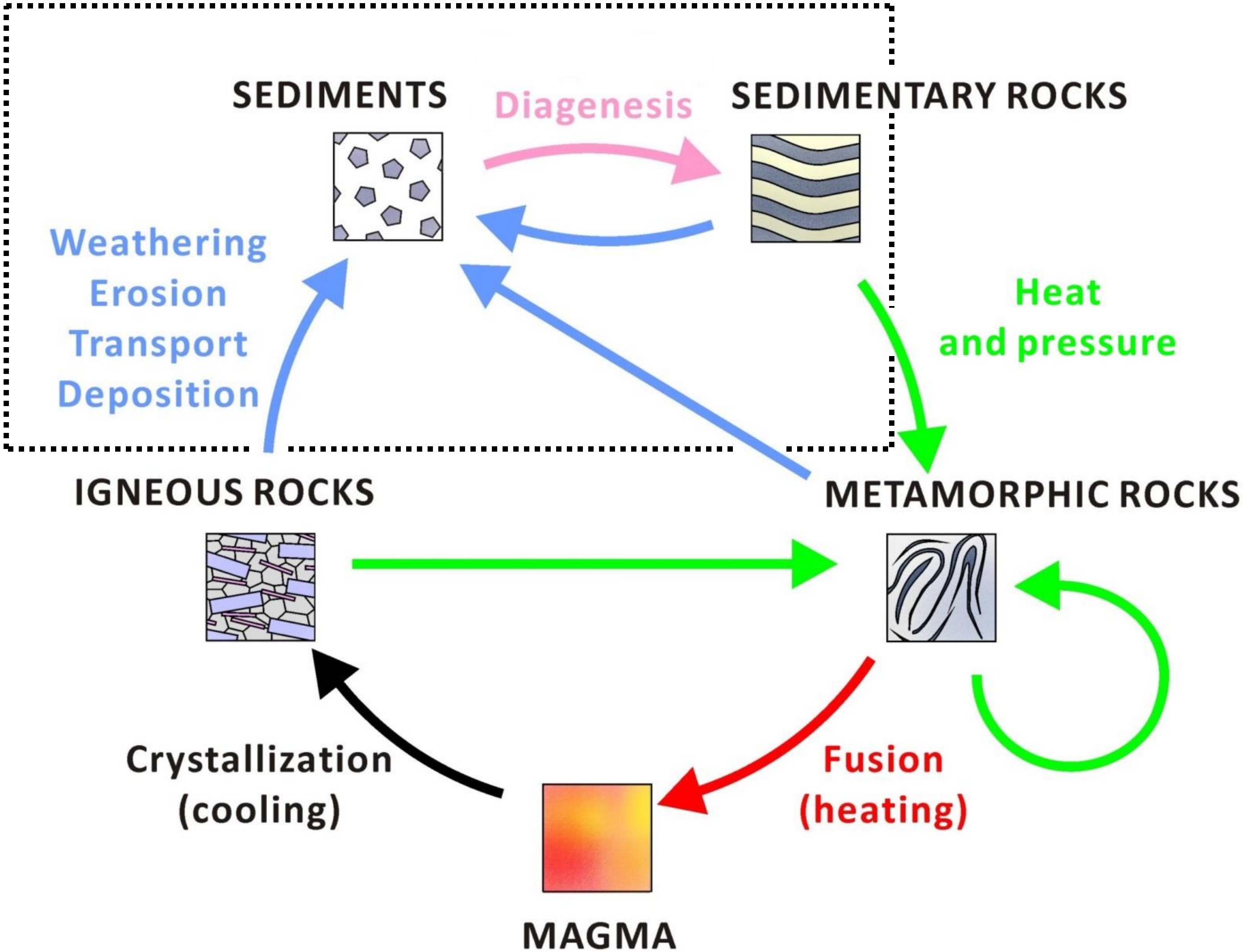
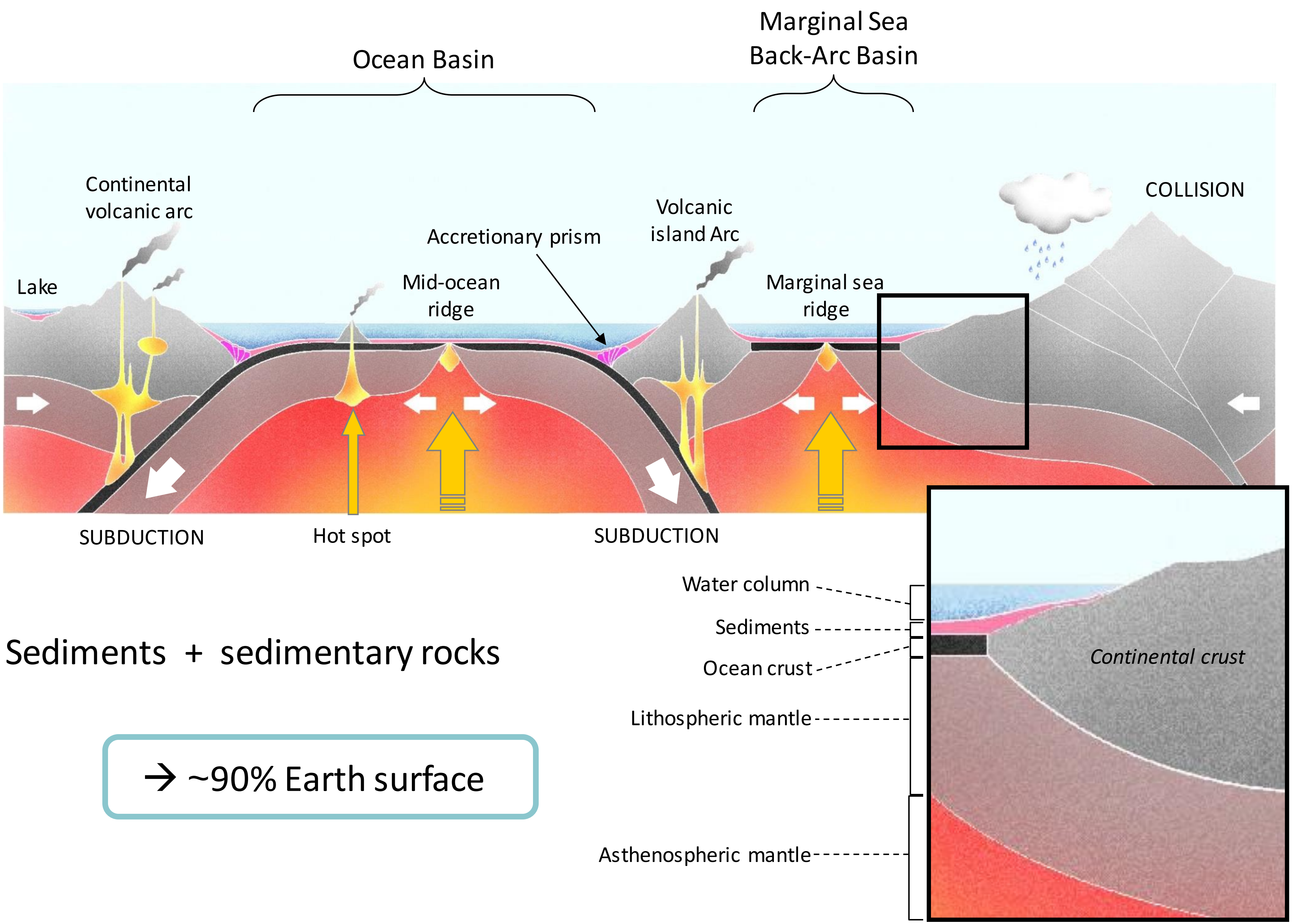
Sedimentary rocks


SEDIMENTS
Diagenesis
SEDIMENTARY ROCKS
Weathering
Erosion
Transport
Deposition
Heat
and pressure
IGNEOUS ROCKS
METAMORPHIC ROCKS
Crystallization
(cooling)
Fusion
(heating)
MAGMA



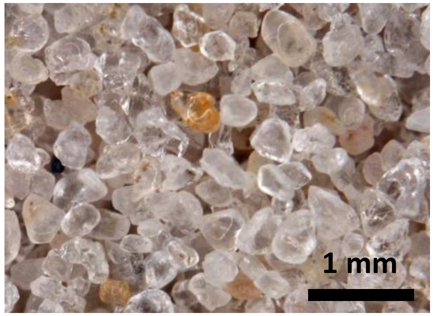
Sediments + sedimentary rocks

→ ~90% Earth surface

✶ What are sediments?

Sediments are	Examples of sedimentary rocks ↓
1. Solid particles	
• Rocks/minerals	
Ex.: Quartz sand	Sandstone
• Hard parts of organisms (biominerals)	
Ex.: Foraminiferal sand ($CaCO_3$)	Foraminiferal limestone
• Organic material	
Ex.: Plant debris (peat)	Coal
2. Dissolved chemicals	
• Abiotic precipitation	
Ex.: Na^+, K^+, Cl^-	Evaporite: NaCl, KCl
• Biotic precipitation	
Ex.: Corals ($CaCO_3$)	Reef limestone

Quartz sand



www.microimaging.ca

→ *Sandstone*

www.pitt.edu

Foraminiferal sand

Wikipedia

→ *Foraminiferal limestone*

Peat

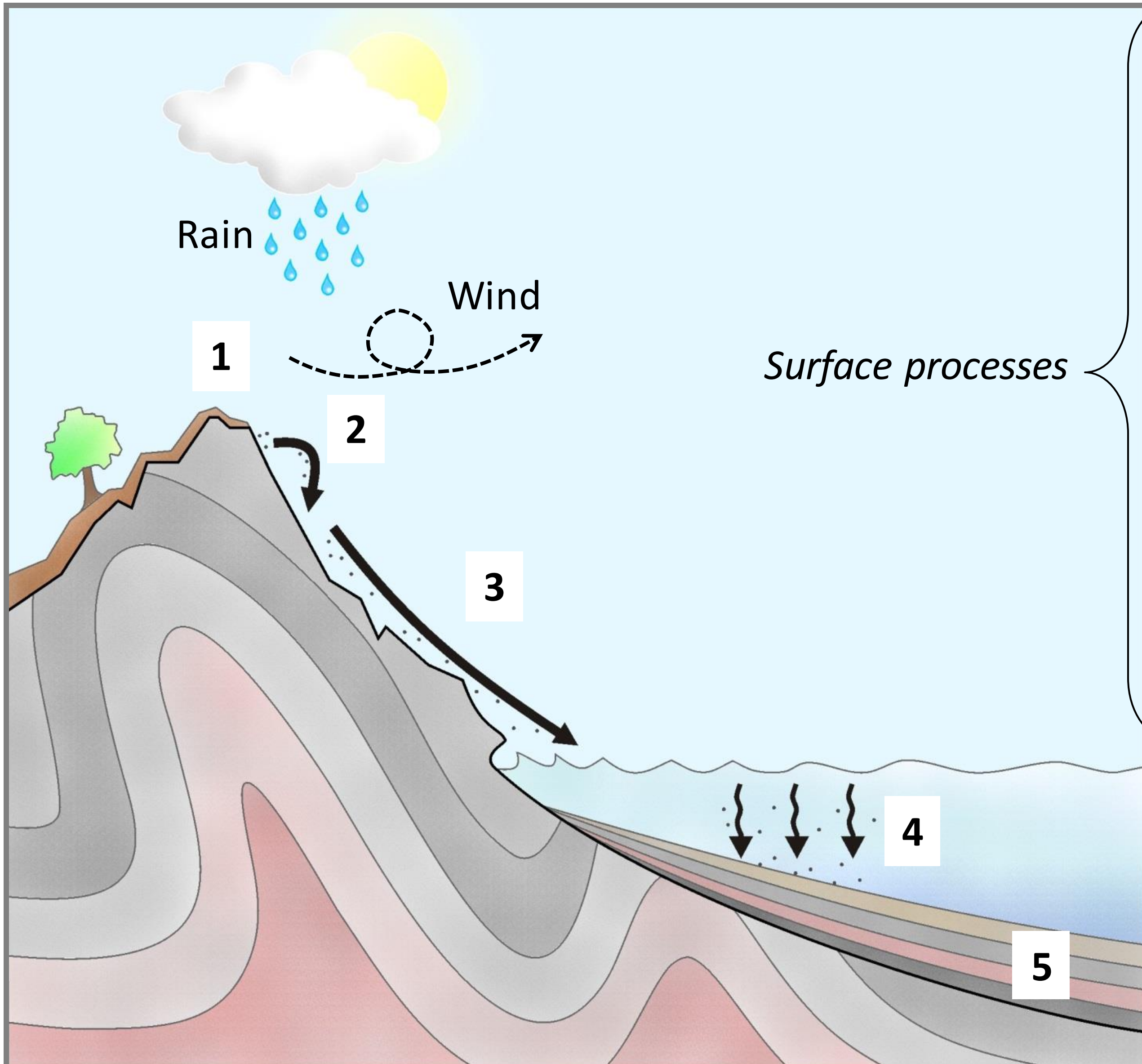
→ *Coal*

Coral reef ($CaCO_3$)

Wikipedia

→ *Reef limestone*

✶ Formation of sediments and sedimentary rocks



1. Weathering

Destruction of rocks and production of sediments (source area)

2. Erosion

Mobilization and removal of sediments from source area

3. Transport

Sediments are moved to the site of deposition

4. Deposition

“sink area”

5. Burial

Processes transforming sediments into sedimentary rocks (**diagenesis**)

Weathering processes

1. **Physical** weathering

- **Mechanical** weathering by **wind** (1), **water** (2) and **ice** (3, 4)
- **Biophysical** weathering e.g. **root wedging** (5)

(1) Weathering by **wind**

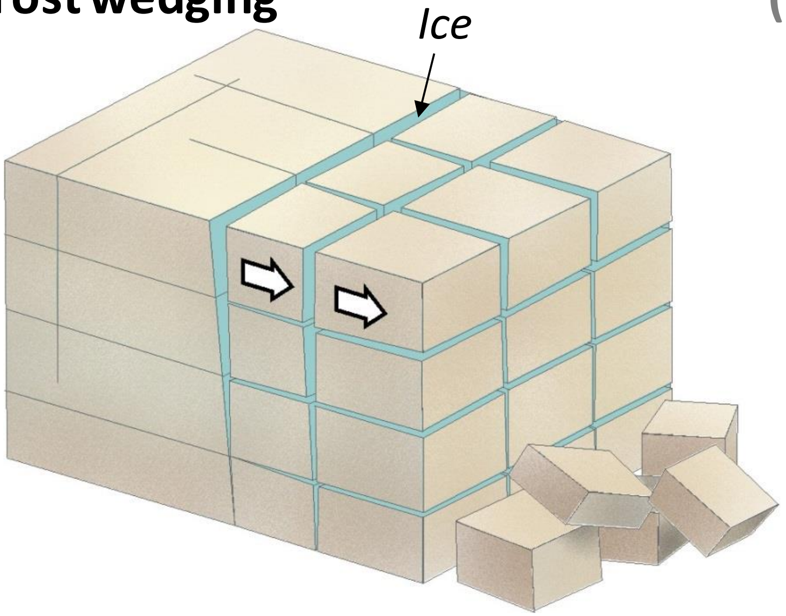
Moroccan desert pavement

Mars

(2) Weathering by **waves**

(3) Weathering by **glaciers**

(4) **Frost wedging**



(5) **Root wedging**

2. **Chemical** weathering

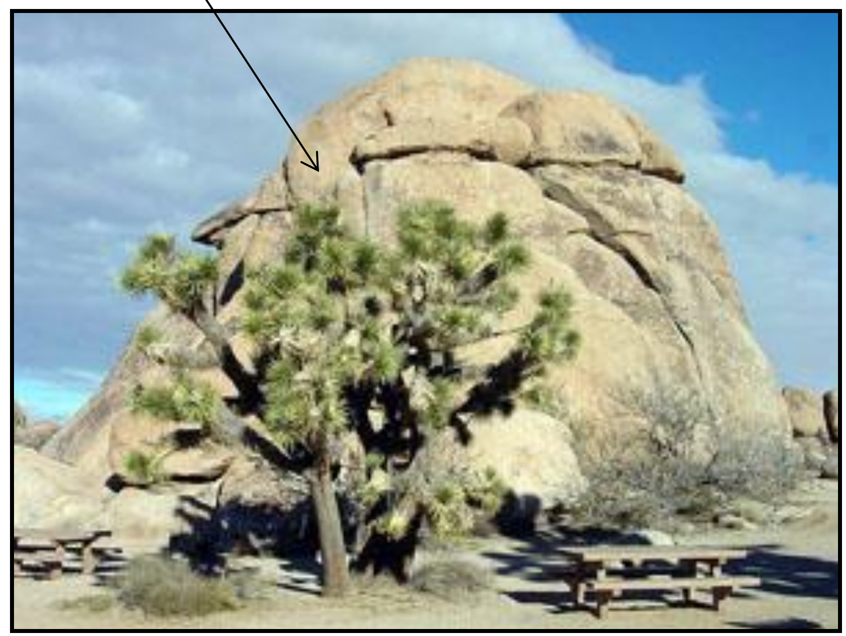
- **Dissolution of minerals (mainly $CaCO_3$)** by mildly acidic water (1)
- **Biotic mineral dissolution** e.g. microbes, lichen, clionid sponge (2,3)

(1) Weathering/dissolution of carbonates (karst, e.g. caves)

Carsten Peter, National Geographic *Vietnam*

Weathering/dissolution of silicates

Body of granite rounded by weathering and erosion



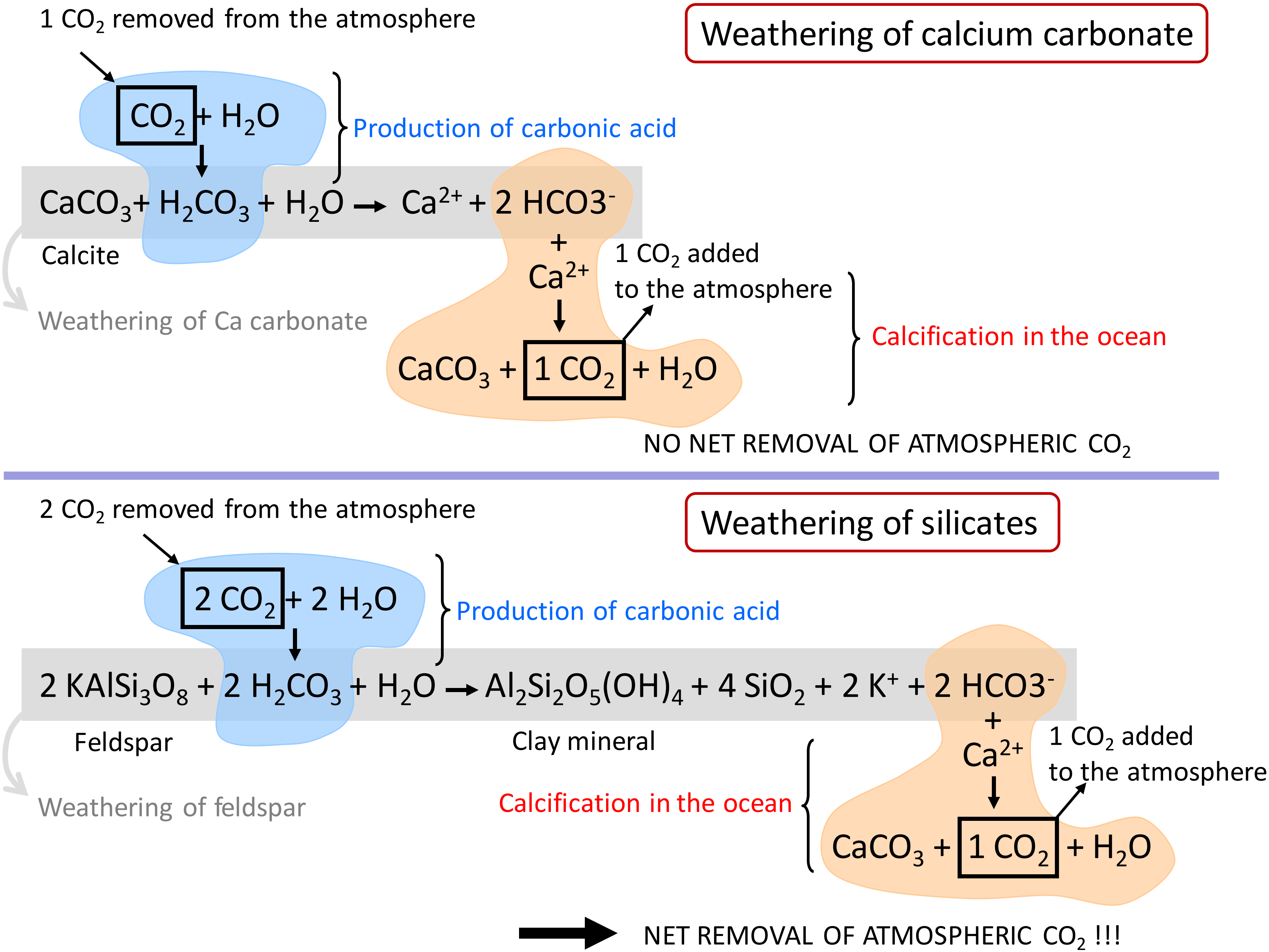
USGS

(2) Boreholes of clionid sponge

Mark A. Wilson
(Dep. of Geology, College of Wooster)

(3) Boreholes of bivalve

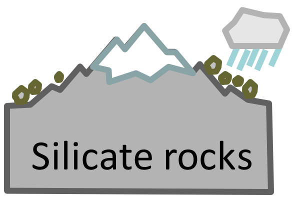
Biolib



1 CO2 removed from the atmosphere
Weathering of calcium carbonate
CO2 + H2O
Production of carbonic acid
CaCO3+ H2CO3 + H2O → Ca2+ + 2 HCO3-
Calcite
+
Ca2+
1 CO2 added
to the atmosphere
Weathering of Ca carbonate
Calcification in the ocean
CaCO3 + 1 CO2 + H2O
NO NET REMOVAL OF ATMOSPHERIC CO2
2 CO2 removed from the atmosphere
Weathering of silicates
2 CO2 + 2 H2O
Production of carbonic acid
2 KAlSi3O8 + 2 H2CO3 + H2O → Al2Si2O5(OH)4 + 4 SiO2 + 2 K+ + 2 HCO3-
Feldspar
Clay mineral
+
Ca2+
1 CO2 added
to the atmosphere
Weathering of feldspar
Calcification in the ocean
CaCO3 + 1 CO2 + H2O
NET REMOVAL OF ATMOSPHERIC CO2 !!!

Carbonate-silicate cycle on Earth

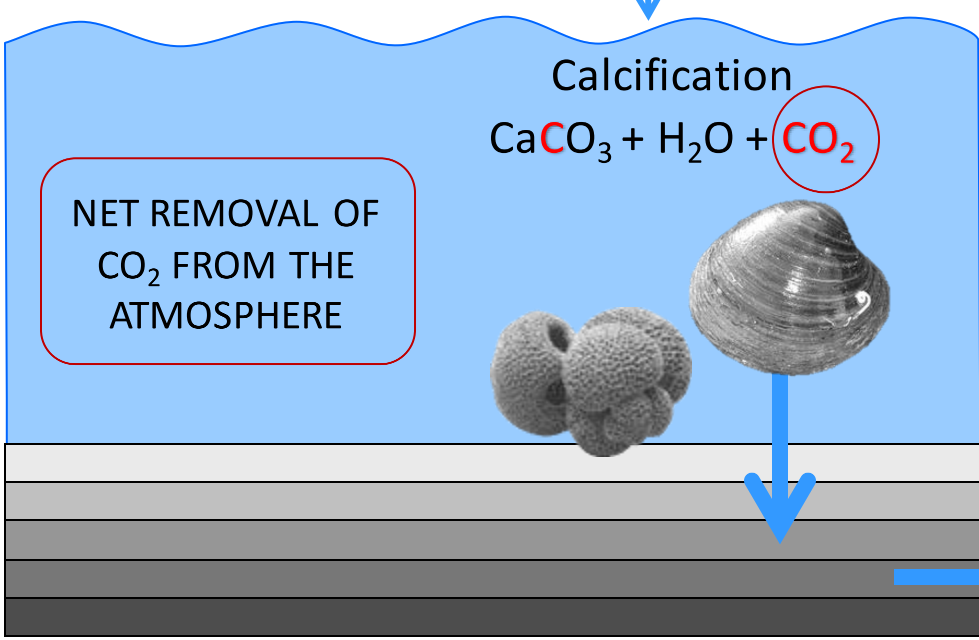
Stabilizing effect on long-term climate
Time scale: millions of years

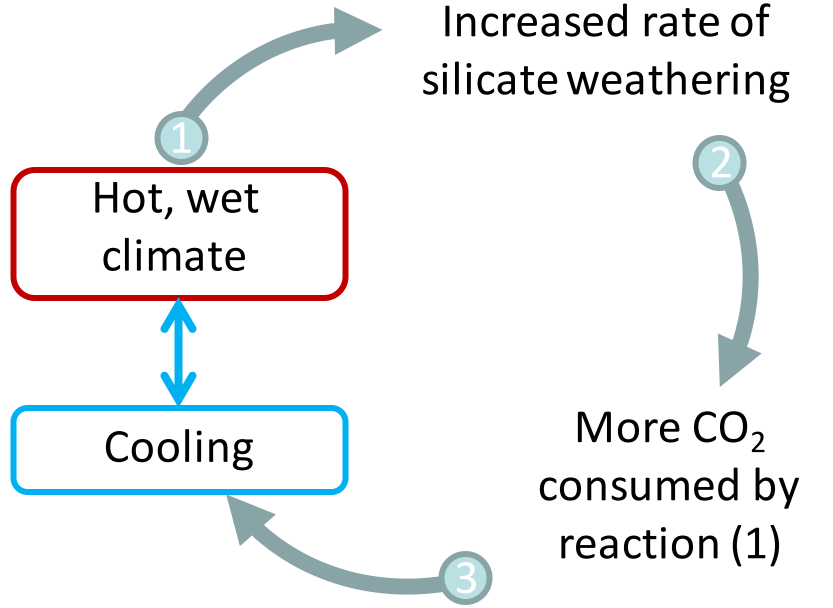


SILICATE WEATHERING

$CaSiO_3 + 2CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^- + SiO_2$ (1)

Carried by streams, rivers to ocean





Stabilizing mechanism (buffer)

NEGATIVE FEEDBACK MECHANISM

NB: abiotic precipitation of $CaCO_3$ can also take place

Process returning CO_2 into atmosphere is **carbonate metamorphism** (CO_2 released through volcanism) $CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2$

Link between long-term climate and silicate weathering

Beginning of the collision between India and Eurasia 50-40 Myr ago

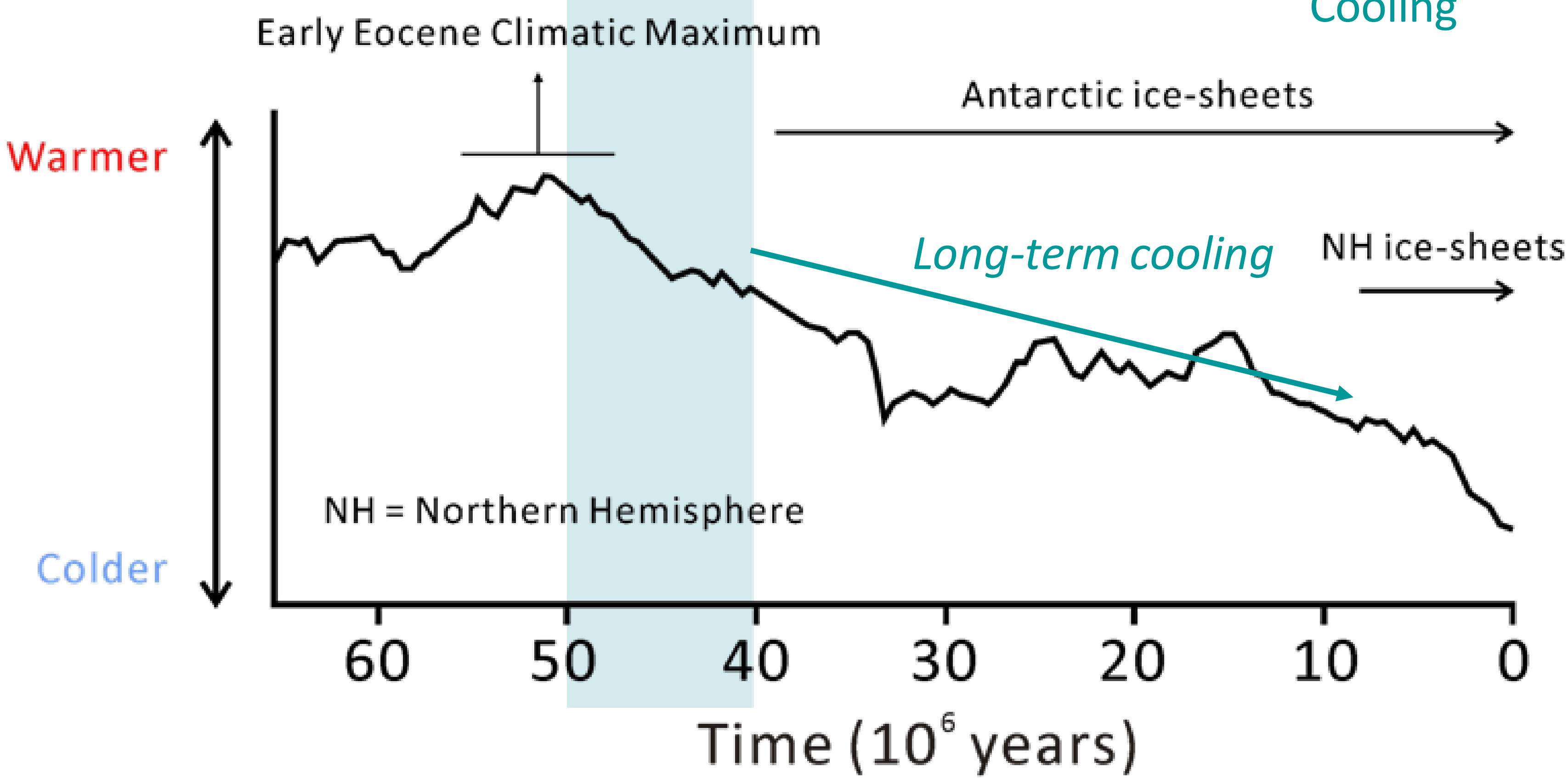
Himalaya formation → Increased weathering

↓

Atm. CO_2 drops

↓

Cooling



$$4KAlSi_3O_8 + 4H^+ + 2H_2O \rightarrow 4K^+ + Al_4Si_4O_{10}(OH)_8 + 8SiO_2$$

Orthoclase — Kaolinite — Quartz

Kaolinite ↓ Remobilized and transported by rain water and deposited in depressions

Hydrolysis of granite

Kaolin quarry (Japan)

http://www.eacrh.net/ojs/index.php/crossroads/article/view/14/Vol3_Seyock_html

NB: Kaolinite is primarily used in the paper industry (paper coating)

Erosion and transport

"As soon as a rock particle (loosened by one of the two weathering processes) moves, we call it **erosion** or **mass wasting**. Mass wasting is simply movement down slope due to gravity. Rock falls, slumps, and debris flows are all examples of mass wasting. We call it erosion if the rock particle is moved by some flowing agent such as air, water or ice."

From USGS

1. **Wind**
2. **Water**
3. **Ice**

} Erosion by ~

4. **Gravity (mass wasting)**

1. Wind

Great Sand Dunes National Park (Colorado, USA)

Walter Meayers Edwards, National Geographic

Whirlwind (dust devil) on Mars

NASA

2. Water

Idaho (USA)

Michael Melford, National Geographic

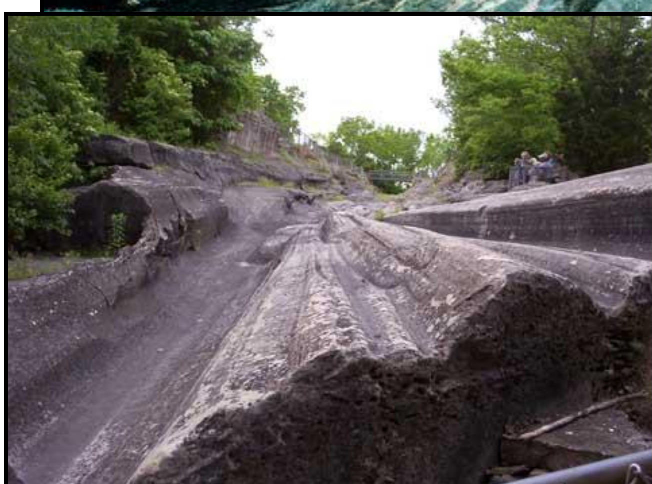
Ancient fluvial deposit on Mars

NASA

3. Ice

Glacier in British Columbia (Canada)

Sarah Leen, National Geographic

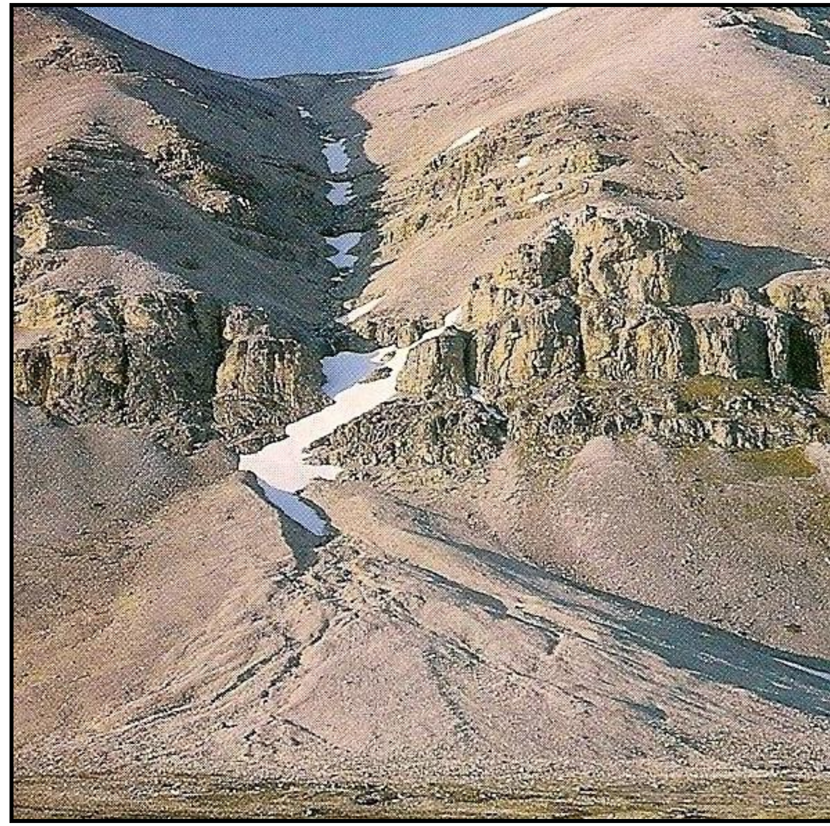


Glacial grooves formed during the last glaciation (Kelleys Island, Ohio)

Wikipedia

4. Gravity

Debris cone (Spitzberg, Norway)



Chenuet (1993)

Martian avalanche *NASA*

Sediment deposition

1. Water/wind

As **wind/water current** decreases, it can no longer keep the largest particles suspended.

The stronger the current, the larger the particles it can carry:

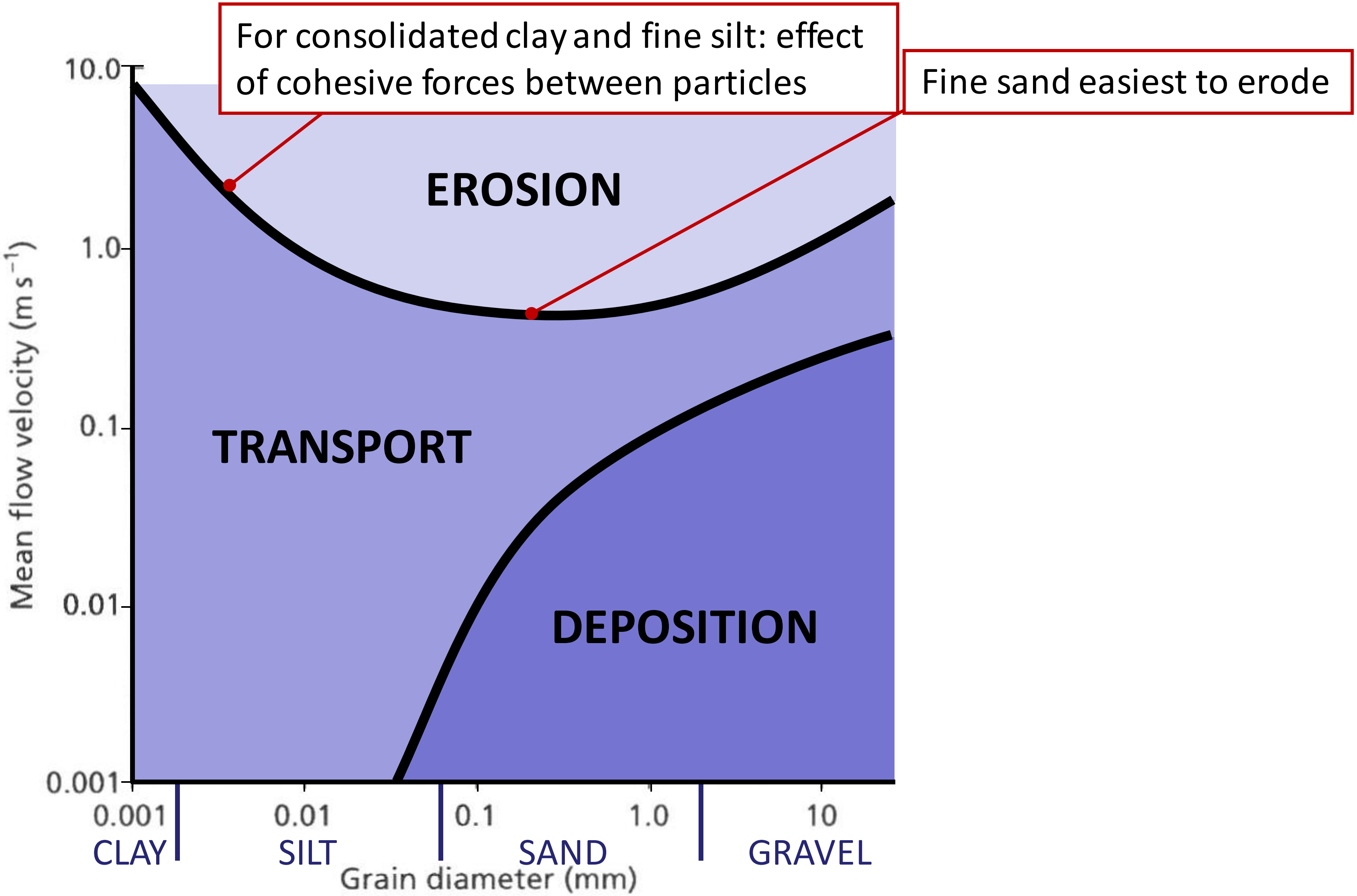
Strong currents (>50 cm/s): carry gravels (>2 mm) and smaller particles
Moderately strong currents (20-50 cm/s): carry sand grains (62.5 µm-2 mm) and smaller particles
Weak currents (<20 cm/s): carry silt and clay particles (mud; <62.5 µm)

2. Ice

Sediments are deposited as ice melts and retreats.

3. Gravity

Deposition is controlled by topography (slope steepness) and the nature of sediments (size, shape)



HJÜLSTROM DIAGRAM
Deduced experimentally
(for sediments transported by water)

Fig. 2.14 Schematic representation of relationship between current velocity and sediment erosion, transport and deposition (Hjülstrom's diagram, deduced experimentally from flows of 1 m depth). Note that sediment may continue to be transported after the current velocity has fallen below the level at which it was initially eroded. (simplified)


Beach gravels and sand
http://gravelbeach.blogspot.com/2016/10/mulranny-beach.html


Estuary mud flats
https://geologicalintroduction.baffl.co.uk/?attachment_id=453

Glacial erratic

Robert Siegel (Stanford Uni.)

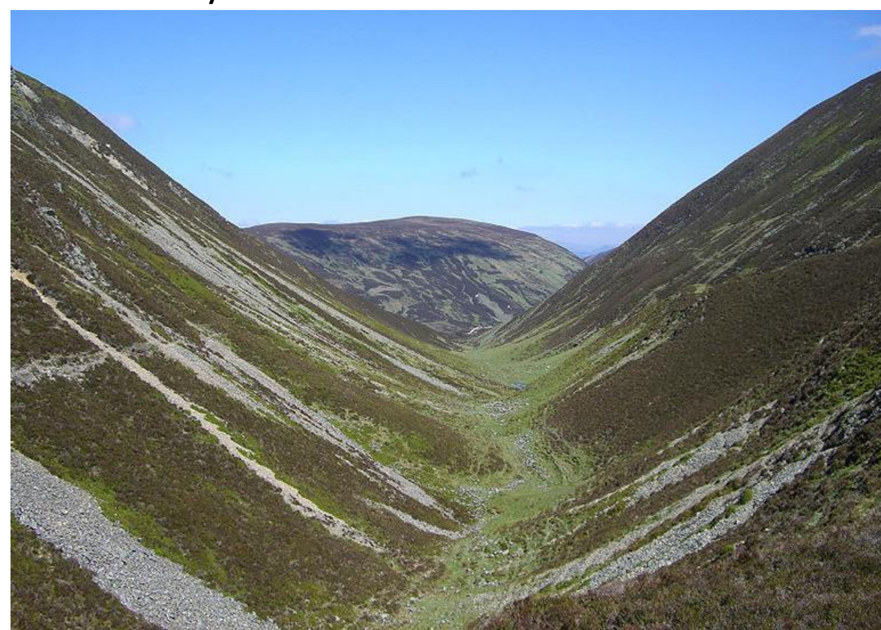
Glacial striation

Wikipedia

Glacial till (moraine) – *coarse unsorted sediment in fine-grained (clay) matrix*

USGS

Glacial valley



Wikipedia (Mick Knapton)

Burial and diagenesis: sedimentary rock formation

- **Burial**: process by which sediments are buried under new layers of sediments → increase in **temperature** and **pressure**

- **Diagenesis**: set of physical and chemical changes affecting **sediments** after they are buried.

Diagenetic processes leading to **lithification**:

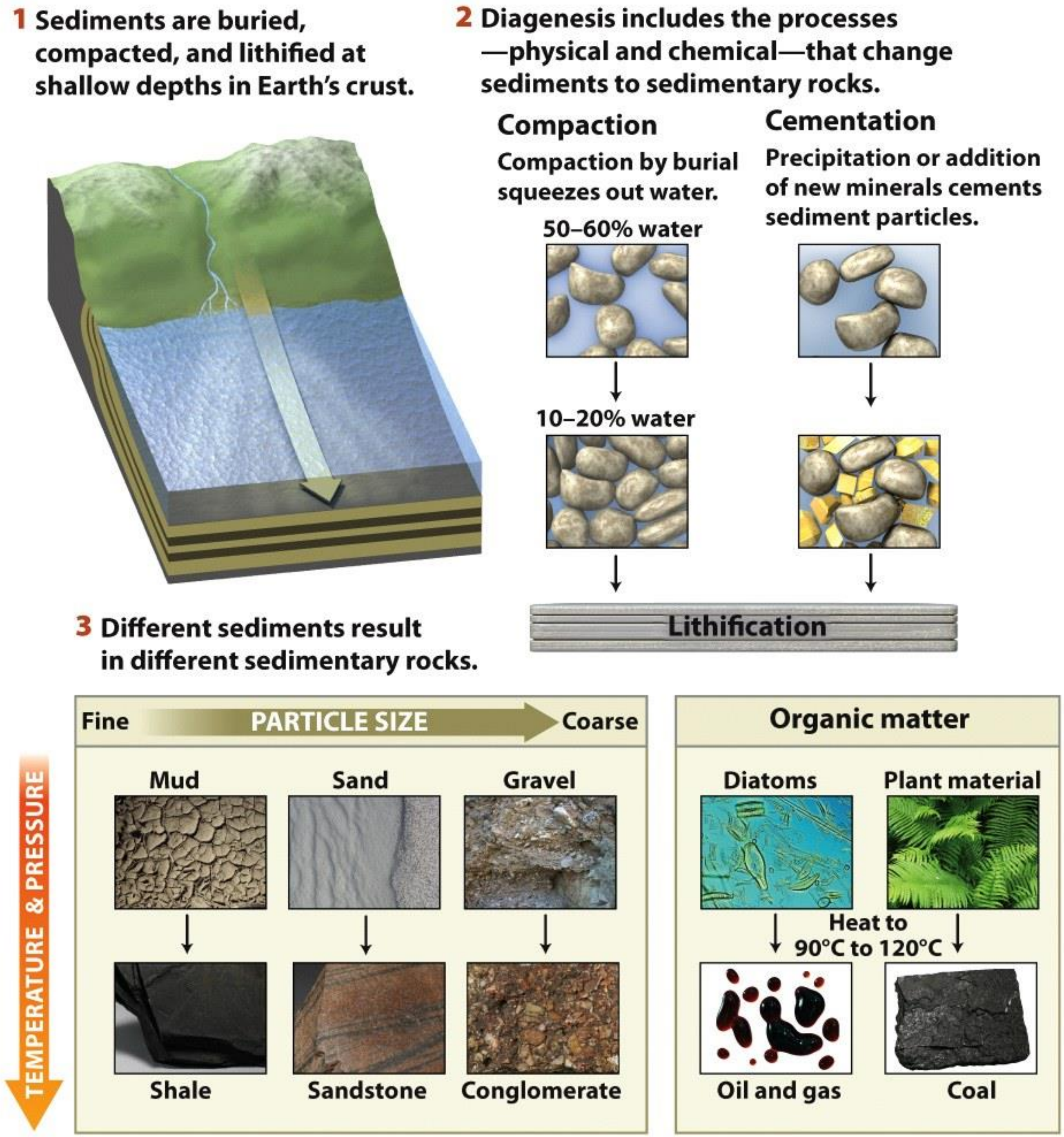
- **Compaction** (due to burial)
- **Cementation**

} ➡ **Decrease in porosity** (% of rock's volume consisting of open space / pores)

⬇

Transformation of soft sediments into hard sedimentary rocks

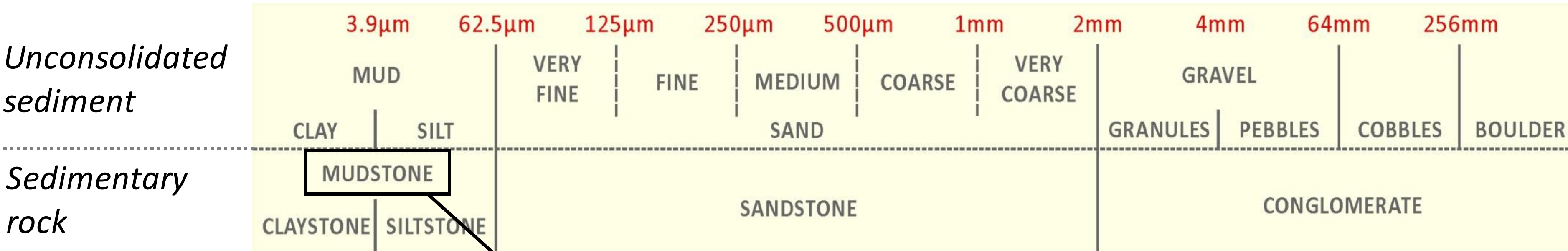
= **Lithification**



Understanding Earth 6th Ed.

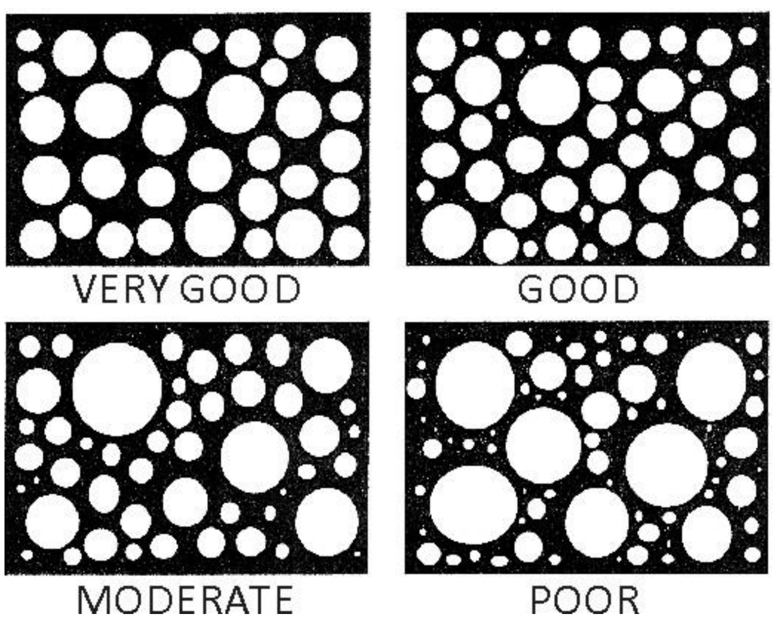
✶ Properties of sediments and sedimentary rocks

- **Grain size** → Influenced by wind/water velocity



or shale
(Shale breaks along stratification planes, mudstone does not)

- **Sorting**

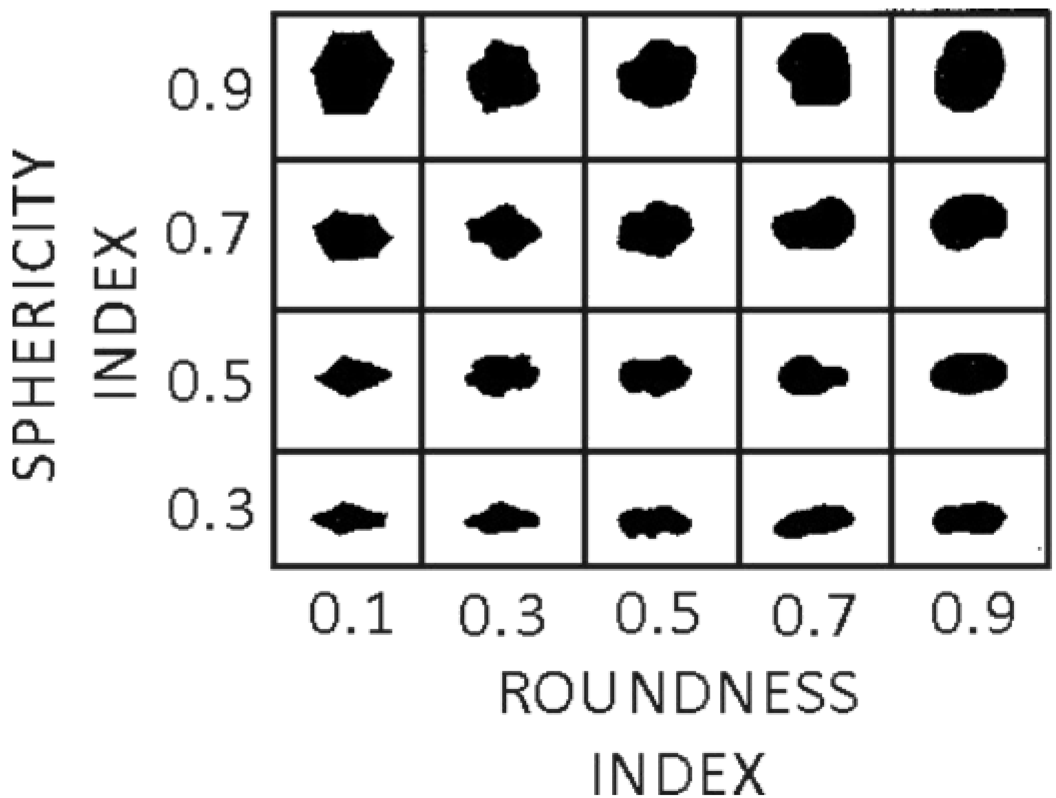


Good sorting indicates a transport agent of constant strength

Poor sorting indicates a transport agent of variable strength

- **Grain morphology**

The degree of abrasion (roundness) depends on the distance of transport.



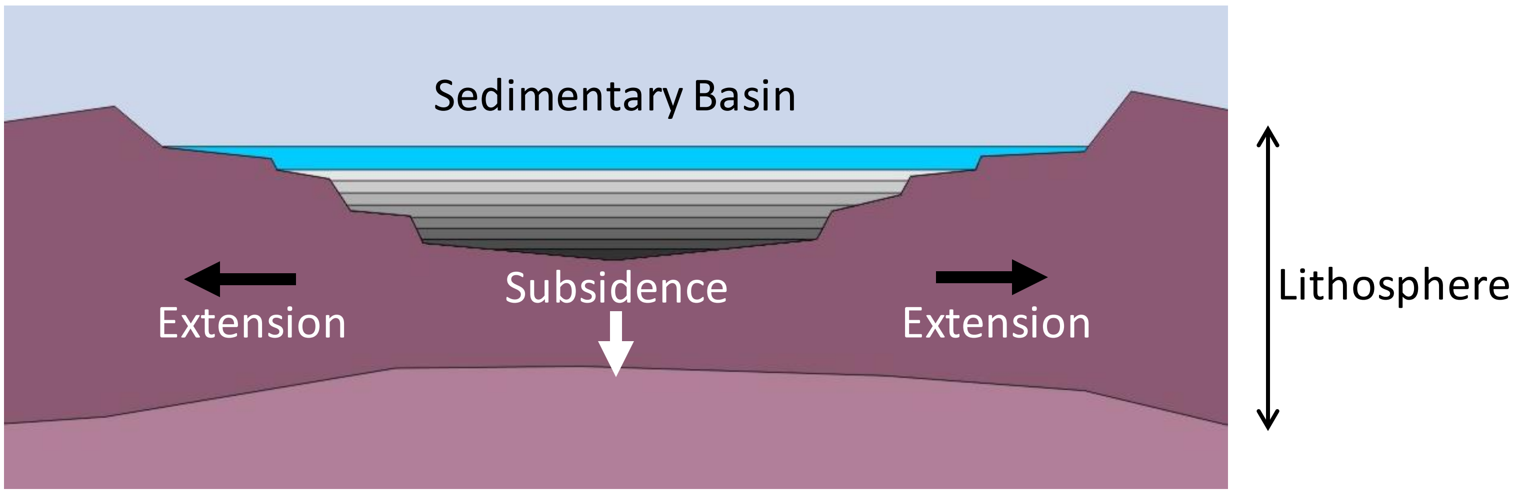
✶ Sedimentary basins and sedimentary environments

- Sediments tend to accumulate in **depressions**.

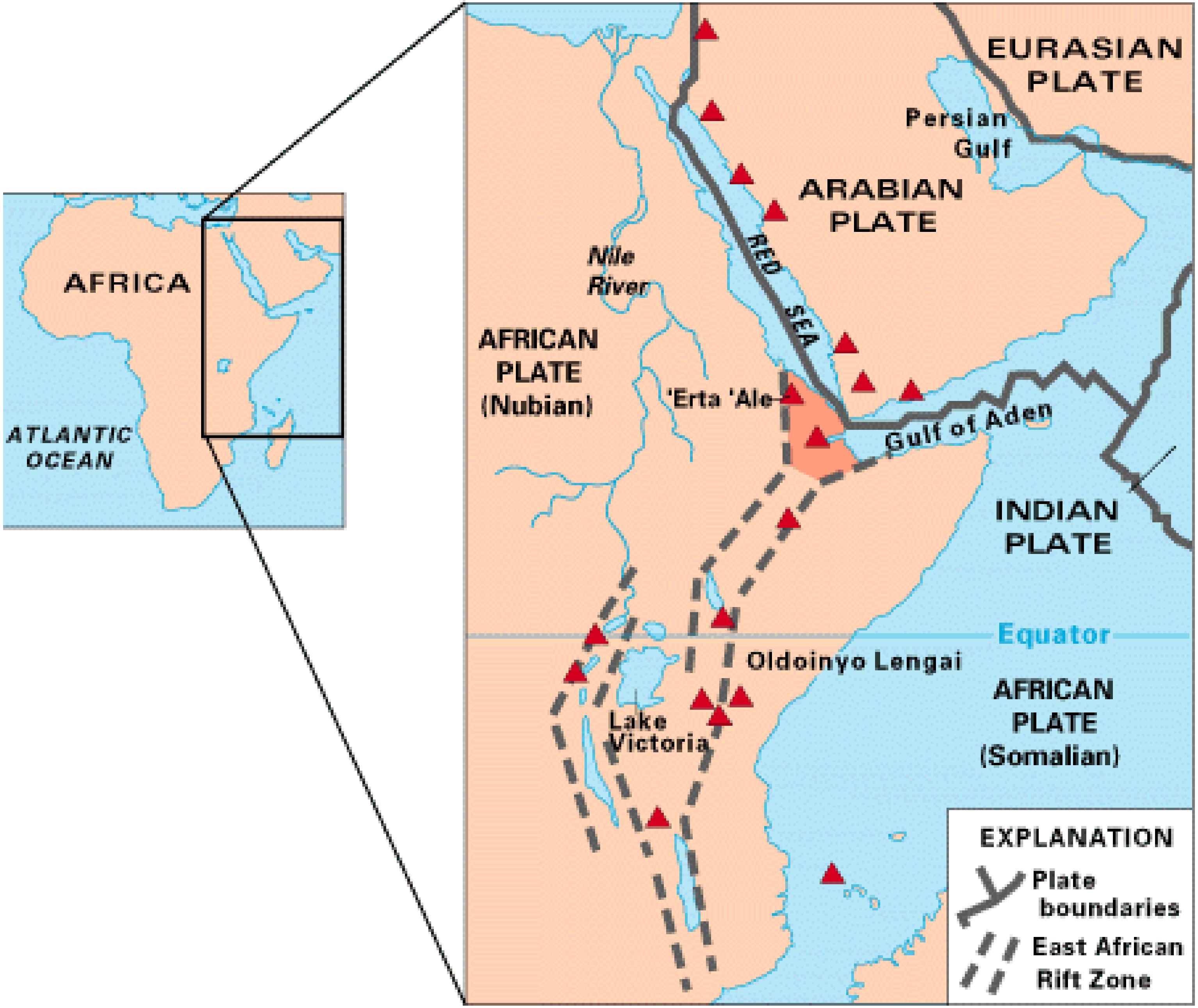
- Large depressions are formed by **subsidence**.

  Subsidence is the process by which a broad area of the crust sinks (subsides) relative to the surrounding crust. It is mainly due to **tectonic deformation** of the lithosphere (stretching) and accentuated by the **weight of sediments**.

- Regions characterized by thick accumulations of sediments and sedimentary rocks are called **sedimentary basins**.



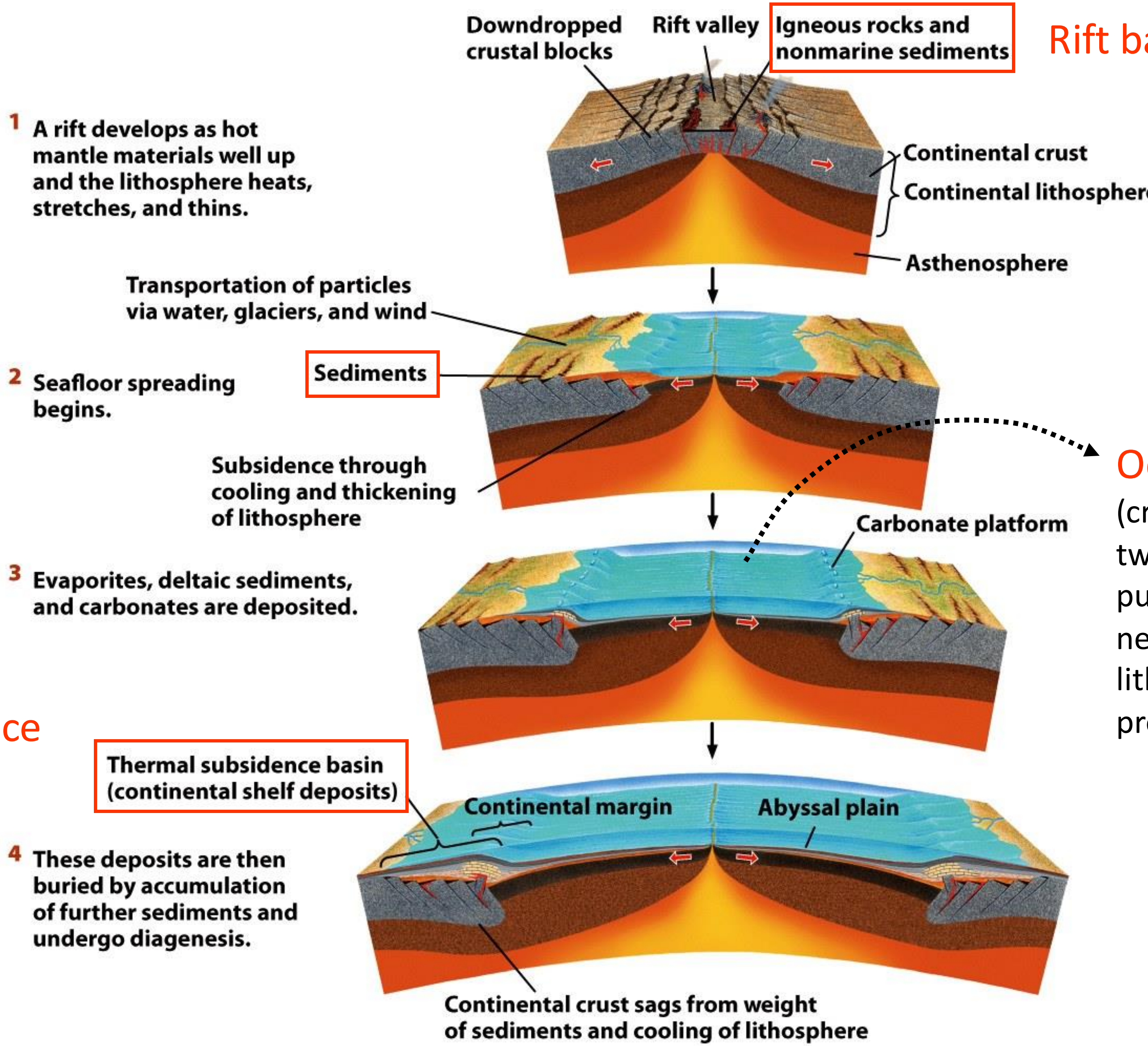
East African Rift



USGS

Rift basin

(created as continental lithosphere is stretched and breaks up)



Ocean basin

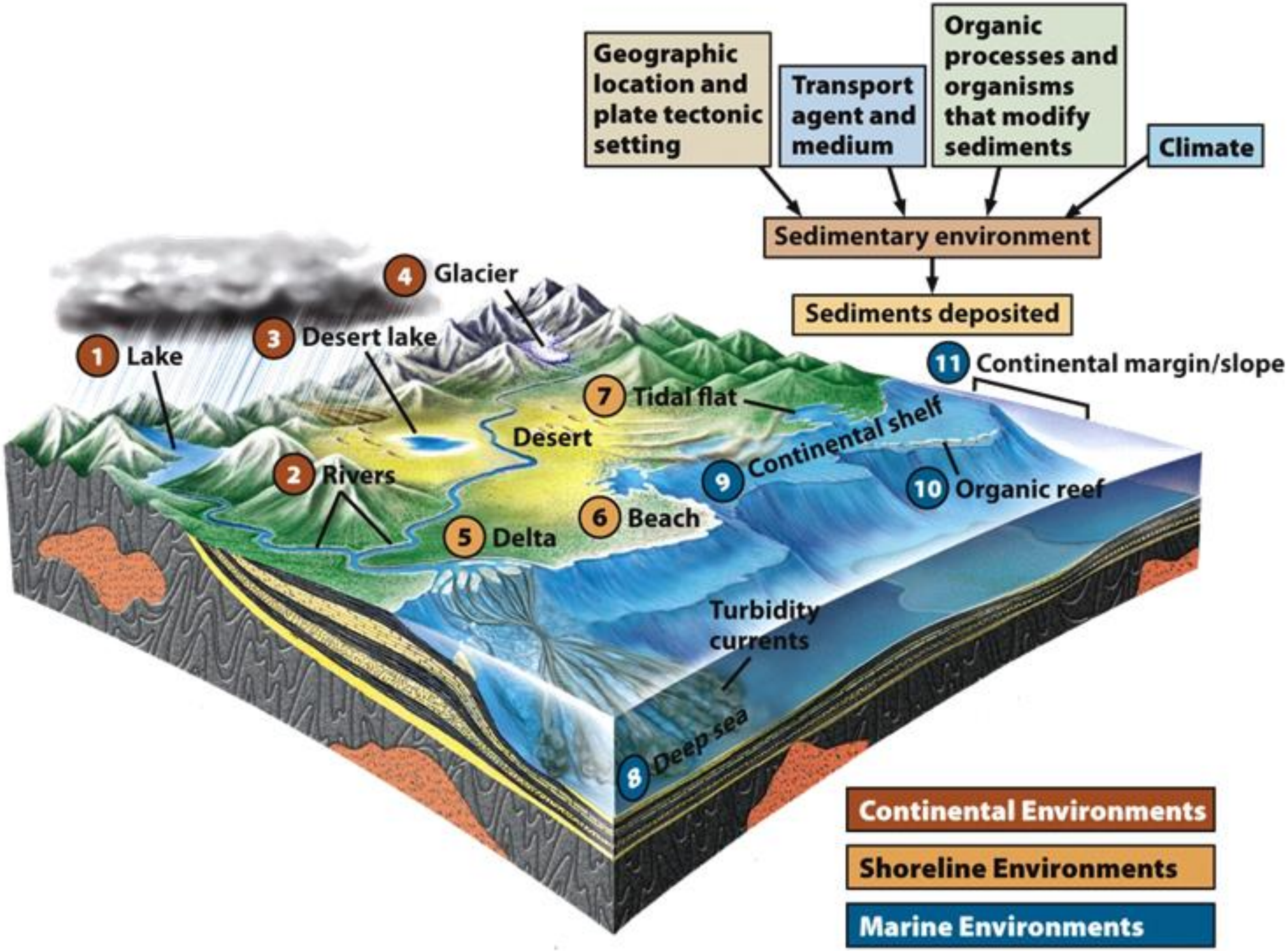
(created as the two plates are pulled apart and new oceanic lithosphere is produced)

Thermal subsidence basin

(created as the lithosphere cools and contracts)

Understanding Earth 6th Ed.

Sedimentary environments



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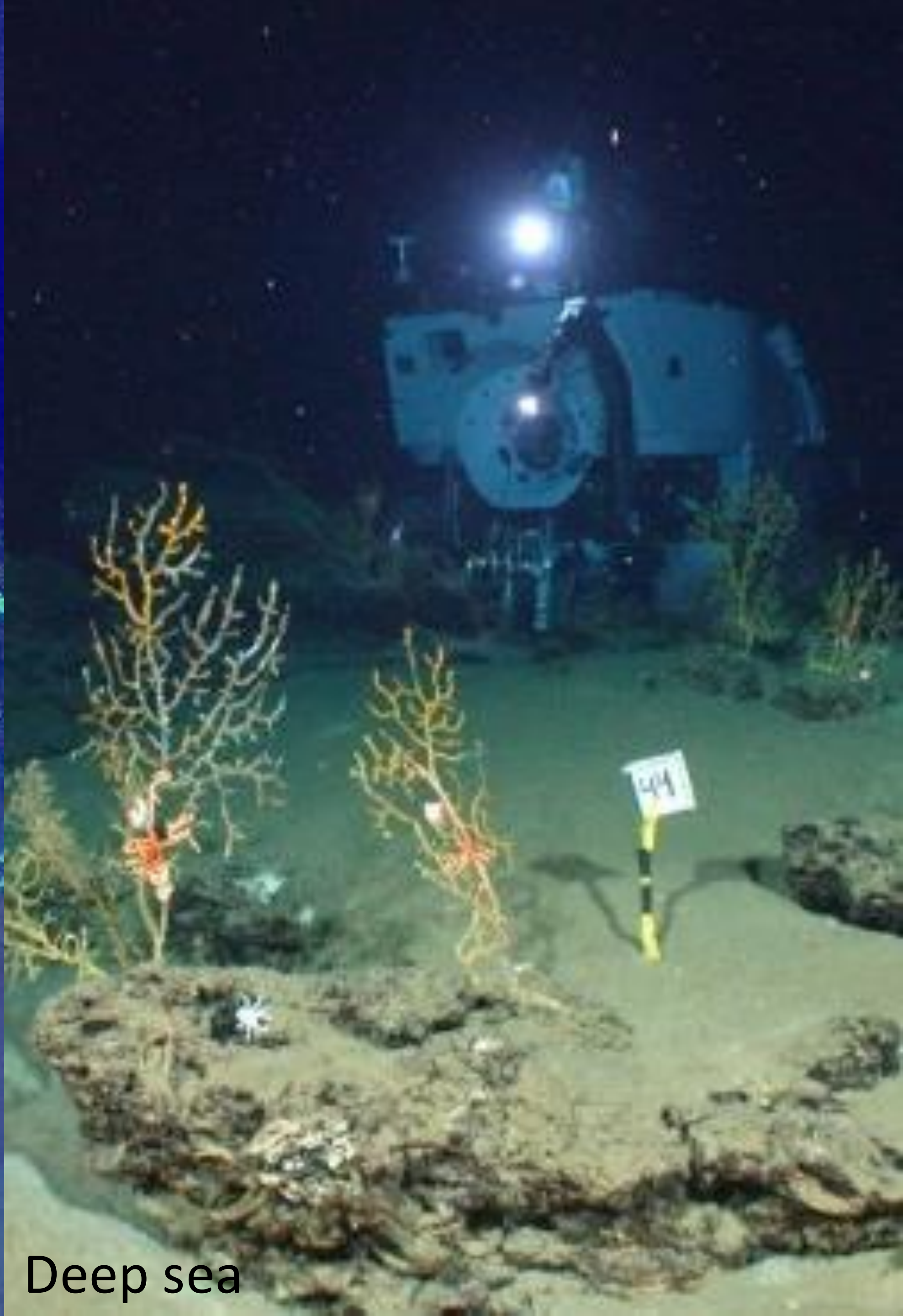
Continental environments

Shoreline environments

Marine environments



✶ Examples of sedimentary structures

1. Ripple marks

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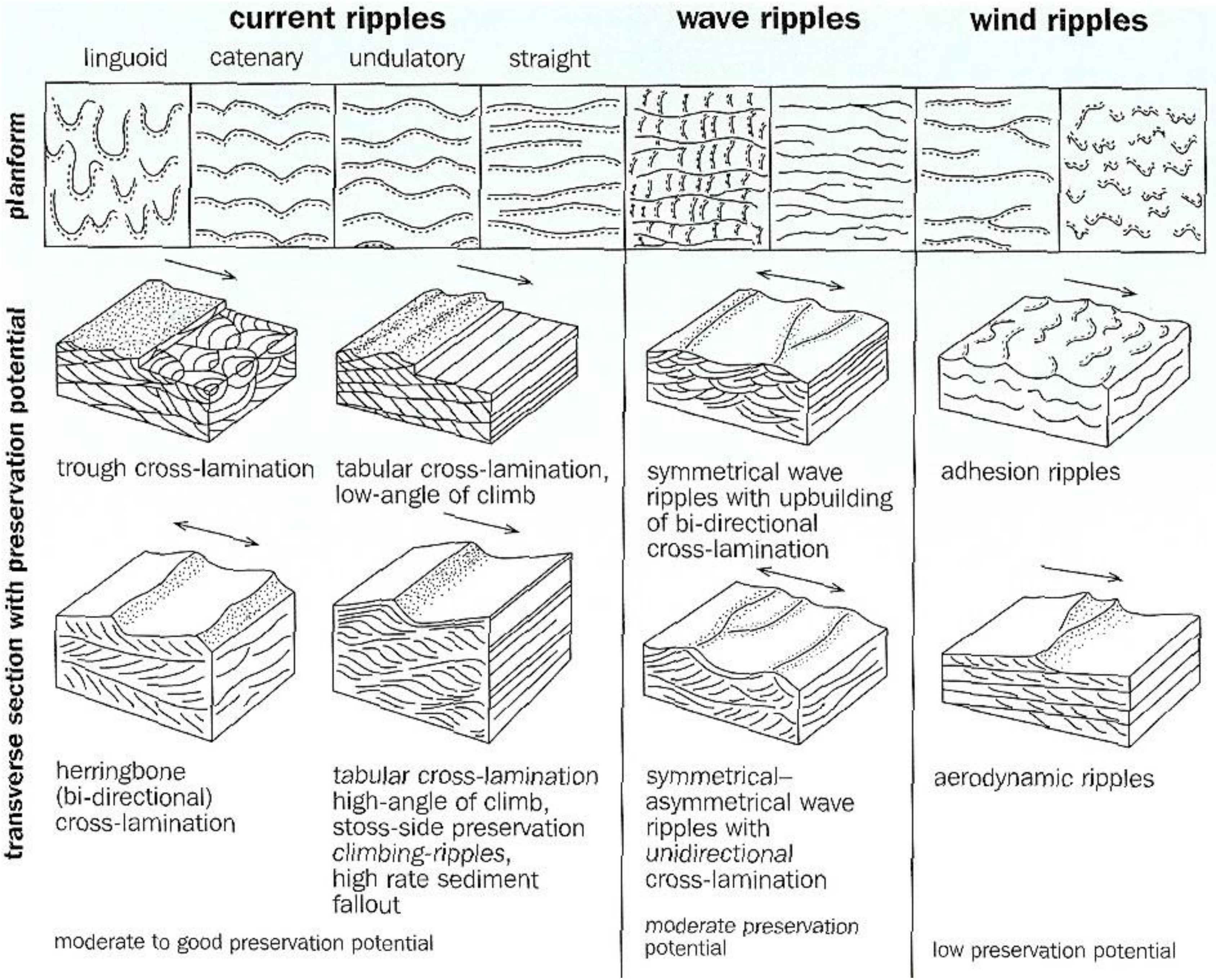
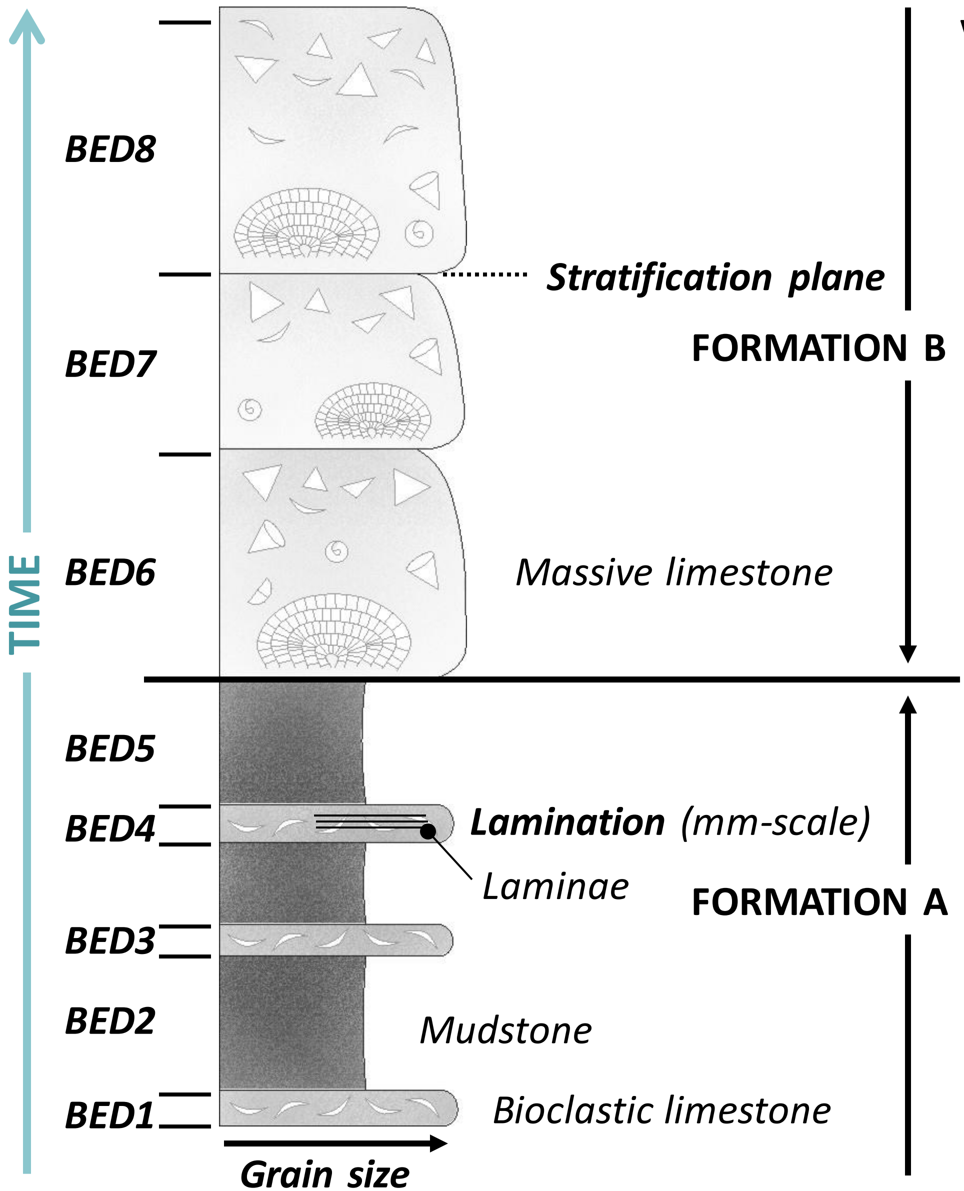


From Stow (2005)

2. Bedding

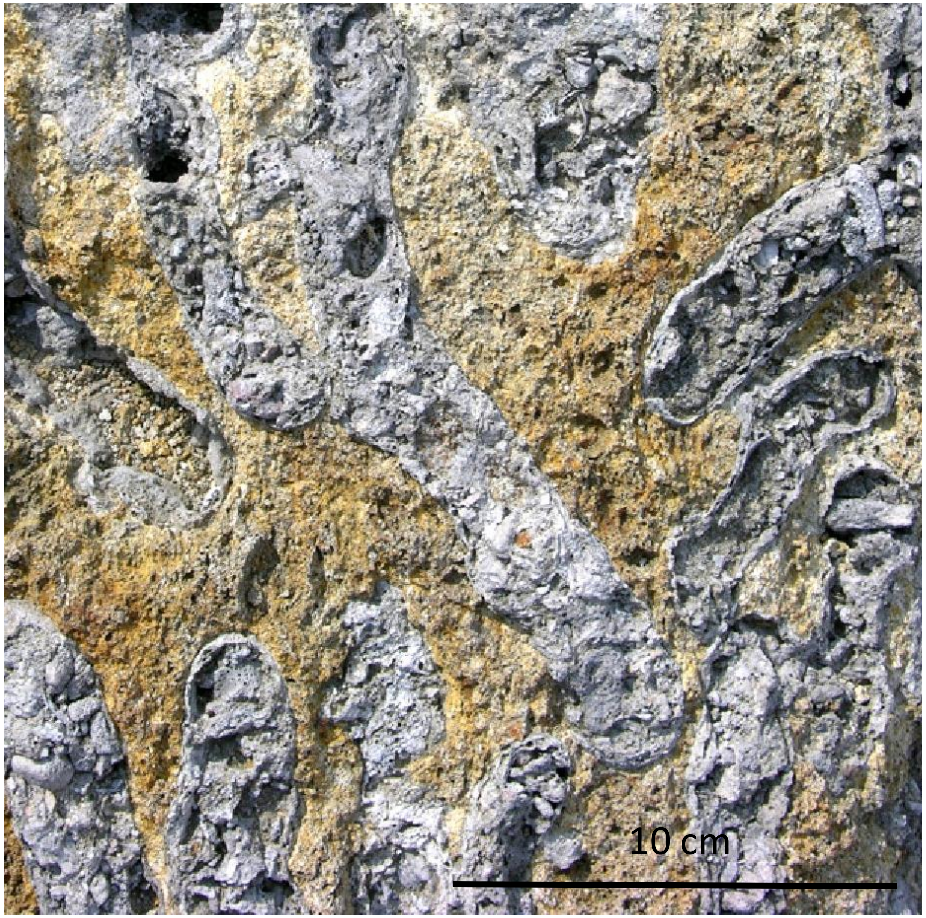
Stratification plane: separation between two beds (originally horizontal if sediments were deposited as flat-lying layers or inclined if they were deposited on a slope)



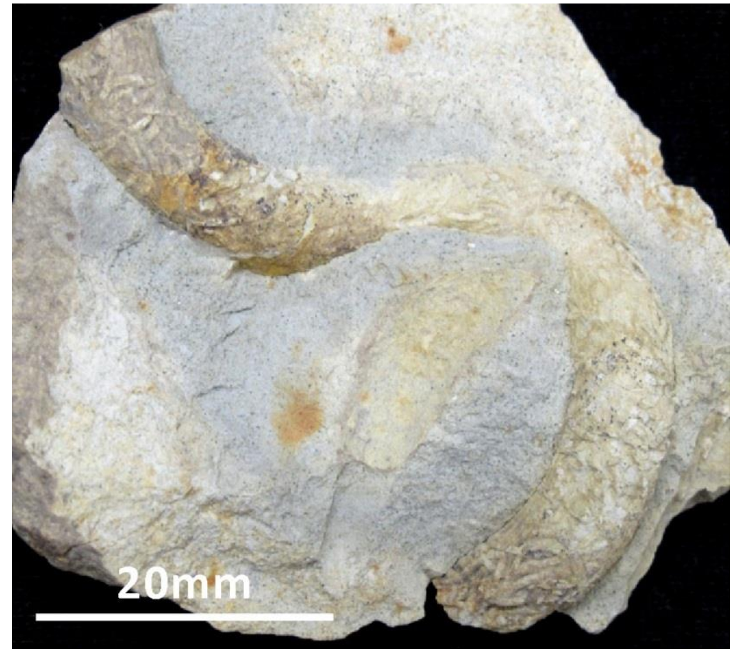
www.edupic.net

3. **Bioturbation** (disturbance of soils and sediments by animals or plants)

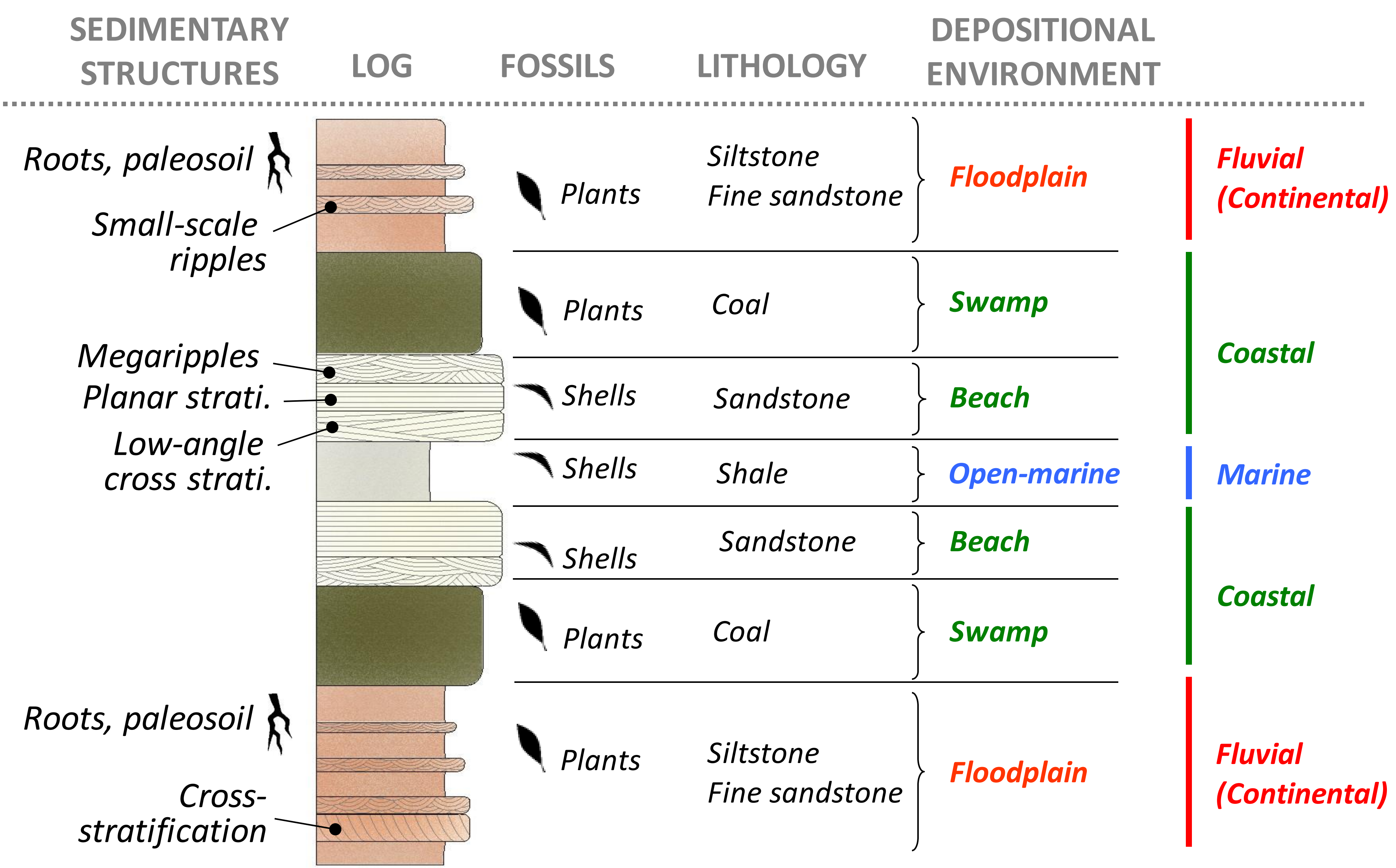
Large burrows in volcanic tuff
(Holocene, Japan)



Small burrow
(Paleozoic, Belgium)

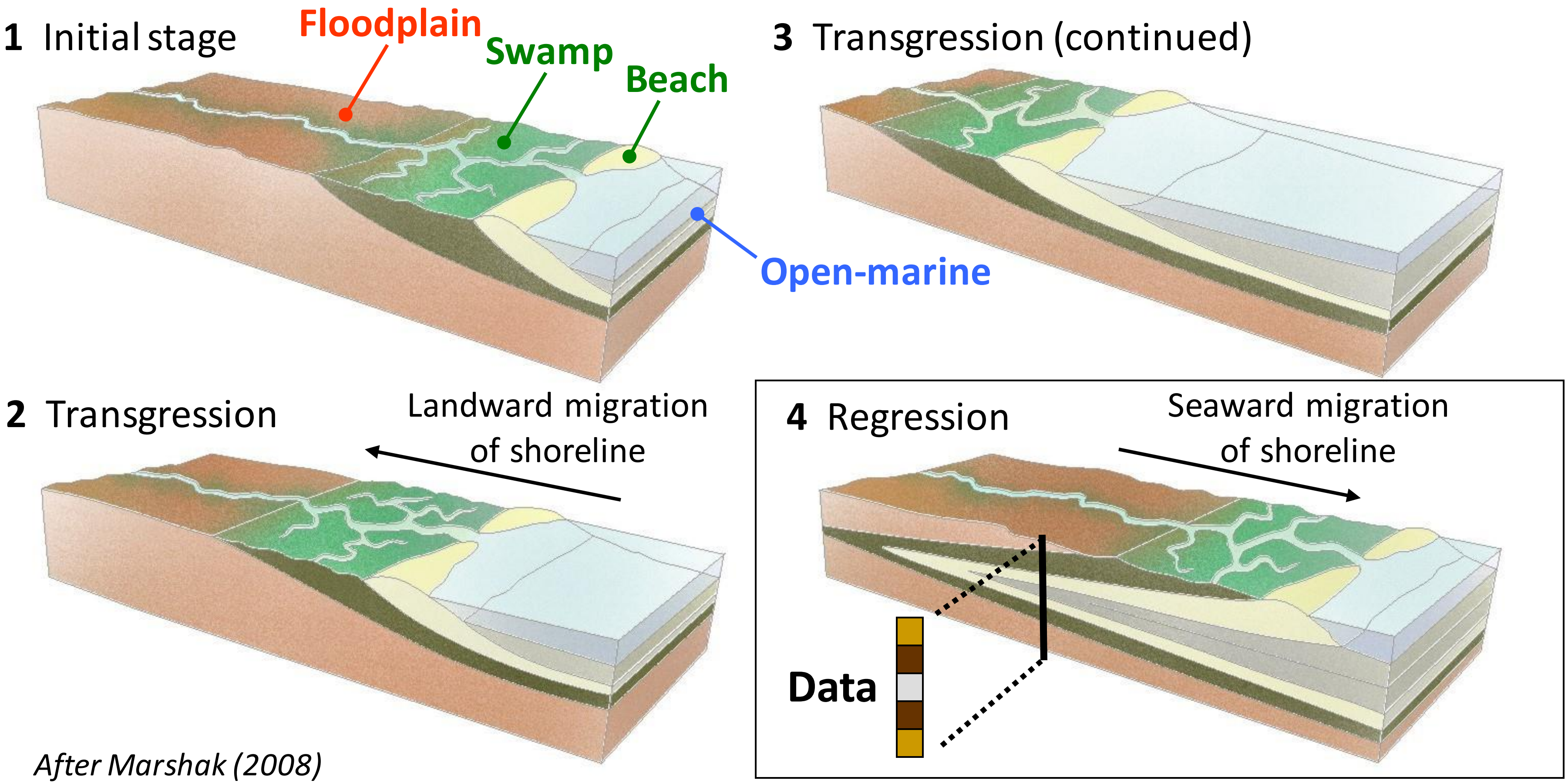


✶ Reconstruction of past sea level and environmental changes



After Marshak (2008)

Data interpretation



After Marshak (2008)

Transgression = sea level rises and shoreline moves landward

Regression = sea level falls and shoreline moves seaward

✶ Types of sedimentary rocks

1. **Siliciclastic sedimentary rocks**
   - Derived from accumulation of mineral fragments and/or lithic (rock) fragments composed mainly of silicate minerals

2. **Biochemical sedimentary rocks**
   - Derived from precipitation (direct or indirect) of a mineral by organisms (most commonly $CaCO_3$ or SiO_2)

3. **Chemical sedimentary rocks**
   - Derived from abiotic precipitation of minerals in a saline pond, lake or embayment undergoing intense evaporation (→ EVAPORITES)

4. **Organic sedimentary rocks**
   - Derived from accumulation and preservation of organic matter

1. Siliciclastic sedimentary rocks

- CLASSIFICATION BASED ON **GRAIN SIZE**:

COARSE-GRAINED **Conglomerate**	MEDIUM-GRAINED **Sandstone**	FINE-GRAINED **Shale**
		

- CLASSIFICATION BASED ON **GRAIN COMPOSITION**

Example: sandstones

Lithic sandstone	**Arkose**	**Quartz arenite**	**Graywacke**
Rich in rock fragments	Feldspar-rich	Pure quartz	Space between sand grains filled with mud

2. Biochemical sedimentary rocks

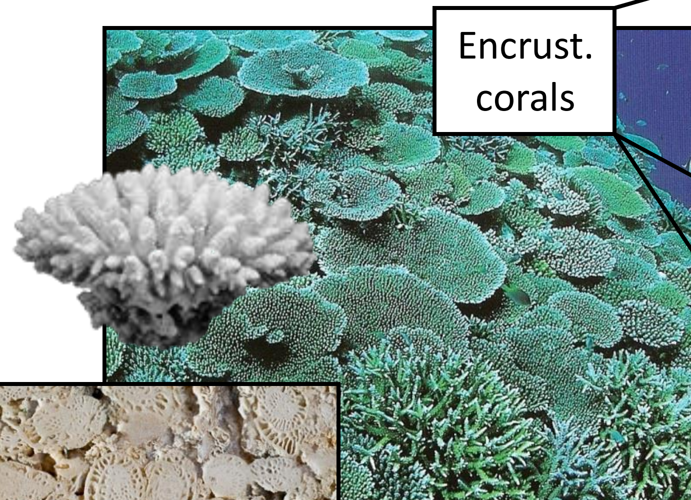
A **Direct precipitation** of $CaCO_3$ by corals, mollusks, foraminifera, diatoms
= LIMESTONES

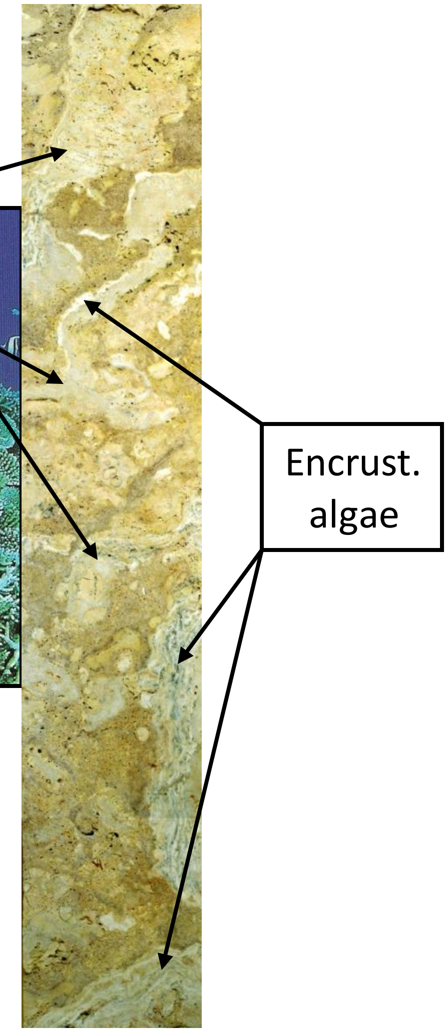
SiO_2 by diatoms, radiolarians

Bioclastic limestones

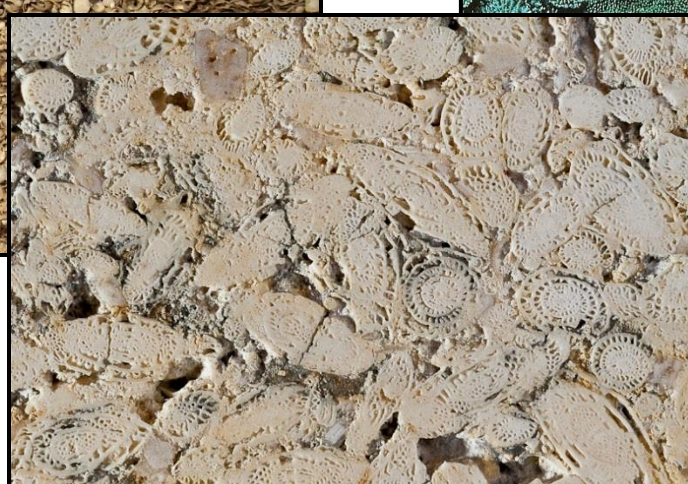
Accumulation of shell debris

Reef limestones

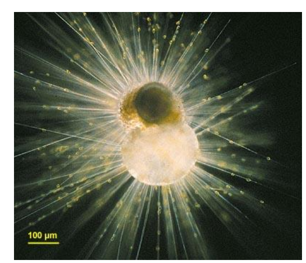




Foraminifers →



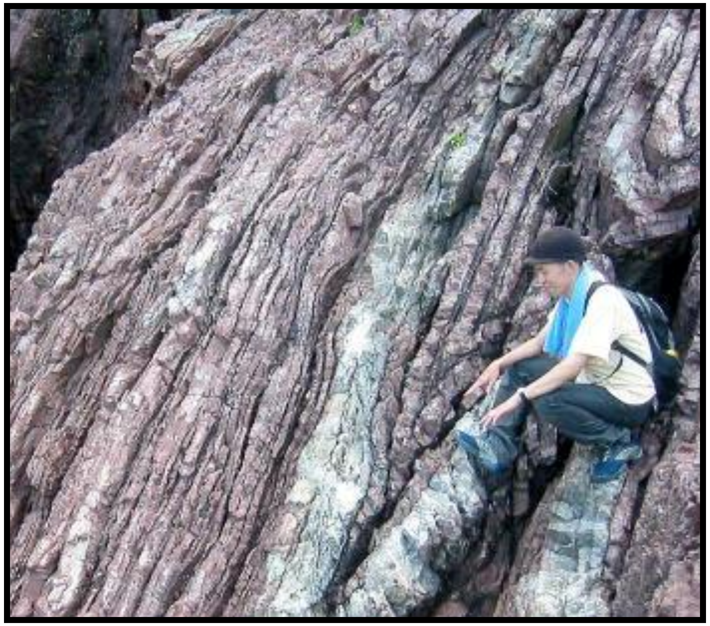
http://petrographica.ru/fossils/foto/90.html



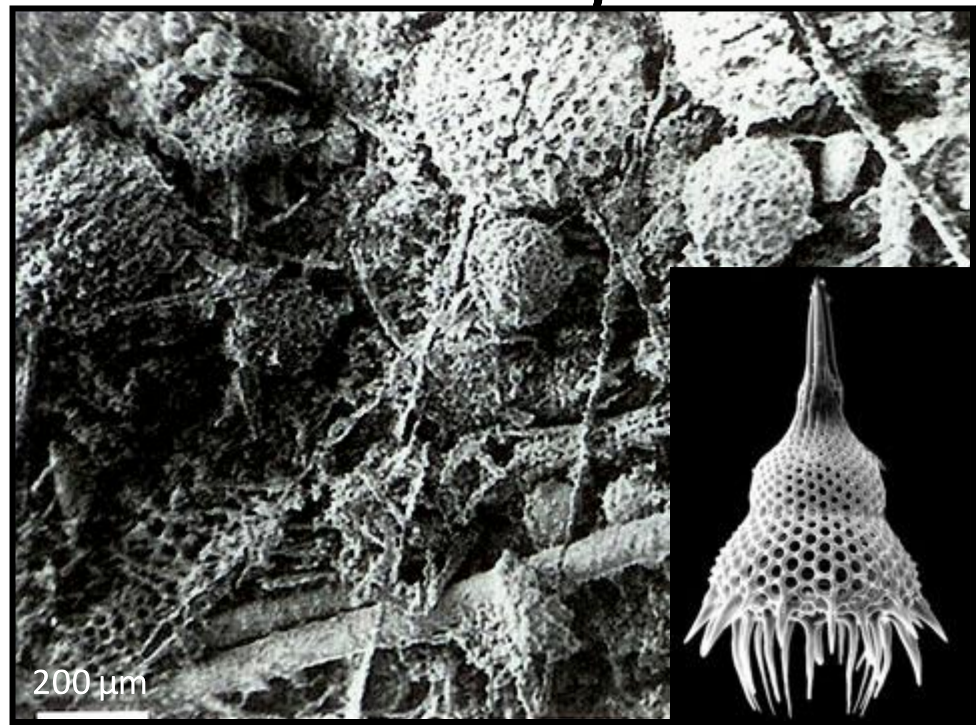
O. R. Anderson
(serc.carleton.edu)

CHERT = siliceous sedimentary rock (composed of silica)

Radiolarite (Japan)



Radiolarian



www.radiolaria.org

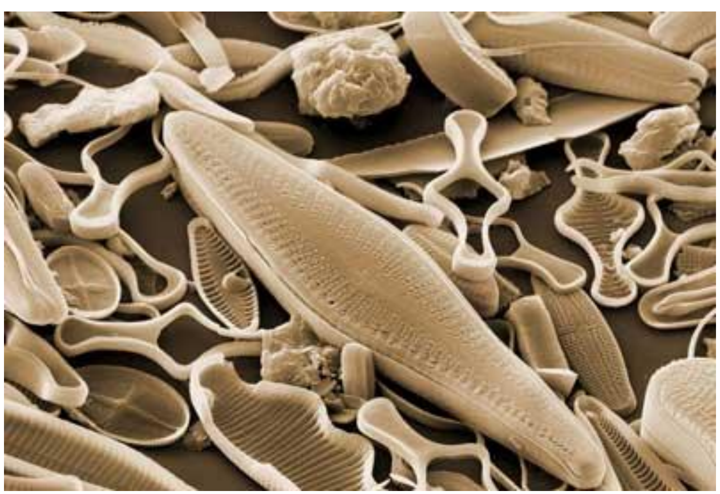


Photo: Sarah Spaulding

→ Diatoms

Like foraminifers and radiolarians, diatoms are single-celled organisms. However, diatoms can sometimes form colonies of attached individuals.

B Indirect precipitation of $CaCO_3$ induced by photosynthetic activity of microbes

3.4-billion years stromatolite
Strelley Pool Chert (Australia)

Photosynthesis:

$$6H_2O + \mathbf{6CO_2} + \text{sunlight} \rightarrow C_6H_{12}O_6 + 6O_2$$

Calcification

$$Ca^{2+} + 2HCO^{3-} \leftrightarrow CaCO_3 + \mathbf{CO_2} + H_2O$$

(1) Modern stromatolites at Shark Bay, Australia (P. Harrison, Wiki.)

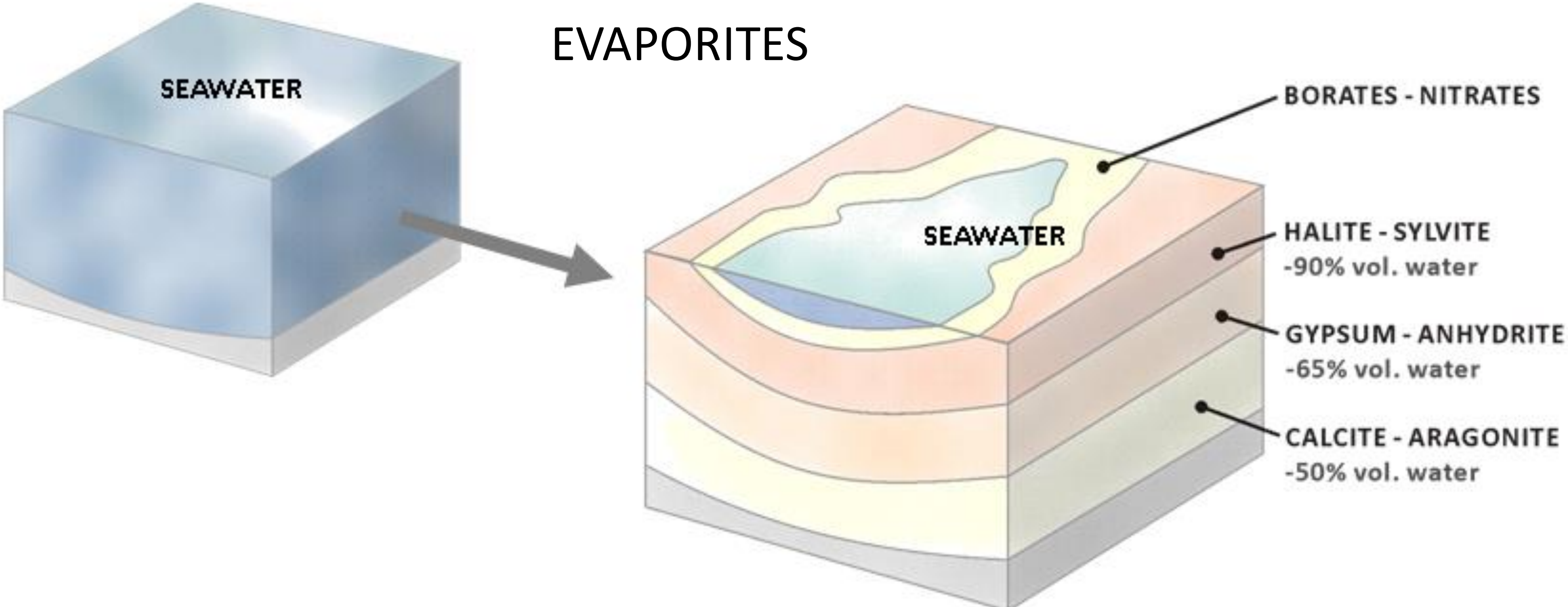
(2) Modern stromatolite (http://phys.org)

(3) Fossil stromatolite (K. McNamara, www.geolsoc.org.uk)

(4) Fossil stromatolite (Alwood et al. 2006, Nature)

3. Chemical sedimentary rocks

EVAPORITES

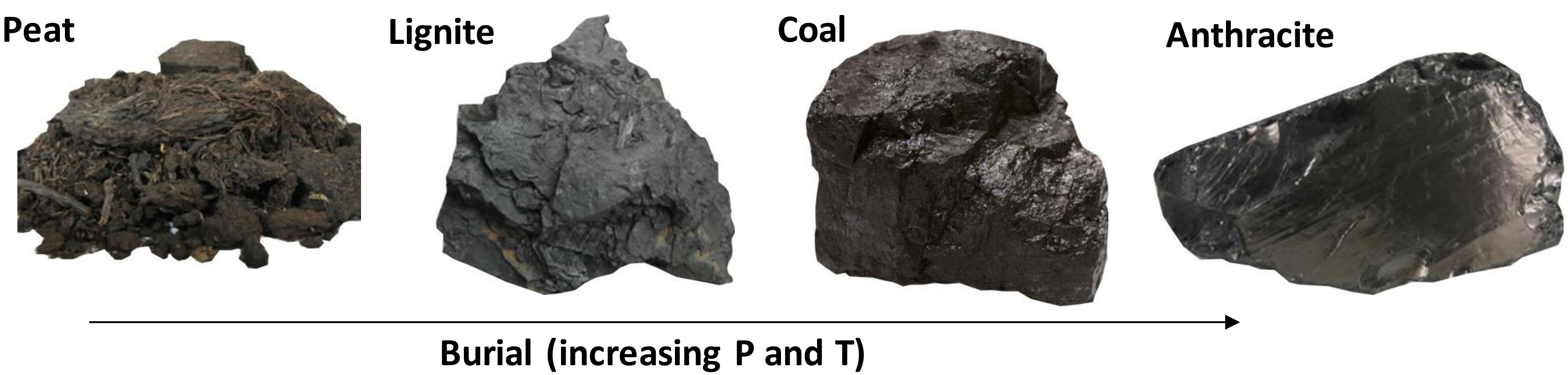


Calcite-aragonite	$CaCO_3$
Gypsum	$CaSO_4.2H_20$
Anhydrite	$CaSO_4$
Halite	NaCl
Sylvite	KCl
Borates	Ex: $Na_2B_4O_7{\cdot}5H_2O$
Nitrates	Ex: KNO_3

Messinian (~5.5 Ma) evaporite composed of gypsum
Source: F. Boulvain (University of Liege)

4. Organic sedimentary rocks

Note that biochemical and organic sedimentary rocks can be called biological sedimentary rocks



Another example: oil shale

- **Problems of preservation**:

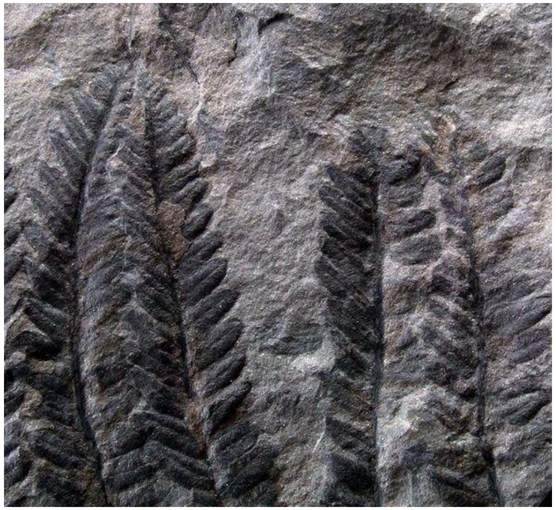
  1. **RECYCLING** (organic matter in water column consumed by organisms)
  2. **OXIDATION** (bacterial and abiotic decay of organic matter)

  $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$

- **Conditions of preservation**:

  1. **HIGH ACCUMULATION RATE** (e.g. plant debris, micro-organisms)
  2. **ANOXIA or LOW [O_2]** (e.g. restricted water circulation)

Coal mine (Carboniferous, Graissessac, France)



F. Boulvain (ULg)

Different origin of coal and oil

Biogenic CH_4

Thermo-genic CH_4

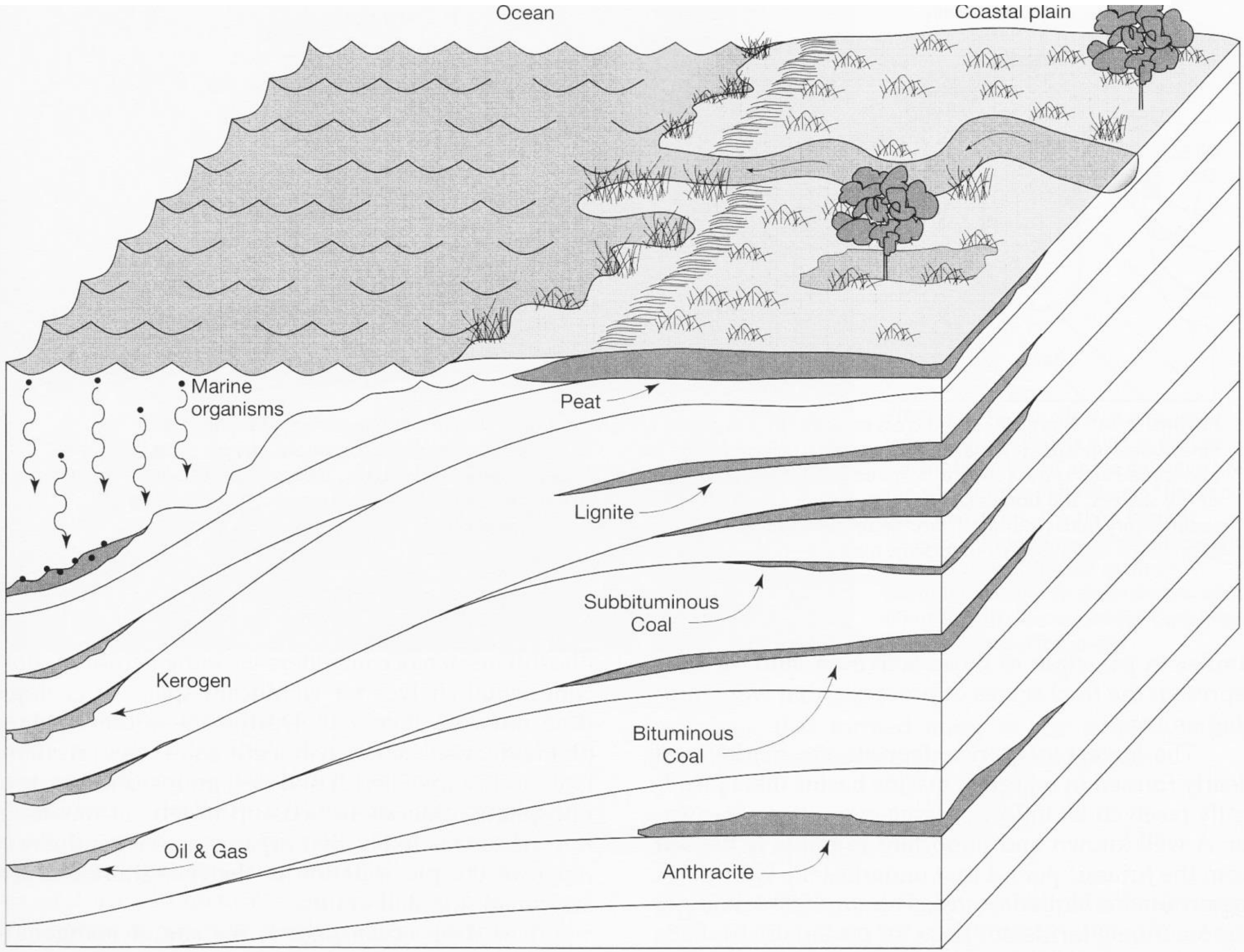


FIGURE 2.13 Schematic diagram illustrating how the burial of terrestrial organic matter can result in the formation of coal, and the burial of marine organic matter can result in the formation of oil and gas. The increasing temperature and pressure at greater depths of burial both compact and modify the terrestrial matter as it progresses through the various ranks of coal. Marine organic debris is converted into a waxy material called *kerogen;* upon additional heating, the kerogen is converted into petroleum.

Craig et al. (2011)

TABLE 5.2 Representative compositions of living matter and fossil fuels

Part A: Living Matter

Substances	Lipids	Proteins	Carbohydrates
	Major Constituents (wt%)		
Green plants	2	7	75
Humus	6	10	77
Phytoplankton	11	15	66
Zooplankton	15	53	5
Bacteria (veg.)	20	60	20
Spores	50	8	42

Part B: Petroleum

Substances	C	H	S	N	O
	Elemental Composition (wt%)				
Lipids	80	10	—	—	10
Proteins	53	7	2	16	22
Carbohydrates	44	6	—	—	50
Lignin	63	5	0.1	0.3	31
Kerogen	79	6	5	2	8
Natural gas	75–80	20–25	trace–0.2	trace–minor	—
Asphalt	81–87	9–11	0.3–6	0.8–2.2	0–4
Petroleum	82–87	12–15	0.15	0.1–5	0.1–2

Part C: Coal

Substances	C	H	S	N	O
	Elemental Composition (wt%)				
Peat	21.0	8.3	—	1.1	62.9*
Lignite	42.4	6.6	1.7	0.6	42.1
Sub-bituminous	76.3	4.7	0.5	1.5	17.0
Bituminous	87.0	5.4	1.0	1.4	5.2
Semianthracite	92.2	3.8	0.6	1.2	2.2
Anthracite	94.4	1.8	1.0	0.7	2.1

*Remainder is ash and moisture.

(From Chilingarian and Yen. *Bitumens, Asphalts, and Tar Sands*, and from *Coal Development*, S. Bureau of Land Management, 1983.)

Craig et al. (2011)