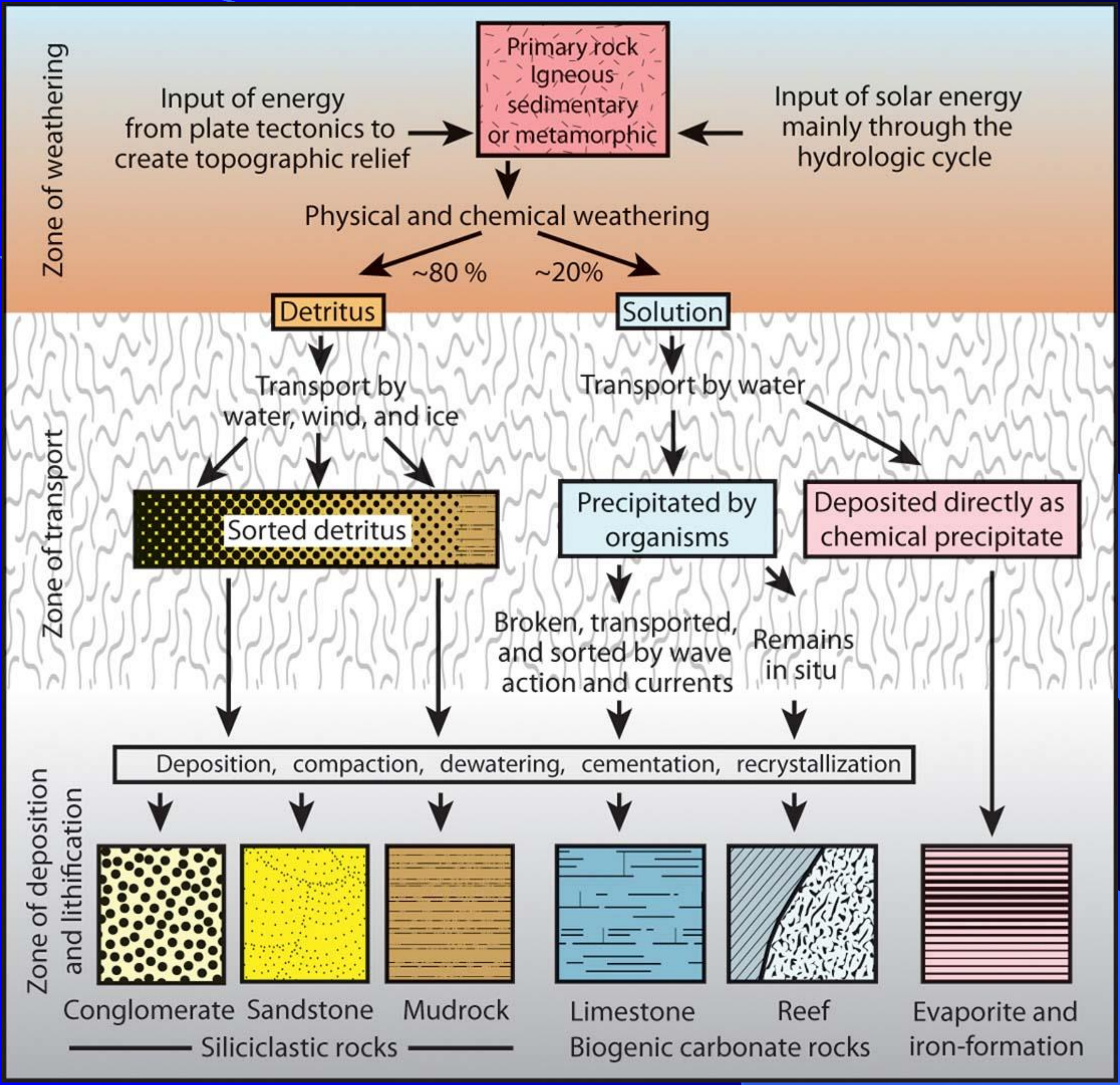
Formation, Transport and Lithification of Sediment



Zone of weathering

Primary rock
Igneous
sedimentary
or metamorphic

Input of energy
from plate tectonics to
create topographic relief

Input of solar energy
mainly through the
hydrologic cycle

Physical and chemical weathering

~80 %

~20%

Detritus

Solution

Zone of transport

Transport by
water, wind, and ice

Sorted detritus

Transport by water

Precipitated by
organisms

Deposited directly as
chemical precipitate

Broken, transported,
and sorted by wave
action and currents

Remains
in situ

Zone of deposition
and lithification

Deposition, compaction, dewatering, cementation, recrystallization

Conglomerate

Sandstone

Mudrock

Siliciclastic rocks

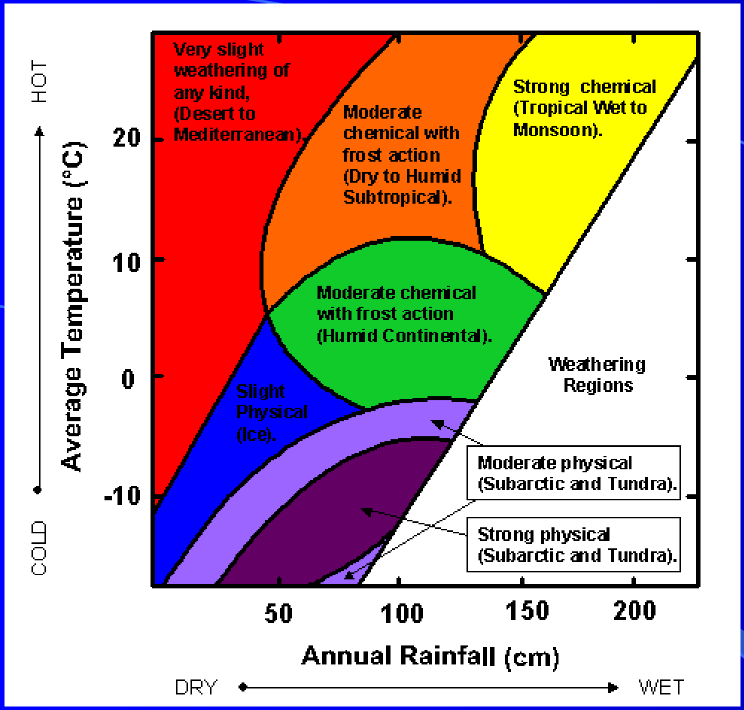
Limestone

Reef

Biogenic carbonate rocks

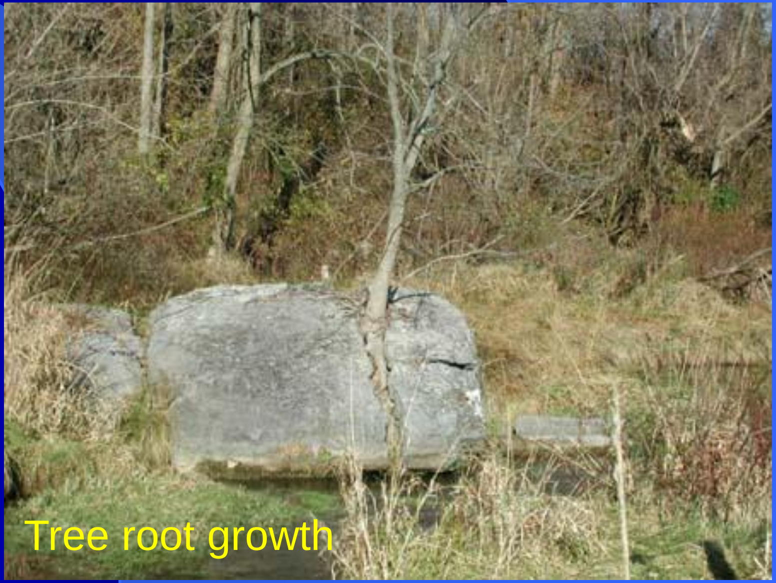
Evaporite and
iron-formation

Physical weathering

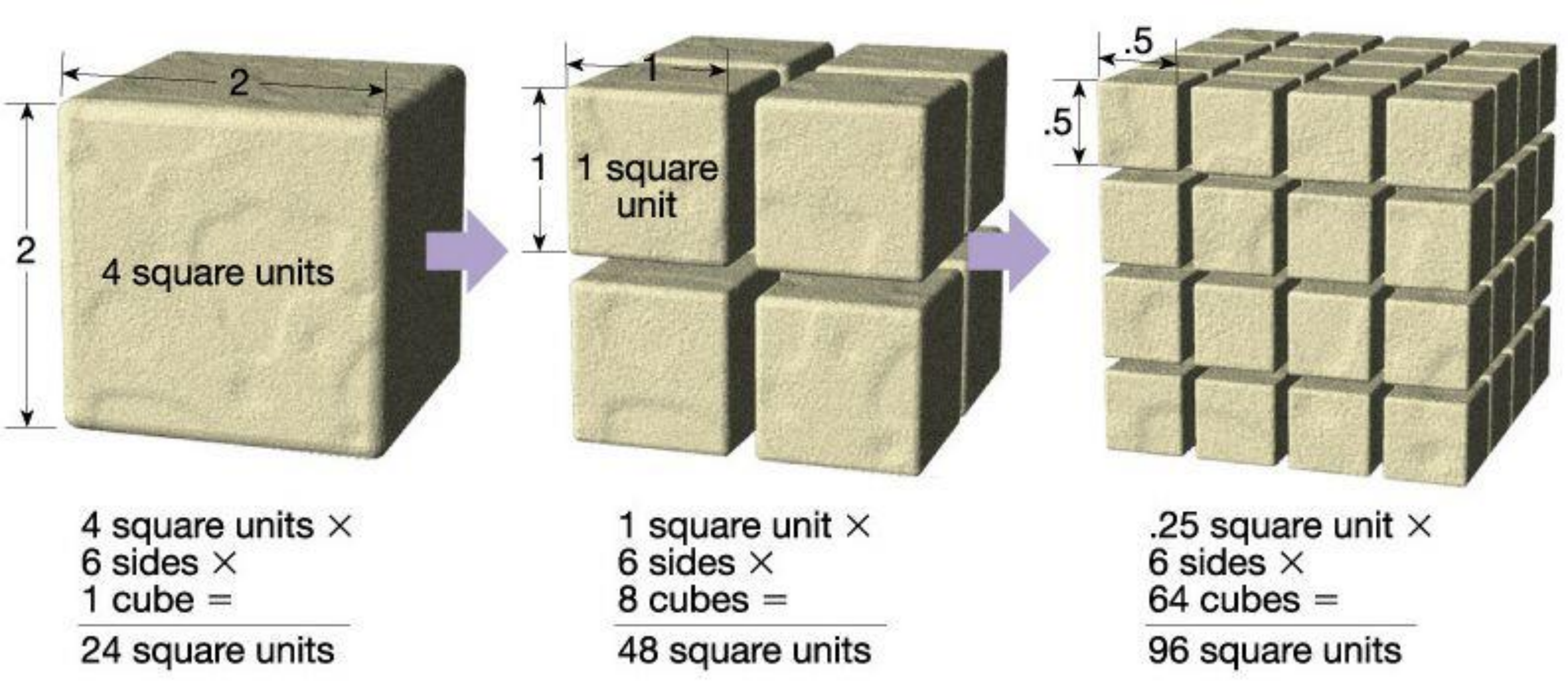



Freeze-thaw weathering


Sheeting


Tree root growth

The main role of mechanical weathering is to increase the surface to volume ratio so chemical weathering will be more effective.



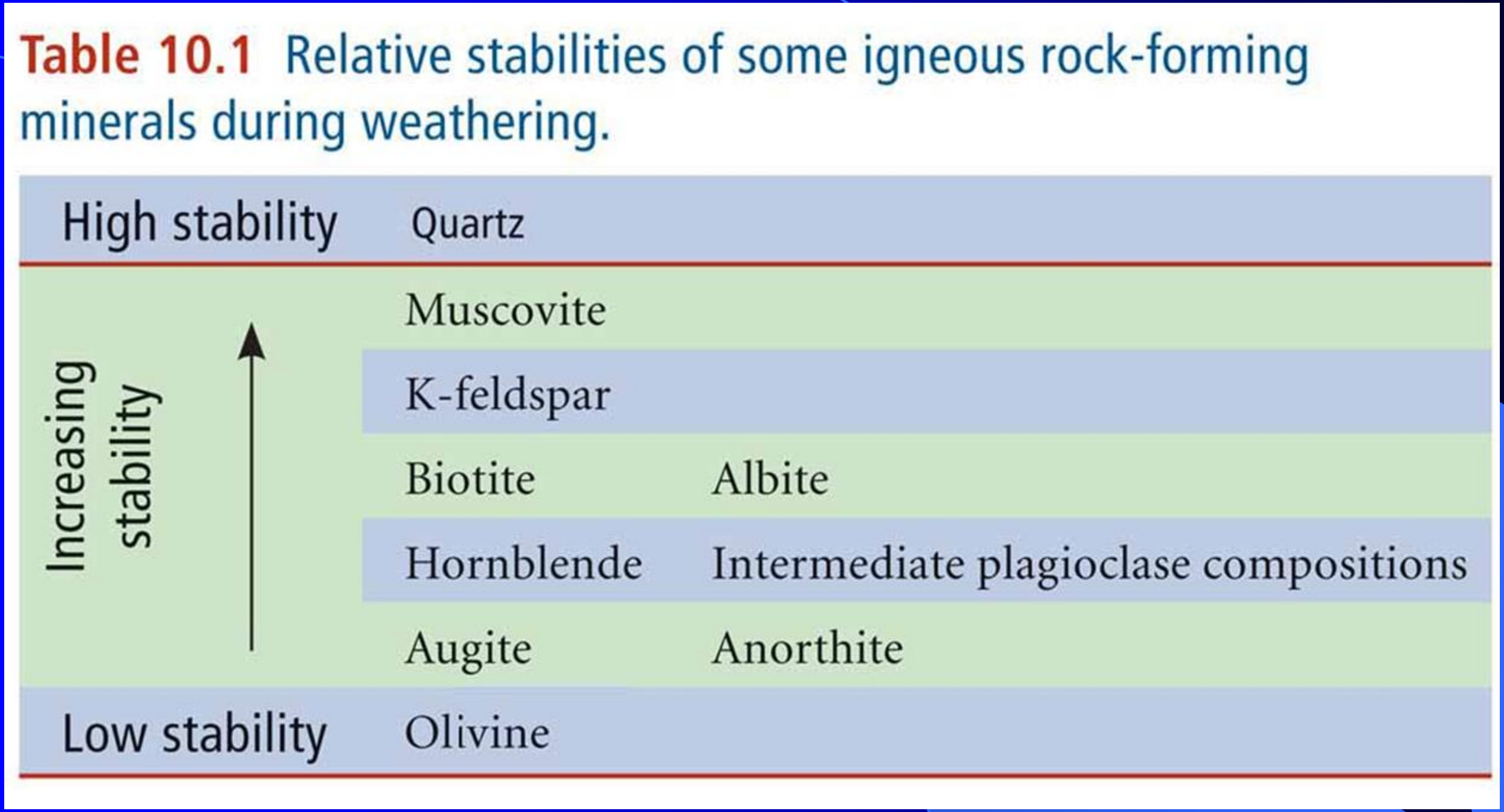
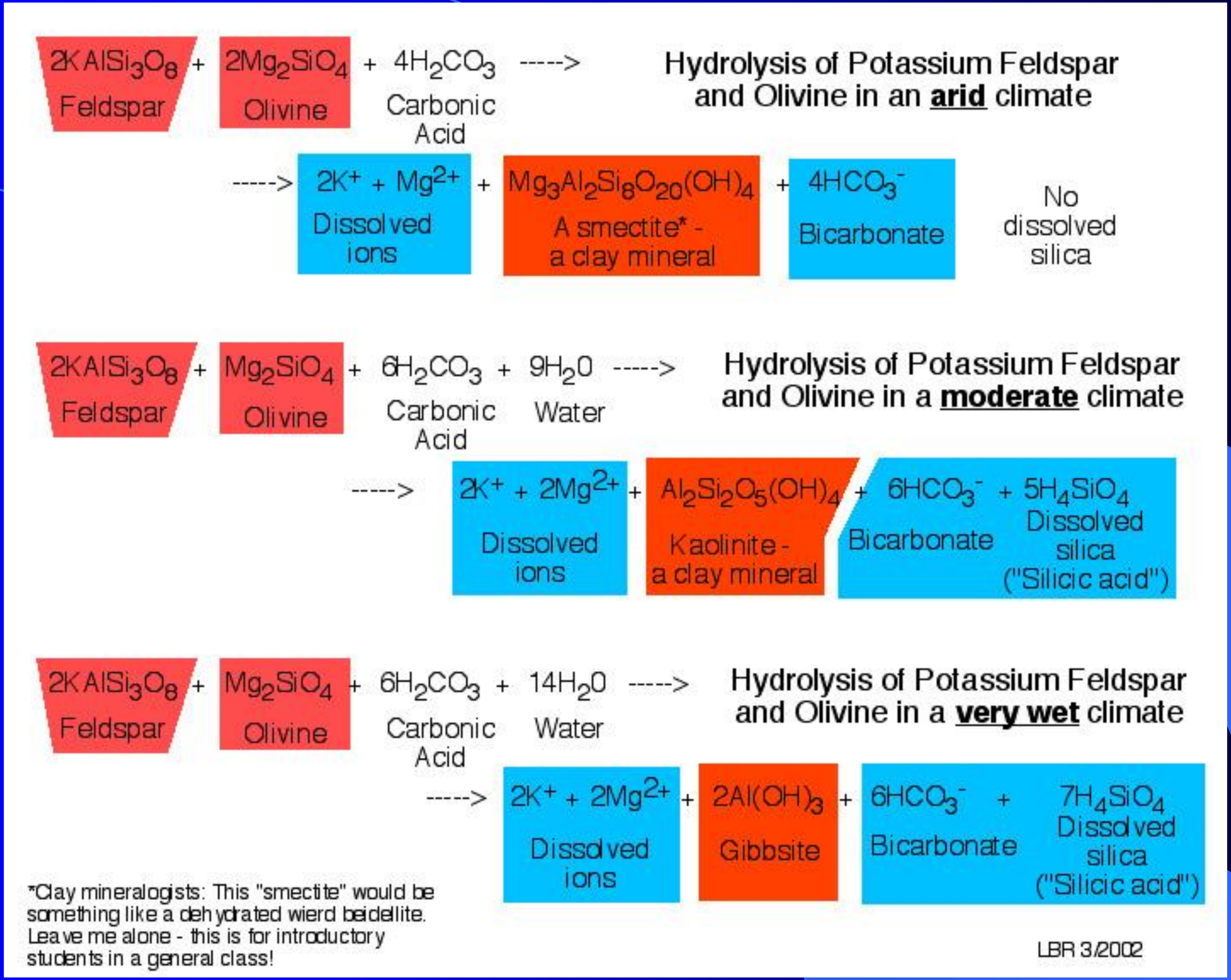


Table 10.1 Relative stabilities of some igneous rock-forming minerals during weathering.

High stability	Quartz	
Increasing stability ↑	Muscovite	
	K-feldspar	
	Biotite	Albite
	Hornblende	Intermediate plagioclase compositions
	Augite	Anorthite
Low stability	Olivine	



Hydrolysis of Potassium Feldspar and Olivine in an **arid** climate

$2KAlSi_3O_8$ Feldspar + $2Mg_2SiO_4$ Olivine + $4H_2CO_3$ Carbonic Acid ----->

-----> $2K^+ + Mg^{2+}$ Dissolved ions + $Mg_3Al_2Si_8O_{20}(OH)_4$ A smectite* - a clay mineral + $4HCO_3^-$ Bicarbonate

No dissolved silica

Hydrolysis of Potassium Feldspar and Olivine in a **moderate** climate

$2KAlSi_3O_8$ Feldspar + Mg_2SiO_4 Olivine + $6H_2CO_3$ Carbonic Acid + $9H_20$ Water ----->

-----> $2K^+ + 2Mg^{2+}$ Dissolved ions + $Al_2Si_2O_5(OH)_4$ Kaolinite - a clay mineral + $6HCO_3^-$ Bicarbonate + $5H_4SiO_4$ Dissolved silica ("Silicic acid")

Hydrolysis of Potassium Feldspar and Olivine in a **very wet** climate

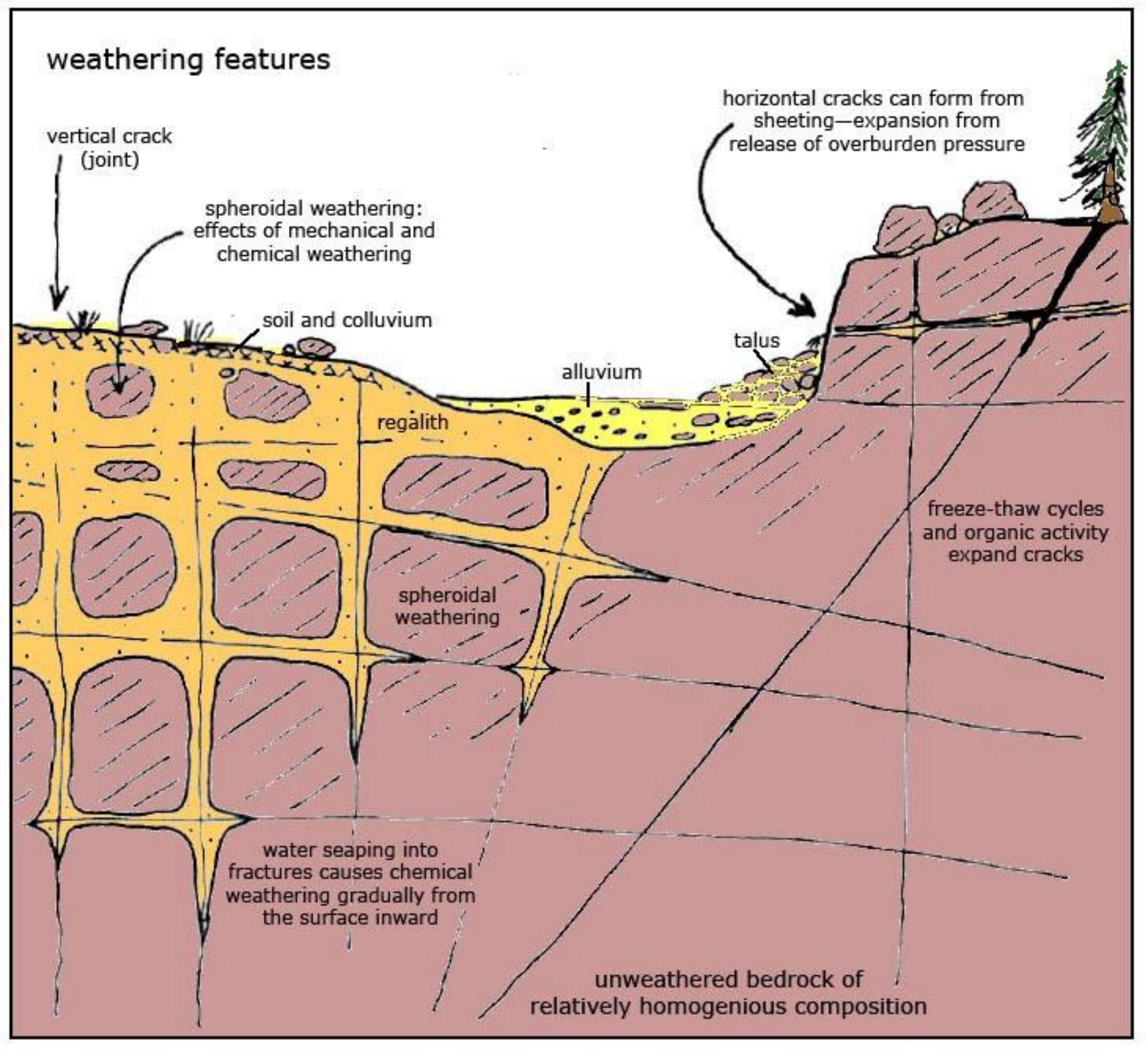
$2KAlSi_3O_8$ Feldspar + Mg_2SiO_4 Olivine + $6H_2CO_3$ Carbonic Acid + $14H_20$ Water ----->

-----> $2K^+ + 2Mg^{2+}$ Dissolved ions + $2Al(OH)_3$ Gibbsite + $6HCO_3^-$ Bicarbonate + $7H_4SiO_4$ Dissolved silica ("Silicic acid")

*Clay mineralogists: This "smectite" would be something like a dehydrated wierd beidellite. Leave me alone - this is for introductory students in a general class!

LBR 3/2002

Depth of weathering is a function of time and access (fractures)



Detrital material (detritus) – quartz, heavy minerals, etc.

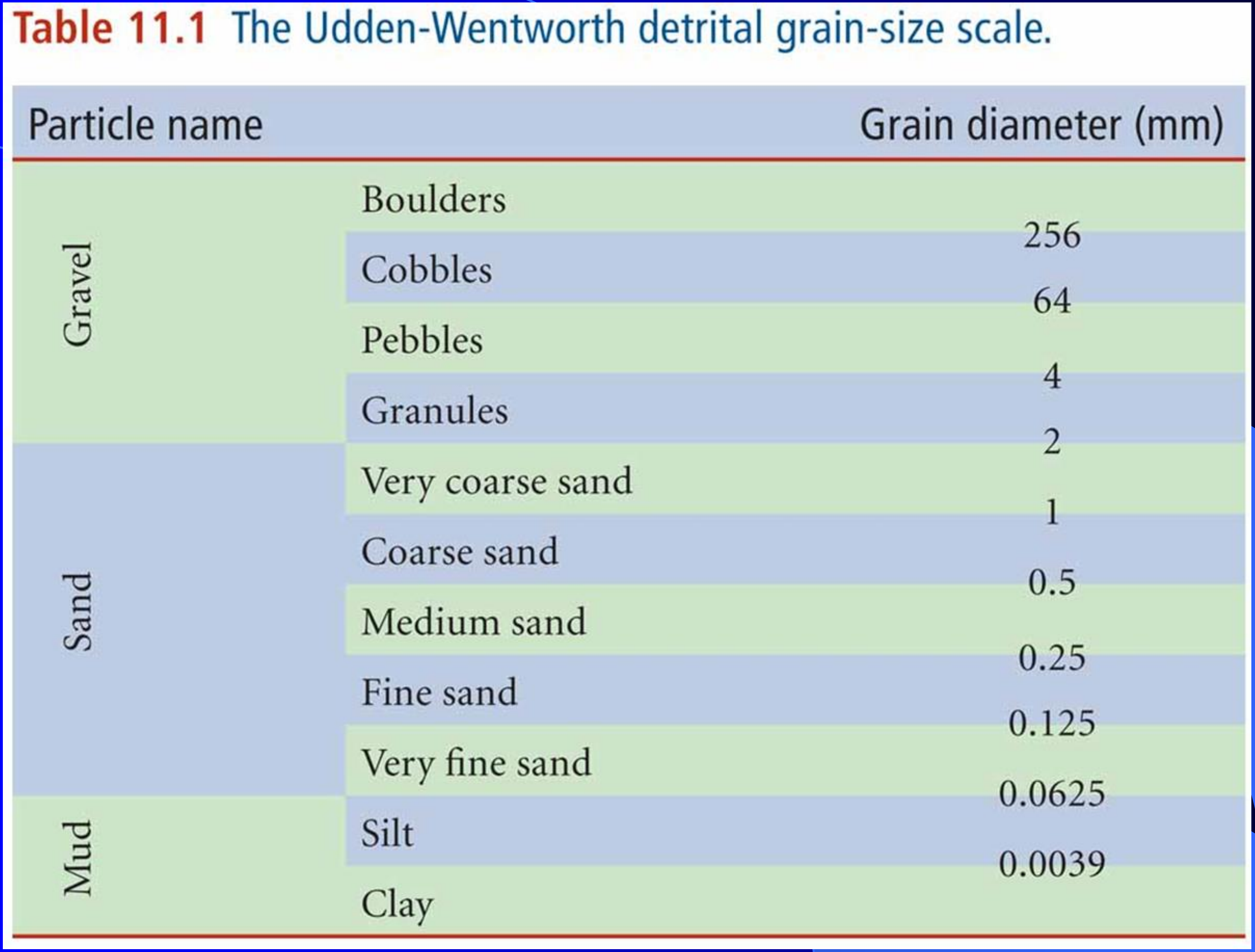
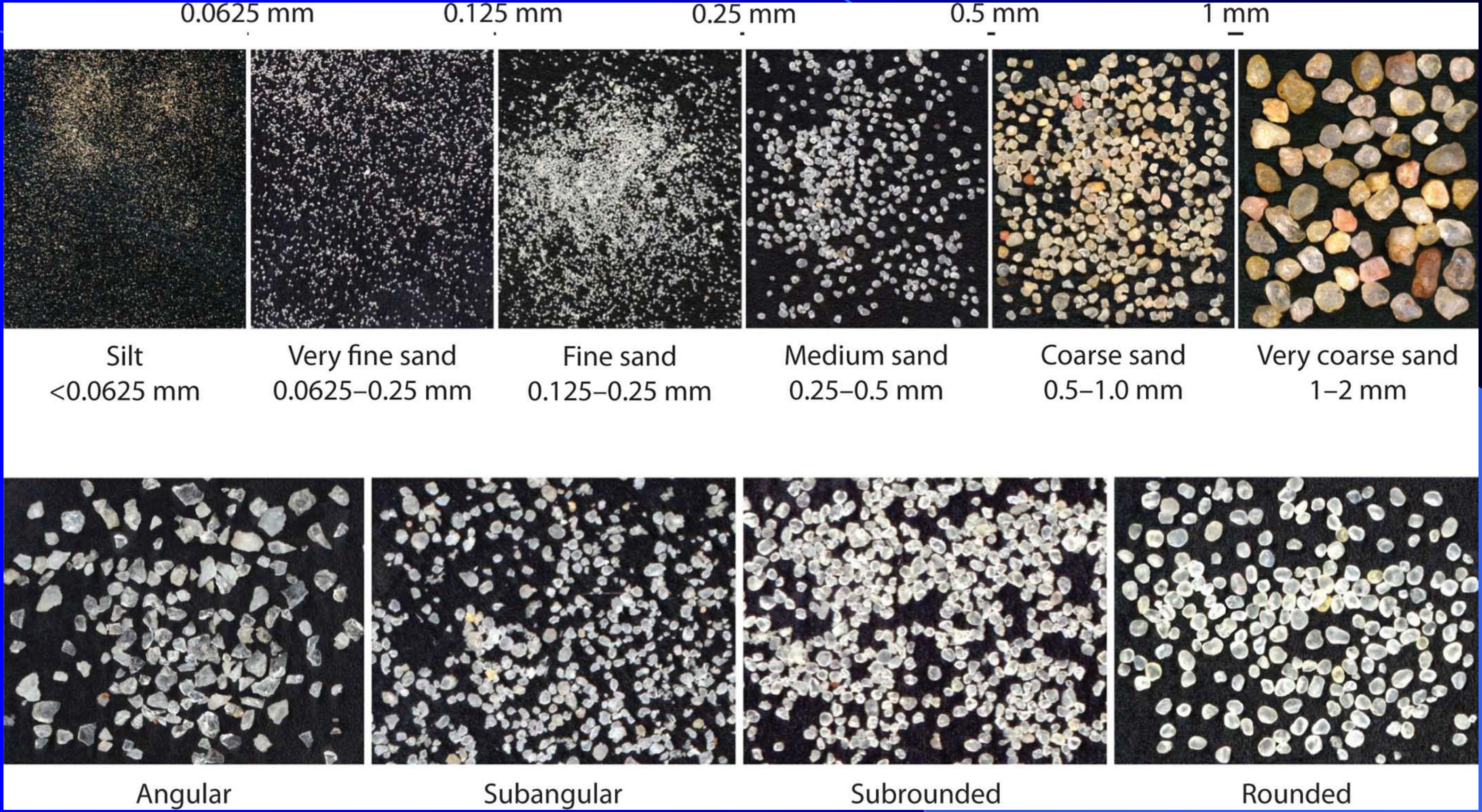


Table 11.1 The Udden-Wentworth detrital grain-size scale.

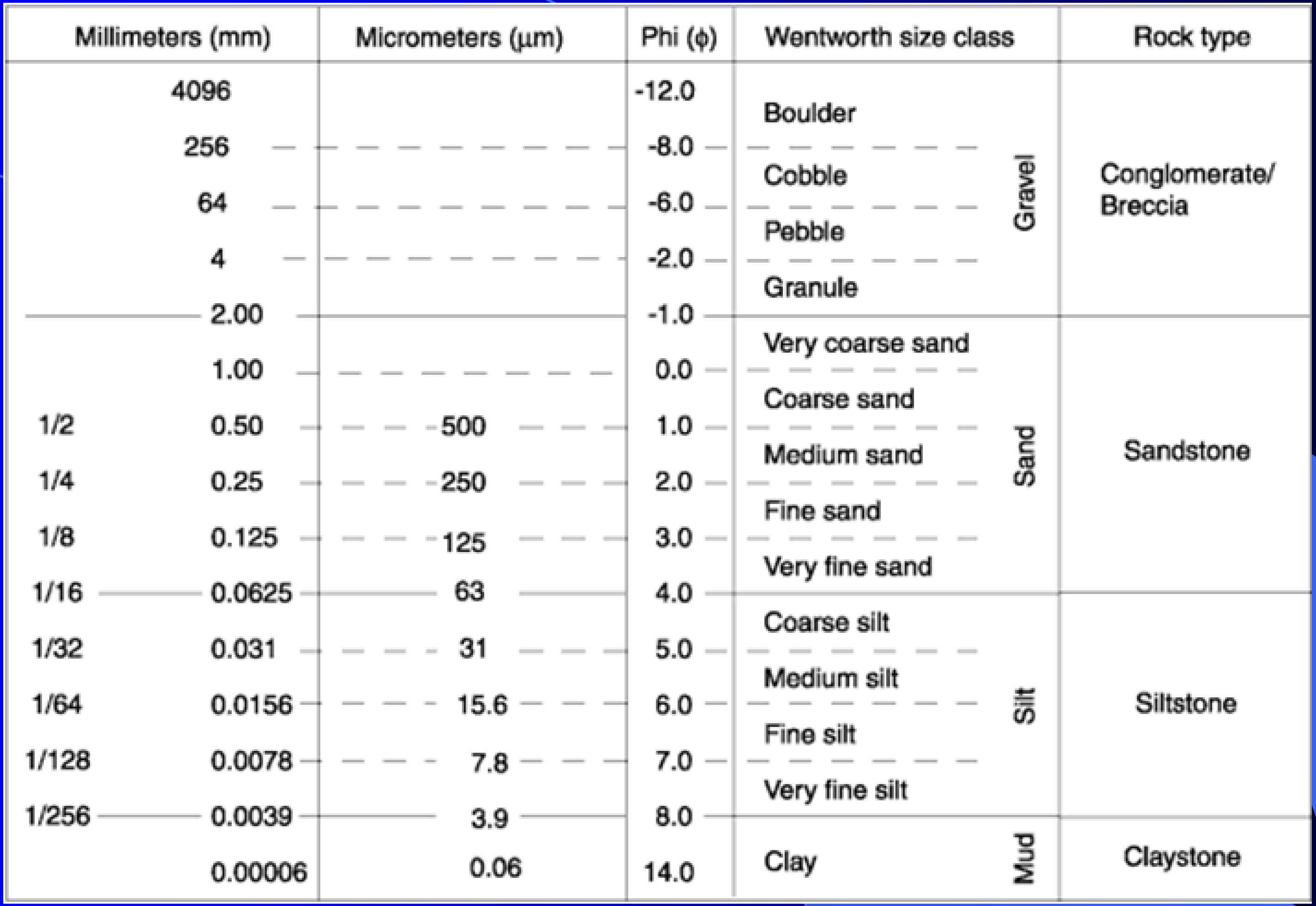
Particle name		Grain diameter (mm)
Gravel	Boulders	256
	Cobbles	64
	Pebbles	4
	Granules	2
Sand	Very coarse sand	1
	Coarse sand	0.5
	Medium sand	0.25
	Fine sand	0.125
	Very fine sand	0.0625
Mud	Silt	0.0039
	Clay	

Shape and size of grains is a function of transport processes



http://www.scienceofsand.info/sand/oneaday.htm

Sediment Size Classification

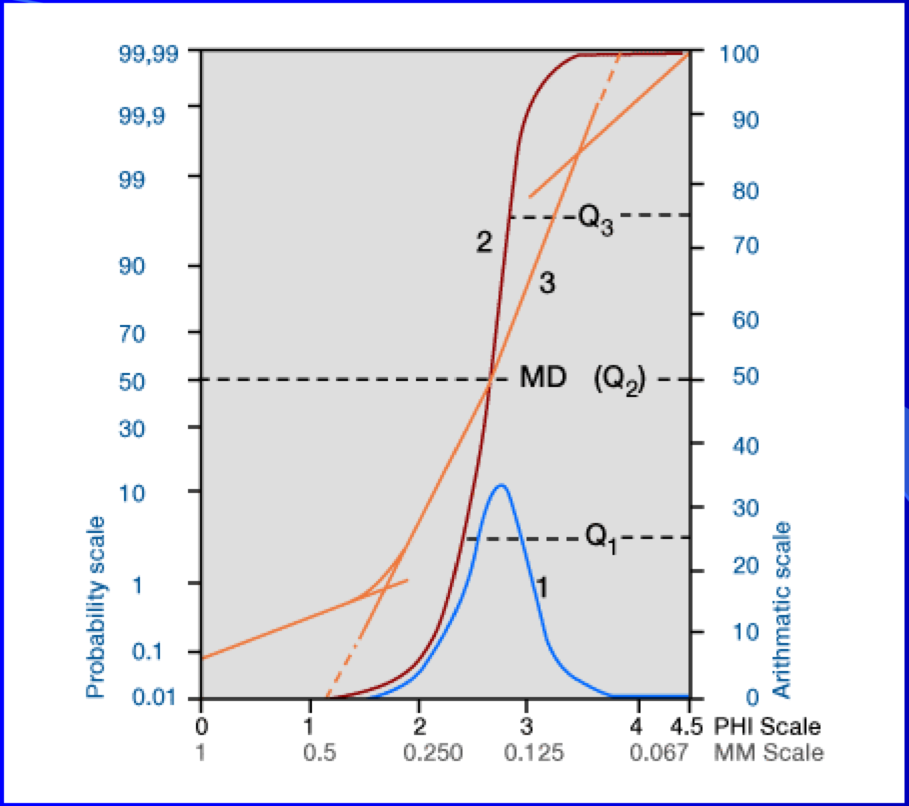


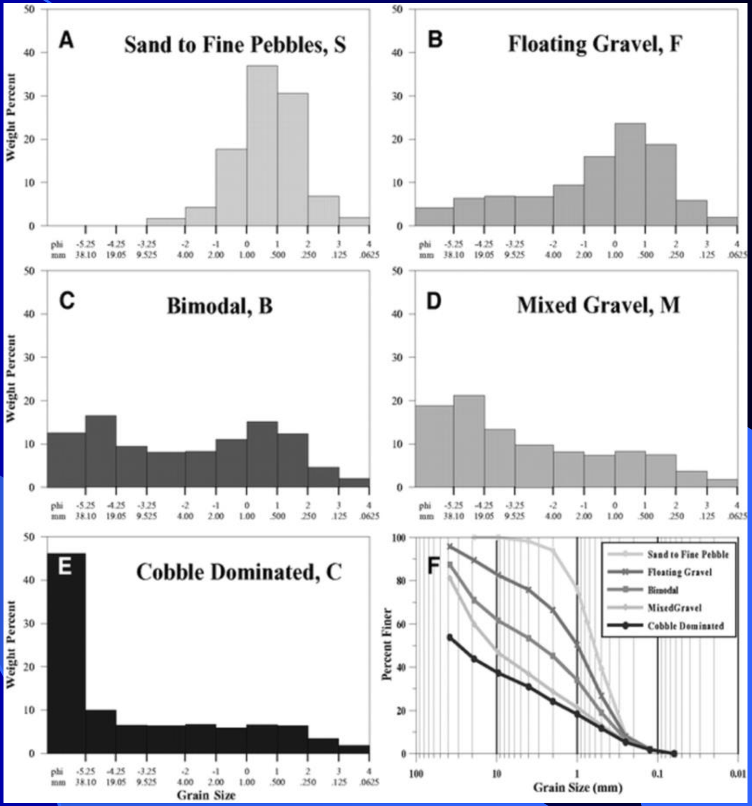
Millimeters (mm)		Micrometers (µm)	Phi (ϕ)	Wentworth size class		Rock type
	4096		-12.0			
				Boulder	Gravel	Conglomerate/ Breccia
	256		-8.0			
				Cobble		
	64		-6.0			
				Pebble		
	4		-2.0			
				Granule		
	2.00		-1.0			
				Very coarse sand	Sand	Sandstone
	1.00		0.0			
				Coarse sand		
1/2	0.50	500	1.0			
				Medium sand		
1/4	0.25	250	2.0			
				Fine sand		
1/8	0.125	125	3.0			
				Very fine sand		
1/16	0.0625	63	4.0			
				Coarse silt	Silt	Siltstone
1/32	0.031	31	5.0			
				Medium silt		
1/64	0.0156	15.6	6.0			
				Fine silt		
1/128	0.0078	7.8	7.0			
				Very fine silt		
1/256	0.0039	3.9	8.0			
				Clay	Mud	Claystone
	0.00006	0.06	14.0			

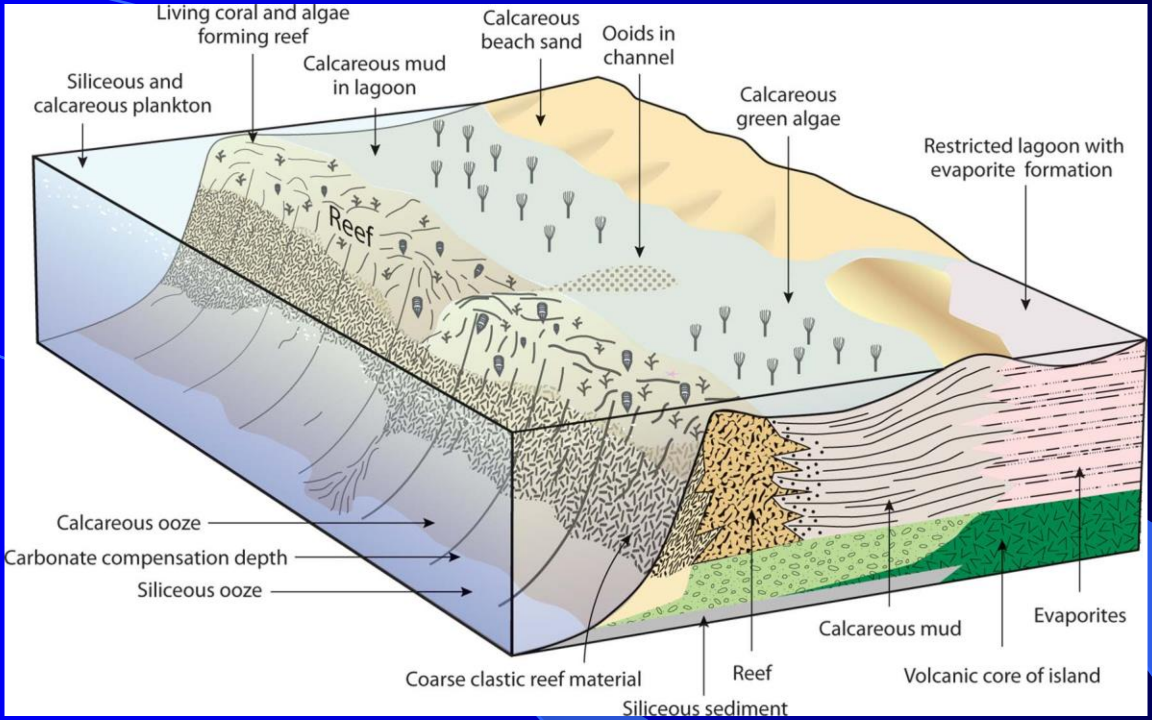
$\Phi = -\log_2 D/D_o$

D = diameter of particle D_o = reference diameter (1 mm)

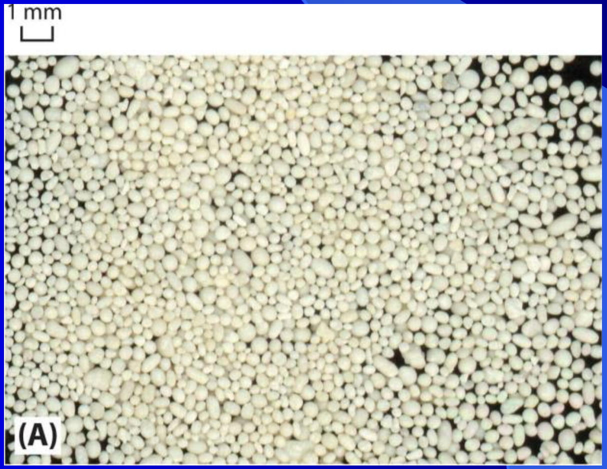
Sediment size distribution is a function of transport and the environment of deposition

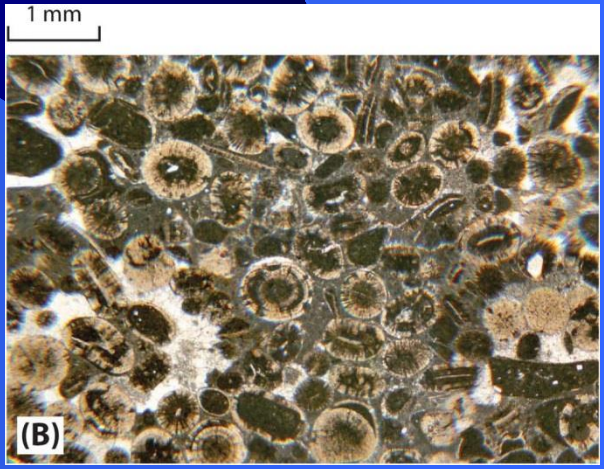




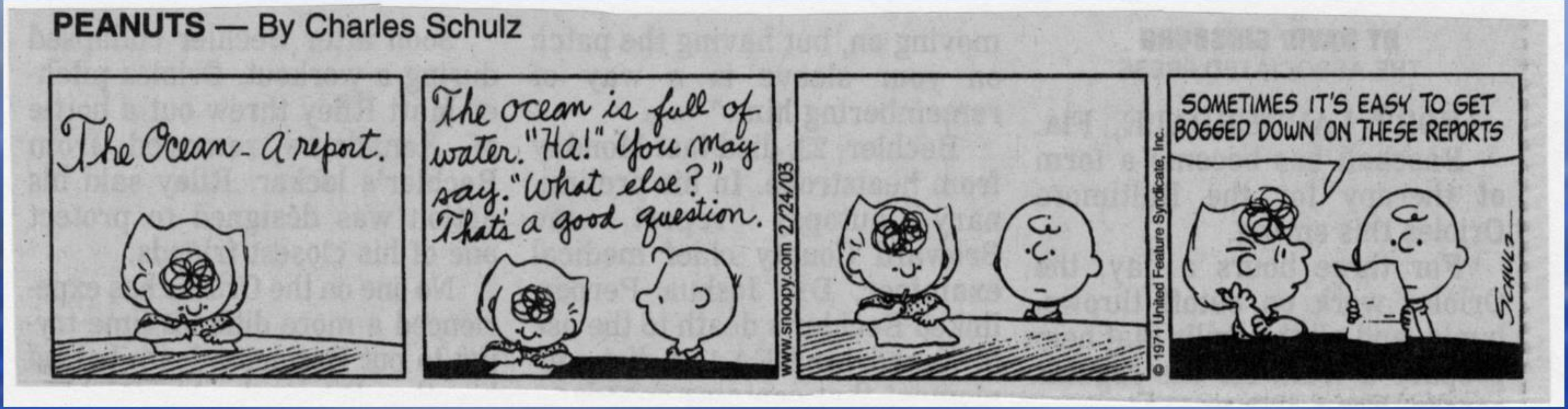

Living coral and algae forming reef
Calcareous beach sand
Ooids in channel
Calcareous mud in lagoon
Siliceous and calcareous plankton
Calcareous green algae
Restricted lagoon with evaporite formation
Reef
Calcareous ooze
Carbonate compensation depth
Siliceous ooze
Coarse clastic reef material
Siliceous sediment
Reef
Calcareous mud
Evaporites
Volcanic core of island


1 cm
Conch shell fragment
Coralline algae
Echinoderm
Holes created by boring organisms
Coral
(A)


1 mm
(A)


1 mm
(B)

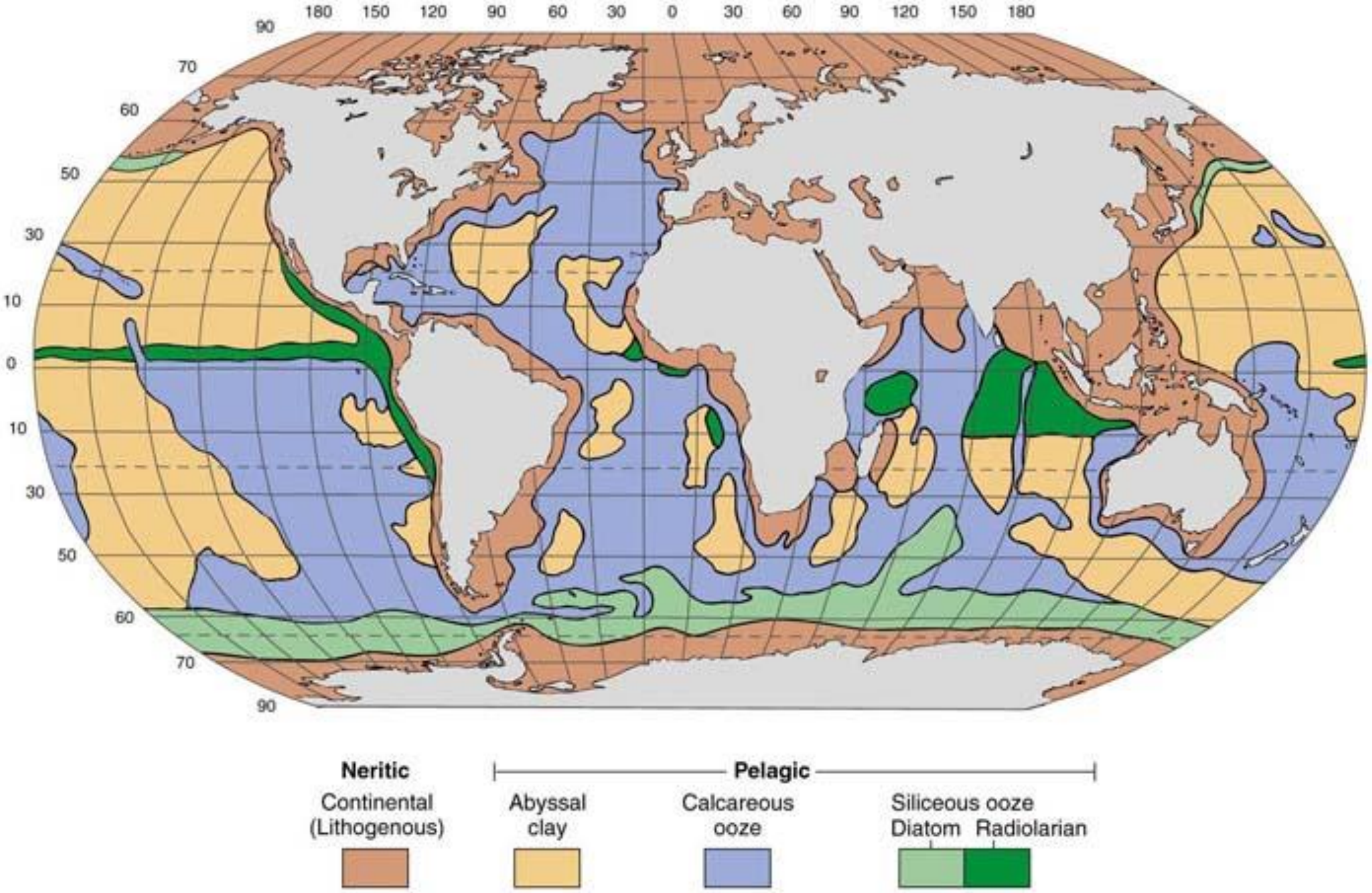
Origin and Distribution of Marine Sediments



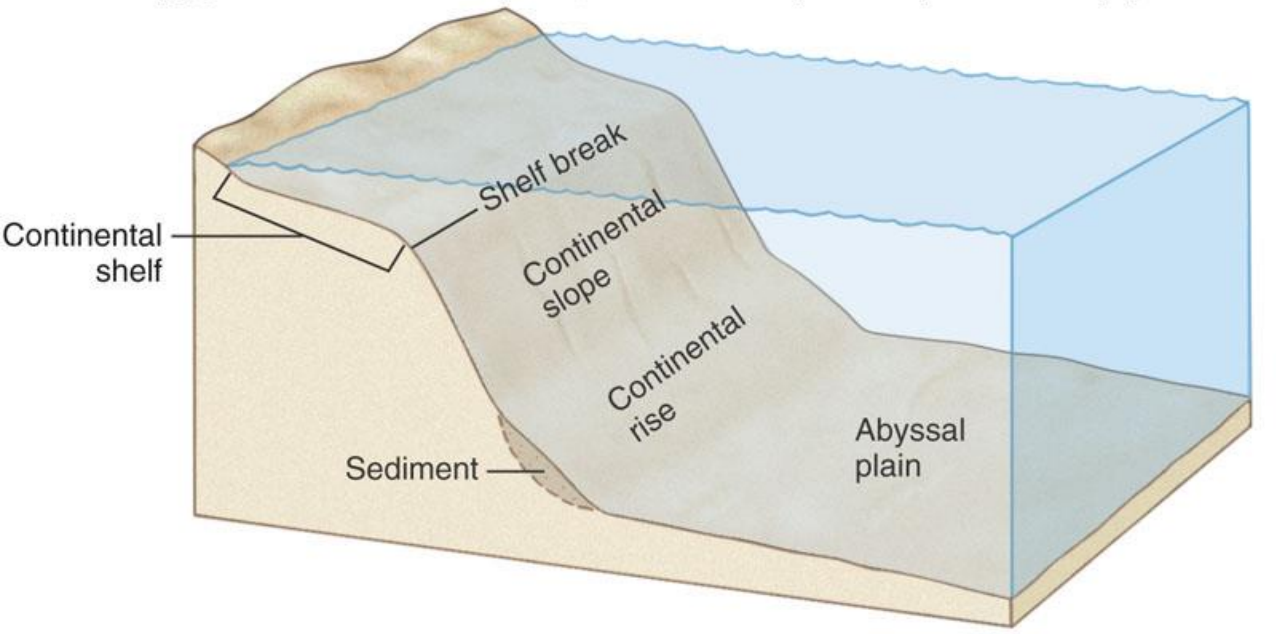
What's all that squishy muck at the bottom of the ocean?

What can we learn from it?

Sediment distribution in the ocean



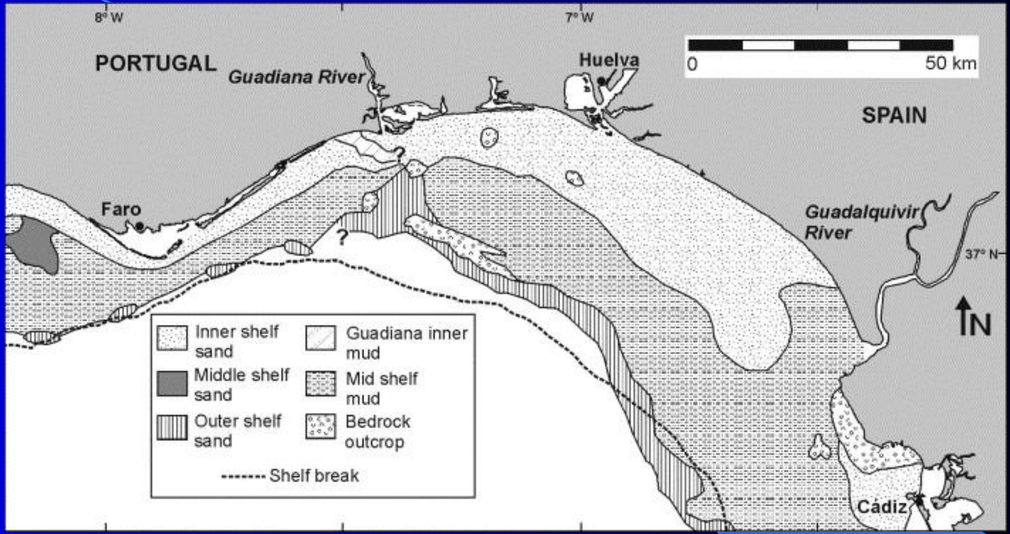
Continental Shelves



Processes affecting continental shelves
1. Glaciation
2. Sea-level change (±130 m during continental glaciation)
3. Waves and currents
4. Sedimentation
5. Carbonate deposits
6. Faulting and volcanism

Sedimentation on the Continental Shelf

Theoretical distribution – coarse near shore to fine-grained further out. Stoke's Law in action.
Observed – coarse to fine to coarse.

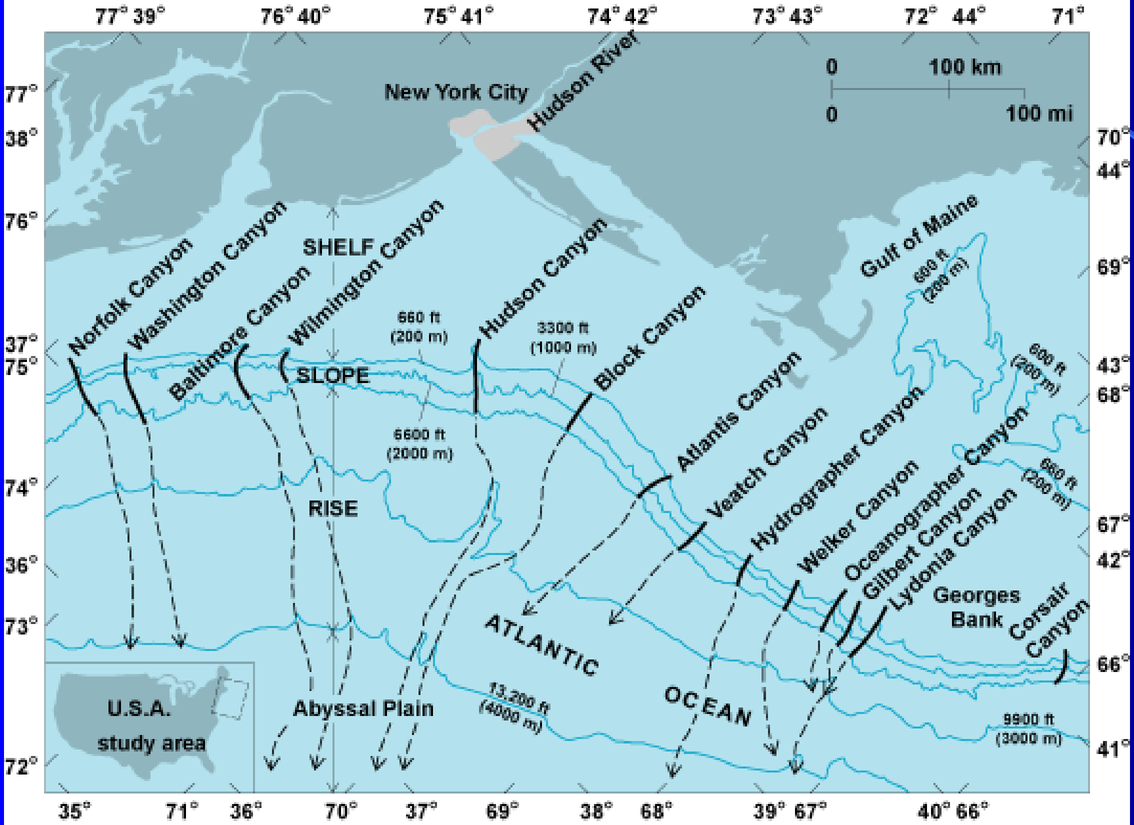


Holocene transgression – starts 10,000 years ago as continental glaciers formed during the maximum advance of the ice sheet begin to melt. Sea level rises ~125 m and continental margins are flooded.

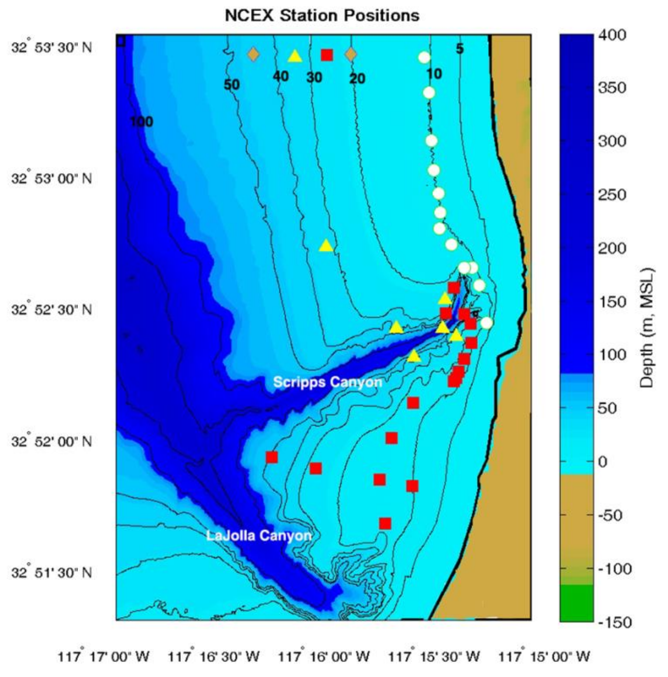
Sedimentary division of the shelf

a) Inner shelf – zone of modern sedimentation
b) Outer shelf – beyond the influence of modern sedimentation. Zone of relict sediment.

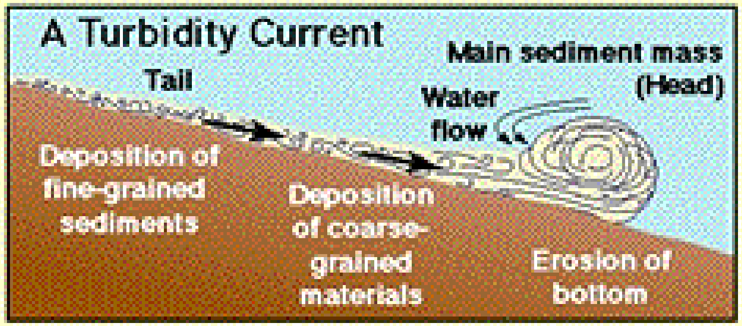
Submarine Canyons

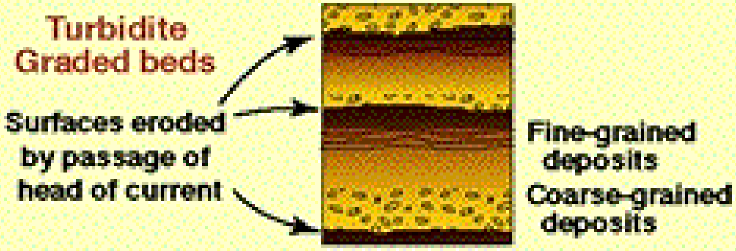


US Atlantic coast – passive continental margin

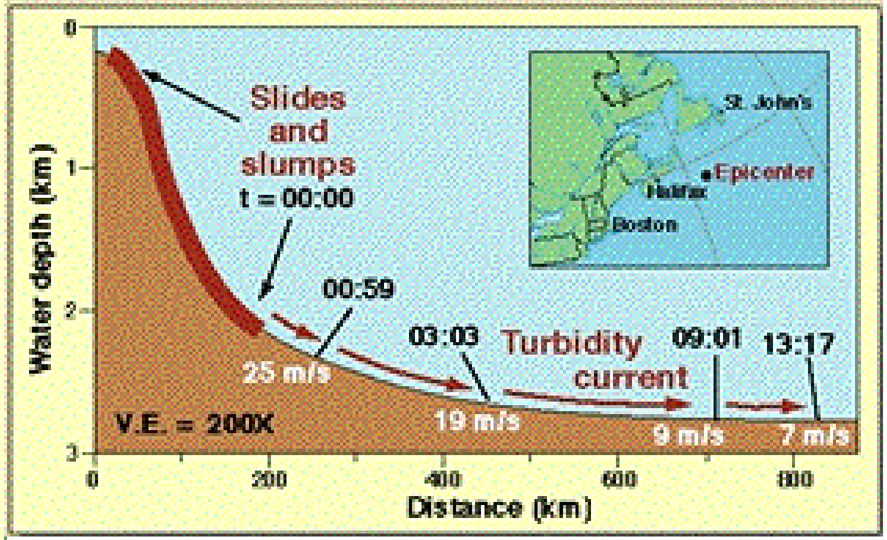

NCEX Station Positions

West coast of the US – active continental margin

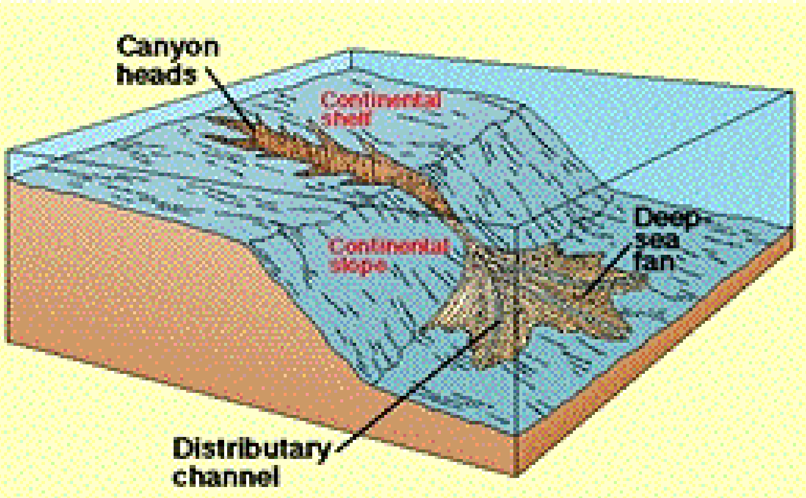




The 1929 Grand Banks Earthquake



A Submarine Canyon-Fan System



Deep Ocean Sediments

Sources of sediments:

1. Terrigenous – land derived (from elevated land masses)
2. Biogenic – marine plant and animal materials. May include inorganic material but only that created by marine organisms.
3. Volcanic – submarine volcanic materials. Volcanic material added directly to the seafloor.
4. Hydrogenic – materials crystallized directly from seawater. For example, manganese nodules.
5. Cosmic – particles of extraterrestrial origin. Cosmic dust, meteoritic particles

Major components of deep sea sediments

1. Detrital – derived mainly from erosion of the continents. Mostly alumino-silicate minerals.

Mineral	Composition
Quartz	SiO_2
Orthoclase	$KAlSi_3O_8$
Plagioclase	$NaAlSi_3O_8 \rightarrow CaAl_2Si_2O_8$
Kaolinite	$Al_2Si_2O_5(OH)_4$
Illite	$KAlSi_3O_{10}(OH)_2$
Montmorillonite	$Al_2Si_4O_{10}(OH)_2 \cdot xH_2O$
Chlorite	$Mg_5Al_5Si_3O_{10}(OH)_8$

2. Authigenic – formed by spontaneous crystallization either on the seafloor or within the sediment column

Manganese nodules – concretions found on the deep seafloor that consist of layers of iron and manganese oxide around a core.

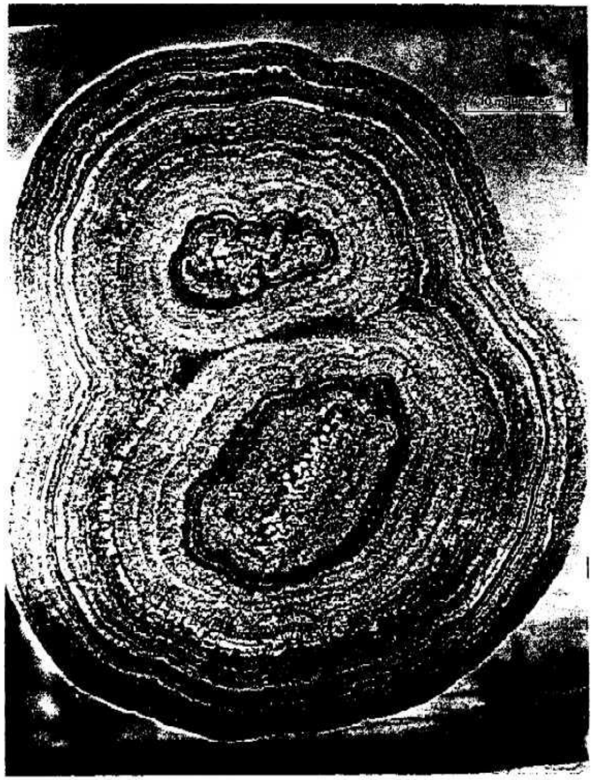
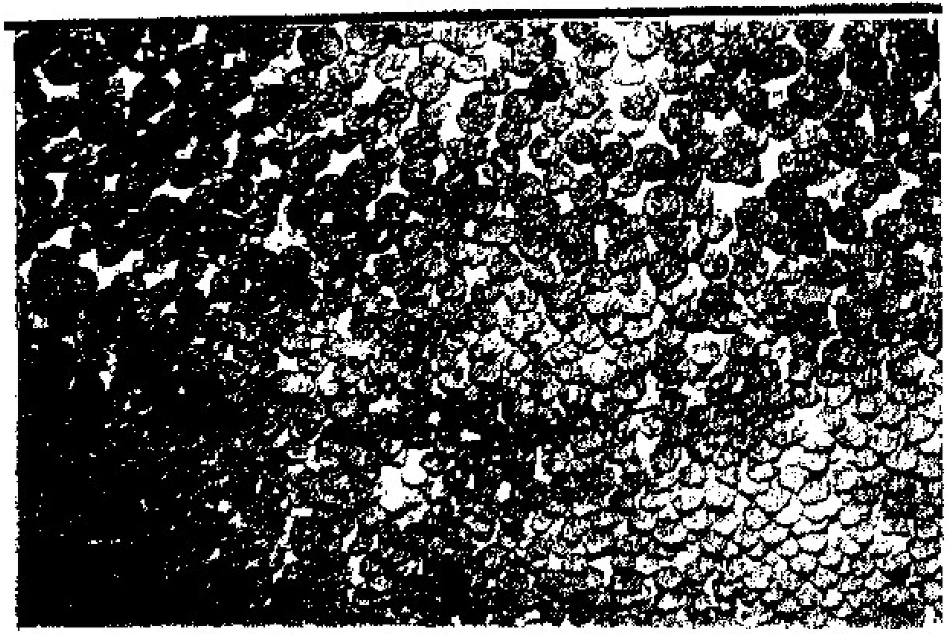
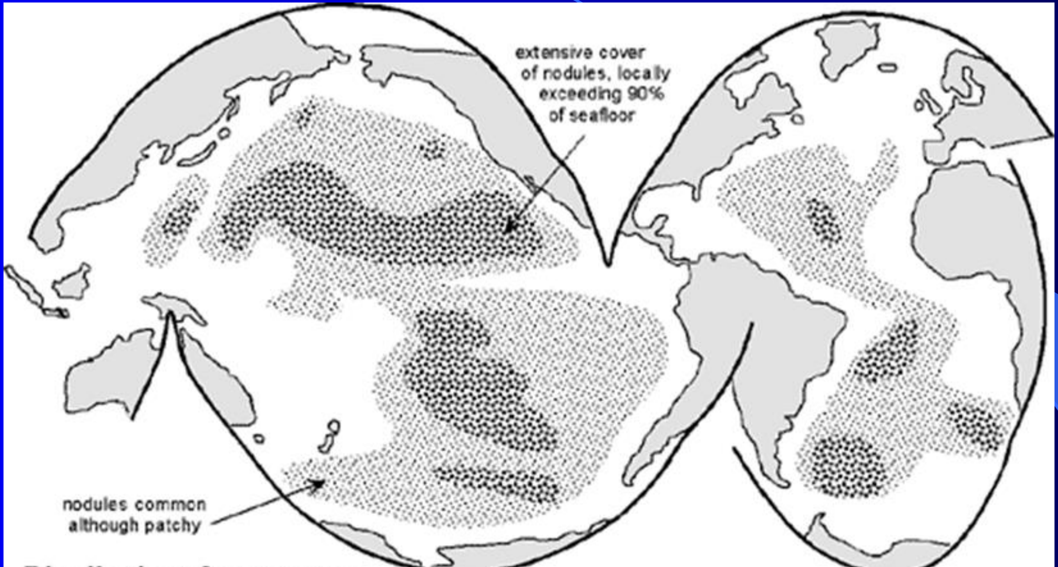


Figure 4-8 Photograph of a cross-sectional cut through a manganese nodule with two growth centers. The altered volcanic material at the centers nucleated the nodule's growth. Crude growth rings representing temporal changes in texture and composition can be seen. This nodule has a radius of 2 centimeters. At a growth rate of 2 mm/10^6 yrs, it must have commenced about 10,000,000 years ago.



A field of closely spaced manganese nodules at the bottom of the Antarctic Ocean. The average diameter of the nodules is 6 cm.

Manganese nodules occur in fields located in the deepest part of the ocean basins.



Distribution of manganese nodules in the Pacific and Atlantic Oceans

Most nodules are found within one meter of the surface. Given their inferred slow growth rates, millions of years, and the rate of sediment accumulation on the deep seafloor (~0.1 cm/1000 years = 1 m/million years) why they are found so close to the surface is a puzzle. Also not understood is how they achieve a concentric growth pattern given that bottom currents are very weak and the nodules are not moved along the seafloor.

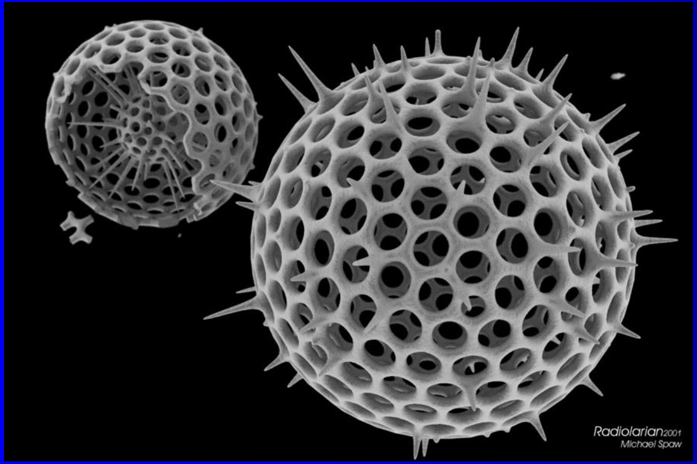
Major components of deep sea sediments

3. Biogenic – hard parts of organisms

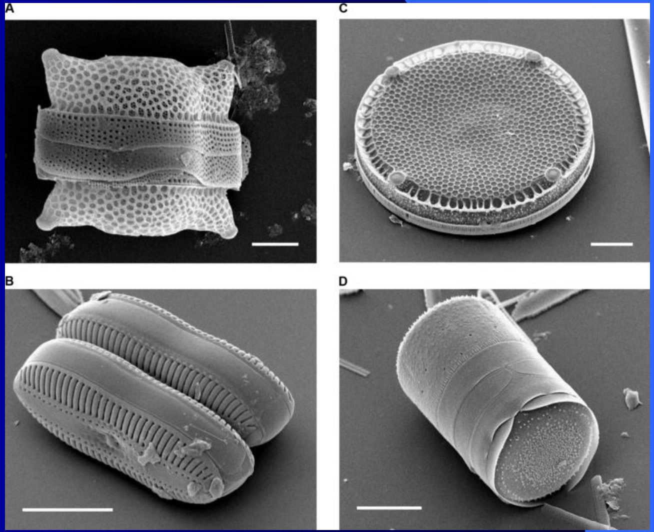
a. Calcite or aragonite shells (polymorphs of $CaCO_3$). Example –foraminifera

b. Opal – $SiO_2 \cdot xH_2O$. Examples – diatoms (cold water), radiolaria (warm water).

Foraminifera



Diatoms



Radiolaria

Transport of terrigenous material to the open ocean

1. Suspension – sinking velocity of particle (as determined by Stoke's Law) less than upward velocity due to turbulence.

   $$V = \frac{2}{9}\frac{g(\rho_s - \rho_f)r^2}{\mu}$$

   for water (at 20^{o}C), $\mu = 1.0 \times 10^{-3}$ Pa·s

2. Ice Rafting – glacial marine deposits around areas of glaciation.
3. Winds
4. Mudslides, landslides, turbidites
5. Marine algae anchored to rocks
6. Marine mammals (e.g. gastroliths)

Biogenic Sediments

Opal ($SiO_2 \cdot xH_2O$)

1. The oceans are undersaturated in opal at all depths.
2. Various microscopic organisms make opaline shells.
3. Preservation of this shell material is a function of
   a) Wall thickness
   b) Surface/volume ratio
   c) Organic coatings
4. Production is the key to the preservation of opal in deep sea sediments.
5. In the sediment column, opal is preserved because the pore waters become saturated in silica.

Calcite and aragonite ($CaCO_3$)

1. Production of $CaCO_3$ hard parts is more uniform than opal. Limiting factor is nutrient elements.
2. The upper part of the ocean is saturated in $CaCO_3$ (both aragonite and calcite).
3. Spontaneous precipitation takes place very slowly or not at all in the saturated part of the ocean. Organisms are primarily responsible for the precipitation of $CaCO_3$.
4. For calcite or aragonite in the ocean

$$Degree\ of\ saturation = D = \frac{([Ca^{2+}][CO_3^{2-}\ )_{measured\ in\ seawater}}{([Ca^{2+}][CO_3^{2-}])_{saturated\ seawater}}$$

since Ca^{2+} is more or less constant in seawater

$$D = \frac{[co_3^{2-}]_{measured}}{[co_3^{2-}]_{saturated\ seawater}}$$

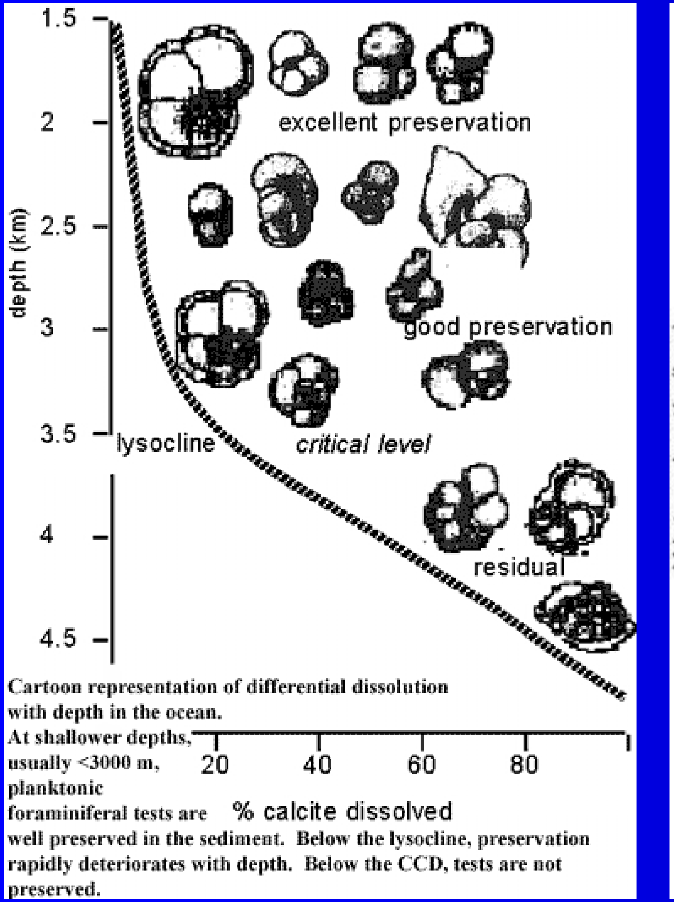
5. Solubility of calcite and aragonite f(T,P). 100 Atm = 1000 m depth

		Saturation $[CO_3^{2-}]$ 10^{-6} moles/liter	
T(°C)	P(Atm)	Calcite	Aragonite
24	1	53	90
2	1	72	110
2	250	97	144
2	500	130	190

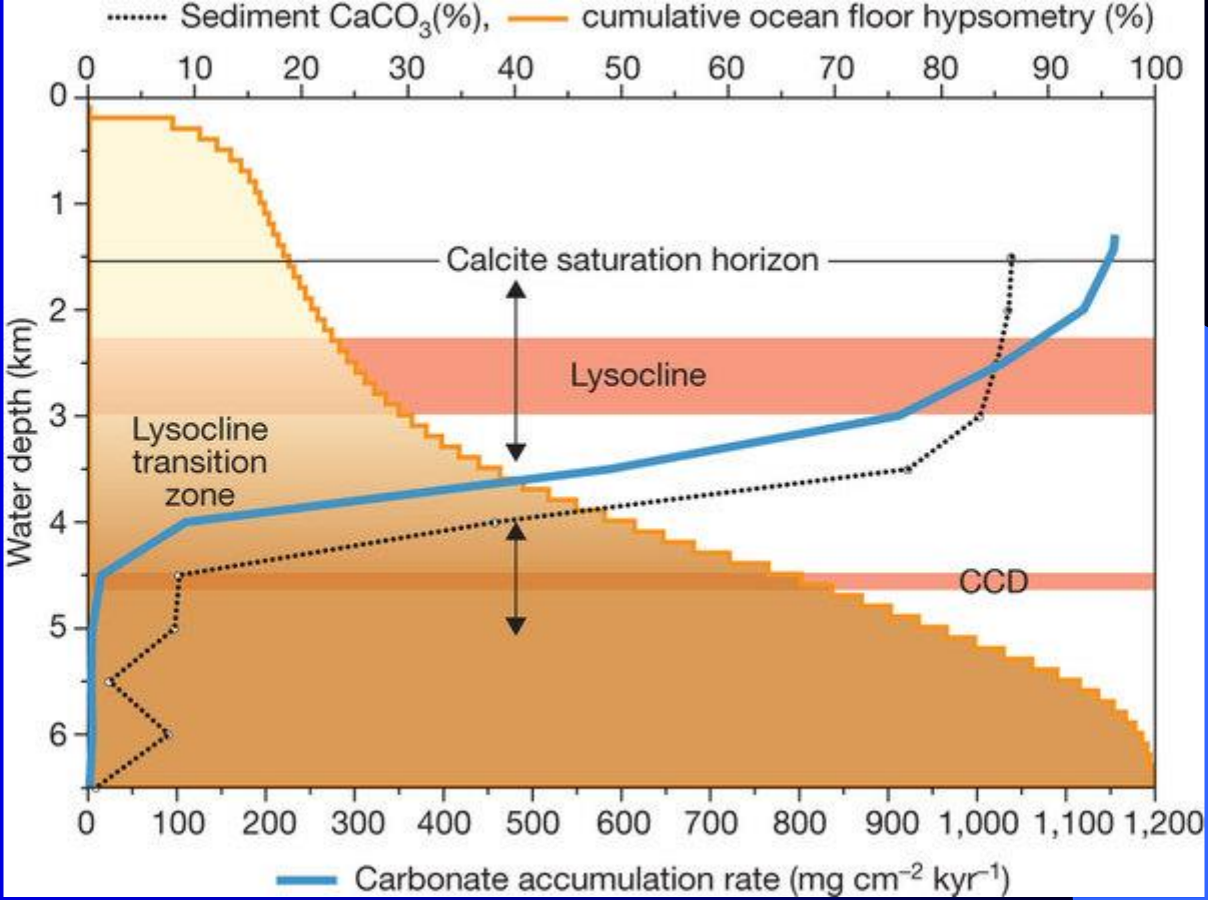
6. **Saturation horizon** – depth at which ocean becomes undersaturated in carbonate.

7. **Lysocline** – region of rapidly changing carbonate saturation.

8. **Carbonate compensation depth (CCD)** – depth below which carbonates are not found in the seafloor sediments.



Cartoon representation of differential dissolution with depth in the ocean. At shallower depths, usually <3000 m, planktonic foraminiferal tests are well preserved in the sediment. Below the lysocline, preservation rapidly deteriorates with depth. Below the CCD, tests are not preserved.



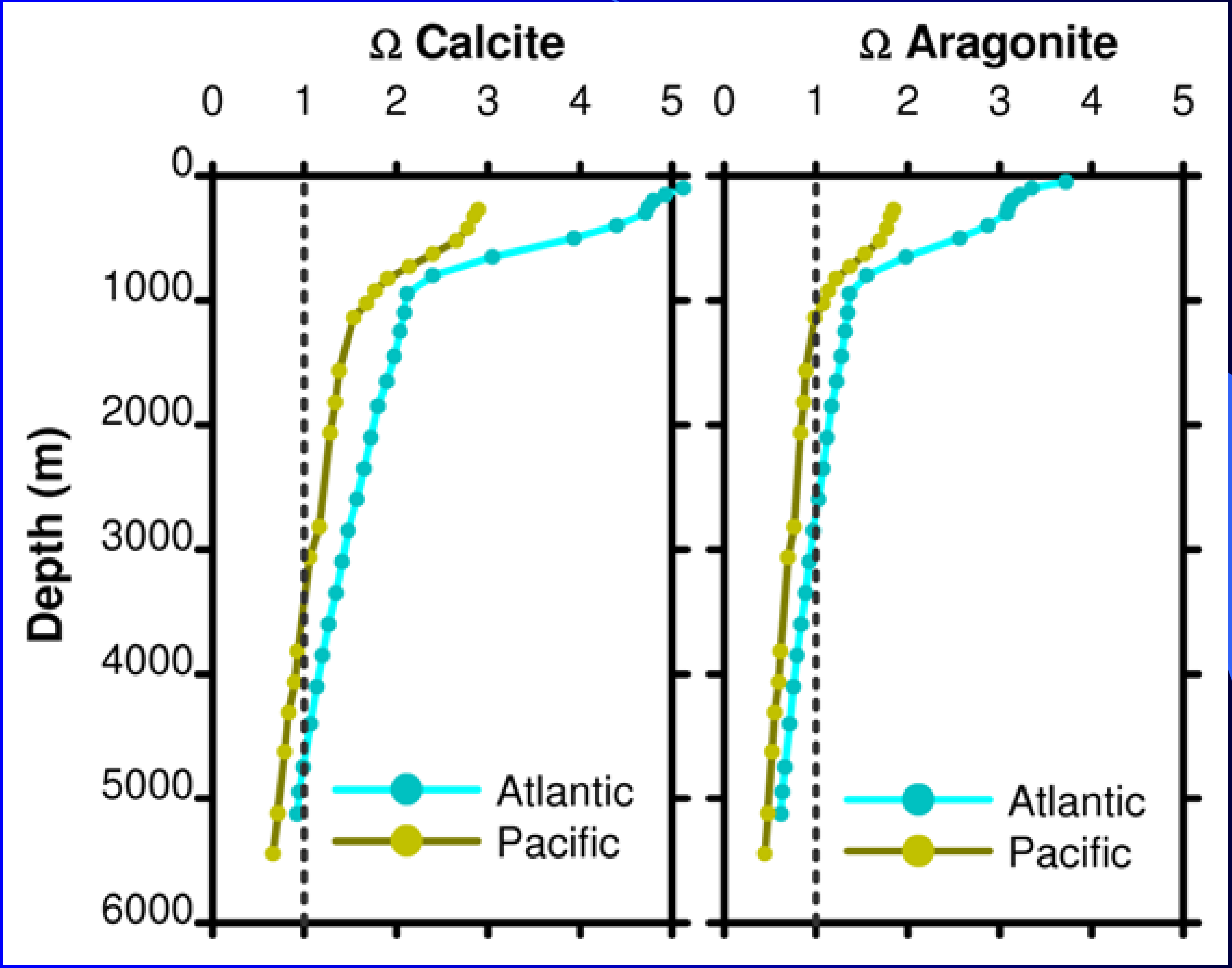
8. Throughout the ocean red clay (alumino-silicate debris) is raining down at an average rate of 0.3 g/cm^2·1000 yrs and $CaCO_3$ at a rate of 1.0 g/cm^2·1000 yrs. If a particular location is above the saturation horizon the sediment is 3 parts clay to 10 parts carbonate ooze. Below the saturation horizon the sediment is dominantly composed of red clay.

9. 60% of the Atlantic seafloor is above the saturation horizon and carbonate ooze is the dominant sediment. 15% of the Pacific seafloor is above the saturation horizon and red clay is the dominant sediment type.

10. Location of the saturation horizon compared to the CCD

	Aragonite		**Calcite**	
	Calc.	CCD	Calc.	CCD
Atlantic	200-400 m	~300 m	400-3500 m	3500 m
Pacific	2000 m	2500 m	4500 m	5000 m

Calcite and Aragonite Saturation in Ocean



Variations of sediment types due to seafloor spreading

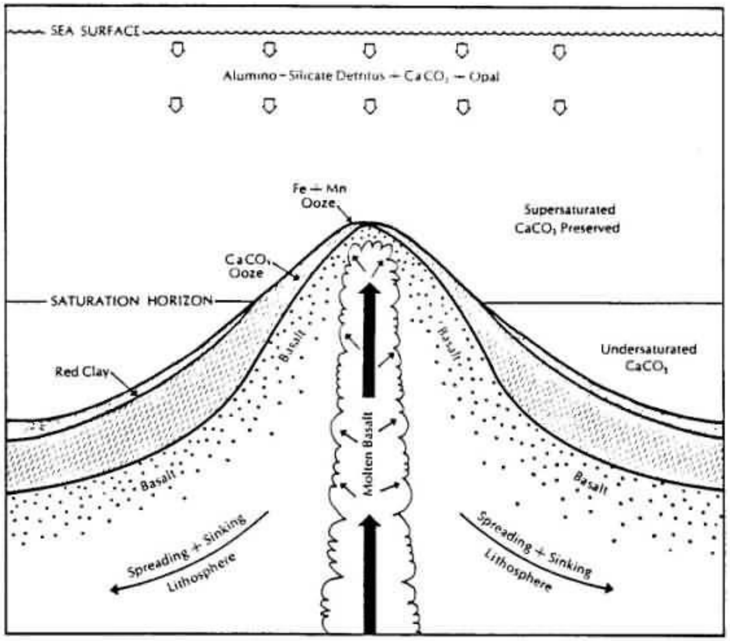


Figure 2-8 Sequence of sediment types accumulated by the great lithospheric plates as they move away from the crests of mid-ocean rises. The first sediment to be deposited is iron (Fe) + manganese (Mn) oxide, a product of volcanism. When a point a few kilometers away from the crest is reached, the sediment no longer receives volcanic products and is dominated by $CaCO_3$ falling from the surface. At a point several hundred kilometers from the crest, the plate subsides below the saturation horizon for calcite and $CaCO_3$ no longer accumulates. Beyond this point, continental detritus and perhaps opal dominate the sediment. A core bored through sediment capped with red clay would encounter buried $CaCO_3$ and then a thin layer of Fe + Mn-rich sediment before entering the underlying basalt (hard rock).

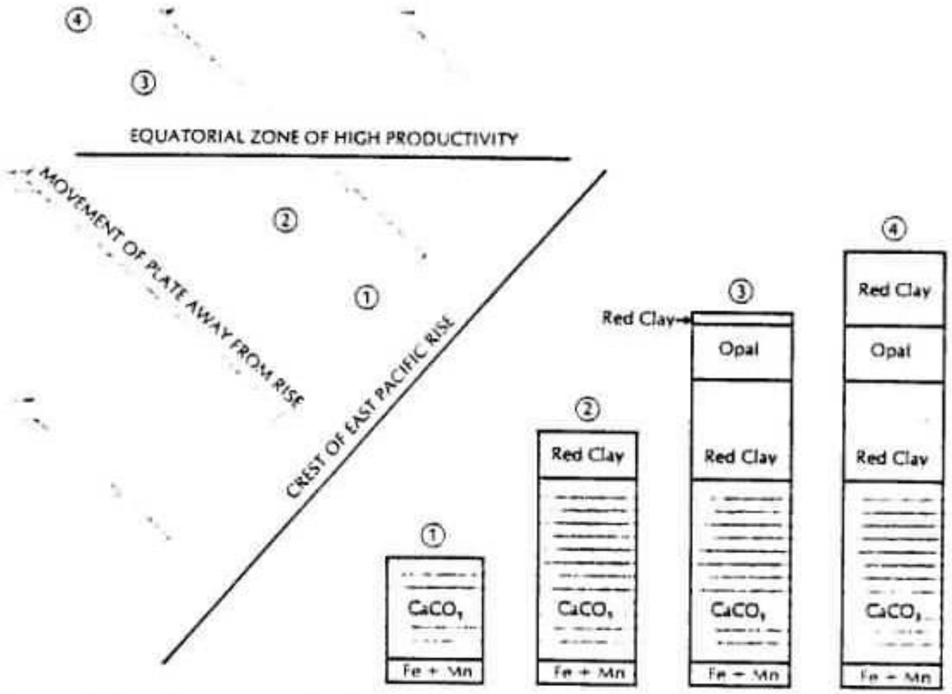
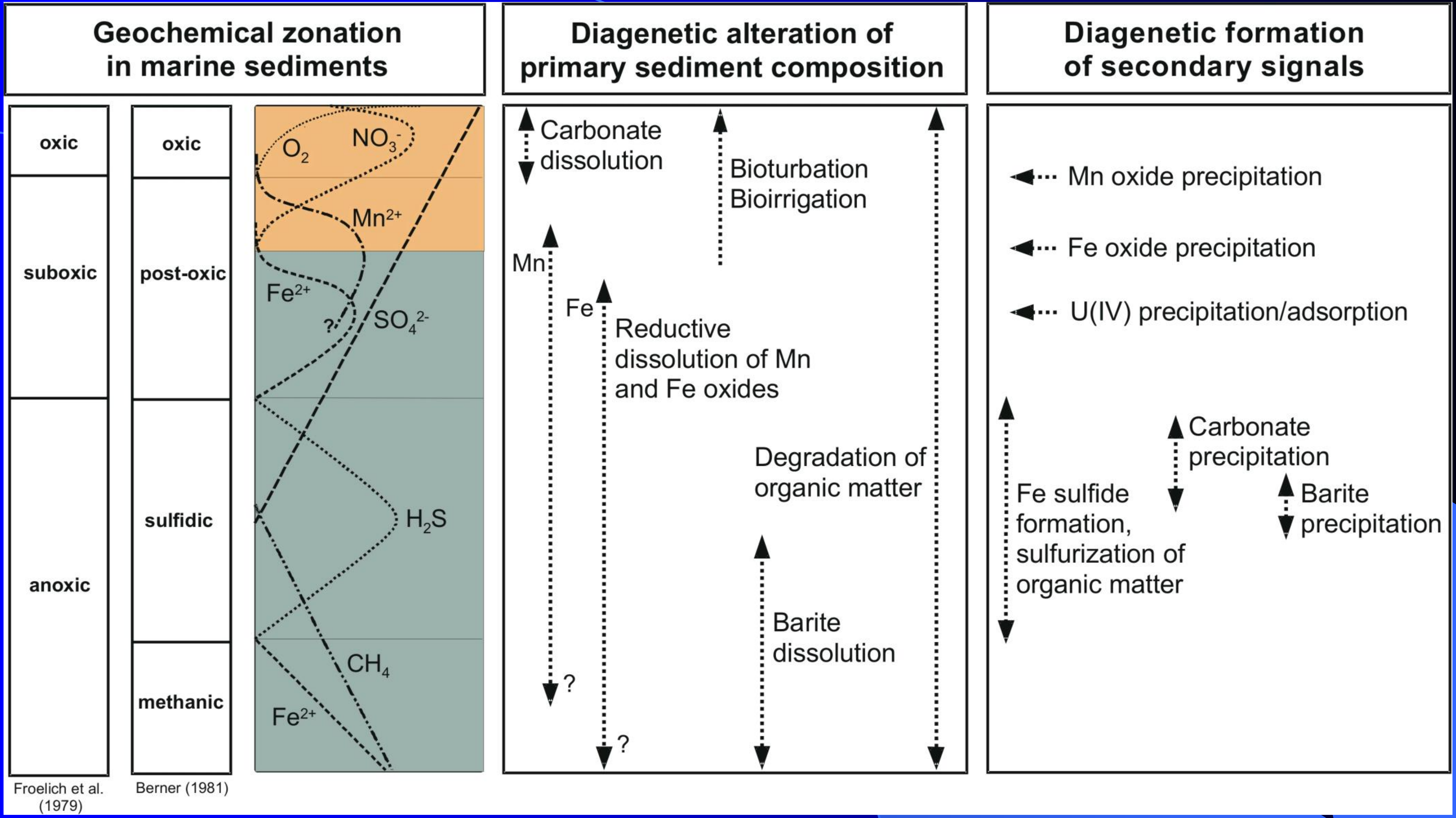
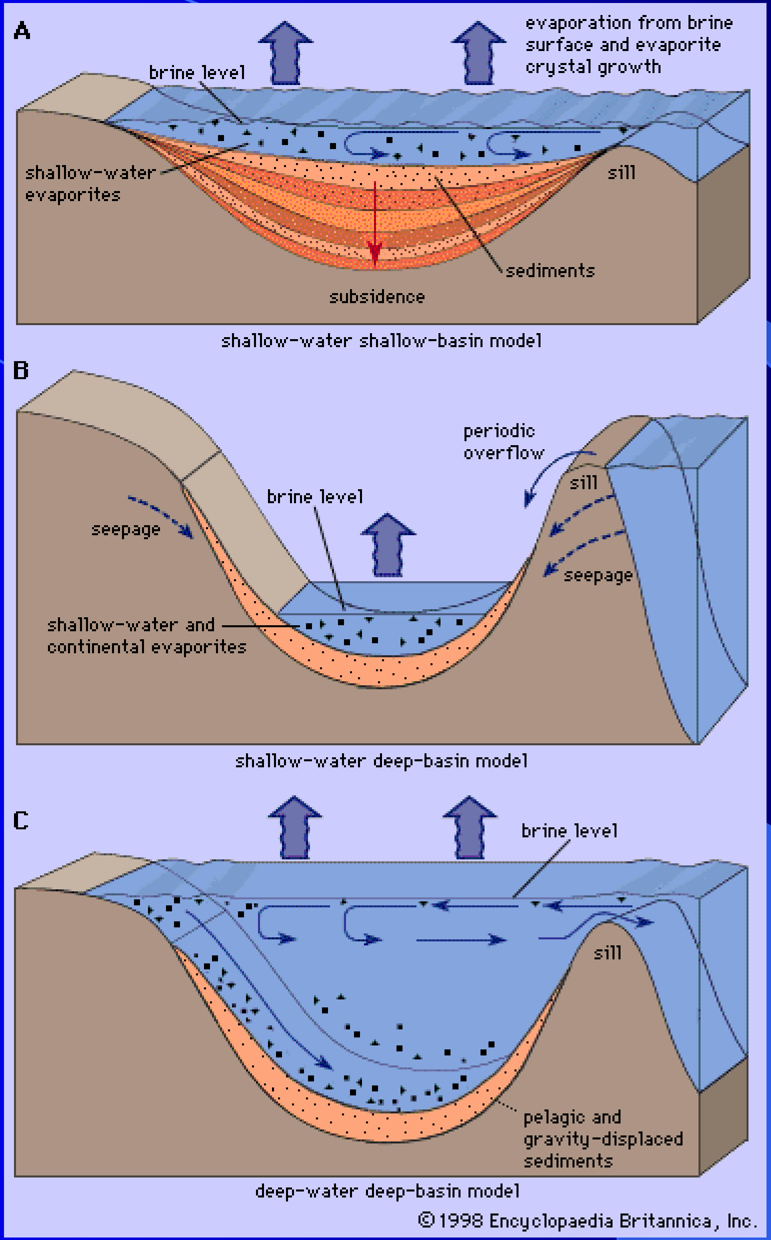


Figure 2-9 Sequence of sediments accumulating on a plate which crosses the high productivity equatorial belt in its movement away from a ridge crest. The numbers relate the map locations to the corresponding sedimentary sequences found in borings made at these points.


Geochemical zonation in marine sediments
oxic
suboxic
anoxic
Froelich et al. (1979)
oxic
post-oxic
sulfidic
methanic
Berner (1981)
O_2
NO_3^-
Mn^{2+}
Fe^{2+}
?
SO_4^{2-}
H_2S
CH_4
Fe^{2+}
Diagenetic alteration of primary sediment composition
Carbonate dissolution
Bioturbation Bioirrigation
Mn
?
Fe
?
Reductive dissolution of Mn and Fe oxides
Degradation of organic matter
Barite dissolution
Diagenetic formation of secondary signals
Mn oxide precipitation
Fe oxide precipitation
U(IV) precipitation/adsorption
Carbonate precipitation
Fe sulfide formation, sulfurization of organic matter
Barite precipitation

Evaporite Deposits

Gypsum layers



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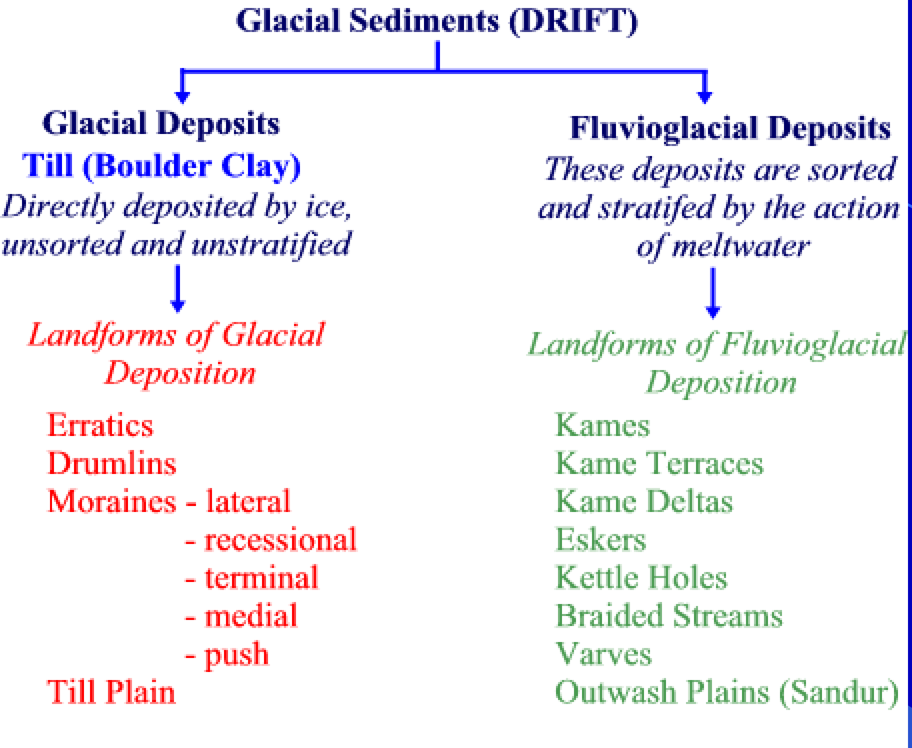
Gypsum and marl in Triassic deposits in the spanish Pyrenees.



Glacial Sediments (DRIFT)

Glacial Deposits

Till (Boulder Clay)

Directly deposited by ice, unsorted and unstratified

Landforms of Glacial Deposition

- Erratics
- Drumlins
- Moraines - lateral
  - recessional
  - terminal
  - medial
  - push
- Till Plain

Fluvioglacial Deposits

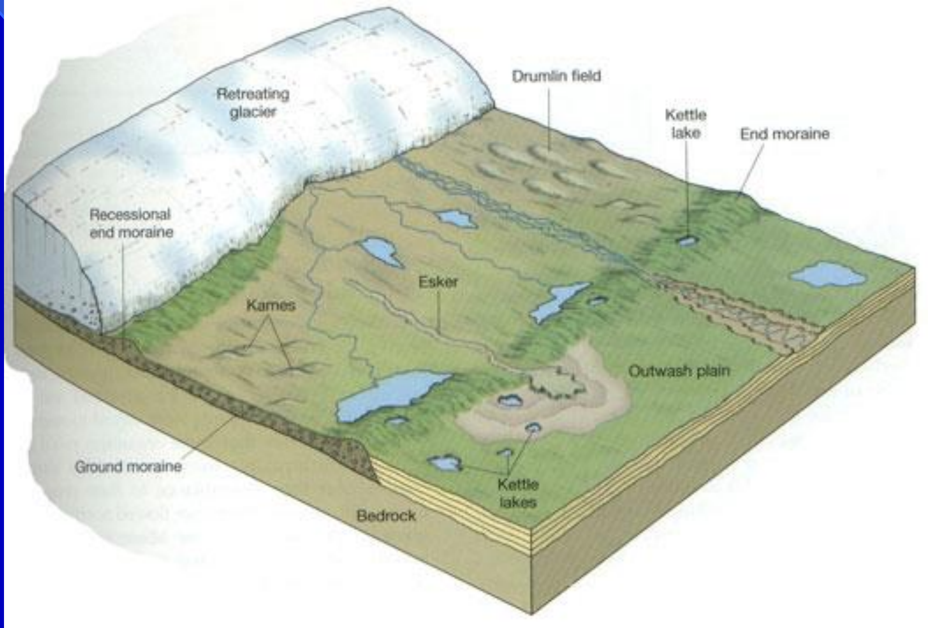
These deposits are sorted and stratifed by the action of meltwater

Landforms of Fluvioglacial Deposition

- Kames
- Kame Terraces
- Kame Deltas
- Eskers
- Kettle Holes
- Braided Streams
- Varves
- Outwash Plains (Sandur)

Varves

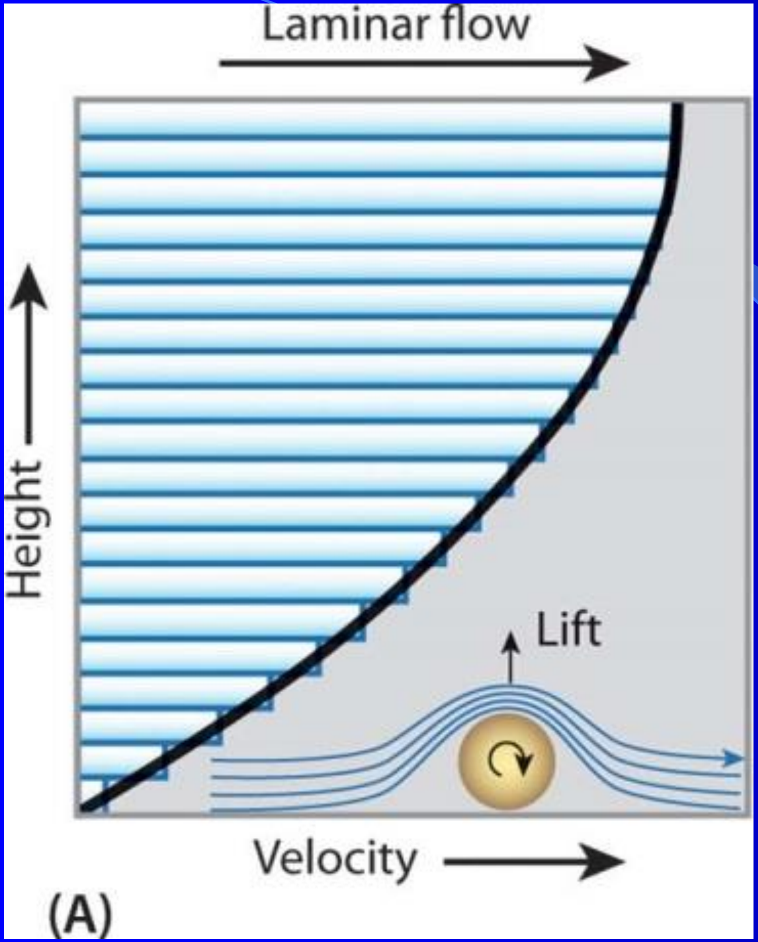
Till

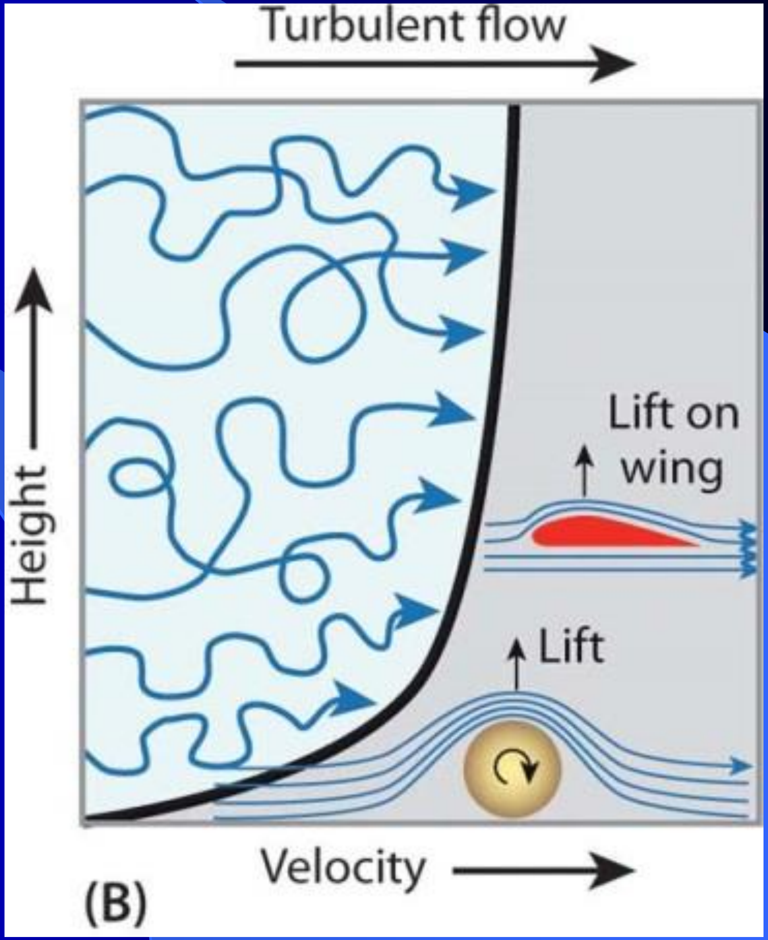


R_e = (4 x hydraulic radius x density x average velocity)/viscosity

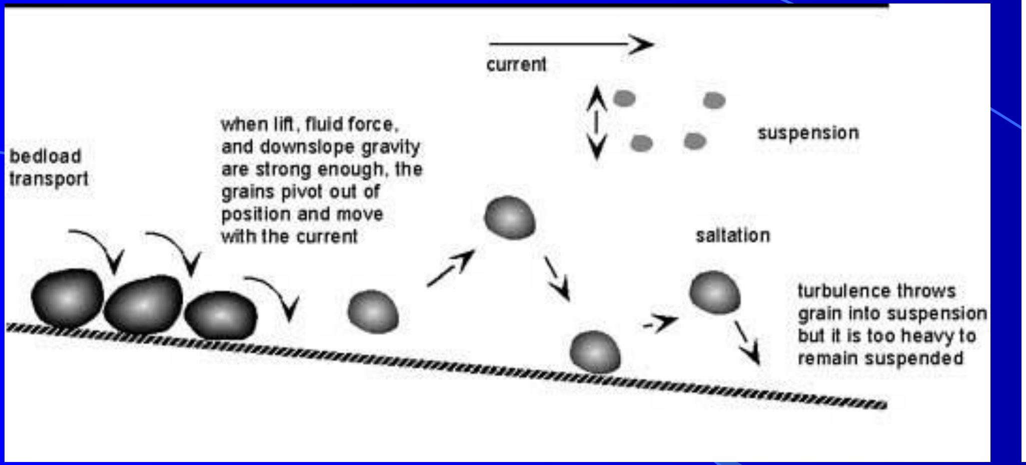
R_e <500 Laminar

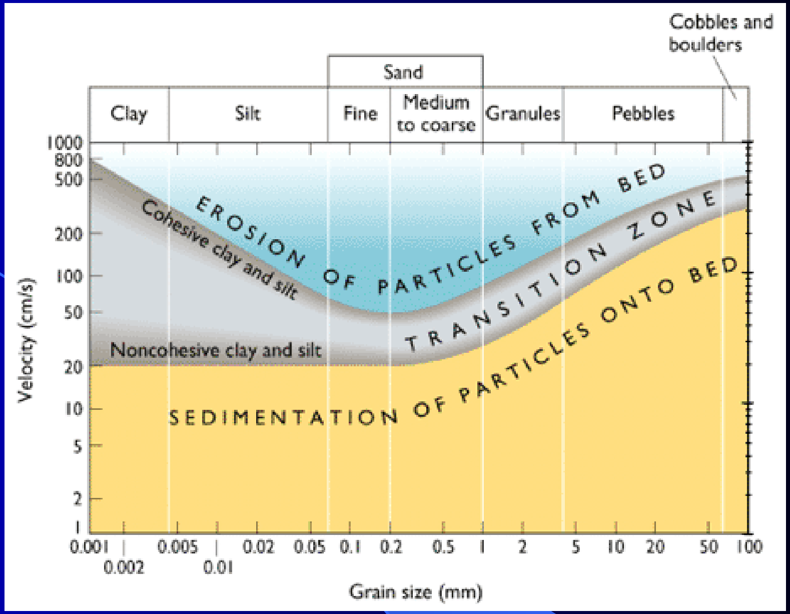
R_e >2000 Turbulent

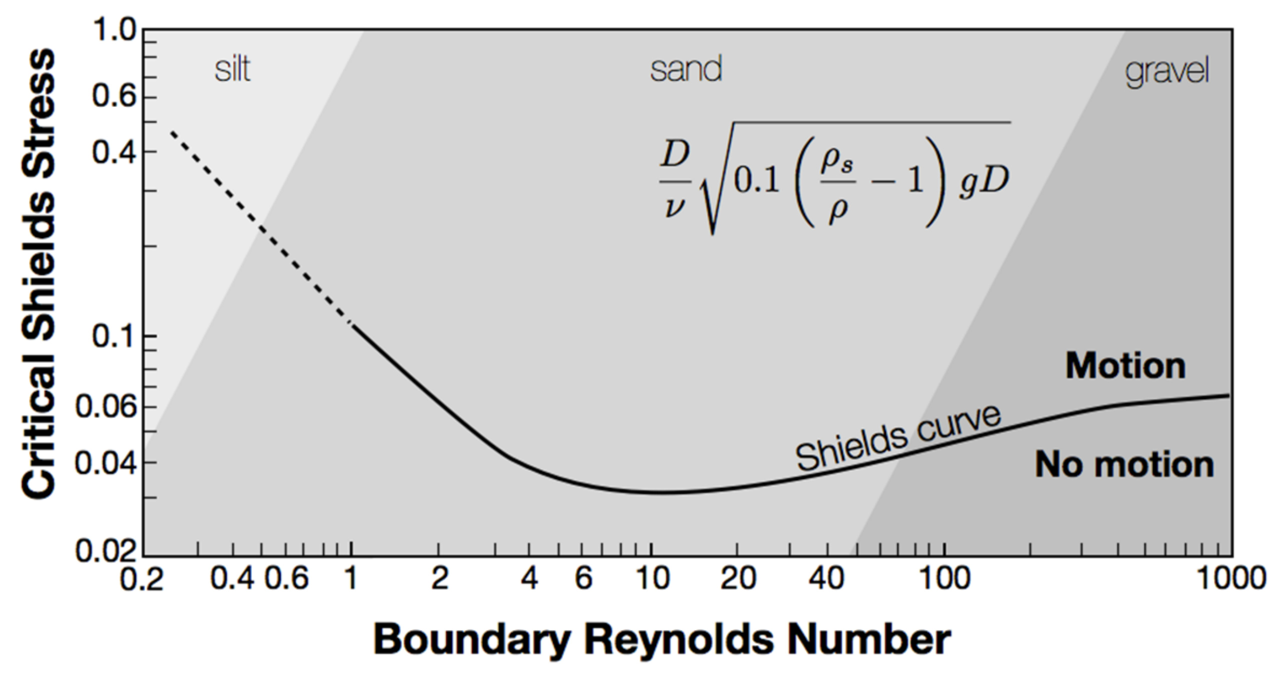




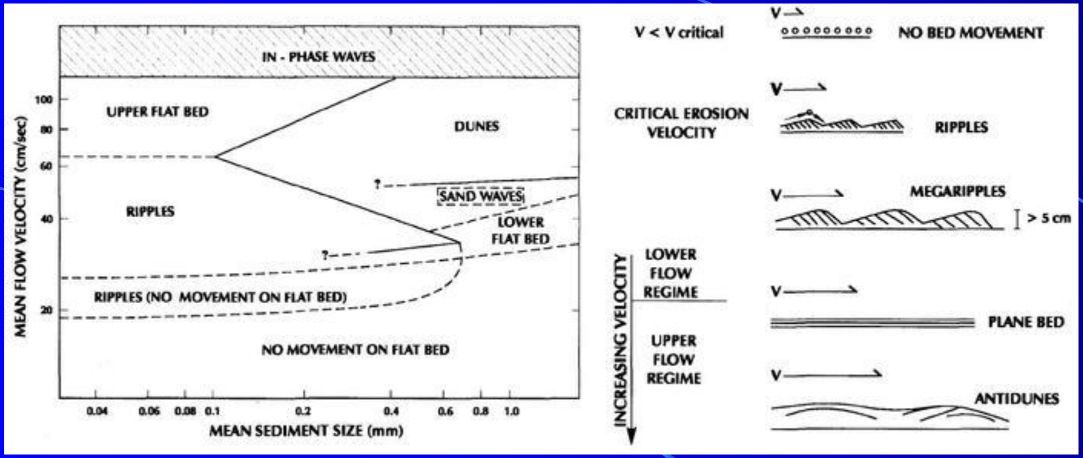
Sediment Transport

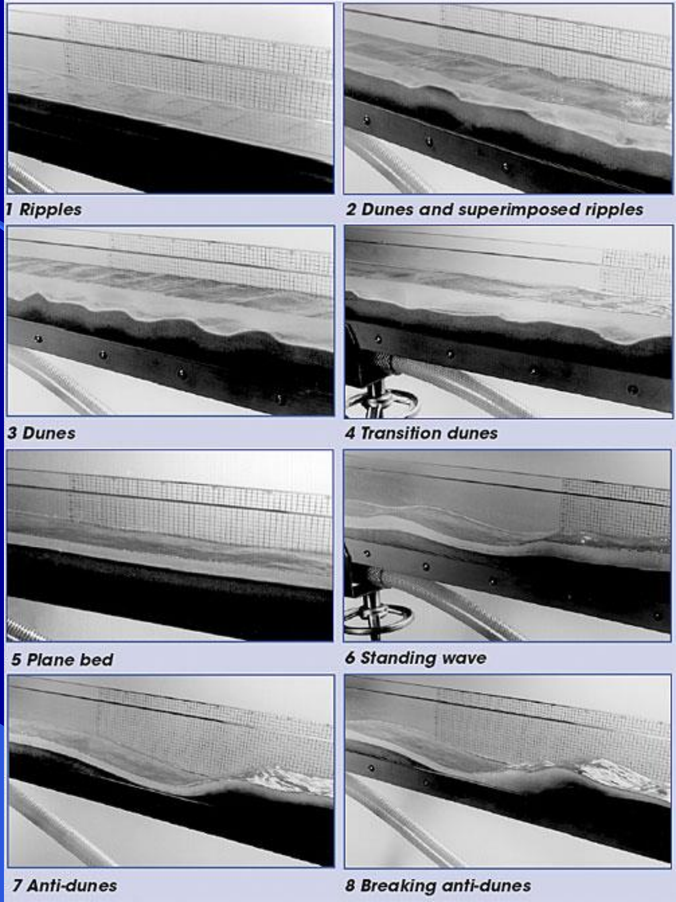






Bedforms




1 Ripples
2 Dunes and superimposed ripples
3 Dunes
4 Transition dunes
5 Plane bed
6 Standing wave
7 Anti-dunes
8 Breaking anti-dunes

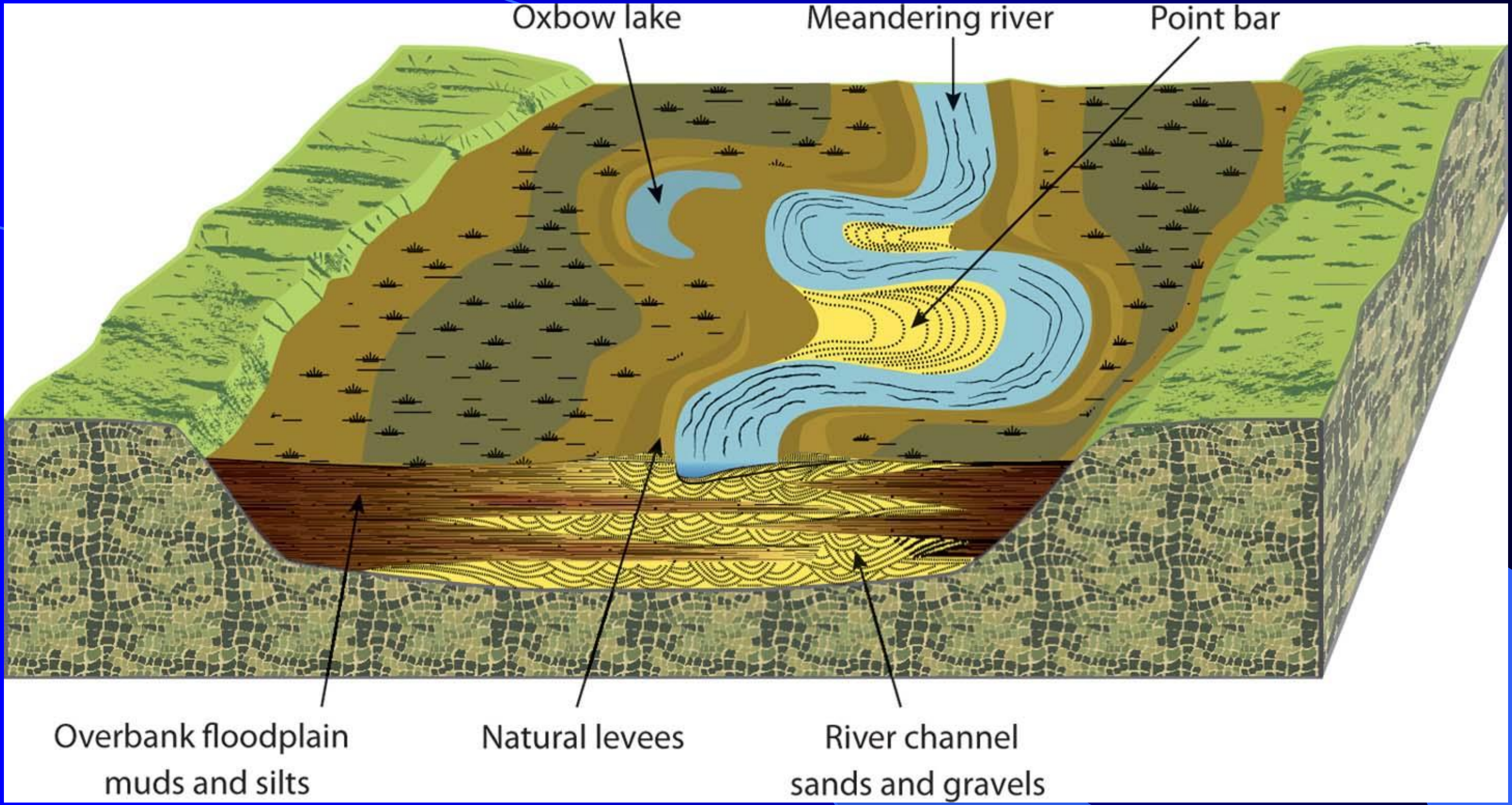

Ripples

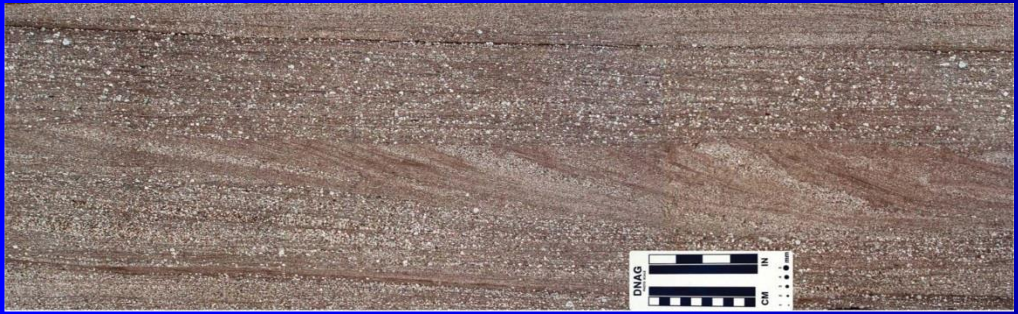

Antidunes

Ripple Migration

Oscillation Ripples

Antidunes/Upper Plane Bed

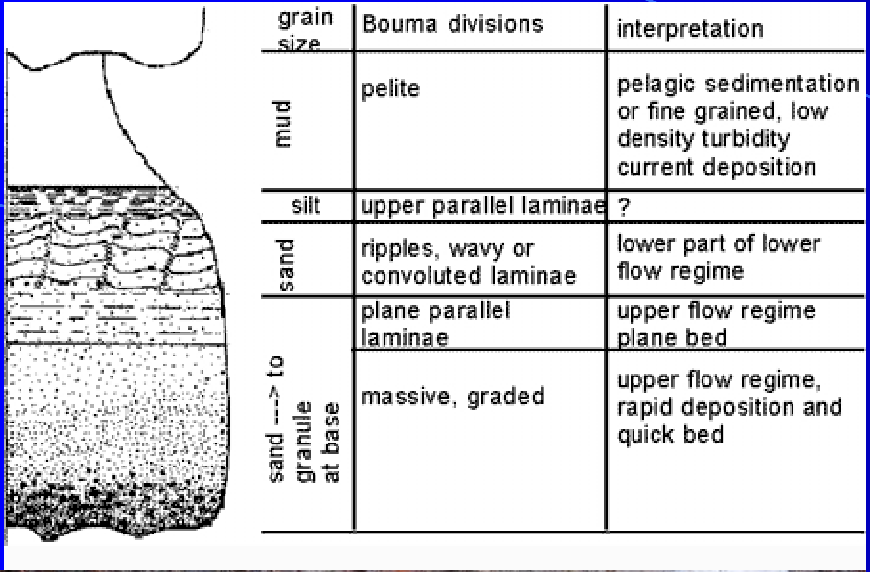

Oxbow lake
Meandering river
Point bar
Overbank floodplain muds and silts
Natural levees
River channel sands and gravels


DNAG
IN
CM

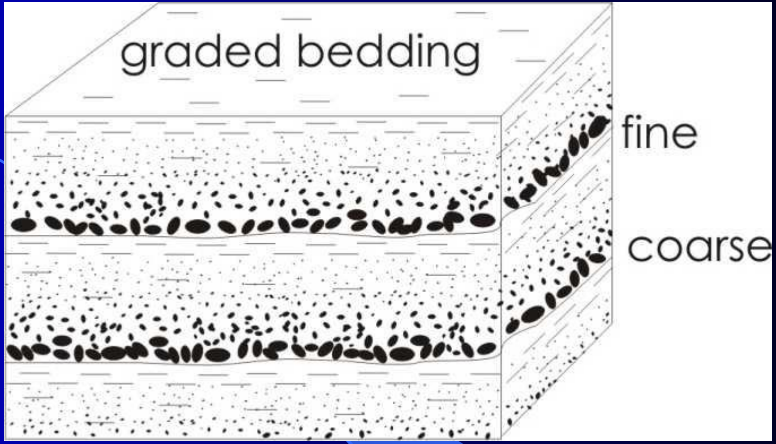

3


4

Turbidity Currents



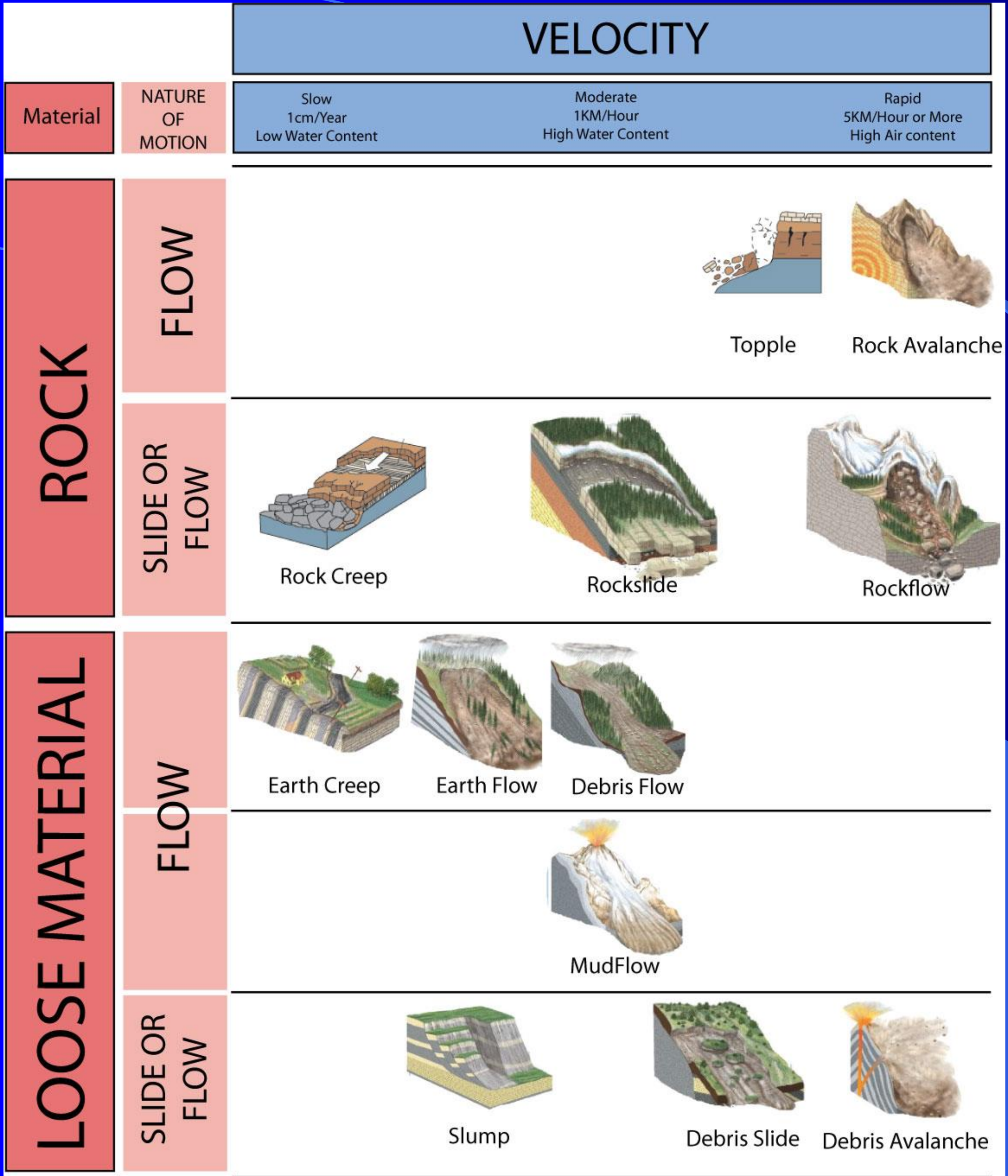
grain size	Bouma divisions	interpretation
mud	pelite	pelagic sedimentation or fine grained, low density turbidity current deposition
silt	upper parallel laminae	?
sand	ripples, wavy or convoluted laminae	lower part of lower flow regime
sand ---> to granule at base	plane parallel laminae	upper flow regime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

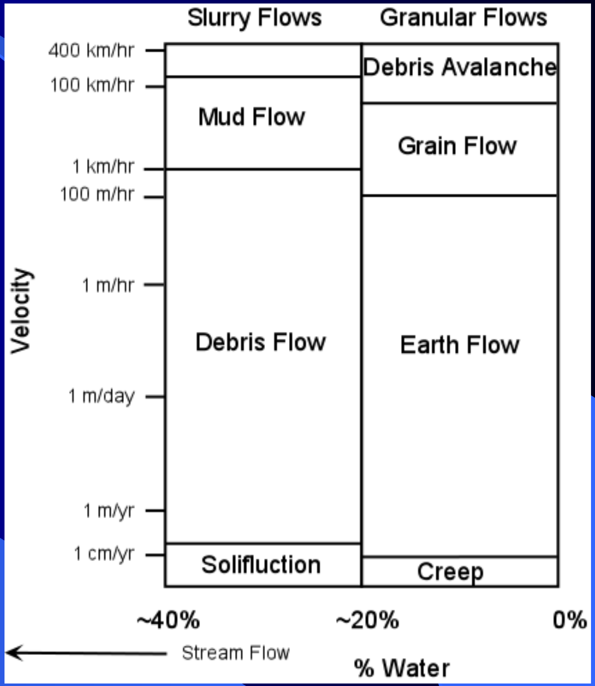


Turbidity current I

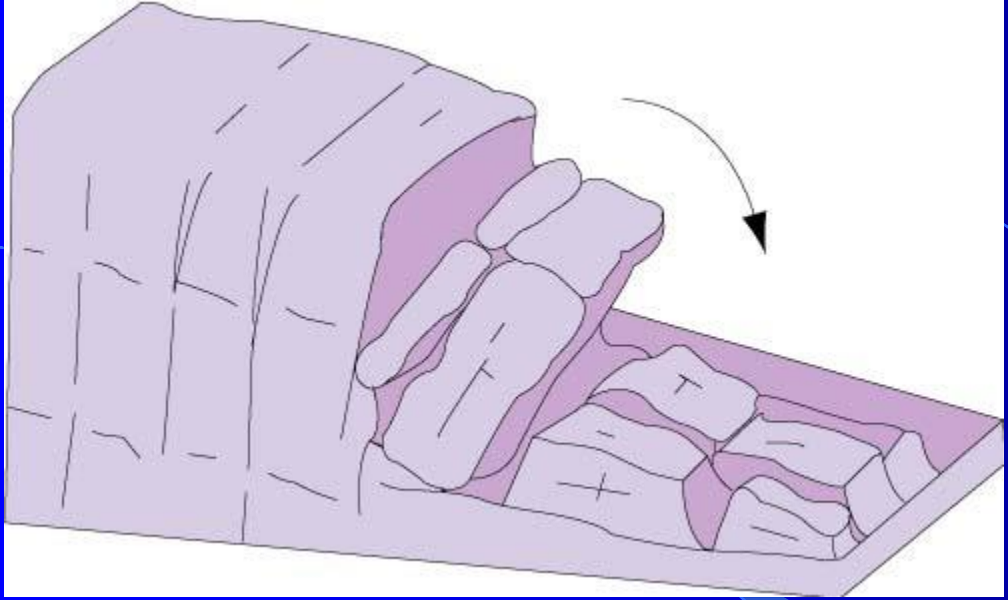
Turbidity current II

Mass Movement


VELOCITY
Material
NATURE OF MOTION
Slow
1cm/Year
Low Water Content
Moderate
1KM/Hour
High Water Content
Rapid
5KM/Hour or More
High Air content
ROCK
FLOW
Topple
Rock Avalanche
SLIDE OR FLOW
Rock Creep
Rockslide
Rockflow
LOOSE MATERIAL
FLOW
Earth Creep
Earth Flow
Debris Flow
FLOW
MudFlow
SLIDE OR FLOW
Slump
Debris Slide
Debris Avalanche


Slurry Flows
Granular Flows
400 km/hr
100 km/hr
1 km/hr
100 m/hr
1 m/hr
1 m/day
1 m/yr
1 cm/yr
Velocity
Mud Flow
Debris Flow
Solifluction
Debris Avalanche
Grain Flow
Earth Flow
Creep
~40%
~20%
0%
Stream Flow
% Water

Topple



Topple in Portland Stone, south of Mutton Cove, Portland.
'The Leaning Stack' Ian West (c) 2002.

Topple video

Rock Avalanche

Rock Avalanche video

Rock creep

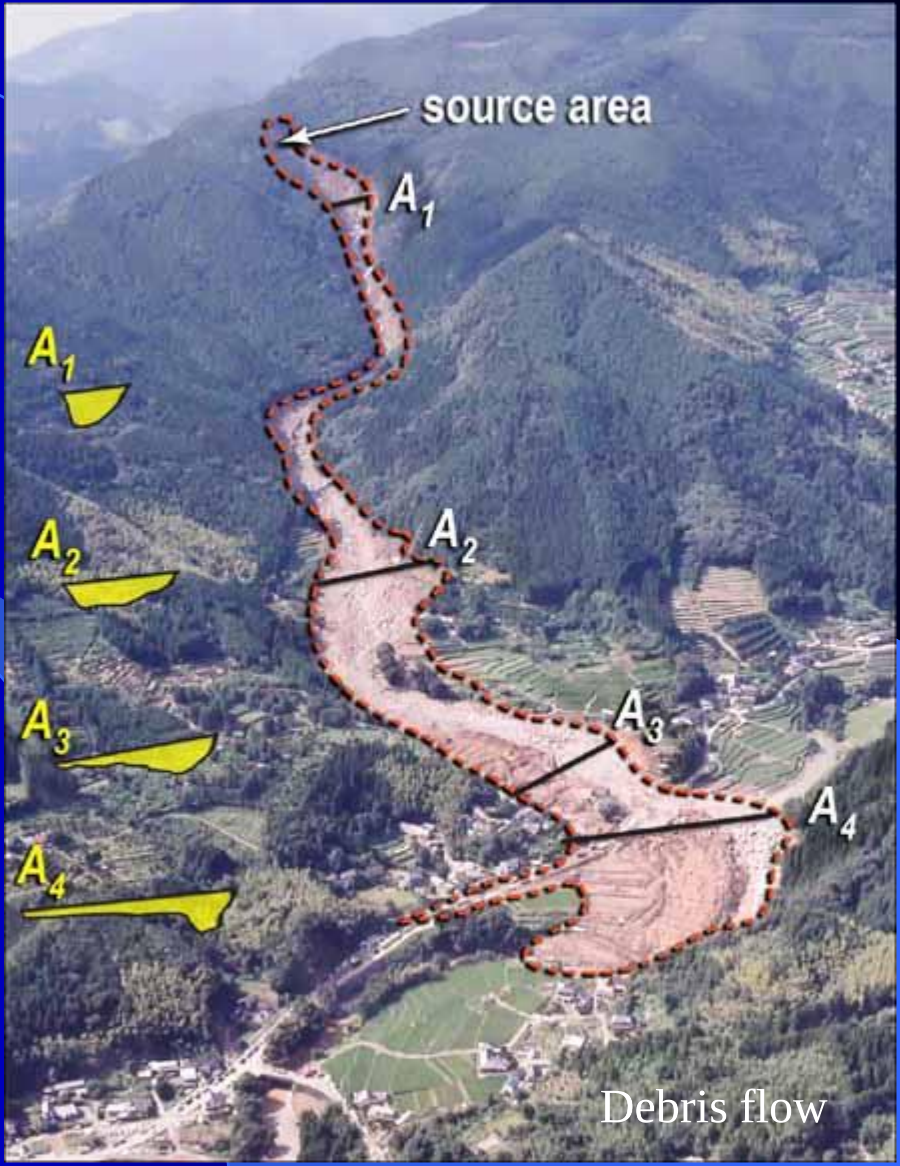
[Rock fall video]

Rock slide

Rock flow

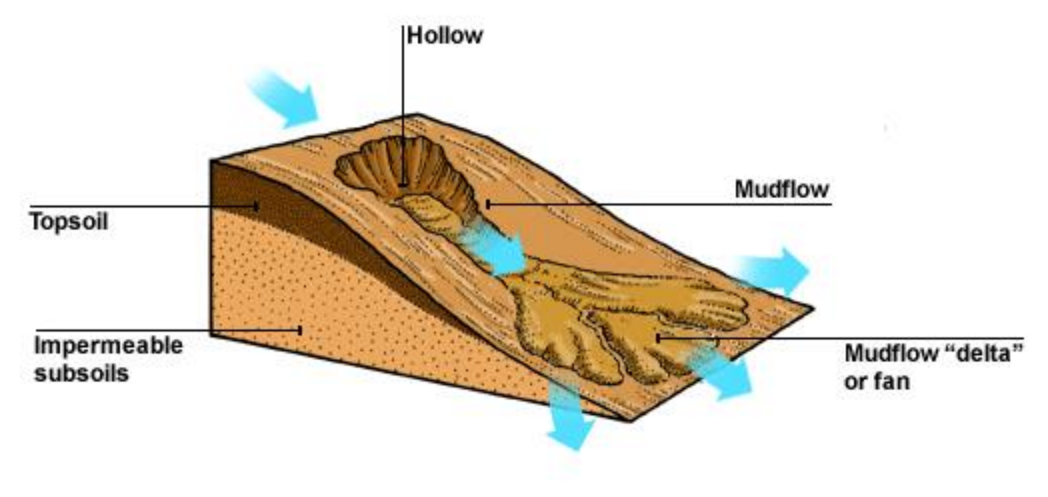
Creep

Earth flow



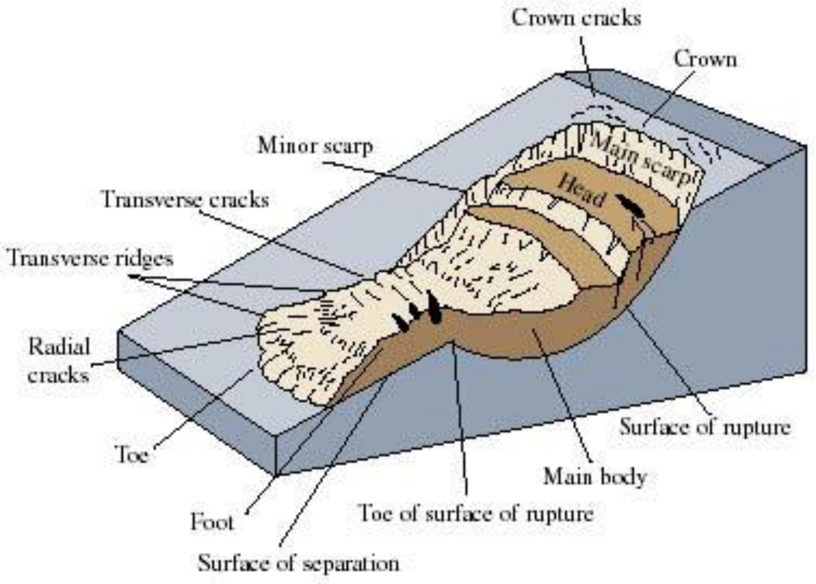
Debris flow

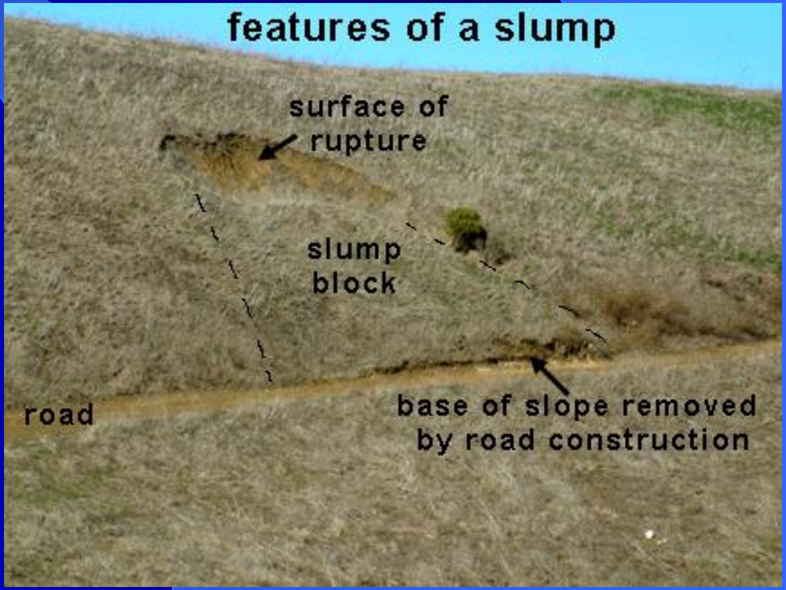
Mudflow


Hollow
Mudflow
Topsoil
Impermeable subsoils
Mudflow "delta" or fan

Slump

Slump video





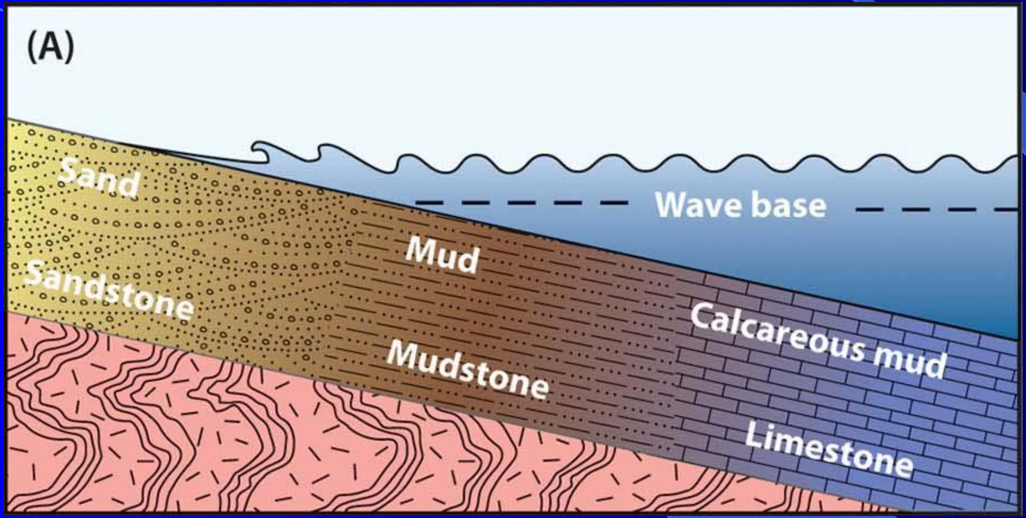
Debris slide

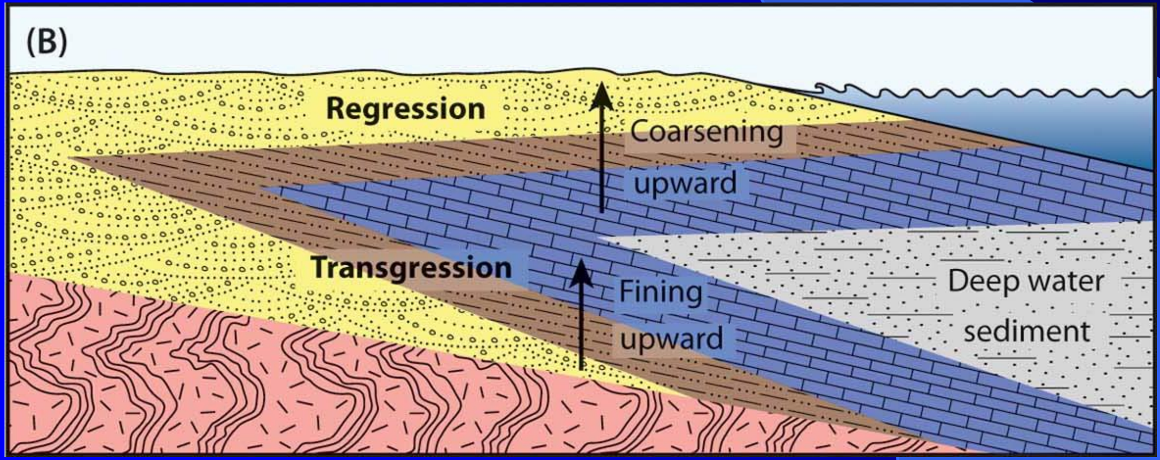
Debris avalanche

Bedding

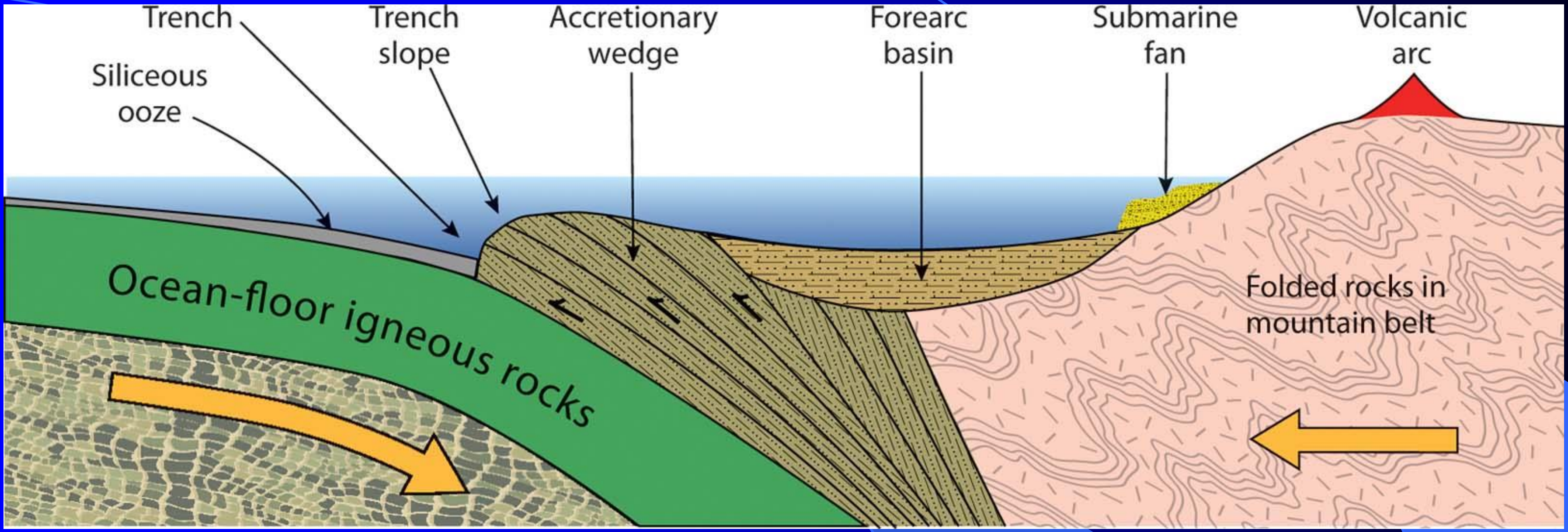
Law of Superposition

Transgressive and regressive sequences due to relative changes in sea level





Convergent Plate Boundaries

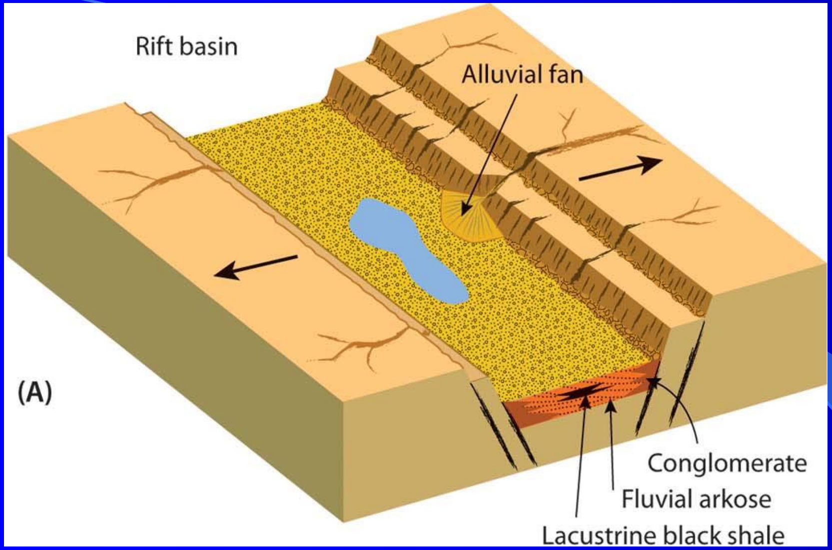


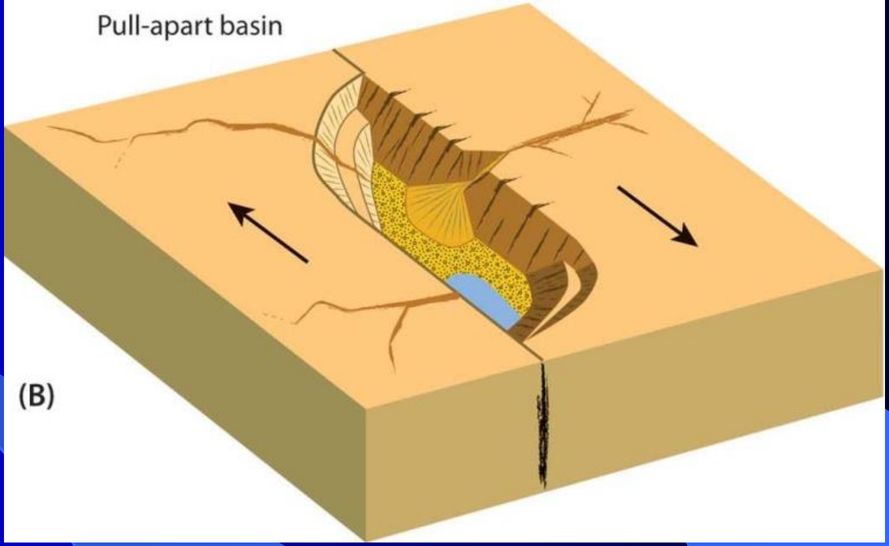
Melange in Accretionary wedge

Immature sediments in Submarine fan, more mature in Forearc basin

Passive continental margins - Mature sediments and deltas

Rift and Pull-apart basins



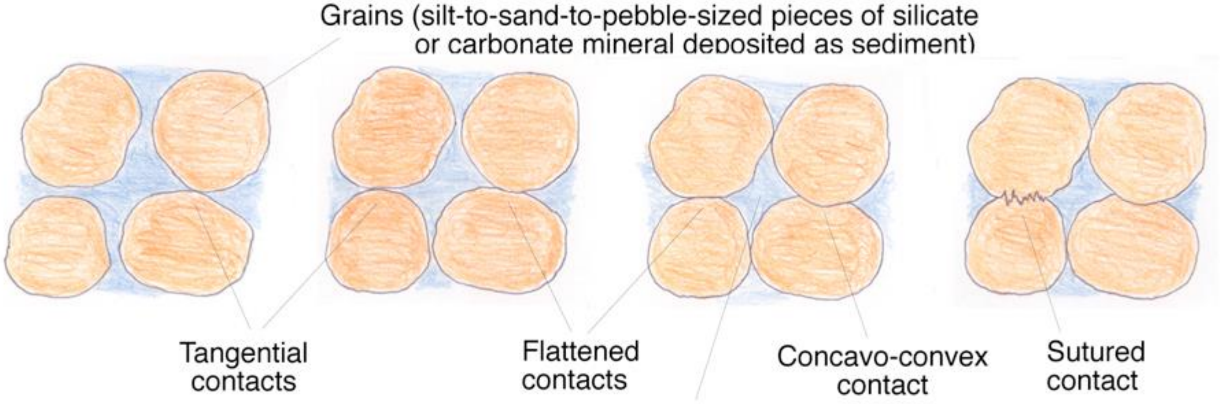


Lithification of sediments to form sedimentary rocks, Part I: Processes

Sediments are consolidated or lithified ("rock-ified") to form sedimentary rocks by some combination of two major post-depositional processes, compaction and cementation. In addition, other processes noted below modify these rocks significantly. As a result, sediments become physically solid rocks, and their porosity and permeability is decreased.

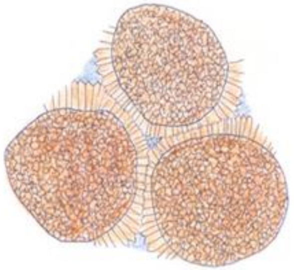
Compaction

Compaction is the process in which pressure causes grains of sediment to move closer together, generating a more dense collective material. As compaction progresses, contacts between grains become more abundant (on a contact-per-grain basis) and they progress in shape from tangential to flattened to concavo-convex to sutured.[1] These modified contacts lock the grains together.

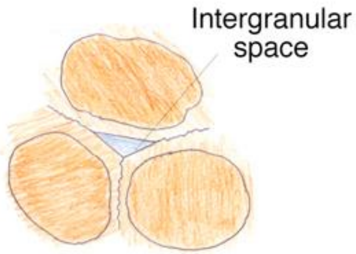


Cementation

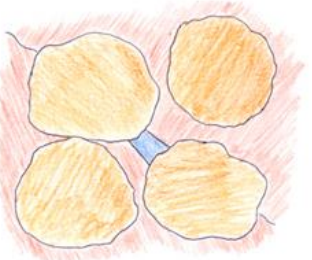
Cementation is the chemical precipitation of new mineral material from dissolved solids of porewaters to fill intergranular space in sediments. These cementing crystals form on the surfaces of the grains. As the crystals grow, they meet or engulf other grains or other cementing crystals and thus bond the grains into a solid material. The volumetrically most common cementing minerals are quartz (typically in sandstones) and calcite (in either sandstones or limestones).



Polycrystalline grains, and thus grains with many different substrates for growth of cementing crystals of the same mineral



Monocrystalline grains, and thus grains with just one substrate apiece for growth of cementing crystals of the same mineral



Grains cemented by cementing crystals of a different mineral

Dissolution of grains

Dissolution of a grain with no subsequent infilling by minerals leaves a *mold,* a void in the shape of the original grain.

Replacement of grains

Dissolution of a grain and subsequent infilling by another mineral results in a *pseudomorph,* a crystal of one mineral with the shape of pre-existing mineral material.

Alteration of grains

Atom-by-atom rearrangement or replacement of atoms in a grain can alter the grain to a different mineral. In sandstones, *albitization* transforms more anorthitic feldspars to albite, and in limestones *neomorphism* transforms aragonite to calcite.

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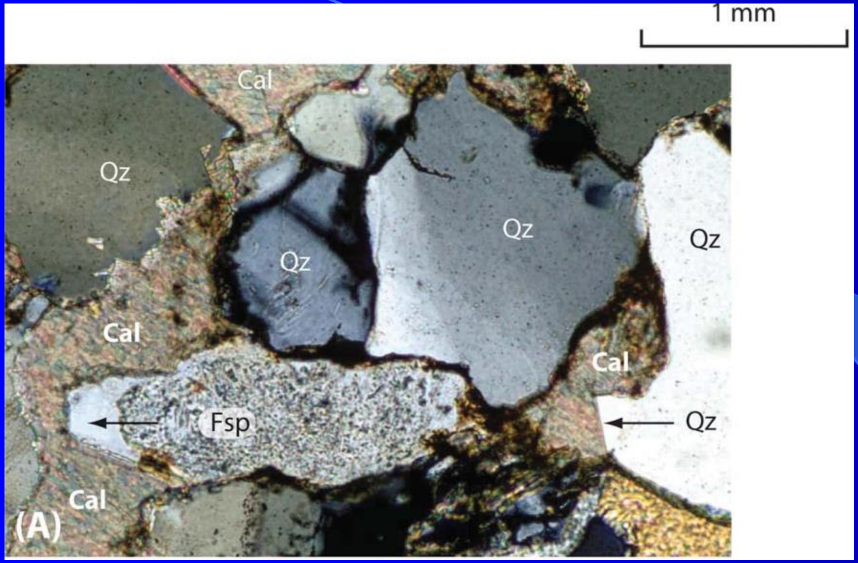
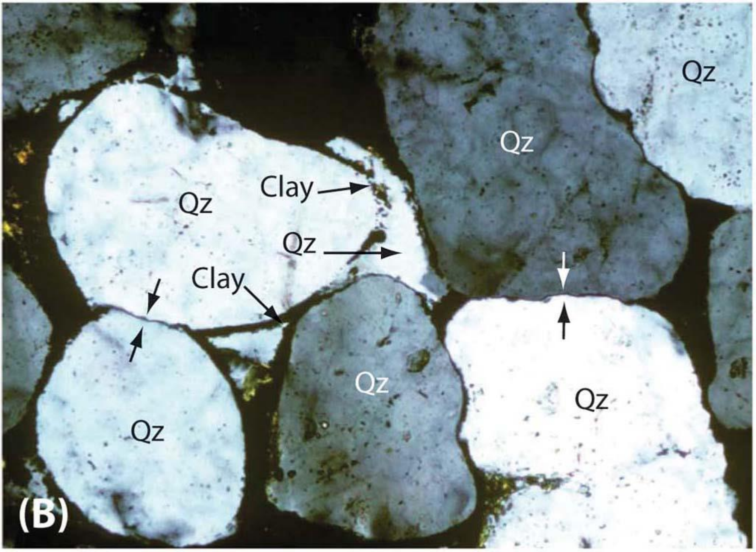
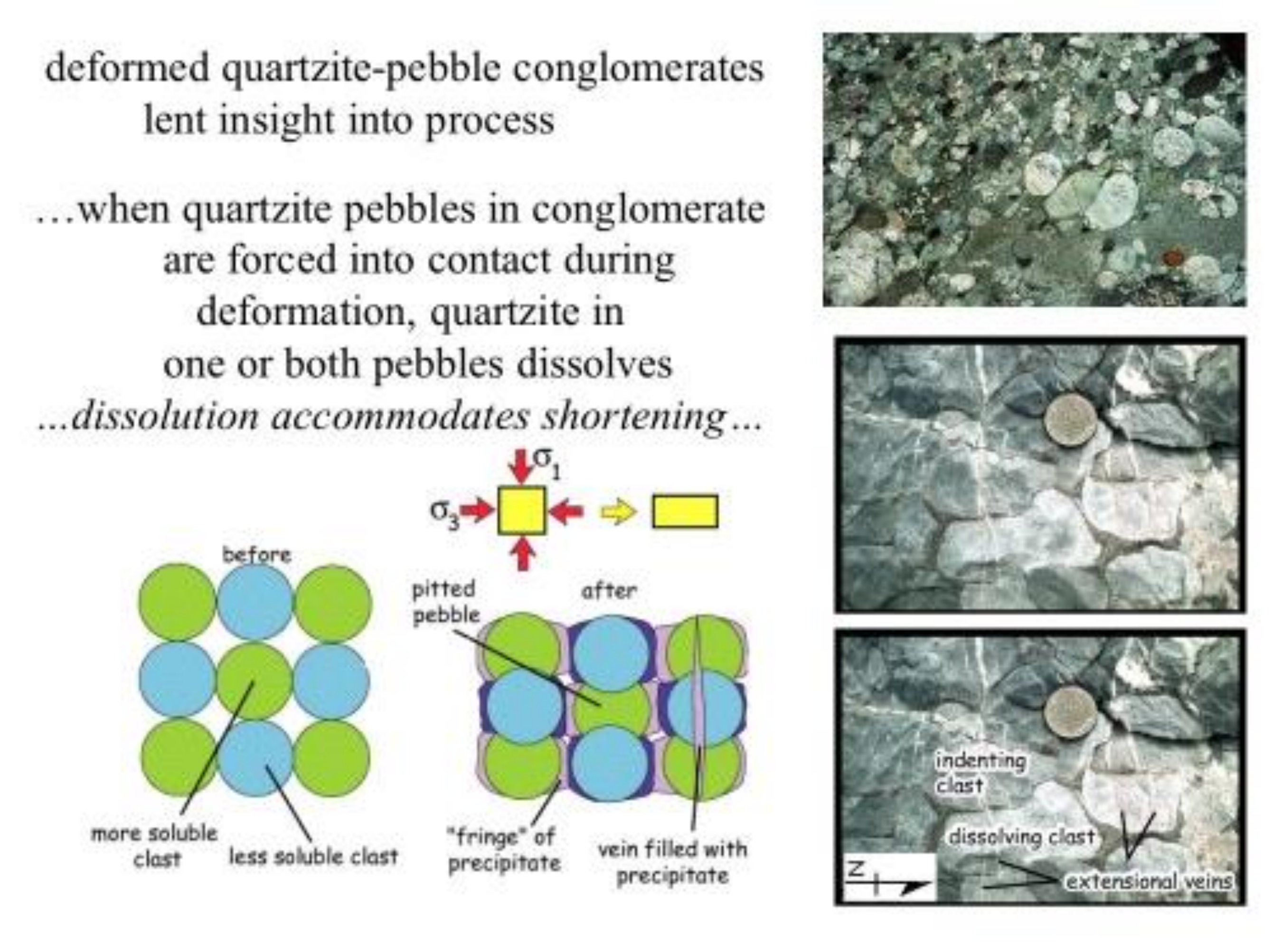
[1] Taylor, J.M., 1950, Pore-space reduction in sandstones: *Amer. Assoc. Petrol. Geol. Bull.*, v. 34, p. 701-716.

Cementation





Pressure solution



deformed quartzite-pebble conglomerates lent insight into process

…when quartzite pebbles in conglomerate are forced into contact during deformation, quartzite in one or both pebbles dissolves

…dissolution accommodates shortening…

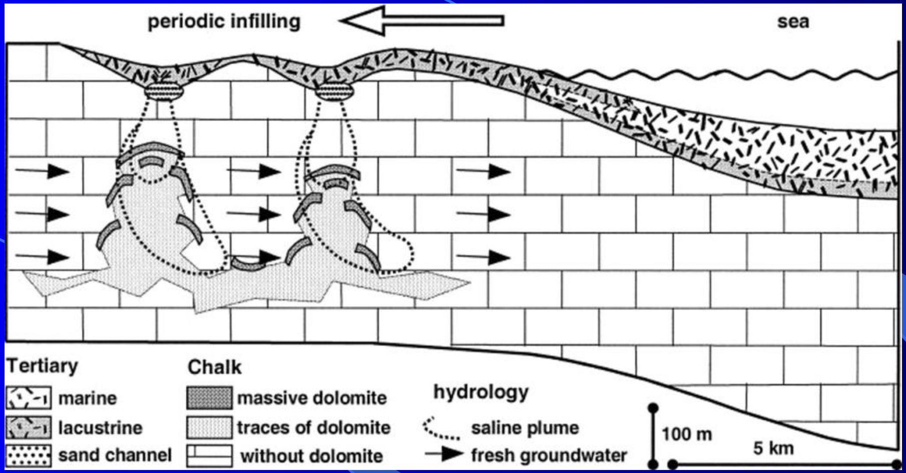
Recrystallization, Replacement, Dolomitization

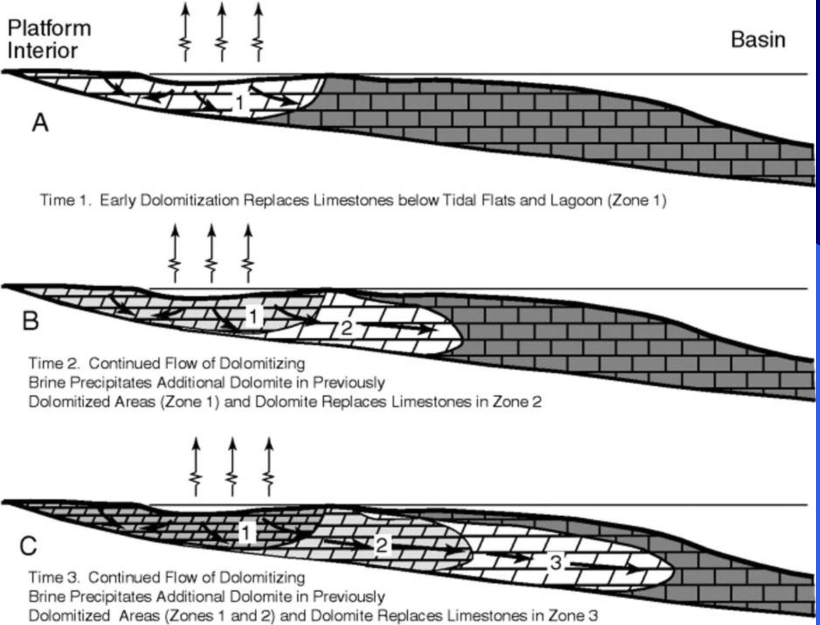
Recrystallization – less stable minerals convert to more stable minerals. For example aragonite converts to calcite.

Replacement – one minerals replaces another.

Example, pyrite replaces calcite in shell.

Dolomitization is a process by which dolomite is formed when magnesium ions replace calcium ions in calcite.





Time 1. Early Dolomitization Replaces Limestones below Tidal Flats and Lagoon (Zone 1)

Time 2. Continued Flow of Dolomitizing Brine Precipitates Additional Dolomite in Previously Dolomitized Areas (Zone 1) and Dolomite Replaces Limestones in Zone 2

Time 3. Continued Flow of Dolomitizing Brine Precipitates Additional Dolomite in Previously Dolomitized Areas (Zones 1 and 2) and Dolomite Replaces Limestones in Zone 3