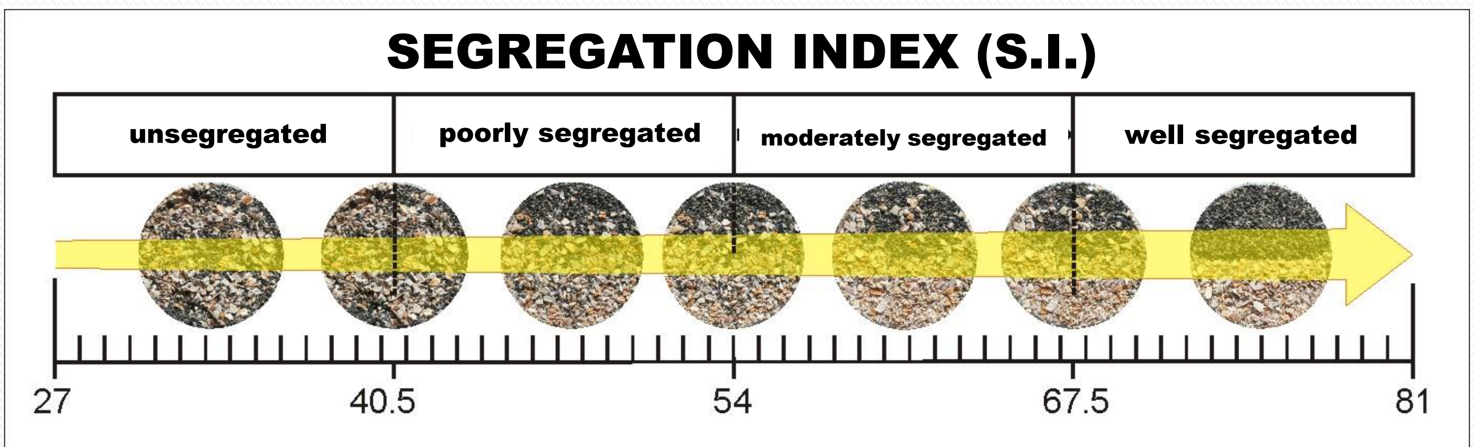
SiliclClastic = **1**

Bioclastic = **2**

Mixed = **0,5**

0.5	0.5	0.5	0.5	0.5	2	0.5	0.5	1	6.5
0.5	0.5	0.5	0.5	2	2	2	1	1	10
0.5	0.5	0.5	0.5	0.5	1	0.5	1	2	7
0.5	0.5	1	1	1	0.5	0.5	0.5	0.5	6
1	2	1	0.5	1	2	2	2	2	13.5
0.5	0.5	0.5	2	2	0.5	0.5	2	2	10.5

53.5



International degree on

Geosciences and Georesources

Course of
Applied Stratigraphy and Sedimentology

3. Sedimentology

3a. Origin of sediments; **3b.** Clastic and non-clastic sediments; **3c.** Main processes of erosion, transport and sedimentation; **3d.** Main sedimentary processes (tractive, mass, etc ...); **3e.** Facies, facies associations, depositional environments and systems. **3f**. Georisources of sedimentary origin.

1) SELECTIVE PROCESSES (Tractive)

Selective processes generate both a transport (TRACTIONAL TRANSPORT) but also a modelling of the sediment, producing structures (TRACTIONAL STRUCTURES).

(Ex.: marine currents; waves; river floods).

2) MASS PROCESSES

Mass processes produce a ‘mass transport’ of large amount (masses) of sediment, both in subaerial and subaqueous settings.

(Ex.: landslides; mudflows, etc.).

2.1) Gravitative Processes

The gravitative processes represent a type of mass process, which occur mostly under the effect of the gravity force.

(Ex.: *debris flow*, *grain flow, mud flow; turbidity flow*).

2.2) NON Gravitative Processesi

The gravitative processes represent a type of mass process, whose energy exceeds those of the gravity force, in case of excpetional events.

(Ex.: river catastrophic floods; ciclones, hurricanes, tiphoons; volcanic *surges*).


Structures deriving from
TRACTIONAL PROCESSES
ORGANISED ASSECT


Structures deriving from MASS
PROCESSES
CAHOTIC or UNGORGANISED ASSET

Selective processes shaping a mud/mudrock unit

MUDROCK UNIT

THICKNESS → **BOUNDARIES**

Sharp or transitional?
What's the unit's shape?

SILT CONTENT

None →
Little →
Much →

FISSILITY

Absent	Present
= claystone	= clayshale
= mudstone	= mudshale
= silty mudstone (or muddy siltstone)	= siltshale

SILT/SAND INTERLAYERS

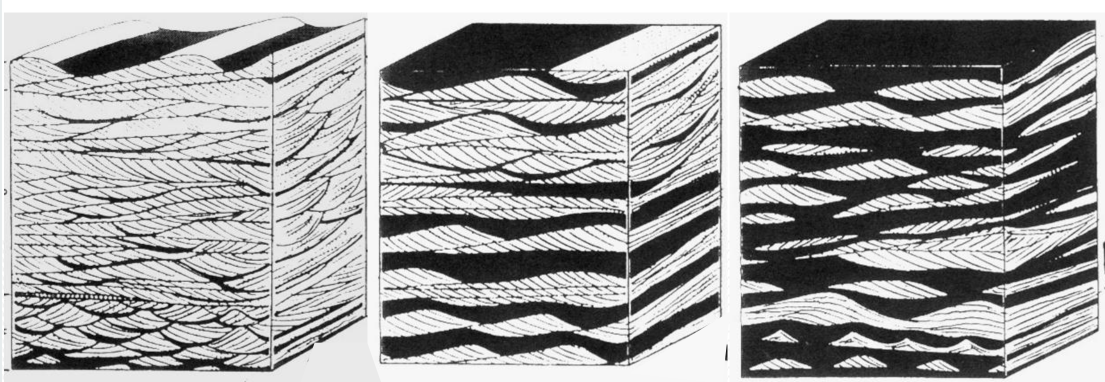
Absent	Present
uniform mudrock	heterolithic deposit

What kind of interlayers?
- Interlaminae (≤ 2 mm)?
  - Continuous or discontinuous ("streaky")?
  - What's their grain size?
- Interbeds (> 2 mm)?
  - Flat or undulatory? Continuous or not?
  - What's their grain size?
  - What's their internal structure?
  - What's the interbedding type? (flaser? wavy? lenticular?)
- Any soft-sediment deformation?

BIOTURBATION

Plant root-casts?
- What length and diameter?
- Branching or singular?
- Coaly matter present or not?

Animal burrows?
- How strong (dense)?
- What kind of trace fossils?



Flaser bedding — Wavy bedding — Lenticular bedding

Selective processes shaping a sand/sandstone unit

SANDSTONE UNIT (BED)

THICKNESS → BOUNDARIES

Sharp or gradational?
Erosive base? (What's its relief?)
What's the bed's shape (geometry)?

MINERAL COMPOSITION

Siliciclastic or calcareous?
More exact composition is usually difficult to specify without a thin-section analysis

TEXTURE

Mean grain size
What's the sand's grain-size category?

v. coarse	1-2 mm
coarse	0.5-1 mm
medium	0.25-0.5 mm
fine	0.125-0.25 mm
v. fine	0.062-0.125 mm
silt	< 0.062 mm

Sorting
Arenite (< 15 vol.% mud) or wacke?

Any "outsized" particles?
What's their size & spatial distribution?

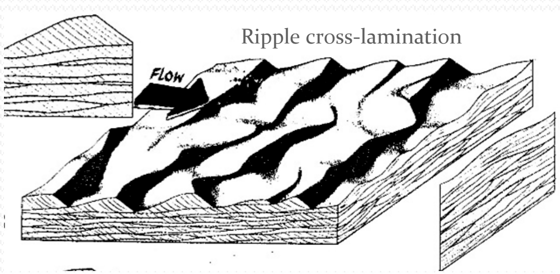
STRUCTURE

Stratified?
What type(s) of stratification?
What kind of spatial changes?
What's the palaeotransport direction?

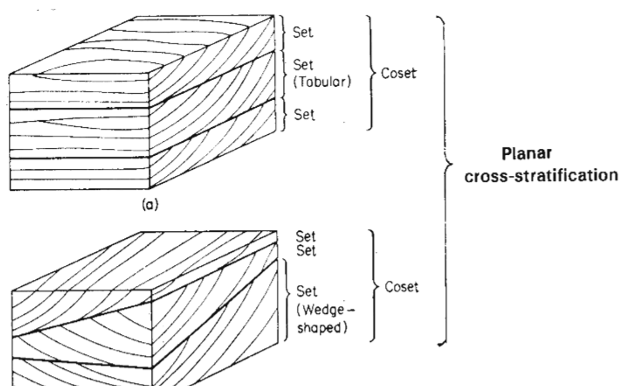
Non-stratified ("massive")?
Normal? Inverse? Inverse-to-normal?

Any soft-sediment deformation or water-escape structures?

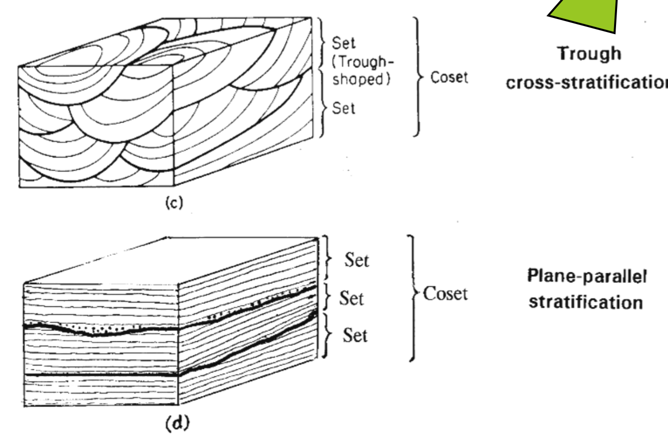
Any biogenic structures?
Any trace fossils? What kind?
Any plant-root traces or other pedogenic/paleosol features?
How dense?



SMALL-SCALE PLANAR/TROUGH CROSS-STRATIFICATION



LARGE-SCALE PLANAR/TROUGH CROSS-STRATIFICATION



Selective processes shaping a gravel/gravelstone unit

CONGLOMERATE UNIT (BED)

THICKNESS

BOUNDARIES

Distinct or indistinct ("amalgamated")?
Even (flat) or uneven?
Sharp base? Loaded?
- Is it erosive?
- What's the scour relief, if any?

MINERAL COMPOSITION

Monomictic?
Oligomictic?
Polymictic?
What components?
Any "intraclasts"? Where?

TEXTURE

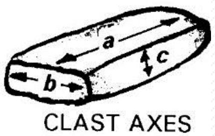
Clast- or matrix-supported?
Mean grain size (D_{mean})
- boulder gravel > 512 mm
- cobble gravel 64-512 mm
- pebble gravel 4-64 mm
- granule gravel 2-4 mm

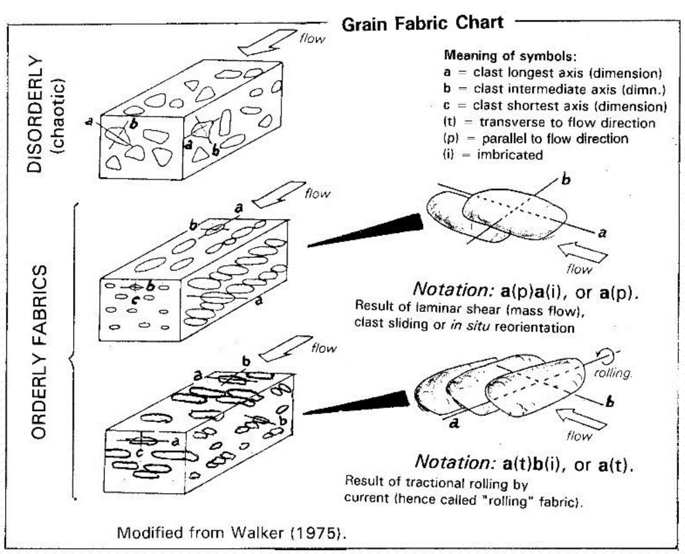
Maximum grain size (D_{max})
Clast sorting
Clast shape
Clast roundness
Clast fabric
- Flow-transverse ***a***(t) ? With imbrication ***a***(t)***b***(i) ?
- Flow-parallel ***a***(p) ? With imbrication ***a***(p)***a***(i) ?
- Disorderly (chaotic) fabric?

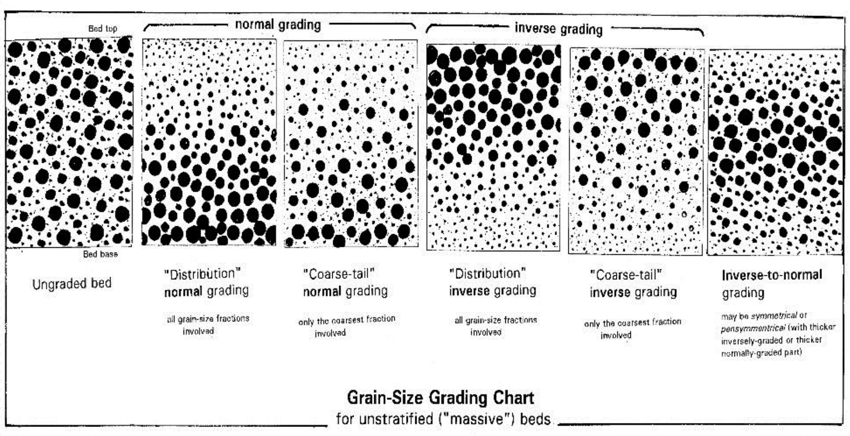
STRUCTURE

Stratified?
- What type of stratification?

Non-stratified ("massive")?
Any clast-size grading?
- Normal? Inverse?
- Inverse-to-normal? (Symmetric or pensymmetric?)
- Non-graded?







Mass Processes

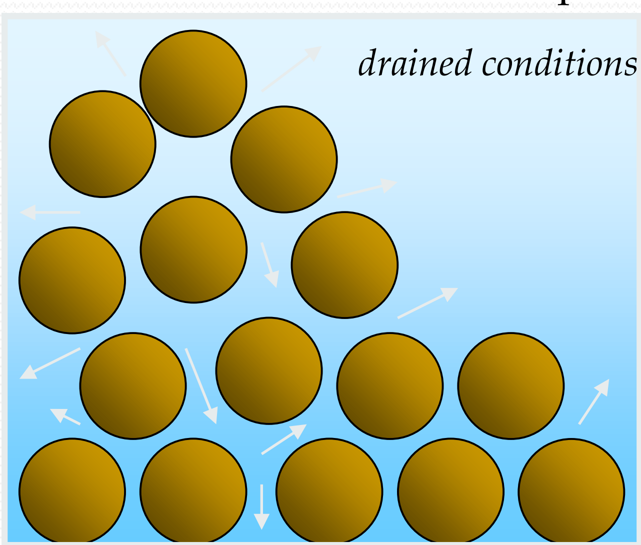
Selective processes generate both a transport (TRACTIONAL TRANSPORT) but also a modelling of the sediment, producing structures (TRACTIONAL STRUCTURES).

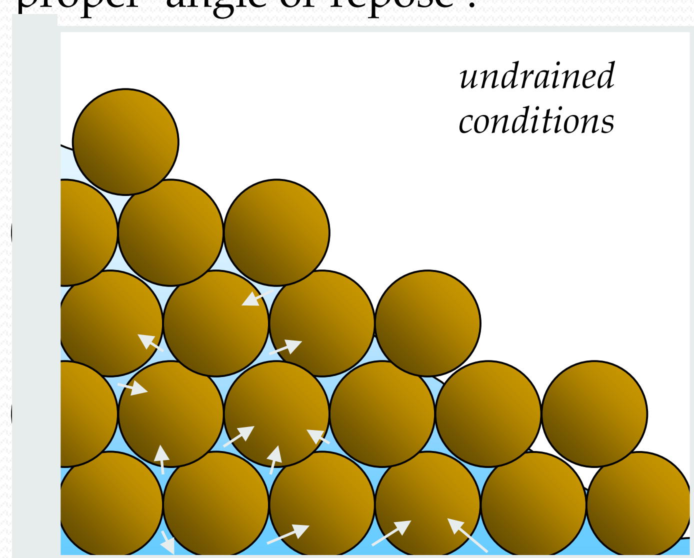
(Ex.: marine currents; waves; river floods).

LANDSLIDE

1) **Subaqueous** (more rare; the interstitial pressure does not have any relevant effect, because sediments are in *drained conditions*, with dips even more than 15°-20°;

2) **Subaerial** (more frequent; the interstitial pressure has an important effect onto the sediments because they are in *undrained conditions*; even few degrees of dip can be sufficient to mobilize these masses, but it depend on their proper 'angle or repose'.

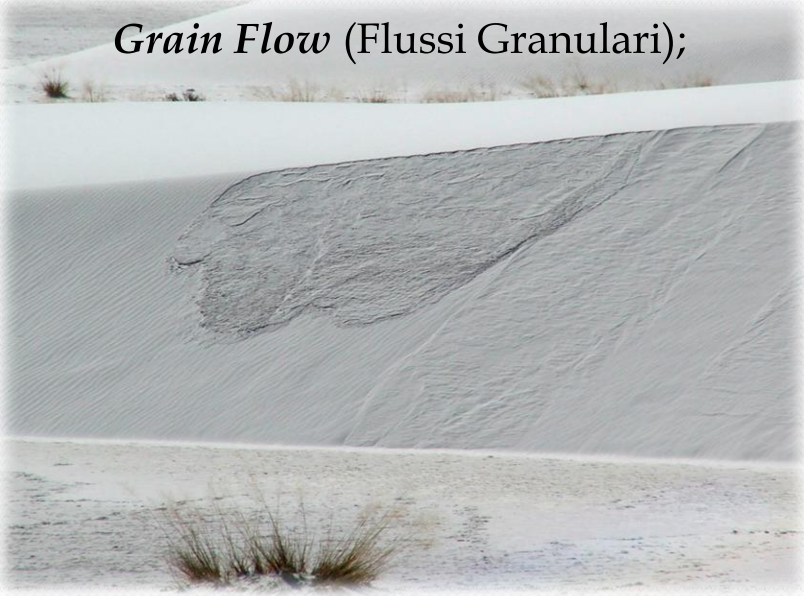




THERE ARE FOUR MAIN TYPES OF MASS (GRAVITATIVE) PROCESSES:

Mud Flow (Colate di Fango);

Debris Flow (Flussi di Detrito)



Grain Flow (Flussi Granulari);

Turbidity Flow
(Flussi o Correnti di Torbida)

Mud Flow

Mass Gravitative Process :

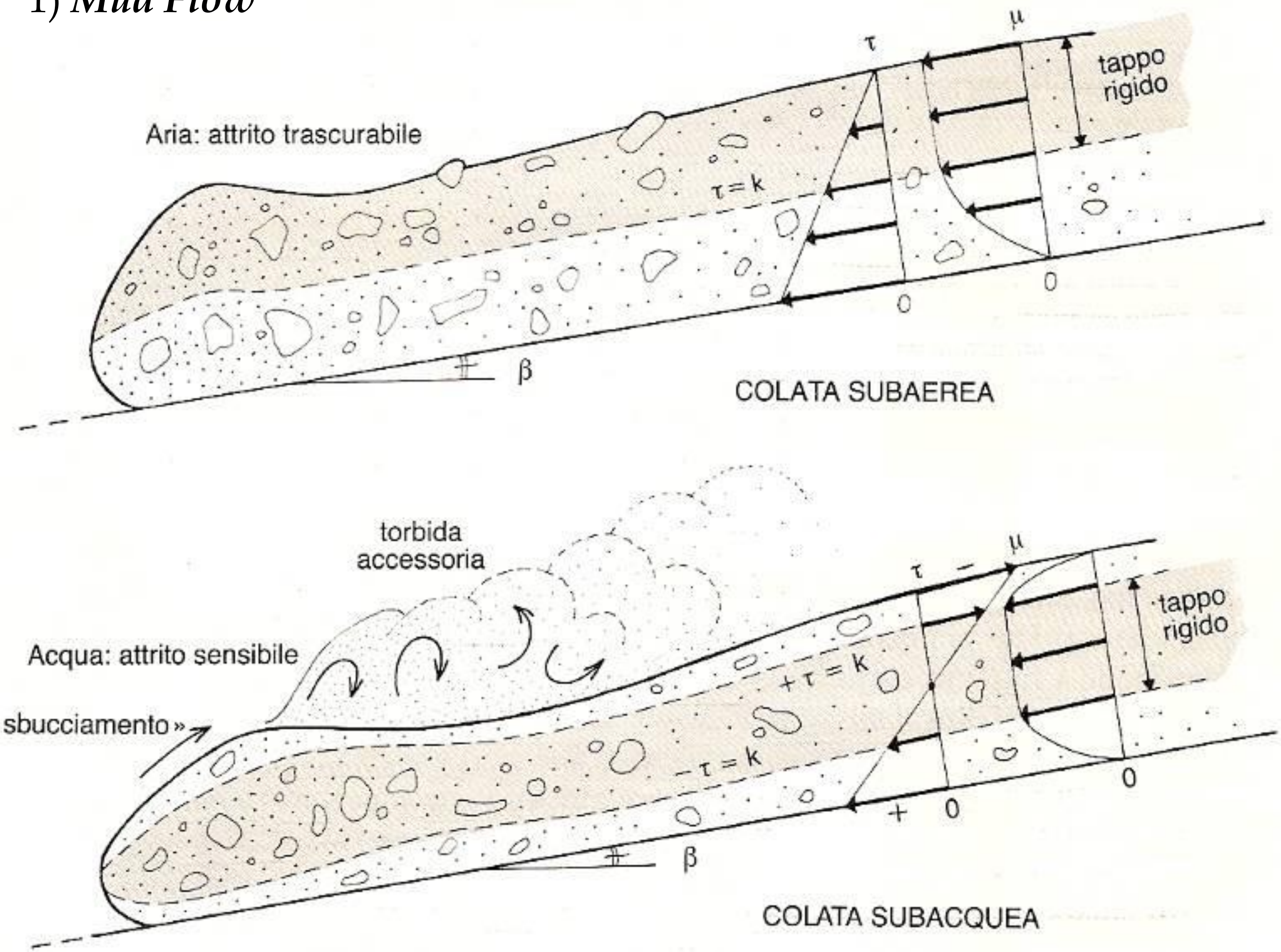
1) *Mud Flow*

Mass Gravitative Process :

1) ***Mud Flow***

Mass Gravitative Process :

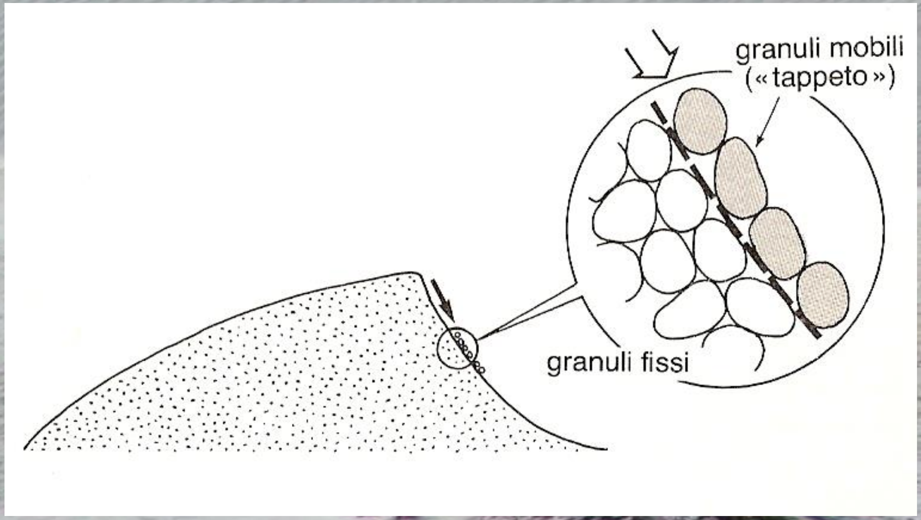
1) ***Mud Flow***

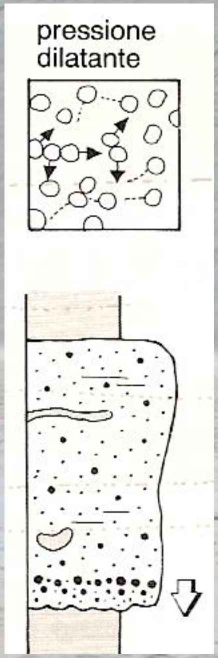


Grain Flow

Mass Gravitative Process :

1) ***Grain Flow***





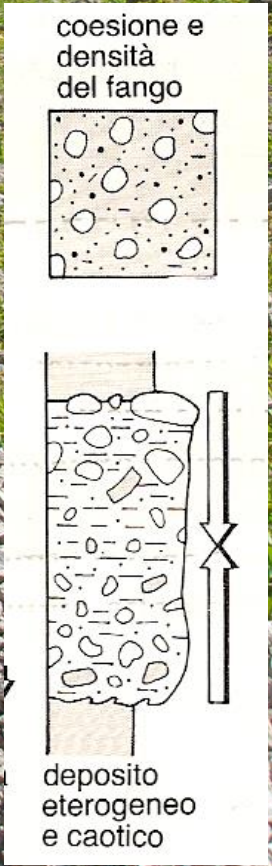
Mass Gravitative Process :

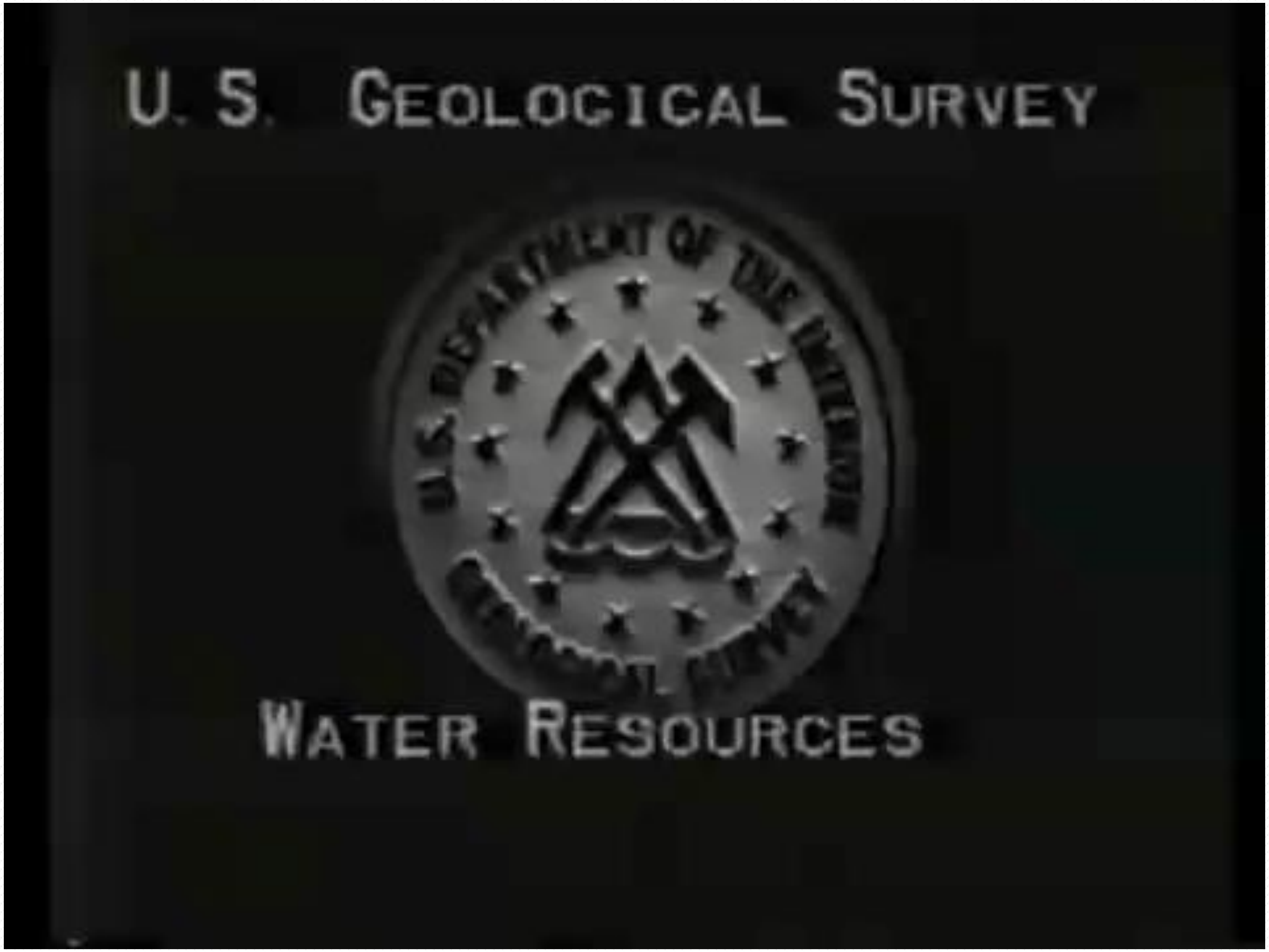
1) ***Mud Flow***

Debris Flow

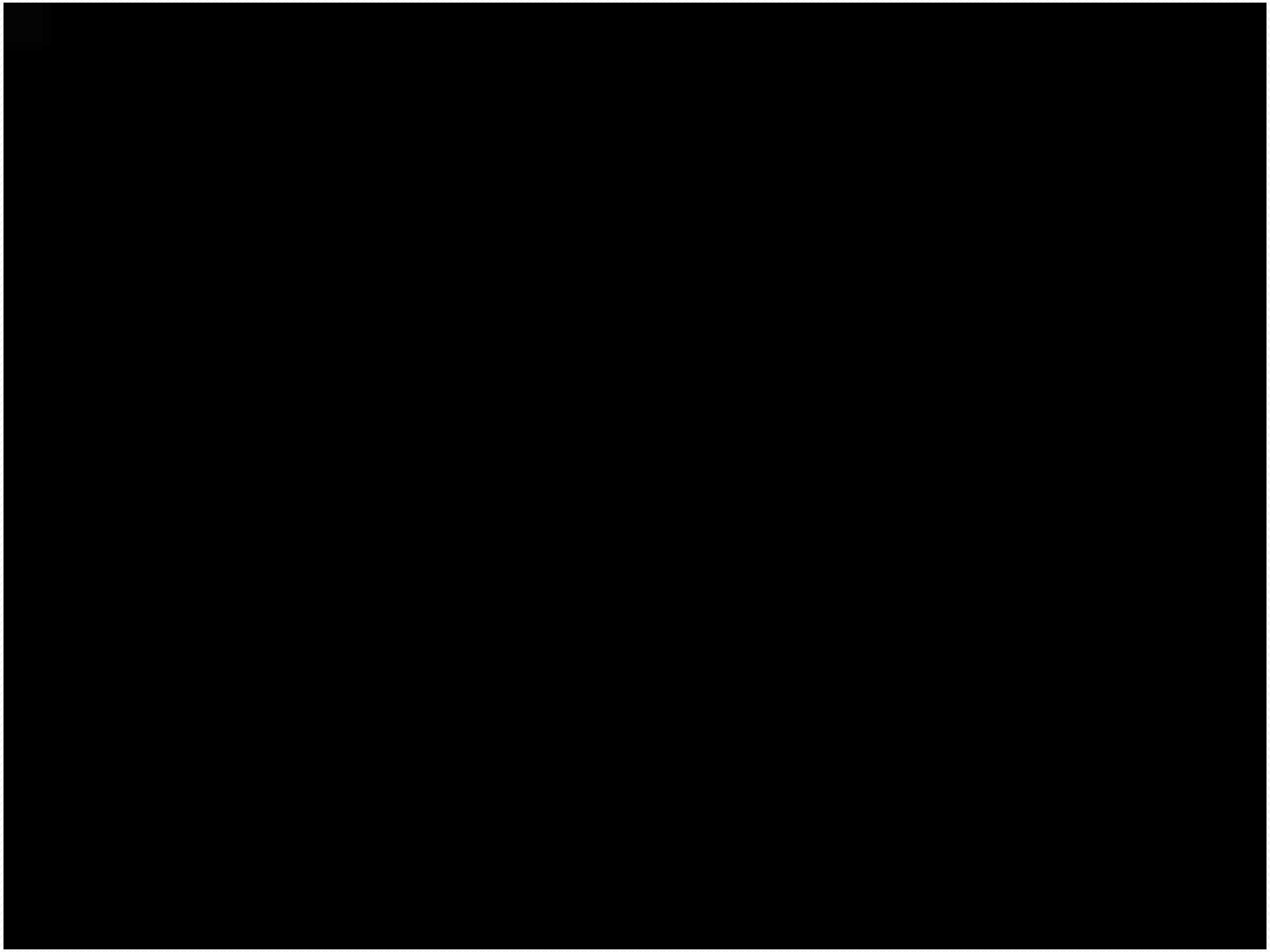
Mass Gravitative Process :

1) ***Debris Flow***



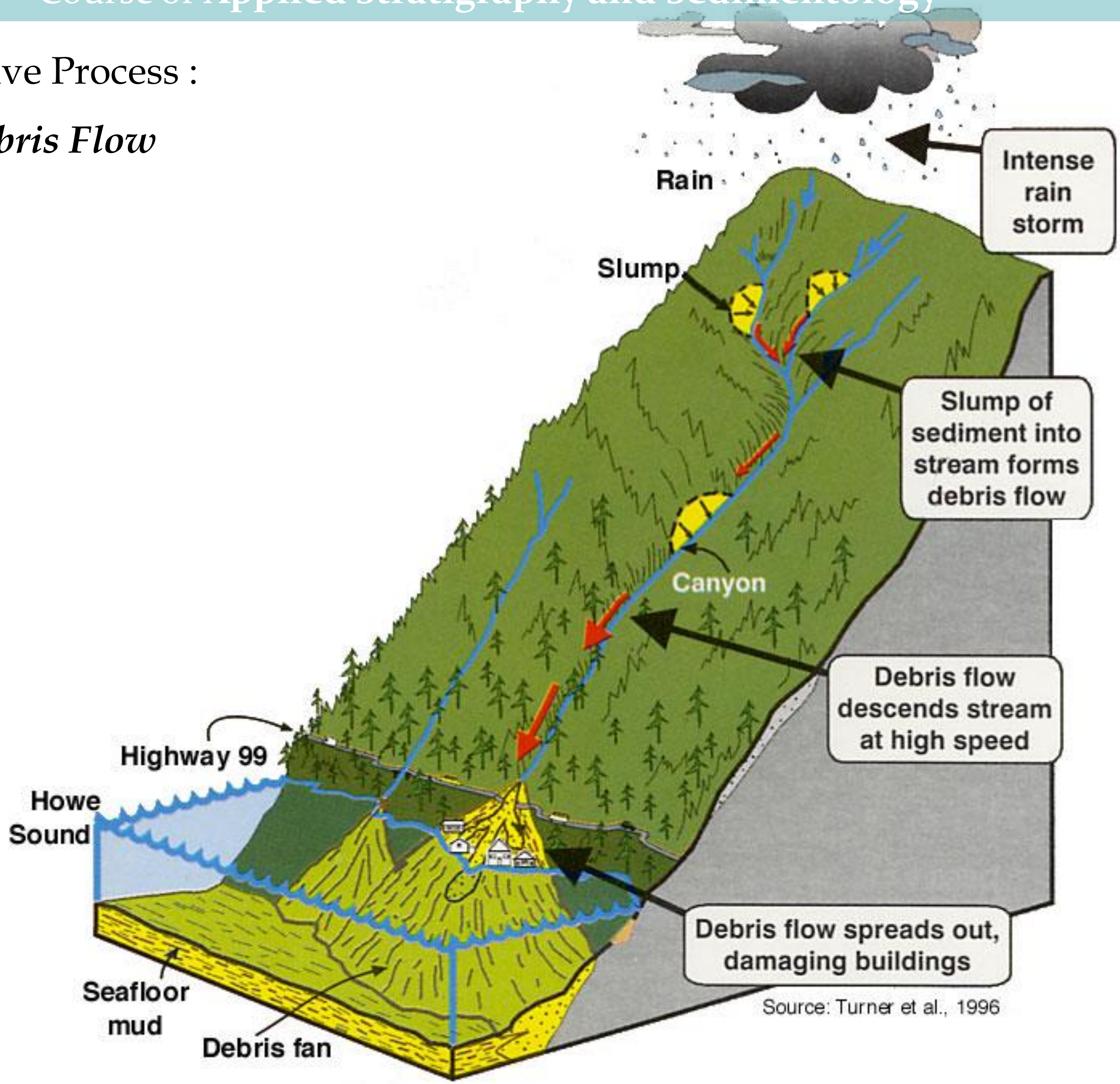

U. S. GEOLOGICAL SURVEY
WATER RESOURCES

Mass

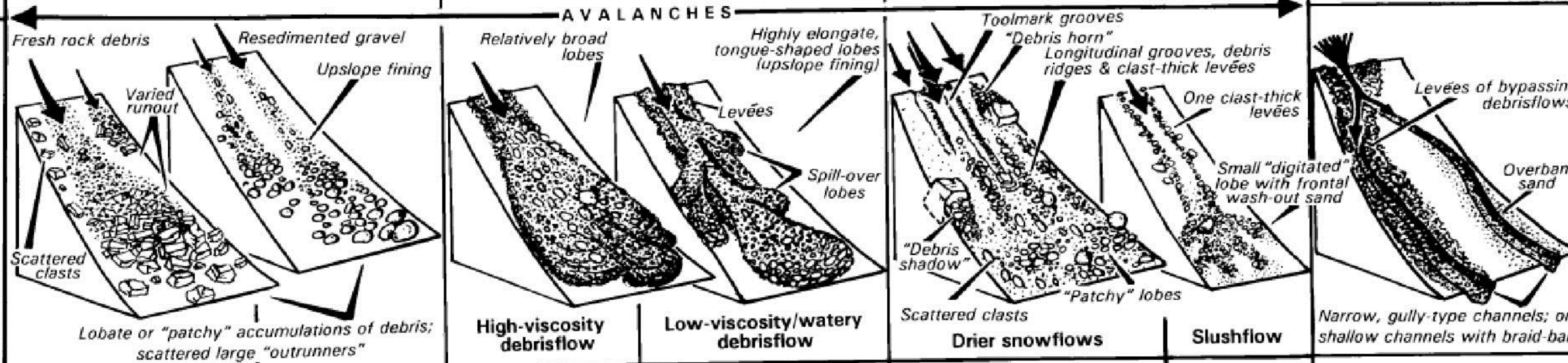


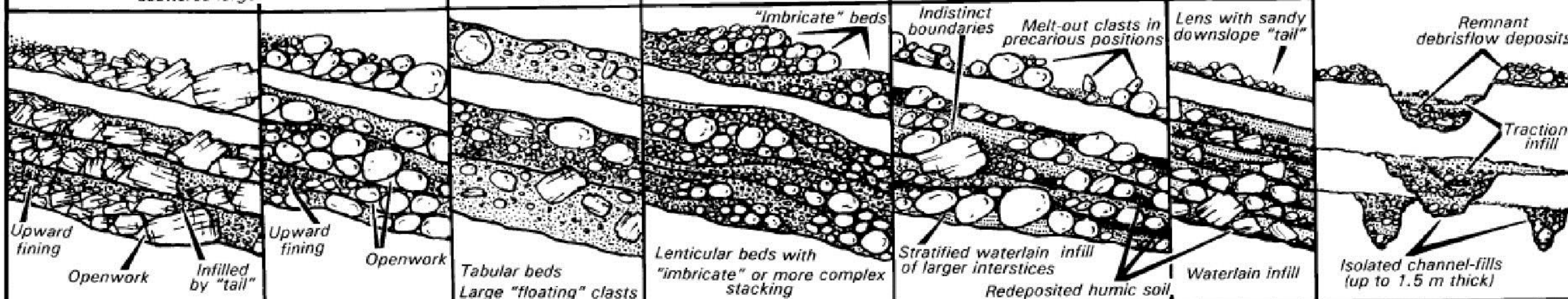
Mass Gravitative Process :

1) ***Debris Flow***



SEDIMENTARY FEATURES	DEPOSITIONAL PROCESSES: rockfall/debrisfall		debrisflow		snowflow	waterflow
TYPE/GEOMETRY OF DEPOSITS	← AVALANCHES →					

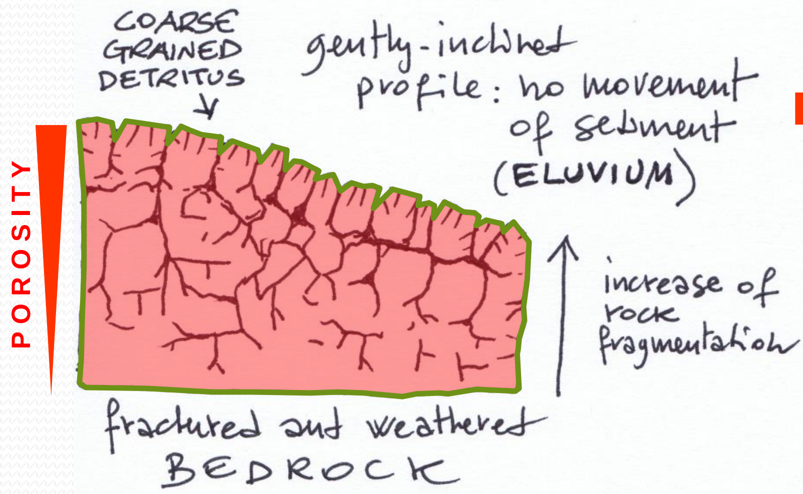




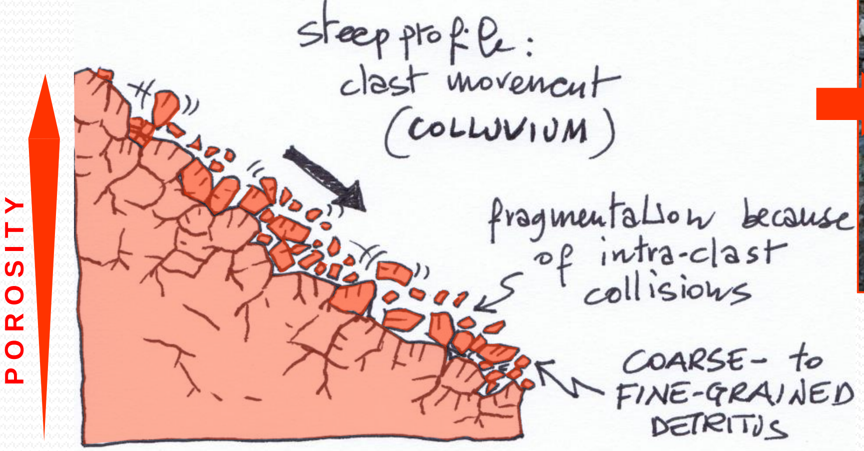
SEDIMENTARY FEATURES	rockfall/debrisfall		debrisflow (high-viscosity)	debrisflow (low-viscosity/watery)	snowflow	waterflow
TEXTURE AND STRUCTURE	Highly immature debris; mainly angular clasts Boulder to sand size grade. Clast-supported and commonly openwork, with pebbly to sandy infill at the top. Deposits often infilled with waterlain sand and/or redeposited soil material.	Mature debris; subrounded to rounded clasts	Matrix-rich to clast-supported. Sandy/muddy matrix. Common "coarse-tail" inverse grading and outsized cobbles or boulders.	Clast-supported, bouldery to cobbly "heads" and clast- to matrix-supported, pebbly upslope "tails". Common normal grading.	Unsorted, scattered clasts and gravel "patches" infilled with waterlain sand or pebbly sand. The sand in large interstices shows stratification, but is massive, very fine/silty and possibly shell-bearing in submarine deposits.	Clast-supported, pebbly to cobbly gravel interlayered with poorly sorted/stratified sand. Matrix-supported gravel occurs as debrisflow remnants.
CLAST FABRIC	Boulders and large cobbles often show "rolling" fabric, *a*(t) or *a*(t)*b*(i), when emplaced frontally in isolation. Many large clasts upslope show "sliding" fabric *a*(p), but a disorderly "adjustment" fabric predominates; "shear" fabric *a*(p) often typifies the avalanche's overriding tail, when evolved into a grainflow.		Large clasts mainly aligned downflow, *a*(p) or *a*(p)*a*(i), but showing *a*(t) orientation along the lobe front.	Common "rolling" fabric *a*(t) in the frontal and top part of the debrisflow head; common "shear" fabric *a*(p) or *a*(p)*a*(i) in the flow's tail.	Mainly disorderly (chaotic "melt-out" fabric). Boulders and cobbles deposited from turbulent snowflows may have "rolling" fabric *a*(t), but the scattered debris is vulnerable to rotation by subsequent avalanches. Dense snowflows and slushflows may create "shear" fabric *a*(p), but this loses order during the melt-out.	Common tractional fabric; poorly developed in gullies due to clast pivoting and adjustment to banks. Many large clasts are rotated *in situ* to *a*(p) position by less competent waterflow.
DEBRIS SOURCE	Weathered bedrock.	Glacial till and valley-side kame terraces.	Glacial till, kame terraces and upper-slope colluvium.		Glacial till and upper-slope colluvium, including fresh bedrock. Common slope-soil erosion.	Upper-slope colluvium and glacial till.

Eluvial vs. **colluvial** process

ELUVIAL PROCESS and DEPOSIT



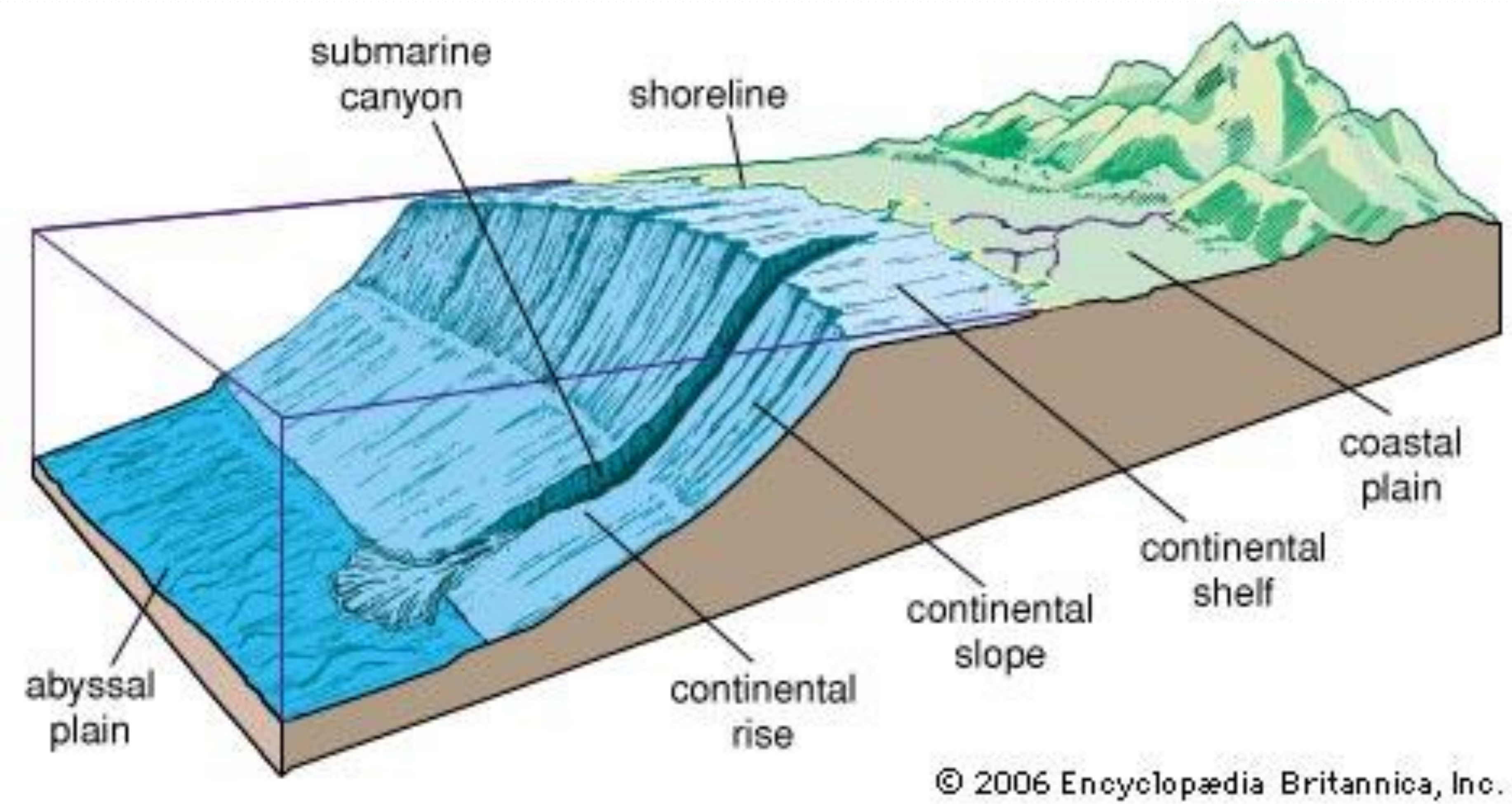
COLLUVIAL PROCESS and DEPOSIT



Turbidity Flow

TURBIDITIC DEPOSITIONAL SYSTEMS represent deep-marine complexes, which can be originated along the continental shelf edge, along the continental slope (through submarine canyons) in the form of rapidly-accelerating water + sediment flows, accumulating submarine fans in the abyssal plain, at the base of the slope.

The onset of turbiditic flows can be generated by earthquakes, tsunami or anomalous waves or, more simply, by sediment overload along the continental shelf edge.

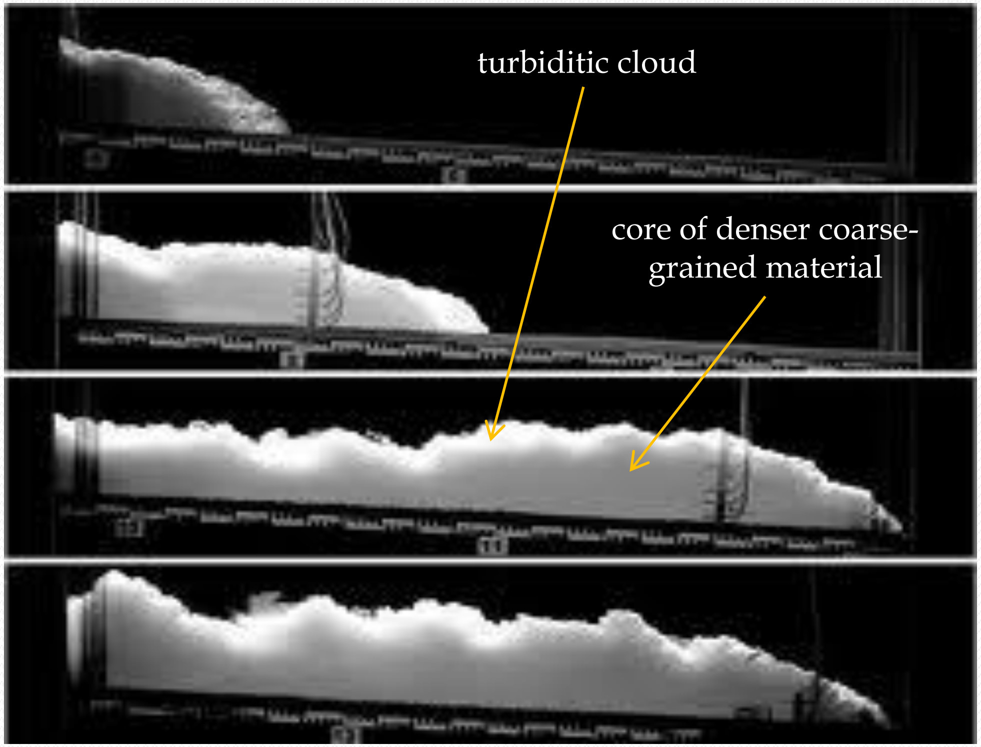


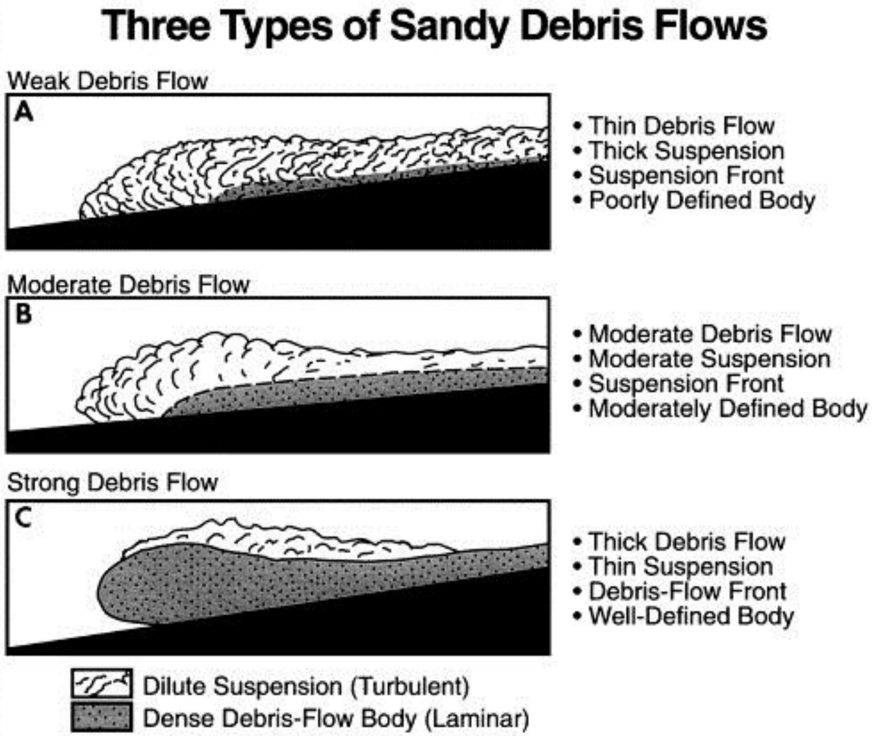
A **TURBIDITY CURRENT** is thus a highly-concentrated flow of high-density of sediment + water which, mrapidly descending the continental slope due to the gravity, it propagates at high velocity (turbitidy currents were measured with a velocity of ca. 300 km/h), concentrated into submarine canyons.

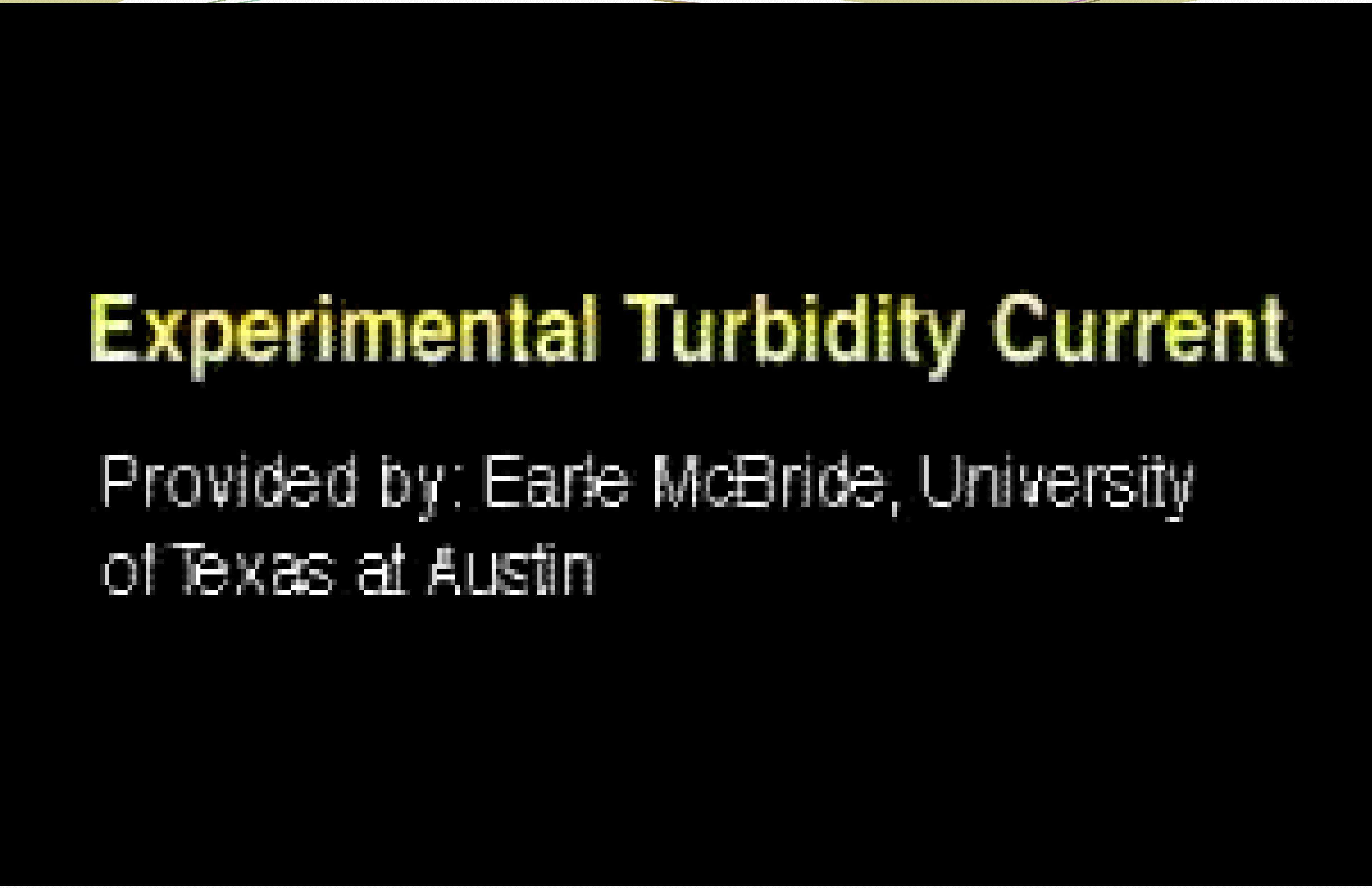
A **TURBIDITY CURRENT**, reconstructed in laboratory, has shown a 'core' of coarse-grained material, which is transported as bedload, and an associated 'turbiditic cloud', which runs at lower velocity, and formed by fine-grained sediment transported in suspension.

A turbiditic current can be characterised by three types of debris flows:

1) Weak debris flow;
2) Moderate debris flow;
3) Strong debris flow.





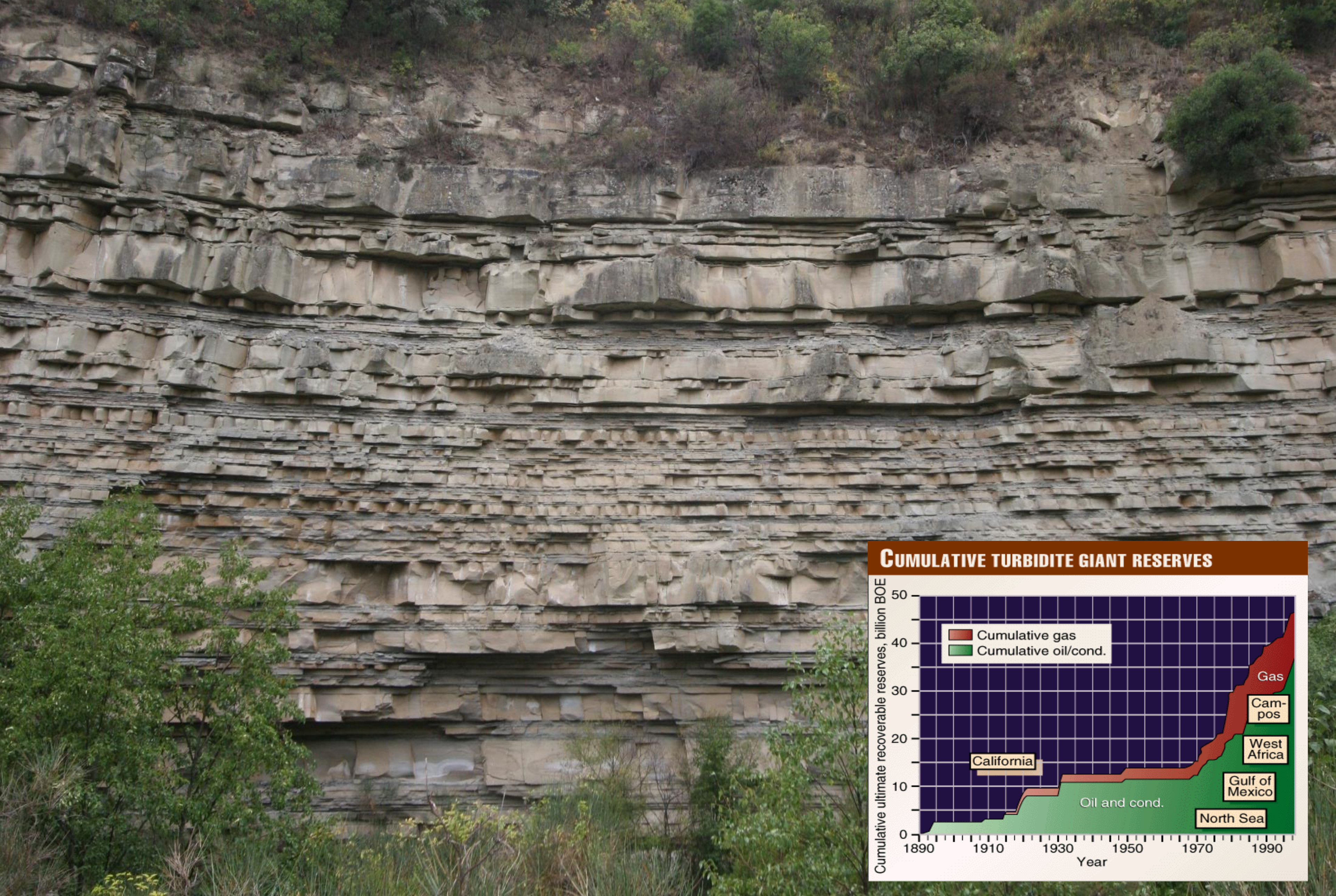

Experimental Turbidity Current
Provided by: Earle McBride, University of Texas at Austin

TURBIDITY CURRENT ACCELERATION

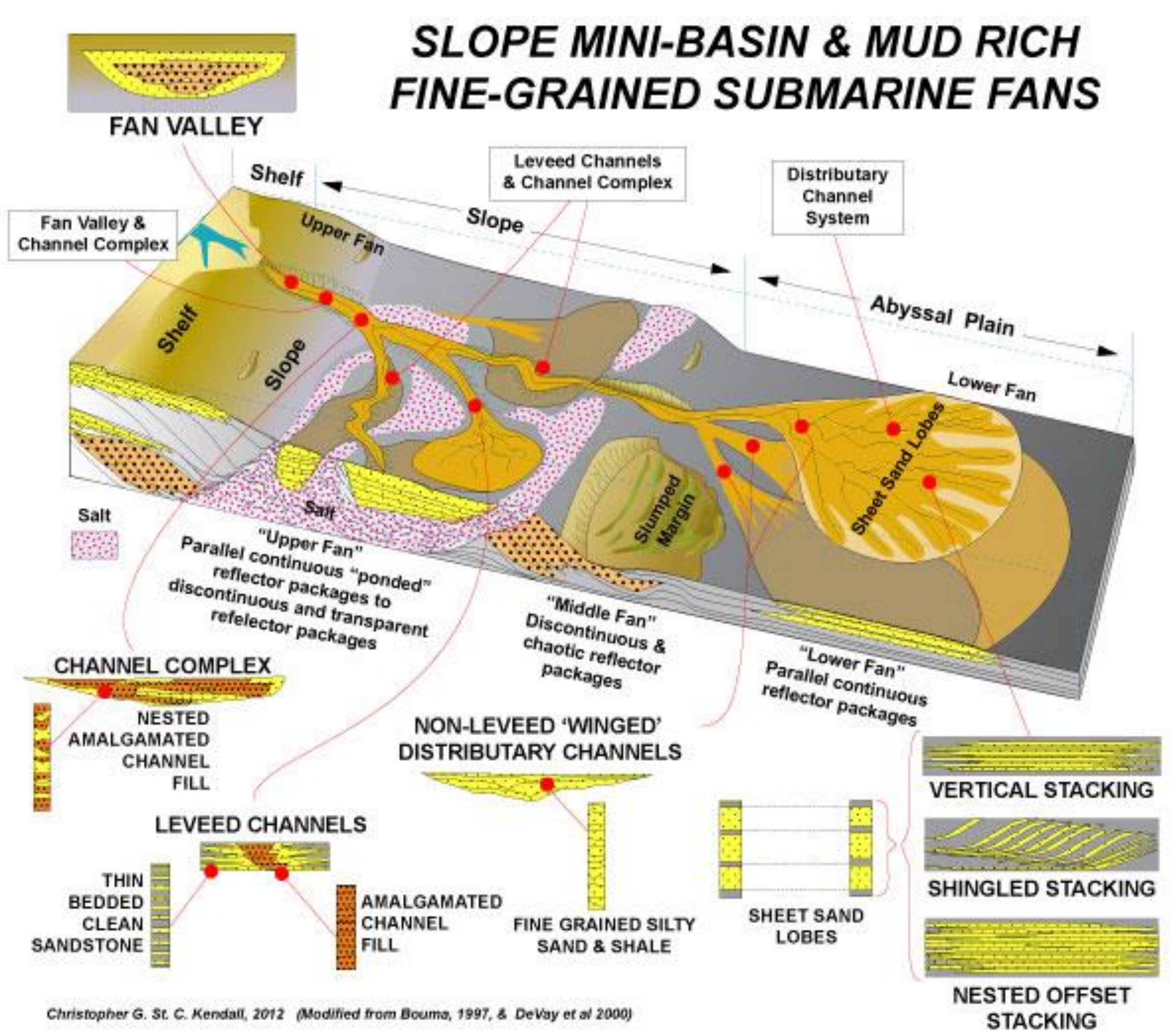
Provided by: Gary Parker, St. Anthony Falls Laboratory, University of Minnesota

Note: As turbidity current spills over break in slope it accelerates. The flow becomes more turbulent and entrains sediment from underlying bed.

TURBIDITES (i.e., the sedimentary product of a turbidite current) FORM EXCEPTIONALLY-GOOD WATER, OIL and GAS RESERVOIRS

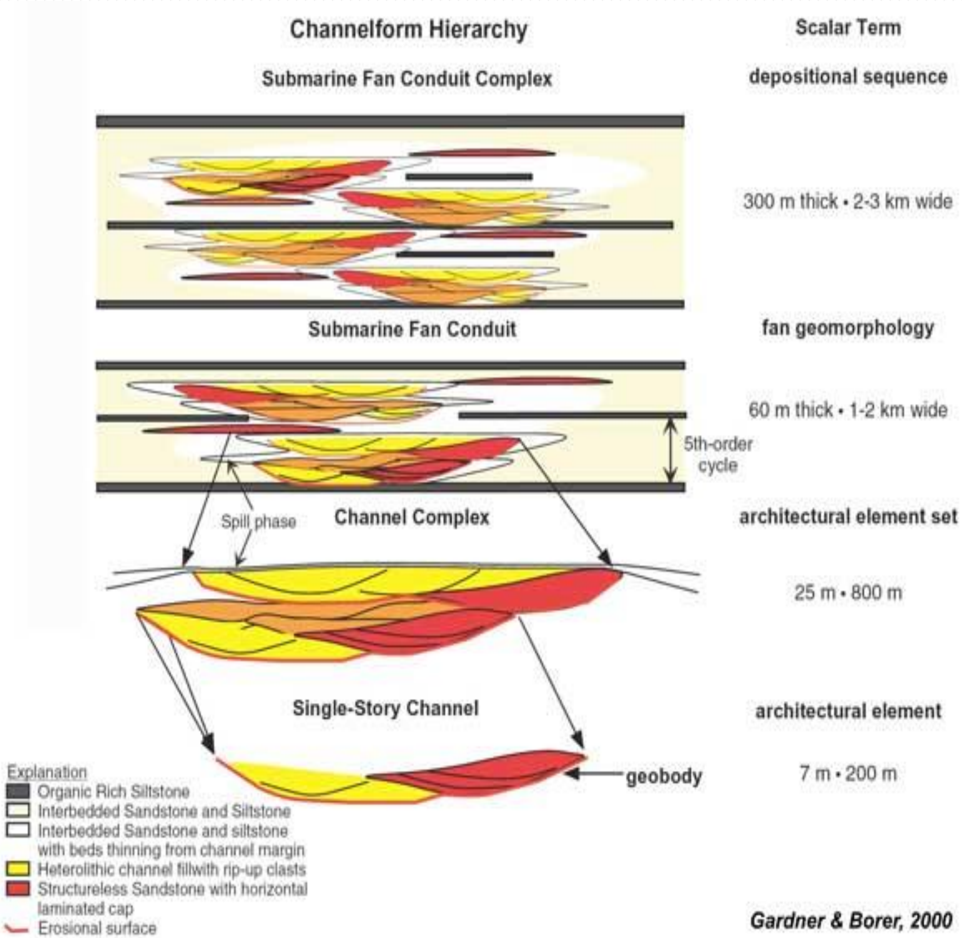


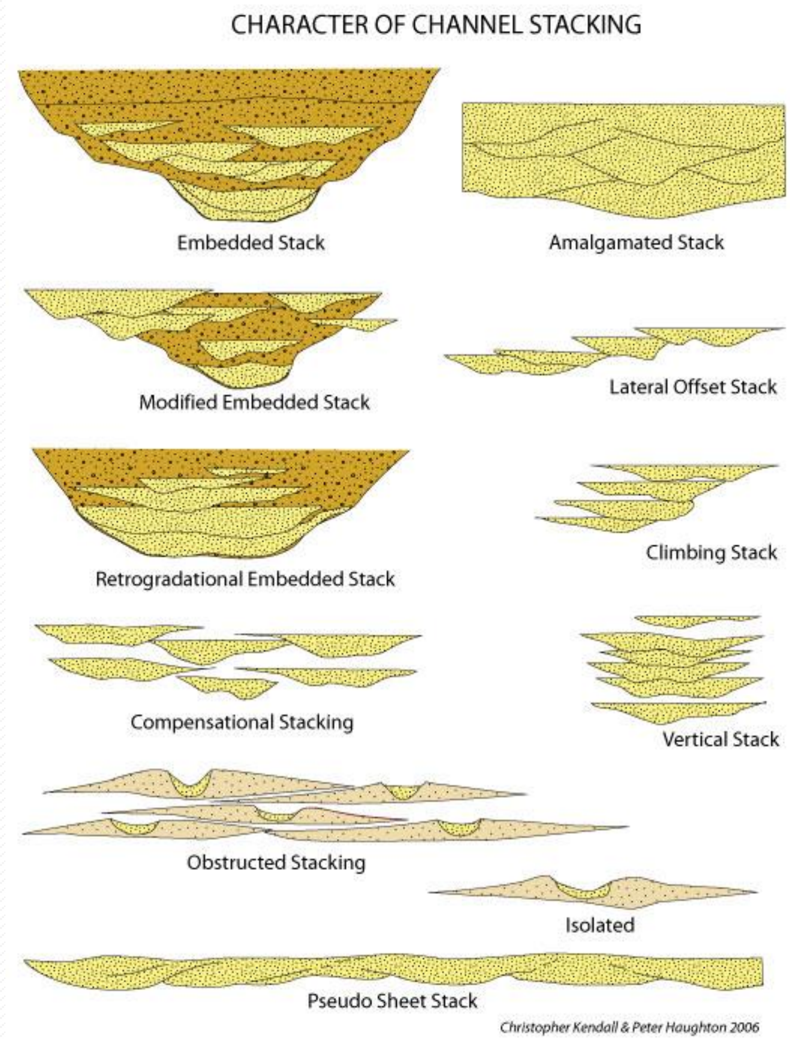
TURBIDITY CURRENTS can be set into motion when mud and sand on the continental shelf are loosened by earthquakes, collapsing slopes, and other geological disturbances. The turbid water then rushes downward like an avalanche, picking up sediment and increasing in speed as it flows.



TURBIDITES contain “architectural elements" which can be recognized at various scales or hierarchies in the sedimentary record. These genetically related stratigraphic building blocks form the sedimentary architecture of the deepwater depositional system.

This hierarchical framework of the units is based solely on the physical stratigraphy of the strata and their thickness is time independent. The elements show a progressive increase in scale from the deposit of a single sediment gravity flow (bed) to the accumulated deposits that comprise entire slope or basin floor successions (complex system set).





International degree on
Geosciences and Georesources

Course of
Applied Stratigraphy and Sedimentology

3. Sedimentology

3a. Origin of sediments; **3b.** Clastic and non-clastic sediments; **3c.** Main processes of erosion, transport and sedimentation; **3d.** Main sedimentary processes (tractive, mass, etc ...); **3e.** Facies, facies associations, depositional environments and systems. **3f**. Georisources of sedimentary origin.

An useful method to analyse sedimentary bodies is the FACIES ANALYSIS.
This approach allow us to describe and interpret sedimentary bodies occurring in outcrop or in the Earth subsurface.

A SEDIMENTARY FACIES is the ensemble of physical features of a sedimentary accumulation, including lithology, grain size, structures, fossil content etc. and that can be used in order to distinguish it from adjacent different deposits.

A SEDIMENTARY FACIES can be recognise through three main phases of investigation:

1) Observation of the physical features;
2) Documentation by using standards;
3) Interpretation as processes.

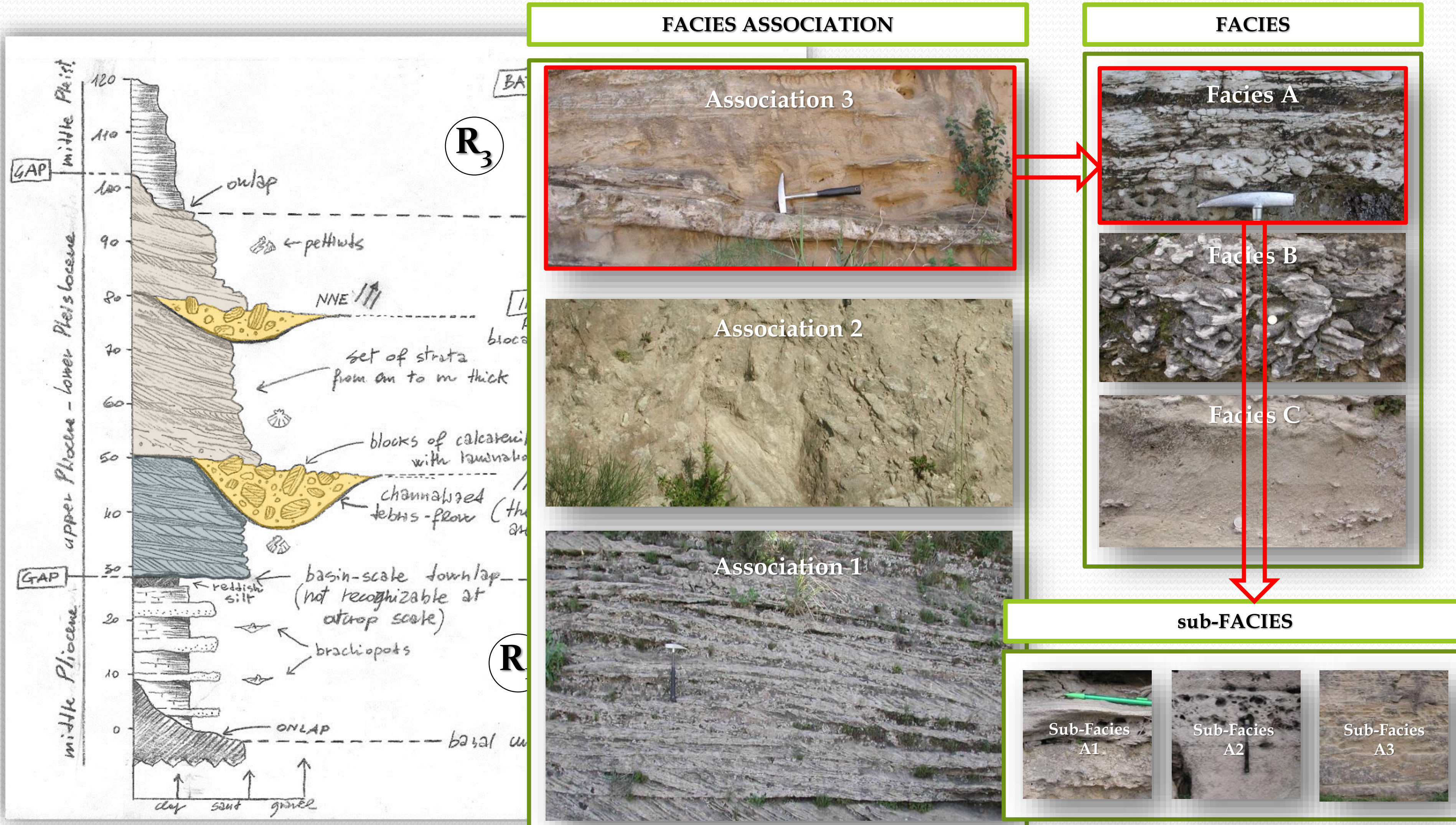
} **FACIES ANALYSIS**

observation

description

interpretation

A SEDIMENTARY FACIES is the ensemble of physical features of a sedimentary accumulation, including lithology, grain size, structures, fossil content etc. and that can be used in order to distinguish it from adjacent different deposits. Each SEDIMENTARY FACIES can be subdivided into minor components (sub-facies) or adjacent facies can be grouped into a FACIES ASSOCIATION.



The concept of sedimentary facies

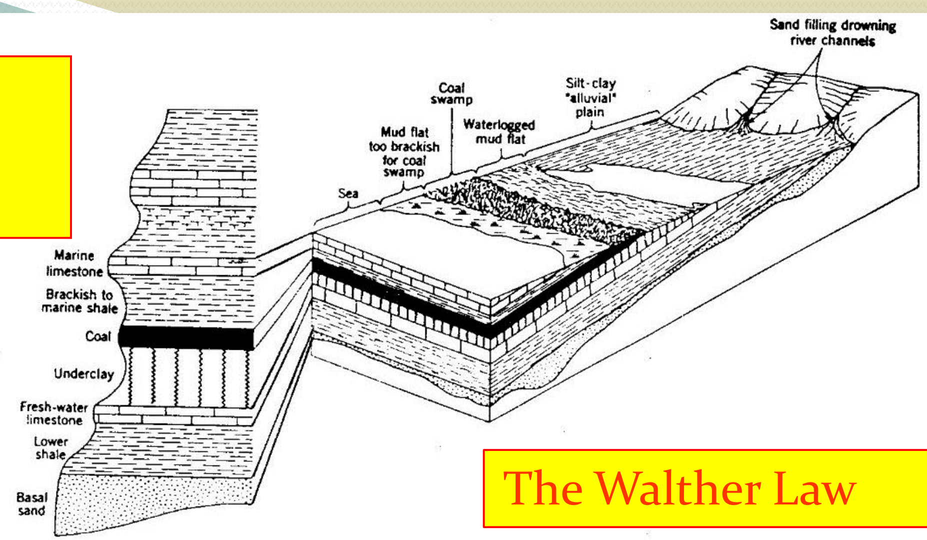
The notion of facies used by researcher depends on the scope of a particular study.

SCOPE OF STUDY	RESOLUTION LEVEL	EXAMPLE DEPOSIT TYPES
Very broad, inter-regional or 'global-scale' palaeogeographic study	VERY LOW (with facies as the record of whole classes of depositional environmets)	• Terrestrial vs. marine facies • Shallow-marine vs. deep-marine facies • Carbonate vs. siliciclastic facies • Evaporitic vs. carbonate facies
Broad, regional-scale palaeogeographic study	LOW (with facies as the record of broadly-defined depositional environments)	• Alluvial, aeolian, shoreline/deltaic, nears… • Barrier/lagoon and estuarine facie… • Patch reef and carbonate p… • Submarine fan/apr…
Basin-scale palaeogeographic study and sequence stratigraphy	MODERATE (with facies as the record of depositional subenvironments or narrowly-defined specific environments)	• Braided vs… • Cha… …acies • Pro… …pe, delta front and delta top facies • Fore… …oreface, lower shoreface, offshore tranis… …d offshore facies • Tidal sandflat, mixed flat, mudflat and channel/creek facies • Subtidal, intertidal and supratidal facies • Upper, middle and lower submarine fan facies; or channel-fill vs. overbank turbidites
Sedimentological study of a basin-fill succession or its selected part	HIGH (with facies as the record of depositional processes)	• Nonstratified (massive), planar parallel-strati… cross-stratified, planar cross-stratifi… sandstone facies • Massive, cross-strati… …gravel facies • Turbidite … …a divisions, such as T*abcde*, T*a*… …T*cde*, T*de*, etc.

Genetic categorizations of deposits, based on an *a-priori* interpretation of sedimentary (sub)environments

Descriptivive categorization of deposits on the basis of their sedimentological characteristics

The concept of lithostratigraphic logging
and the interest in vertical facies organization stem
from the Walther Law.



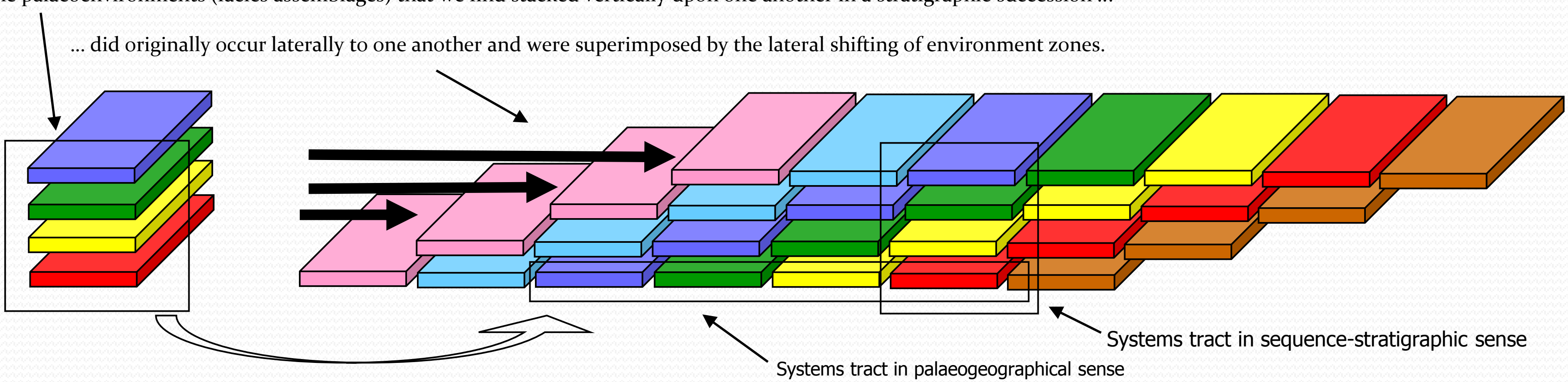
The Walther Law

Fig. 1-1. Schematic illustration of the Walther law: a lithostratigraphic profile as the record of the lateral migration and vertical stacking of sedimentary facies belts within a depositional environment (from Shaw, 1964).

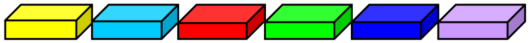
Johannes Walther in 1894 formulated the following Rule of Facies Succession: "*The deposits of the same facies area* [environment] *and, similarly, the sum of the deposits of different facies areas* [environments] *were formed beside each other in space, but in a lithostratigraphic profile we see them lying on top of each other.*" This was a basic statement of far-reaching significance: only those facies belts can be vertically superimposed that occur laterally to one another (although not necessarily next to each other, as the lateral shift of a facies belt may be erosive and erase the deposits of the adjacent belt) (see review and discussion by Middleton, 1973).

The palaeoenvironments (facies assemblages) that we find stacked vertically upon one another in a stratigraphic succession ...

... did originally occur laterally to one another and were superimposed by the lateral shifting of environment zones.



Facies analysis scheme

STRATIGRAPHIC ELEMENTS	SEDIMENTOLOGICAL ANALYSIS	INFORMATION DERIVED
 **SEDIMENTARY FACIES** are the basic ***types*** of sedimentary deposits, distinguished macroscopically on a descriptive basis as the elementary “building blocks” of a sedimentary succession.	The sedimentary succession is logged by being divided into more-or-less uniform “units”, or beds, on the basis of: •**sediment texture** (grain characteristics) •**sediment structures** (grain organization characteristics) •**colour** and **biogenic features** (if present) •**geometry** (thickness, lateral extent, shape, boundary types). Units with similar characteristics are classified as one facies. Each facies is separately described and interpreted.	The principal processes of sediment transport and deposition are recognized. Some processes may be directly diagnostic of a particular sedimentary environment and others may not, but as a group – or association – they invariably are (see the next step of analysis).

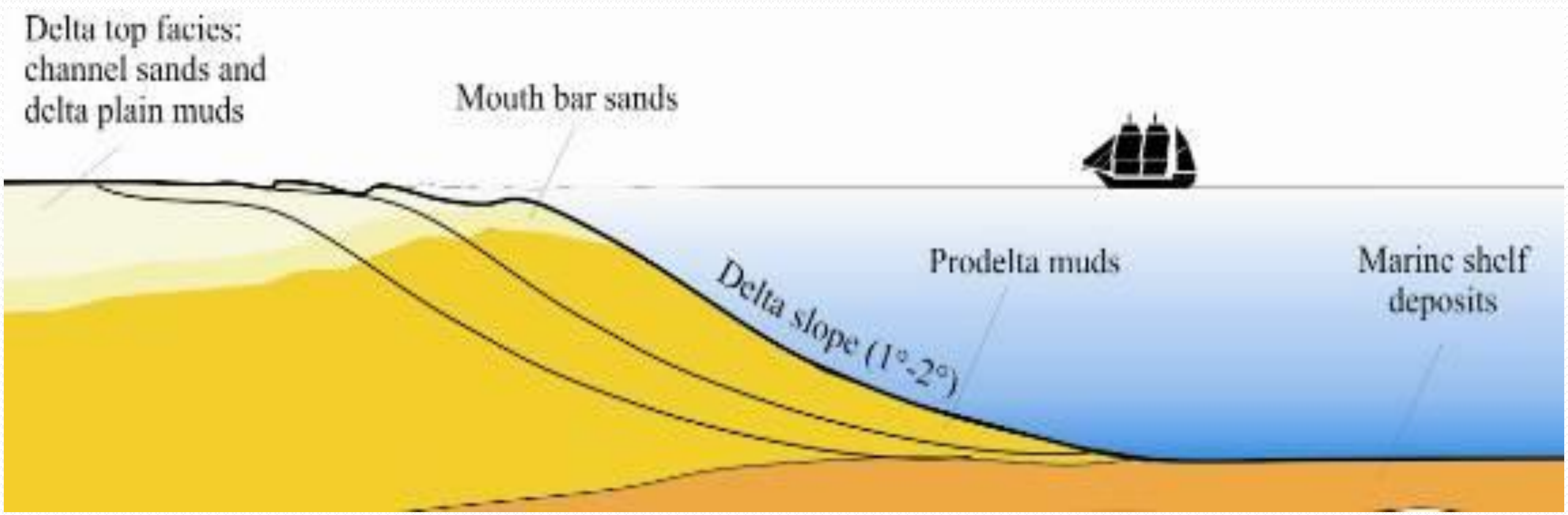
Depositional environments and systems

Hierarchies of environments, examples of continental, transitional, shallow and deep-marine depositional systems

Definition:

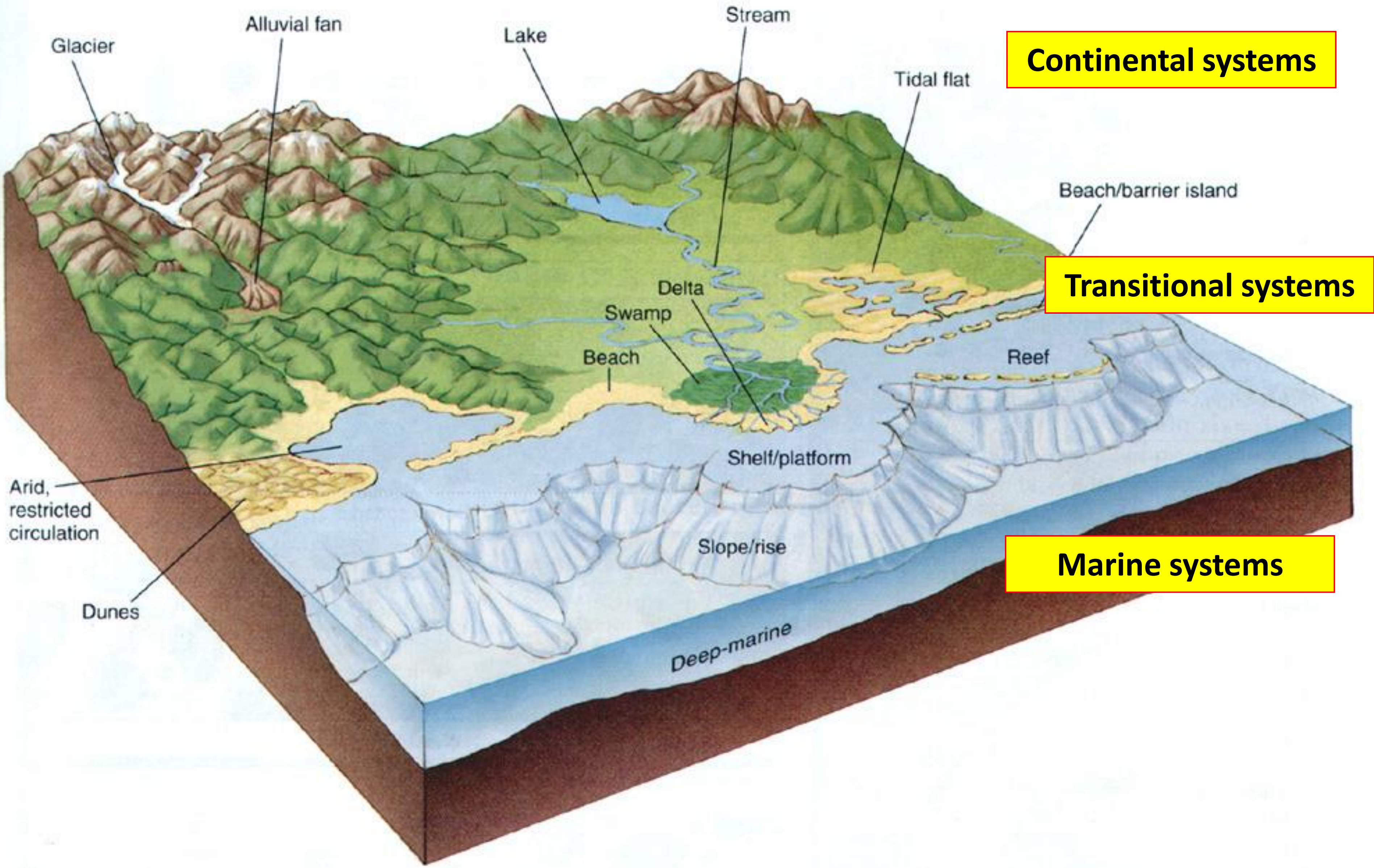
A DEPOSITIONAL SYSTEM is an assemblage of of multiple process-based sedimentary facies which record genetically-related depositional environments

(e.g.: a RIVER DELTA is a depositional system; it can be subdivided into ‘components’ represented by constituent depositional environments, including: the delta plain, the delta front, the delta slope, etc …



There are sveral types of DEPOSITIONAL SYSTEMS in the Earth surface.

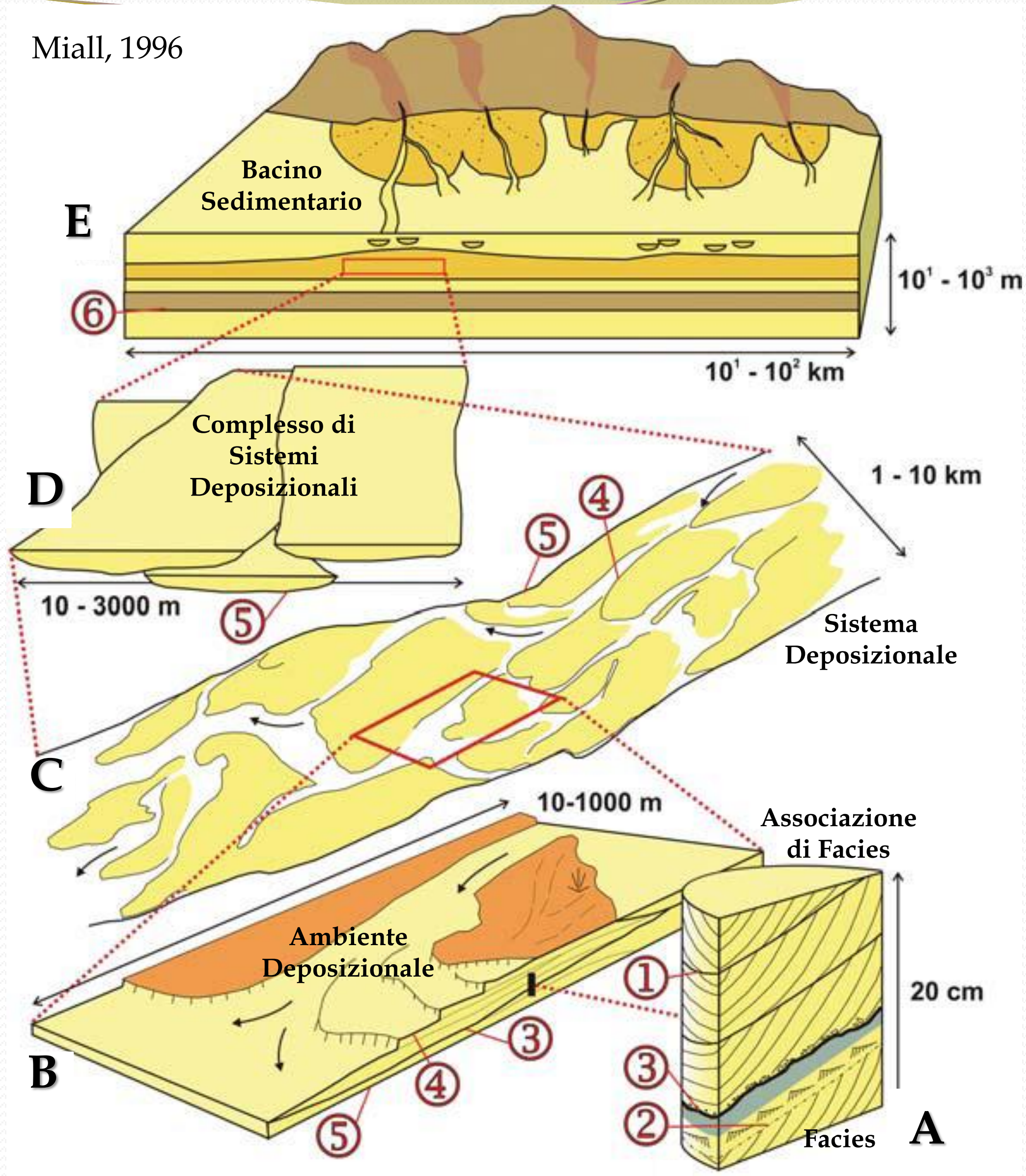
We can distinguish them on the basis of their genesis: continental, transitional or marine.



A HIERARCHICAL RELATIOSHIP LINKS THE VARIOUS PHYSICAL ELEMENTS WHICH DEFINE A SEDIMENTARY FACIES, A DEPOSITIONAL ENVIRONMENTS AND A DEPOSITIONAL SYSTEM

1. A FACIES, together with other genetically-related facies, forms a FACIES ASSOCIATION [for example: cross-laminated sands (**A**)];
2. A FACIES ASSOCIATION represents the sedimentary product of a DEPOSITIONAL ENVIRONMENT [for example: fluvial channel filled by gravels and sands (**B**)];
3. An ensemble of depositional environments forms a DEPOSITIONAL SYSTEM (for example: braided fluvial system (**C**)];
4. Two or more depositional systems coexist in a COMPLEX of DEPOSITIONAL SYSTEMS [for example: alluvial fans with fluvial systems (**D**)];
5. Finally, an ensamble of complexes represent a part of a SEDIMENTARY BASIN (**E**).

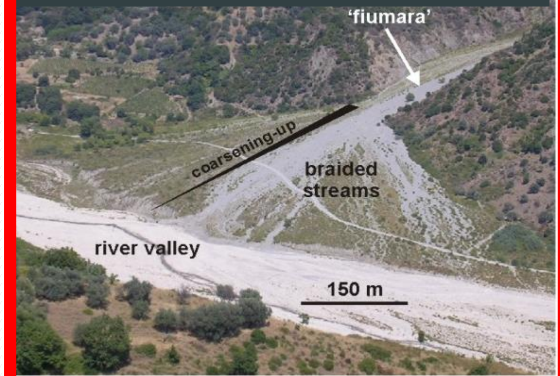
Miall, 1996



There is a multitude of different types of depositional systems on the Earth's surface

COLLUVIAL FANS

ALLUVIAL FANS



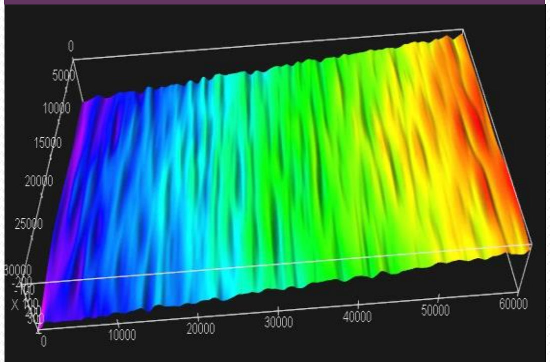
RIVERS & DELTAS

ESTUARIES

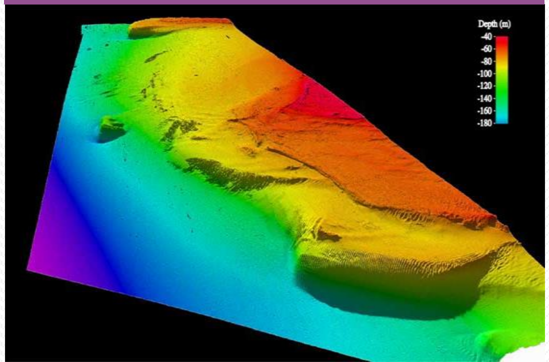
TIDAL FLATS

TIDAL STRAITS

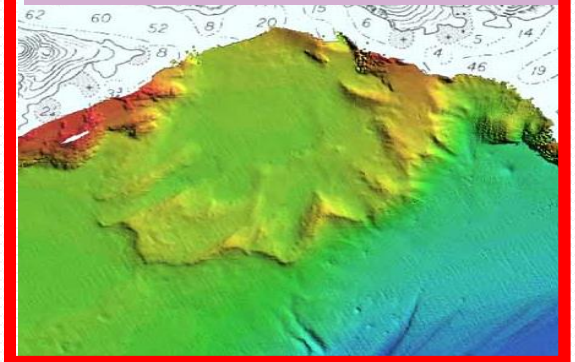
SHOREFACES



SHELVES

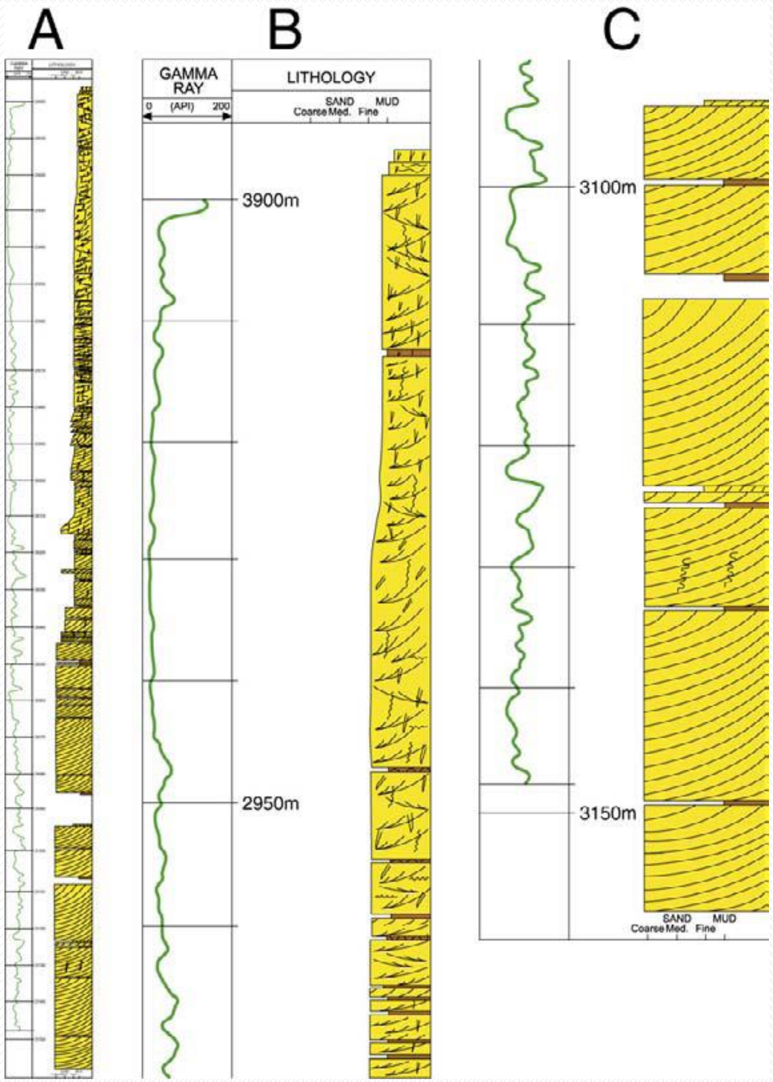


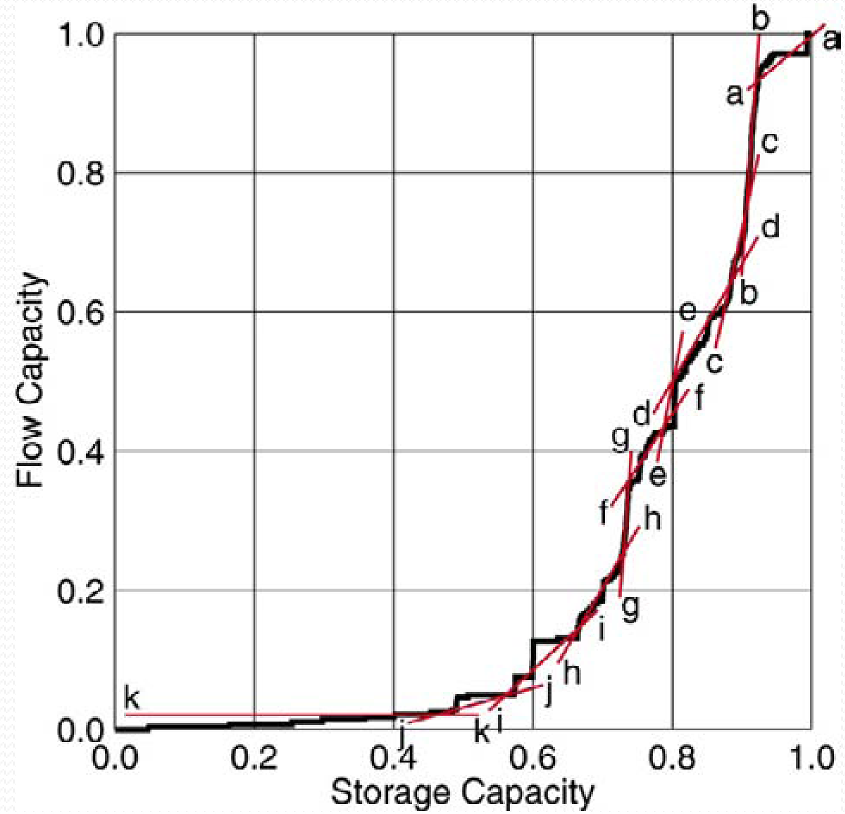
DEEP-SEA FANS



Clastic depositional systems

From a ‘reservoir’ point of view, clastc depositional systems are storage elements for oil and gas. The possibility to detect and produce hydrocarbon from them depends on the their degree of internal complexity and on their degree of knowledge that we can able to resume from them.



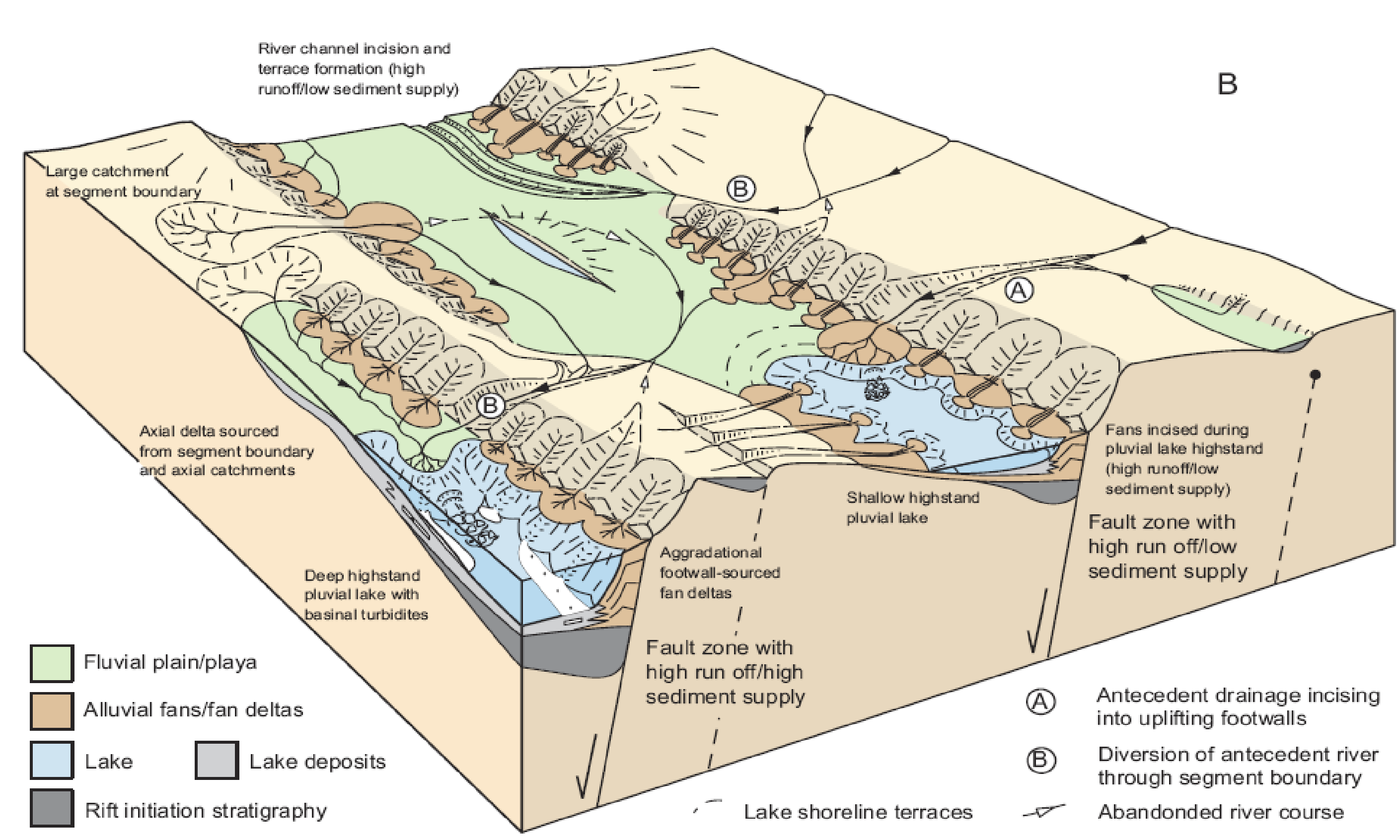


Clastic depositional systems

Continental systems

Continental depositional systems are those where sediment accumulation and distribution occur far from marine environments.

Most of the more ‘HC-bearing’ continental systems are: (1) alluvial systems and (2) fluvial systems.



Gawthorpe & Leeder, 2000

Clastic depositional systems

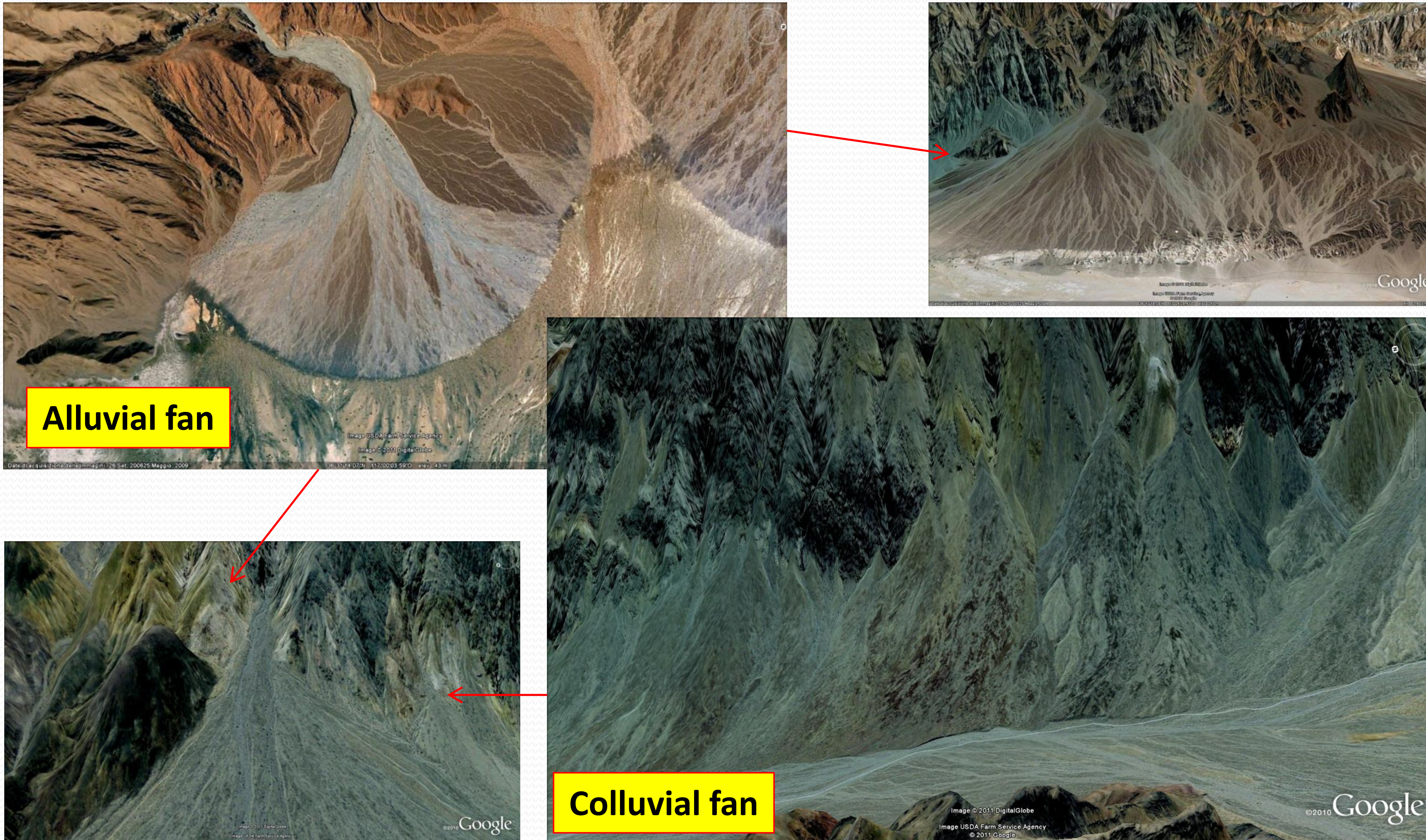
Continental systems: colluvial/alluvial fans

Alluvial fans are fan-shaped sediment bodies that form at the bases of mountain slopes at the mouths of rivers.

TYPICAL CHARACTERISTICS	colluvial fan	alluvial fan
Geomorphic setting:	mountain slope and its base (slope fan)	mountain footplain or broad valley floor (footplain fan)
Catchment:	mountain-slope ravine	intramontane valley or canyon
Apex location:	high on the mountain slope (at the base of ravine)	at the base of mountain slope (valley/canyon mouth)
Depositional slope:	35-45° near the apex, to 15-20° near the toe	seldom more than 10-15° near the apex, often less than 1-5° near the toe
Plan-view radius:	less than 0.5 km, rarely up to 1-1.5 km	commonly up to 10 km, occasionally more than 100 km
Sediment:	mainly gravel, typically very immature	gravel and/or sand, immature to mature
Grain-size trend:	coarsest debris in the lower/toe zone	coarsest debris in the upper/apical zone
Depositional processes:	avalanches, including rockfall, debrisflow and snowflow; minor waterflow, with streamflow chiefly in gullies	debrisflow and/or waterflow (braided streams)
EXAMPLES	 The Brotfonna colluvial fan, Trollvegen near Romsdal, Norway; one of the world's largest colluvial fans, with a height of 830 m and a plan-view radius of 1.5 km.	 The Badwater alluvial fan, eastern side of Death Valley, California; a modest fan, with a radius of *c.* 6 km.

Clastic depositional systems

Continental systems: colluvial/alluvial fans



Clastic depositional systems

Continental systems: colluvial/alluvial fans

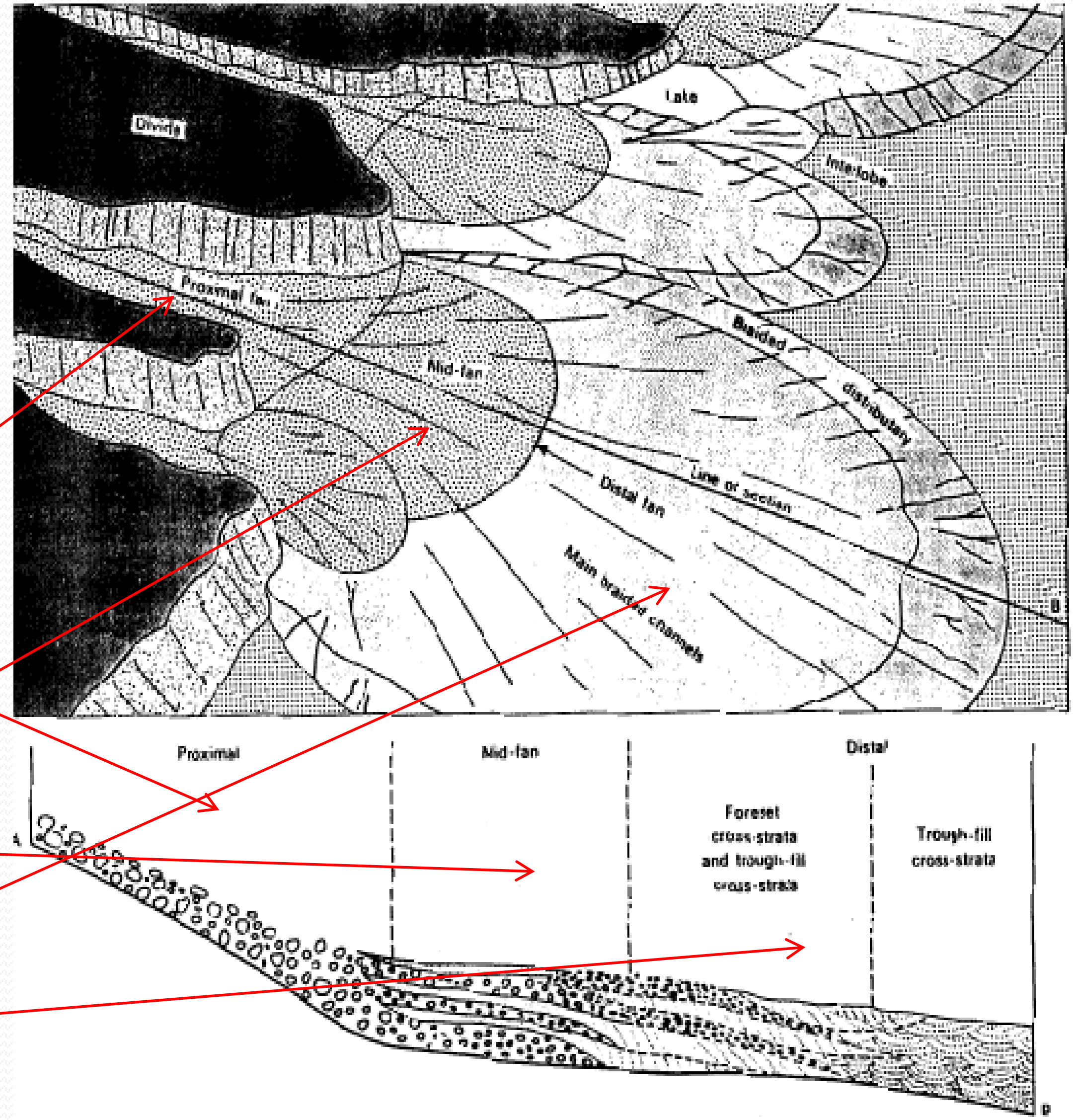
Depositional environments in an alluvial fan (less easy in a colluvial fan) can be distinguished on the base of their respective relationships of **proximality** and **distality** from the 'point of sediment source' (apex).

Sediment grain size, sorting and internal structures are highly varying depending on their relative distance.

Proximal fan

Mid fan

Distal fan

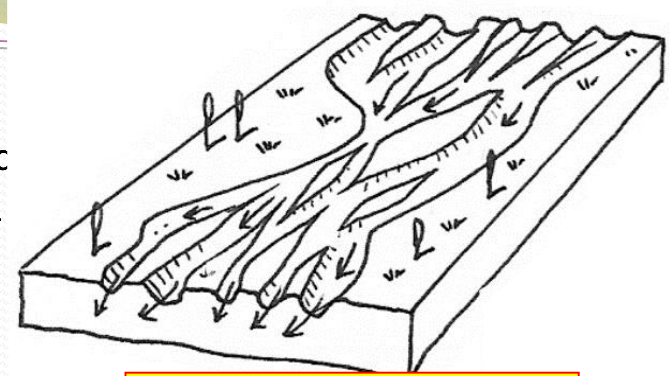


Clastic depositional systems

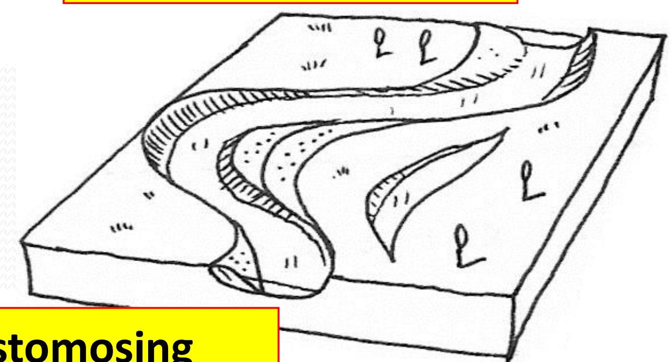
Continental systems: fluvial systems

Fluvial deposits are sediments that are transported and depositec by rivers in a continental environment. There are several types of fluvially derived deposits, including: (1) **braided-river** deposits, which form at and beyond the bases of mountains, where the gradient of the ground surface is relatively steeply inclined, (2) **meandering-river** deposits, which form on more gently inclined floodplains, (3) anastomosing-river deposits, where channels are slightly sinuous but laterally stable, and (4) **straight-channel river** deposits which fill quasi rettilineous valleys.

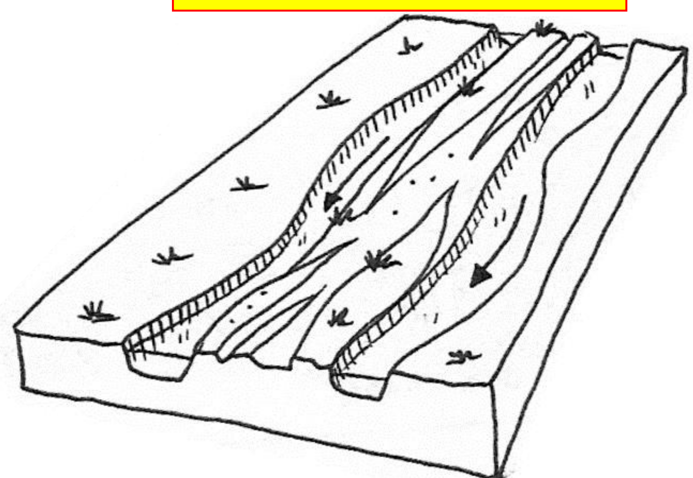
Braided



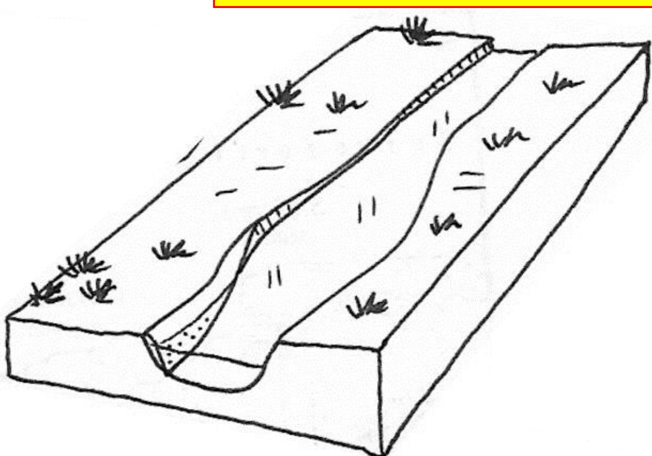
Meandering



Anastomosing



Straight



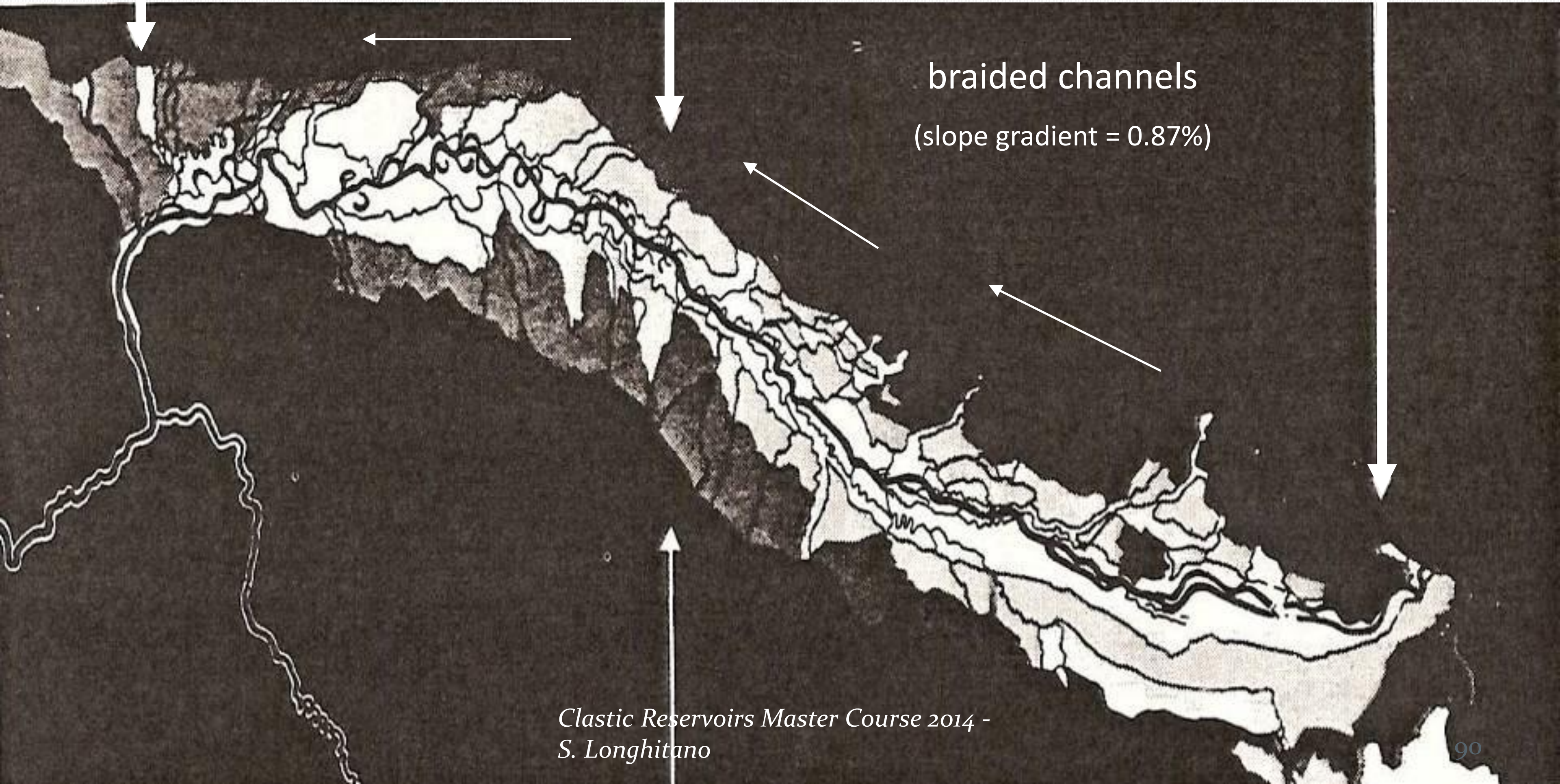
Clastic depositional systems

Continental systems: fluvial systems

The Rhone River

meanders

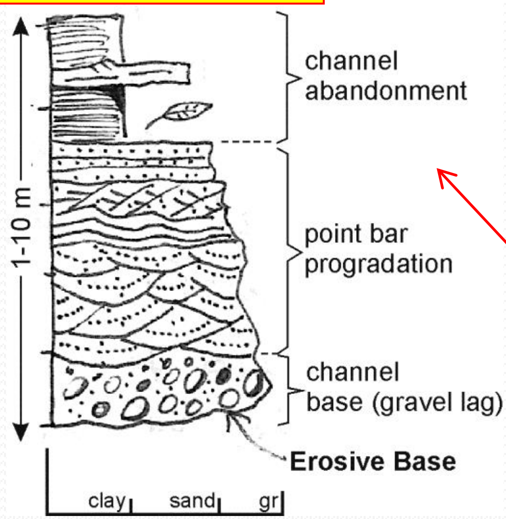
(slope gradient = 0.025%)



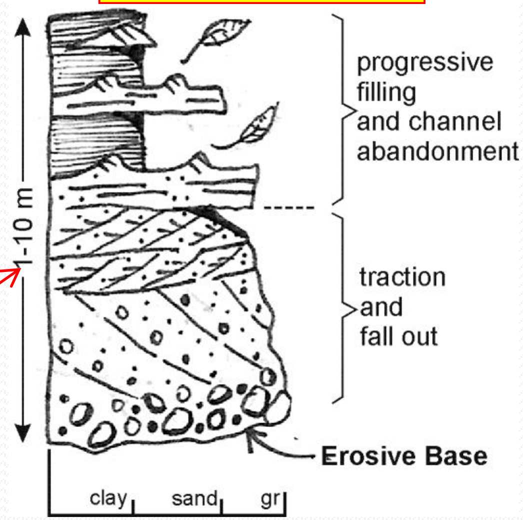
Clastic depositional systems

Continental systems: fluvial systems

Braided

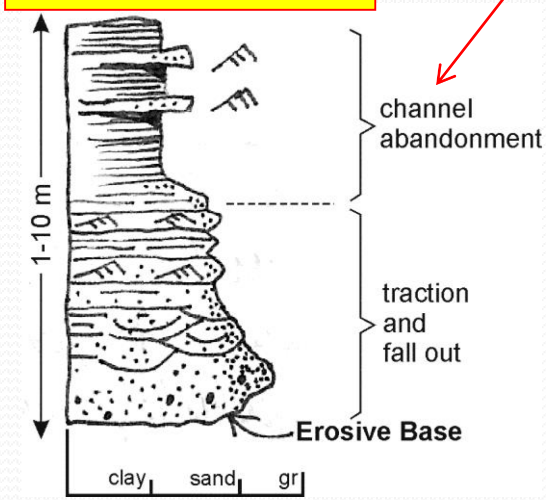


Meandering

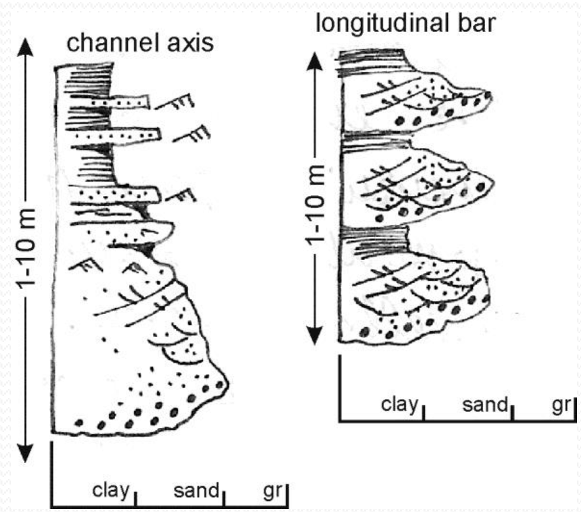


CHANNEL-FILL: FINING-UPWARD SEQUENCE

Straight

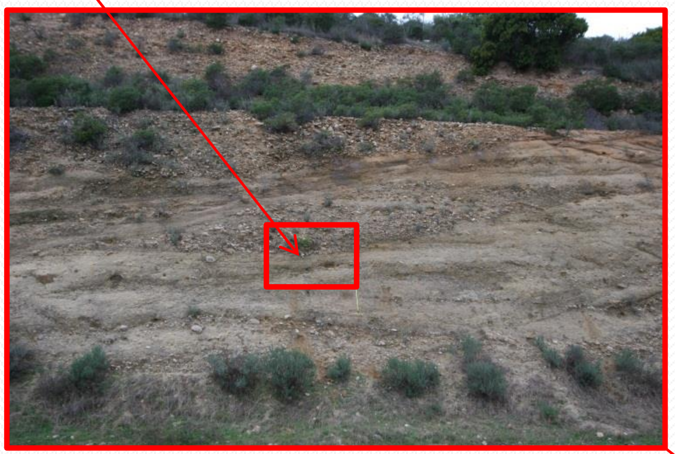


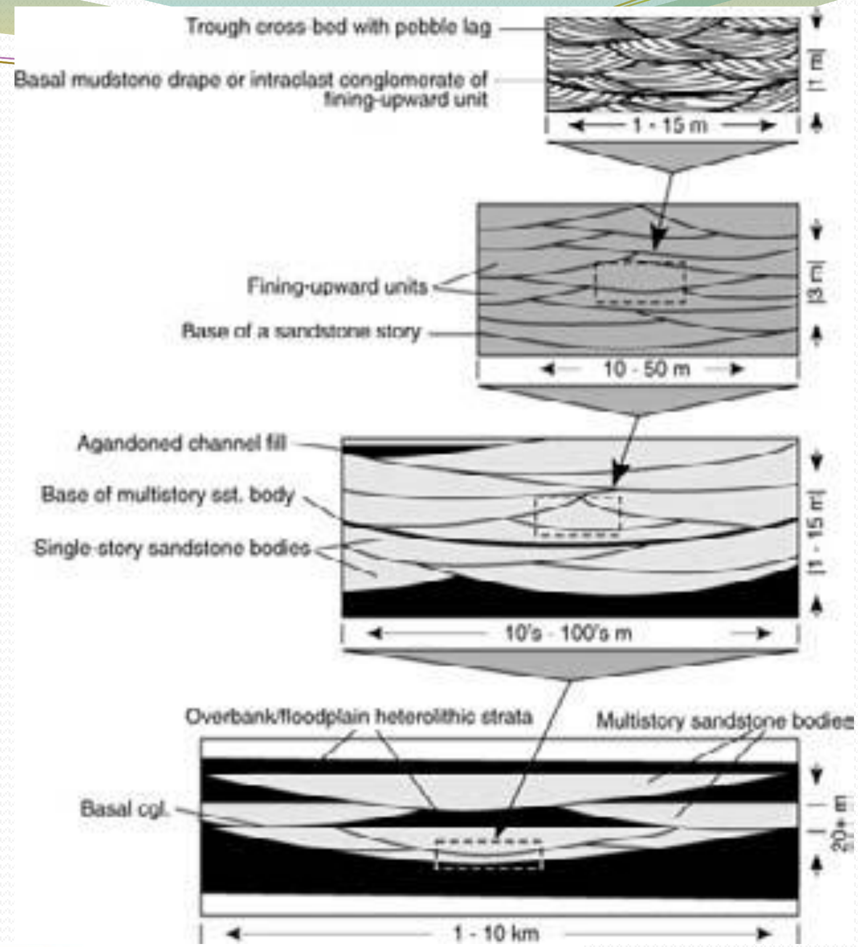
Anastomosing

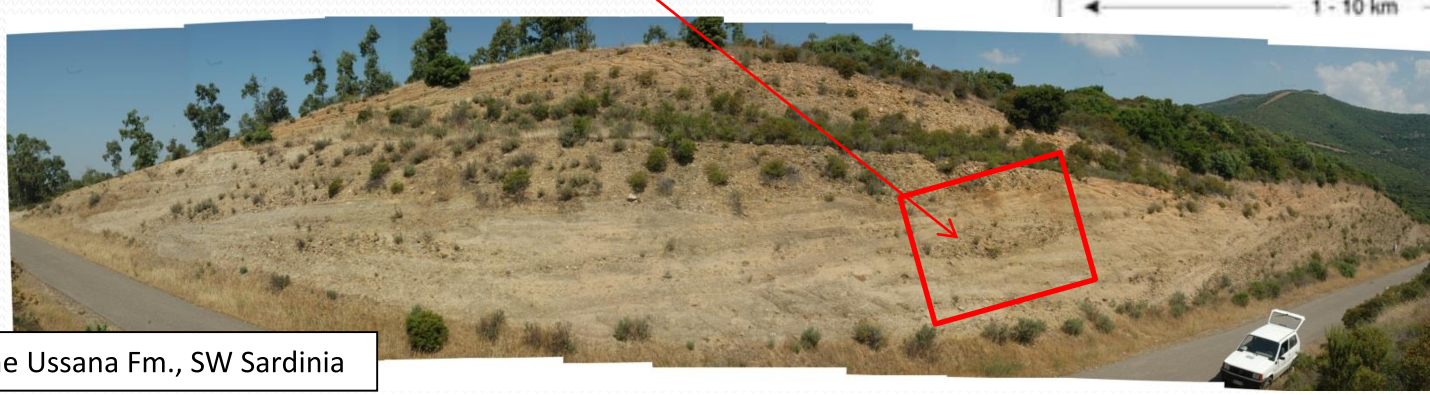


Clastic depositional systems

Continental systems: fluvial systems







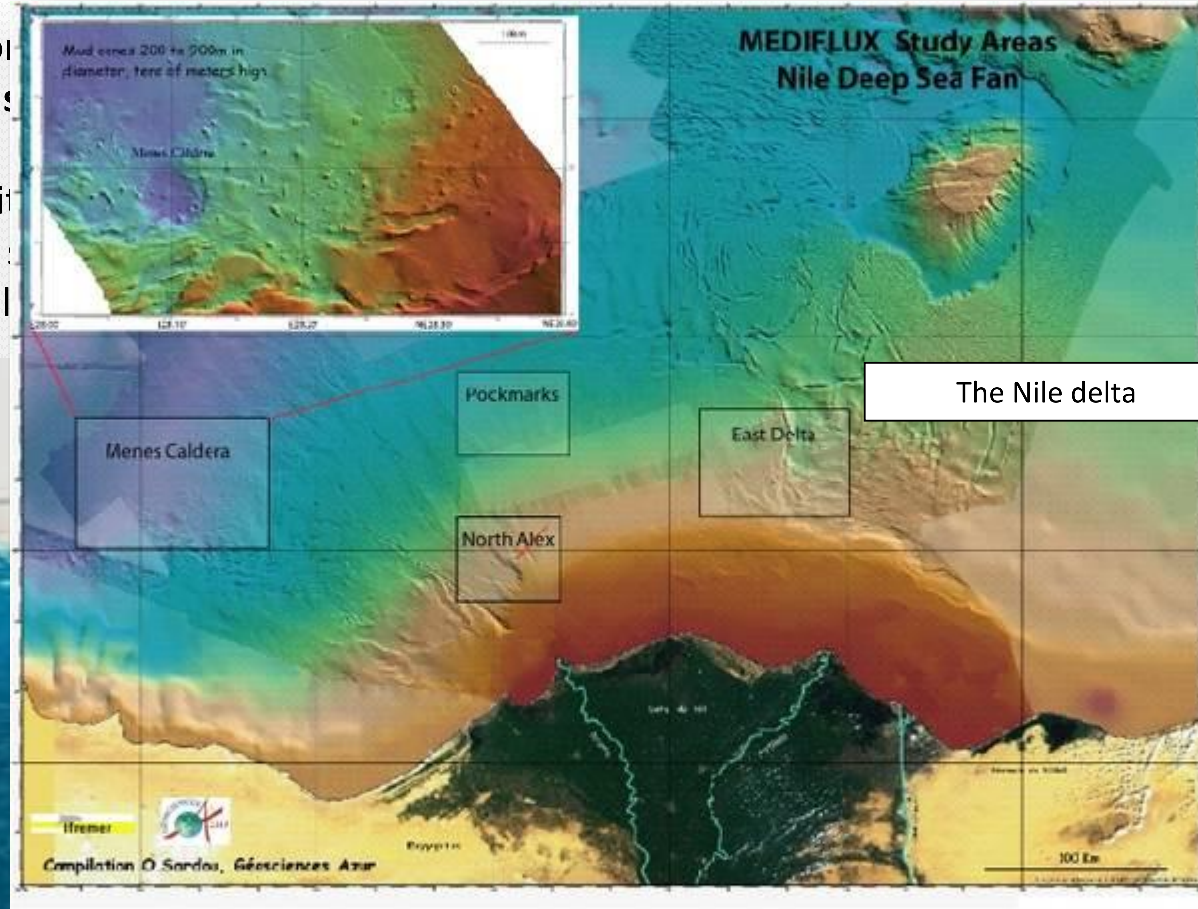
Oligocene Ussana Fm., SW Sardinia

Clastic depositional systems

Transitional systems: deltas

A depositional system that lies both o
component environments develop in s

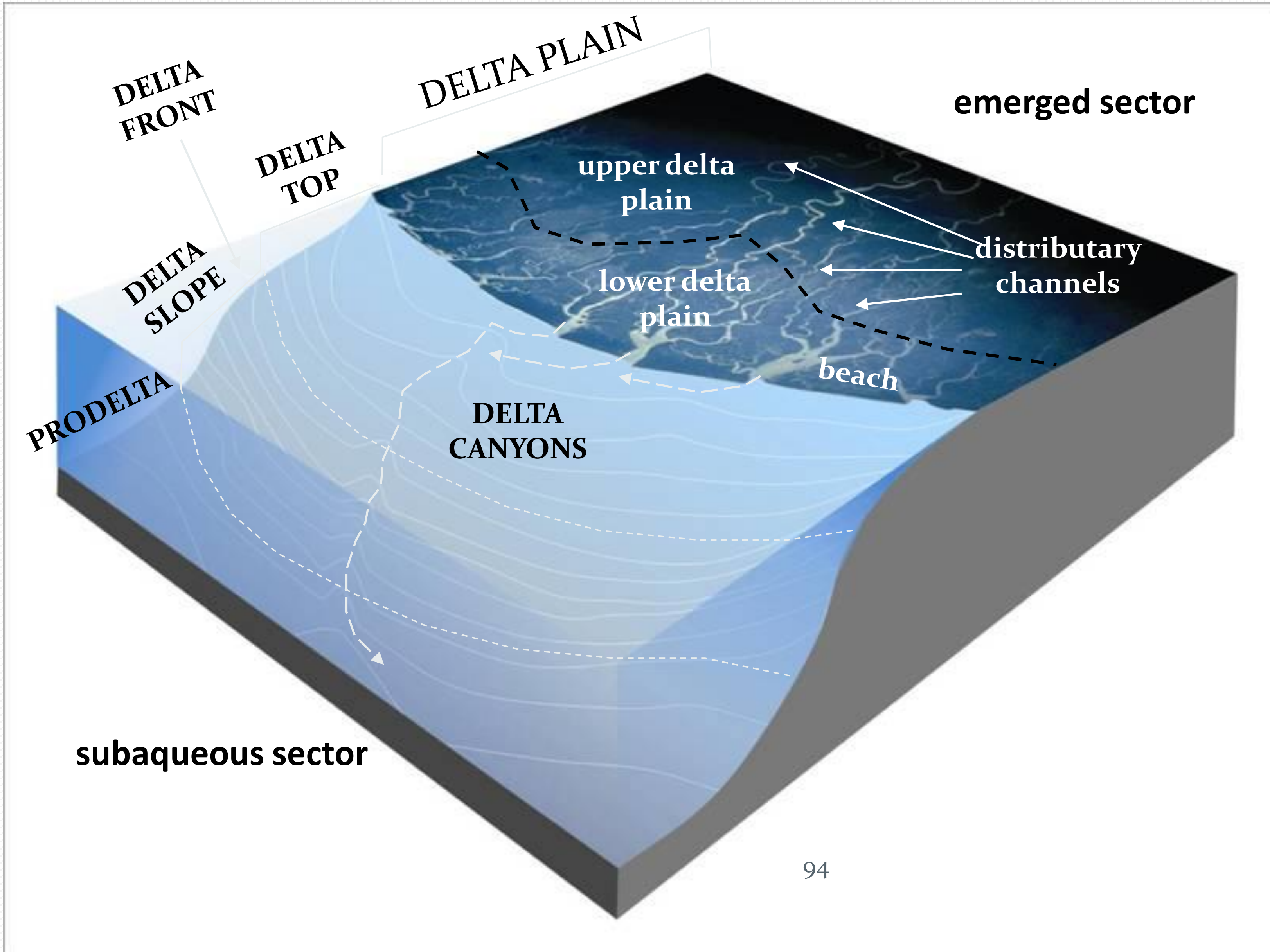
One of the most representative transi
When a river debouches into a basin, s
distributed and deposited. Then, a del



The Nile delta

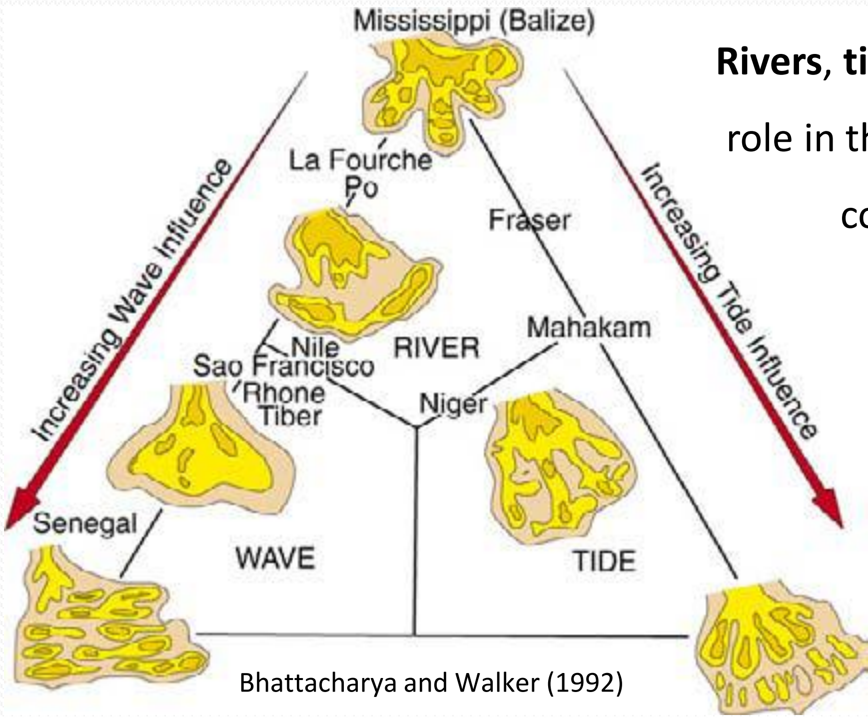
Clastic depositional systems

Transitional systems: deltas



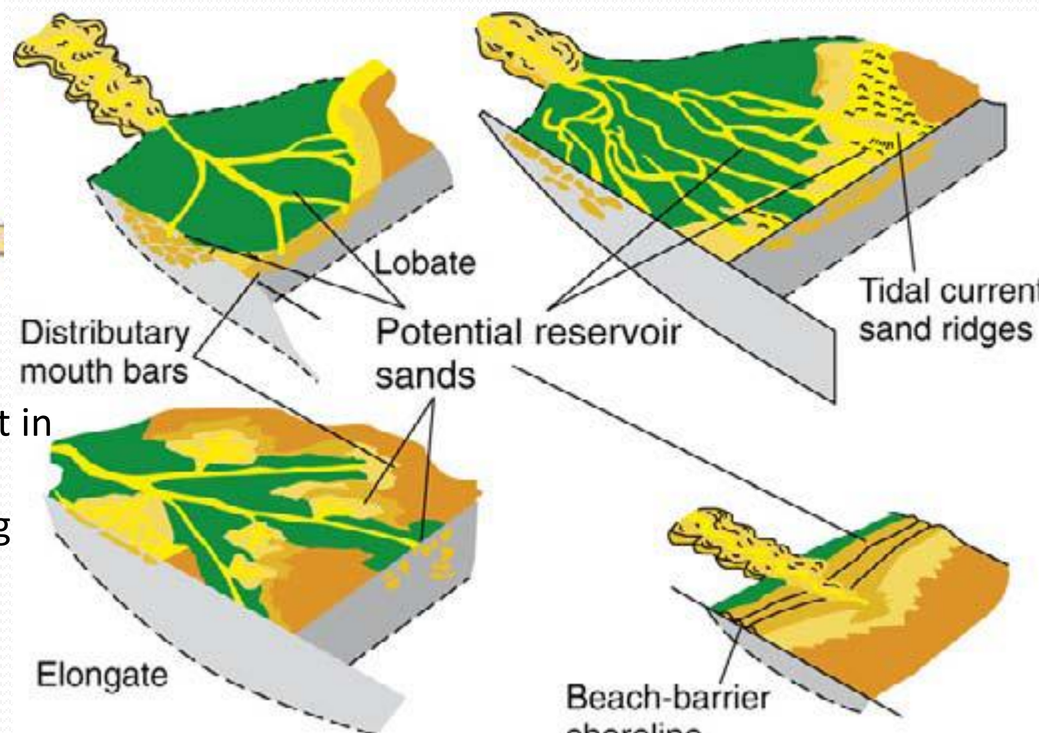
Clastic depositional systems

Transitional systems: deltas



Bhattacharya and Walker (1992)

Rivers, **tides**, **waves**, and **currents**, in varying proportions, all play a role in the ultimate distribution of deltaic sediment along different coastlines. A six-fold subdivision of deltas is one of the most common way to classify deltas, on the function of the respective influences of waves, tides, and rivers.

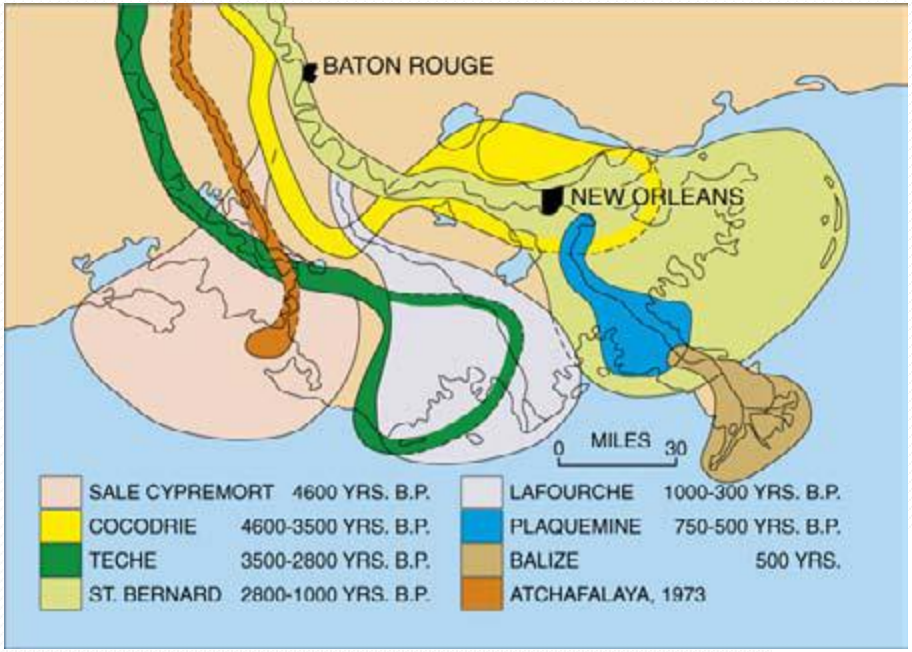


With deltaic reservoirs of hydrocarbons, it is essential to determine the type of deltaic deposit in order to maximize reservoir development and production. Errors are easily made in interpreting types of deltas in the subsurface environment, where we have only scattered wells and limited cores or image logs from which to identify depositional processes and environments.

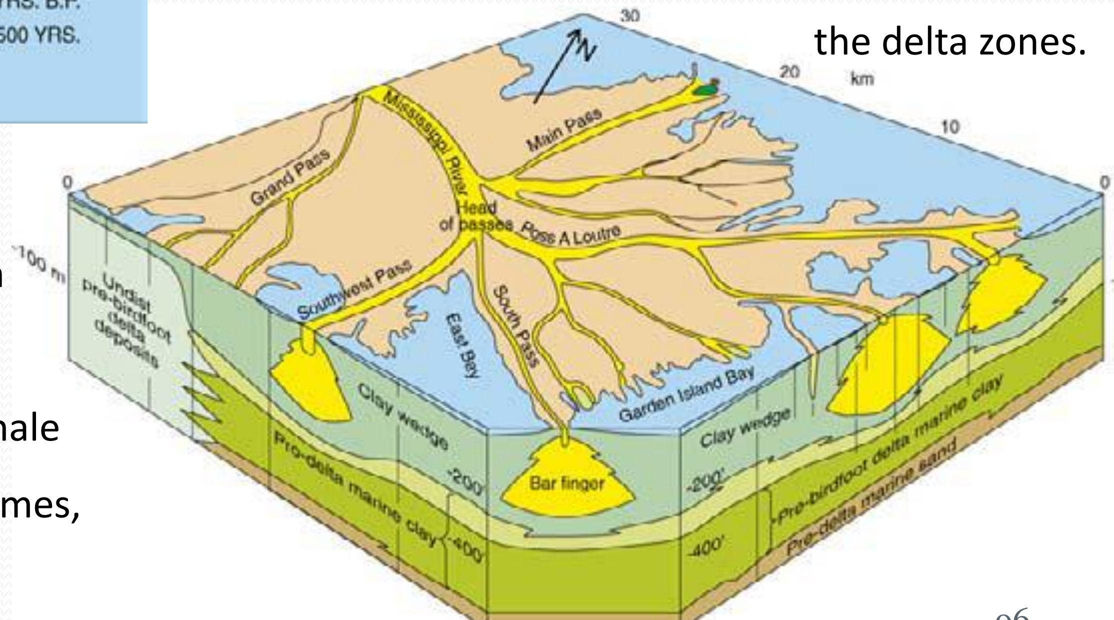
Clastic depositional systems

Transitional systems: river-dominated deltas

The Mississippi River delta has long been considered the "type" **river-dominated** delta. Strong waves and currents do not impinge upon its protected shoreline, so sediment deposited at and near the shore zone is not reworked or dispersed laterally. With time, and sufficient accommodation space between the sea surface and seafloor to accept sediment, such a delta will prograde seaward, as will the delta zones.



Sandy reservoir facies are deposits of distributary channels and distributary mouth bars. Interdistributary bays, marshes, and lagoons separate sandy facies and provide shale barriers in subsurface reservoirs, and sometimes, they provide hydrocarbon source rocks.

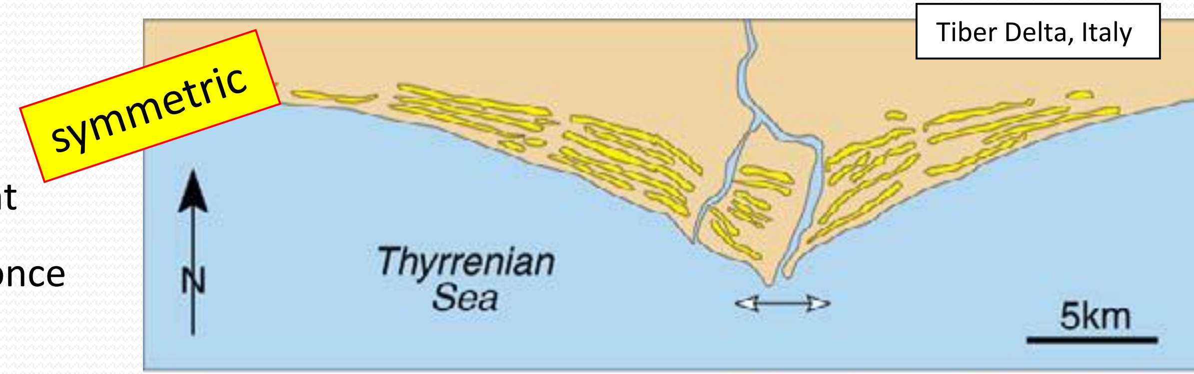


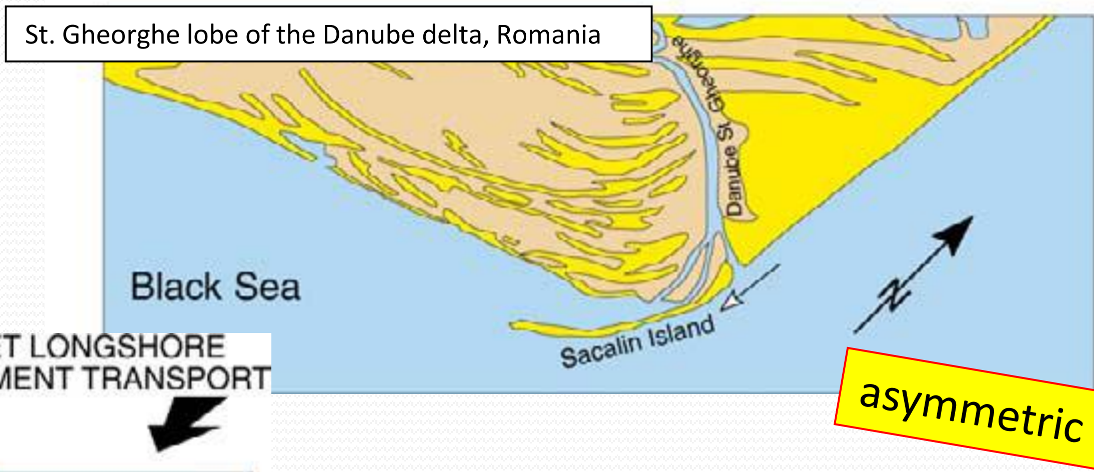
Clastic depositional systems

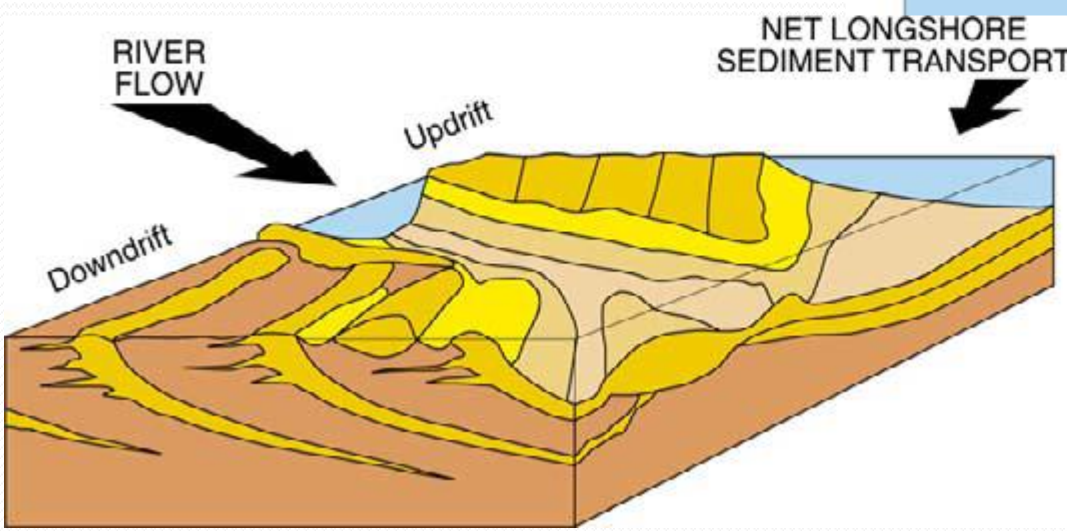
Transitional systems: wave-dominated deltas

Symmetric and/or asymmetric, wave-dominated deltas, result from dominant redistribution of sediments by waves, once the sediments reach the shoreline.

Sandy barrier bar complexes and associated prodelta muds form in the downcurrent portion of the delta and represent very good reservoirs!

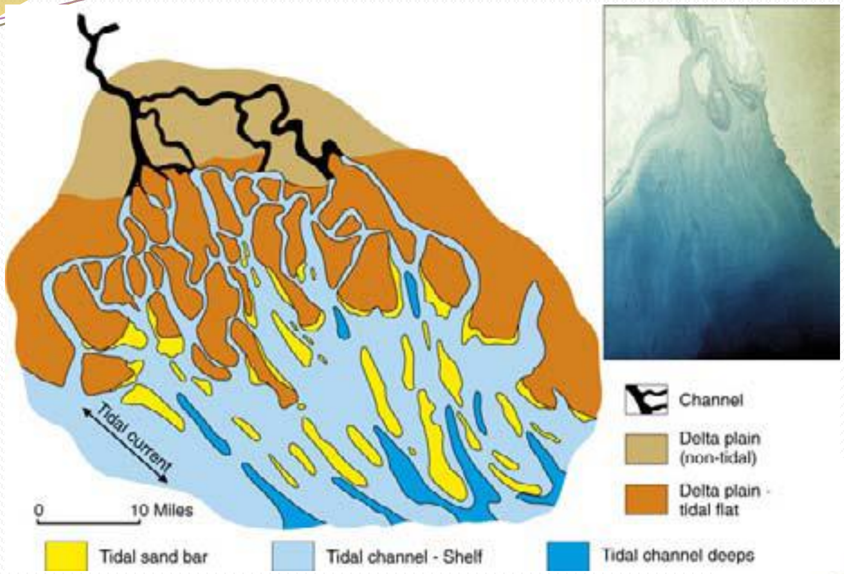




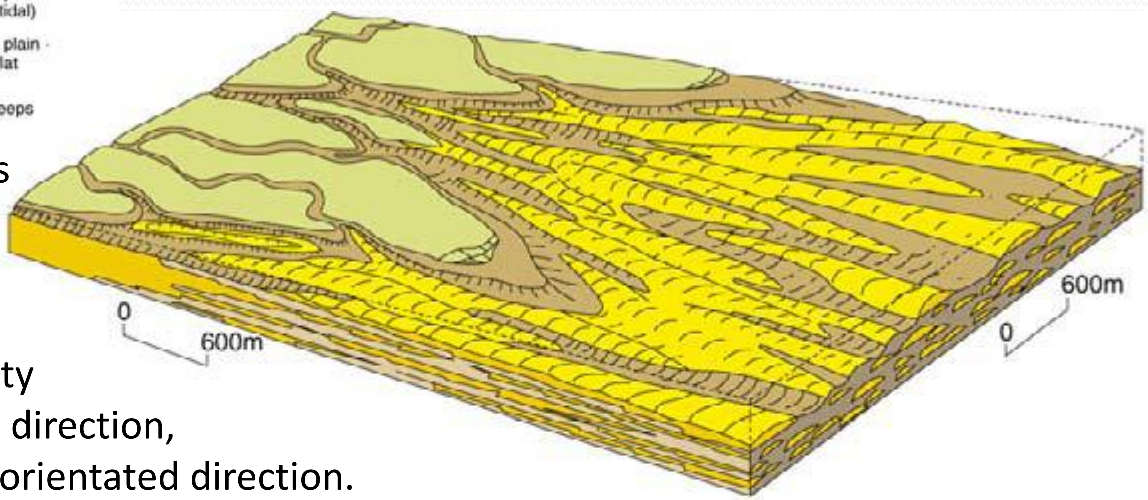


Clastic depositional systems

Transitional systems: tide-dominated deltas



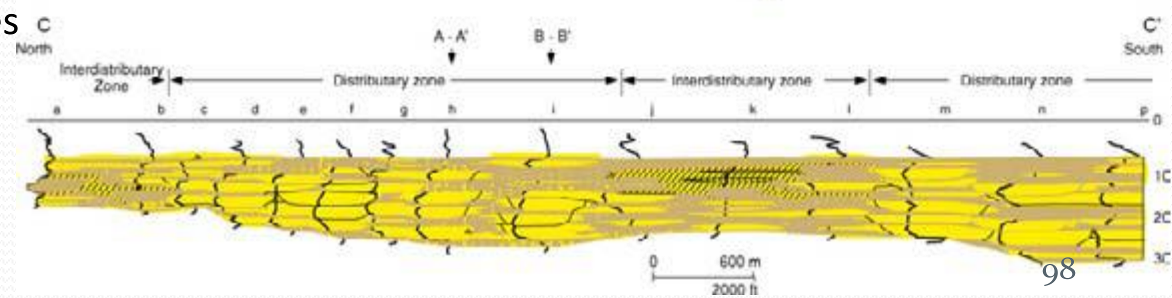
In an embayed coastline, waves and tides can interact closely, depending upon the configuration of the embayment and the orientation of the incoming waves. Particularly in narrow embayments, tidal energy can build progressively landward, giving rise to a very large tidal range. Thus, the tide-dominated delta can be a very high-energy environment, and the sediments will berelatively coarse grained.



Reservoir continuity and fluid-flow patterns are highly dependent upon depositional processes in this tide-dominated delta system.

Reservoir sandstones exhibit good continuity and fluid-flow potential in the dip-elongate direction, but they have poor continuity in the strike-orientated direction.

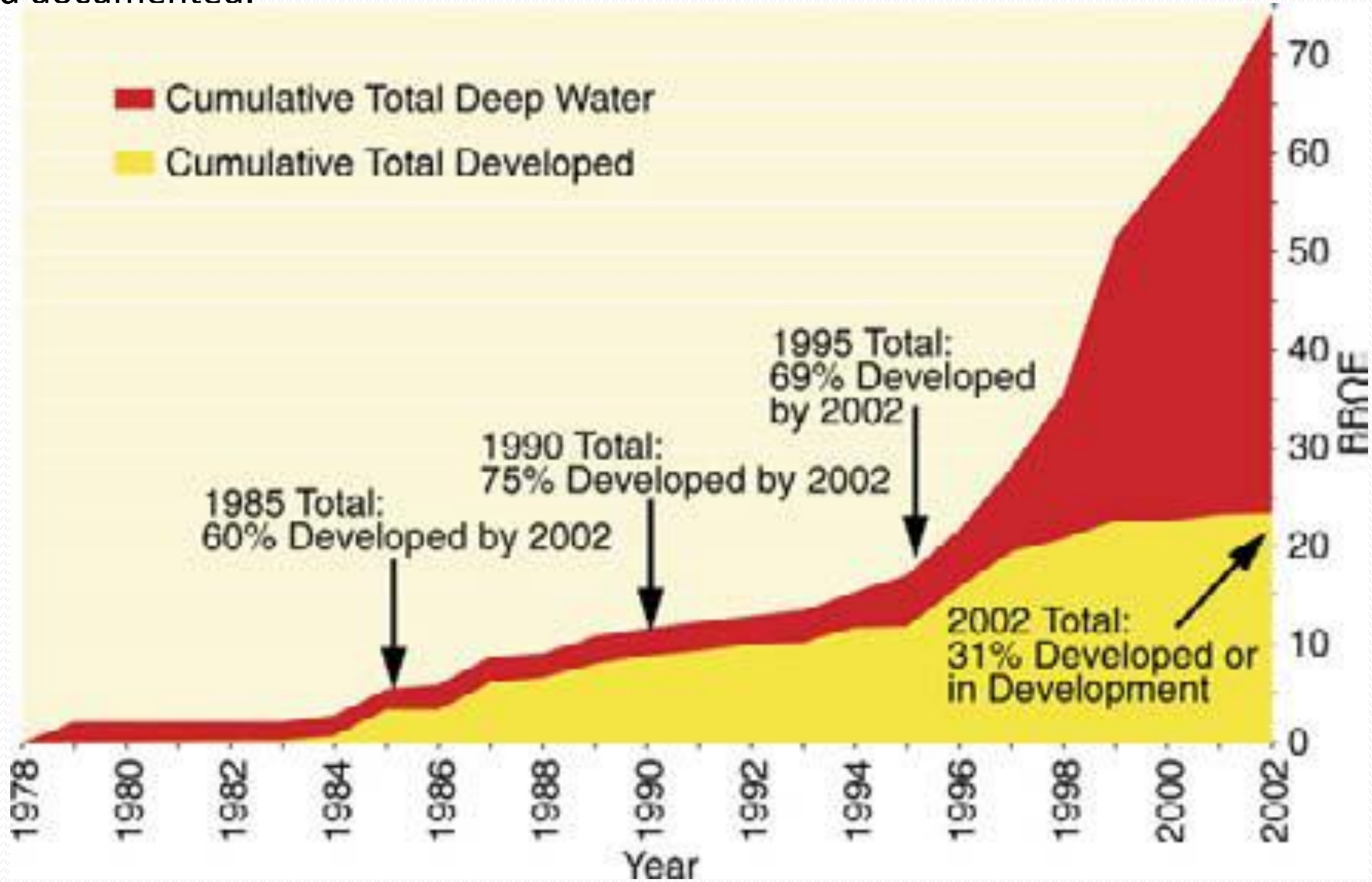
Advanced hydrocarbon-recovery strategies must account for this architectural style if production is to be maximized.



Clastic depositional systems

Deep-sea marine systems

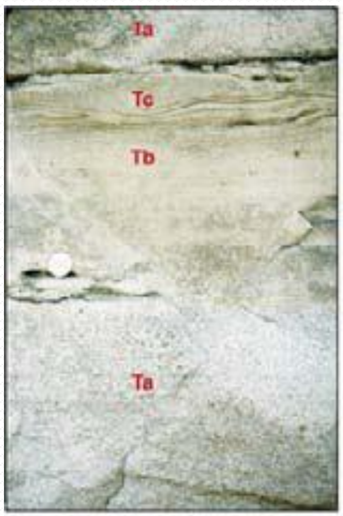
The deepwater depositional system is the one type of reservoir system that cannot be easily reached, observed, and studied in the modern environment. The study of deepwater systems requires many different remote-observation techniques, each of which can provide information on just one part of the entire system. As a consequence, the study and understanding of deepwater depositional systems as reservoirs has lagged behind that of the other reservoir systems, whose modern processes are more easily observed and documented.

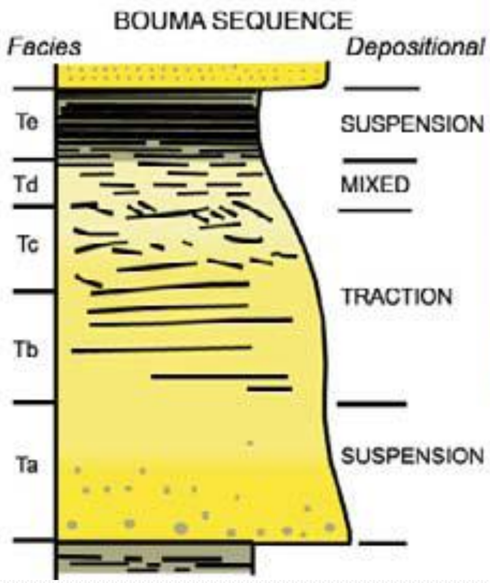


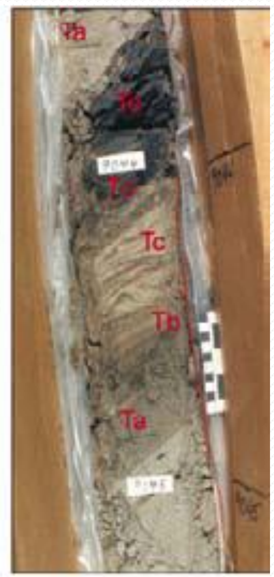
Clastic depositional systems

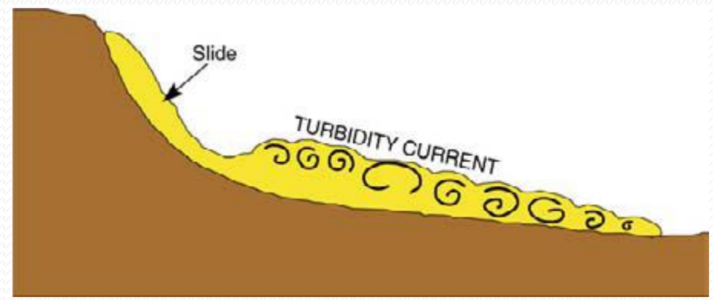
Deep-sea marine systems: turbidites

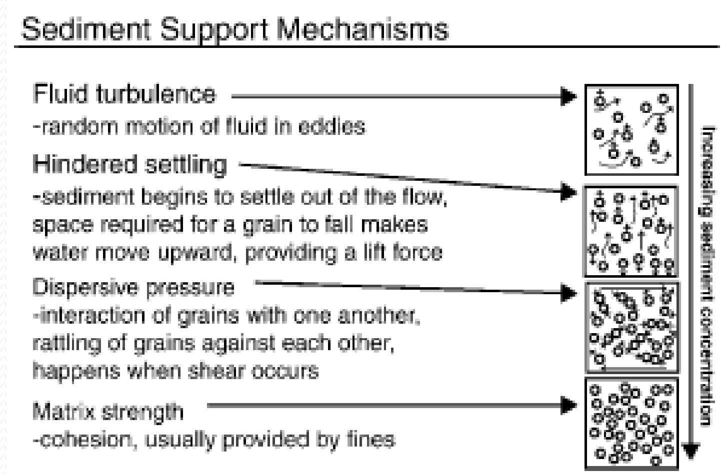
The first real recognition of deepwater (geologic definition) processes and deposits evolved from a classic paper by Kuenen and Migliorini (1950), who described "graded beds" from laboratory flume experiments and outcrop observations. They advanced the concept of turbidity currents as an important process by which sediment is transported from shallow water to deep water.







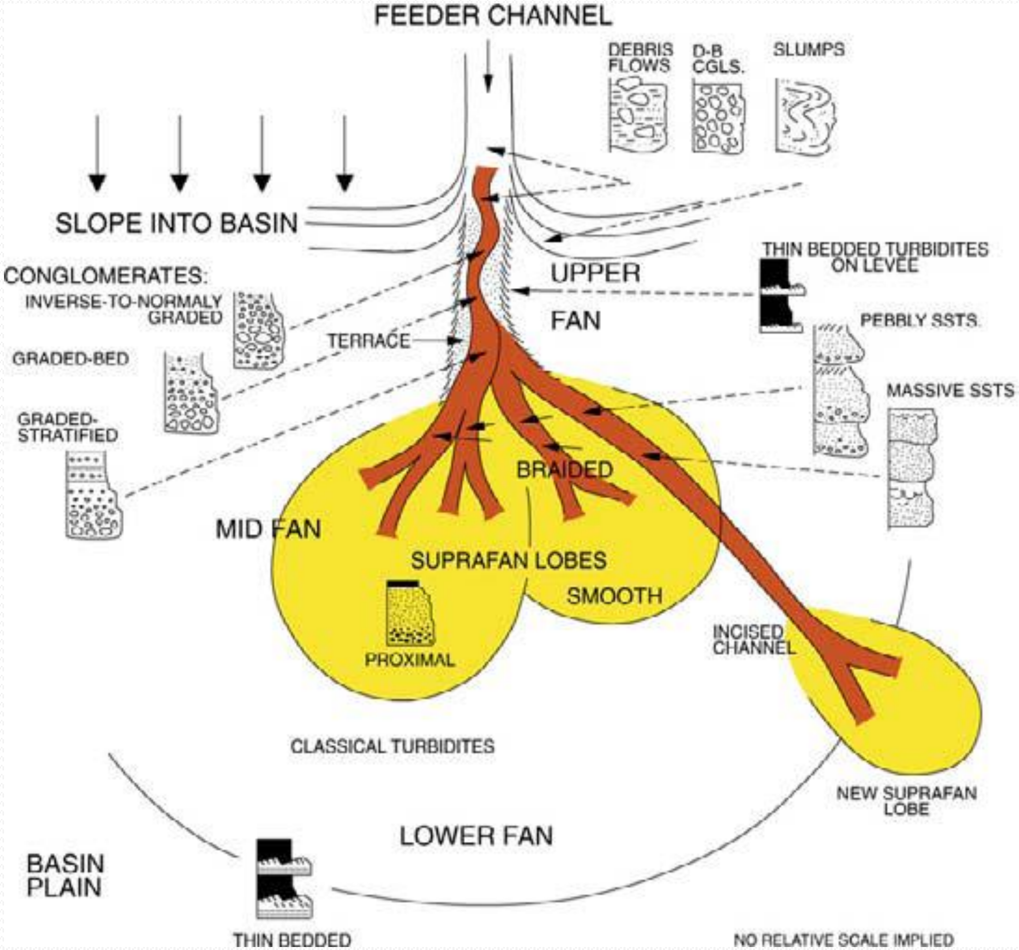




Clastic depositional systems

Deep-sea marine systems: submarine fans

Pioneering work by Bouma (1962), Mutti and Ricci Lucchi (1972), and Normark (1978) provided early geologic models for submarine fans and their component strata. Walker (1978) attempted to combine models into a comprehensive submarine-fanmodel composed of a feeder canyon, a proximal suprafan lobe, and amore distal lobe fringe, all sitting on a basin-plain deposit



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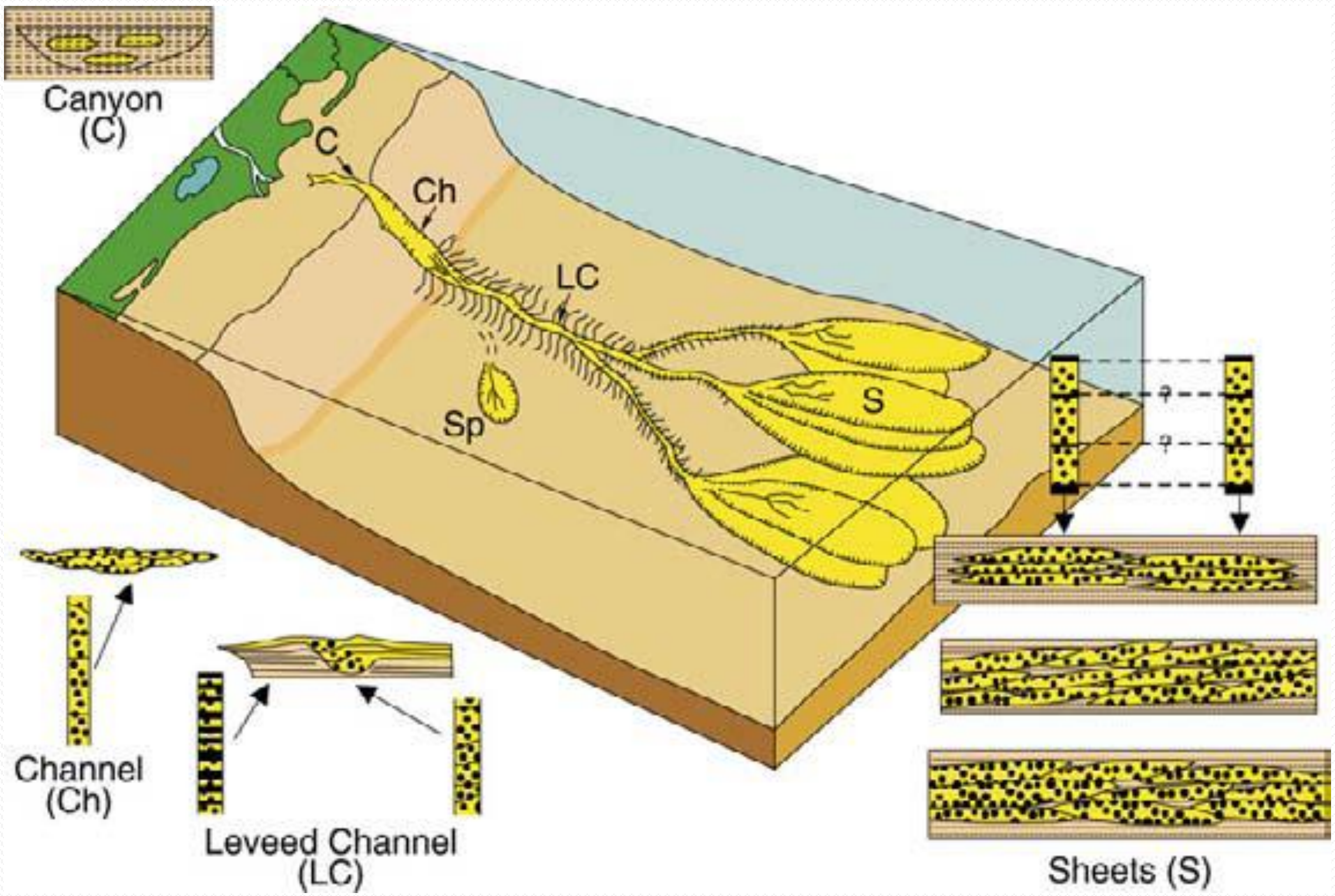

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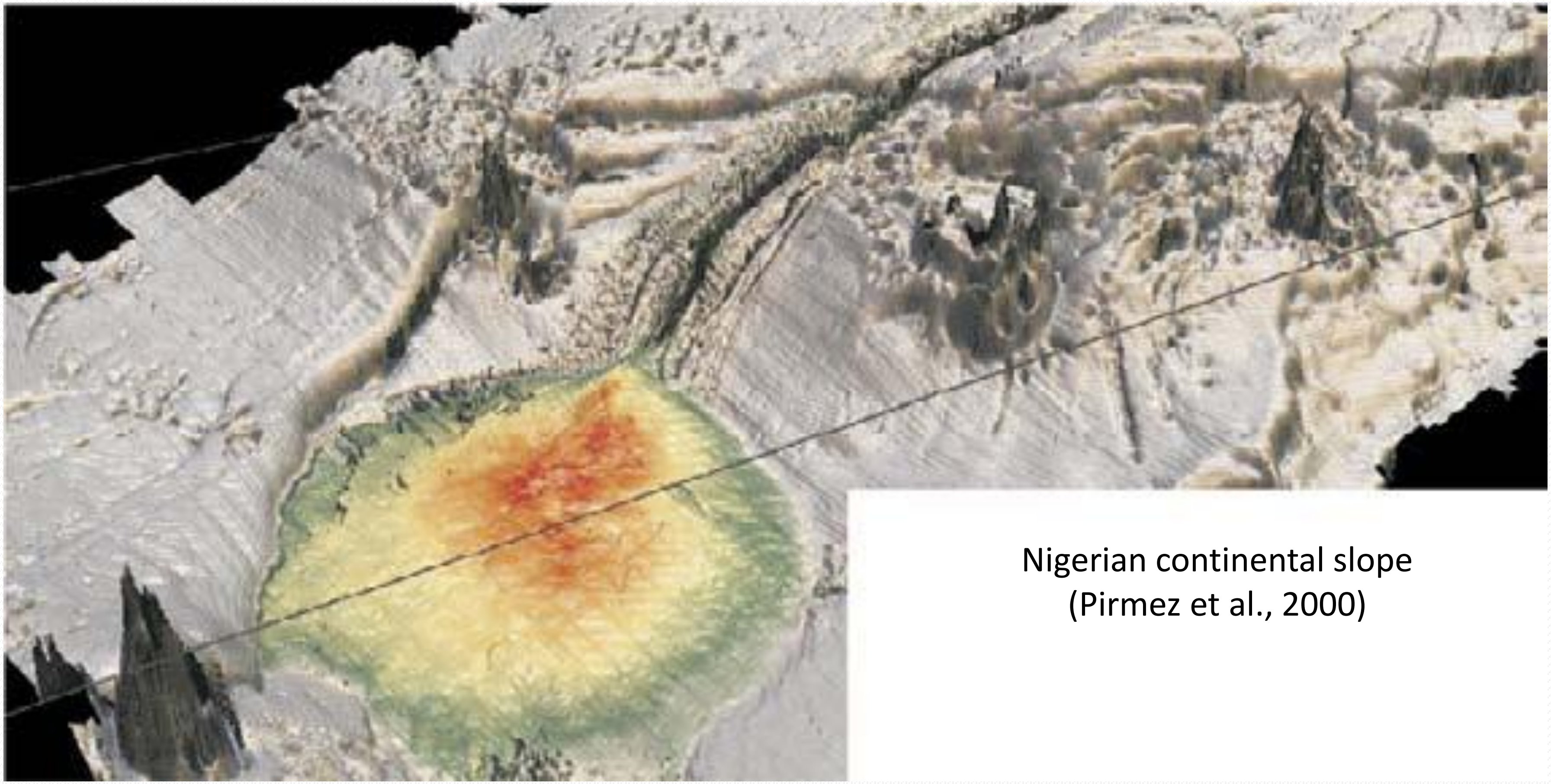
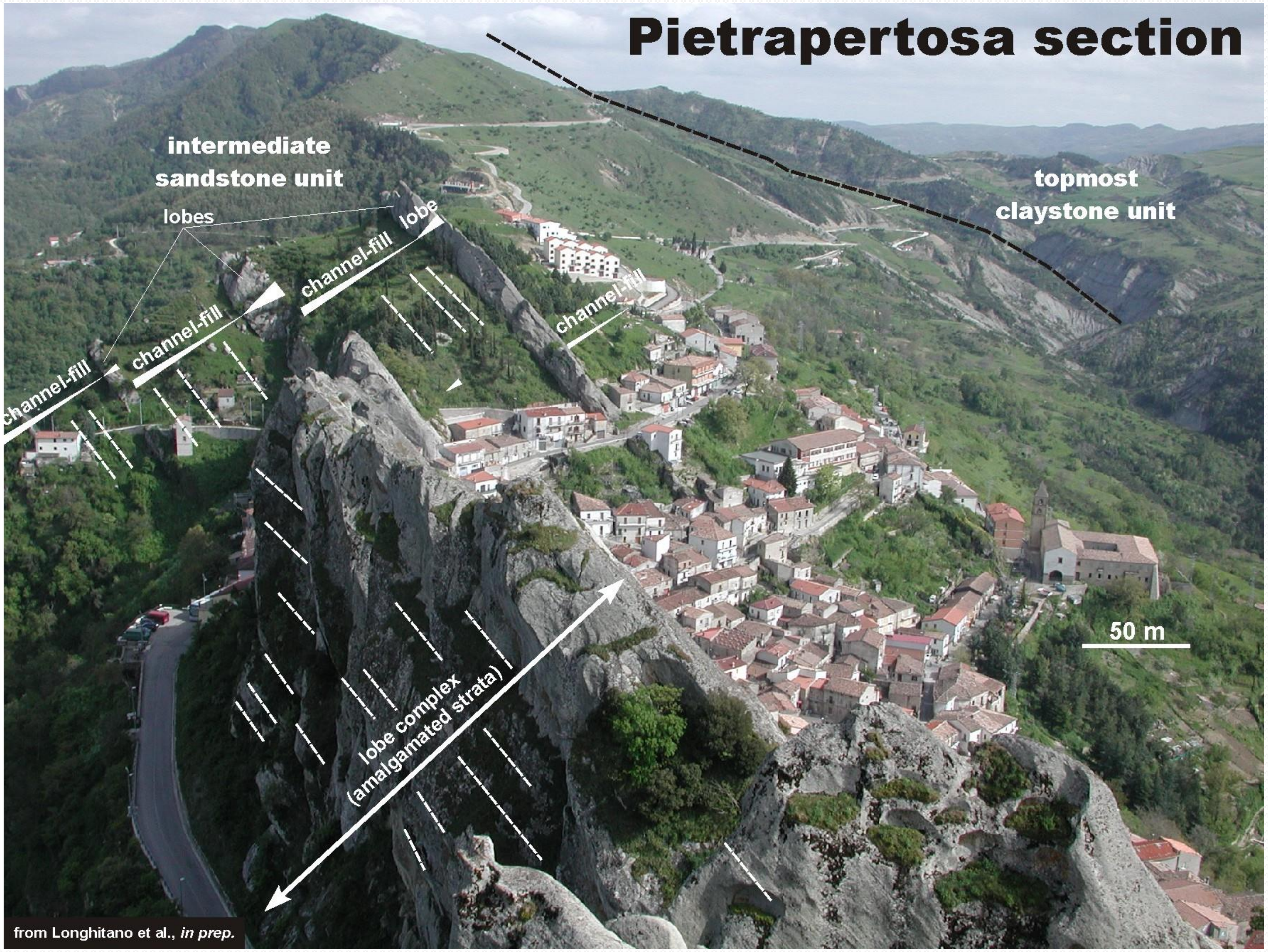


Nigerian continental slope
(Pirmez et al., 2000)

Deep-sea marine systems: submarine fans

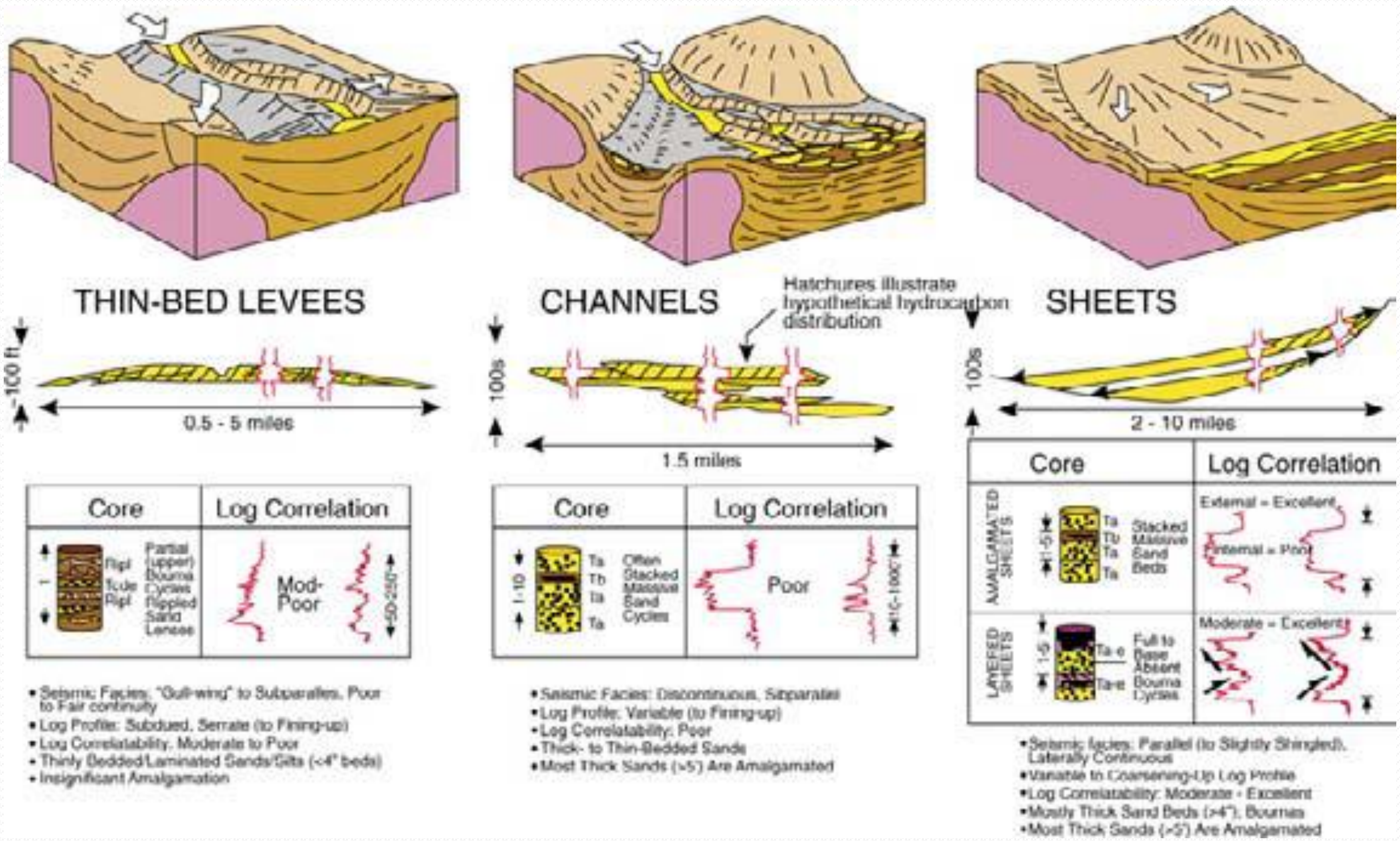
Channel-lobe transition deposits: the example of the Middle Miocene Gorgoglione Flysch Southern Apennine)



Clastic depositional systems

Deep-sea marine systems: submarine fans

The main architectural elements that comprise deepwater depositional systems are: canyons, (erosional) channels, (aggradational) leveed channels, and sheets or lobes. It is important to note that one should include different types of data in a reservoir characterization, because each type may provide details at a different scale.



Clastic depositional systems

Deep-sea marine systems: submarine fans and associate channels

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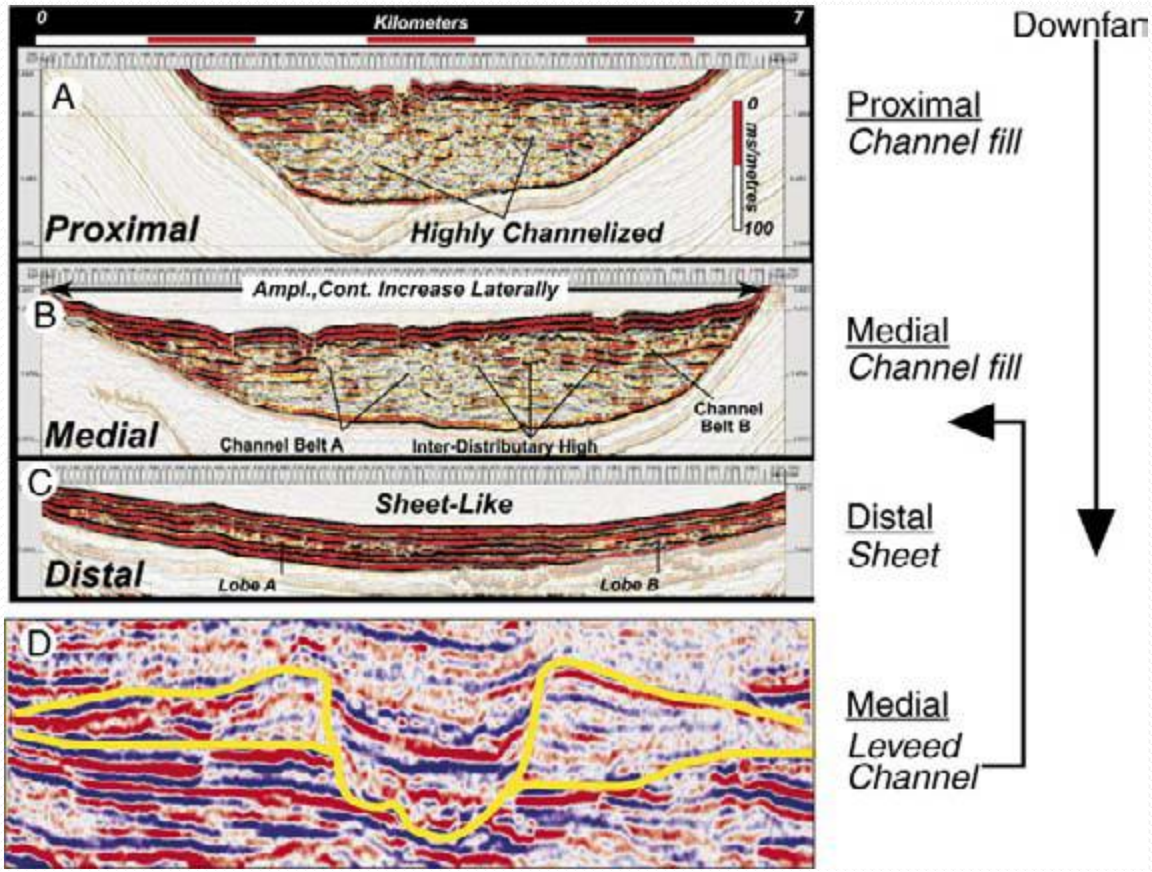


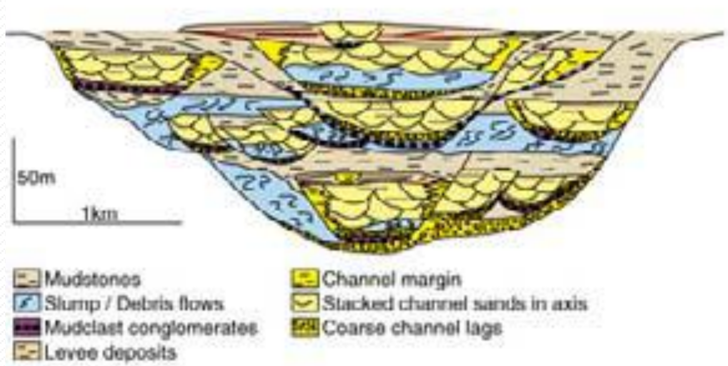
For example, at the reservior scale, seismicreflection patterns for the three elements are distinctly different. A, B, C are three high-resolution seismic profiles from one shallow intra-slope minibasin, northern deep Gulf of Mexico. (A) Proximal and (B) medial profiles cross the up-fan channelized systems. (C) A distal profile crosses the sheet deposits. Note that lobes A and B have a slightly mounded appearance among the laterally continuous, sheetlike reflections. The deposits are as large as 50 ms in two-way traveltime. These have laterally continuous reflections that lapout against the side of basins. (D) Seismic profile of a leveed channel complex from the western Gulf of Mexico (Beaubouef et al., 2003).

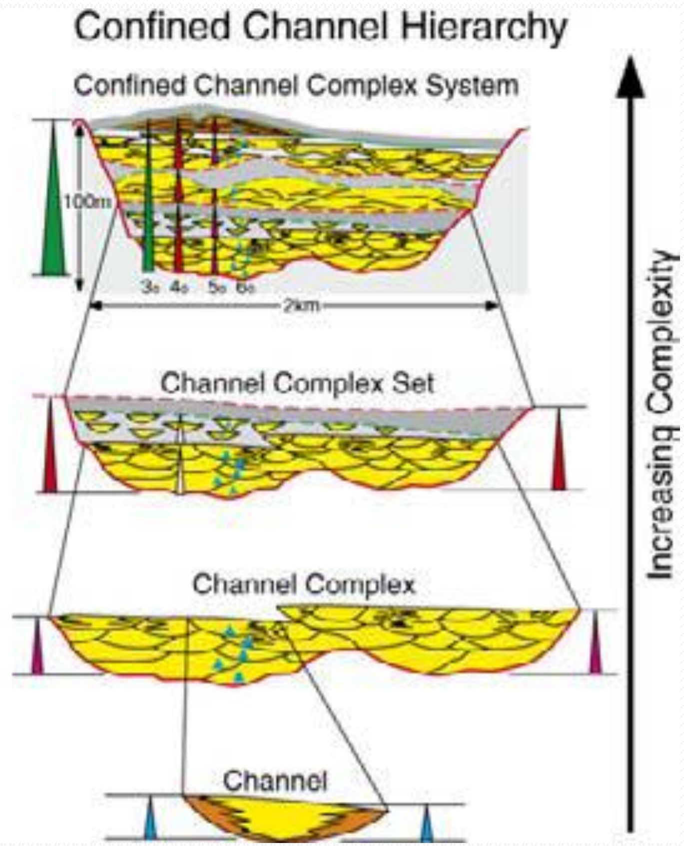
Clastic depositional systems

Deep-sea marine systems: submarine channels

Although the final internal fill of a channel normally is quite complex, channel fill often can be subdivided into an organized, recognizable pattern or hierarchy of strata.

Confined channel hierarchy from a single channel element, through a complex of elements, through a complex set of elements, and finally to a complex system. Multiple channel fills and intervening shale from levee deposits create significant heterogeneity, with many potential flow barriers and baffles.

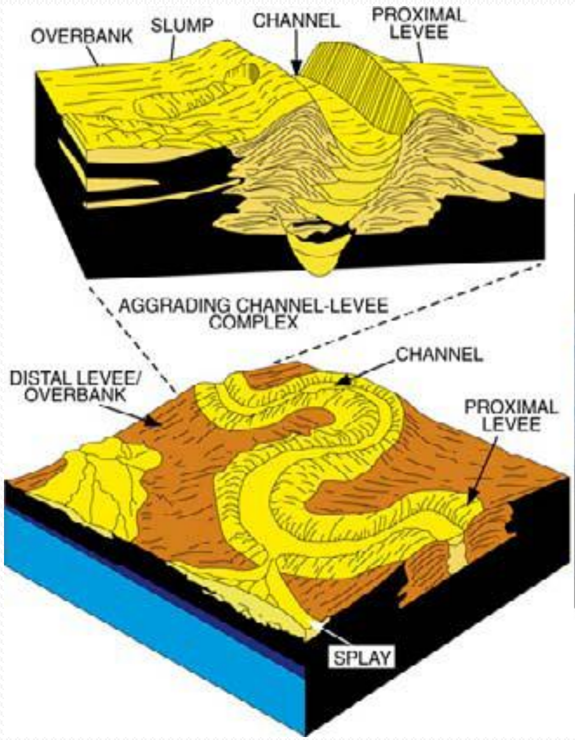


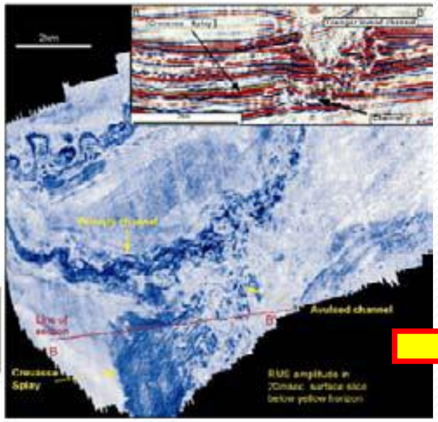


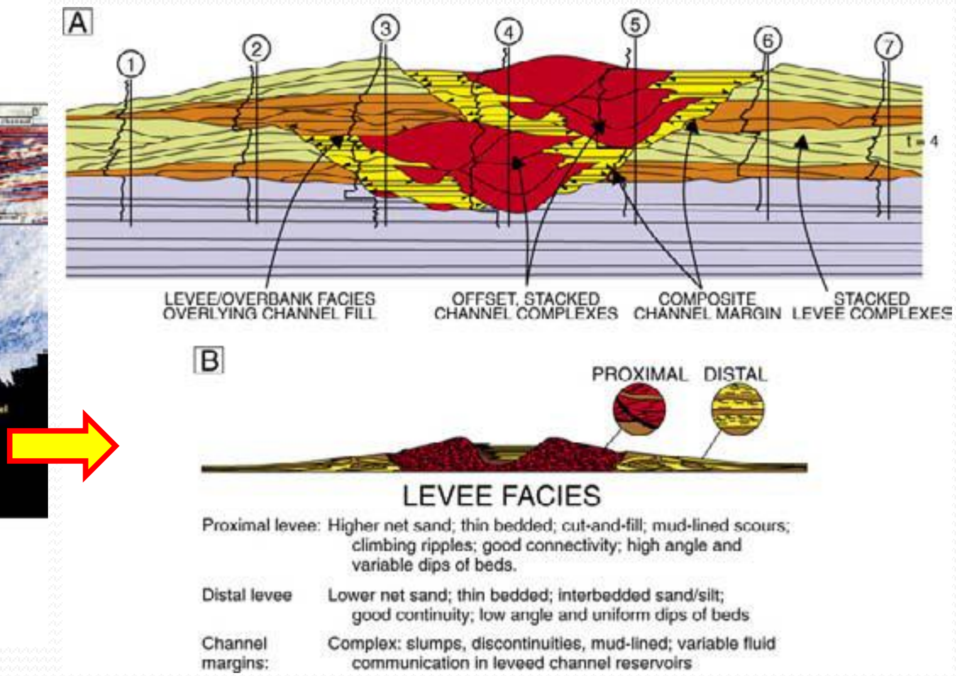
Clastic depositional systems

Deep-sea marine systems: facies models

For the past decade, most major oil and gas companies have focused on developing channel-fill or sheet-sandstone reservoirs. Much less is known about levee-overbank deposits as potential reservoirs. Levee-overbank deposits consist primarily of muds and thinly bedded (millimeters- to centimeters thick), laminated sands and sandstones (hereafter termed "thin beds") that form adjacent to sinuous channels. They sometimes exhibit excellent porosity and darcy-range permeability.







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