Fundamentals of Earth Sciences (ESO 213A)

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Department of Earth Sciences

Sedimentary Rocks

Previous Class: Volcanoes

Important Announcements

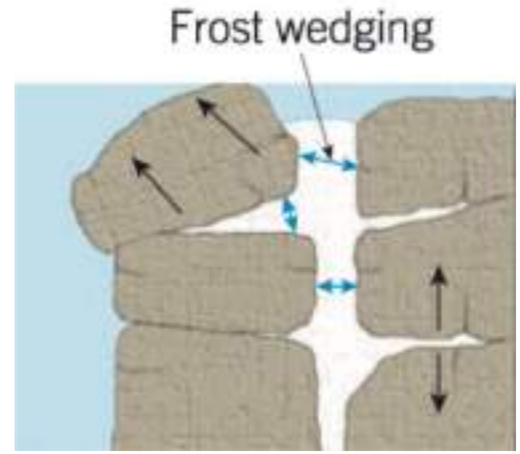
- Quiz 1 will be conducted during normal class hours (11:00 -11:40 AM)
- Date: 2nd September 2022
- Venue: L-16
- Syllabus: Material covered up to 29th August
- Type: MCQ (30 questions/1 mark each/0.25 marks negative marking, you can open notes, books and internet but no discussion)

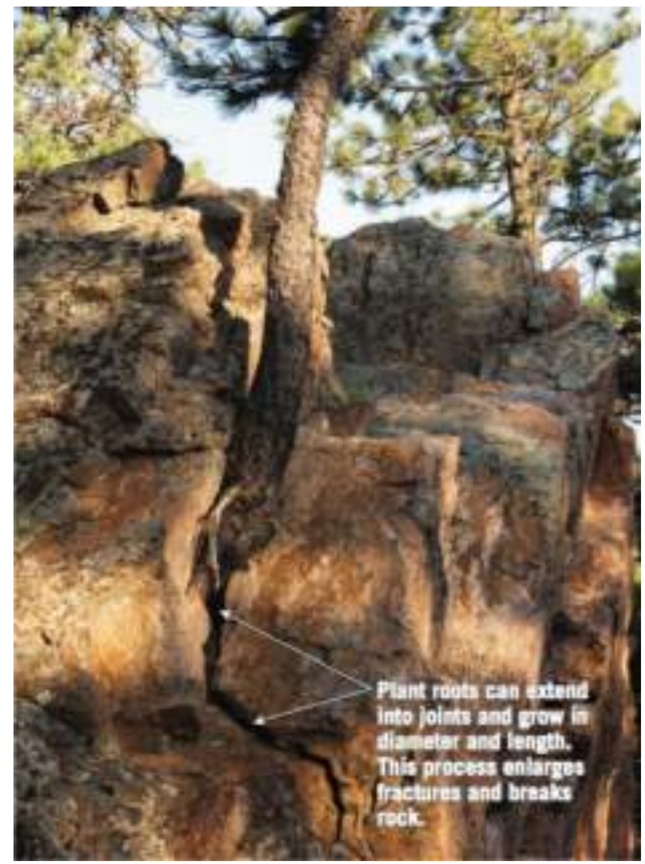
What Is a Sedimentary Rock?

- Sedimentary rocks are products of mechanical and chemical weathering.
- They comprise about 5% (by volume) of Earth's outer and are concentrated at or near the surface
- Contain evidence of past environments:
    - Provide information about sediment transport
    - Often contain fossils
    - Hydrocarbon, grounwater reservoirs

Physical Weathering

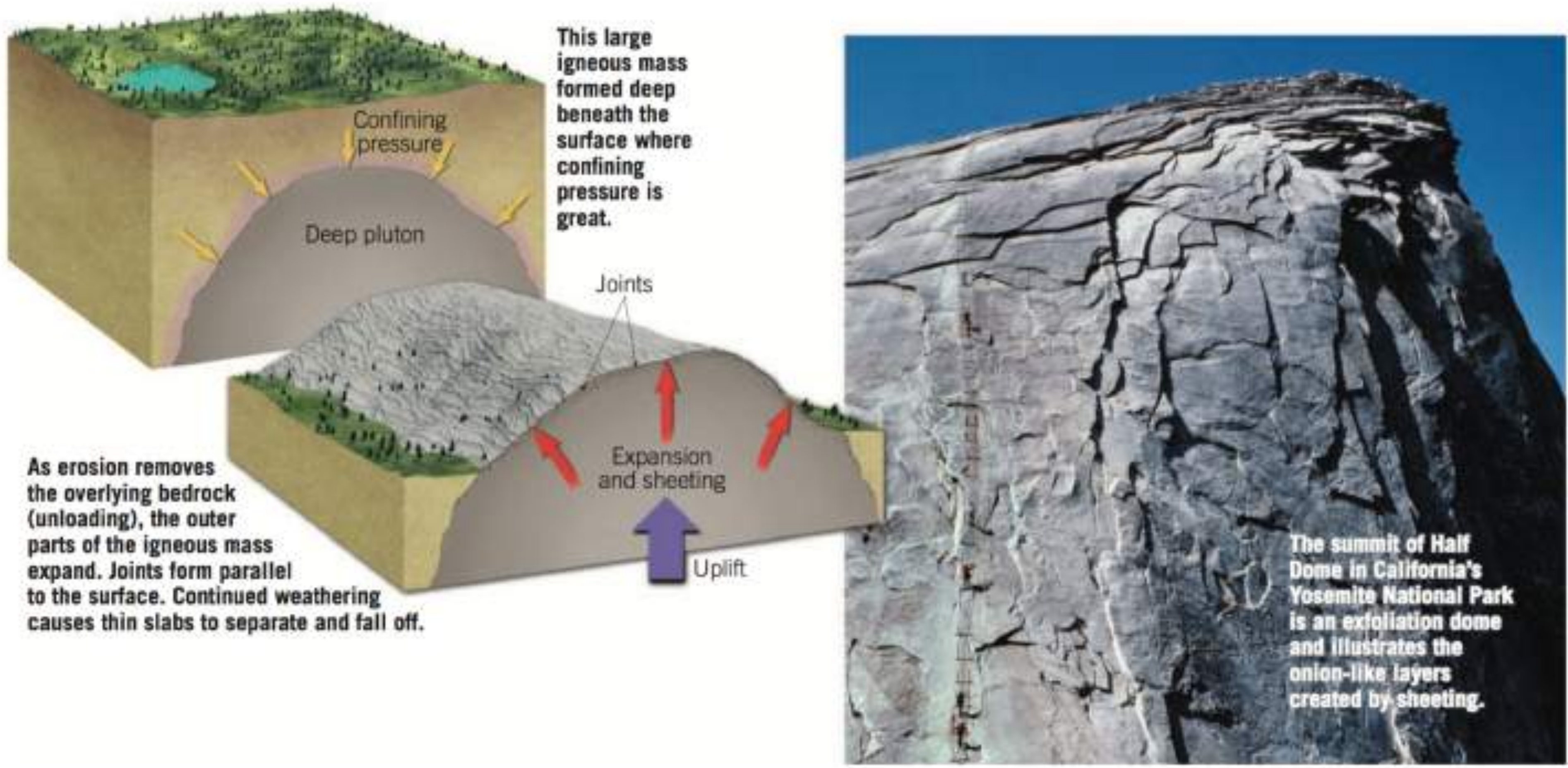
- **Frost wedging:** When liquid water freezes, it expands by 9% and expands cracks producing fragments of rocks
- **Salt crystal growth:** Salty groundwater penetrates pores or crevices. As water evaporates, salt crystals form and grow pushing surrounding grains, opening up of tiny cracks.
- **Biological activity:** Plant root grows into fractures and wedge rocks apart.
- Plant roots, algae, and decaying animals occupy fractures in rocks and produces acids promoting decomposition





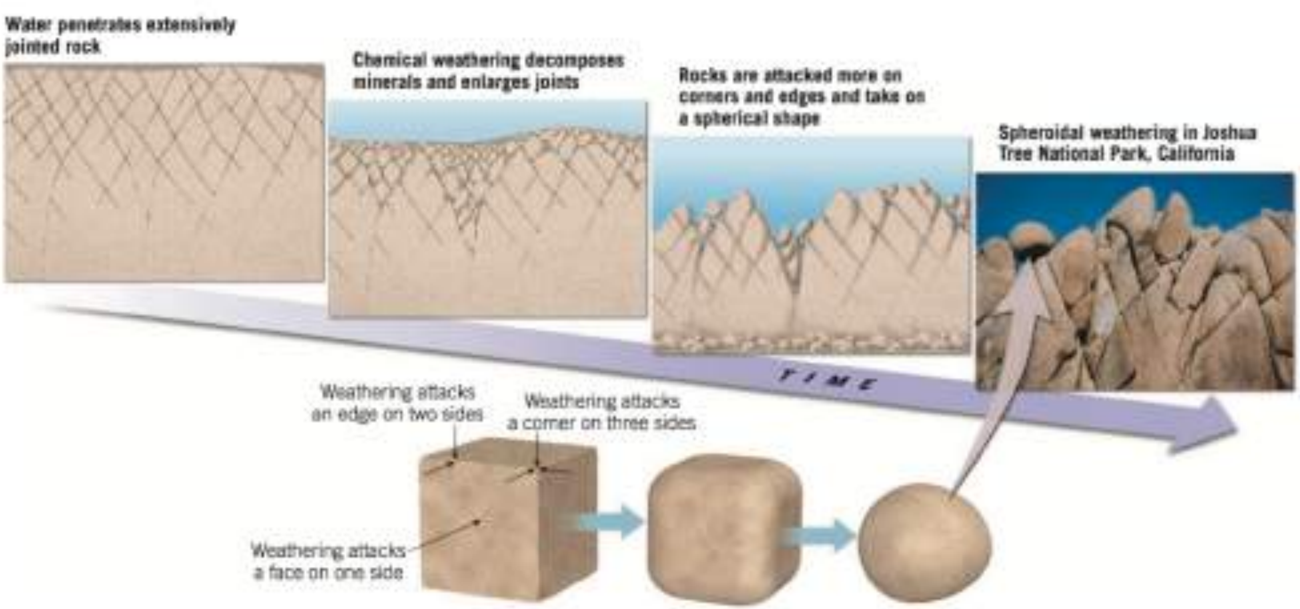
Physical Weathering

Sheeting: If large mass of igneous rocks are exposed to erosion, the outer part of igneous mass expands. Continued weathering causes thin slabs to fall off.



Chemical Weathering

- In chemical weather the structure of minerals changes
- H_2O is most important agent of chemical weathering. It can liberate and transport ions from some minerals through dissolution.
- Water may also directly react with exposed minerals, producing new minerals that are stable at Earth's surface. The hydrolysis of feldspar to form kaolinite clay is an example. Clays are stable minerals at Earth's surface conditions, and they are profusely generated by the hydrolysis of silicate minerals.
- CO_2 dissolves in H_2O and forms acids that can decompose many minerals
- Spheroidal weathering: Many rock outcrops have a rounded appearance. This occurs because chemical weathering works inward from exposed surfaces.



Turning Sediment into Rock

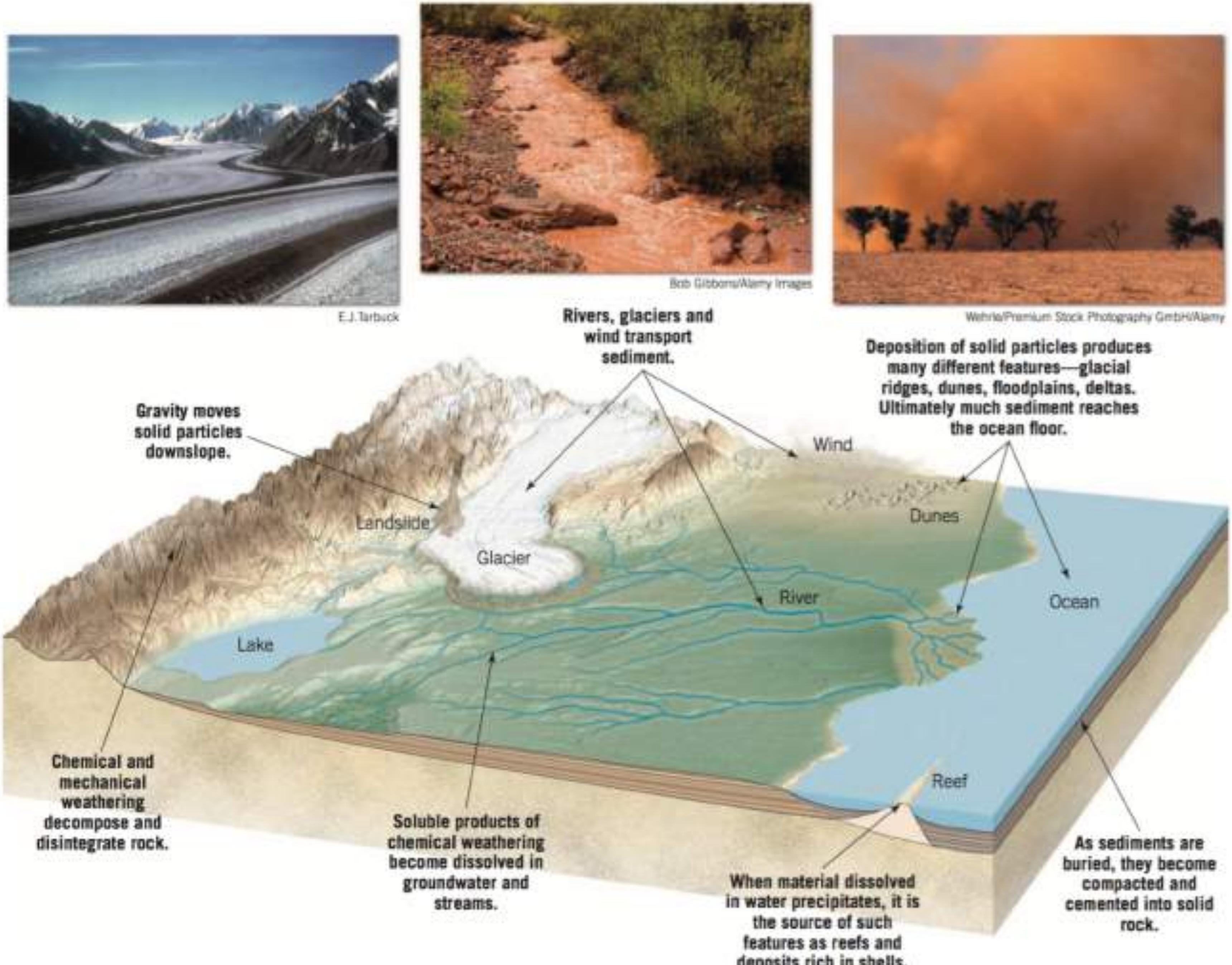
- Many changes occur to sediment after it is deposited.
- Diagenesis—chemical, physical, and biological changes that take place after sediments are deposited
  - Occurs within the upper few kilometers of Earth's crust at temperatures < 150^{O} -200^{O}C

Turning Sediment into Rock

Diagenesis

- **Includes:**
  - **Recrystallization—development of more stable minerals from less stable ones (e.g., aragonite → calcite).**
  - **Lithification—sediments are transformed into solid rock by:**
    - » **Compaction and cementation**
    - » **Natural cements, which include calcite, silica, and iron oxide**

An outline of the portion of the rock cycle that pertains to the formation of sedimentary rocks.



Types of Sedimentary Rocks

- **Sediment originates from mechanical and/or chemical weathering, or accumulation of remains of plants.**
- **Rock types are based on the source of the material.**
  - ***Detrital sedimentary rocks*** **- transported sediment as solid particles**
  - ***Chemical sedimentary rocks*** **- sediment that was once in solution and was precipitated by either inorganic or biologic processes**
  - ***Organic sedimentary rocks***

I. Detrital Sedimentary Rocks

- The chief constituents of detrital rocks include:
    - Clay minerals
    - Quartz
    - Feldspars
    - Micas
- Particle size is used to distinguish among the various rock types.

Detrital Sedimentary Rocks

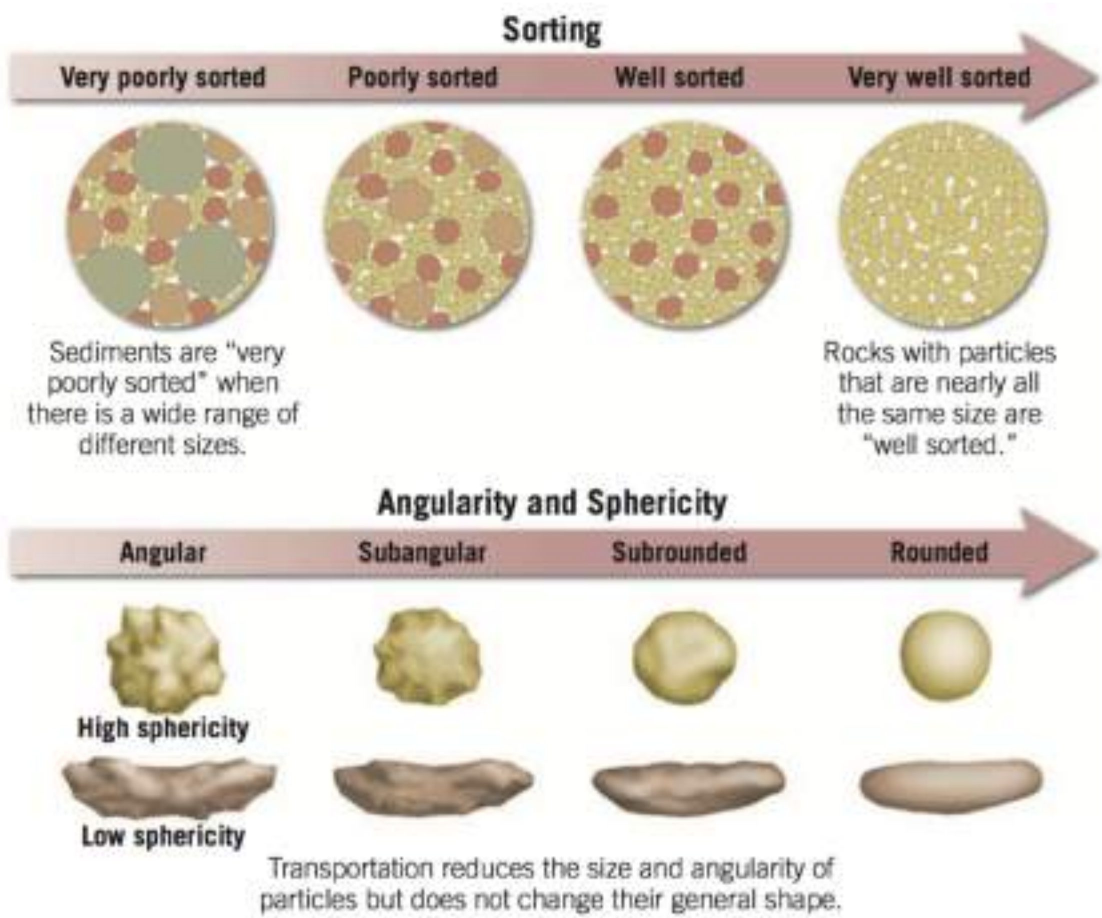
Common detrital sedimentary rocks

- **1. Shale**
  - **Mud-sized particles in thin layers that are called lamina (→ fissibility)**
  - **Most common sedimentary rock**
  - **Environments of deposition: lake, lagoons, deep-ocean basins**
  - **<u>Impermeable</u> rock**

Detrital Sedimentary Rocks

2. Sandstone

- Sand-sized particles
- Forms in a variety of environments
- Predominant mineral = quartz
- Quartz-rich sandstone with highly rounded grains implies a long transport and several cycles of weathering
- Sandstone with feldspar and angular fragments of ferromagnesian minerals implies little chemical weathering and transport



Detrital Sedimentary Rocks

- **3. Conglomerate and breccia**
  - **Both are composed of particles greater than 2 millimeters in diameter (gravel).**

Conglomerate **consists largely of rounded gravels (imply long transport from their source area)**

  - **Poorly sorted**
  - **Gravels indicate turbulent currents and action of energetic mountain streams**

Gravel Deposits, if Lithified, Would Become Conglomerate

Detrital Sedimentary Rocks

- **3. Conglomerate and breccia**
  - **Both are composed of particles greater than 2 millimeters in diameter (gravel).**

Breccia **is composed mainly of large angular particles (imply short transport from their source area)**

Question

This detrital rock consists of angular grains and is rich in potassium feldspar and quartz. (Photo by E. J. Tarbuck)

Question 1 What do the angular grains indicate about the distance the sediment was transported?

Question 2 The source of the sediment in this rock was an igneous mass. Name the likely rock type.

Question 3 Did the sediment in this sample undergo a great deal of chemical weathering? Explain.

II. Chemical Sedimentary Rocks

- **Consist of precipitated material that was once in solution and carried to lakes and seas**

- **Classified according to their mineralogical composition**

- **Precipitation of material occurs by:**
    - **Inorganic processes (chemical origin)**
    - **Organic processes (biochemical origin)**

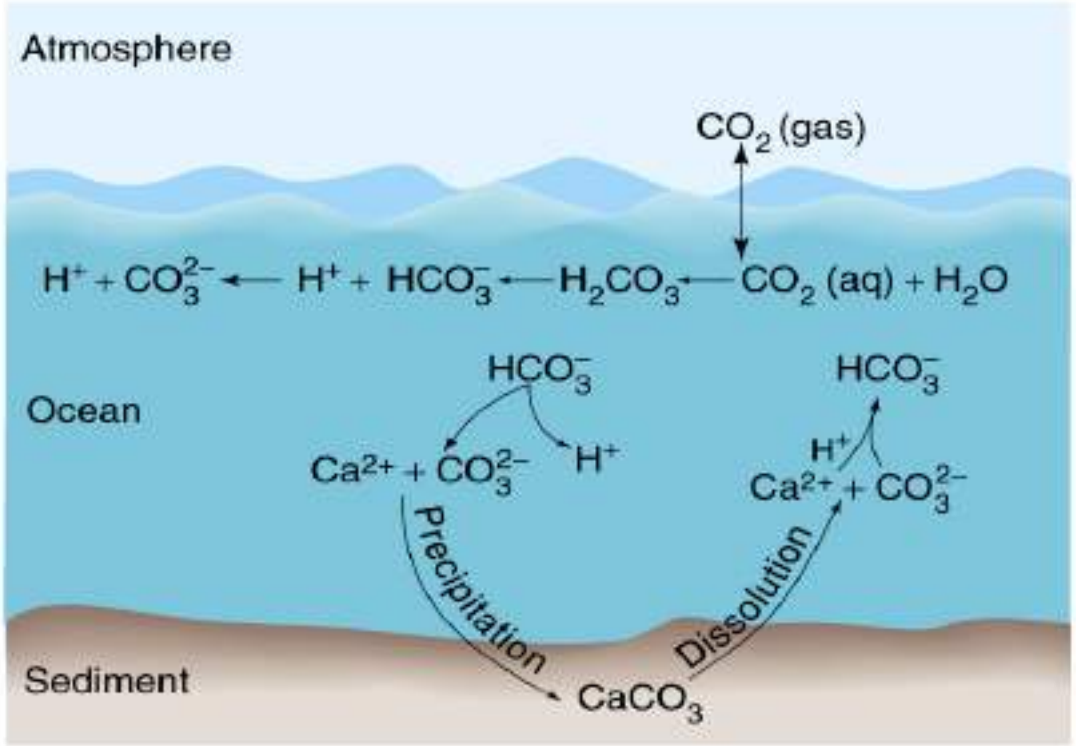
Chemical Sedimentary Rocks

- **Common chemical sedimentary rocks**
  - **1. Limestone ($CaCO_3$)**
    - **Most abundant chemical rock**
    - **Composed mainly of the mineral calcite ($CaCO_3$)**
    - **Marine *biochemical* limestones form as coral reefs, coquina (broken shells), and chalk (hard parts of microscopic organisms).**
    - **Inorganic limestones (*chemical*) include travertine and oolitic limestone (spherical grains with concentric layers of calcite/aragonite around a central nucleus).**

Example of Shells for limestone

Carbonate buffering

- Oceans can absorb CO_2 from atmosphere without much change in pH
- Keeps ocean pH about same (8.1)
- pH too high, carbonic acid releases H+
- pH too low, bicarbonate combines with H+
- Precipitation/dissolution of calcium carbonate $CaCO_3$ buffers ocean pH



Travertine

It is formed by a process of rapid precipitation of calcium carbonate, often at the mouth of a hot spring or in a limestone cave.

- **Commonly deposited in caves**

- **Groundwater is the source of $CaCO_3$**

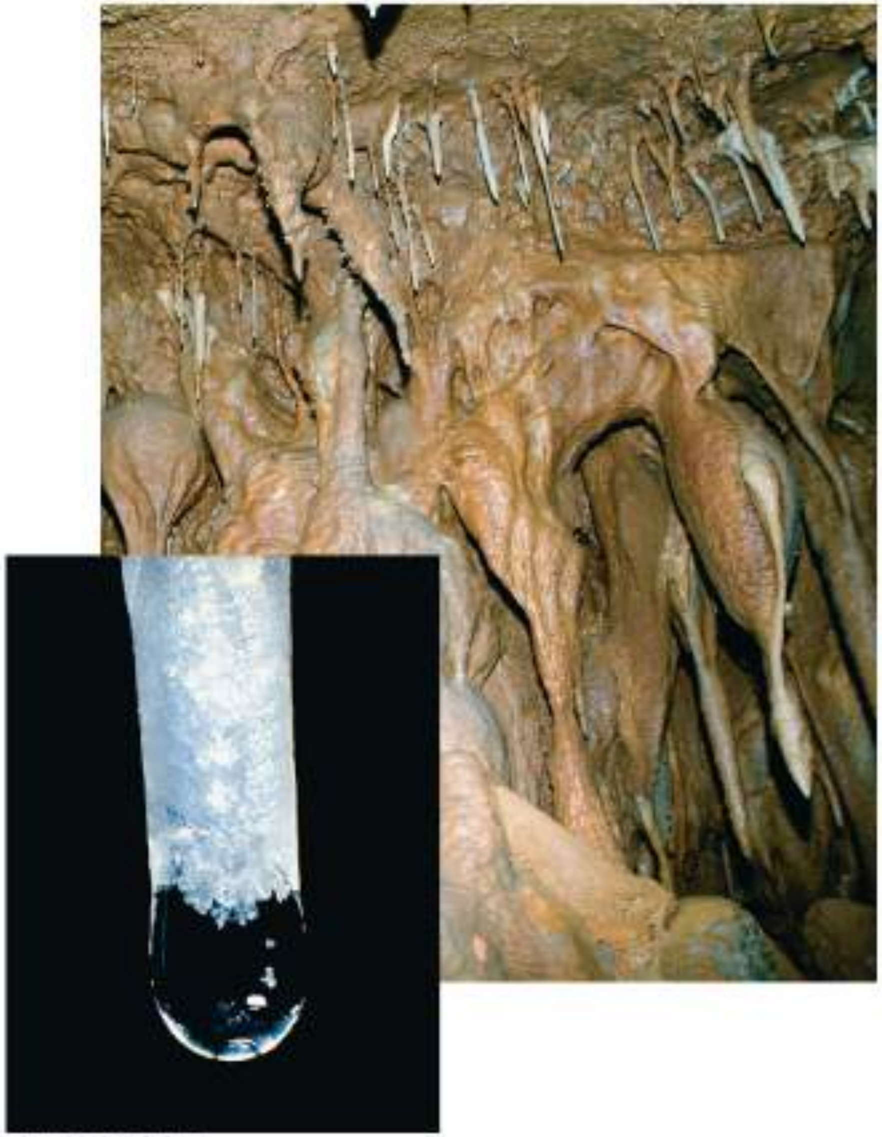
$$CaCO_3(s) + H_2O(l) + CO_2(aq) \rightarrow$$

$$Ca(HCO_3)_2(aq)$$

Ca bicarbonate

$$Ca(HCO_3)_2(aq) \rightarrow$$

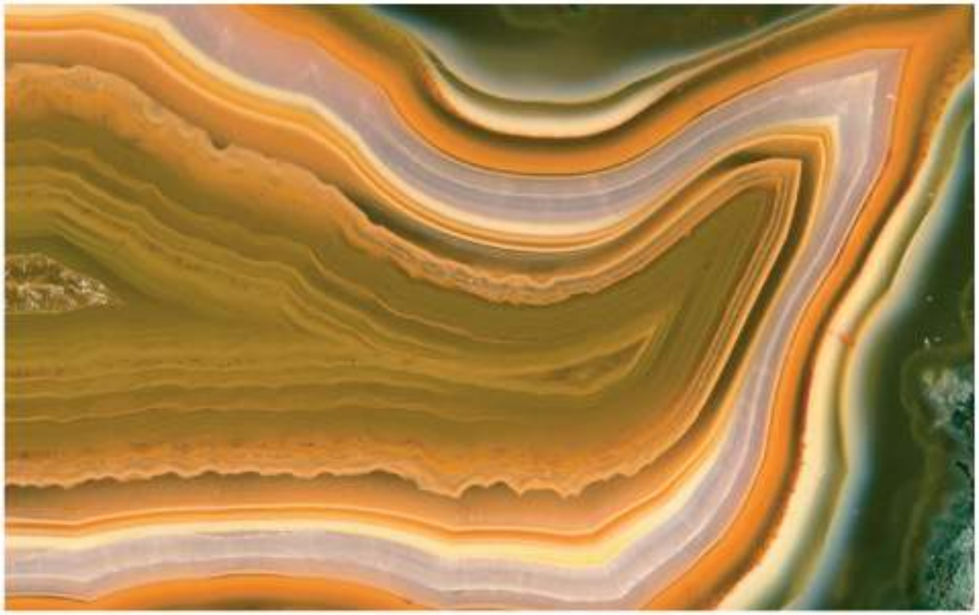
$$CaCO_3(s) + H_2O(l) + CO_2(aq)$$



Chemical Sedimentary Rocks

- **Common chemical sedimentary rocks**
  - **2. Dolostone [$CaMg(CO_3)_2$]**
    - **Typically formed secondarily from limestone when Mg-rich waters circulate through limestone**
  - **3. Chert (SiO_2)**
    - **Extremely hard and compact**
    - **Precipitated by *Diatoms* and *Radiolarians* (marine microorganisms)**
    - **Varieties include agate, flint and jasper.**

Varieties of Chert



A. Agate

B. Flint

C. Jasper

D. Chert arrowhead

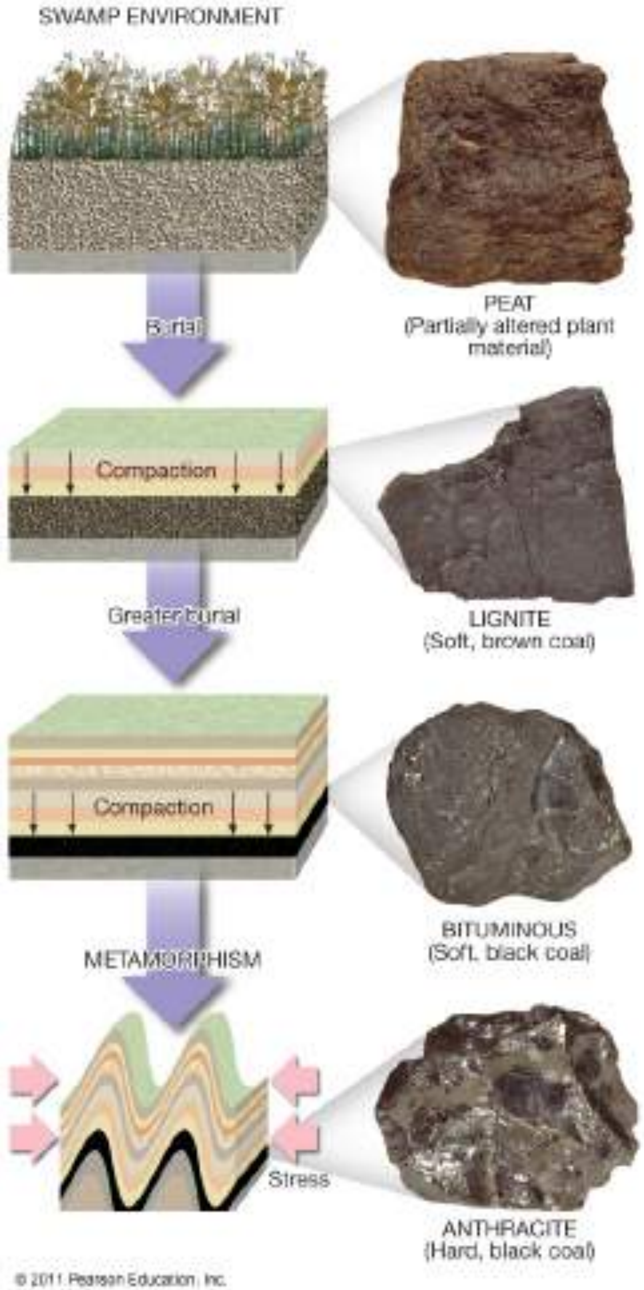
Chemical Sedimentary Rocks

Common chemical sedimentary rocks

- **4. Evaporites**
  - **Evaporation triggers deposition of chemical precipitates.**
  - **Examples include rock salt (NaCl) and rock gypsum ($CaSO_4 \bullet 2H_2O$).**
  - **Sequence of precipitation:**
    - » **80% of seawater evaporates → gypsum**
    - » **90% of seawater evaporates → halite**

III. Organic Sedimentary Rocks

- **Common chemical sedimentary rocks**
  - **Coal**
    - **Different from other rocks because it is composed of organic material.**
    - **The end product of large amounts of plant material, buried for millions of years**
    - **Stages in coal formation (in order):**
      1. **Plant material**
      2. **Peat**
      3. **Lignite (sedimentary rock)**
      4. **Bituminous (sedimentary rock)**
      5. **Anthracite (metamorphic rock)**



Stages of Coal Formation

Classification of Sedimentary Rocks

- **Sedimentary rocks are classified according to the type of material.**
- **Two major groups**
    1. **Detrital – classified according to particle size**
    2. **Chemical / Organic – classified according to mineral composition**

Classification of Sedimentary Rocks

Two major <u>textures</u> are used in the classification of sedimentary rocks:

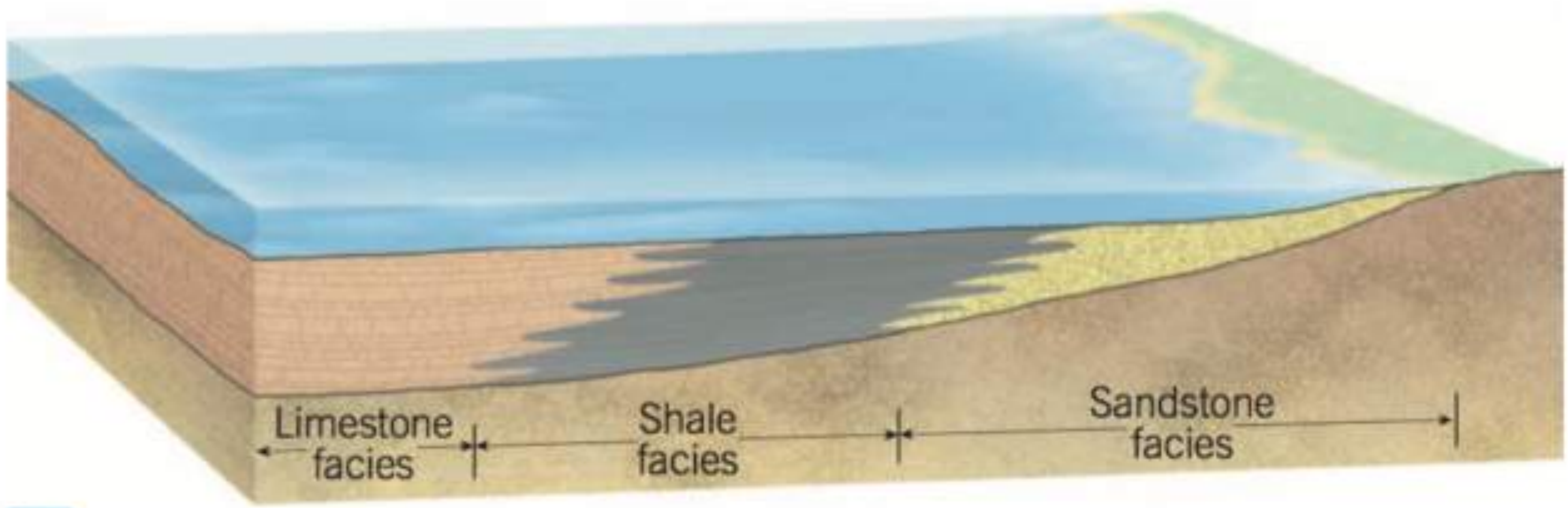
1. **Clastic**
   - **Discrete fragments and particles**
   - **All detrital rocks have a clastic texture**
   - **Some chemical rocks (e.g., Coquina, Oolitic L.)**
2. **Nonclastic or Crystalline**
   - **Pattern of interlocking crystals**
   - **Evaporites, some Limestone**
   - **May resemble an igneous rock – however, easy to distinguish**

Classification of Sedimentary Rocks

Detrital Sedimentary Rocks		
Clastic Texture (particle size)	**Sediment Name**	**Rock Name**
Coarse (over 2 mm)	Gravel (Rounded particles)	**Conglomerate**
Coarse (over 2 mm)	Gravel (Angular particles)	**Breccia**
Medium (1/16 to 2 mm)	Sand (If abundant feldspar is present the rock is called **Arkose**)	**Sandstone**
Fine (1/16 to 1/256 mm)	Mud	**Siltstone**
Very fine (less than 1/256 mm)	Mud	**Shale or Mudstone**

Chemical and Organic Sedimentary Rocks			
Composition	**Texture**	**Rock Name**	
Calcite, $CaCO_3$	Nonclastic: Fine to coarse crystalline	**Crystalline Limestone**	
Calcite, $CaCO_3$	Nonclastic: Fine to coarse crystalline	**Travertine**	
Calcite, $CaCO_3$	Clastic: Visible shells and shell fragments loosely cemented	**Coquina**	**Biochemical Limestone**
Calcite, $CaCO_3$	Clastic: Various size shells and shell fragments cemented with calcite cement	**Fossiliferous Limestone**	**Biochemical Limestone**
Calcite, $CaCO_3$	Clastic: Microscopic shells and clay	**Chalk**	**Biochemical Limestone**
Quartz, SiO_2	Nonclastic: Very fine crystalline	**Chert (light colored) Flint (dark colored)**	
Gypsum $CaSO_4 \cdot 2H_2O$	Nonclastic: Fine to coarse crystalline	**Rock Gypsum**	
Halite, NaCl	Nonclastic: Fine to coarse crystalline	**Rock Salt**	
Altered plant fragments	Nonclastic: Fine-grained organic matter	**Bituminous Coal**	

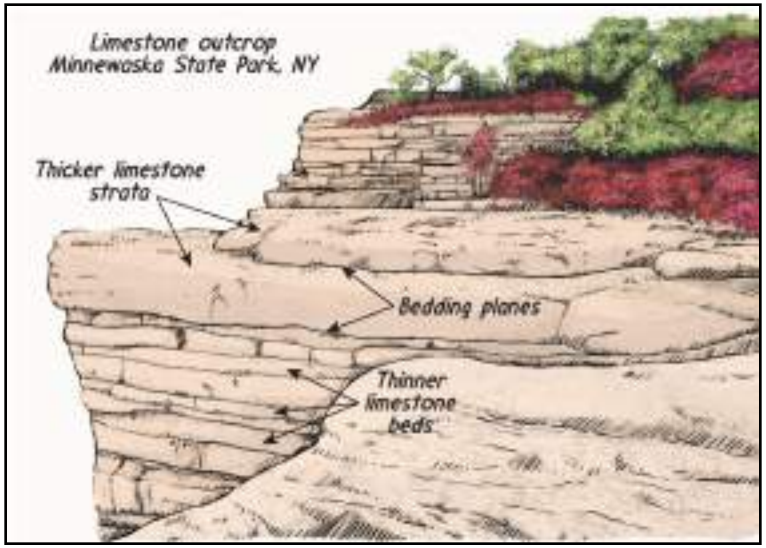
Sedimentary Facies



When a sedimentary layer is traced laterally, we may find that it is made up of several different rock types. This occurs because many sedimentary environments can exist at the same time over a broad area. The term facies is used to describe such sets of sedimentary rocks. Each facies grades laterally into another that formed at the same time but in a different environment.

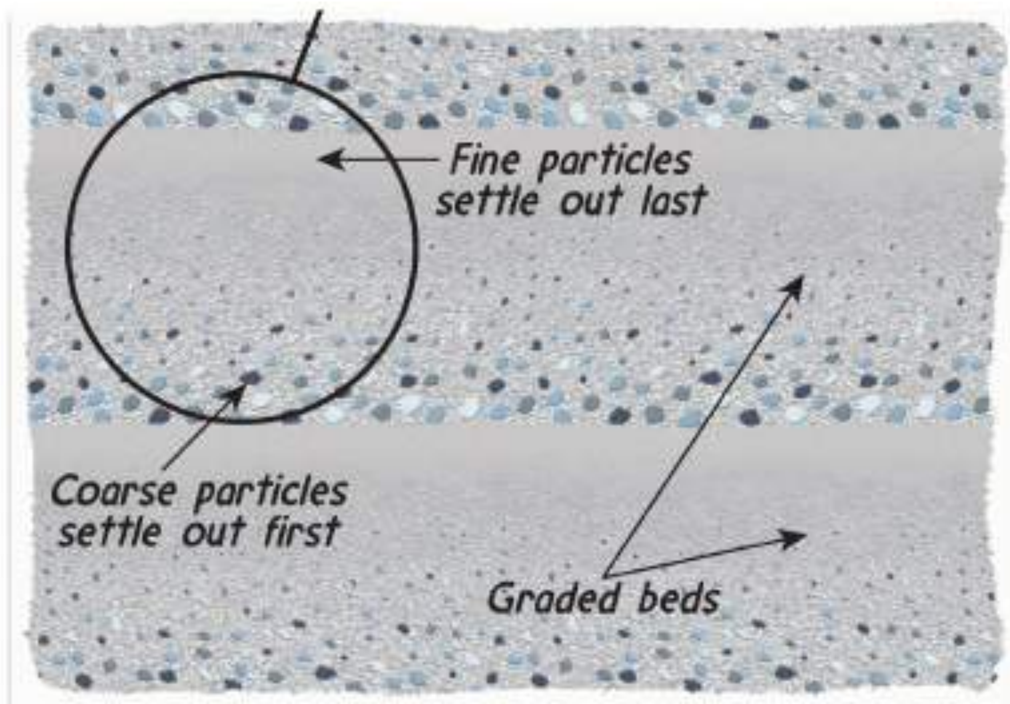
Sedimentary Structures

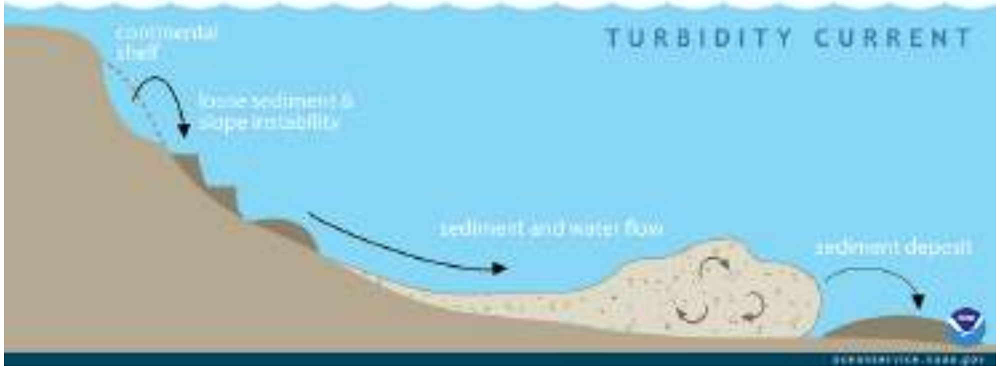
- **Provide information useful in the interpretation of Earth's history**
- **Types of sedimentary structures**
  - ***Strata*, or beds (most characteristic of sedimentary rocks, which form as layer upon layer of sediment accumulates in various depositional environments)**
  - ***Bedding planes* separate strata**



Sedimentary Structures

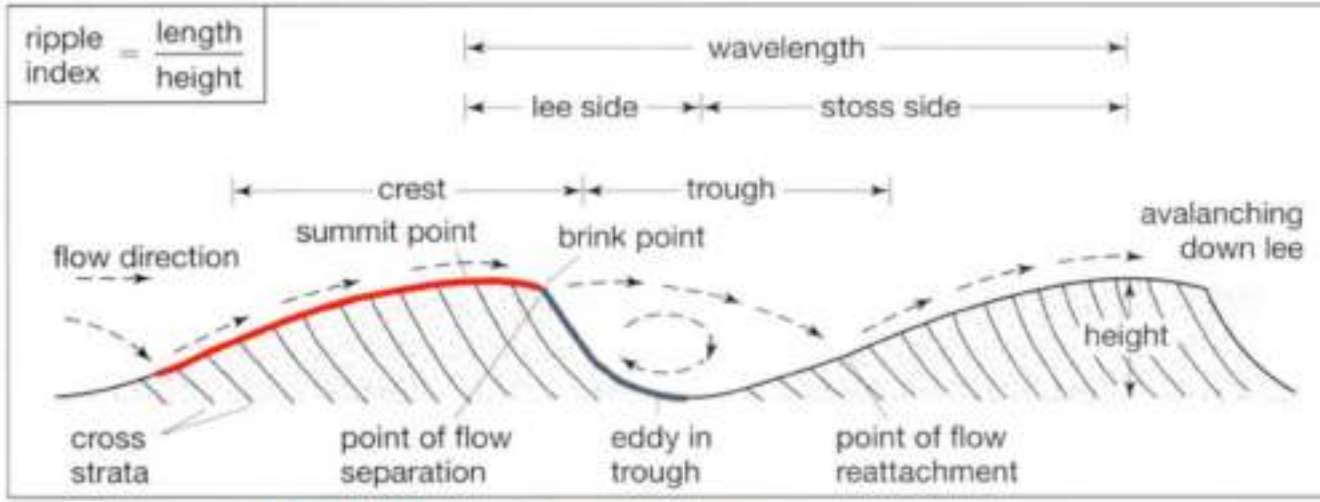
- **Types of sedimentary structures**
  - **Graded beds** **(characteristic of rapid deposition from water containing sediment of different sizes)**





Cross-bedding

(characteristic of sand dunes, river deltas)



Erosion Deposition

B.

Flow Direction

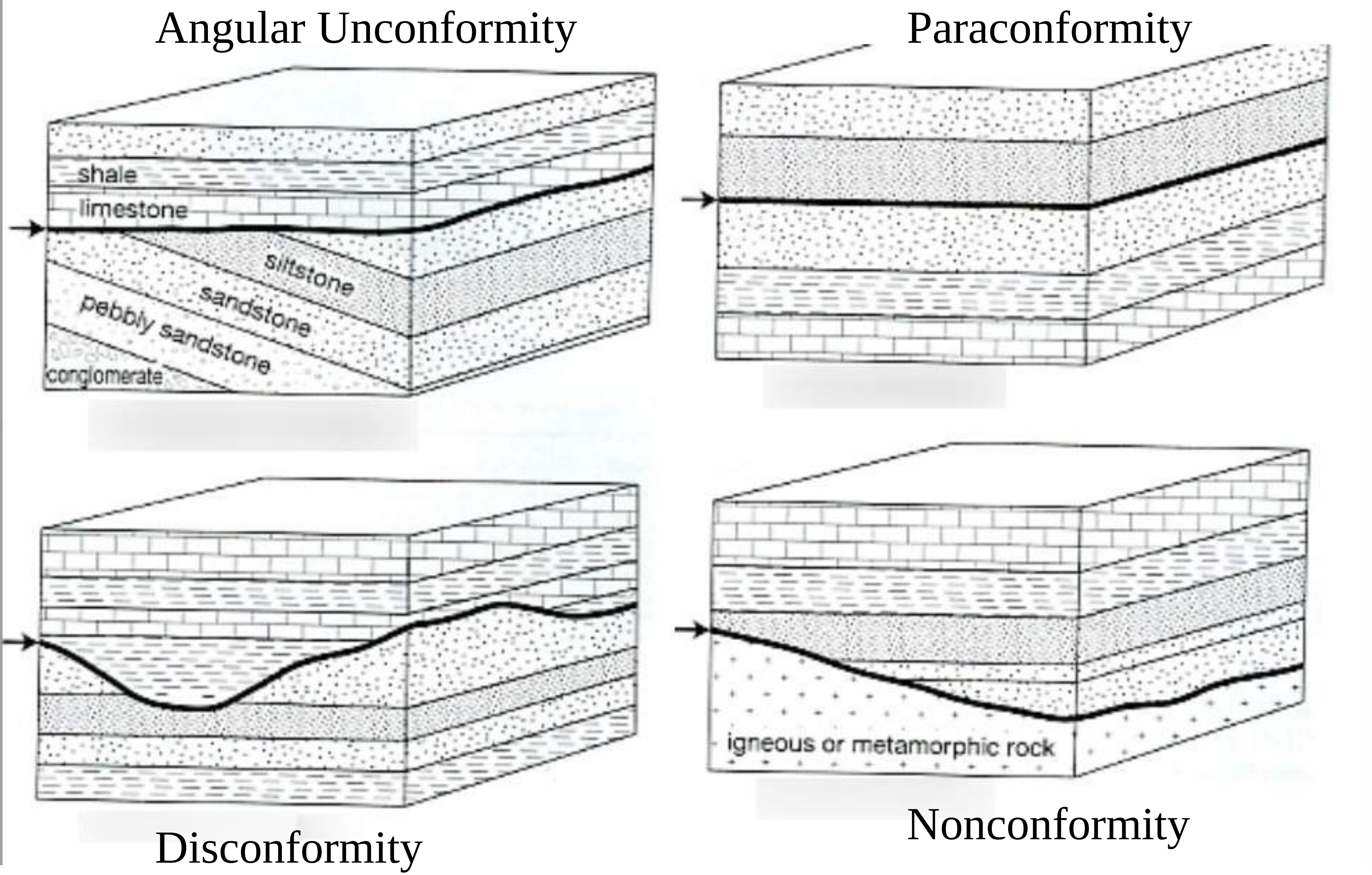
Mode of grain transport

Sedimentary Structures

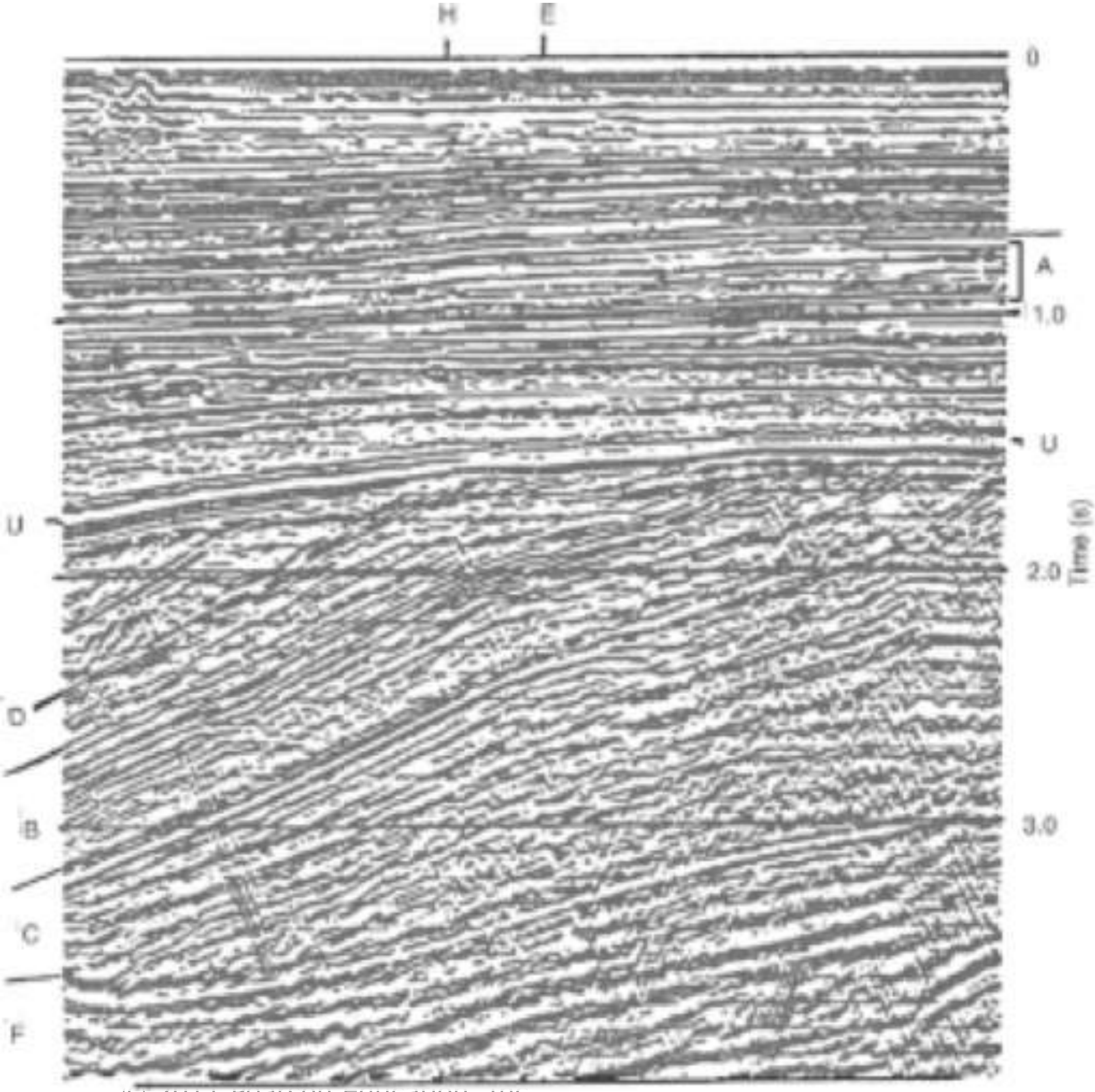
- **Types of sedimentary structures**
  - **Ripple marks (small waves of sand developed on the surface of a sediment layer by the action of moving water or air)**

A.

Unconformity



Example of angular unconformity

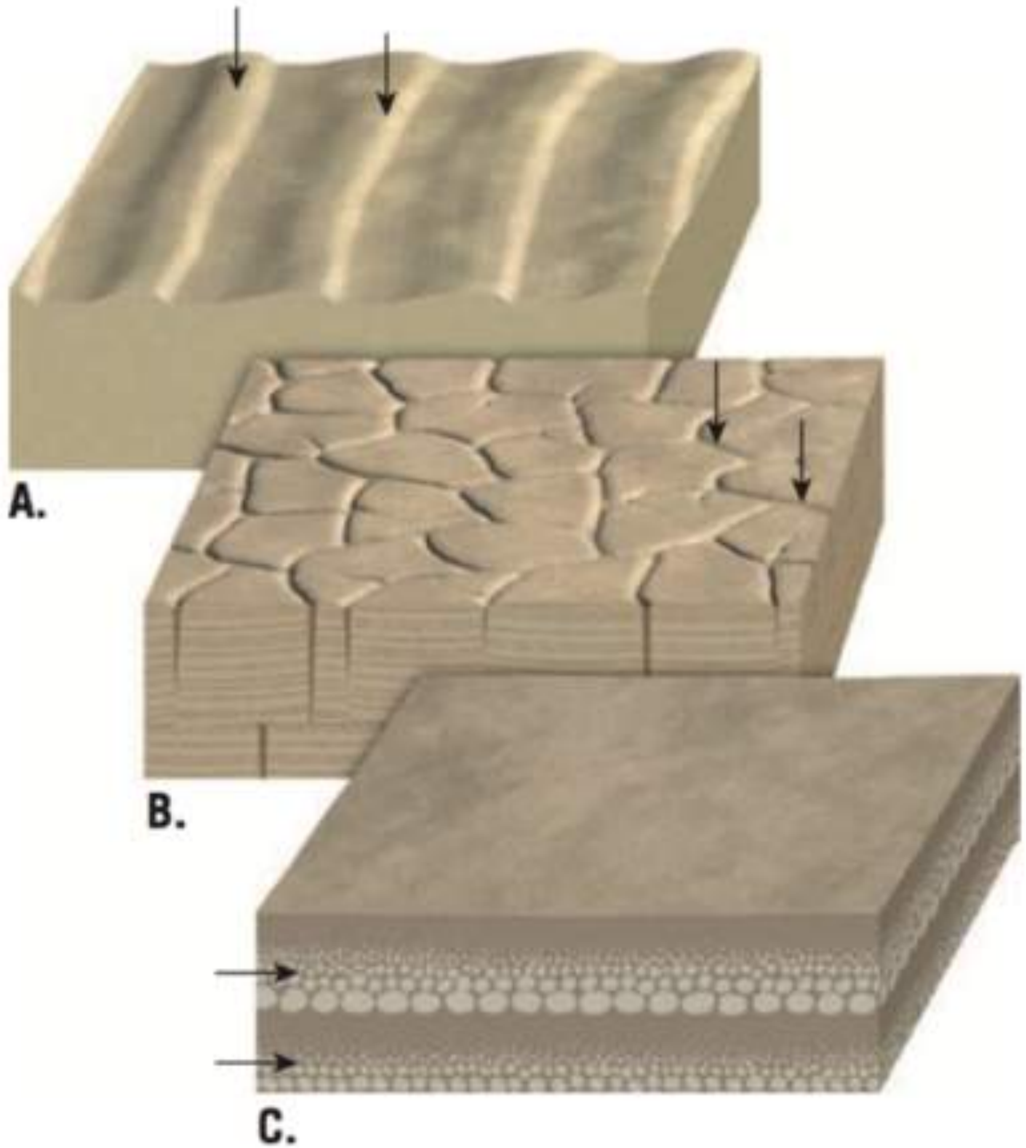


Question

Q1: One of the labeled sedimentary layers in the photo is sandstone and the other is mostly shale. How can you determine which one is which just by looking at the photo?
Q2: How does such a geologic setup develop?
Q3:Is there any unconformity present?

Question

INTERPRET THEM Identify and describe each of the sedimentary structures shown here.



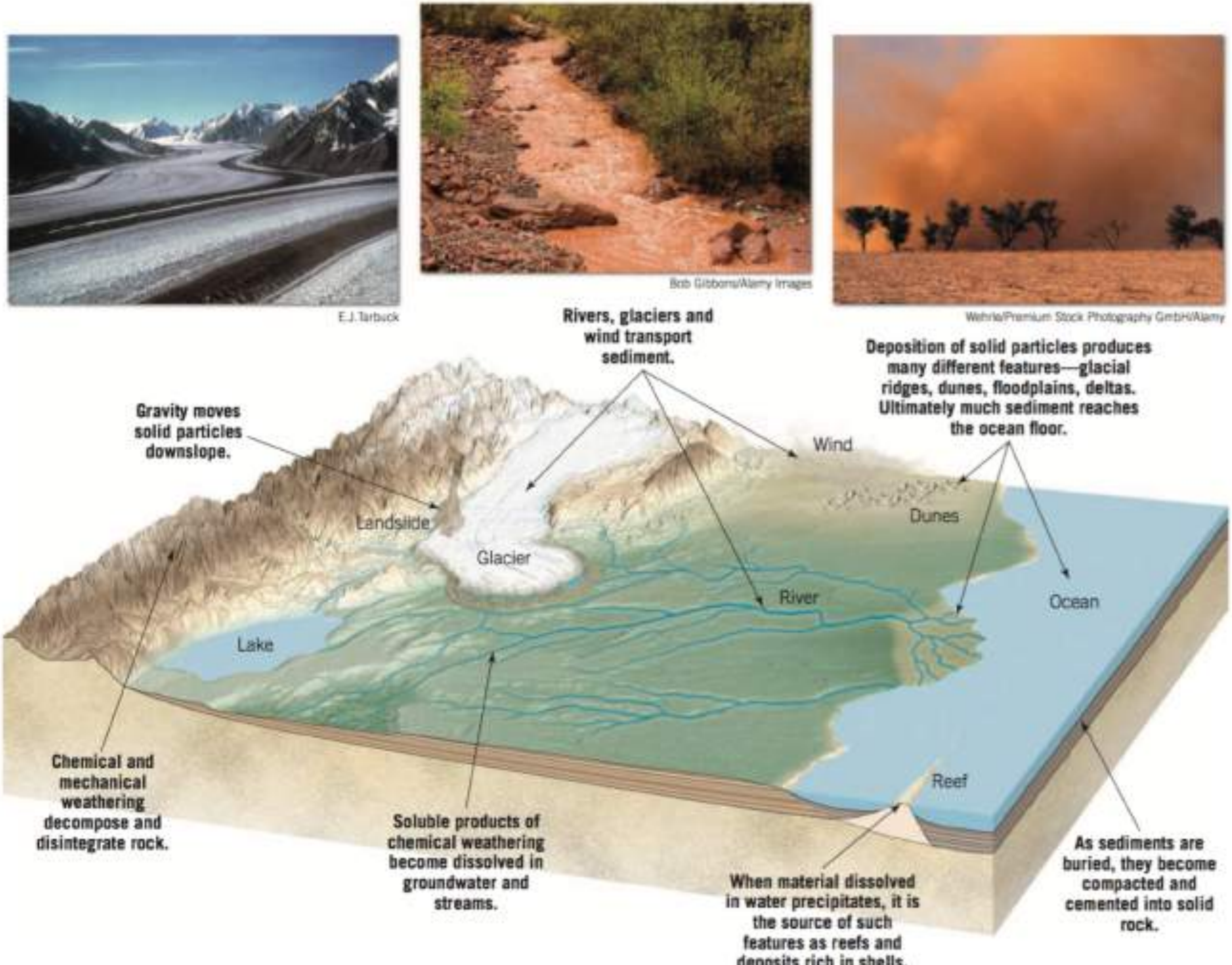
FUNDAMENTALS OF EARTH SCIENCES (ESO 213A)

DIBAKAR GHOSAL
DEPARTMENT OF EARTH SCIENCES

Metamorphic rocks "Marbles"

Previous Class: Sedimentary rocks

An outline of the portion of the rock cycle that pertains to the formation of sedimentary rocks.



Classification of Sedimentary Rocks

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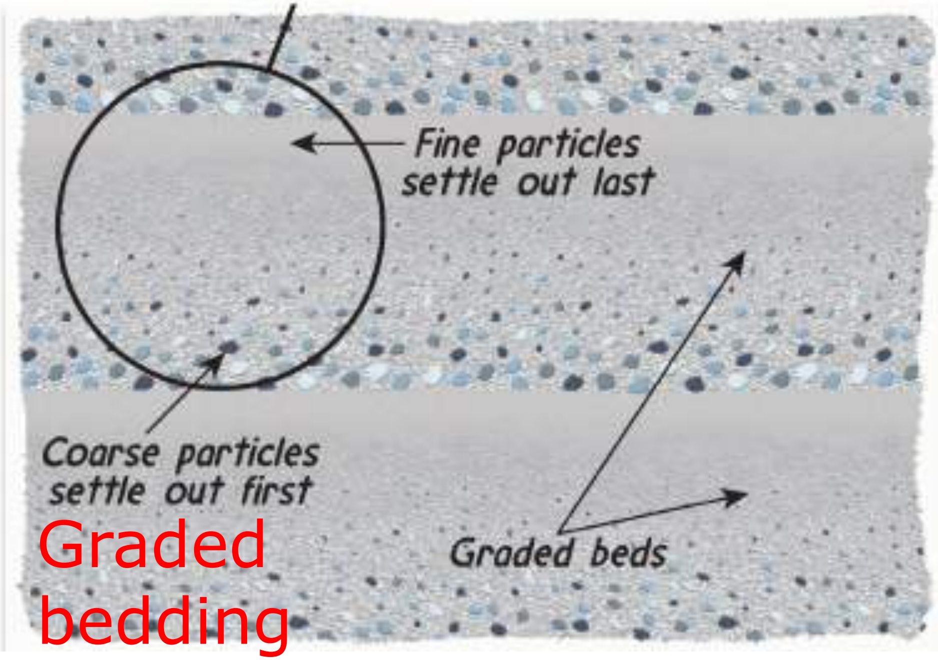

Fine particles settle out last
Coarse particles settle out first
Graded beds
Graded bedding

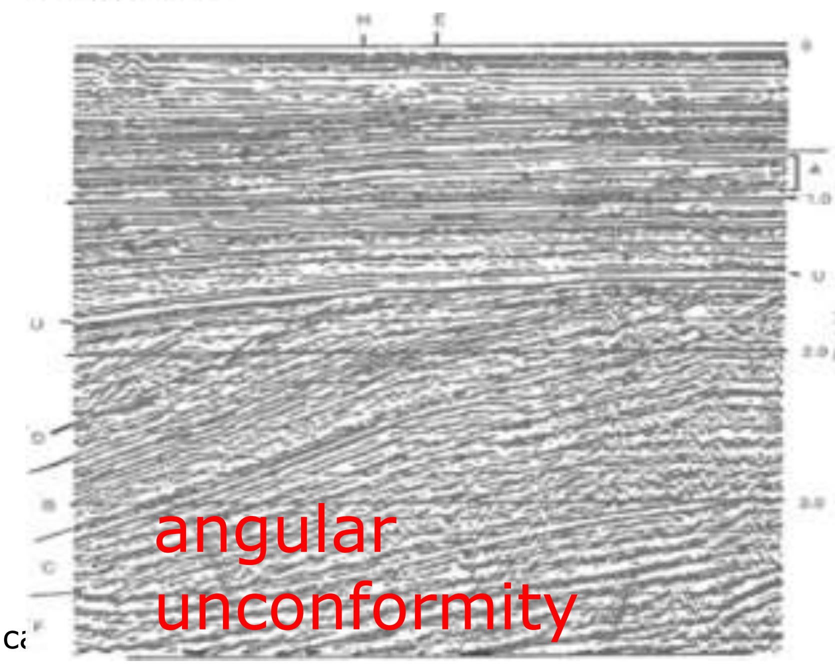

Ripple marks

A.


Cross bedding

B.

son Educa


angular unconformity

Taj Mahal Constructed primarily of marble.

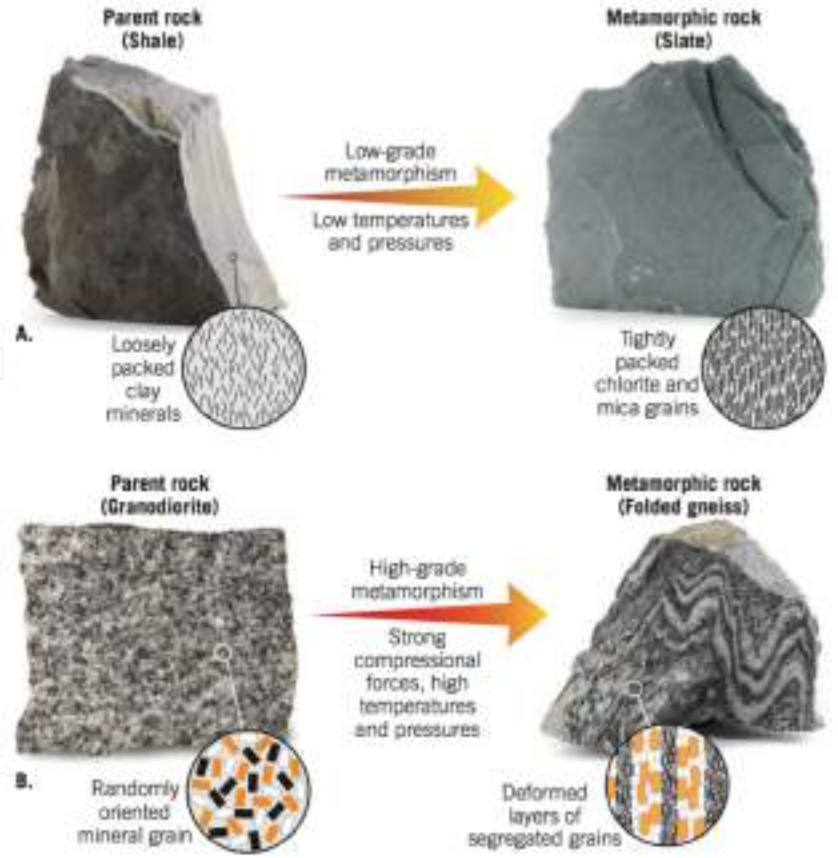
Metamorphic rocks

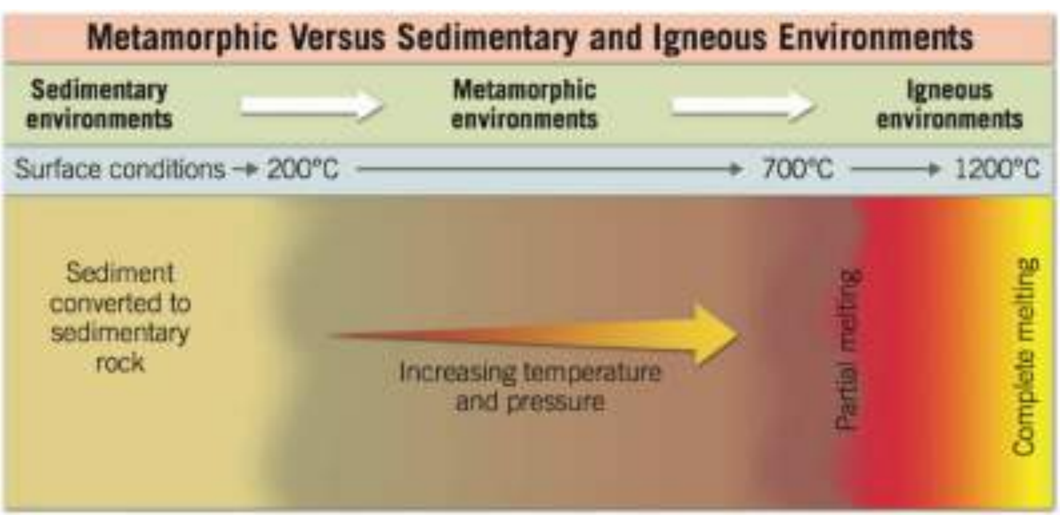
Metamorphism

<u>**Metamorphism is the transformation of one rock type into another rock type.**</u>

Metamorphic rocks are produced from pre-existing sedimentary and igneous rocks, as well as from other metamorphic rocks.

- **Metamorphism progresses occurs incremental from low grade to high grade.**
- **During metamorphism, the rock must remain essentially <u>solid</u>.**

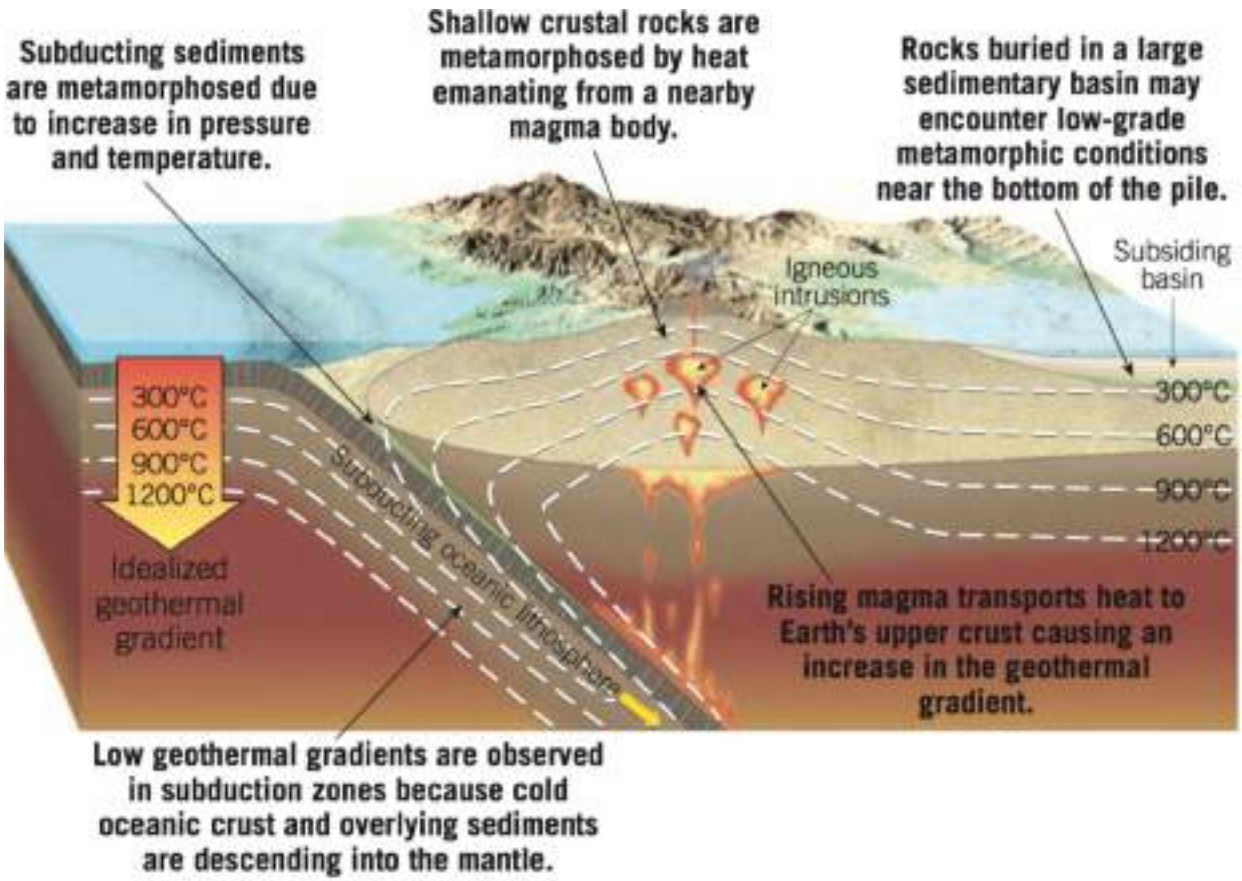




Agents of Metamorphism

I. Heat

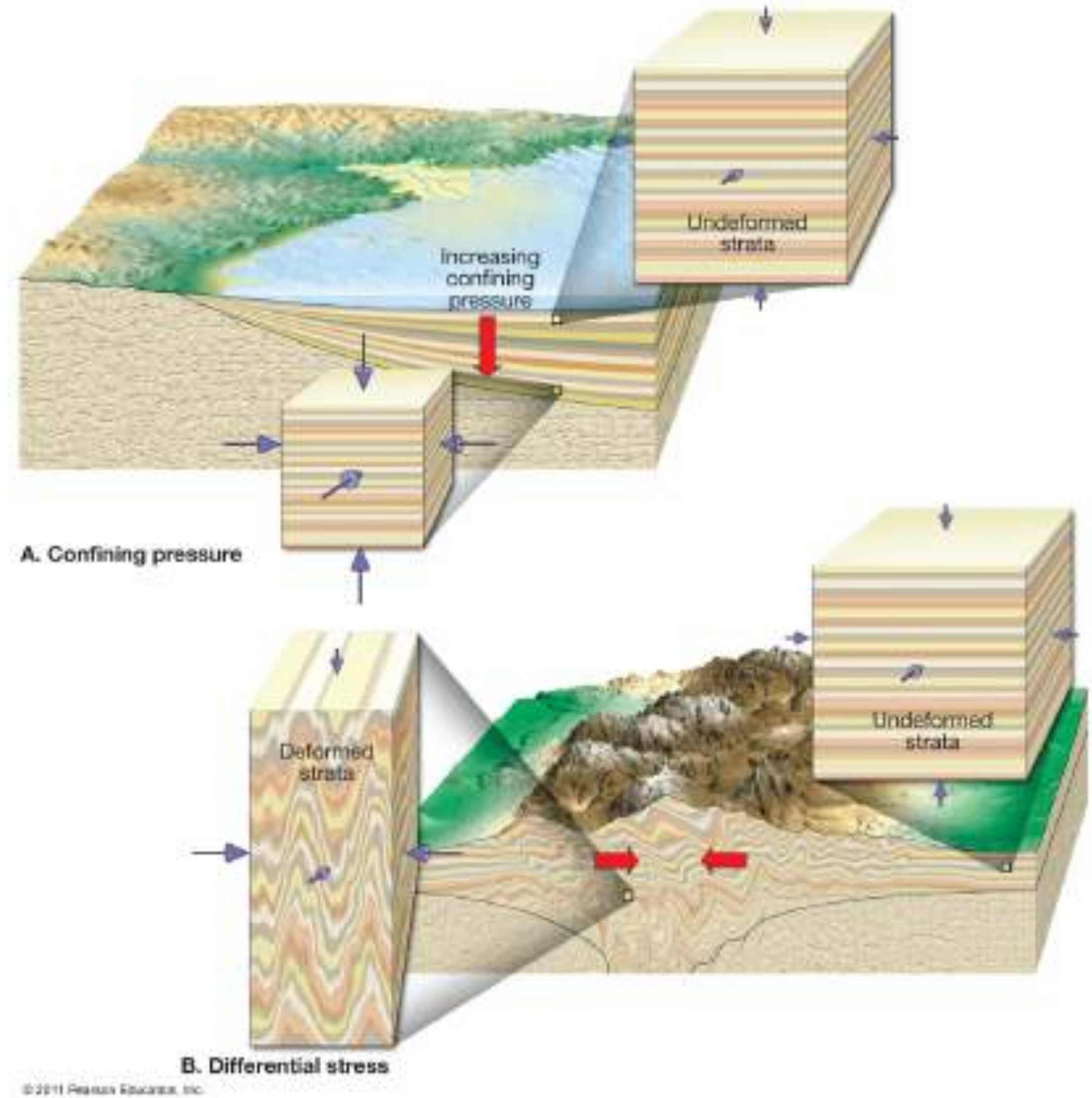
- Most important agent
- Recrystallization results in new, stable minerals.
- Two sources of heat:
  1. Contact metamorphism—heat from magma
  2. An increase in temperature with depth—geothermal gradient



Agents of Metamorphism

II. Confining Pressure and differential stress

- **Increases with depth**
- **Confining pressure applies forces equally in all directions (does not fold and deform rocks)**
- **Rocks may also be subjected to differential stress, which is unequal in different directions (folds and flattens rocks)**



Question

This metamorphic rock outcrop located in Purgatory Chasm in Newport, Rhode Island, is made of cobbles that are composed mainly of quartz.

Question 1 What name would you give to this metamorphic rock?

Question 2 Which set of arrows (red or black) best represents the direction of maximum directional stress?

Agents of Metamorphism

III. Chemically active fluids

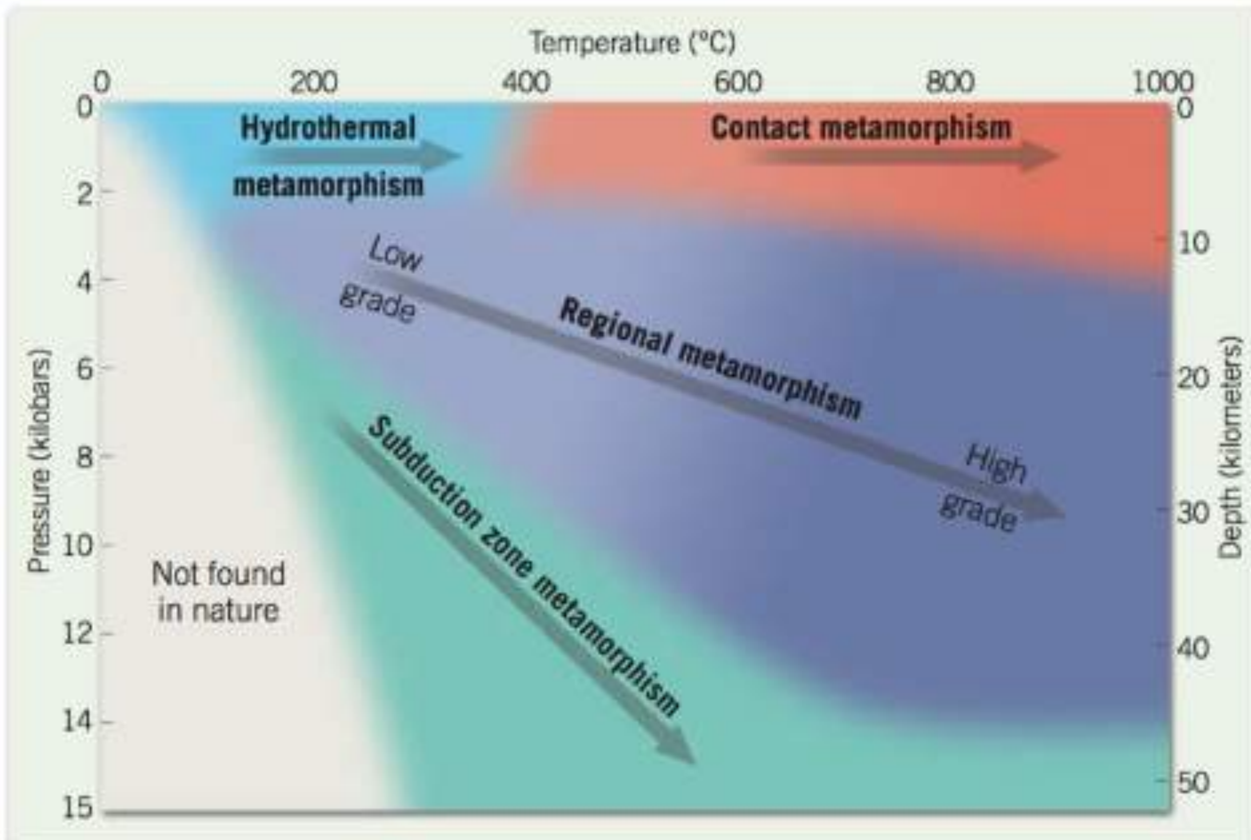
- **Mainly water**
- **Enhances migration of ions**
- **Aids in recrystallization of existing minerals**
- **Sources of fluids**
  - **Pore spaces of sedimentary rocks**
  - **Fractures in igneous rocks**
  - **Hydrated minerals such as clays, micas, amphiboles**

Metasomatism Example

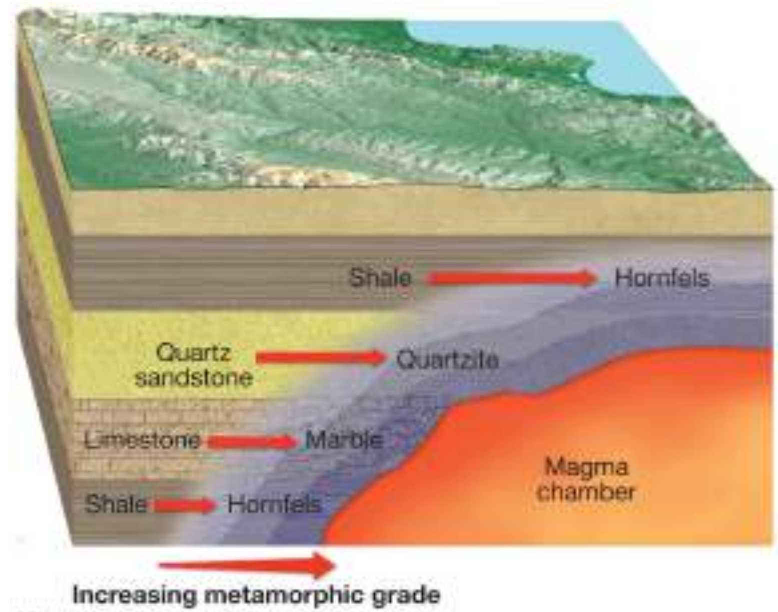
$CaCO_3$ (Calcite) + SiO_2 = $CaSiO_3$ (Wollastonite) + CO_2

Metamorphic settings

- **Contact** or **thermal metamorphism**—driven by a rise in temperature within the host rock
- **Hydrothermal metamorphism**—chemical alterations from hot, ion-rich water
- **Regional metamorphism**
  - Occurs during mountain building
  - Produces the greatest volume of metamorphic rock
  - Rocks usually display zones of contact and/or hydrothermal metamorphism.

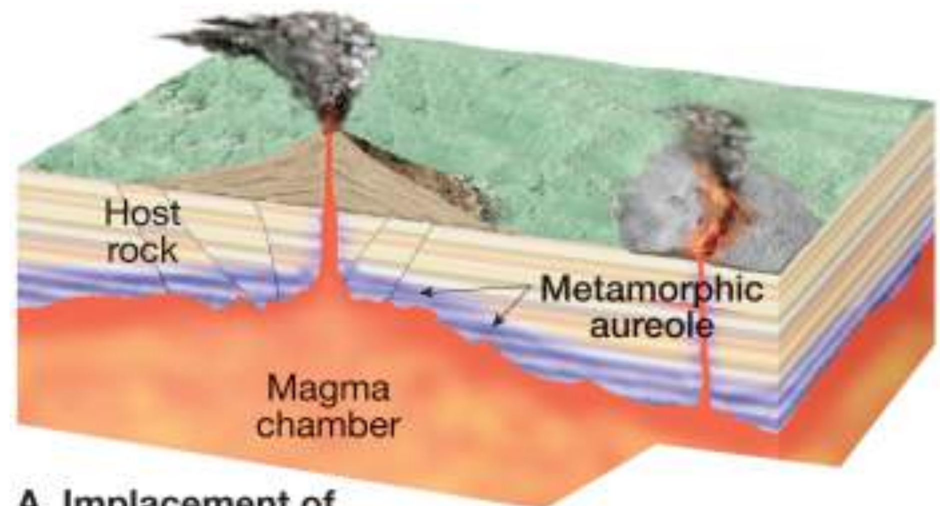


Metamorphic Environments



I. Contact or thermal metamorphism (High T and low P)

- Result from a rise in temperature when magma invades a host rock
- The zone of alteration (aureole) forms in the rock surrounding the magma.
- Most easily recognized when it occurs at or near Earth's surface.

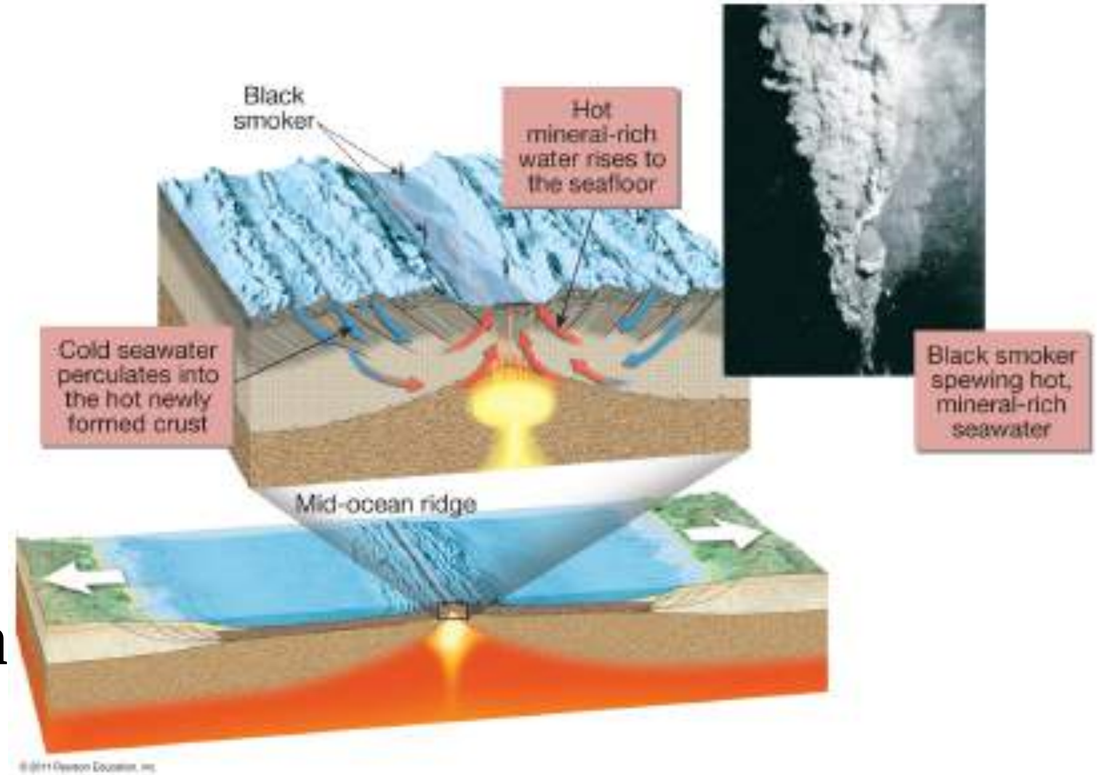


A. Implacement of igneous body and metamorphism

Metamorphic Environments

II. Hydrothermal metamorphism

- Chemical alteration caused when hot, ion-rich fluids circulate through fissures and cracks that develop in rock



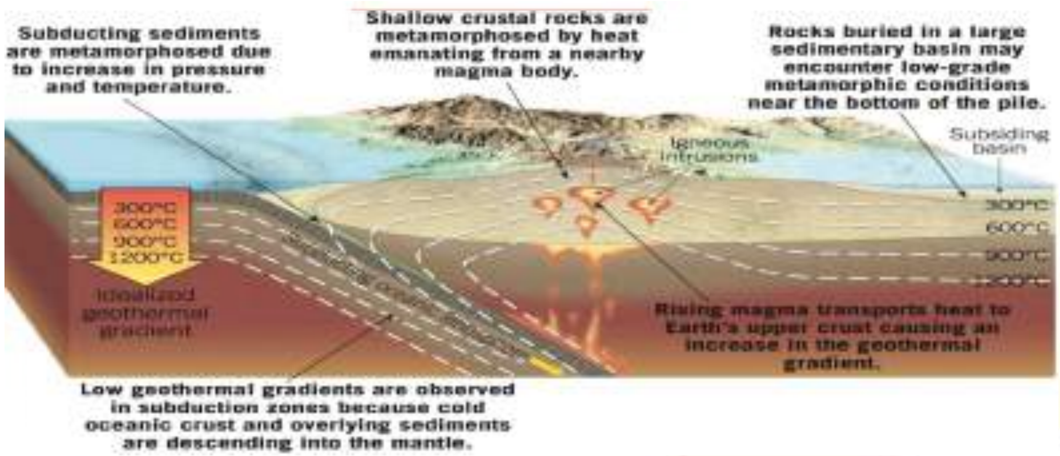
- Most widespread along the axis of the mid-ocean ridge system

Hydrothermal solutions circulating through the seafloor remove large amounts of metals (Fe, Co, Ni, Ag, Au, Cu) from the newly formed crust.

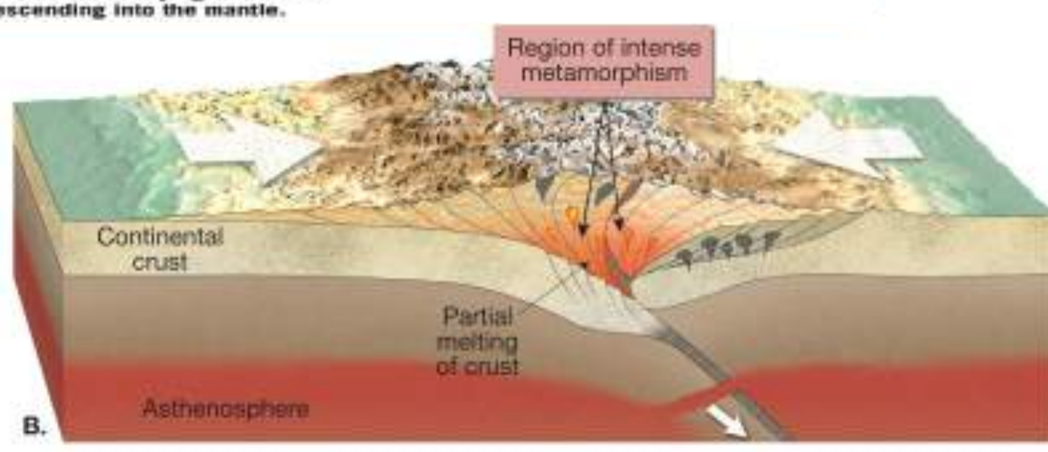
Metamorphic Environments

III. Regional metamorphism (Low P,T→High P,T over large area)

- Produces the greatest quantity of metamorphic rock
- Associated with mountain building, burial and migrating fluid
- Deep in the roots of mountains, high temperatures cause the most intense metamorphic activity within a mountain belt



Mostly contain foliation



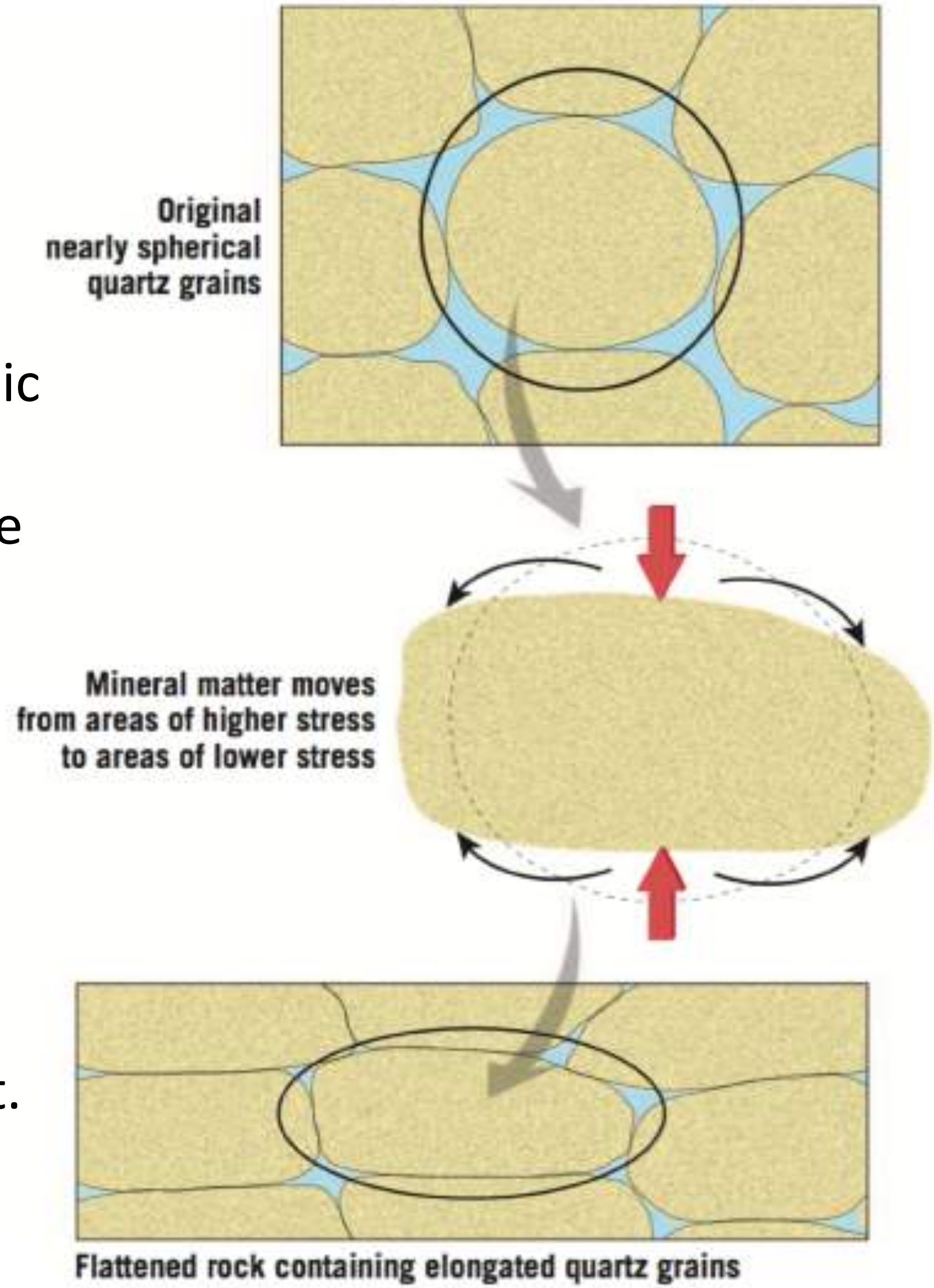
Processes for metamorphism

1. Recrystallization:
1 or more mineral breakdown to
Form a new mineral

2. Solid-state flow: Slippage disrupting crystal lattice and atomic bonds

3. Pressure solution: The pressure causes the crystal contacts to dissolve and to precipitate else where in the rock mostly at low stressed zone.

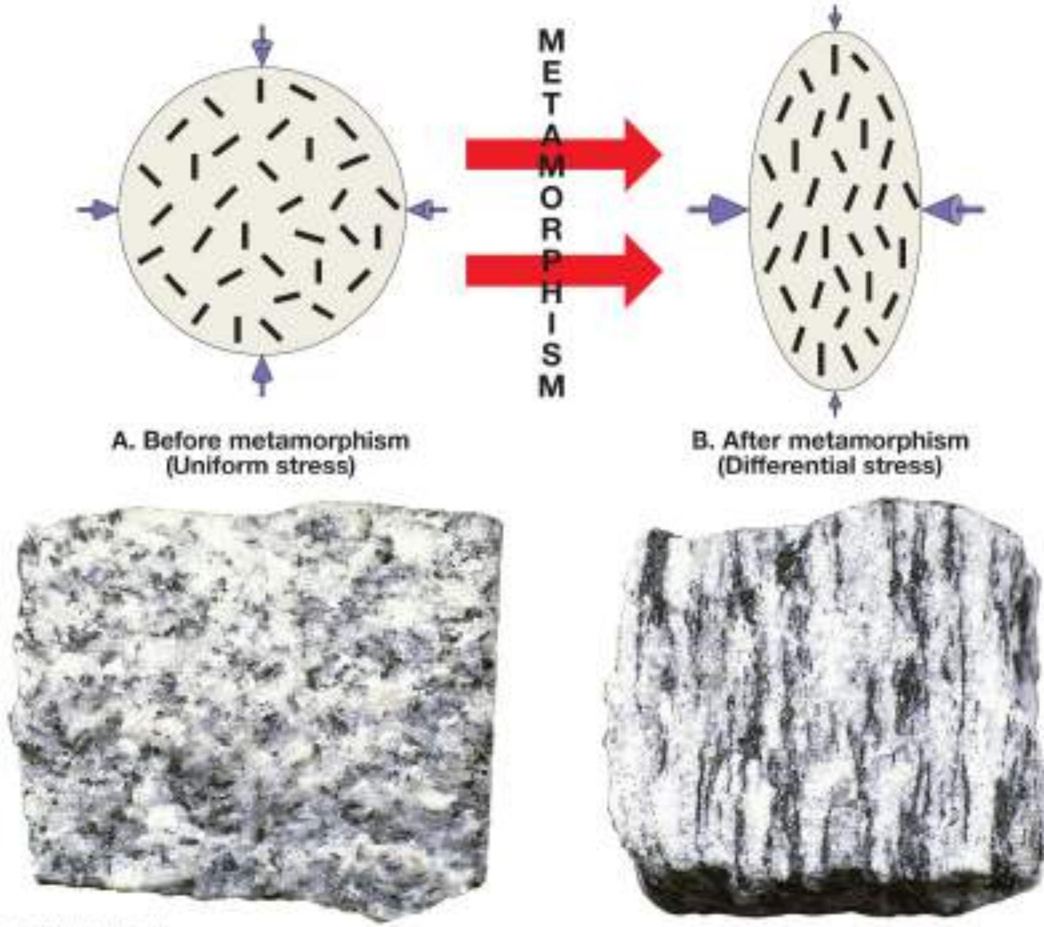
4. Remobilization: High P and T can cause certain minerals to breakdown allowing them to diffuse, dissolve and partially melt. The mineral then reprecipitate to low stressed zone.



Metamorphic Textures

Foliation (planner arrangement of minerals in a rock)

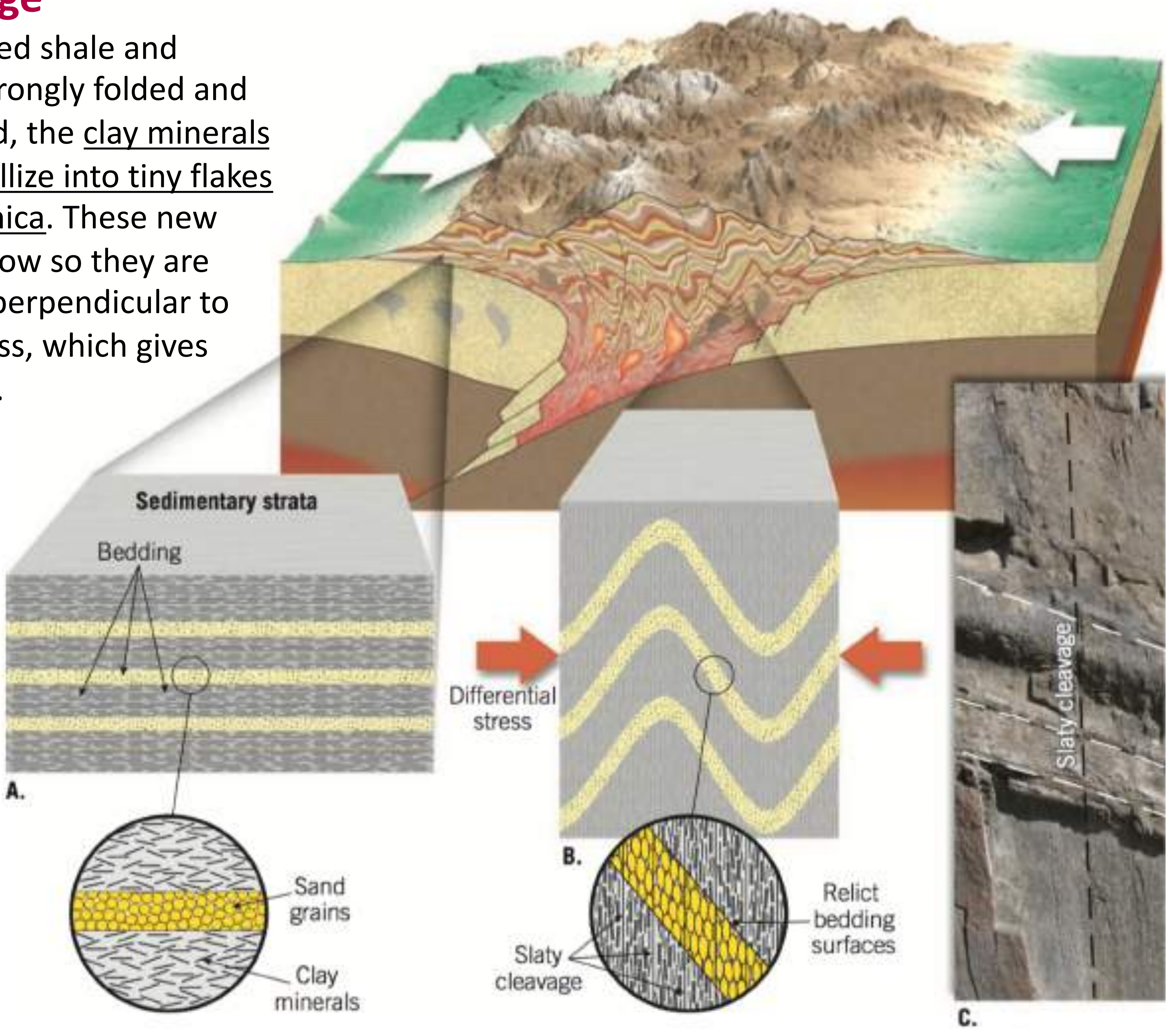
- **Examples of foliations**
  - **Parallel alignment of flattened / platy mineral grains and pebbles**
  - **Parallel alignment of elongated minerals**
  - **Compositional banding (separation of light and dark minerals causes a layered appearance)**
  - **Slaty cleavage where rocks can be easily split into thin, tabular sheets**



Foliation Resulting from Directed Stress

Slaty Cleavage

When interbedded shale and sandstone are strongly folded and meta-morphosed, the clay minerals begin to recrystallize into tiny flakes of chlorite and mica. These new platy minerals grow so they are aligned roughly perpendicular to the directed stress, which gives slate its foliation.



Metamorphic Textures

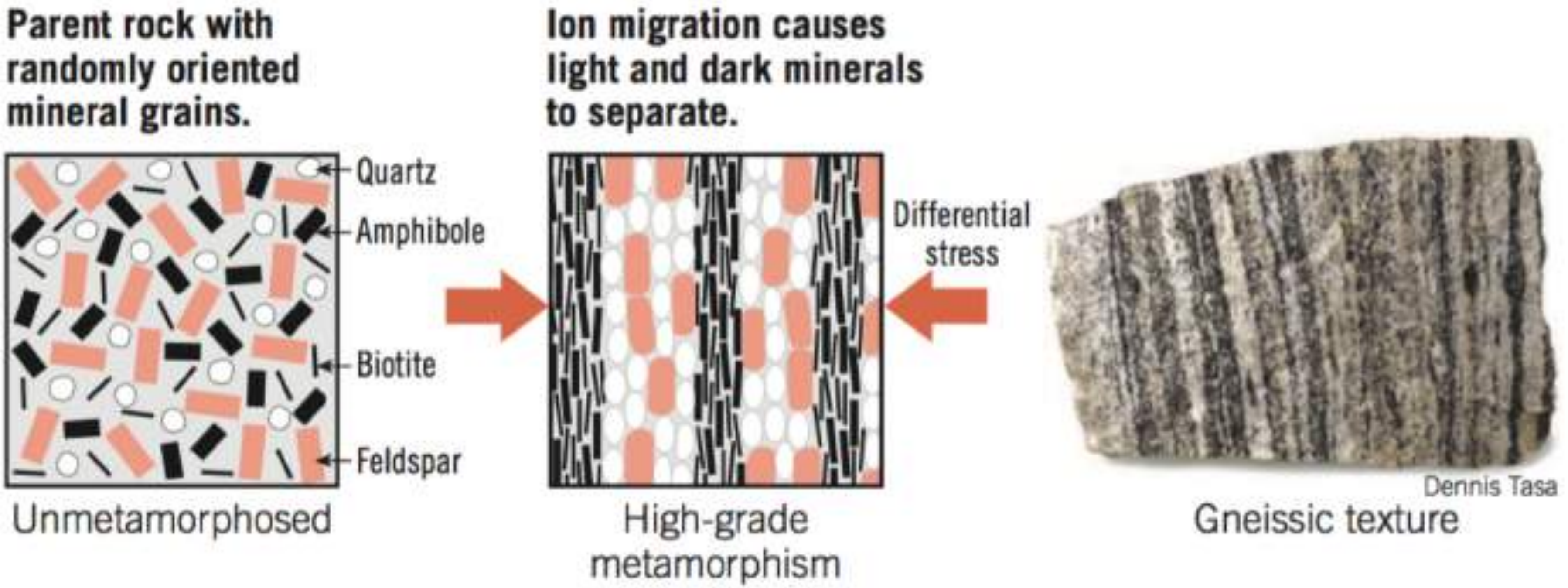
I. Foliated textures

- Schistosity
  - Platy minerals are visible with the unaided eye (medium- to high-grade metamorphism)
  - Mainly micas (muscovite, biotite)
  - Exhibit a planar or layered structure
  - Rocks having this texture are referred to as *SCHIST*

Metamorphic Textures

I. Foliated textures

- **Gneissic**
  - **During higher grades of metamorphism, ion migration results in the segregation of minerals (dark biotite vs. light silicates).**
  - **Gneissic rocks exhibit a distinctive banded appearance.**
  - **Typical in case of *GNEISS***



Metamorphic Textures

Other metamorphic textures

- **II. Those metamorphic rocks that lack foliation are referred to as *nonfoliated (granoblastic)***
  - **Develop in environments where deformation is minimal**
  - **Typically composed of minerals that exhibit equidimensional crystals (e.g., quartz - *QUARTZITE*)**

Question

This metamorphic rock outcrop is found in the Southern Alps, located on the South Island of New Zealand. The continued growth of the Southern Alps is somewhat unique in that these mountains lie where the Pacific and Australian plates collide and simultaneously slide past one anther along a large transform fault called the Alpine Fault.

Question 1 Do the rocks in this outcrop display foliation?.

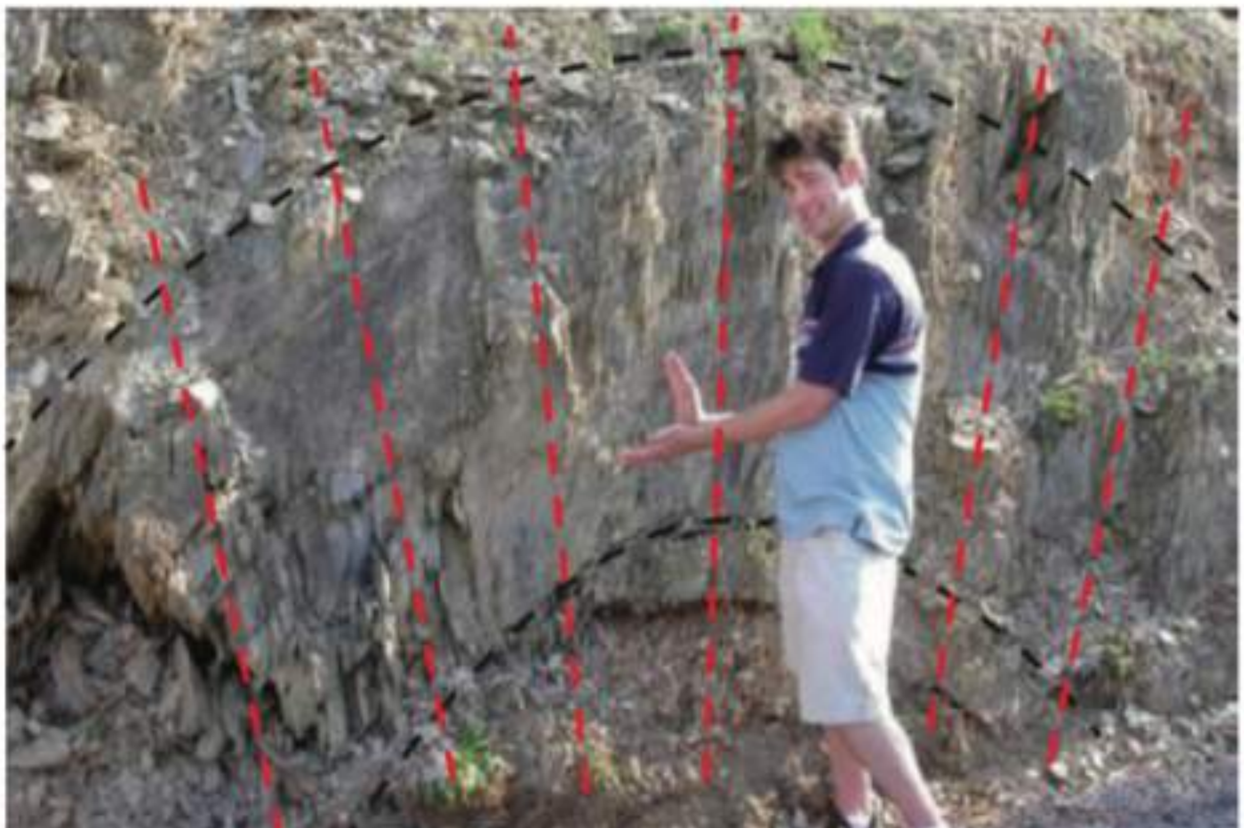
Question 2 Do these rocks appear to have experienced high-grade or low-grade metamorphism?

Question

The accompanying image shows folded and metamorphosed rock that displays slaty cleavage.

a. Which colored dashed lines (red or black) represent the slaty cleavage, and which represent relic bedding surfaces?

b. Was the maximum directional stress oriented horizontally or vertically?

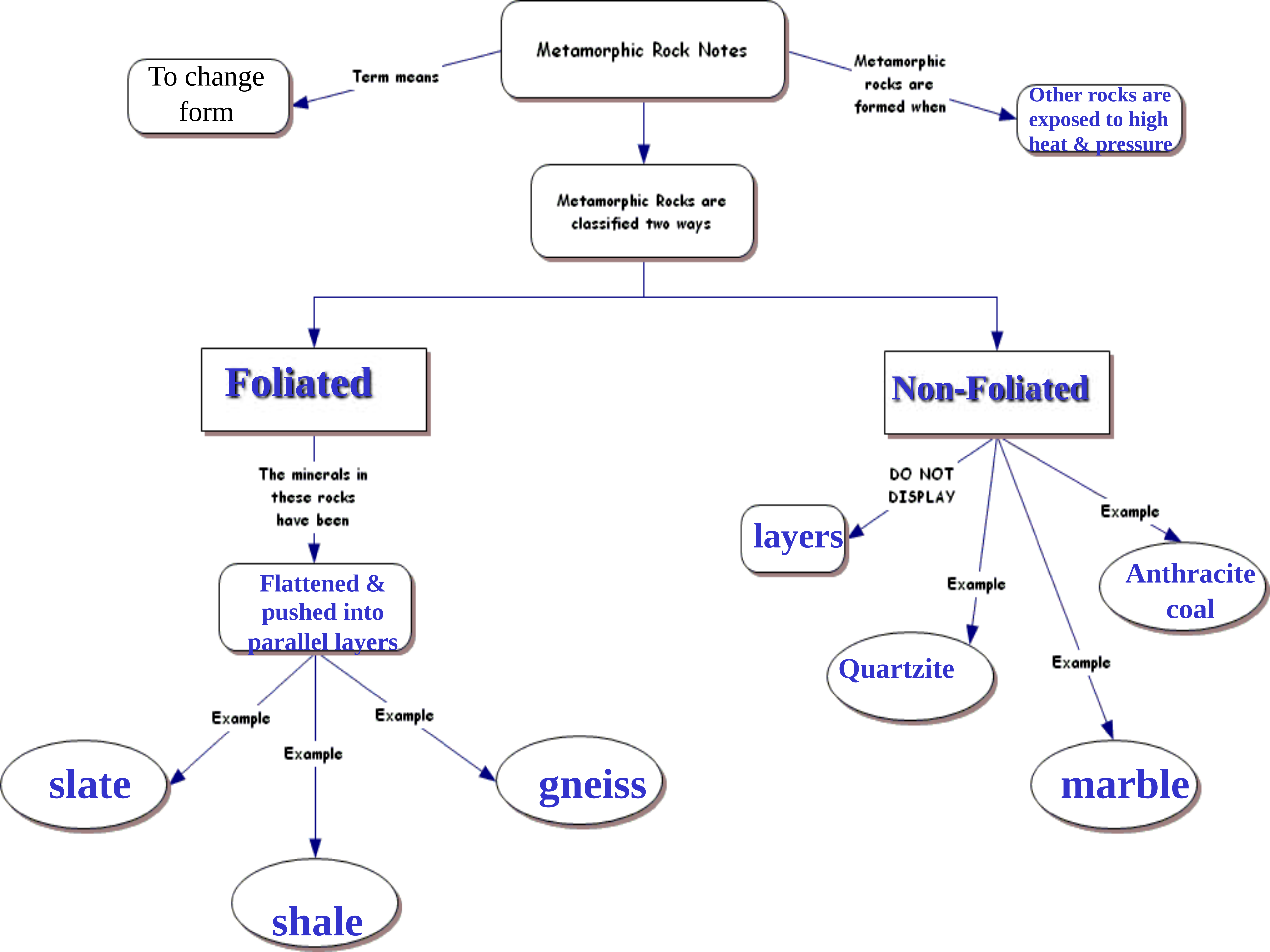


Callan Bentley

Common Metamorphic Rocks

Nonfoliated rocks

- Marble
  - Coarse, crystalline
  - Parent rock was limestone or dolostone
  - Composed essentially of calcite or dolomite crystals
  - Used as a decorative and monument stone
  - Exhibits a variety of colors


Metamorphic Rock Notes
Term means
To change form
Metamorphic rocks are formed when
Other rocks are exposed to high heat & pressure
Metamorphic Rocks are classified two ways
Foliated
Non-Foliated
The minerals in these rocks have been
Flattened & pushed into parallel layers
Example
slate
Example
shale
Example
gneiss
DO NOT DISPLAY
layers
Example
Quartzite
Example
marble
Example
Anthracite coal

Classifying Metamorphic Rocks

Rock Name		Texture	Grain Size	Comments	Original Parent Rock
Slate	Increasing Metamorphism	Foliated	Very fine	Excellent rock cleavage, smooth dull surfaces	Shale, mudstone, or siltstone
Phyllite			Fine	Breaks along wavy surfaces, glossy sheen	Shale, mudstone, or siltstone
Schist			Medium to Coarse	Micaceous minerals dominate, scaly foliation	Shale, mudstone, or siltstone
Gneiss			Medium to Coarse	Compositional banding due to segregation of minerals	Shale, granite, or volcanic rocks
Migmatite			Medium to Coarse	Banded rock with zones of light-colored crystalline minerals	Shale, granite, or volcanic rocks
Mylonite		Weakly Foliated	Fine	When very fine-grained, resembles chert, often breaks into slabs	Any rock type
Metaconglomerate			Coarse-grained	Stretched pebbles with preferred orientation	Quartz-rich conglomerate
Marble		Nonfoliated	Medium to coarse	Interlocking calcite or dolomite grains	Limestone, dolostone
Quartzite			Medium to coarse	Fused quartz grains, massive, very hard	Quartz sandstone
Hornfels			Fine	Usually, dark massive rock with dull luster	Any rock type
Anthracite			Fine	Shiny black rock that may exhibit conchoidal fracture	Bituminous coal
Fault breccia			Medium to very coarse	Broken fragments in a haphazard arrangement	Any rock type

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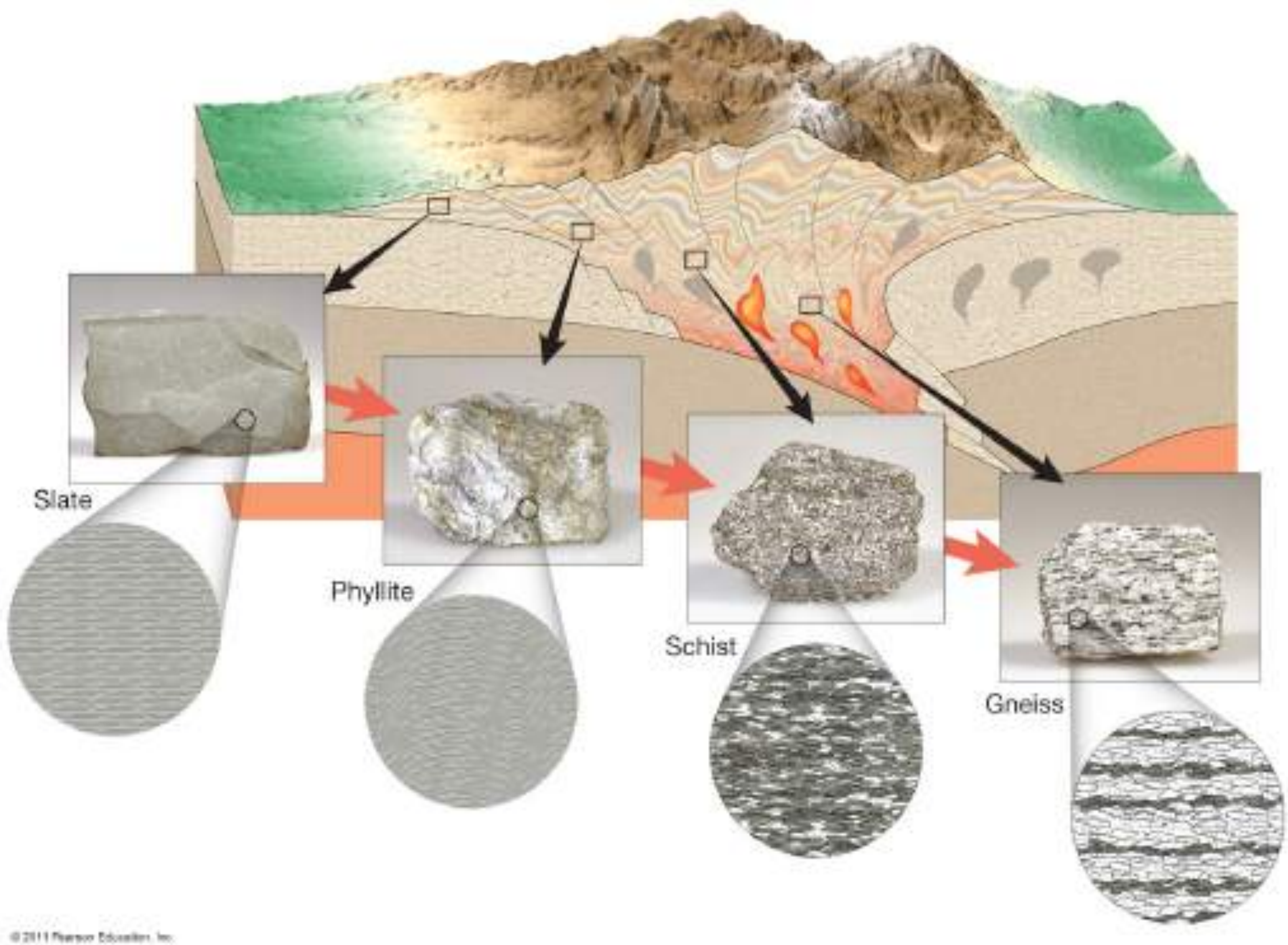
Metamorphic Zones

- **Systematic variations in the mineralogy and textures of metamorphic rocks are related to the variations in the degree of metamorphism.**

Starting rock:

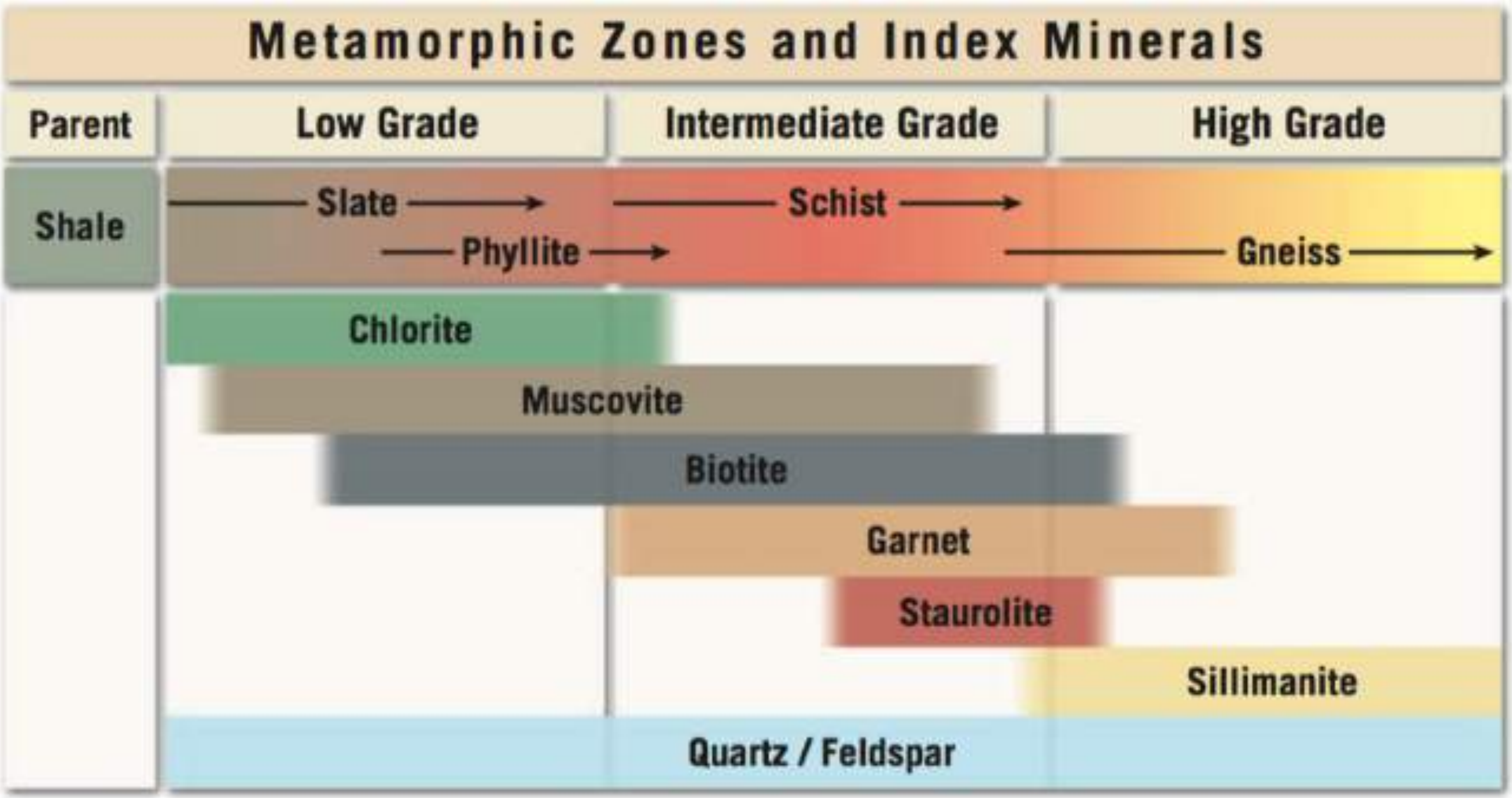
SHALE



Metamorphic Zones

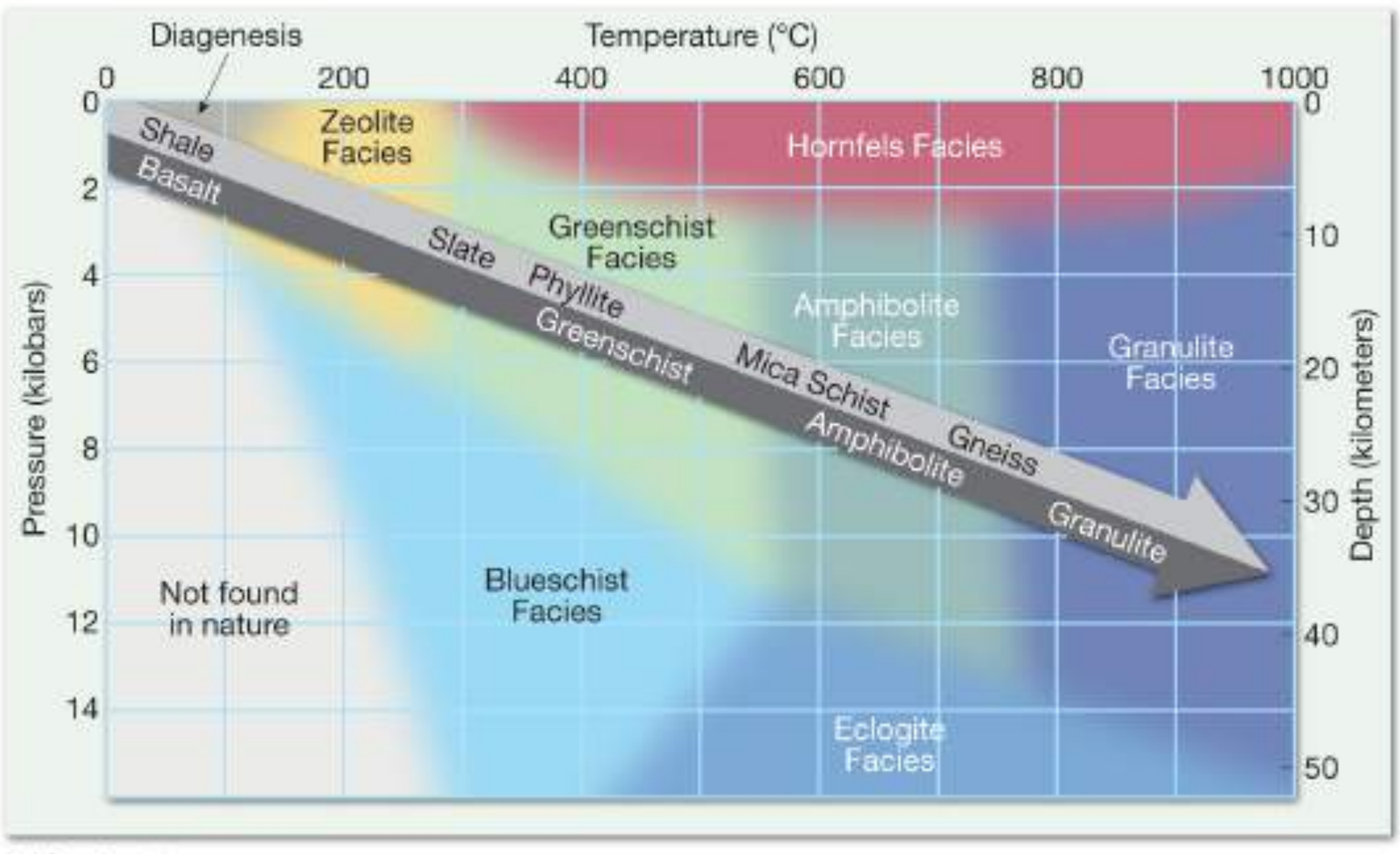
Index minerals and metamorphic grade

- **Changes in mineralogy occur from regions of low-grade metamorphism to regions of high-grade metamorphism.**

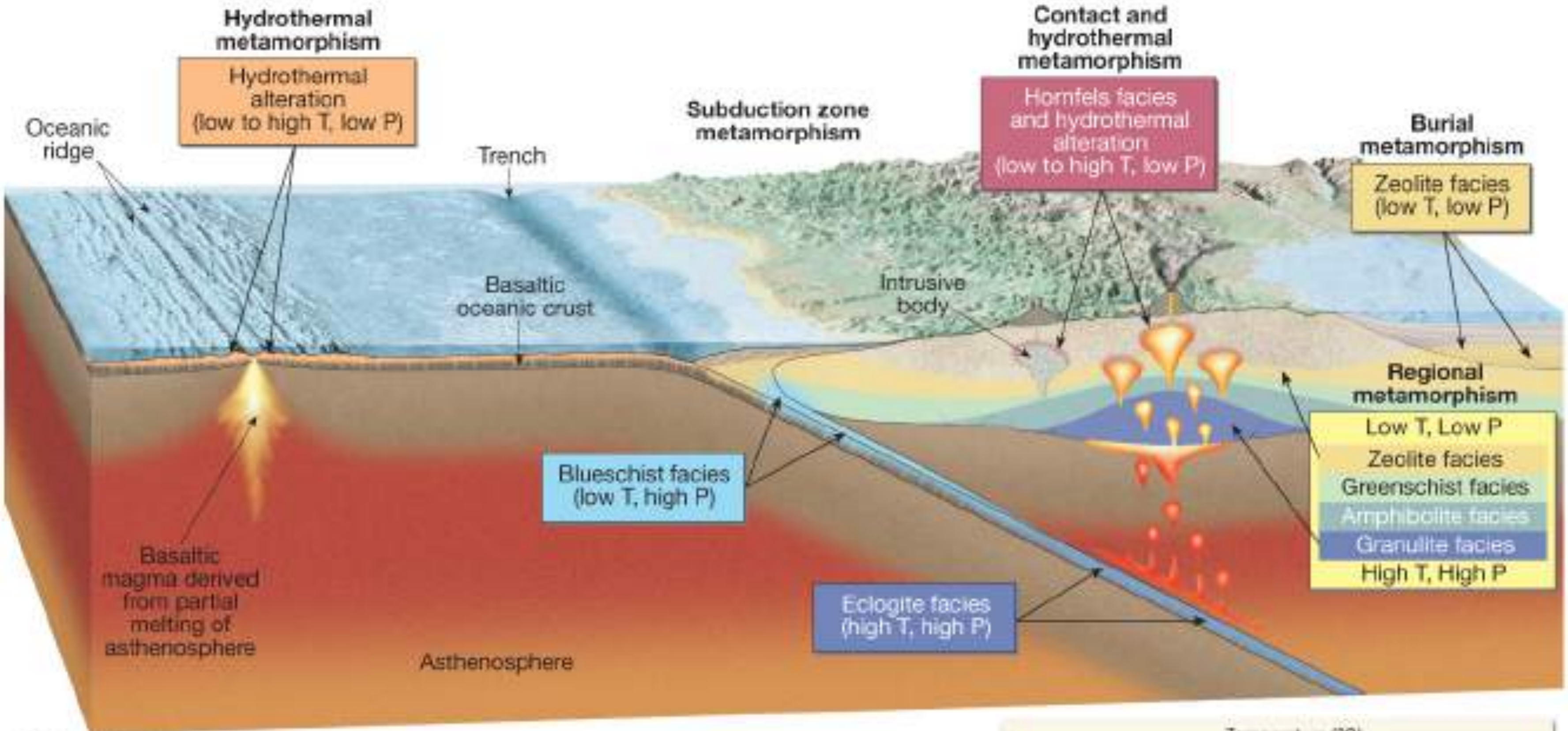


Metamorphic Facies

- Metamorphic rocks that contain the same assemblage of minerals
- Formed in very similar metamorphic environment
- Name based on minerals that define them

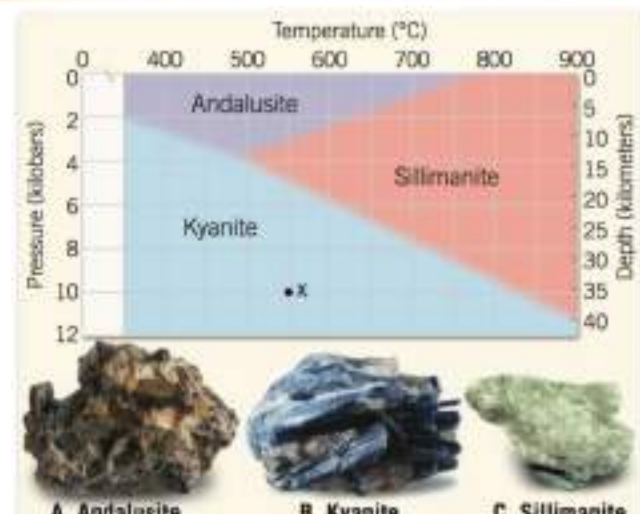


Metamorphic Facies and Plate Tectonics



A. Blueschist forms in low-temperature, high-pressure environments

B. Eclogite forms in high-temperature and extreme high-pressure environments

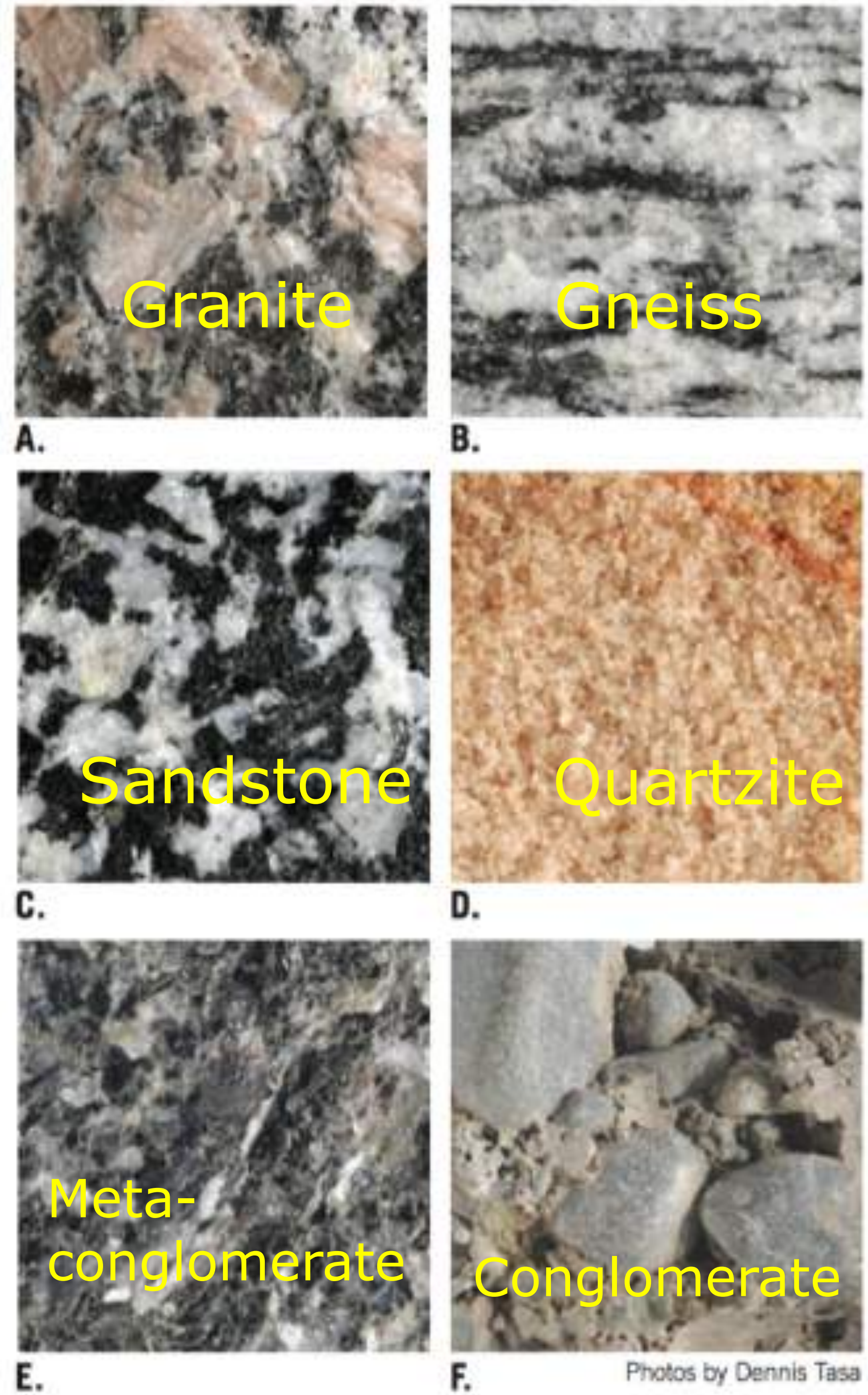


Question

Examine the accompanying close-up images of six different rocks labeled A–F.

Q1: Classify them as igneous, sedimentary, or metamorphic, based on texture.
(*Hint:* There are two of each rock type.)

Q2: Which figure show distinct foliation and high grade of metamorphism?



Fundamentals of Earth Sciences (ESO 213A)

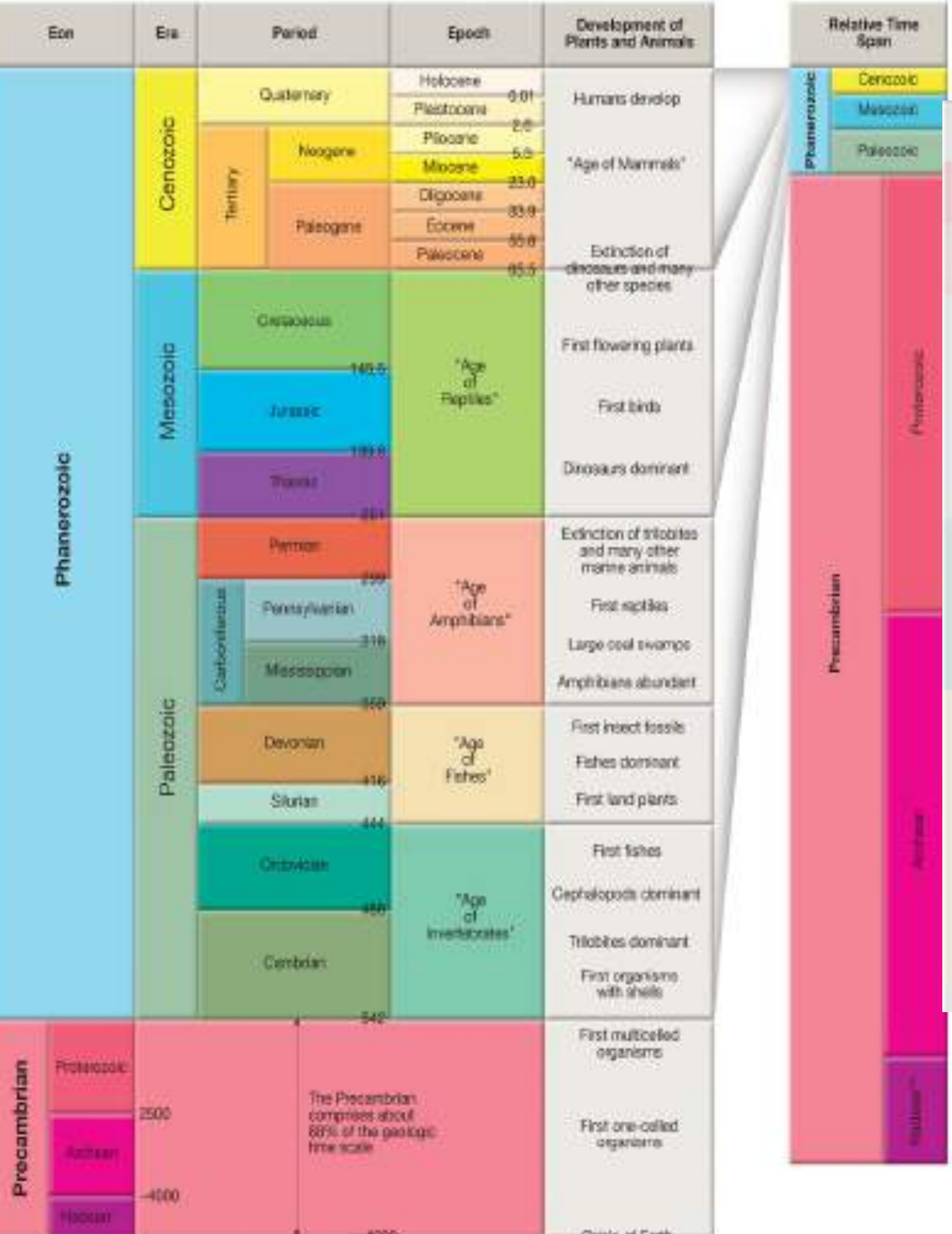
Dibakar Ghosal
Department of Earth Sciences

Earth's history and Geological Time Scale

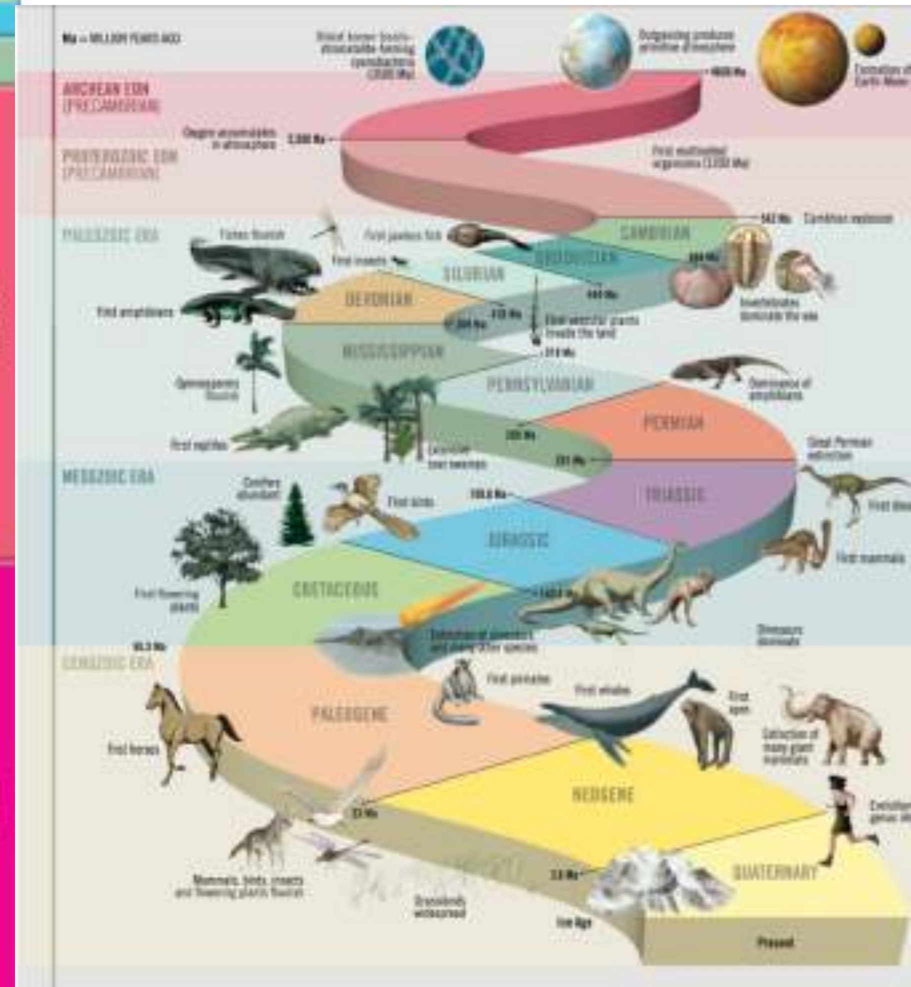
Previous Class: Hand specimen

Identify hand specimens (color, grain size, features, name)

Geologic time scale



Hadean is the informal name for the span that begins at Earth's formation and ends with Earth's earliest-known rocks.



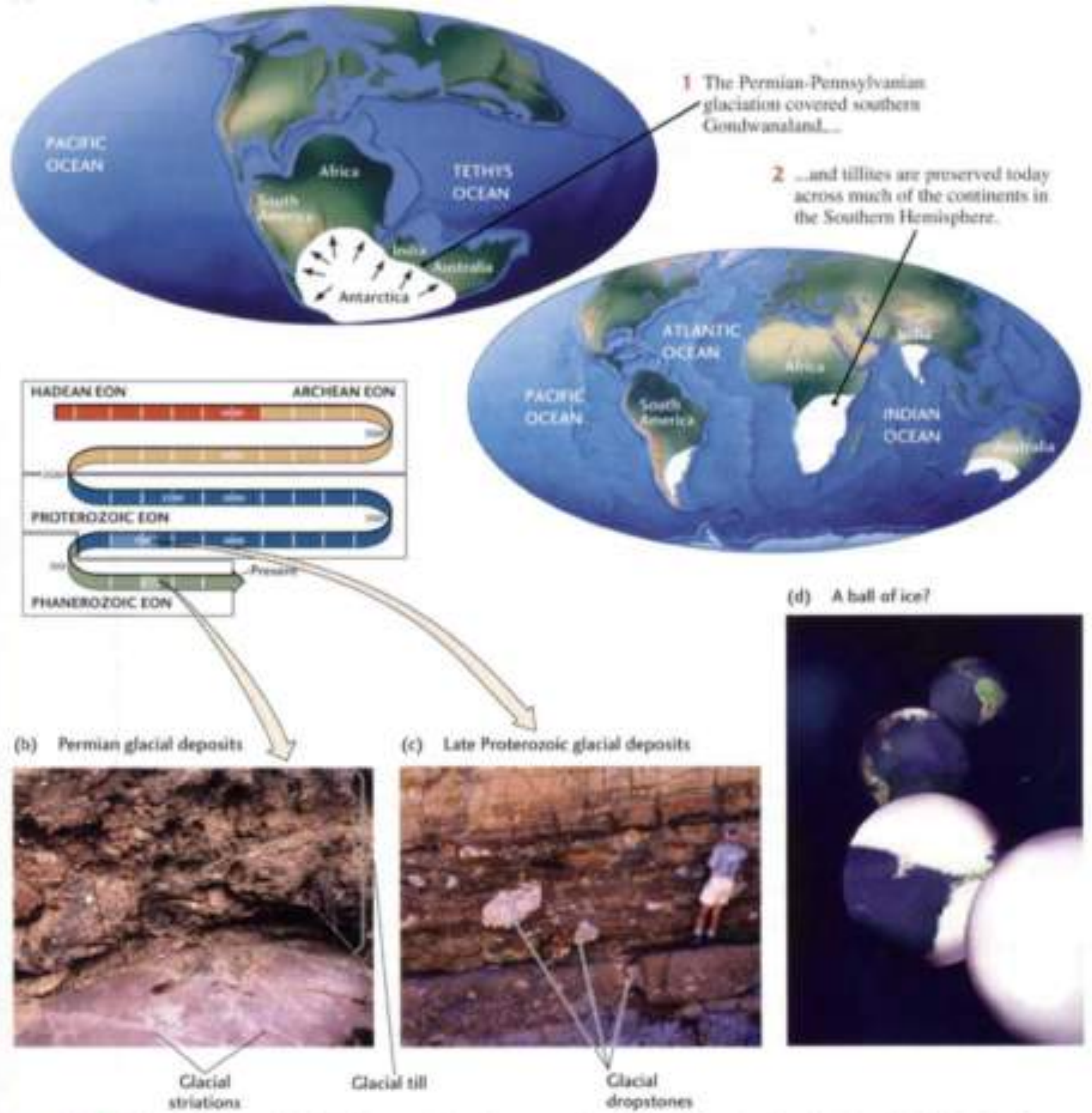


Figure 21.26 Ancient glacial epochs. (a) The first map shows the distribution of Permian-Pennsylvanian glacial deposits, formed more than 350 million years ago. At this time, the continents were assembled as the supercontinent Gondwanaland and the ice was situated in the Southern Hemisphere, centered over Antarctica, as the modern-day ice fields are. The second map shows the distribution of Permian-Pennsylvanian glacial deposits today. (b) Permian glacial deposits from South Africa. [John Grotzinger] (c) Late Proterozoic glacial deposits. [John Grotzinger] (d) The development of a late Precambrian Snowball Earth. Geologists debate the extent to which ice covered the globe, but some think even the oceans became frozen.

Snowball Earth

Mass extinctions & reefs

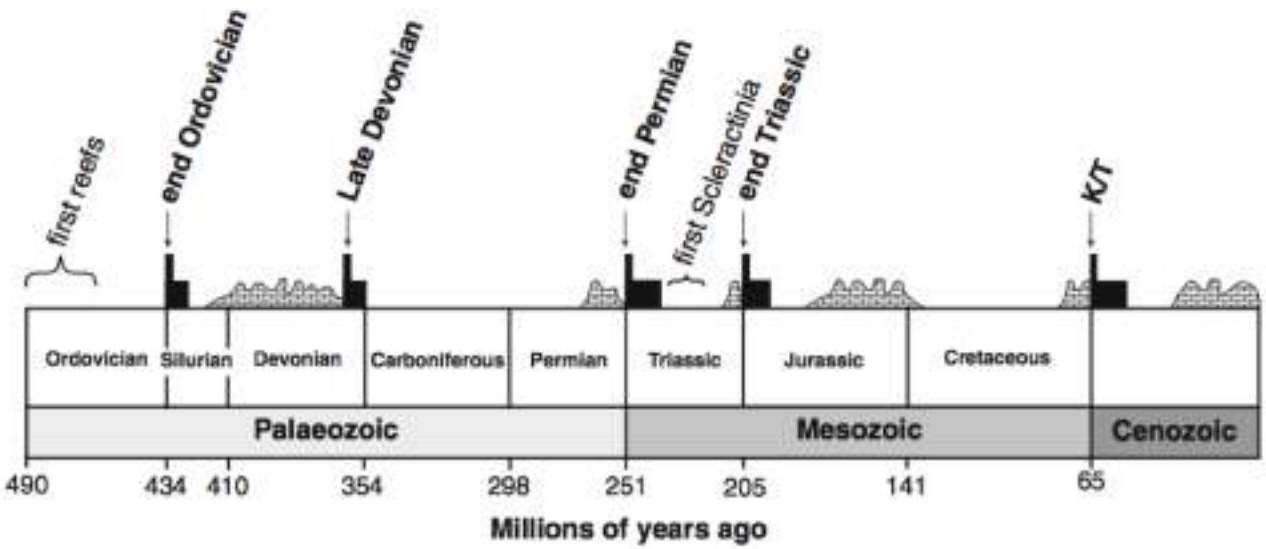
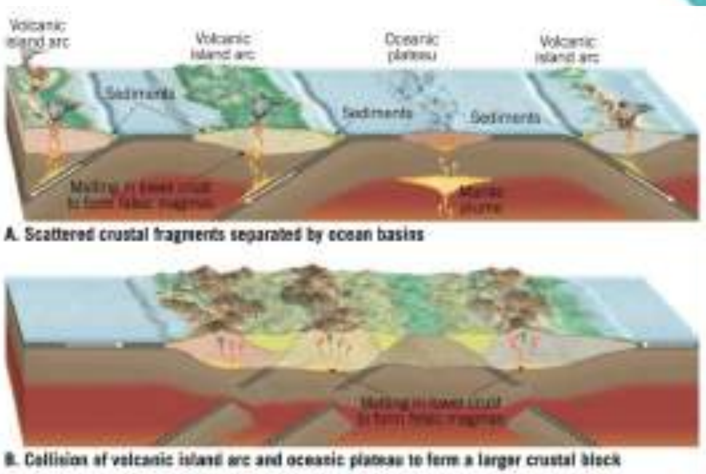
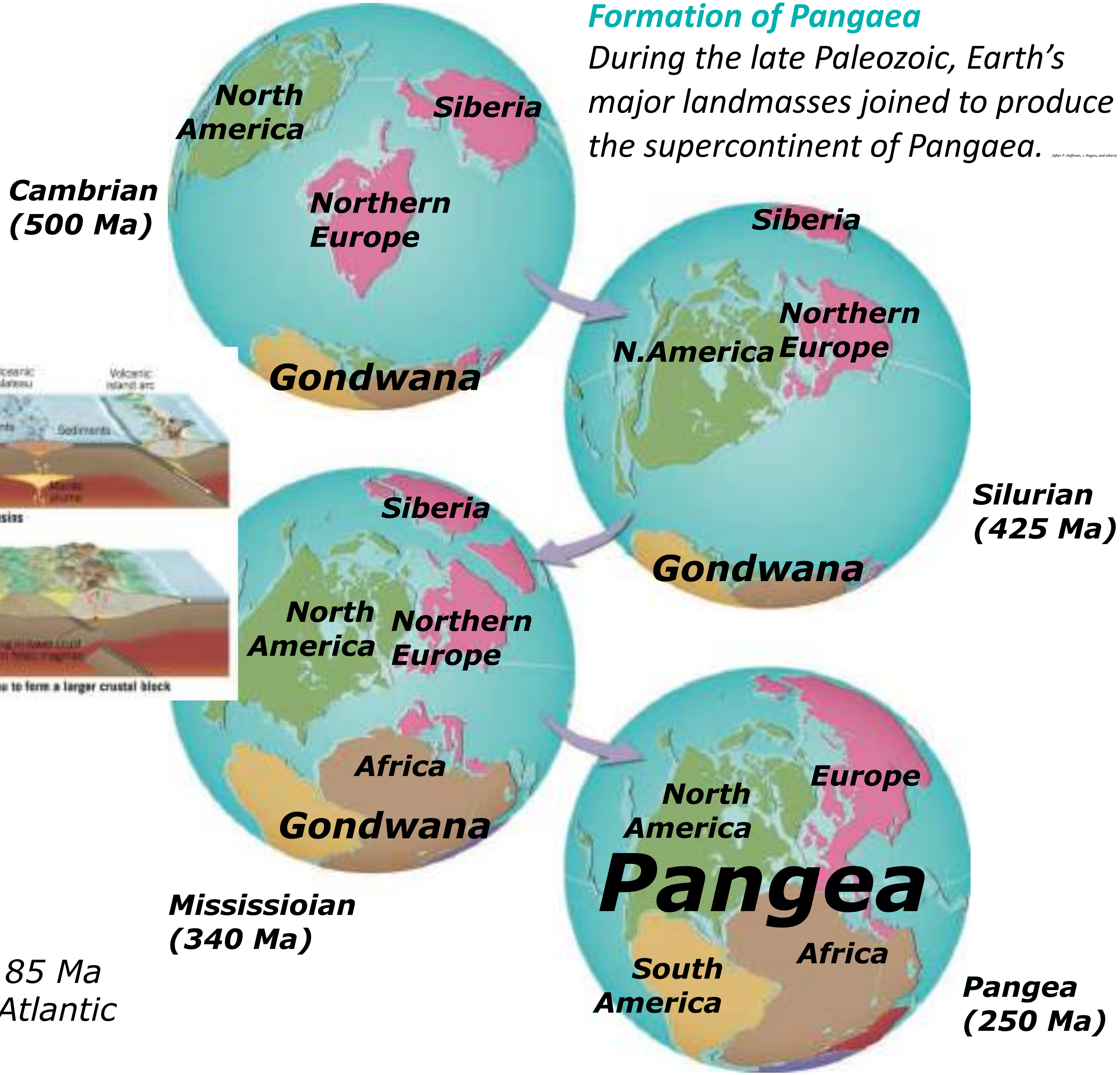


Fig. 1 Timeline of mass extinction events. The five named vertical bars indicate mass extinction events. Black rectangles (drawn to scale) represent global reef gaps and brick-pattern shapes show times of prolific reef growth. At other times reef growth appears to have been between these extremes, although there were many gaps not associated with mass extinctions and there were intervals of prolific growth in limited geographic regions not indicated here (after Veron 2008)

Formation of Pangaea

During the late Paleozoic, Earth's major landmasses joined to produce the supercontinent of Pangaea.





Pangea broke ~ 185 Ma and formation of Atlantic Ocean initiated

Relative and Radiometric Dating

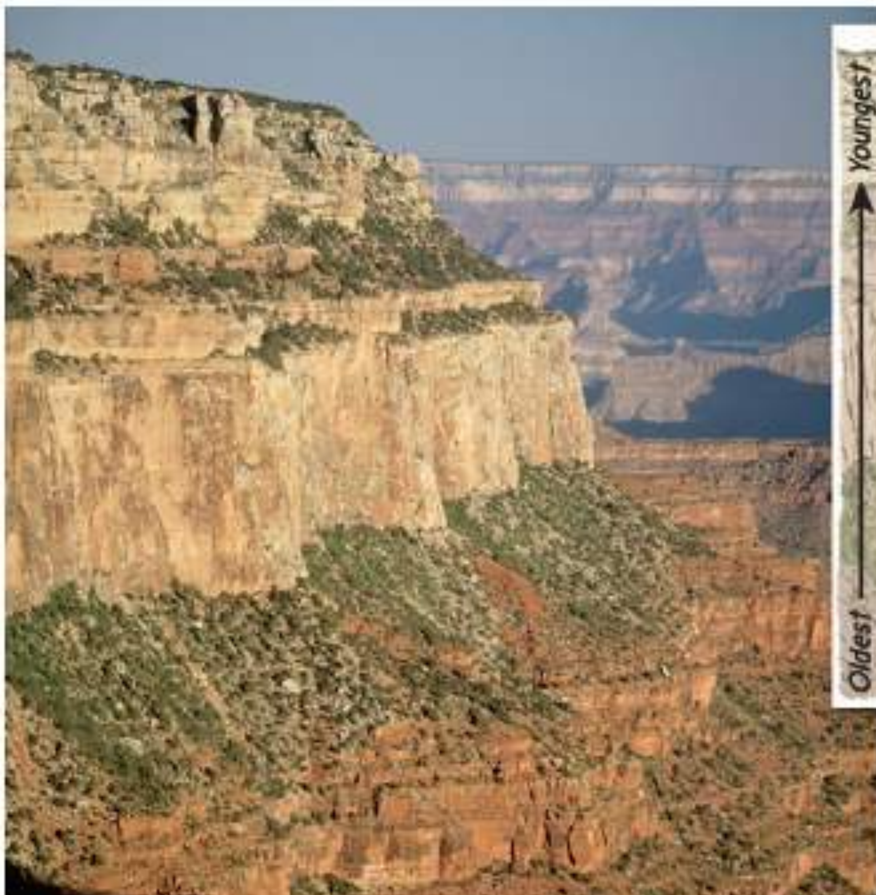
- **Relative Dating**
    - **Rocks are placed in their proper sequence of formation**
    - **Numerical values are not assigned to rocks**
- ***Radiometric / Numerical Dating***
    - ***Specifies the actual number of years that have passed since an event occurred***
    - ***Radioactivity***

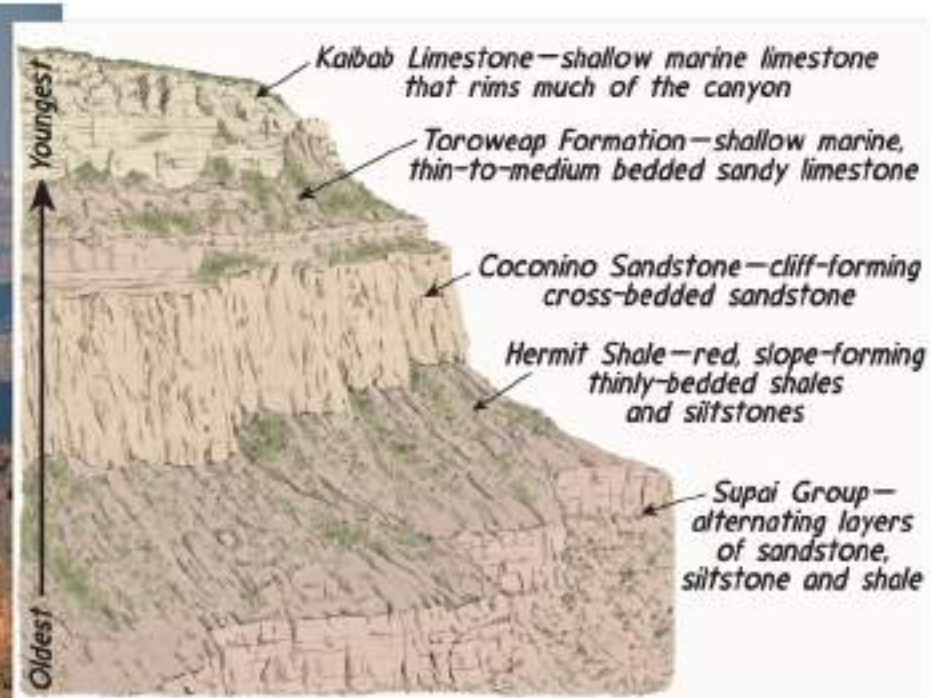
Relative Dating

- **Follows a few principles / rules**

I. *Law of superposition*

- **Developed by Nicolaus Steno in 1669**
- **In an <u>undeformed sequence</u> of sedimentary rocks (or layered igneous rocks), each rock is older than the one above and younger than the one below**





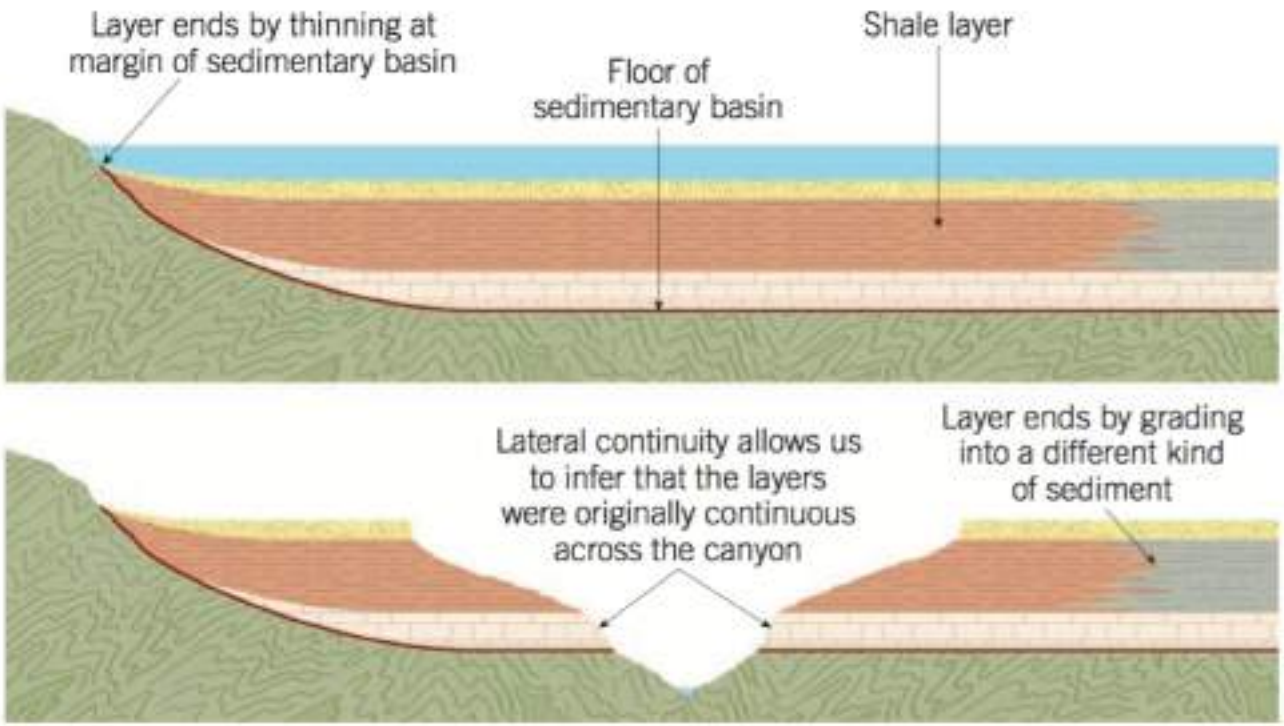
Geologist's Sketch

Superposition Is Well Illustrated by the Strata in the Grand Canyon

Relative Dating

II. Principle of original horizontality

- ***Originally*, layers of sediment are deposited in a horizontal position.**
- **Rock layers that are flat have not been disturbed.**
- **Rocks that are folded or inclined at a steep angle must have been moved into that position by crustal disturbances *after* their deposition.**



Folded Layers on the Island of Crete

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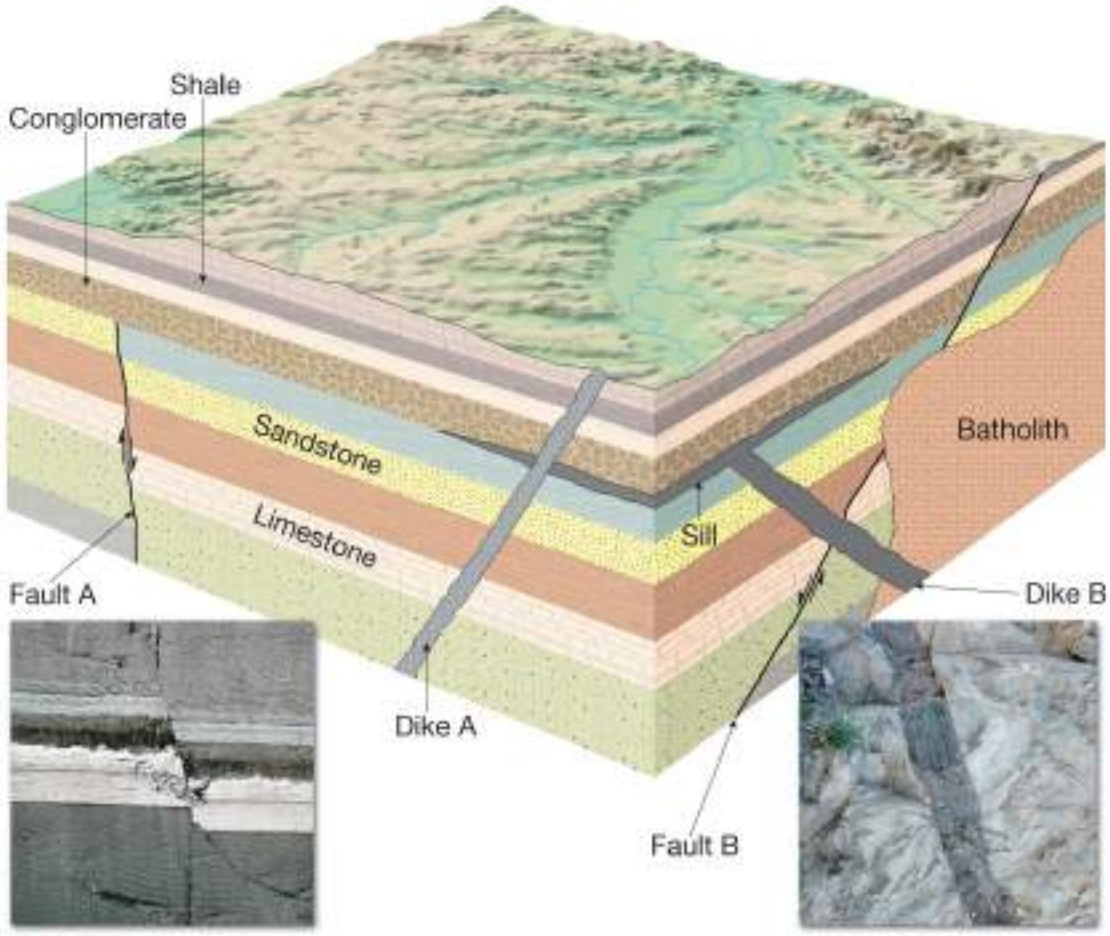
Relative Dating

III. Principle of cross-cutting relationships

- **Younger features cut across older features.**

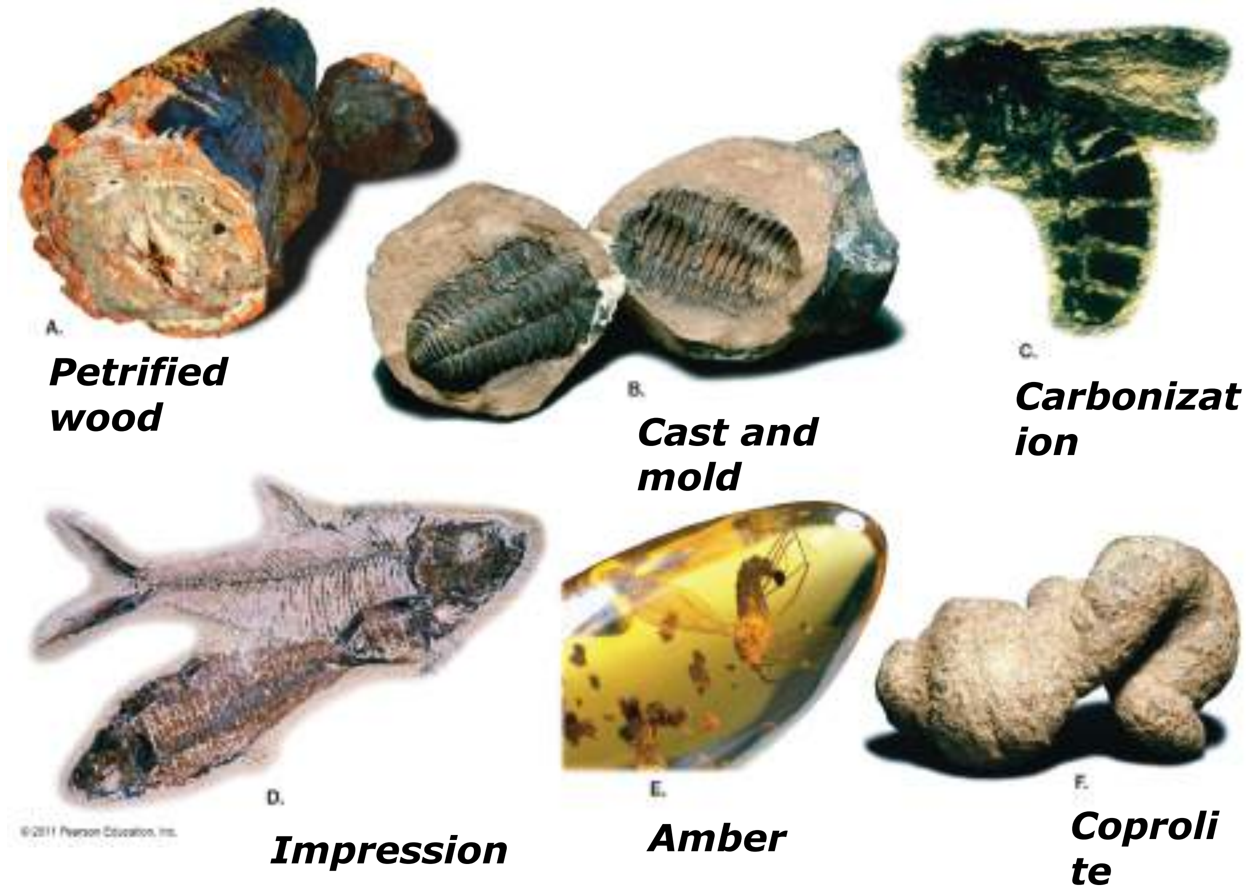


Relative Dating

IV. Principle of fossil succession

***Fossils* are traces or remains of prehistoric life that are now preserved in rock.**

Fossil organisms succeed one another in a definite and determinable order, and therefore any time period can be recognized by its fossil content



Fossils—Evidence of Past Life

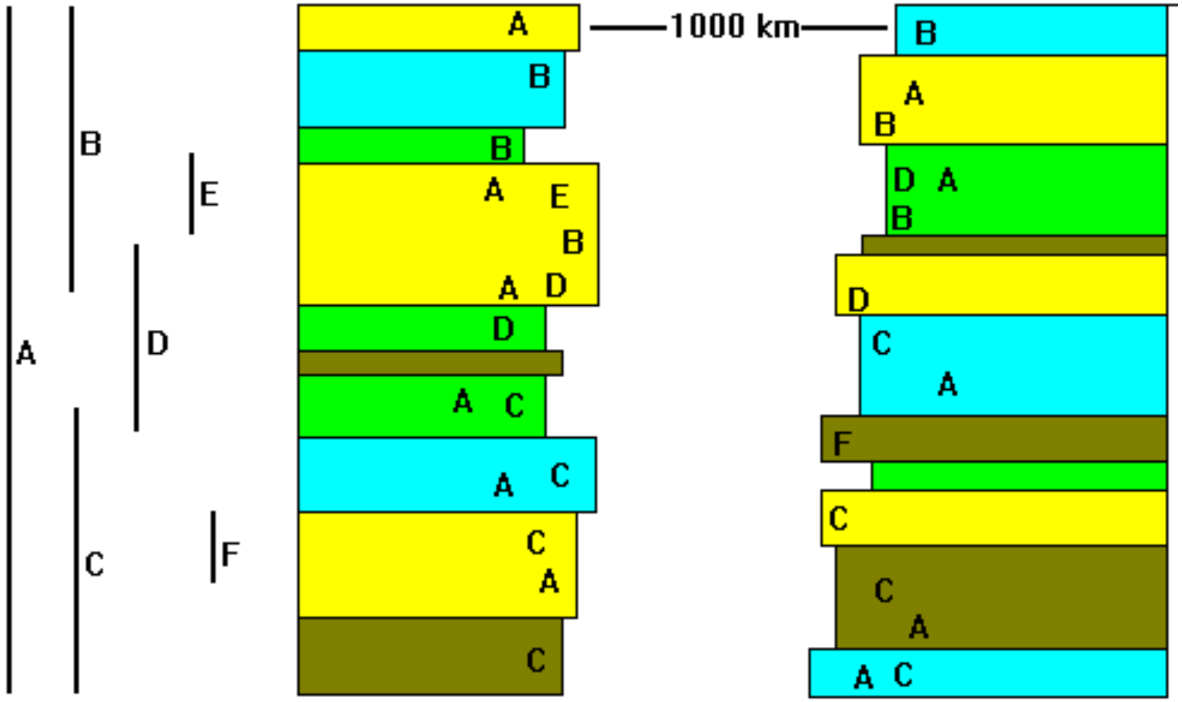
- **Fossils are generally found in sedimentary rock (rarely in metamorphic and never in igneous rock).**
- **Paleontology is the study of fossils.**
- ***Geologically fossils are important because they:***
    - ***Aid in interpretation of the geologic past***
    - ***Serve as important time indicators***
    - ***Allow for correlation of rocks from different places***

- **Conditions favoring preservation**
    - **Rapid burial**
    - **Possession of hard parts (skeleton, shell, bone, teeth, etc.)**

Dinosaur Tracks, Texas

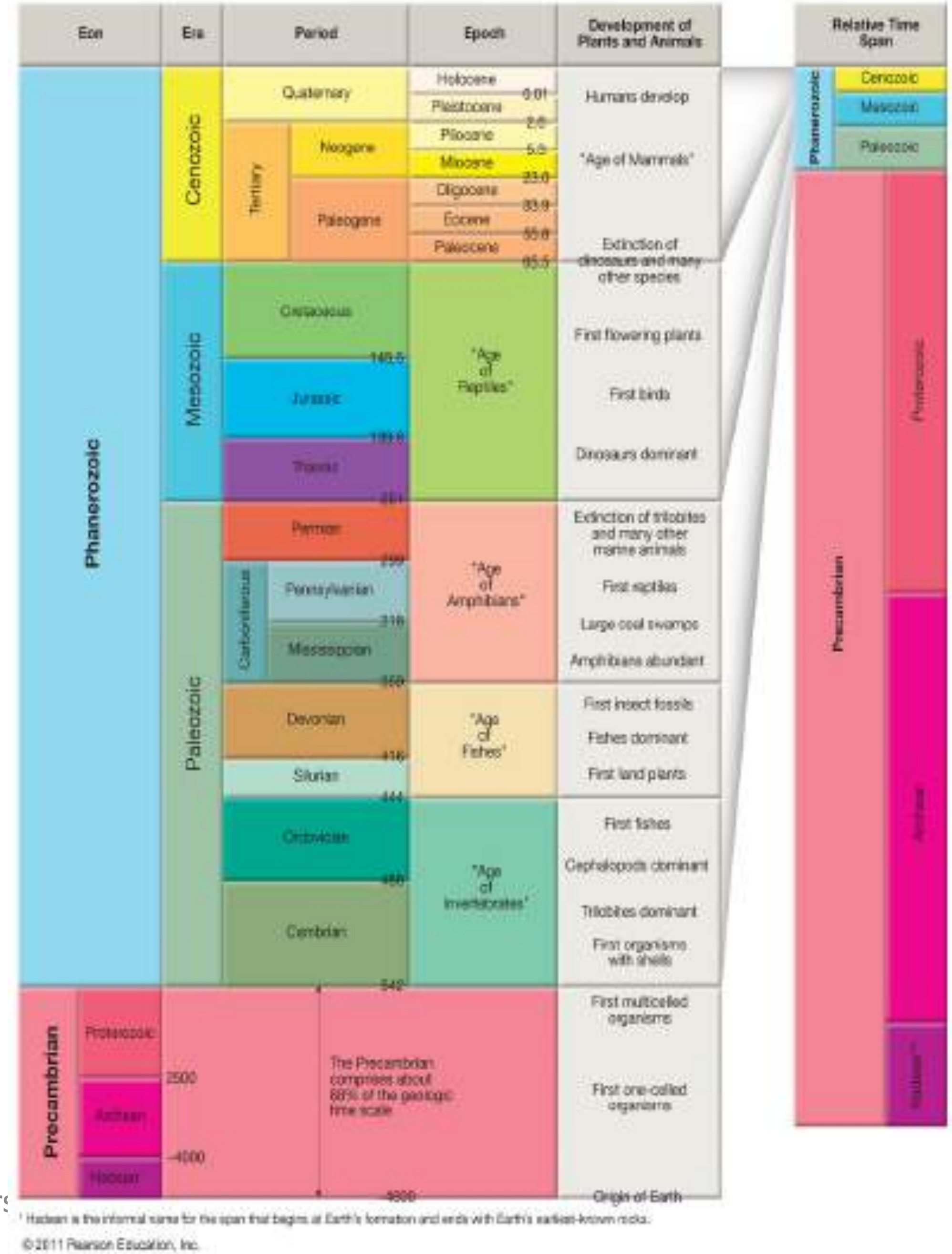
Fossils and Correlation

- **Matching of rocks of similar ages in different regions is known as correlation.**
- **Correlation often <u>relies upon fossils</u>.**
  - **William Smith (in the late 1700s) noted that sedimentary strata in widely separated areas could be identified and correlated by their distinctive fossil content.**



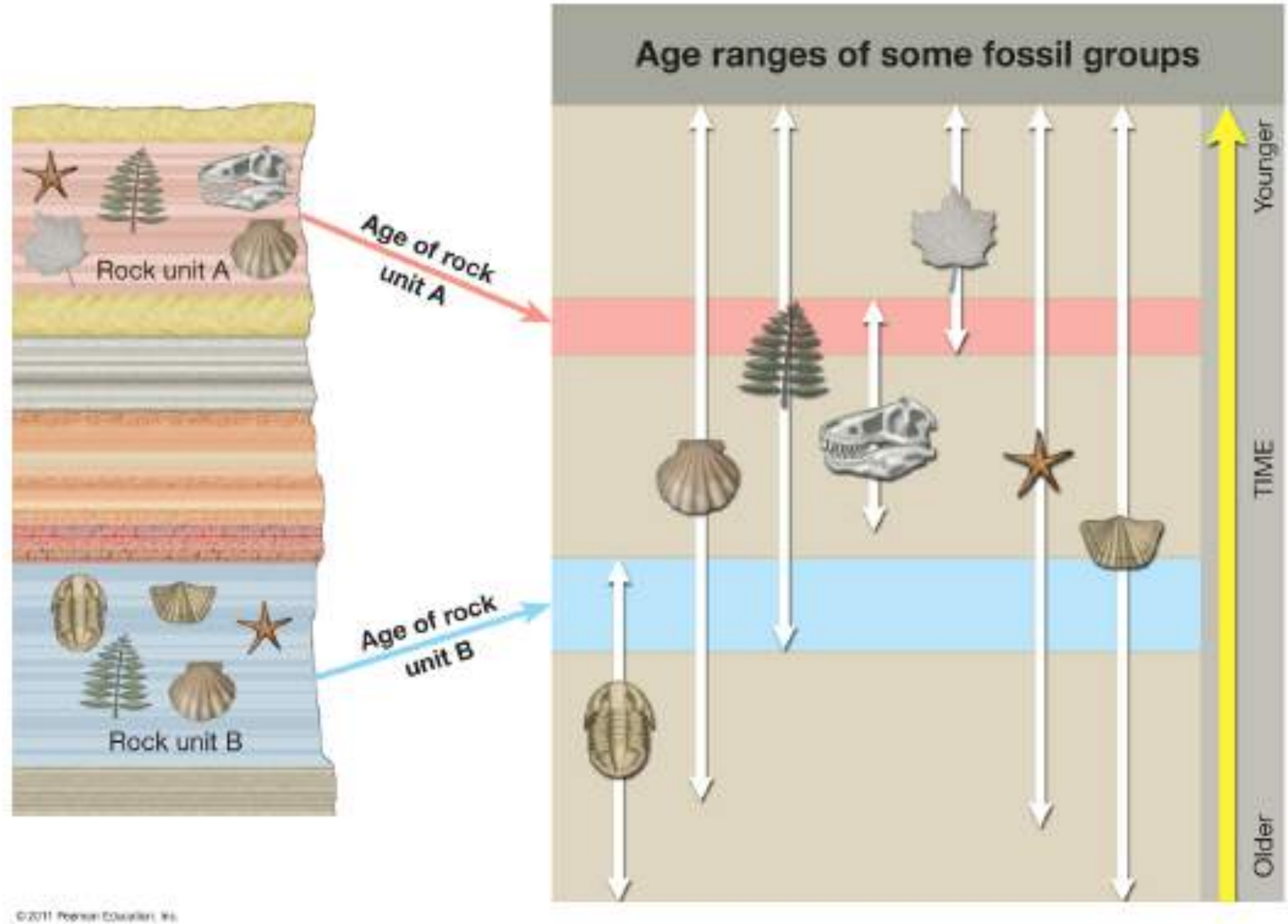
Fossils and Correlation

- **Principle of fossil succession**— fossil organisms succeed one another in a definite and determinable order. Therefore, <u>any time period can be recognized by its fossil content.</u>
- Fossils document the evolution of life through time (Age of Trilobites, Age of Fishes, Age of Coal Swamps, Age of Reptiles, Age of Mammals)
- An **index fossil** is a geographically widespread fossil that is limited to a short span of geologic time.



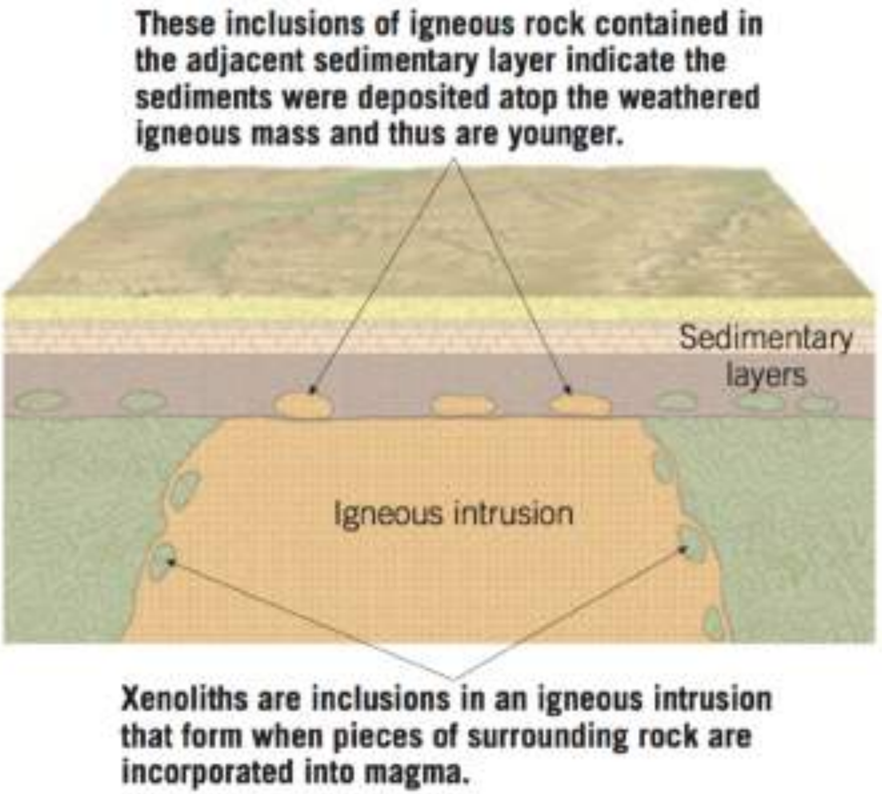
Dating Rocks Using Overlapping Fossil Ranges

Overlapping ranges of fossils help date rocks more exactly than using a single fossil.

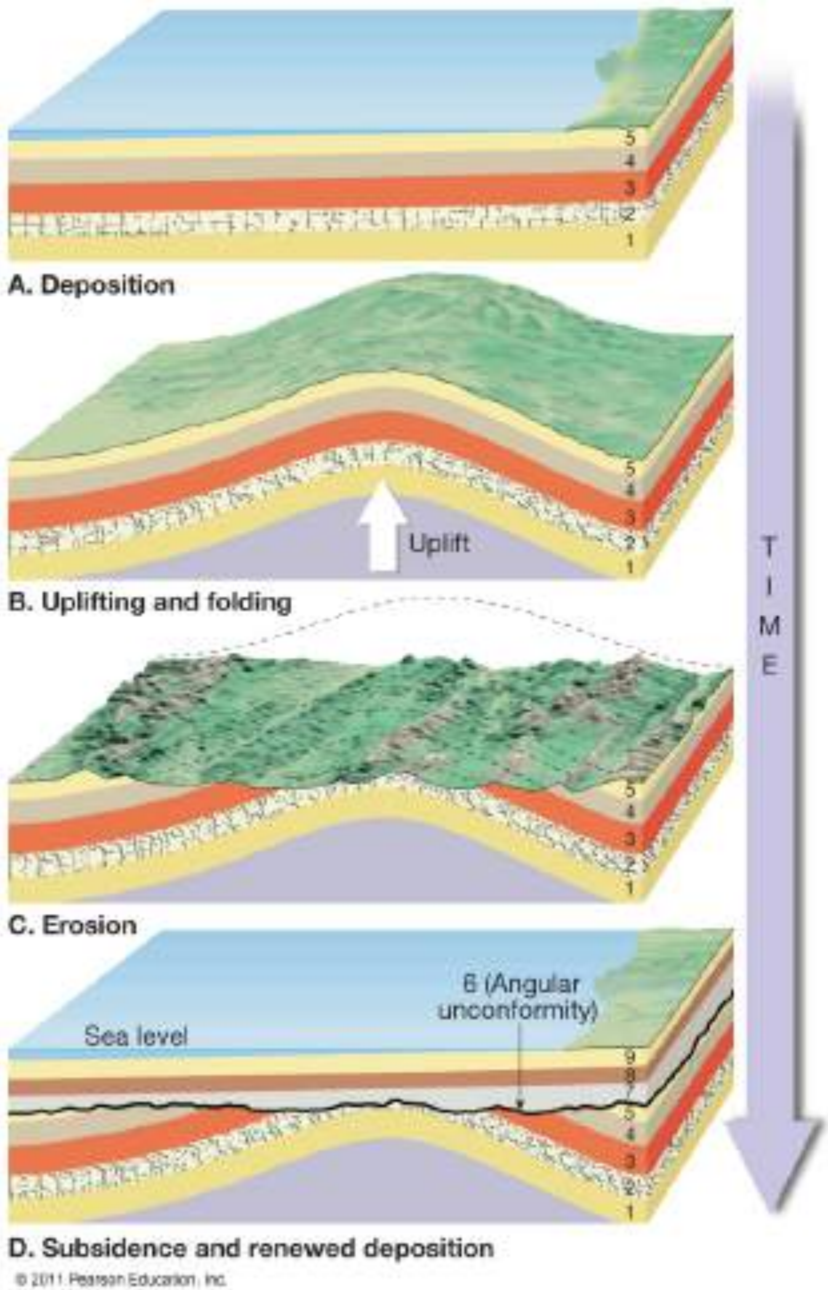


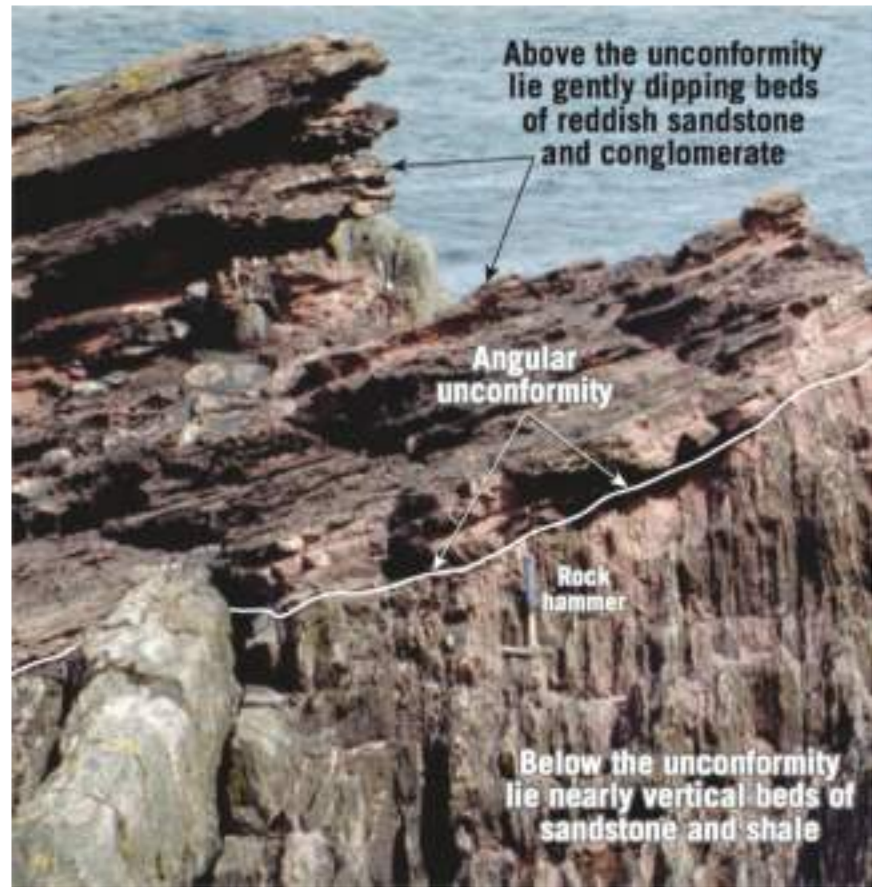
Relative Dating

- **Inclusions**
  - **An inclusion is a piece of rock that is enclosed within another rock.**
  - **The rock containing the inclusion is younger.**
- **Unconformity**
  - **An unconformity is a *break in the rock record*: deposition ceased, erosion removed previously formed rocks, and then deposition resumed**
  - **Uplift, erosion → Subsidence, renewed deposition**



Formation of an Angular Unconformity



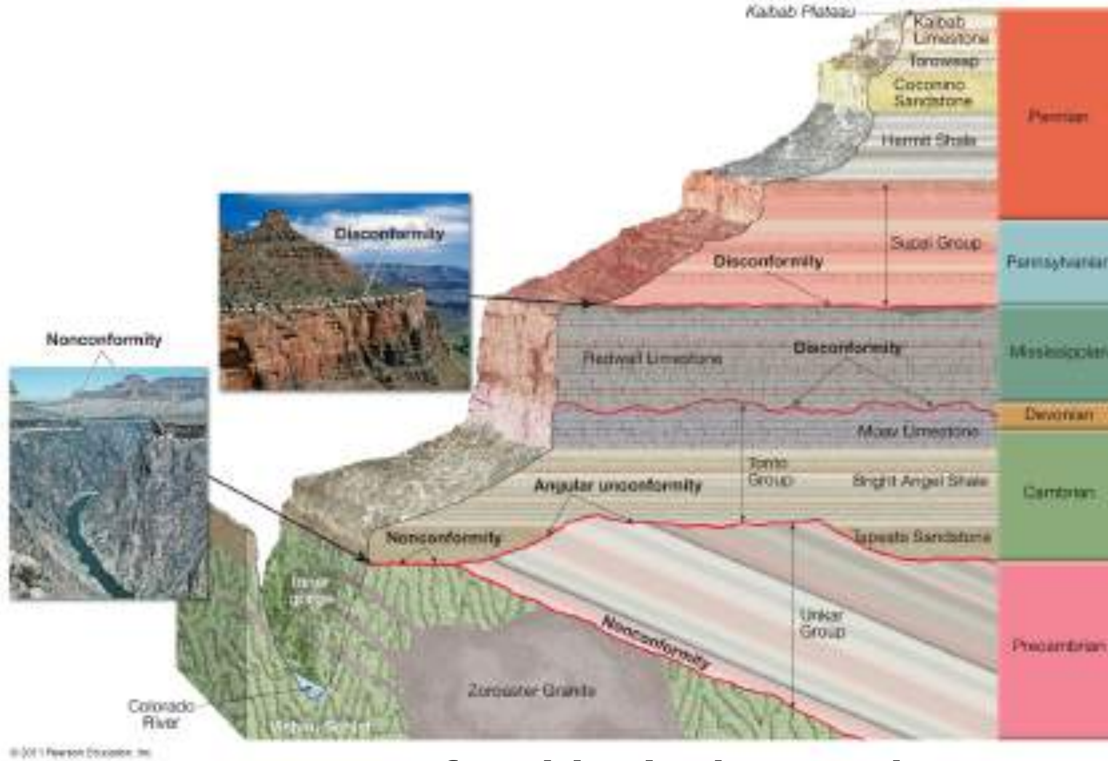


Relative Dating

Unconformity

Types of unconformities

- **Angular unconformity**—tilted rocks are overlain by flat-lying rocks
- **Disconformity**—strata on either side of the unconformity are parallel
- **Nonconformity**—metamorphic or igneous rocks in contact with sedimentary strata



Unconformities in the Grand Canyon

Arrange A to K in terms of oldest to youngest!

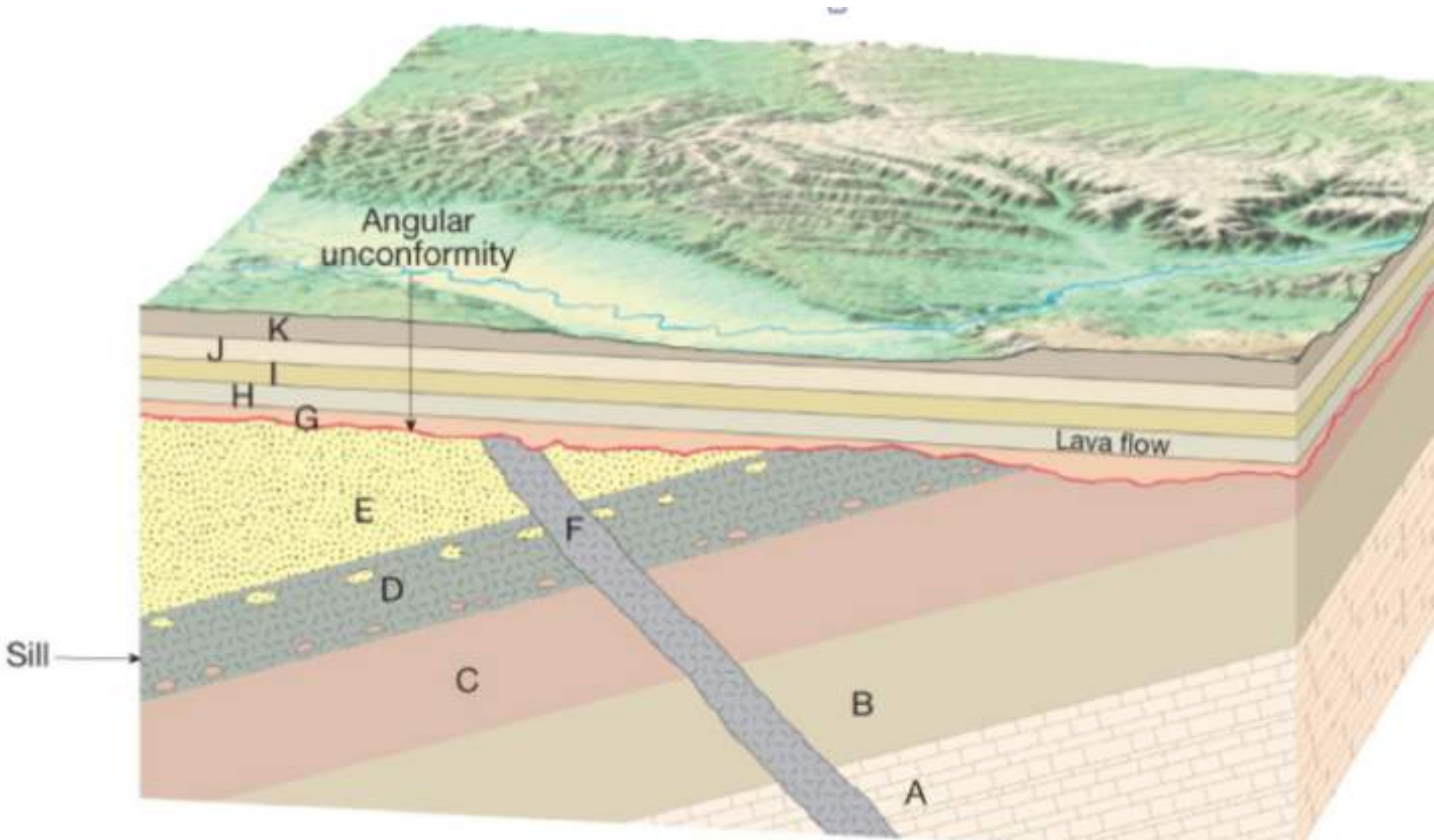
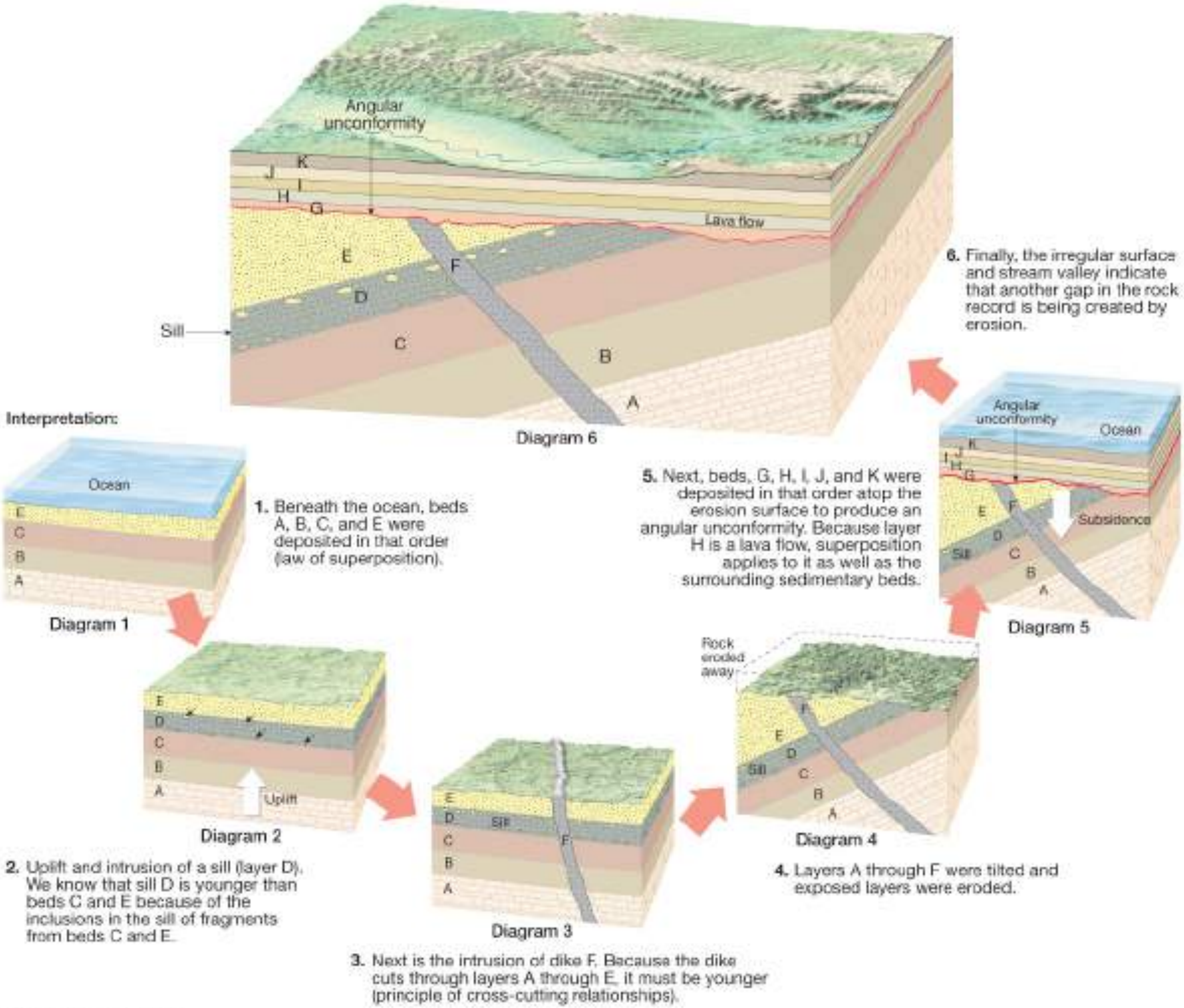
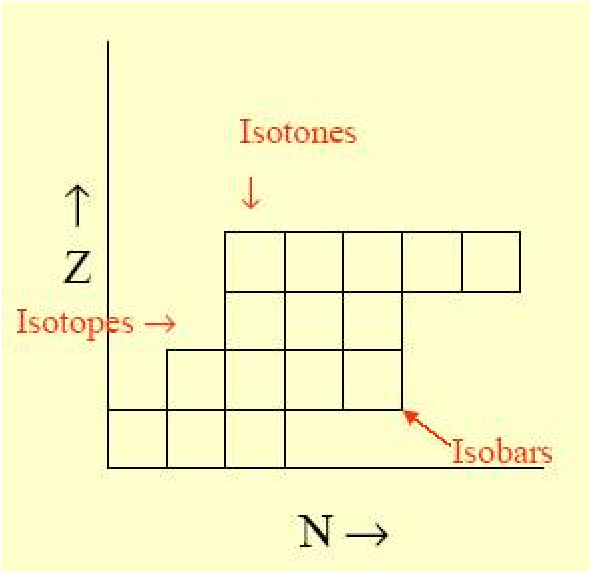


Diagram 6


Angular unconformity
K
J
I
H
G
Lava flow
E
F
D
Sill
C
B
A
Diagram 6
6. Finally, the irregular surface and stream valley indicate that another gap in the rock record is being created by erosion.
Interpretation:
Ocean
E
C
B
A
Diagram 1
1. Beneath the ocean, beds A, B, C, and E were deposited in that order (law of superposition).
E
D
C
B
A
Uplift
Diagram 2
2. Uplift and intrusion of a sill (layer D). We know that sill D is younger than beds C and E because of the inclusions in the sill of fragments from beds C and E.
E
D
Sill
F
C
B
A
Diagram 3
3. Next is the intrusion of dike F. Because the dike cuts through layers A through E, it must be younger (principle of cross-cutting relationships).
Rock eroded away
F
E
D
Sill
C
B
A
Diagram 4
4. Layers A through F were tilted and exposed layers were eroded.
Angular unconformity
Ocean
K
J
I
H
G
E
F
D
Sill
C
B
A
Subsidence
Diagram 5
5. Next, beds, G, H, I, J, and K were deposited in that order atop the erosion surface to produce an angular unconformity. Because layer H is a lava flow, superposition applies to it as well as the surrounding sedimentary beds.

Absolute dating: Dating with Radioactivity

Z = proton number = No. of protons in the nucleus; defines an element
N = neutron number = No of neutrons in the nucleus
A = mass number = Z + N;
Notation: $^{A}_{Z}X$



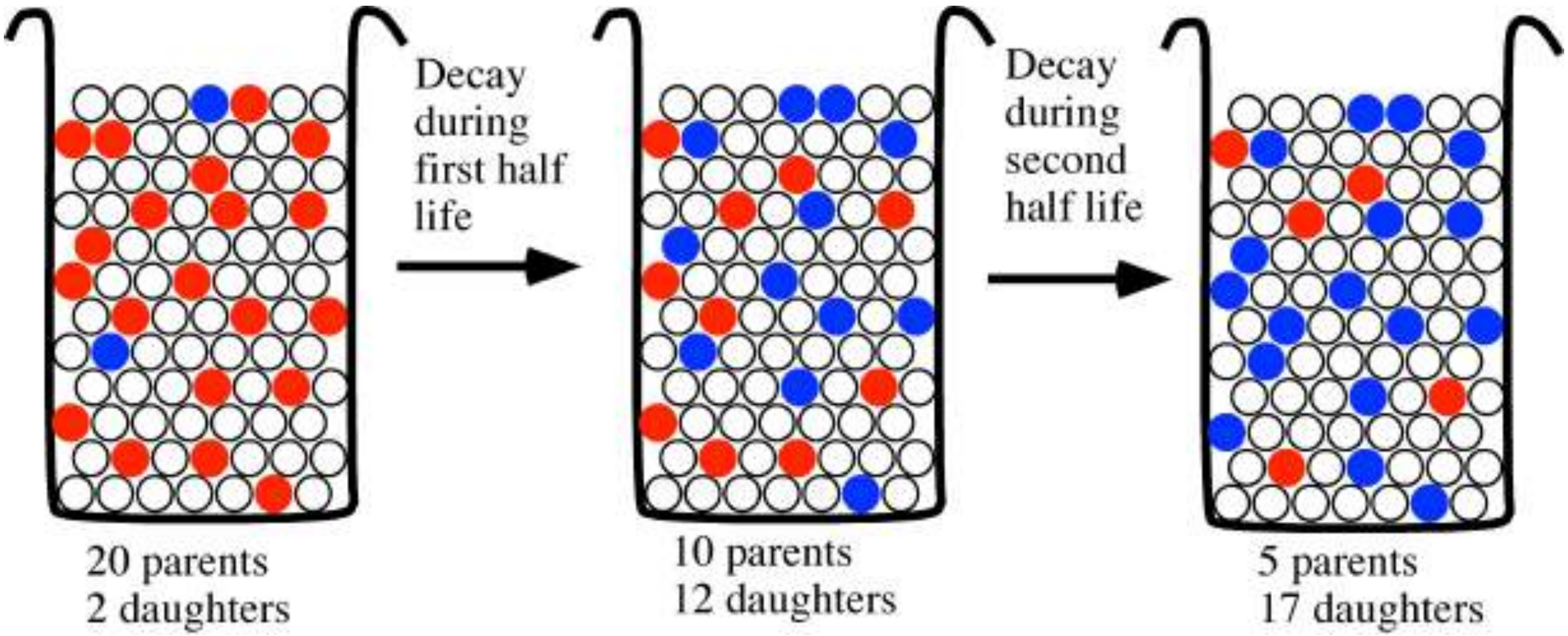
Isotope = line of equal Z (no. of proton);
nuclides with the same No. of protons (therefore they are the same element), but variable N;
e.g. ^{12}C, ^{13}C, ^{14}C ***are isotopes***

Isotone = line of equal N (no. of neutrons);
nuclides with the same # of neutrons, but variable Z;
e.g. ^{37}Cl & ^{39}K ***are isotones (both have 20 neutrons)***

Isobar = Equal mass;
nuclides with the same mass number, but variable N and Z;
e.g. ^{12}C, ^{12}B, ^{12}Be ***are isobars***

- **Parent—an unstable radioactive isotope**
- **Daughter product—the isotopes resulting from the decay of a parent**
- **Half-life—the time required for one-half of the radioactive nuclei in a sample to decay**

Dating with Radioactivity



The actual number of atoms that decay (radioactive parent) continually decreases and the number of stable daughter atoms (radiogenic daughter) increases.

Simple Radioactive Decay

Radioactive decay is a stochastic process linked to the stability of nuclei. The rate of change in the number of radioactive nuclei is a function of the total number of nuclei present and the decay constant λ.

$$- dN / dt = \lambda N$$

The sign on the left hand is negative because the number of nuclei is decreasing. Rearranging this equation yields

$$- dN / N = \lambda\, dt$$

and integrating yields

$$- \ln N = \lambda t + C$$

C is the integration constant. We solve for C by setting $N = N_0$ and $t = t_0$. Then

$$C = - \ln N_0$$

Substituting for C gives

$$- \ln N = \lambda t - \ln N_0$$

We rearrange

$$\ln N - \ln N_0 = - \lambda t$$

Rearrange again

$$\ln N/N_0 = - \lambda t$$

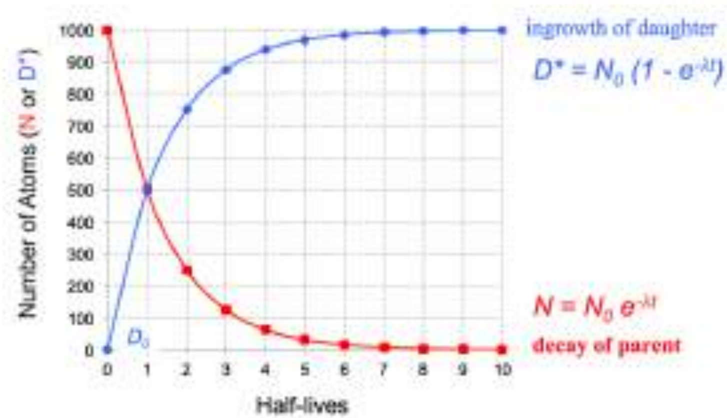
Eliminate the natural log

$$N/N_0 = e^{-\lambda t}$$

And rearrange

$$N = N_0 e^{-\lambda t}$$

Simple Decay: Radioactive Parent ⇒ Stable Daughter



…continue…

Unfortunately, we don't know N_0 a priori, but decayed N have produced radiogenic daughters D*.

Therefore $$D^* = N_0 - N$$

Replacing N_0 with $N\,e^{\lambda t}$ yields $$D^* = N\,e^{\lambda t} - N$$

Rearranged $D^* = N\,(e^{\lambda t} - 1)$ or, for small λt, $D^* = N\,\lambda\,t$,

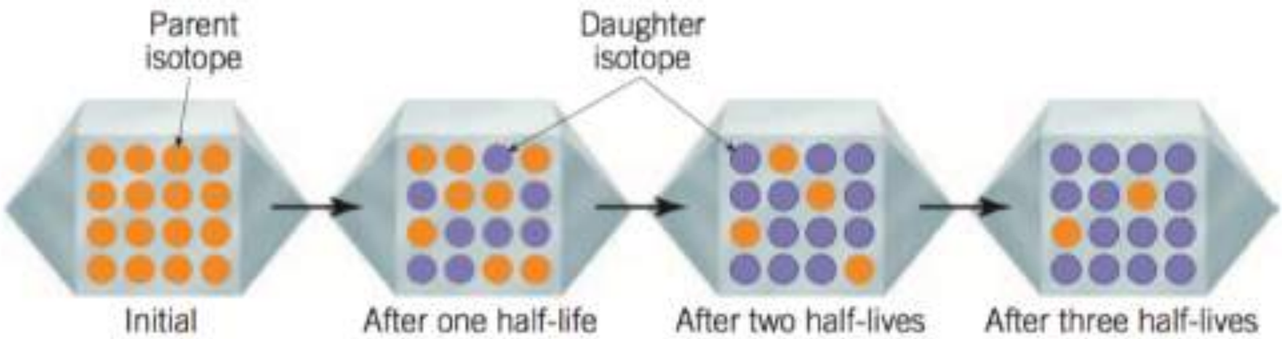
The number of daughter isotopes is the sum of those initially present plus those radiogenically produced.

$$D = D_0 + D^*$$

Therefore, $D = D_0 + N\,(e^{\lambda t} - 1)$ or, for small λt, $D = D_0 + N\,\lambda\,t$,

This is the basic radioactive decay equation used for determining ages of rocks, minerals and the isotopes themselves. D and N can be measured and λ has been experimentally determined for nearly all known unstable nuclides. The value D_0 can be either assumed or determined by the **isochron method**.

CALCULATE IT Measurement of zircon crystals from a granite yield parent/daughter ratios of 25 percent parent (uranium-235) and 75 percent daughter (lead-206). The half-life of uranium-235 is 704 million years. How old is the granite?



Radioactive Parent	Stable Daughter Product	Currently Accepted Half-Life Values
Uranium-238	Lead-206	4.5 billion years
Uranium-235	Lead-207	704 million years
Thorium-232	Lead-208	14.1 billion years
Rubidium-87	Strontium-87	47.0 billion years
Potassium-40	Argon-40	1.3 billion years

Isotopes Frequently Used in Radiometric Dating

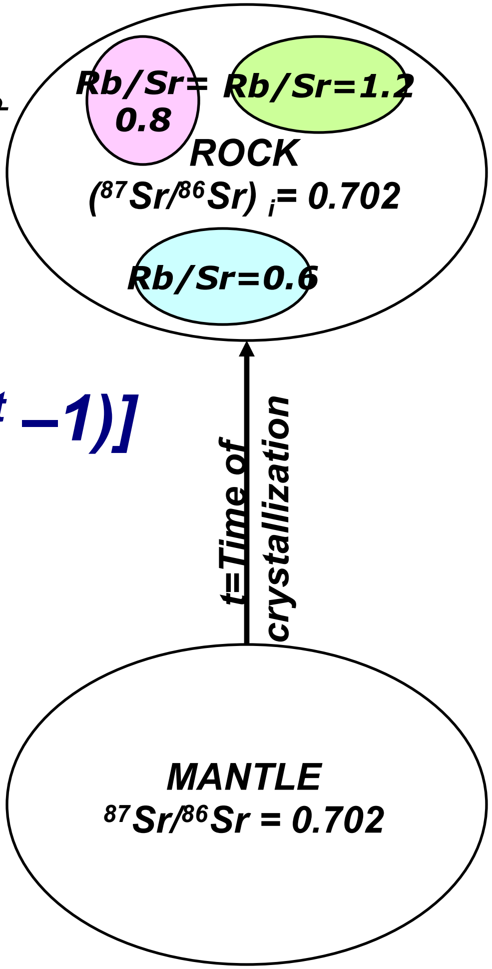
The only equation you have to memorize

$$D = D_0 + N\,(e^{\lambda t} - 1)$$

D = radiogenic daughter, N daughter atoms produced by radioactive decay of a parent, D_0=initial daughter atoms

^{87}Rb-^{87}Sr decay equation (Isochron equation)

Divide by a stable, non-radiogenic isotope of the daughter element to get ratios e.g. for $^{87}Rb \rightarrow {}^{87}Sr + \beta^-$



$$\frac{^{87}Sr}{^{86}Sr} = \left(\frac{^{87}Sr}{^{86}Sr}\right)_i + \frac{^{87}Rb}{^{86}Sr}(e^{\lambda t} - 1)$$

[$D = D_0 + N\,(e^{\lambda t} - 1)$]

measured

measured

when you crystallize a rock, you will always have some Sr present

<u>So how do you determine the initial $^{87}Sr/^{86}Sr$ ratio?</u>

Because igneous rocks are so heterogeneous, different mineral phases will have different Rb/Sr ratios, even though they have the same crystallization age and the same $^{87}Sr/^{86}Sr$ initial.

The Isochron

The radioactive decay equation is in the form of a line:

$D = D_0 + P(e^{\lambda t}-1)$ … $y = b + xm$

Plot D ratio vs. P/D for several comagmatic or cogenetic samples and draw a best fit line through the data

y-intercept = initial D ratio, slope is related to t

This line is called an "Isochron"

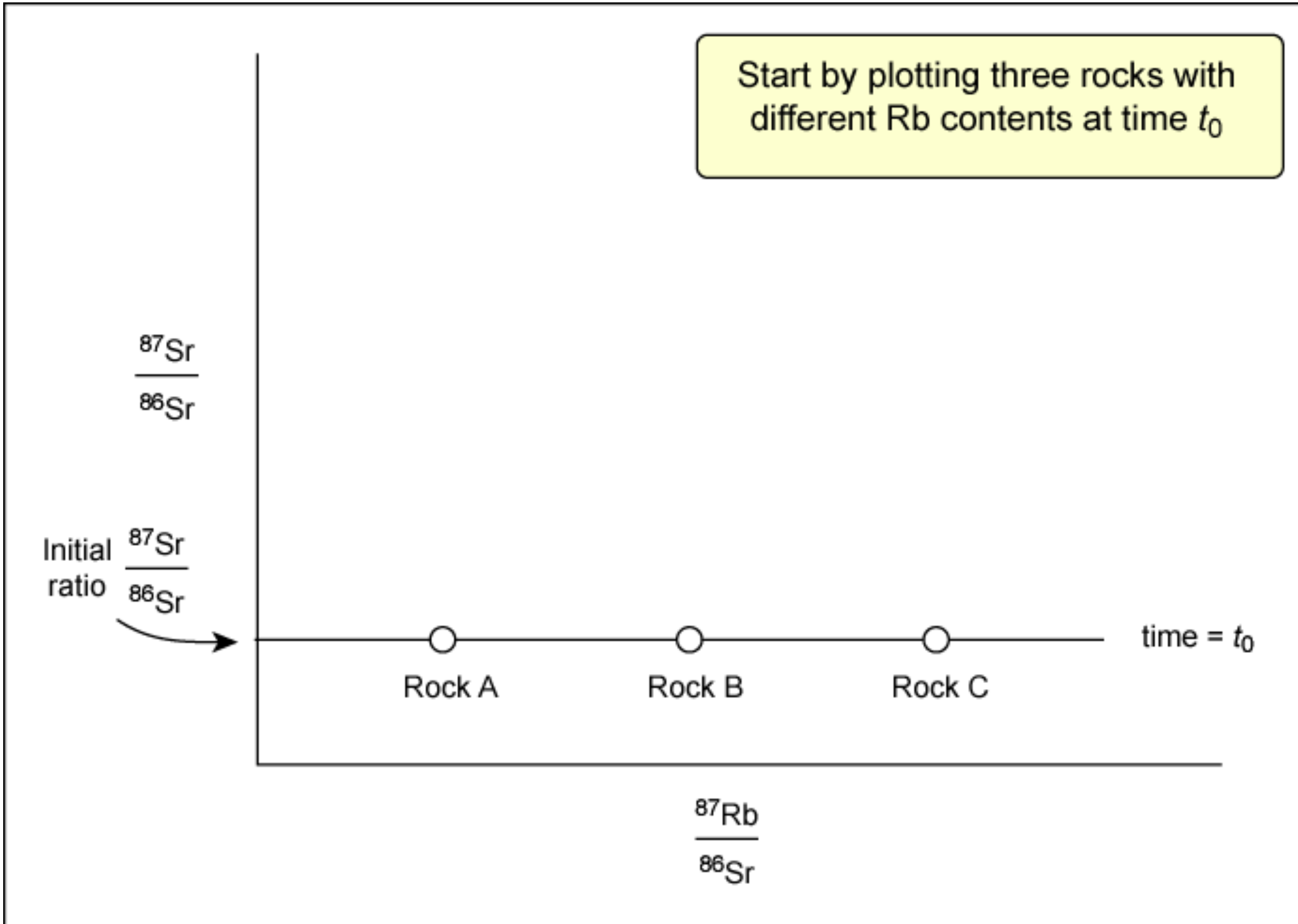
Represents true age if:

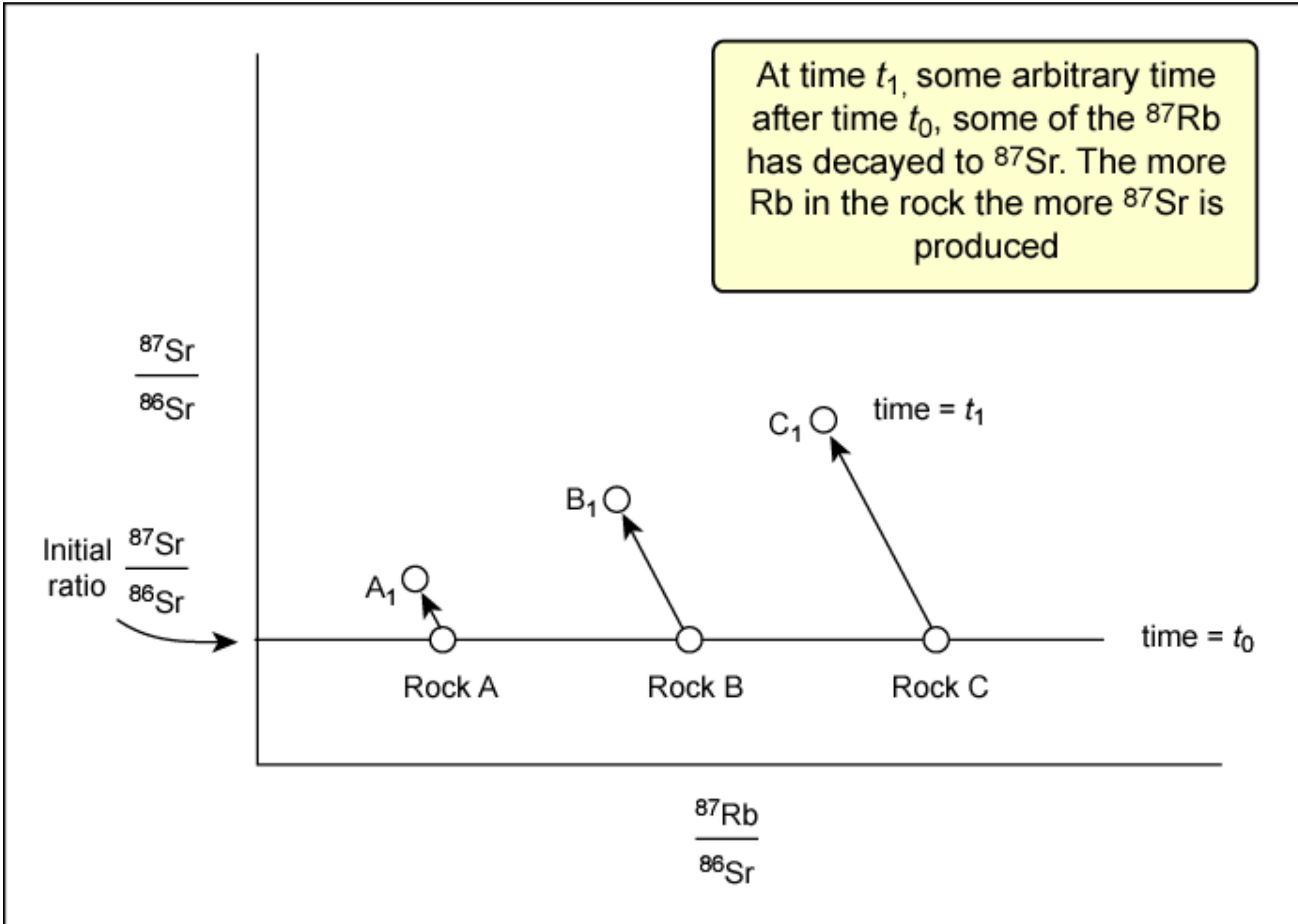
(1) The system was at isotopic equilibrium at time t = 0. I.e. all the samples formed with the same initial daughter isotope ratio

(2) Closed system since formation

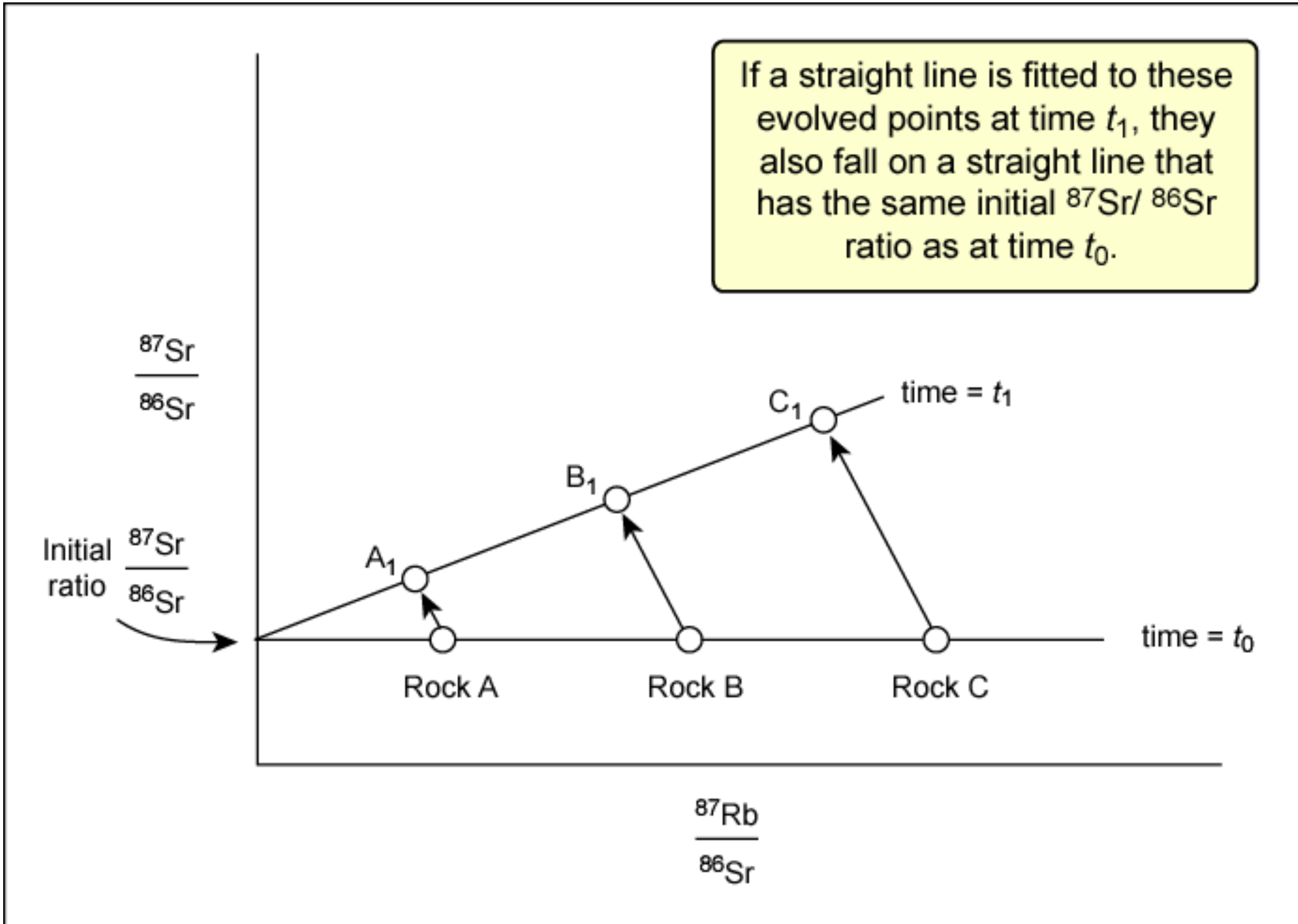
Whole-rock isochron represents age of formation

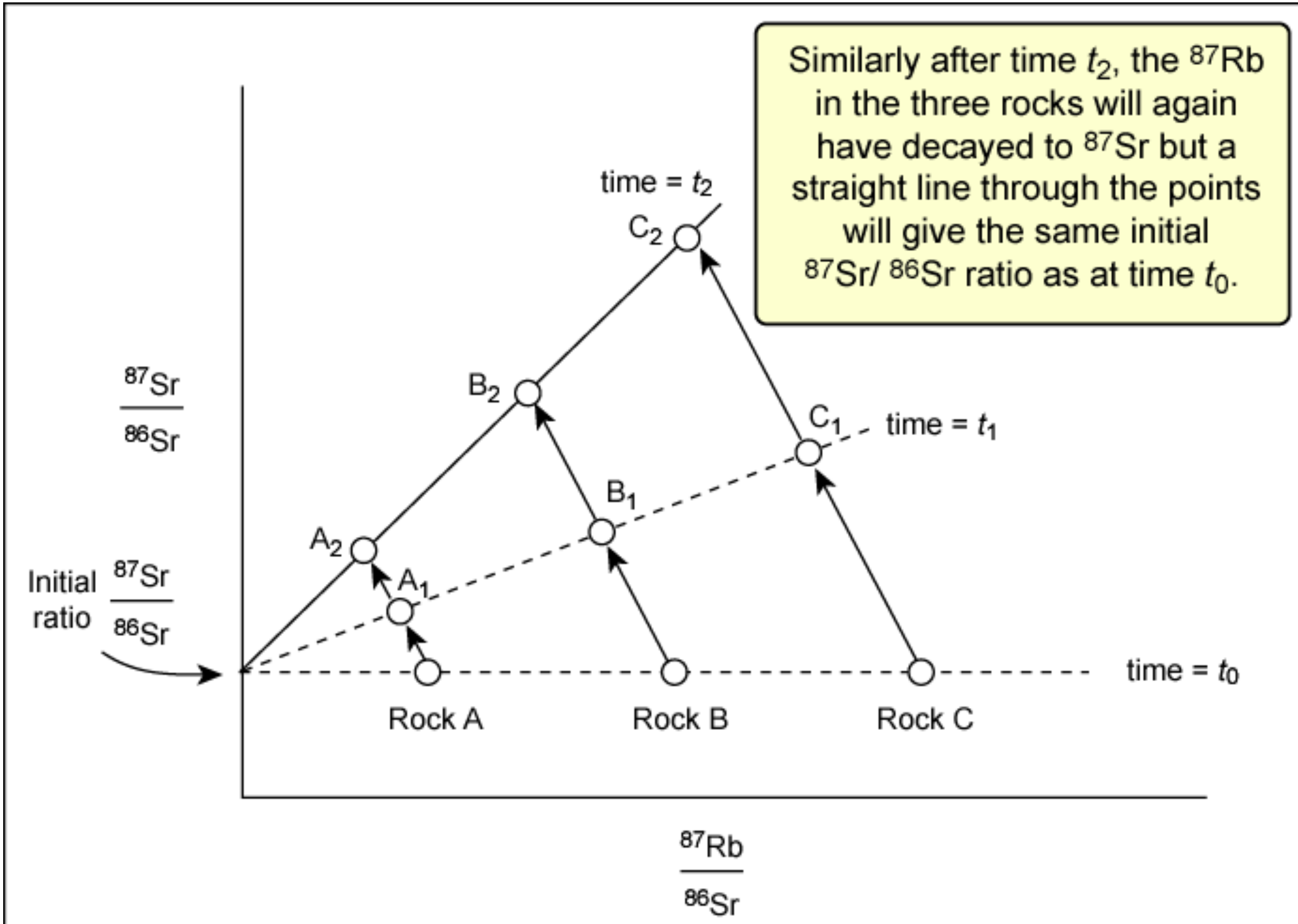
Mineral isochron represents age of last metamorphosis


Start by plotting three rocks with different Rb contents at time t_0
$\frac{^{87}Sr}{^{86}Sr}$
Initial ratio $\frac{^{87}Sr}{^{86}Sr}$
time = t_0
Rock A
Rock B
Rock C
$\frac{^{87}Rb}{^{86}Sr}$



At time t_1, some arbitrary time after time t_0, some of the ^{87}Rb has decayed to ^{87}Sr. The more Rb in the rock the more ^{87}Sr is produced
$\frac{^{87}Sr}{^{86}Sr}$
Initial ratio $\frac{^{87}Sr}{^{86}Sr}$
C_1
time = t_1
B_1
A_1
time = t_0
Rock A
Rock B
Rock C
$\frac{^{87}Rb}{^{86}Sr}$


If a straight line is fitted to these evolved points at time t_1, they also fall on a straight line that has the same initial $^{87}Sr/^{86}Sr$ ratio as at time t_0.
$\frac{^{87}Sr}{^{86}Sr}$
Initial ratio $\frac{^{87}Sr}{^{86}Sr}$
A_1
B_1
C_1
time = t_1
time = t_0
Rock A
Rock B
Rock C
$\frac{^{87}Rb}{^{86}Sr}$


Similarly after time t_2, the ^{87}Rb in the three rocks will again have decayed to ^{87}Sr but a straight line through the points will give the same initial $^{87}Sr/^{86}Sr$ ratio as at time t_0.
time = t_2
time = t_1
time = t_0
C_2
B_2
A_2
C_1
B_1
A_1
$\frac{^{87}Sr}{^{86}Sr}$
Initial ratio $\frac{^{87}Sr}{^{86}Sr}$
Rock A
Rock B
Rock C
$\frac{^{87}Rb}{^{86}Sr}$

Fundamentals of Earth Sciences (ESO 213A)

Dibakar Ghosal
Department of Earth Sciences

Crustal Deformation

Previous Class: Geological Time Scale and Radioactive Dating

Structural Geology

- **Structural geologists study the architecture and processes responsible for deformation of Earth's crust.**
- **The basic features resulting from the forces generated by the interactions of tectonic plates = *tectonic structures***
  - » **folds**
  - » **faults**
  - » **joints**
  - » **foliation, rock cleavage**

Deformation, Stress, and Strain

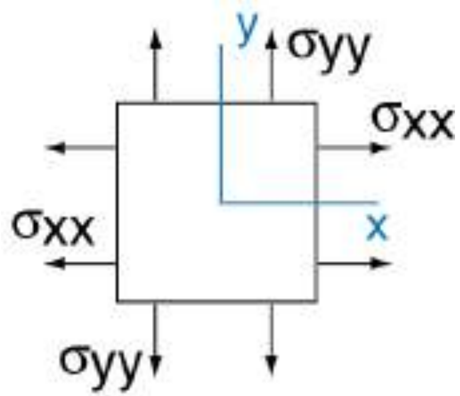
- **Deformation is a general term that refers to all changes in the original form and/or size of a rock body.**

- **Most crustal deformation occurs along plate margins.**

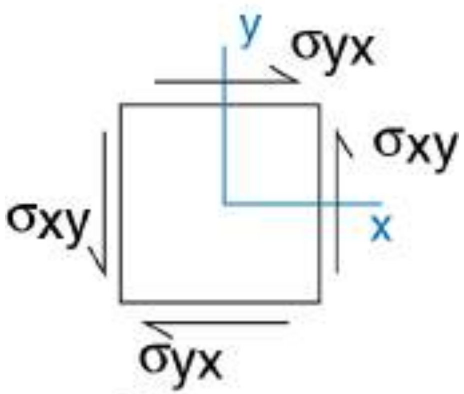
Stress

Deformation involves:

- **Stress**—Stresses refer to balanced internal "forces (per unit area)". They differ from force vectors, which, if unbalanced, cause accelerations
- **Types of stress**
  - » Compressional stress shortens a rock body.
  - » Tensional stress tends to elongate or pull apart a rock unit.
  - » Shear stress produces a motion similar to slippage that occurs between individual playing cards when the top of the stack is moved relative to the bottom.



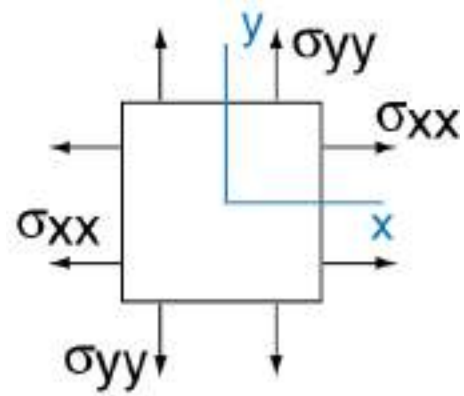
Normal stresses



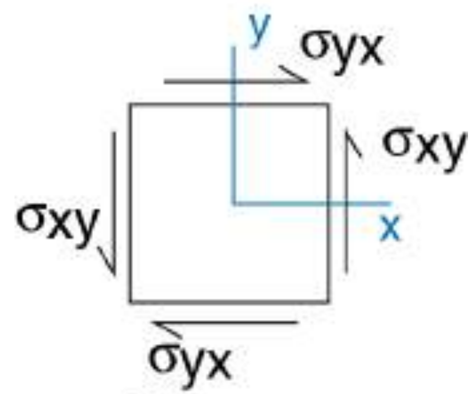
Shear stresses

•*Convention for stresses (in geology)*

- *Tension is negative*
- *Compression is positive*
- *"On -in convention": The stress component σ_{ij} acts on the plane normal to the i- direction and acts in the j- direction*
- *Counter to most mechanics books*



Normal stresses



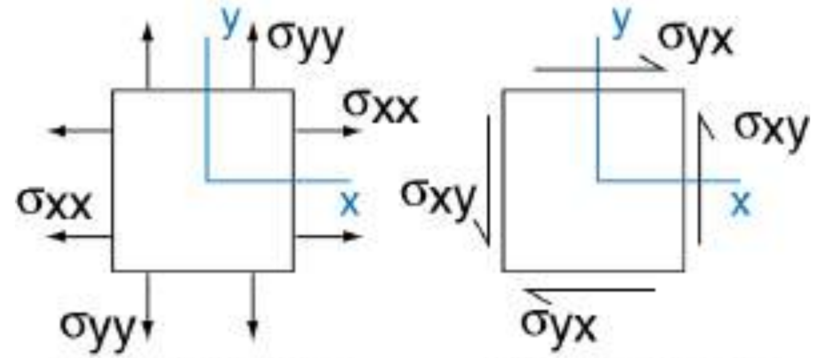
Shear stresses

$$\sigma_{ij} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix}$$ ***3-D (9 components)***

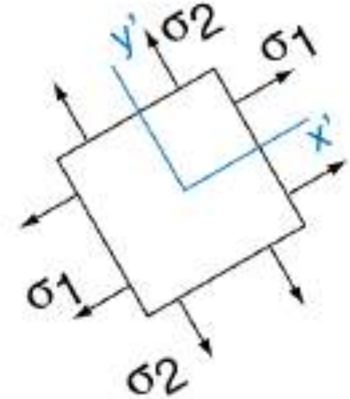
Principal Stresses

- *Have magnitudes and orientations and represents the stress state most simply*
- *Principal stresses act on planes which feel no shear stress*
- *Principal stresses are normal stresses*
- *Principal stresses act on perpendicular planes owing to symmetry of stress tensor*
- *The maximum, intermediate, and minimum principal stresses are usually designated σ_1, σ_2, and σ_3, respectively*

** If σ1 = σ2 = σ3, the state of stress is called isotropic. This occurs beneath a still body of water.*



Normal stresses Shear stresses



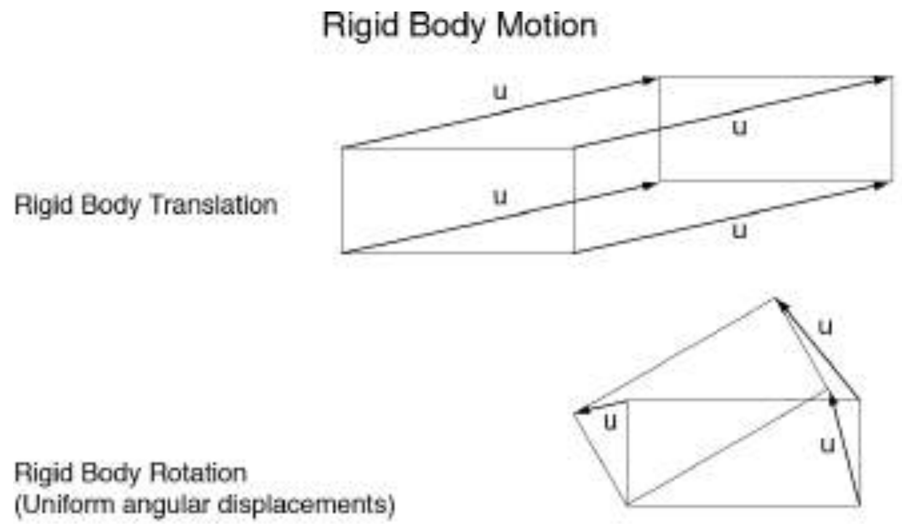
Principal stresses

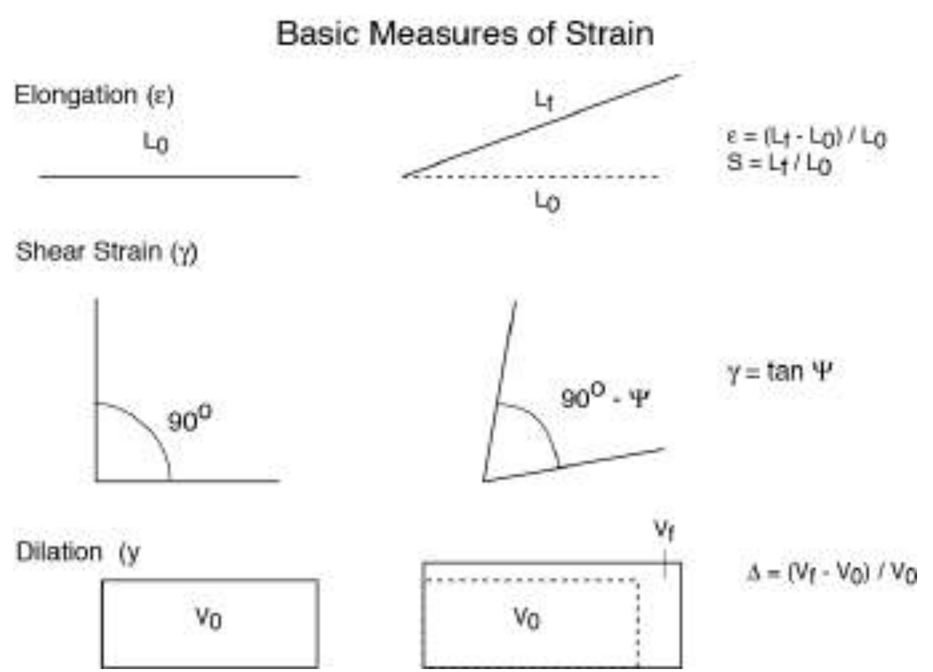
$$\sigma_{ij} = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix}$$

3-D components

Strain

- Strain—changes in the shape or size of a rock body caused by stress
- Strained bodies lose their original configuration during deformation
- Normal strain (ε): change in relative line length
- Shear strain (γ): change in angle between originally perpendicular lines
- Volumetric strain (Δ): change in relative volume
- Strains are dimensionless





Calculate strain from the Trilobite fossil

Rheology

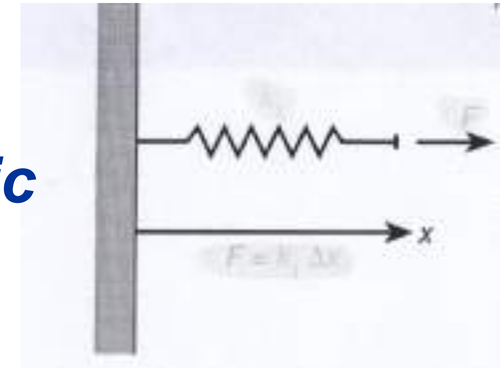
Different materials deform differently under the same state of stress. The material response to a stress is known as rheology.

Ideal materials fall into one of the following categories:

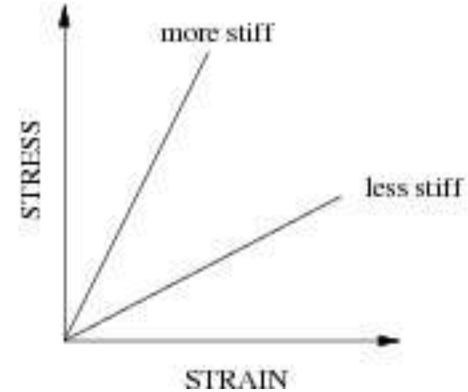
- ***Elasticity.***
- ***Viscosity.***
- ***Plasticity.***

Mechanical analogues | *Stress-Strain relations*

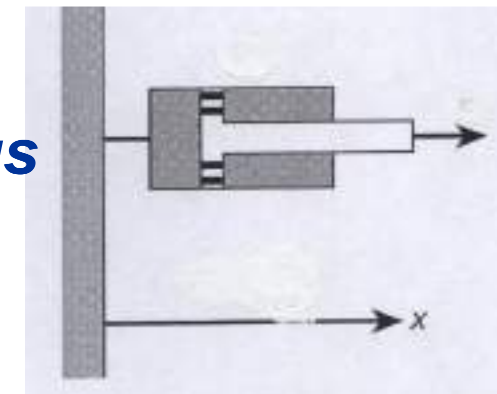
Elastic



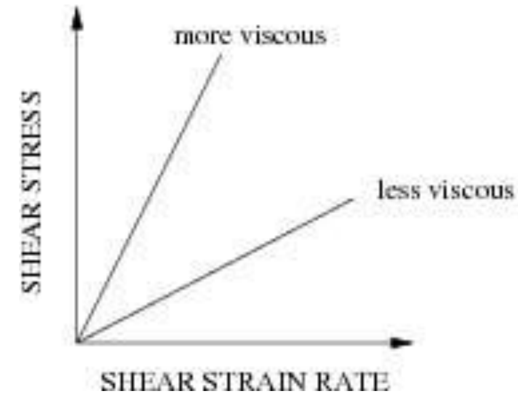
$$\sigma = C\varepsilon$$



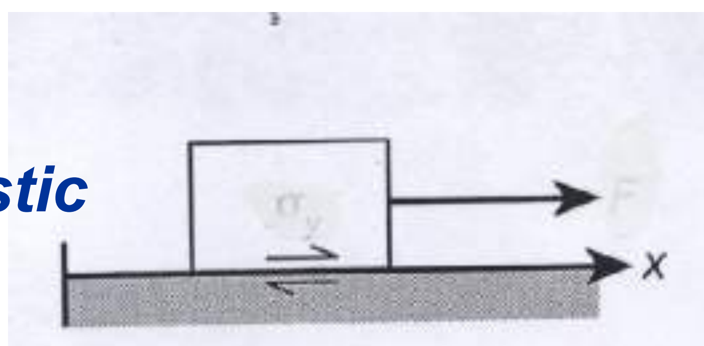
Viscous



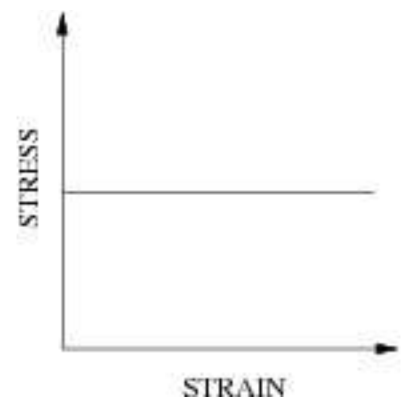
$$\sigma_s = \eta \frac{d\varepsilon_s}{dt}$$



Plastic



$$\text{slip} = 0 \text{ if}$$
$$\sigma_s < \mu\sigma_n$$



Recoverable versus permanent:

The deformation is **recoverable** if the material returns to its initial shape when the stress is removed.

Deformation is **permanent** if the material remains deformed when the stress is removed.

While elastic deformation is recoverable, viscous and plastic deformations are not.

Real materials exhibit a variety of behaviors:

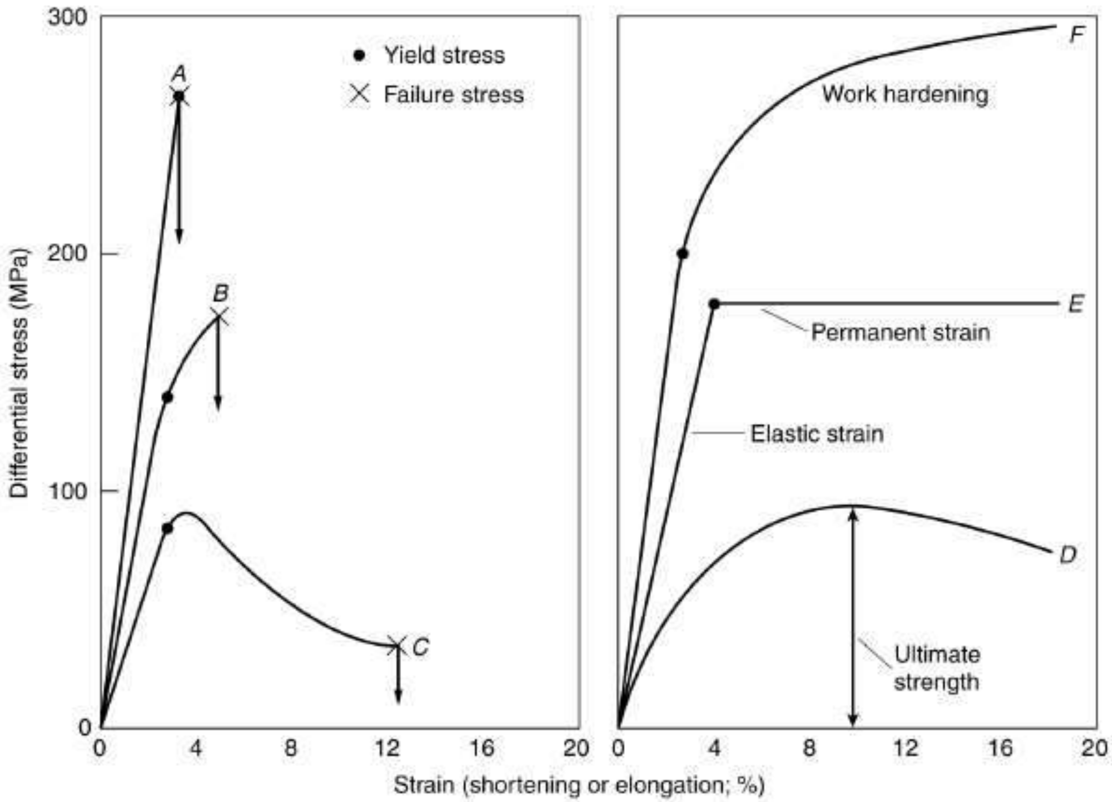
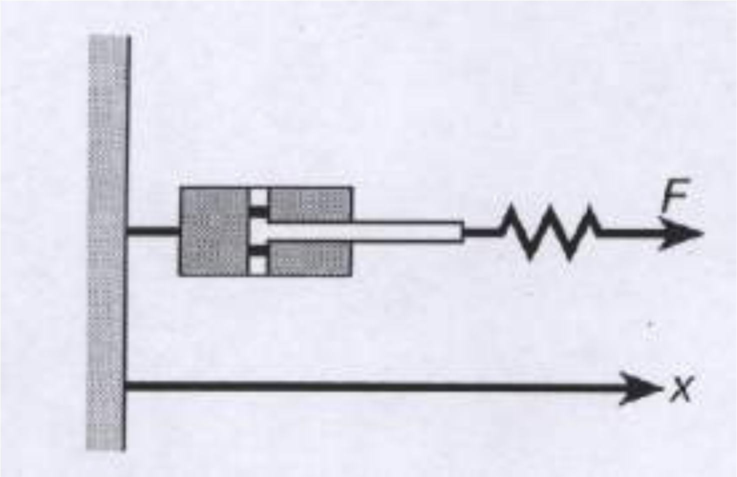


FIGURE 5.18 Representative stress–strain curves of brittle (*A* and *B*), brittle-ductile (*C*), and ductile behavior (*D*–*F*). *A* shows elastic behavior followed immediately by failure, which represents brittle behavior. In *B*, a small viscous component (permanent strain) is present before brittle failure. In *C*, a considerable amount of permanent strain accumulates before the material fails, which represents transitional behavior between brittle and ductile. *D* displays no elastic component and work softening. *E* represents ideal elastic-plastic behavior, in which permanent strain accumulates at constant stress above the yield stress. *F* shows the typical behavior seen in many of the experiments, which displays a component of elastic strain followed by permanent strain that requires increasingly higher stresses to accumulate (work hardening). The yield stress marks the stress at the change from elastic (recoverable or nonpermanent strain) to viscous (non-recoverable or permanent strain) behavior; failure stress is the stress at fracturing.

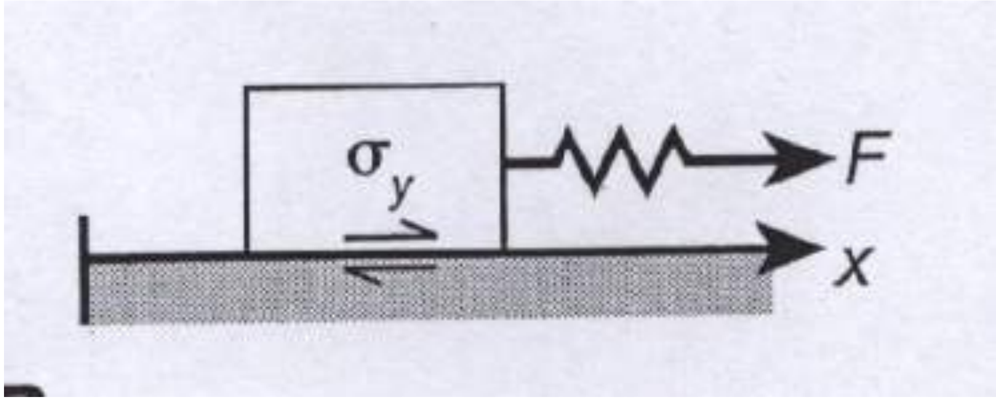
from ic.ucsc.edu/~casey/eart150

The behavior of real materials is better described by combining simple models in series or parallel. For example:

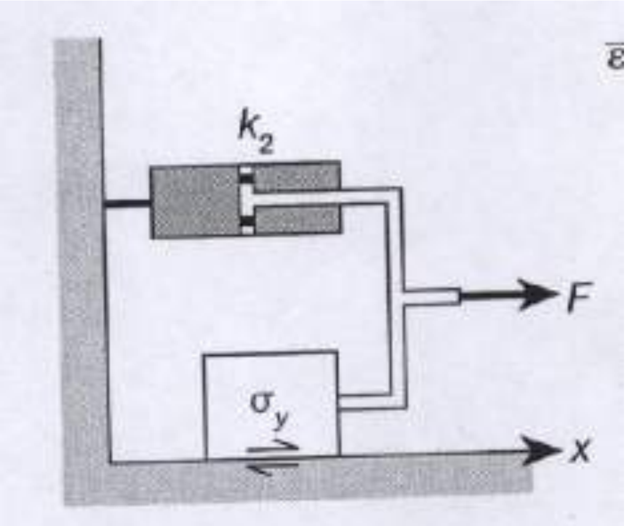
A visco-elastic (or Maxwell) solid:



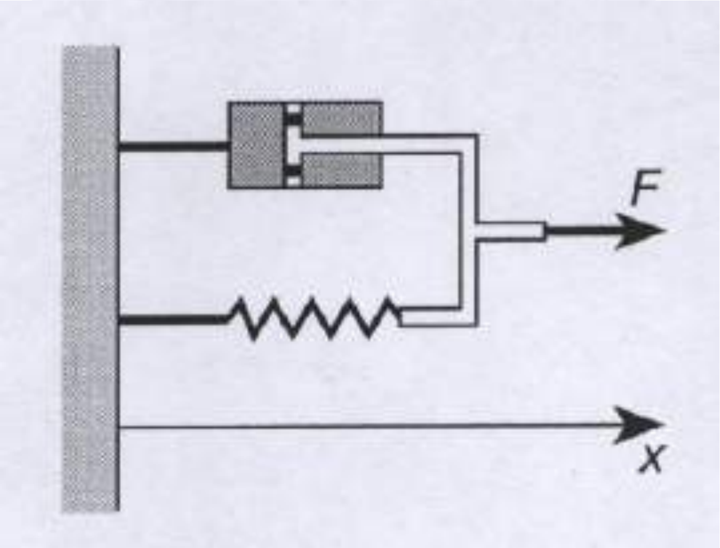
An elasto-plastic (Prandtl) material:



A visco-plastic (or Bingham) material:



A firmo-viscous (Kelvin or Voight) material:



It turns out that rocks subjected to small strains (seismic waves, slip on faults, etc.) behave as linear elastic materials.

Elasticity
:

The one-dimensional stress-strain relationship may be written as:

$$\sigma = C\varepsilon^{n}$$

where C is an elastic constant.

Note that:

- ***The response is instantaneous.***
- ***Here the strain is the infinitesimal strain.***

The material is said to be linear elastic if n=1.

Hooke's law:

$$\sigma = C\varepsilon$$

In three dimensions, Hooke's law is written as:

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl}$$

where C_{ijkl} is a matrix whose entries are the stiffness coefficients.

It thus seems that one needs 81(!) constants in order to describe the stress strain relations.

$$\sigma_{11} = C_{1111}\varepsilon_{11} + C_{1112}\varepsilon_{12} + C_{1113}\varepsilon_{13} + C_{1121}\varepsilon_{21} + C_{1122}\varepsilon_{22} + C_{1123}\varepsilon_{23} + C_{1131}\varepsilon_{31} + C_{1132}\varepsilon_{32} + C_{1133}\varepsilon_{33}$$
$$\sigma_{12} = C_{1211}\varepsilon_{11} + C_{1212}\varepsilon_{12} + C_{1213}\varepsilon_{13} + C_{1221}\varepsilon_{21} + C_{1222}\varepsilon_{22} + C_{1223}\varepsilon_{23} + C_{1231}\varepsilon_{31} + C_{1232}\varepsilon_{32} + C_{1233}\varepsilon_{33}$$
$$\sigma_{13} = C_{1311}\varepsilon_{11} + C_{1312}\varepsilon_{12} + C_{1313}\varepsilon_{13} + C_{1321}\varepsilon_{21} + C_{1322}\varepsilon_{22} + C_{1323}\varepsilon_{23} + C_{1331}\varepsilon_{31} + C_{1332}\varepsilon_{32} + C_{1333}\varepsilon_{33}$$
$$\sigma_{21} = C_{2111}\varepsilon_{11} + C_{2112}\varepsilon_{12} + C_{2113}\varepsilon_{13} + C_{2121}\varepsilon_{21} + C_{2122}\varepsilon_{22} + C_{2123}\varepsilon_{23} + C_{2131}\varepsilon_{31} + C_{2132}\varepsilon_{32} + C_{2133}\varepsilon_{33}$$
$$\sigma_{22} = C_{2211}\varepsilon_{11} + C_{2212}\varepsilon_{12} + C_{2213}\varepsilon_{13} + C_{2221}\varepsilon_{21} + C_{2222}\varepsilon_{22} + C_{2223}\varepsilon_{23} + C_{2231}\varepsilon_{31} + C_{2232}\varepsilon_{32} + C_{2233}\varepsilon_{33}$$
$$\sigma_{23} = C_{2311}\varepsilon_{11} + C_{2312}\varepsilon_{12} + C_{2313}\varepsilon_{13} + C_{2321}\varepsilon_{21} + C_{2322}\varepsilon_{22} + C_{2323}\varepsilon_{23} + C_{2331}\varepsilon_{31} + C_{2332}\varepsilon_{32} + C_{2333}\varepsilon_{33}$$
$$\sigma_{31} = C_{3111}\varepsilon_{11} + C_{3112}\varepsilon_{12} + C_{3113}\varepsilon_{13} + C_{3121}\varepsilon_{21} + C_{3122}\varepsilon_{22} + C_{3123}\varepsilon_{23} + C_{3131}\varepsilon_{31} + C_{3132}\varepsilon_{32} + C_{3133}\varepsilon_{33}$$
$$\sigma_{32} = C_{3211}\varepsilon_{11} + C_{3212}\varepsilon_{12} + C_{3213}\varepsilon_{13} + C_{3221}\varepsilon_{21} + C_{3222}\varepsilon_{22} + C_{3223}\varepsilon_{23} + C_{3231}\varepsilon_{31} + C_{3232}\varepsilon_{32} + C_{3233}\varepsilon_{33}$$
$$\sigma_{33} = C_{3311}\varepsilon_{11} + C_{3312}\varepsilon_{12} + C_{3313}\varepsilon_{13} + C_{3321}\varepsilon_{21} + C_{3322}\varepsilon_{22} + C_{3323}\varepsilon_{23} + C_{3331}\varepsilon_{31} + C_{3332}\varepsilon_{32} + C_{3333}\varepsilon_{33}$$

Thanks to the <u>symmetry of the stress tensor</u>, the number of independent elastic constants is reduced to 54.

$$\sigma_{11} = C_{1111}\varepsilon_{11} + C_{1112}\varepsilon_{12} + C_{1113}\varepsilon_{13} + C_{1121}\varepsilon_{21} + C_{1122}\varepsilon_{22} + C_{1123}\varepsilon_{23} + C_{1131}\varepsilon_{31} + C_{1132}\varepsilon_{32} + C_{1133}\varepsilon_{33}$$
$$\sigma_{22} = C_{2211}\varepsilon_{11} + C_{2212}\varepsilon_{12} + C_{2213}\varepsilon_{13} + C_{2221}\varepsilon_{21} + C_{2222}\varepsilon_{22} + C_{2223}\varepsilon_{23} + C_{2231}\varepsilon_{31} + C_{2232}\varepsilon_{32} + C_{2233}\varepsilon_{33}$$
$$\sigma_{33} = C_{3311}\varepsilon_{11} + C_{3312}\varepsilon_{12} + C_{3313}\varepsilon_{13} + C_{3321}\varepsilon_{21} + C_{3322}\varepsilon_{22} + C_{3323}\varepsilon_{23} + C_{3331}\varepsilon_{31} + C_{3332}\varepsilon_{32} + C_{3333}\varepsilon_{33}$$
$$\sigma_{12} = C_{1211}\varepsilon_{11} + C_{1212}\varepsilon_{12} + C_{1213}\varepsilon_{13} + C_{1221}\varepsilon_{21} + C_{1222}\varepsilon_{22} + C_{1223}\varepsilon_{23} + C_{1231}\varepsilon_{31} + C_{1232}\varepsilon_{32} + C_{1233}\varepsilon_{33}$$
$$\sigma_{13} = C_{1311}\varepsilon_{11} + C_{1312}\varepsilon_{12} + C_{1313}\varepsilon_{13} + C_{1321}\varepsilon_{21} + C_{1322}\varepsilon_{22} + C_{1323}\varepsilon_{23} + C_{1331}\varepsilon_{31} + C_{1332}\varepsilon_{32} + C_{1333}\varepsilon_{33}$$
$$\sigma_{23} = C_{2311}\varepsilon_{11} + C_{2312}\varepsilon_{12} + C_{2313}\varepsilon_{13} + C_{2321}\varepsilon_{21} + C_{2322}\varepsilon_{22} + C_{2323}\varepsilon_{23} + C_{2331}\varepsilon_{31} + C_{2332}\varepsilon_{32} + C_{2333}\varepsilon_{33}$$

Thanks to the <u>symmetry of the strain tensor</u>, the number of independent elastic constants is further reduced to 36.

$$\sigma_{11} = C_{1111}\varepsilon_{11} + C_{1112}\varepsilon_{12} + C_{1113}\varepsilon_{13} + C_{1122}\varepsilon_{22} + C_{1123}\varepsilon_{23} + C_{1133}\varepsilon_{33}$$
$$\sigma_{22} = C_{2211}\varepsilon_{11} + C_{2212}\varepsilon_{12} + C_{2213}\varepsilon_{13} + C_{2222}\varepsilon_{22} + C_{2223}\varepsilon_{23} + C_{2233}\varepsilon_{33}$$
$$\sigma_{33} = C_{3311}\varepsilon_{11} + C_{3312}\varepsilon_{12} + C_{3313}\varepsilon_{13} + C_{3322}\varepsilon_{22} + C_{3323}\varepsilon_{23} + C_{3333}\varepsilon_{33}$$
$$\sigma_{12} = C_{1211}\varepsilon_{11} + C_{1212}\varepsilon_{12} + C_{1213}\varepsilon_{13} + C_{1222}\varepsilon_{22} + C_{1223}\varepsilon_{23} + C_{1233}\varepsilon_{33}$$
$$\sigma_{13} = C_{1311}\varepsilon_{11} + C_{1312}\varepsilon_{12} + C_{1313}\varepsilon_{13} + C_{1322}\varepsilon_{22} + C_{1323}\varepsilon_{23} + C_{1333}\varepsilon_{33}$$
$$\sigma_{23} = C_{2311}\varepsilon_{11} + C_{2312}\varepsilon_{12} + C_{2313}\varepsilon_{13} + C_{2322}\varepsilon_{22} + C_{2323}\varepsilon_{23} + C_{2333}\varepsilon_{33}$$

The following formalism is convenient for problems in which the strains components are known and the stress components are the dependent variables:

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl}$$

In cases where the strain components are the dependent parameters, it is more convenient to use the following formalism:

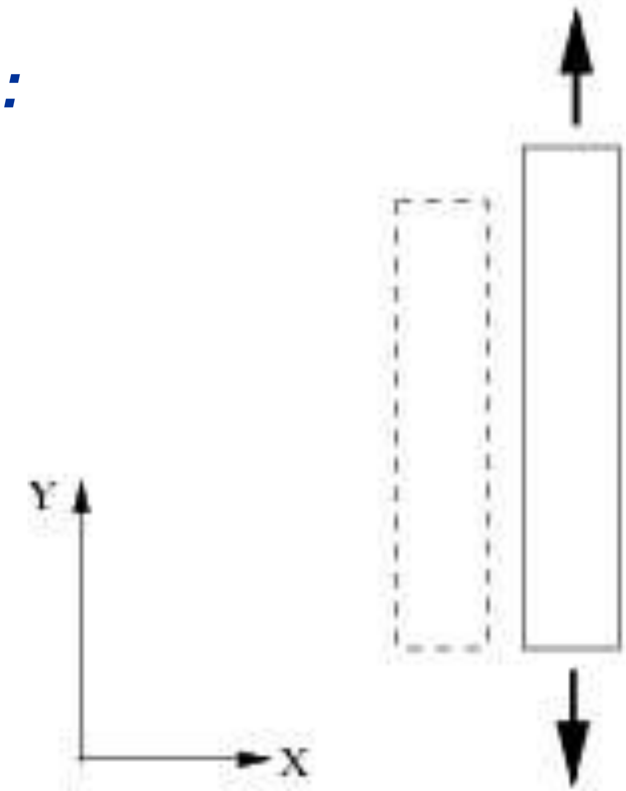
$$\varepsilon_{ij} = S_{ijkl}\sigma_{kl}$$

Where S_{ijkl} is a matrix whose entries are the compliance coefficients.

The case of isotropic materials:

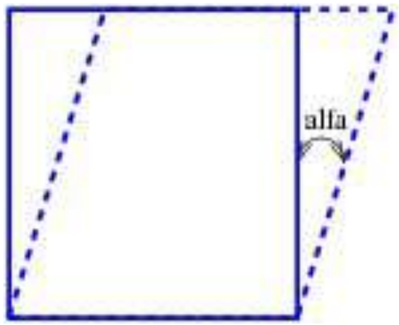
- *A material is said to be **isotropic** if its properties are independent of direction.*
- *In that case, the number of non-zero stiffnesses (or compliances) is reduced to 12, all are a function of only 2 elastic constants.*

Young modulus:



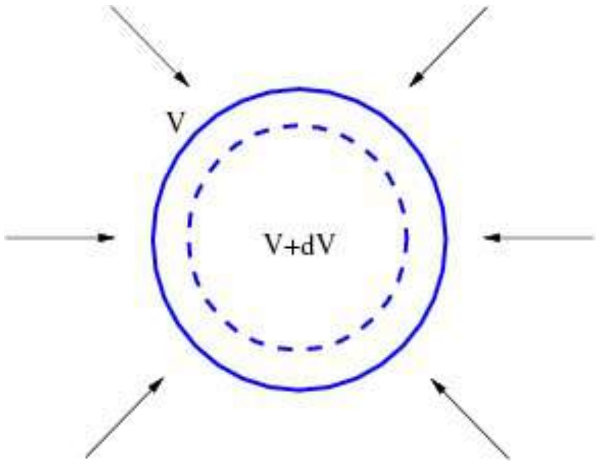
$$E = \frac{\sigma_y}{\varepsilon_y}$$

Shear modulus (rigidity):



$$G = \frac{\text{shear stress}}{\text{shear strain}}$$

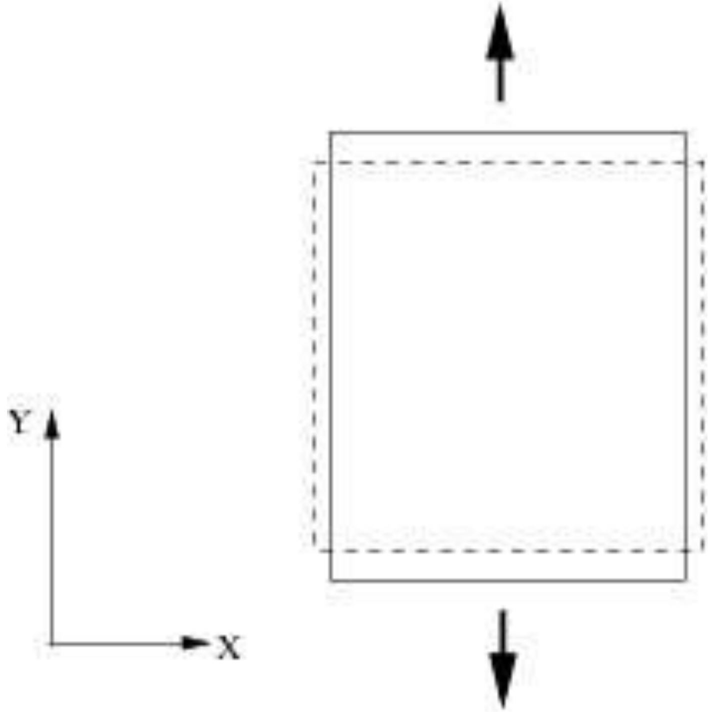
Bulk modulus (compressibility):



$$K = \frac{\text{pressure}}{\text{volumetric change}}$$

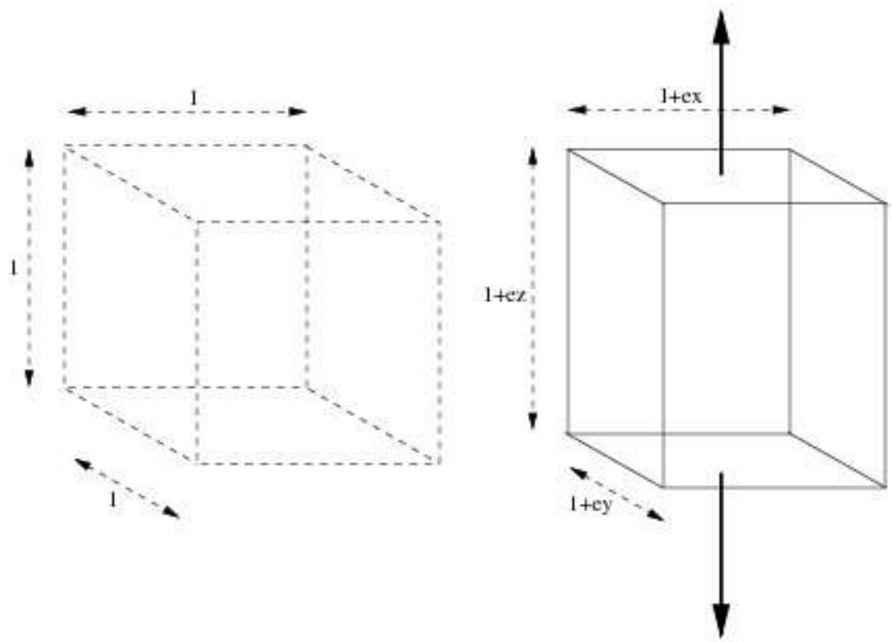
Poisson's ratio:

Poisson's ratio of incompressible isotropic materials equals 0.5:



$$\nu = -\frac{\varepsilon_x}{\varepsilon_y}$$

Real materials are compressible and their Poisson ratio is less than 0.5.



All elastic constants can be expressed as a function of only 2 elastic constants. Here is a conversion table:

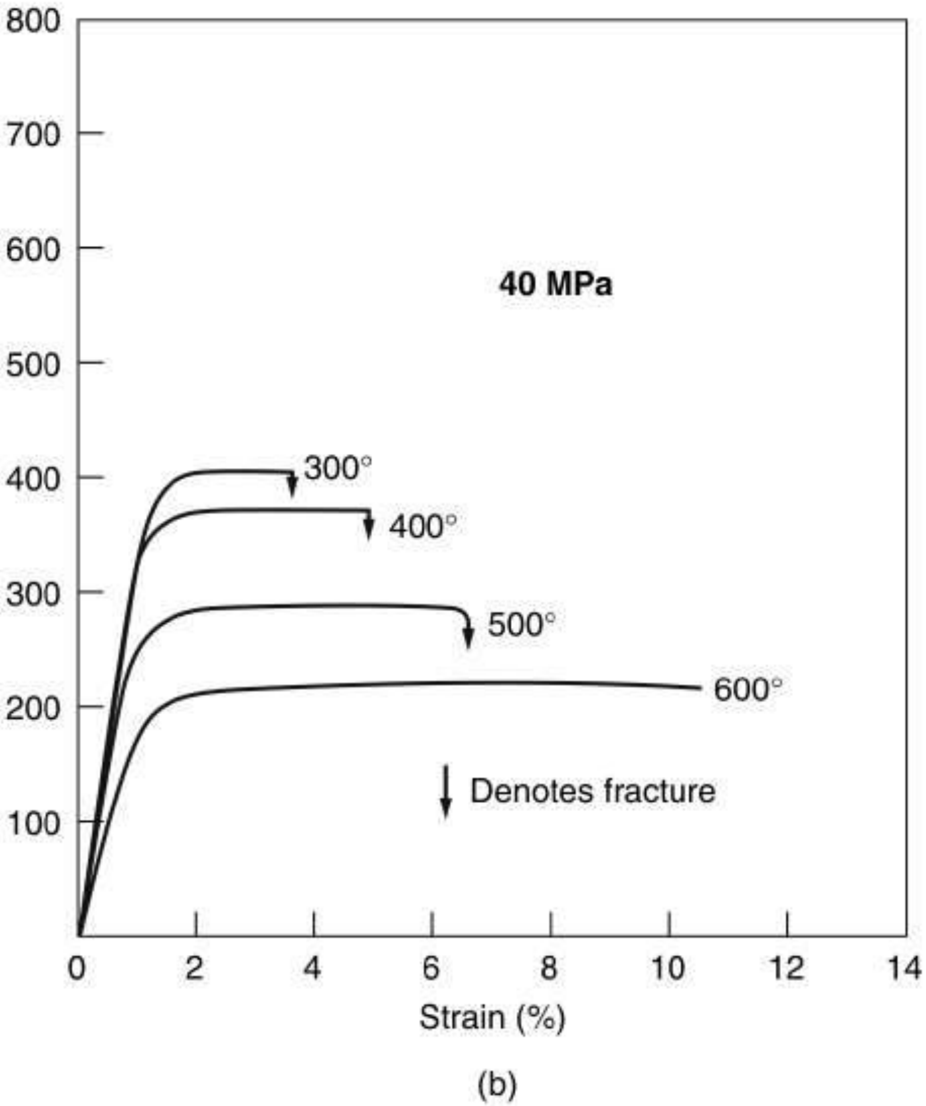
Known Elastic Constants	**E**	ν	μ	κ	λ
Shear modulus μ, Bulk modulus κ	$\frac{9\kappa\mu}{3\kappa+\mu}$	$\frac{3\kappa-2\mu}{6\kappa+2\mu}$	μ	κ	$\frac{3\kappa-2\mu}{3}$
Young's modulus E, Poisson's ratio ν	E	ν	$\frac{E}{2(1+\nu)}$	$\frac{E}{3(1-2\nu)}$	$\frac{E\nu}{(1+\nu)(1-2\nu)}$
Young's modulus E, Shear modulus μ	E	$\frac{E-2\mu}{2\mu}$	μ	$\frac{E\mu}{3(3\mu-E)}$	$\frac{\mu(E-2\mu)}{3\mu-E}$
Young's modulus E, Bulk modulus κ	E	$\frac{3\kappa-E}{6\kappa}$	$\frac{3\kappa E}{9\kappa-E}$	κ	$\frac{3\kappa(3\kappa-E)}{9\kappa-E}$
Shear modulus μ, Lame's constant λ	$\frac{\mu(3\lambda+2\mu)}{\lambda+\mu}$	$\frac{\lambda}{2(\lambda+\mu)}$	μ	$\frac{3\lambda+2\mu}{3}$	λ

How Rocks Deform

- Rocks subjected to stresses greater than their own strength (elastic limit) begin to deform by flowing or fracturing.

- General characteristics of rock deformation
  - Elastic deformation—The rock returns to nearly its original size and shape when the stress is removed.
  - Once the elastic limit (strength) of a rock is surpassed, it either flows (ductile deformation) or fractures (brittle deformation).

Triaxial experiments: Increasing temperature weakens rocks.

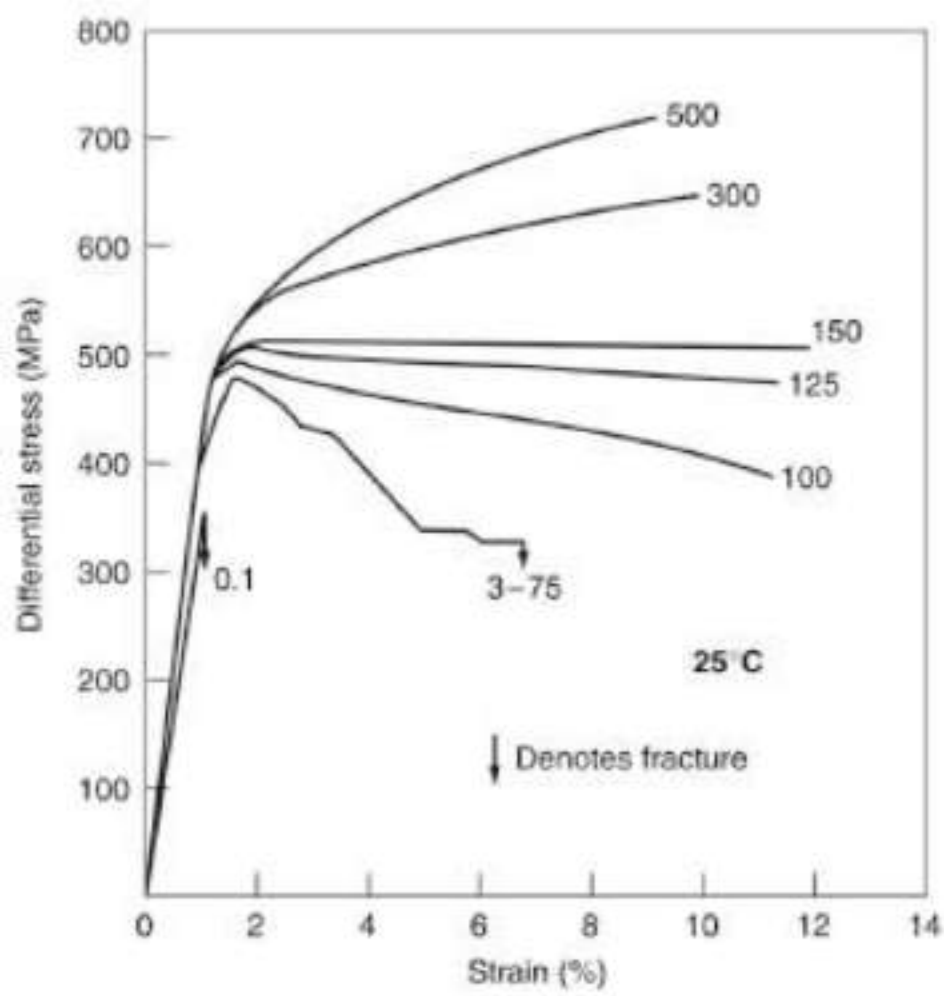


Triaxial testing machine

Weakening of fine-grained limestone with increasing temperature. Vertical axis is stress in MPa.

ic.ucsc.edu/~casey/eart150/Lectures/Rheology/13rheology.htm

Triaxial experiments: Increasing pressure strengthen rocks.



Strengthening of fine-grained limestone with increasing Pressure. Vertical axis is stress in MPa. This effect is much more pronounced at low temperatures (less than 100$^{o)}$ and diminishes at higher temperatures (greater than 100^{o})

ic.ucsc.edu/~casey/eart150/Lectures/Rheology/13rheology.htm

Triaxial experiments: In the Earth both temperature and confining pressure increase with depth and temperature overcomes strengthening effect of confining pressure resulting in generally ductile behavior at depths.

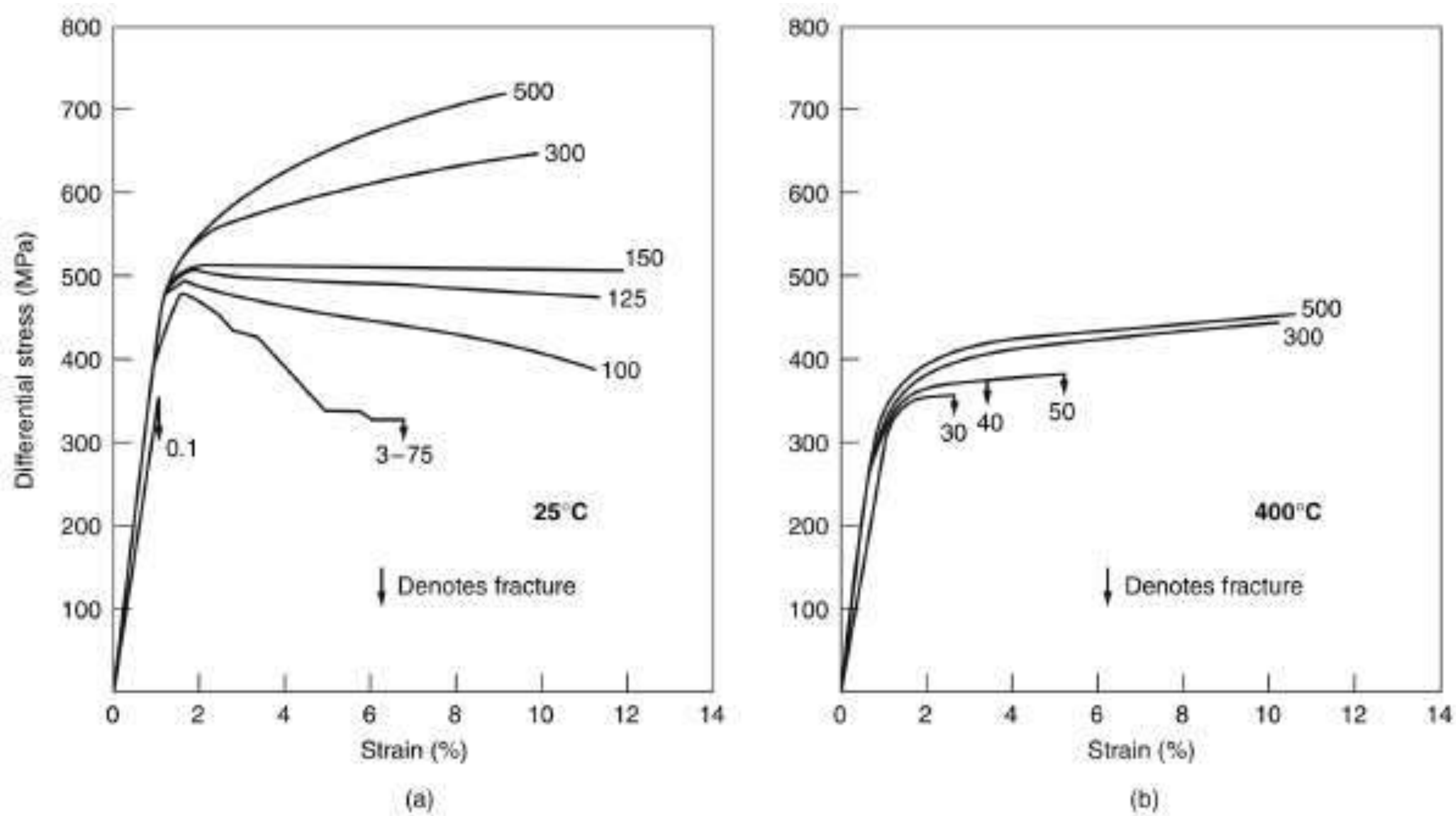
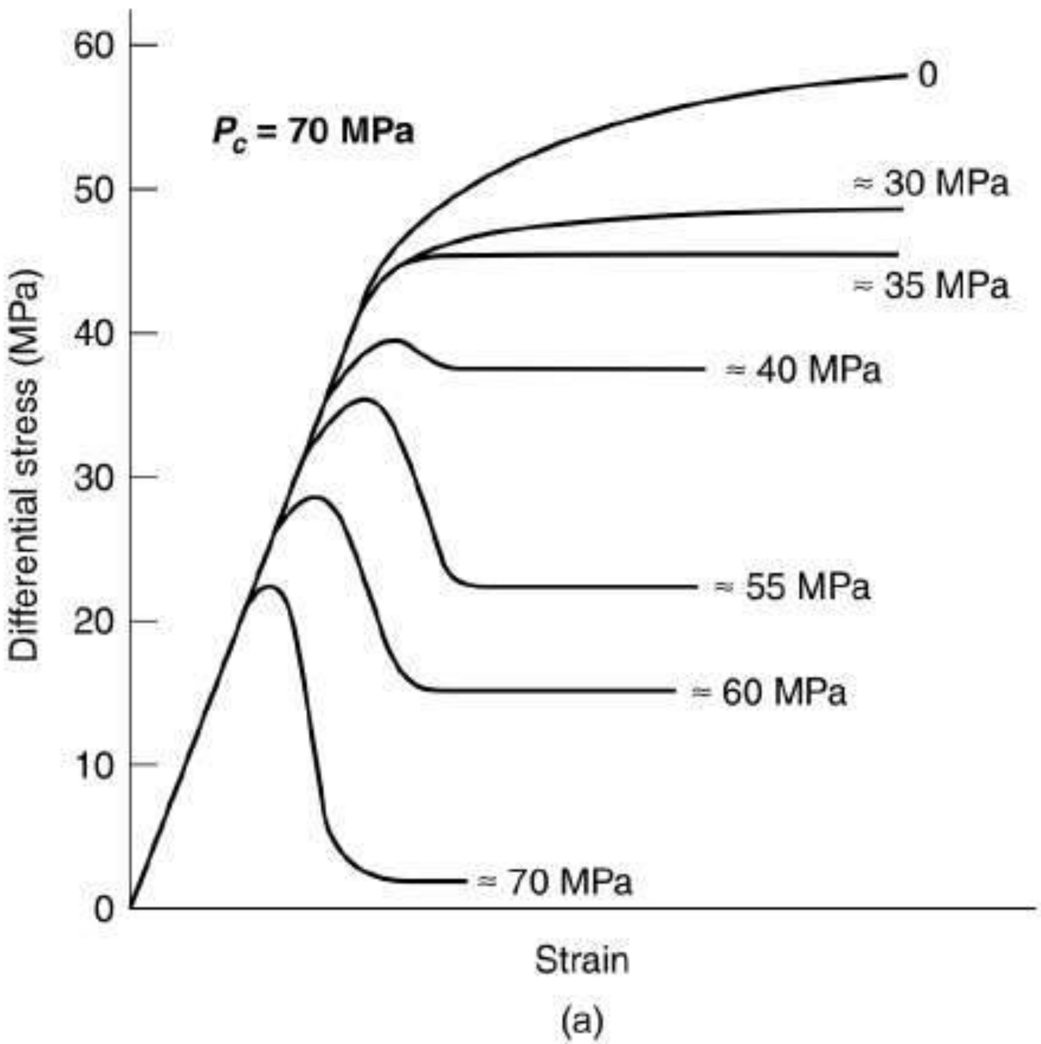


FIGURE 5.10 Compression stress–strain curves of Solnhofen limestone at various confining pressures (indicated in MPa) at (a) 25°C and (b) 400°C.

ic.ucsc.edu/~casey/eart150/Lectures/Rheology/13rheology.htm

Triaxial experiments: Pore pressure weakens rocks.



- ***Fluid pressure weakens rocks, because it reduces the effective stresses.***
- ***Water weakens rocks, by affecting bonding of materials.***

ic.ucsc.edu/~casey/eart150/Lectures/Rheology/13rheology.htm

Triaxial experiments: Rocks are weaker under lower strain rates.

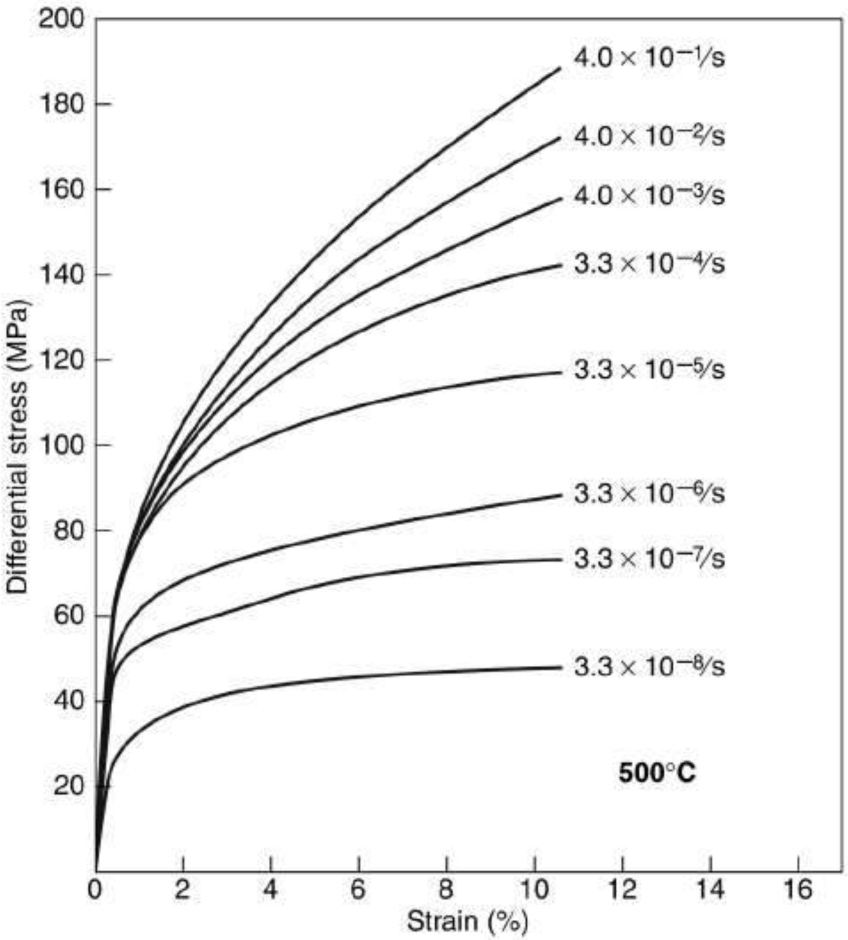
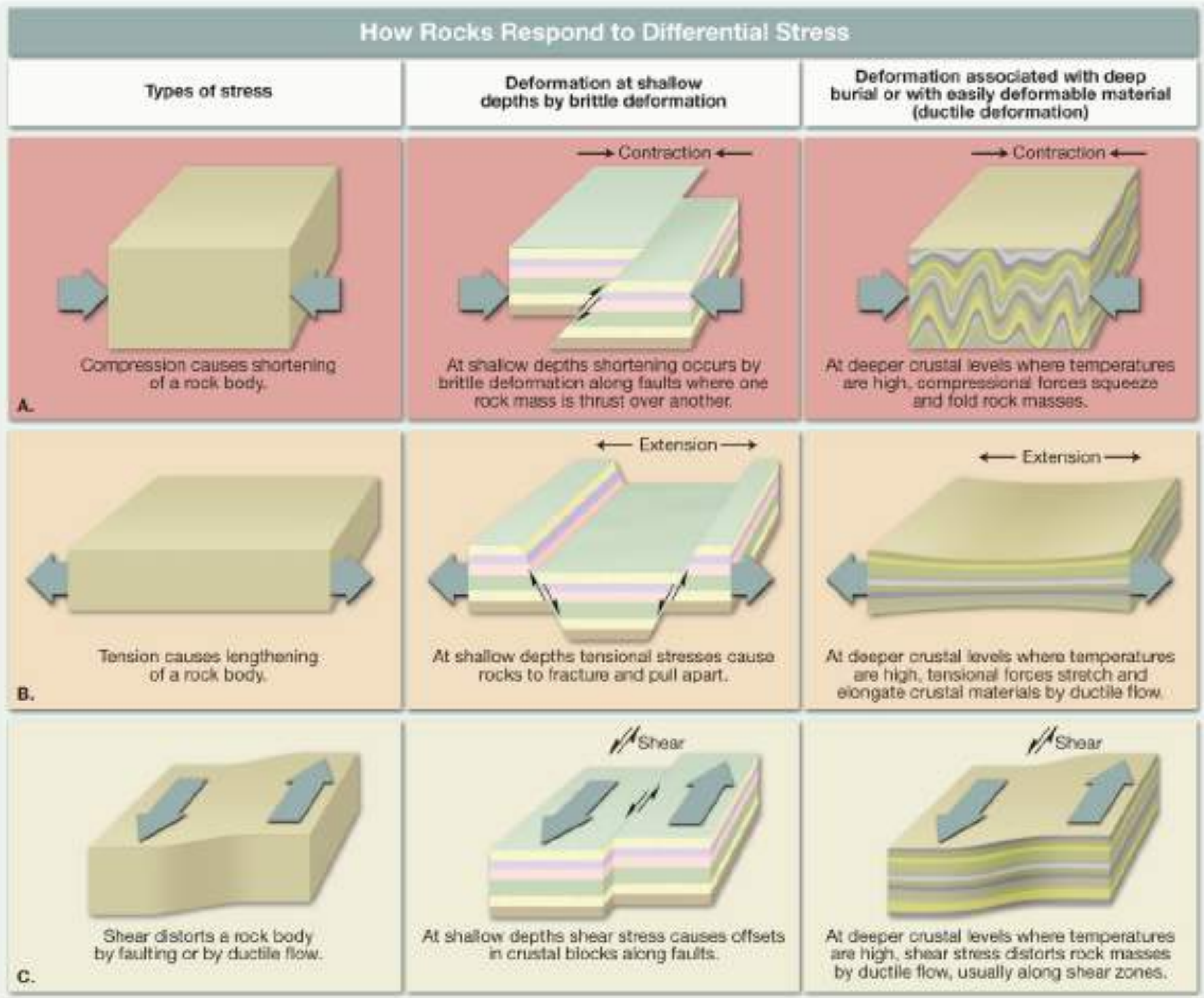


FIGURE 5.14 Stress versus strain curves for extension experiments in weakly foliated Yule marble for various constant strain rates at 500°C.

Slow deformation allows diffusional crystal-plastic processes to more closely keep up with applied stresses.

ic.ucsc.edu/~casey/eart150/Lectures/Rheology/13rheology.htm

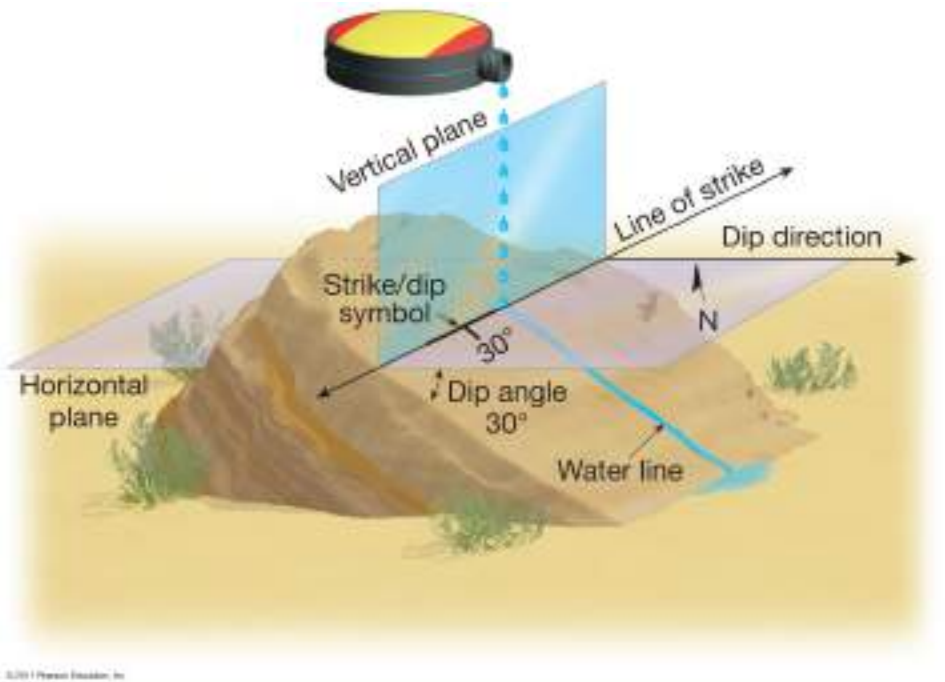
Deformation of Rocks



Mapping Geologic Structures

Describing and mapping the orientation or attitude of a rock layer involves determining the features.

- Strike (trend)
  - The compass direction of the line produced by the intersection of an inclined rock layer or fault with a horizontal plane
  - Generally expressed as an angle relative to north
- Dip (inclination)
  - The angle of inclination of the surface of a rock unit or fault measured from a horizontal plane
  - Includes both an of inclination and a direction toward which the rock is inclined.

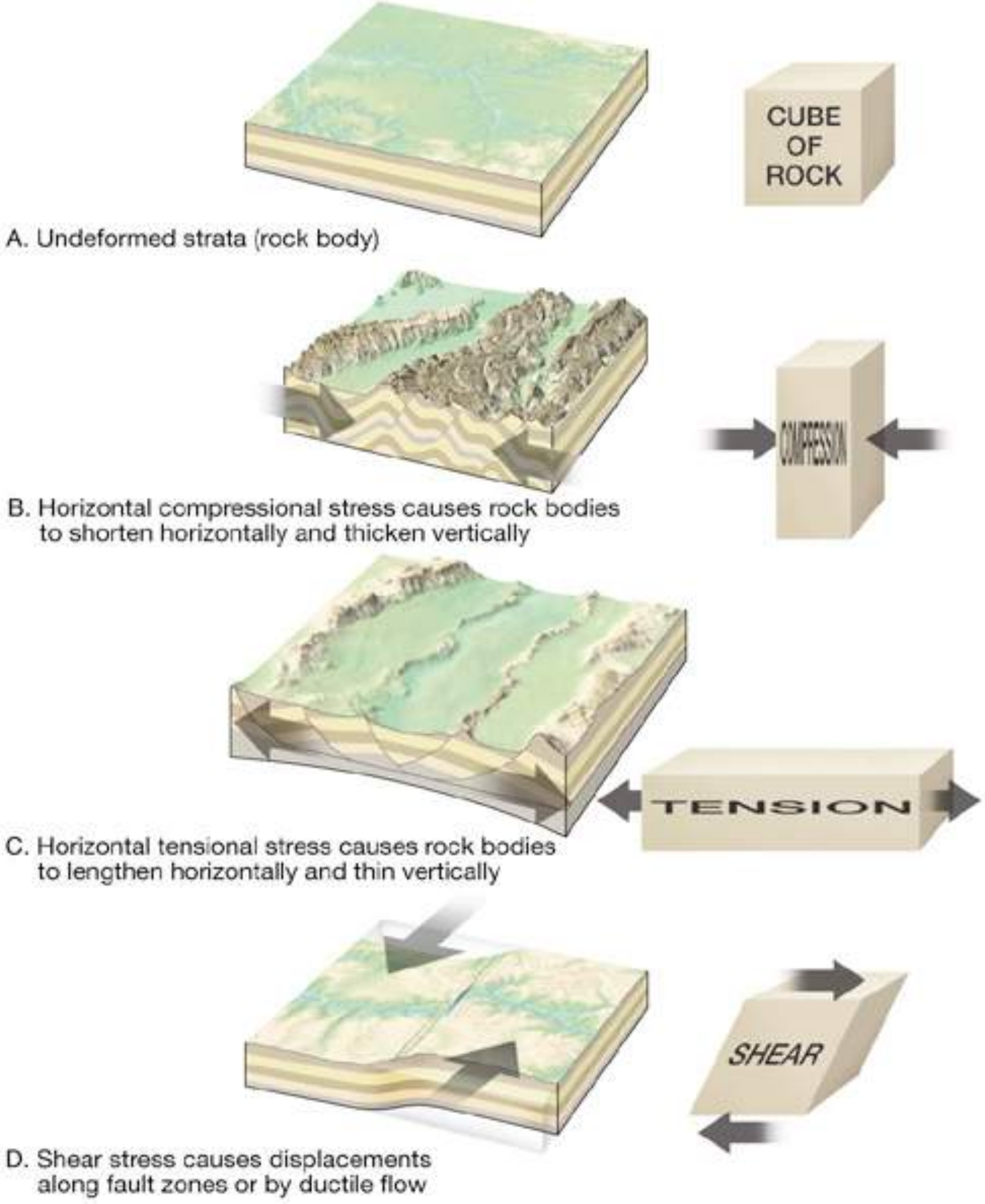


Fundamentals of Earth Sciences (ESO 213A)

Dibakar Ghosal
Department of Earth Sciences

Crustal Deformation (Fold/Fault/Joint)

Previous Class: Crustal deformation



Deformation of the Earth's Crust Caused by Tectonic Forces & Associated Stresses Resulting from the Movement of Lithospheric Plates

At least 6 factors control how rock deforms

e.g. at shallow depth a rock may fracture whereas at depth it may flow.

Factors are:

(1) rock type

(2) Confining and directed pressure

(3) temperature

(4) Fluids

(5) Time

(6) Rate of deformation

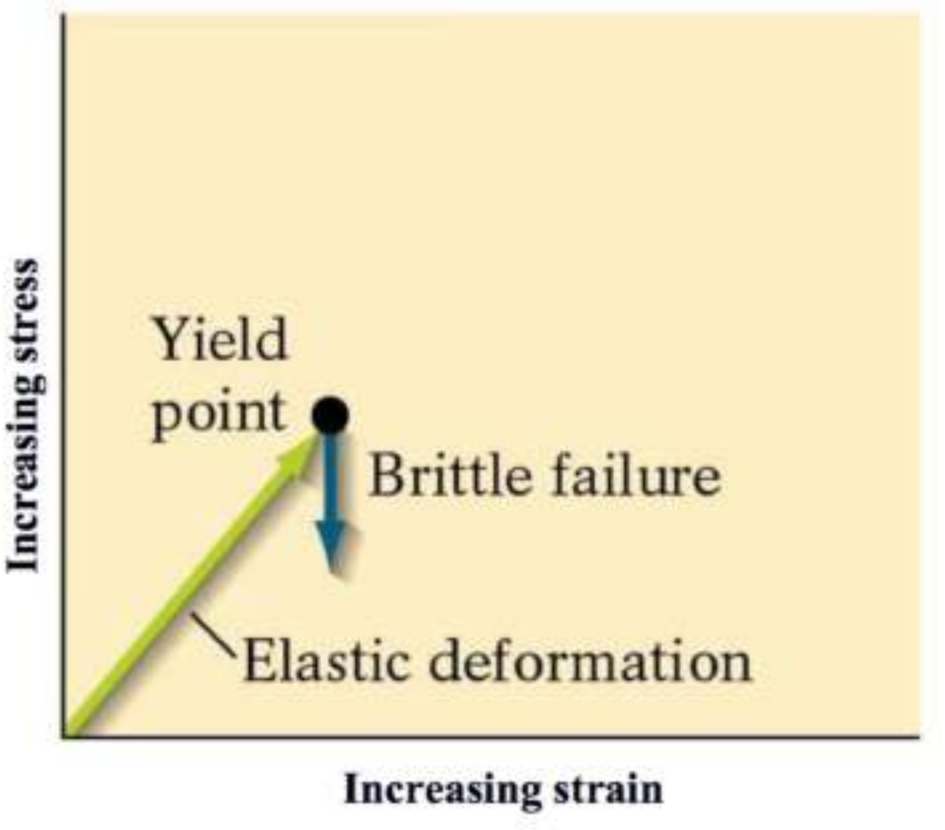
Deformation of Marble Cylinders in the Laboratory Reveals that Rocks Fracture Under Low Confining Pressure, But Flow Plastically Under Higher Pressure

Undeformed | **Low Confining Pressure** | **Moderate Confining Pressure** | **High Confining Pressure**

Types of Deformation: Elastic vs Plastic
Brittle vs Ductile

Brittle Deformation (Rupture)

•When an external force is applied to buried rocks under low confining pressure, such as near the surface of the earth, the rock typically deform by simple fracturing. This is known as **brittle** deformation.

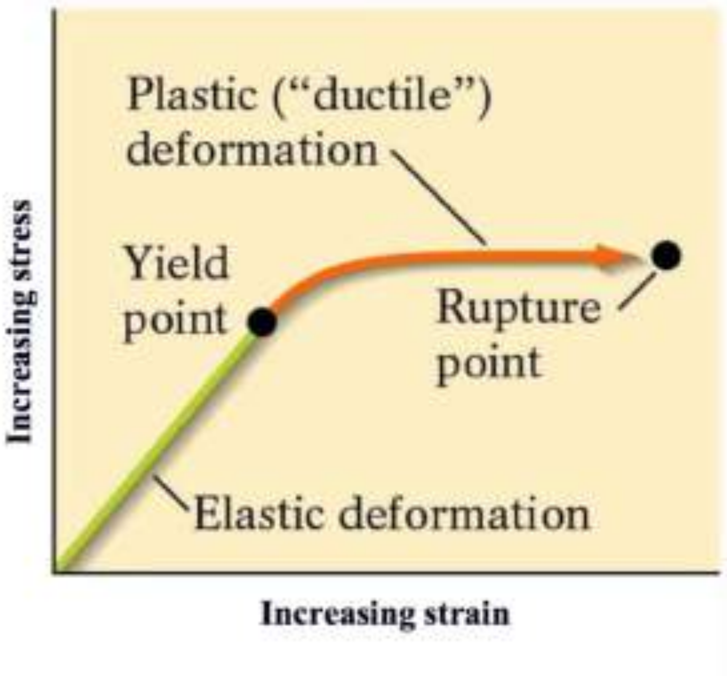


Brittle failure

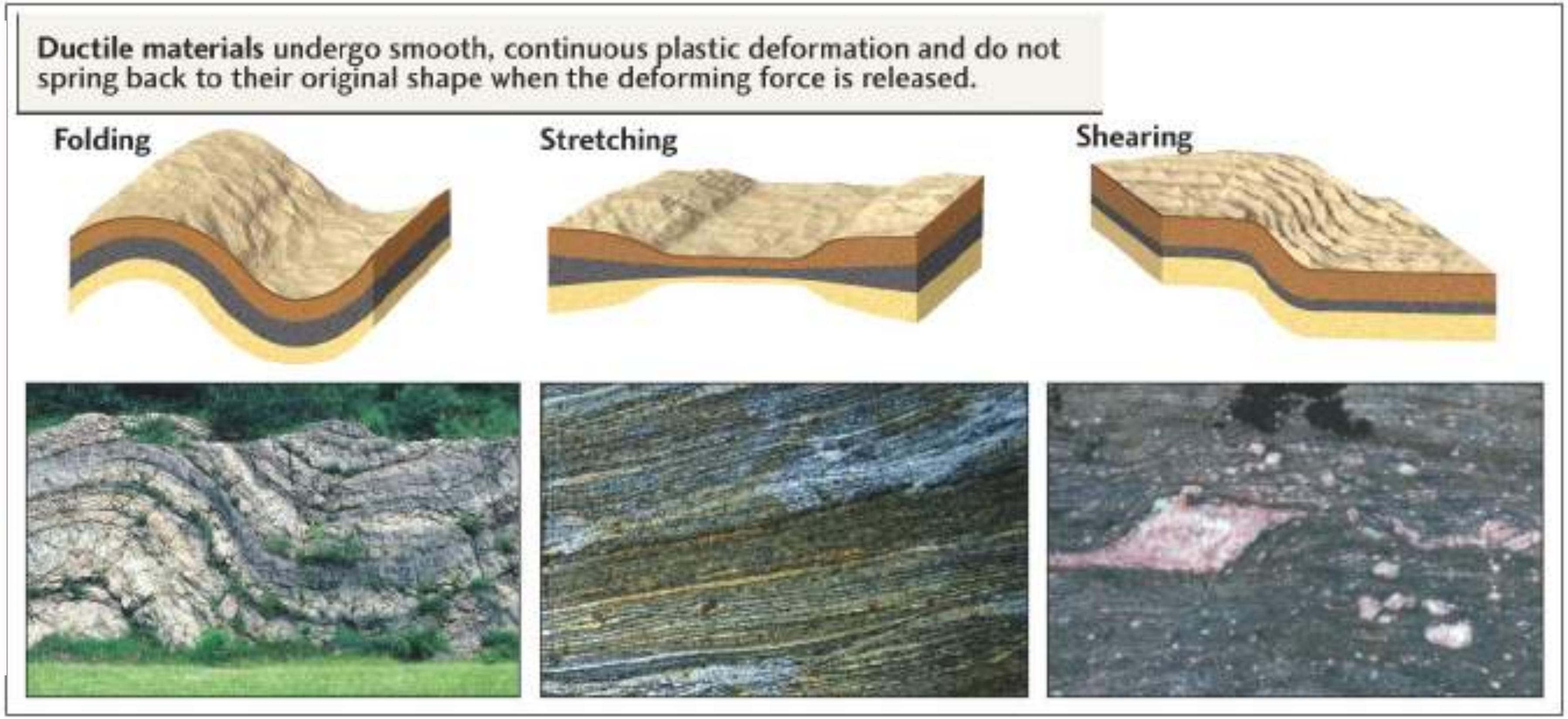
Ductile (Plastic) Deformation

•At higher confining pressures, a similarly directed external force will cause the deeply buried rock to actually flow and deform without fracturing. This is known as **ductile** deformation and the rock is said to behave **plastically**.

•Occurs by the slippage of atoms or small groups of atoms past each other in the deforming material, without loss of cohesion

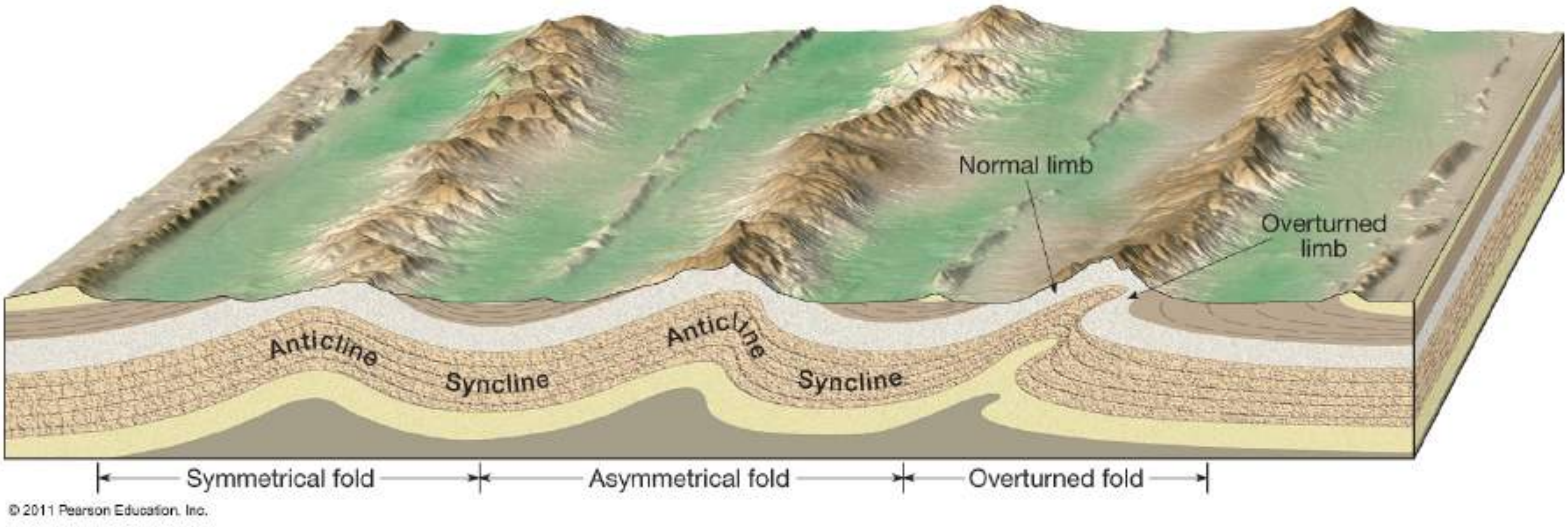


Plastic deformation

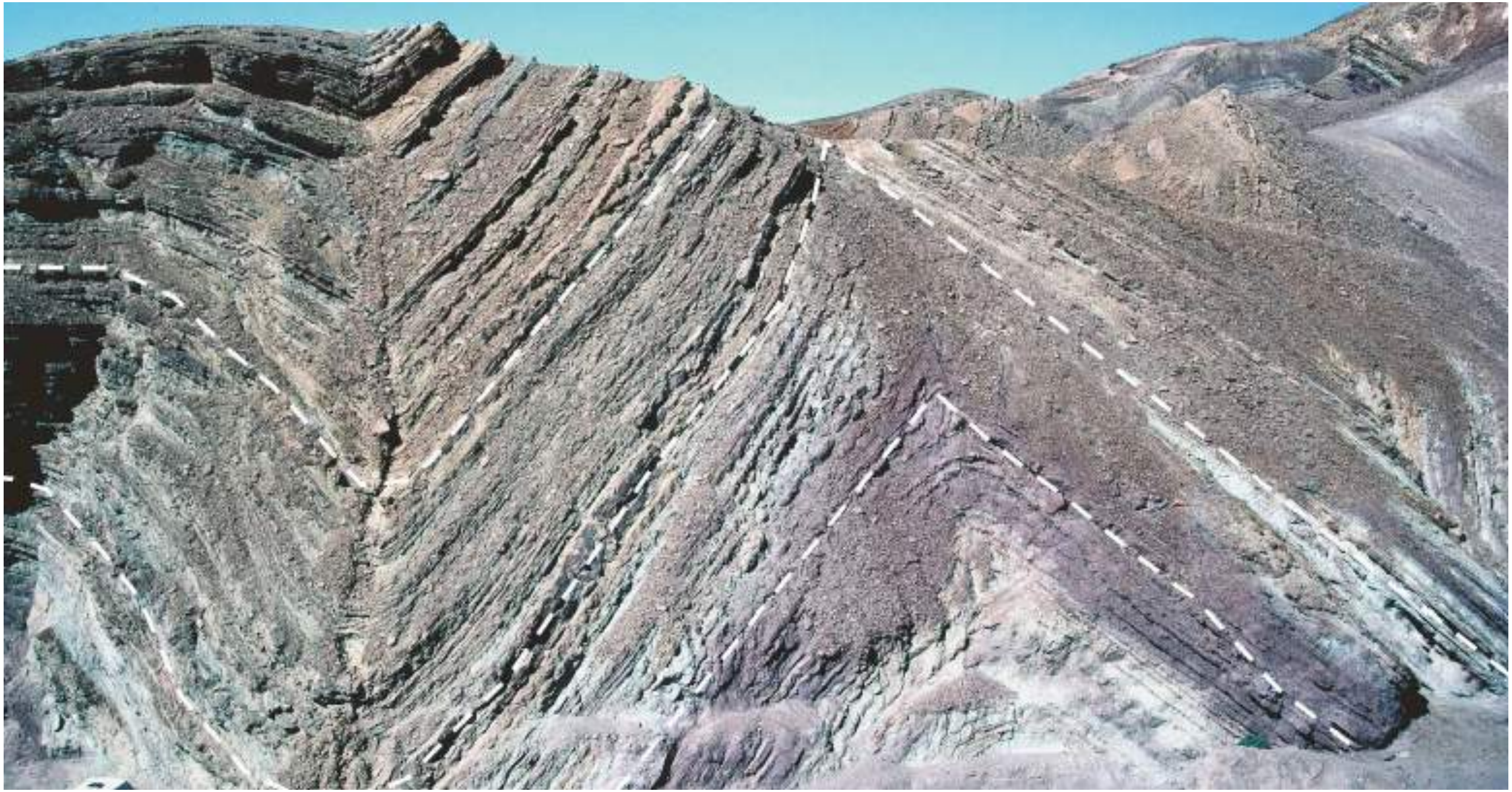


Folds (Ductile Deformation)

- **Along convergent plate boundaries, rocks are often bent into a series of wave-like undulations called folds.**
- **Characteristics of folds**
  - **Most folds result from compressional stresses that shorten and thicken the crust.**

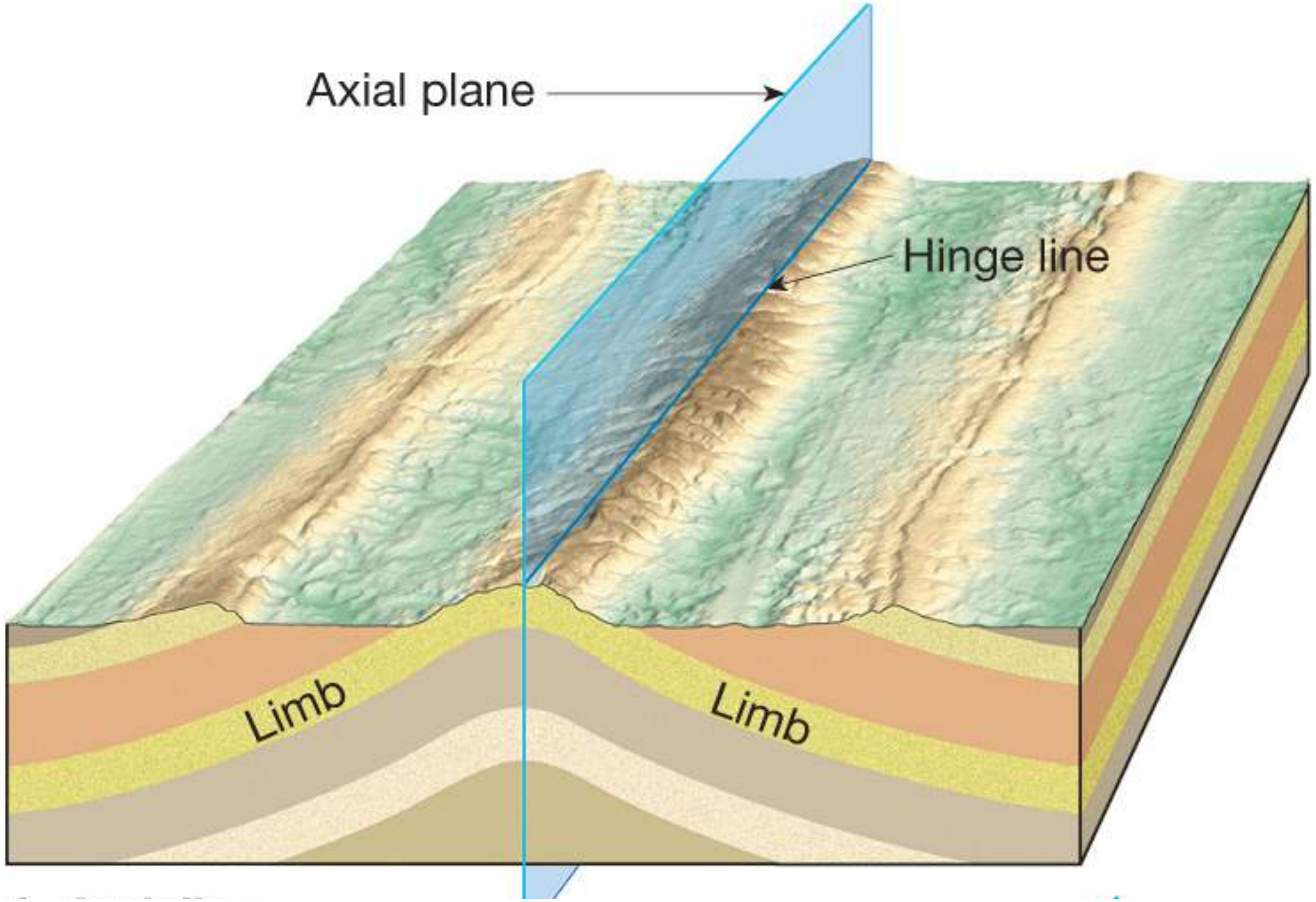


Outcrop Example of a Syncline (Left) and Anticline (Right). Note They Share a Common Limb



Characteristics of folds

- **Parts of a fold**
  - *Limbs* refer to the two sides of a fold.
  - An *axial plane* is an imaginary surface that connects all hinge lines of folded strata
  - A line drawn along the points of max curvature of each layer is the *hinge*

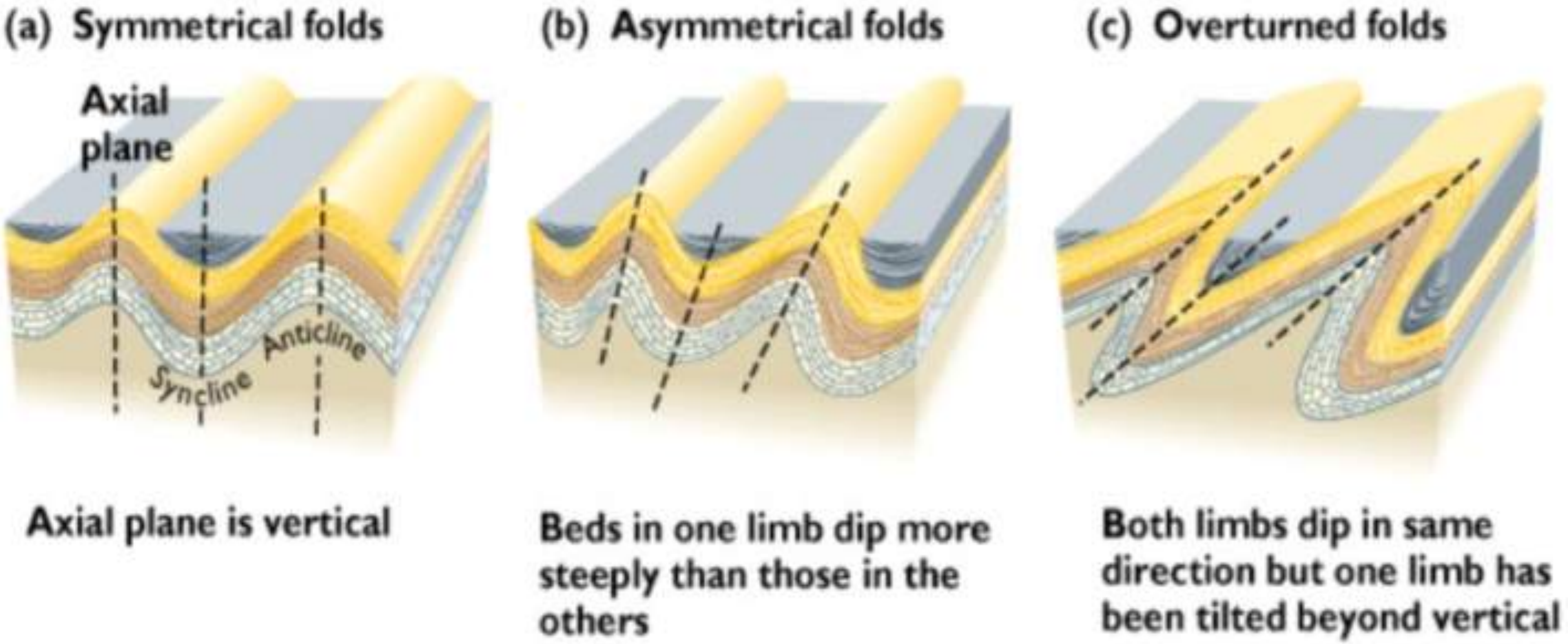


Folds

- **Common types of folds (based on age and fold closure)**
  - **1. Anticline—older rocks at core**
  - **2. Syncline—older rocks away from core**

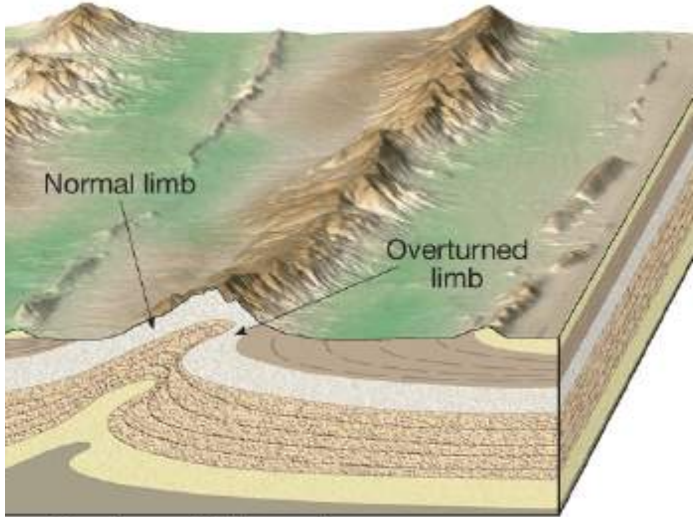
Anticlines and Synclines

- **Depending on axial plane orientation:**
  a) Symmetrical - the limbs are mirror images of each other
  b) Asymmetrical - one limb dips more steeply than the other
  c) Overturned – one or both limbs are tilted beyond vertical and limbs dip same direction and are found in areas with intense deformation



Anticlines and Synclines

Asymetric fold



Overturned fold

Anticlines and Synclines

d) Recumbent – a plane extending through the axis of the fold is horizontal (it "lies" on its side)

» **Common in highly deformed mountainous regions**

Question : This image features a large geologic structure that outcrops in Death Valley National Park, California.

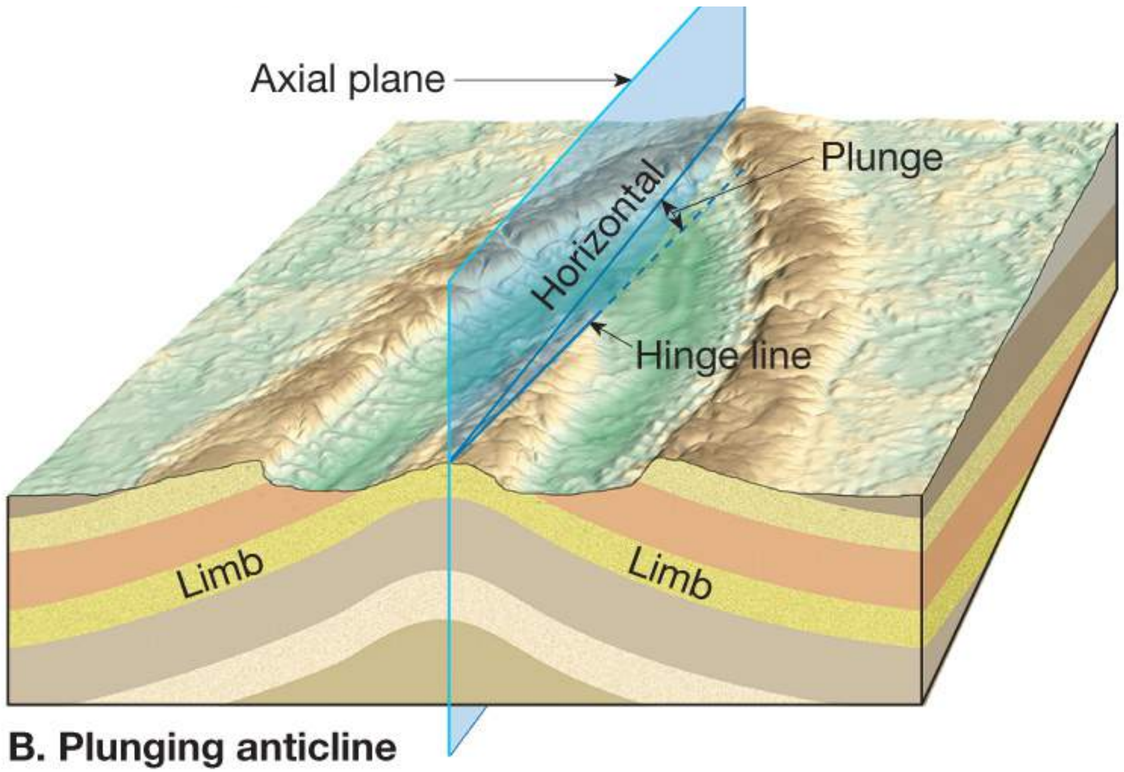
Q1: What name would you give to this geologic structure?

Q2: Based on this image, would you describe this fold as symmetrical or asymmetrical?

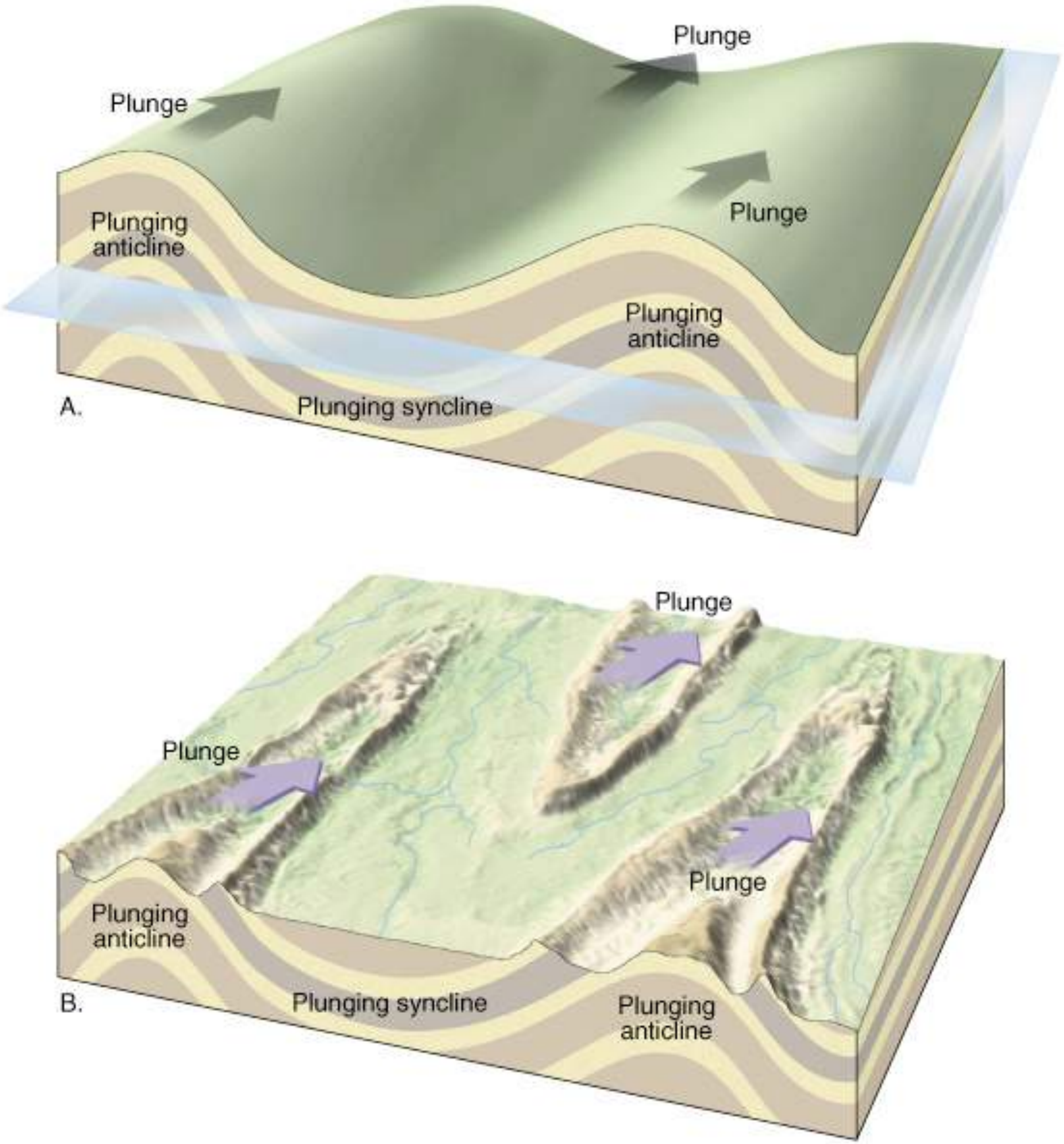
Q3: Do these rock units mainly display ductile deformation or brittle deformation?

Anticlines and Synclines

- **Depending on the fold axis:**
  - Plunging – the axis of the fold penetrates the ground



Sheep Mountain, Wyoming, A Doubly Plunging Anticline (It Dips into the Subsurface on Both Ends)



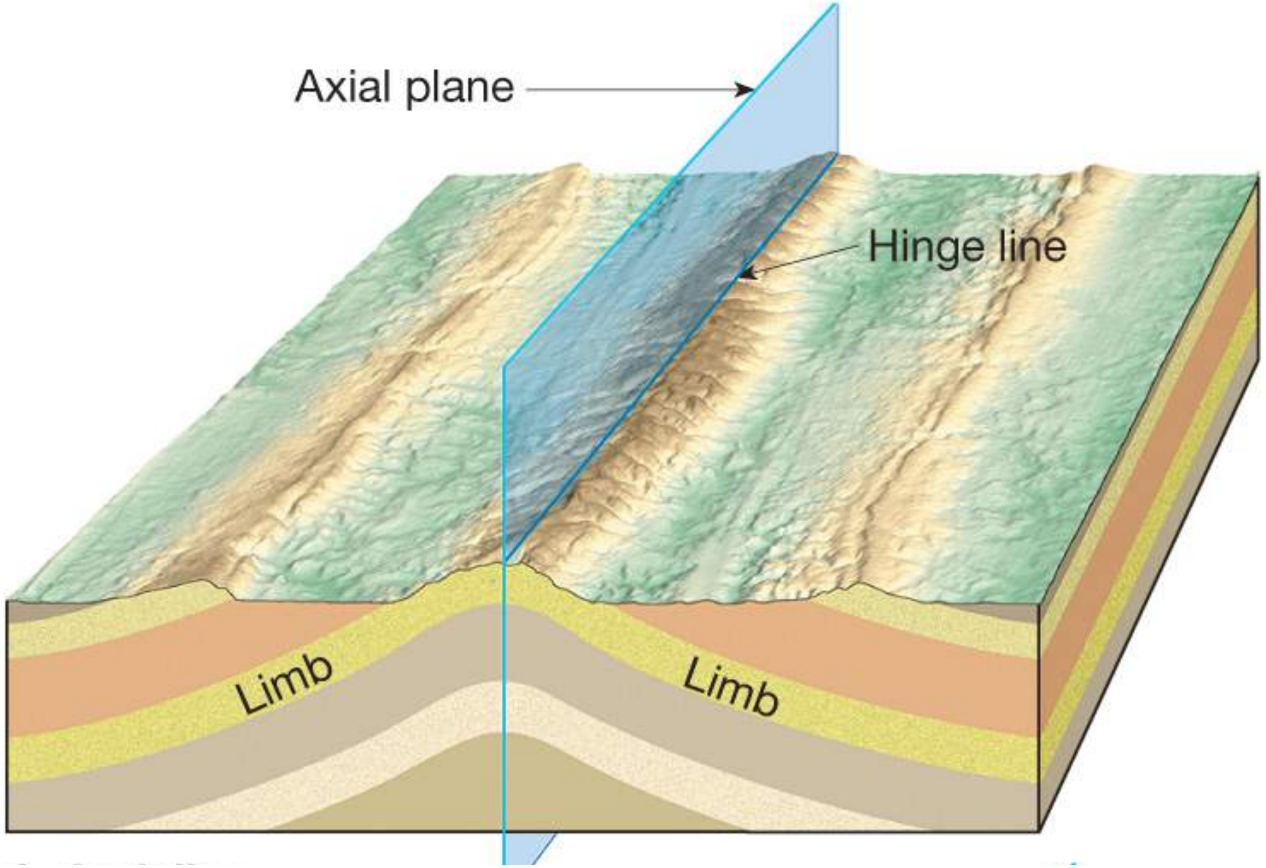
Plunging Folds

A. An Idealized View

B. What the Same Structures Would Look like on the Surface After Erosion. (Note that in Anticlines the Outcrop Points in the Direction of Plunge, in Synclines it Points Opposite to Plunge)

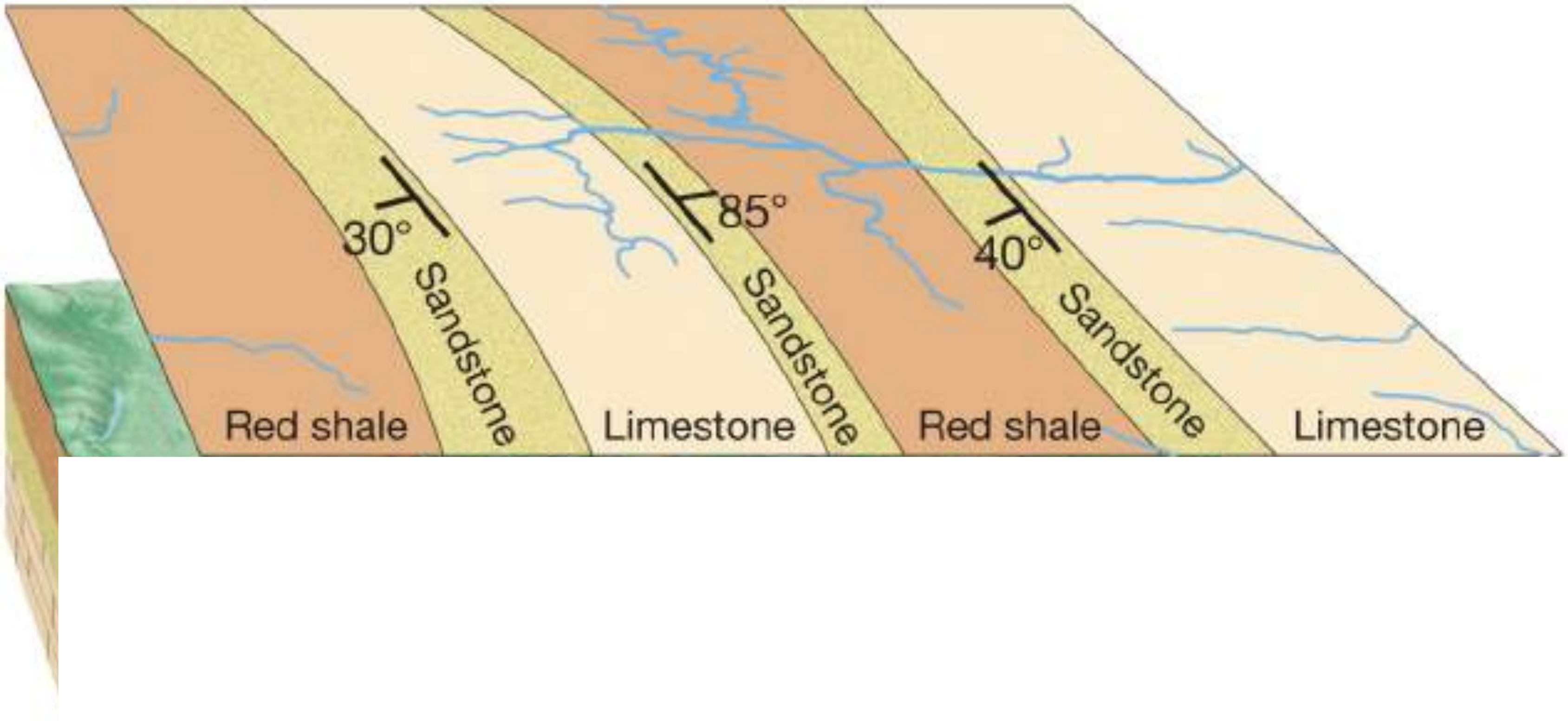
Anticlines and Synclines

- **Depending on the fold axis:**
  - **Non-plunging – the axis of the fold is horizontal**



Question

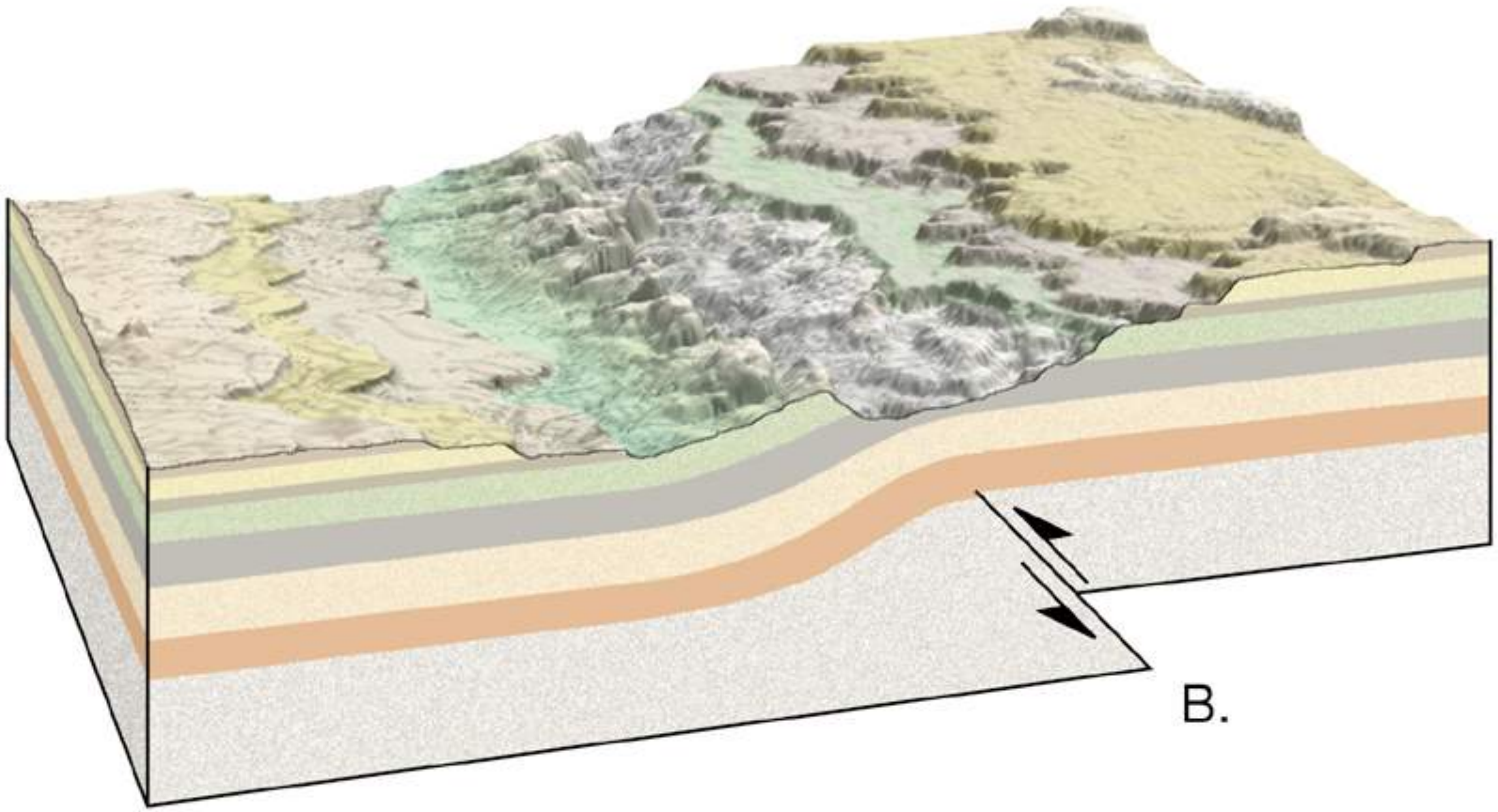
A. Map view



A Geologic Map Showing the Strike and Dip of Structures:
Q1: Identify the Anticline and Syncline
Q2: What will be the nature of the anticlines?

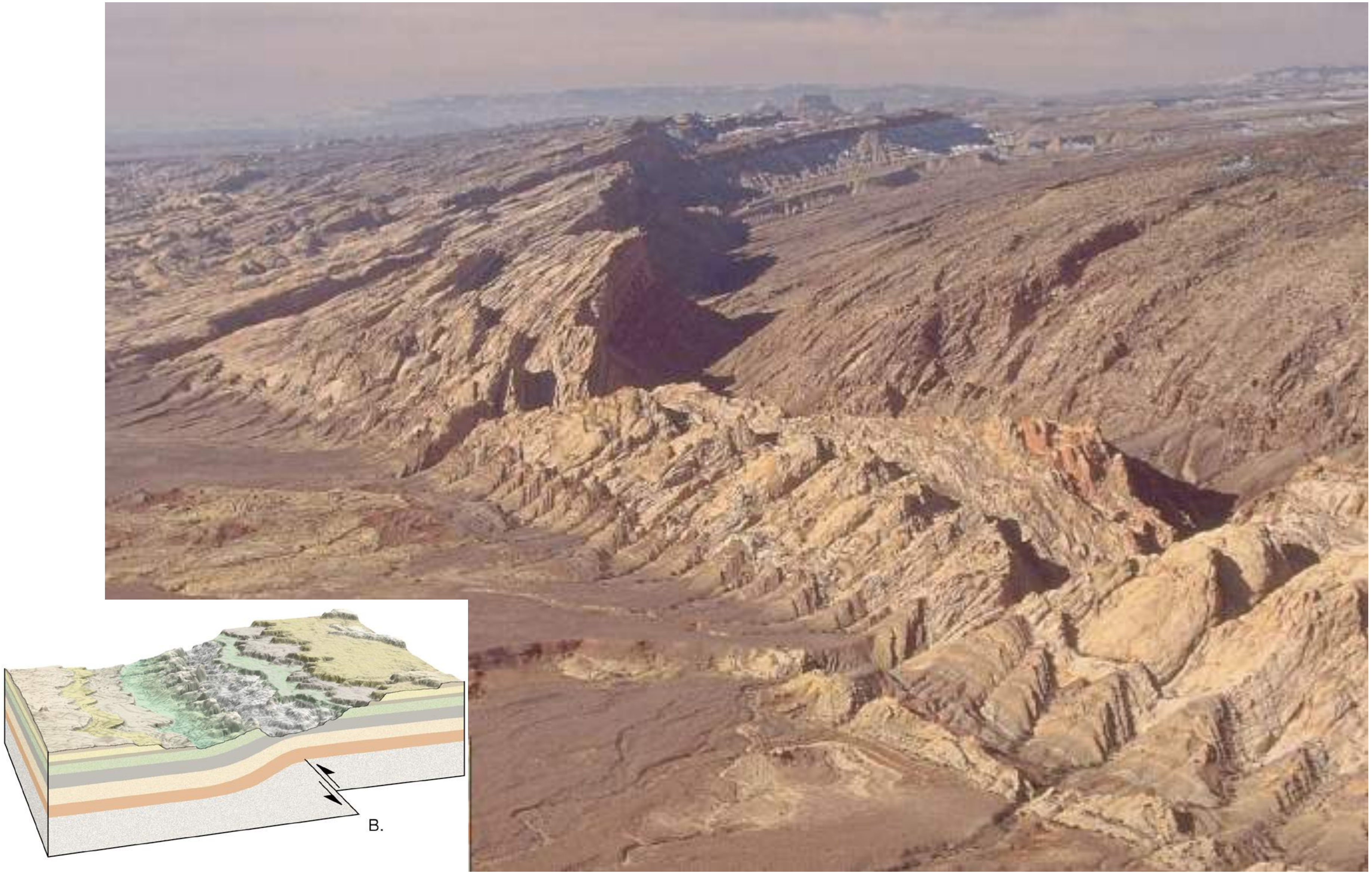
 B. Block diagram

- **Monoclines – large, step-like folds in otherwise horizontal sedimentary strata**



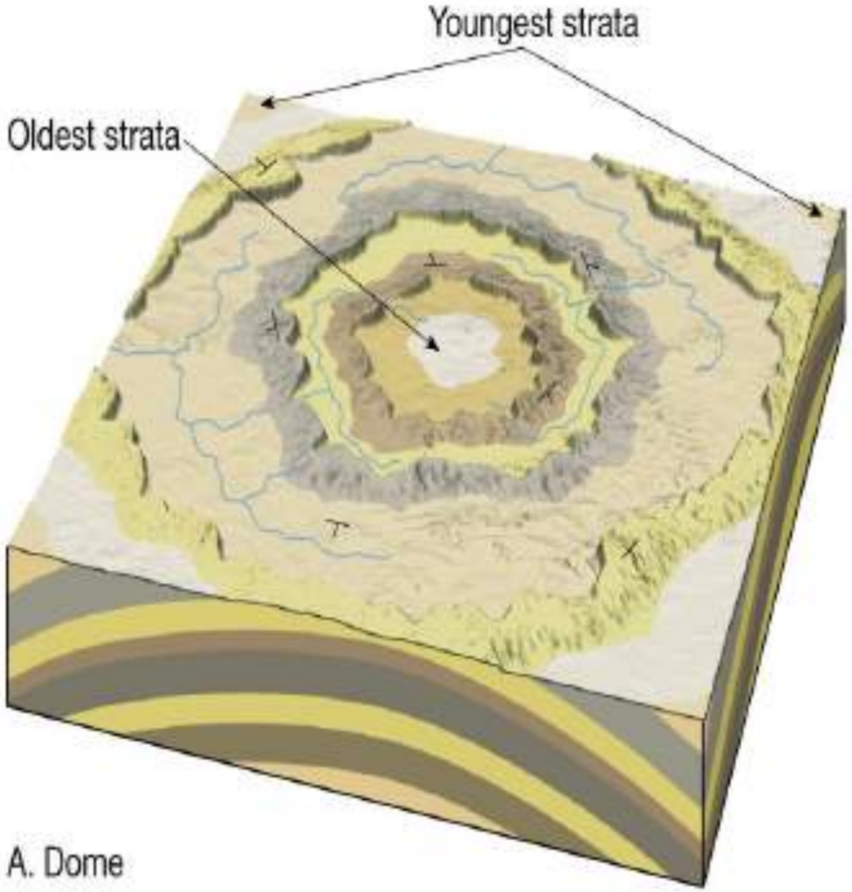
Monoclines (Structures that Are Folded on Only One Side) Are Often Produced by Faulting in the Underlying Strata

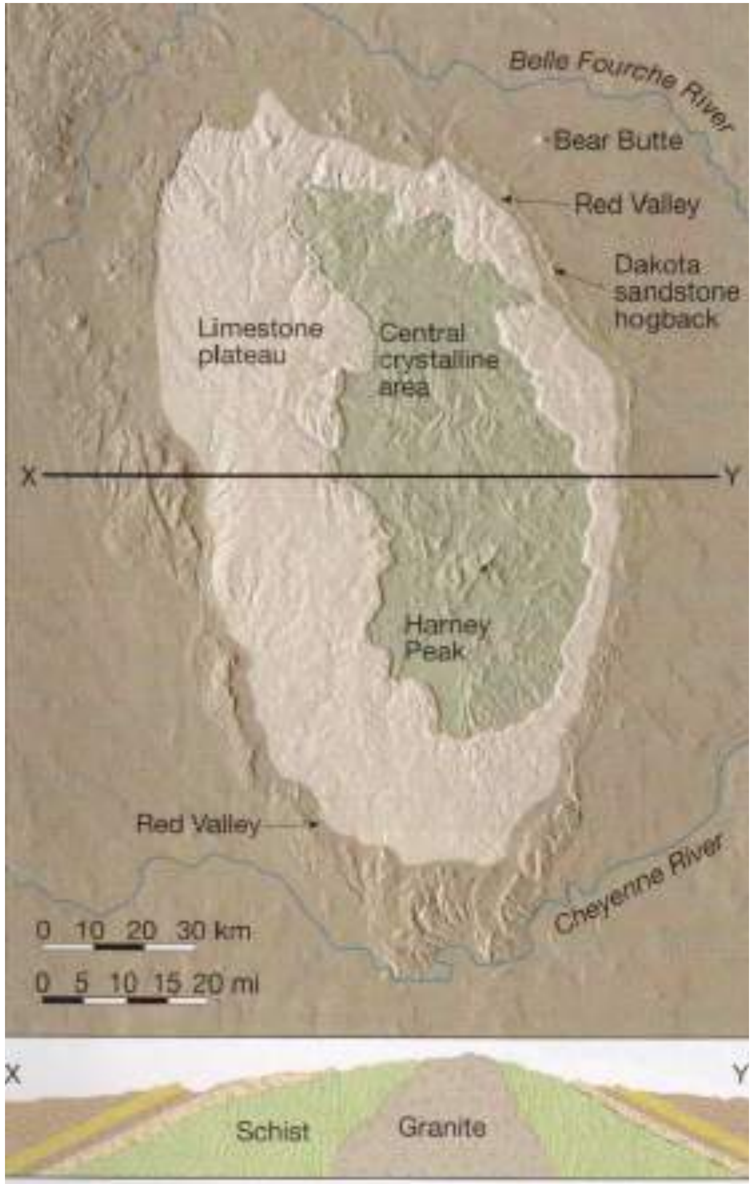
The San Rafael Swell (Utah) Shows the Edge of a Monocline (Dips on One Side Only).



- **Other types of folds**
  - **Dome**
    - **Upwarped displacement of rocks**
    - **Circular or slightly elongated structure**
    - **Oldest rocks in center, younger rocks on the flanks**

A Dome Exhibits a Circular Outcrop Pattern with the Oldest Rocks in the Center

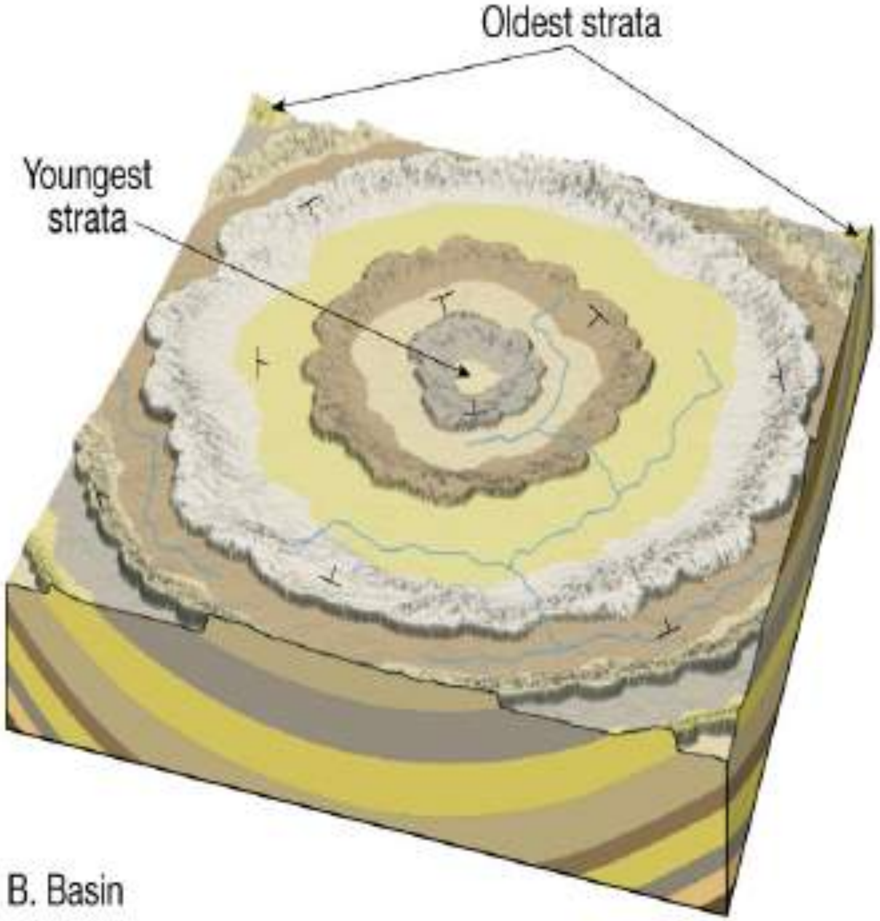


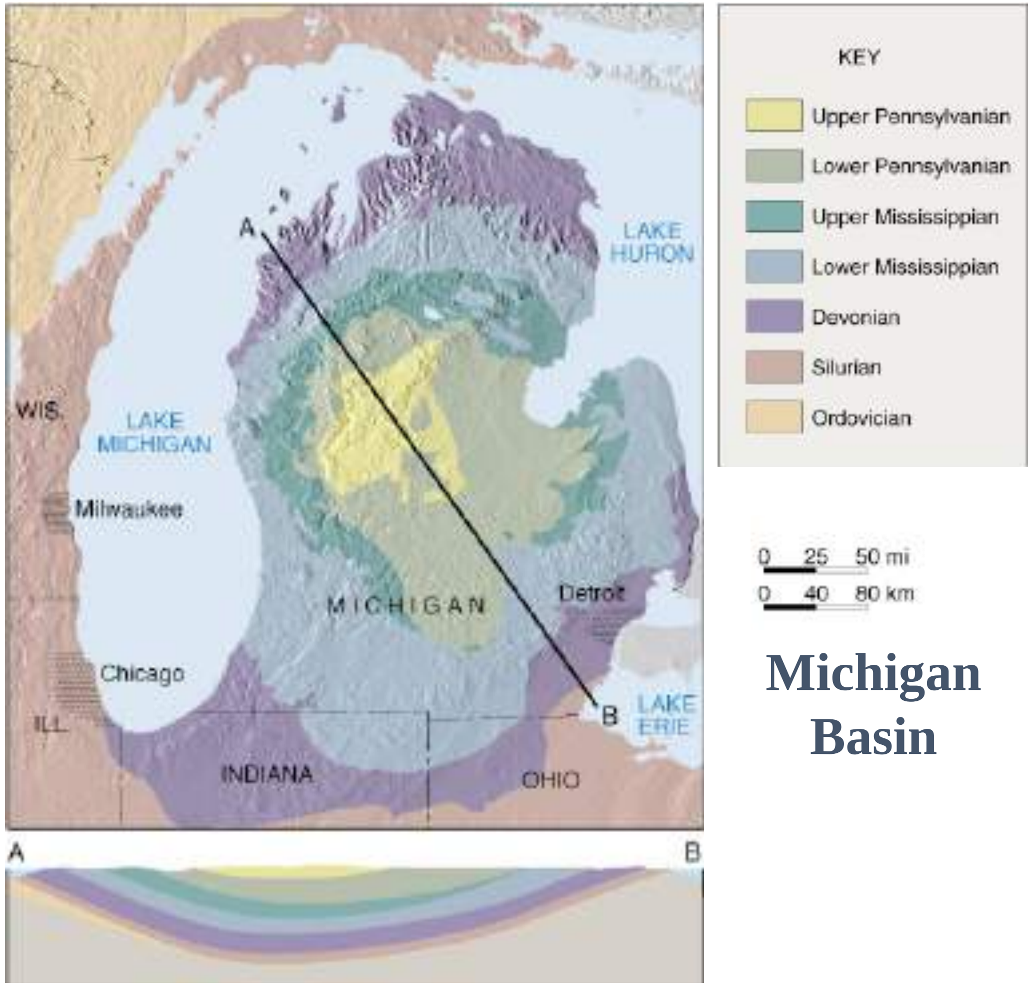


The Black Hills of South Dakota Are a Good Example of a Dome

- Other types of folds
    - Basin
        - Circular or slightly elongated structure
        - Downwarped displacement of rocks
        - Youngest rocks are found near the center, oldest rocks on the flanks

A Basin Exhibits a Circular Outcrop Pattern with the Youngest Rocks in the Center





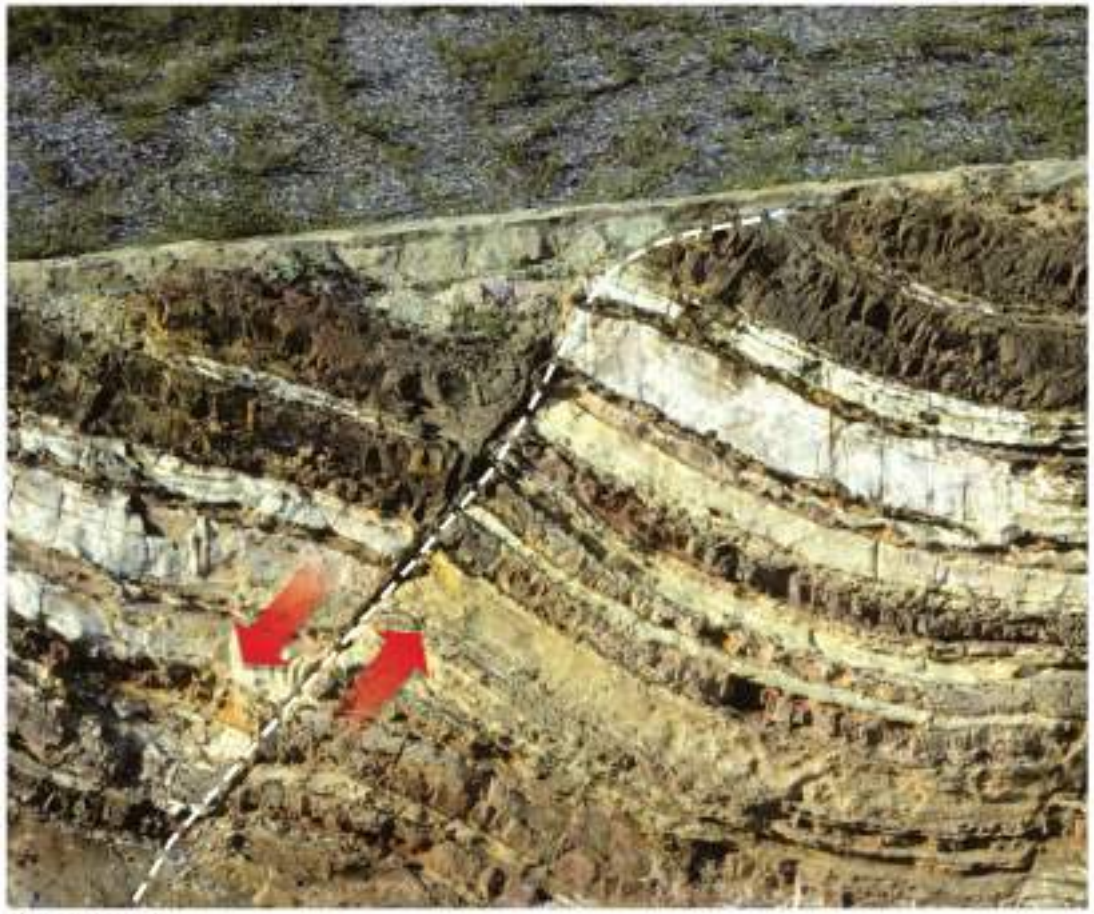
Michigan Basin

Fractures

- ***Most common Brittle response to stress***
- ***With displacement or slip = Fault***
- ***Without displacement or slip=Joint***

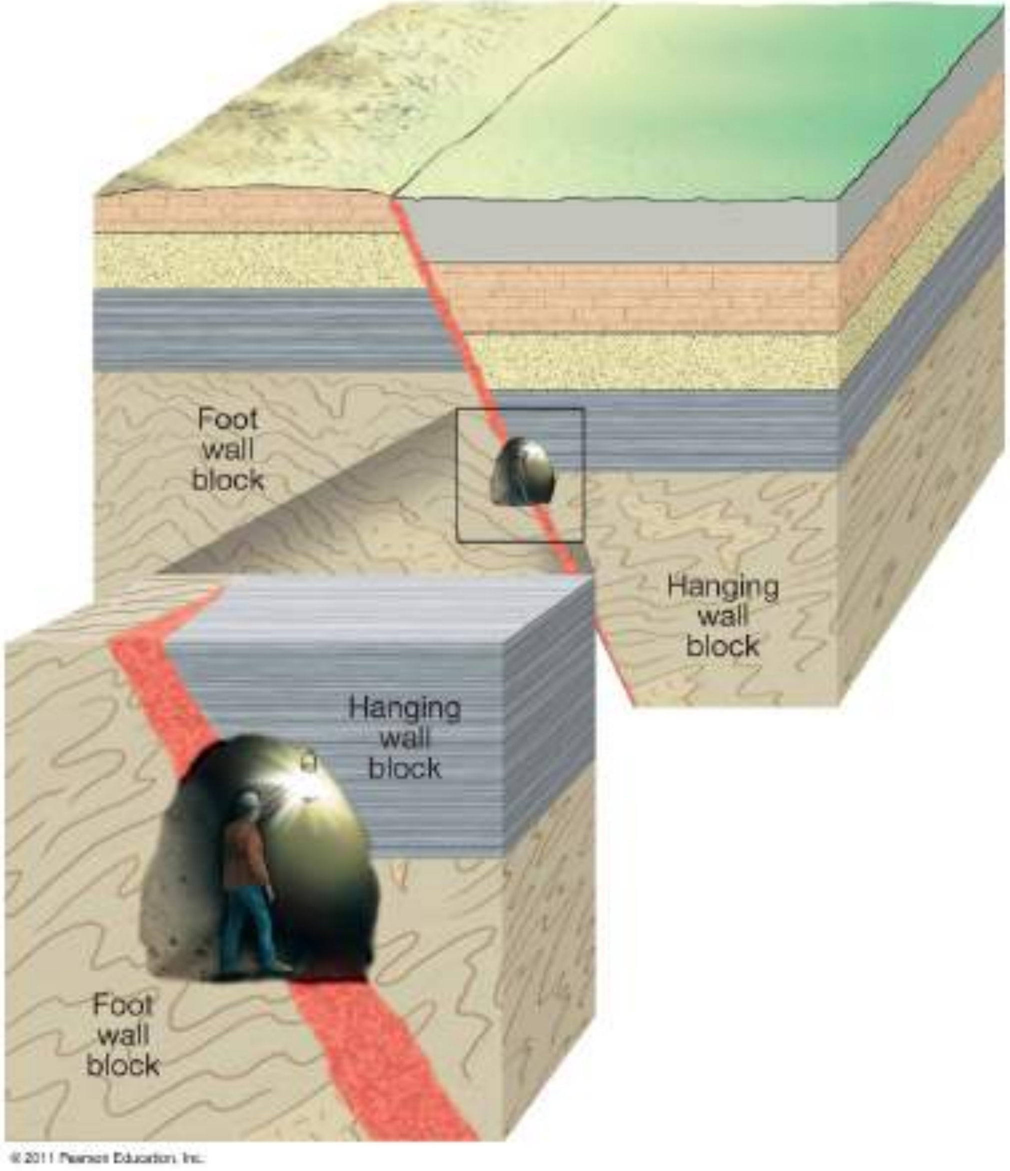
Faults

- **Faults are fractures in rocks along which appreciable displacement has taken place.**
- **Sudden movements along faults are the cause of most earthquakes.**
- **Classified by their relative movement, which can be horizontal, vertical, or oblique.**



Faults

- **Types of faults**
  - **1. Dip-slip faults**
    - **Movement is mainly parallel to the dip (inclination) of the fault surface**
    - **Parts of a dip-slip fault include the hanging wall (rock surface above the fault) and the footwall (rock surface below the fault)**



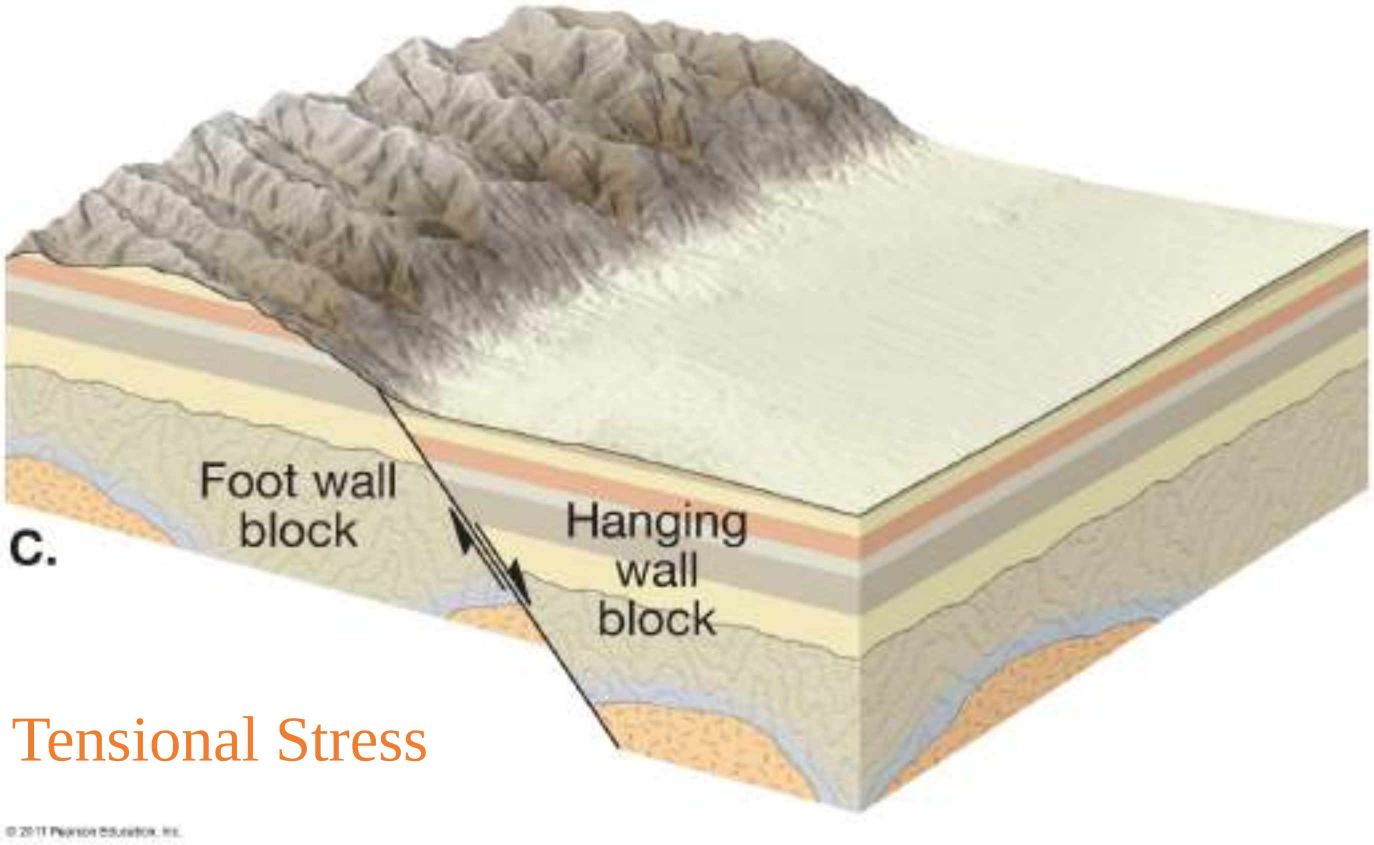
Hanging Wall and Footwall Along a Dip-Slip Fault Surface

Dip-Slip Faults

- **Types of dip-slip faults**

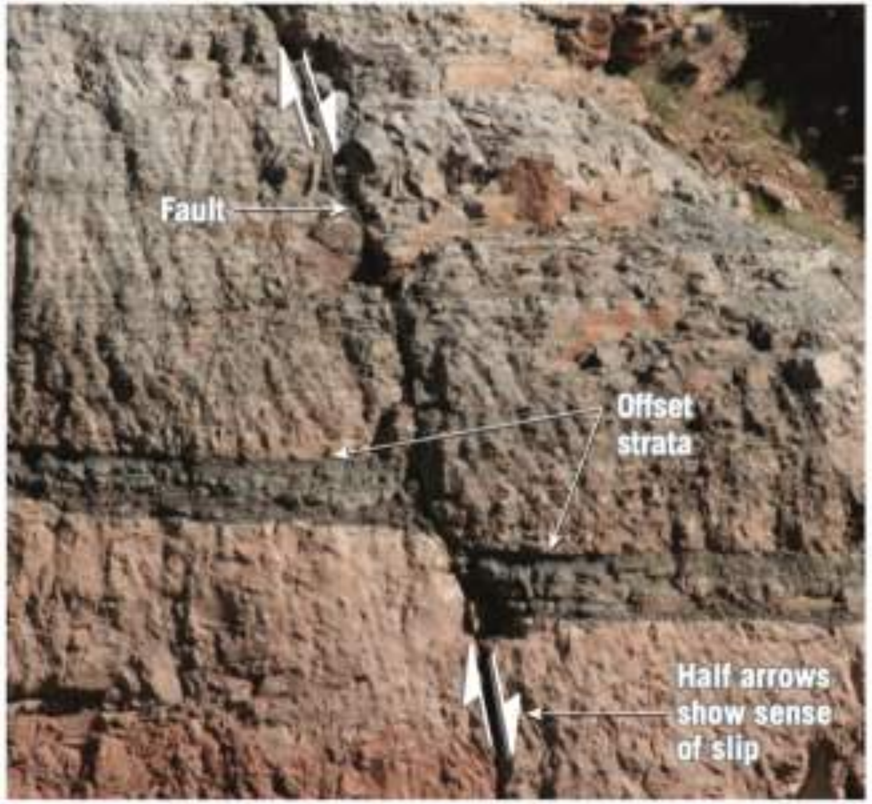
  a) Normal faults

  - **The hanging wall moves down relative to the footwall.**
  - *Accommodate lengthening or extension of the crust*
  - **Most are small with displacements of 1 meter or so.**

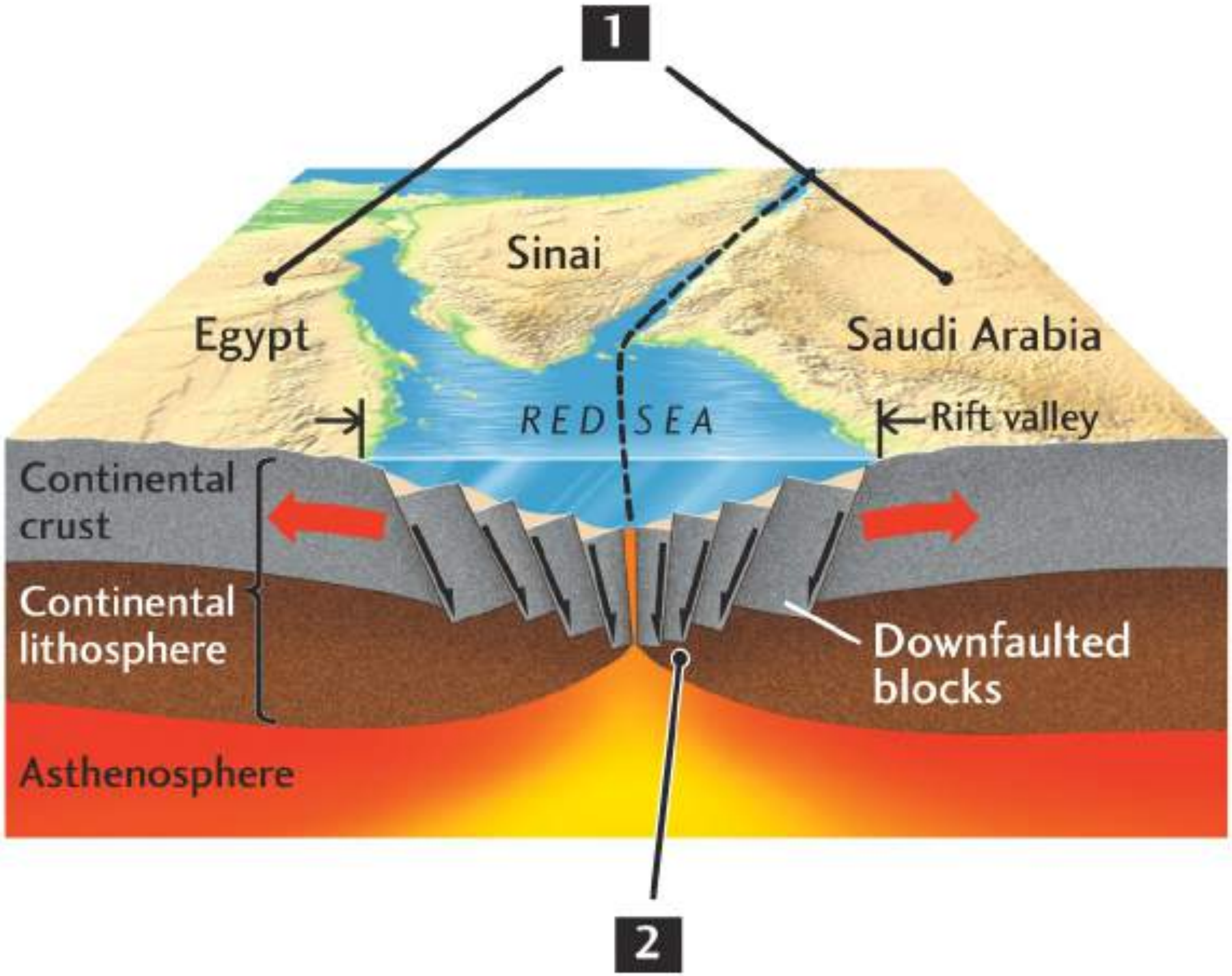


Tensional Stress

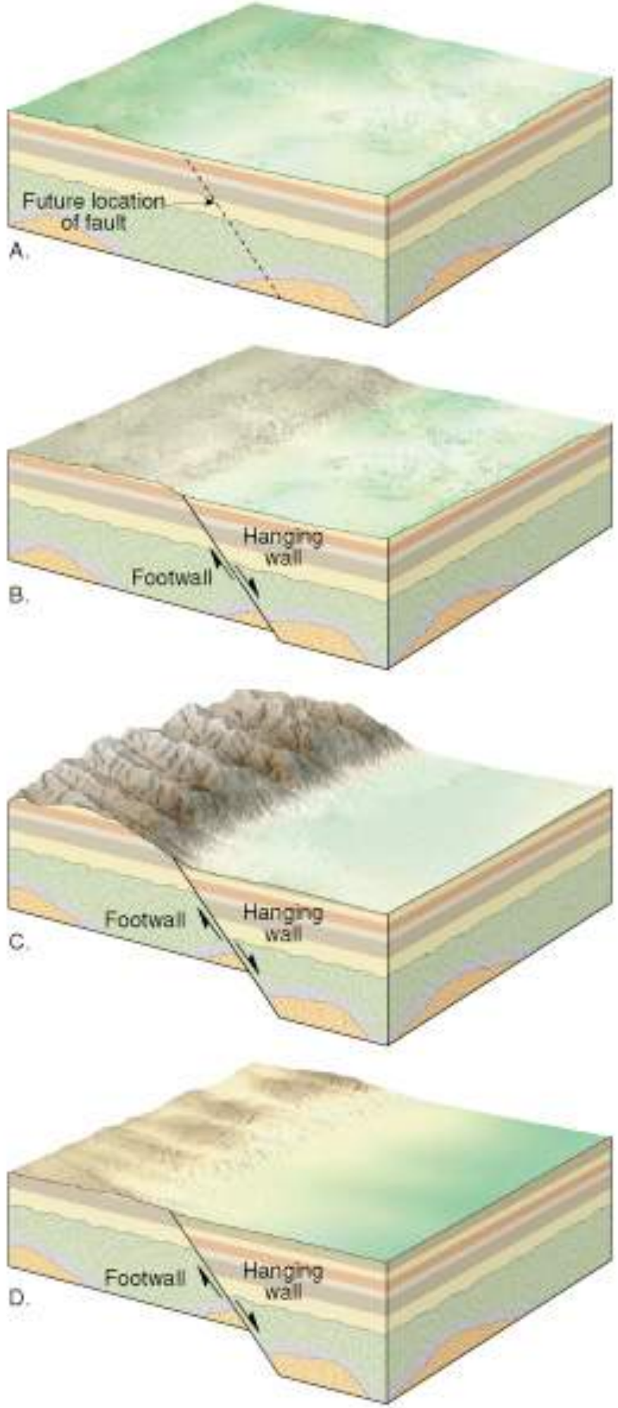
"Normal" Dip-Slip Fault (Hanging Wall Moves Down)



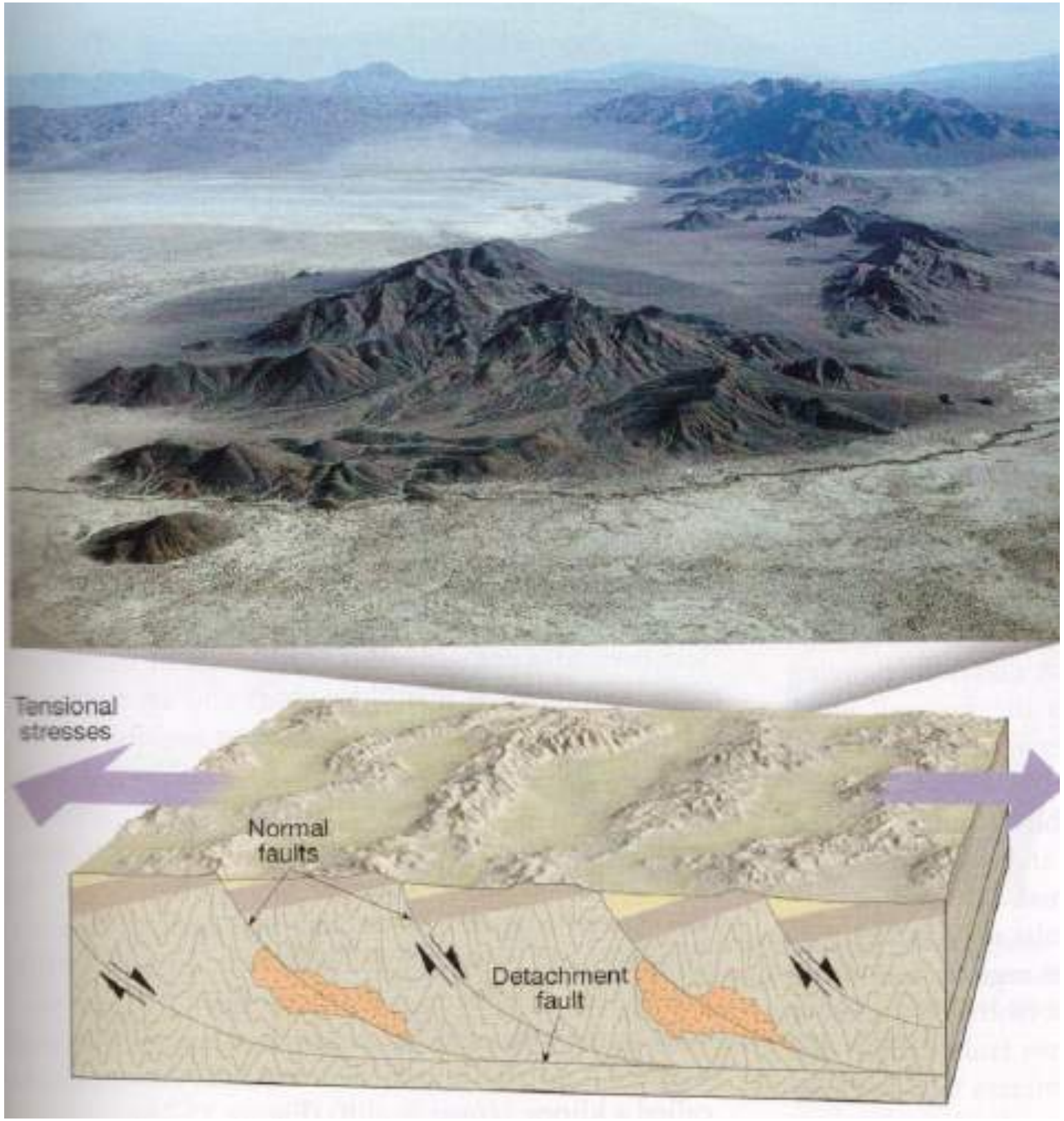
Example


1
Sinai
Egypt
Saudi Arabia
RED SEA
Rift valley
Continental crust
Continental lithosphere
Asthenosphere
Downfaulted blocks
2


MEDITERRANEAN SEA
Sinai
Saudi Arabia
Egypt
RED SEA



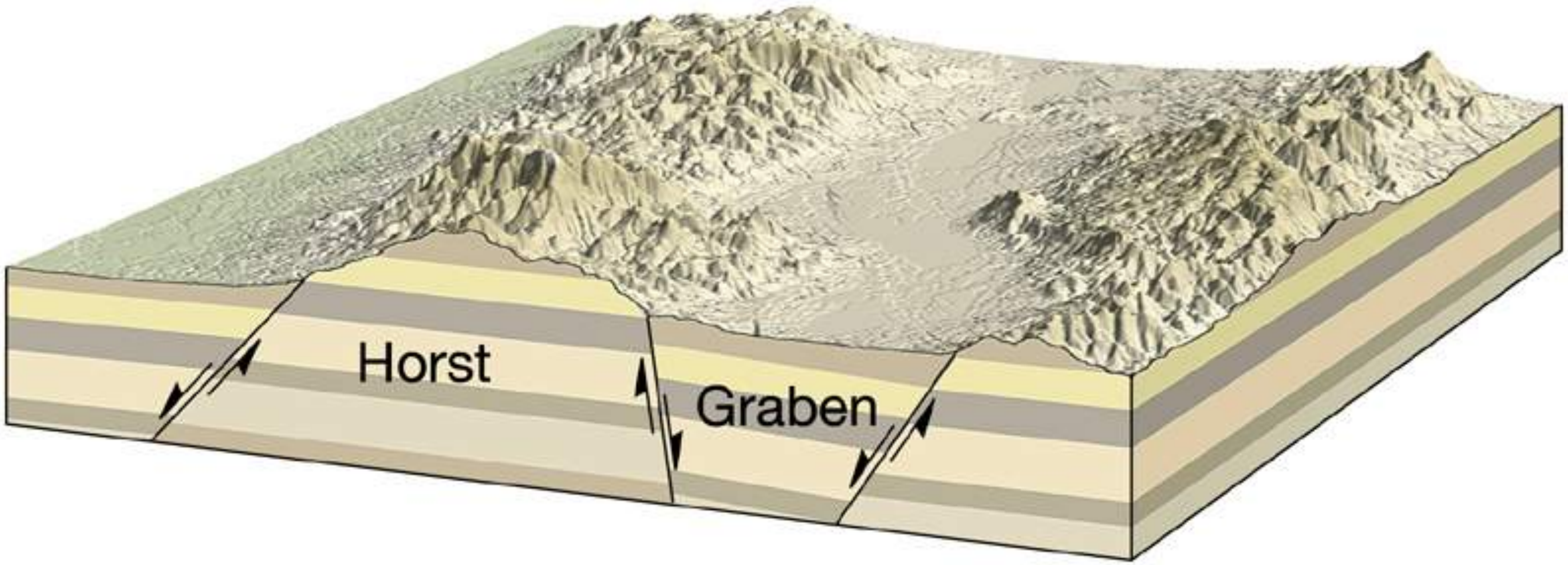
Block Diagrams Illustrating the Movement on a Normal Dip-Slip Fault. Subsequent Erosion Can Often Produce Mountains on the Upthrown Side of a Normal Fault



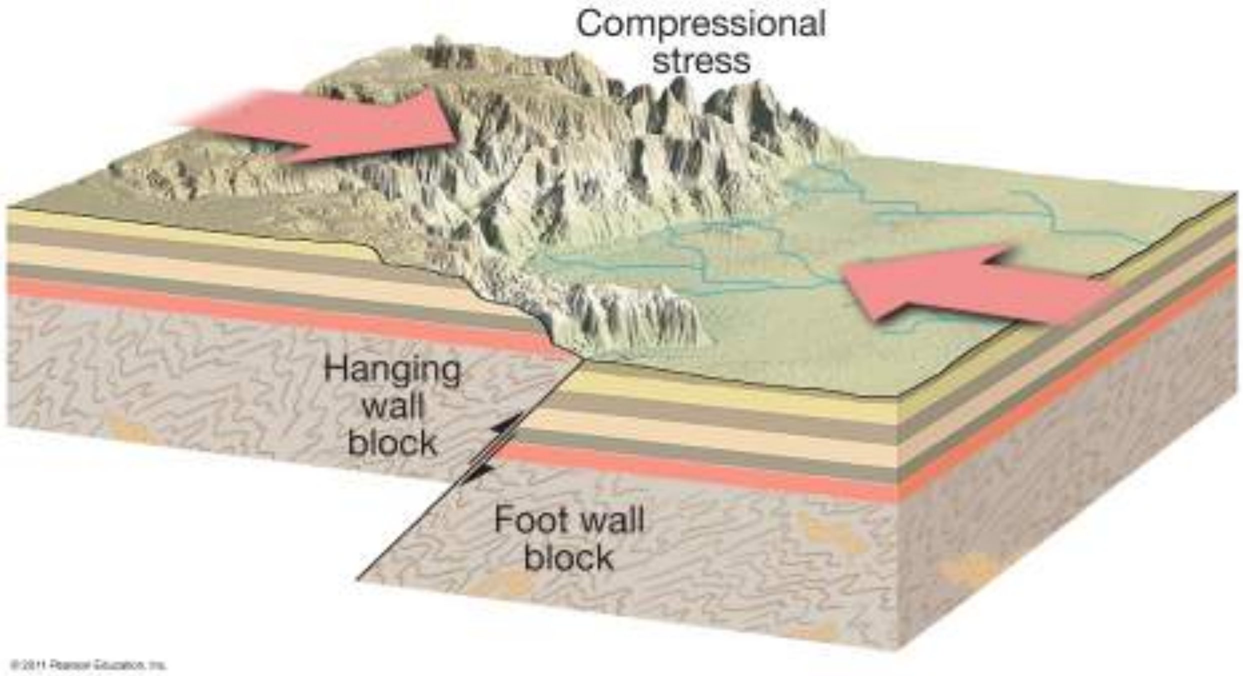
At brittle-ductile transitions

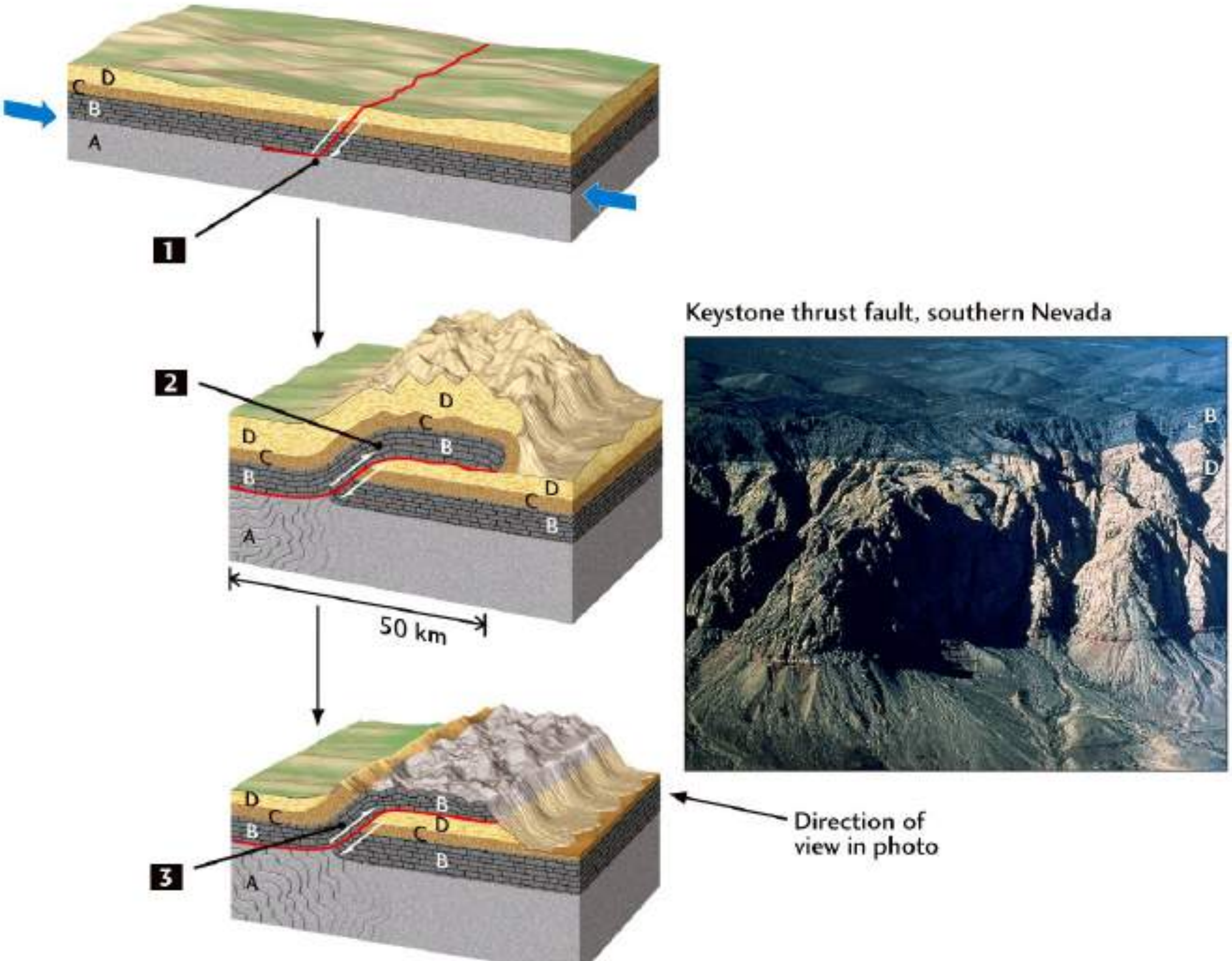
Typical "Block Faulting" (Normal Faulting) Creates the Basin and Range Topography in Parts of the Western United States

Most Block Faulted Mountains in the Basin & Range Are Actually Horsts and Grabens. The Mountains Are Faulted on Both Sides and Moved “Up” Relative to the Intervening Valleys



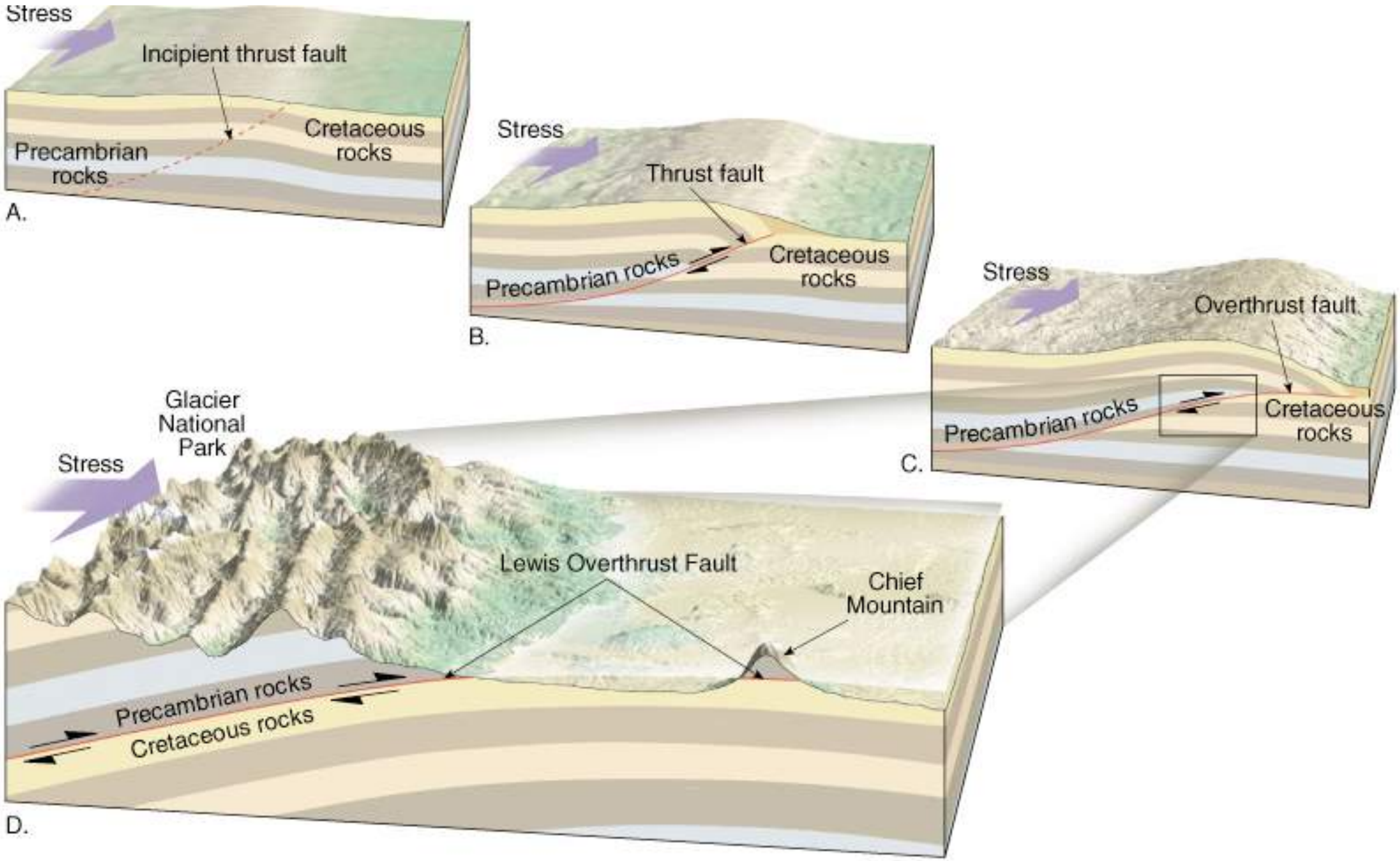
- **Types of dip-slip faults**
  - **b) Reverse and thrust faults**
    - **The hanging wall block moves up relative to the footwall block.**
    - **Reverse faults have dips greater than 45 degrees and thrust faults have dips less then 45 degrees.**
    - ***Accommodate shortening of the crust***
    - **Strong compressional forces**
    - **Thrust faults are most pronounced along convergent plate boundaries**



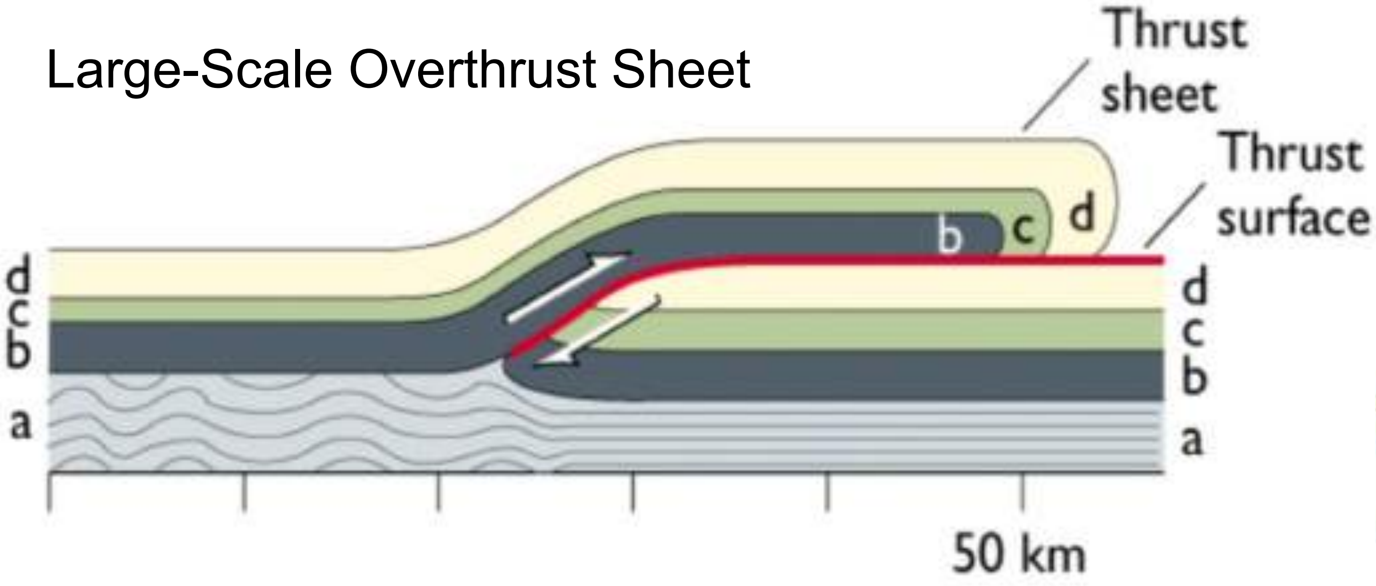


D
C
B
A
1
2
D
C
D
C
B
B
D
C
B
A
50 km
Keystone thrust fault, southern Nevada
B
D
D
C
B
B
D
C
C
B
3
A
Direction of
view in photo

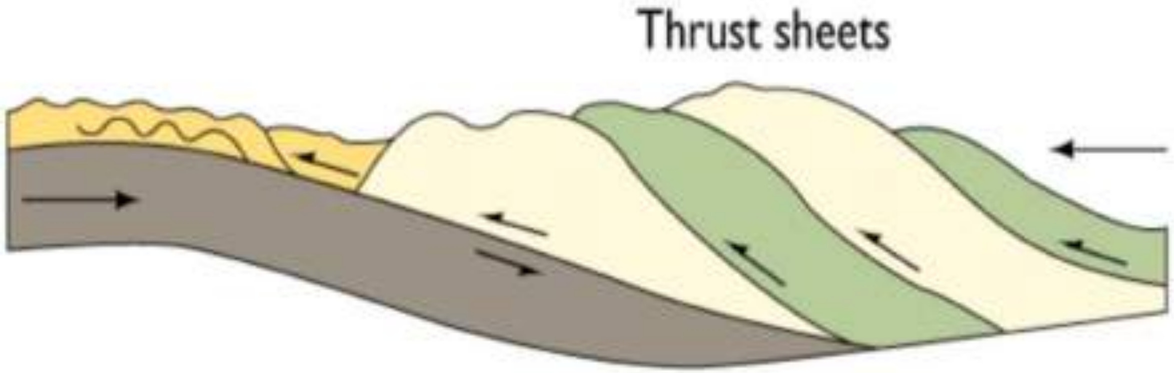
Example : Development of Thrust Faults in Glacier National Park



Large-Scale Overthrust Sheet



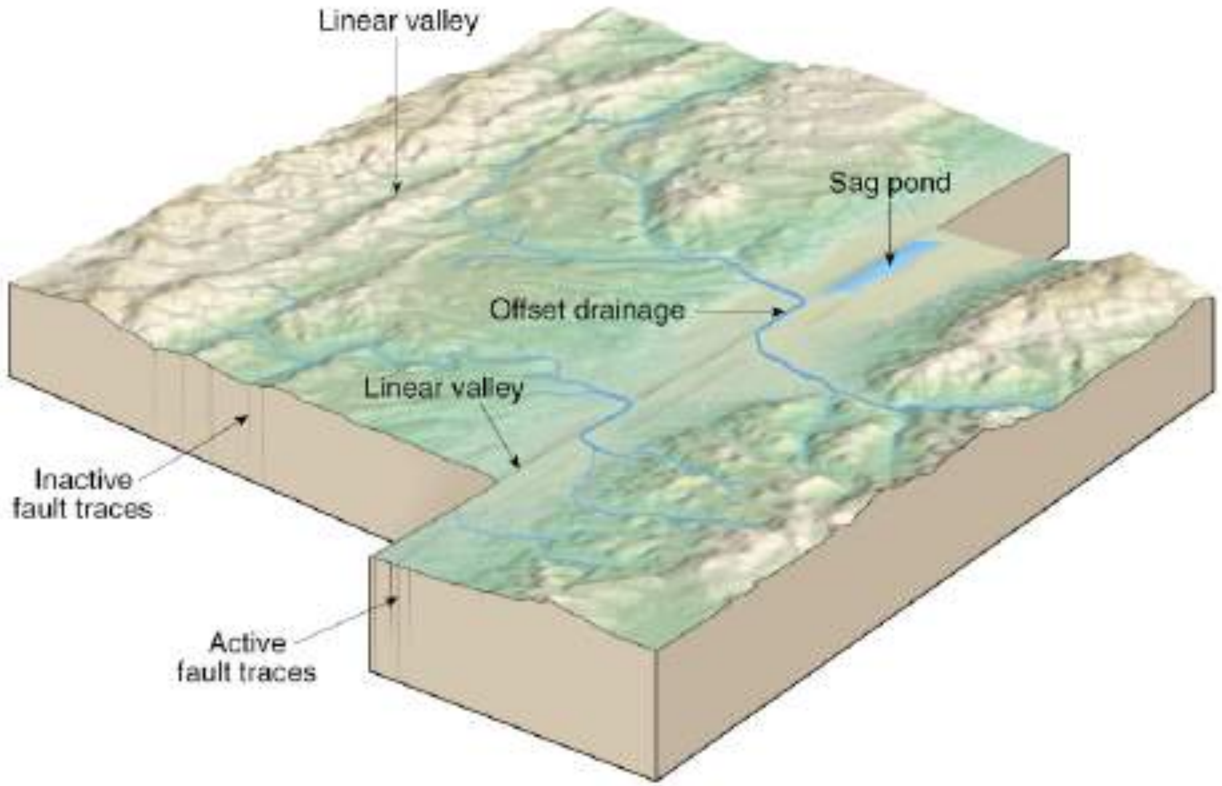
Stacked Sheets of Continental Crust Due to Convergence of Continental plates



(e) Thrust

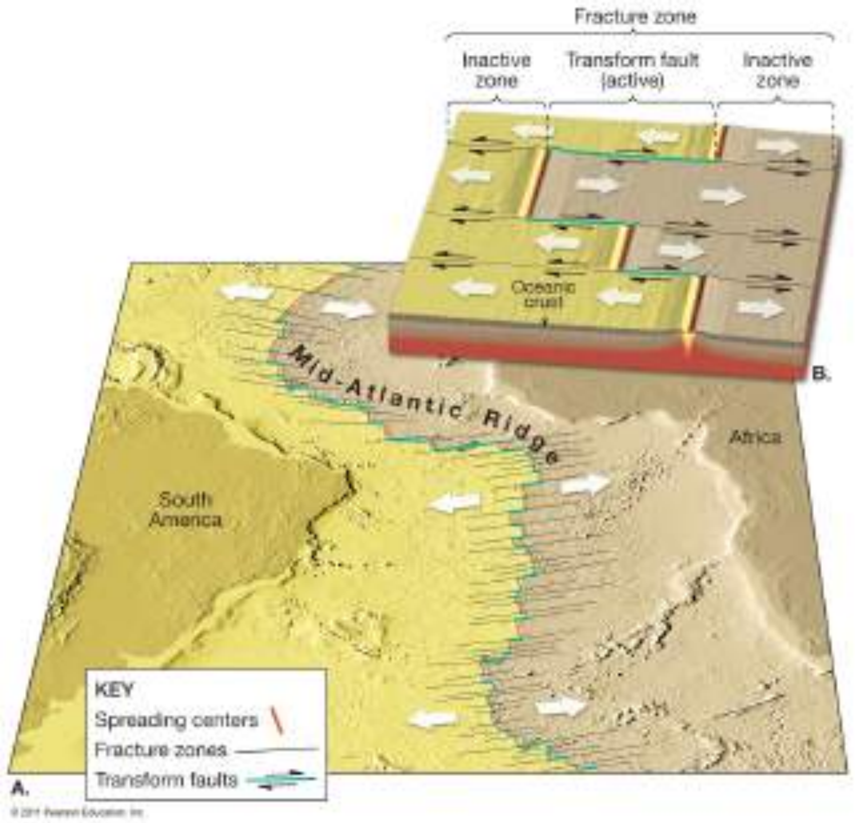
Overlapping Thrust Faults, Himalaya

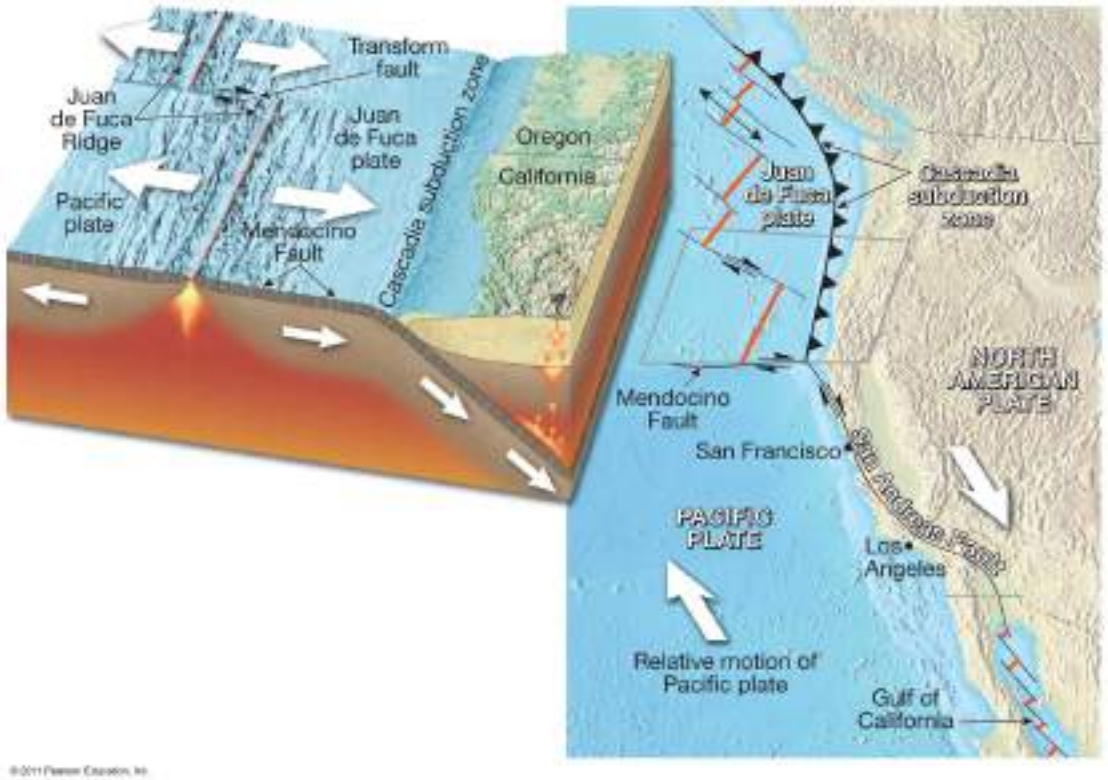
- **Strike-slip fault**
    - **Dominant displacement is horizontal and parallel to the strike of the fault**
    - **Types of strike-slip faults**
        - **Right-lateral – as you face the fault, the block on the opposite side of the fault moves to the right**
        - **Left-lateral – as you face the fault, the block on the opposite side of the fault moves to the left**



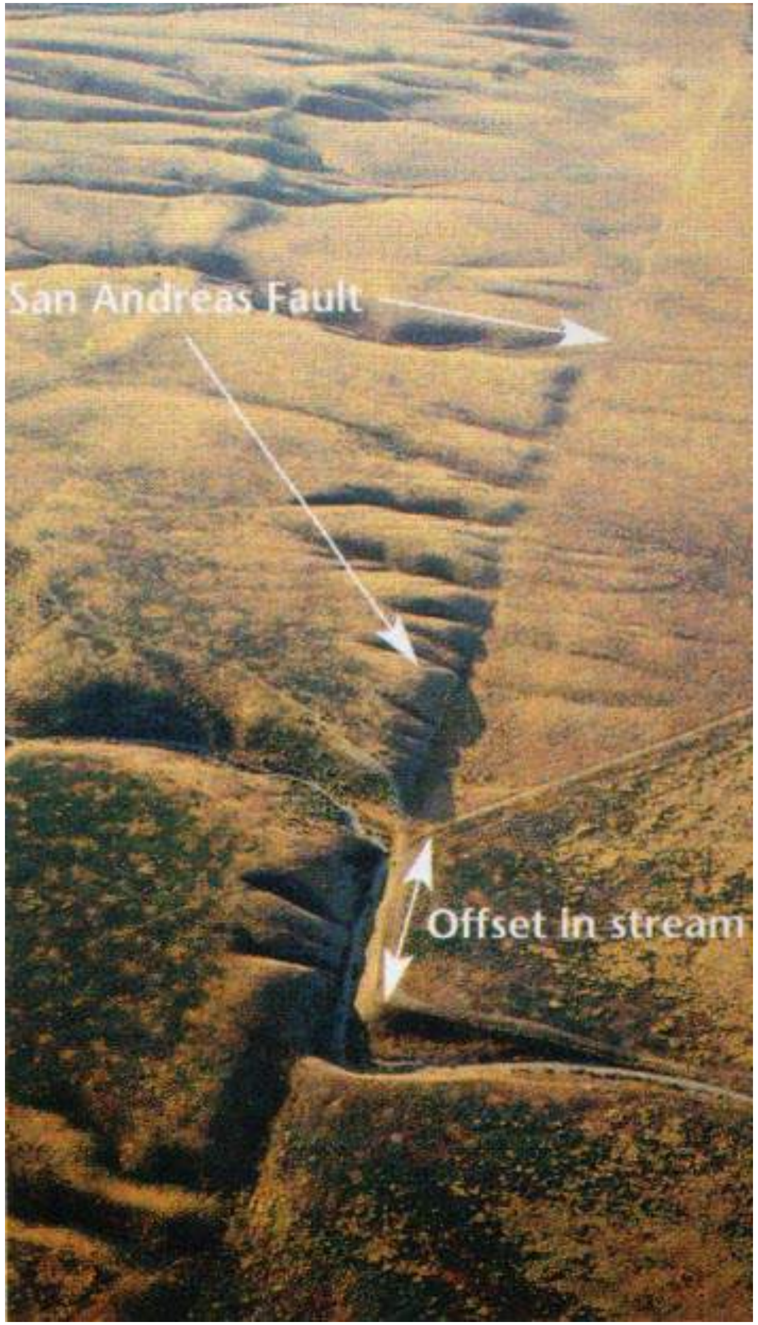
Aerial View of a Right Lateral Strike-Slip Fault in Nevada

- **Strike-slip faults**
  - **Transform faults**
    - **Large strike-slip faults that cut through the lithosphere**
    - **Accommodate motion between two large crustal plates**
    - **Many cut the oceanic lithosphere and link spreading ridges**
    - **Others accommodate displacement between continental plates that move horizontally with respect to each other**





The San Andreas Fault System

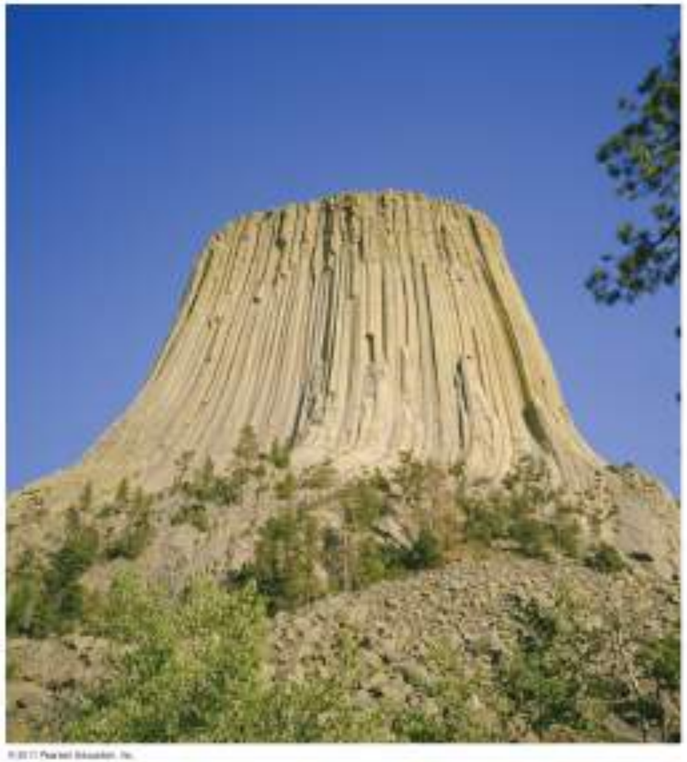


Aerial View of Offset Along the San Andreas Fault

Joints

- A joint is a fracture with no appreciable displacement
- When tectonic forces cause upwarping of the crust, rocks near the surface are stretched and pulled apart to form fractures
- Due to cooling of volcanic rocks
- Most occur in roughly parallel groups
- Chemical weathering tends to be concentrated along joints

Arches Natl. Park, UT



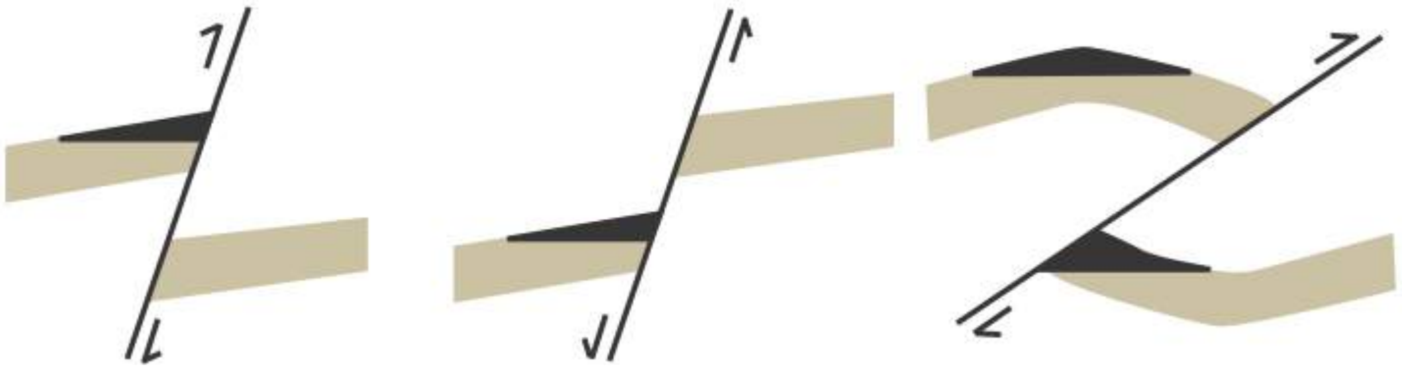
Devil’s Tower, WY

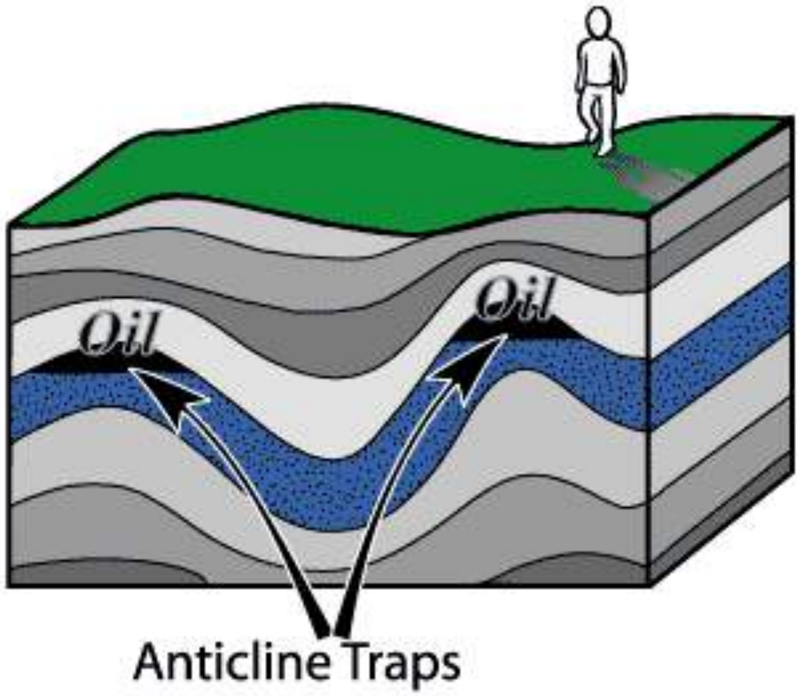
Columnar Jointing in Basalt, Giants Causeway, Ireland

Petroleum Exploration

- Significance of folds/faults/joints
  - Folds and faults are good petroleum reservoirs
  - Many economically important mineral deposits are emplaced along joint systems (important for Cu, Ag, Au, Zn, Pb, and U).
  - Chemical weathering tends to be concentrated along joints.

Structural traps are primarily the result of folding and (or) faulting, or both.





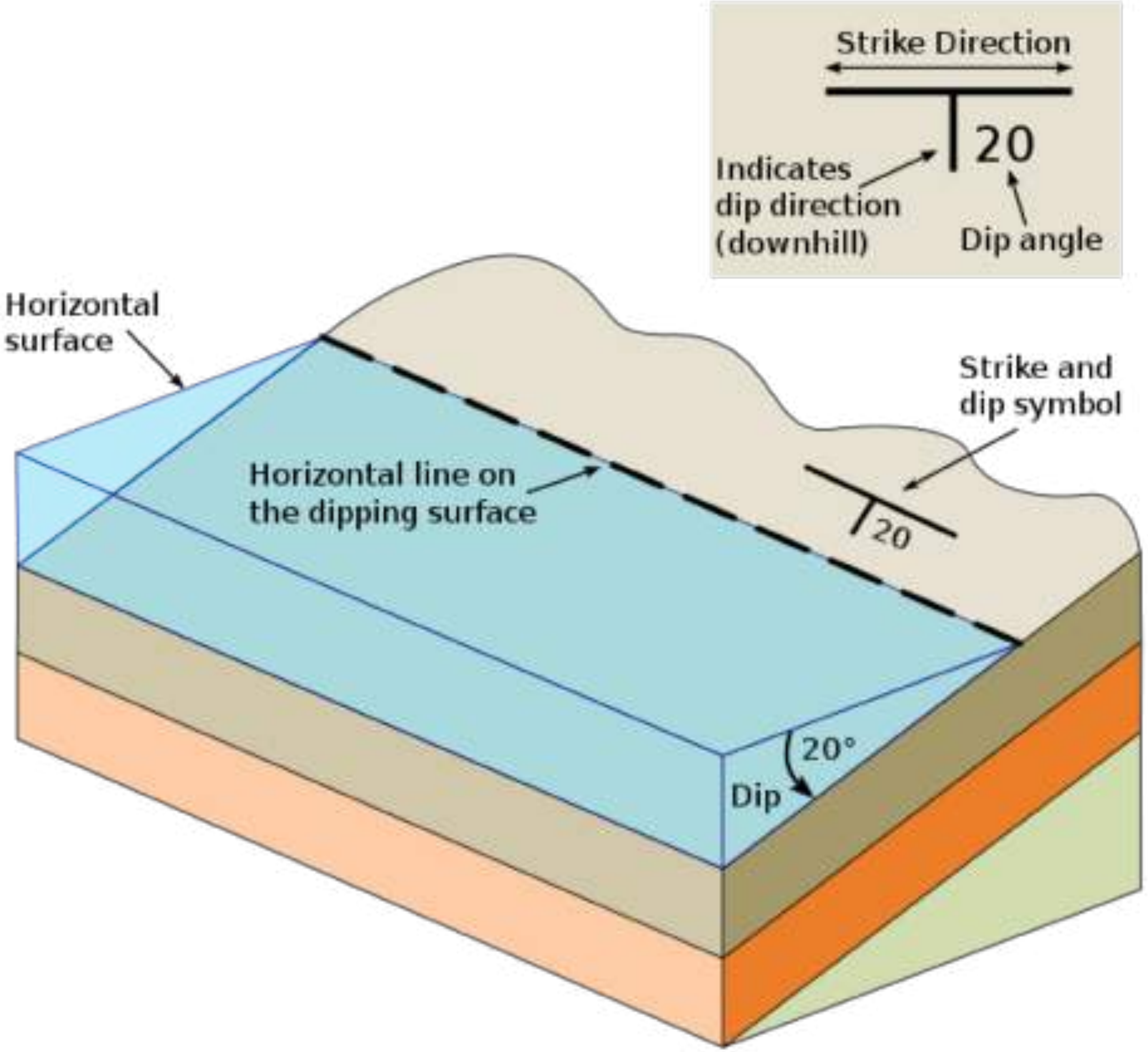
A cross section of the Earth showing typical Anticline Traps. Reseroir rock that isn't completely filled with oil also contains large amounts of salt water.

Fundamentals of Earth Sciences (ESO 213A)

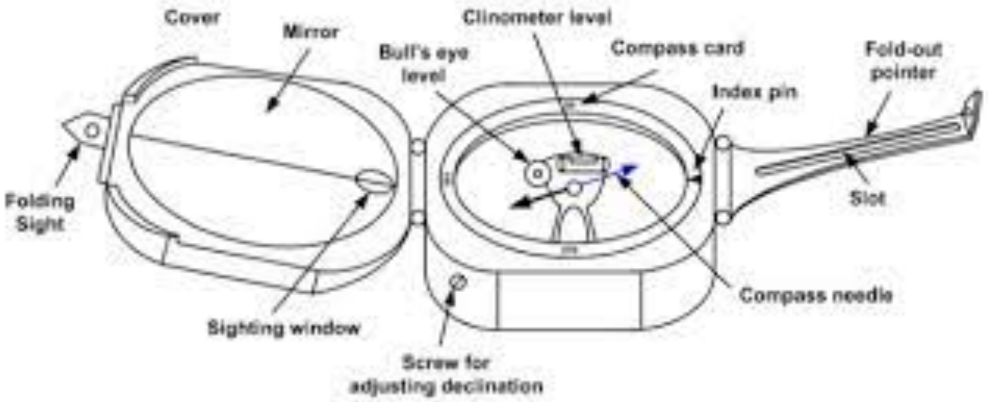
Dibakar Ghosal
Department of Earth Sciences

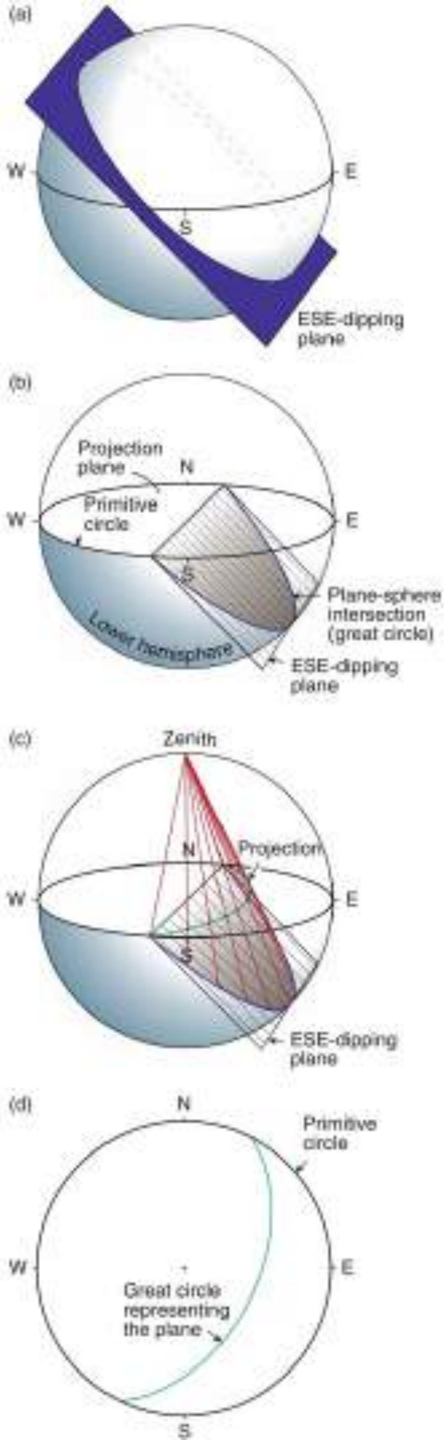
Attribute plotting in Stereonet plotting

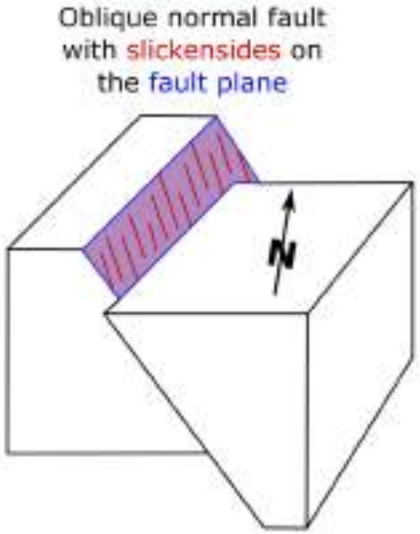
Previous Class: Crustal deformation

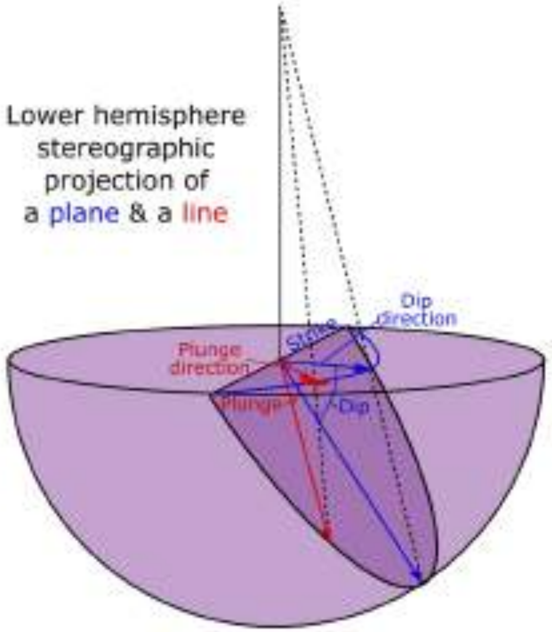


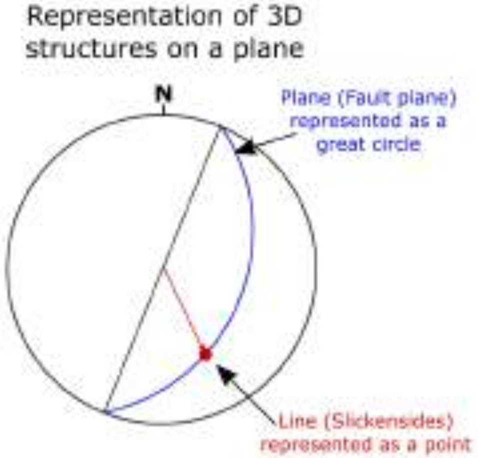
Brunton compass

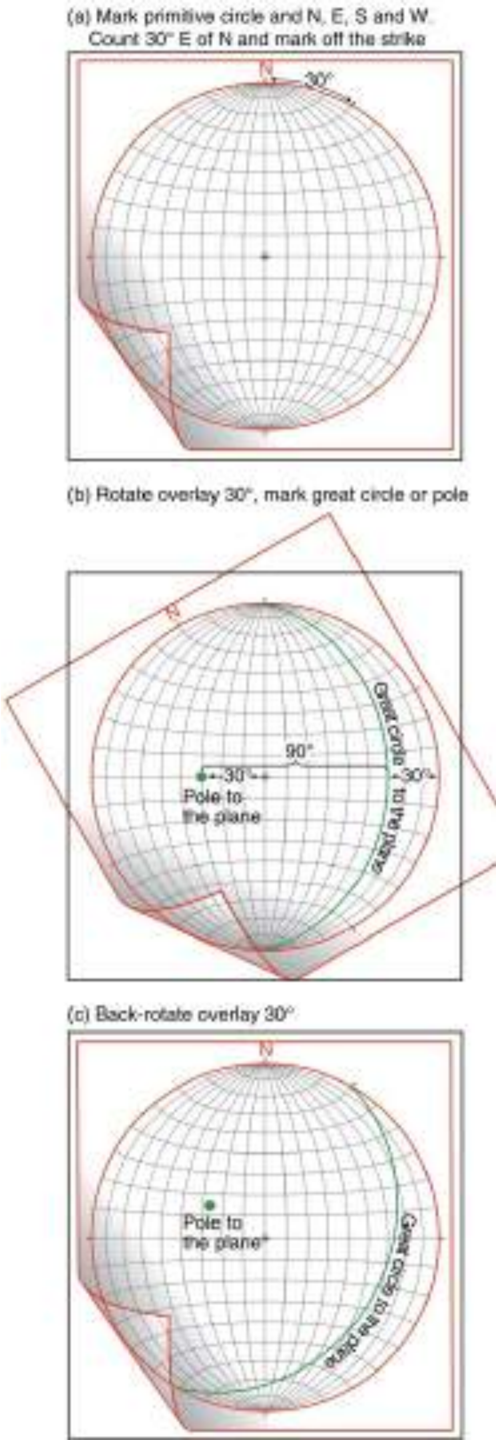



(a)
W
E
S
ESE-dipping plane
(b)
Projection plane
N
Primitive circle
W
E
S
Plane-sphere intersection (great circle)
Lower hemisphere
ESE-dipping plane
(c)
Zenith
N
Projection
W
E
S
ESE-dipping plane
(d)
N
Primitive circle
W
E
Great circle representing the plane
S


Oblique normal fault with slickensides on the fault plane
N


Lower hemisphere stereographic projection of a plane & a line
Strike
Dip direction
Plunge direction
Plunge
Dip


Representation of 3D structures on a plane
N
Plane (Fault plane) represented as a great circle
Line (Slickensides) represented as a point


(a) Mark primitive circle and N, E, S and W. Count 30° E of N and mark off the strike
N
30°
(b) Rotate overlay 30°, mark great circle or pole
N
90°
30°
30°
Pole to the plane
Great circle to the plane
(c) Back-rotate overlay 30°
N
Pole to the plane
Great circle to the plane

Practice problems on stereonet

1. Plot each of the following beds on the tracing paper overlay.
a) 260˚/12 ˚; b) 180˚/90 ˚

2. Plot the following lineations on tracing paper overlays.
a) 43 ˚, 217 ˚; b) 86 ˚, 270 ˚

3. A fault plane has slip lineations oriented in the true-dip direction of the fault plane. The orientation of the lineation is measured as 49 ˚ →041 ˚. Plot and calculate the fault plane orientation, i.e., strike and dip, on a tracing paper.

4. Two limbs of a synform have the following attitudes 042 ˚ /65 ˚ SE and 105 ˚ /40 ˚ N. Determine the trend and plunge of the fold axis.

5. A planar fault contact contains lineation that trend N60 ˚W. The fault plane contact has an attitude of 010˚/80 ˚. Find the following:
(i) What is the plunge of the lineation?
(ii) What is the rake/pitch of the lineation on the fault plane?

Fundamentals of Earth Sciences (ESO 213A)

Dibakar Ghosal
Department of Earth Sciences

Earthquakes

Previous Class:* *Stereonet problems

The most common question that is asked?

- Can earthquake be predicted?
- Will more earthquakes be felt after a strong earthquake? [aftershock]
- Can we generate an earthquake?
- Does a foreshock indicate a large earthquake?

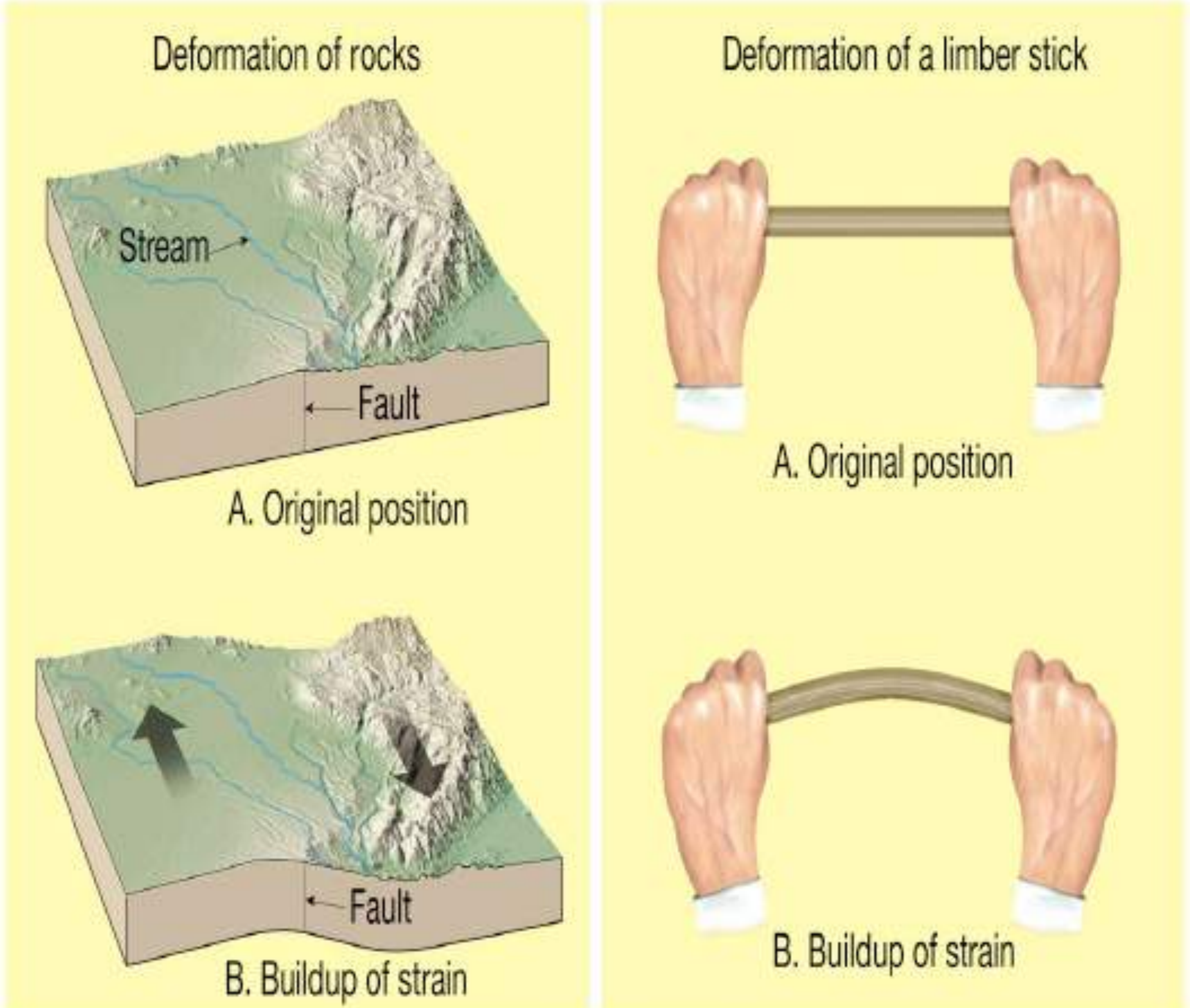
What Is an Earthquake?

- An earthquake is the vibration of Earth, produced by the rapid release of energy.
  - Energy released radiates in all directions from its source, the focus or hypocenter.
  - Energy is in the form of waves.
  - Sensitive instruments around the world record the event.

How do earthquakes occur?

- Stresses build up in the crust, usually due to lithospheric plate motions

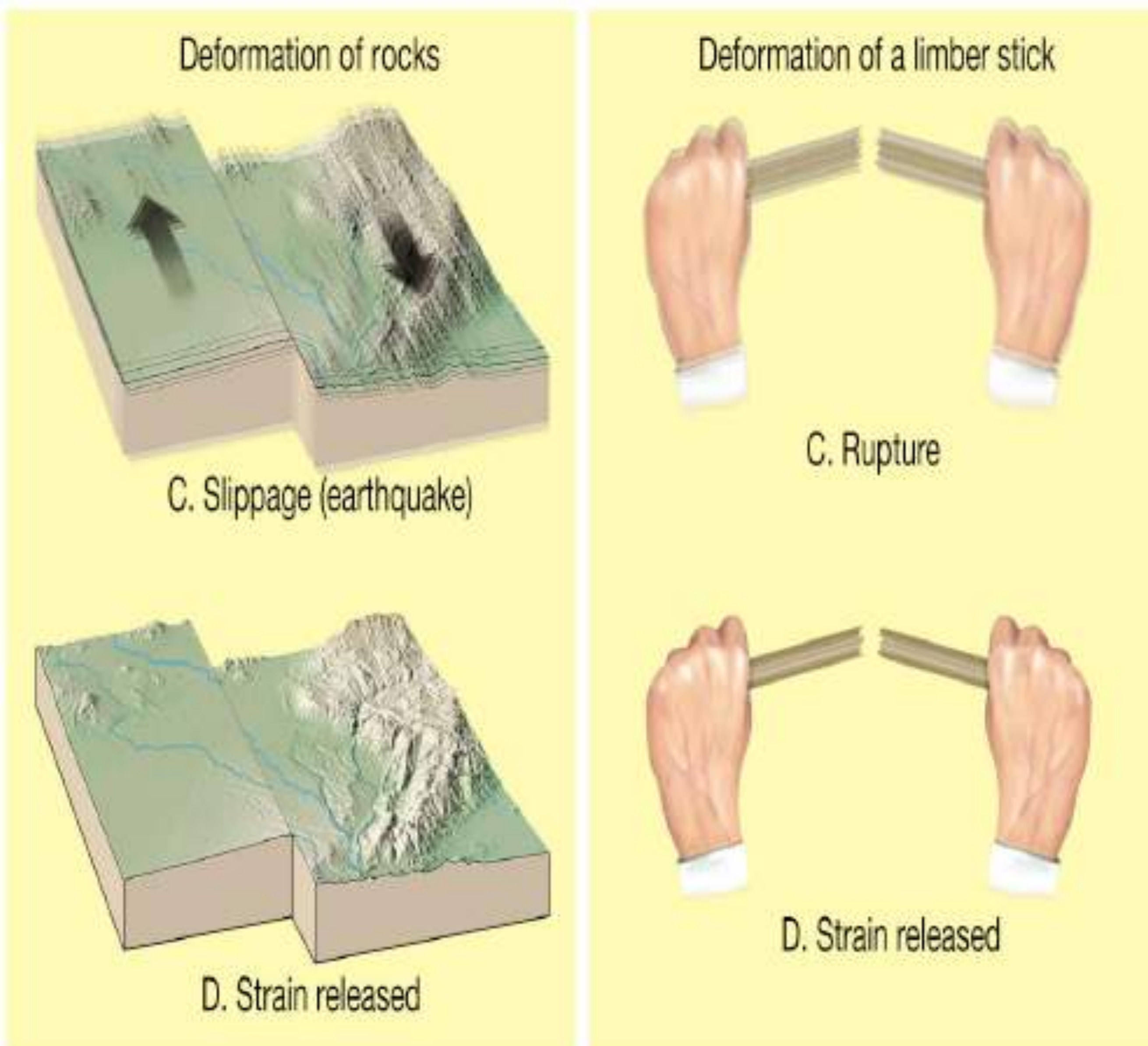
- Rock deform (strain) as the result of stress. The strain is energy stored in the rocks.



How do earthquakes occur?

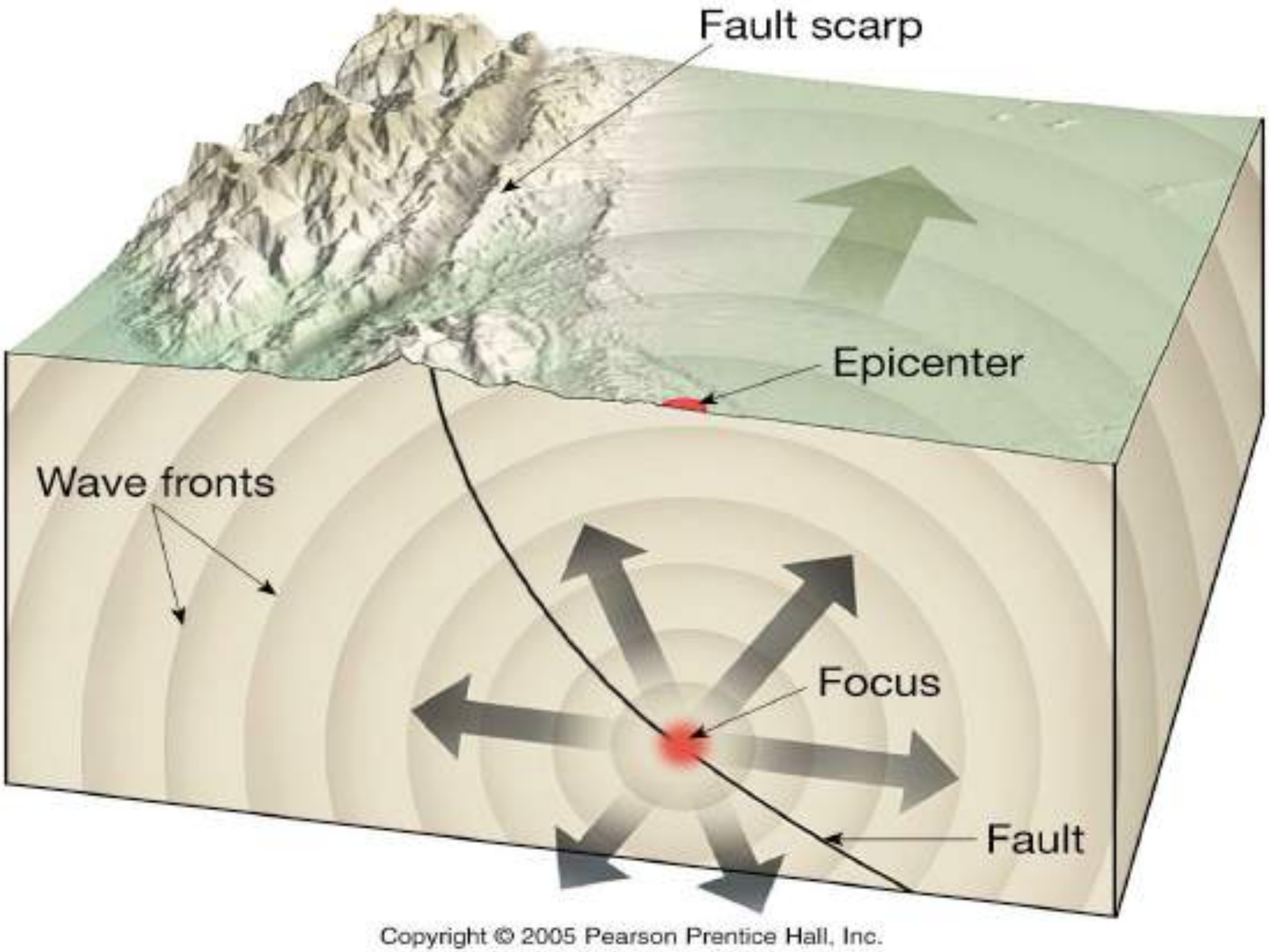
- When the rocks reach their elastic limit, they break, and energy is released in the form of seismic waves, radiating out from the earthquake focus

- The rocks return to their original shape, with a displacement (slip) along the fault



Earthquake focus: center of rupture or slip, seismic waves radiate out from the *focus*

Earthquake ***epicenter*** – the point on the Earth's surface over the focus

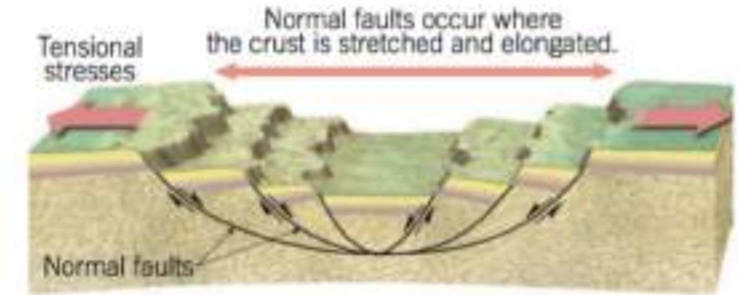


Foreshocks and aftershocks

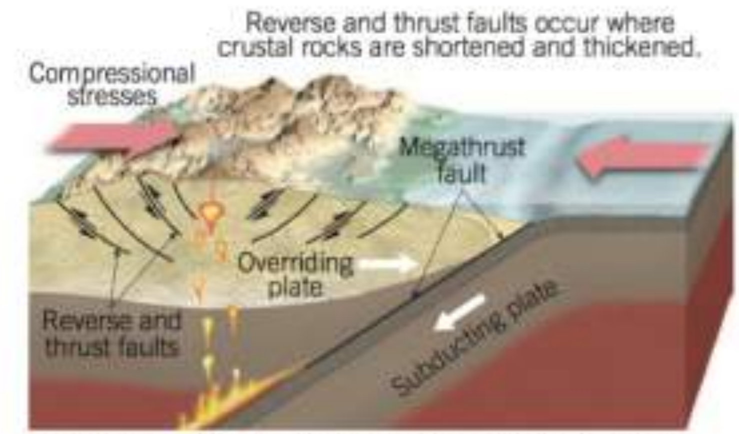
- **Foreshocks and aftershocks**
  - **Adjustments that <u>follow a major earthquake</u> often generate smaller earthquakes called aftershocks.**
  - **Small earthquakes, called foreshocks, often <u>precede</u> <u>a major earthquake</u> by days or, in some cases, by as much as several years.**

Where it occurs?

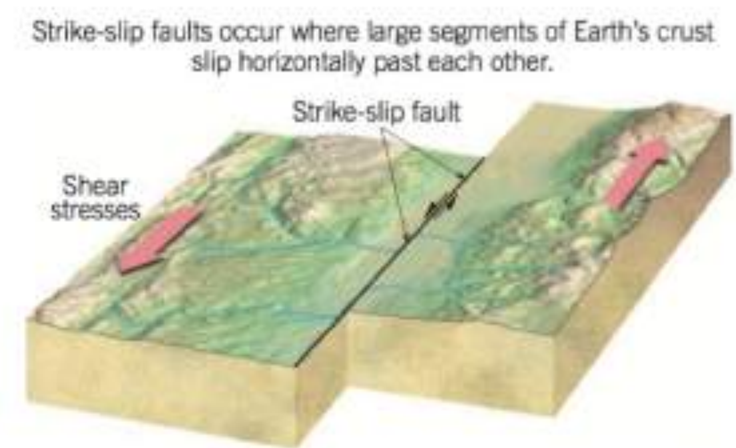
- Faults
  - Movements that produce earthquakes are usually associated with large fractures in Earth's crust called faults.
  - Most of the motion along faults can be explained by the plate tectonics theory.



A. Normal faults are associated with divergent plate boundaries, mainly seafloor spreading centers and continental rifting.



B. Reverse and thrust faults are associated with subduction zones and continental collisions.

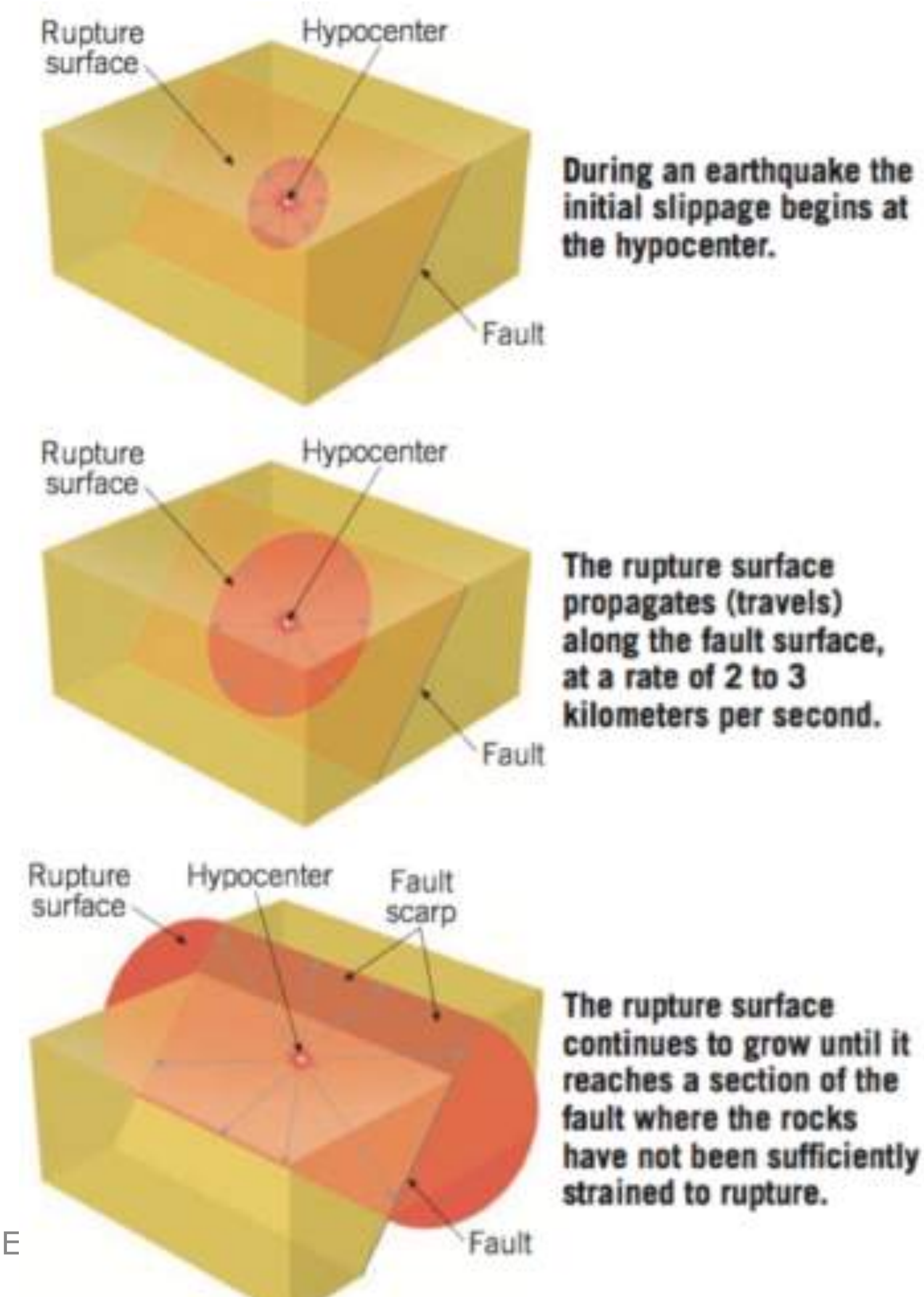


C. Large strike-slip faults may form transform plate boundaries.

Fault rupture and propagation

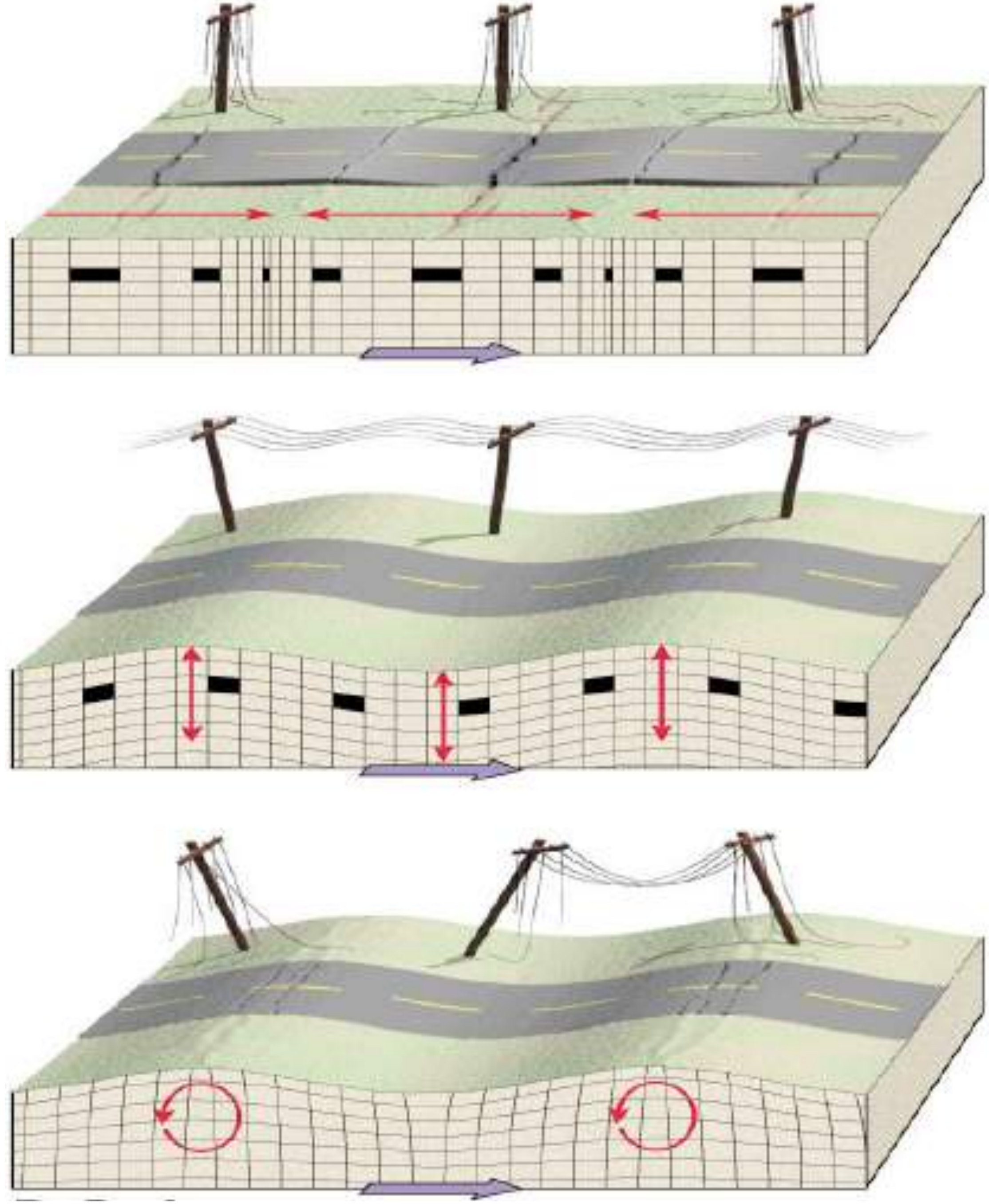
Most faults are locked. Faults do not slip at all once. The initial slip begins at the hypocenter and propagates (travels) along the fault surface, at 2 to 4 kilometers per second.
Slippage on one section of the fault adds stress to the adjacent segment that may also slip. As this zone of slippage advances, it can slow down, speed up, or even jump to a nearby fault segment. Earthquake waves are generated at every point along the fault as that portion of the fault begins to slip.

Displacement on the fault surface, called **fault slip**, is typically no more than a few meters. Slippage usually stops when the rupture reaches a section of the fault where the rocks have not been sufficiently strained to overcome frictional resistance, such as in a section of the fault that has recently experienced an earthquake. The rupture may also stop if it encounters a large kink, or an offset along the fault surface.

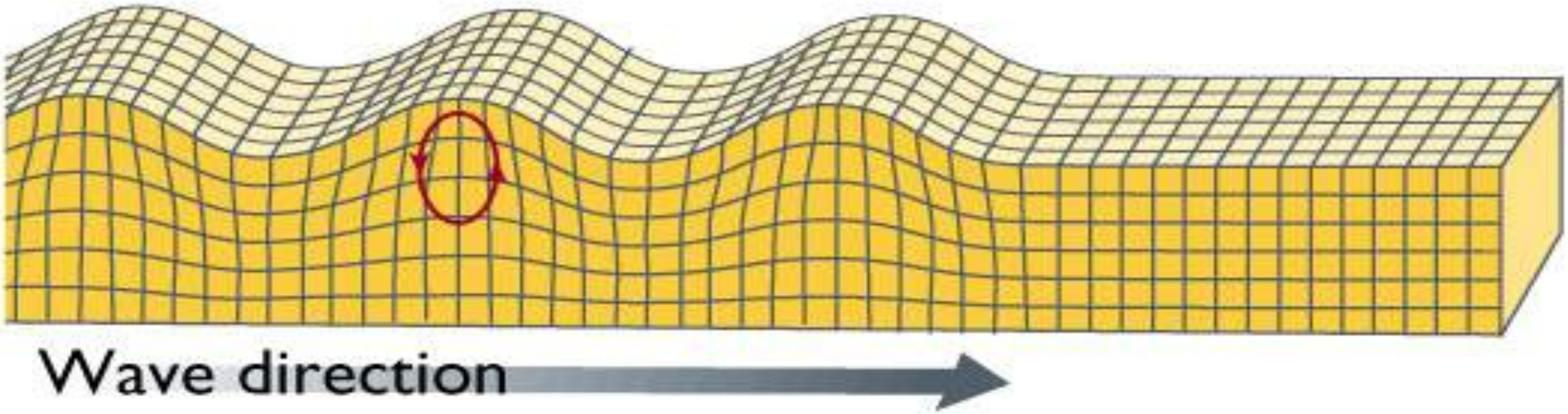


Kind of seismic waves

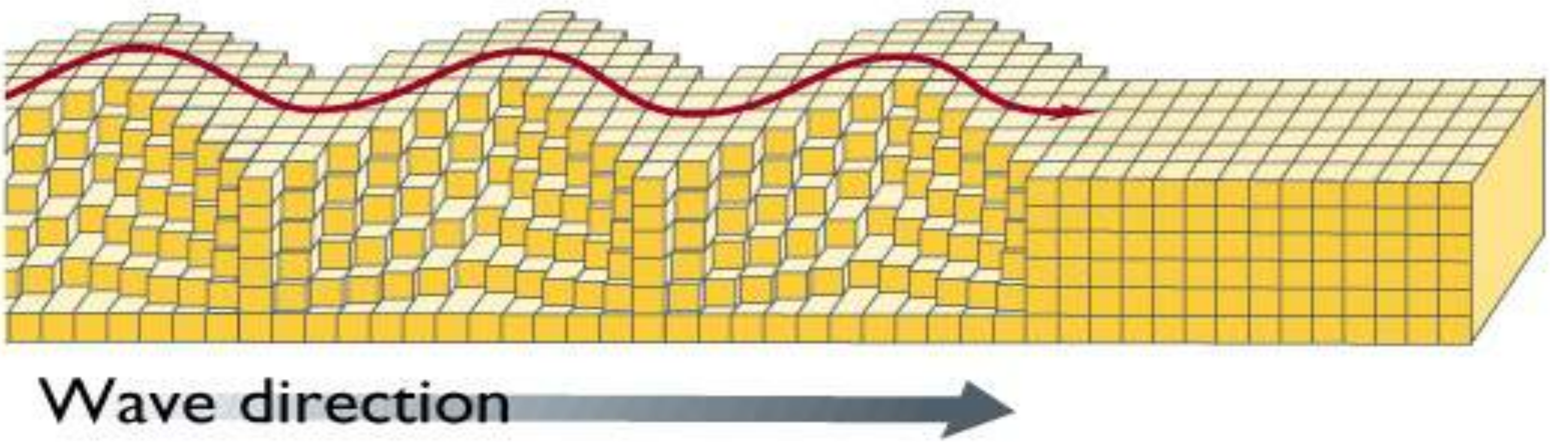
- **P-waves** – most rapid (8 km/sec)
- **S-waves** – slower (5 km/sec), cannot move through liquids
- **Surface waves** – even slower, move only on surface, most destructive



Surface waves



(a)

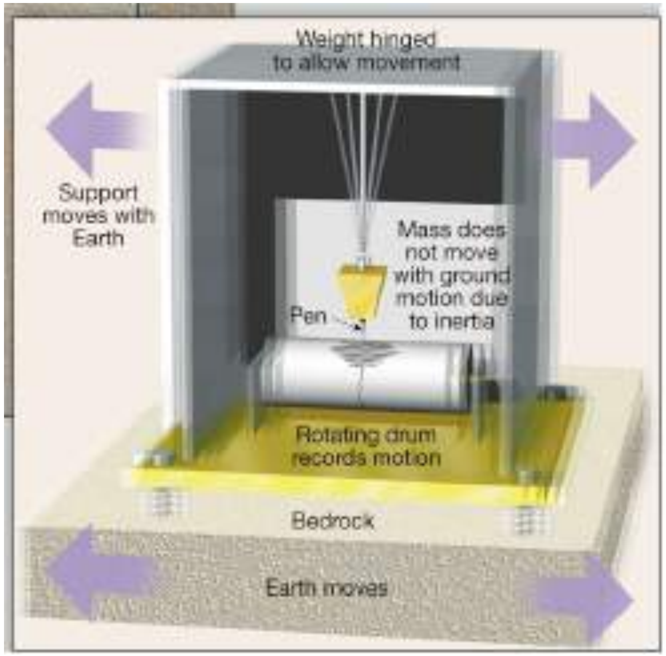


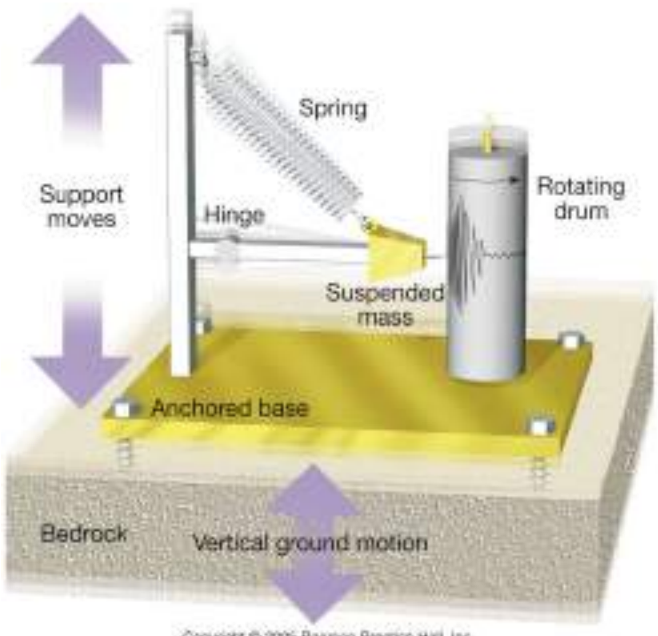
(b)

Seismology

- The study of earthquake waves, seismology.
- Seismographs are instruments that record seismic waves.
  - Records the movement of Earth in relation to a stationary mass on a rotating drum or magnetic tape
  - More than one type of seismograph is needed to record both vertical and horizontal ground motion.
  - Records obtained are called seismograms.

Detecting and measuring seismic waves



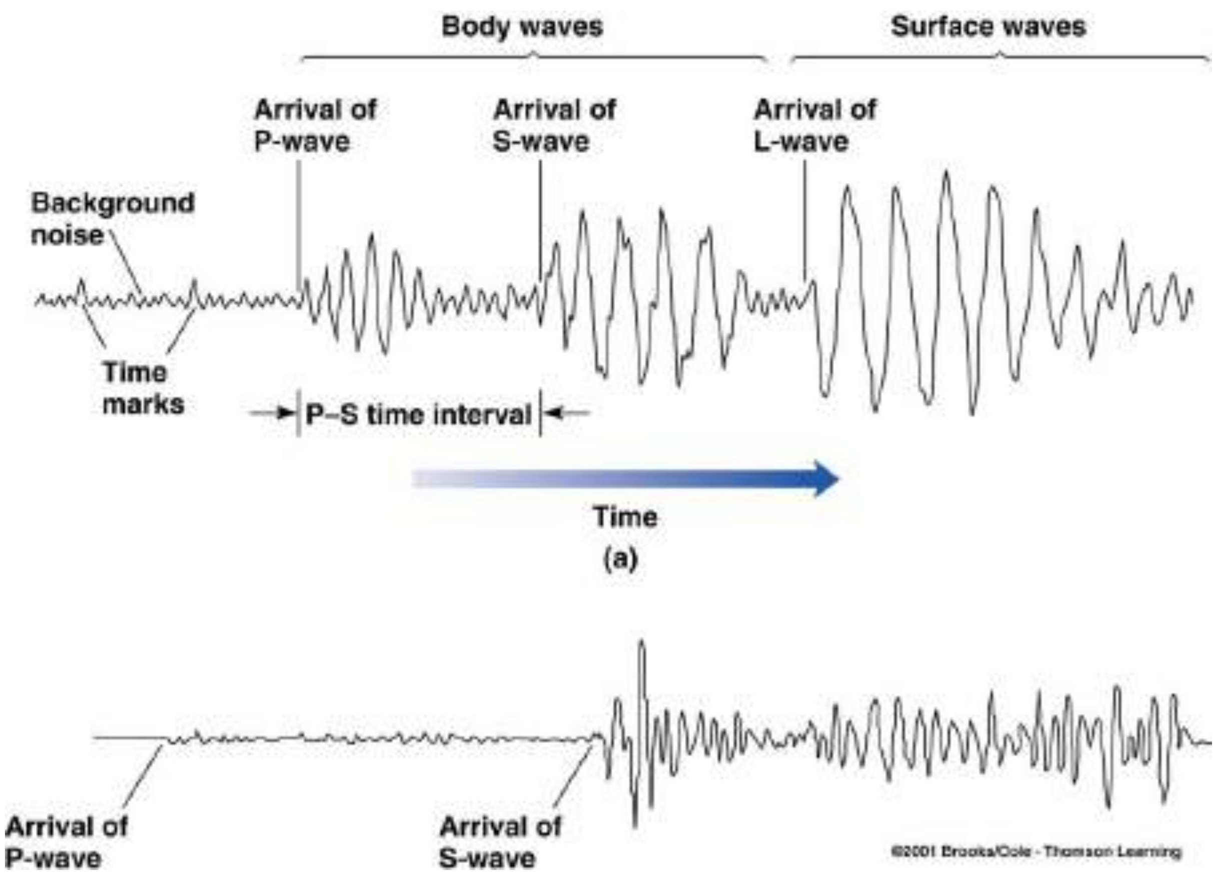


Seismometers:
•The paper roll moves with the ground
•The pen remains stationary, because of the spring, hinge and weight

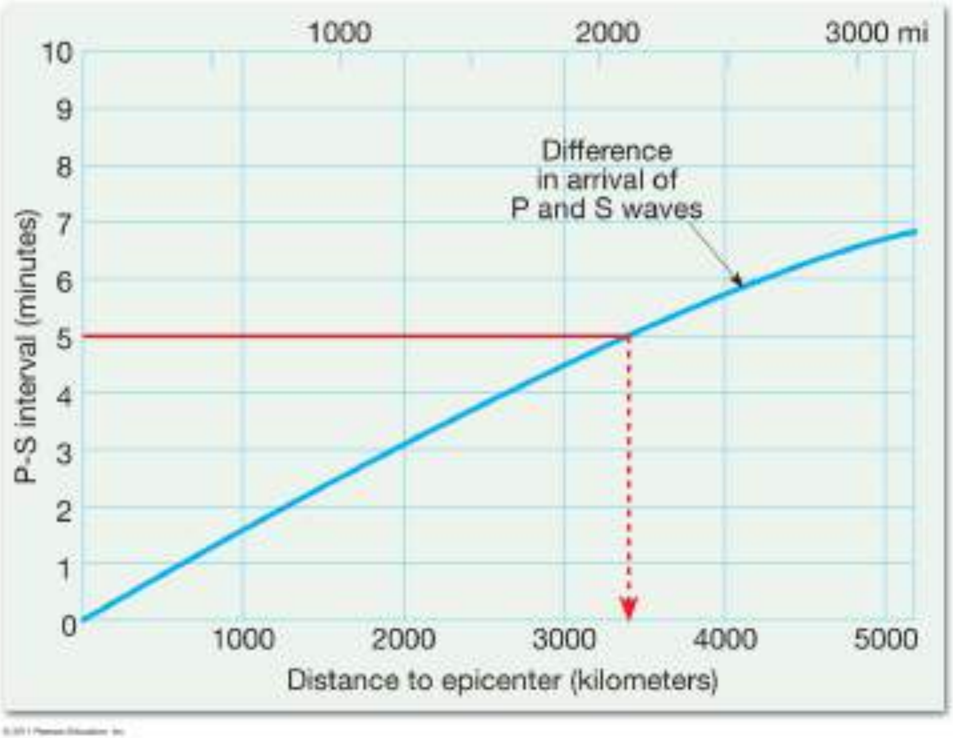
Earthquake Seismic Waves

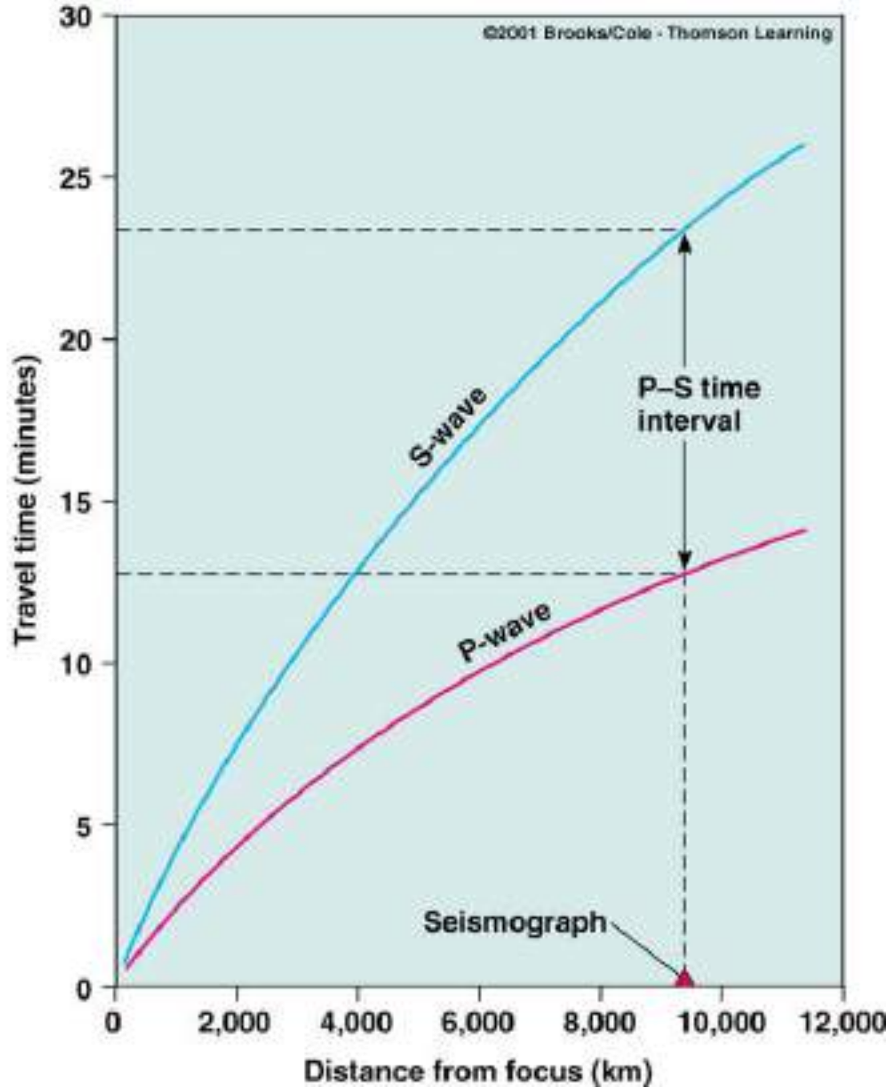
Seismic wave behavior

- **P waves arrive first, then S waves, then surface waves**
- **Average speeds for all these waves is known**
- **After an earthquake, the difference in arrival times at a seismograph station can be used to calculate the distance from the seismograph to the epicenter.**

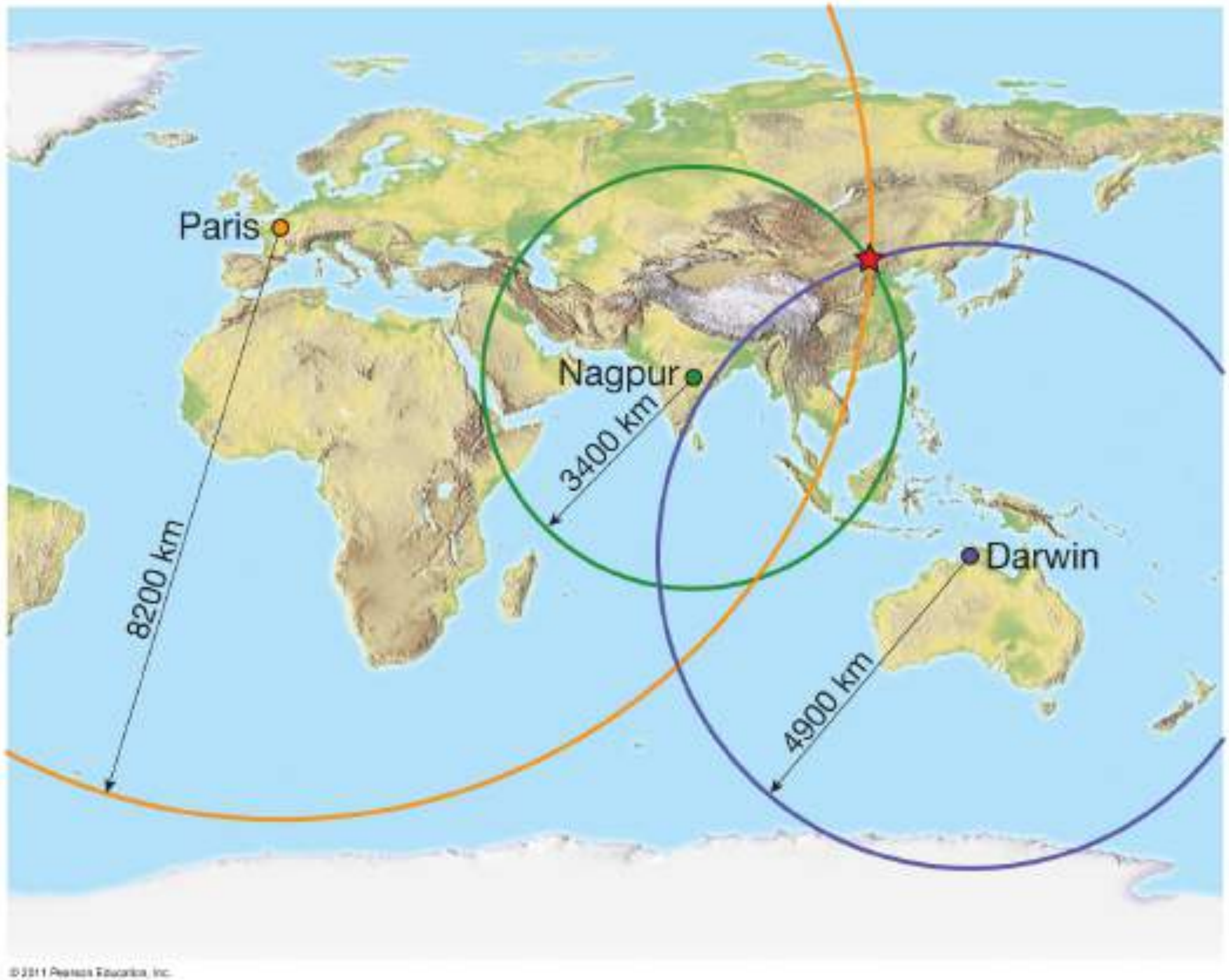


A Travel-Time Graph





Finding an Earthquake Epicenter



Locating the Source of Earthquakes

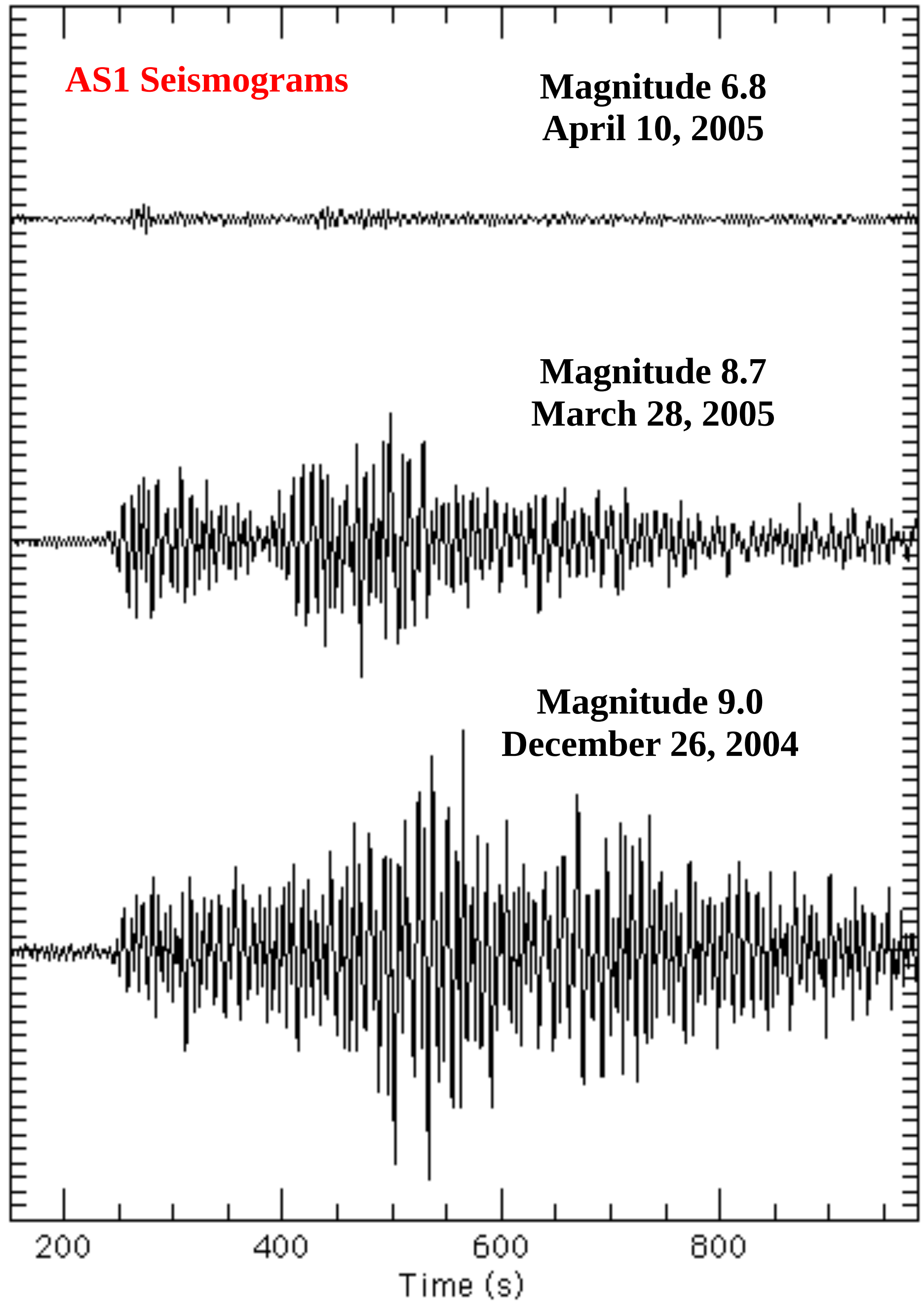
- The epicenter is located using the difference in velocities of P and S waves.
- Locating the epicenter of an earthquake
    - Three station recordings are needed to locate an epicenter.
    - Each station determines the time interval between the arrival of the first P wave and the first S wave at their location.
    - A travel-time graph is used to determine each station's distance to the epicenter.
    - A circle with a radius equal to the distance to the epicenter is drawn around each station.
    - The point where all three circles intersect is the earthquake epicenter.

Example:

Same Distance,
Different Magnitudes

Three Sumatra Earthquakes
Recorded at
Weston Observatory
Boston College

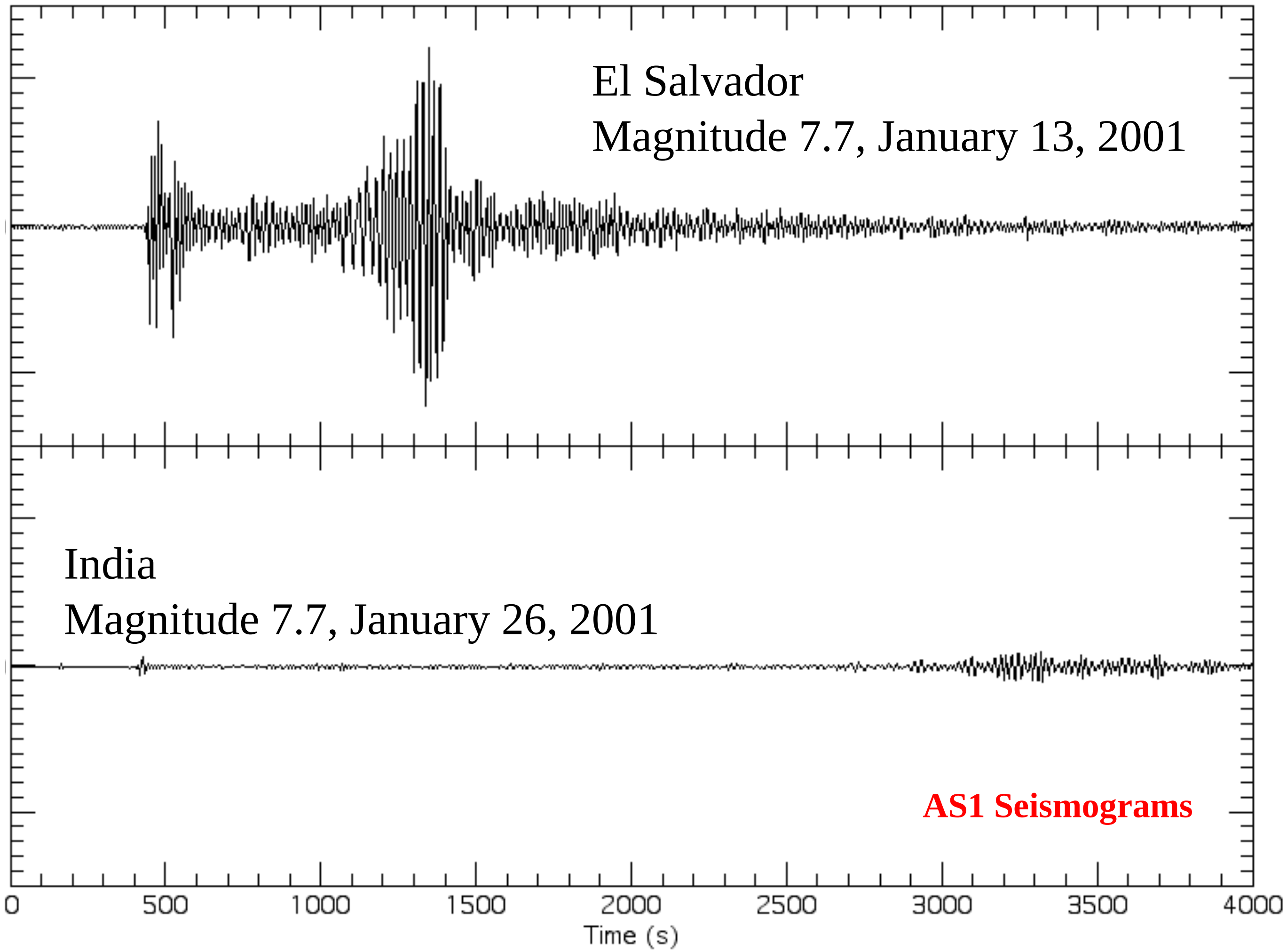
Seismograms are shown on the same scale.



Example:

Same Earthquake, Different Distances

Seismograms are shown on the same scale.



El Salvador and India Earthquakes
Recorded at Devlin Hall Boston College

Figure 3.4-5: Ray path effects for increasing velocity.

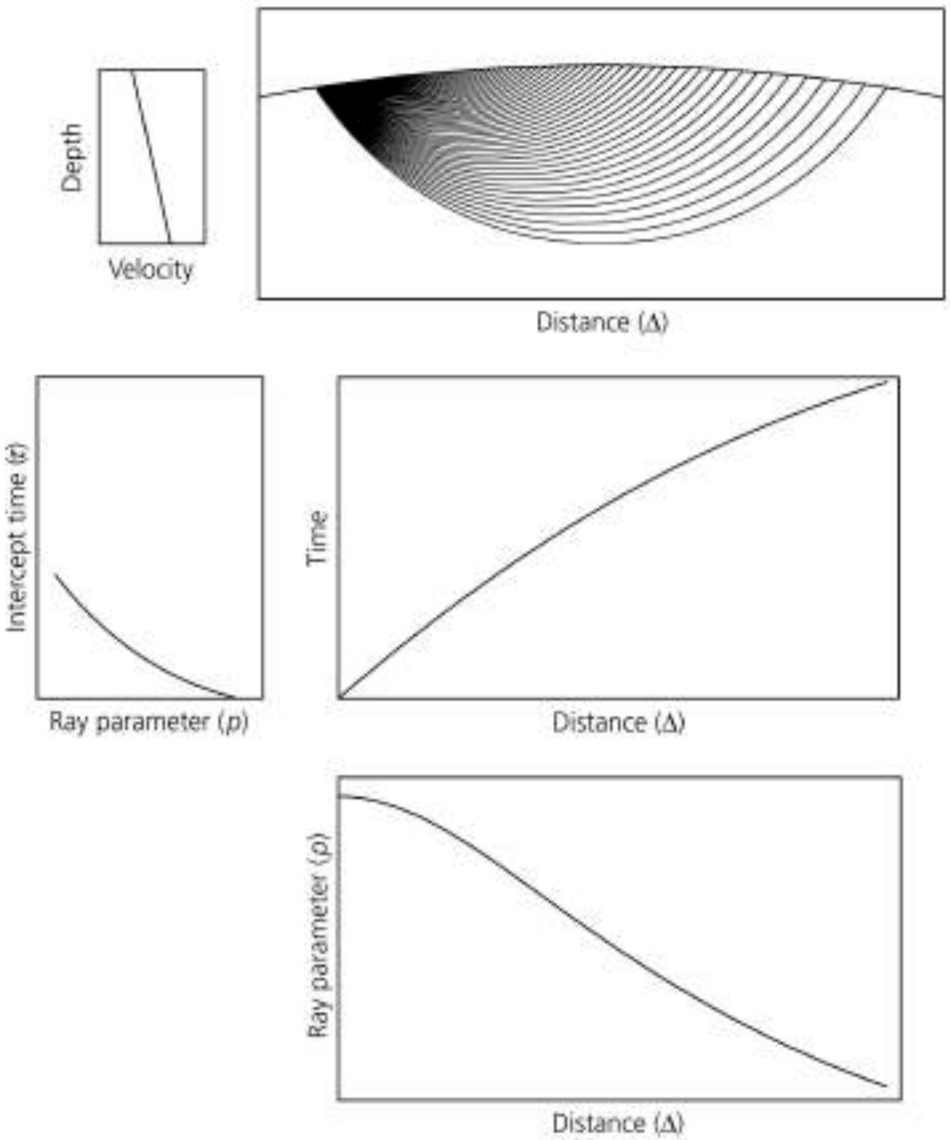


Figure 3.4-6: Ray path triplication effects for a velocity increase.

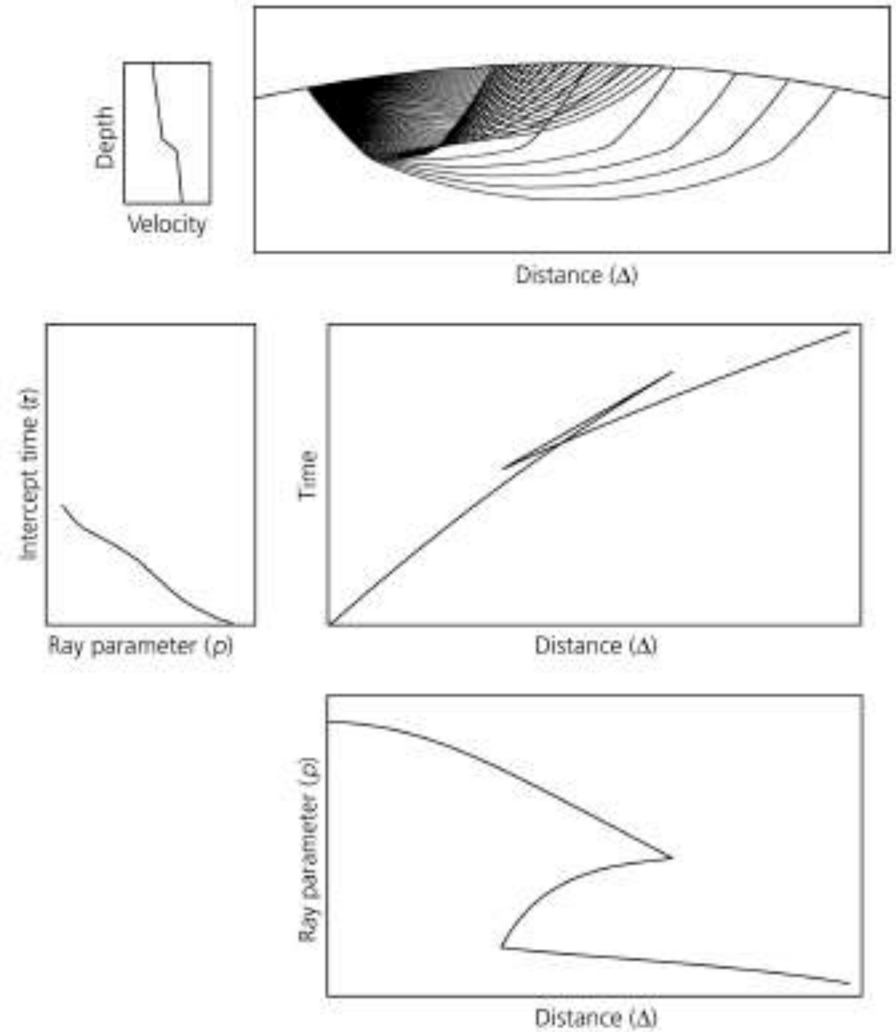


Figure 3.4-7: Ray path shadow-zone effects for a velocity decrease.

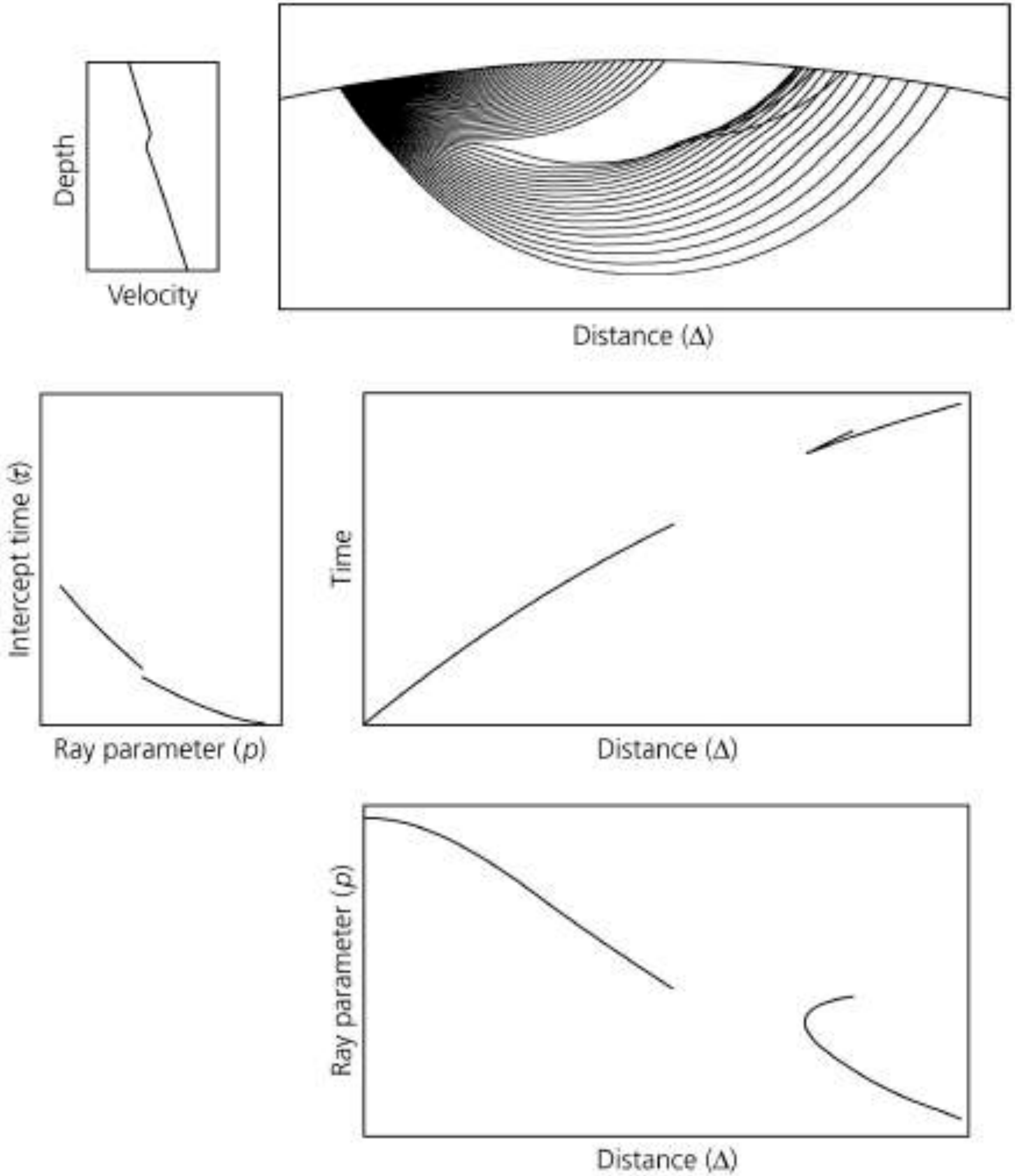


Figure 3.5-5: Illustration of various body wave phases.

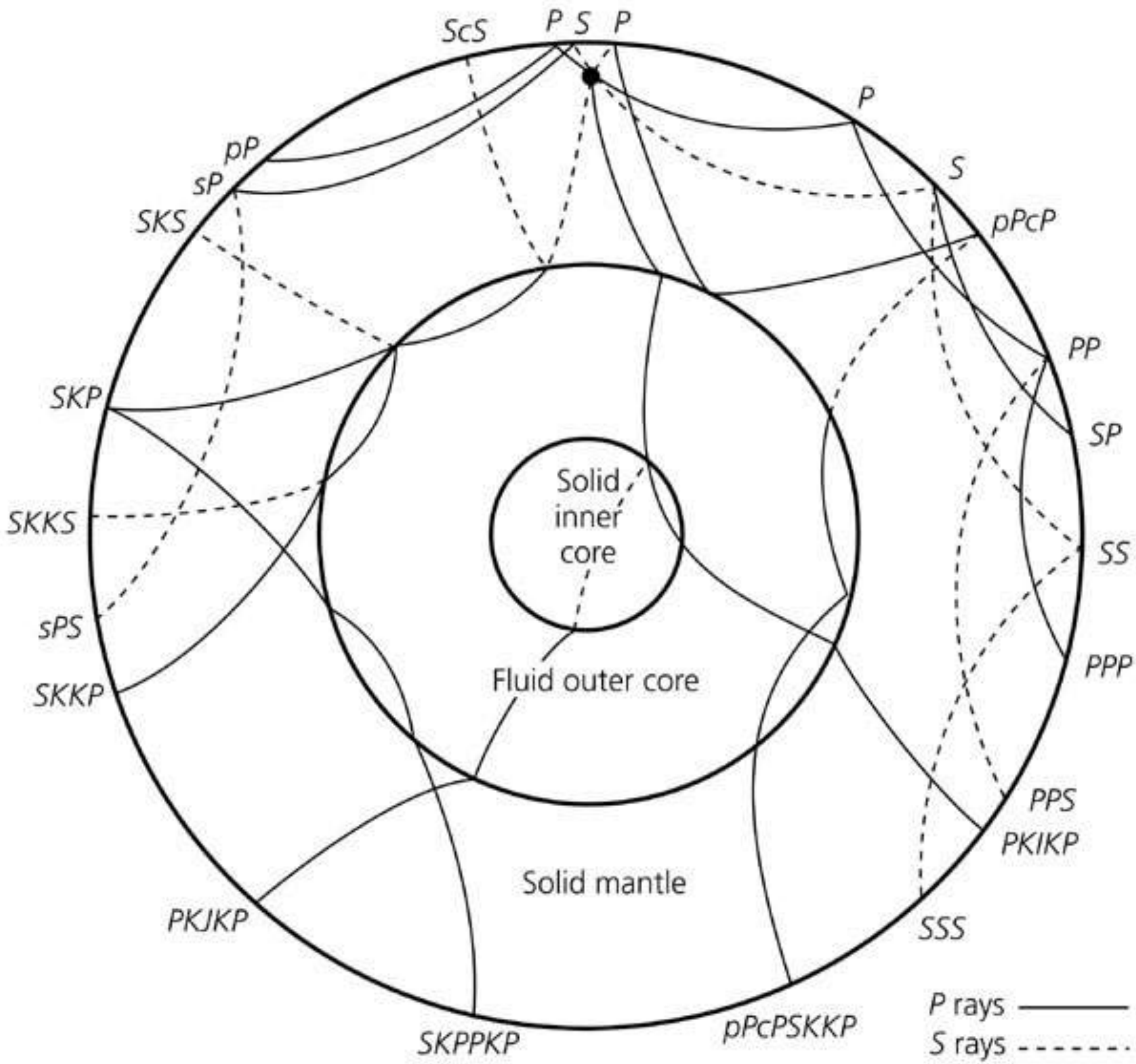


Table 3.5-2: Body wave phase nomenclature

Name	Description
P	Compressional wave
S	Shear wave
K	*P* wave through outer core
I	*P* wave through inner core
J	*S* wave through inner core
PP	*P* wave reflected at surface
PPP	*P* wave reflected at surface twice
SP	*S* wave reflected at surface as *P* wave
PS	*P* wave reflected at surface as *S* wave
pP	*P* wave upgoing from focus, reflected at surface
sP	*S* wave upgoing from focus, converted to *P* at surface
c	Wave reflected at core-mantle boundary (e.g. *ScS*)
i	Wave reflected at inner core-outer core boundary (e.g. *PKiKP*)
P′	Abbreviation for *PKP*
P_d or P_{diff}	*P* wave diffracted along core-mantle boundary

Figure 3.5-3: Travel time data and curves for the IASP91 model.

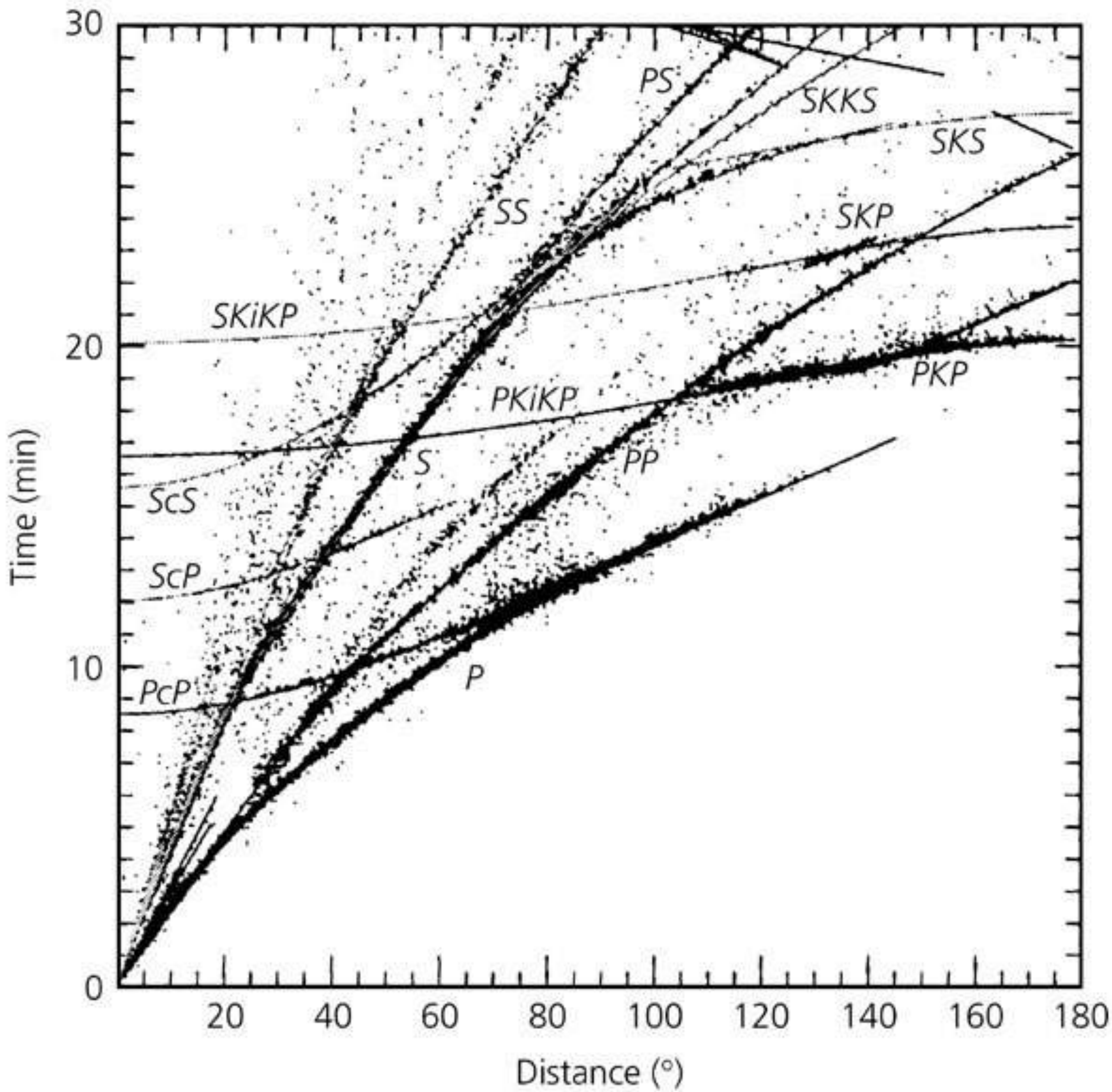


Figure 3.5-1: Comparison of the J-B and IASP91 earth models.

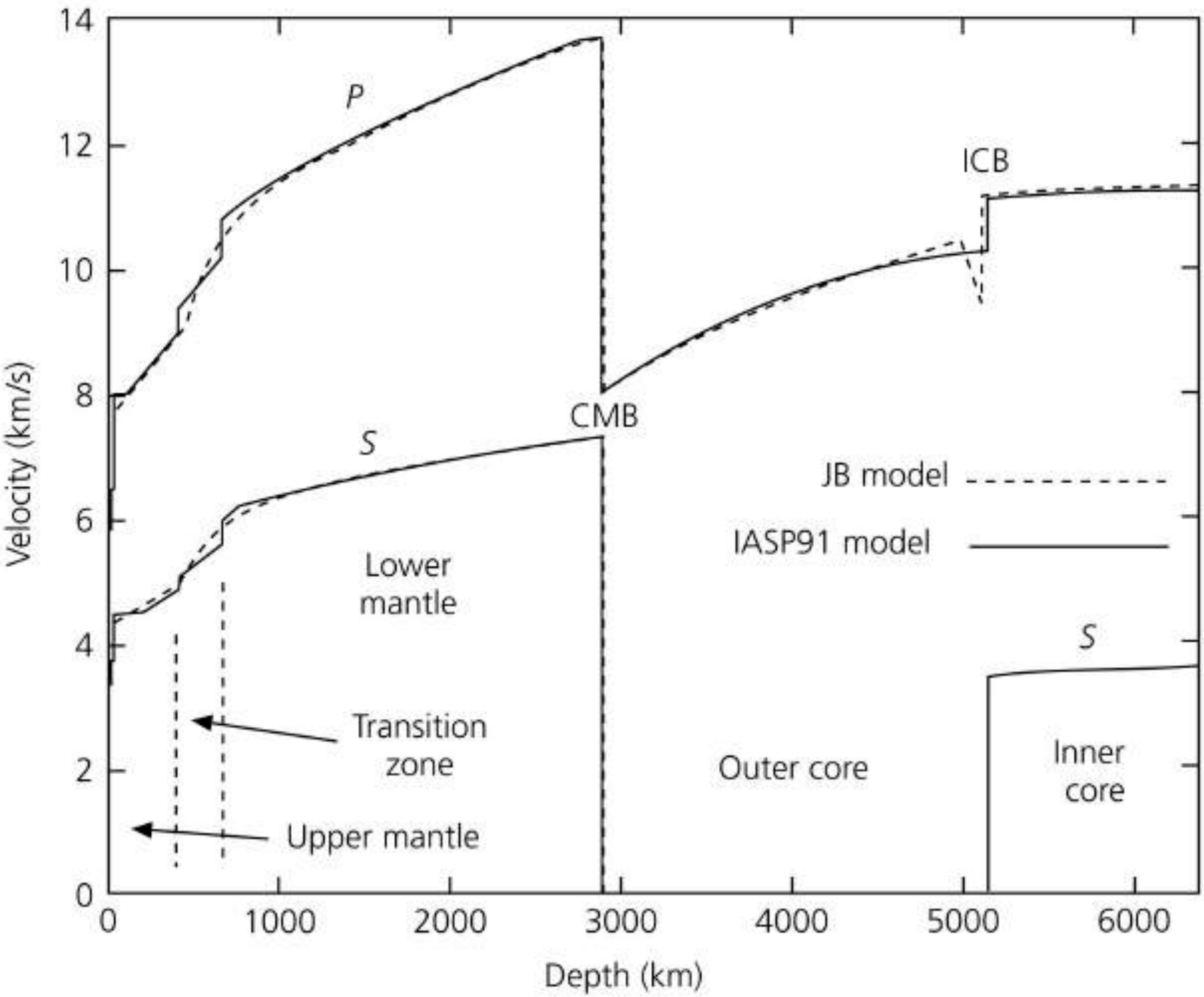


Table 3.5-1: Regions in Jeffreys-Bullen earth model

Region	Depth (km)	Features of region
A		Crustal layers
	33	
B		Upper mantle: steady positive *P* and *S* velocity gradients
	413	
C		Mantle transition region
	984	
D		Lower mantle: steady positive *P* and *S* velocity gradients
	2898	
E		Outer core: steady positive *P* velocity gradient
	4982	
F		Core transition: negative *P* velocity gradient
	5121	
G		Inner core: small positive *P* velocity gradient
	6371	

After *Bullen and Bolt* [1985]

Figure 7.3.9: Example of whole-mantle tomography using an inversion of waveforms and travel times.

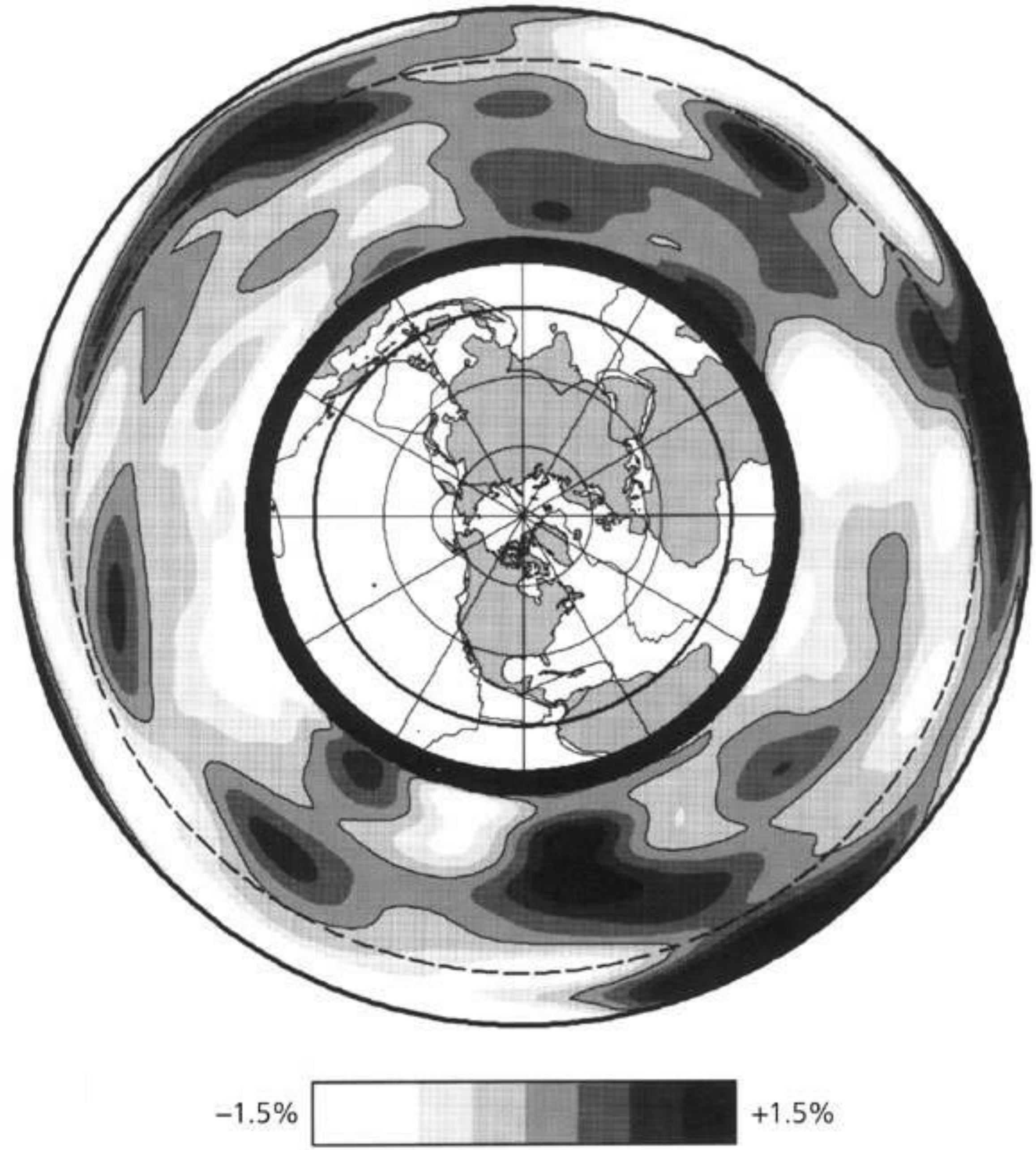


Figure 2.7-1: Seismograms recorded at a distance of 110°, showing surface waves.

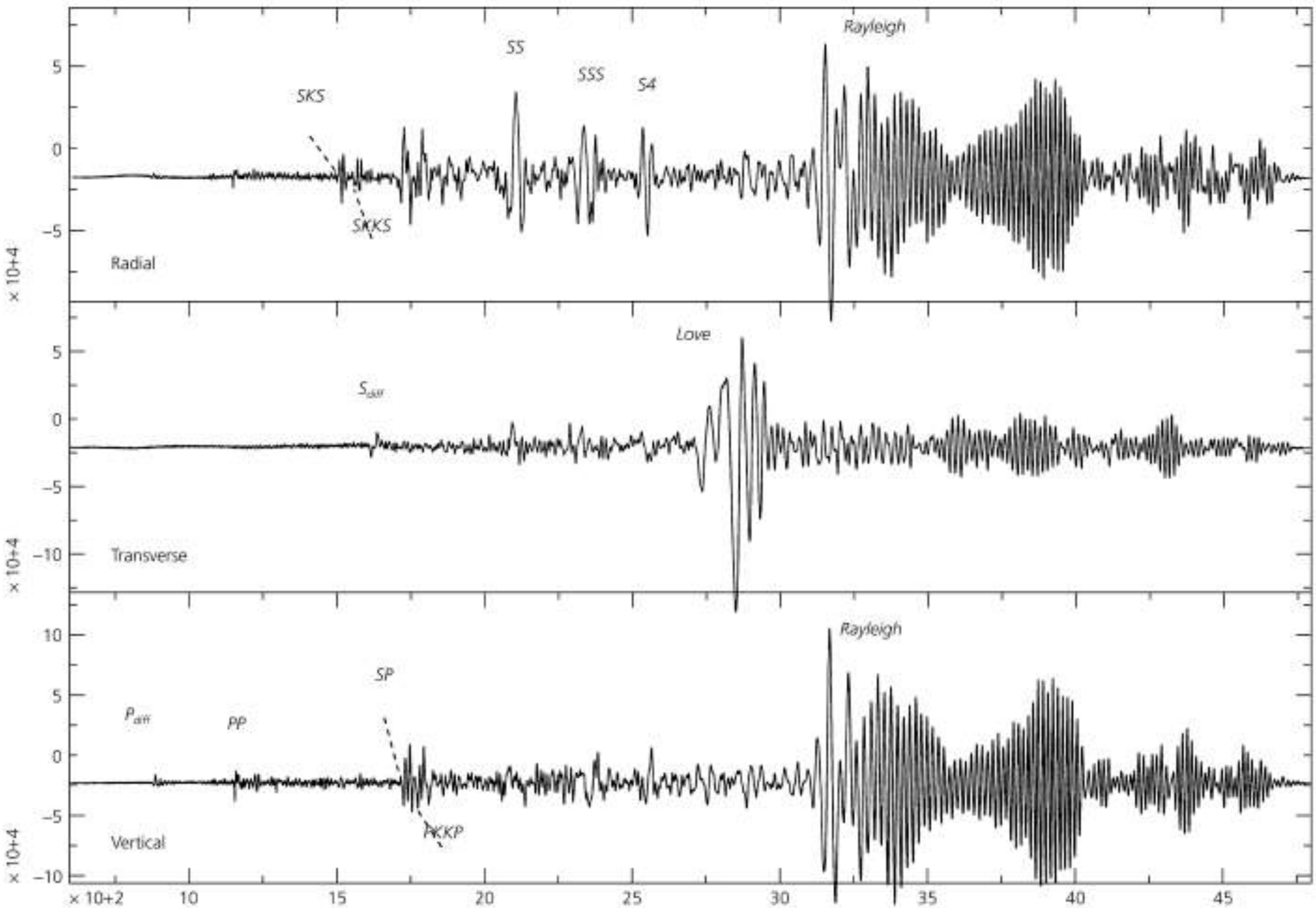


Figure 2.7-2: Geometry for Love and Rayleigh wave motions.

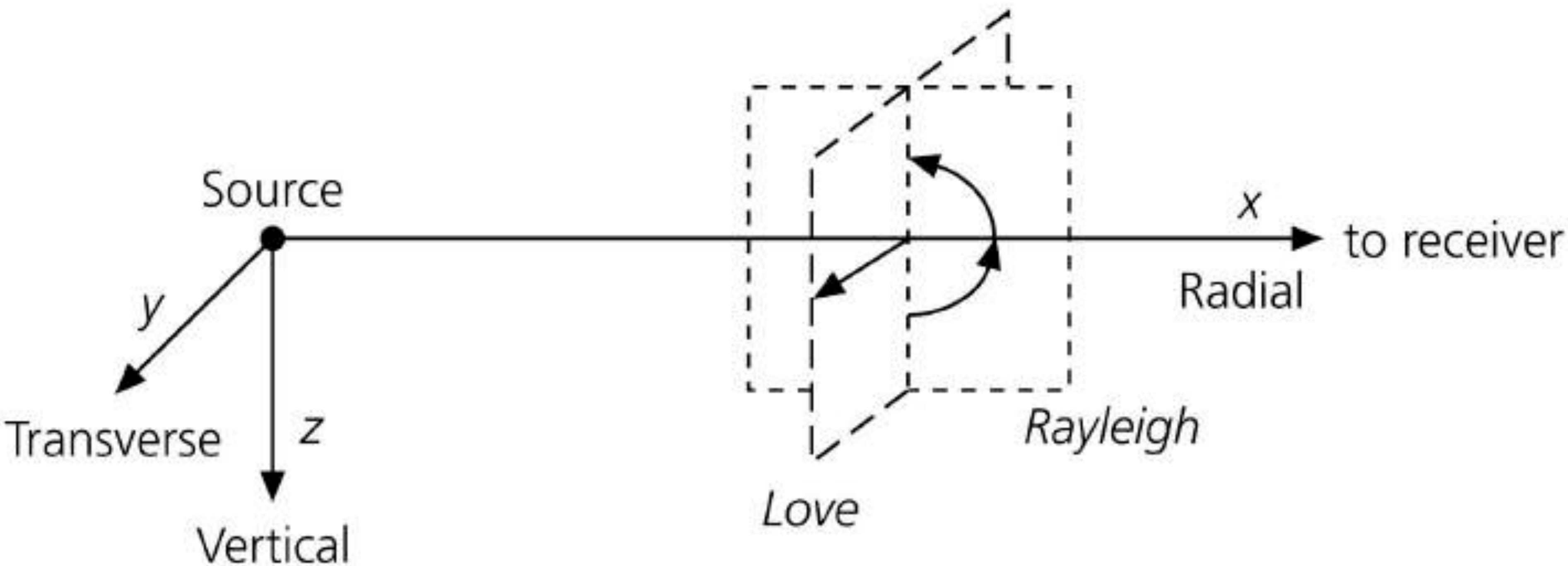


Figure 2.7-3: Multiple surface waves circle the earth.

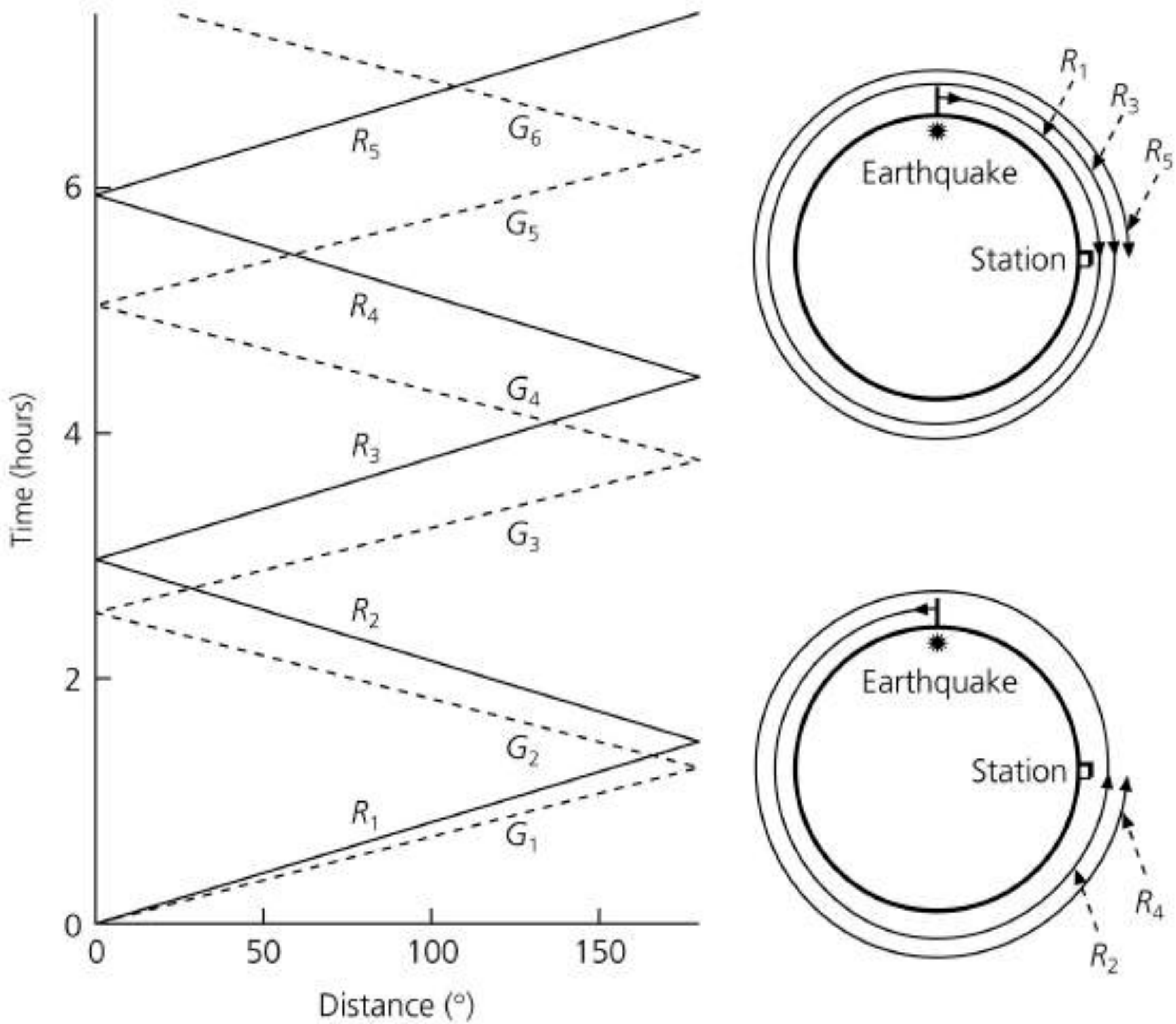


Figure 2.7-4: Six-hour stacked IDA record section.

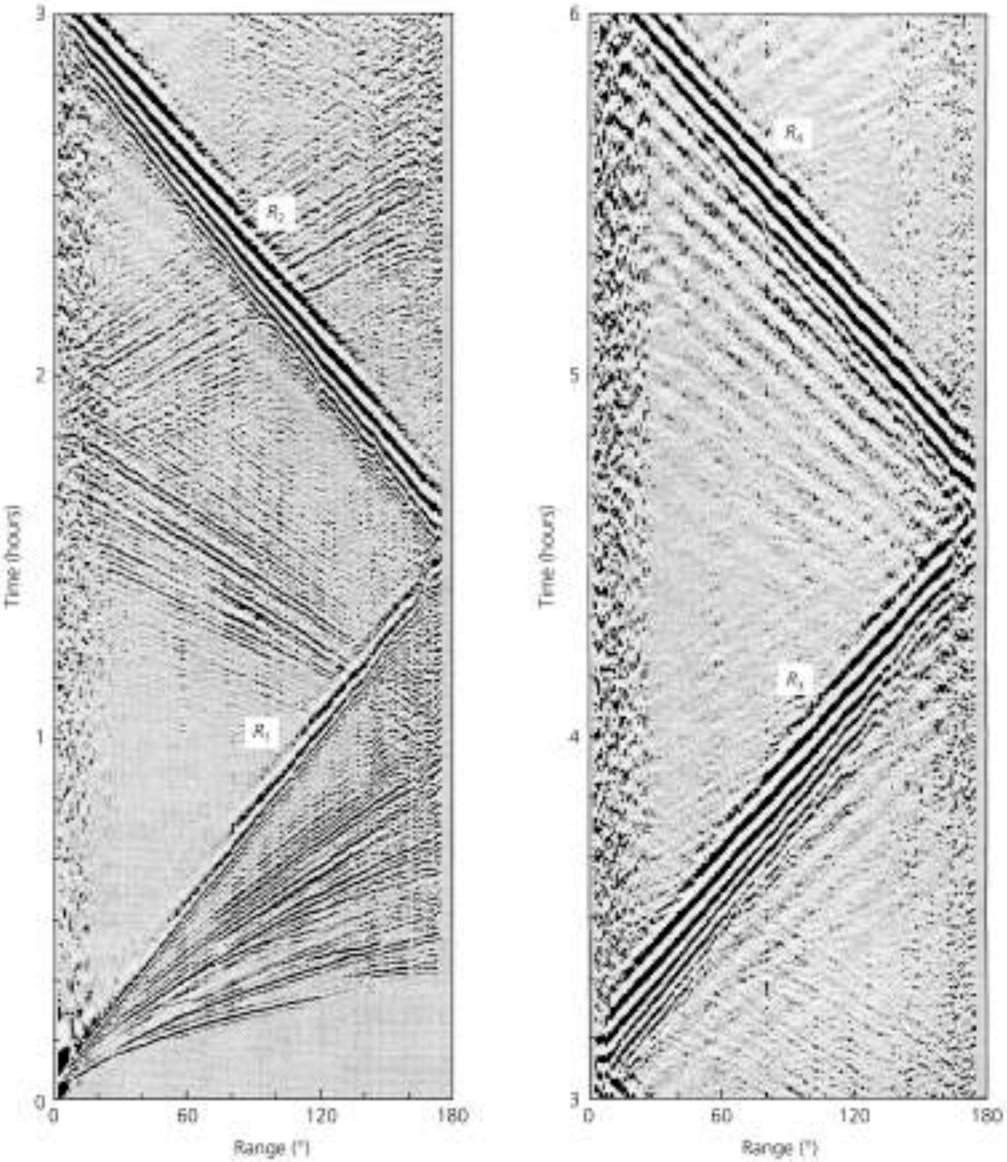


Figure 2.7-10: Displacements of for Love waves in a layer over a halfspace.

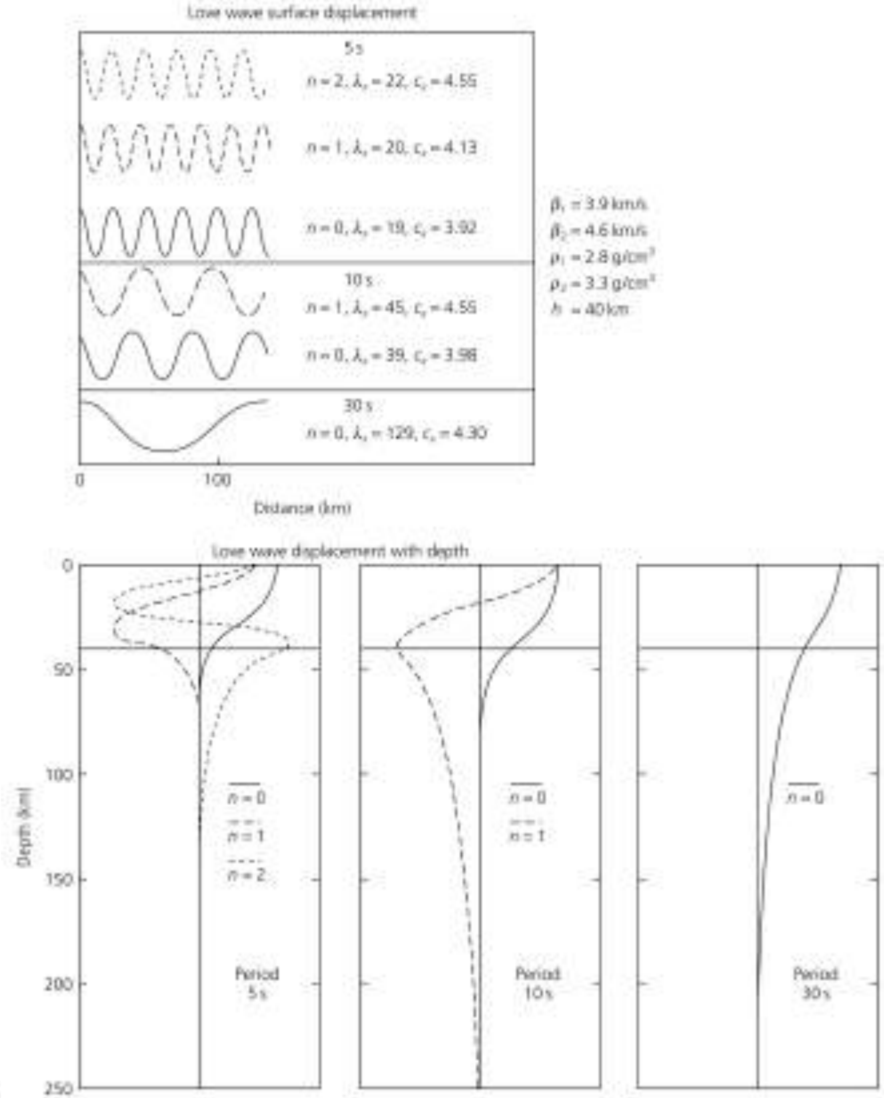


Figure 2.8-1: Demonstration of group and phase velocities for the sum of two sine waves.

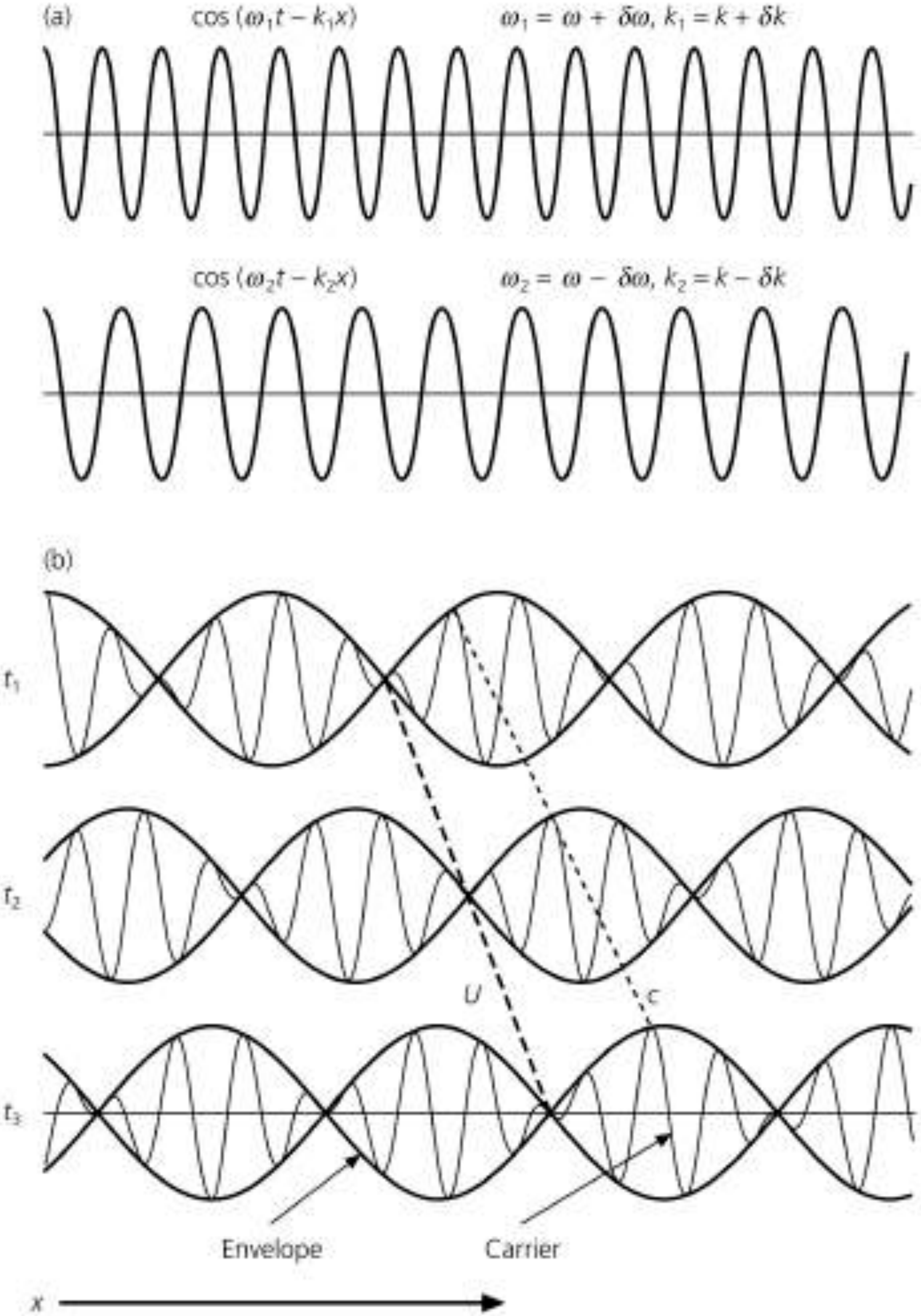
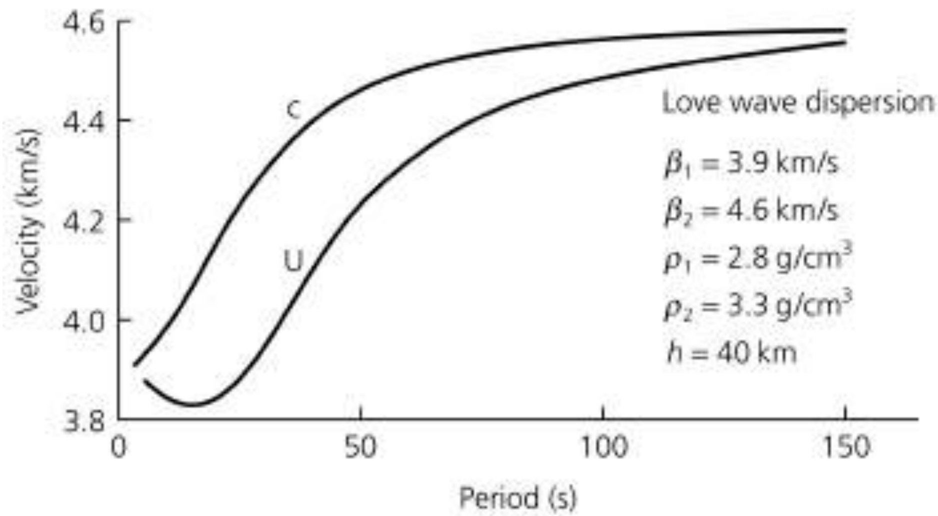


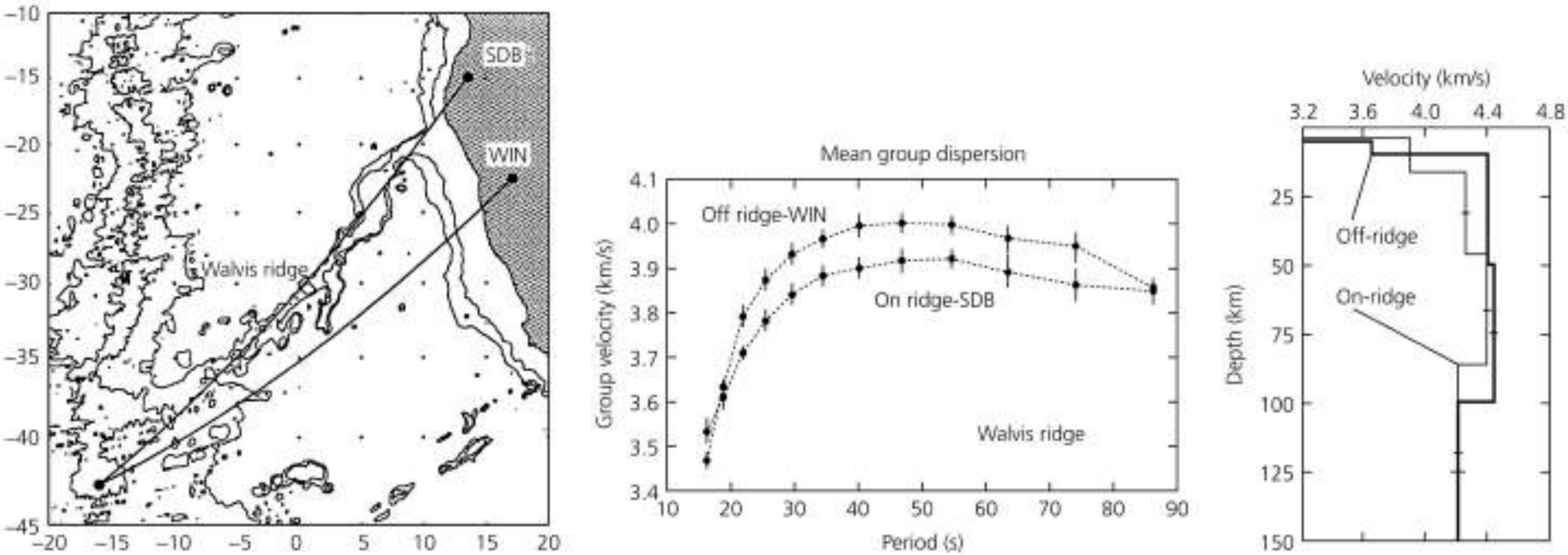
Figure 2.8-2: Fundamental mode Love wave group and phase velocities.



$$U = \frac{d\omega}{dk} = \frac{d(ck)}{dk} = c + k\frac{dc}{dk} = c - \lambda\frac{dc}{d\lambda}$$

U=group velocity (envelop)
C=phase velocity (carier)

Figure 2.8-5: Rayleigh wave group velocity study of the Walvis ridge.



Fundamentals of Earth Sciences (ESO 213A)

Dibakar Ghosal
Department of Earth Sciences

Earthquakes continued

Previous Class:* *Earthquakes

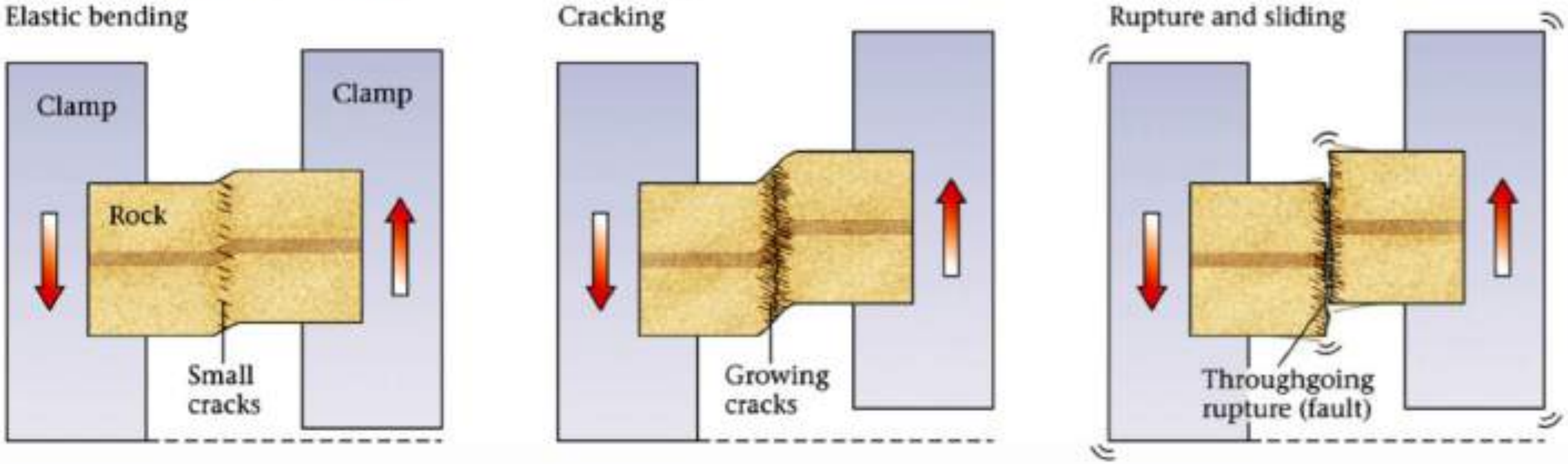
Formation of Faults

- Faults and thus earthquakes form because of stress & strain
  - Plate motion causes rocks to deform or bend
  - Stress and strain become localized
  - Eventually the strength of the rock is overcome
  - BAM!! The rock ruptures and snaps forward releasing the accumulated stress/strain.
    - The process is known as ***elastic rebound theory***

Elastic strain: strain that is recoverable

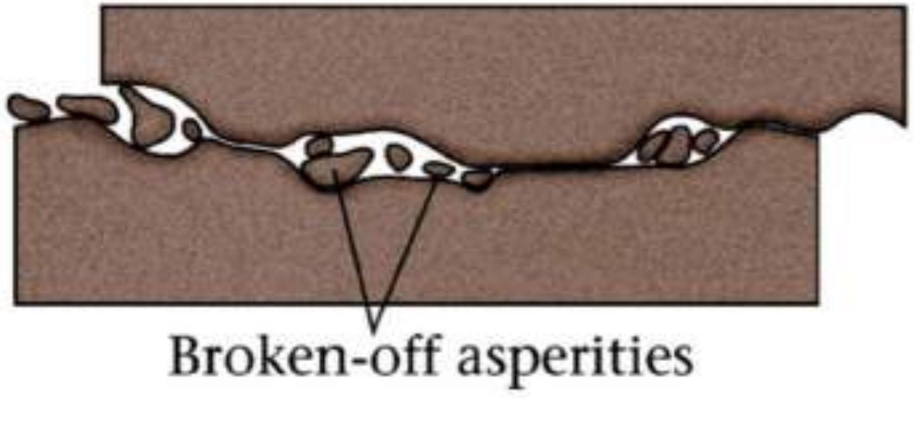
New cracks form and link together

A through-going fault forms and sliding occurs causing a ***stress drop***

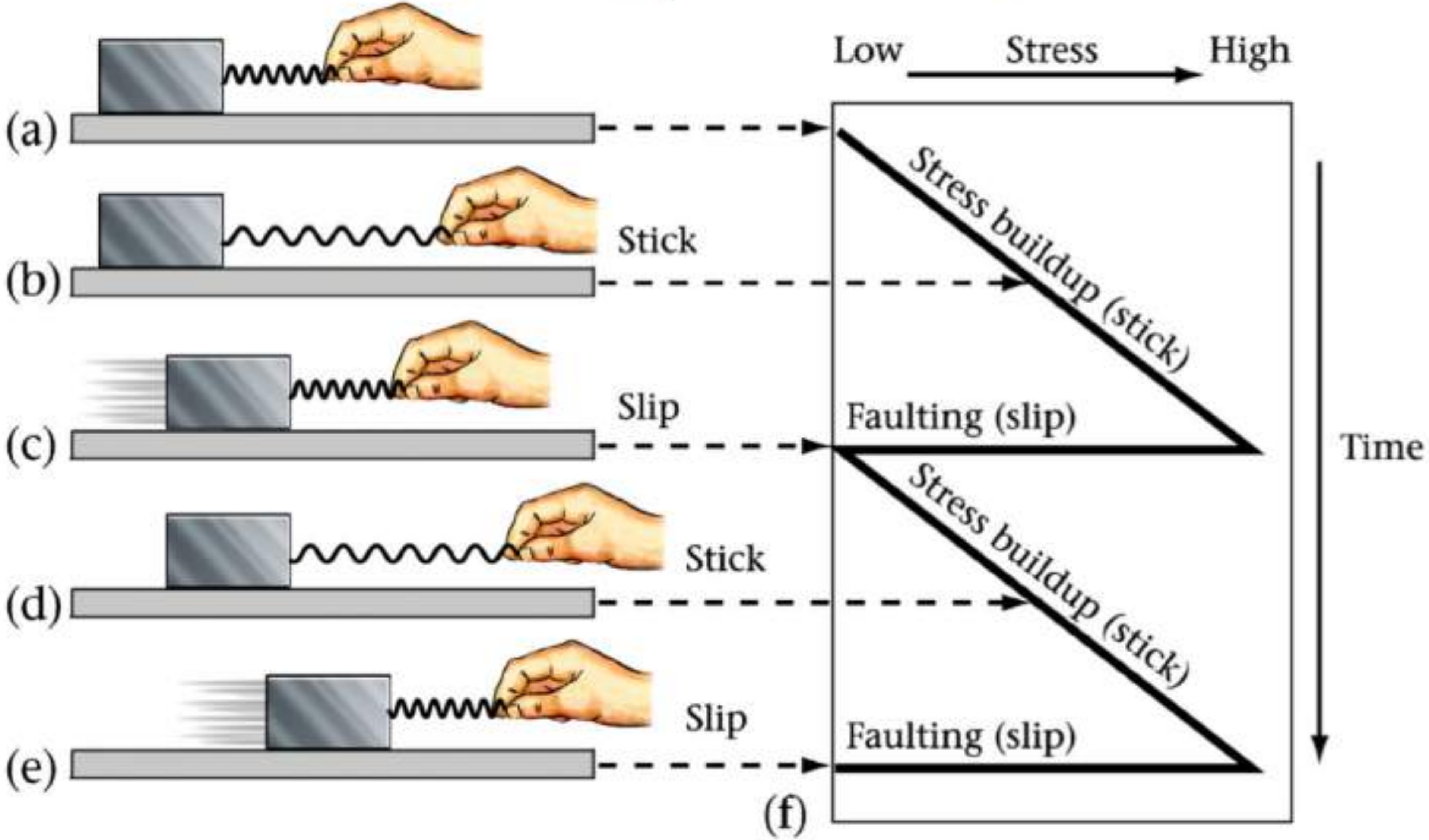


Faults & Friction

- Like a brick sliding across a table, faults, too, are subject to friction
- Friction, on the micro-scale, is caused by **asperities**, bumps and irregularities along a surface that resist sliding
- All other factors equal, faults with more cumulative slip may be smoother and therefore have lower friction (e.g. the San Andreas Fault has very low friction)
  - Once a fault is formed it is a permanent scar that is weaker than the surrounding rock



Stick Slip Behavior



- Without stick slip behavior, large earthquakes would not happen!
    - Faults would constantly move (i.e. ***creep***) and not build up significant stress

Measuring the Size of Earthquakes

Two measurements that describe the size of an earthquake are:

1. Intensity—a measure of the degree of earthquake shaking at a given locale based on the amount of damage
2. Magnitude estimates the amount of energy released at the source of the earthquake.

Measuring the Size of Earthquakes

- Intensity scales
  - The Modified Mercalli Intensity Scale was developed using California buildings as its standard.
  - The drawback of intensity scales is that destruction may not be a true measure of the earthquake's actual severity.

TABLE 11.1 Modified Mercalli Intensity Scale

I	Not felt except by a very few under especially favorable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings.
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake.
IV	During the day felt indoors by many, outdoors by few. Sensation like heavy truck striking building.
V	Felt by nearly everyone, many awakened. Disturbances of trees, poles, and other tall objects sometimes noticed.
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; few instances of fallen plaster or damaged chimneys. Damage slight.
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight-to-moderate in well-built ordinary structures; considerable in poorly built or badly designed structures.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. (Fall of chimneys, factory stacks, columns, monuments, walls.)
IX	Damage considerable in specially designed structures. Buildings shifted off foundations. Ground cracked conspicuously.
X	Some well-built wooden structures destroyed. Most masonry and frame structures destroyed. Ground badly cracked.
XI	Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground.
XII	Damage total. Waves seen on ground surfaces. Objects thrown upward into air.

Measuring the Size of Earthquakes

Earthquake *magnitude* is based on the measured amplitude recorded on a seismogram as wave amplitude reflects the earthquake size after correction for geometrical spreading and attenuation applied.

General form of Magnitude scales:

$$M = \log(A/T) + F(h, \Delta) + C$$

A is the amplitude of the signal

T is its dominant period

F is a correction for the variation of amplitude with the earthquake's depth h and distance Δ from the seismometer

C is a regional scale factor

Richter scale

Based on the amplitude of the largest seismic wave recorded
Accounts for the decrease in wave amplitude with increased distance
The largest magnitude recorded on a Wood–Anderson seismograph was 8.9.
Magnitudes less than 2.0 are not felt by humans.
Each unit of Richter magnitude increase corresponds to a tenfold increase in wave amplitude and a 32-fold energy increase.

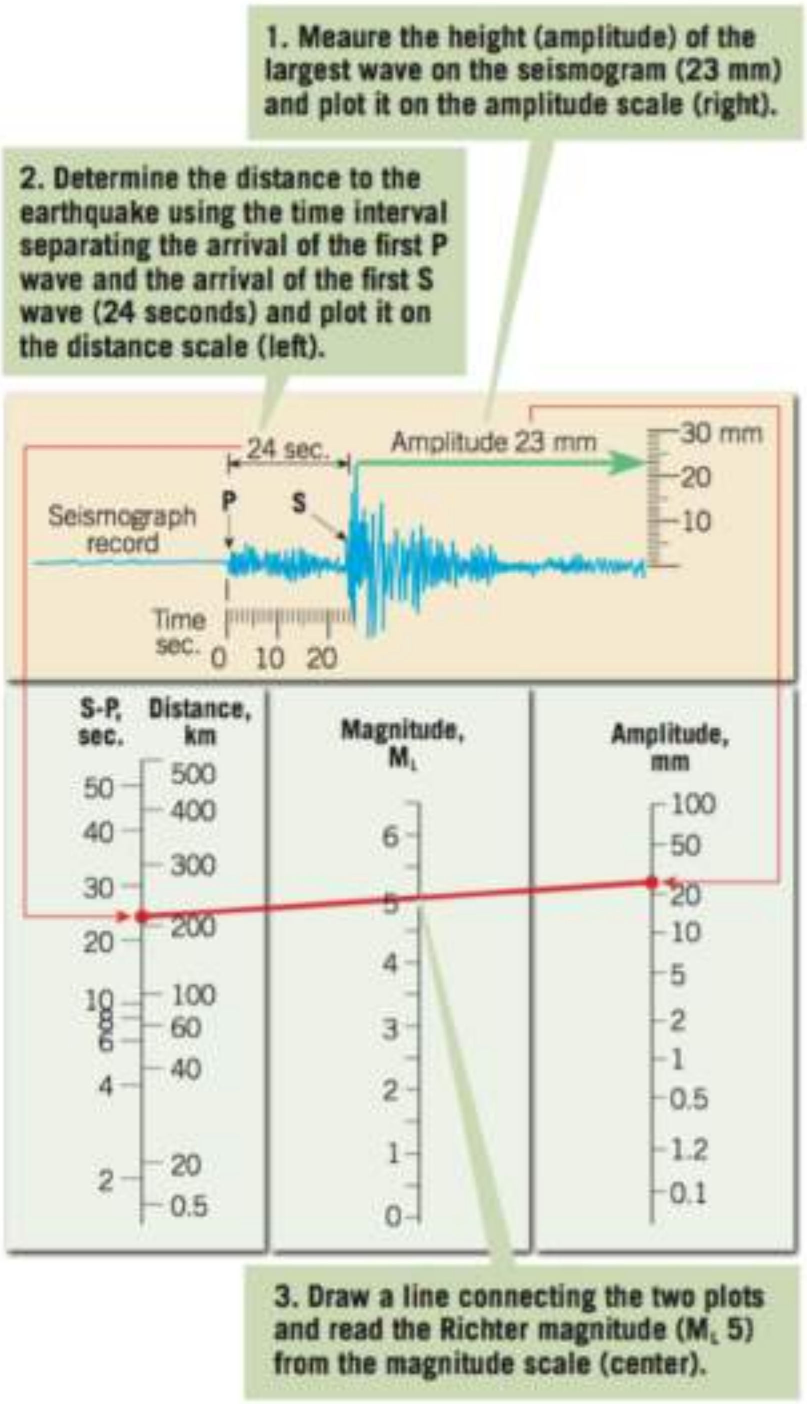
Magnitude scales are logarithmic, so an increase in one unit, as from magnitude "5" to a "6", indicates a ten-fold increase in seismic wave amplitude.

Measured magnitudes range more than 10 units because the displacements measured by seismometers span more than a factor of 10^{10}.

"Richter scale" (local magnitude) was introduced by Charles Richter in 1935 for Southern California earthquakes measured on a *Wood-Anderson* seismograph.

$$M_L = \log A + 2.76 \log \Delta - 2.48$$

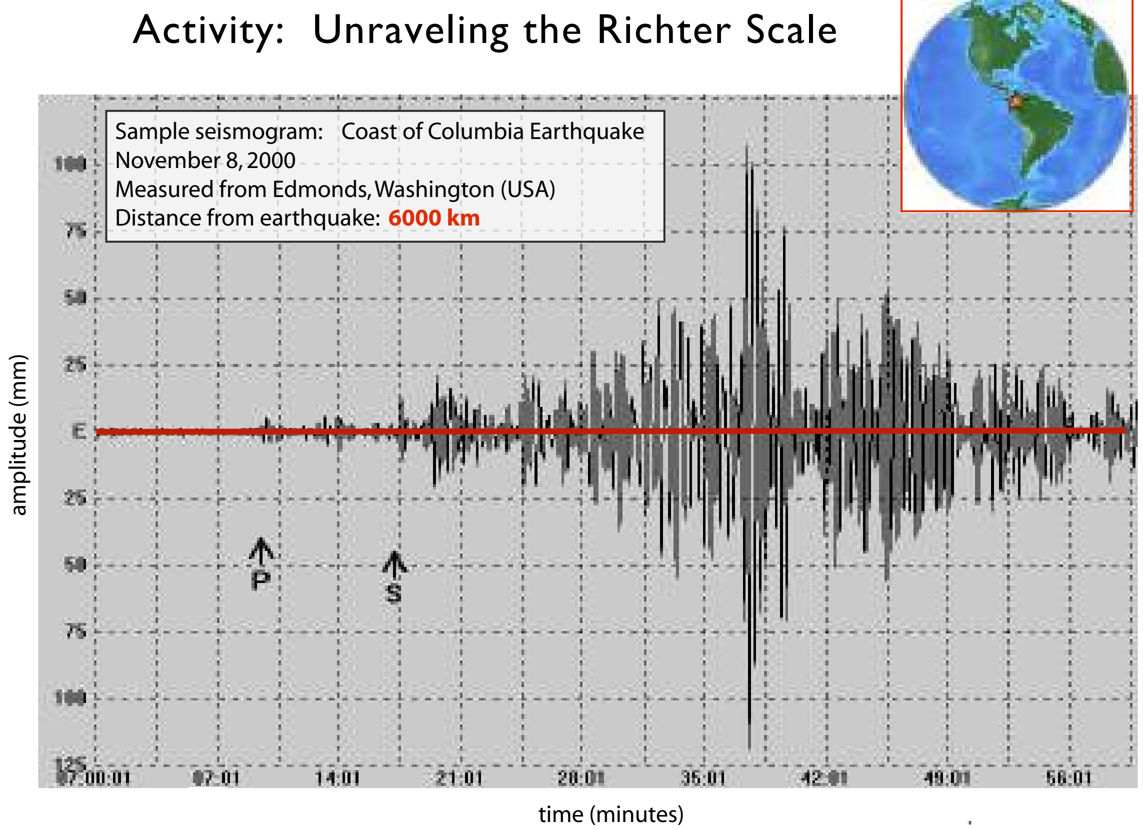
The instrument period (0.8 s) and nearly constant (shallow) depth are incorporated in the constants, and the distance is in km.

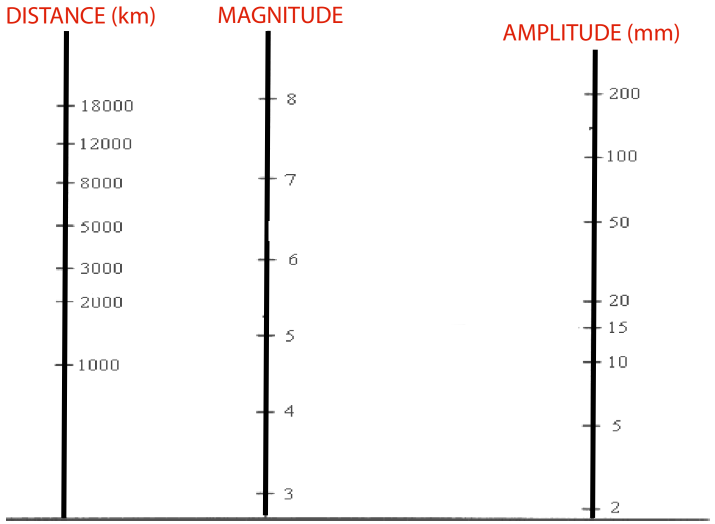


Magnitude vs. Ground Motion and Energy

Magnitude Change	Ground Motion Change (amplitude)	Energy Change (approximate)
4.0	10,000 times	1,000,000 times
3.0	1000 times	32,000 times
2.0	100 times	1000 times
1.0	10.0 times	32 times
0.5	3.2 times	5.5 times
0.1	1.3 times	1.4 times

Activity: Unraveling the Richter Scale





What is the magnitude? ____________________

Body wave magnitude:

$$m_b = \log(A/T) + Q(h, \Delta)$$

A is the ground motion amplitude in microns after the effects of the seismometer are removed

T is the wave period in seconds

Q is an empirical term depending on the distance and focal depth.

Surface wave magnitude (measured using the largest amplitude, zero to peak, of the surface waves):

$$M_s = \log(A/T) + 1.66 \log \Delta + 3.3 \qquad \text{(general form)}$$

$$M_s = \log A_{20} + 1.66 \log \Delta + 2.0 \qquad \text{(for 20 second period Rayleigh waves)}$$

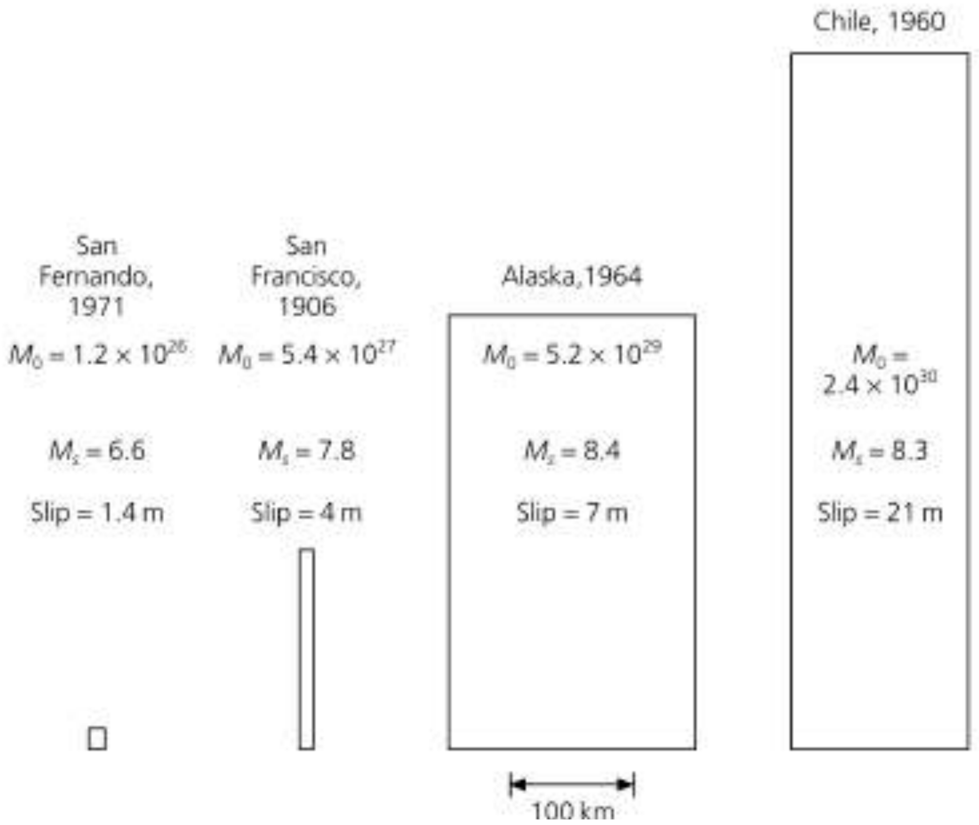
(Δ is in degrees)

Measuring the Size of Earthquakes

Other Magnitude scales

- Several "Richter-like" magnitude scales have been developed.
- **Moment magnitude** was developed because none of the "Richter-like" magnitude scales adequately estimate very large earthquakes.
- Derived from the amount of displacement that occurs along a fault

Figure 4.6-3: Comparison of the magnitudes of four earthquakes.



Moment magnitude:

$$M_w = \frac{\log M_0}{1.5} - 10.73$$

(with M_0 in dyn-cm)

Earthquake	Body wave magnitude m_b	Surface wave magnitude M_s	Fault area (km^2) length × width	Average dislocation (m)	Moment (dyn-cm) M_0	Moment magnitude M_w
Truckee, 1966	5.4	5.9	10 × 10	0.3	8.3×10^{24}	5.8
San Fernando, 1971	6.2	6.6	20 × 14	1.4	1.2×10^{26}	6.7
Loma Prieta, 1989	6.2	7.1	40 × 15	1.7	3.0×10^{26}	6.9
San Francisco, 1906		8.2	320 × 15	4	6.0×10^{27}	7.8
Alaska, 1964	6.2	8.4	500 × 300	7	5.2×10^{29}	9.1
Chile, 1960		8.3	800 × 200	21	2.4×10^{30}	9.5

Earthquake Magnitude and Energy Equivalent

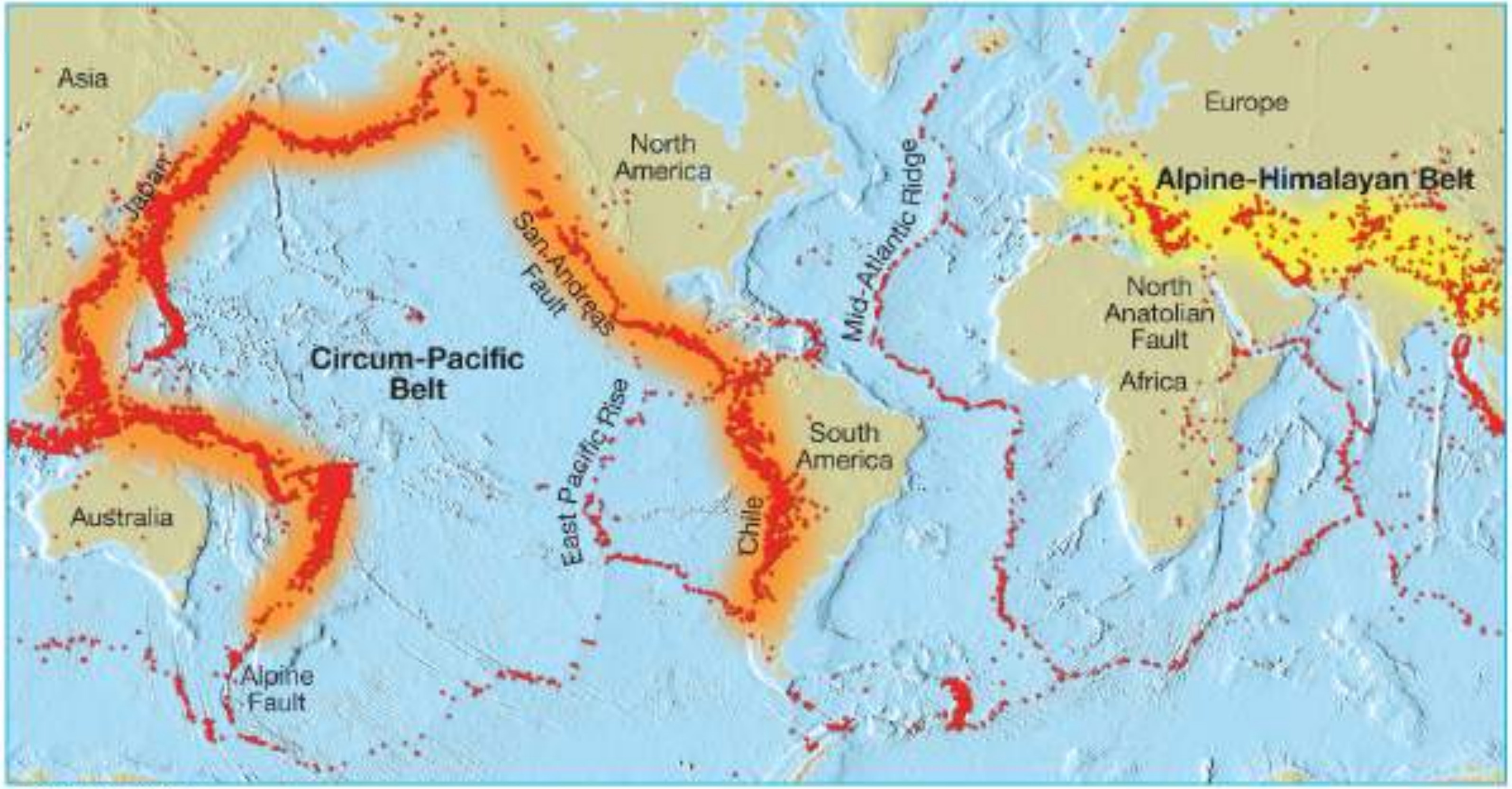
Frequency and Energy Released by Earthquakes of Different Magnitudes

Magnitude (Mw)	Average Per Year	Description	Examples	Energy Release (equivalent kilograms of explosive)
9	<1	**Largest recorded earthquakes–** destruction over vast area massive loss of life possible	Chile, 1960 (M 9.5); Alaska, 1964 (M 9.0); Japan, 2011 (M 9.0)	56,000,000,000,000
8	1	**Great earthquakes–** severe economic impact large loss of life	Sumatra, 2006 (M 8.6); Mexico City, 1980 (M 8.1)	1,800,000,000,000
7	15	**Major earthquakes–** damage ($ billions) loss of life	New Madrid, Missouri 1812 (M 7.7); Turkey, 1999 (M 7.6); Charleston, South Carolina, 1886 (M 7.3)	56,000,000,000
6	134	**Strong earthquakes–** can be destructive in populated areas	Kobe, Japan, 1995 (M 6.9); Loma Prieta, California, 1989 (M 6.9); Northridge, California, 1994 (M 6.7)	1,800,000,000
5	1319	**Moderate earthquakes–** property damage to poorly constructive buildings	Mineral, Virginia, 2011 (M 5.8); Northern New York, 1994 (M 5.8); East of Oklahoma City, Oklahoma, 2011 (M5.6)	56,000,000
4	13,000	**Light earthquakes–** noticable shaking of items indoors, some property damage	Western Minnesota, 1975 (M 4.6); Arkansas, 2011 (M 4.7)	1,800,000
3	130,000	**Minor earthquakes–** felt by humans, very light property damage, if any	New Jersey, 2009 (M3.0) Maine, 2006 (M3.8)	56,000
2	1,300,000	**Very minor earthquakes–** felt by humans, no property damage		1,800
	Unknown	Generally not felt by humans, but may be recorded		56

Data from USGS

Locating the Source of Earthquakes

- Earthquake belts
  - About 95% of the energy released by earthquakes originates in a few relatively narrow zones that wind around the globe.
  - Major earthquake zones include the Circum-Pacific belt, Mediterranean Sea region to the Himalayan complex, and the oceanic ridge system.

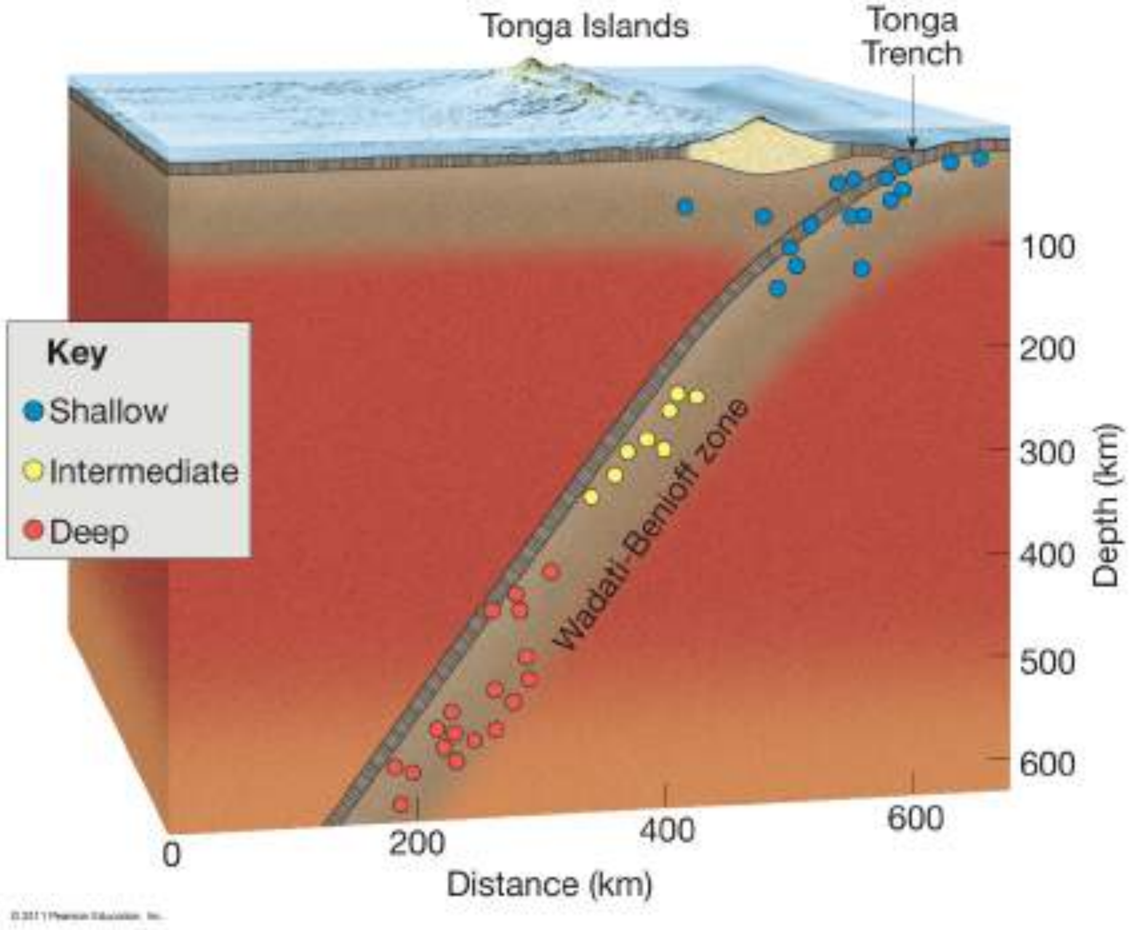


Can Earthquakes Be Predicted?

- Short-range predictions
    - The goal is to provide a warning of the location and magnitude of a large earthquake within a narrow time frame.
    - Research has concentrated on monitoring possible precursors—phenomena that precede a forthcoming earthquake, such as measuring uplift, subsidence, and strain in the rocks.
    - **Currently, no reliable method exists for making short-range earthquake predictions.**
- Long-range forecasts
    - Give the probability of a certain magnitude earthquake occurring on a time scale of 30 to 100 years, or more.
    - Based on the premise that earthquakes are repetitive or cyclical
        - Using historical records or paleoseismology
    - Are important because they provide information used to:
        - Develop the Uniform Building Code
        - Assist in land-use planning

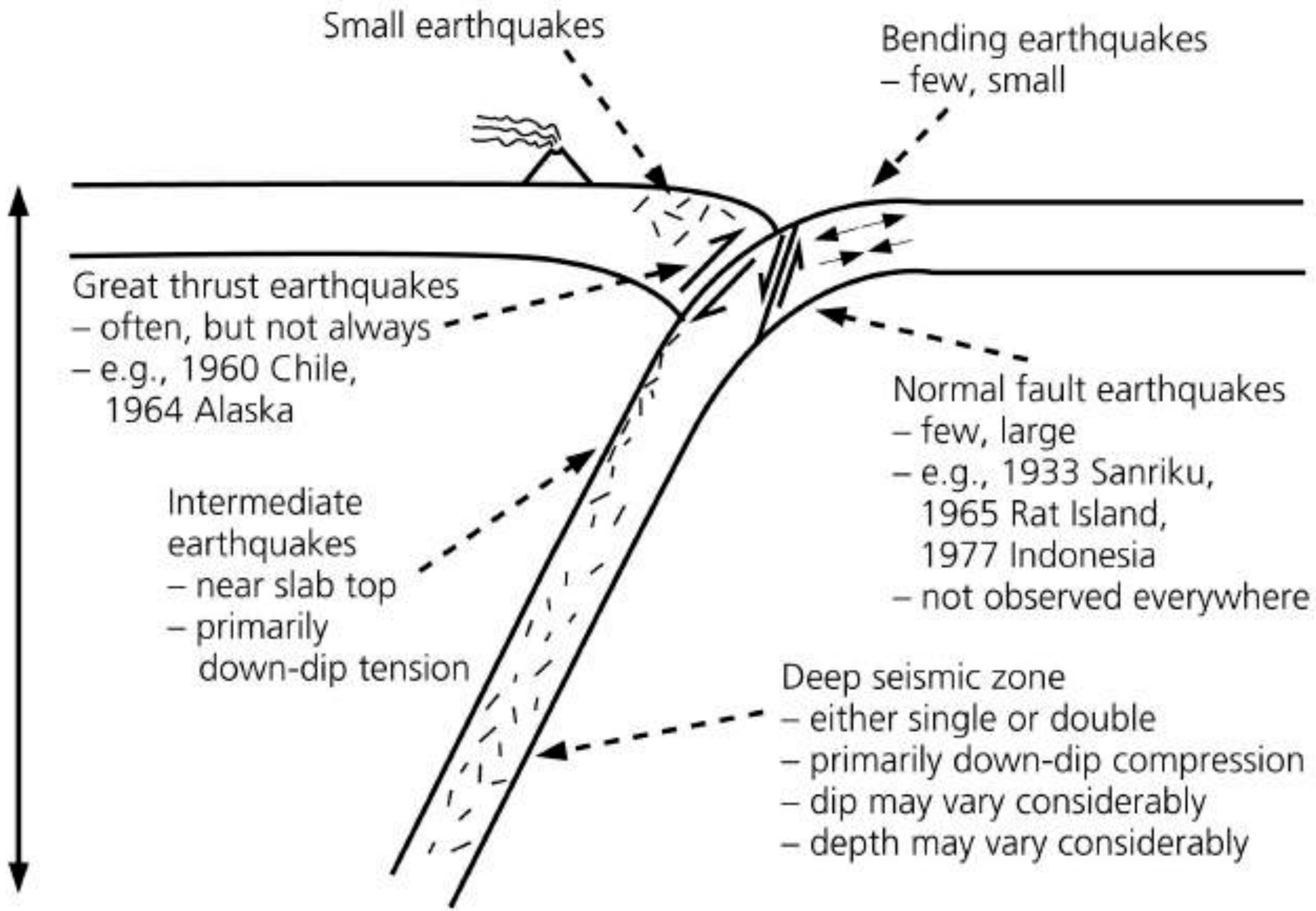
Earthquakes—Evidence for Plate Tectonics

- A good fit exists between the plate tectonics model and the global distribution of earthquakes.
  - The connection of deep-focus earthquakes and oceanic trenches is further evidence.
  - Only shallow-focus earthquakes occur along divergent and transform fault boundaries.
- Earthquake depths
  - Earthquakes originate at depths ranging from 5 to nearly 700 kilometers.
  - Earthquake foci are arbitrarily classified as:
    - Shallow (surface to 70 kilometers)
    - Intermediate (between 70 and 300 kilometers)
    - Deep (over 300 kilometers)
- Definite patterns exist.
  - Shallow-focus earthquakes occur along the oceanic ridge system.
  - Almost all deep-focus earthquakes occur in the circum-Pacific belt, particularly in regions situated landward of deep-ocean trenches.



Earthquake Distribution Near the Tonga Trench

Figure 5.4-2: Various earthquake types observed at subduction zones.



Global Distribution of Earthquakes

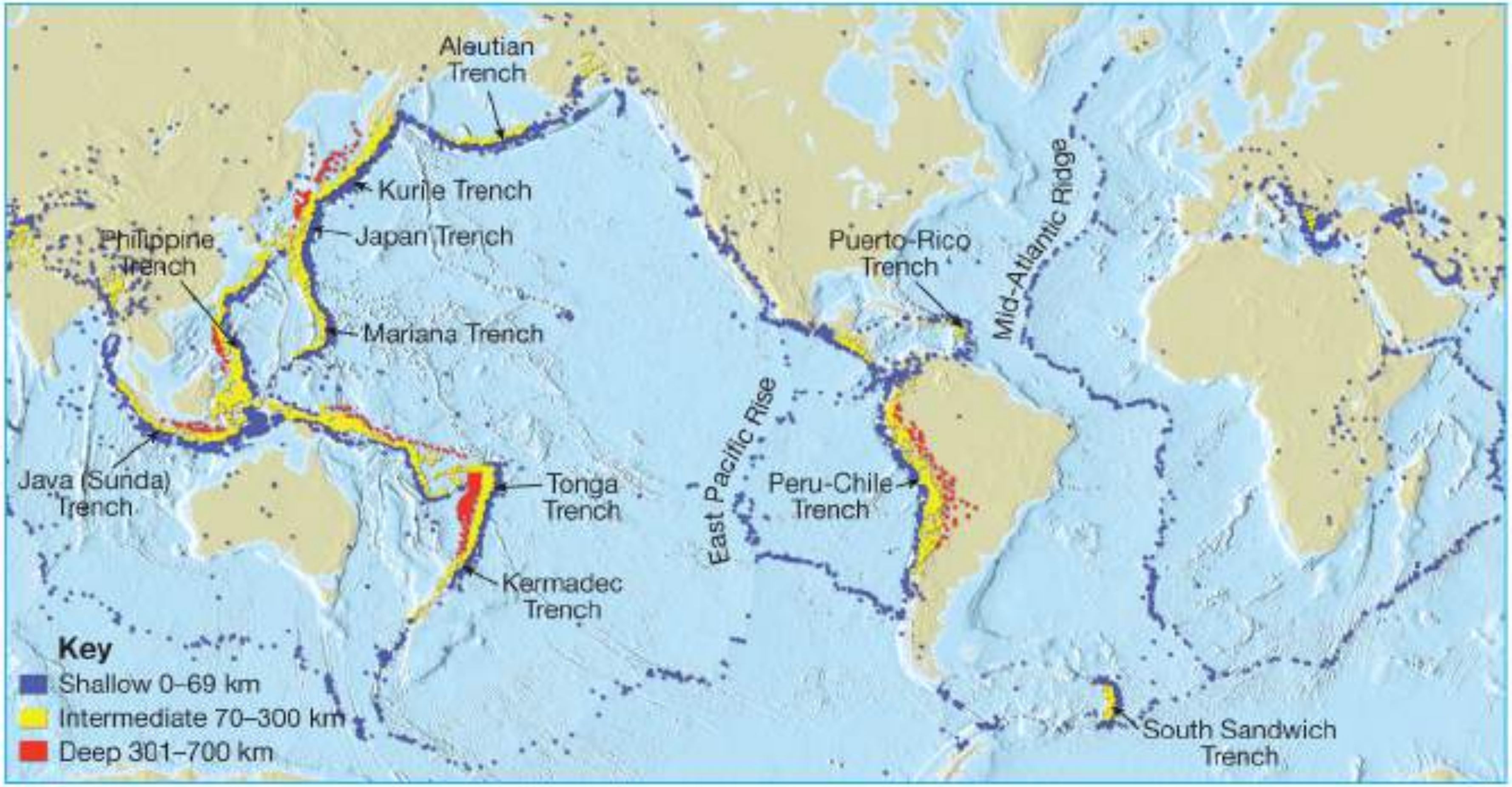


Figure 5.1-1: Cartoon of plate tectonics.

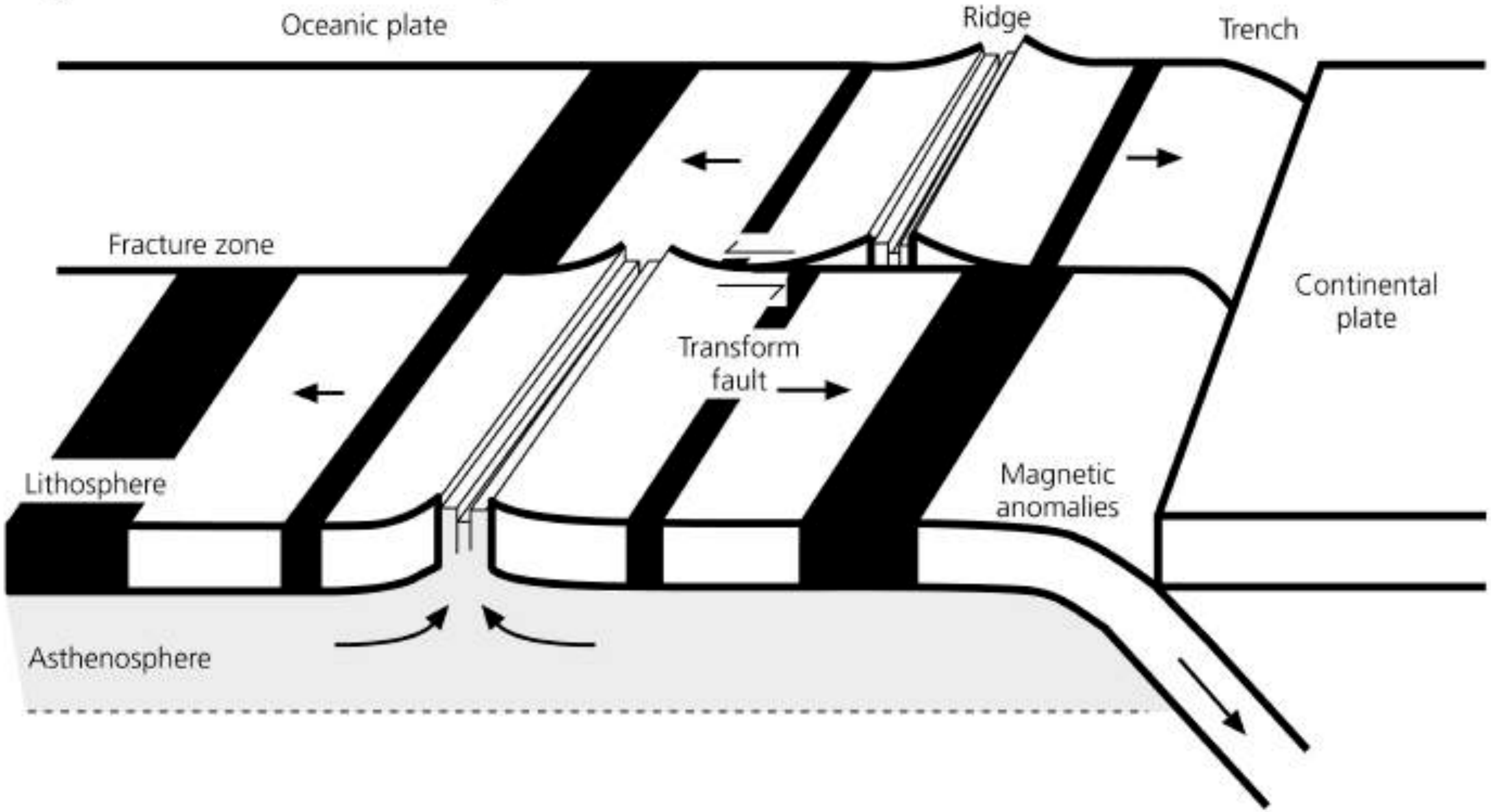


Figure 4.2-14: Focal mechanisms for various fault mechanisms.

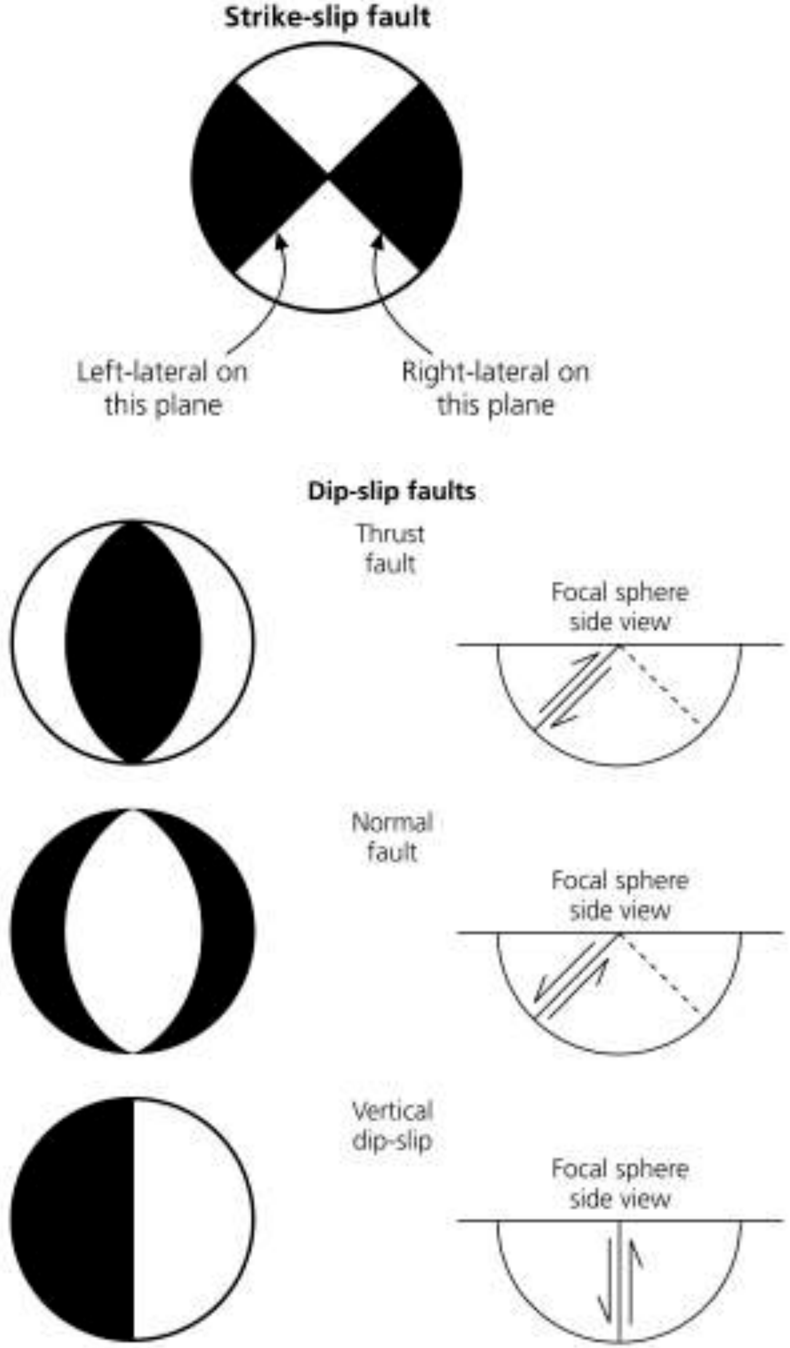


Figure 4.2-15: Fault mechanisms for earthquakes with one identical fault plane.

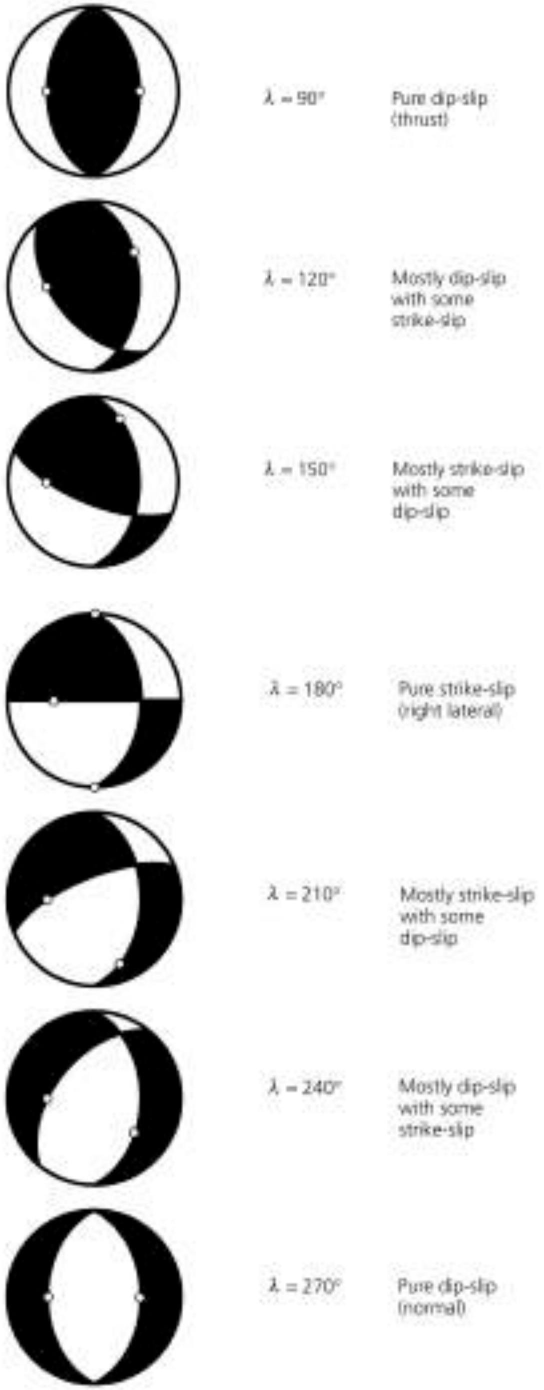
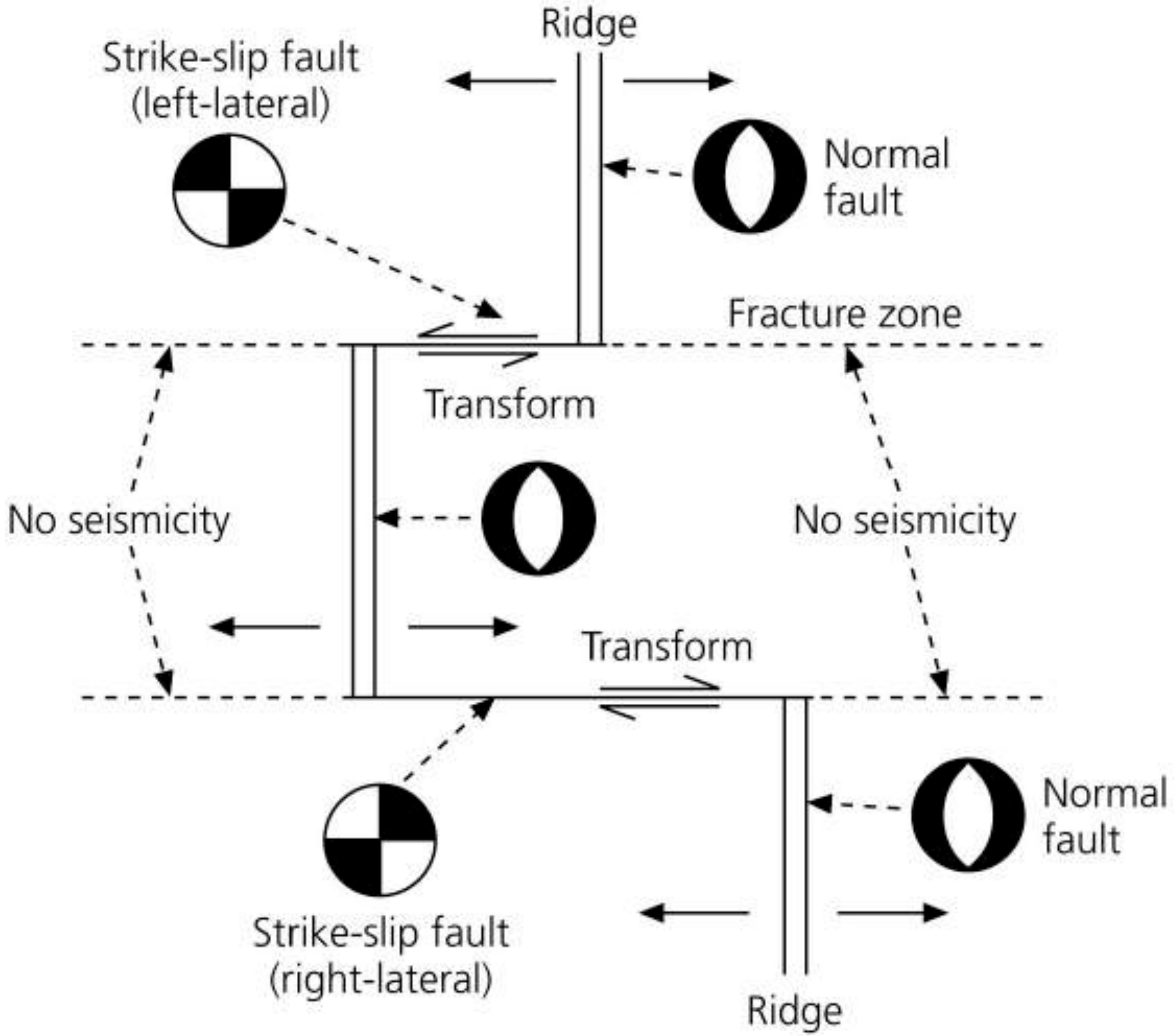
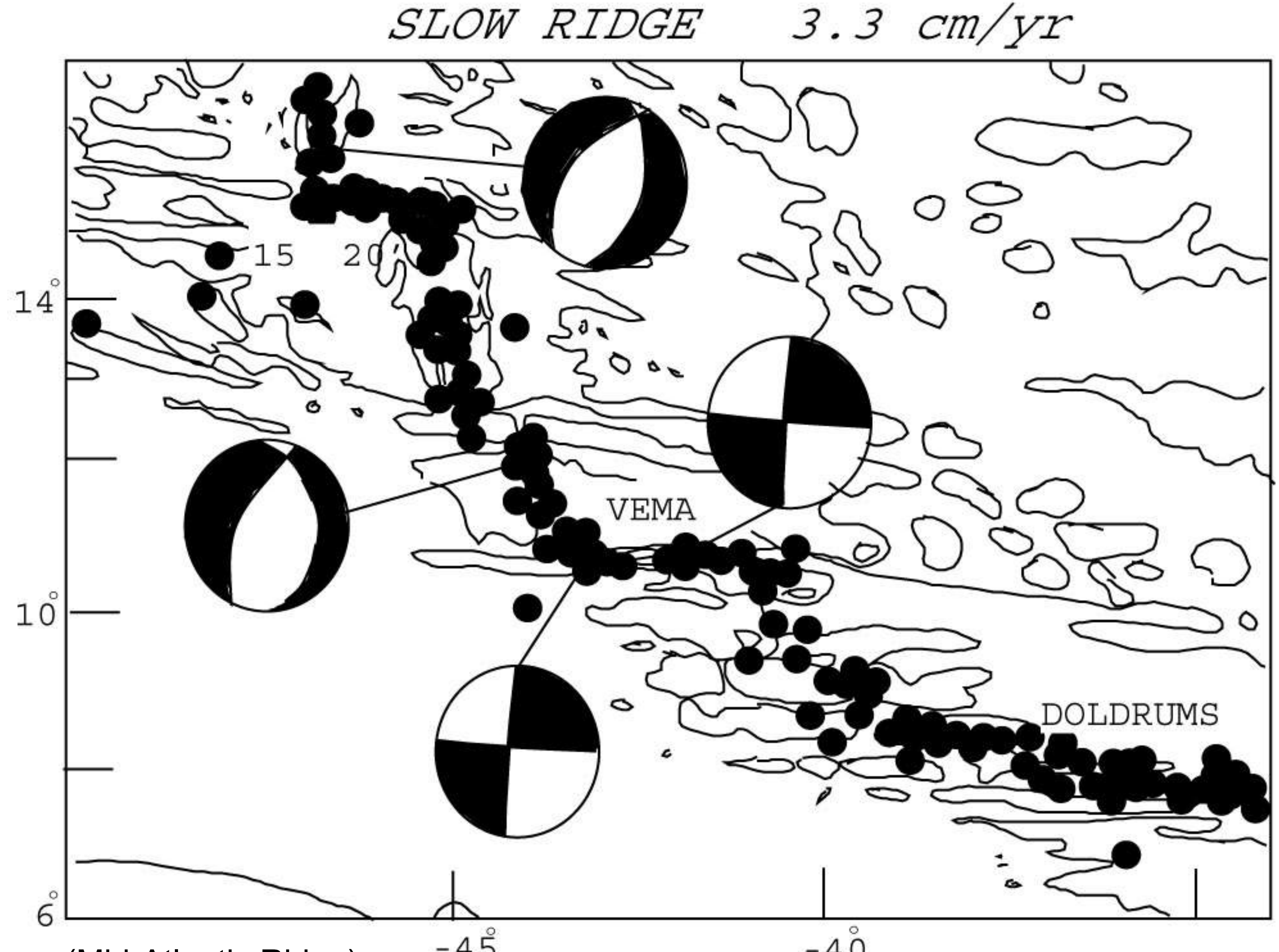
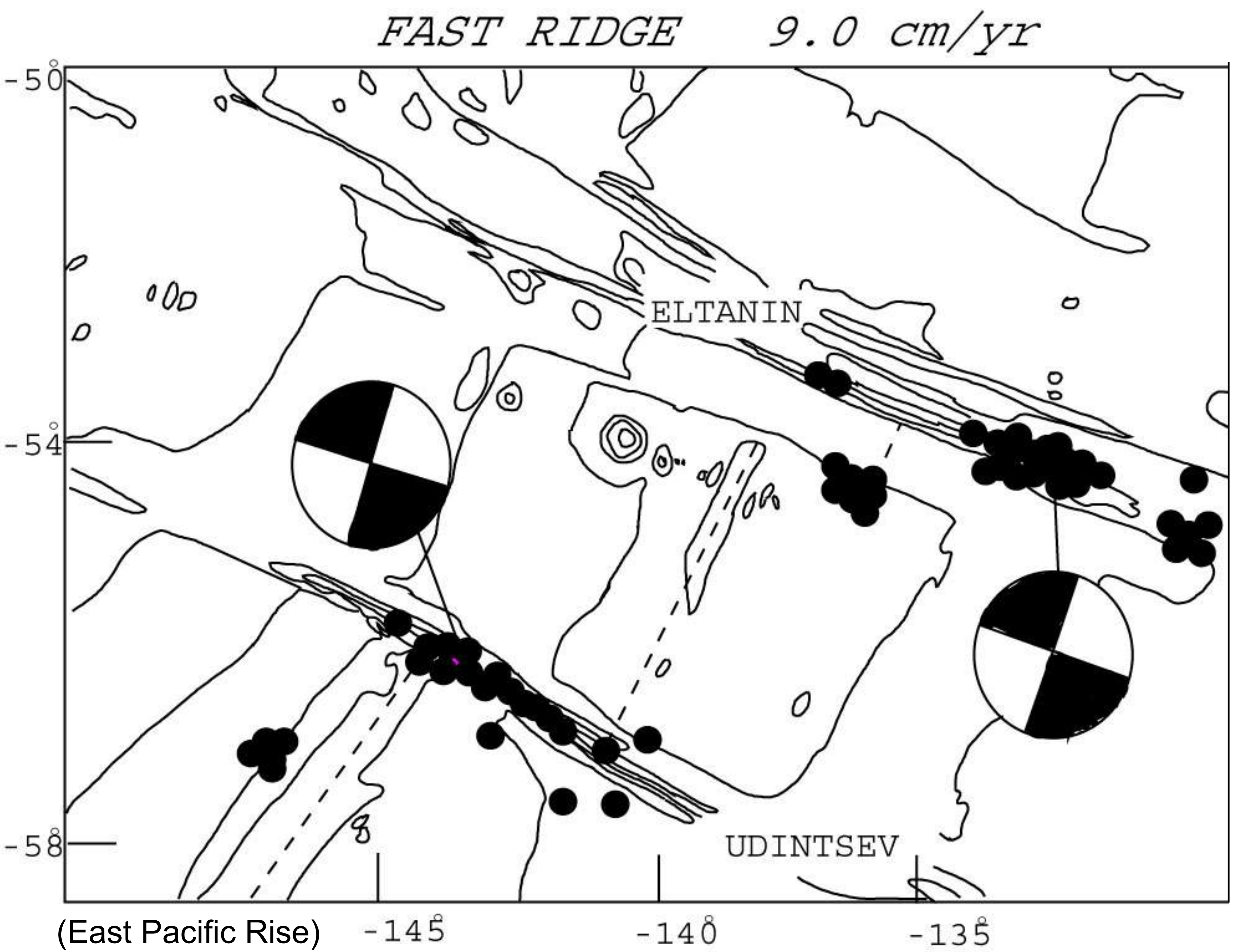


Figure 5.3-1: Tectonic settings of earthquakes along an oceanic spreading center.



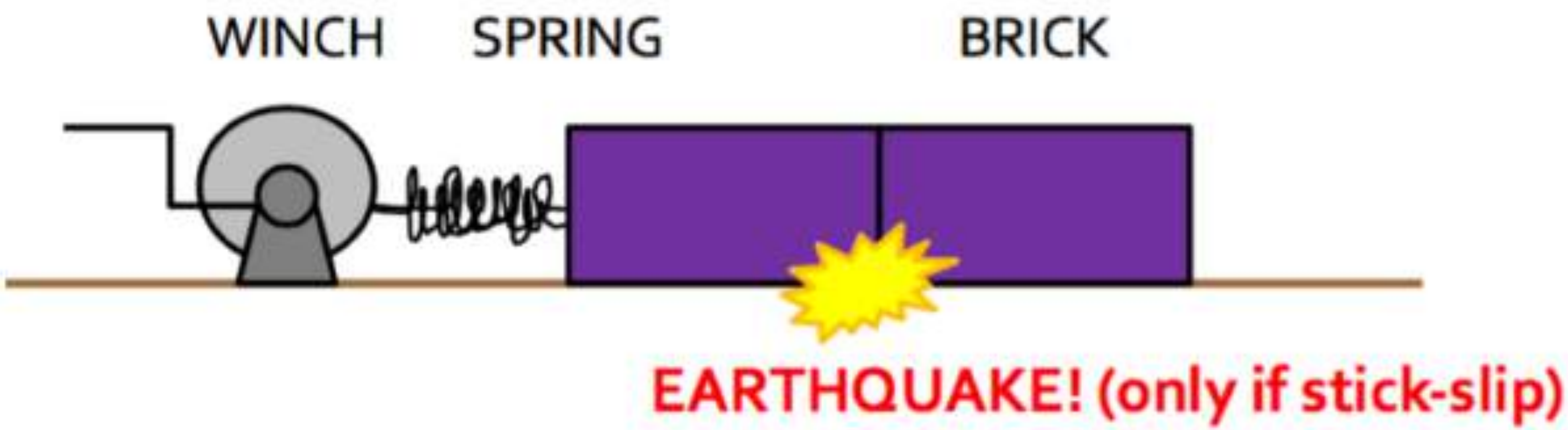


(Mid-Atlantic Ridge)


FAST RIDGE 9.0 cm/yr
-50°
-54°
-58°
ELTANIN
UDINTSEV
(East Pacific Rise)
-145°
-140°
-135°

Coulomb theory

Hypothesis: Faults interact by the transfer of stress

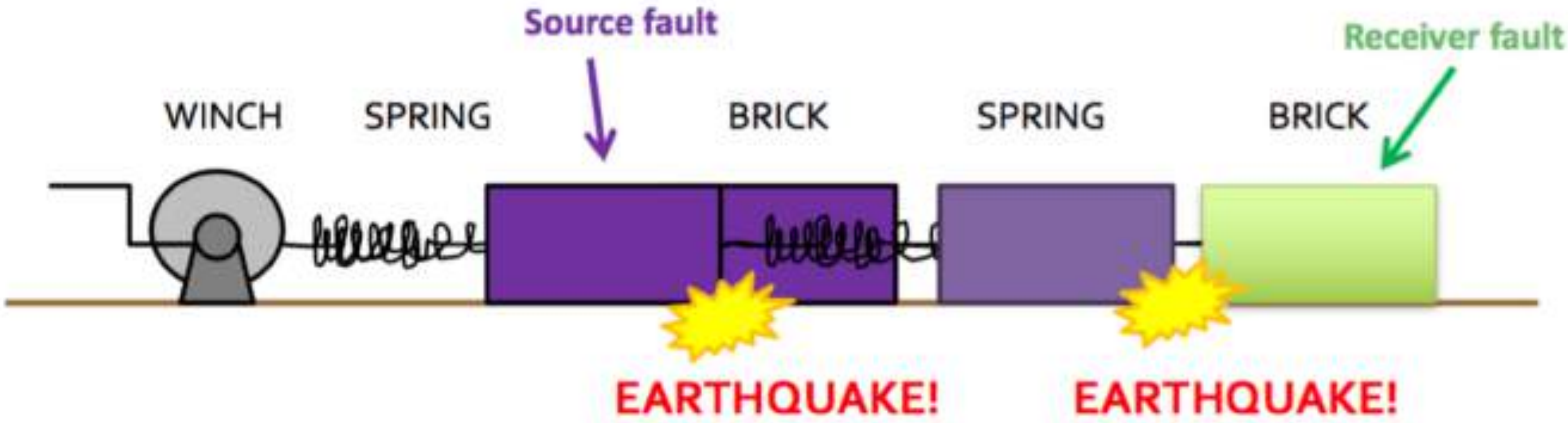


<u>Force Balance – Brick will not move until</u>:

Force on spring > **Force resisting motion**

(its length change x its stiffness) (the weight of the brick x friction on surface)

Coulomb theory



- Add another spring & brick
- If you start cranking winch, **PURPLE** will move first. Then tension on spring will move **GREEN**.

+ ΔCFS = closer to failure

- ΔCFS = farther from failure

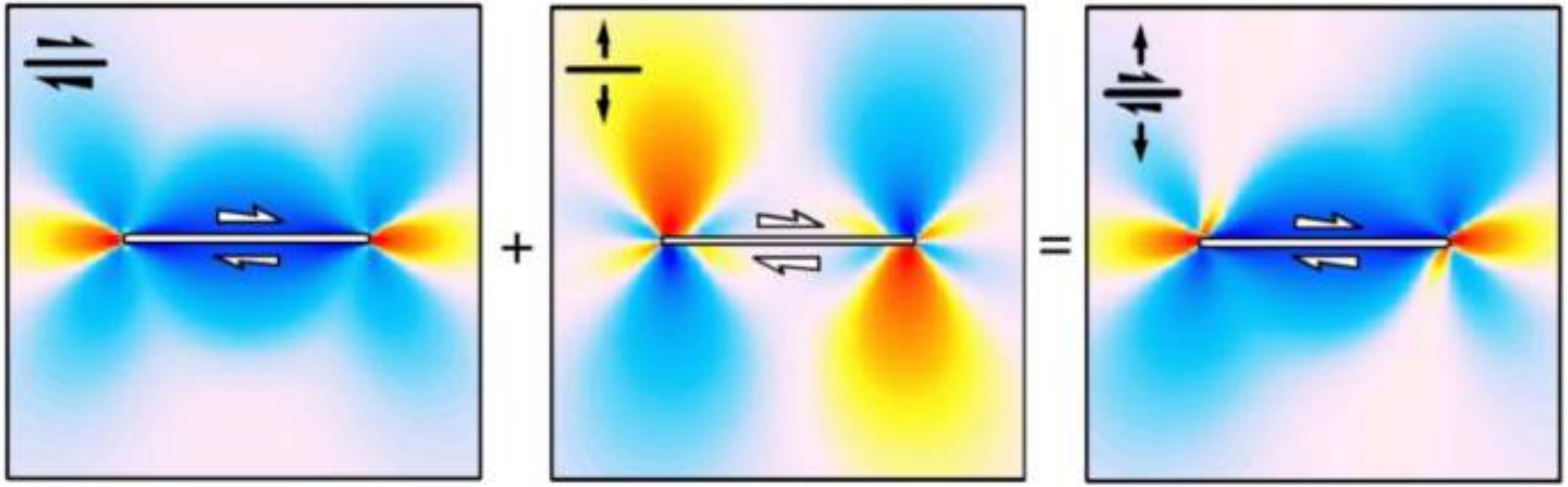
Coulomb stress calculation

Coulomb stress change = shear stress change + (coefficient of friction x normal stress change)

$$\Delta CFS = \Delta\tau_s + \mu' \Delta\sigma_n$$

How the Coulomb Stress Change is Calculated

Stress Rise Drop
promotes or inhibits failure



Shear stress change	+	Friction coefficient **x** normal stress change	=	Coulomb failure stress change
$\Delta\tau_s$	+	$\mu' (\Delta\sigma_n)$	=	$\Delta\sigma_f$

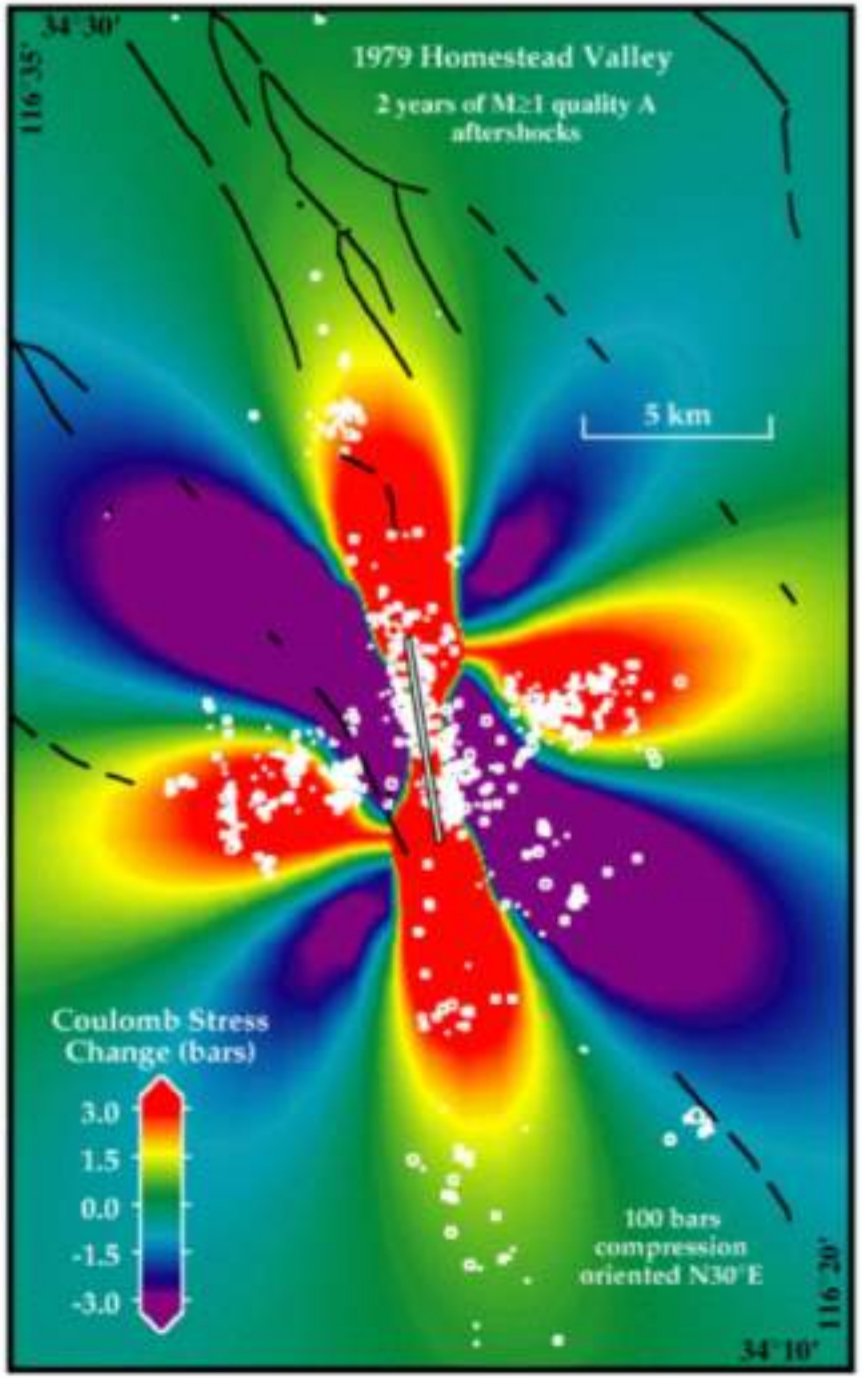
- Example calculation for faults parallel to master fault

From King et al (BSSA, 1994)

Coulomb stress changes after 1979 Homestead Valley Earthquake, California. Aftershocks are plotted in white.
(King, 1994)

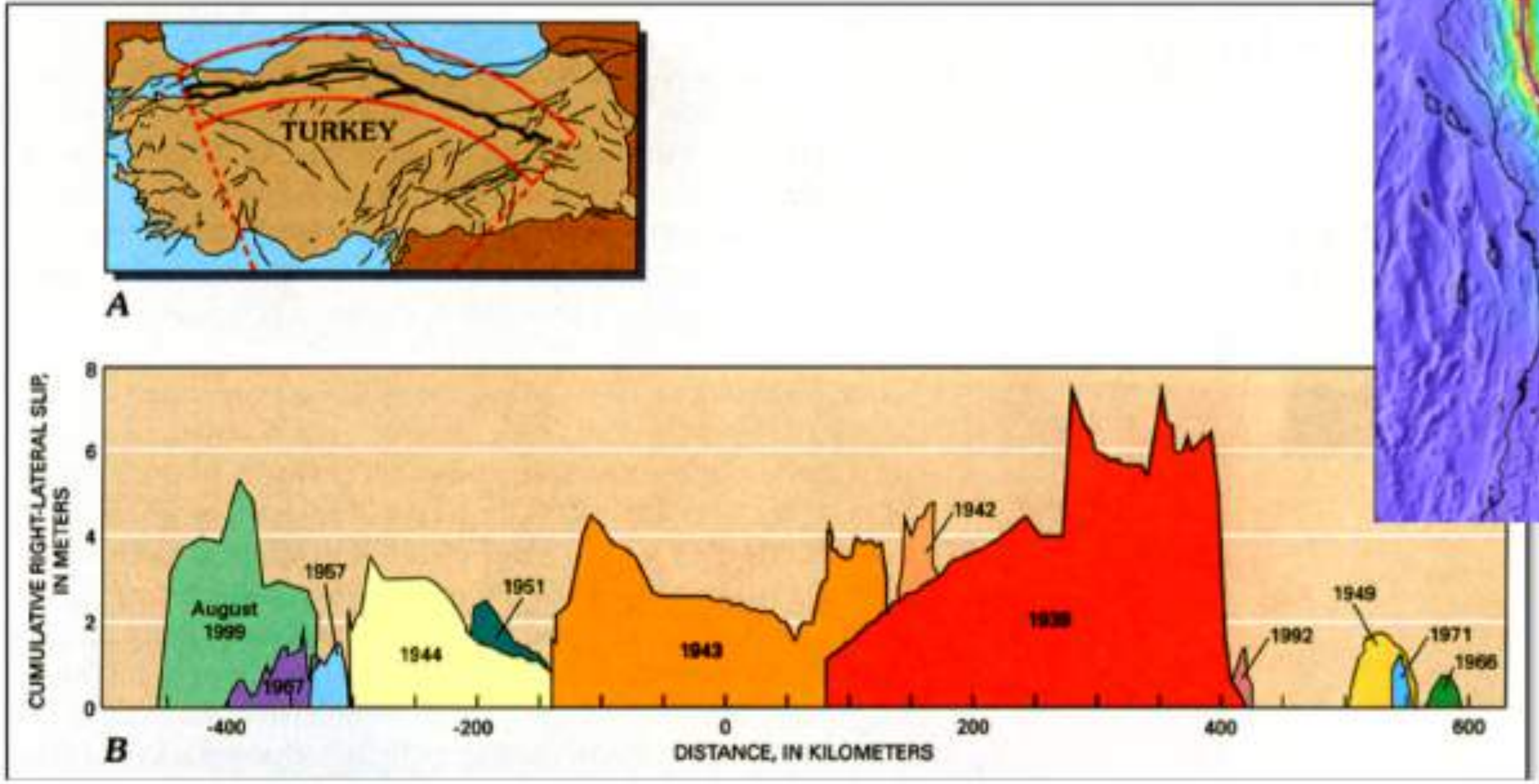
The location of aftershocks tend to cluster in areas of <u>increased</u> coulomb stresses.

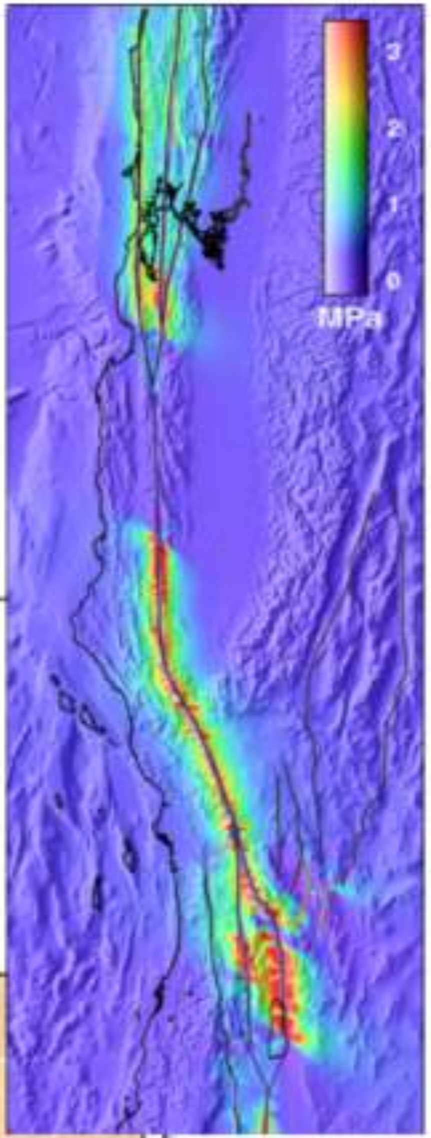
Aftershocks take place with decreased regularity in areas of decreased stress. These areas are known as "<u>stress shadows</u>".

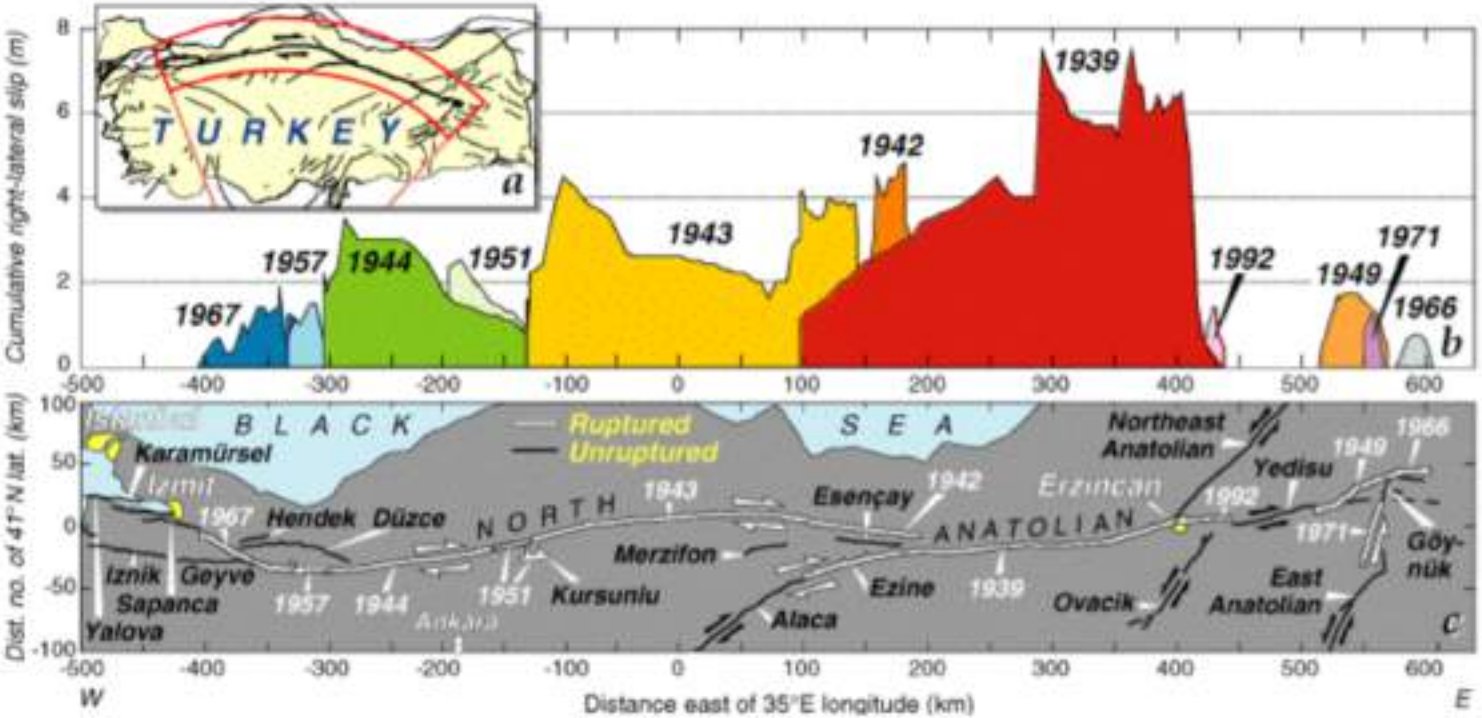


Seismic Gaps & Stress Triggering

- ***Seismic Gaps***: Areas where the fault has not moved in a long time
  - These regions may be the next to go (i.e. San Andreas)→
- ***Stress Triggering***: When an earthquake happens, the motion changes the stress on nearby faults, possibly making them more or less likely to fail.
  - The North Anatolian Fault (below) is an excellent example of both of these phenomenon





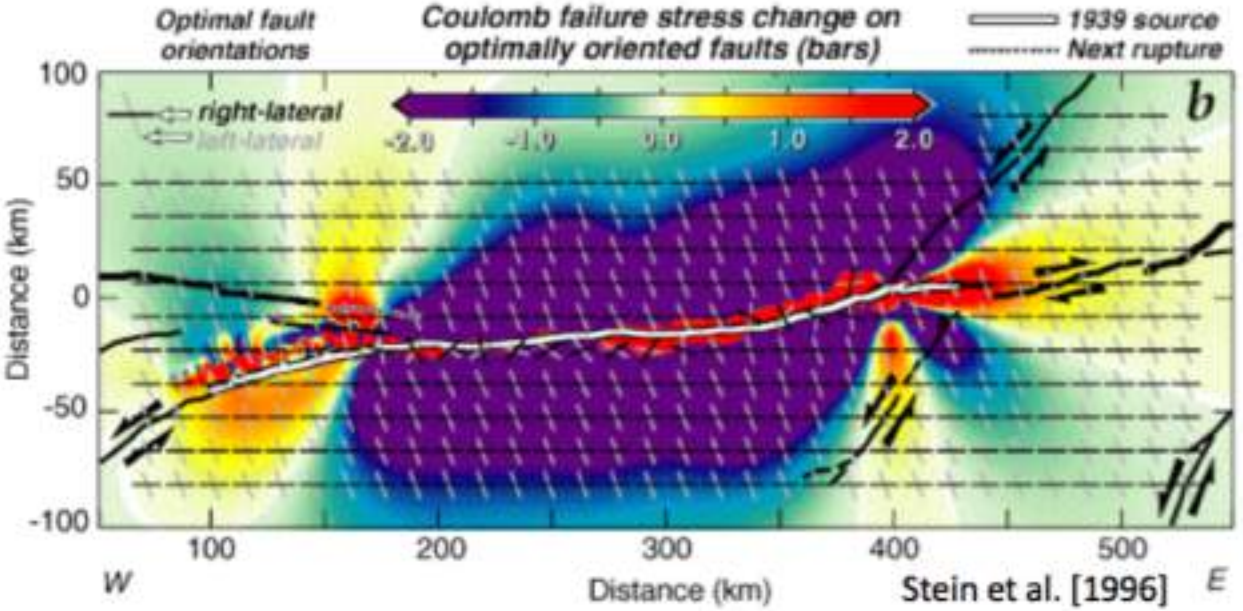


(b) Cumulative right-lateral slip associated with M>=6.7 earthquakes; the sequence ruptured from warm to cool colors.

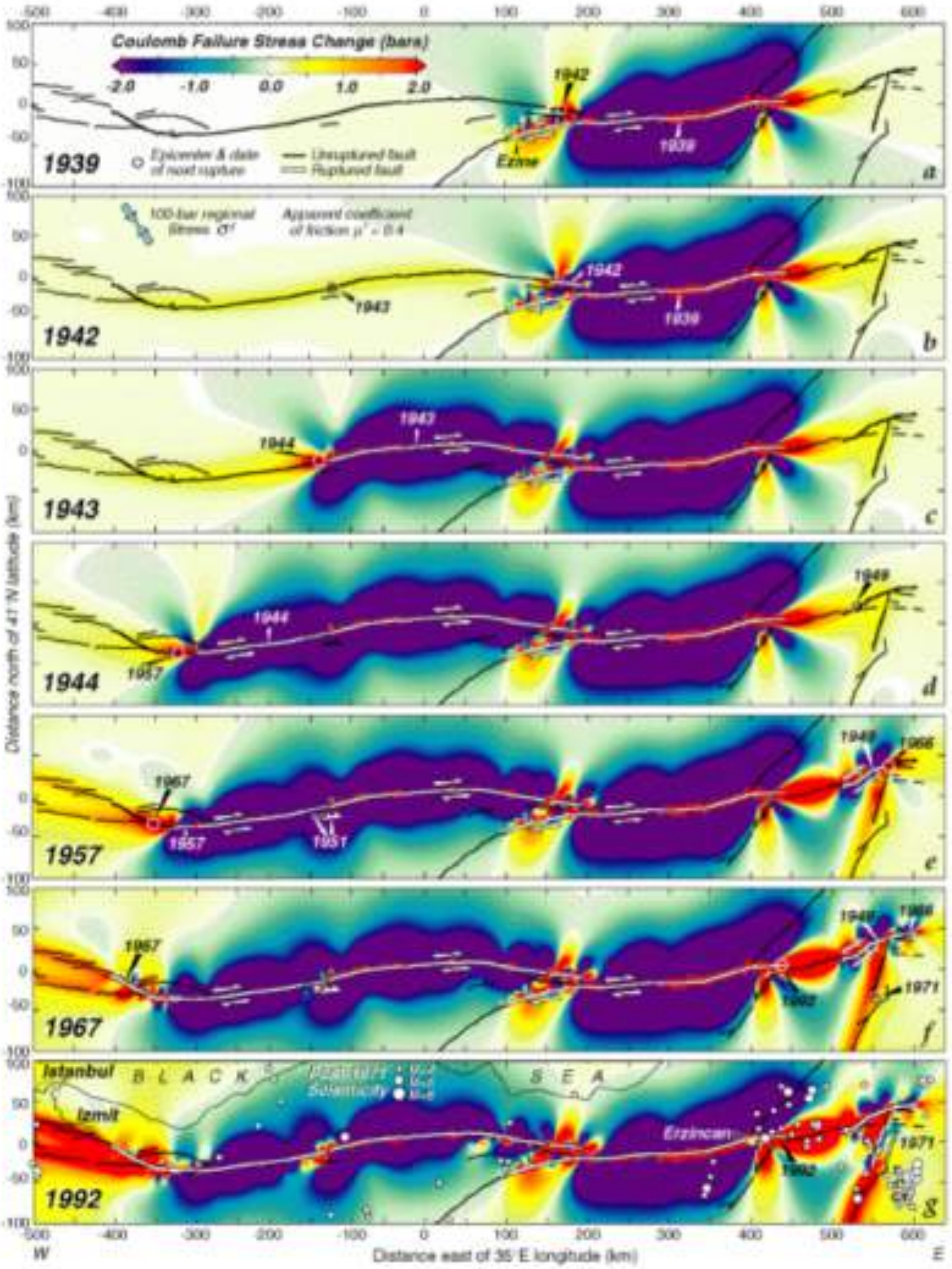
(c) The region inscribed by the solid red line in a is projected relative to the Anatolia-Eurasia rotation pole, so that a transform fault would strike due east-west; the North Anatolian fault is seen to deviate less than 40 km from being a simple right-lateral transform.

Stress changes associated with the 1939 earthquake. Color gradients show the Coulomb stress change on optimally oriented vertical strike-slip faults at a depth of 8 km.

Large rotations of the optimal planes are restricted close to the fault rupture, where the earthquake stress change is significant relative to the regional stress. Far from the 1939 rupture, rotation of the optimal planes is negligible.



Stein et al. [1996]

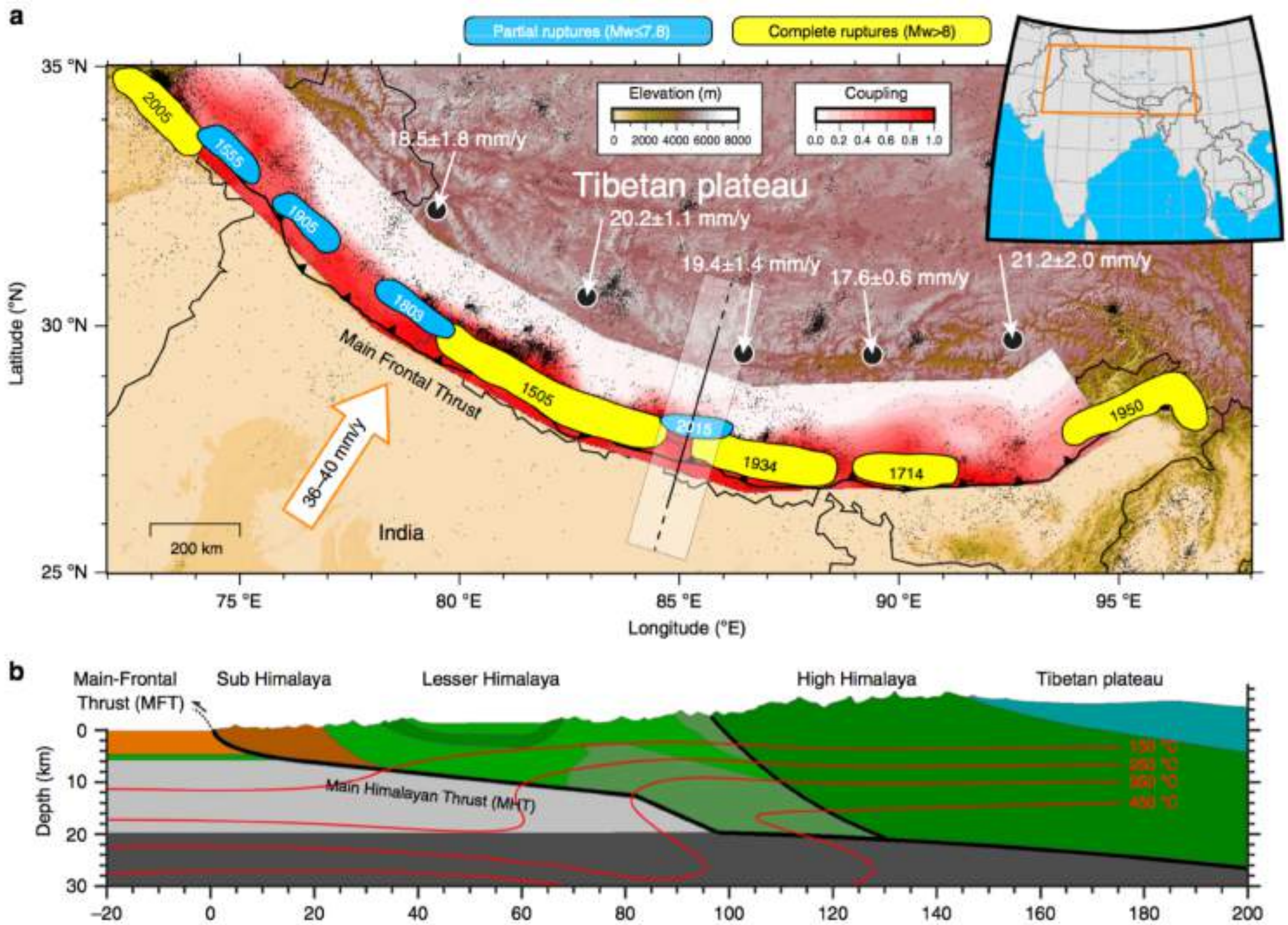


Cumulative stress changes caused by large earthquakes and steady deep slip on the North Anatolian fault since 1939.

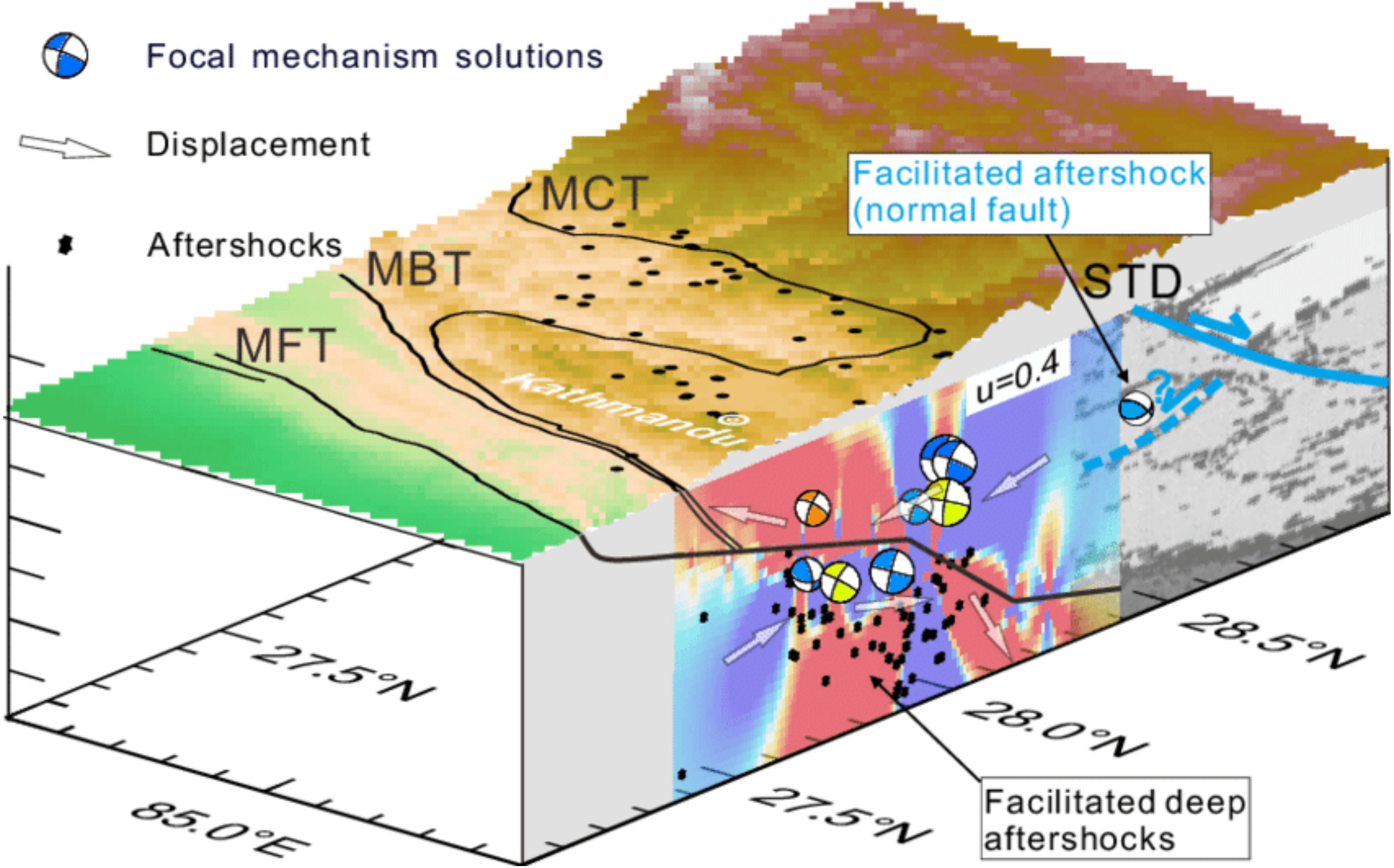
In each panel, the epicenter of the next earthquake to rupture is circled. All but the 1943 epicenter lie in regions where the stress rose significantly, typically by 2-5 bars, owing to the foregoing shocks and deep fault slip.


INDIA
SEISMIC ZONE
N
AFGHANISTAN
PAKISTAN
CHINA
(TIBET)
NEPAL
BHUTAN
BANGLADESH
MYANMAR
SRI LANKA
JAMMU & KASHMIR
HIMACHAL PRADESH
PUNJAB
HARYANA
UTTARAKHAND
DELHI
New Delhi
UTTAR PRADESH
SIKKIM
ARUNACHAL PRADESH
ASOM (ASSAM)
NAGALAND
MEGHALAYA
MANIPUR
TRIPURA
MIZORAM
RAJASTHAN
BIHAR
JHARKHAND
WEST BENGAL
GUJARAT
MADHYA PRADESH
CHHATTISGARH
(ODISHA) ORISSA
DADRA & NAGAR HAVELI
MAHARASHTRA
TELANGANA
GOA
KARNATAKA
ANDHRA PRADESH
TAMIL NADU
KERALA
LAKSHADWEEP (INDIA)
ANDAMAN & NICOBAR ISLANDS (INDIA)
ARABIAN SEA
BAY OF BENGAL
INDIAN OCEAN
LEGEND
International Boundary
State Boundary
Country Capital
Zone - II (Least Active)
Zone - III (Moderate)
Zone - IV (High)
Zone - V (Highest)
Map not to Scale
Copyright © 2014 www.mapsofindia.com
(Updated on 2nd June 2014)

Example from Himalaya



Dal Zilio et al., (2019)



Zhao et al., (2019)

Fundamentals of Earth Sciences (ESO 213A)

Dibakar Ghosal
Department of Earth Sciences

Landslides

Previous Class: Earthquake

LANDSLIDES

Landslide: refers to the downward sliding of huge quantities of land mass which occur along steep slopes of hills or mountains and may be sudden or slow. It encompasses all categories of gravity-related slope failures in Earth materials.

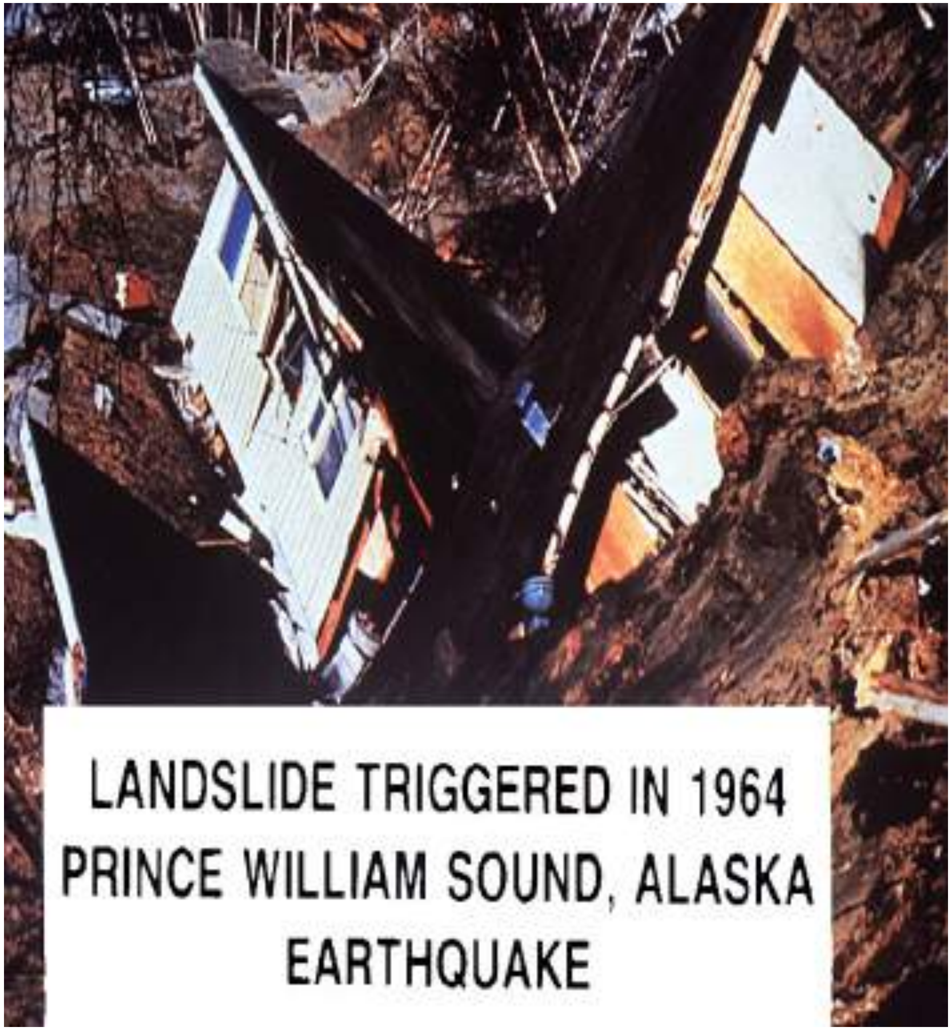
For convenience, definition of *landslide* includes all forms of ***mass-wasting*** movements

Natural phenomena that occur with or without human activity

Essential knowledge for societal sustainability

La Conchita 'slide', 2005

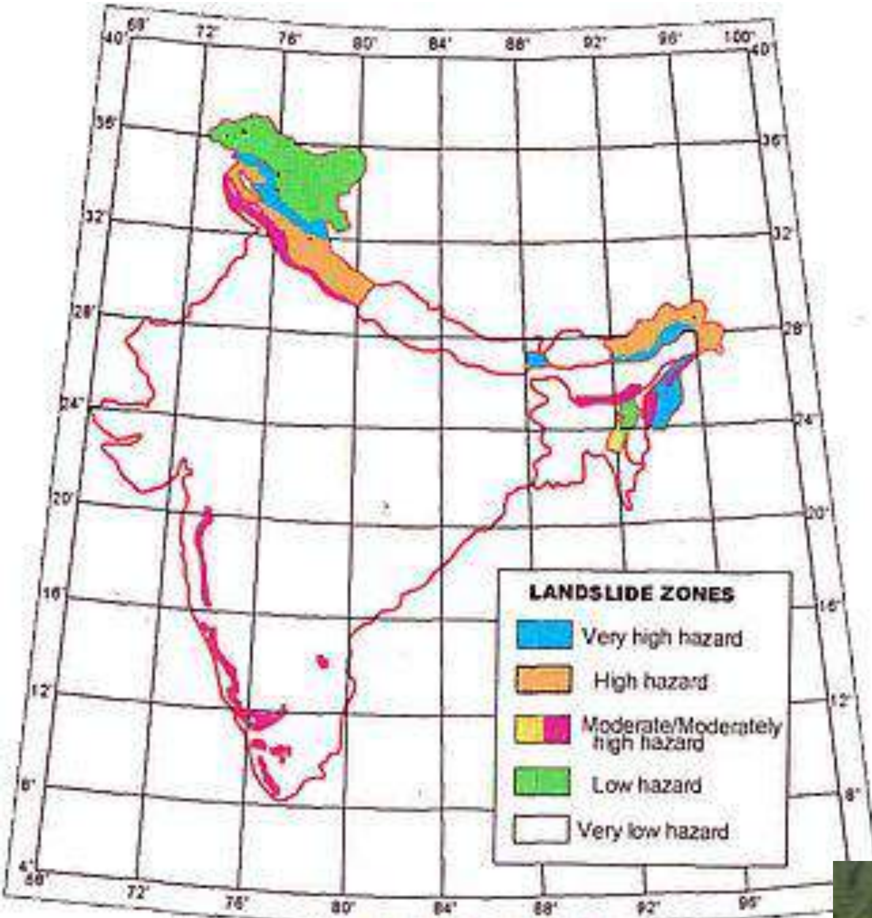
LANDSLIDE HAZARD: ALASKA



- The 1964 prince william sound earthquake triggered a large volume landslide at turnagain heights.
- Millions of cubic meters of soil and rock moved down slope.
- Slope failure was induced by ground shaking of "Quick Clay."

LANDSLIDE HAZARD: JAPAN

Landslides in NE India



Landslides and fooding by heavy rain fall at Kedarnath in 2013

Classification of Earth Movements

- **All movement of land masses are referred as landslides, but differ in many respects, therefore all types of landslides are categorized as <u>Earth Movements</u>.**

These are classified as

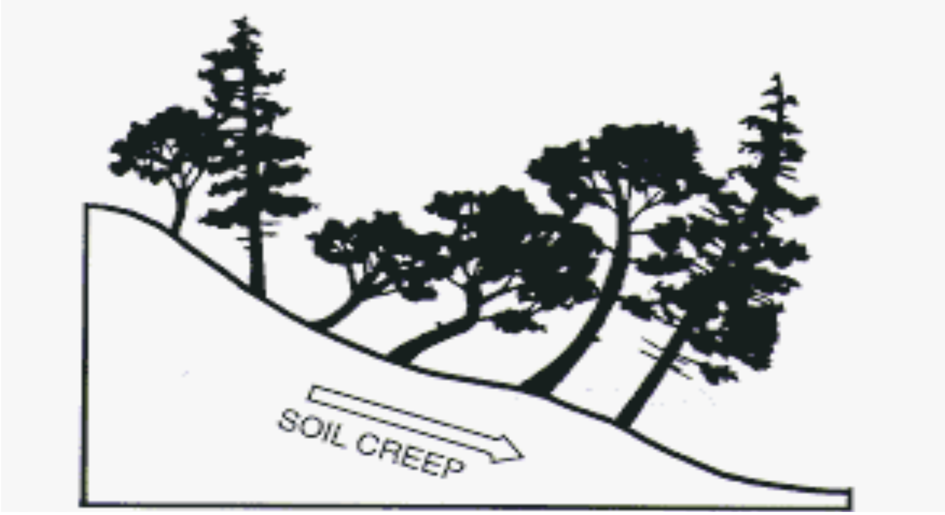
- Earth Flow
  - Solifluction
  - Creep
  - Rapid flows
- Landslides
  - Debris slide or slump
  - Rock slides
  - Rock falls
- Subsidence
  - Plastic flow
  - collapse

SOLIFLUCTION

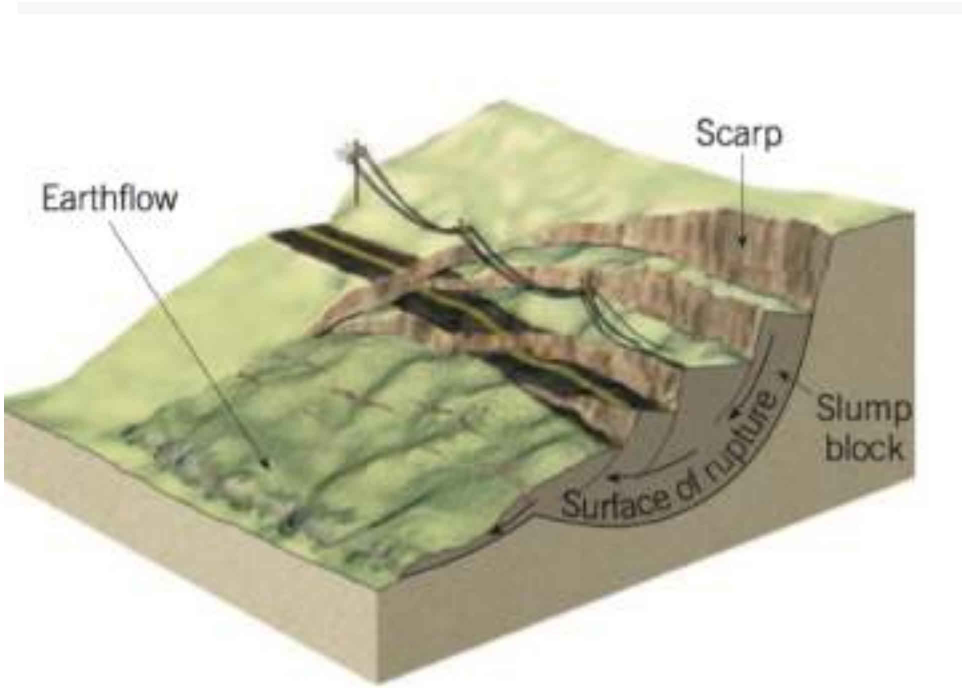
- Solifluction is a downward movement of wet soil along the slopes under the influence of gravity.

SOIL CREEP

- Creep is extremely slow downward movement of dry surfacial matter.
- Movement of the soil occurs in regions which are subjected to freeze-thaw conditions. The freeze lifts the particles of soil and rocks and when there is a thaw, the particles are set back down, but not in the same place as before.
- It is very important for Civil Engineers to know the rate of movement

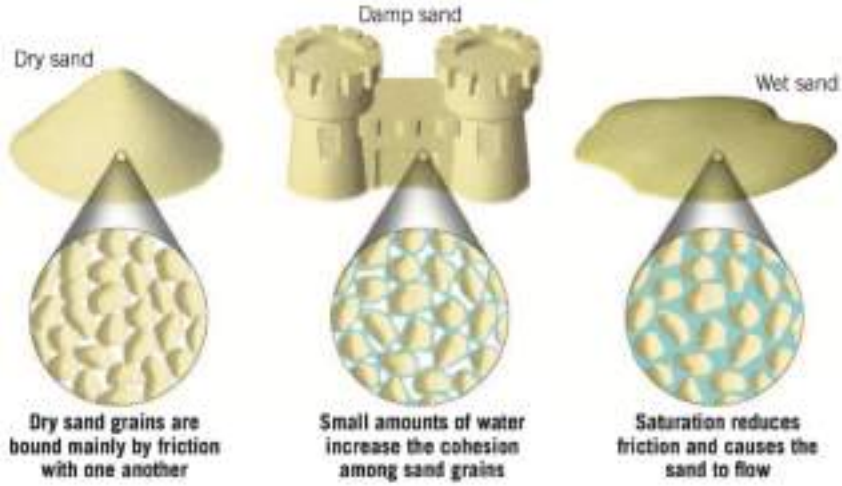


- *RAPID FLOWS: Rapid flow is similar to the creep, but differ in terms of speed and depth. It is faster.*
- *Creep is involved upto shallow depth (app. 1-2 m), whereas the rapid flow is involved to greater depth (app. upto 5 m or more)*

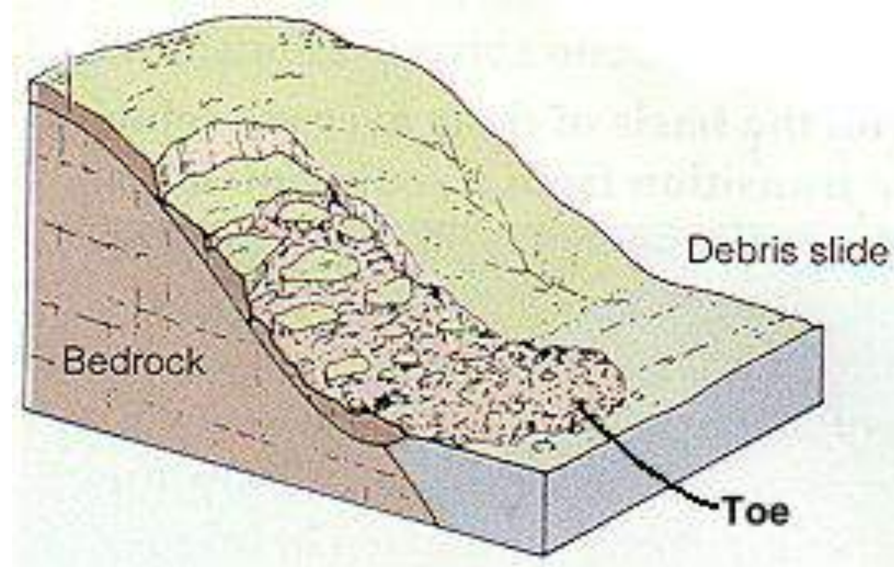


Landslides

- <u>Large block known as a slump block moves during the landslide.</u>
- The scar above a landslide is easily visible.
- <u>They can occur along a slope where the internal resistance of the rocks are reduced or they loose their holding capacity.</u>
- Common after earthquakes or after removal of part of the slope due to construction, particularly for construction of roads.



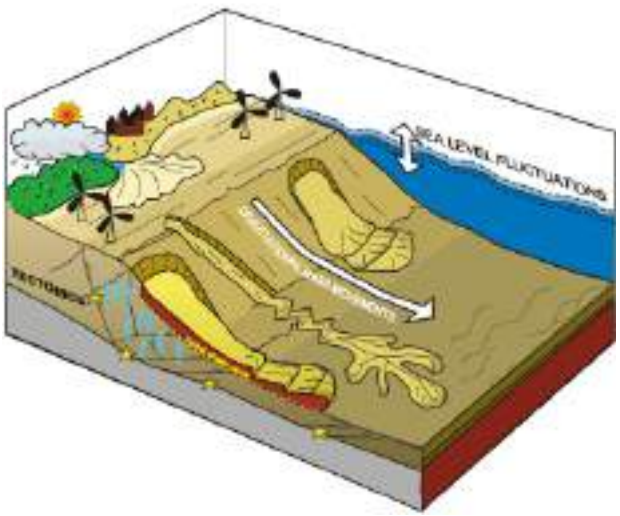
- Landslide can result into:
- Debris slides - are failure of unconsolidated material on a surface;
- Rock slide or Rock Fall – where movement of large rock block rolls



- They are also common along the steep banks of rivers, lakes etc.

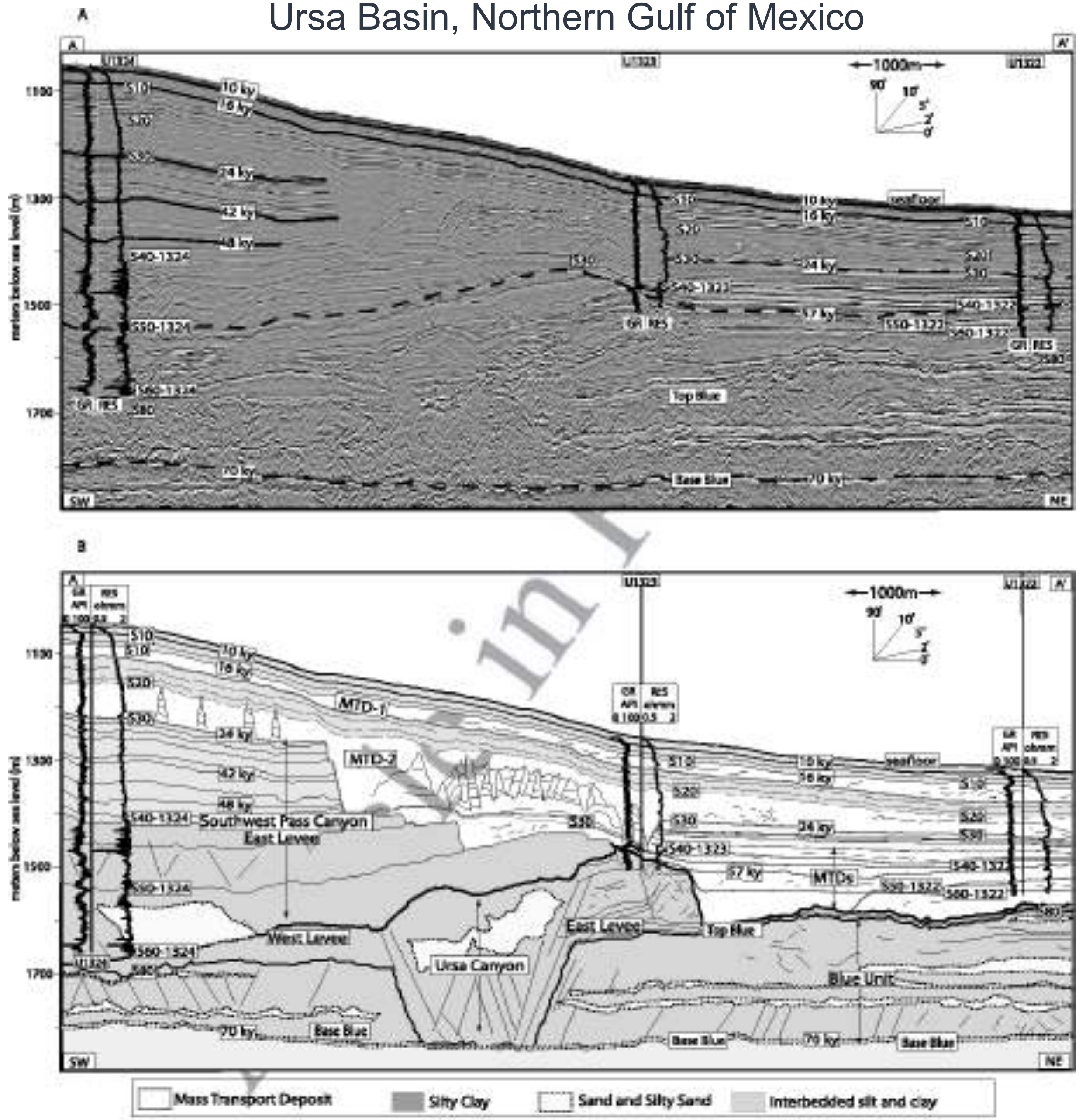
- Pore Water Pressure is the key to monitoring landslides. Shear strength (a resisting force) decreases and the weight (a driving force increases).
- **Talus** – accumulation formed by the coarser rock fragments resulted from the mechanical weathering along a slope under influence of gravity

Marine Landslides



Mass Transport Deposits (MTD)

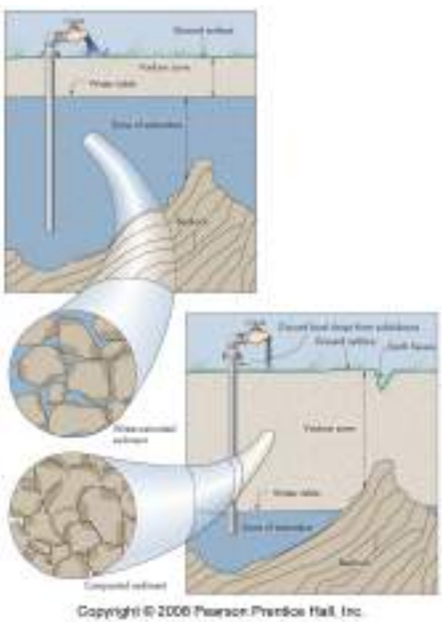
Ursa Basin, Northern Gulf of Mexico



Sawyer et al., 2009

Subsidence

- It represents the downward movement of the surface
- It may occur due to plastic outflow of the underlying strata or due to the compaction of the underlying material
- (1) ***<u>Subsidence due to Plastic outflow:</u>*** It may occur when a plastic layer like <u>*clay bed is squeezed outward*</u> *due to overlying heavy load*
- (2) **<u>Subsidence due to collapse:</u>** It occur due to extensive <u>*pull out of large volume of underground water, oil, gas*</u> or due to subsurface solution activity in limestone terrain.



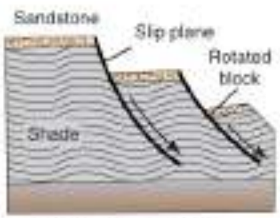
- The Leaning Tower of Pisa, Italy, the tilting of which accelerated as groundwater was withdrawn from aquifers to supply the growing city.

Removal of Solid Materials

- Sinkholes
  - Dissolution of carbonate rocks, limestone, and dolomite
  - Natural or artificial fluctuations in water table increasing the problem

- Salt and coal **mining**
  - Salt dissolution and pumping
  - Active coal mines and abandoned coal mines
  - Ground failure due to depleted subsurface pressure
  - More than 8000 km^2 of land subsidence due to underground coal mining

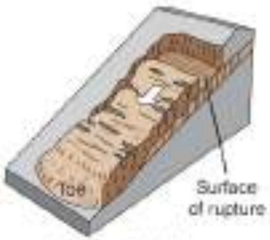
Summary: Types of Landslides



(a) Rock slump

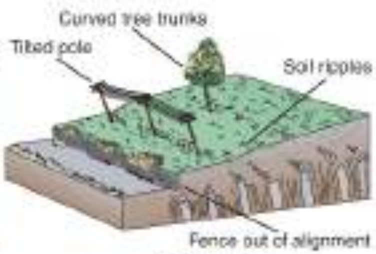
(b) Soil slump

(c) Rock slide



(d) Soil slide


(e) Rockfall

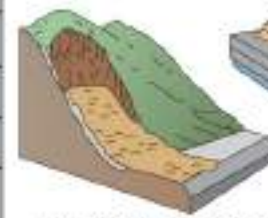


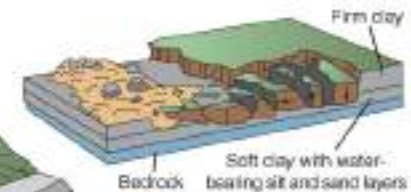
(f) Soil creep

Type of Movement	Materials	
	Rock	Soil
Landslides with variable water content and rate of movement	Rotational	
	Slump(a)	Slump(b)
	Translational	
	Rock slide(c)	Soil slide (slip)(d)
Falls	Rock fall(e)	Soil fall
Flows — Slow	Rock creep	Soil creep(f)
	Unconsolidated rock and soil (saturated)	
Rapid	Earth flow(g)	
	Debris flow / mud flow(h)	
Very rapid	Debris avalanche(i)	
Lateral spread	Rock(j)	Soil
Subsidence	Rock(k)	Soil
Complex	Combination of slides, slumps, and flows(l)	

(g) Earthflow

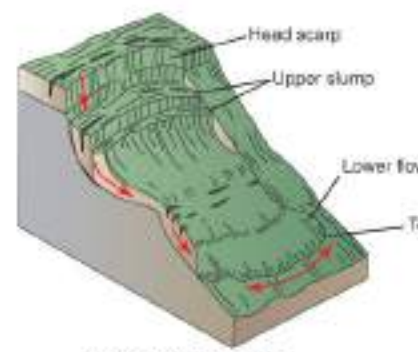

(h) Debris flow


(i) Debris avalanche



(j) Lateral spread


(k) Subsidence



(l) Complex slide

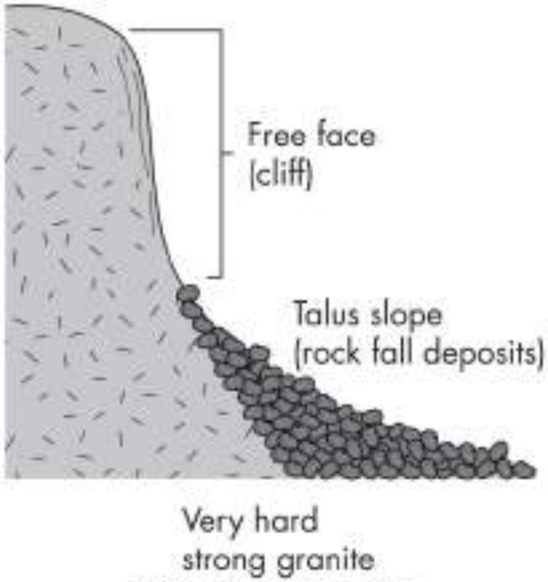
Causes Of landslides

- ***LANDSLIDES OCCUR DUE OF VARIOUS REASONS***
- ***Internal Causes:***

- Influence of slope- Slopes are the most common landforms.
- Although they appear stable and static, slopes are actually dynamic, evolving systems.
- Provides favourable condition for landslides; steeper slope are prone to slippage of land. It is known that most of the materials are stable upto certain angle- “Critical angle” or “angle of repose” – it varies from 30^0 for unconsolidated sediments to 90^0 for massive rocks and 60^0-90^0 for partially jointed rocks.

- Material is constantly moving on slopes at rates varying from imperceptible creep to thundering avalanches and rock falls moving at high velocities.
- Consists of cliff face (“free face”) and talus slope ***or*** upper convex slope, a straight slope, and a lower concave slope

Slopes



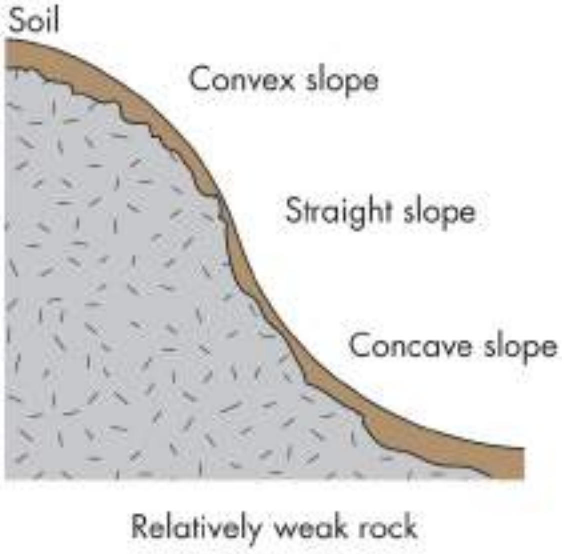


Figure 9.3

Slope Stability

- **Safety Factor**: = Resisting/Driving Forces

  If SF >1, then safe or stable slope

  If SF <1, then unsafe or unstable slope
- Driving and resisting force **variables**:
  - Slip surface – “plane of weakness”
  - Type of Earth materials
  - Slope angle and topography
  - Climate, vegetation, and water
  - Shaking
- Causes vs. triggers

- Ground water or associated water- Main factor responsible for slippage. Suppose the hard or massive rocks are underlained by softer rocks (shale or clay bed). When rain water percolates through some fractures or joints the clayey beds become very plastic and act as slippery base, which enhance the chances of loose overburden to slip downward.
- Water is the most powerful solvent, which not only causes decomposition of minerals but also leaches out the soluble matter of the rock and reduces the strength.
- **Lithology-** rock which are rich in clay (montmorillonite, bentonite), mica, calcite, gypsum etc are prone to landslide because these minerals are prone to weathering.
- **Geological structures-** Occurrence of inclined bedding planes, joints, fault or shear zone are the planes of weakness, which create conditions of instability.
- **Human Influence-** undercutting along the hill slopes for laying roads or rail tracks, Dam construction can result into instability.
- Deforestation in the uplands, result into more erosion during the rainy season.

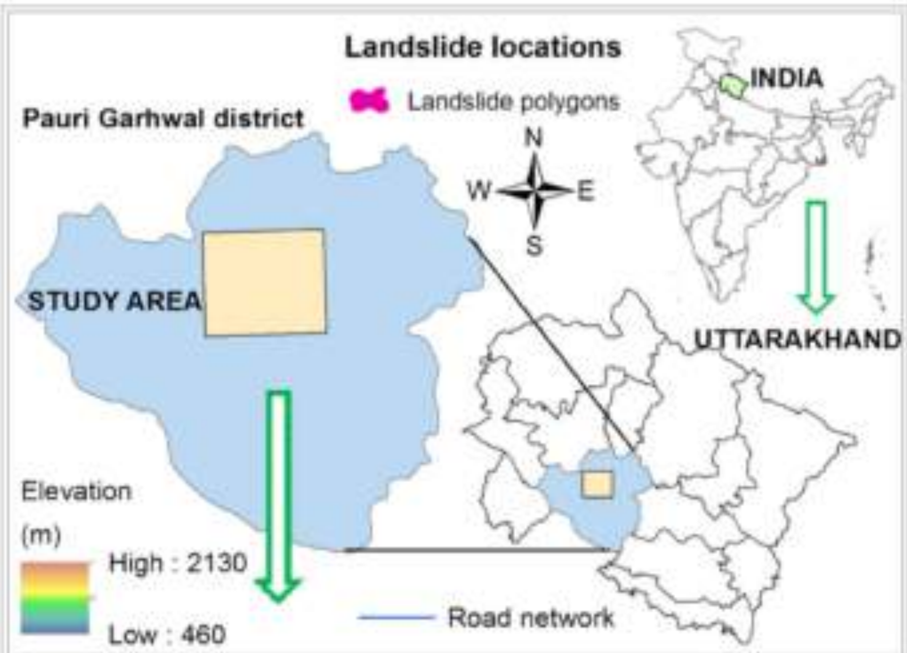
- **External factors**

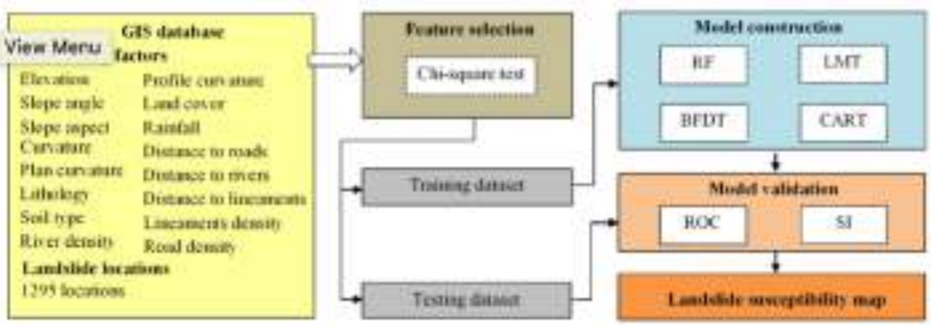
- Most common is the vibration resulted due to earthquakes; blasting to explosives; volcanic eruption etc.
- Earthquakes often initiate mass failures on large scale eg. 1897 Assam quake produced gigantic landslide ever recorded in the region.

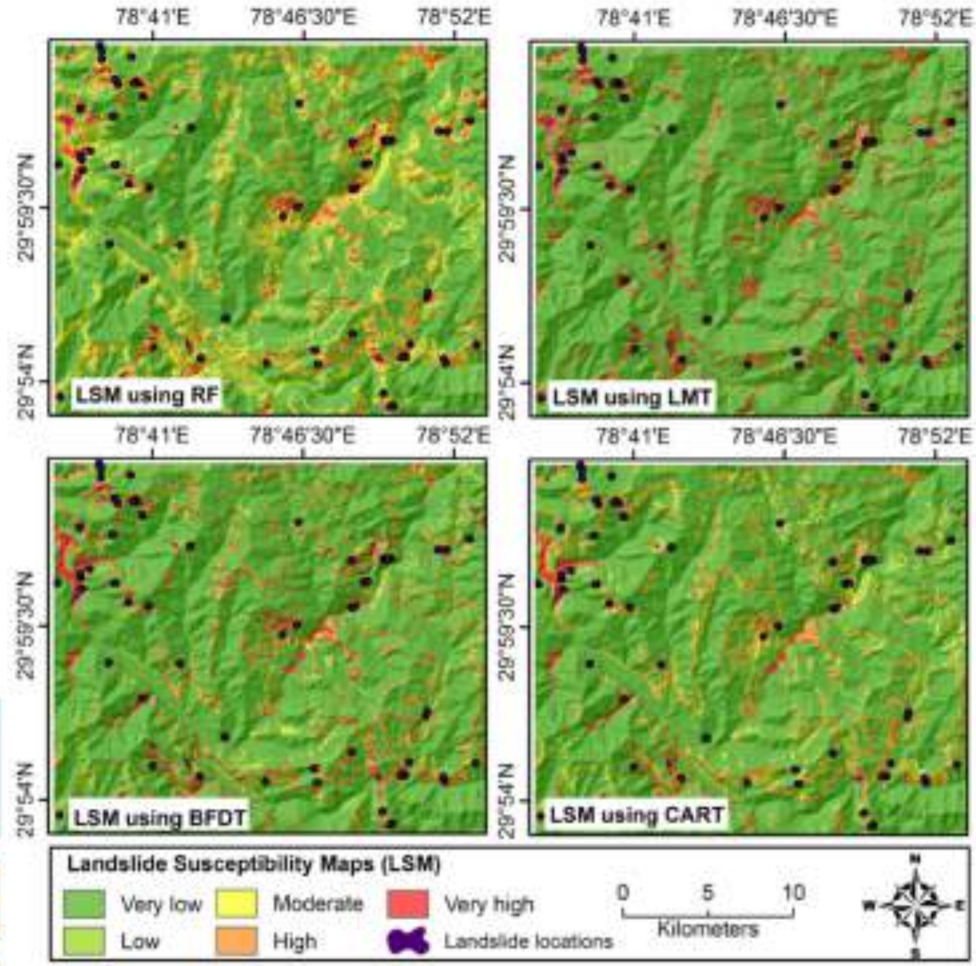
Preventive measures

- The main factors which contribute to landslides are ***Slope, water content, geological structure, unconsolidated or loose sediments, lithology and human interference.***
- ***Slope:*** Retaining wall may be constructed against the slopes, which can prevents rolling down of material. Terracing of the slope is an effective measure. Plant ground cover on slopes and build retaining walls.
- ***Effect of water:*** Make proper drainage network for quick removal of percolating moisture or rain water by constructing ditches and water ways along the slope. In mudflow areas, build channels or deflection walls to direct the flow around buildings.
- ***Geological structures:*** Weak planes or zones may be covered to prevent percolation of water, this increases the compaction of loose material.
- Install flexible pipe fittings to avoid gas or water leaks.
- **Identify** potential landslides
  - Photographic analysis
  - Topographic map and detailed field check
  - Historic data
  - Human surveillance
  - Instrumental survey: Tilt meter and geophones
- Landslide hazard inventory map
  - Grading code from the least stable to the most stable

Landslide Susceptibility map







Pham et al., (2017)

Application of geologic and engineering knowledge before any hillside development

What Can You Do?

- Development of landslide early warning systems
- Professional geologic evaluation for a property on a slope
- Avoid building at the mouth of a canyon, regardless of its size
- Consult local agencies for historical records
- Watch signs of little slides—often precursor for larger ones
- Look for signs of structure cracks or damage prior to purchase
- Be wary of pool leaking, tilt of trees and utility poles
- Look for linear cracks, subsurface water movement
- Put observations into perspective, one aspect may not tell the whole story

Fundamentals of Earth Sciences (ESO 213A)

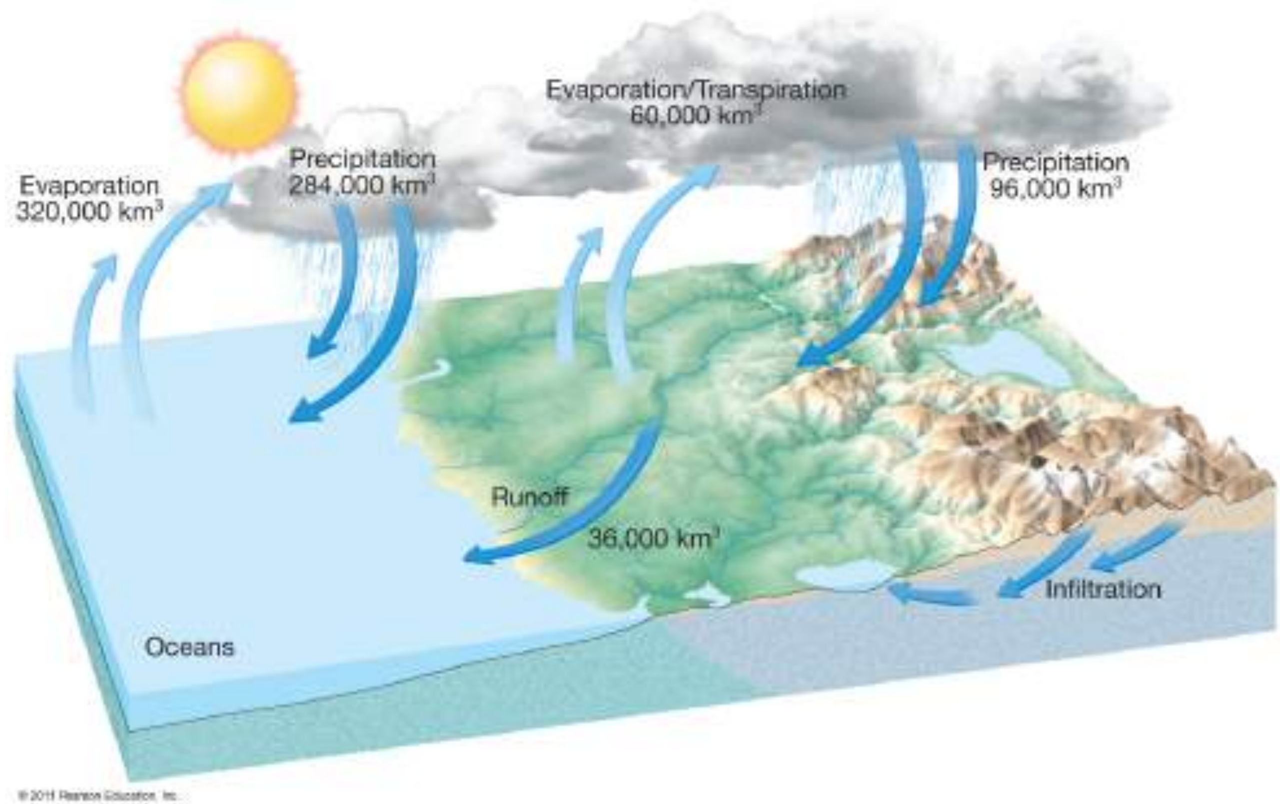
Dibakar Ghosal
Department of Earth Sciences

Hydrological Cycles (Glaciers)

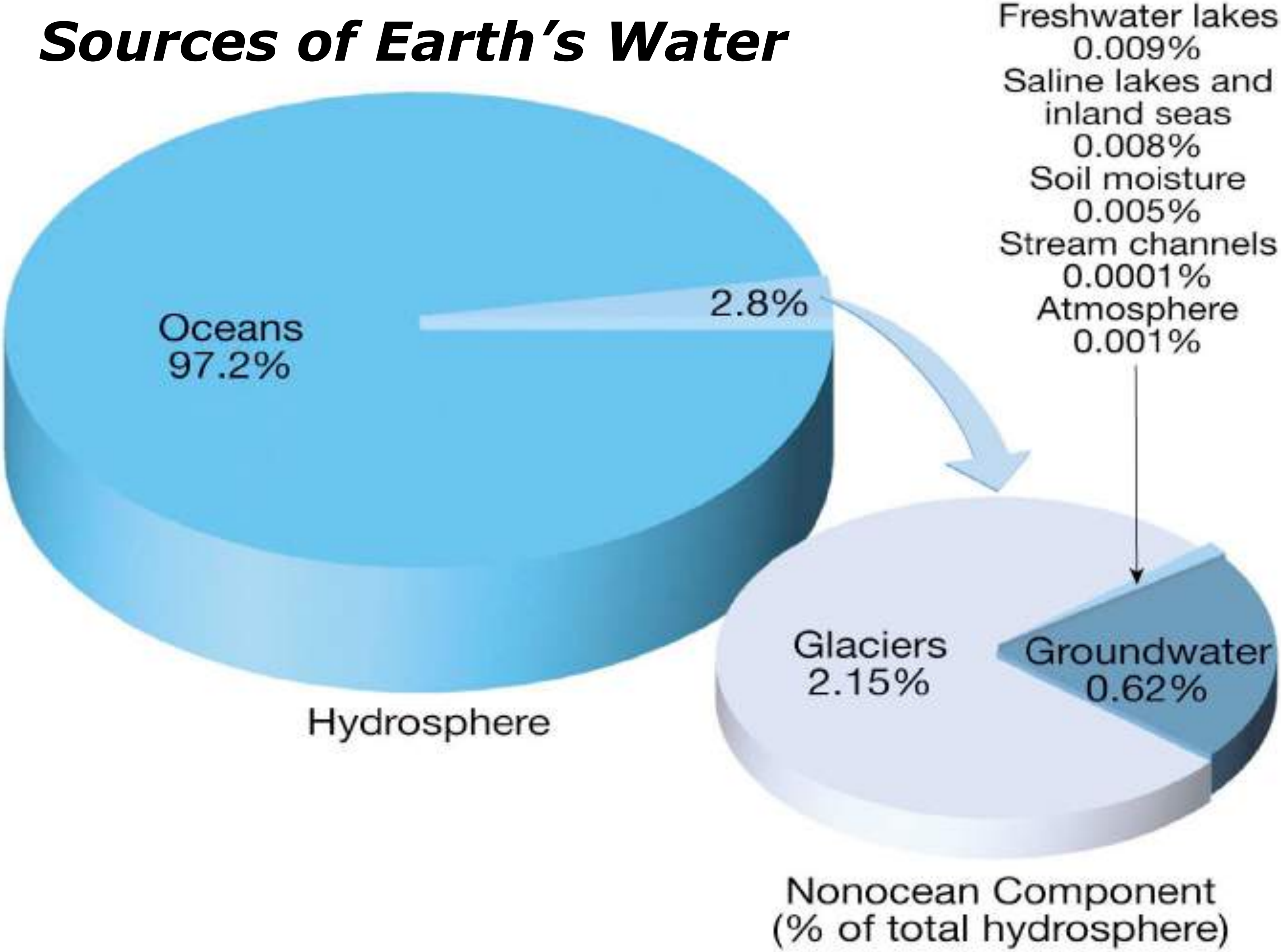
Previous class: Landslides

Hydrologic Cycle

- The hydrologic cycle is a summary of the circulation of Earth's water supply among different spheres: hydrosphere, atmosphere, geosphere, biosphere
- Processes involved in the hydrologic cycle are:
    - Precipitation
    - Evaporation
    - Infiltration
    - Runoff
    - Transpiration



Sources of Earth's Water



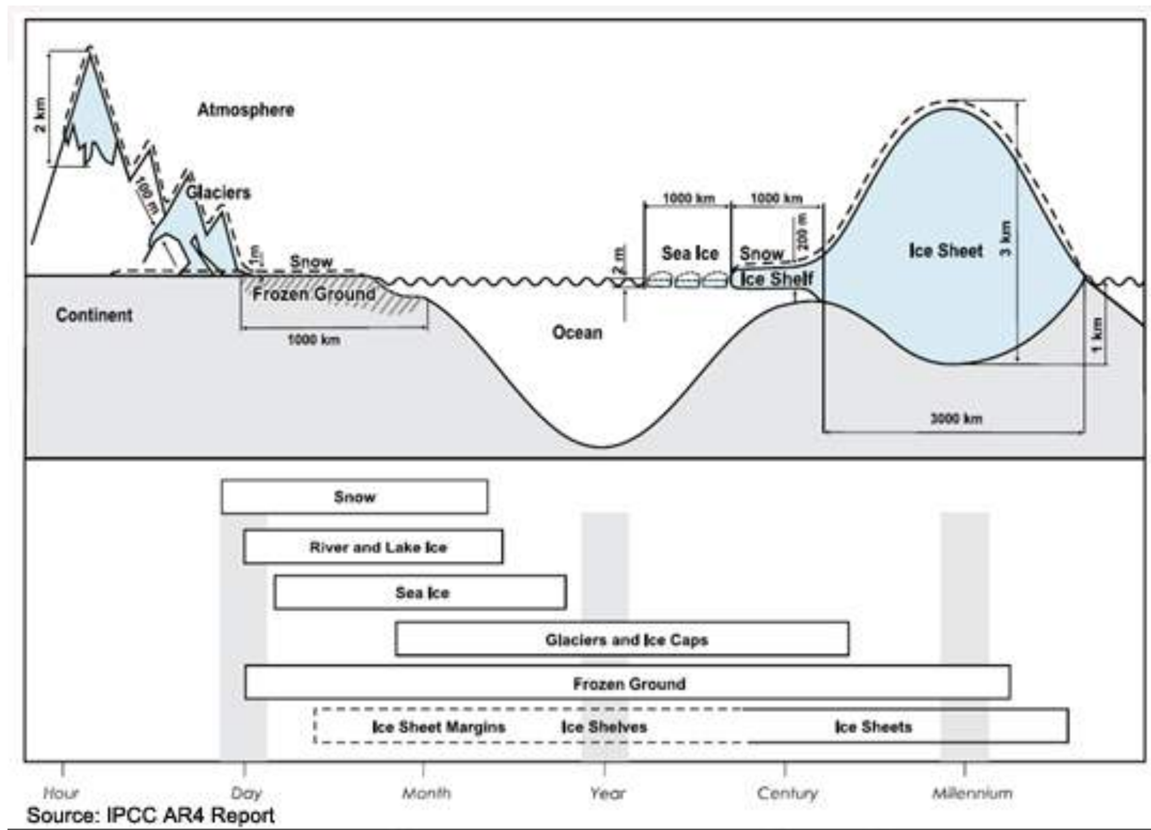
Cryosphere

<u>Some places on Earth are so cold that water is a solid—ice or snow.</u> Such places where water is in its solid form, where low temperatures freeze water and turn it into ice. The word "cryosphere" comes from the Greek word for cold, "kryos

Components

The main components of the cryosphere are :-

- Glaciers & ice caps.
- Snow.
- River and lake ice.
- Sea ice.
- Ice shelves.
- Ice sheets.
- Frozen Ground.



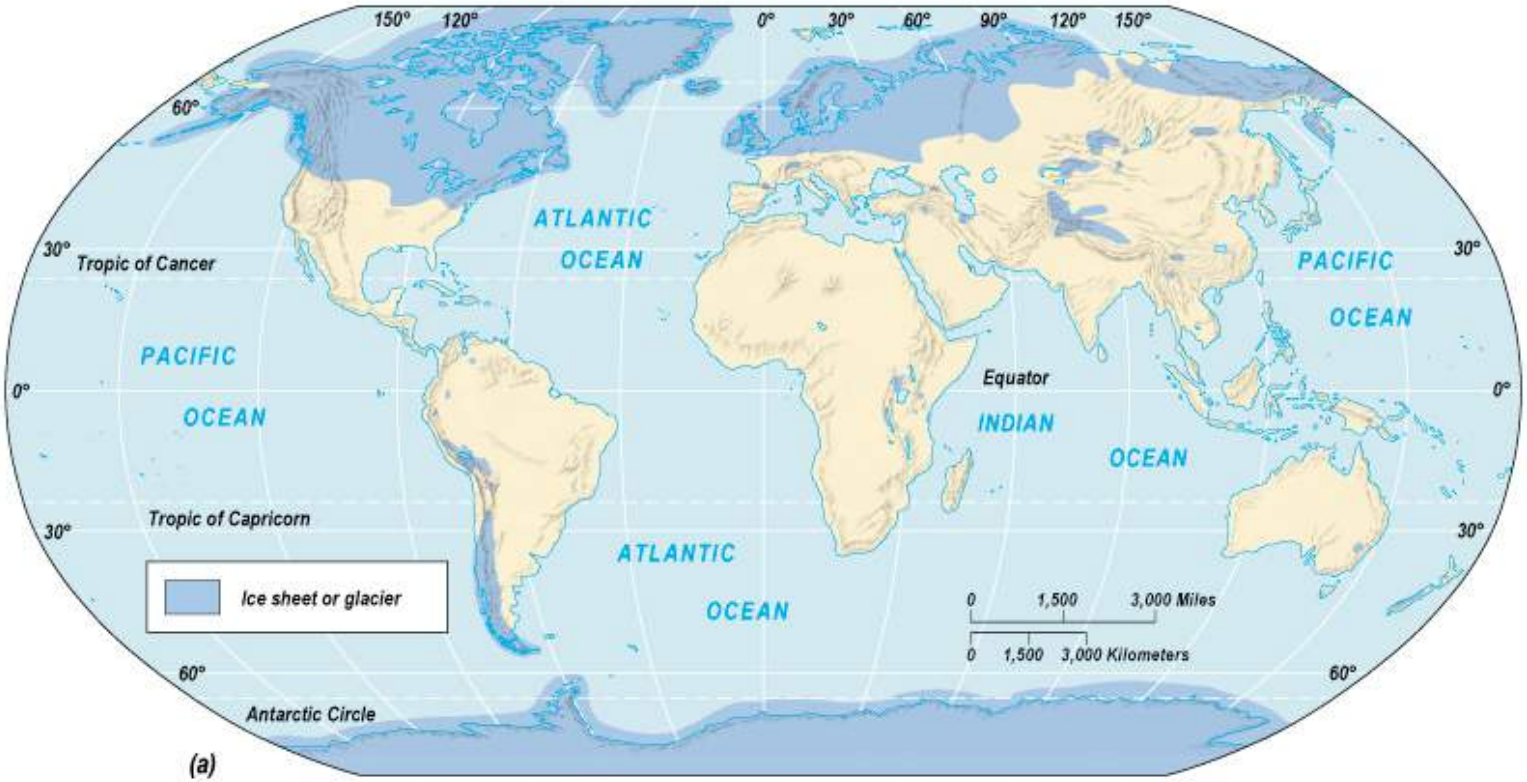
COMPONENTS OF THE CRYOSPHERE AND THEIR TIME SCALES

Glaciers

Glaciers are parts of two basic cycles:

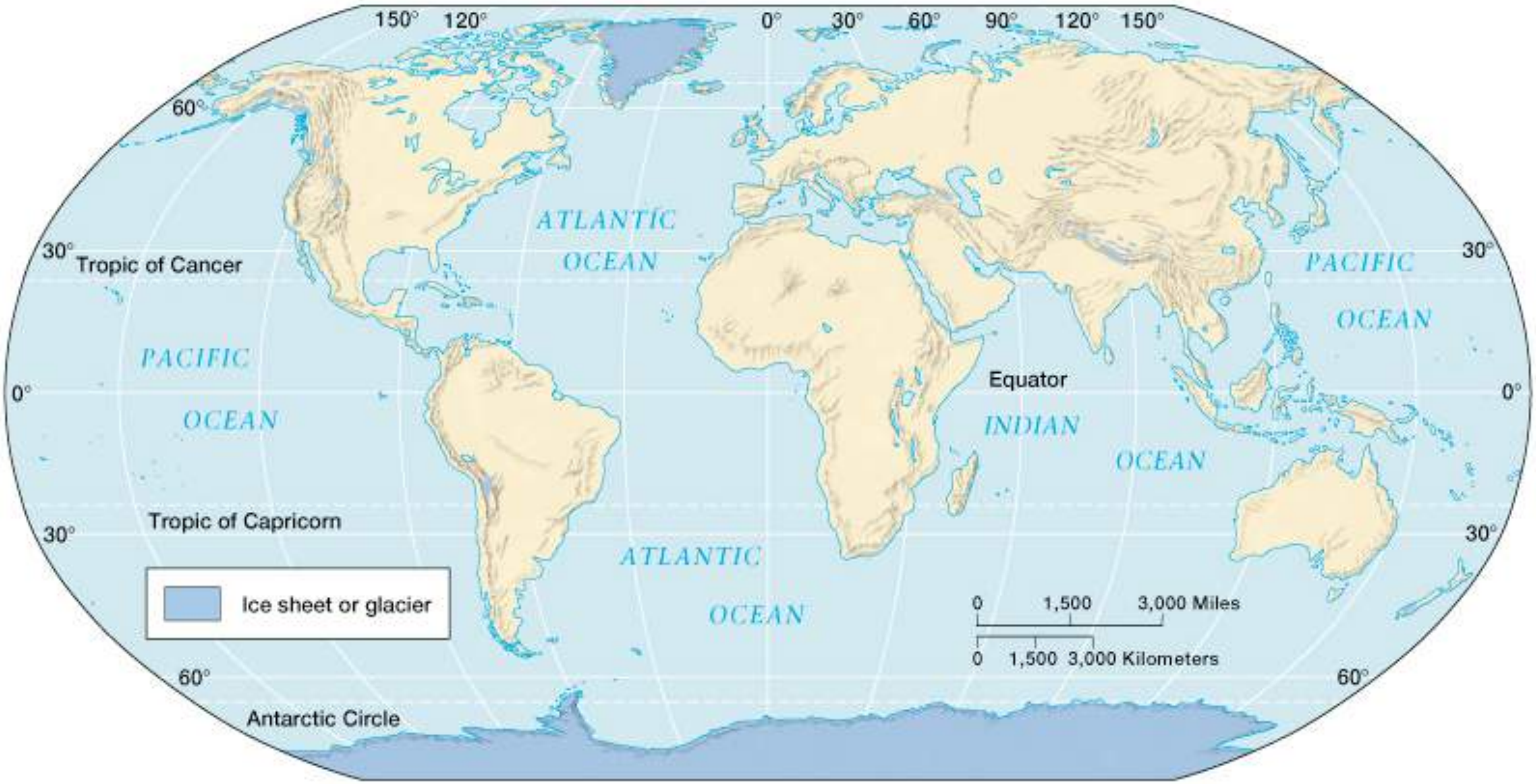
1. Hydrologic cycle
2. Rock cycle

A glacier is a <u>thick mass of ice that originates on land from the accumulation, compaction, and recrystallization of snow</u>.



Maximum Extent of <u>Pleistocene</u> Glaciation - 1/3 of land surface

Most recent glacial maximum peaked 18,000 years ago and is considered to have ended 10,000 B.P.



Current Extent of Glaciation - about 10% of land surface

Glaciers

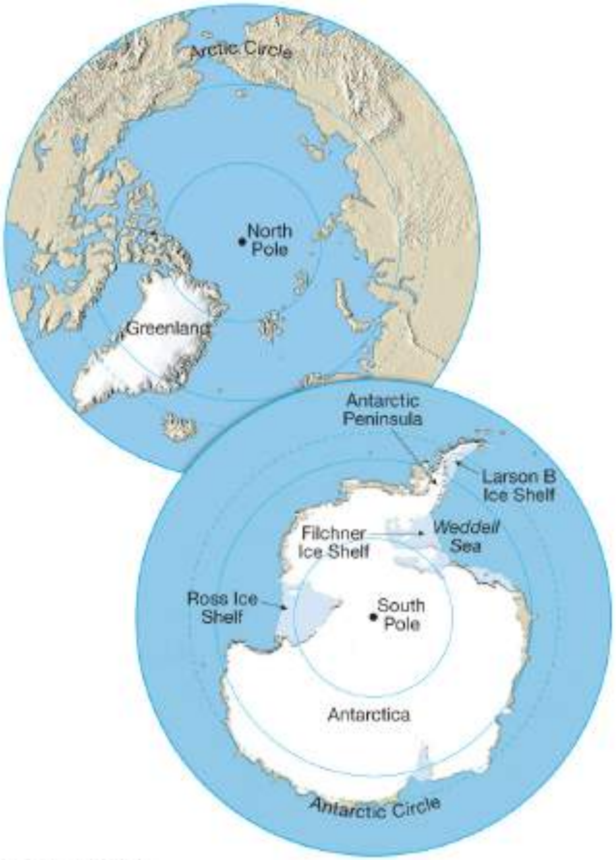
Types of glaciers

Valley (alpine) glaciers

- Exist in mountainous areas
- Flow down a valley from an accumulation center at its head

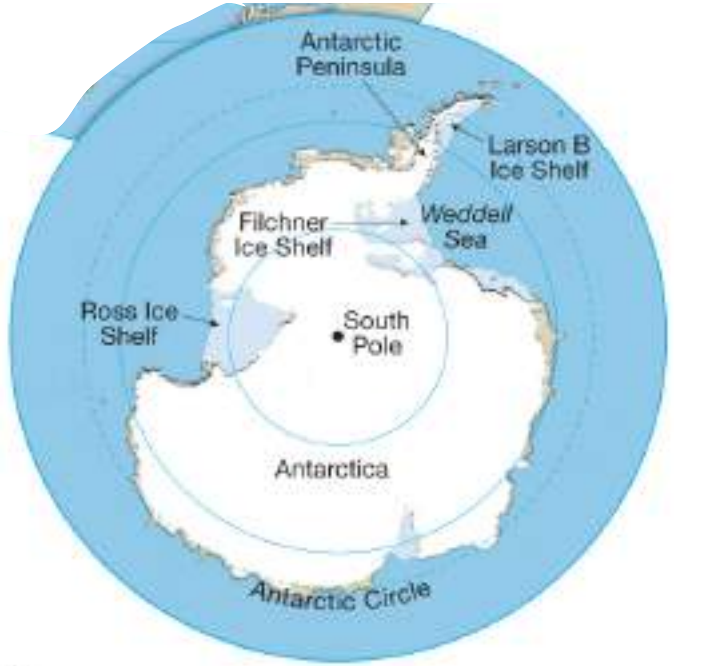
Ice sheets

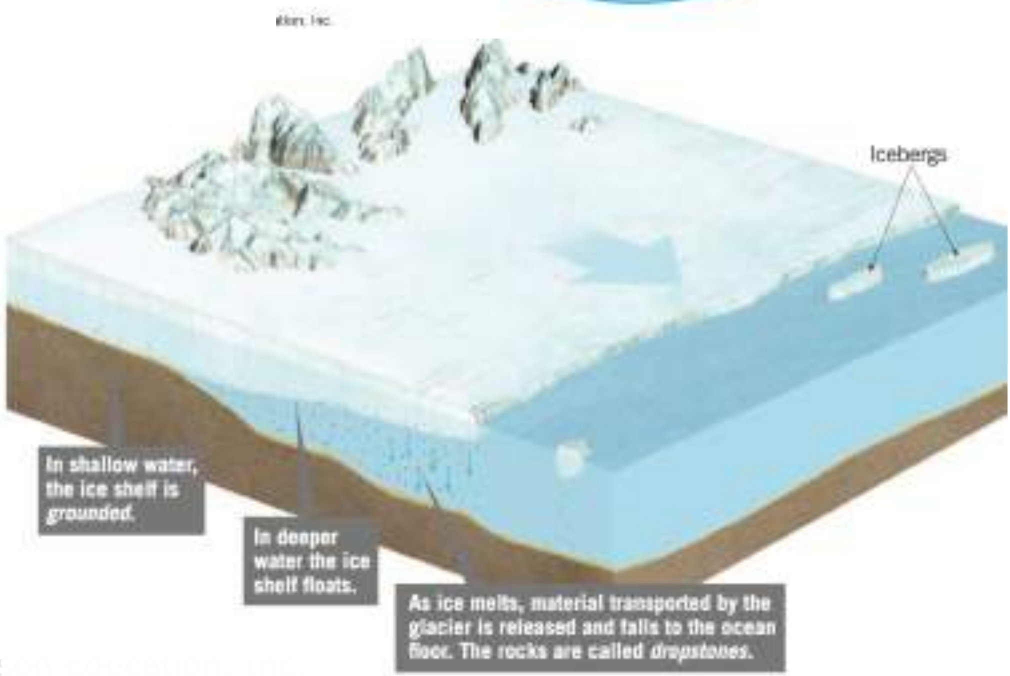
- Exist on a larger scale than valley glaciers
- Forms due to low annual solar radiation
- Two major ice sheets on Earth are over Greenland and Antarctica.
- Often called *continental ice sheets*
- Ice flows out in all directions from one or more snow accumulation centers.



Glaciers

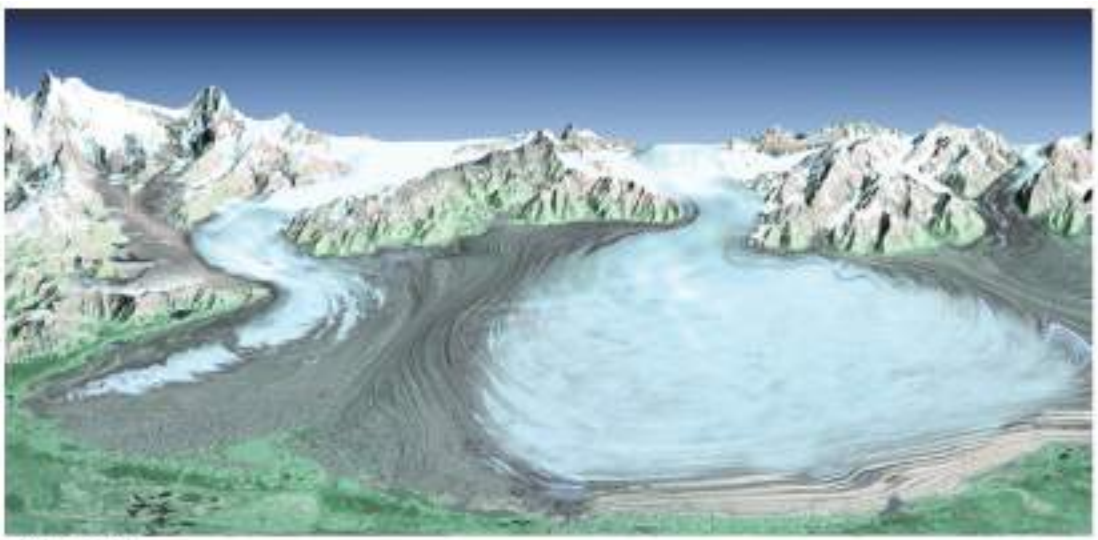
- Ice sheets continued
  - Along portions of the Antarctic coast, <u>glacial ice flows into the adjacent ocean</u>, creating features called *ice shelves*
  - Ross, Filchner, Larson B
  - Some are unstable and break apart → *icebergs*





Glaciers

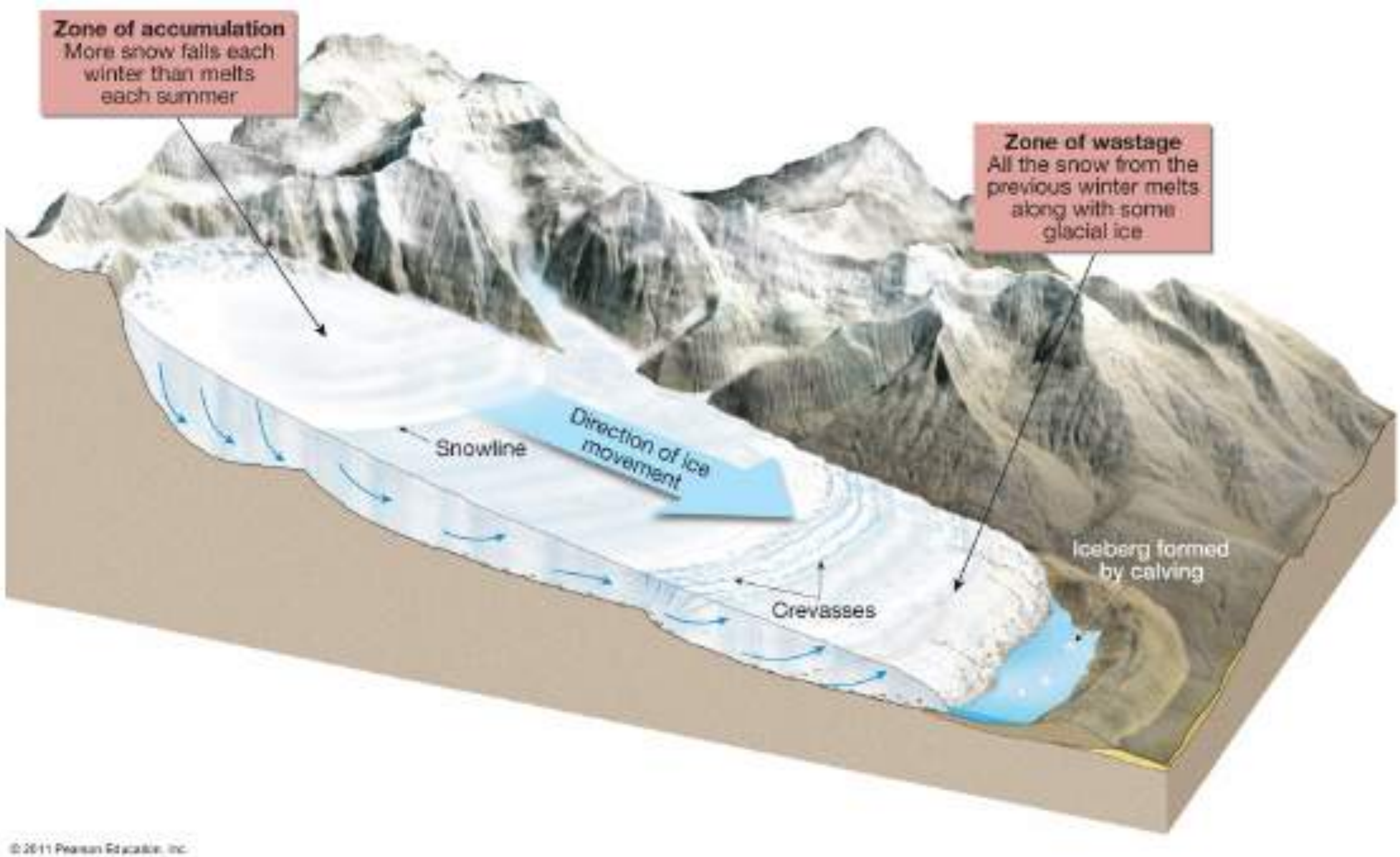
- Other types of glaciers
  - Ice caps – similar, but much smaller, than ice sheets
  - Piedmont glaciers – form when one or more alpine glaciers emerge from the confining walls of mountain valleys



Inc.

Formation of Glacial Ice

- Glaciers form in areas where more snow falls in winter than melts during the summer (very high latitudes and altitudes)
- The elevation above which snow remains throughout the year is called *snowline*



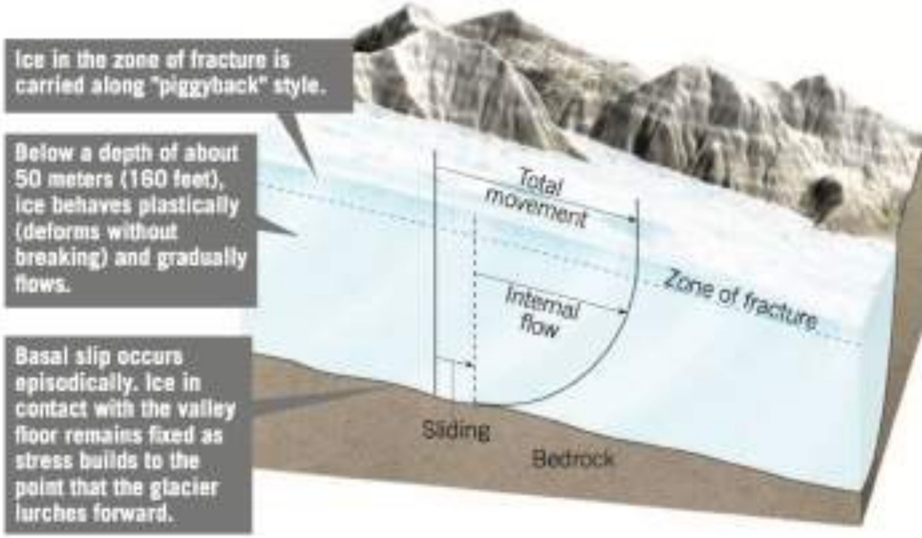
Formation of Glacial Ice

- Steps in the formation of glacial ice
  - Air infiltrates *snow*
  - Snowflakes become smaller, thicker, and more spherical
  - Air is forced out
  - Snow is recrystallized into a much denser mass of small grains called *firn*
  - Once the thickness of the ice and snow exceeds 50 meters, firn fuses into a solid mass of interlocking ice crystals—*glacial ice*

Movement of Glacial Ice

Movement is referred to as flow

- Two basic types
  1. Plastic flow
     - » Occurs within the ice
     - » Under pressure (equivalent to weight of ~ 50 m of ice), ice behaves as a plastic material
  2. Basal slip
     - » Entire ice mass slipping along the ground
     - » Most glaciers are thought to move by this sliding process
- Zone of fracture
  - – Occurs in the uppermost 50 meters
  - – Tension causes crevasses to form in brittle ice



Movement of Glacial Ice

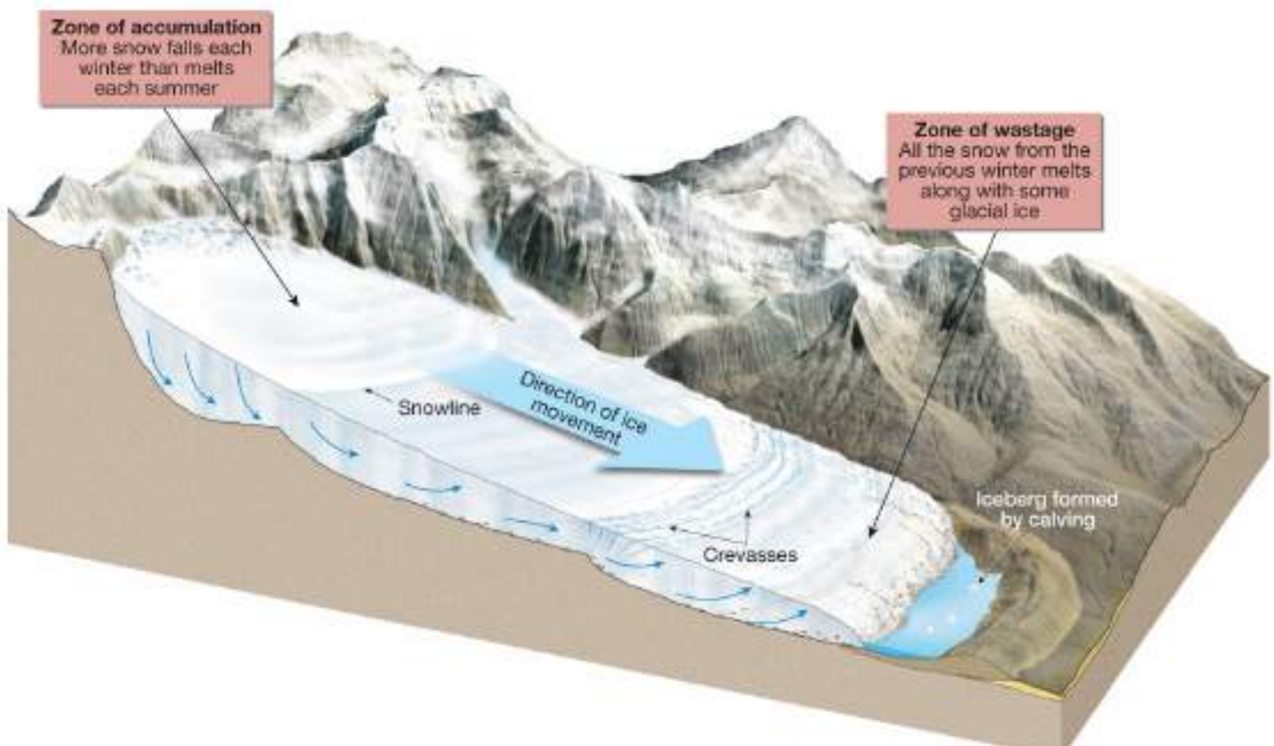
- Rates of glacial movement
    - Unlike streamflow, glacial movement is not obvious
    - Average velocities vary considerably from one glacier to another
    - Rates of up to <u>several meters per day</u>
    - Some glaciers exhibit periods of extremely rapid movements called surges (flow rates are as much as 100 times the normal rate)

Movement of Glacial Ice

Glacial Zones

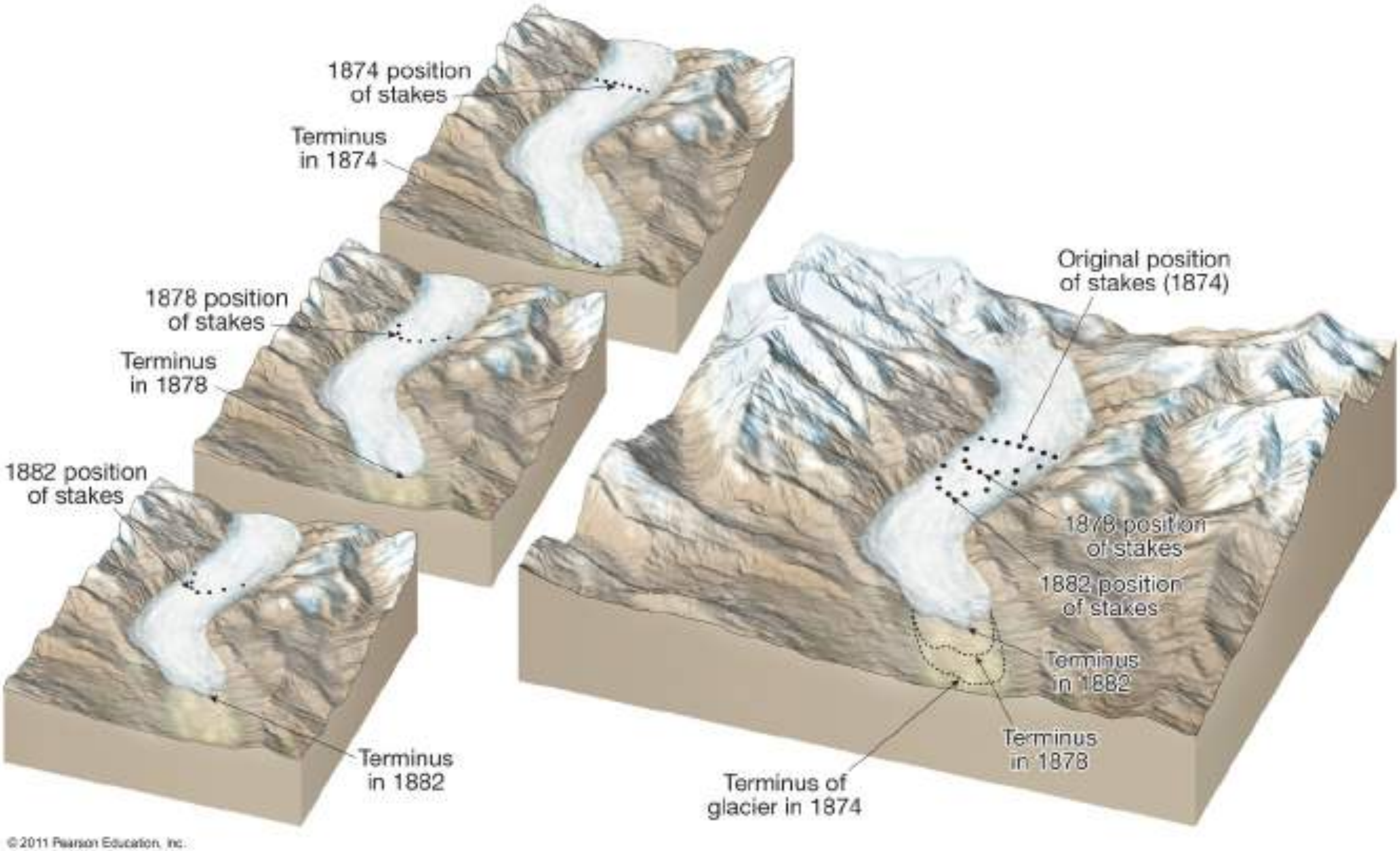
- The *zone of accumulation* is the area where a glacier forms
- The outer limits = snowline
- Elevation of the snowline varies greatly (from sea level in polar regions to 5000 m near equator)
- The *zone of wastage* is the area where there is a net loss of ice due to:
  - Melting
  - Calving—the breaking off of large pieces of ice (icebergs where the glacier has reached the sea)

The Glacial Budget



Movement of Glacial Ice

- Budget of a glacier
  - **Whether the margins of a glacier is advancing, retreating, or remaining stationary depends on the *glacial budget* = balance, or lack of balance, between accumulation at the upper end and loss at the lower end**
    - If accumulation exceeds loss (ablation), the glacial front advances
    - If ablation increases and/or accumulation decreases, the ice front will retreat

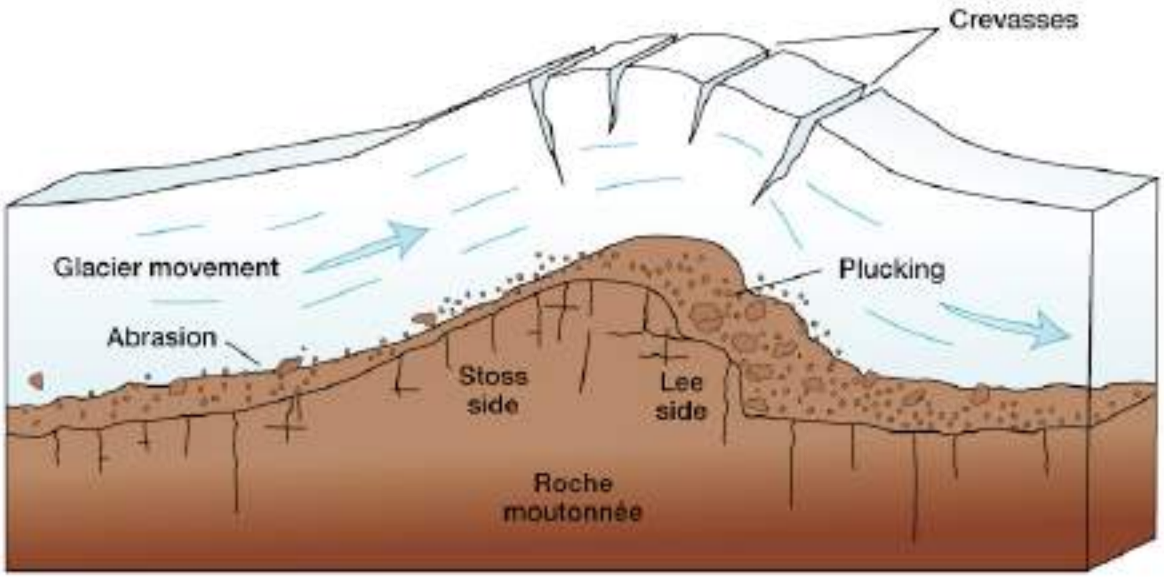

1874 position
of stakes
Terminus
in 1874
1878 position
of stakes
Terminus
in 1878
1882 position
of stakes
Terminus
in 1882
Original position
of stakes (1874)
1878 position
of stakes
1882 position
of stakes
Terminus
in 1882
Terminus
in 1878
Terminus of
glacier in 1874
© 2011 Pearson Education, Inc.

Glacial Erosion

- Glaciers are capable of great erosion and sediment transport;
- Can carry huge blocks – *glacial erratics* (sometimes as far as 500 – 1000 km from their source area)

Glacial Erosion

- Glaciers erode the land primarily in two ways:
  1. Plucking - lifting of rocks and incorporation into ice
  2. Abrasion - rocks within the ice acting like sandpaper to smooth and polish the surface below
  - Glacial abrasion produces:
    – Rock flours (pulverized rock)
    – Glacial striations (scratches and grooves in the bedrock, in case of large rock fragments)
    – Highly polished surface (in case of finer particles)



Glacial Erosion

A.

Glacial striations

B.

Glacially polished granite

Differential erosion by ice is largely controlled by four factors:

(1) rate of glacial movement;
(2) thickness of the ice;
(3) shape, abundance, and hardness of the rock fragments contained in the ice at the base of the glacier; and
(4) the erodibility of the surface beneath the glacier.

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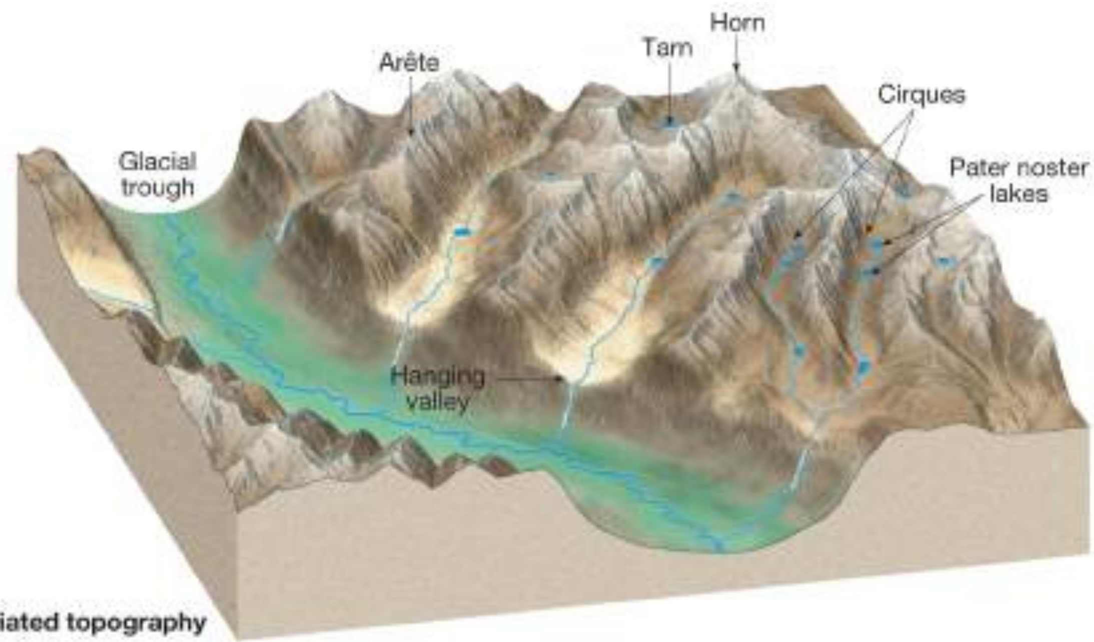
Landforms Created by Glacial Erosion

Glaciated Valleys

Glacial troughs – mountain valleys transformed during glaciation (wider, deeper, U-shaped)

Hanging valleys – after glaciation, valleys of tributary glaciers are left standing above the main glacial trough

U-Shaped Glacial Trough, Norway



C. Glaciated topography

Landforms Created by Glacial Erosion

Glaciated Valleys

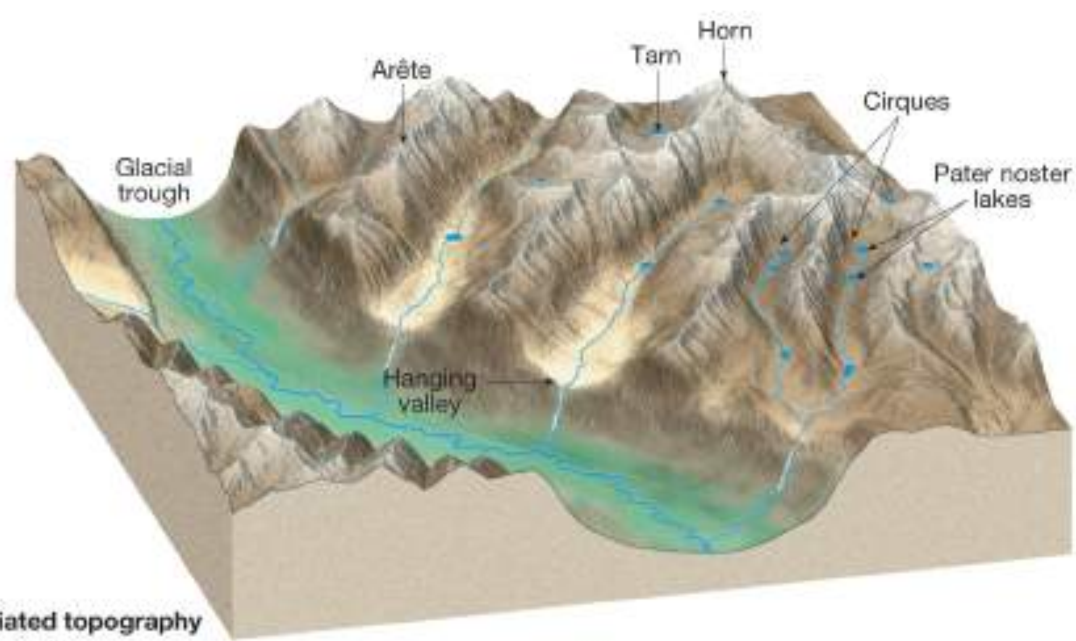
Pater noster lakes – in a glacial trough

Cirques – at the head of a glacial valley, bowl-shaped depressions

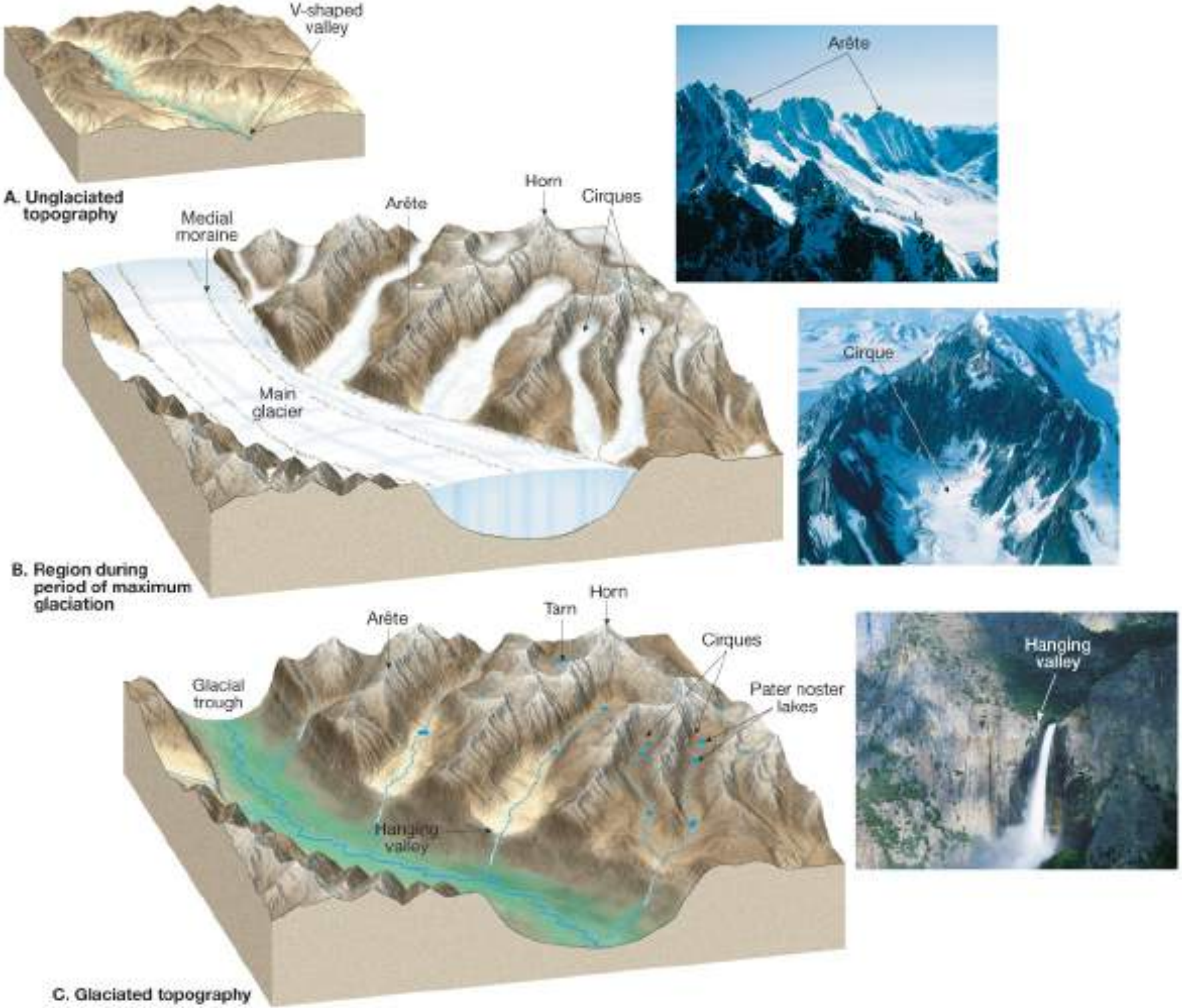
Tarns – small lake in the cirque basin

Arêtes – sharp-edged ridges

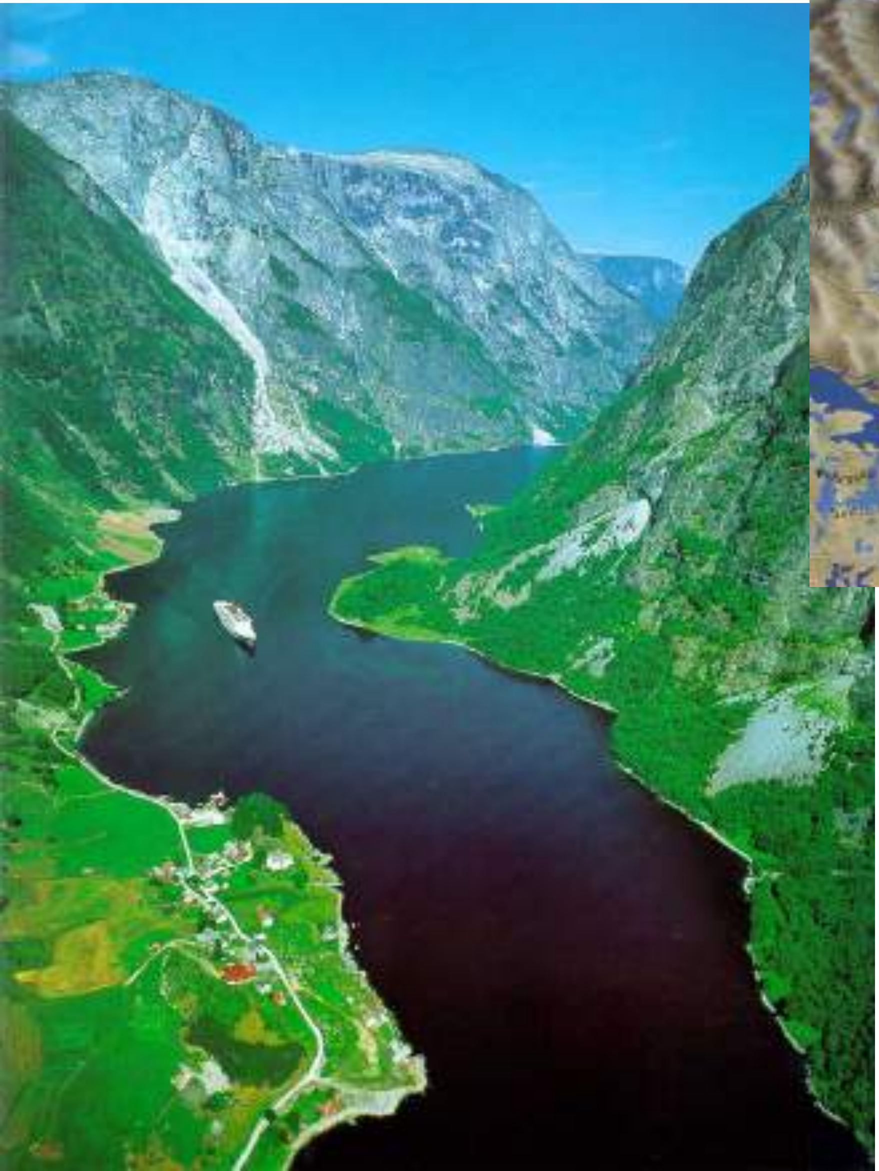
Horns – sharp pyramid-like peaks



C. Glaciated topography


V-shaped valley
A. Unglaciated topography
Medial moraine
Arête
Horn
Cirques
Main glacier
B. Region during period of maximum glaciation
Arête
Tarn
Horn
Cirques
Glacial trough
Pater noster lakes
Hanging valley
C. Glaciated topography
Arête
Cirque
Hanging valley

Fjords



Glacial Deposits

- *Glacial drift* refers to all sediments of glacial origin
- Different from sediments laid down by other erosional agents: *consist of mechanically-weathered rock debris that underwent little or no chemical weathering prior to deposition*
  - Types of glacial drift
    - Till—material that is deposited directly by the ice (unstratified, unsorted)
    - Stratified drift—sediments laid down by glacial meltwater

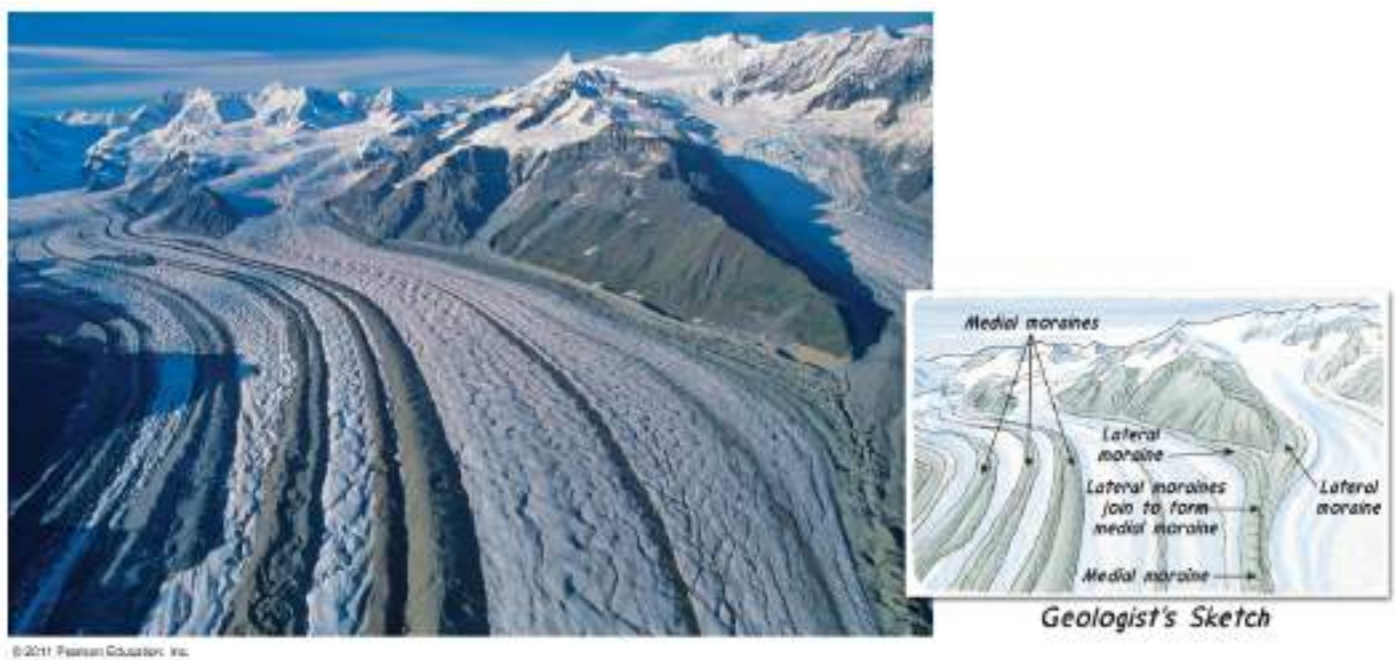
•***Glacial erratics*** are enormous boulders transported and deposited by glaciers, often far from their source region.

Glacial Till Is Typically Unstratified and Unsorted

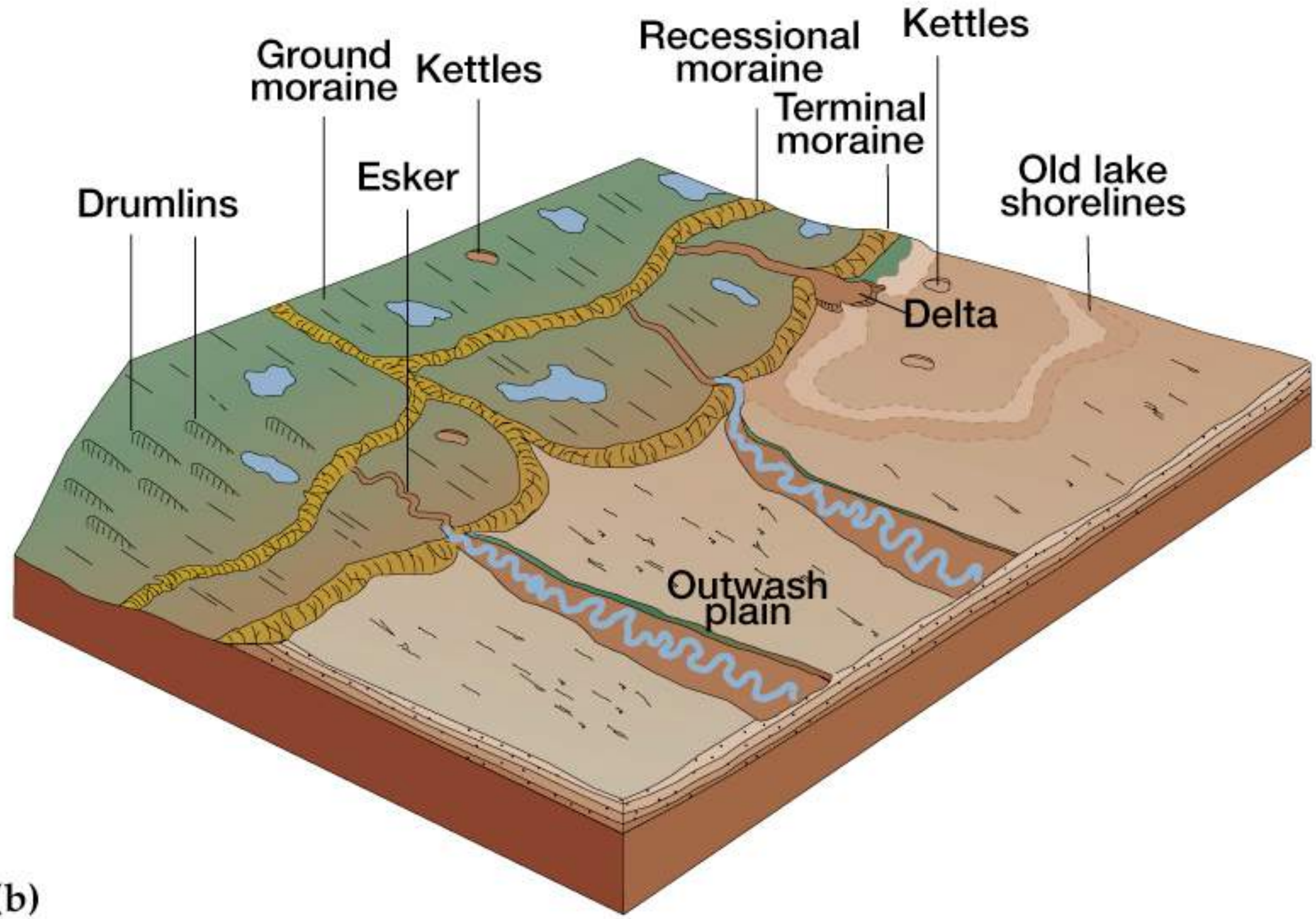
Glacial Deposits

Landforms made of till

- *Moraines*
  - Layers or ridges of till
- Moraines produced by alpine glaciers
  - Lateral moraine – ridges of till paralleling the sides of the valley
  - Medial moraine – created when two alpine glaciers coalesce to form a single ice stream
  - Layers or ridges of till
- Other types of moraines (valley glaciers; ice sheets)
  - End moraine – forms at the terminus of a glacier; equilibrium between ablation and ice accumulation
  - Terminal moraine – outermost end moraine; marks the limit of the glacial advance

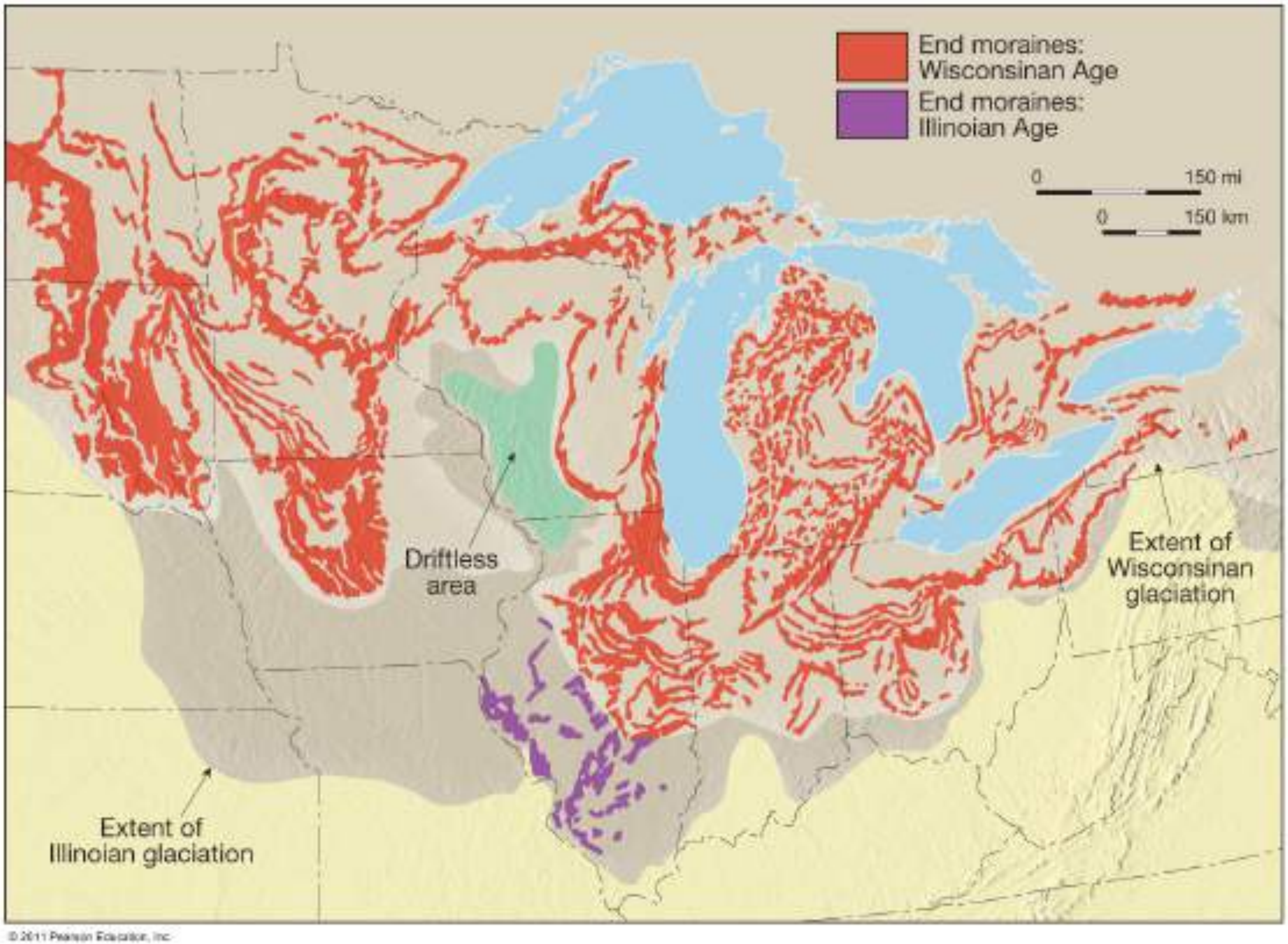


Continental Glaciers or Ice Sheets

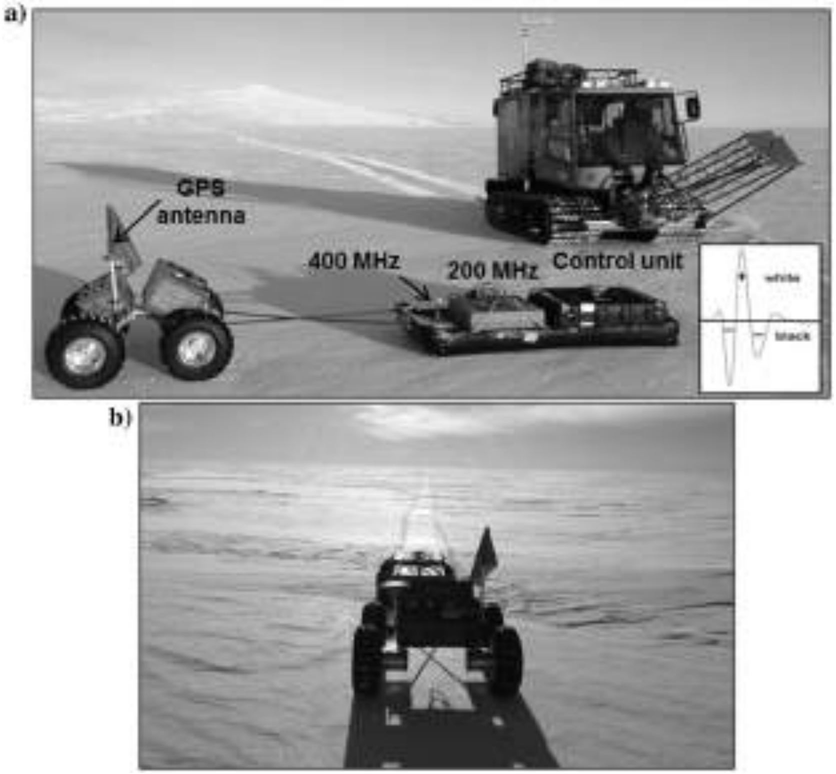


(b)

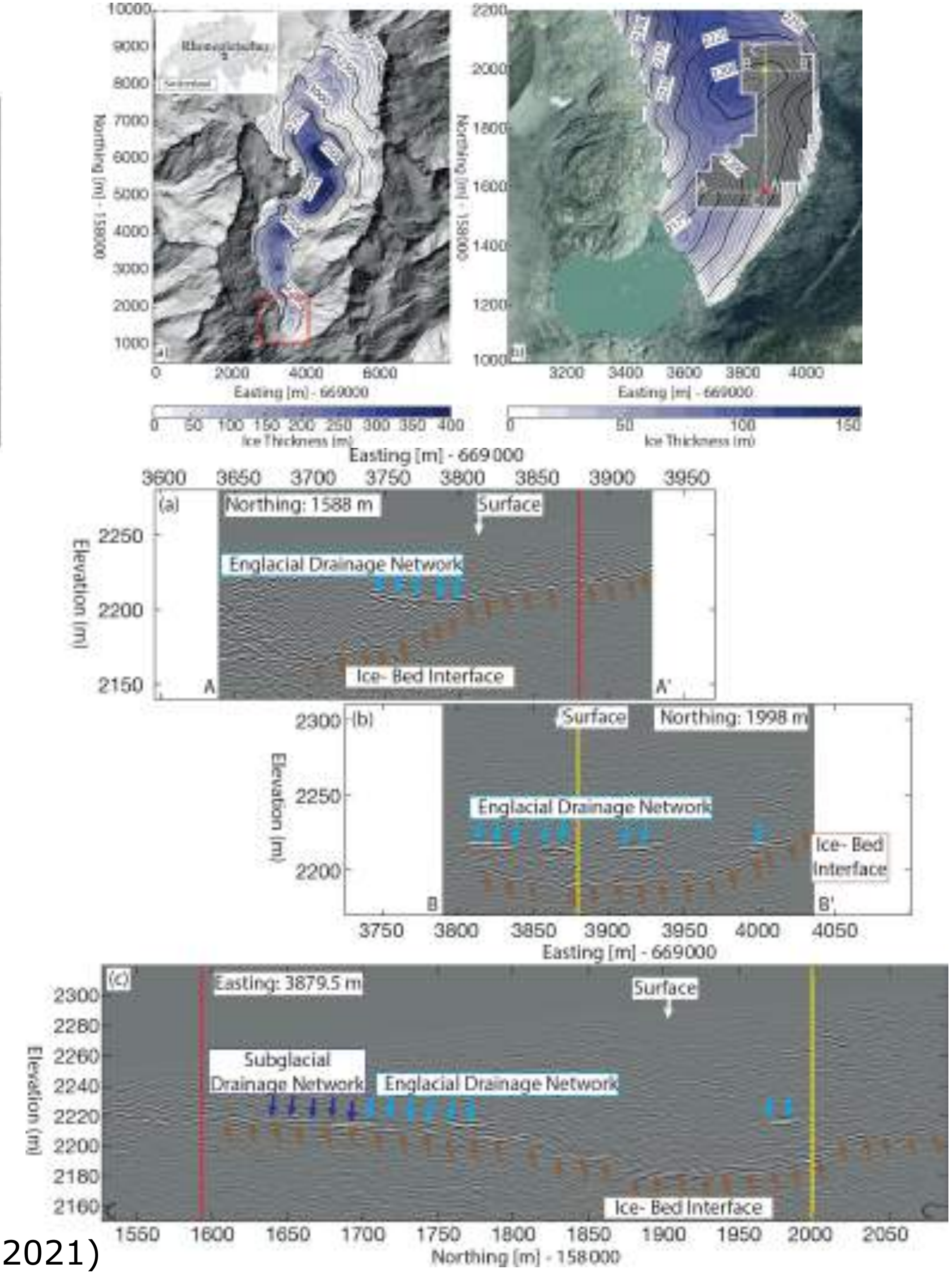
End Moraines of the Great Lakes Region



GPR studies

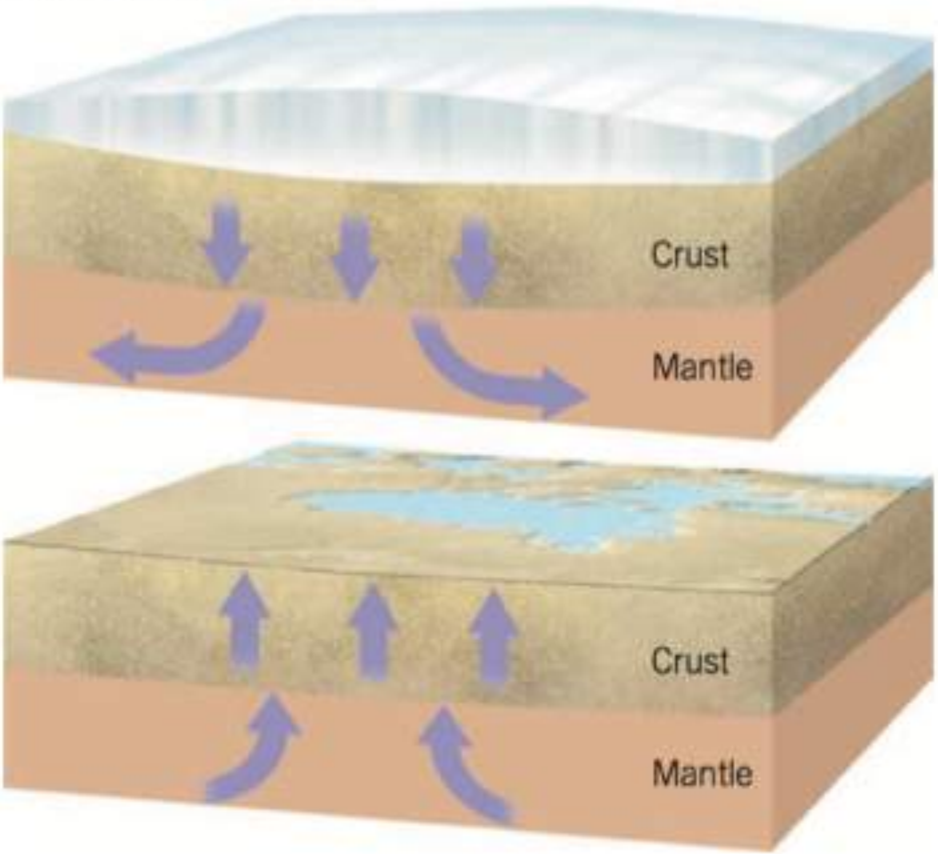


(a) GPR inline profile (perpendicular to ice flow direction): the glacier surface, drainage network, and basal interface are marked, and the red line represents the crossing point for profile (c). (b) GPR inline profile (perpendicular to ice flow direction): the yellow line represents the crossing point for profile (c). (c) GPR crossline profile (parallel to ice flow direction).

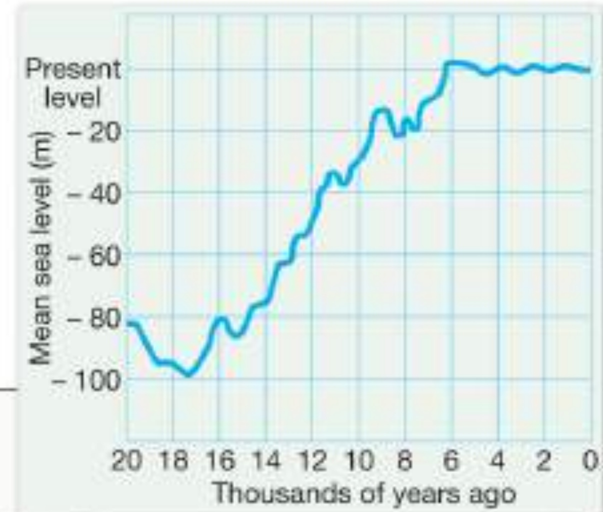


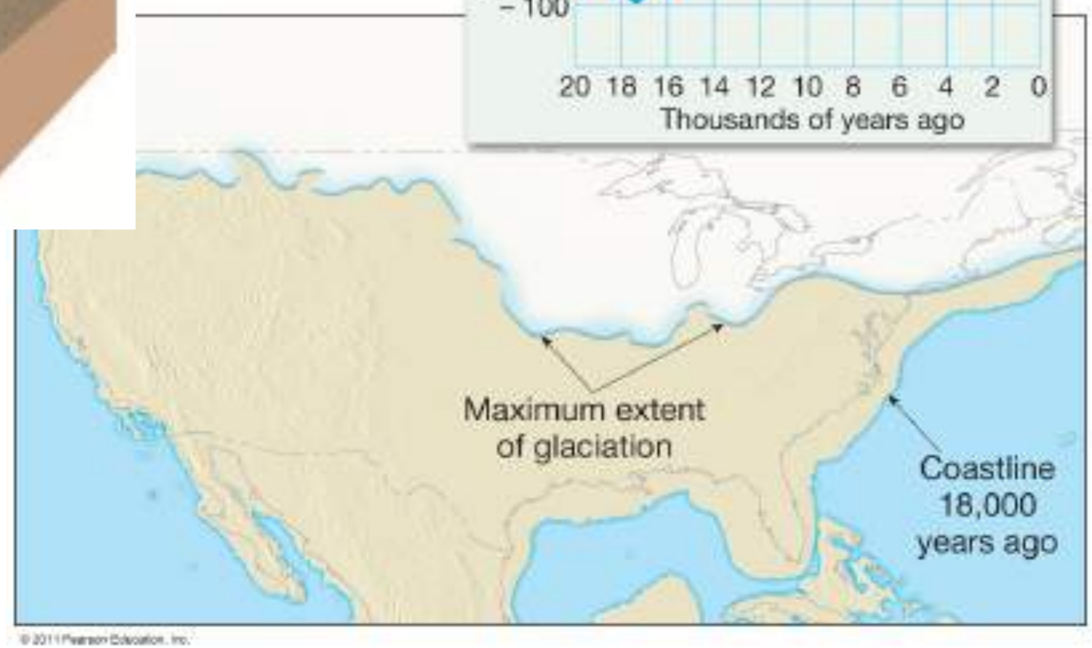
Church et al., (2021)

In northern Canada and Scandinavia, where the greatest accumulation of glacial ice occurred, the added weight caused downwarping of the crust.



Sea Level Changes Over the Past 20,000 Years





What if the ice on Earth melted?

- Slightly more than 2% of the world's water is tied up in glaciers.
- Antarctic ice sheet
  - 80 % of the world's ice
  - 65 % of Earth's fresh water
  - Covers almost one and a half times the area of the United States
  - If melted, sea level would rise 60 to 70 meters.

Indian glaciers: Drang-Drung Glacier (Ladhak)

Indian glaciers

State & Fate of Himalayan Glaciers

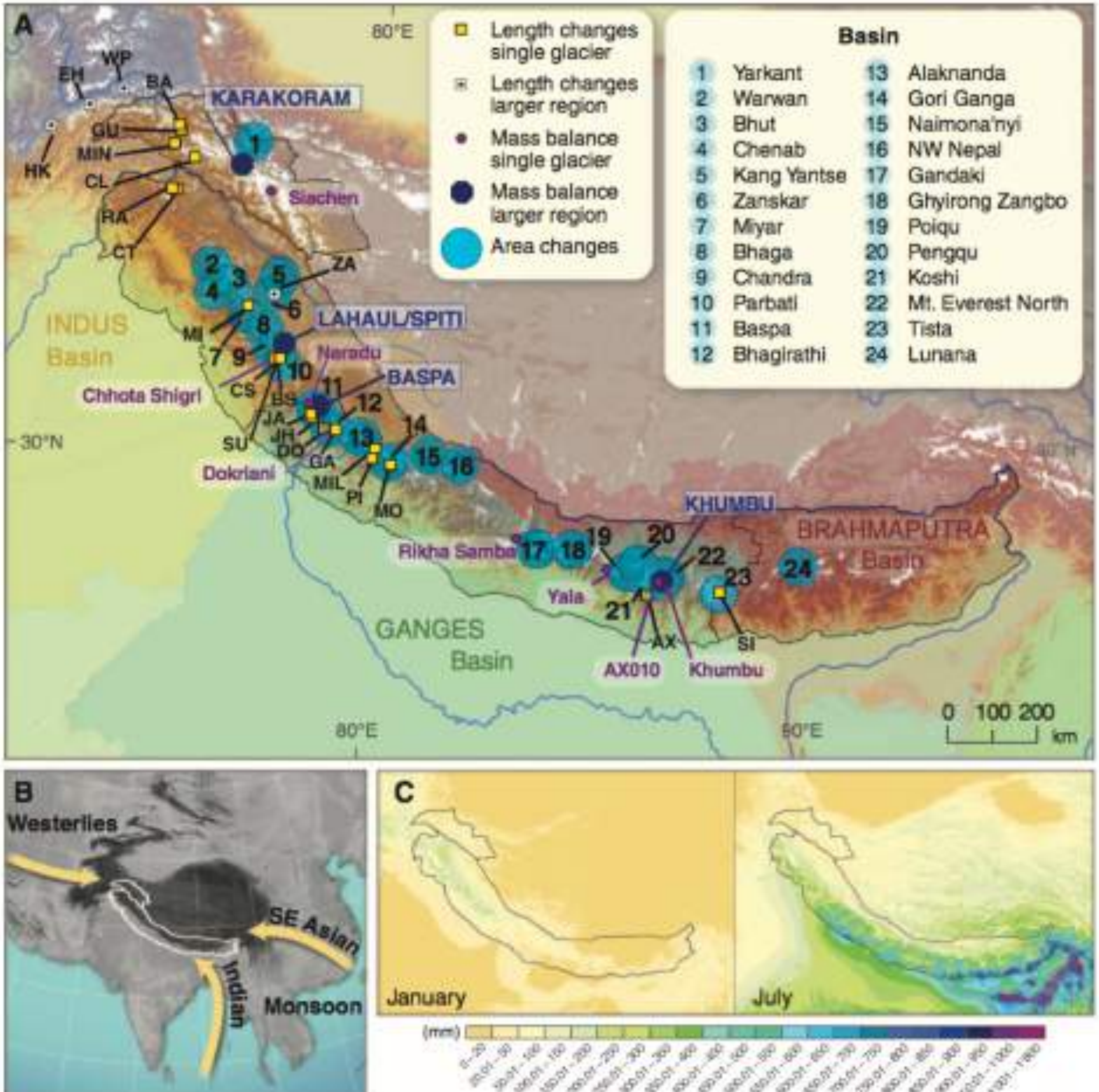
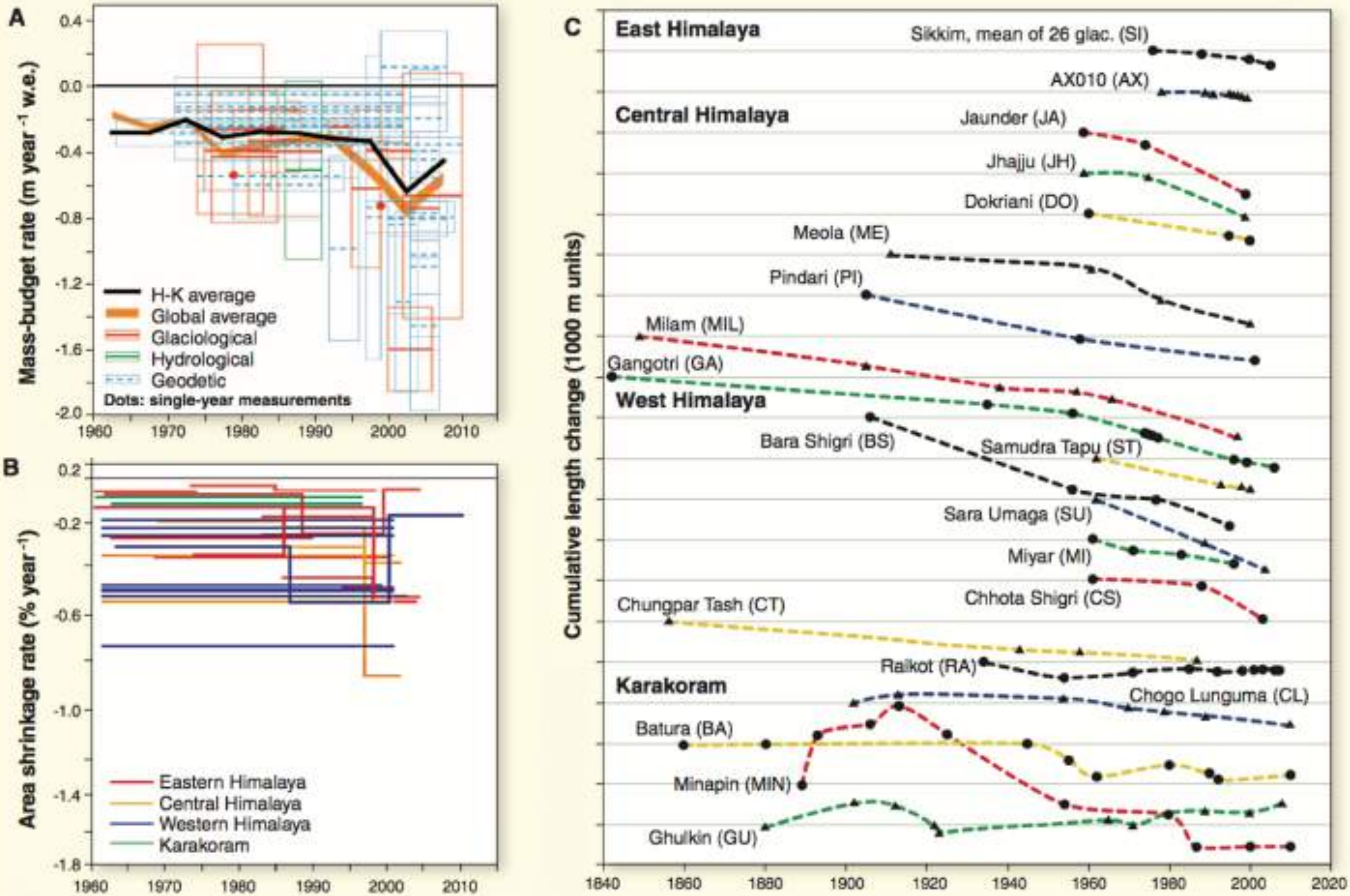


Fig. 1. (**A**) Map of the Karakoram and Himalaya showing the major river basins and the locations of measured rates of change in area and of a sample of glacier length change and mass budget measurements (*4*) (tables S3, S5, and S6). (**B**) Main wind systems. (**C**) Mean precipitation in January and July. [Source: (*9*)]

Bolch et al., 2012, Science



Bolch et al., 2012, Science

Causes of Glaciation

- *Ice Age* - began between 2 and 3 million years ago, during mainly the *Pleistocene Epoch*

  - very complex event, characterized by glacial / interglacial cycles that occurred about every 100,000 years (~ 20 cycles)

- Any successful theory must account for:
  - What causes the onset of glacial conditions
  - What caused the alteration of glacial and interglacial stages that have been documented for the Pleistocene epoch

Causes of Glaciation

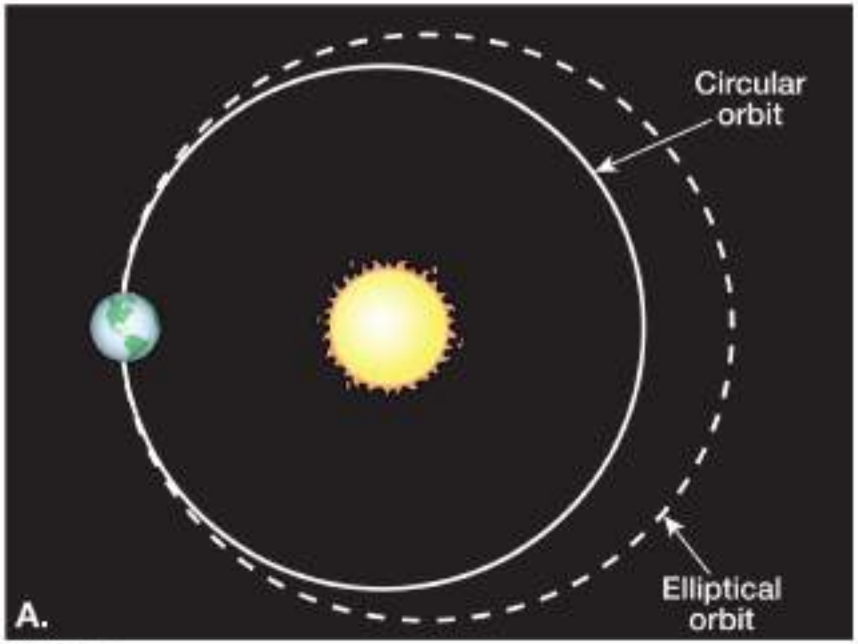
- Variations in Earth's orbit

Milankovitch hypothesis – based on the premise that variations in incoming solar radiation are a main factor in controlling Earth's climate

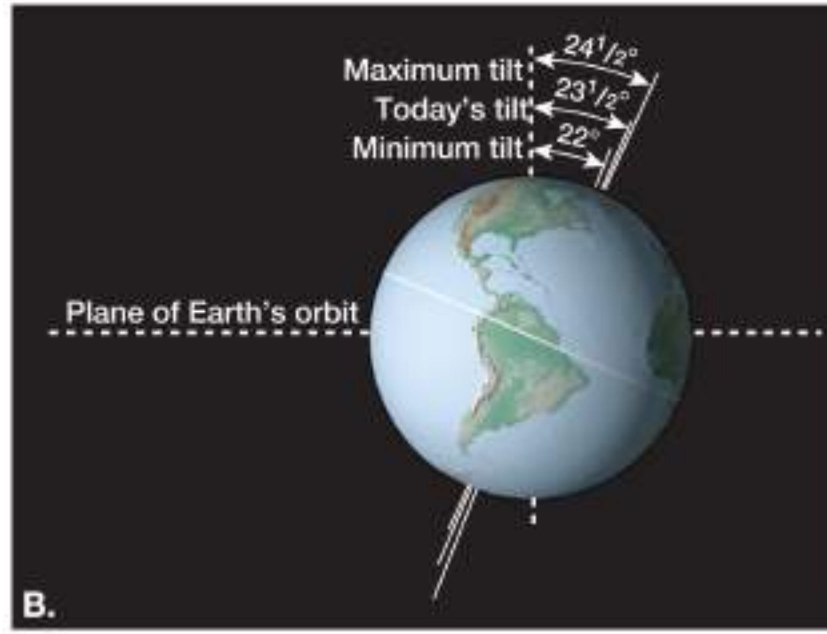
  - Shape (eccentricity) of Earth's orbit varies
  - Angle of Earth's axis (obliquity) changes
  - Earth's axis wobbles (precession)

  - Changes in climate over the past several hundred thousand years are closely associated with variations in the geometry of Earth's orbit.

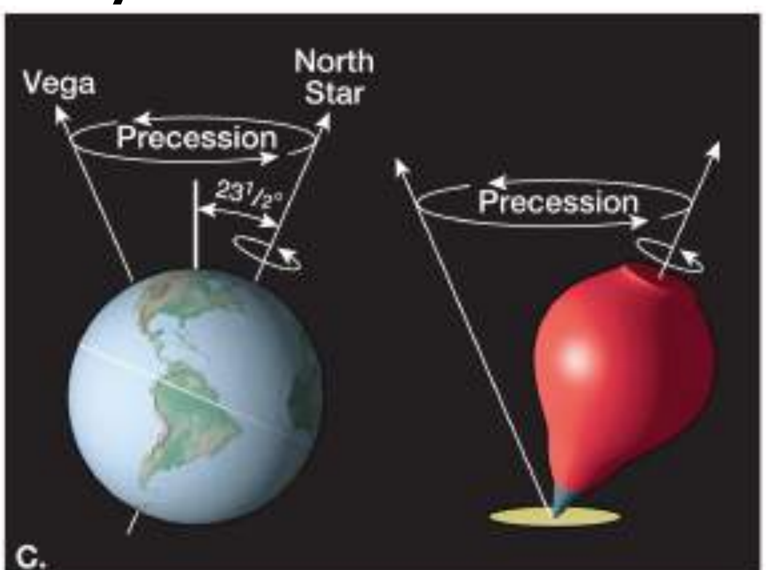
Orbital Variations



Cycle: 100,000 years



Cycle: 41,000 years



Cycle:

26,000 years

Other factors:

1. Reduction in Green house gasses
2. Changes in Ocean Circulation during Ice age

Fundamentals of Earth Sciences (ESO 213A)

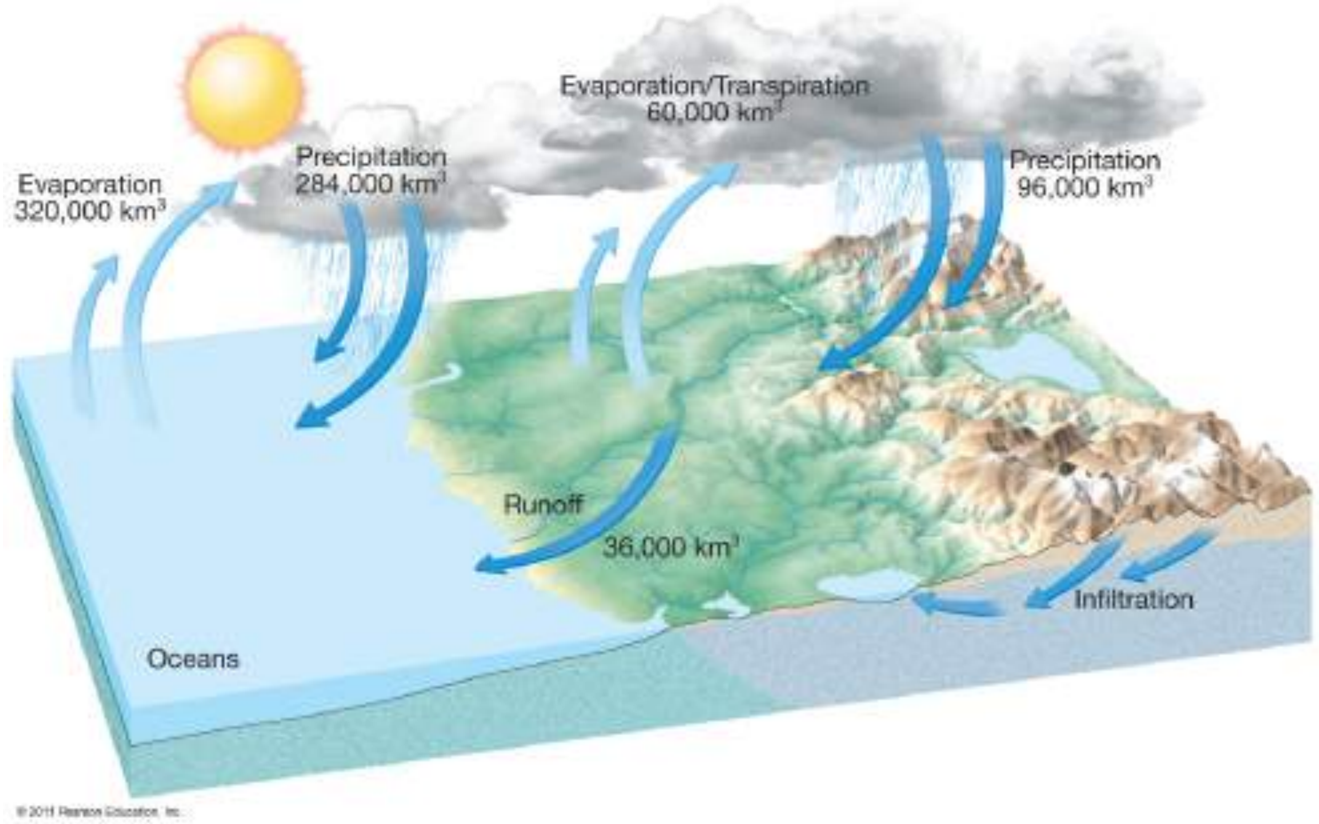
Dibakar Ghosal
Department of Earth Sciences

Groundwater

Previous Class: Glaciers

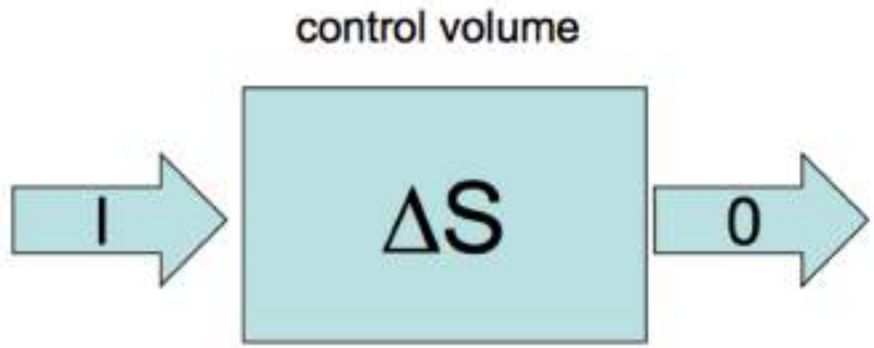
Ground Water

- *Ground Water* lies beneath the ground surface, filling pores in sediments and sedimentary rocks and fractures in other rock types
- Represents *0.6%* of the hydrosphere
  - Resupplied by slow *infiltration of precipitation*
  - Generally cleaner than surface water
  - Accessed by *wells*

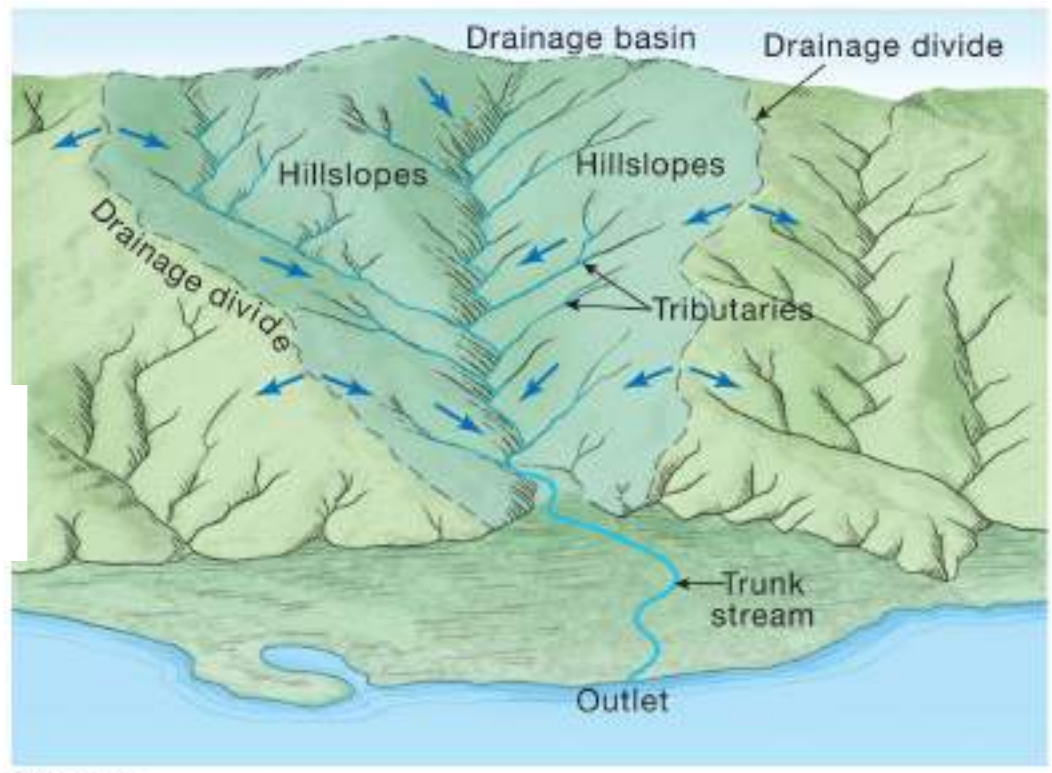


The water balance and principle of conservation

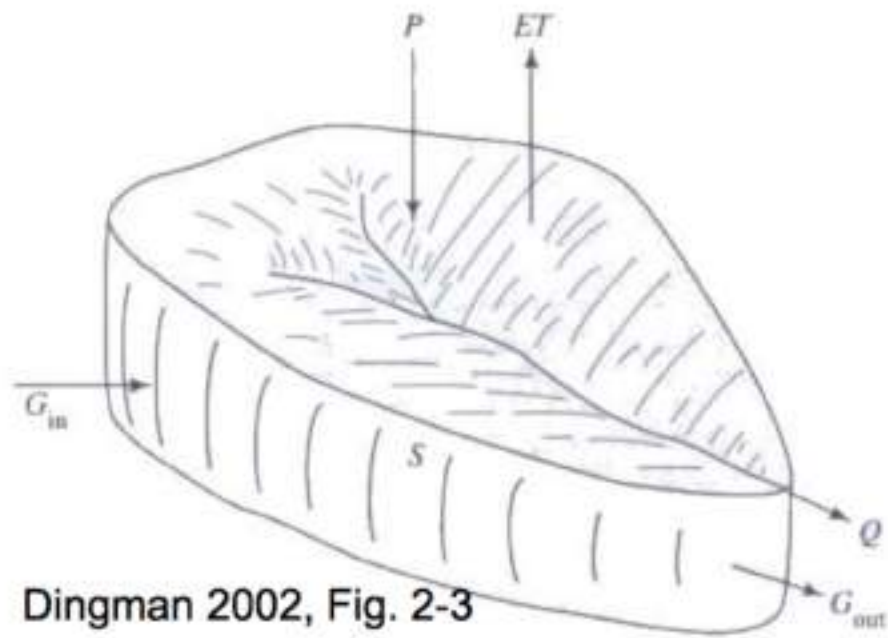
Conservation: inputs (I) – outputs (O) = change in storage (S)



$$I - O = \Delta S$$



The water balance of a watershed



Dingman 2002, Fig. 2-3

Inputs (I), outputs (O) and storage (S):
I: Precipitation (P)
Groundwater in (G_{in})
O: Evapotranspiration (ET)
Groundwater out (G_{out})
River discharge (Q)
Storage (S): In groundwater, rivers and lakes

$\Delta S = P + G_{in} - (Q + ET + G_{out})$

If we assume that G_{in} and G_{out} are negligible, and that for the long-term annual mean, ΔS is zero, then:

$P = ET + Q$, or $ET = P - Q$

What can we usually measure?

P: rain gauges
Q: stream gauges
ET: hard to get except local values
G_{in}: hard to get, assume zero
G_{out}: hard to get, assume zero
S: often hard to get

Dimensions and Units

Length = L (meters)

Volume = V

V = L^3 , typically m^{-3} or km^{-3}

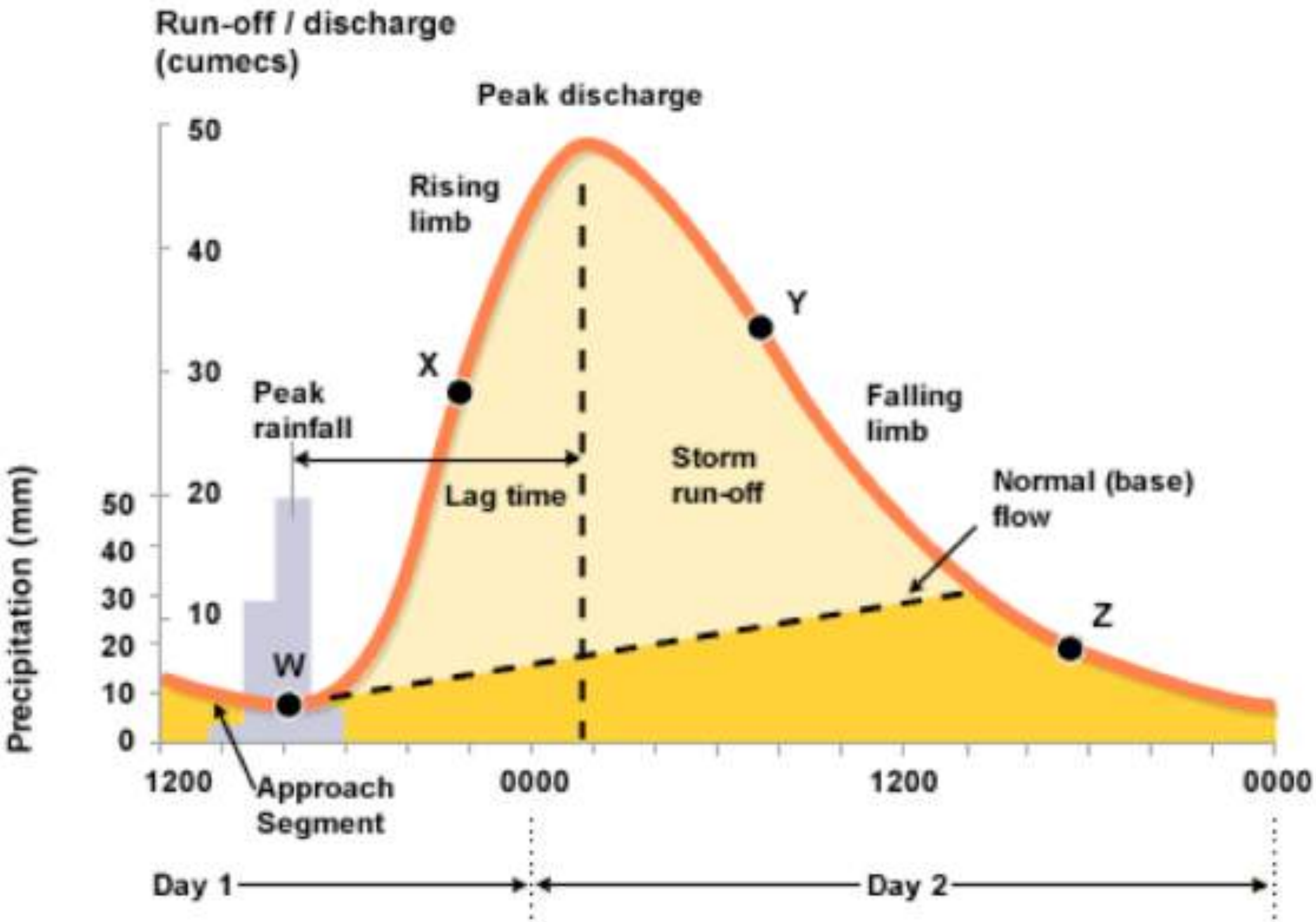
Mass = m (kilograms)

Density (ρ) is often assumed to be constant for liquid water (1000 kg m^{-3}) hence water mass m = ρ V (this means that conservation of mass equals conservation of volume)

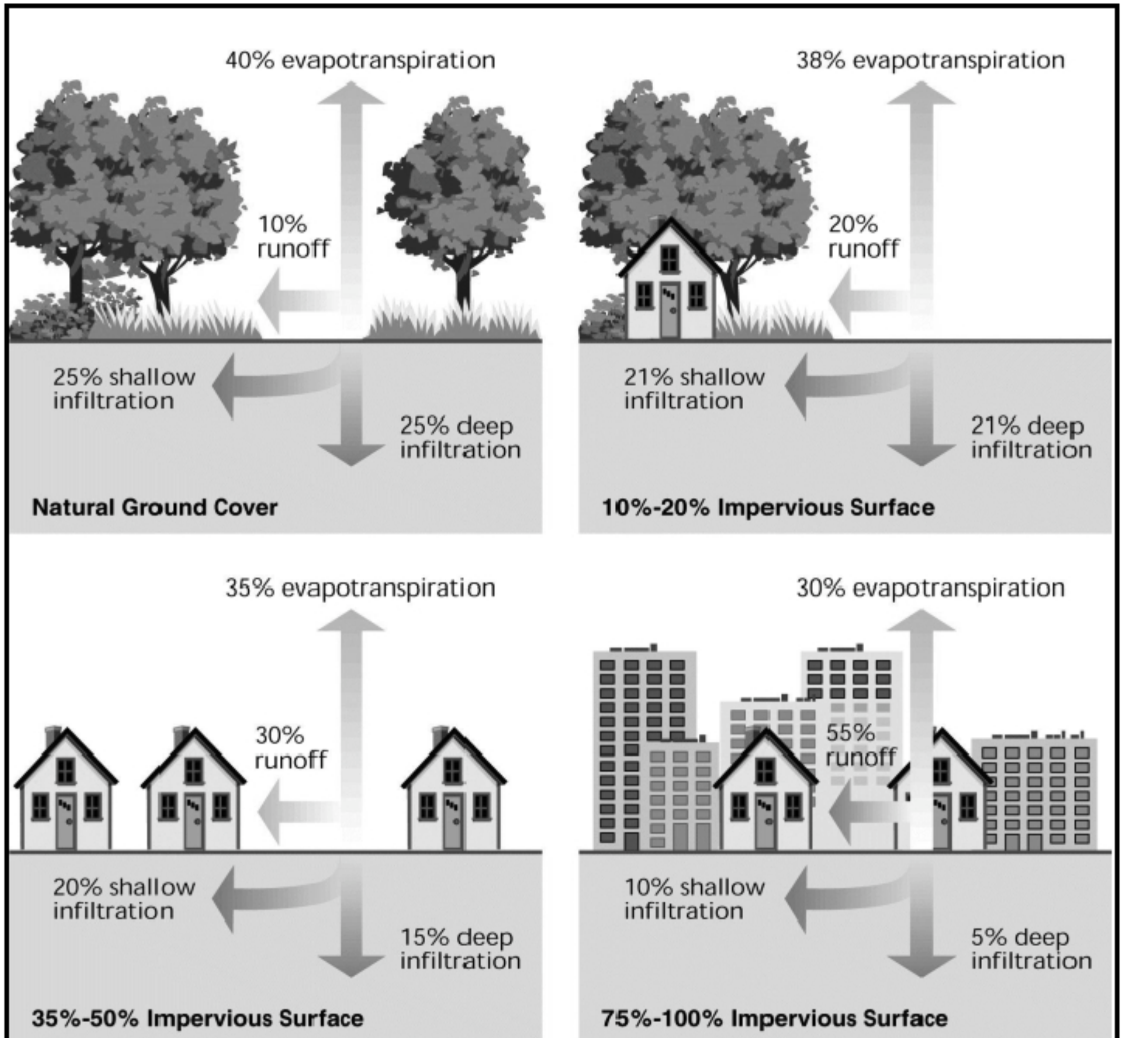
Inputs (I) and outputs (O) are often expressed as rates of fluxes, or volume/time (e.g., m^{-3} s^{-1}); storage changes must have the same units.

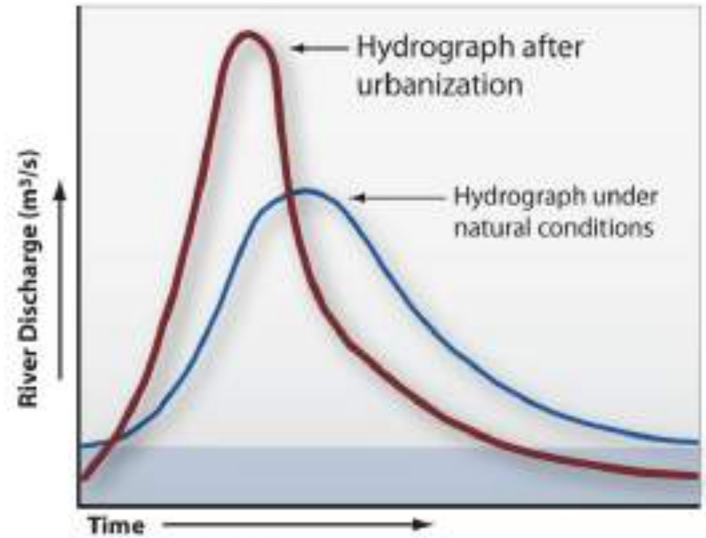
Inputs, outputs and storage changes can also be expressed as a change in water depth (m) averaged over the watershed. Simply divide by the area of the watershed (m^{-3} s^{-1} / m^2 = m s^{-1}). In this case, instead of discharge Q we speak of runoff R.

A Typical Hydrograph (water flow in streams)



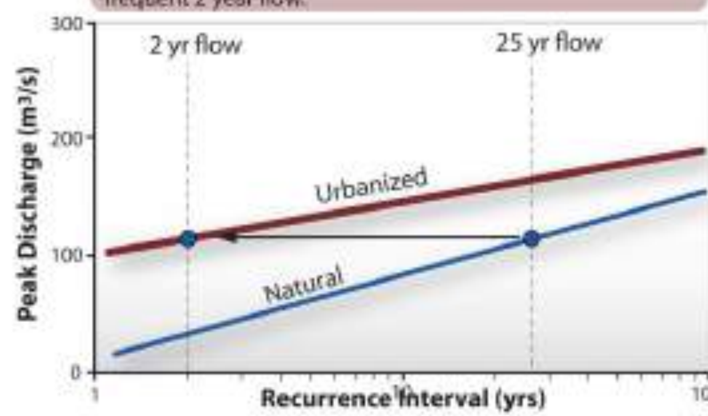
Watershed Urbanization

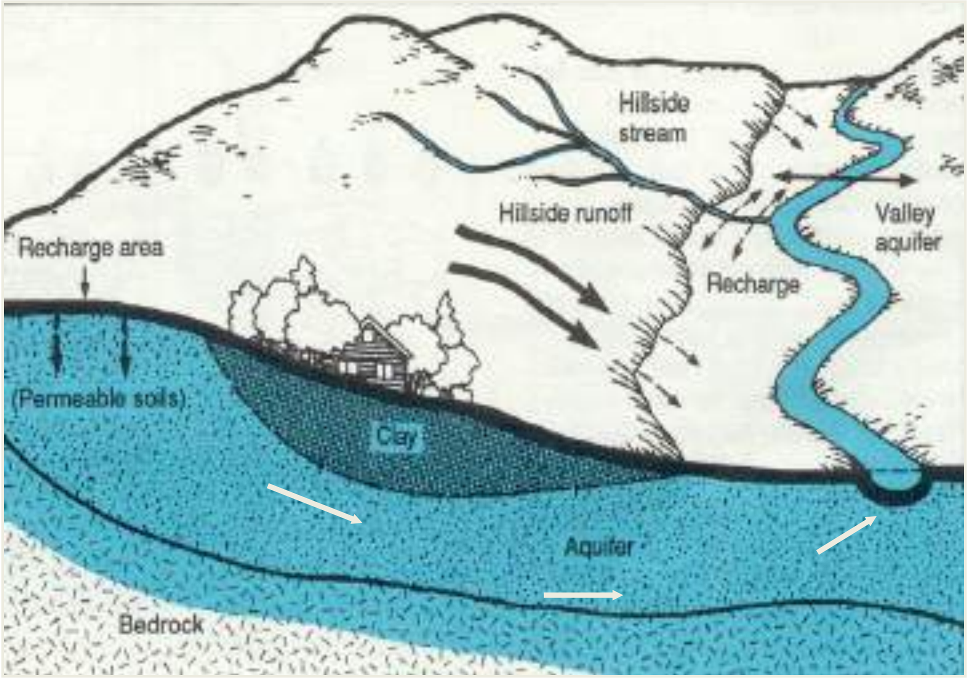




Before development, rainfall followed a more convoluted path through the landscape - held in detention storage by pit and mound topography, infiltrating into organic-rich forest soil and moving slowly to the channel. The infiltrating water fed baseflow during times when it was not raining. Flood peaks were lower and came later.

After urbanization, rainfall moves rapidly to the channel with little chance to infiltrate during storms, thus baseflow is reduced. Flowing directly off impervious surfaces such as parking lots, runoff enters streams quickly raising their level. Flood peaks now come sooner and are higher, increasing flood hazards and the tempo of geomorphic change. For example, the natural 25 yr flow becomes the much more frequent 2 year flow.

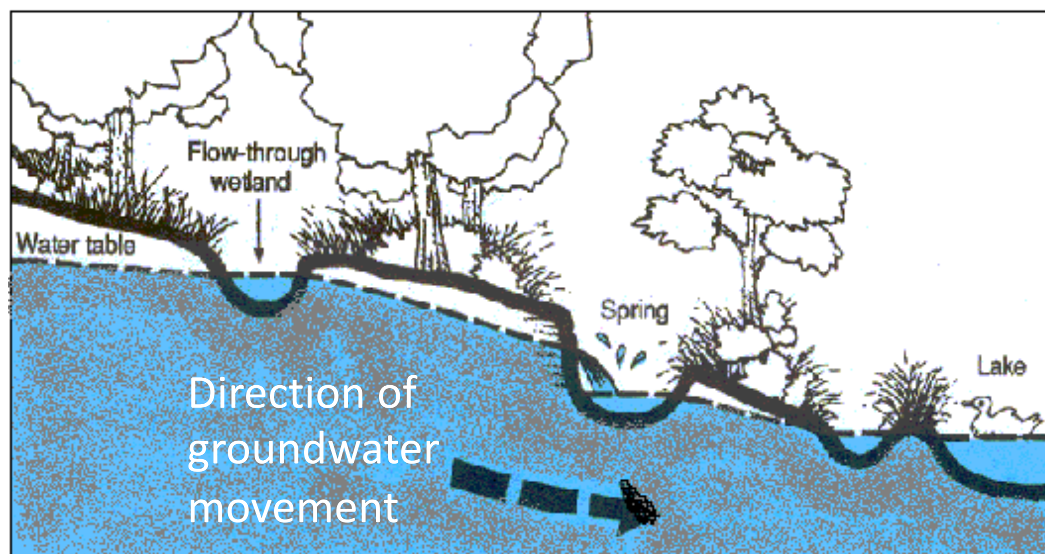




Groundwater Basics

- Groundwater occurs **almost everywhere** within the pore spaces of saturated rock beneath the land surface.

- Groundwater is not like an underground river or lake. In fact, groundwater is more like the **water in a sponge**, held within the tiny pores.



Porosity, Permeability, Specific yield and Specific retention

Porosity - the percentage of rock or sediment that consists of voids or openings

- Measurement of a rock's ability to hold water
- Loose sand has ~30-50% porosity
- Compacted sandstone may have only 10-20% porosity

Permeability - the capacity of a rock to transmit fluid through pores and fractures

- Interconnectedness of pore spaces
- Most sandstones and conglomerates are porous *and* permeable
- Granites, schists, unfractured limestones are *impermeable*

Specific yield: the portion that will drain under the influence of gravity.

Specific retention: the part that is retained as a film on particle and rock surfaces and in tiny openings.

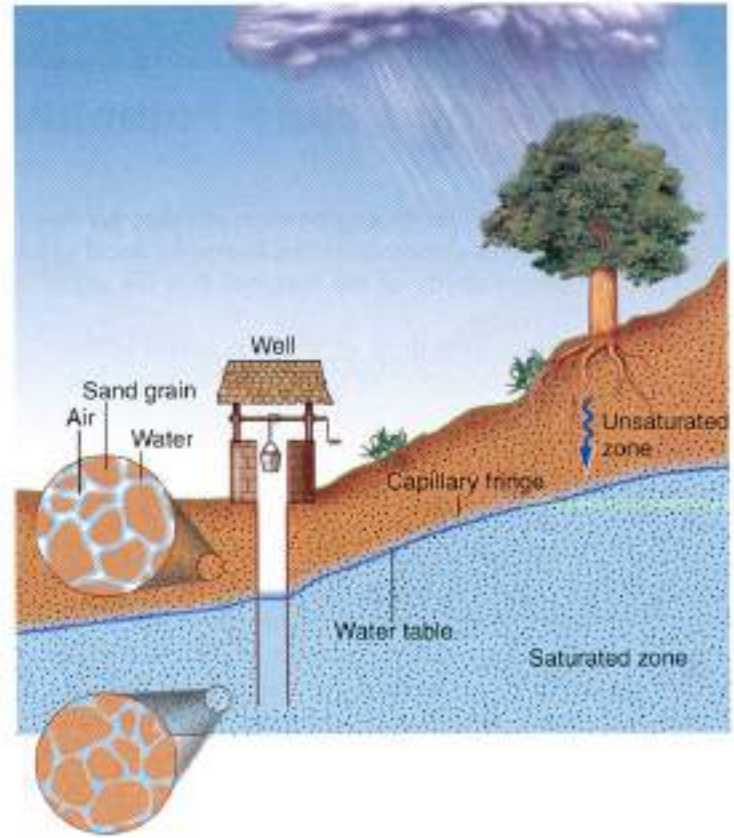
TABLE 17.1 Selected Values of Porosity, Specific Yield, and Specific Retention*

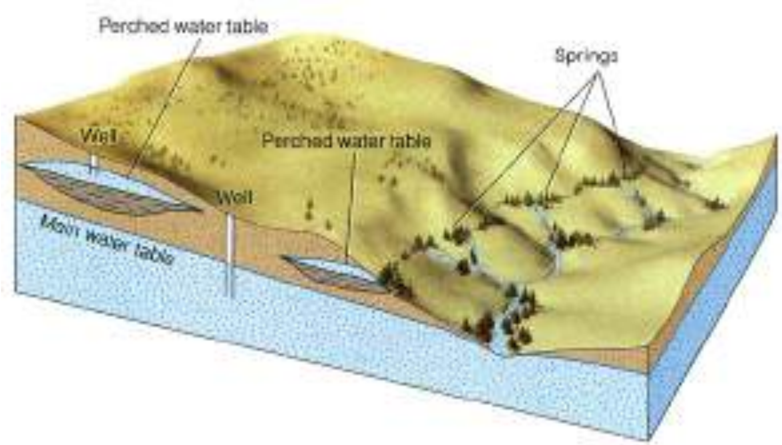
Material	Porosity	Specific Yield	Specific Retention
Clay	50	2	48
Sand	25	22	3
Gravel	20	19	1
Limestone	20	18	2
Sandstone (semiconsolidated)	11	6	5
Granite	0.1	0.09	0.01
Basalt (fresh)	11	8	3

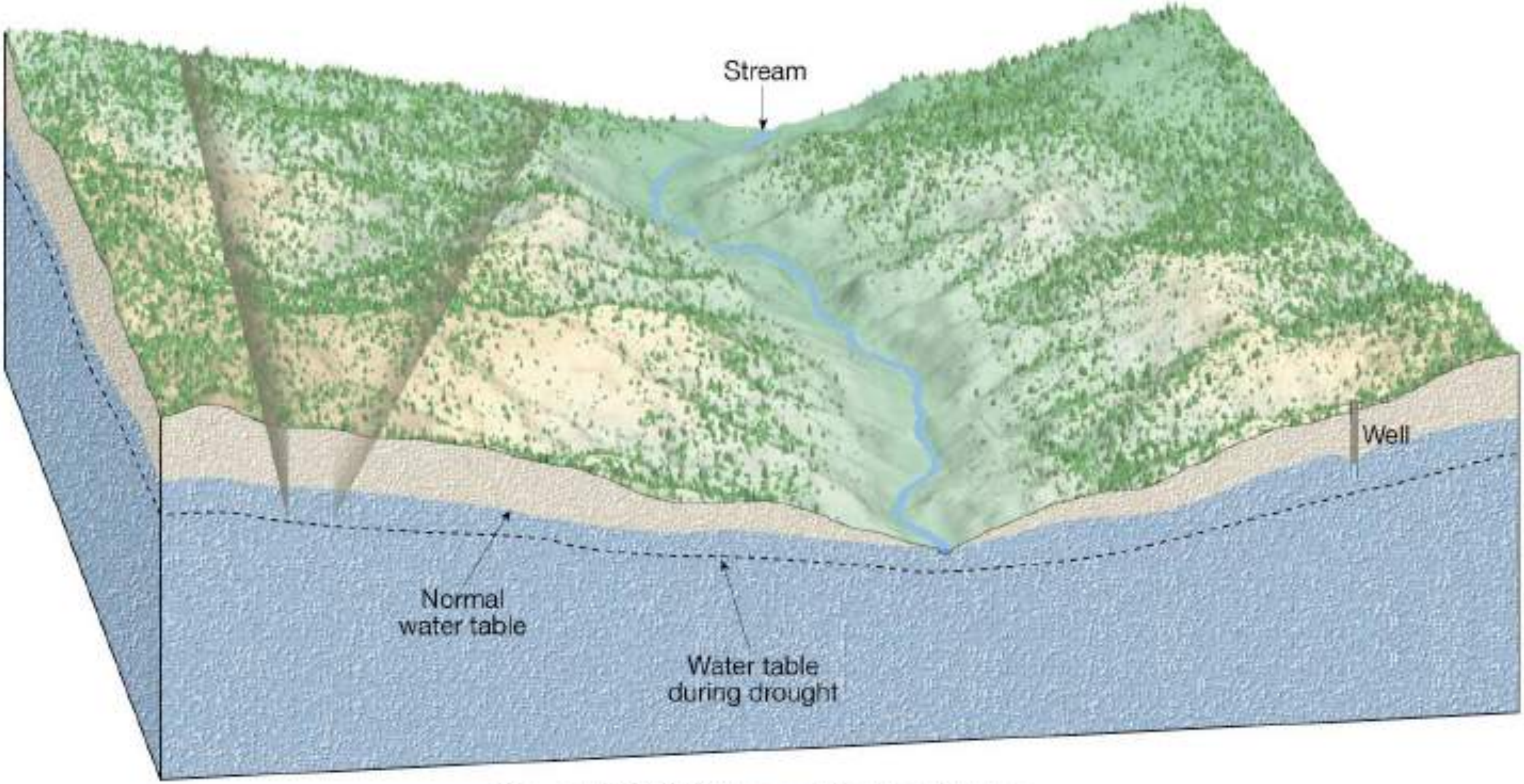
*Values in percent by volume.

Zones and Water Table

- *Well* - a deep hole dug or drilled into the ground to obtain water from an aquifer
- Subsurface zone in which all rock openings are filled with water is the *phreatic, or saturated zone*
- Top of the saturated zone is the *water table*
  - Water level at surface of most lakes and rivers corresponds to local water table
- Above the water table is an *unsaturated* region (*zone of aeration*) called the *vadose zone*
- A *perched water table* is above and separated from main water table by an unsaturated zone
  - Commonly produced by thin lenses of impermeable rock (e.g., shales or clays) within permeable ones



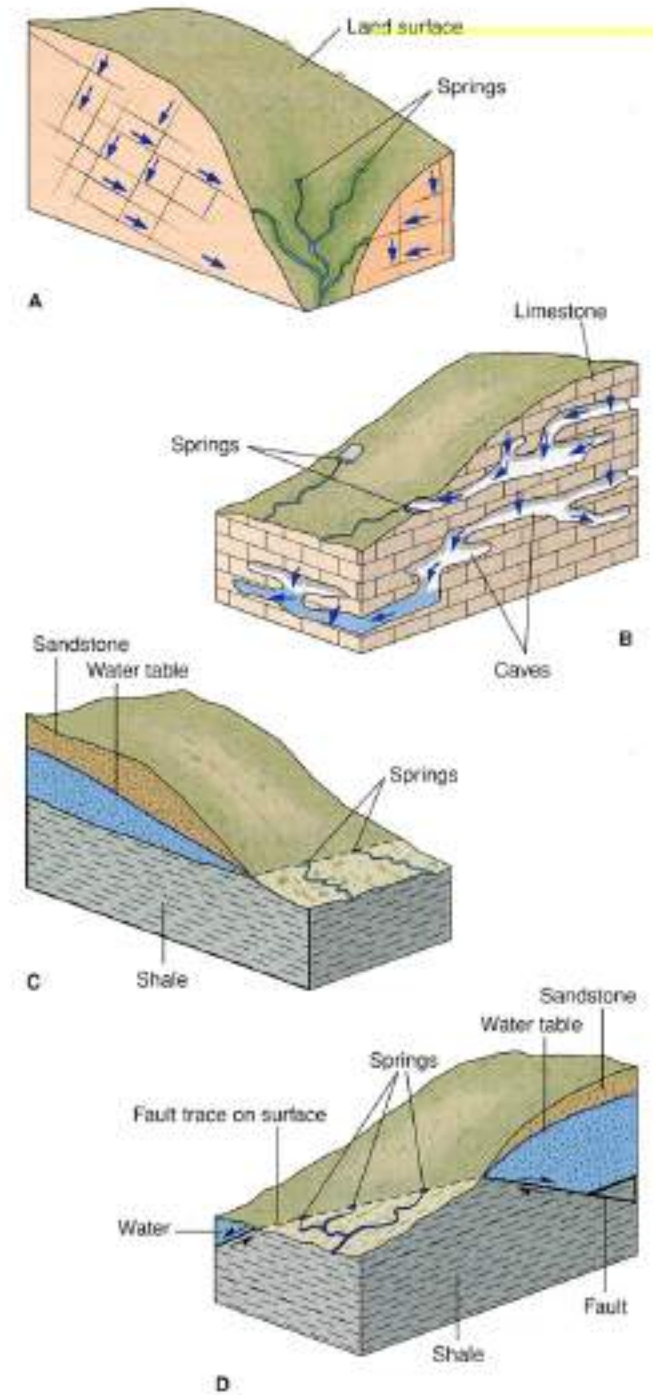




The *water table* separates the saturated and unsaturated zones. The water table is exposed at the surface in streams and lakes. The water table rises and falls as the balance between precipitation and evaporation changes.

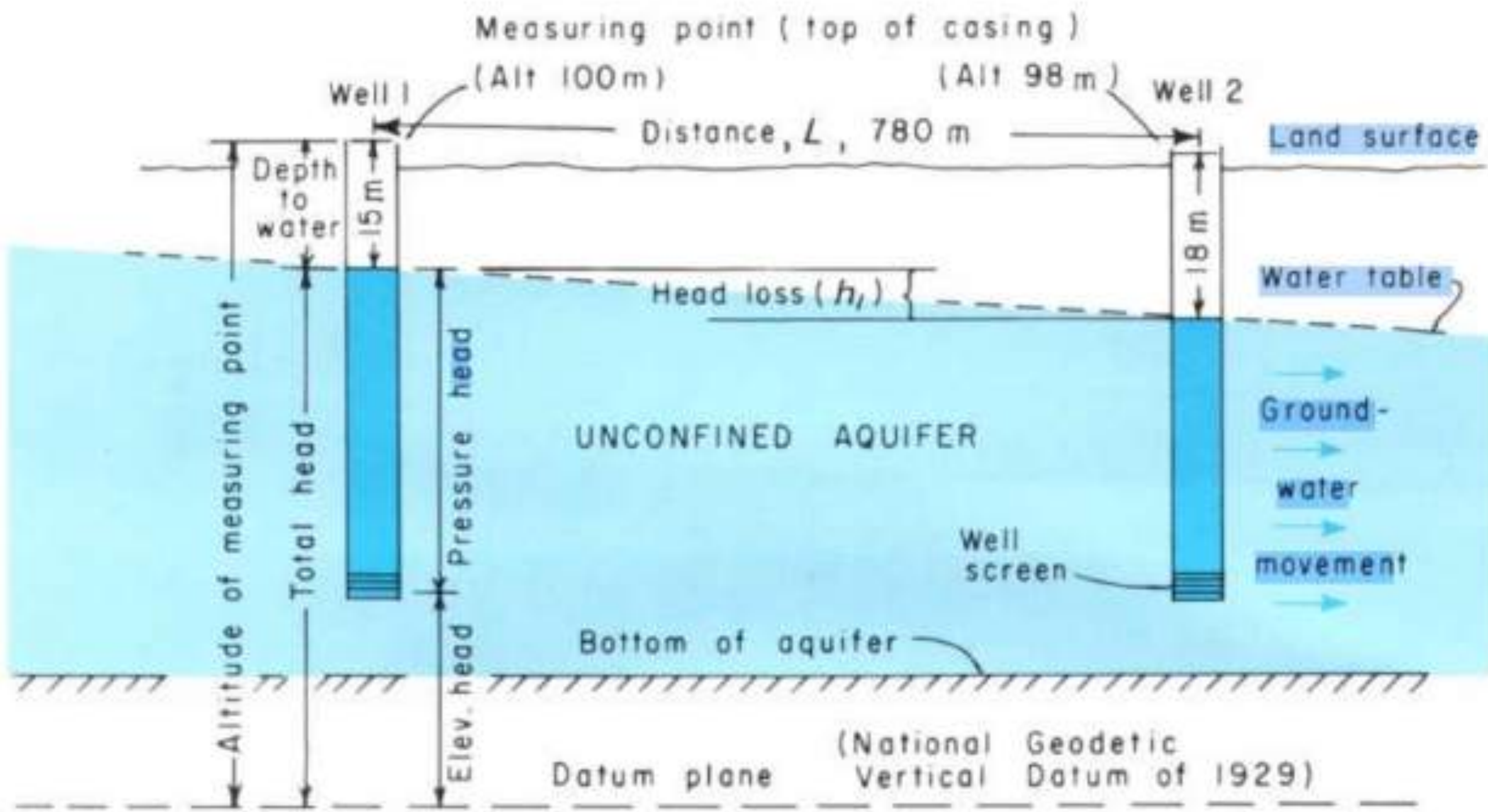
Springs

- *Spring* - a place where water flows naturally from rock or sediment onto the ground surface



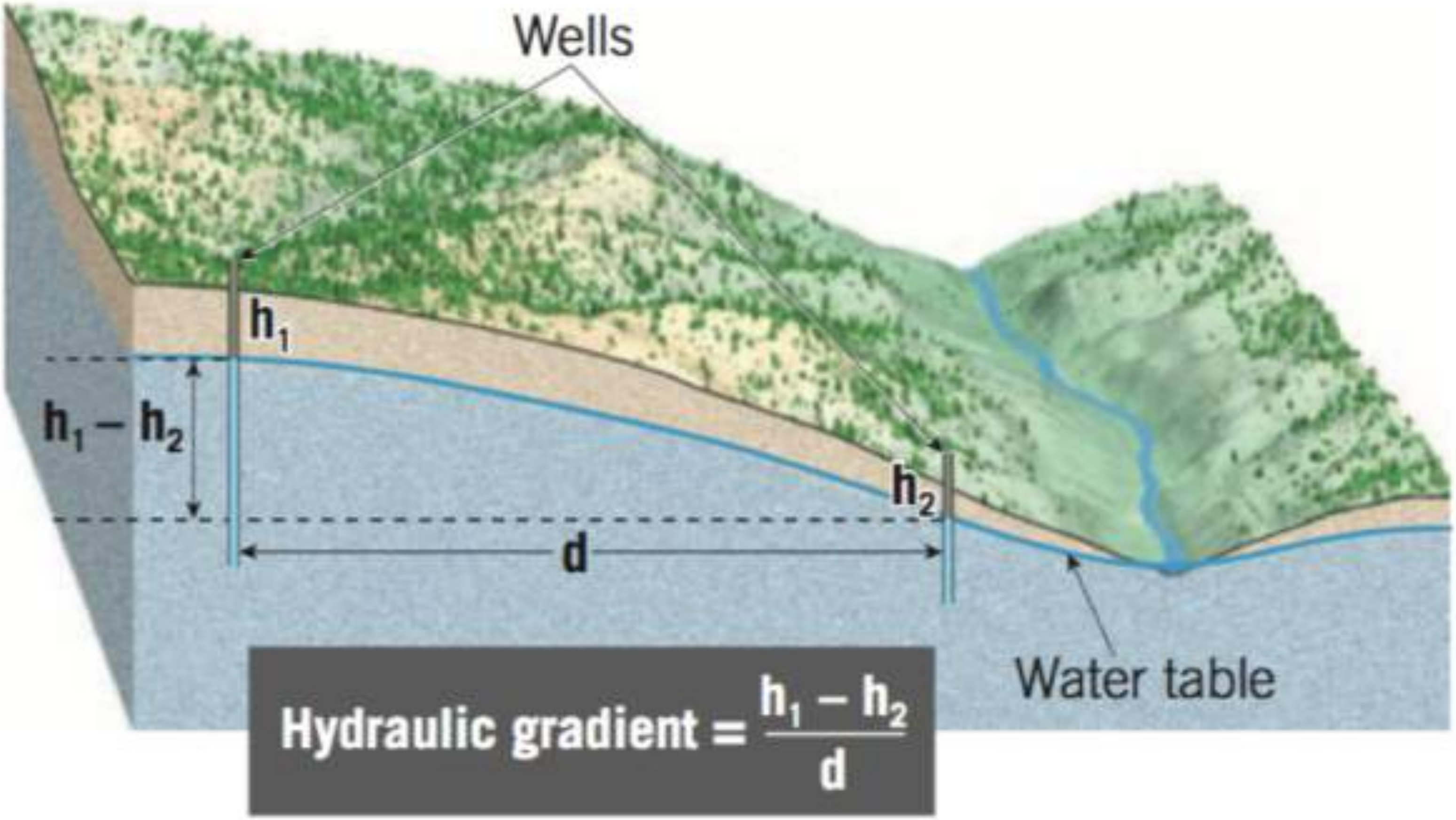
How Ground water flows? Head and Gradient

Total Head = Elevation head + pressure head



Hydraulic Gradient = h_L/L

$$\frac{h_L}{L}=\frac{(100\text{ m}-15\text{ m})-(98\text{ m}-18\text{ m})}{780\text{ m}}=\frac{85\text{ m}-80\text{ m}}{780\text{ m}}=\frac{5\text{ m}}{780\text{ m}}$$

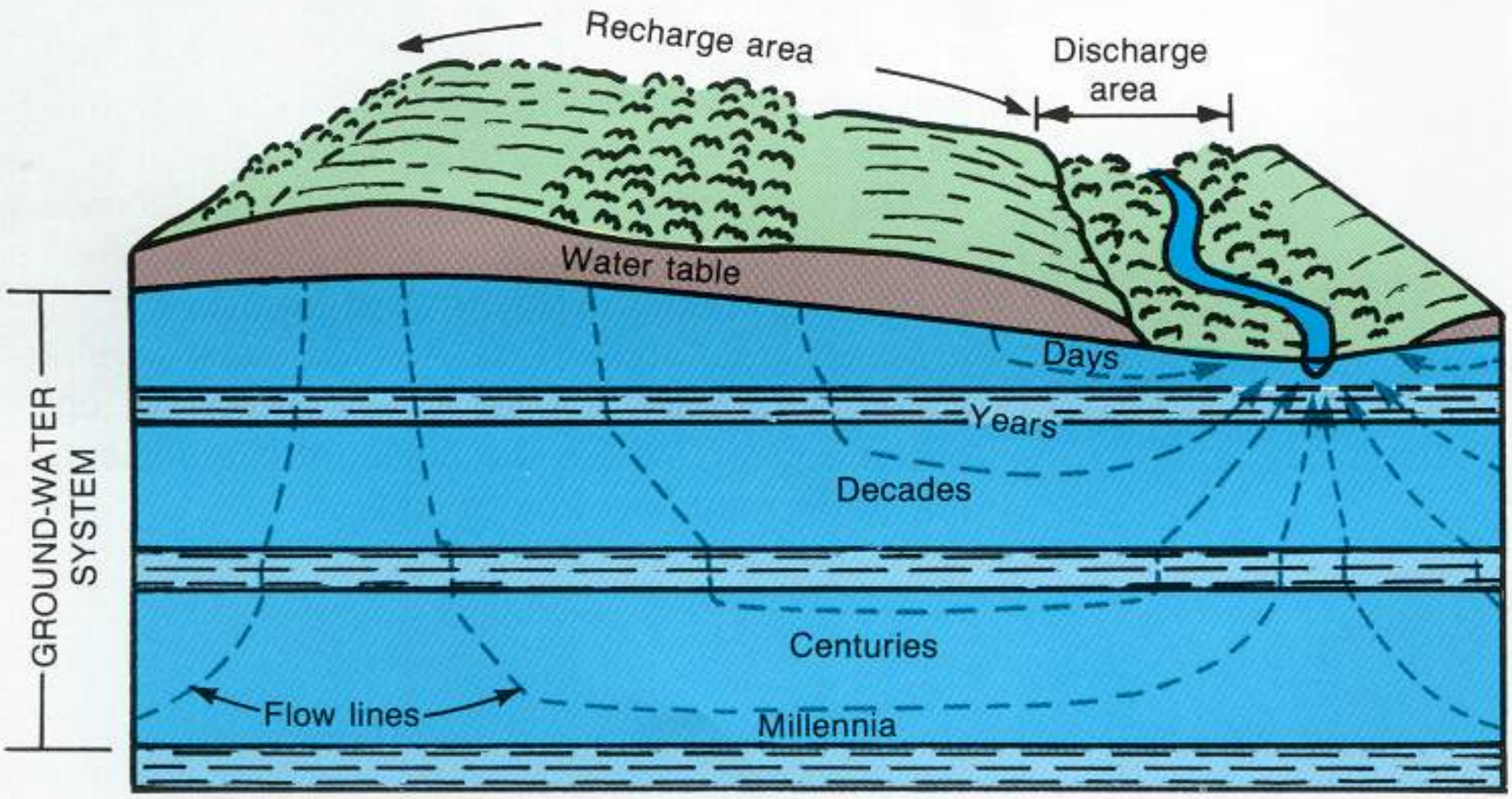


Rate of groundwater flow is proportional to: 1) the hydraulic gradient
2) the hydraulic conductivity

Darcy's law: Q=K*A*I

K= hydraulic conductivity
A= cross-sectional area
I = hydraulic gradient [a measure of change of head between two wells located at a given distance [dh/dl]

Groundwater



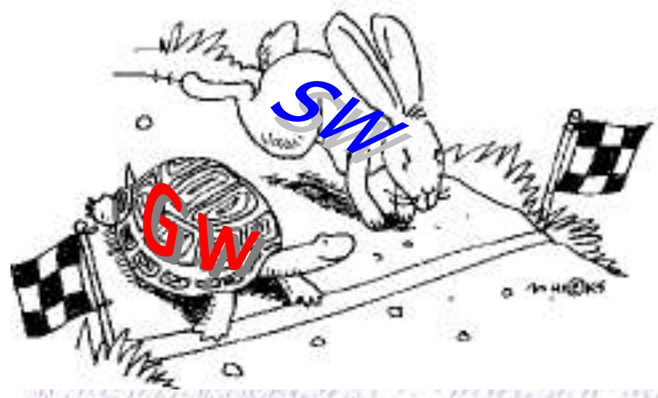
Direction and rate of ground-water movement.

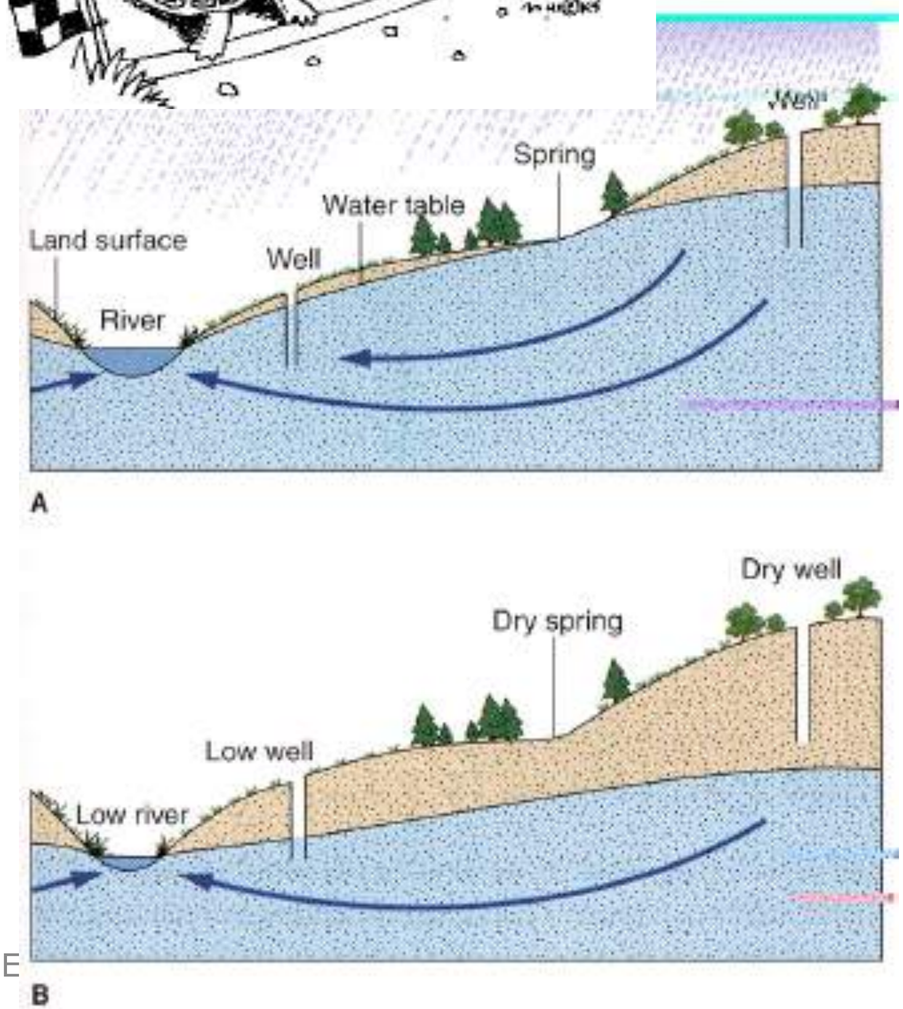
Ground Water Movement

- Movement of ground water through pores and fractures is *relatively slow* (cms to meters/day) compared to flow

  of water in surface streams
  - Flow velocities in cavernous limestones can be much higher (kms/day)

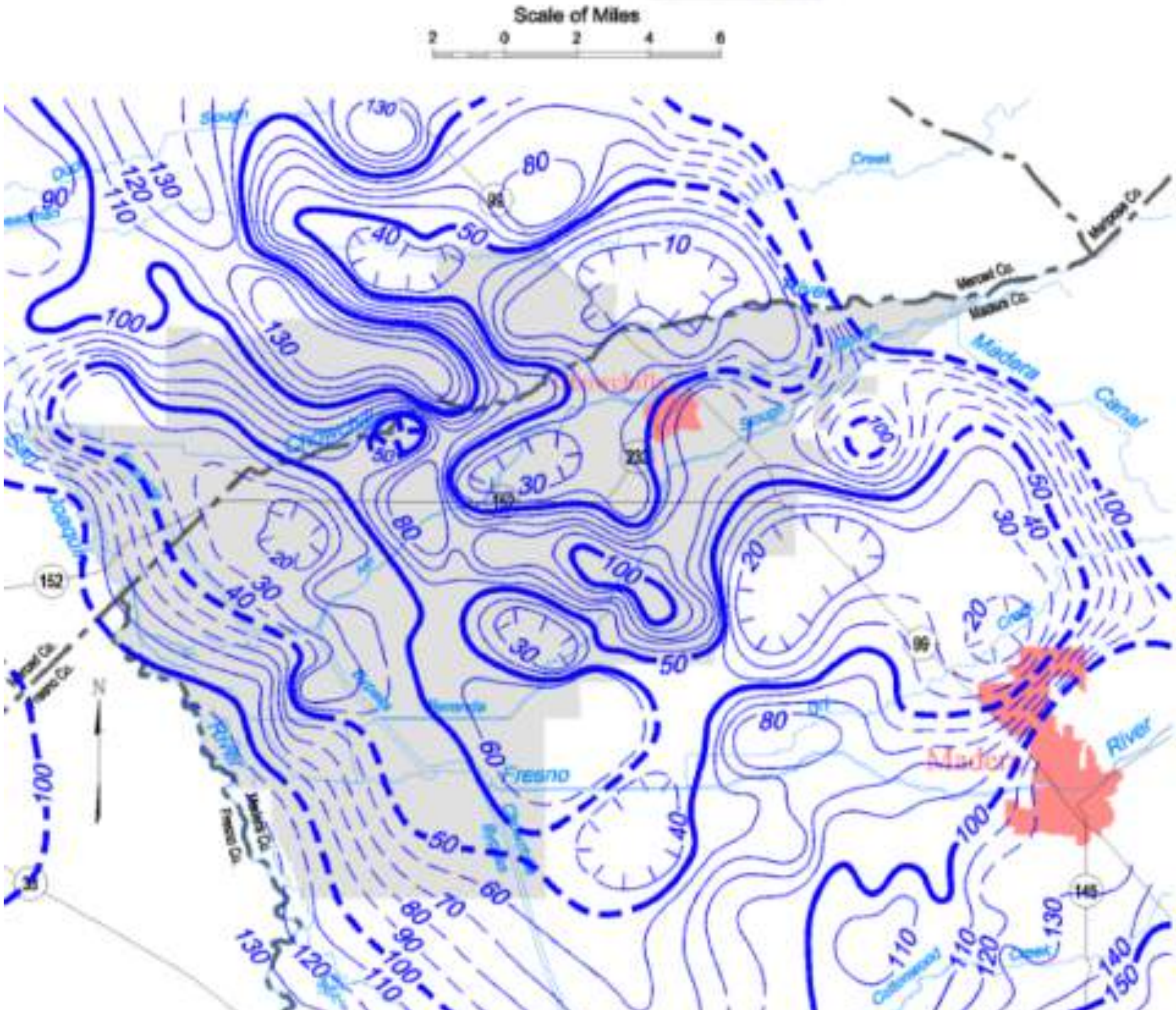
- Flow velocity depends upon:
  - *Slope* of the water table
  - *Permeability* of the rock or sediment





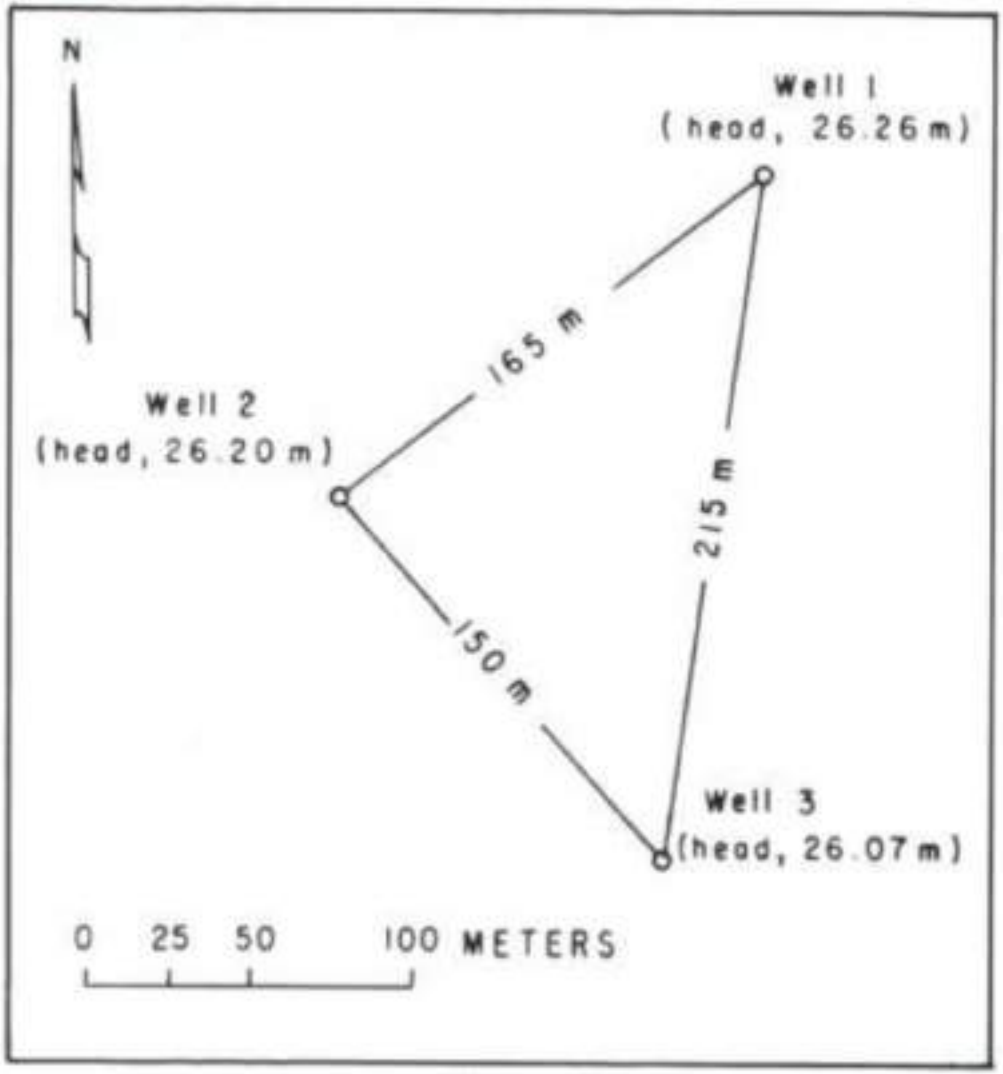
Chowchilla Groundwater Basin

Spring 2008, Lines of Equal Elevation of Water in Wells, Unconfined Aquifer



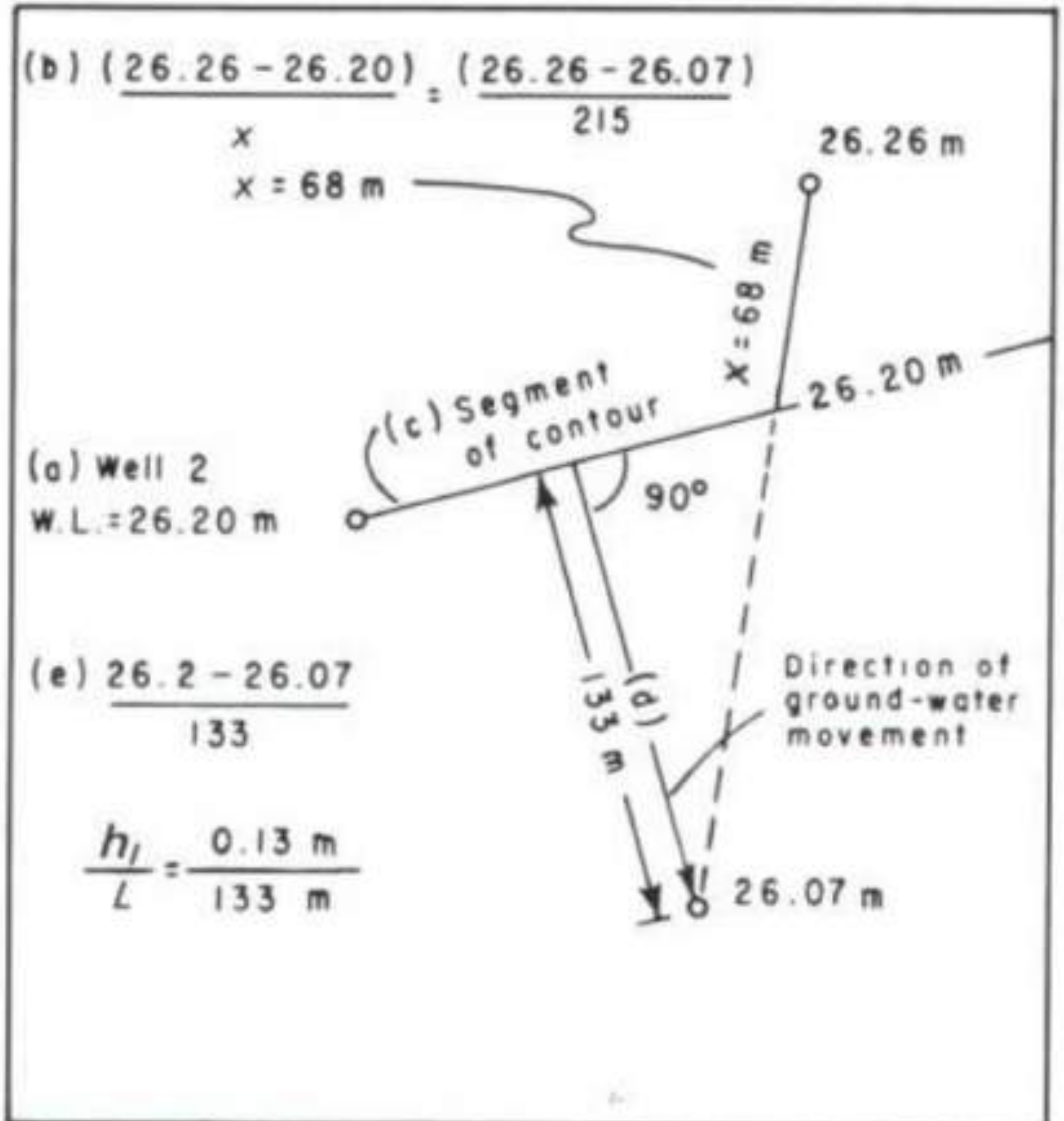
Contours are dashed where inferred. Contour interval is 10 feet.

Water-Level Contour Map



Questions -

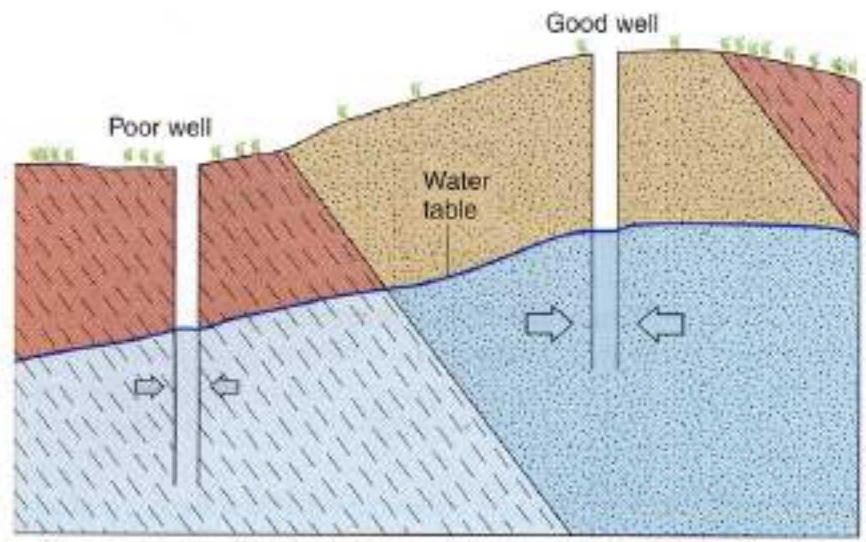
1. Identify the well that has the intermediate water level
2.Calculate the position between the well having the highest head and the well having the lowest head at which the head is the same as that in the intermediate well.
Draw a water level contour along which the total head is the same as that in the intermediate well



What is the hydraulic gradient between water-level contour and well 3?

Aquifers and Aquitards

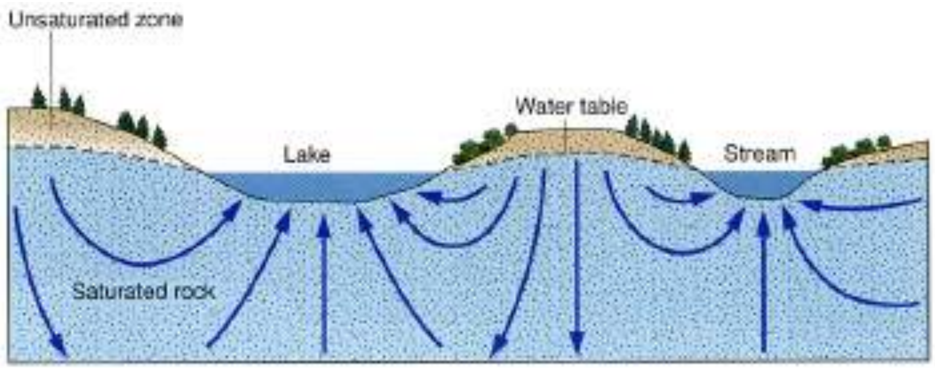
- *Aquifer* - Aquifers are water-bearing layers of rock or sediment that contain **usable quantities of water** that can move easily
  - Sandstone
  - Conglomerate
  - Well-jointed limestone
  - Sand and gravel
  - Highly fractured volcanic rock



- *Aquitard* - rock/sediment that retards ground water flow due to low porosity and/or permeability
  - Shale, clay, unfractured crystalline rocks

Unconfined vs. Confined Aquifers

- *Unconfined Aquifer*
  - Has a water table, and is only partly filled with water
  - Rapidly *recharged* by precipitation infiltrating down to the saturated zone

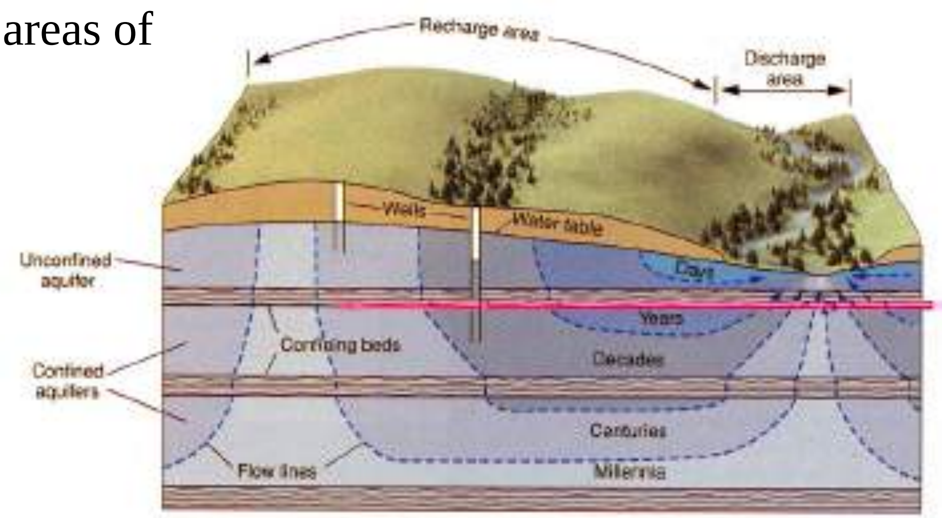


  -- Influenced by **gravity** and flows from higher to lower groundwater elevations, much like river water.

  --The steeper the slope of the groundwater "table," the faster the groundwater will flow.

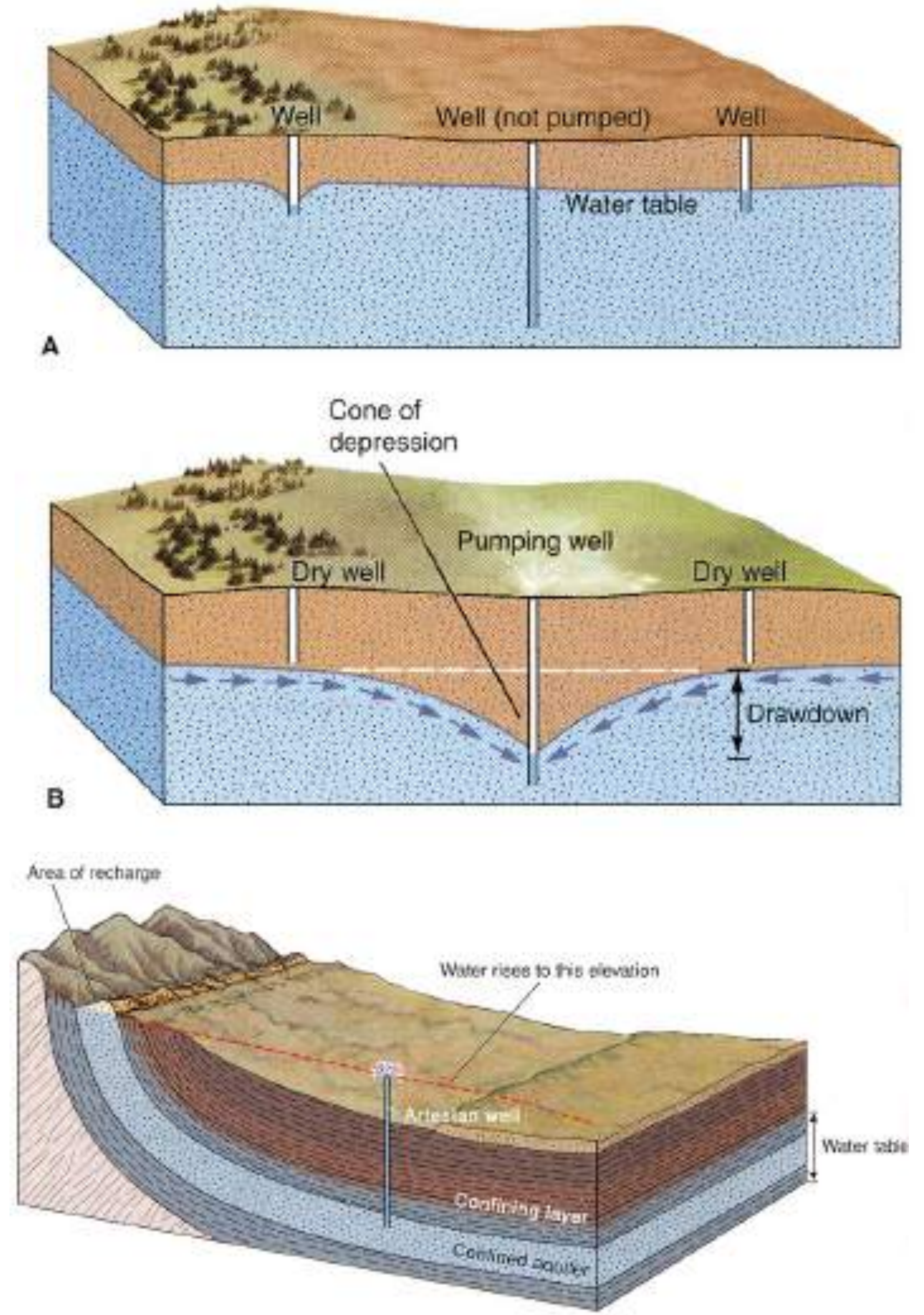
  --**Pressure**, rather than gravity, makes water move in confined aquifers. Water moves from areas of high to low pressure.

- *Confined Aquifer*
  - Completely filled with water under pressure (*hydrostatic head*)
  - Separated from surface by impermeable *confining layer/aquitard*
  - *Very slowly* recharged



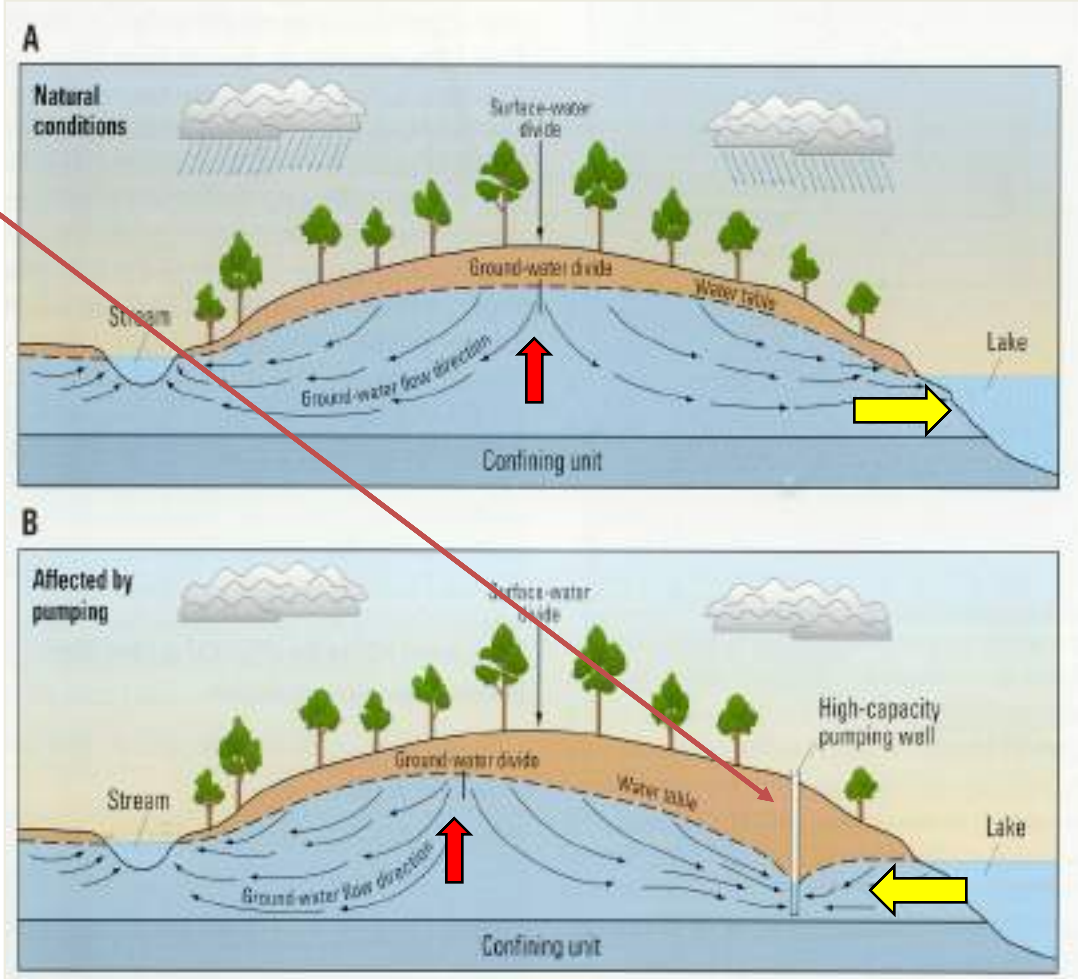
Cone of depression and storativity

- For wells in unconfined aquifers, water level before pumping is the water table
- Water table can be lowered by pumping, a process known as *drawdown* and create a **cone of depression**.
- Water flows toward the cone of depression. The area affected by the well is called the **area of influence**.
- Water may rise to a level above the top of a confined aquifer, producing an *artesian well*
- *Storativity (S):* Aquifer storage is measured by storativity, which is a volume of water that aquifer releases per unit area per unit pressure drop
- Transmisivity (T): Product of hydraulic conductivity (K) and thickness of acquifer (b) (T=Kb)



Pumping Water from Wells

- Pumping water from aquifers can lower groundwater levels.
- Pumping changes groundwater flow patterns.
- For example, water used to flow from groundwater to lake. Now flowing from lake to groundwater.
- Could lead to change in groundwater quality.

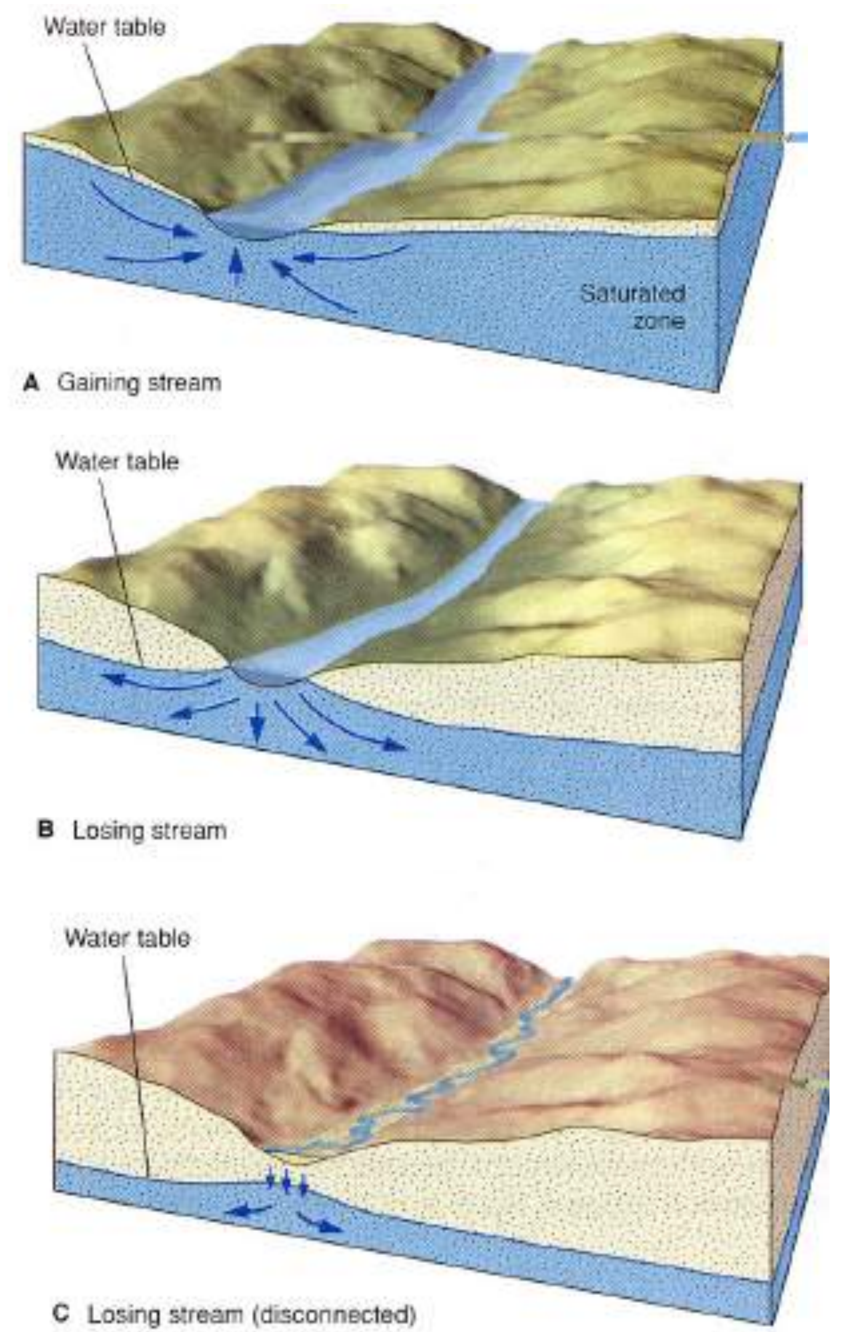


Generalized ground-water flow (A) under natural conditions and (B) affected by pumping (Note that surface- and ground-water divides are coincident in A but not in B).

Streams and Groundwater

- *Gaining streams* - receive water from the saturated zone
  - Gaining stream surface is local water table

- *Losing streams* - lose water to the saturated zone
  - Stream beds lie above the water table
  - Maximum *infiltration* occurs through streambed, producing permanent “mound” in the water table beneath dry channel



Residence time of water?

- **Rate of movement varies greatly in each component**
  - **Atmospheric water: 100’s kms /day**
  - **Stream water: only a few tens of kms/day;**
  - **Water in glaciers: cm-meters/day**
  - **Underground water: meters or less/ year.**

- **MRT [Mean Residence Time] – amount of time an average water molecule spends within any one reservoir before moving to another reservoir.**

MRT’ S OF RESERVOIRS

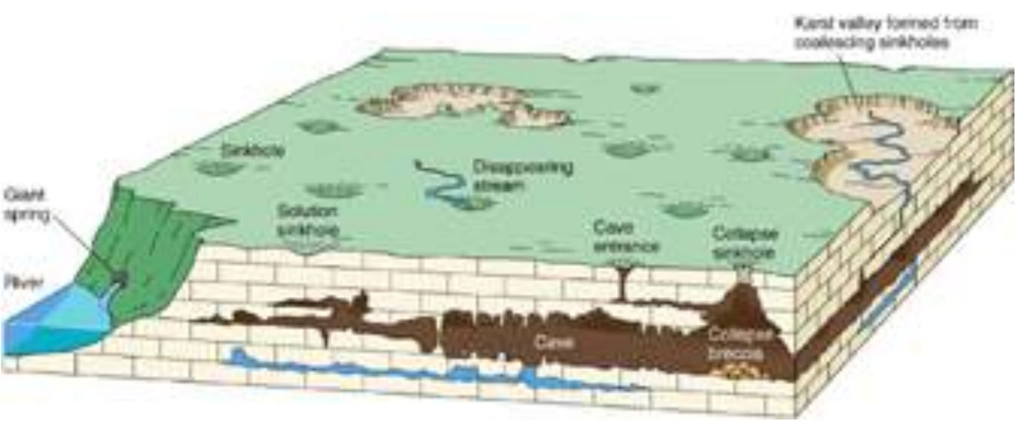
- ATMOSPHERIC WATER: ~ 8-10 DAYS

- OCEANS (on average): > 3000 Years
  - Shallow oceans: Few days to weeks
  - Deep ocean water: 100’ s – 1000’ s years

- GROUNDWATER (on average): 10,000 Years
  - Shallow aquifers: 1-5 Years
  - Deep aquifers: 10,000-100,000 Years]

Caves, Sinkholes, and Karst

- *Caves* - naturally-formed underground chambers
  - Acidic ground water dissolves limestone along joints and bedding planes
- Caves near the surface may collapse and produce *sinkholes*
- Rolling hills, disappearing streams,   and sinkholes are common in areas with *karst topography*



Hot Water Underground

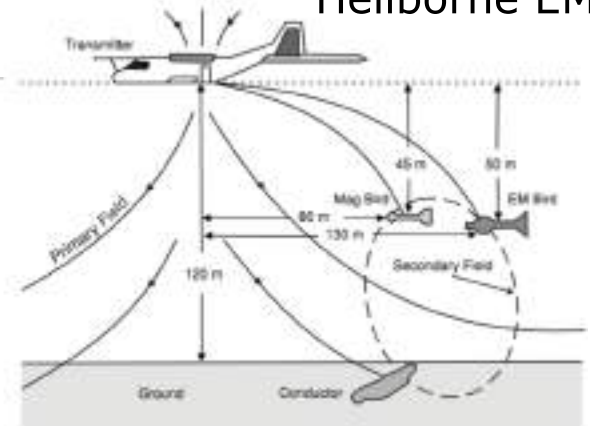
- *Hot springs* - springs in which the water is warmer than human body temperature
  - Ground water heated by nearby magma bodies or circulation to unusually deep (and warm) levels within the crust
  - Hot water is less dense than cool water and thus rises back to the surface on its own
- *Geysers* - hot springs that periodically erupt hot water and steam
  - Minerals often precipitate around geysers as hot water cools rapidly in the air

Geothermal Energy

- *Geothermal energy* is produced using natural steam or superheated water
  - No CO_2 or acid rain are produced (*clean* energy source)
  - Some toxic gases given off (e.g., sulfur compounds)
  - Can be used directly to heat buildings
  - Superheated water can be very corrosive to pipes and equipment

Indian Ground water scenerio

Heliborne EM



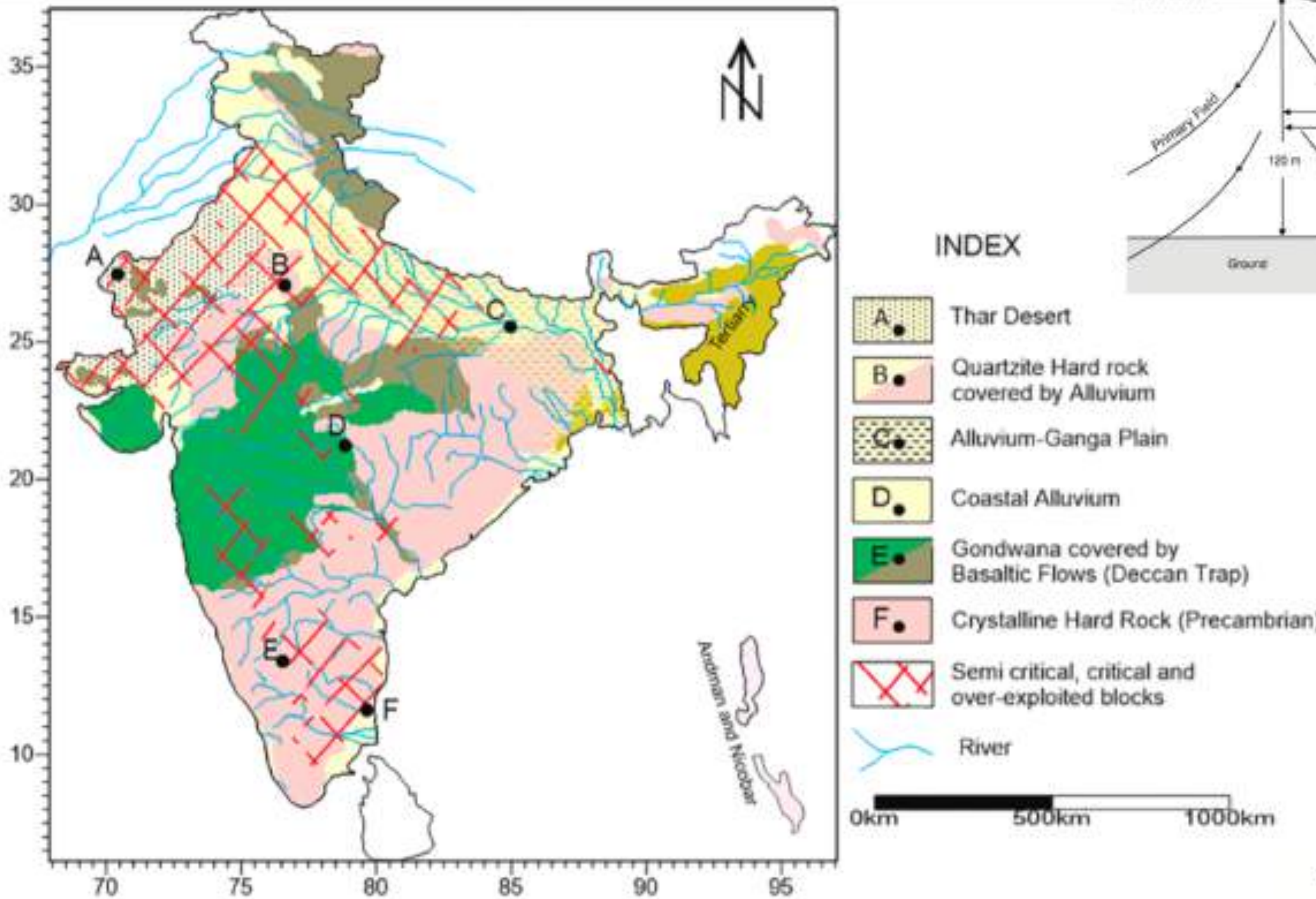
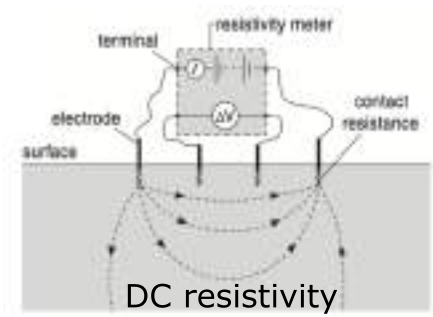
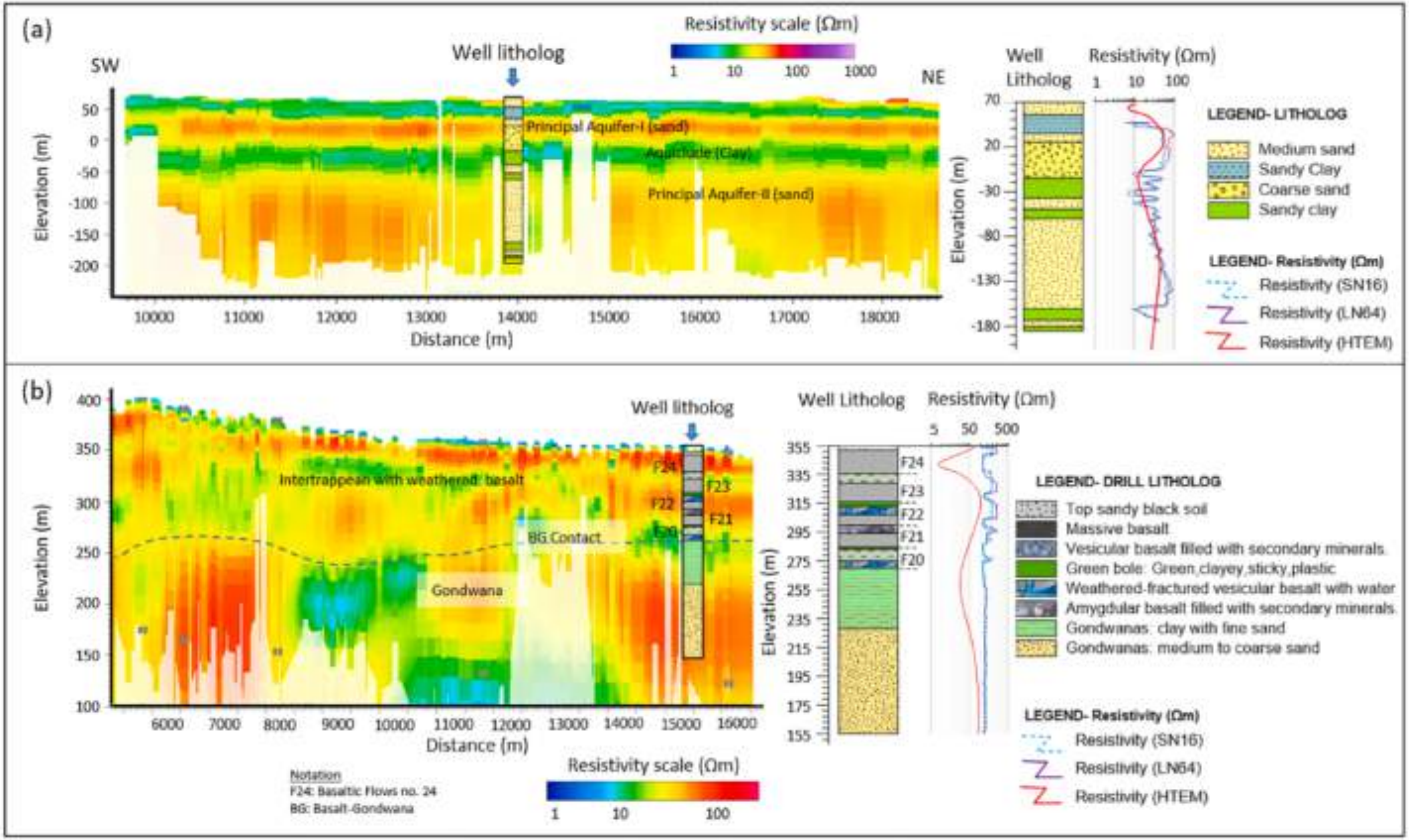


Fig. 1. Pilot study areas located in representative hydrogeological settings of India.



Chandra et al., 2022

Resistivity-EM results



(a) HTEM resistivity sections of Ganga Alluvium, Patna (Bihar) with well litholog and borehole resistivity (SN16 & LN64) logs located almost at the center of the pro le; (b) HTEM resistivity sections Deccan basalt near Nagpur (Maharashtra) with well litholog and borehole resistivity (SN16 & LN64) logs.

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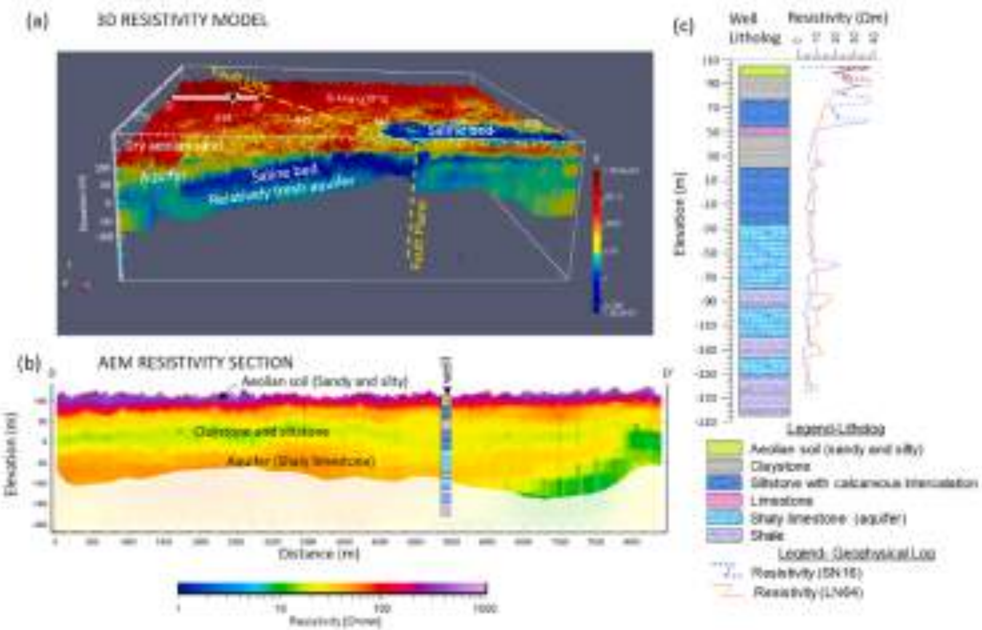
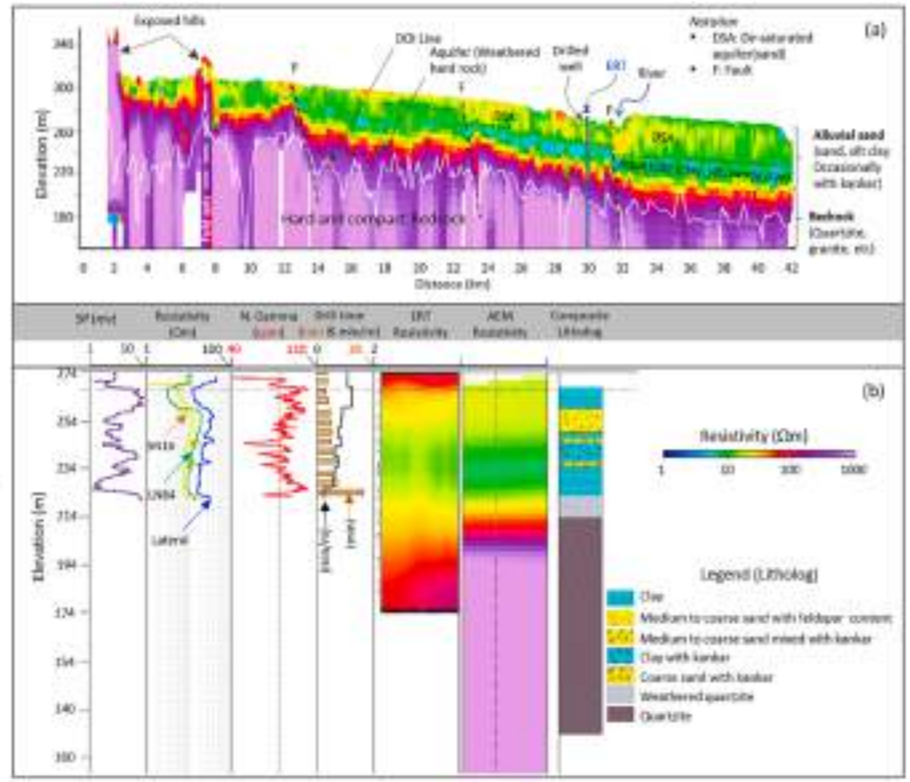
Resistivity-EM results



HTEM results of Thar desert, Jaisalmer showing: (a) 3D Resistivity model; (b) resistivity section along DD’ pro le line with borehole litholog; and (c) drilling litholog and electrical resistivity (SN16 & LN64) logs.



(a) HTEM resistivity pro le of Dausa district, Rajasthan; and (b) comparative plot of HTEM resistivity, ERT, borehole geophysical logs and drilling litholog at the drilled well site

Chandra et al., 2022

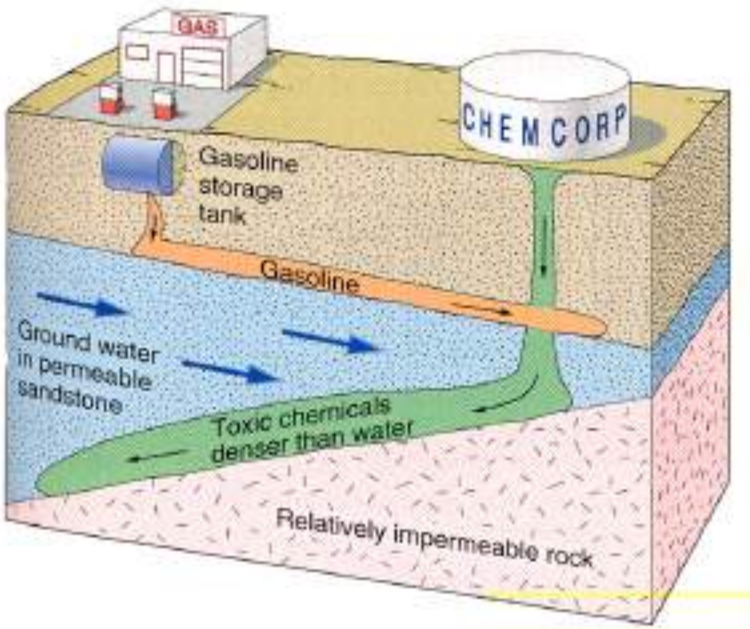
Ground Water Contamination

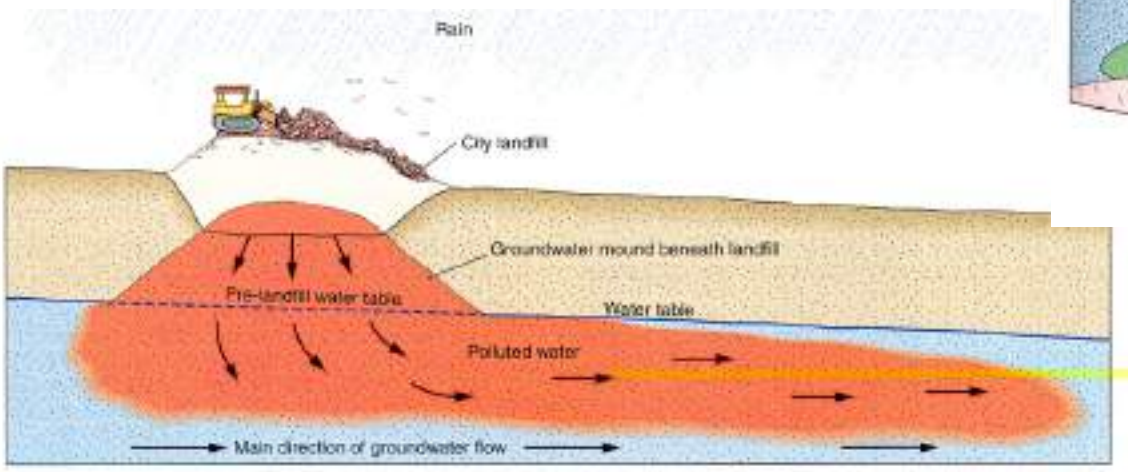
Infiltrating water may bring contaminants down to the *water table*, including (but not limited to):

- Pharmaceuticals
- Pesticides/herbicides
- Fertilizers
- Feed lots
- Mercury and gold mining
- Landfill pollutants
- Heavy metals
- Bacteria, viruses and parasites from sewage
- Industrial chemicals (PCBs, TCE)
- Acid mine drainage
- Radioactive waste
- Oil and gasoline

Ground Water Contamination

- *Contaminated ground water* can be *extremely difficult and expensive* to clean up





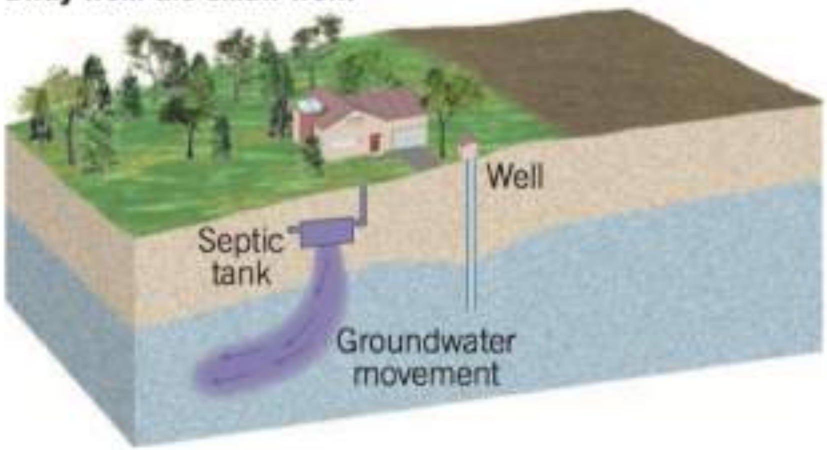
A Cross section

Inc.

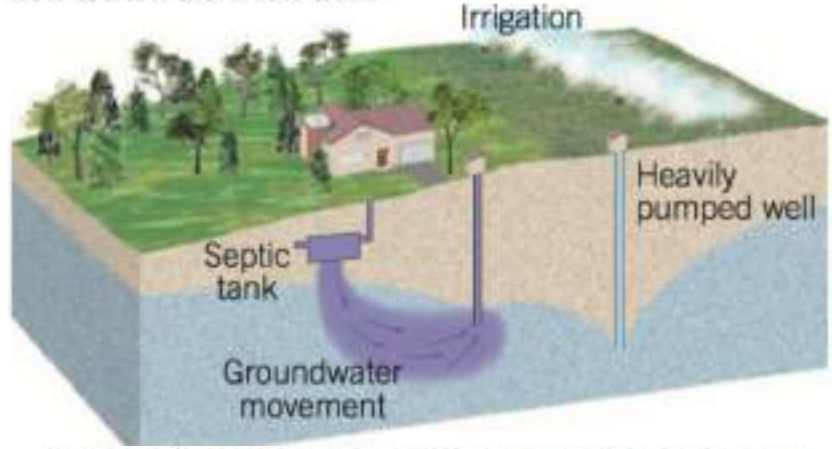
How Does Pumping Water from Wells Influence Water Quality?

- Pumping water from a well draws the water table down and can pull in contaminants from the well's **area of influence**.

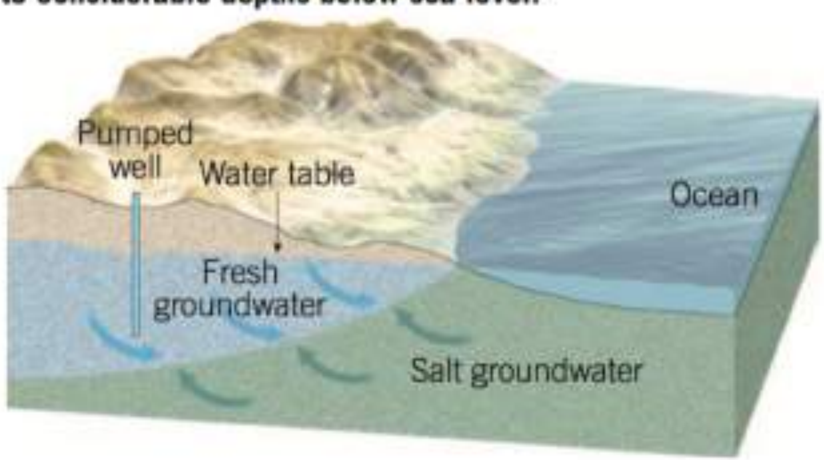
Originally the outflow from the septic tank moved away from the small well.



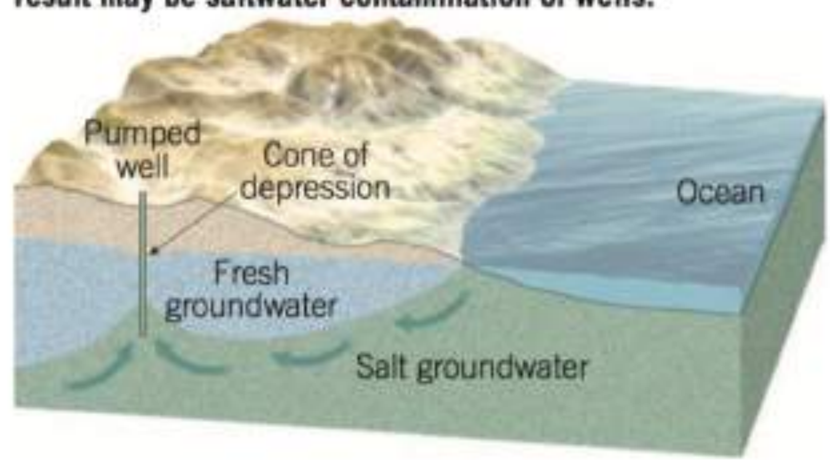
The heavily pumped well changed the slope of the water table, causing contaminated groundwater to flow toward the small well.



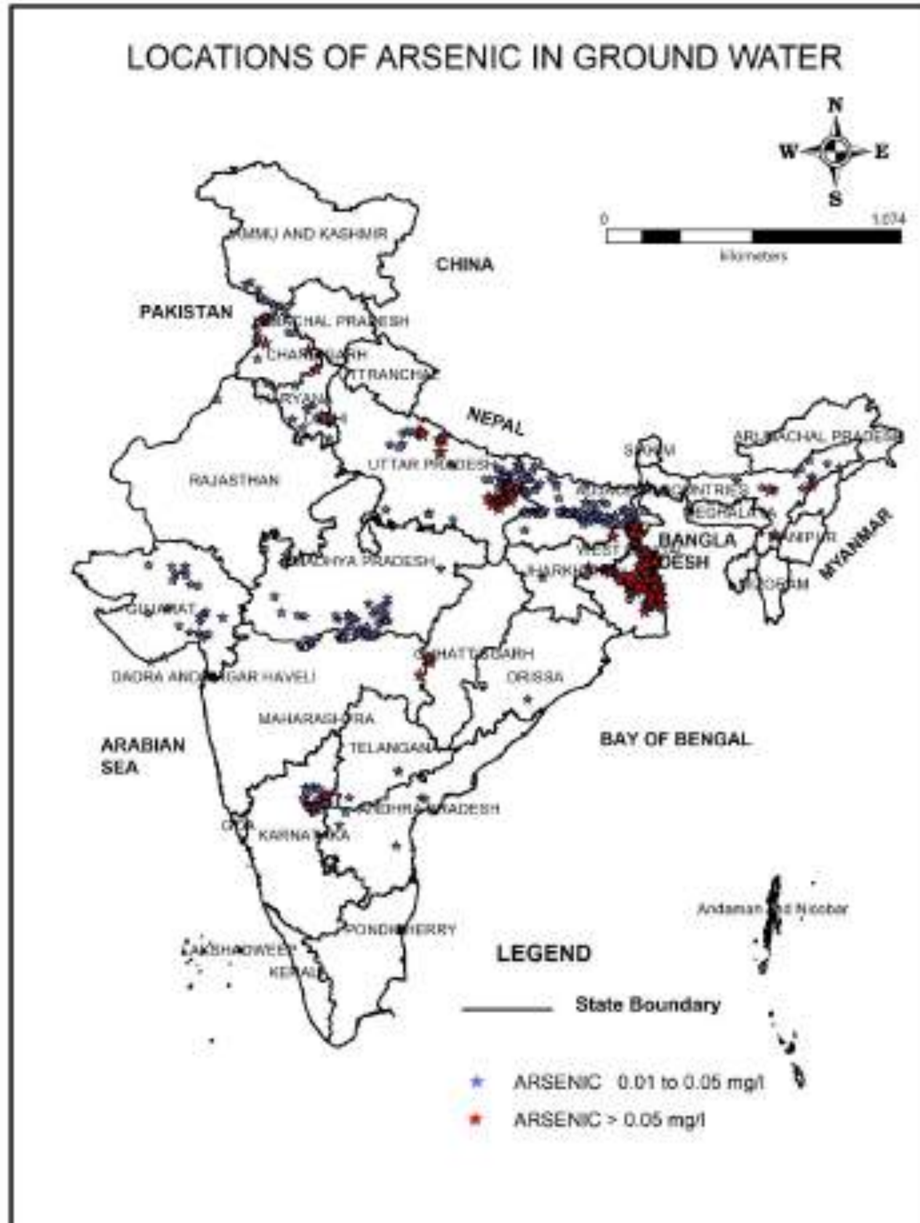
Because freshwater is less dense than saltwater, it floats on the saltwater and forms a lens-shaped body that may extend to considerable depths below sea level.



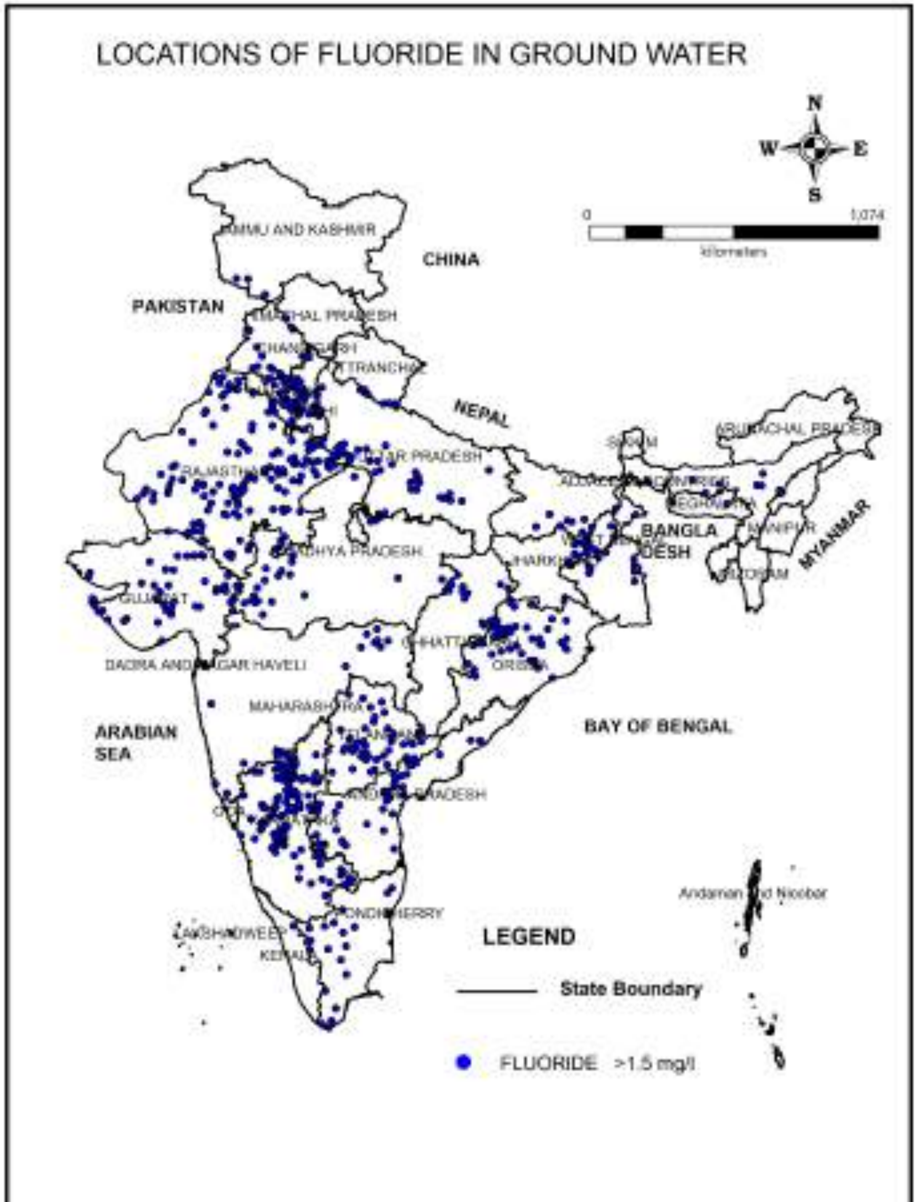
If excessive pumping lowers the water table, the base of the freshwater zone will rise 40 times that amount. The result may be saltwater contamination of wells.



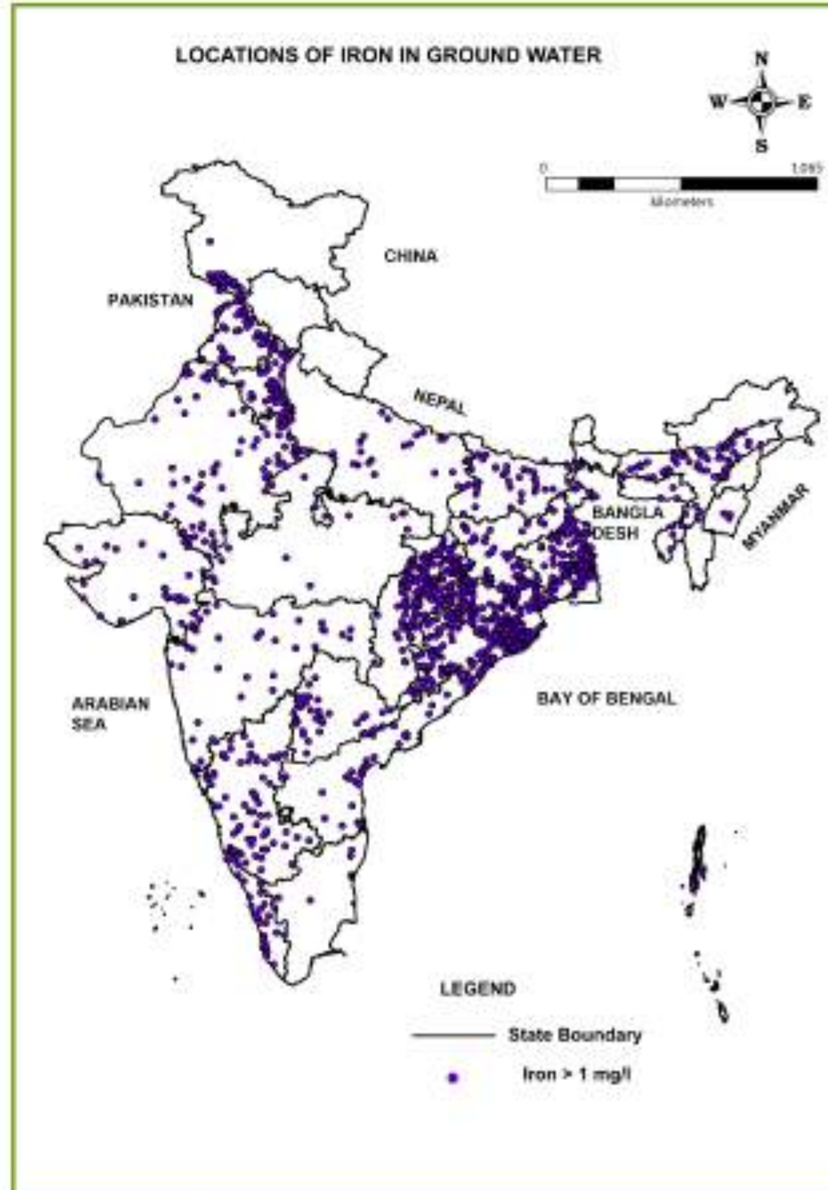
Arsenic is a naturally occurring trace element found in rocks, soils and the water in contact with them. Arsenic has been recognized as a toxic element and is considered a human health hazard.



Source:CGWB

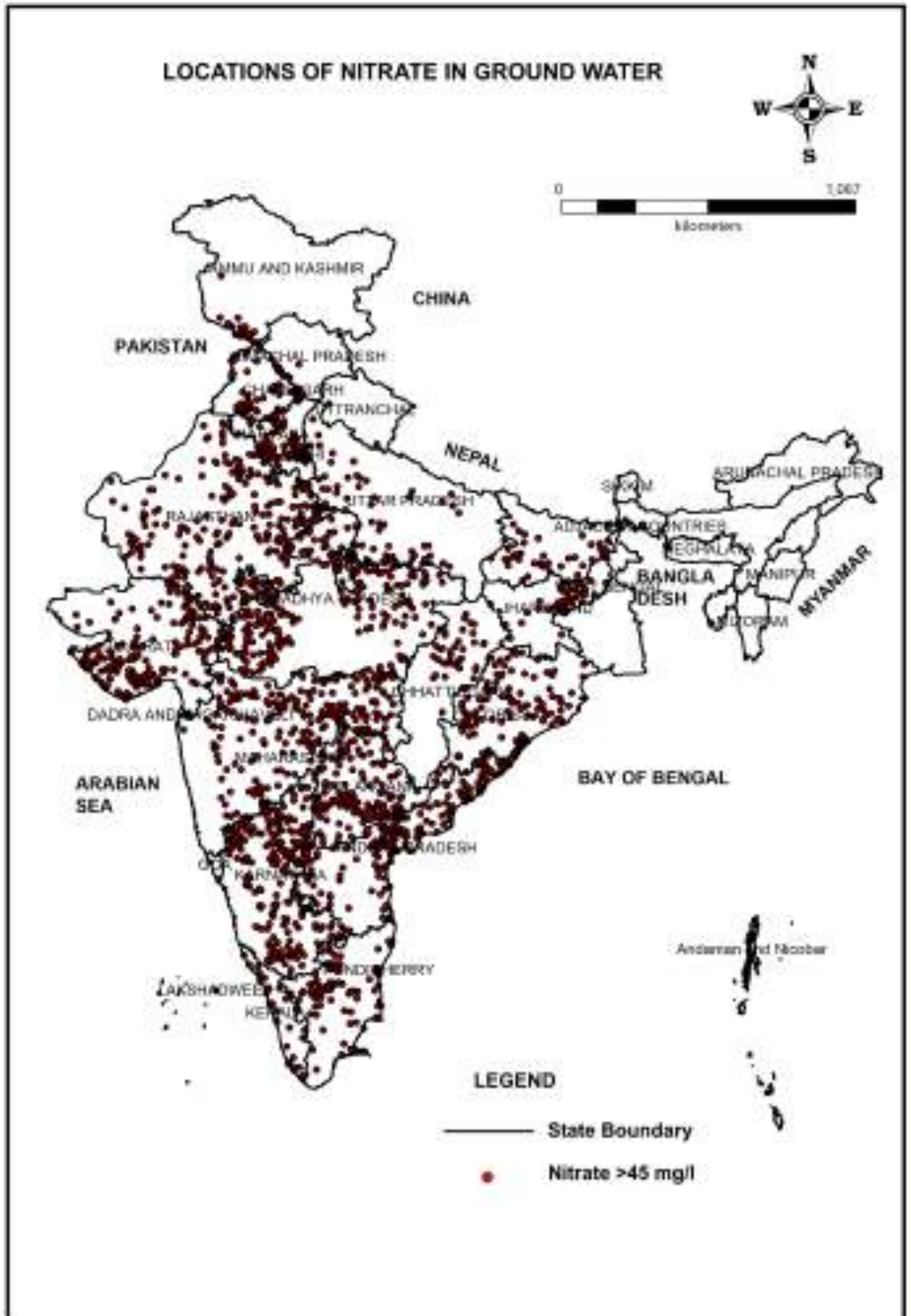


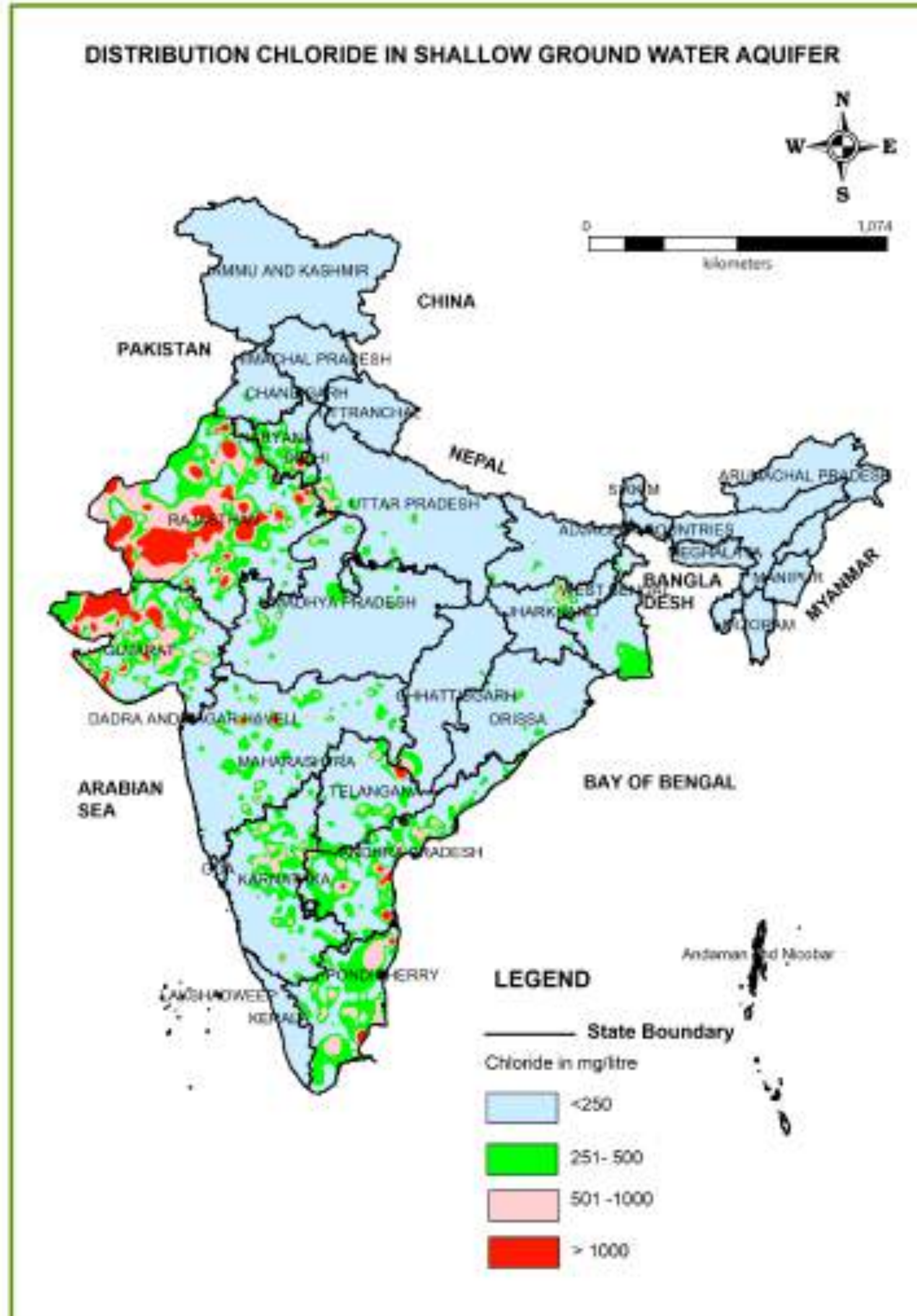
LOCATIONS OF FLUORIDE IN GROUND WATER
N
W
E
S
0
1,074
kilometers
JAMMU AND KASHMIR
CHINA
PAKISTAN
NEPAL
BANGLA DESH
MYANMAR
ARABIAN SEA
BAY OF BENGAL
ARUNACHAL PRADESH
MADHYA PRADESH
DADRA AND NAGAR HAVELI
Andaman and Nicobar
LEGEND
State Boundary
FLUORIDE >1.5 mg/l



LOCATIONS OF IRON IN GROUND WATER
N
W
E
S
0
kilometers
CHINA
PAKISTAN
NEPAL
BANGLA DESH
MYANMAR
ARABIAN SEA
BAY OF BENGAL
LEGEND
State Boundary
Iron > 1 mg/l

Source:CGWB

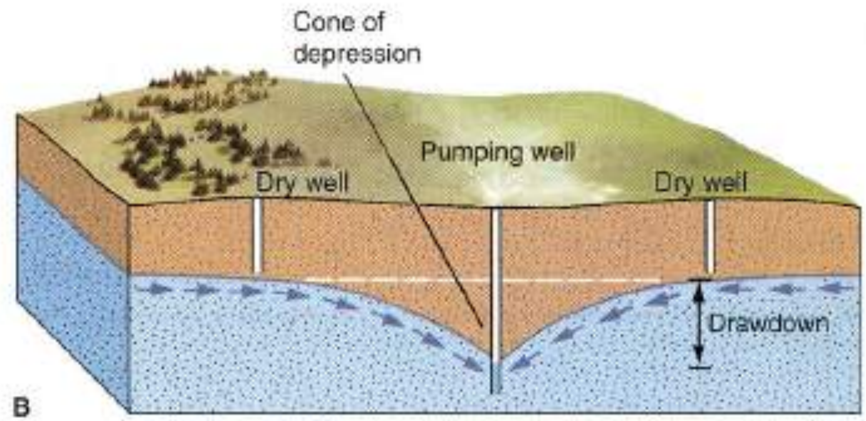

LOCATIONS OF NITRATE IN GROUND WATER
N
W
E
S
kilometers
CHINA
PAKISTAN
NEPAL
BANGLA DESH
MYANMAR
ARABIAN SEA
BAY OF BENGAL
LEGEND
State Boundary
Nitrate >45 mg/l


DISTRIBUTION CHLORIDE IN SHALLOW GROUND WATER AQUIFER
N
W
E
S
0
1,074
kilometers
CHINA
PAKISTAN
NEPAL
UTTAR PRADESH
BANGLA DESH
MYANMAR
ORISSA
TELANGANA
ARABIAN SEA
BAY OF BENGAL
LEGEND
State Boundary
Chloride in mg/litre
<250
251- 500
501 -1000
> 1000

Source:CGWB

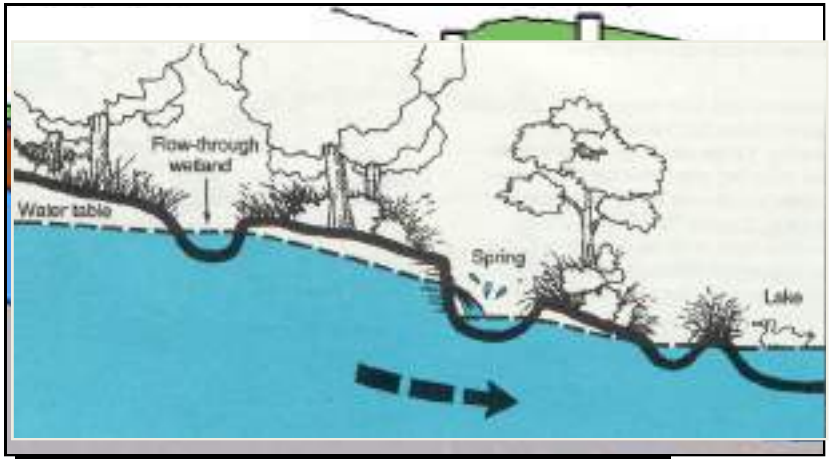
Balancing Withdrawal and Recharge

- If ground water is withdrawn more rapidly than it is recharged, the *water table* will drop
  - Dropping water table can lead to ground *subsidence*
    - surface of the ground drops as buoyancy from ground water is removed, allowing rock or sediment to compact and sink
  - Subsidence can crack foundations, roads and pipelines
  - Areas of extremely high *ground water pumping* (such as for crop irrigation in dry regions) have subsided 7-9 meters



Groundwater Susceptibility

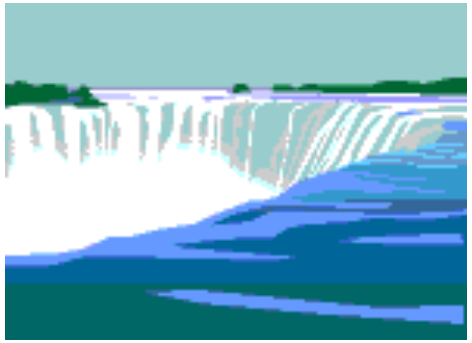
Things to keep in mind:



- Unconfined aquifers with no cover of dense material are susceptible to contamination.
- Bedrock with large fractures is susceptible, because the fractures provide pathways for contaminants.
- Confined, deep aquifers tend to be better protected than surface aquifers with a dense layer of clay material.
- Wells that connect two aquifers increase the chance of cross contamination between the aquifers.

The Surface Water System: Rivers

Rajiv Sinha



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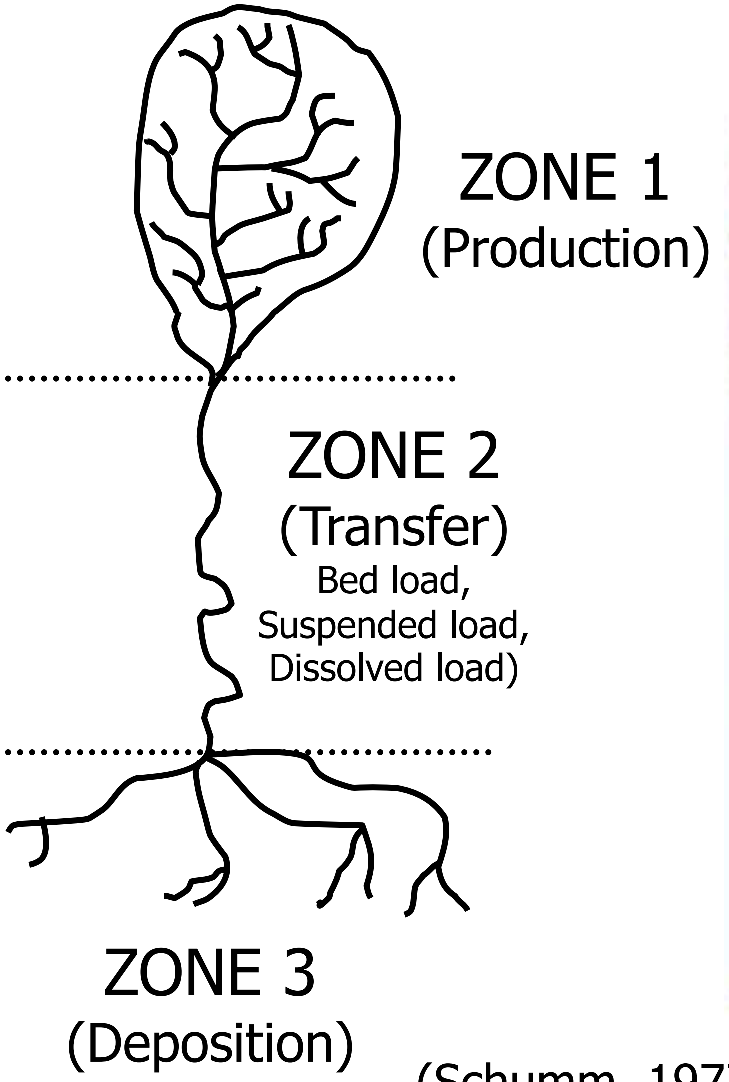
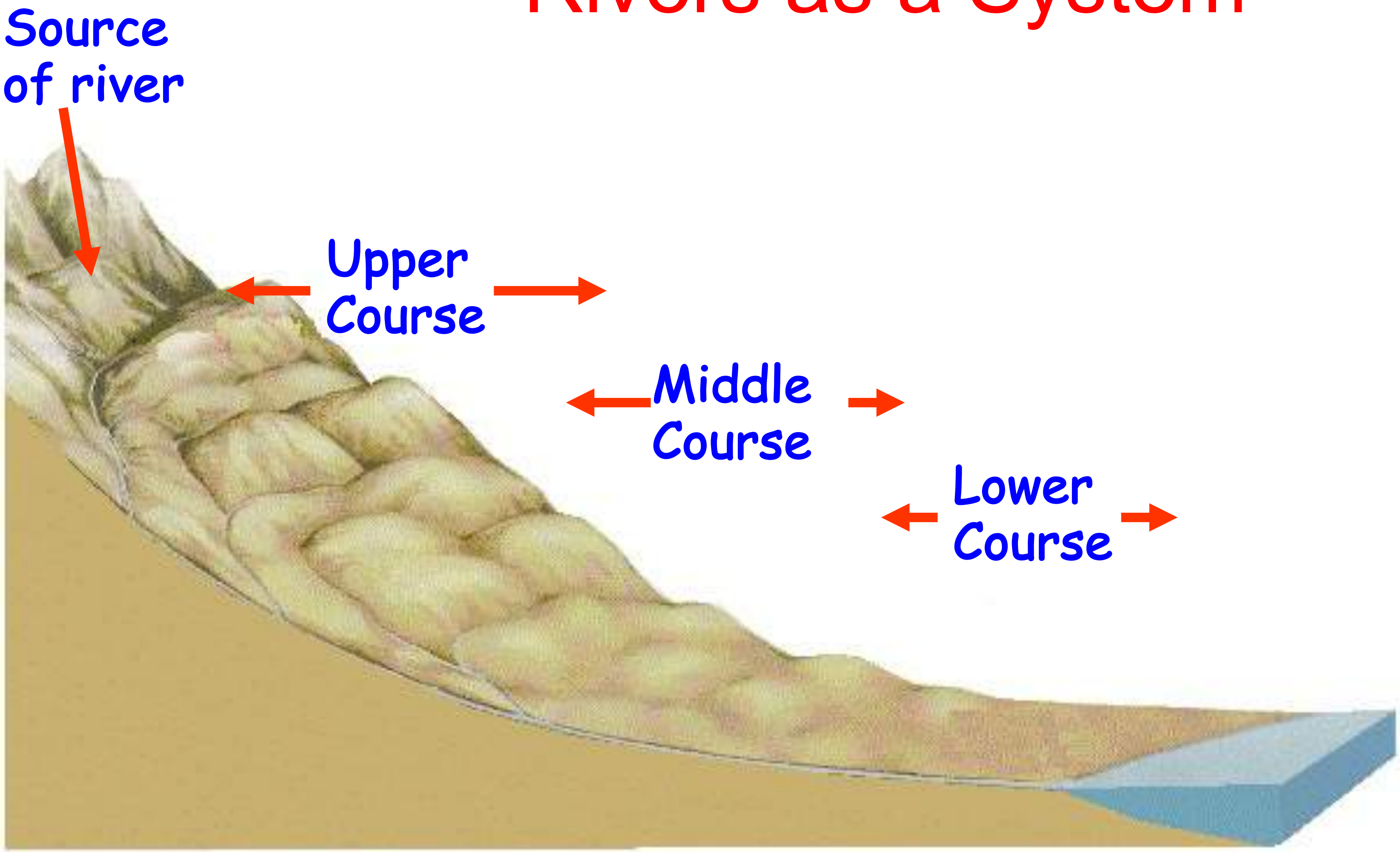
Rivers as a System

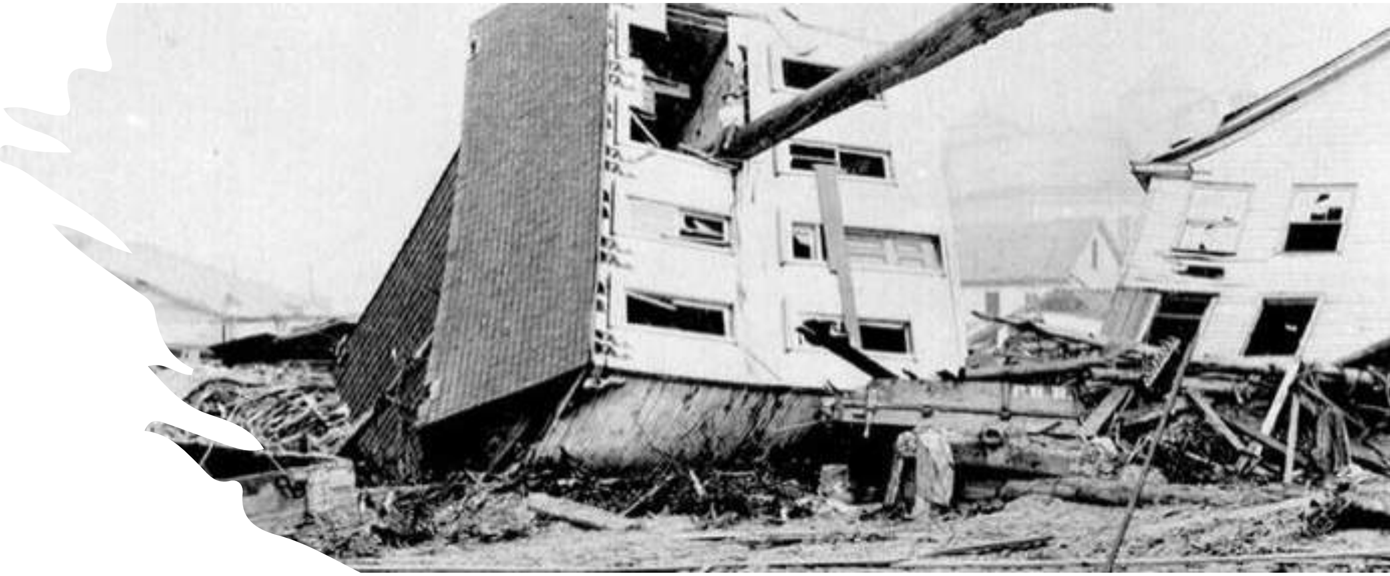


(Schumm, 1977)



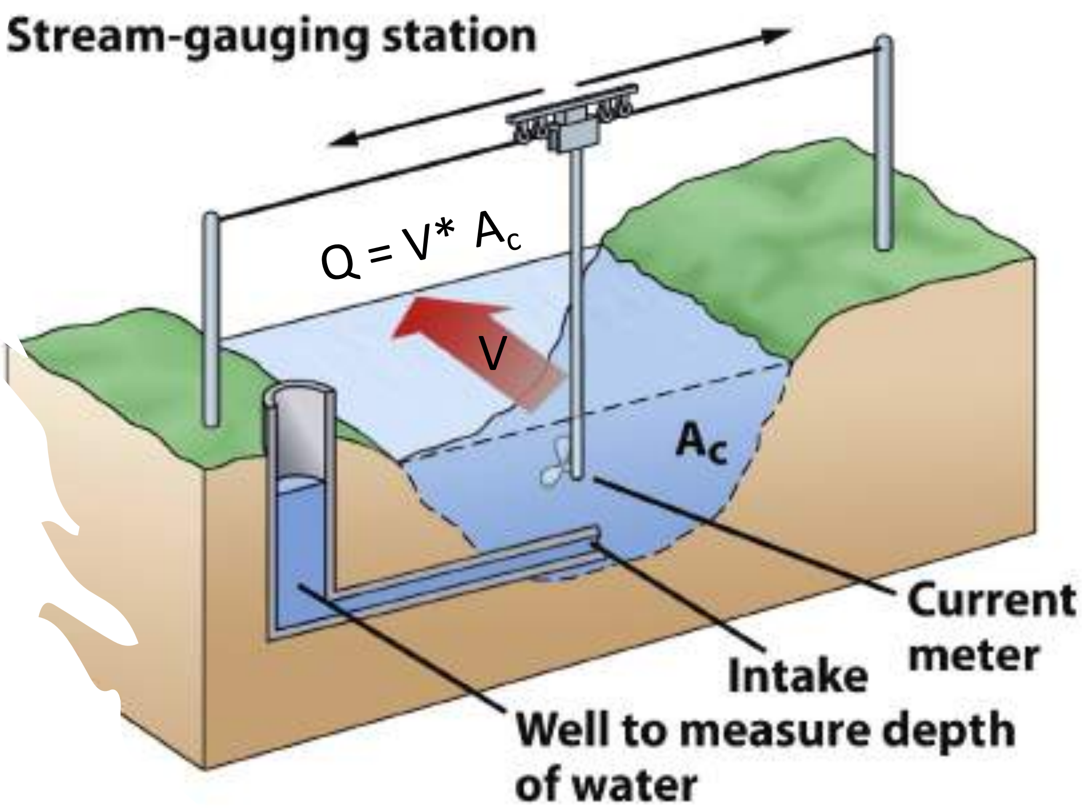
Streamflow

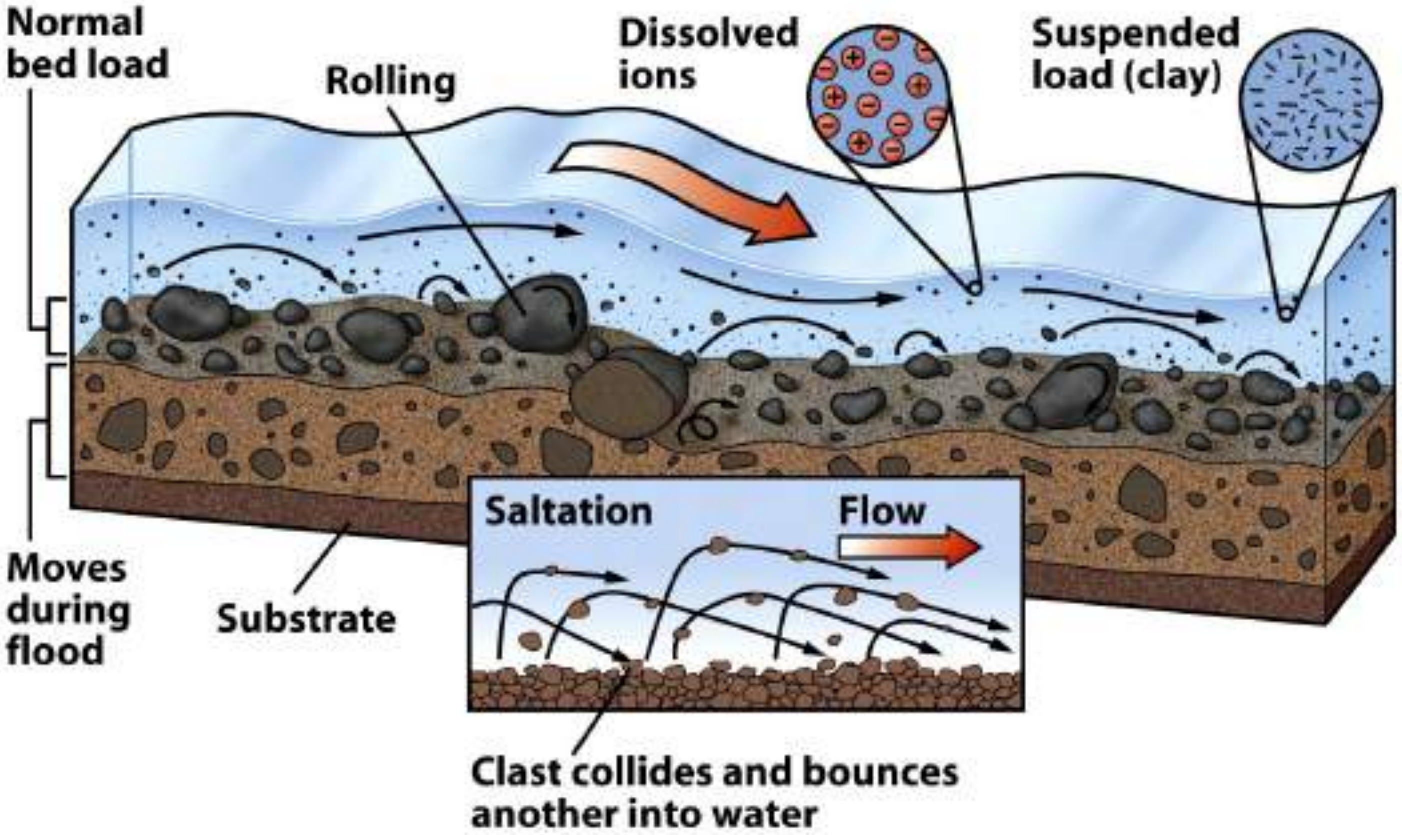
- Stream runoff is an important geomorphic agent.
  - Flowing water…
    - Erodes, transports, and deposits sediments.
    - Sculpts landscapes.
    - Transfers mass from continents to ocean basins.
  - Earth: only planet in the solar system with flowing water.
  - Without flowing water, Earth might resemble Mars.
- Stream runoff also causes many problems.
  - Flooding destroys lives and property.



Discharge

- The amount water flowing in a channel.
  - Volume of water passing a point per unit time ($Q = V * A_c$).
    - Cubic feet per second (ft^3/s).
    - Cubic meters per second (m^3/s).
- Given by cross-sectional area x flow velocity.
- Varies seasonally due to precipitation and runoff.



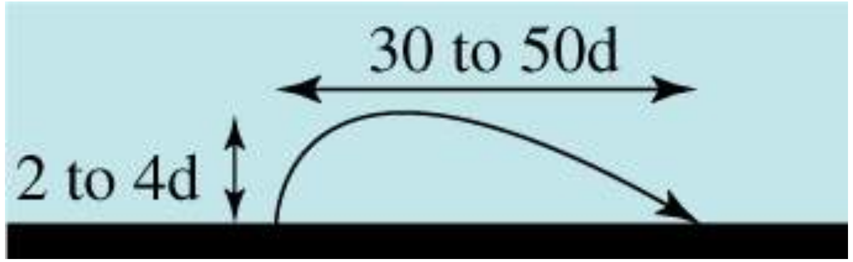


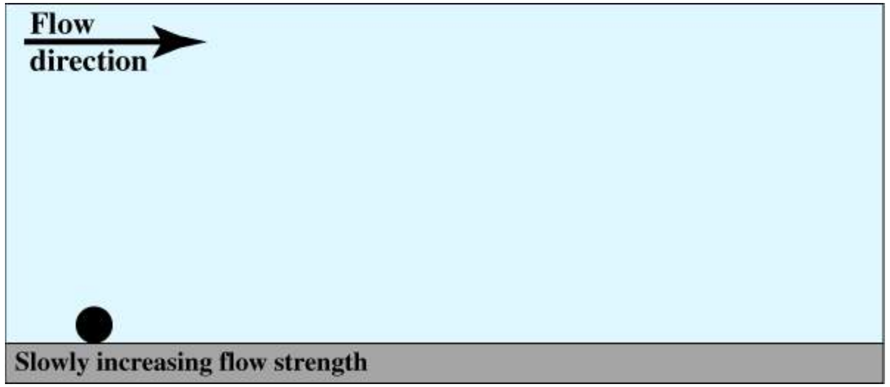
Sediment Transport

- The material moved by streams is the sediment load.
- There are 3 types of load.
    - Dissolved load – Ions from mineral weathering.
    - Suspended load – Fine particles (silt and clay) in the flow.
    - Bed load – Larger particles roll, slide, and bounce along.

Sediment transport

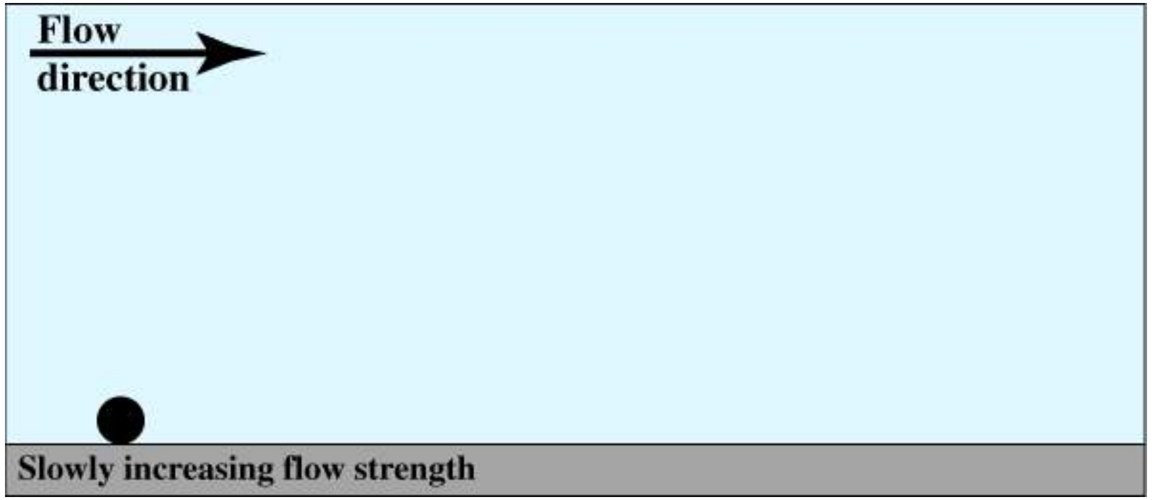
- *Contact load*: particles that move in contact with the bed by sliding or rolling over it.
- *Saltation load*: movement as a series of “hops” along the bed, each hop following a ballistic trajectory.



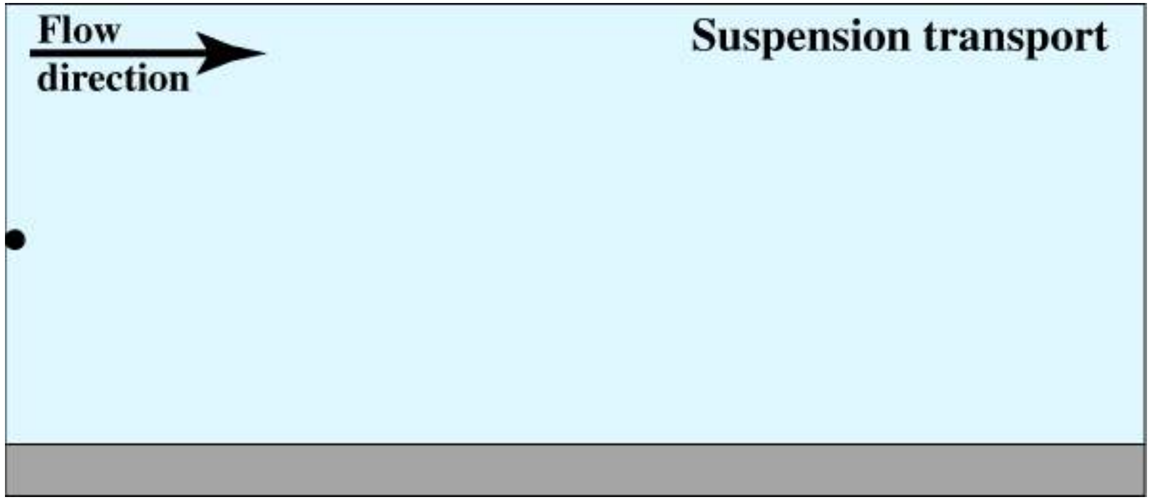


Sediment transport

- When the ballistic trajectory is disturbed by turbulence the motion is referred to as *Suspensive saltation*



- *Intermittent suspension load*: carried in suspension by turbulence in the flow.



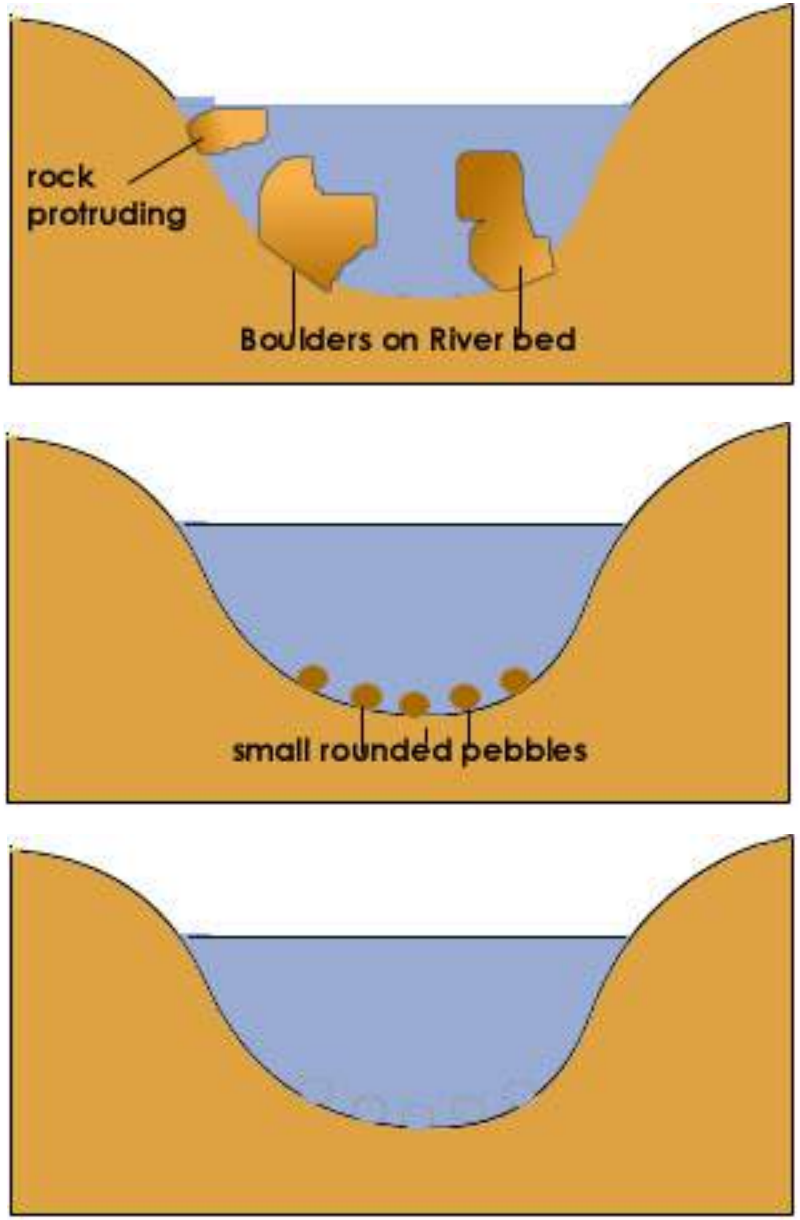
- “Intermittent” because it is in suspension only during high flow events and otherwise resides in the deposits of the bed.

- Bursting is an important process in initiating suspension transport.

Sediment Deposition

- When flow velocity decreases…
    - Competence is reduced and sediment drops out.
    - Sediment grain sizes are sorted by water.
        - Sands are removed from gravels; muds from both.
        - Gravels settle in channels.
        - Sands drop out in near channel environments.
        - Silts and clays drape floodplains away from channels.

Contrasting river landforms from source to mouth



Upper Course

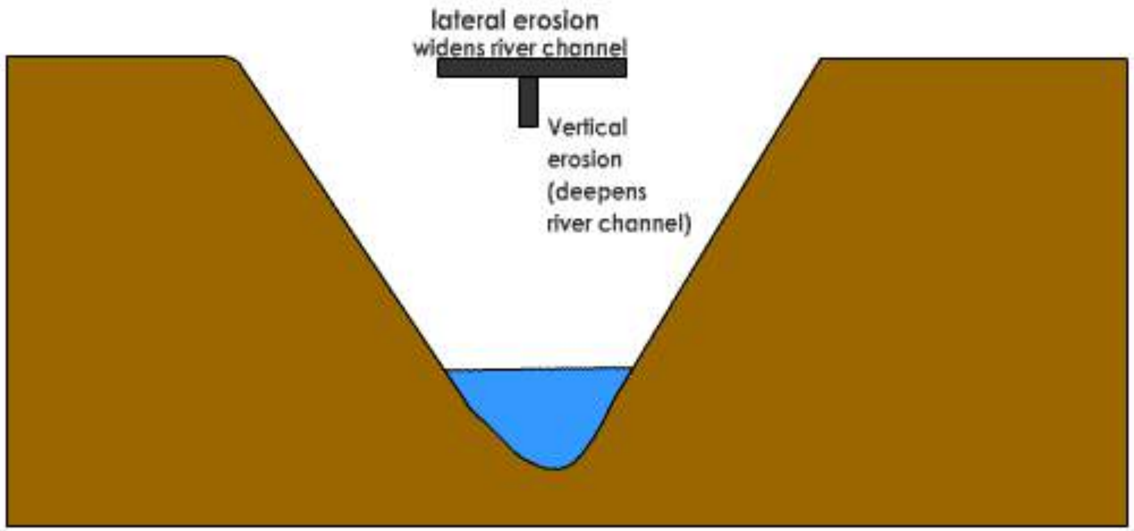
- Channel features
- Valley features
- Long profile

Lower Course

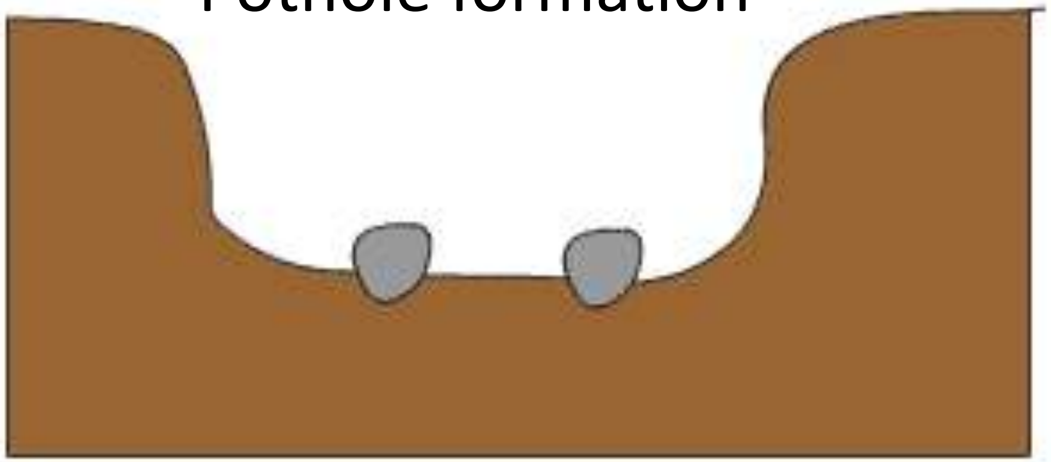
Upper Course - Channel features

- River channel is rocky.
- Covered with various shapes and sizes of boulder.
- Discharge is low.
- Under flood conditions rivers energy is expended on vertical erosion with hydraulic action and corrosion processes at work.
- Potholes may form.

Vertical erosion

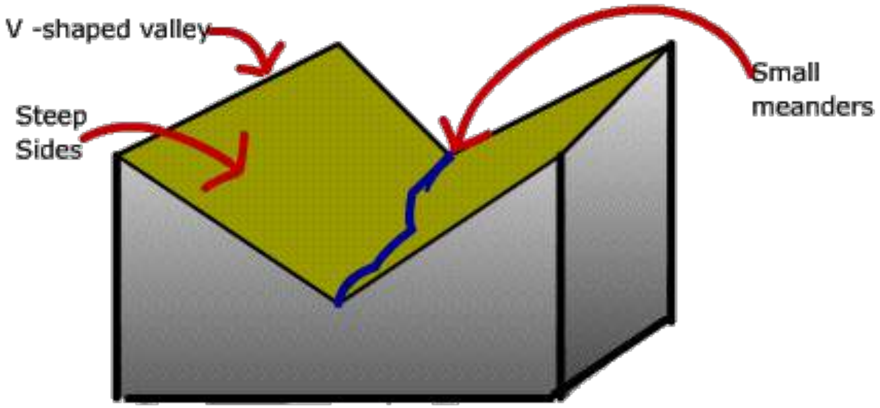


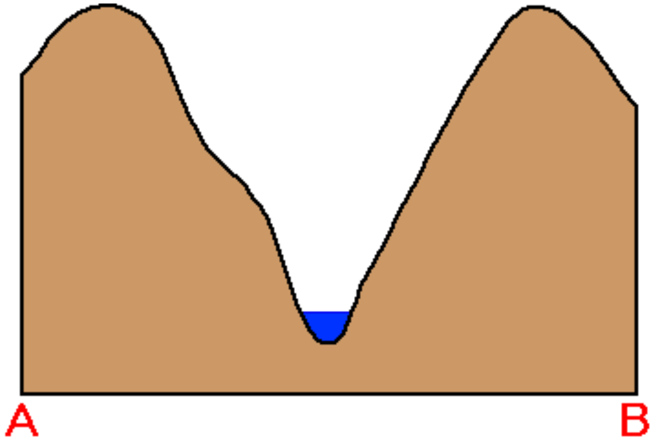
Pothole formation



Upper Course - Valley features

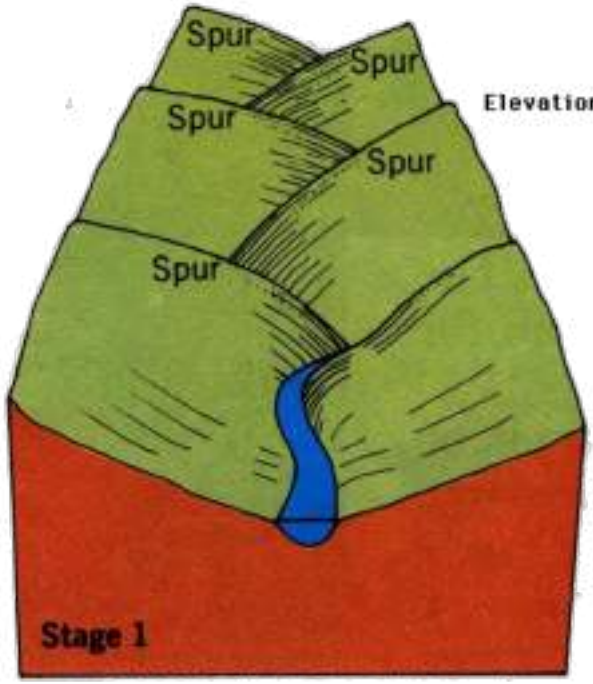
- Valley sides are steep and form a ‘V’ shaped cross section.
- Interlocking spurs.

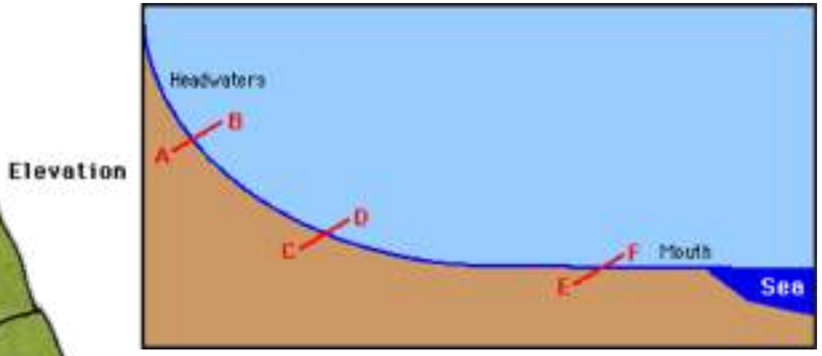




Form due to a combination of the following processes:

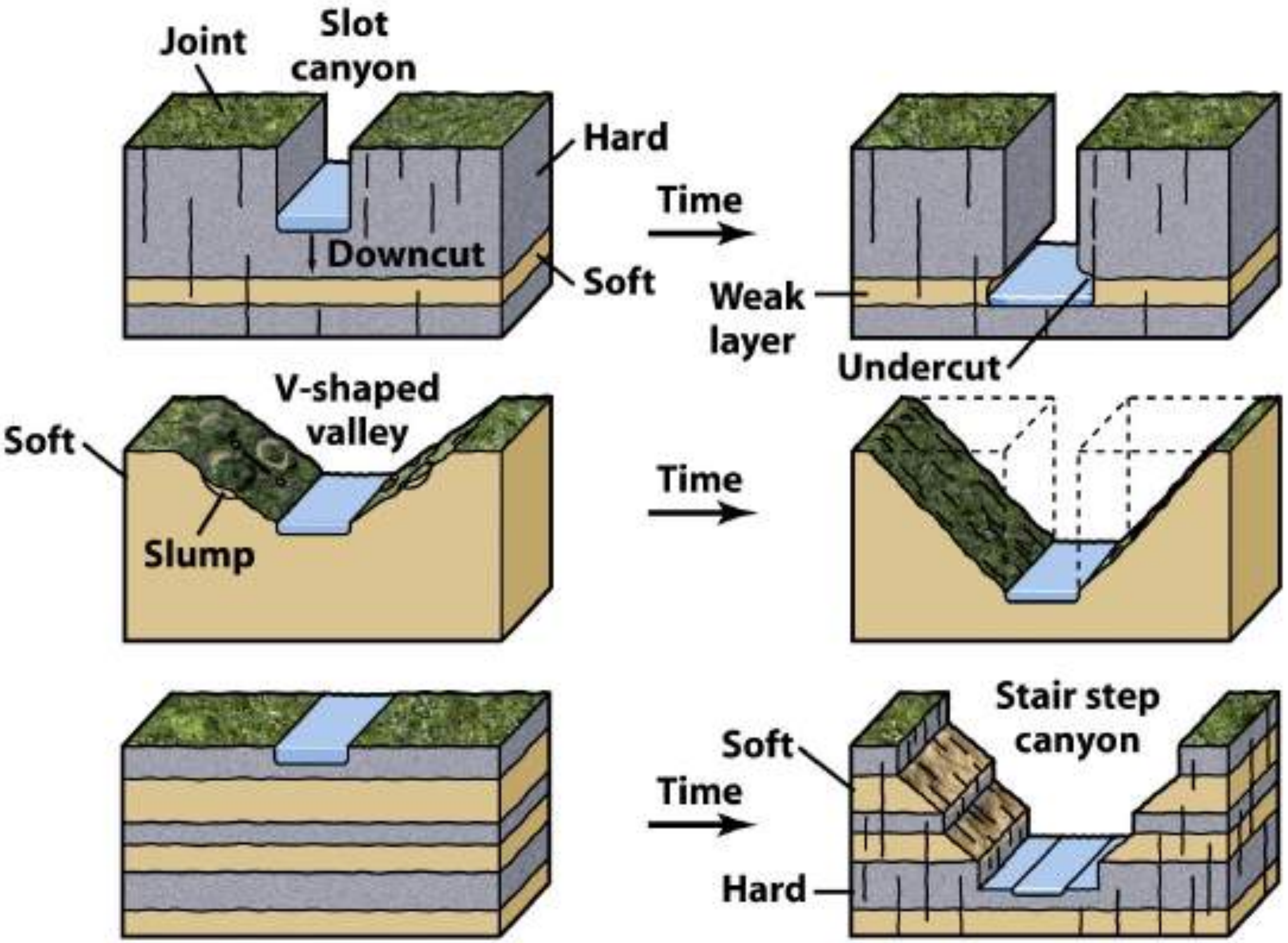
- Vertical erosion by the river itself.
- Physical weathering (eg: frost action) which provides debris to move down slope.
- Mass movement (including soil creep & landslides) to move debris down slope.



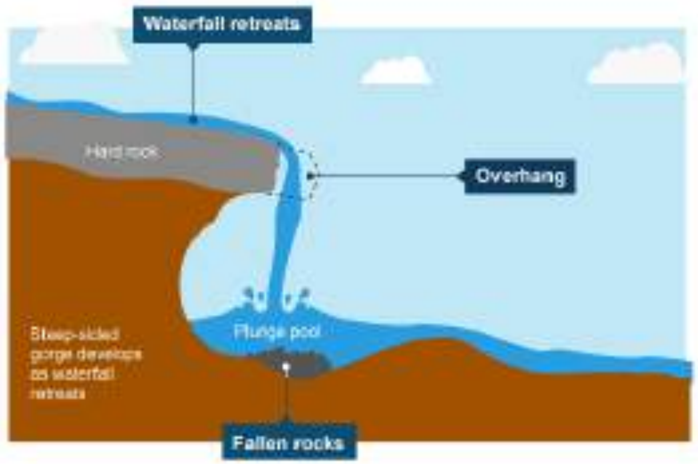


River flows around interlocking spurs

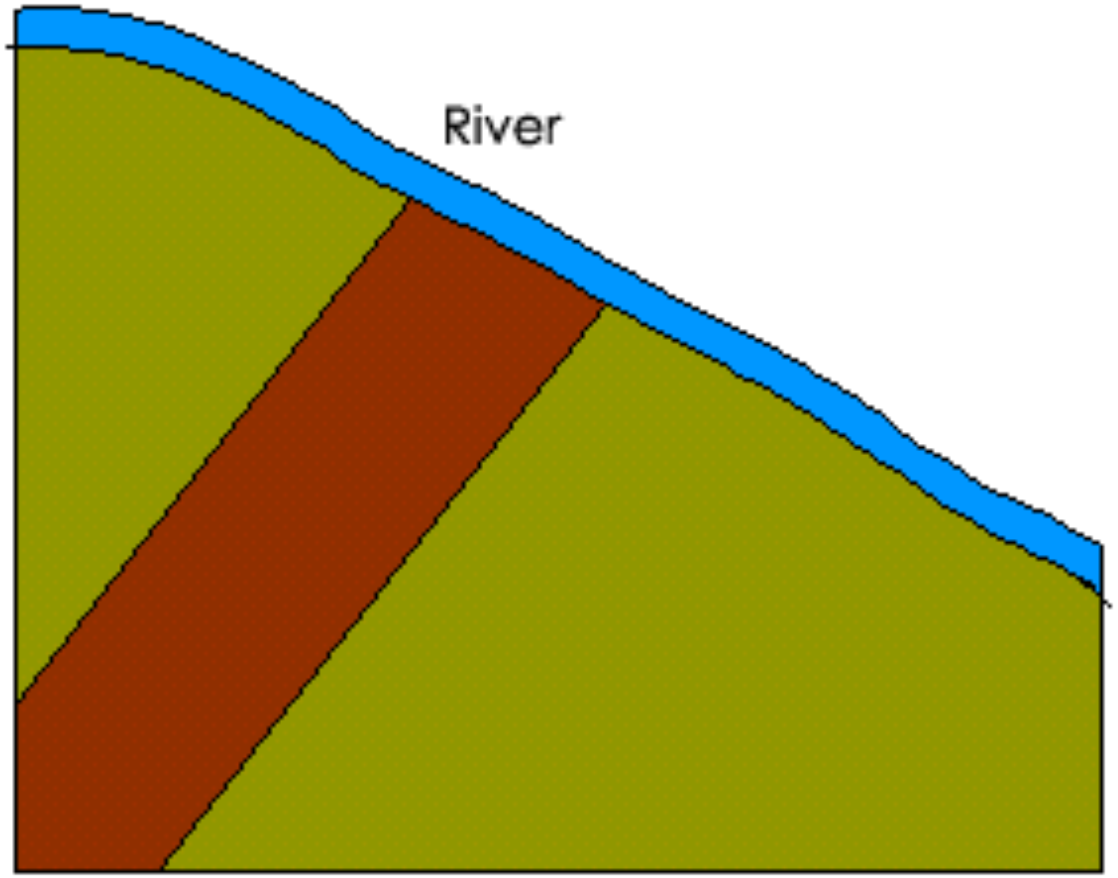
Erosional Landforms



Waterfalls

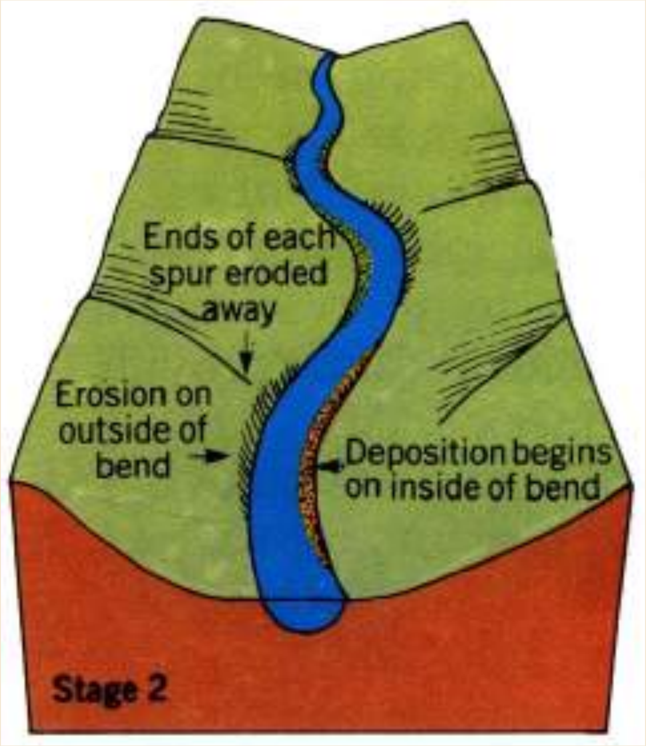


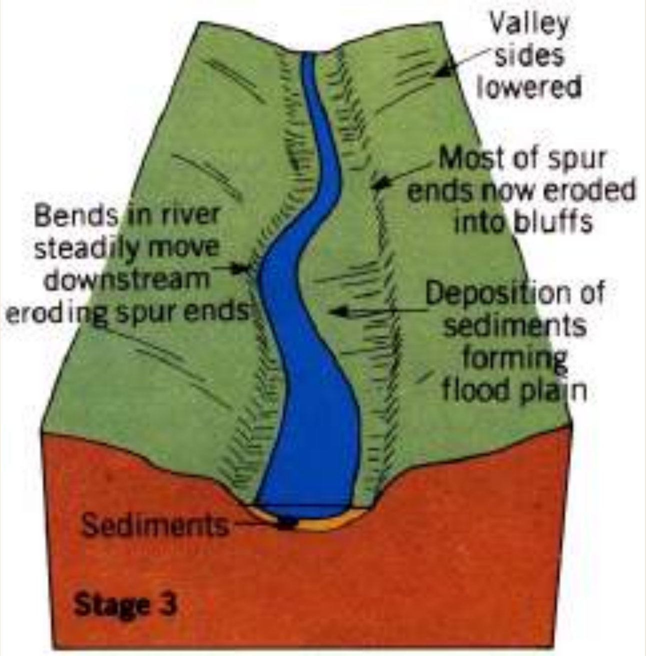
Raneh Falls, Khajuraho
(Grand Canyon of India)



1. The river flows across rocks of different resistance.

Middle Course - Channel and Valley features



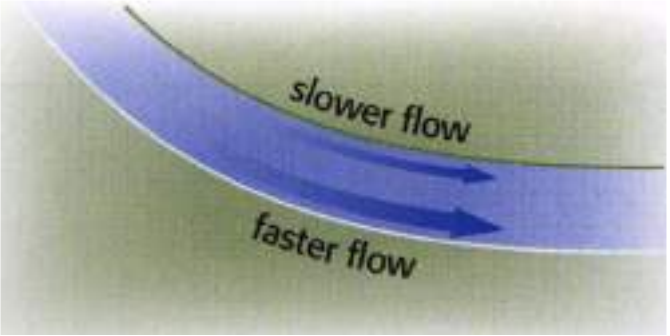


- Channel is now wider and has smoother banks and bed compared to the upper course.
- River erosional energy is now increasingly expended horizontally rather than vertically.
- Lateral erosion by the river's meanders broadens the valley floor into a narrow flood plain.
- Meanders gradually shift their course downstream.

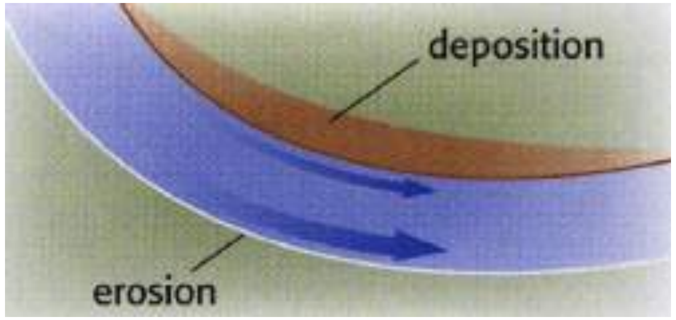
Meanders

A meander starts as a slight bend:

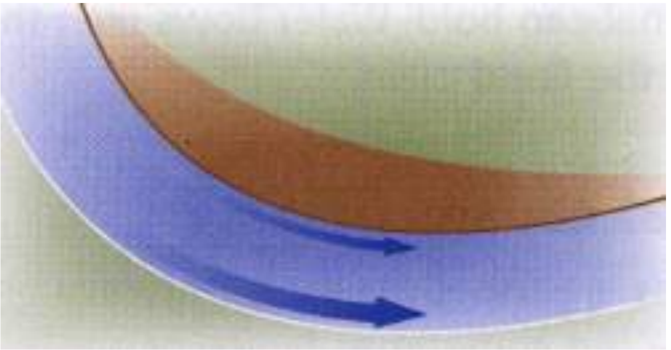
- Alternating series of irregularities develop
- Pools – **deeper** stretches of **slow** moving water
- Riffles – **shallower** section of **faster** flow, flowing above coarser material
- River develops a **winding** or sinuous course
- **Faster** flow on **outer bend** results in erosion and formation of River Cliff
- **Slower** flow on **inside** of bend results in deposition and formation of Slip-off Slope



Water flows faster on the outer curve of the bend (more energy), and slowest on the inner curve (less energy).



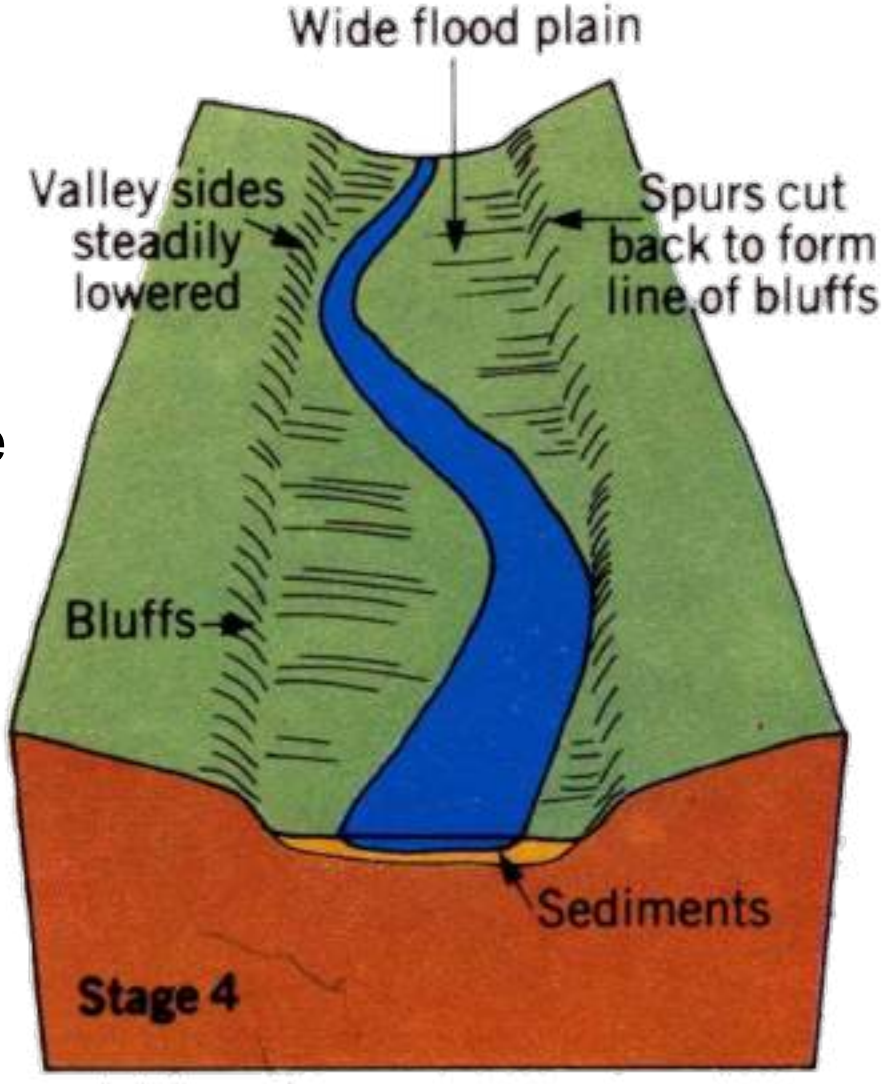
So the outer bank gets eroded while material is deposited at the inner bank.



Over time the outer bank gets worn away (river cliff) and the inner one builds up (river beach). The bend grows into a meander.

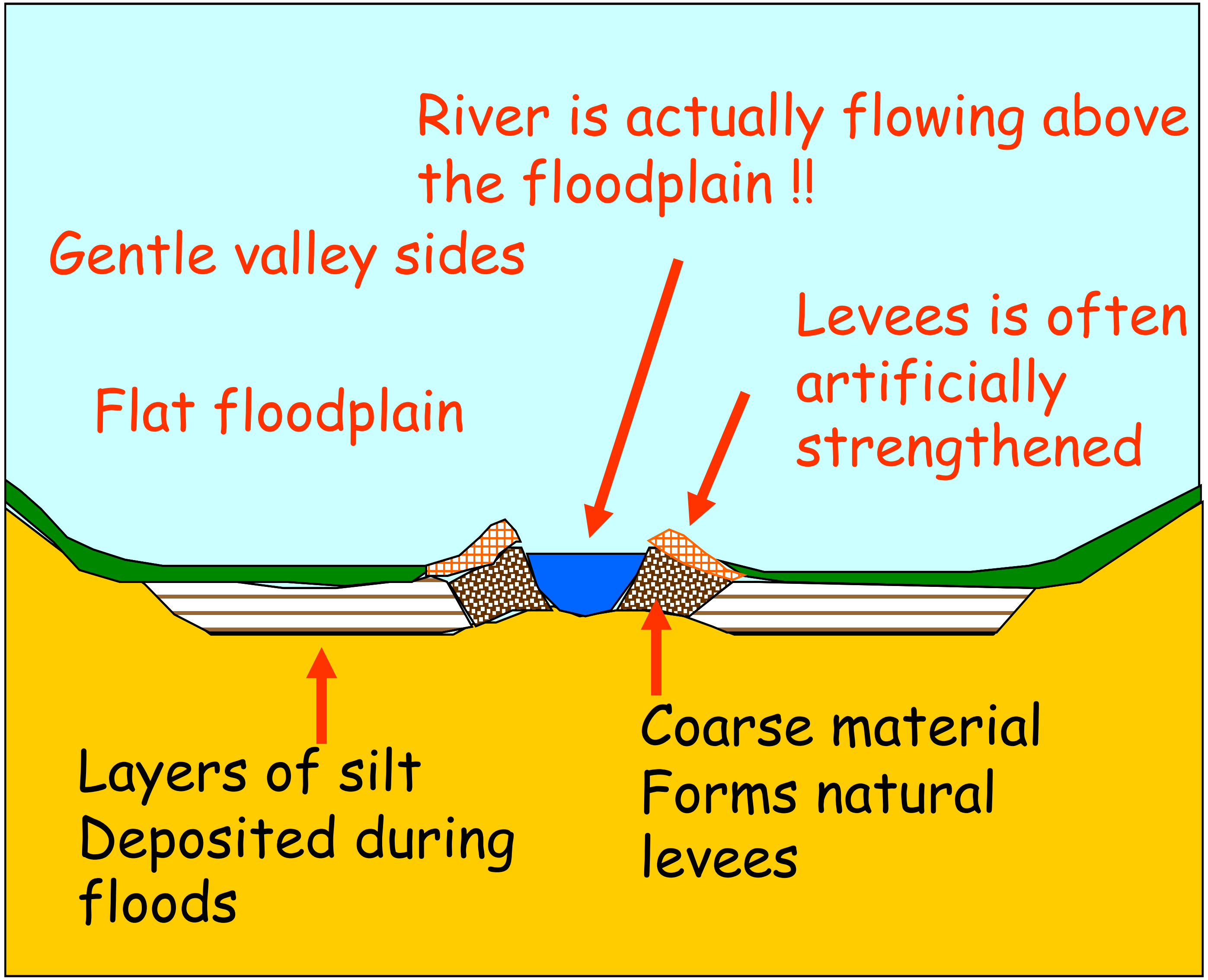
Lower Course – Channel and Valley features

- The channel is now at its broadest and deepest.
- Bedload is carried entirely in suspension and is solution.
- Deposition now dominates – particularly during floods.
- Erosion also occurs – in the formation of meanders
- Thanks to lateral erosion, the valley sides may now be several kilometres away.
- Typically, it may also contain the following features:
  - Floodplain & natural levees
  - Braided channels
  - Meanders
  - Oxbow lakes
  - Estuaries and deltas

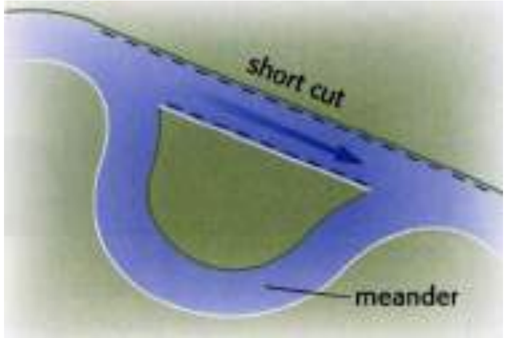


Natural levees

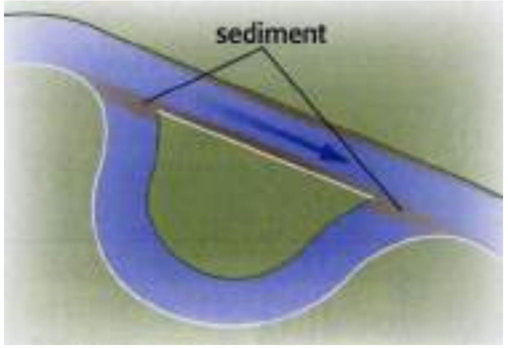
- As the river floods, sediment is dropped over all the flooded areas but most falls along the river channel itself.
- This sediment raises the height of the banks is flooding occurs regularly
- Levees themselves do not prevent flooding because as the banks are raised, more sediment is dropped on the river bed, raising the water level.



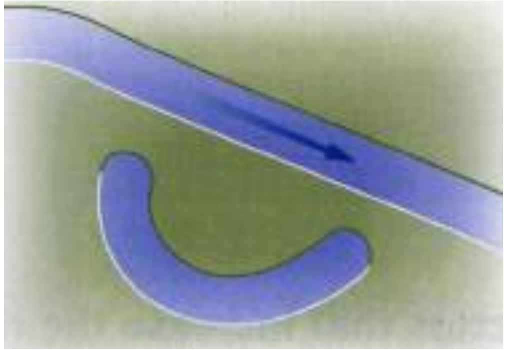
Oxbow lakes



An Oxbow lake starts as a meander. During a flood the river cuts across the meander, forming a new channel.

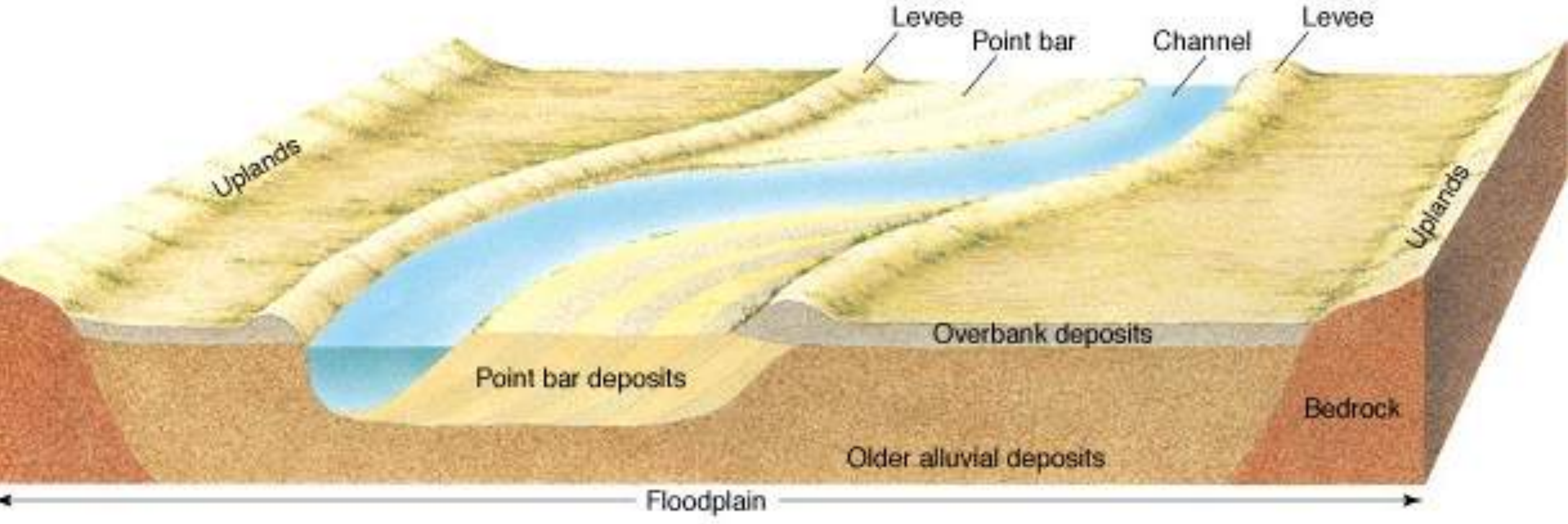


Sediment is deposited along the sides of the new channel. The loops gets sealed off and an oxbow lake forms.



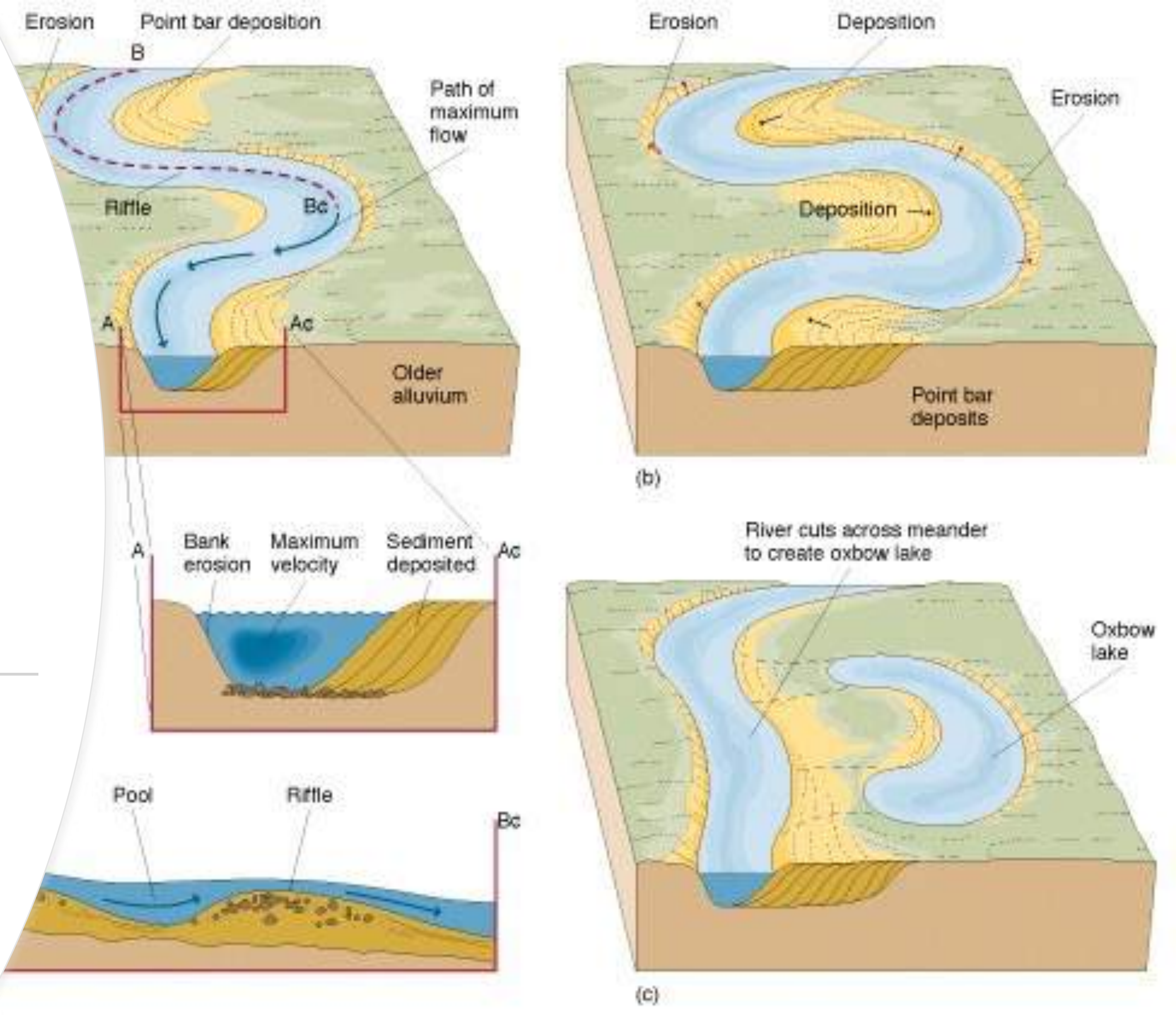
The water in it becomes stagnant. The lake will remain sealed of until either the river floods into it or it dries out.


NARROW MEANDER NECK
FUTURE
OX-BOW LAKE



Floodplains

Meandering River Landforms: Summary

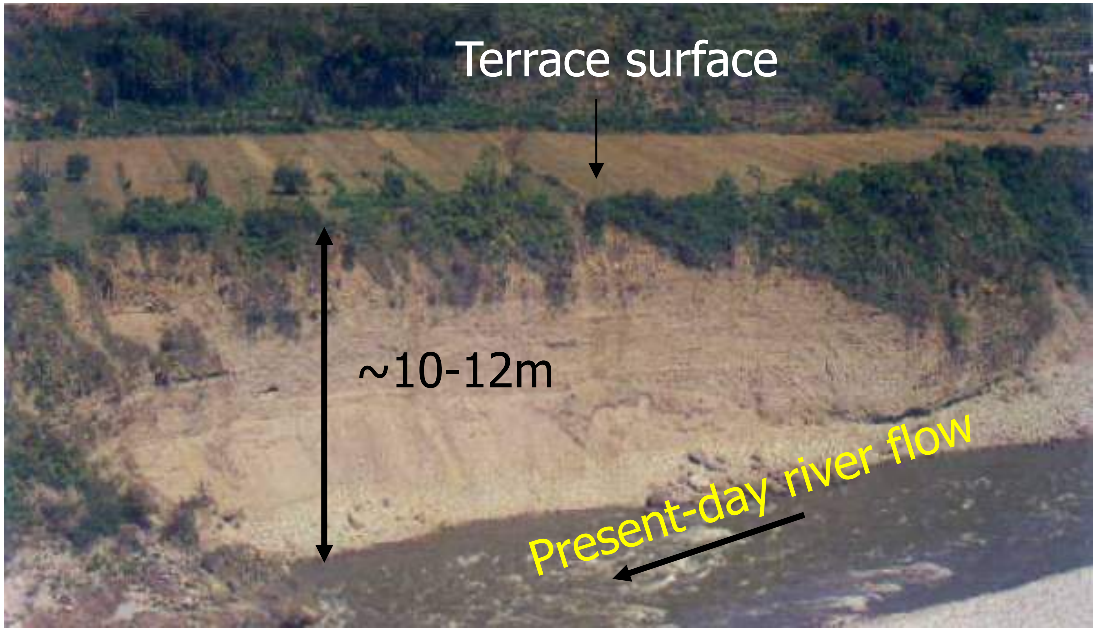


Braided channels

- Formed by the choking of the main channel by the deposition of a considerable amounts of the river load.

- The channel splits into several smaller channels which flow around fresh ‘islands’ of deposited material before rejoining.

River Terraces

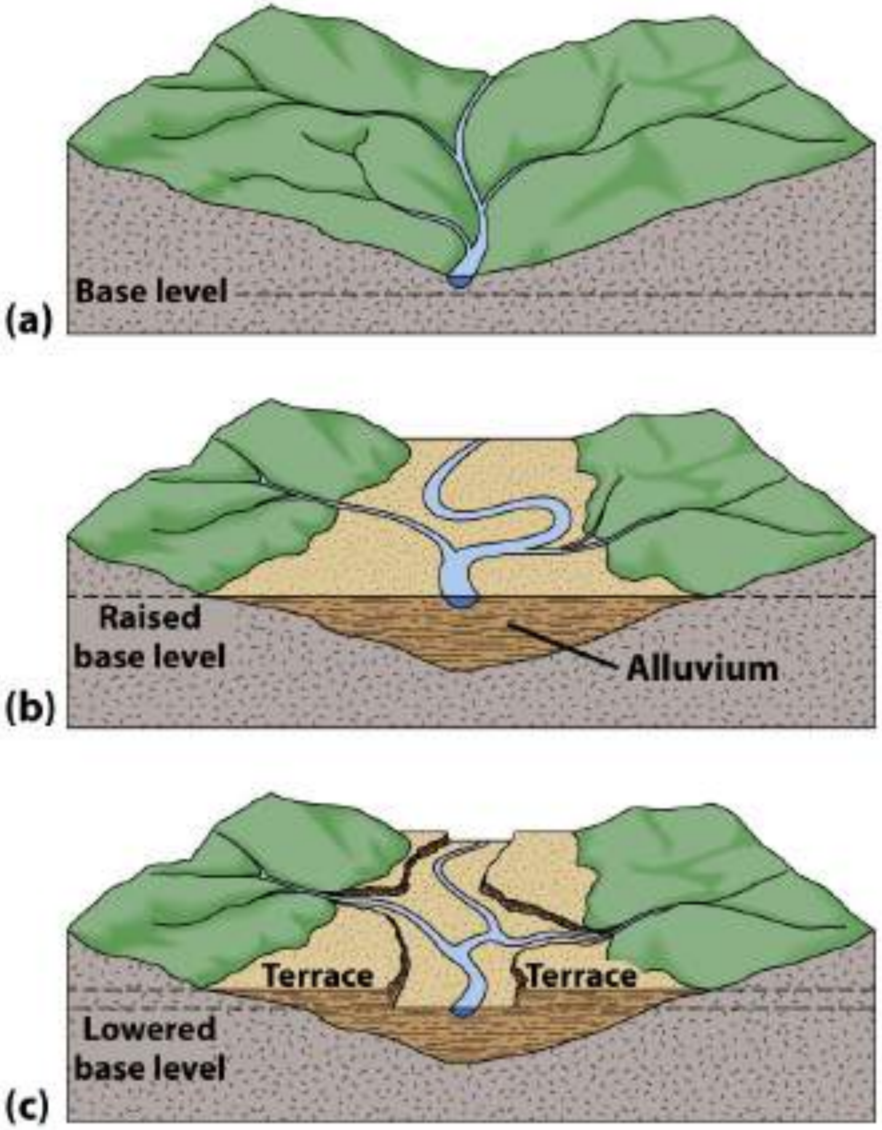


Aggradational terraces:

Aggradation + downcutting

Degradational terraces: Incision of bedrock channels (strath terraces)

Paired/unpaired



Summary

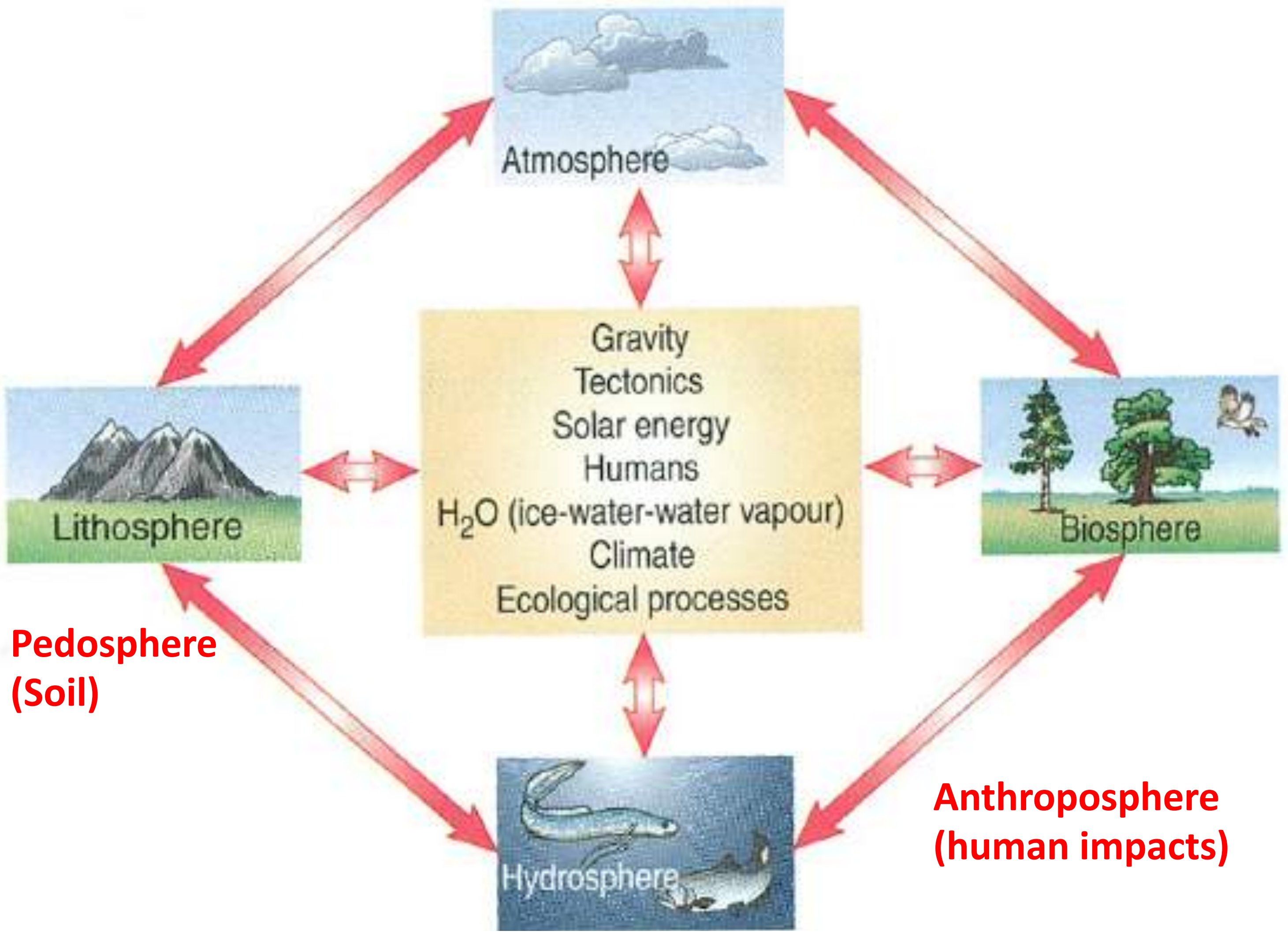
- Rivers produce a variety of landforms produced by erosional and depositional processes.
- These landforms are specific to the terrain through which the river moves – distinctive landforms in upper, middle and lower reaches.
- Meandering and Braided rivers are the two most distinctive types in terms of channel morphology.
- A river is a dynamic geomorphic agent, and it keeps on adjusting its form and position through time in response to natural as well as anthropogenic perturbations.

Soil System (Pedosphere)

ESO213
Earth Science

Rajiv Sinha
Department of Earth Sciences
Indian Institute of Technology Kanpur

Components of Earth's System

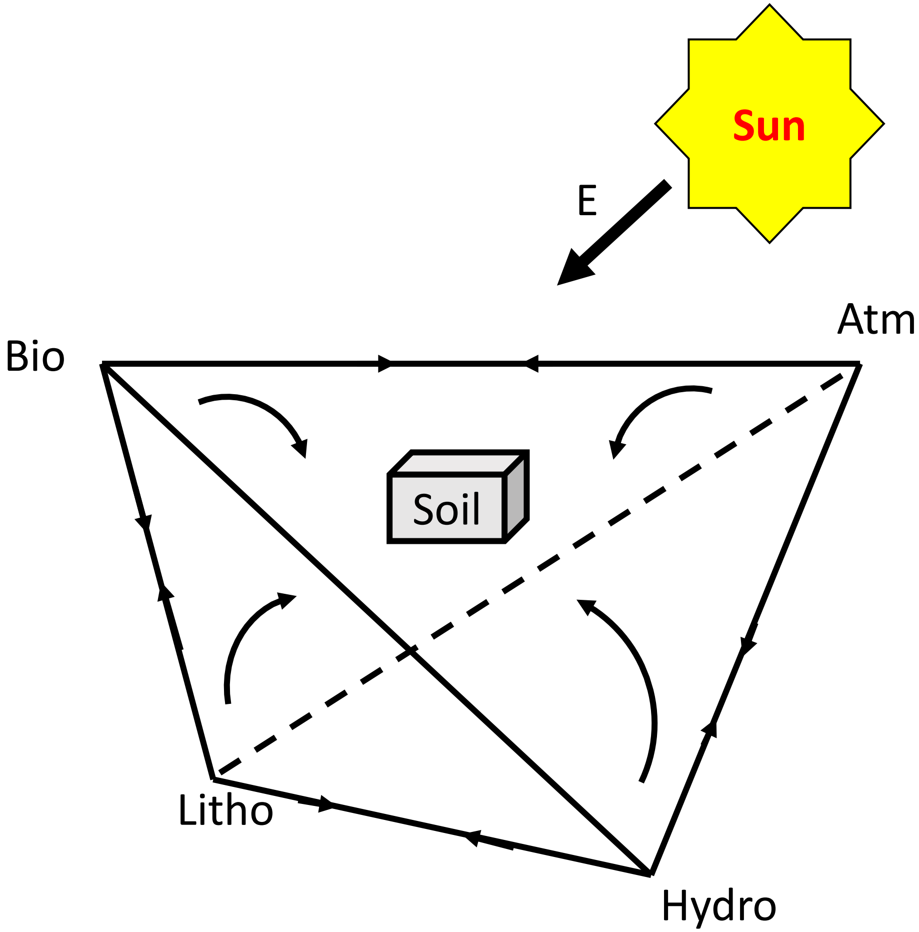


Huddart and Stott, 2010

- Soils – disaggregated and weathered rock debris and organic matter
- 100-200 m thick, supports all terrestrial agricultural activities and food production
- Open system; rate of soil formation depends upon climate, rock type, organic matter, topography and time

How does soil form?

A vertical column of rocks is reduced to a horizontal blanket of loose material!



Soil formation = a +ve feedback process!

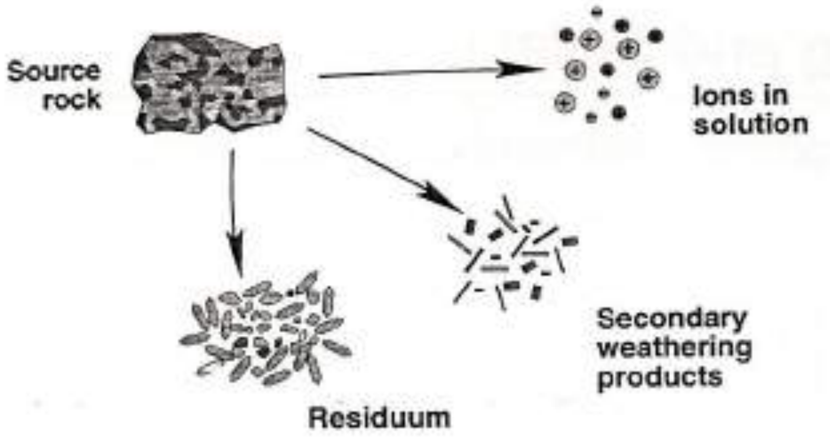
<u>Soil forming factors</u>

(1) *climate,*
(2) *vegetation, fauna, man*
(3) *relief*
(4) *parent material*
(5) *time* span

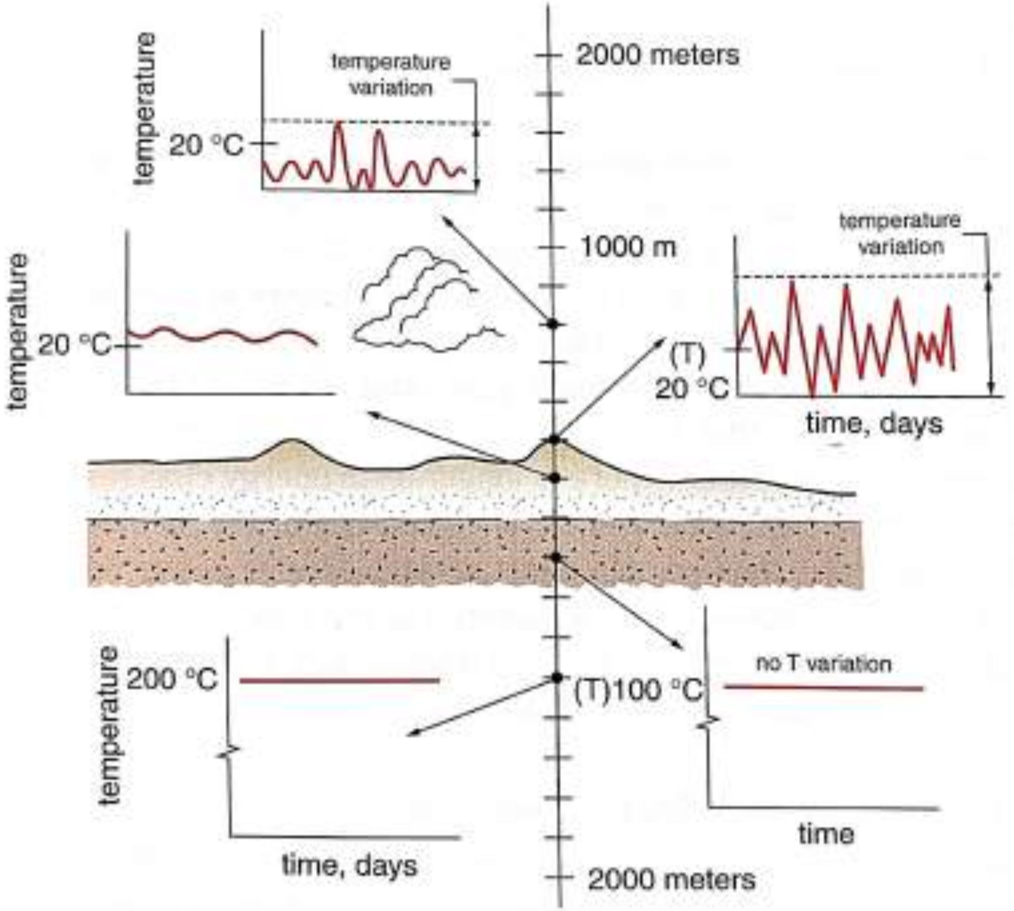
} **Pedogenesis**

Weathering Systems and the Breakdown of Rocks

- Weathering: Normal earth process. Takes place when deep-seated rocks are exposed on the surface of the earth
- Compact and coherent rocks with little porosity get converted into friable and loose material (regolith/soil) with high porosity, and grain size reduction.
- Mineralogical and chemical changes (both loss and gains)



- Water – the solvent
- Surface temperature



Temperature (T) variations over time in the atmosphere, at the Earth's surface, in the soil, and in the crust. Thermal variations are relatively extreme at ground level.

What facilitates weathering ?

Water, air, life, tectonics

(Agents of weathering)

+

Structure in rocks = original planar features (faults, fractures, joints, foliation, bedding planes, lithological boundaries)

+ planar features developed during uplift/unroofing

Types of weathering processes and products

- Chemical
- Mechanical
- Biological

- Loose particles – boulders to fine clays
- Dissolved chemicals – ions of Ca, Mg, Si and others
- Oxides – Fe, Cu etc.
- Clay Minerals

Do different elements behave differently during chemical weathering?

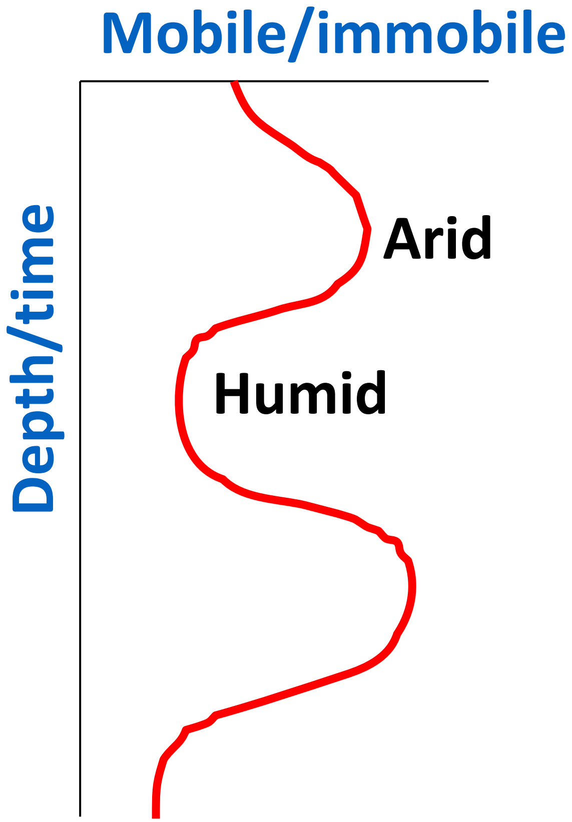
Relative strength

- Si-O 2.4
- Ti-O 1.8
- Al-O 1.65
- Fe^{+3}-O 1.4
- Mg-O 0.9
- Fe^{+2}-O 0.85
- Mn-O 0.8
- Ca-O 0.7
- Na-O 0.35
- K-O 0.25

Ti, Si, Al, Fe – relatively immobile

Na/Al – high in arid condition and low in humid

Mg, Mn, Na, K, Ca – relatively mobile



Chemical Index of Actuation:

$CIA=[Al_2O_3/(Al_2O_3+Na_2O+CaO+K_2O)] \times 100$

UCC = 50 ; Gibbsite/Kaolinite = 100

Weathering reactions – Role of water

$3NaAl\ Si_3O_8 + H_2CO_3 + \mathbf{3H_2O} + Mg^{2+} = 2Na_{0.5}\ Al_{1.5}\ Mg_{.5}\ Si_4O_{10}(OH)_2 + 2Na^+ + HCO3^- + H_4SiO_4$

(albite) (Smectite) **(Less water, semi humid)**

$4NaAlSi_3O_8 + 4H_2CO_3 + \mathbf{18H_2O} = 4Na^+ + 8H_4\ SiO_4 + Al_4Si_4O_{10}(OH)_8 + 4HCO3^-$

(albite) (Kaolinite) **(Moderate rainfall)**

$NaAlSi_3O_8 + H_2CO_3 + \mathbf{7H_2O} = Na^+ + HCO_3^- + 3H_4SiO_4 + Al(OH)_3$

(albite) (Gibbsite) **(Intense rainfall)**

- Na^+ gets dissolved, moves out
- Al^{+3} is completely retained in the new clay mineral
- Type of clay mineral determined by the amount of water flowing through (climate)

Weathering reactions

- **Congruent dissolution** – when the mineral goes into solution and dissolved completely with no precipitation of other substances
- **Incongruent dissolution** – when all or some of the ions released by weathering precipitate to form new substances

- $CaSO_4$ (anhydrite) + 2 $H_2O \Leftrightarrow CaSO_4.2H_2O$ (Gypsum)

  Hydration - absorption of water
- $KAlSi_3O_8 + HOH \Rightarrow HAlSi_3O8 + KOH$

  Hydrolysis - formation of hydroxyl ions
- $H_2O + CO_2 \Leftrightarrow H_2CO_3$

  $2KOH + H_2CO_3 \Rightarrow K_2CO_3 + 2\ HOH$

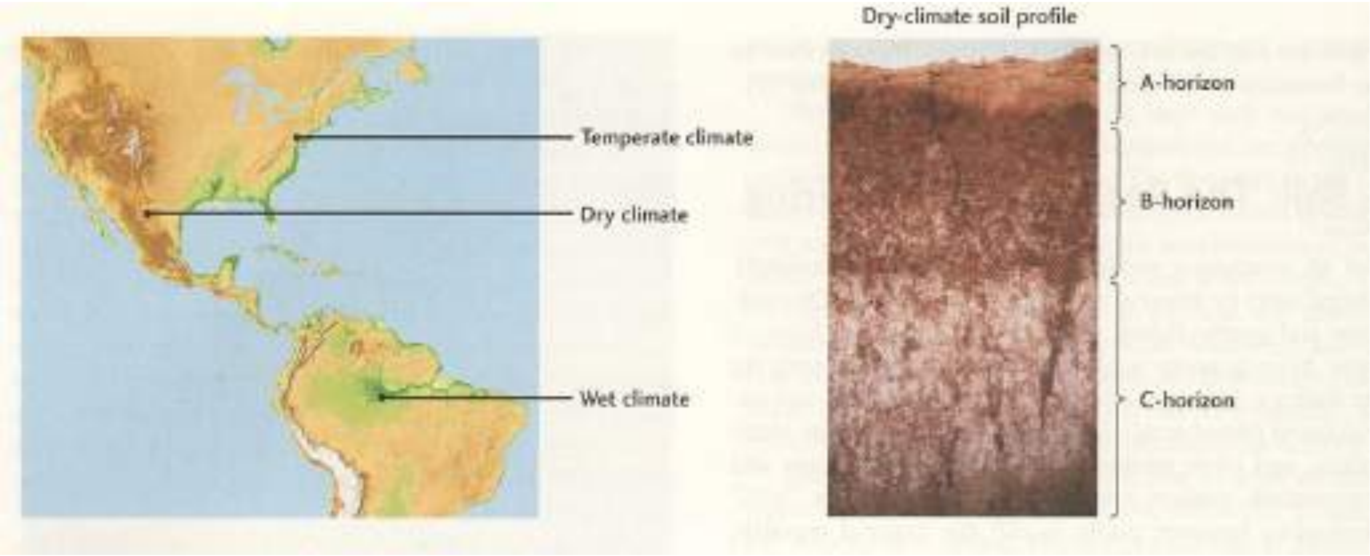
  Carbonation - formation of carbonate
- $MgFeSiO_4 + 2HOH \Rightarrow Mg(OH)_2 + H_2SiO_3 + FeO$

  $4FeO + 2H_2O + O_2 \Rightarrow 2Fe_2O_3.3H_2O$

  Oxidation - normally preceded by hydrolysis
- $CaCO_3 + H_2O + CO_2 \Rightarrow Ca(HCO_3)_2$

  Solution - dissolution

The Soil System- Pedosphere



Interface between geosphere, biosphere, atmosphere & hydrosphere

Engineer- all unconsolidated material

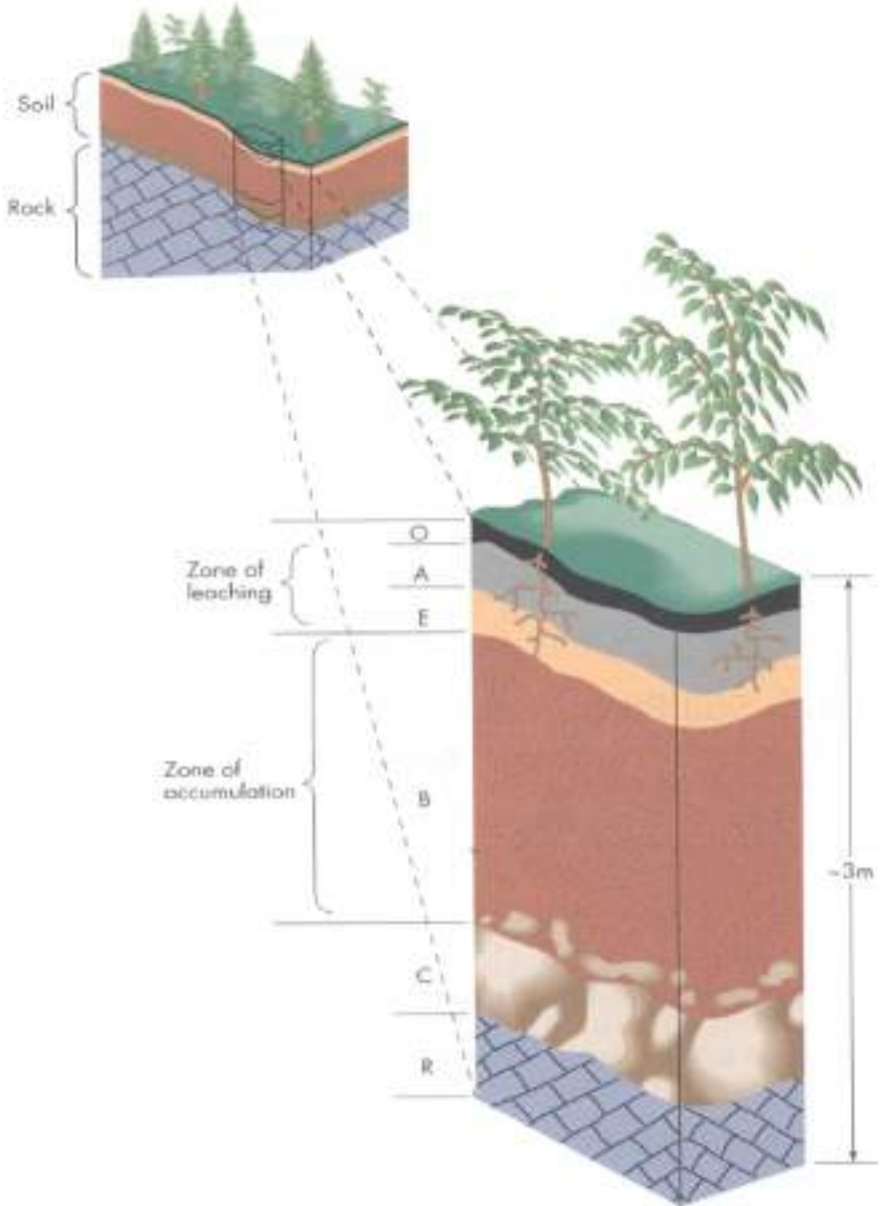
Agriculturist – material on which crops are grown

Geologist – physical substance covering bedrock

Soil scientist – differentiation into different horizons through a complex suit of processes

Mineral weathering
Organic matter transformation

Soil profile



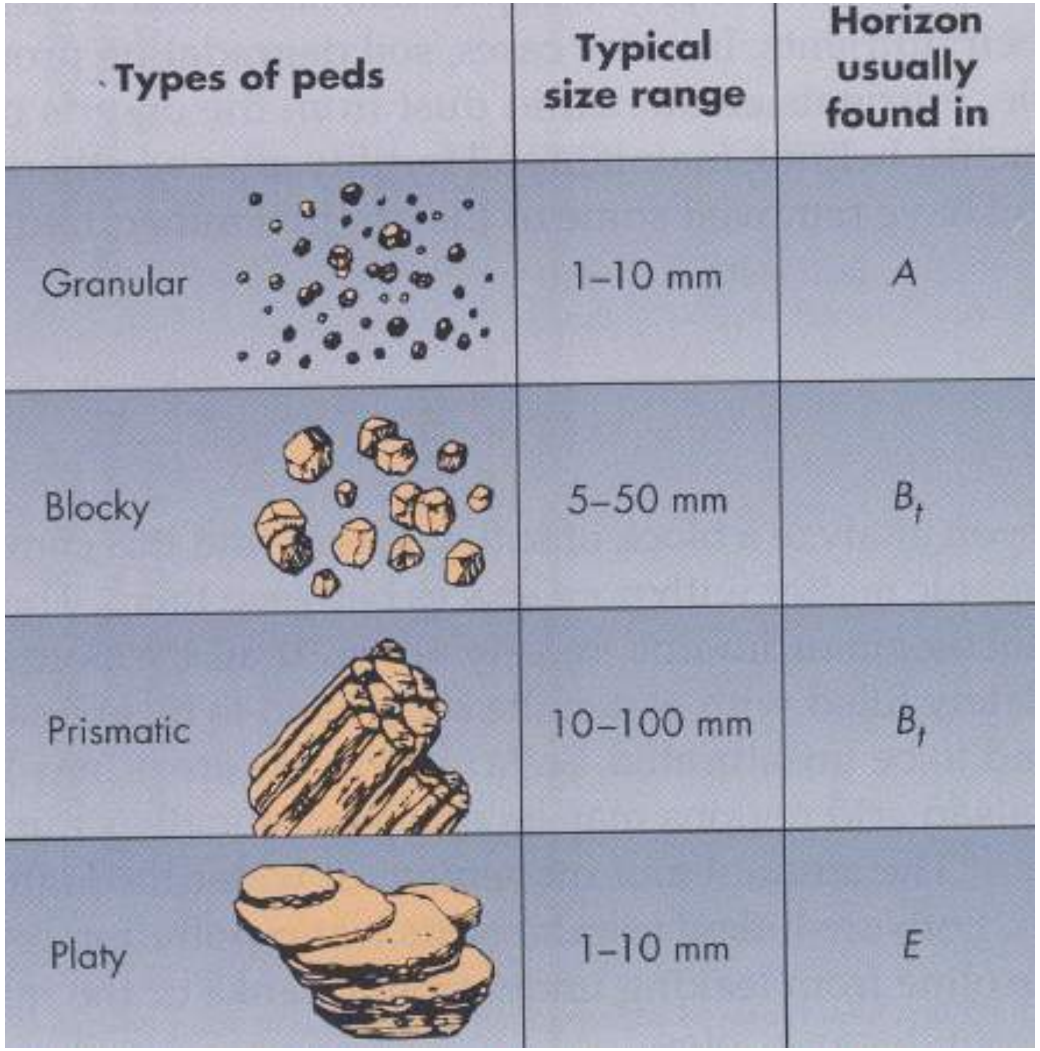
HORIZON	CHARACTERISTICS
O	Organic-rich, decomposed leaves etc.
A	Mineral and organic matter, leaching removes the clay, Fe and Ca to B horizon
E	Similar to A, less in organic matter
B	Rich in clay, Fe-oxides, silica, carbonates etc. leached from A horizon
C	Partially altered parent material
R	Unweathered parent material

Soil Properties

- Color
  - Variable within the profile – indication of composition and processes
  - Indicates how well a soil drains – important for environmental problems
- Texture
  - Function of grain size distribution
  - Field estimation
  - Laboratory measurements

Soil Properties

- Structure
  - Peds – aggregates of soil particles
  - Shape and organization of peds results into soil structure
  - Indicative of soil-forming processes



Types of peds	Typical size range	Horizon usually found in
Granular	1–10 mm	A
Blocky	5–50 mm	B_t
Prismatic	10–100 mm	B_t
Platy	1–10 mm	E

Soils: Interaction of Earth Systems

Processes:

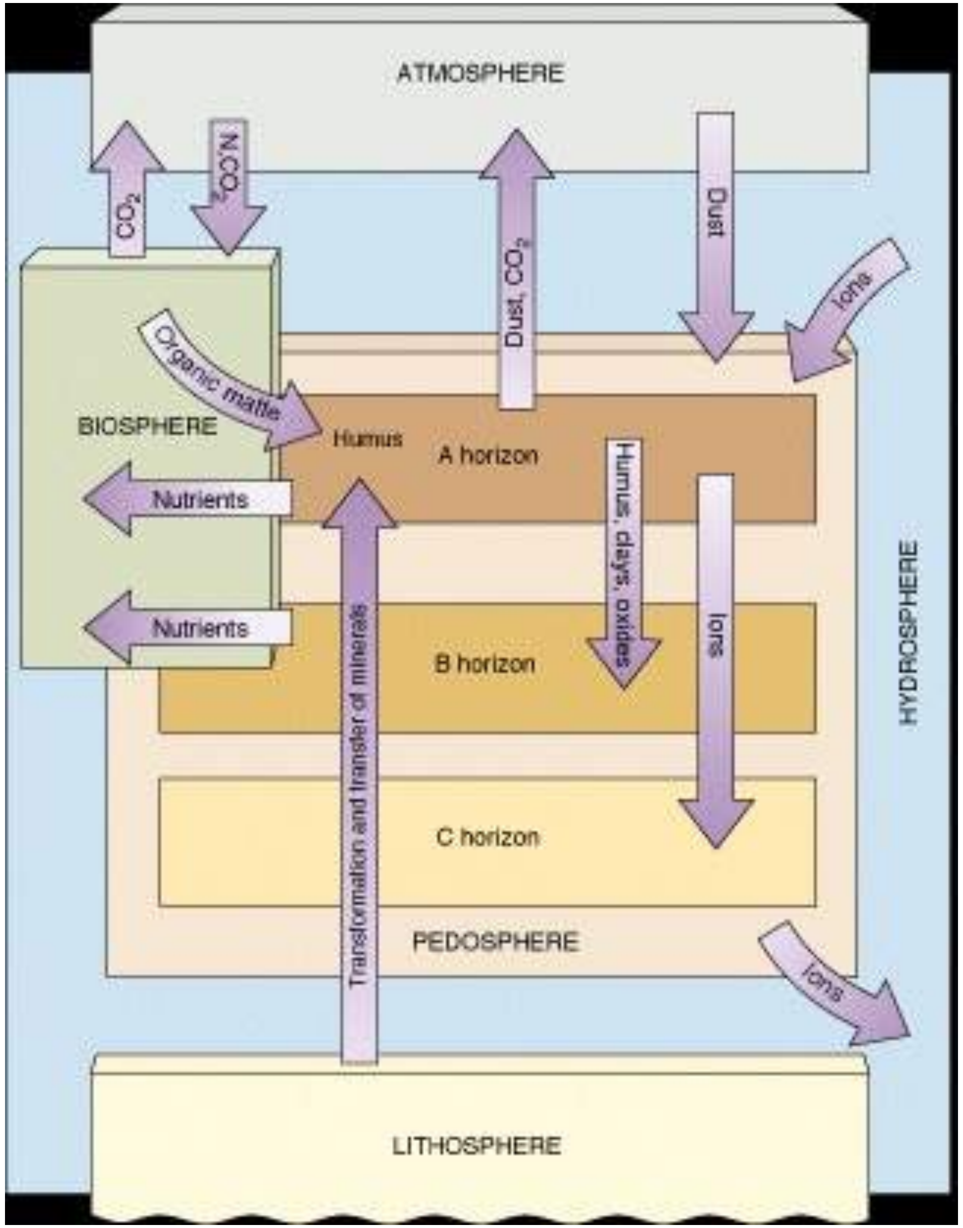
- Additions
- Chemical transformations
- Transfers
- Removals

Lithosphere:
Provides parent material

Hydrosphere:
Transfer of solid and dissolved substances
Removal of ions

Biosphere:
Adds organic matter
Chemical transformations (humus)

Atmosphere:
Adds ions and dust and CO_2, Nitrogen



Soil Processes and Types

Leaching and acidification: Downward movement in solution

Translocation: Downward movement of clays in suspension (Alfisols or Ultisols)

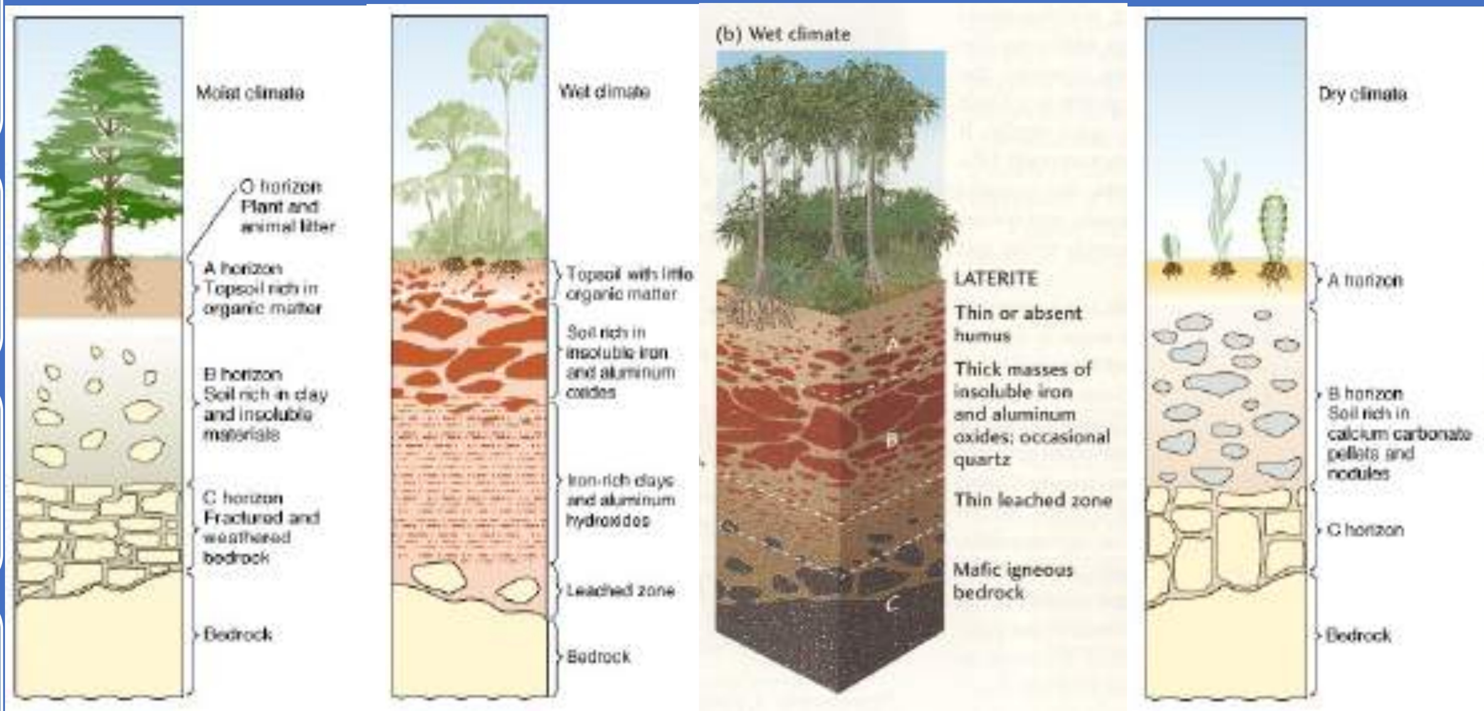
Podzolization: Intense leaching in acidic environment, mobilization in solution (Podosols)

Desilicification: Leaching of SiO_2 and alkali ions from 'A' horizon and accumulation as oxides and hydroxides (Oxisols, laterites)

Gleying: Mobilization of Fe in reducing environment (Gleyed soils)

Calcification: Evaporation and precipitation of carbonates through capillary action in arid regions (Caliche)

Alfisols **Podsols** **Oxisols** **Caliche**



Each of these soil types indicate specific process under different climatic settings – soils as a paleoclimate indicator.

Humans and Soils

- Soils take hundreds to thousands of years to form
- Human activities at a much faster rate
  - Soil erosion and loss of vegetation – agriculture, overgrazing, urbanization
  - Leaching of important nutrients by overuse
  - Build up of toxic elements – fertilizers, industrial wastes
- Impacts
  - Loss of soil cover – affects water resources
  - Loss of fertility – affects food production
  - Soil contamination – goes to food chain
  - Damage to soil ecosystem

Environmental problems and Soil Conservation Practices

- Soil erosion: a major global problem
  - Worldwide, 20 – 30 Gt/y soil eroded by fluvial soil erosion
  - India loses 5334 Mt/y (or 16.4 t/ha/y) of soil due to fluvial soil erosion
- Landuse planning
  - Land capability – a function of soil properties; determines land suitability for urbanization, timber management and agriculture
- Waste disposal problems:
  - Interaction between waste, water and soil
- Evaluation of natural hazards
  - Floods – delineation of floodplains
  - Landslides – relative age of soils – frequency of landslides
  - Earthquakes – age and frequency of earthquakes
- Soil as a paleoclimatic indicator
- Soil as an ecosystem

Soil erosion by water

- Rainsplash
- Sheet wash
- Rill and gully erosion

1m

Headward gully erosion

Desertification

- Exposure and excessive stress dry out the soil
- Native plant species decline - less organic matter production
- Soil fertility reduced; soil hardens – positive feedback to drying
- Increased runoff, scouring, gullying and widespread erosion

- Classification
  - Moderate: 10-50% reduction in crop yield
  - Severe: > 50% reduction in crop yield
  - Very severe: > 90% reduction in crop yield; all vegetation gone

Agriculture

- Traditional agriculture involving plowing in straight lines or furrows – very damaging
- Contour plowing
  - Terracing
- Preservation of remnant woodland (wind barriers)
- Planting vegetation barriers along waterways
- Structures to trap water and sediments

Urbanization

- Soils scraped off and lost; sensitive soils removed and soil strength decreases
- Soils brought from other areas
- Draining of soils – causes desiccation
- Soil pollution due to addition of chemicals
- Filling of streams during construction phase and flooding
- Increased runoff due to urbanisation and flooding

Off Road Vehicles (ORV)

- Soil erosion
- Changes in hydrology
- Damage to plants & animals

Soils: Take Home Points

- Soils form because of interaction of multiple factors including *climate, vegetation, relief and parent material over a time* span
- Specific soil processes such as leaching, gleying, translocation, podsolization, and calcification result in different types of soils.
- Typical soil formation rates : 0.02-0.11 mm/year
- In undisturbed natural system:
  - Soil formation = Soil erosion (steady state)
- Human activity: Rates of erosion = 18-100 x soil renewal
- Environmental impacts
  - Slopes and fields
  - Streams choked up and loss of aquatic life
  - Reduction of soil productivity, less agricultural yield, degraded soils

Fundamentals of Earth Sciences (ESO 213A)

Dibakar Ghosal
Department of Earth Sciences

Oceans and winds

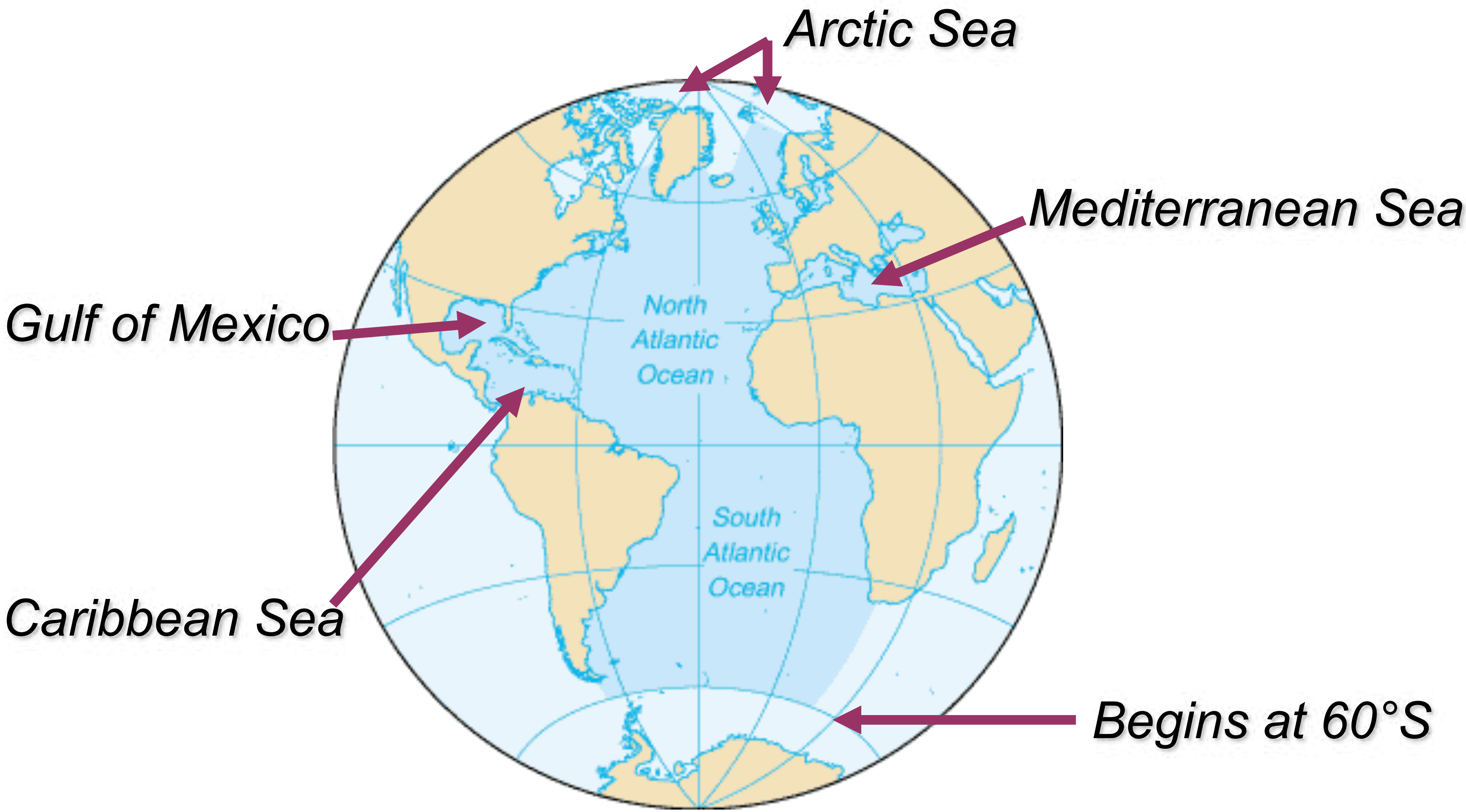
Previous Class: Soil

Why study major bodies of water?

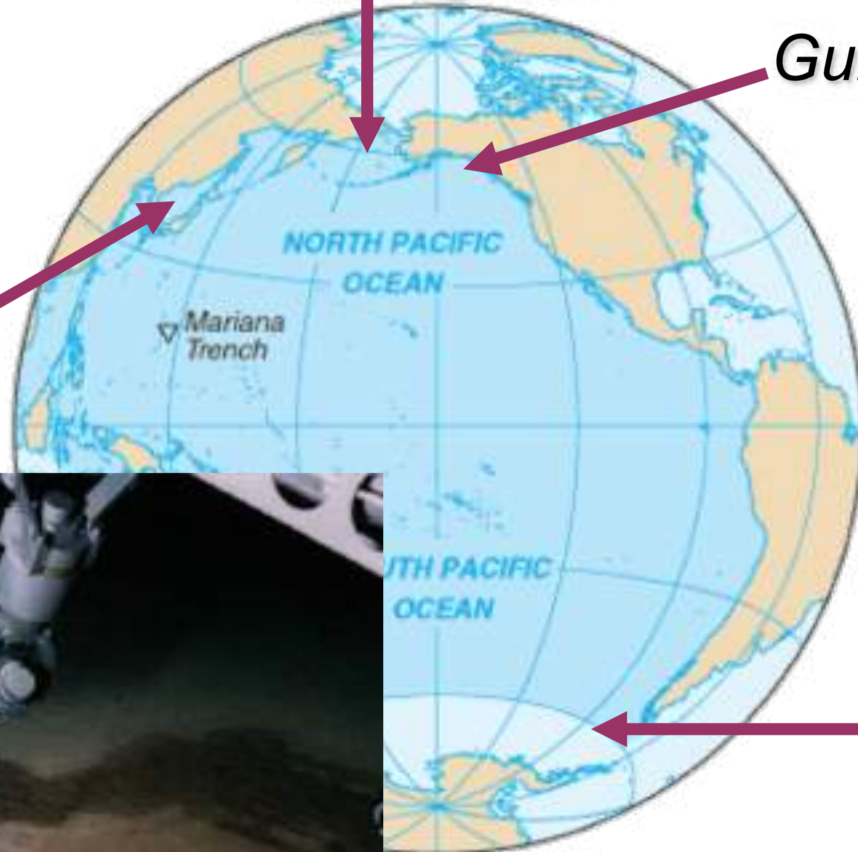
- Water covers nearly ¾ of the earth's surface
- More than 50% of the world's population lives within an hour of the coast
- Plays a role in both climate and day-to-day weather
- FOOD!
  - Cost of your food could depend on it

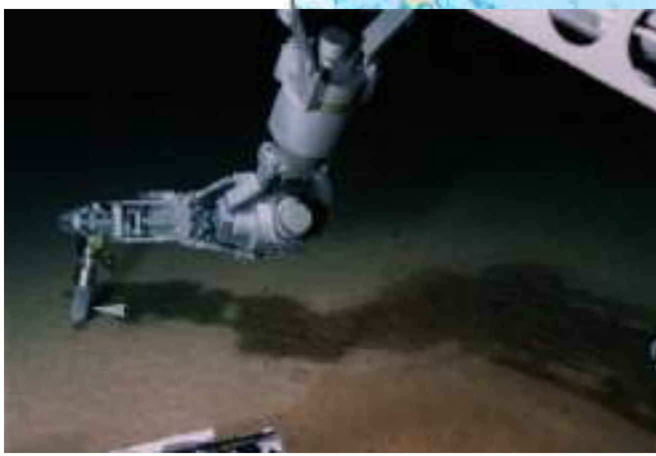
There are ***FOUR*** oceans

- ***ATLANTIC***
- ***PACIFIC***
- ***INDIAN***
- ***SOUTHERN***



The Atlantic Ocean encompasses pretty much everything on the map north of 60° South latitude. The Mediterranean, Caribbean, and Arctic Seas, as well as the Gulf of Mexico are all included in the Atlantic basin. It also provides some of the earth's most heavily trafficked routes.



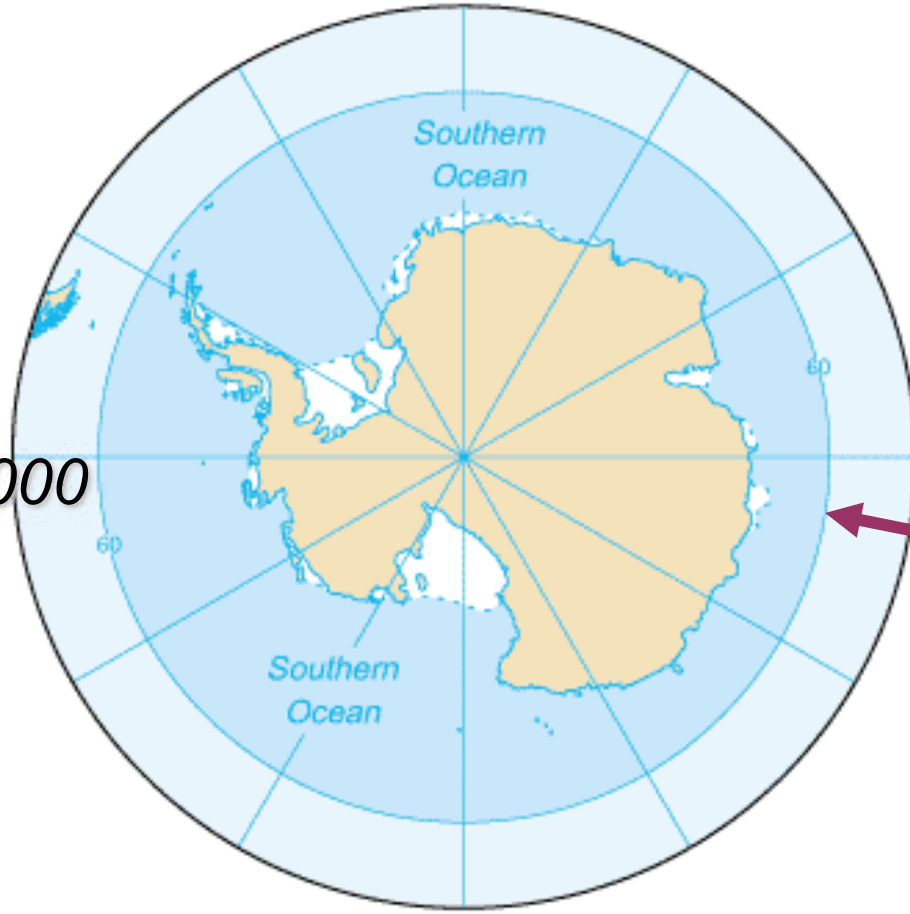


The Pacific Ocean encompasses pretty much everything on the map north of 60° South latitude. The Bering and Japan Seas, as well as the Gulf of Alaska are all included in the Pacific Basin. The Pacific Ocean covers 28% of the global surface and contributes more than half to the world's annual fish catch. Pacific Ocean also has the most coastline of the four oceans. The Mariana Trench is the deepest part of the earth's oceans. The deepest point is called Challenger Deep, named after the British exploration vessel HMS Challenger II. It has a depth of 10,911m or 35,798ft. The U.S. Navy bathyscaphe Trieste reached the bottom at 1:06 PM on January 23, 1960. At the bottom of the trench, the water exerts a pressure of 1086 bar or almost 16,000 psi. That's more than 1,000 times the standard atmospheric pressure at sea level (1013.25mb).

The Indian Ocean encompasses areas between the Indian subcontinent/Asia and 60° South latitude. The Arabian and Red Seas, as well as the Persian Gulf are all included in the Indian Ocean basin. Interesting side notes here – Estimated 40% of the world's offshore oil production comes from the Indian Ocean.

NEW!

NEW!



“Defined” in 2000

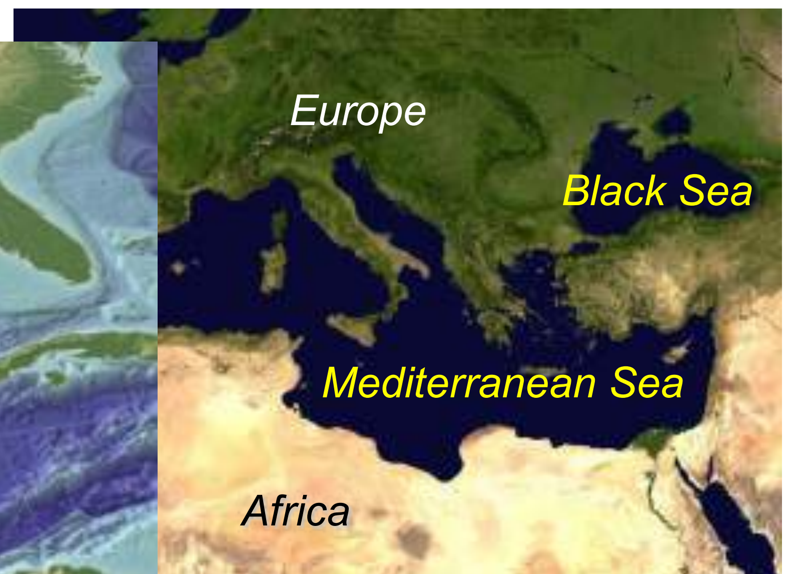
Begins at 60° S

NEW!

The Southern Ocean encompasses anything poleward of South latitude and is made of “parts” of the Atlantic, Pacific, and Indian Oceans. It is also the newest ocean, as it was defined in 2000.

Ocean or Sea, What's the Big Deal?

- SEAS
- Delineated by land masses
  - Doesn't matter if they're largely enclosed
- Also "communicate" with the ocean



Which ocean is the biggest?

OCEAN	SURFACE AREA [km^2]	OF ALL OCEANS…
Atlantic	90,818,000	27.1%
Indian	68,556,000	20.4%
Pacific	155,557,000	46.4%
Southern	20,327,000	6.1%

Which ocean has the most coastline?

OCEAN	COASTLINE LENGTH [km]
Atlantic	111,866
Indian	66,526
Pacific	135,663
Southern	17,968

FRESHWATER	***SALTWATER***
• **Rivers**	• **Oceans**
• **Streams**	• **Gulfs**
• **Lakes**	• **Seas**

QUESTION:

Is saltwater the same everywhere?

ANSWER:

No

- *There are areas of*
  - *HIGH salinity*
  - *LOW salinity*

In general, the Atlantic Ocean is the "saltiest."

So, where are these "highs" and "lows"?

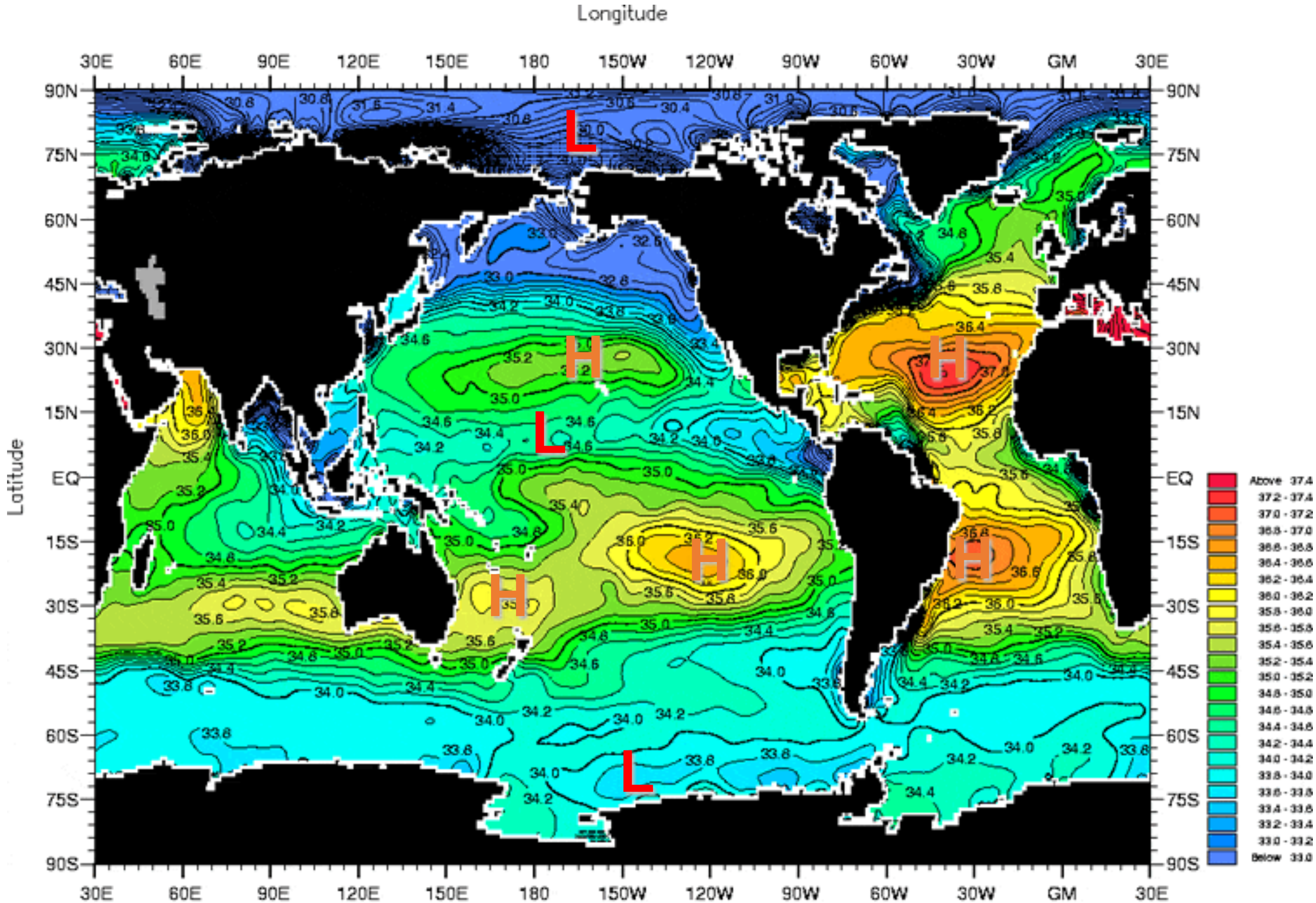


Fig. A2-1. Annual mean salinity (PSS) at the surface .

Minimum Value= 3.57 Maximum Value= 40.02 Contour Interval: 0.20

The first H is over the Persian Gulf/Red Sea area. With 40% salinity, this is the saltiest water on earth. Why? Primarily because there's no real "outlet" for fresh and ocean water to be exchanged. This is also a location of very high evaporation rates. When the water is evaporated, the salt is left behind. The "freshest" water is near the Arctic Circle due to melting ice. Note that there are mins near the equator. Persistent thunderstorm activity in this region keeps the water a little better fresher here.

The Dead Sea is actually a large lake, 47 miles long and about 11 miles wide. The intense evaporation leaves behind the salt, which precipitates onto the sea floor. In fact, the surface of the lake is the least salty. Other trivia facts – the surface of the Dead Sea is over 1300 ft. below sea level, with the very bottom part of the sea is over 2300 ft. below sea level.Christian Monks found no life in the body of water because of the high salinity.

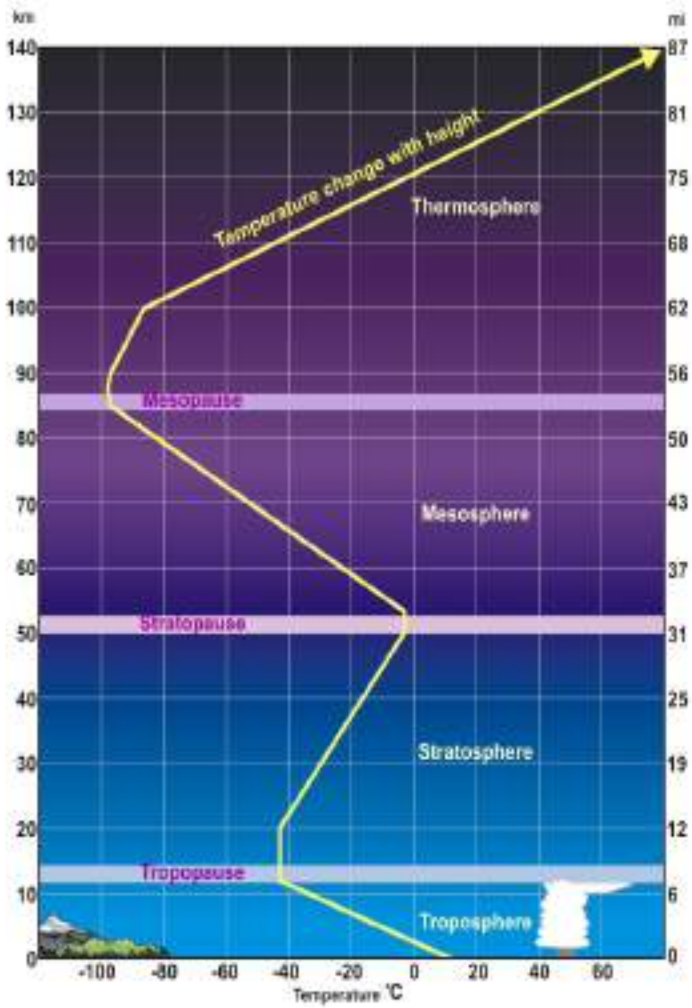
DEAD SEA FACTS:

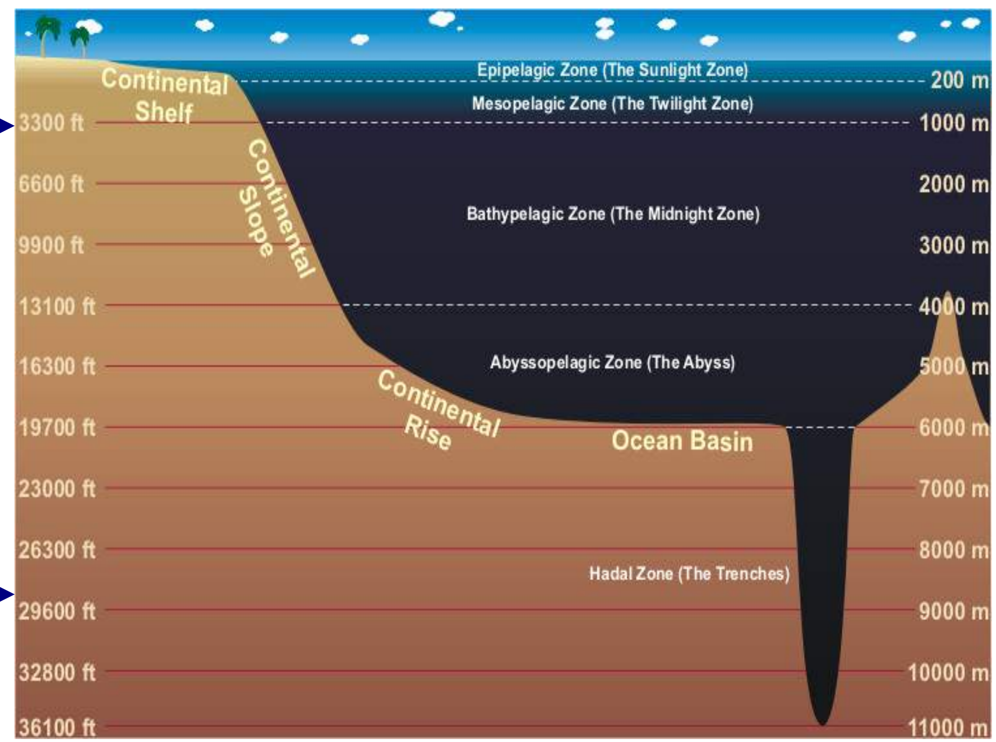
- Really a large lake
- Water gets in, but not out!
  - Fed by River Jordan
  - Evaporation only way out
- Has nearly 10 times the salinity of the oceans!
  - Leads to increased density

CAPT. OBVIOUS SAYS:

Dead Sea was named because it had no life!

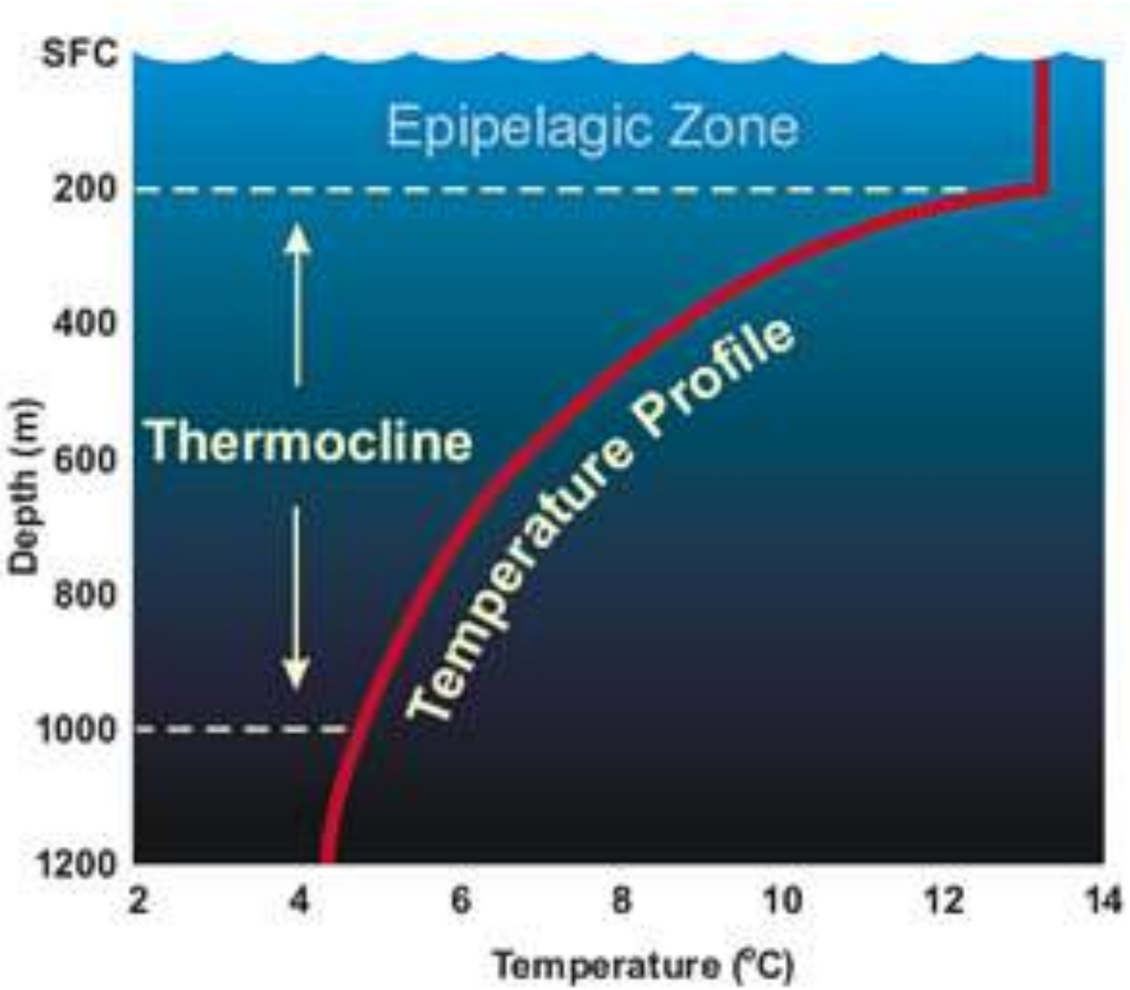
Layerings in ocean water:





Just like the atmosphere, the ocean has layers!

The Epipelagic Zone (Sunlight zone)

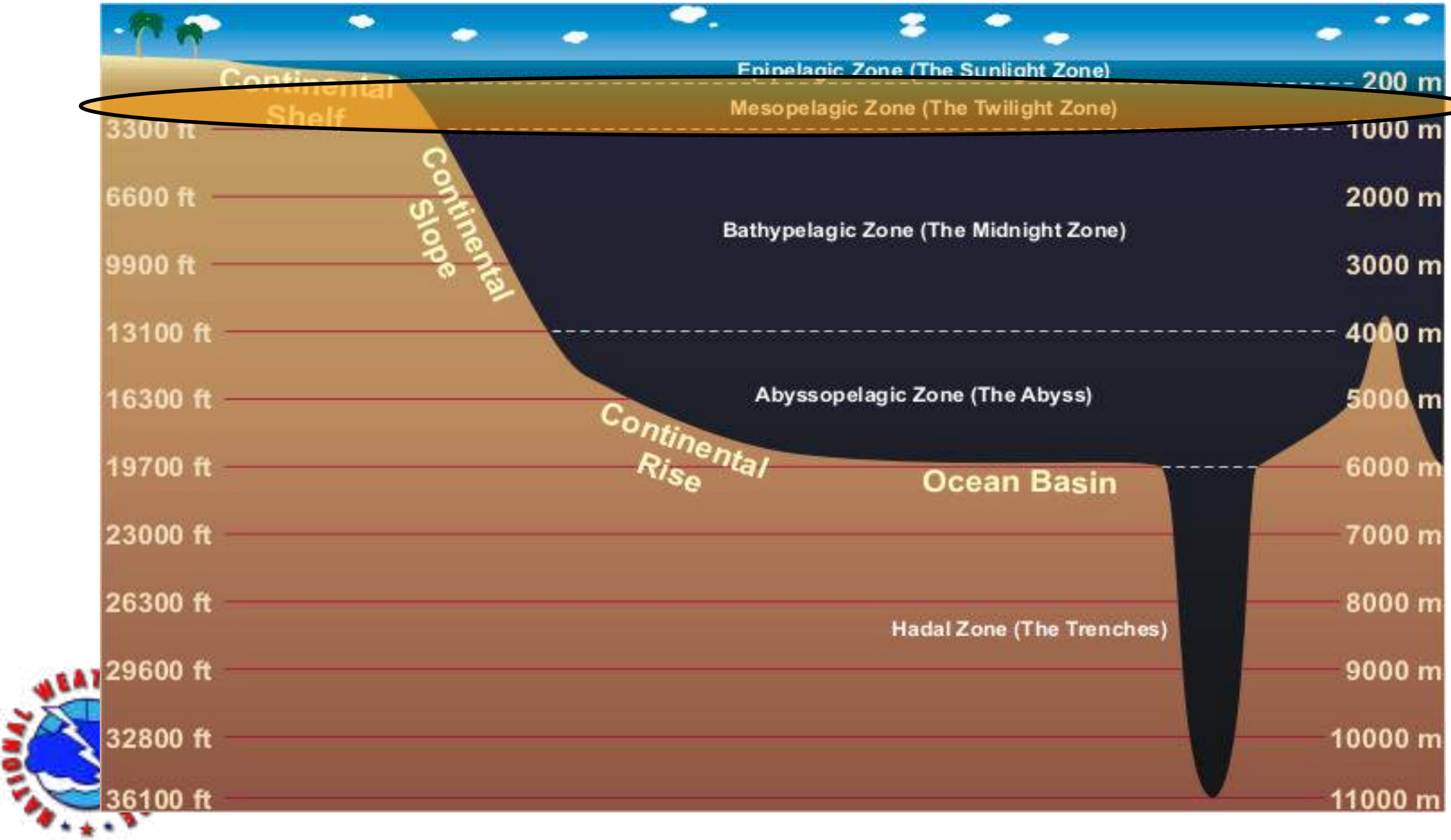


- A transition layer
- Temperature decreases rapidly
- Relevance to you?
  - oxygen is just right

The top layer of the ocean is the epipelagic zone, which receives the most heating from the sun. This results in a wide variation of temperature in a relatively short distance. This is also where the wind has the most influence, and results in mixing and heat distribution

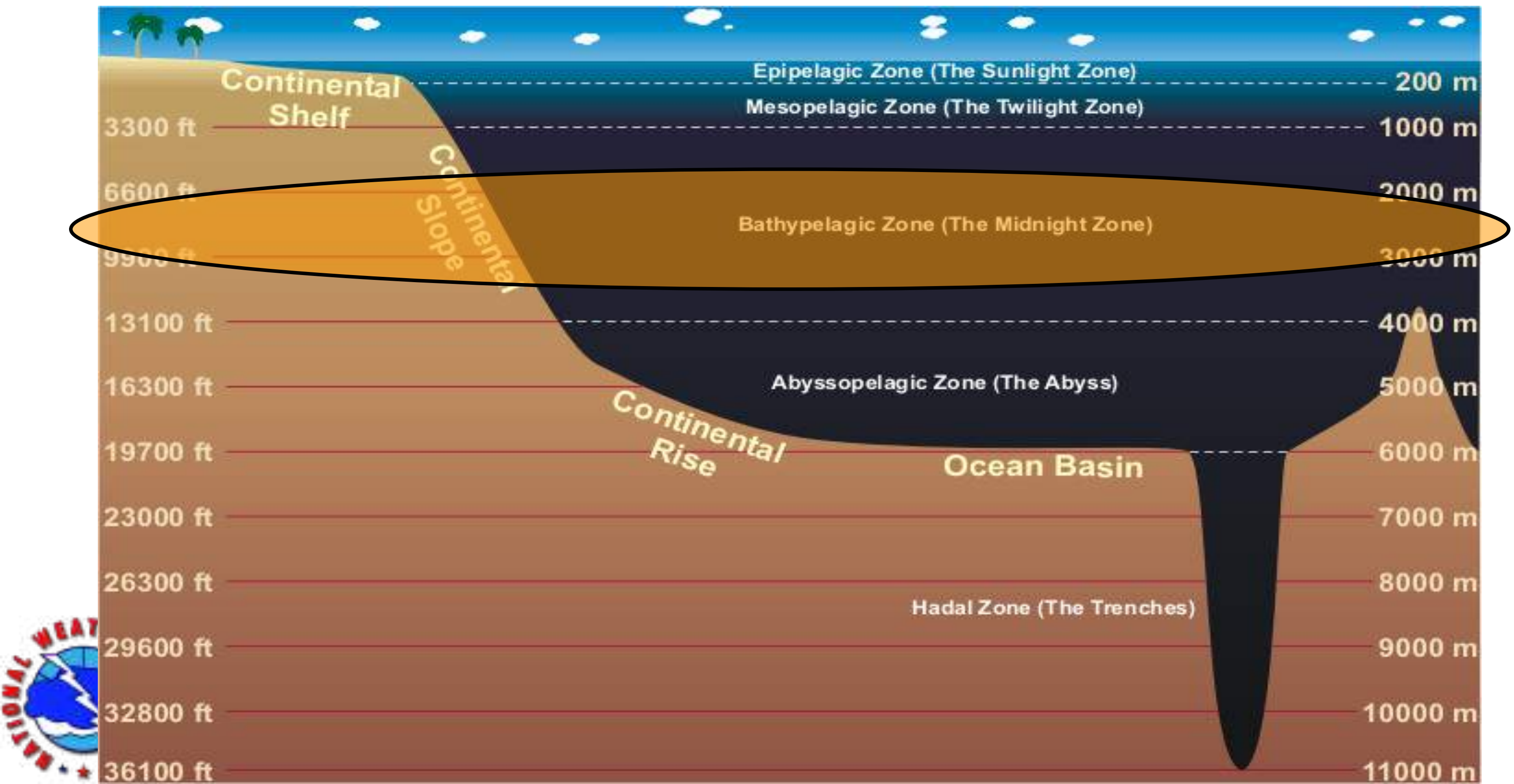
The Mesopelagic Zone

- "Twilight Zone" (sunlight is very faint)
  - Most temperature change near top of layer
- Between 200 and 1000m
- Animal characteristics begin to change (bioluminescent starts)



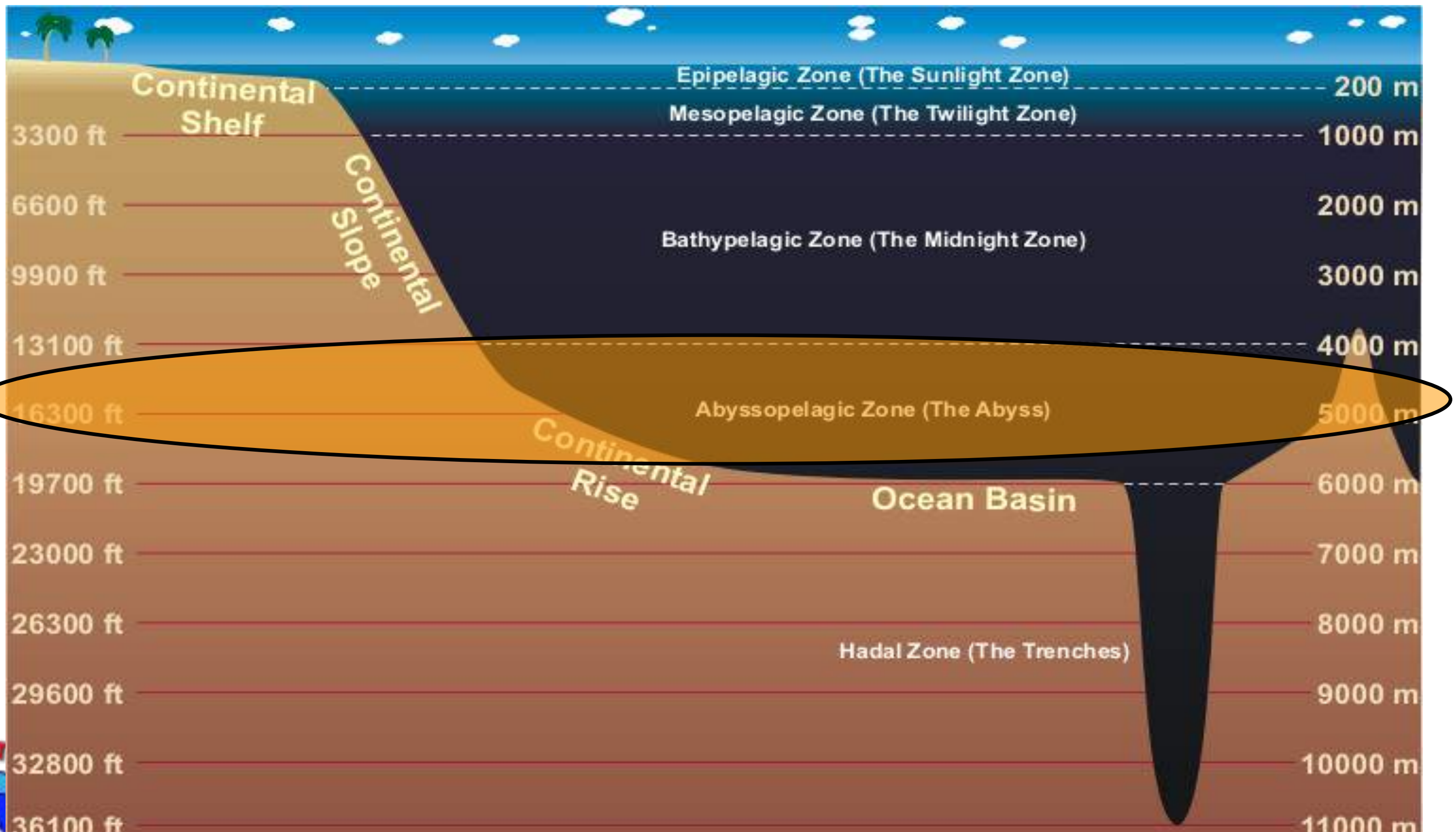
The Bathypelagic Zone

- "Midnight Zone"
  - No light *at all*
  - Only light comes from animals (bioluminescence)
- Very little temperature change
- Pressure reaches over 5800 p.s.i. (pressure at the earth's surface is 14.7 p.s.i.)



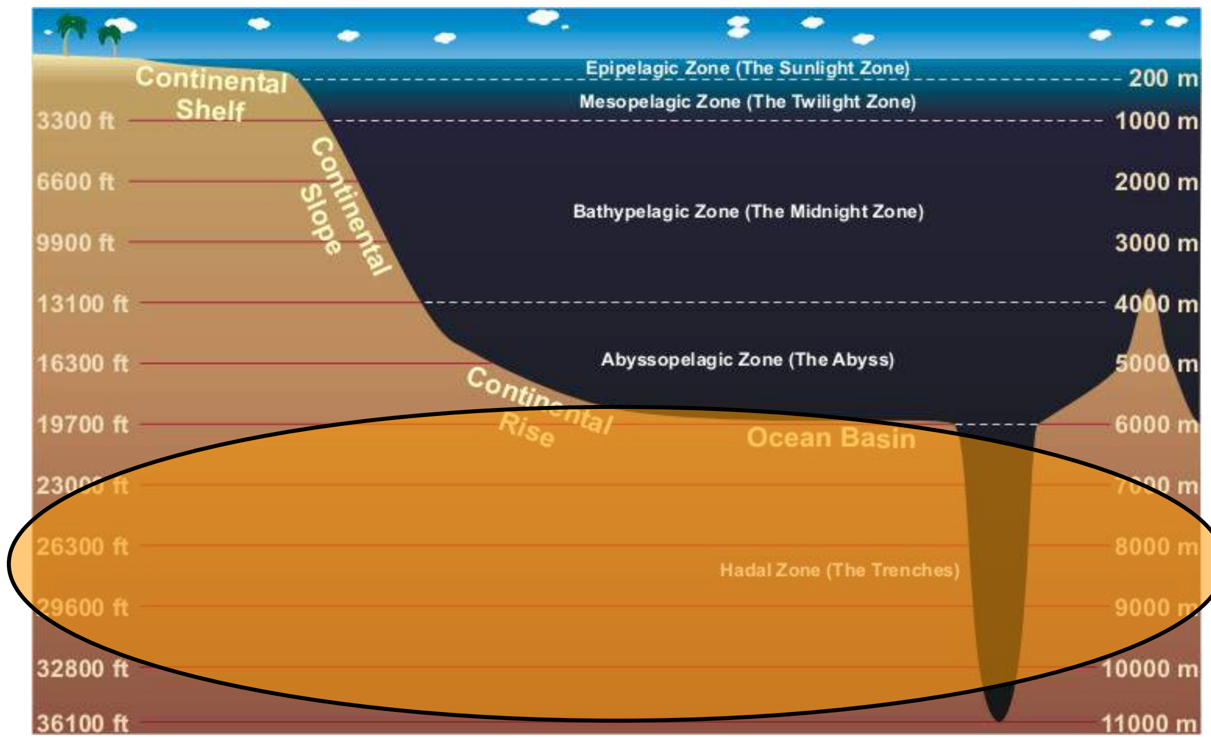
The Abyssopelagic Zone

- "The Abyss"
  - Greek word meaning "no bottom"
- Between 4000 and 6000m
- Water temperature near freezing



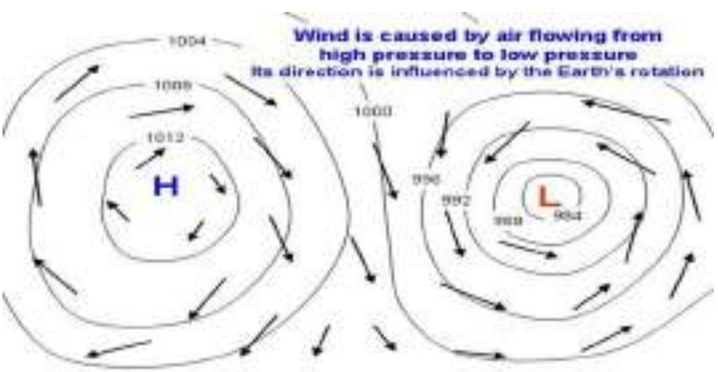
The Hadalpelagic Zone

- "The Trenches"
- Anything below 6000m
- Worth repeating:
  - Deepest trench is the Mariana Trench
  - "Weight": >8 t.s.i.
  (Tons per square inch)
- Life still exists here!
 (in the form of plankton)



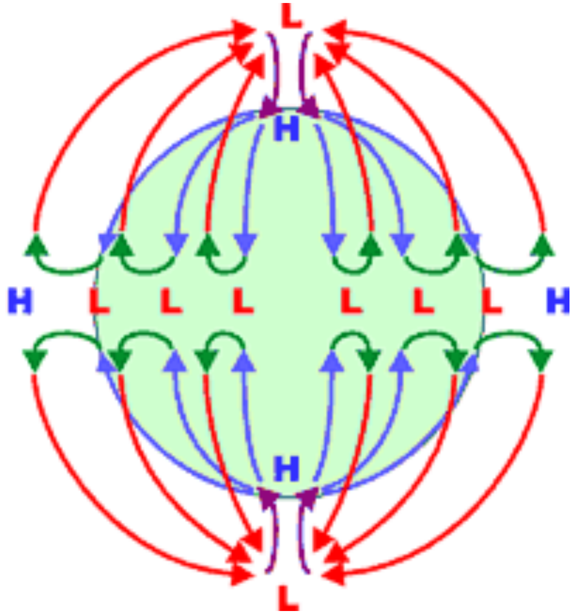
Ocean currents:

- Sun is the driving force
- Solar radiation affects the ocean differently. Incoming solar radiation (or insolation) is the ultimate cause of the weather on the earth. As solar insolation hits the earth's surface, it heats the atmosphere during the day and cools at night. When it heats the ocean, pretty much the same thing happens, only more slowly. As such, once the epipelagic zone is warmed, it stays warmer longer. These temperature differences cause wind.



Ocean Currents

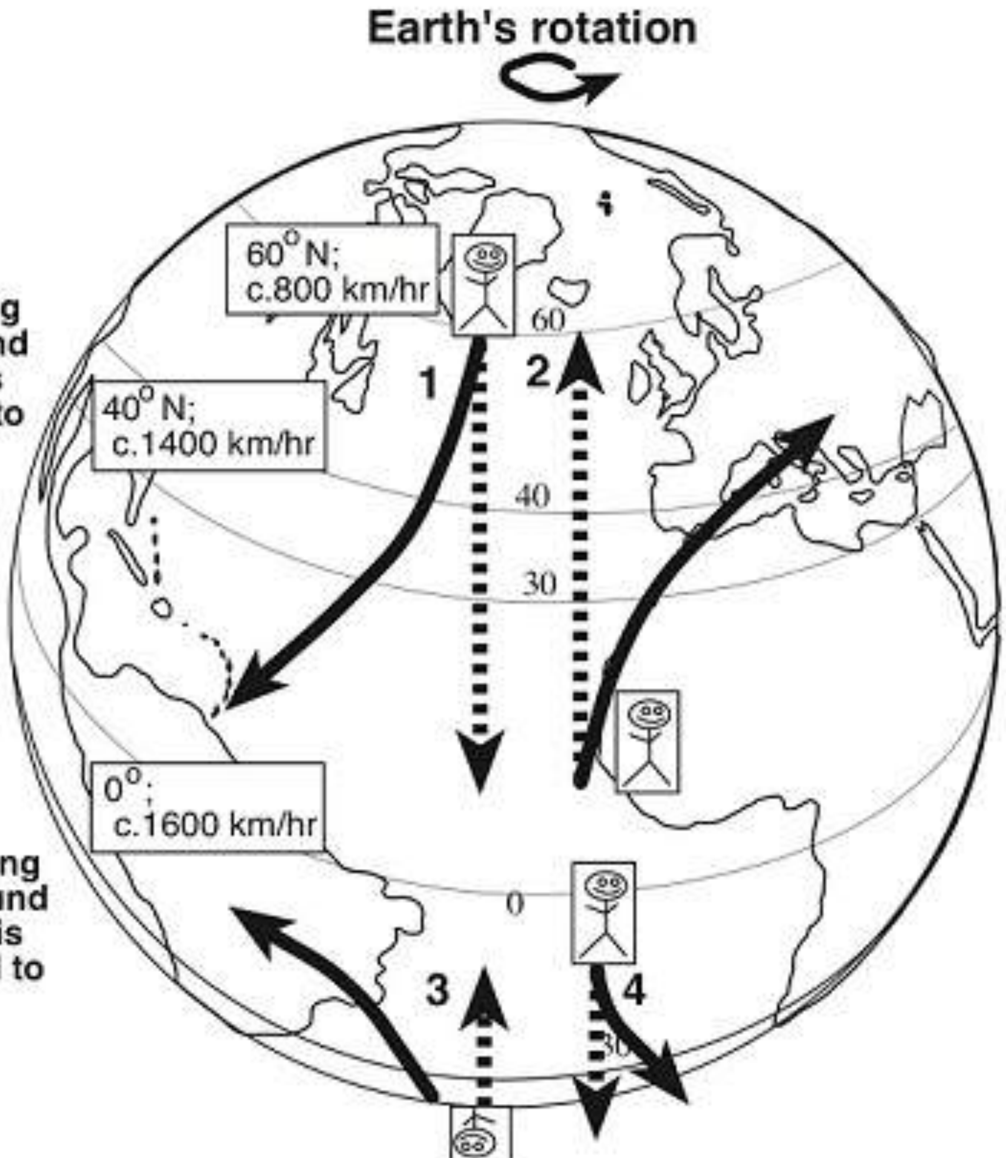
- Two types:
  - Wind-driven Currents
  - Deep Water Currents
- 40% of the global heat transport
- Move slower than surface winds
  - Kilometers per day vs. kilometers per hour
- Long-term climate impacts
  - Gulf Stream most important in our region



- Oceans near equator "heat up" more than the poles
- Sets up…
  - Temperature imbalance
  - Semi-permanent pressure areas
  - Constant push of wind on water

Coriolis force:

Objects moving in air and/or wateron the Earth's surface are decoupled from the solid earth, and move independently. Coriolis deflection is an apparent movement (to an observer), due to the fact that the Earth's speed of rotation is slower at the poles than at the equator. Coriolis deflection also affects air and water masses and governs atmospheric and ocean-surface circulation patterns.

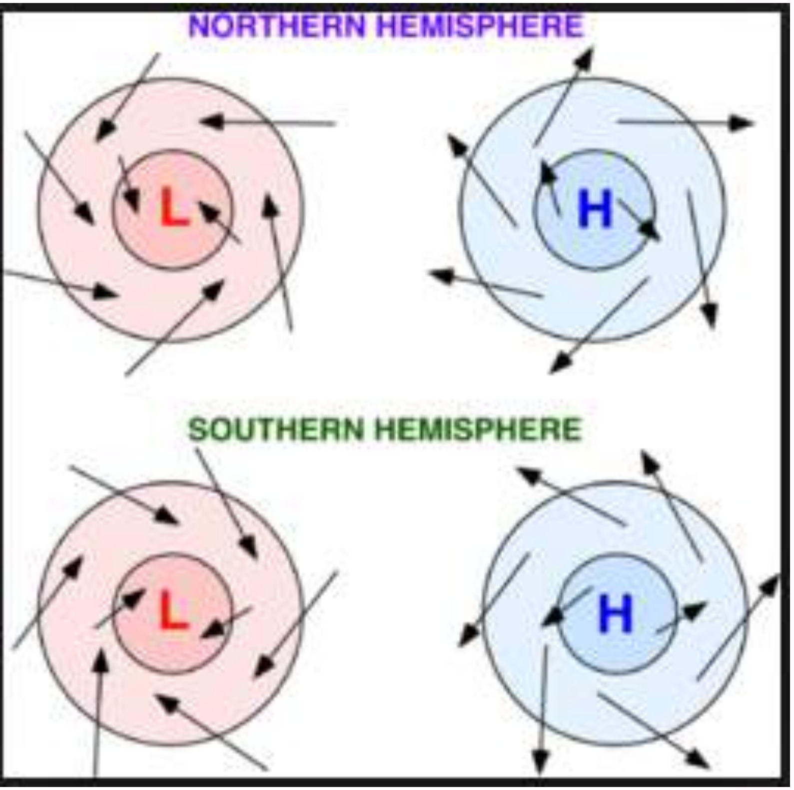


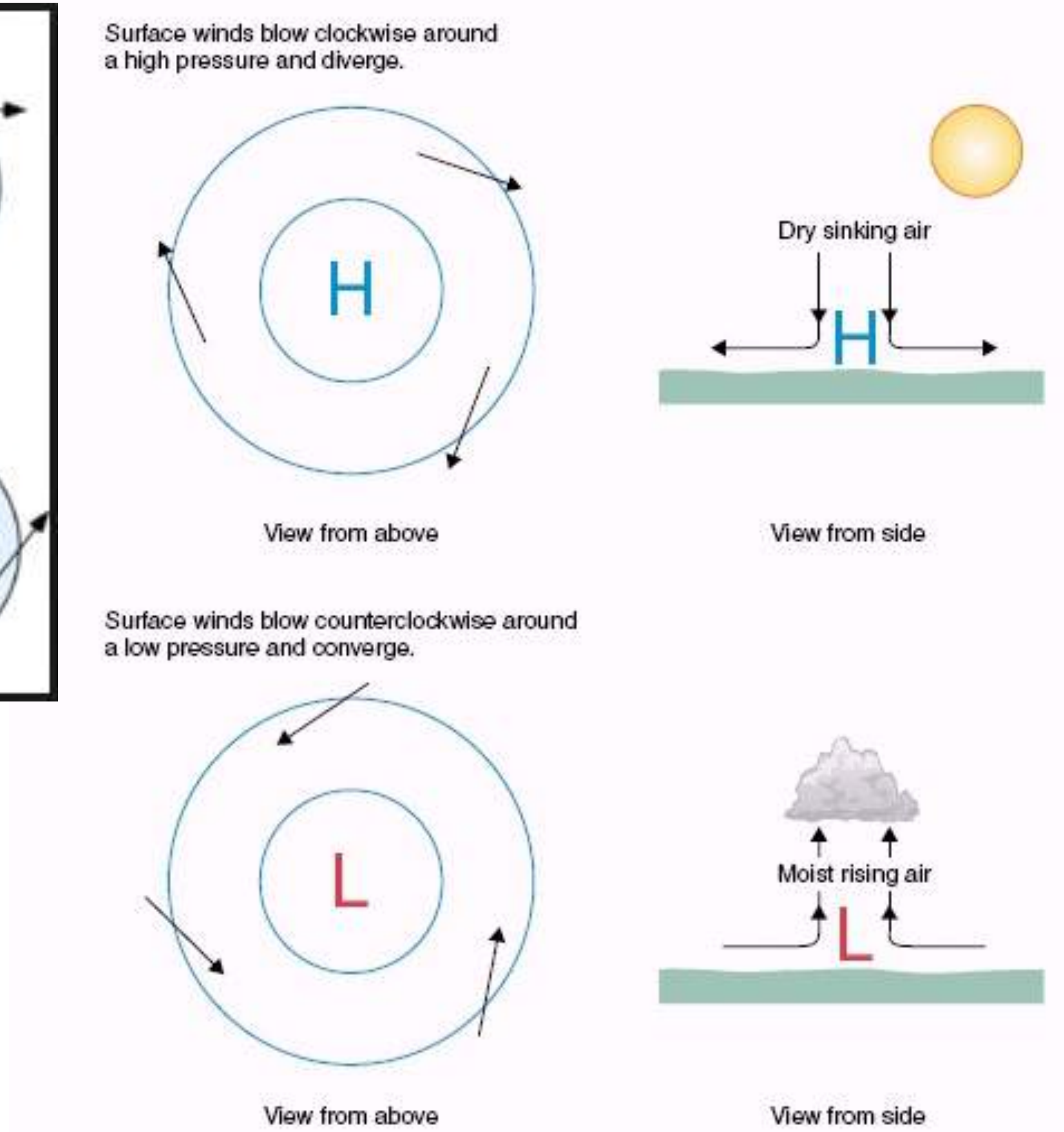
1). Object moving south in northern hemisphere is moving *slower* than the ground underneath, and so is apparently deflected to the *right*;

2). Object moving north in northern hemisphere is moving *faster* than the ground underneath, and so is apparently deflected to the *right*;

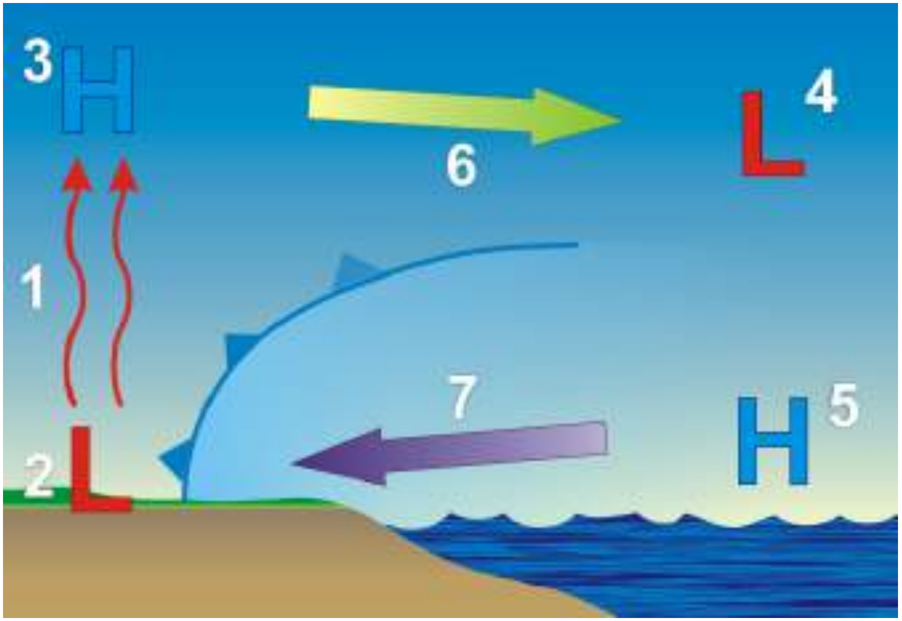
3). Object moving north in southern hemisphere is moving *slower* than the ground underneath, and so is apparently deflected to the *left*;

4). Object moving south in southern hemisphere is moving *faster* than the ground underneath, and so is apparently deflected to the *left*;


NORTHERN HEMISPHERE
L
H
SOUTHERN HEMISPHERE
L
H

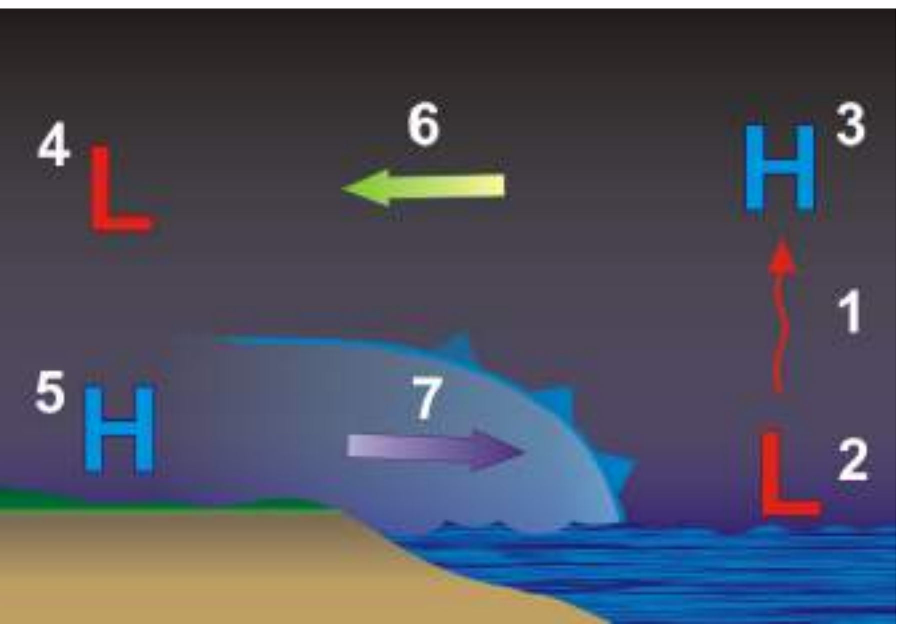

Surface winds blow clockwise around
a high pressure and diverge.
H
Dry sinking air
H
View from above
View from side
Surface winds blow counterclockwise around
a low pressure and converge.
L
Moist rising air
L
View from above
View from side

Seabreeze– During the Day

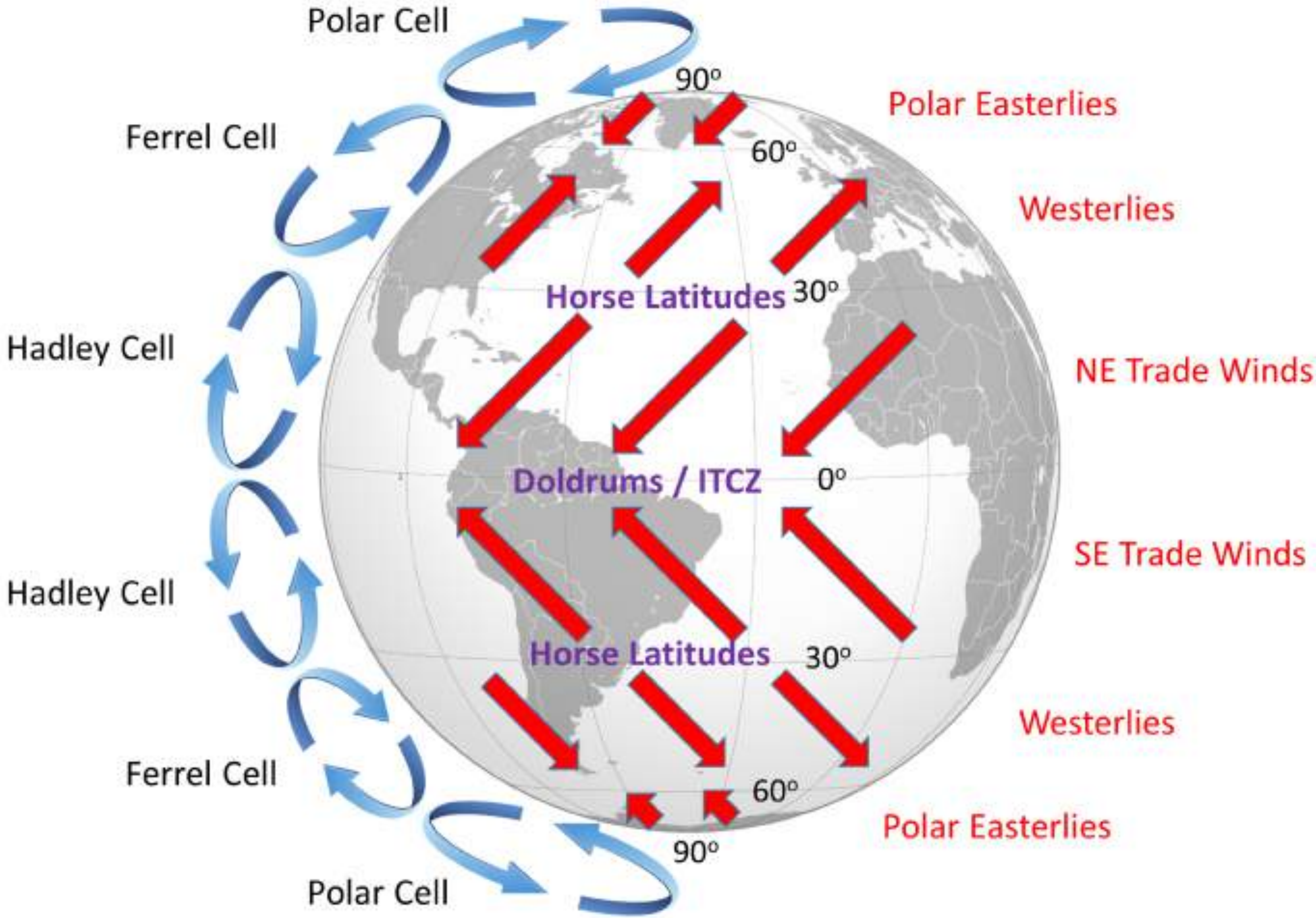


- Beach heats faster than ocean
- Air rises onshore
- Slightly cooler, denser air moves onshore to replace the "lost" air
- Results:
  - Onshore breeze
  - Possible storm development

Landbreeze– During night



- Beach cools faster than ocean
- Air rises offshore
- Slightly cooler, denser air moves offshore to replace the "lost" air
- Results:
  - Offshore breeze
  - Possible storm development


Polar Cell
Ferrel Cell
Hadley Cell
Hadley Cell
Ferrel Cell
Polar Cell
90°
60°
30°
0°
30°
60°
90°
Polar Easterlies
Westerlies
NE Trade Winds
SE Trade Winds
Westerlies
Polar Easterlies
Horse Latitudes
Doldrums / ITCZ
Horse Latitudes

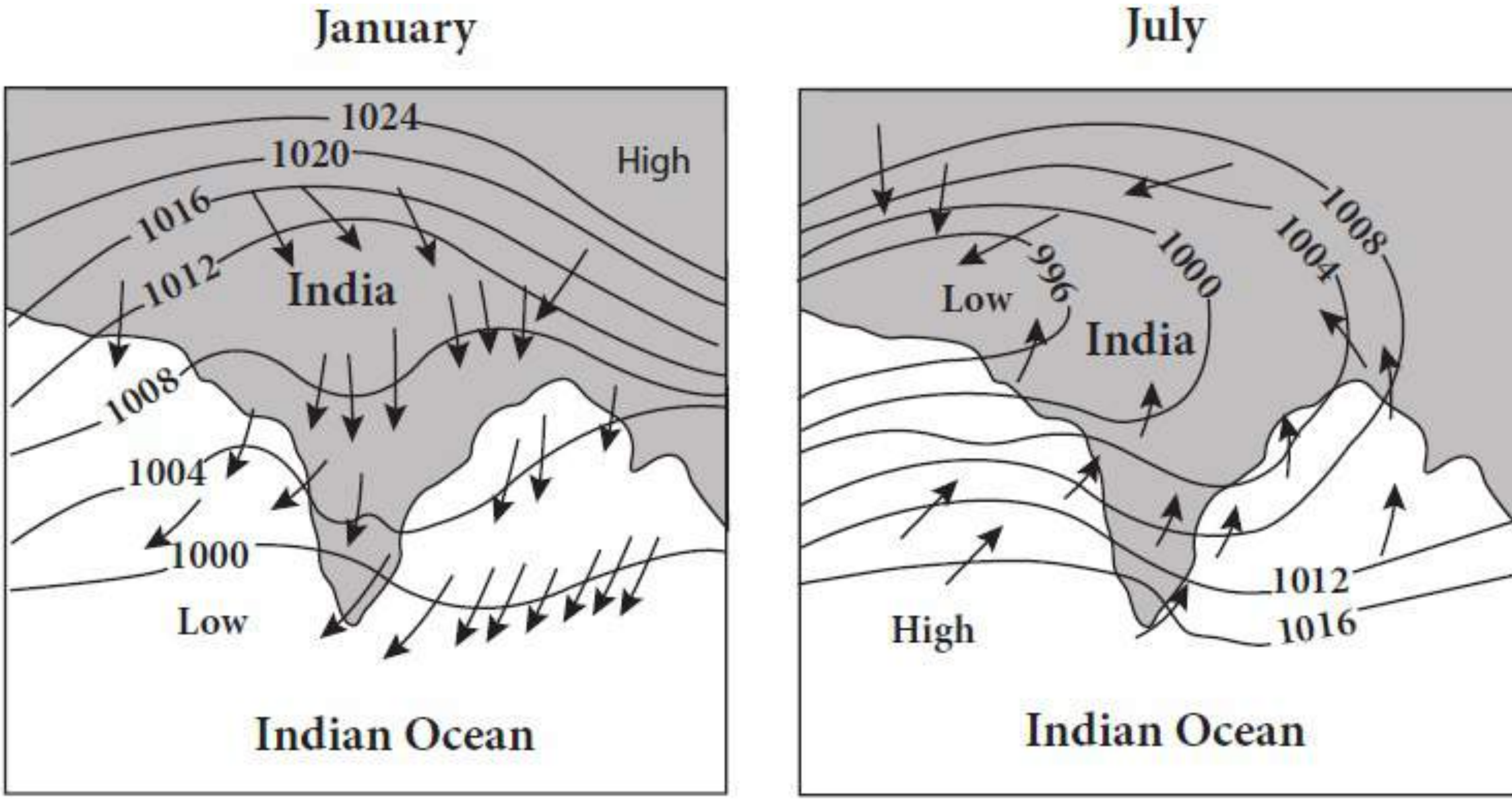
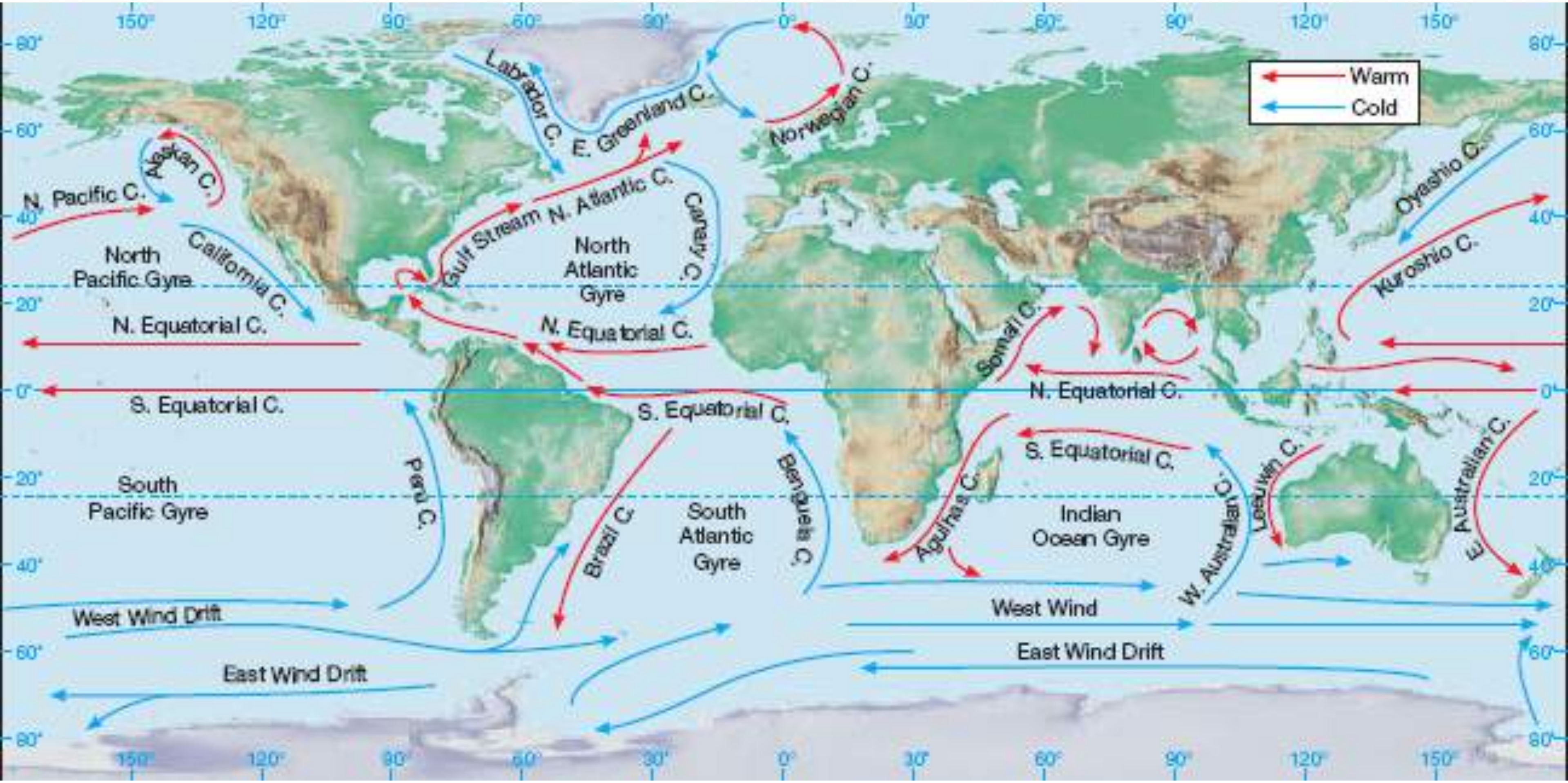


Figure 6.11 Location of High pressure and Low pressure in winter and summer

Wind driven currents

- **Surface Currents** – movements of water that flow horizontally in the upper part of the ocean's surface
- Surface currents develop from friction between the ocean and the wind that blows across its surface
- Some water movements are responses to local or seasonal influences, others are more permanent and extend over large portions of the ocean

Surface Ocean Currents and Gyres

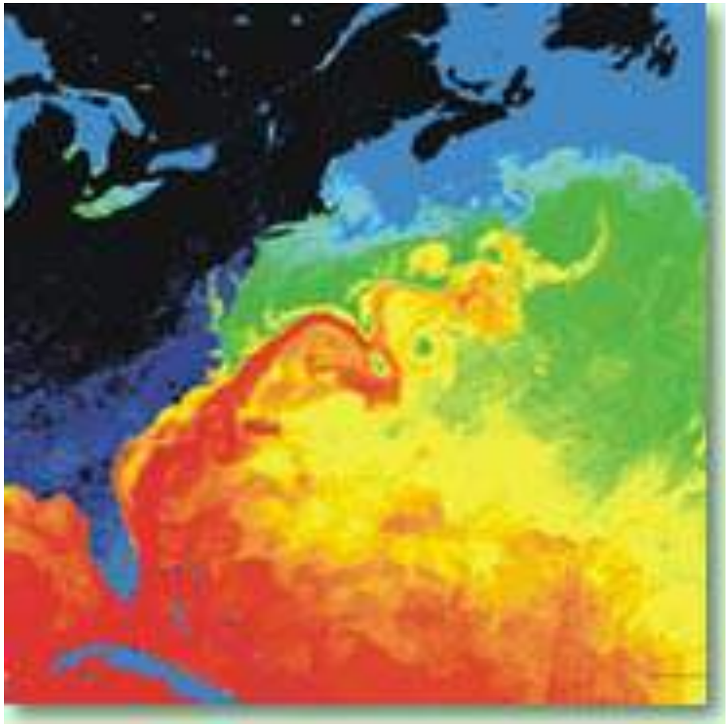


Gyres

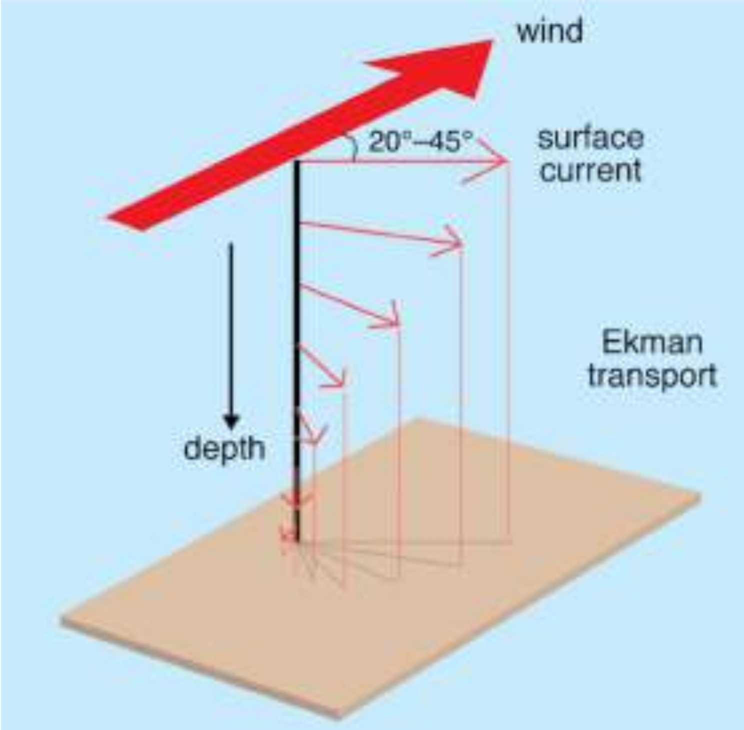
- **Gyre** – huge circular-moving current systems which dominate the surfaces of the oceans
- The 5 main ocean gyres: the North Pacific Gyre, the South Pacific Gyre, the North Atlantic Gyre, the South Atlantic Gyre, and the Indian Ocean Gyre
- **Coriolis Effect** – the deflection of currents away from their original course as a result of Earth's rotation
- Because of Earth's rotation, currents are deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere
- Therefore, gyres flow in opposite directions in the two hemispheres

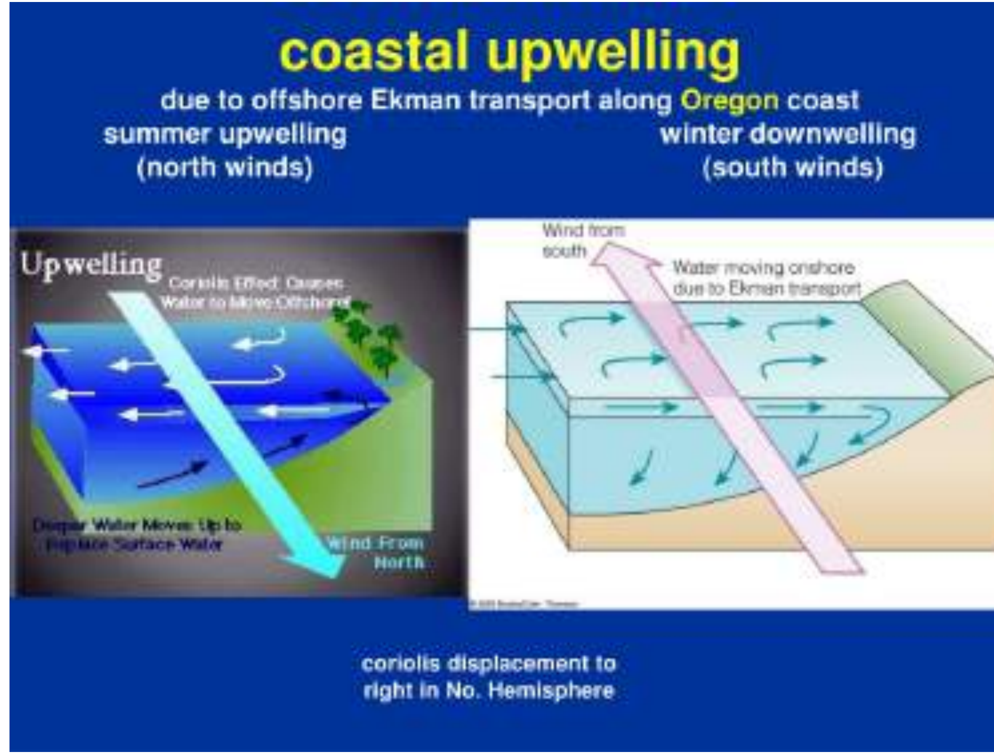
Ocean Currents and Climate

- When currents from low-latitude regions move into higher latitudes, they transfer heat from warmer to cooler areas of Earth
- The Gulf Stream, for example, brings warm water from the equator up to the North Atlantic Current (allowing Europe to be warmer in the winter than expected for those latitudes)
- As cold water currents move towards the equator, they help moderate the warm temperatures of adjacent land areas
- Ocean currents also play a major role in maintaining Earth's heat balance

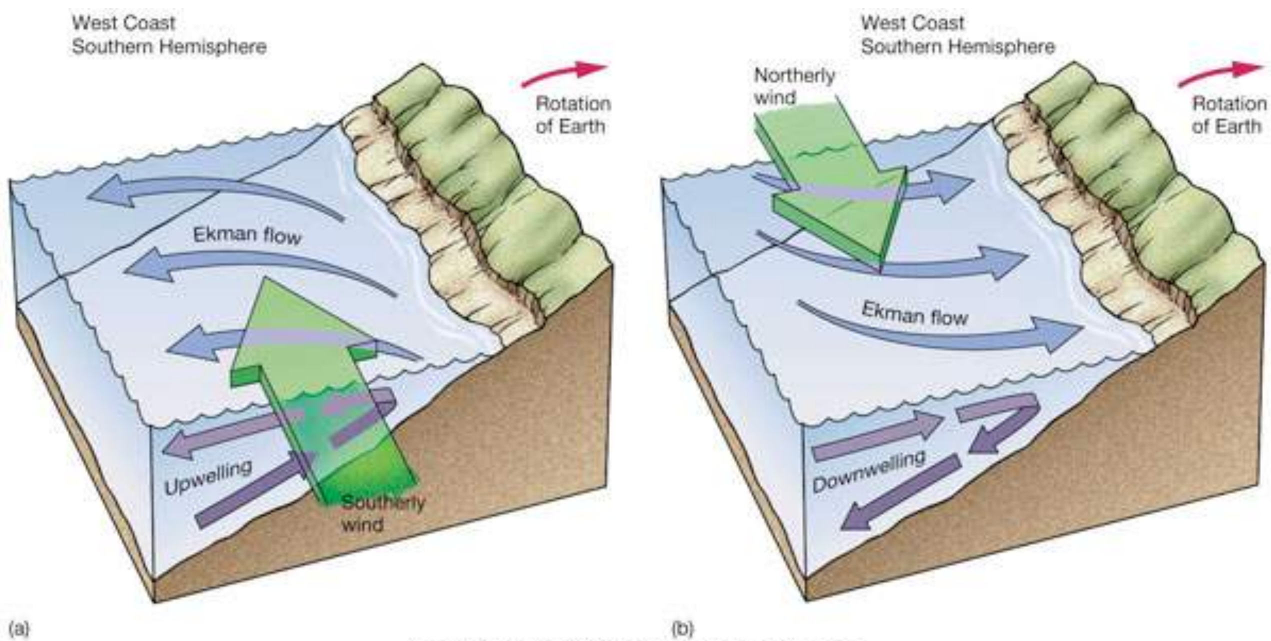


Gulf Stream



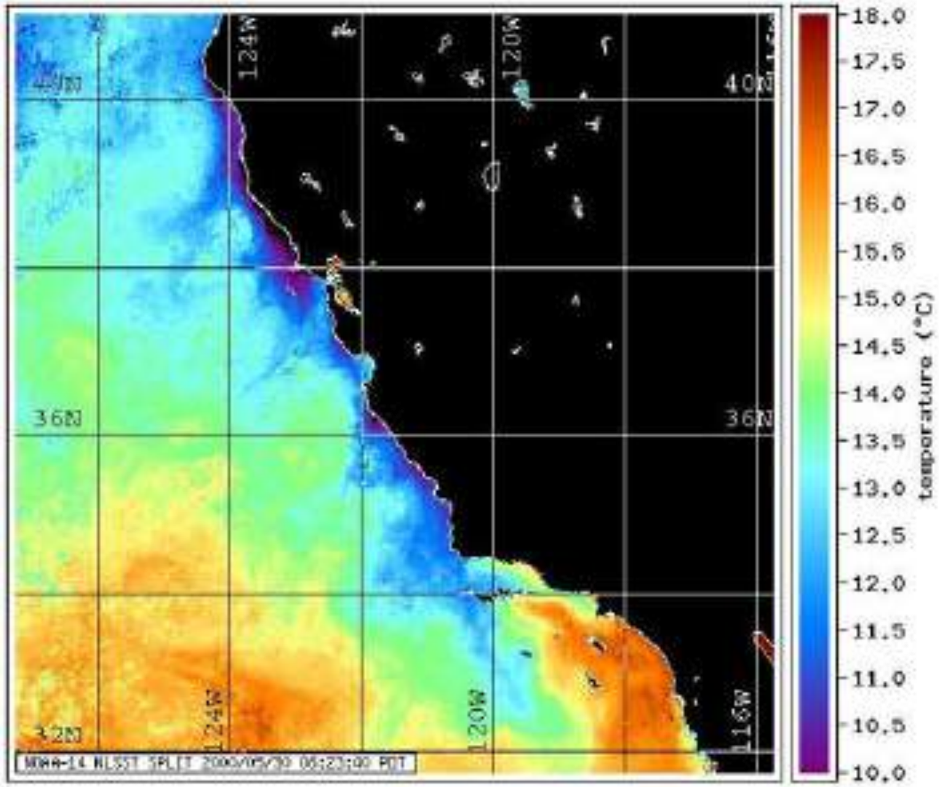


Ekman transport

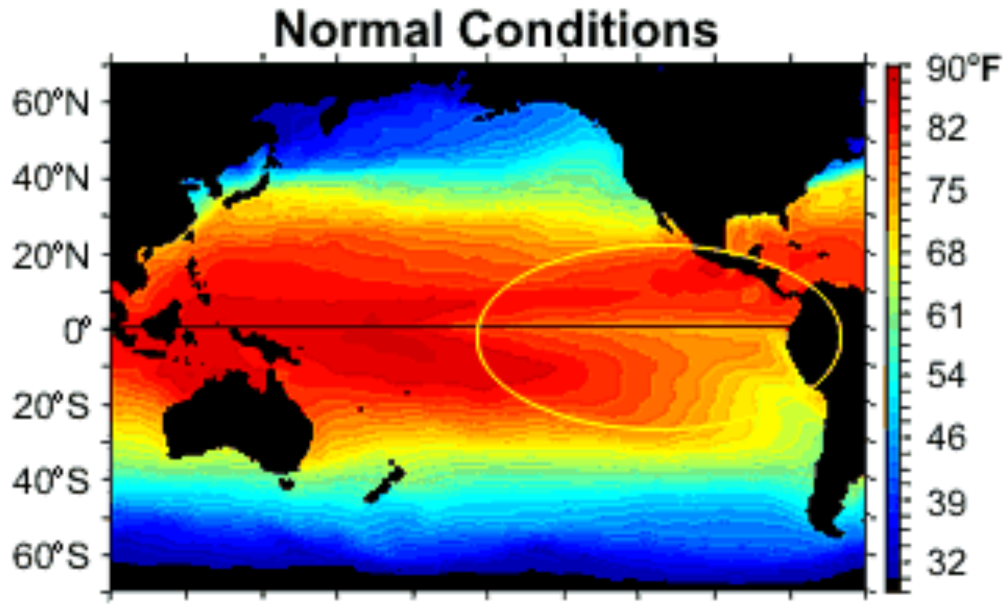


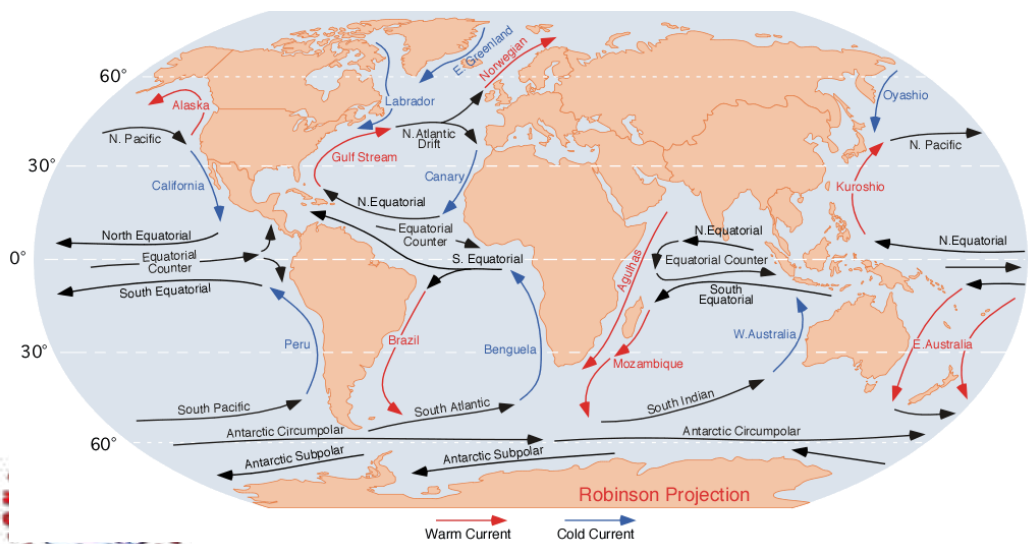
Upwelling

- **Upwelling** – the rising of cold water from deeper layers to replace warmer surface water
- Upwelling is a common wind-induced vertical movement
- Coastal upwelling occurs in areas when winds blow toward the equator and parallel to the coast, this combined with the Coriolis effect cause surface waters to move away from shore and be replaced by water from below the surface
- Upwelling brings greater concentrations of dissolved nutrients, such as nitrates and phosphates to the ocean surface



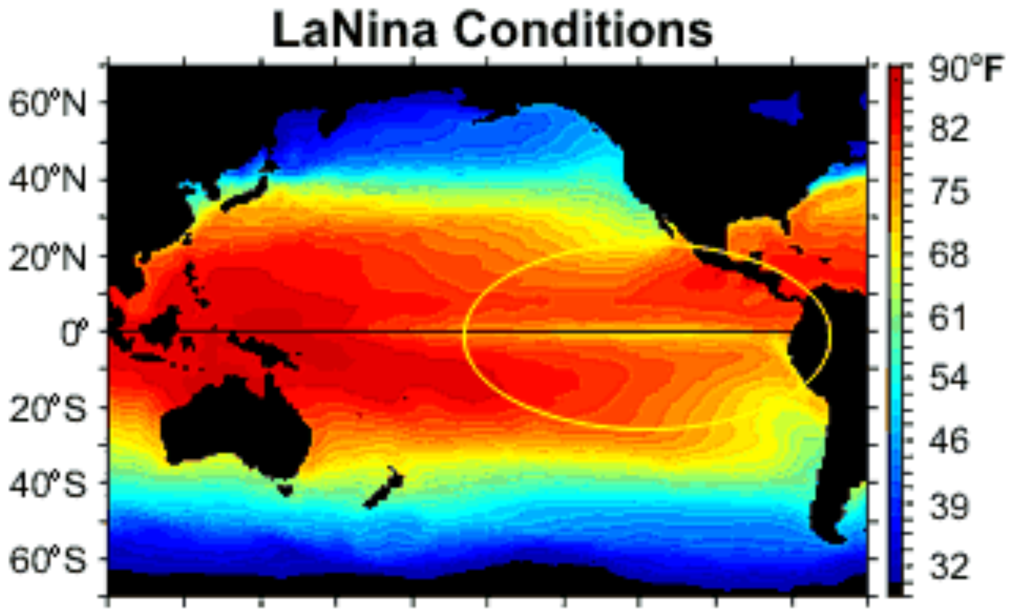
California Coastal Upwelling

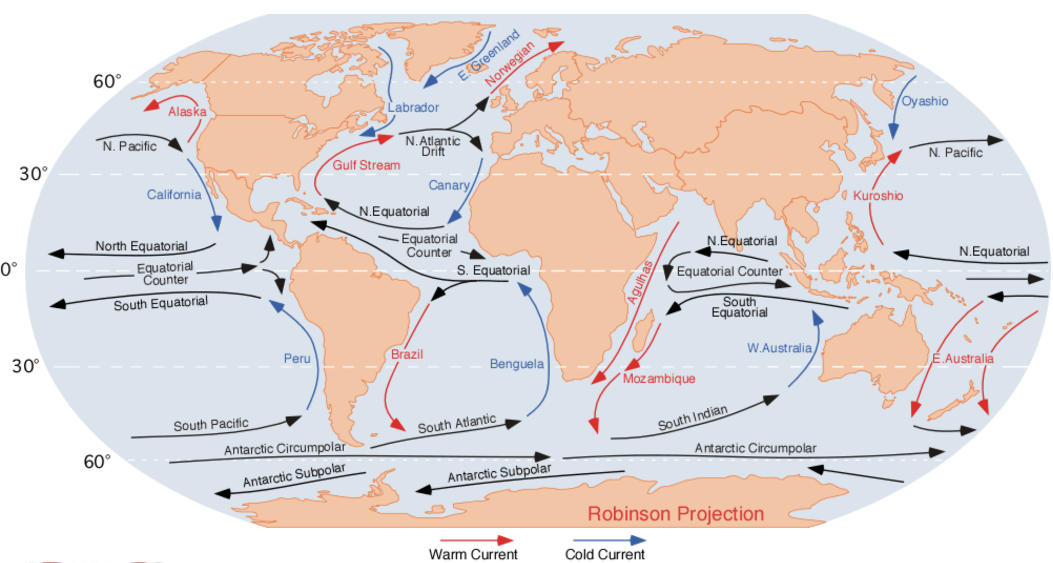




- Normally…
  - Warm waters over Central Pacific
  - Cooler waters off Peruvian coast
- Colder, nutrient-rich waters pulled up from western coast of South America

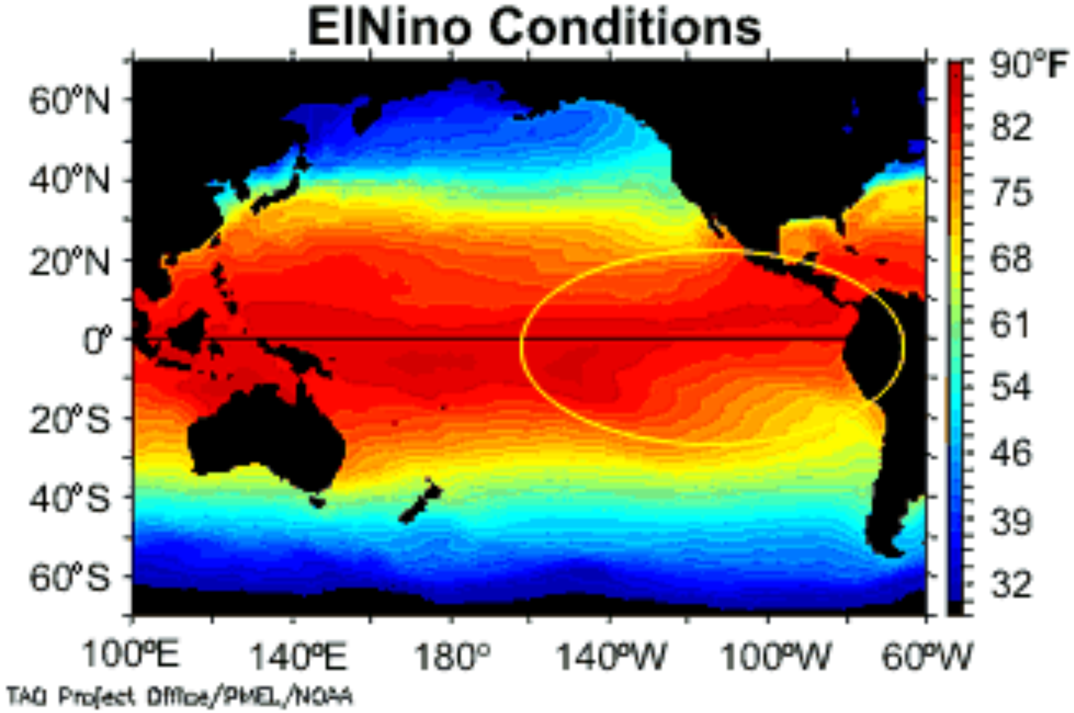
In a normal year, the Peruvian Current brings colder waters from the Southern Ocean northward along the coast of Peru. These waters are filled with lots of nutrients, which feed the fish living in the southern Pacific Ocean. Note also that the Equatorial Countercurrent tries to bring warmer water eastward toward the coast of South America.

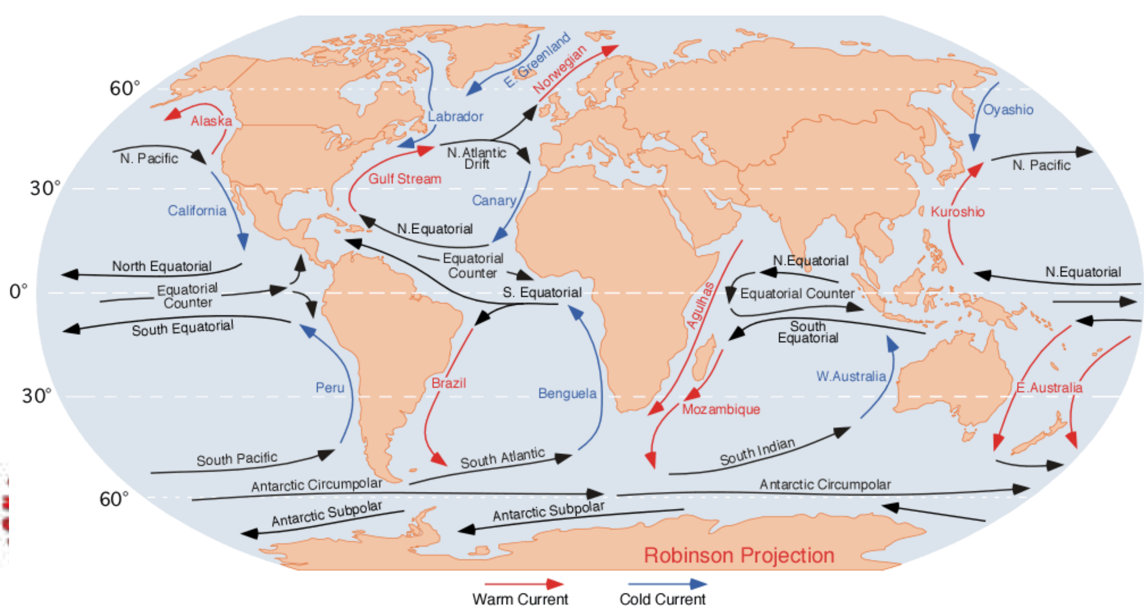




- La Nina:
  - Trade wind strengthens
  - Nutrient-rich water supply increases
- RESULT:
  - Warm waters "pile up" in the western Pacific

During a La Nina year, the Equatorial Countercurrent relaxes, allowing an "abundance" of cooler water to return to the region. When this takes place, the warmer waters will be pushed (so-to-speak) into the western Pacific. This is basically the opposite of El Nino conditions. Like El Nino, though, it can have major effects on the path major storm systems take.





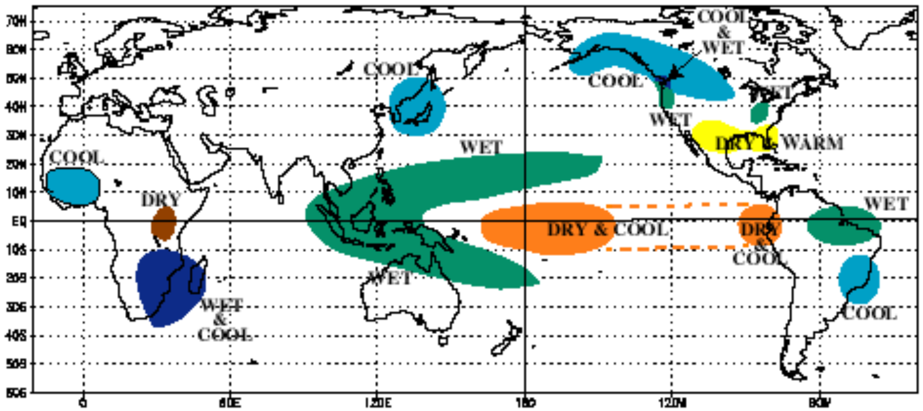
- El Nino:
  - Trade wind weakens
  - Nutrient-rich water supply lessens
- RESULT:
  - Waters warm off Peruvian Coast

El Nino occurs each year. It is actually named for the Christ Child, since it takes place toward the end of December. Usually, we only hear about the bigger El Nino events. When these events occur, there can be a major shift of the warm waters with several effects, especially in regard to the track of major storm systems.

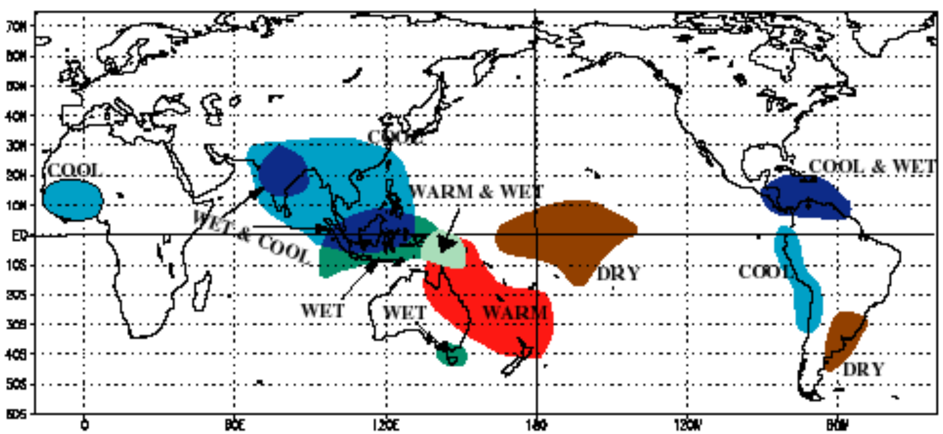
What Does This Mean Weather wise?

For La Nina Events –

COLD EPISODE RELATIONSHIPS DECEMBER - FEBRUARY



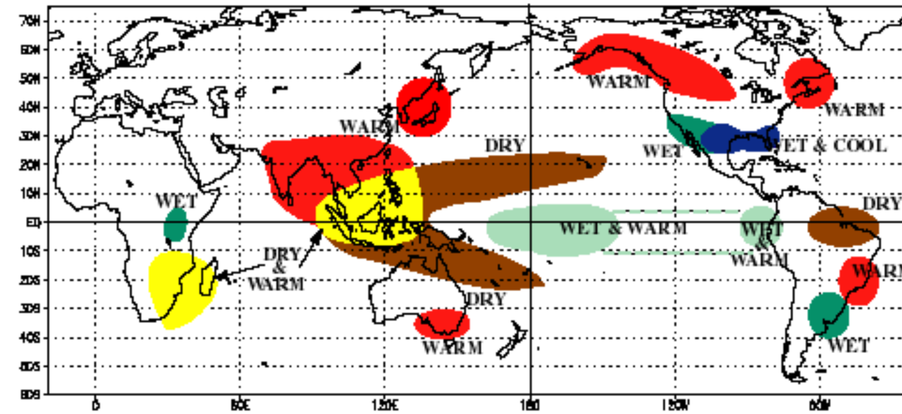
COLD EPISODE RELATIONSHIPS JUNE - AUGUST



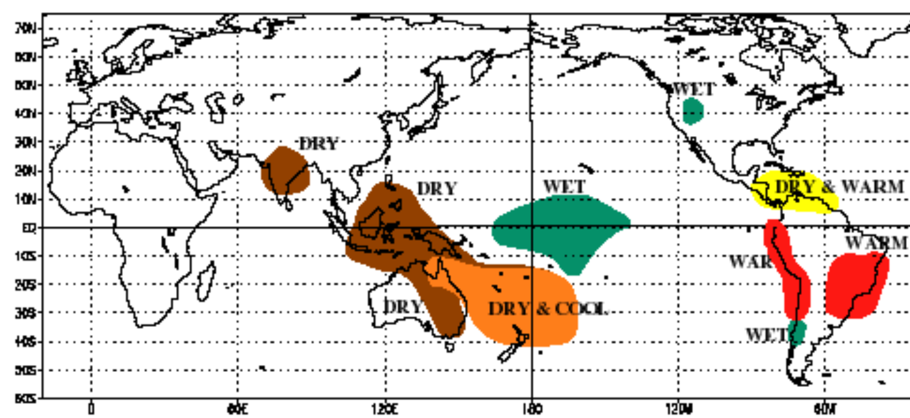
Climate Prediction Center
NCEP

For El Nino Events –

WARM EPISODE RELATIONSHIPS DECEMBER - FEBRUARY



WARM EPISODE RELATIONSHIPS JUNE - AUGUST



Climate Prediction Center
NCEP

So???

- A lot of fishing takes place off the coast of Peru
- Anchovy fish thrive in the nutrient-rich waters of this area
- Anchovies are caught and used to make chicken feed

- **During big El Nino events:**
  - Waters are not full as nutrients
  - Not as many anchovies
  - Cost of chicken feed increases
  - Therefore, the cost of chicken increases

Wave Action

- Waves are byproduct of wind
- Size depends on *THREE* things:
  - Speed

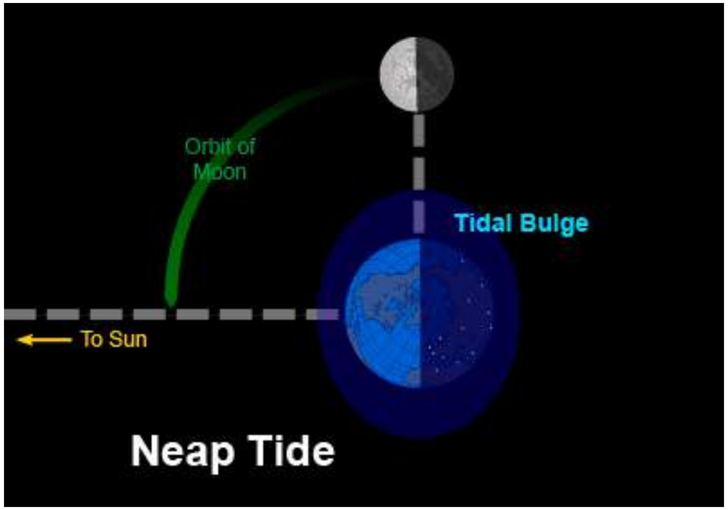
  – The wind has to be blowing faster than the tops of the waves. That meets the speed criteria. The longer that strong wind has been blowing, the better chance it has to generate large waves. The distance criteria is also known as the "fetch". Basically, this is the uninterrupted distance over which the wind blows without a big change in direction.
  - Duration
  - Distance
- Longer the wave, the faster it moves
  - You can estimate the wind speed using the size of waves. Estimating the wind speed using this method is known as the Beaufort Scale.

- Tides are another type of wave action
- **Definition:**
  - A change in the ocean water level, which results from the gravitational pull of the moon

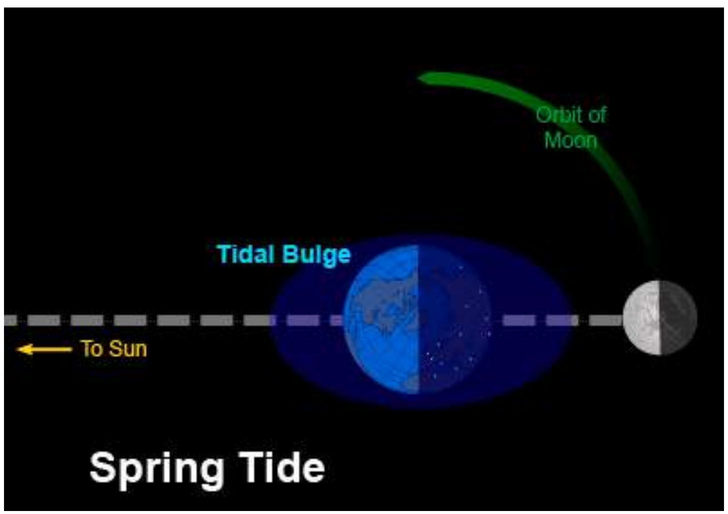
- Why the moon?
  - Sun's gravitational pull is greater
  - But the moon is closer
- Mariners have known for a long time that tides were related to the moon

Two tides? Four tides?

- Number of tides per day related to…
  - Shape of the coastline
  - Sea floor elevation
- Some places have one high/low tide cycle
  - Called a *diurnal tide*
  - Examples:
    - Lake Charles, LA
    - Gulfport, MS
    - Gulf Shores, AL
    - Pensacola, FL
- Other places have two high/low tide cycles
  - Called a *semi-diurnal tide*
  - Examples:
    - Galveston, TX
    - Apalachicola, FL



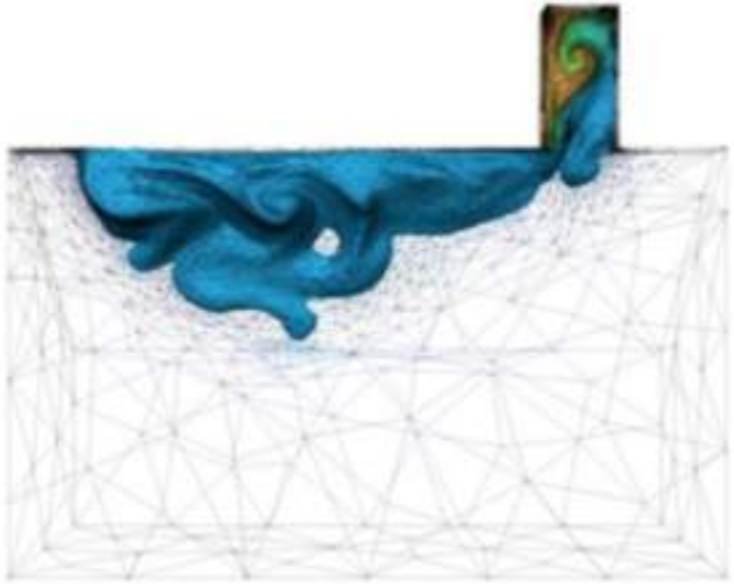
- Occur when the pull of the moon and sun partially cancel each other
- RESULT:
  - Very little change between high and low tides



- Occurs when the pull of the sun and moon act together
- RESULT:
  - Greater than normal tidal range experienced

Density Currents

- **Density Currents** – vertical currents of ocean water that result from density differences among water masses
- Denser water sinks and slowly spreads out beneath the surface
- An increase in seawater density can be caused by a decrease in temperature or an increase in salinity
- Density changes due to salinity variations are very important in the polar regions, where water temperature remains low and relatively constant



High Latitudes

- Most water involved in deep-ocean density currents begins in high latitudes at the surface
- The surface waters become cold, and its salinity increases as sea ice forms
- The water will than sink, initiating deep-ocean density currents
- The water's temperature and salinity will remain relatively unchanged while it is in the deep-ocean currents
- By knowing the temperature, salinity, and density of a water mass, scientists are able to map the slow circulation of water mass through the ocean

Sea Ice

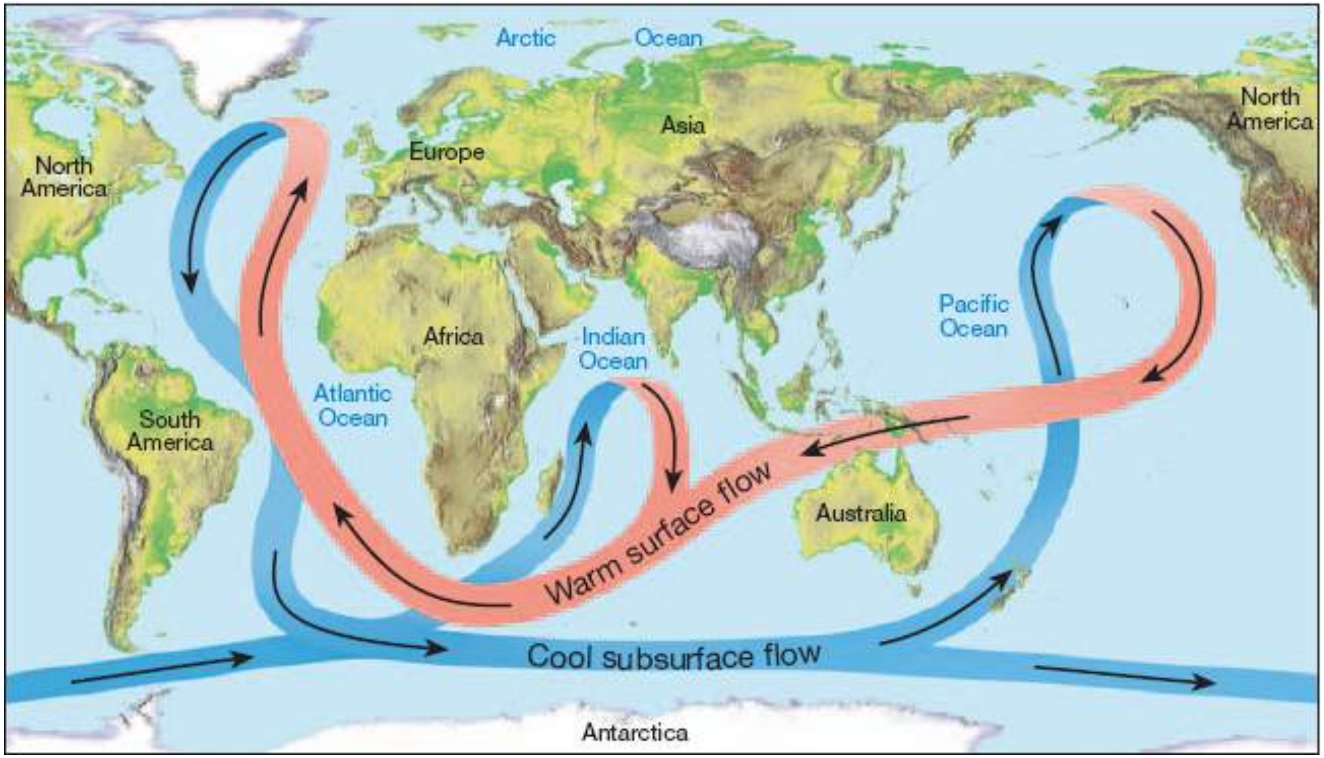
Evaporation

- Density currents can also result from increased salinity of ocean water due to evaporation
- In the Mediterranean Sea, conditions exist where a warm, high salinity water will sink and push its way out to the Atlantic Ocean
- This water has a salinity level of 38‰, compared to the Atlantic having a salinity of 35‰, making the Mediterranean water much more dense
- Scientists have tracked this water mass as far south as Antarctica

Mediterranean Sea

A Conveyor Belt

- A simplified model of ocean circulation is similar to a conveyor belt that travels from the Atlantic Ocean through the Indian and Pacific oceans and back again
- Warm water in the ocean's upper layers flow towards the poles
- When water reaches the poles its temperature drops and salinity increases, it sinks to the bottom and moves towards the equator
- The water will eventually upwells at warmer latitudes to complete the circuit



Global Conveyor Belt

CREDITS:

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www-ocean.tamu.edu

NWS Southern Region Jetstream Program

www.srh.noaa.gov/srh/jetstream

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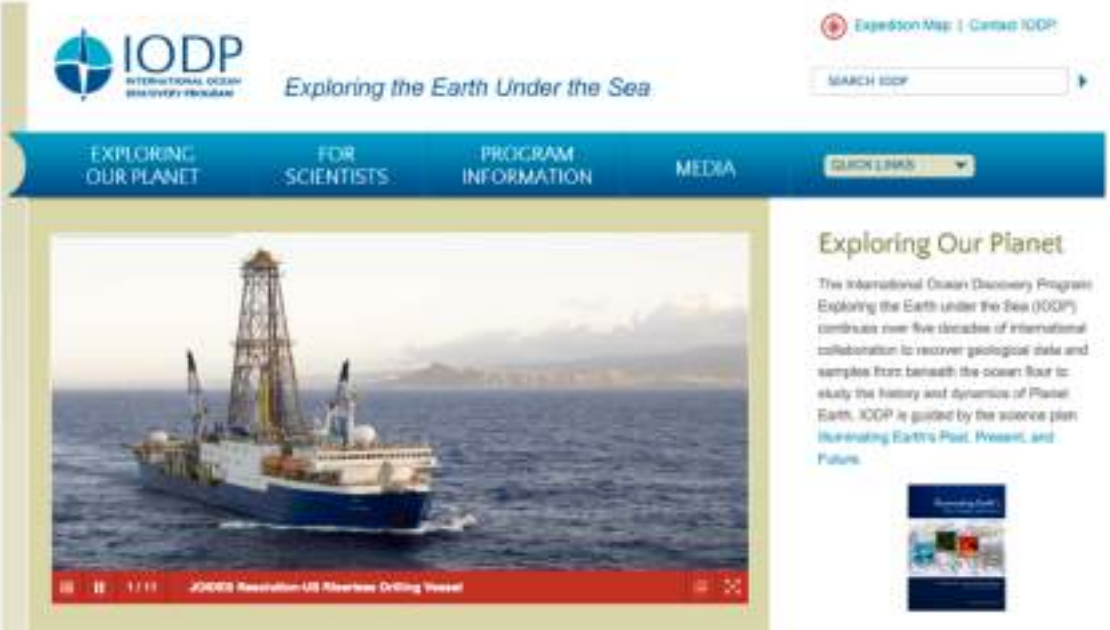
Fundamentals of Earth Sciences (ESO 213A)

Dibakar Ghosal
Department of Earth Sciences



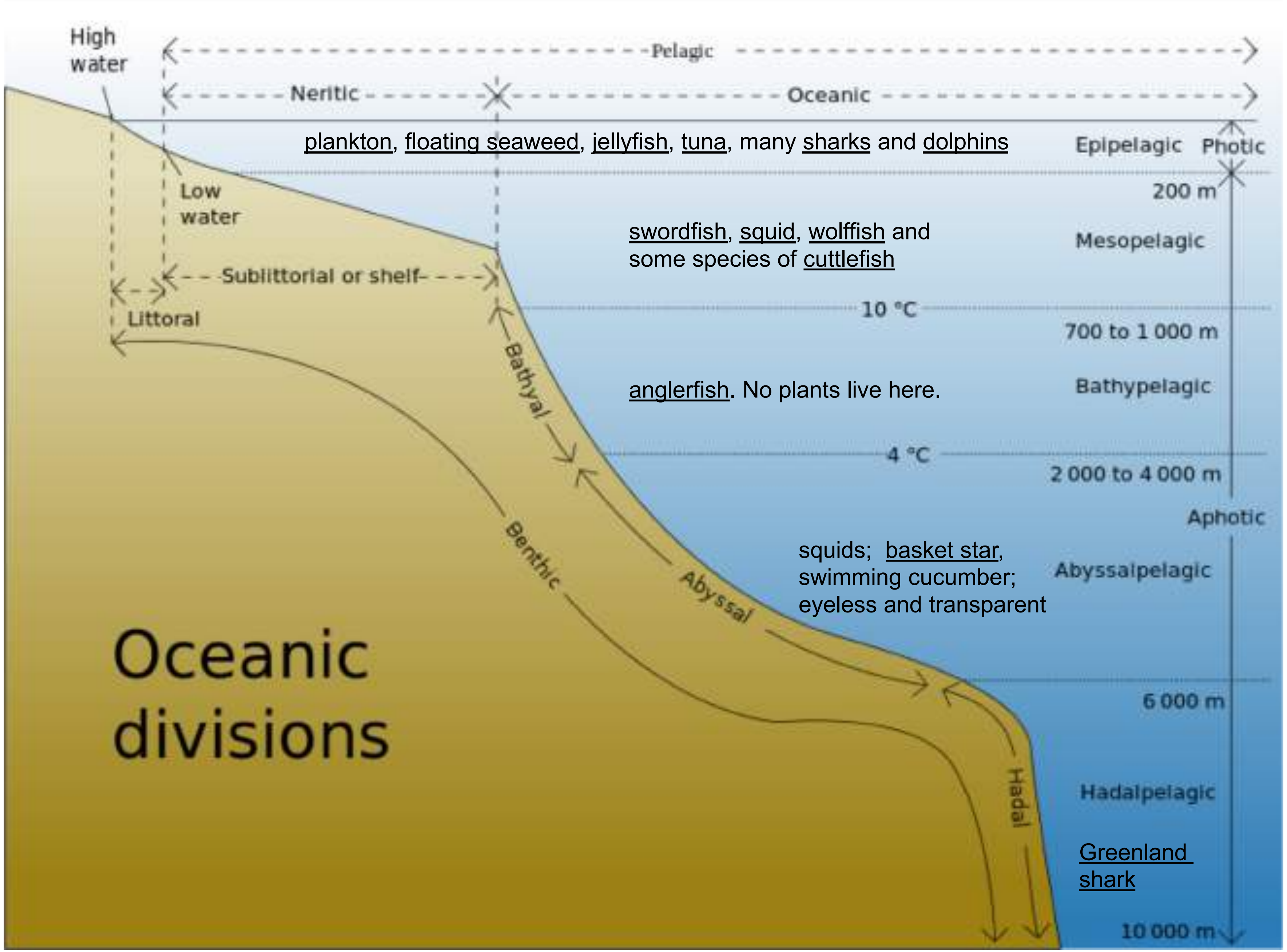
Ocean sediments & acidification

Previous Class: Oceans and winds

Ocean Zones

Based on nutrient supply and sunlight penetration oceanic zones are divided as follows:

1. Littoral zones
2. Neritic zone
3. Photic zone
4. Aphotic zone
5. Pelazic zone
6. Benthic zone



Significance of ocean sediments

a. Continents are sites of erosion. Ocean is site of deposition.
b. Therefore oceans retain a more complete and organized record of Earth history.
c. Law of superposition (sedimentary layers are deposited in a time sequence, the oldest at the bottom and the youngest at the top)

Categories of Marine Sediments

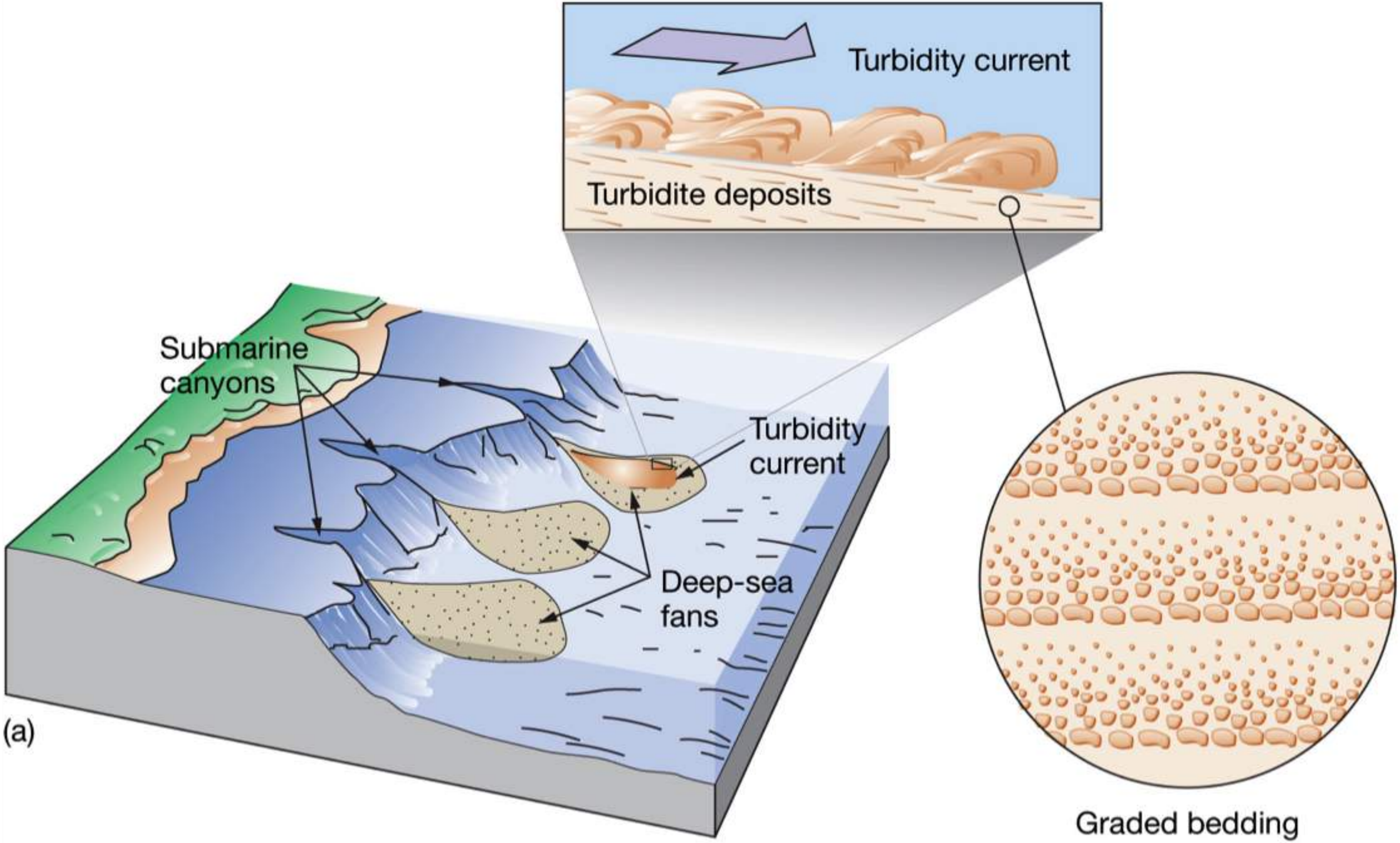
• Classification according to the origin of the components:
• Terrigenous - detritus from continental erosion and explosive vulcanism
• Authigenic-formed insitu by precipitation or submarine alteration
• Biogenic-shells or skeletons of organisms that sink to the sea floor after the organisms death; made of silicate or carbonate
• Cosmogenous-from extraterrestrial

Terrigenous: “from land”.

1. **Desert sand** blows off continent to ocean
2. **Volcanic eruptions-** dust and magma
3. **Rivers**- sediments transported onto continental shelves

4. **Turbidity Currents:** Avalanches of muddy ocean waters made heavy by terrigenous sediments. They flow down continental slopes and submarine canyons forming continental rise. Sorted by size of sediments… **gravel-sand-silt-clay**.

Mt. St. Helens


Turbidity current
Turbidite deposits
Submarine canyons
Turbidity current
Deep-sea fans
(a)
Graded bedding

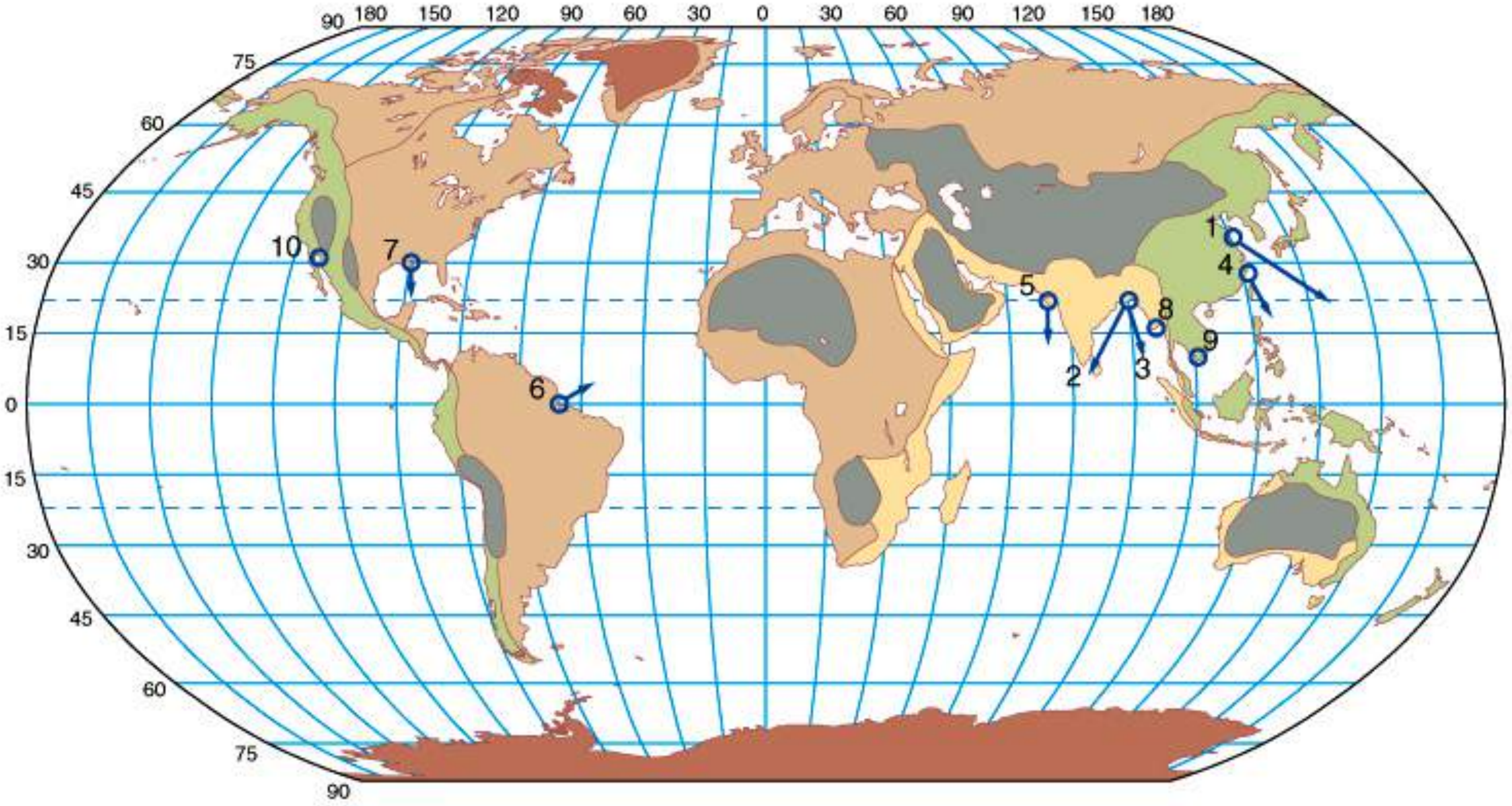
Terrigenous material to the continental margins:

- Mostly lithogenous sediments at continental margins
- Coarser sediments closer to shore
- Finer sediments farther from shore.
- Mainly mineral quartz (SiO_2).

Terrigenous material to the deep sea:

- Volcanic ash, tephra
- Sand to silt sized fragments of glass exploded into the atmosphere and transported by wind
- Useful as a stratigraphic marker
- Useful for regional volcanic history
- Eolian (wind-borne dust); useful for paleo-wind direction and paleo-desert location;
- Glacial marine; dropped from icebergs, useful for paleo-ice-extent;
- Deep sea clays accumulate at very slow rates (meters per millions of years)

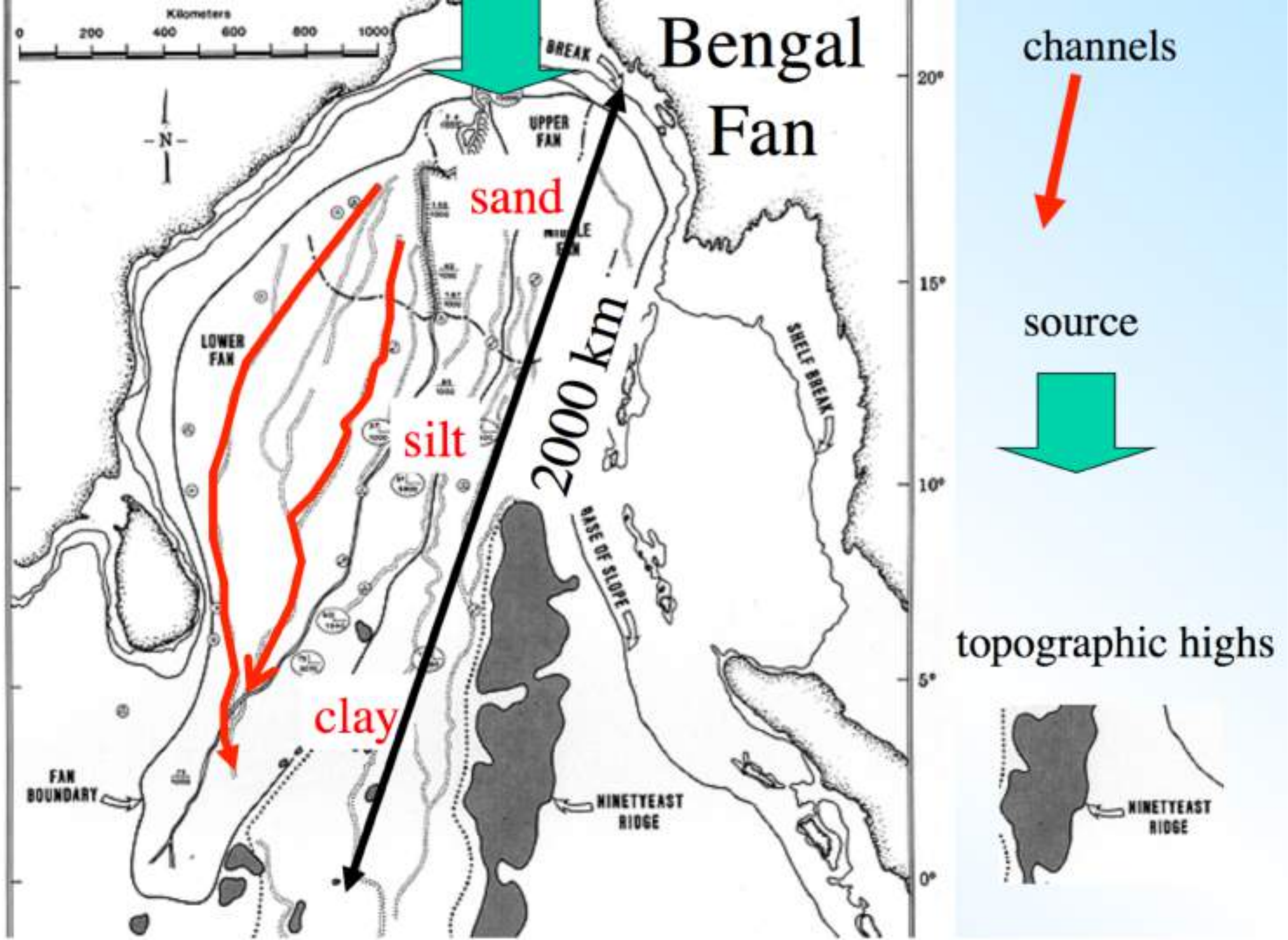
Water



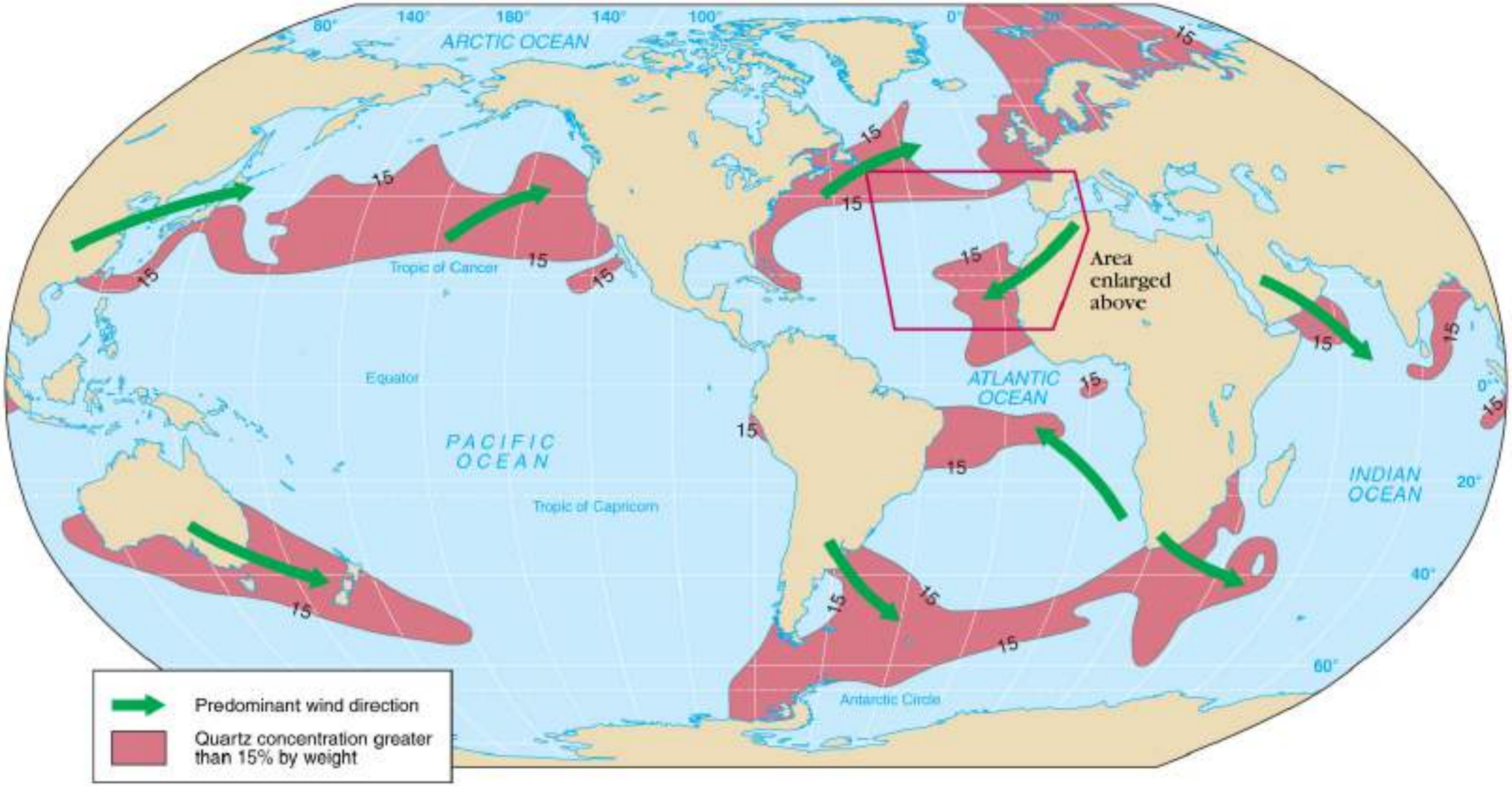
Sediment discharge in millions of tons/year

1. Hwang Ho – 2100	6. Amazon – 400
2. Ganges – 1600	7. Mississippi – 340
3. Brahmaputra – 800	8. Irrawaddy – 330
4. Yangtze – 550	9. Mekong – 190
5. Indus – 480	10. Colorado – 150

- River runoff to Atlantic Ocean and Arctic Sea
- Runoff to Pacific Ocean
- Runoff to Indian Ocean
- No runoff to oceans–source of windblown sediment
- Source of glacial sediment


Kilometers
0 200 400 600 800 1000
N
BREAK
Bengal
Fan
UPPER
FAN
sand
MIDDLE
FAN
LOWER
FAN
silt
2000 km
SHELF BREAK
BASE OF SLOPE
clay
FAN
BOUNDARY
NINETYEAST
RIDGE
20°
15°
10°
5°
0°
channels
source
topographic highs
NINETYEAST
RIDGE

Relationship of fine-grained quartz and prevailing winds



~ fine grained clay particles from wind can make up about 38% of deep sea sediment

Authigenic sediment sources

Form when dissolved materials come out of solution as **precipitates or evaporates**.

Precipitation is caused by a change in conditions including:

a. Changes in **temperature** (evaporation)
b. Changes in **pressure**
c. Addition of chemically active fluids (**like CO_2**)

Types of authigenic/hydrogenous sediment:

1. **Manganese nodules**
2. **Phosphates**
3. **Carbonates**
4. **Metal sulfides**
5. **Evaporite salts**

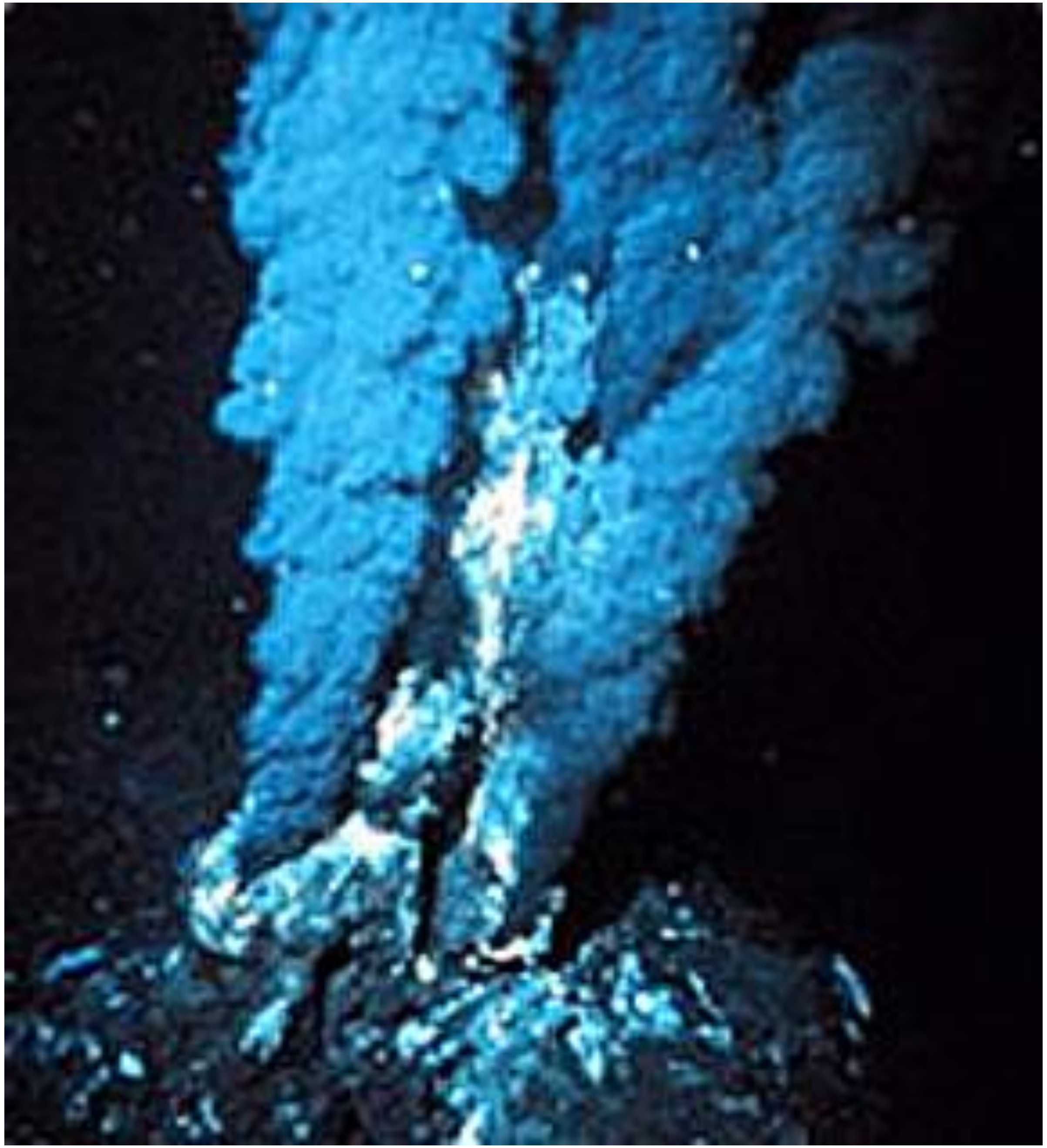
Manganese nodules

1. 1st discovered by **Challenger** expedition (**1873**)
2. **16 million tons** accumulate each year
3. Growth rate: **1-10 mm** every million years
4. Potato to beachball size- grow from nucleii of bone or teeth.
5. **Manganese** and **iron oxides**. Also, Co, Cr, Ni, Cu, Mb, and Zn.

Metal sulfides

Near hydrothermal vents, lots of metal ions are released into the water, and these ions oxidize or combine with silica and precipitate out as dark, metal-rich (Iron, Nickel, copper, zinc, silver) sediment.

→ less common than lithogenous or biogenous sediments. They are almost never the dominant sediment type.



Black smokers

Phosphorites:

• Deposits as the mineral, apatite, in shallow to mid-depths on continental shelf/slope.

•Typically concentrated in coastal areas with:

• (a)intensive upwelling,

- (b)little or no terrigenous input

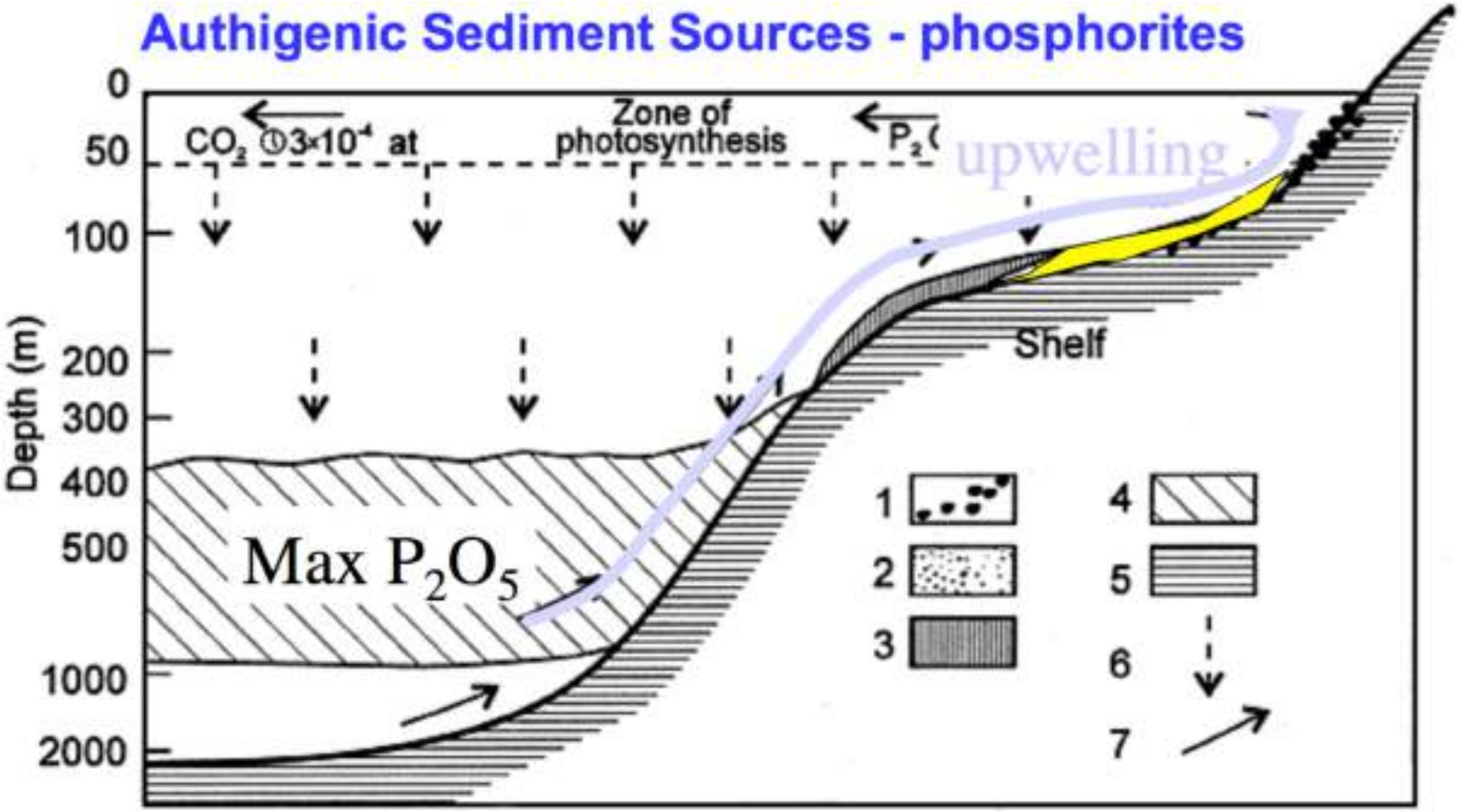
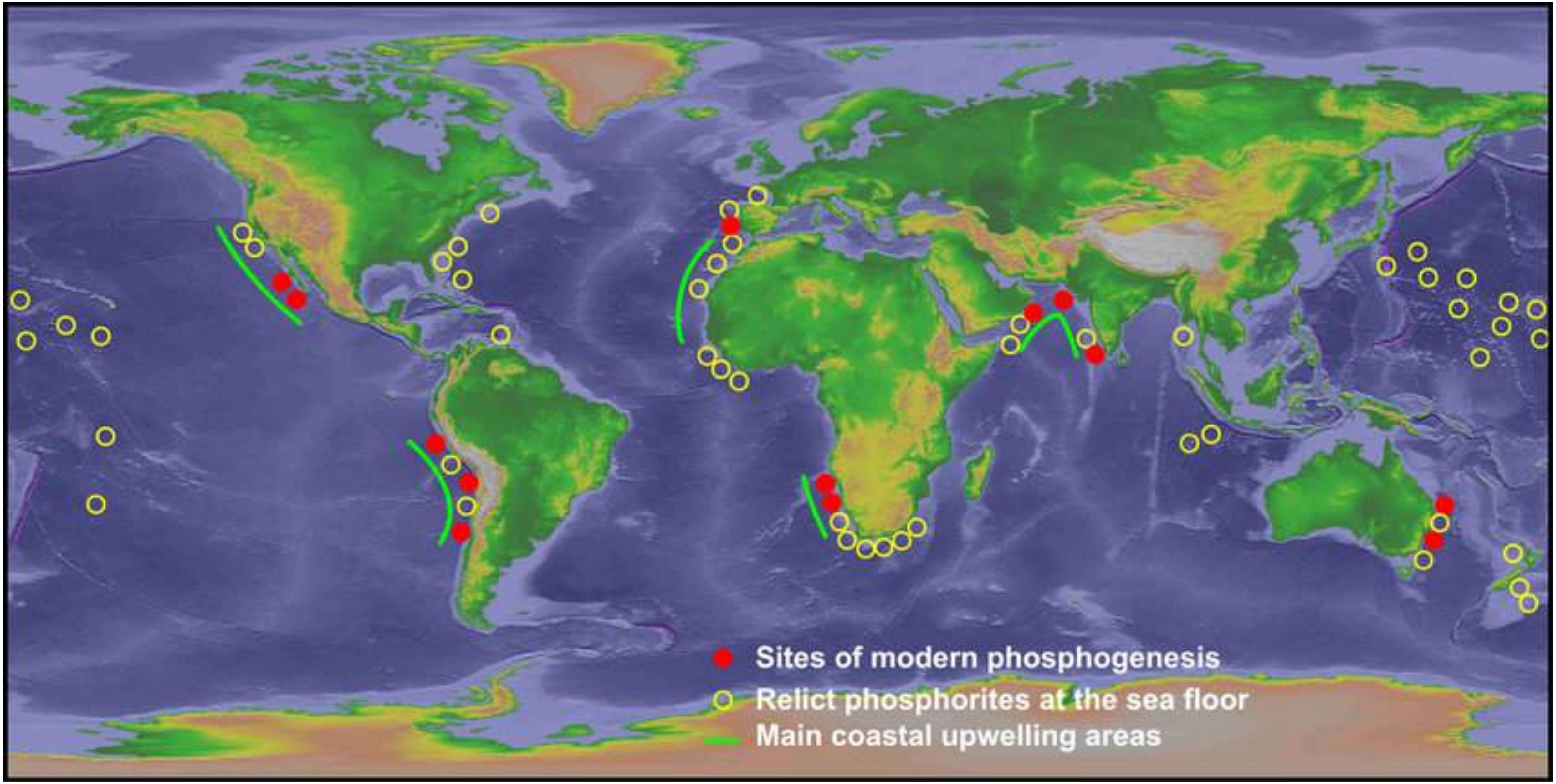


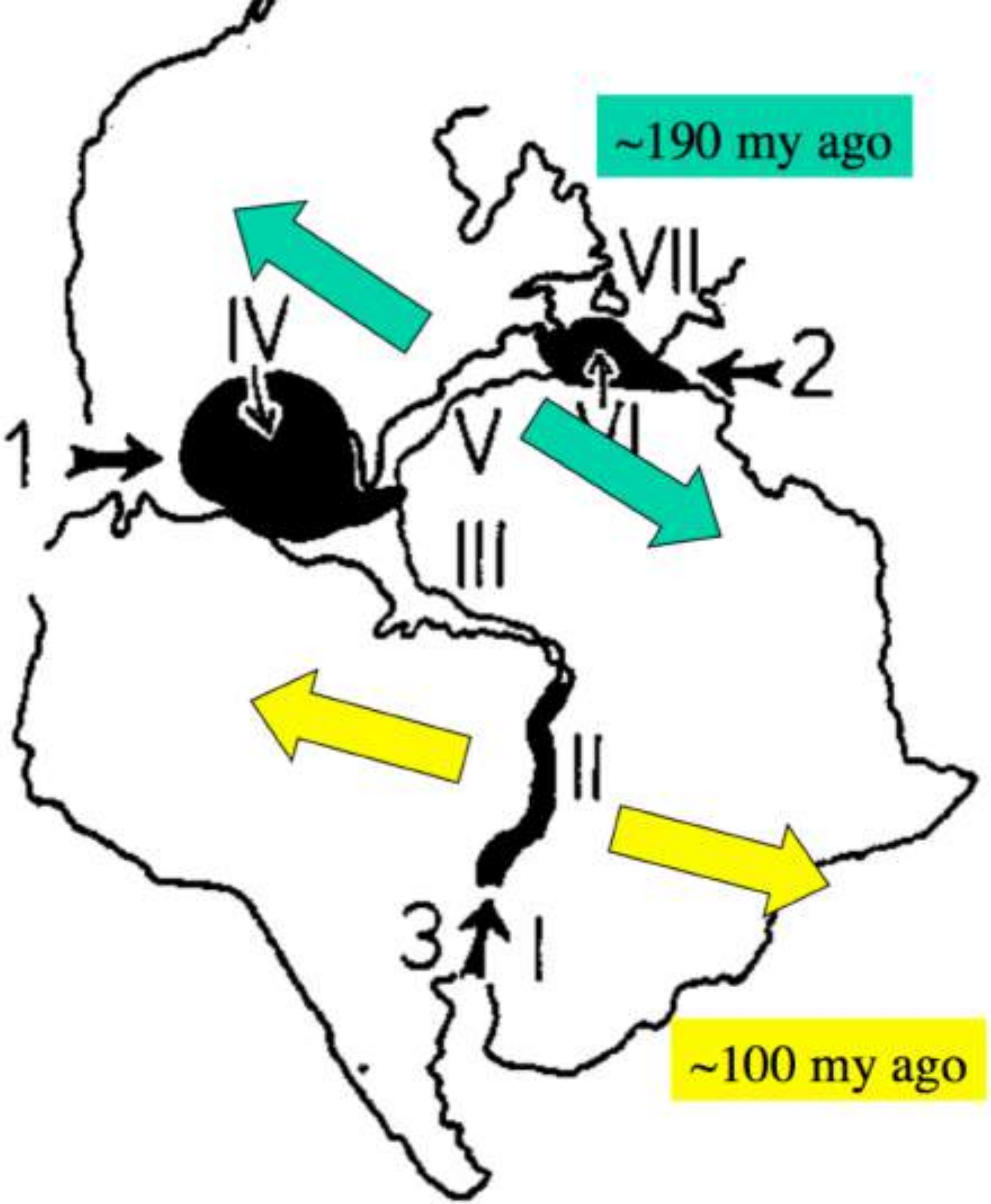
Figure 7.17. Diagram showing the formation of phosphorites (after Kazakov in Strakhov 1962). 1, facies of littoral gravel and sand; 2, phosphate facies; 3, facies of calcareous sediments; 4, zone of maximum CO_2 and organic P_2O_5 content (partial pressure of CO_2 up to 12×10^{-4} atm, P_2O_5 concentration 300-600 mg/m^3); 5, landmass; 6, sedimentation of plankton remains; 7, current directions.

Source: Holland, Heinrich D. and Ulrich Petersen (1995) Living Dangerously: The Earth, Its Resources, and the Environment. New Jersey: Princeton University Press.


Sites of modern phosphogenesis
Relict phosphorites at the sea floor
Main coastal upwelling areas

Evaporites:

- form from evaporation of seawater, (Gypsum, Halite, other Salts)
- Require unusual geological circumstances;
- Examples: (a) Mediterranean isolation from Atlantic ~6mya,
  (b) breakup of Gondwanaland
- As rift valleys form, their floors lie below adjacent oceans



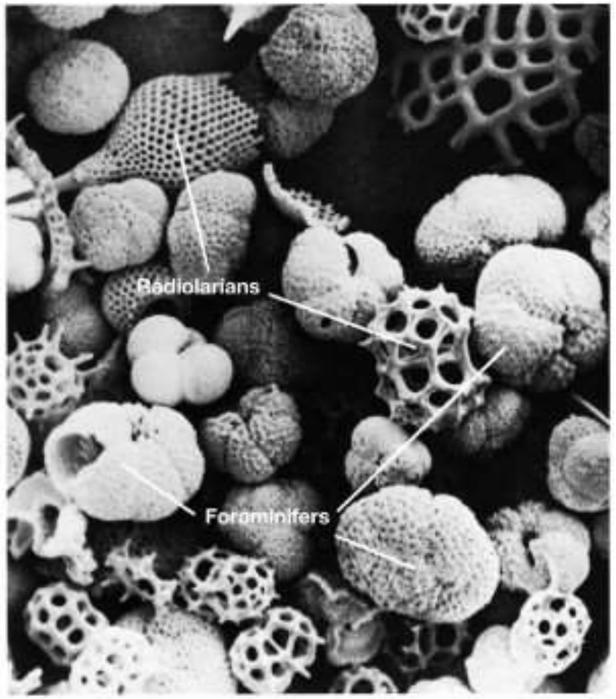
Biogenic Sediment Sources

Biogenic sediments

a. Organisms (marine plants and animals) use dissolved materials delivered from rivers (flux in), especially calcium carbonate and silica

b. Organisms remove these dissolved products from seawater (flux out) to build shells and skeletons.

<u>Oozes</u>: Fine muds with **>30%** biological materials (Shells, bones, teeth of living organisms).



<u>Two Types of Oozes</u>:

1/ calcareous $CaCO_3$

2/ siliceous SiO_3

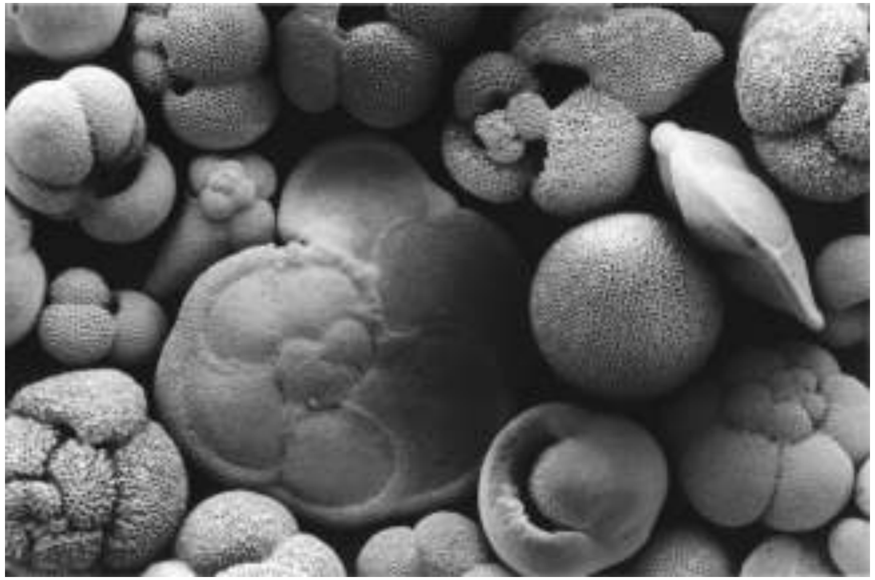
Abundant where ample **nutrients** encourage high biological **productivity** of **plankton** (**zoo, phyto**).

Calcareous Oozes: Composed predominantly of $CaCO_3$ shells of Foraminiferans and Coccolithophores

1. Coccolithophores

(phytoplankton-algae that can bloom over massive areas)

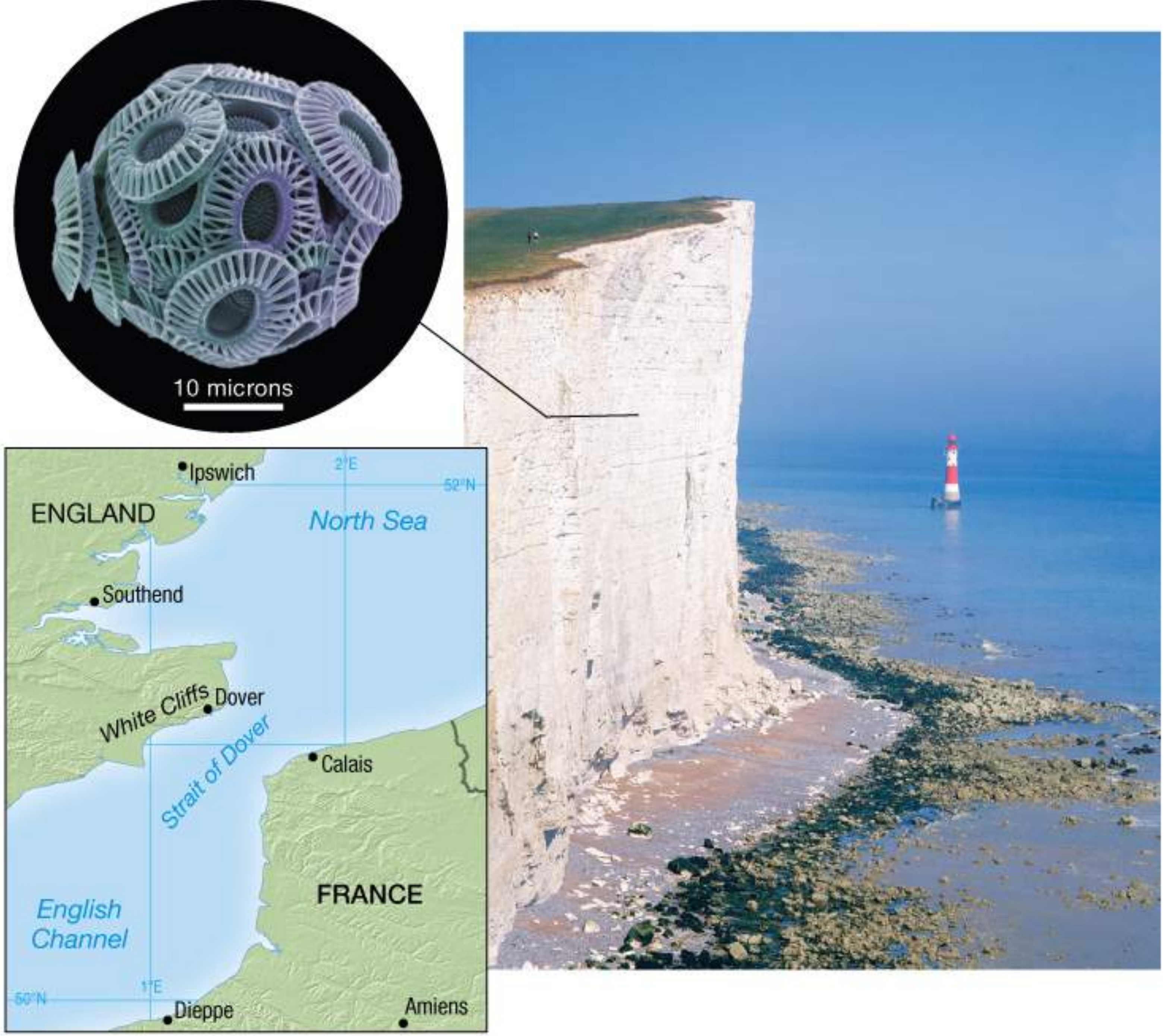
Chalk- Rock made of coccolith rich sediments. White Cliffs of Dover in England.



2. Foraminifers

(zooplankton-protozoa)

Dissolve in deepest waters! Below **CCD** (CaCO3 composition depth)… acidic.



White Cliffs of Dover

Calcareous Ooze

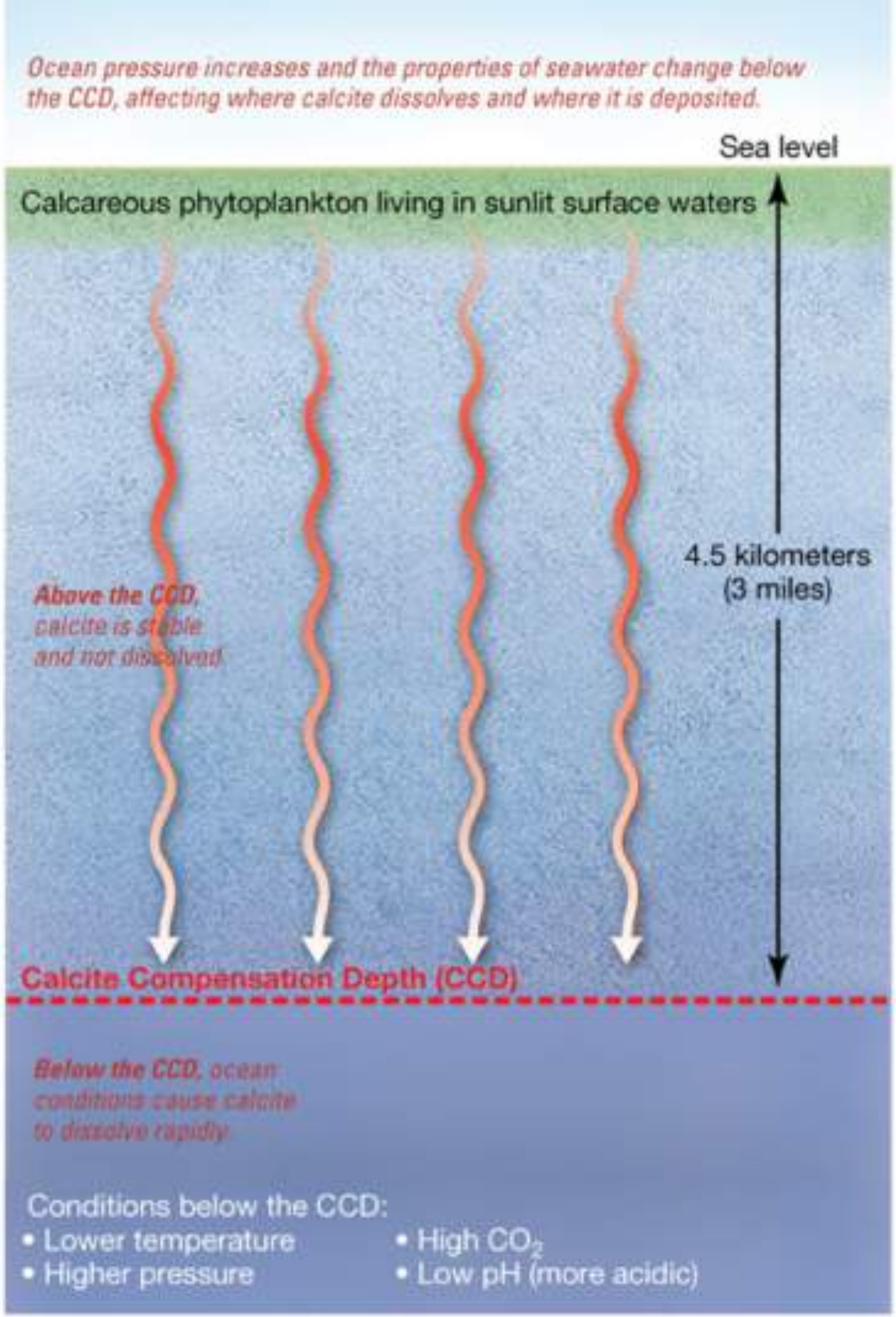
Dominant at low latitudes above the CCD.

<u>Warm, shallow ocean </u>saturated with calcium carbonate

Along the mid-ocean ridges, seamounts and other peaks

- Scarce calcareous ooze below 5000 meters (16,400 feet) in modern ocean

CCD occurs around 6000m in Atlantic and 3500-4000 m in parts of the Pacific.



Kinetic Considerations

- ***Saturation Horizon***
- ***Lysocline*** is where dissolution rate increases in carbonate grains

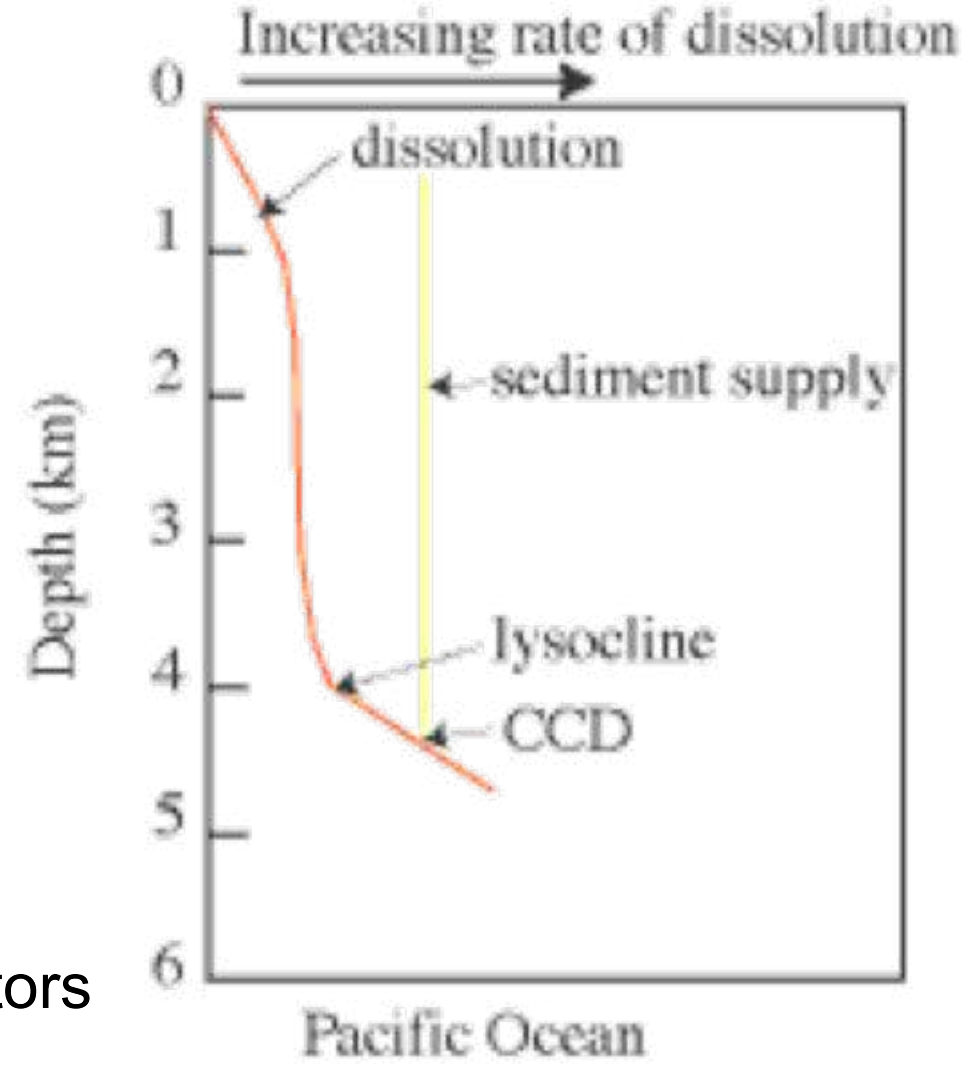
– Since degree of saturation decreases with depth, dissolution rates should increase with depth...

- ***Carbonate Compensation Depth (CCD)*** is

Depth where $CaCO_3$ readily dissolves

Rate of supply = rate at which the shells dissolve

- The lysocline occurs above the CCD, but is at or below the saturation horizon.

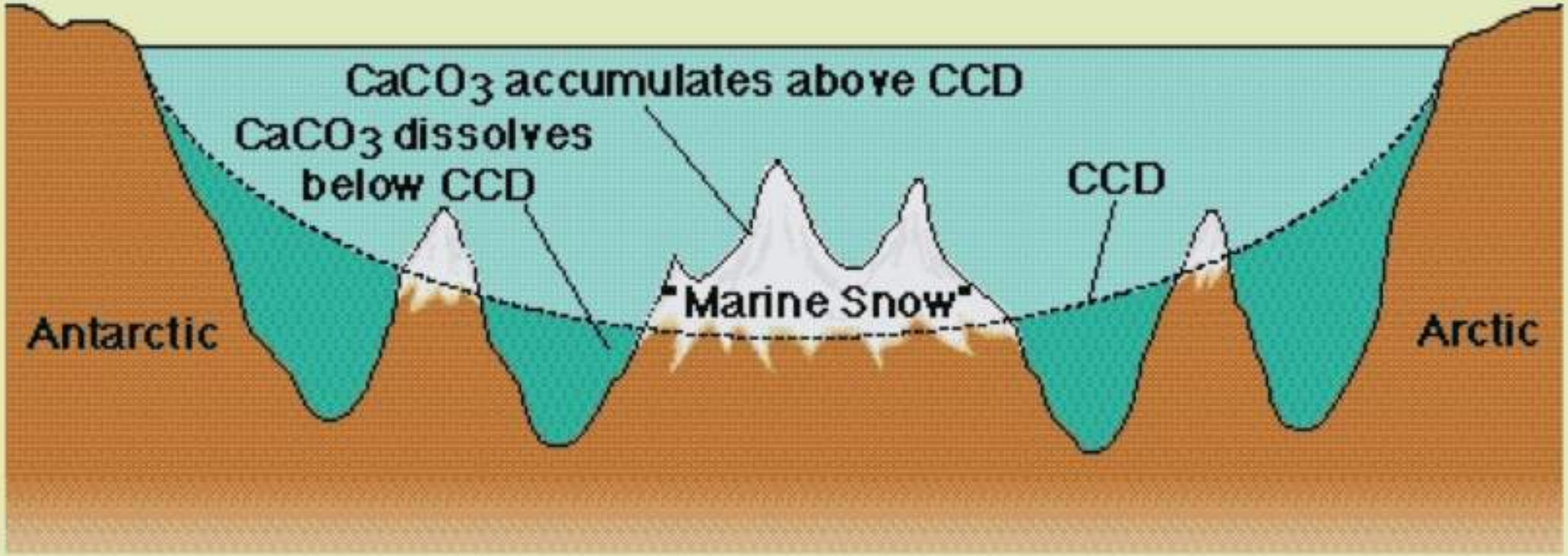


– Likelihood of dissolution of a shell depends on factors that control sinking rate and dissolution rate

– Both influenced by the size, density and shape of a shell

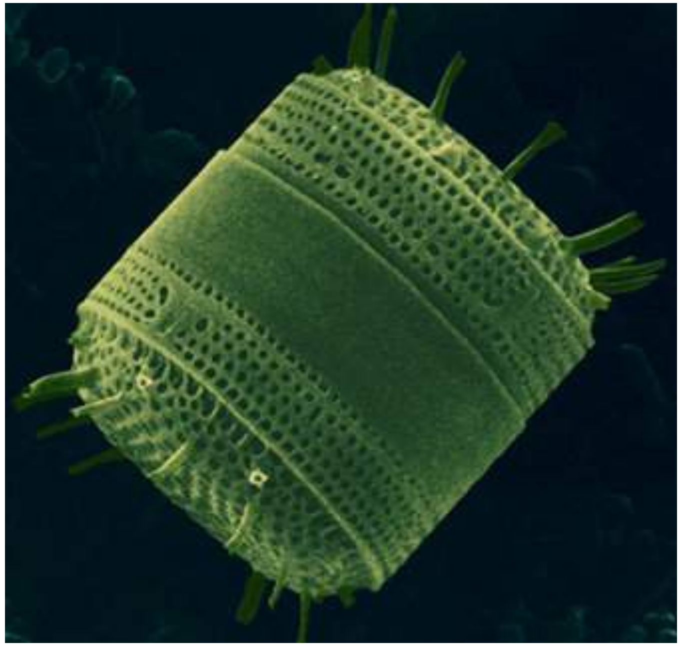
- Dissolution is also controlled by organic coatings and effects of trace ions on shell surfaces

Calcium Carbonate Accumulation



Below the CCD, cold water holds more CO_2, which results in more carbonic acid, which dissolves $CaCO_3$ faster.

Siliceous Oozes: (SiO_2) The dominant deep ocean sediment in high latitude regions, below the CCD and surface current divergences near the equator (where cold water is upwelling)



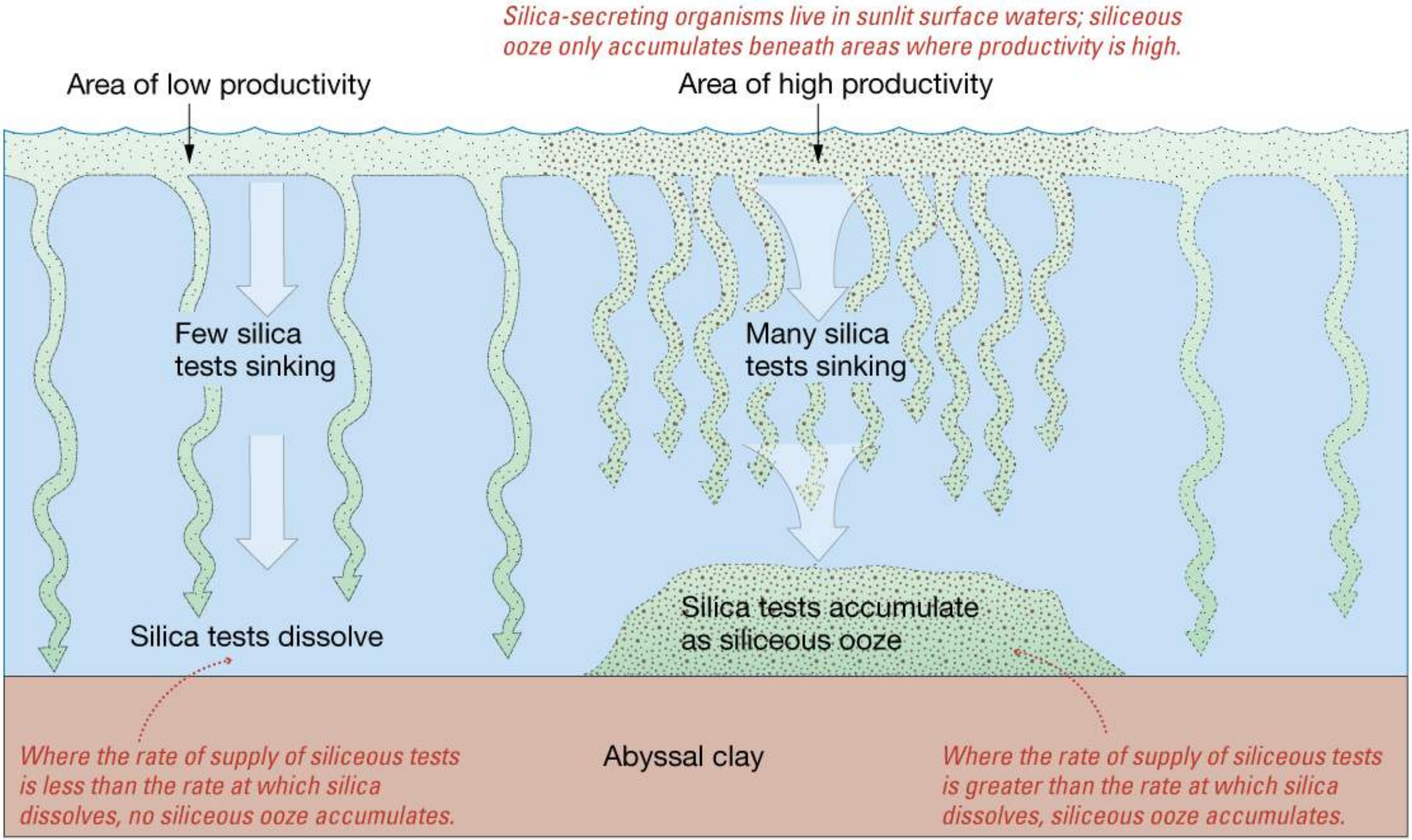
1. radiolarian- zooplankton

Concentrated in deepest waters! Do not dissolve below CCD…not $CaCO_3$!

2. Diatom- phytoplankton

Diatomaceous earth- sediment made up of mostly diatoms.

Siliceous ooze



Biogenous ooze turns to **rock**

When biogenous ooze hardens and lithifies, it can form:

a. **<u>Diatomaceous earth</u>** (if composed of diatom-rich ooze)
b. <u>Chalk</u> (if composed of coccolith-rich ooze)
c. Fossiliferous **limestone**

Distribution of biogenous ooze

Most biogenous ooze found as <u>pelagic</u> deposits at the bottom of the open ocean.

Factors affecting the distribution of biogenous ooze:

a. Productivity (Number of organisms in surface water above ocean floor)
b. Destruction (Skeletal or tests remains dissolve in seawater at depth)
c. Dilution (Deposition of other sediments decreases percentage of biogenous sediments)

Pelagic Sediments:

Sediments that come from open ocean water, not from land. Form in deep seas far from land.

Atlantic: over **3,000** feet thick

Pacific: over **1,600** feet thick

<u>Oozes</u>: Fine muds with **>30%** biological materials (pieces of living things).

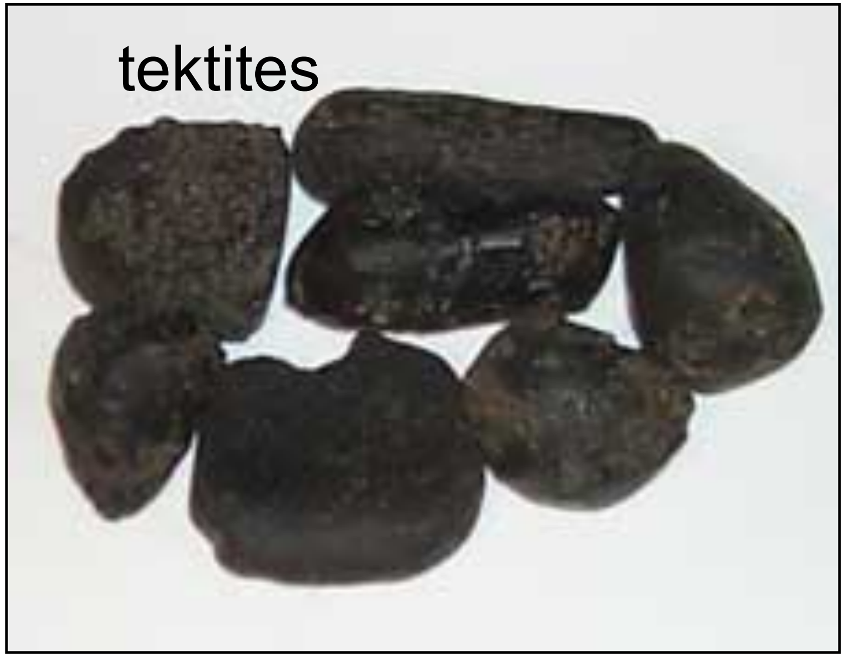
<u>Clays</u>: fine dust size particles containing **<30%** biological materials. Besides clay, contains pieces of living things (marine snow $CaCO_3$), micrometeorites, and volcanic dust.

Red Clays

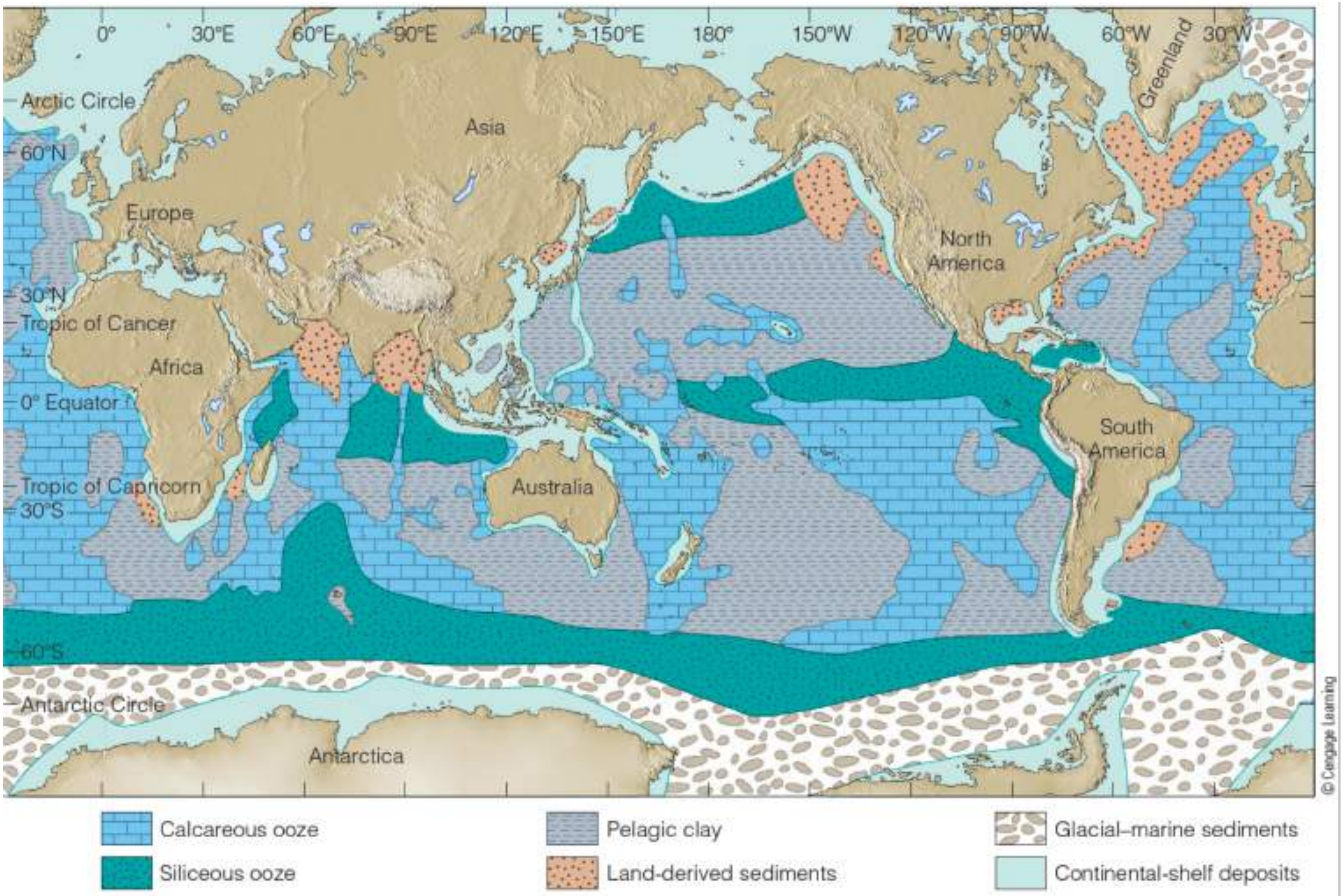
1. Red or brown sediment with **less than 30%** biogenic material.
2. Form in the **deepest calmest** areas of the ocean.
3. Tiny particles take **100 years** to descend.
4. It accumulates very slowly **0.2 cm/1000** years

Cosmogenous sediments:

1. **Extraterrestrial** in origin
2. Two main types:
   a. **Micro**scopic space dust
   b. **Macro**scopic meteor debris
3. Forms an insignificant proportion of ocean sediment



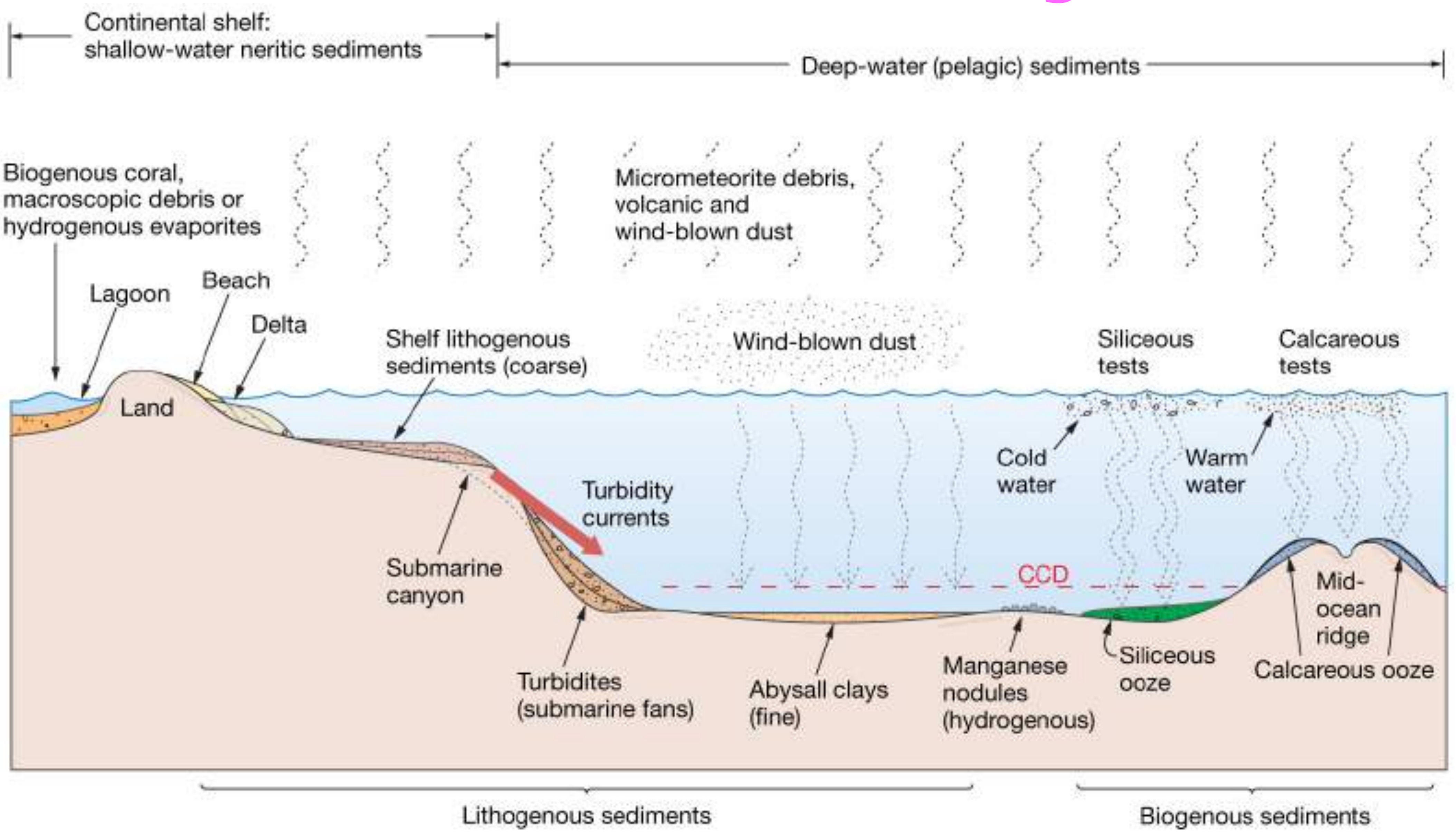
Ocean sediment deposits



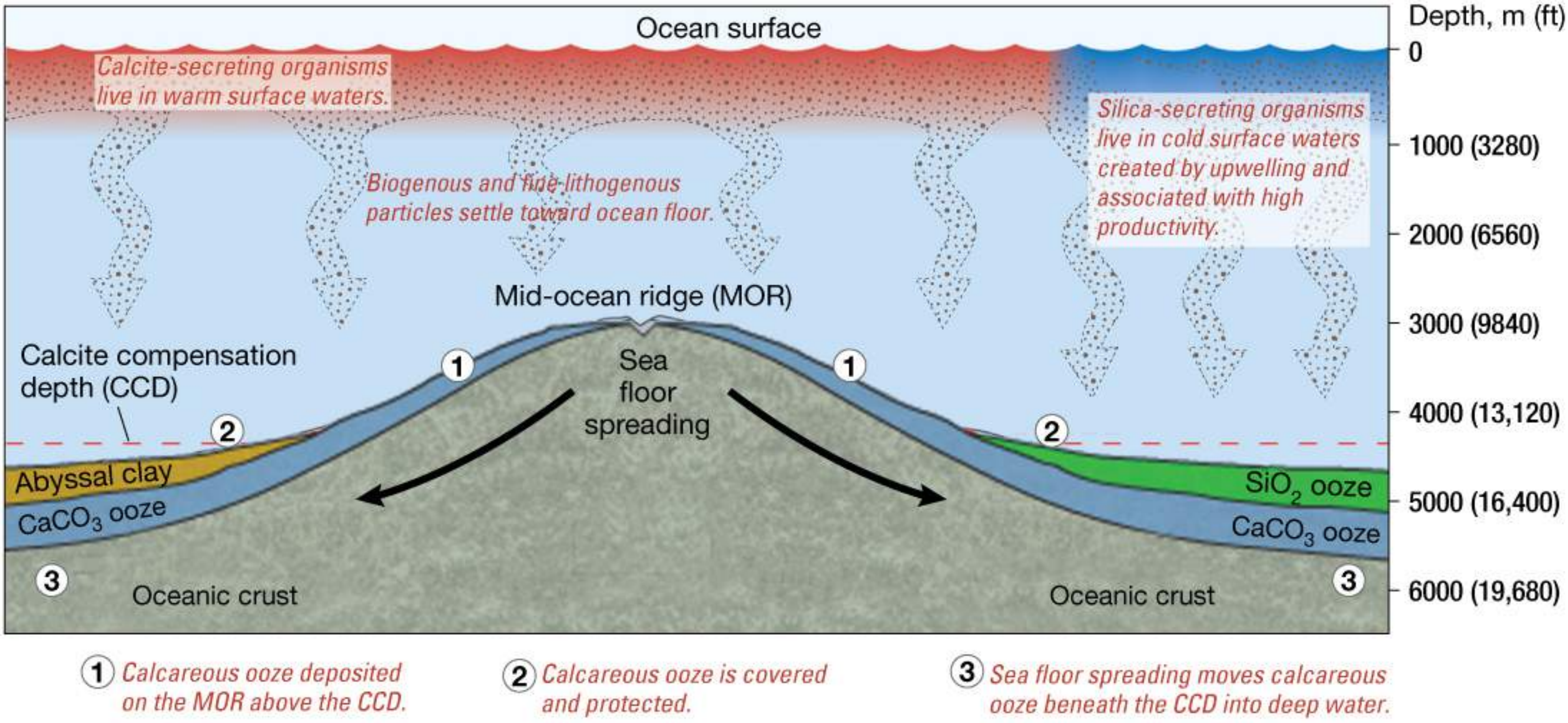
Cross-section of the Ocean

Neritic

Pelagic



Sea Floor Spreading and Sediment Accumulation



Summary of Sediment Map:

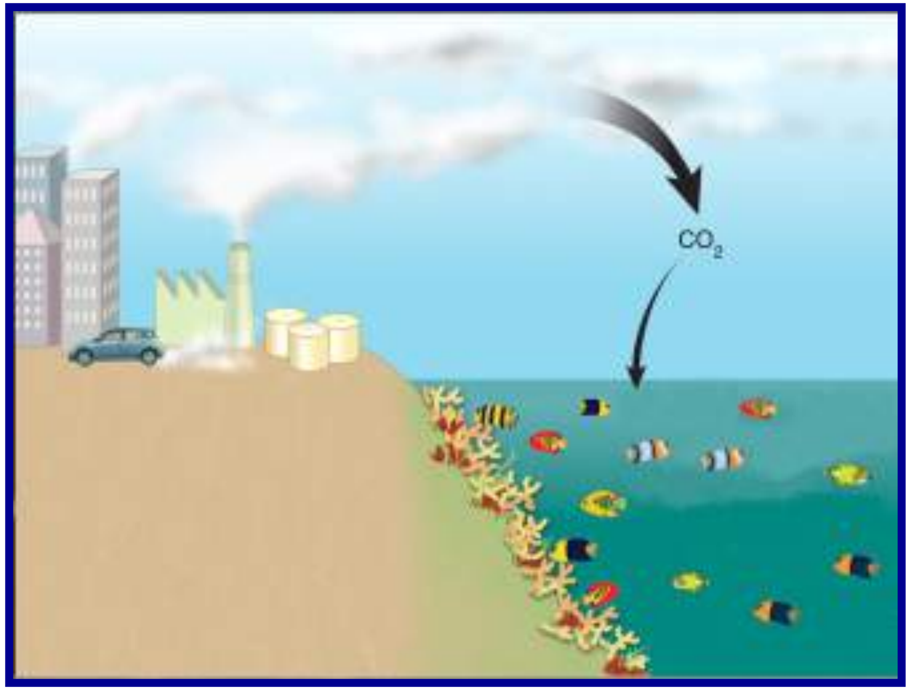
1. Red Clays occur in the deepest calmest parts of the ocean with low productivity.
2. Siliceous oozes occur in the deep oceans below CCD in areas with high productivity.
3. Calcareous oozes occur in areas of ocean with high productivity and above CCD level like plateaus, seamounts, m-o ridges.
4. Terrigenous sediments occur closer to continents along continental margins.
5. Manganeses nodules occur on abyssal plains and some plateaus (Blake).

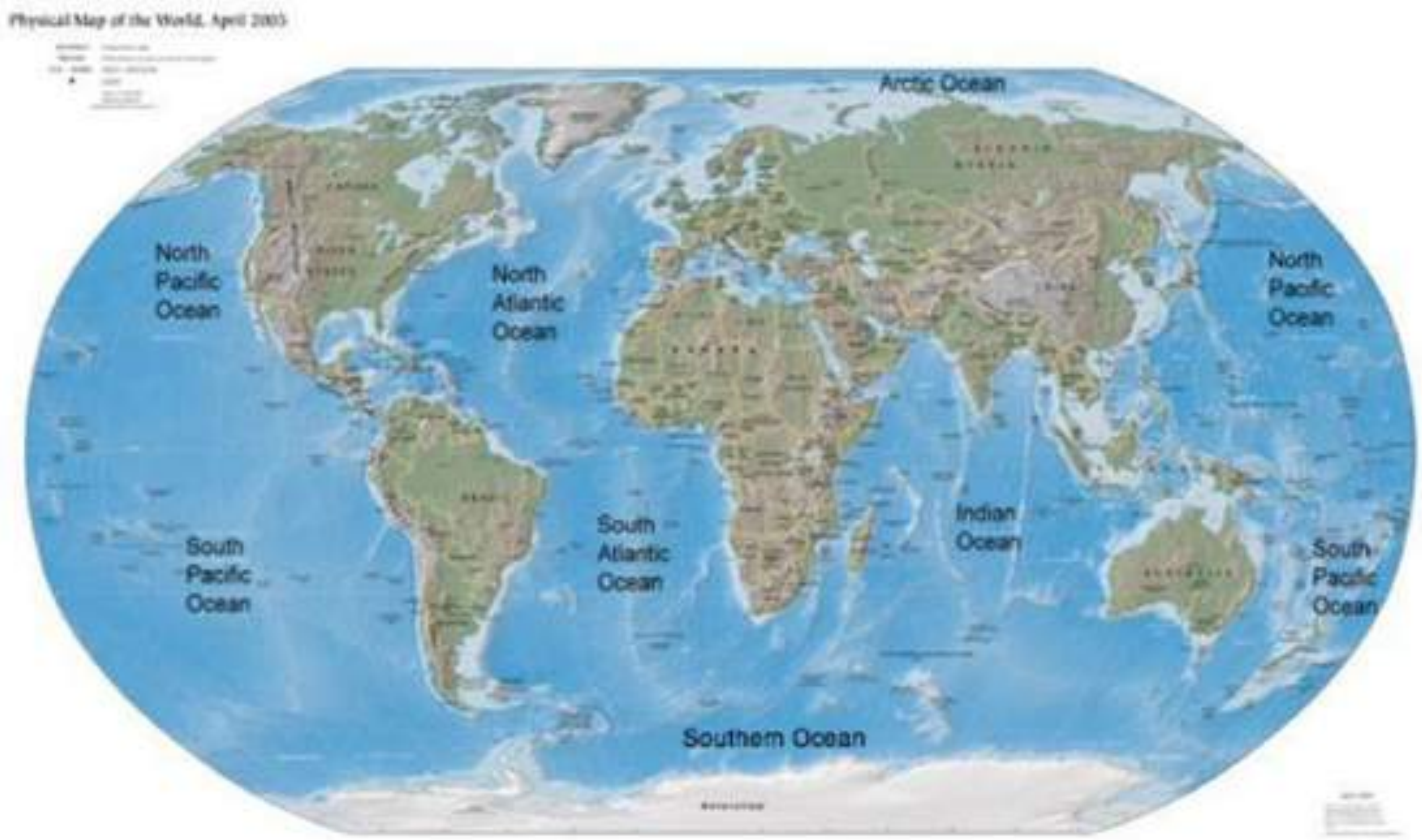
Deep Ocean Characteristics

1. **Cold**
2. **Still**
3. **Stable**
4. **Dark**
5. **Essentially no productivity**
6. **Sparse Life**
7. **Extremely high pressure**
8. **Little food**
9. **Calcium and oxygen ‘starved’**

What is Ocean Acidification?

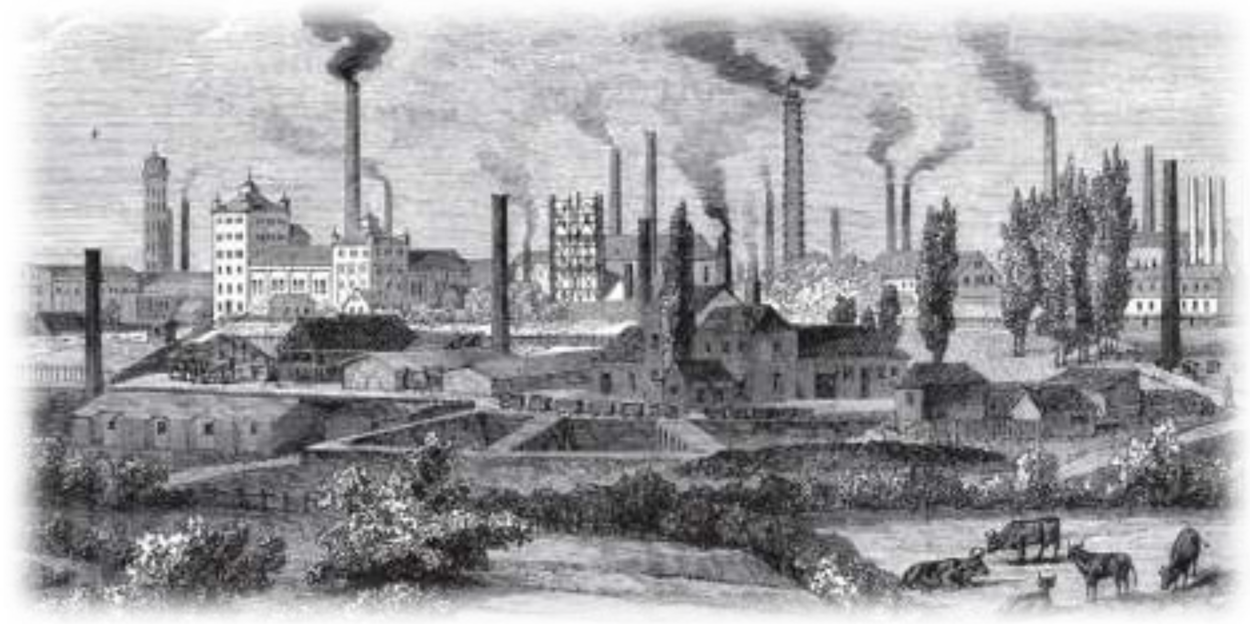
- International experts define <u>ocean acidification (OA) as a decrease in ocean pH over decades or more that is caused primarily by uptake of CO_2 from the atmosphere</u>.
- Because human activities are releasing CO_2 into the atmosphere very quickly, the ocean is taking up CO_2 faster today than it has in the past.
- This is <u>causing global ocean chemistry to change more quickly</u> than ocean systems can handle.





Ocean Acidification Trends

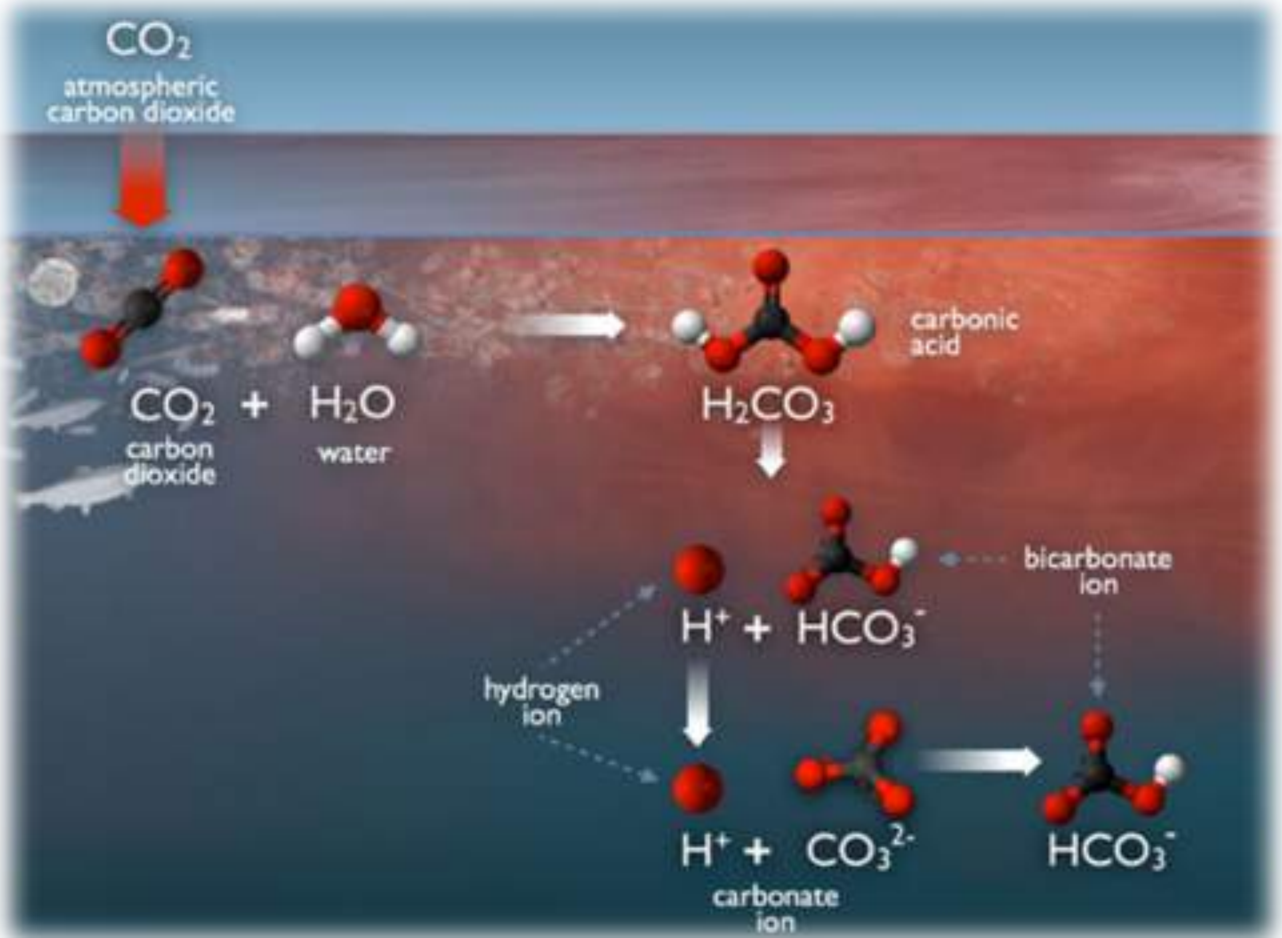
- <u>Ocean acidification,</u> related to the uptake of CO_2 at the ocean surface, <u>causes a relatively slow, long-term increase in the acidity of the ocean, corresponding to a decrease in pH.</u>
- Since the <u>Industrial Revolution, the global average pH of the surface ocean has decreased by 0.11</u>, which corresponds to approximately a <u>30% increase in the hydrogen ion concentration</u>.



pH is the scale on which acidity is measured. The amount of hydrogen ions in a liquid determines how acidic the liquid is.

Ocean Acidification Chemistry

- As carbon dioxide (CO_2) dissolves into seawater it creates carbonic acid.
- Through a series of chemical reactions, carbonic acid releases hydrogen ions (H^+), which decreases seawater pH, and ***decreases the concentration of carbonate ions*** (CO_3^{2-}), which provide chemical building blocks for marine organisms' shells and skeletons.

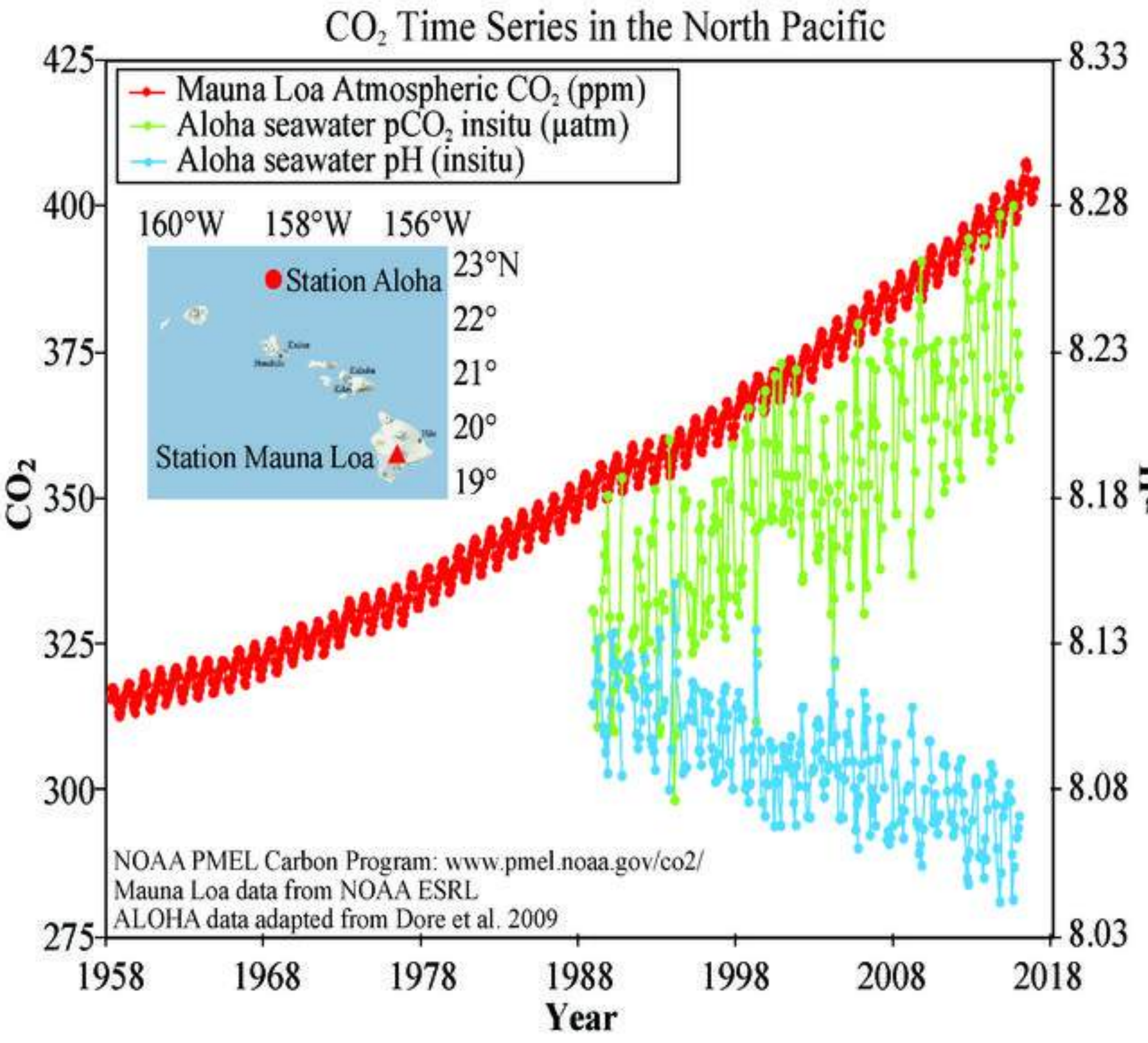


Carbonic acid reduces Ocean pH

Concentration of Carbonate ion decreases

Ocean Absorption of CO2

- The ocean absorbs about a quarter of the CO_2 we release into the atmosphere every year, so as atmospheric CO_2 levels increase, so do the levels in the ocean.
- Initially, many scientists focused on the benefits of the ocean removing this greenhouse gas from the atmosphere. However, decades of ocean observations now show that there is also a downside — the CO_2 absorbed by the ocean is changing the chemistry of the seawater.



Data: Mauna Loa (ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_mm_mlo.txt) ALOHA (http://hahana.soest.hawaii.edu/hot/products/HOT_surface_CO2.txt)
Ref: J.E. Dore et al, 2009. Physical and biogeochemical modulation of ocean acidification in the central North Pacific. *Proc Natl Acad Sci USA* **106**:12235-12240.

Why be concerned with a small change in pH?

- Many organisms are very sensitive to seemingly small changes in pH.
- Many marine organisms are very sensitive to either direct or indirect effects of the change in acidity (or H^+ concentration) in the marine environment.
- Fundamental physiological processes such as respiration, calcification (shell/skeleton building), photosynthesis, and reproduction respond to the magnitude of changes in CO_2 concentrations in seawater.

•As the ocean acidifies, organisms such as corals, snails, and calcifying plankton will not be able to make their shells and grow.

•Zooplankton (Pteropod)

•Coral

•Phytoplankton (Coccolithophore)

Some Issues with lower pH

- Calcium carbonate minerals are the building blocks for the skeletons and shells of many marine organisms.
- In areas where most life now congregates in the ocean, the seawater is supersaturated with respect to calcium carbonate minerals. This means there are abundant building blocks for calcifying organisms to build their skeletons and shells.
- However, continued ocean acidification is causing many parts of the ocean to become under-saturated with these minerals, which is likely to affect the ability of some organisms to produce and maintain their shells.
- Carbonate ions are an important building block of structures such as sea shells and coral skeletons.
- Decreases in carbonate ions can make building and maintaining shells and other calcium carbonate structures difficult for calcifying organisms such as oysters, clams, sea urchins, shallow water corals, deep sea corals, and calcareous plankton.

Food Web - Fish

- The ability of certain fish, like pollock, to detect predators is decreased in more acidic waters. Recent studies have shown that decreased pH levels also affect the ability of larval clownfish to locate suitable habitat.
- When subjected to lower pH levels, the larval clownfish lost their chemosensory ability to distinguish between their favored and protective anemone habitat among the reefs and unfavorable habitats like mangroves.
- Additionally, greater acidity impairs their ability to distinguish between the "smell" of their own species and that of predators. These two factors create an increased risk of predation.
- When these organisms are at risk, the entire food web may also be at risk.

(Run Time ~ 4:26)

[A Climate Calamity in The Gulf of Maine Part 2: Acid in the Gulf]

Is there any advantage to higher CO2 levels in our oceans?

- While some species will be harmed by ocean acidification, <u>photosynthetic algae and seagrasses may benefit from higher CO_2 conditions in the ocean</u>, as they require CO_2 to live just like plants on land.

Our Oceans' Futures

- Estimates of future carbon dioxide levels, based on "business as usual" emission scenarios, indicate that by the end of this century the surface waters of the ocean could be nearly 150% more acidic, resulting in a pH that the oceans haven't experienced for more than 20 million years.
- Ocean acidification is currently affecting the entire world's oceans, including coastal estuaries and waterways.
- Today, more than a billion people worldwide rely on food from the ocean as their primary source of protein.
  - Approximately 20% of the world's population derives at least 1/5 of its animal protein intake from fish.
  - Many jobs and economies in the U.S. and around the world depend on the fish and shellfish that live in the ocean.

What is Next?

It is currently impossible to predict exactly how ocean acidification impacts will cascade throughout the marine food chain and affect the overall structure of marine ecosystems. With the pace of ocean acidification accelerating, scientists, resource managers, and policymakers recognize the urgent need to strengthen the science as a basis for sound decision making and action.

CO_2 sequestration is required.