Fundamentals of Earth Sciences (ESO 213A)

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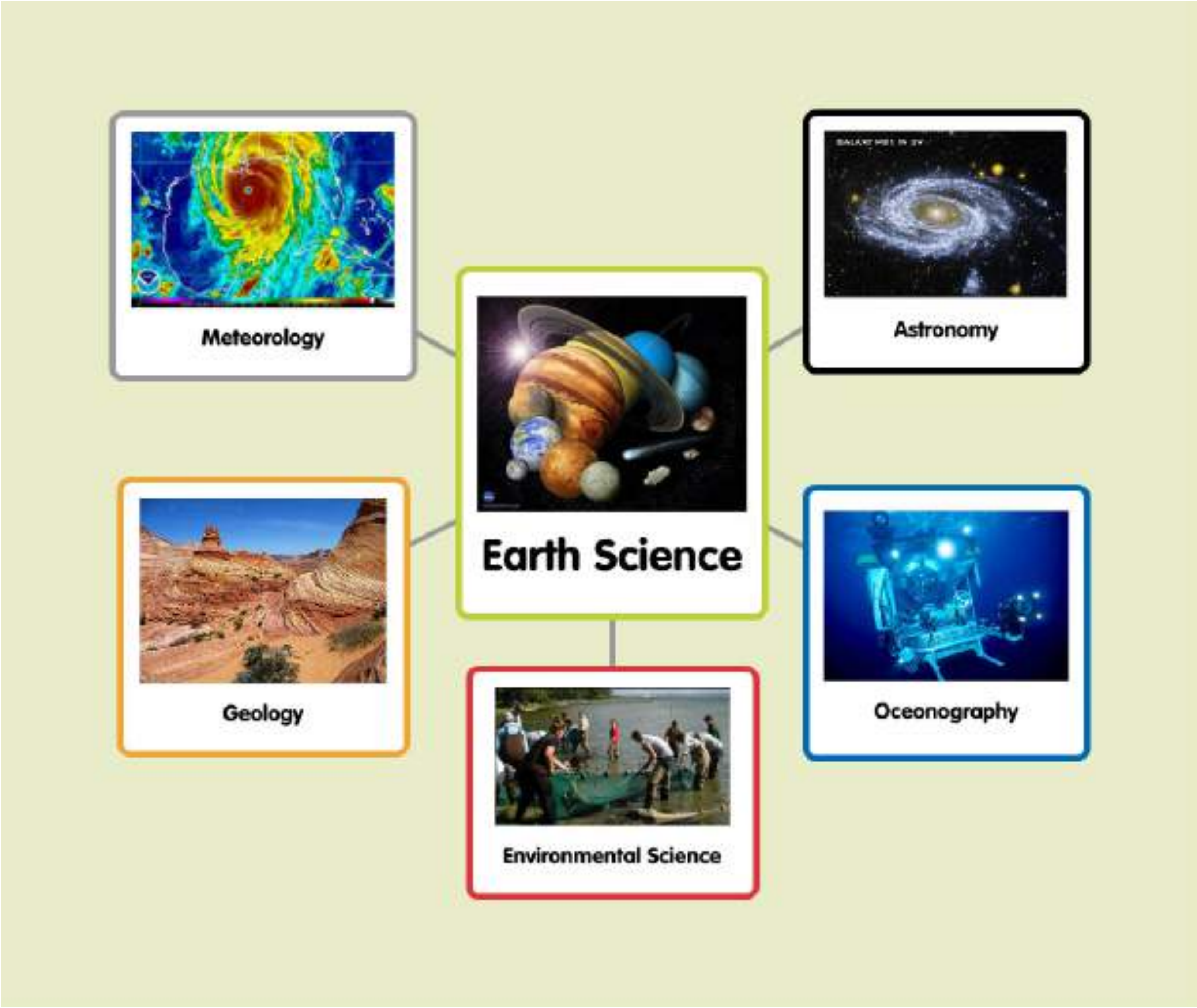
Department of Earth Sciences

Earth Science or Geoscience explains the physical, chemical, and biological processes associated with the planet Earth.

It has major 5 branches:

- Geology
- Meteorology
- Oceanography
- Astronomy
- Environmental Sciences

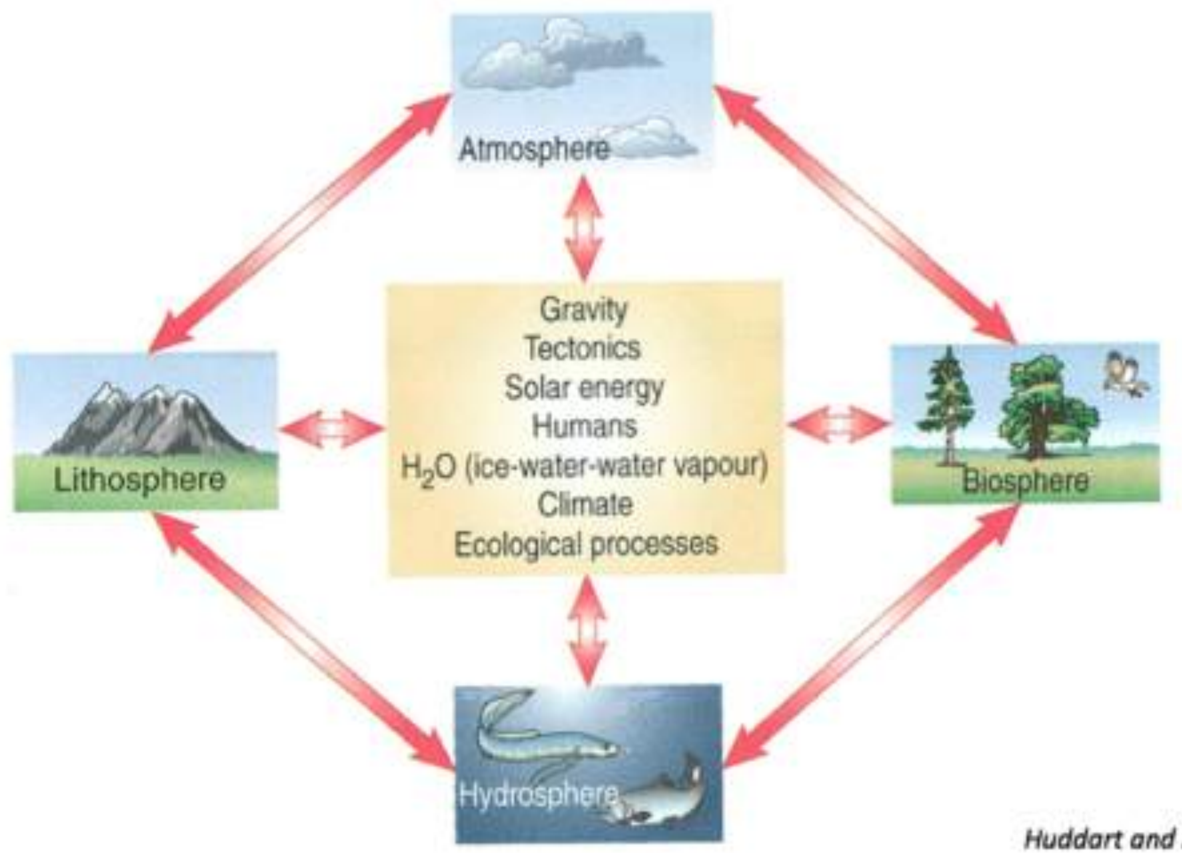
This subject establishes interaction among Geosphere, Biosphere, Atmosphere and Hydrosphere



Why study Earth Science?

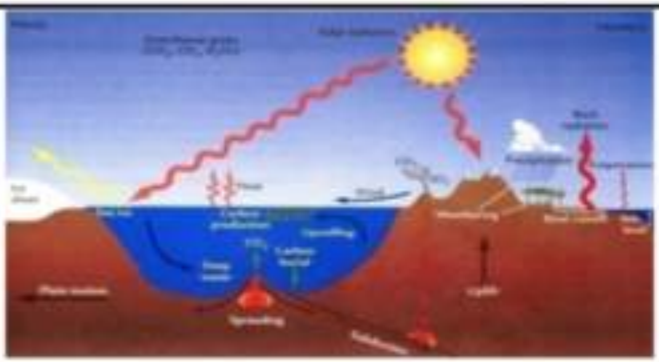
- Understand natural disaster (earthquake, tsunami, hurricane, volcanic eruption, flood......)
- Understand the environment, particularly climate change and its consequences
- Understand, quantify, and predict occurrence of natural resources (precious metals, coal, petroleum, natural gas, ground water...)
- Investigate the strength of bedrock to support roads, dams, tunnels.

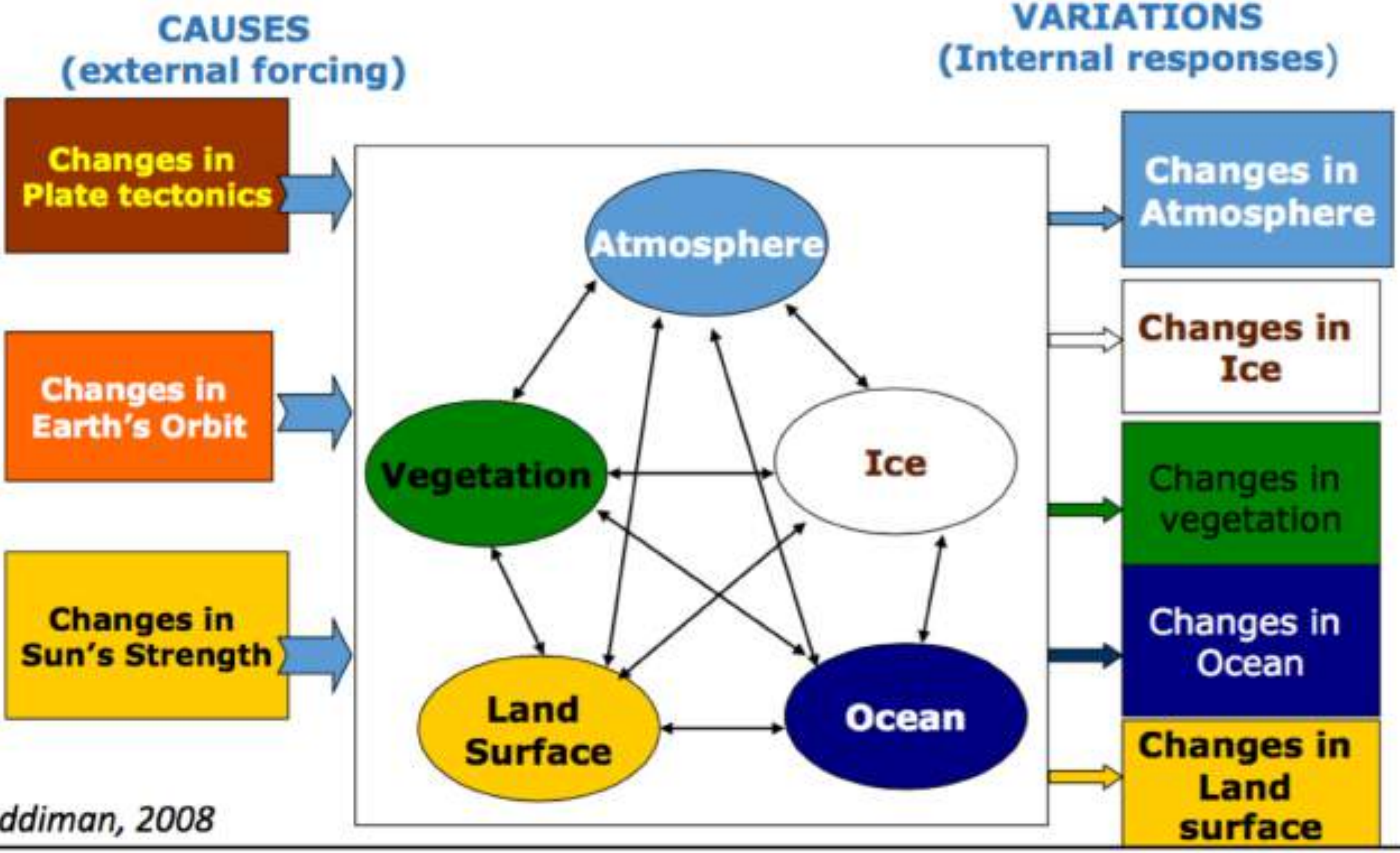
Components of the Earth's system



Huddart and Stott, 2010

Climate Forcing and Responses of Earth Systems

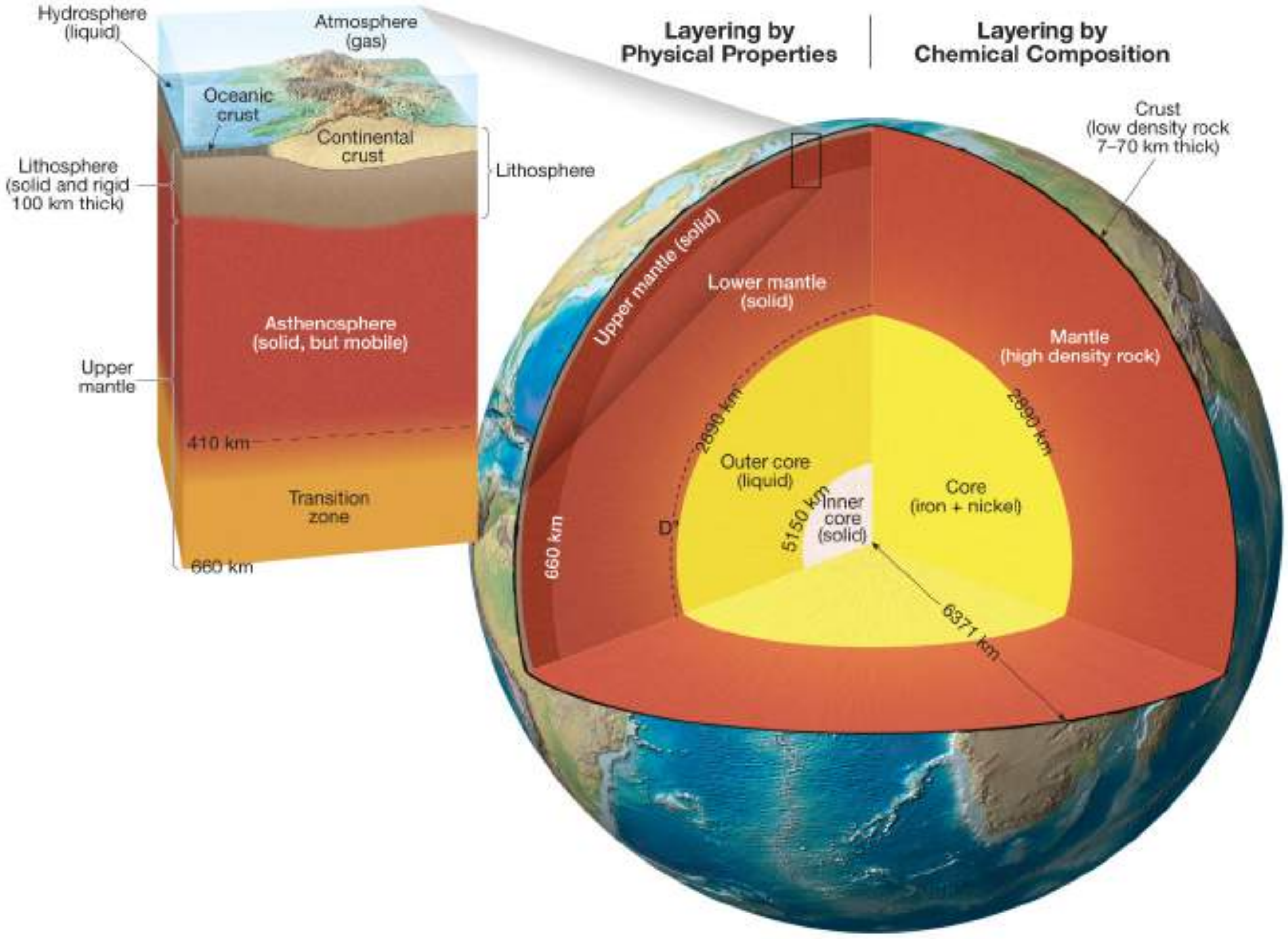




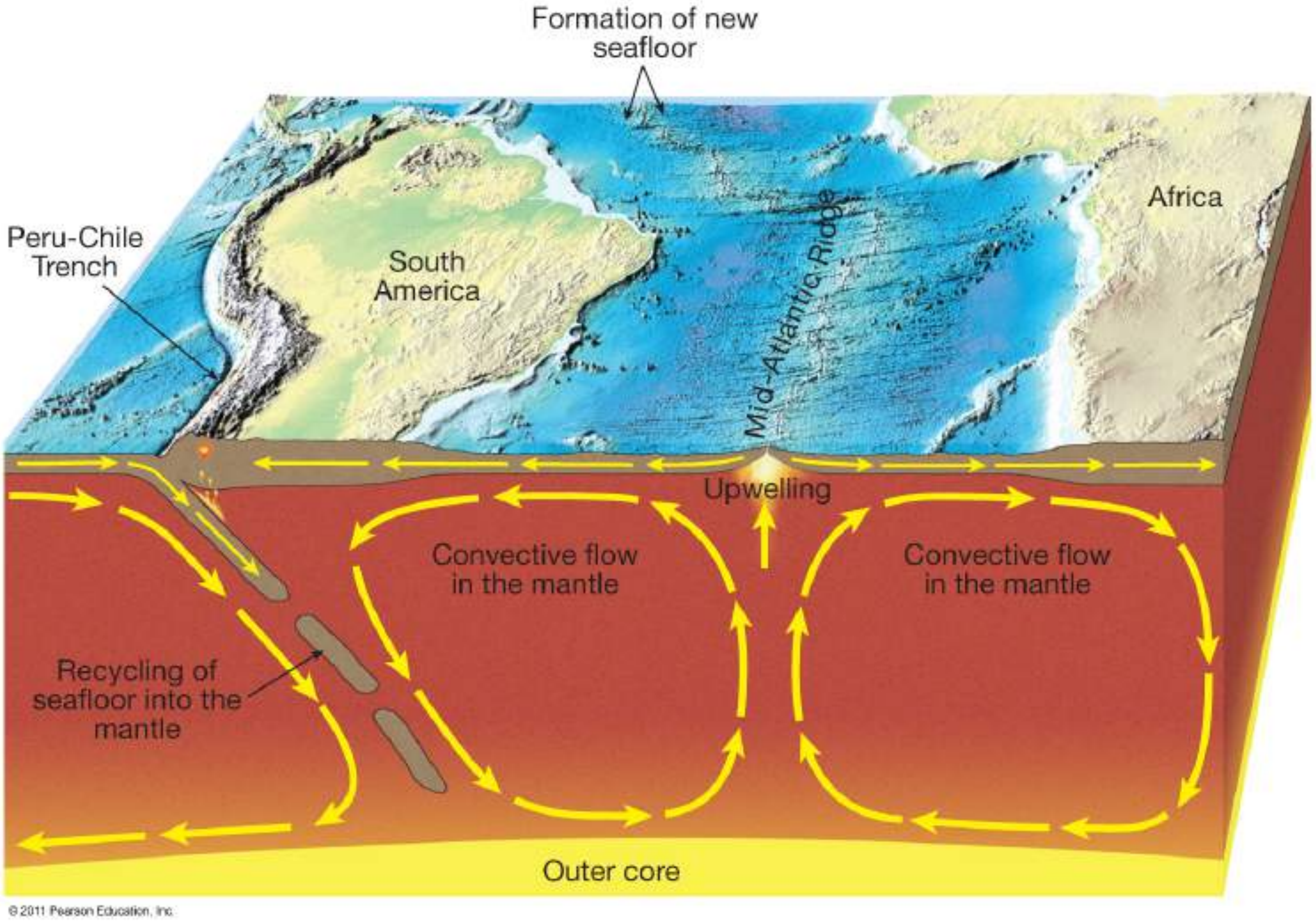
Ruddiman, 2008

Some Questions??

How does Earth's internal structure look like??

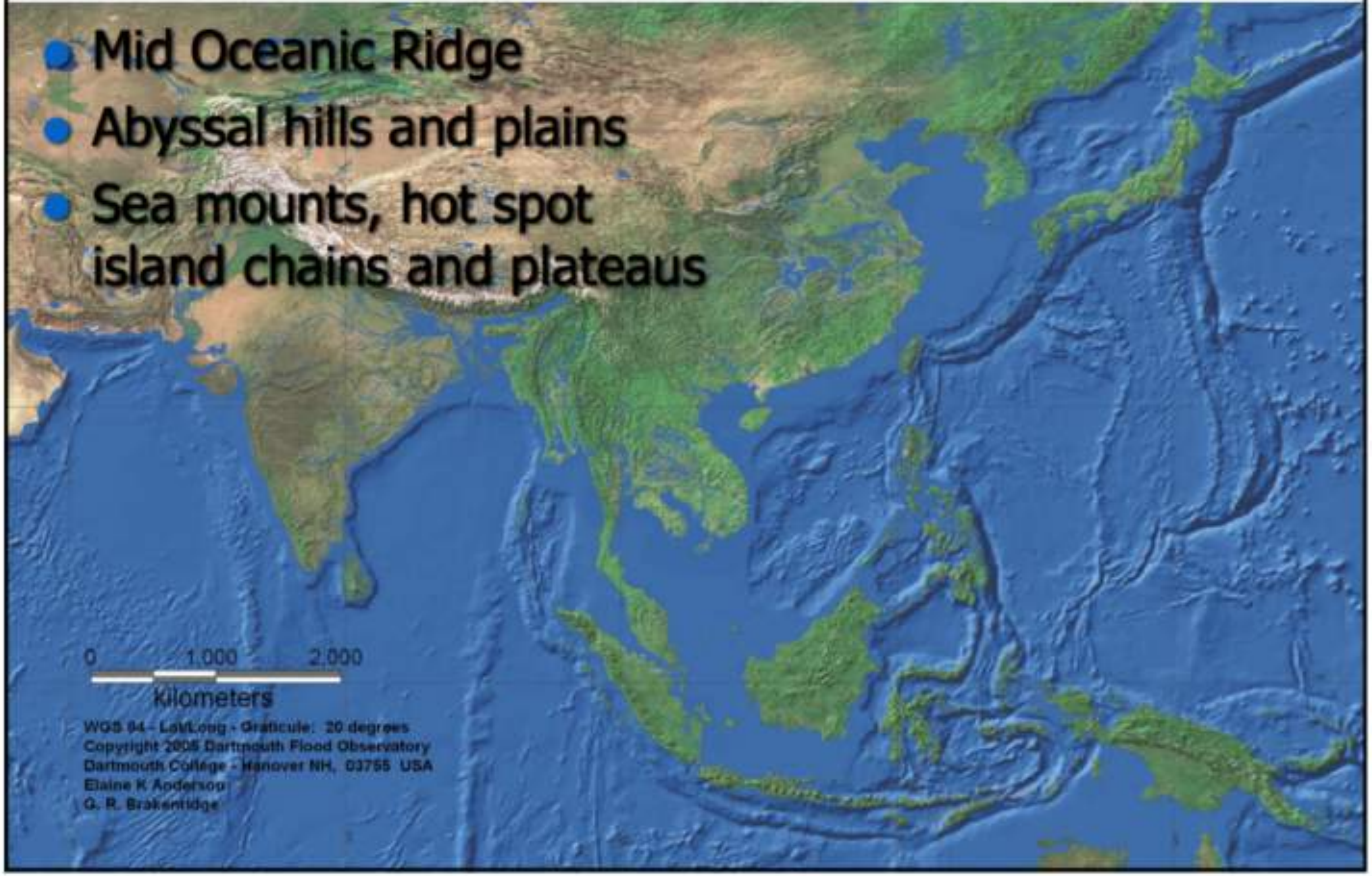


How do continents and ocean form ?

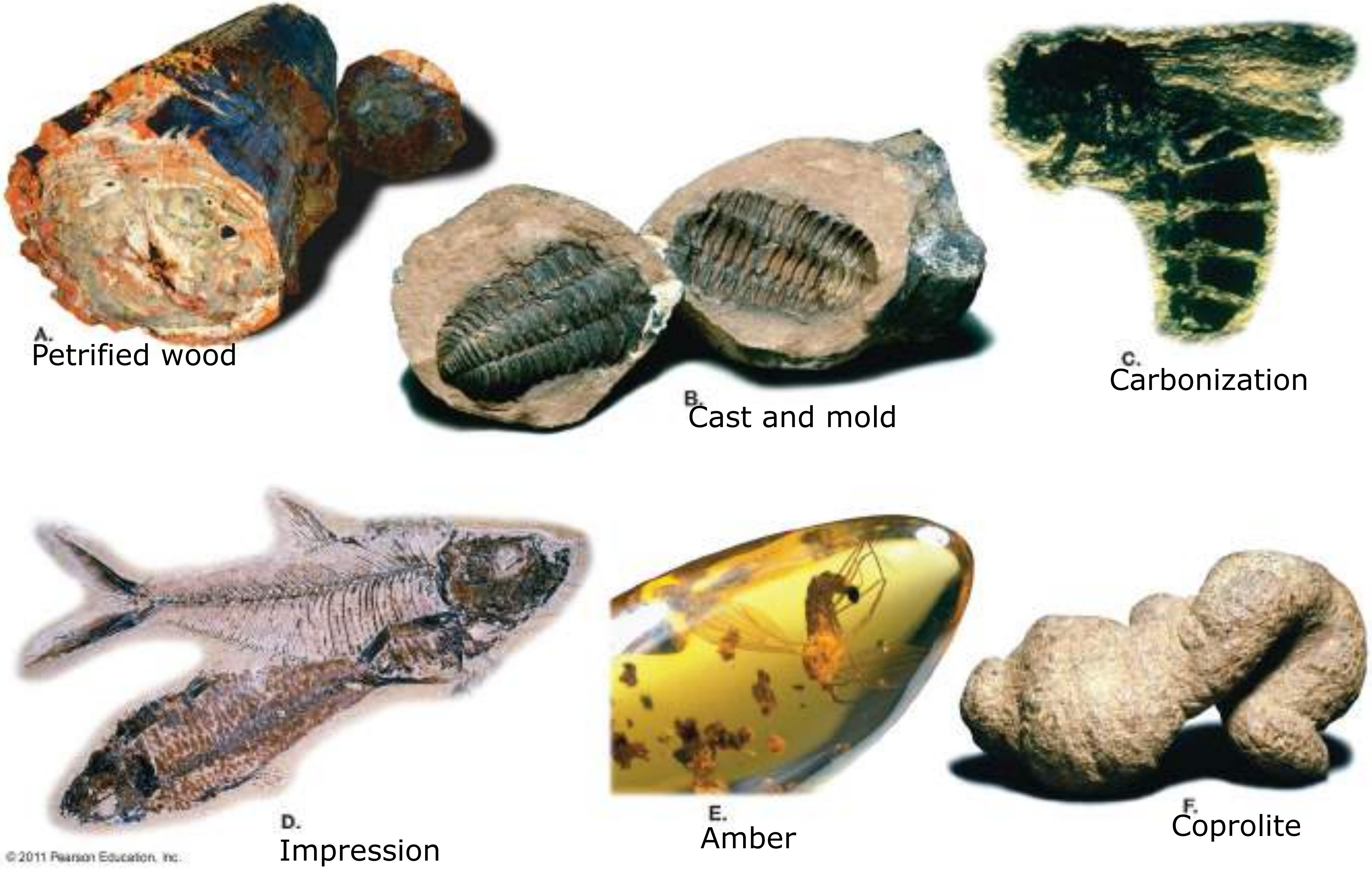


The sea floor is not flat

- Mid Oceanic Ridge
- Abyssal hills and plains
- Sea mounts, hot spot island chains and plateaus



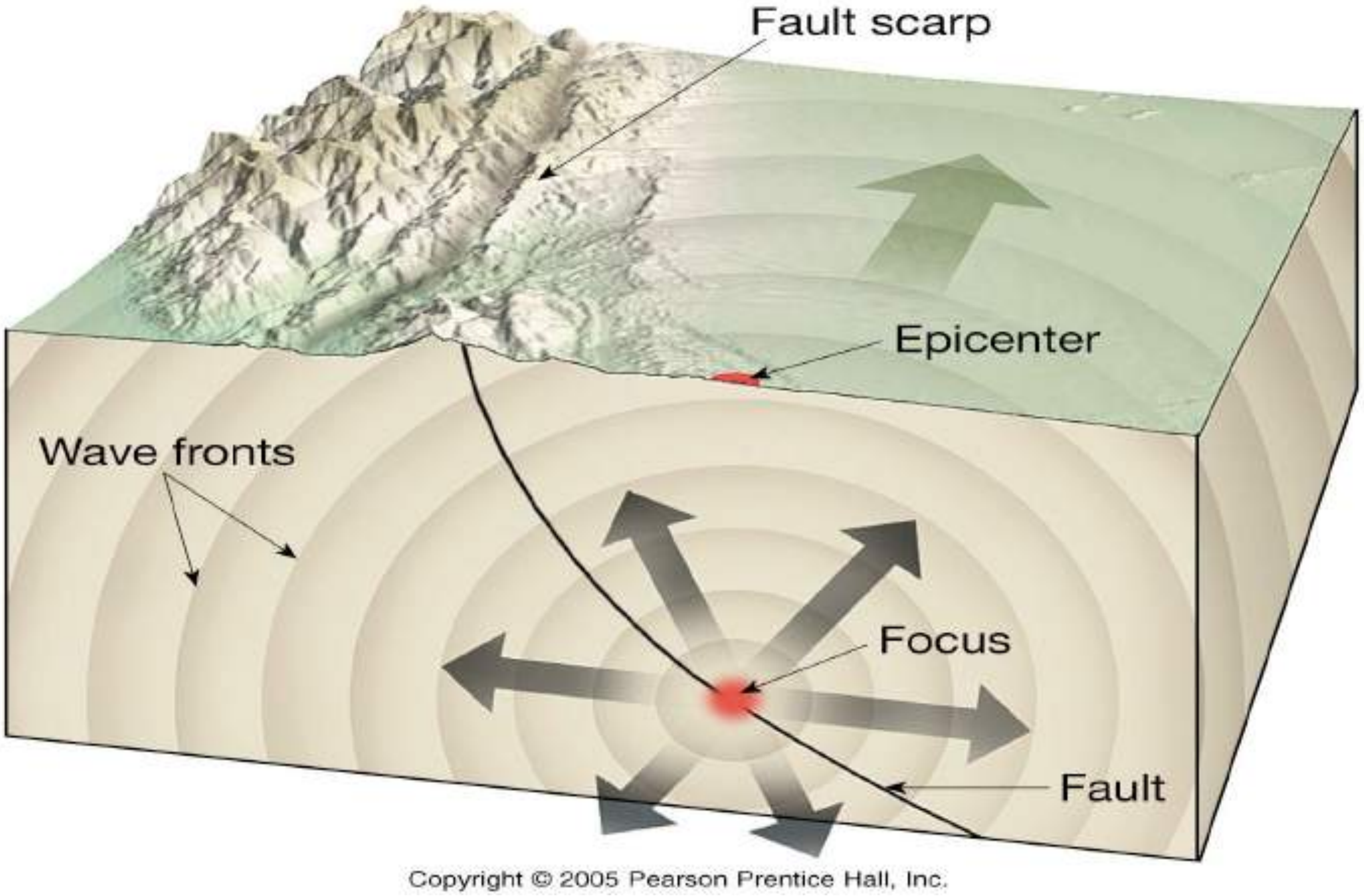
How did life evolve on Earth??



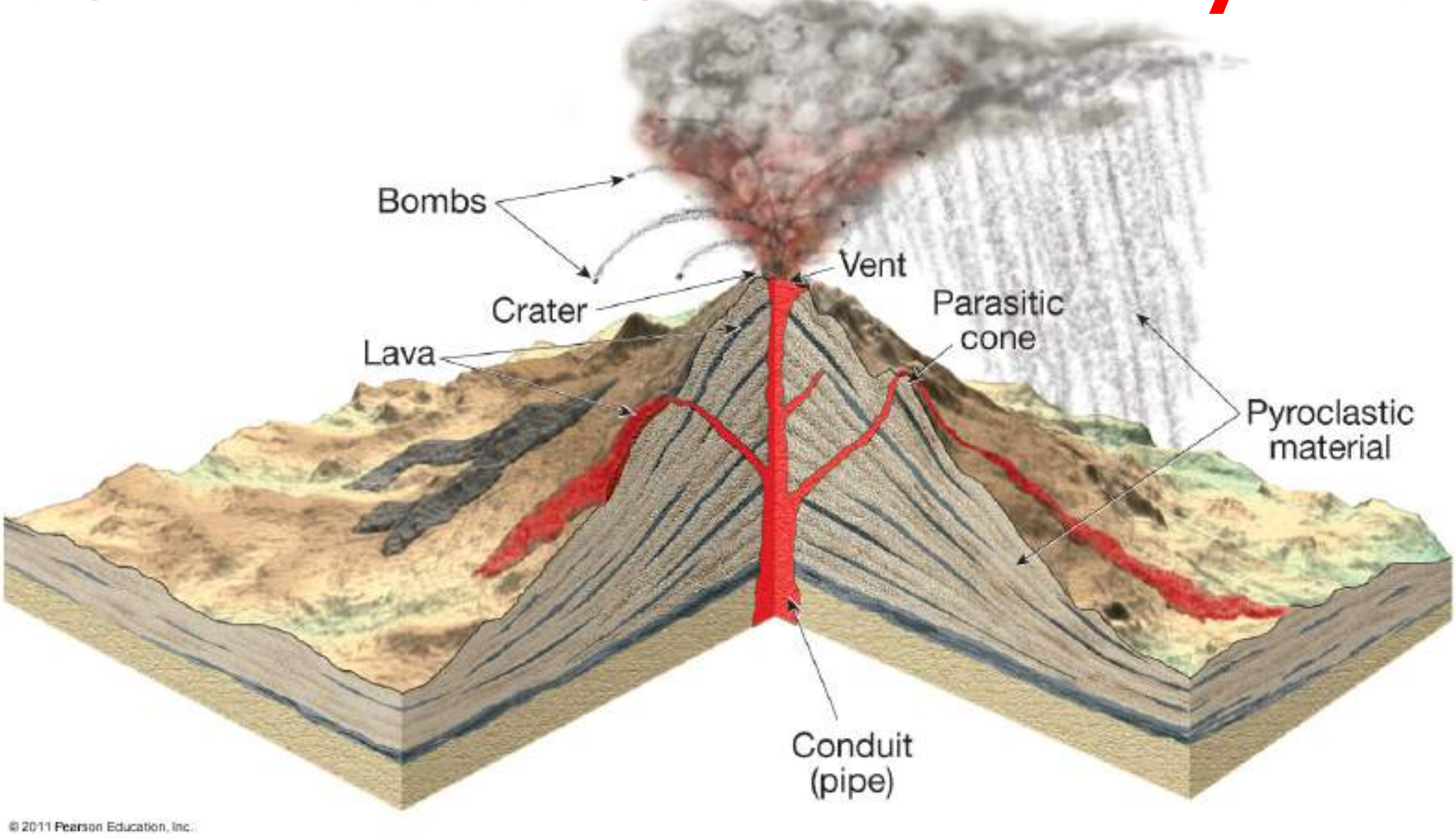

What are the processes that result in first order relief of the Earth's surface?
500 KM
Tibetan Plateau
Himalaya
Himalayan Front
Indo-Gangetic Plains
India

What can cause earthquakes??

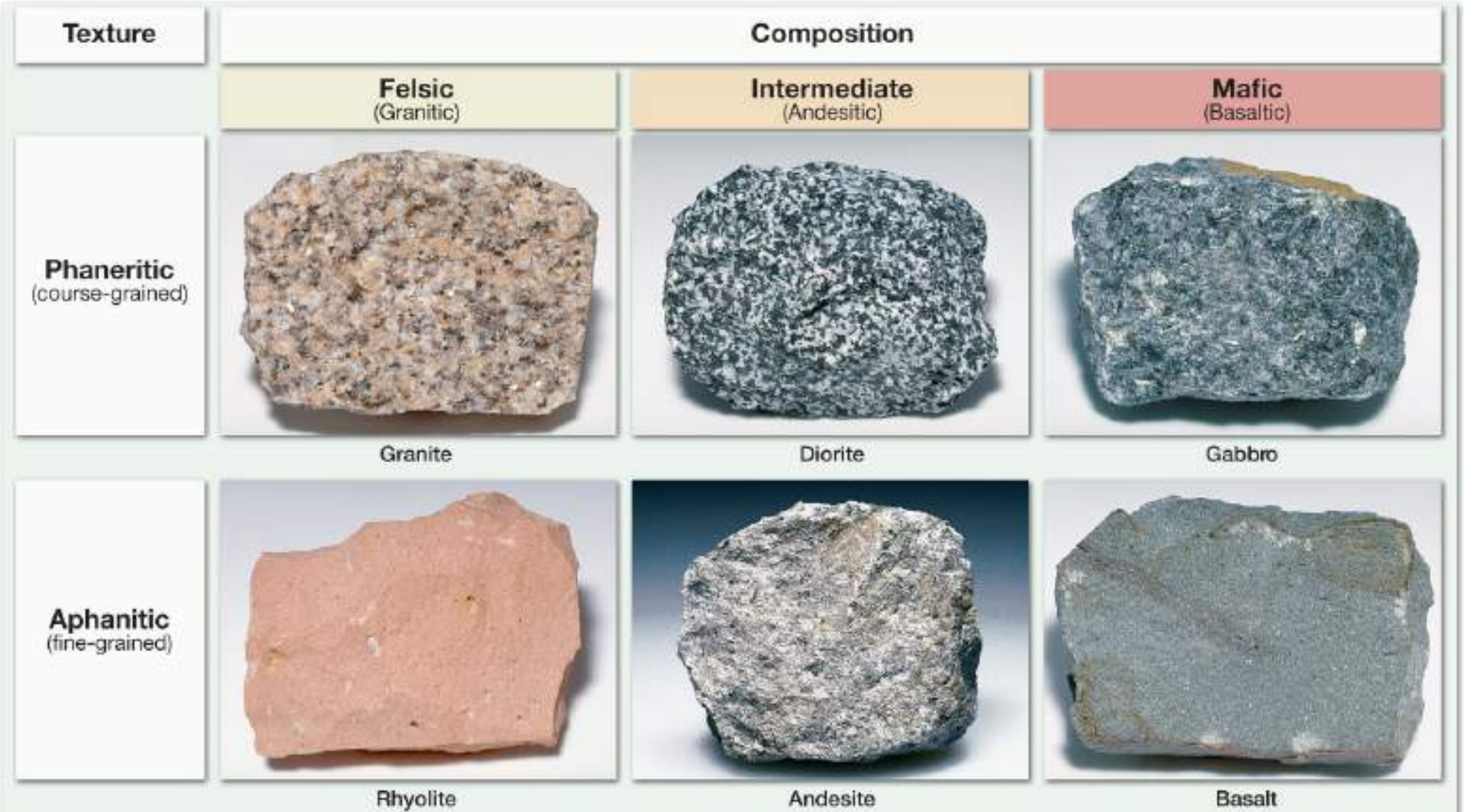
Can we use the earthquake energy and reveal buried information?



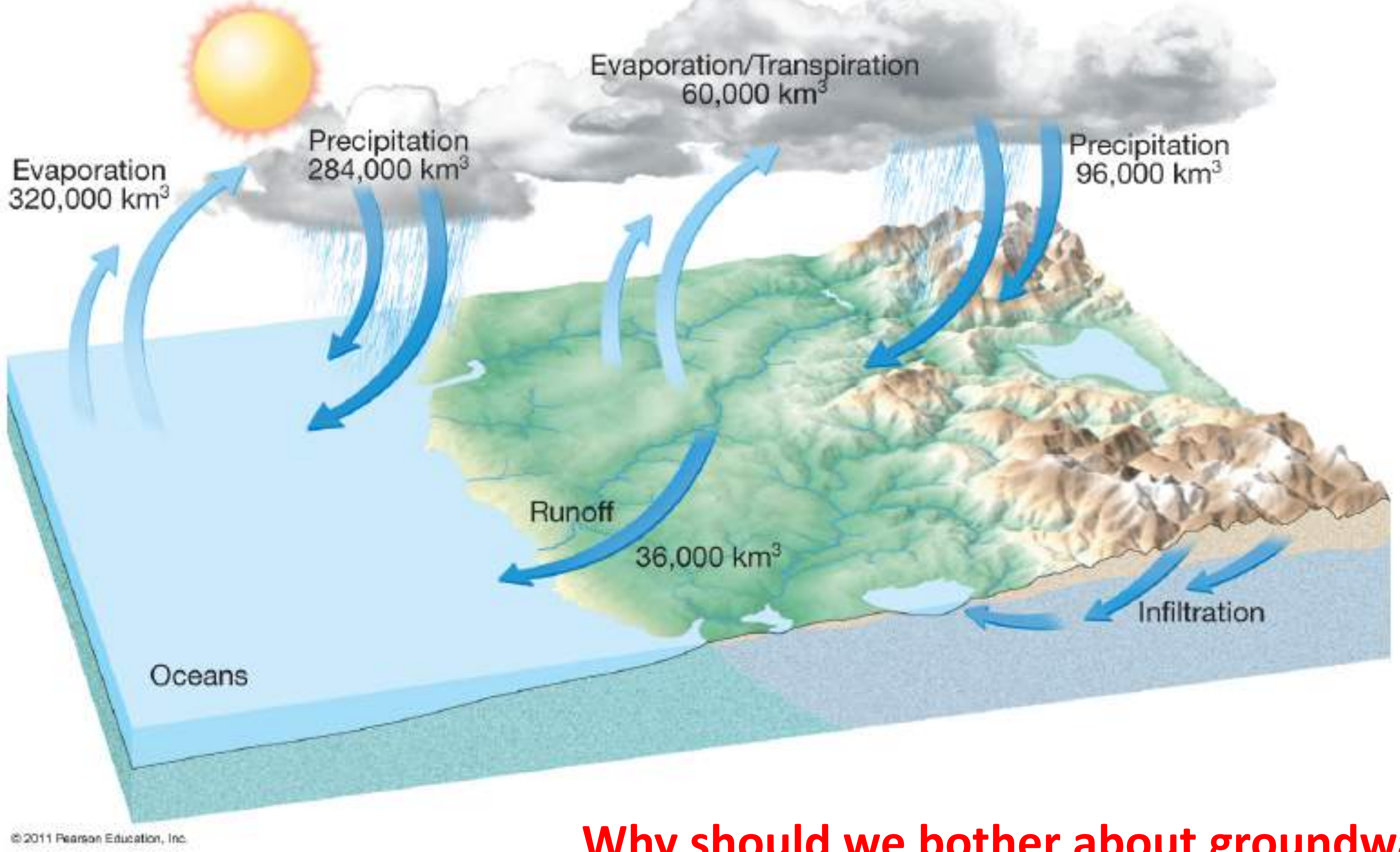
Are volcanoes important?
Why don't we see volcanism everywhere ?



Why do we see different types of rocks? Do they originate from same process?



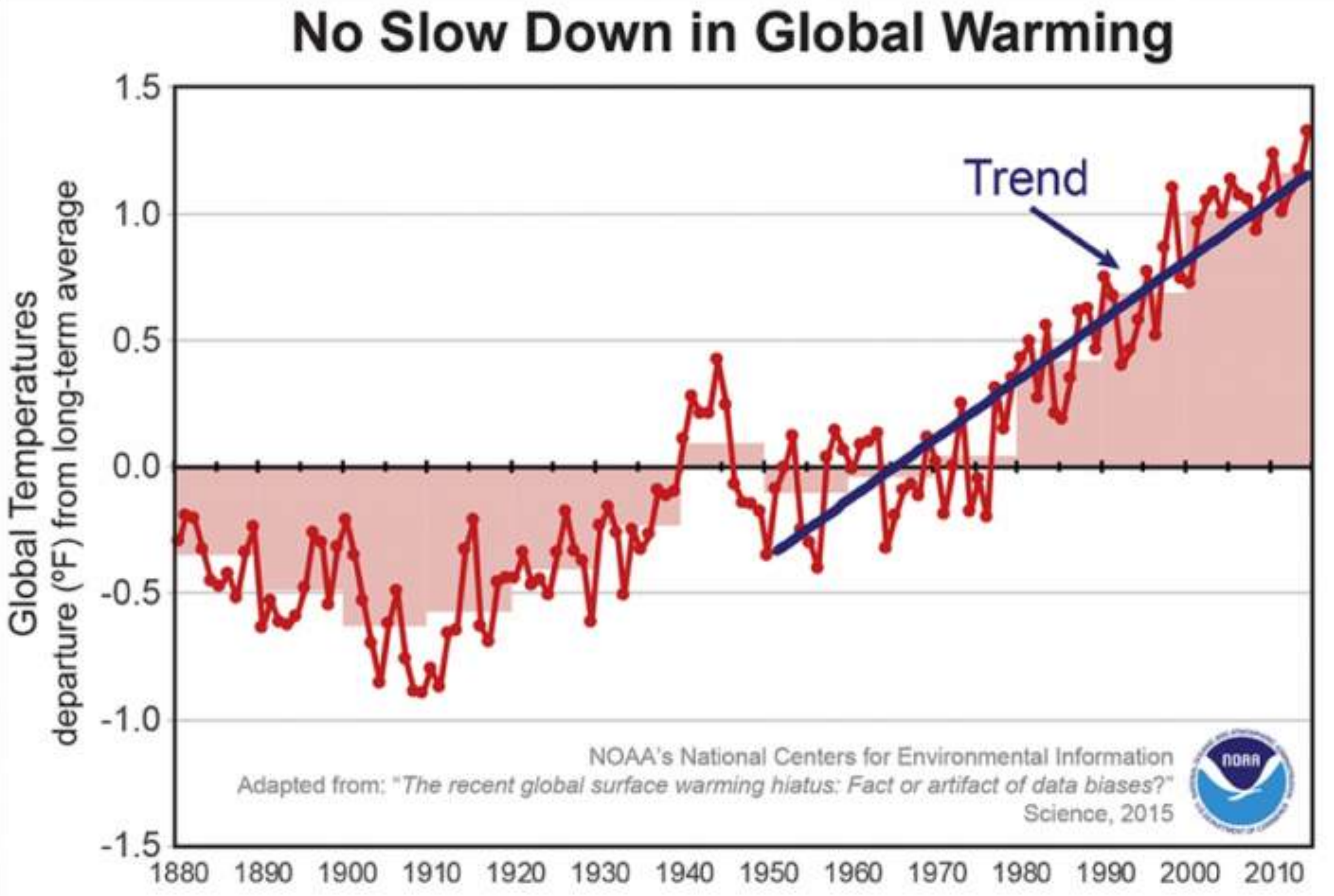
How does Earth's hydrological cycle work?



Why should we bother about groundwater?

How do landscapes influence and record climate and tectonics?

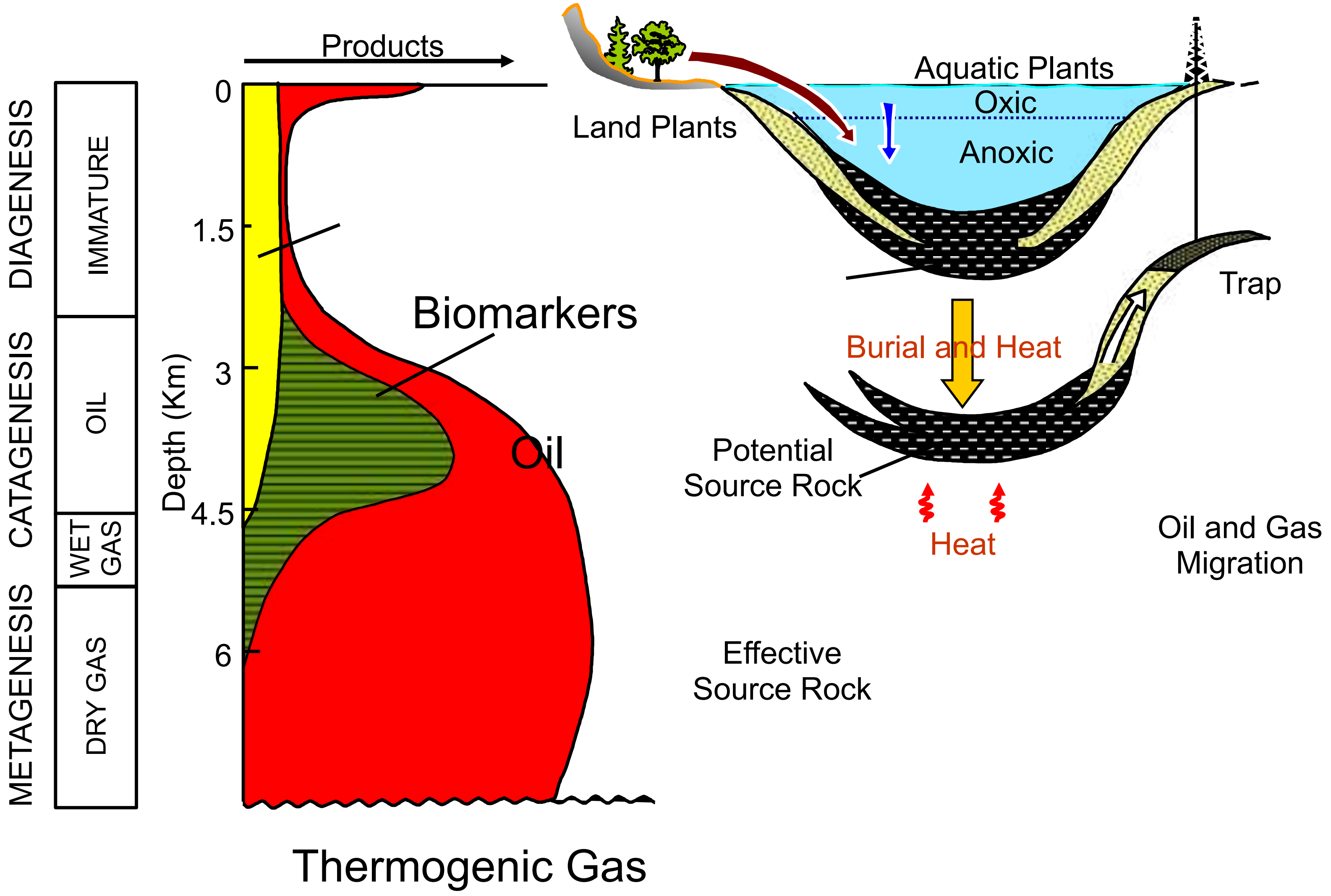
Is there any way to know about the paleoclimate and cycles of past global cooling and warming ?



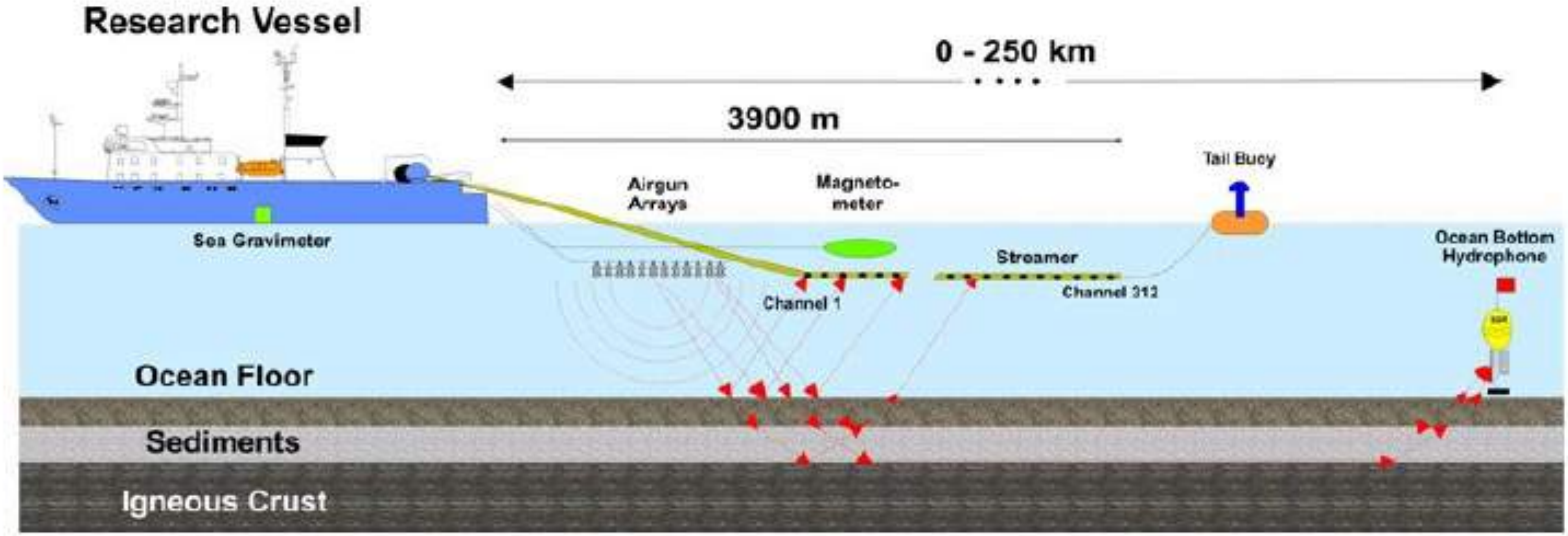
Contrary to much recent discussion, the latest corrected analysis shows that the rate of global warming has continued, and there has been no slow down.

How does a hydrocarbon reservoir look like? Is there any alternative to fossil fuel???

Biogenic Gas/Petroleum/Thermogenic Gas Formation



How can we explore buried structures????



In a nutshell, this subject offers you to *explore*:

mountains to rivers & lakes to Glacier, Deserts, active volcanoes and deep ocean and natural resources and many more ……….

I enjoy this subject, because I love travelling ☺

Joides Resolution

Content

Date	Day	Topics (tentative)
29-Jul	Fri	Introduction
01-Aug	Mon	Universe and Solar System
03-Aug	Wed	Origin of Earth, Moon and Atmosphere
05-Aug	Fri	Internal structure of Earth Assignment 1: Watch the science fiction drama “The Core (2003)”
08-Aug	Mon	Internal structure of Earth continued
10-Aug	Wed	Plate Tectonics
12-Aug	Fri	Divergent boundaries, Convergent and Transform Boundaries
15-Aug	*Mon*	*National Holiday (No class)*
17-Aug	Wed	Magma and Igneous Rocks
19-Aug	*Fri*	*National Holiday (No class)*
22-Aug	Mon	Intrusive Activities and Volcanoes
24-Aug	Wed	Metamorphic rocks
26-Aug	Fri	Sedimentary rocks
29-Aug	Mon	Earth’s history and Geological Time Scale
31-Aug	Wed	Geologic time scale and Radioactive dating
02-Sep	Fri	Quiz 1 Assignment 2: Watch “Jurassic Park (1993)”
05-Sep	Mon	Crustal Deformation
07-Sep	Wed	Earthquakes
09-Sep	Fri	Earthquakes continued
12-Sep	Mon	Landslide
14-Sep	Wed	Instrumentation
16-Sep	Fri	Revision/Discussion Assignment 3: Watch “San Andreas (2015)”
19-23 Sep	**Mid Semester week**	
26-Sep	Mon	Hydrological Cycles and Glacier
28-Sep	Wed	Cryosphere
30-Sep	Fri	Groundwater
03-09 Oct	*Mon*	*Mid semester Recess (No classes)*
10-Oct	Mon	Rivers and Oceans
12-Oct	Wed	Oceans continued
14-Oct	Fri	Earth surface processes (Weathering and Soil) Assignment 4: Watch “Dante’s Peak (1997)”
17-Oct	Mon	Desserts and winds
19-Oct	Wed	Climate system and Greenhouse effect
21-Oct	Fri	Fossil-Fuels
24-Oct	*Mon*	*Restricted Holiday*
26-Oct	Wed	Alternate energy
28-Oct	Fri	Quiz2 Assignment 5: Watch “The day after tomorrow (2004)”
31-Oct	Mon	Geophysical techniques: Imaging subsurface-1
02-Nov	Wed	Geophysical techniques: Imaging subsurface-2
04-Nov	Fri	Geophysical techniques: Imaging subsurface-3
07-Nov	Mon	Geophysical techniques: Imaging subsurface-4
09-Nov	Wed	Geophysical techniques: Imaging subsurface-5
11-Nov	Fri	Geophysical techniques: Imaging subsurface-6
17-26 Nov	**End Semester examination**	

Please read at your leisure 'Deception point by Dan Brown' and 'Journey to the centre of the Earth by Jule Varne'

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Textbook and reading:

Please follow the power point presentations and lecture notes from class. You can also consult the following books

- E. J. Tarbuck, F. K. Lutgens and D. G. Tasa. Earth: An Introduction to Physical Geology, 2013 (11th Ed.). Prentice Hall. 912 p.
- D. R. Prothero and R. H. Dott, Jr. Evolution of the Earth. 2010 (8th Ed.), McGraw Hill, 576 p.
- J. Grotzinger and T. Jordan, Understanding Earth, 2010 (6th Ed.). Freeman, 710 p.

GRADING POLICY

I will follow the system of Relative Grading. Marks will be distributed as per the table –

Quiz (open notes/books/internet).	*30*
Mid Term	*30*
Final Term	*40*

There will 2 announced quizzes of 30 marks. Don’t miss your quizzes, as there will be no make up quizzes. Quizzes will be an open book; notes and you are free to use the Internet as well. Mid term and Final term will cover 70 marks in total. Remember both Mid term and final term will be closed book examination.

NO MARKS on ATTENDENCE

FUNDAMENTALS OF EARTH SCIENCES (ESO 213A)

DIBAKAR GHOSAL
DEPARTMENT OF EARTH SCIENCES

Lecture: Solar System and Origin of Earth

'we are stardasts'

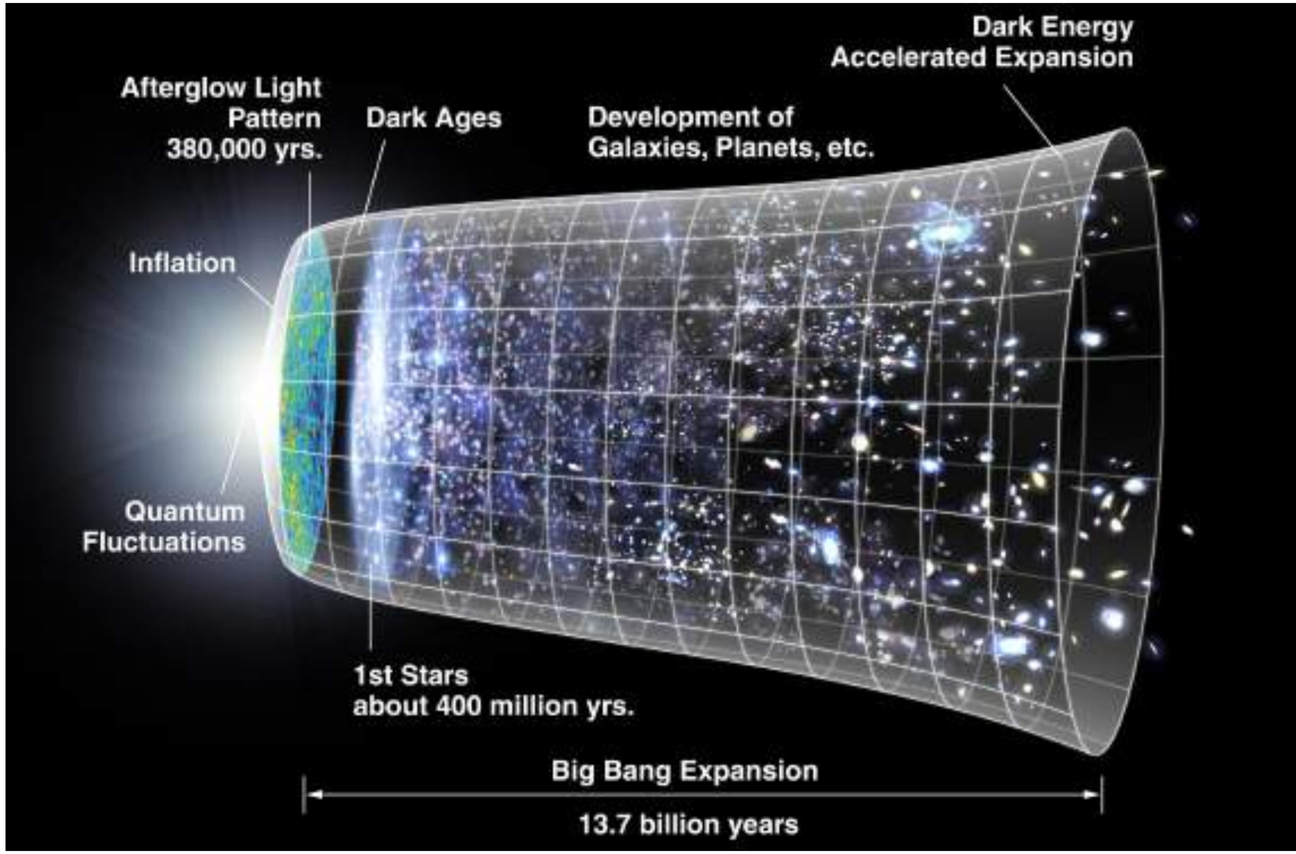
Origin of the Universe

The universe began about ~13.7 billion years ago

The **Big Bang Theory** states that, <u>in the beginning, the universe was all in one place</u>

<u>All of its matter and energy were squished into an infinitely small point</u> (smaller than atom), and then it exploded. In millionth of a millionth second from smaller than a size of atom to galaxy!

After about <u>10 billion years</u>, our <u>solar system began</u> to form



Source: Nasa.gov

The Big Bang mainly created H and He, and the first stars were formed (but still no planets)

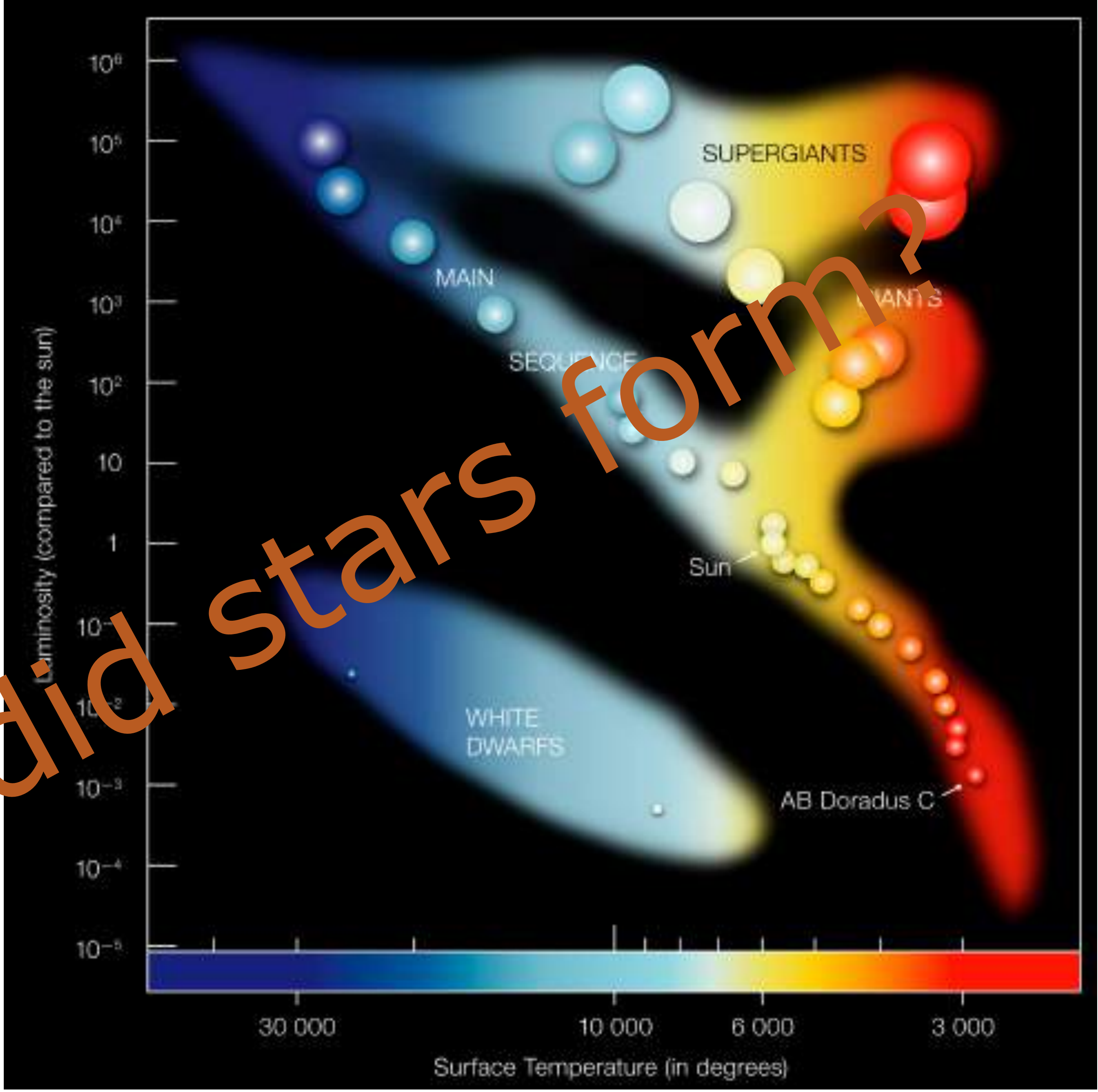
Hertzprung-Russel (H-R) diagram

Most stars, including the sun, are "main sequence stars," fueled by nuclear fusion converting hydrogen into helium.

•As stars begin to die, they become giants and supergiants. These stars have depleted their hydrogen supply and are very old. The core contracts as the outer layers expand. These stars will eventually explode (becoming a planetary nebula or supernova, depending on their mass) and then become white dwarfs, neutron stars, or black holes (again depending on their mass).

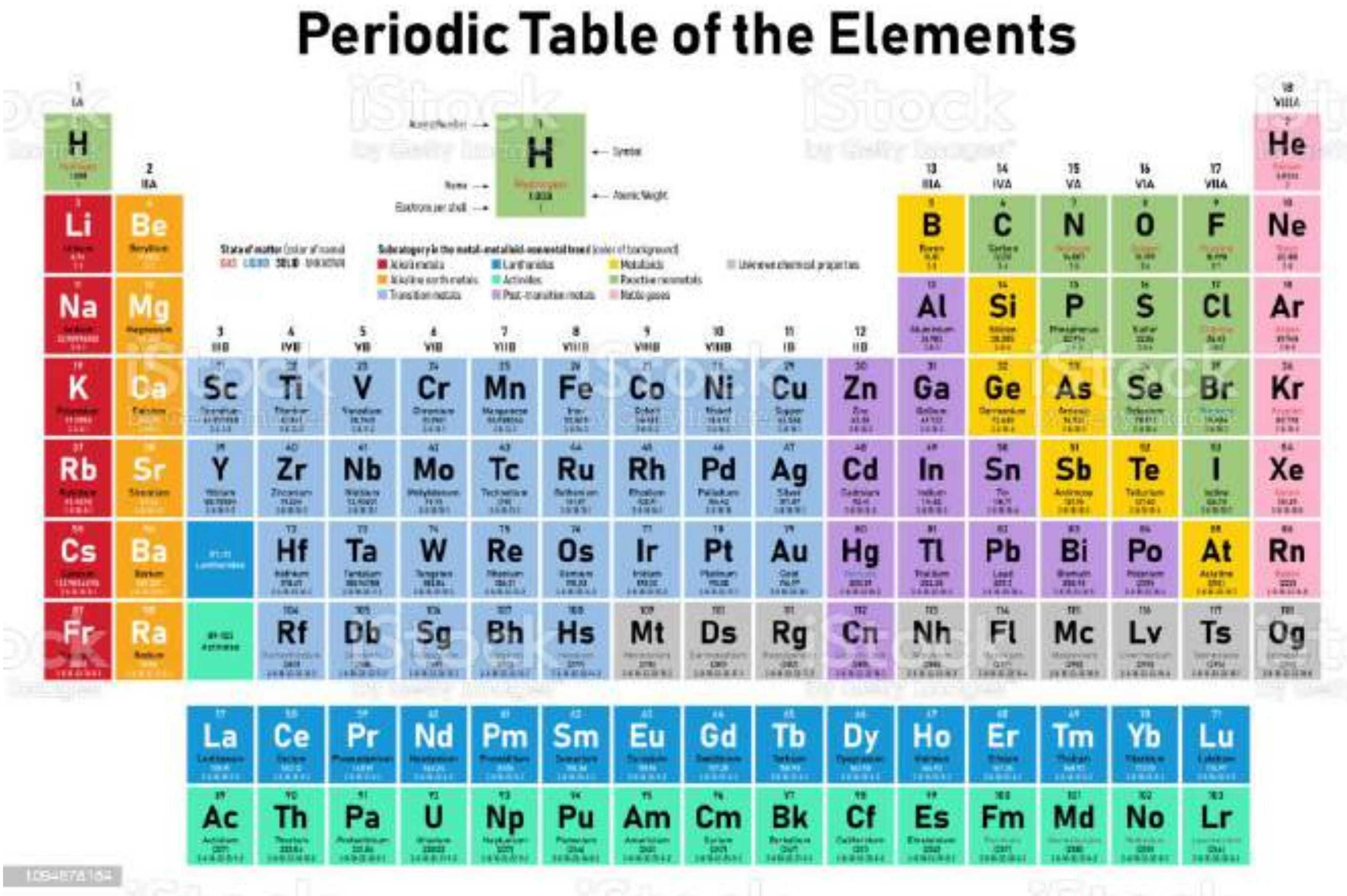
Smaller stars (like our Sun) eventually become faint white dwarfs (hot, white, dim stars) that are below the main sequence.

How did stars form?



Luminosity is the total amount of energy that a star radiates each second

How did elements form?



Nucleosynthesis

Nucleosynthesis is the process that creates new atomic nuclei from pre-existing nucleons and nuclei.

Time	T (K)	Density
10^-43 (s)	10^32	10^96
10^-35 (s)	10^28	10^80
10^-13 (s)	10^16	10^32
15s	3x10^9	10^4
3min	10^9	10^2
10^5 y	4000	10^-20
10^9 y	18	10^-27
13.6x 10^9	2.73	10^-30

1. Big Bang/ Primordial Nucleosynthesis:

According to current theories, the first nuclei were formed a few minutes after the Big Bang.
At the beginning, the universe was only made of "elementary particles", protons, neutrons do not exist, they were not stable (too hot!).
After 10^{-4} seconds temperature was cool enough to form protons and neutrons
After 3 minutes the universe was cool enough to produce ^2H (proton and neutron combined)

2. Stellar Nucleosynthesis:

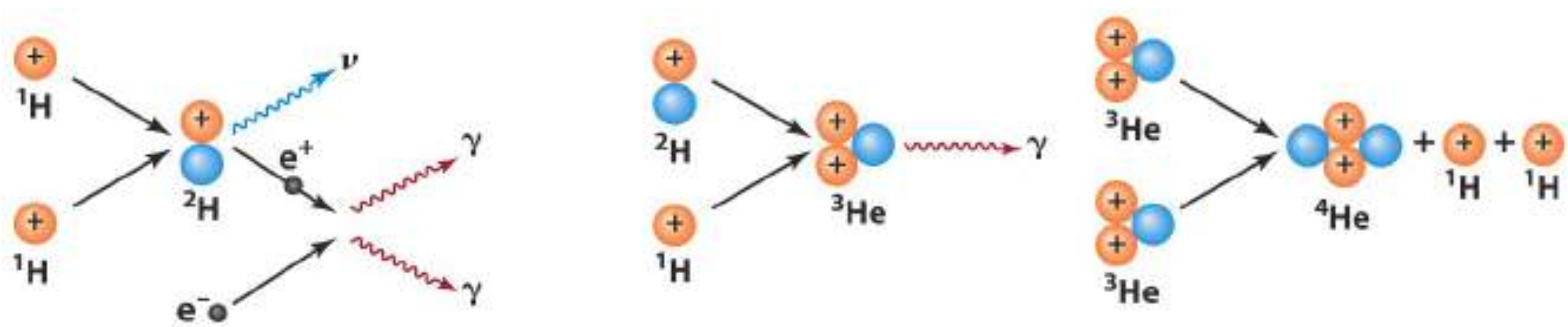
Stellar Nucleosynthesis started more than 12 billion years ago.

Stars are not only the source of light, its an element factory!

Nucleosynthesis

Star "turns on" when nuclear fusion occurs

main sequence star – either proton-proton chain or CNO cycle nucleosynthesis



(a) Step 1:

- Two protons (hydrogen nuclei, ^{1}H) collide.
- One of the protons changes into a neutron (shown in blue), a neutral, nearly massless neutrino (ν), and a positively charged electron, or positron (e^+).
- The proton and neutron form a hydrogen isotope (^{2}H).
- The positron encounters an ordinary electron (e^-), annihilating both particles and converting them into gamma-ray photons (γ).

(b) Step 2:

- The ^{2}H nucleus from the first step collides with a third proton.
- A helium isotope (^{3}He) is formed and another gamma-ray photon is released.

(c) Step 3:

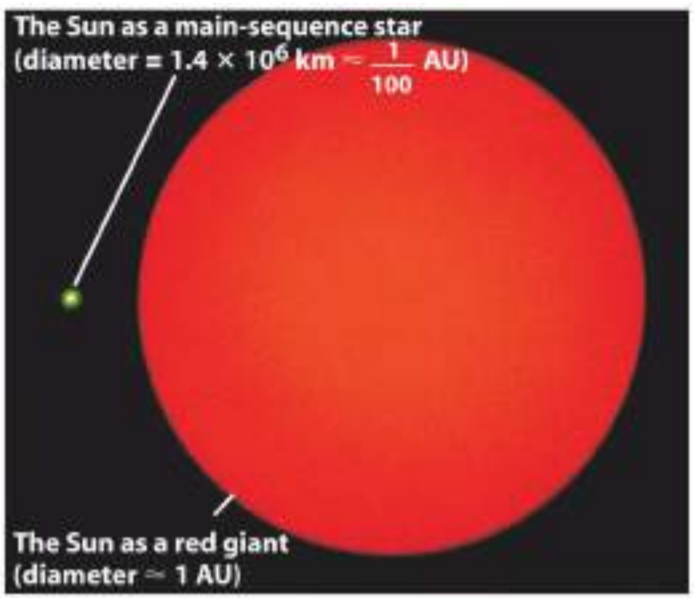
- Two ^{3}He nuclei collide.
- A different helium isotope with two protons and two neutrons (^{4}He) is formed and two protons are released.

P-P chain net: 4 H to 1 He

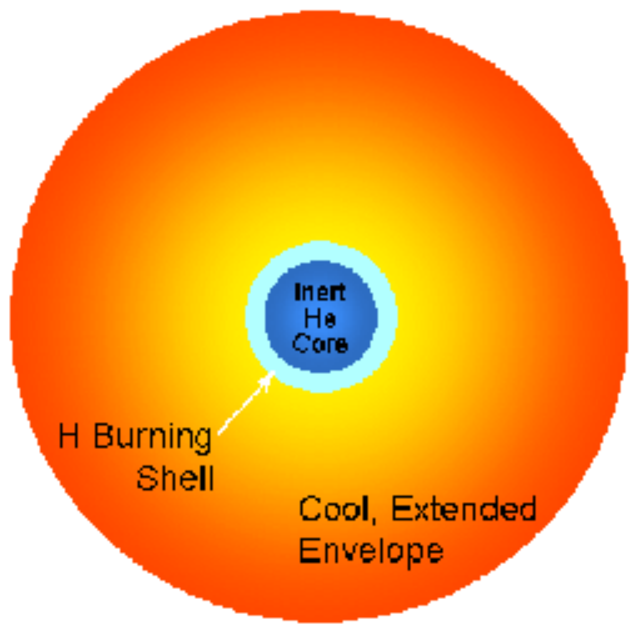
So, what happens when the core runs out of hydrogen?

- Star begins to collapse, heats up
- Core contains He, continues to collapse
- But H fuses to He in shell– greatly inflating star

→ RED GIANT (low mass)
or SUPERGIANT (high mass)



The Sun today and as a red giant



Red Giant (RGB) star: H burning in shell

CNO cycle – more efficient method, but requires higher internal temperature, so only for **stars with mass higher than 1.1 solar masses**

$^{12}C + p \rightarrow {}^{13}N$ $\qquad$ $^{13}N \rightarrow {}^{13}C$

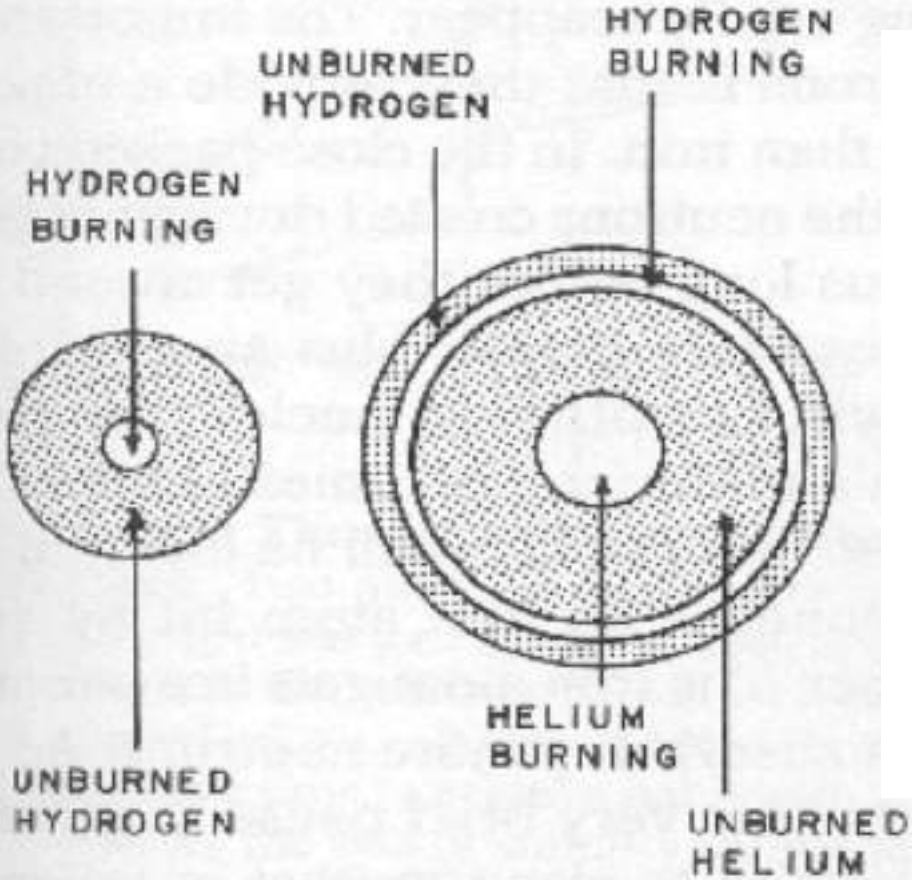
$^{13}C + p \rightarrow {}^{14}N$

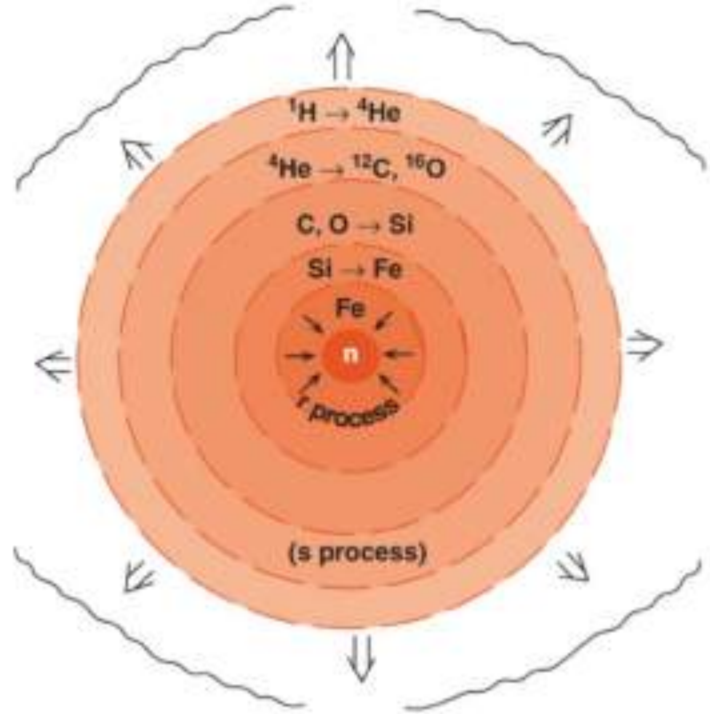
$^{14}N + p \rightarrow {}^{15}O$ $\qquad$ $^{15}O \rightarrow {}^{15}N$

$^{15}N + p \rightarrow {}^{12}C + {}^{4}He$

CNO cycle net reaction : 4 H to 1 He

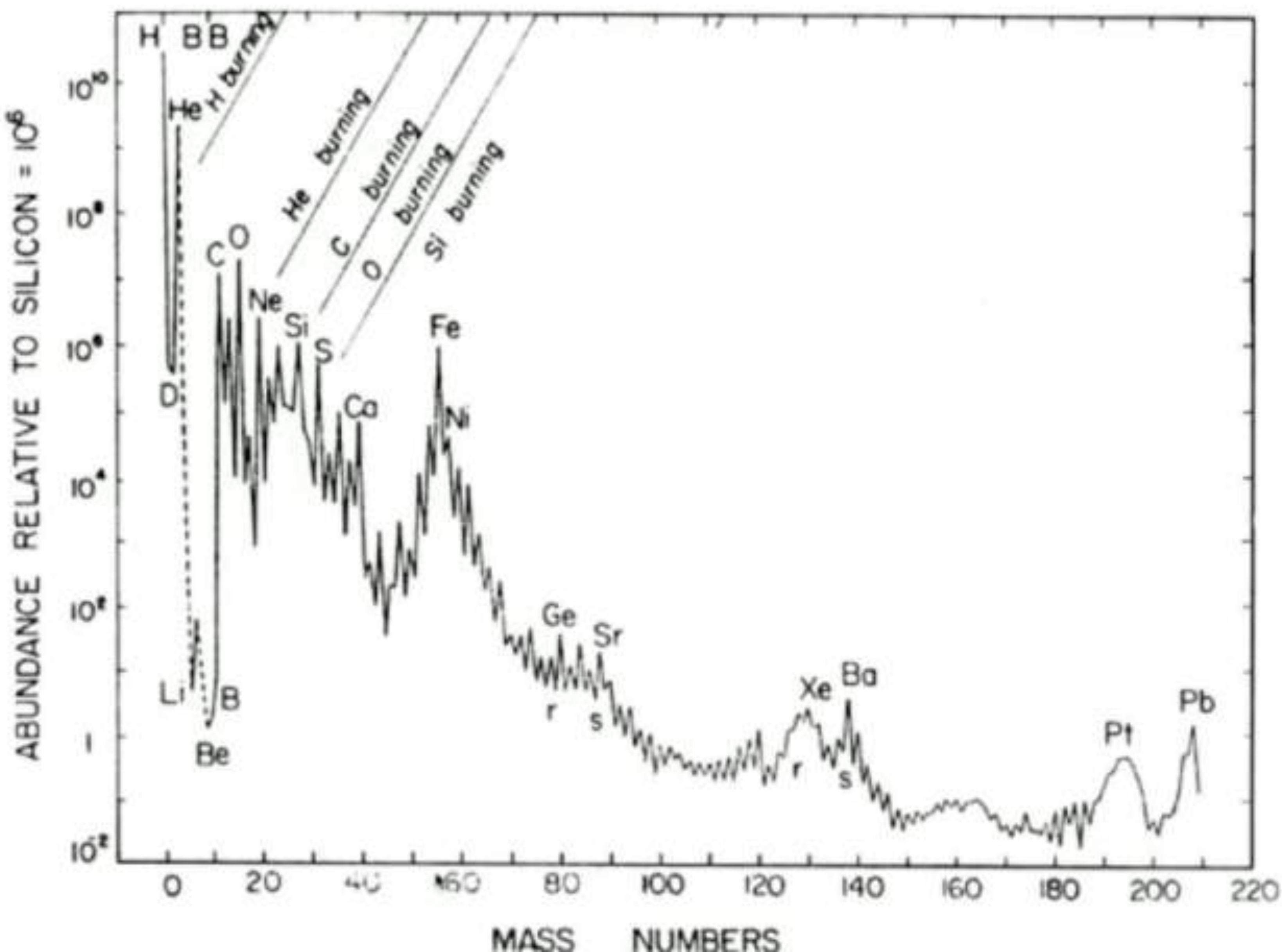
Nucleosynthesis in a Supergiant star





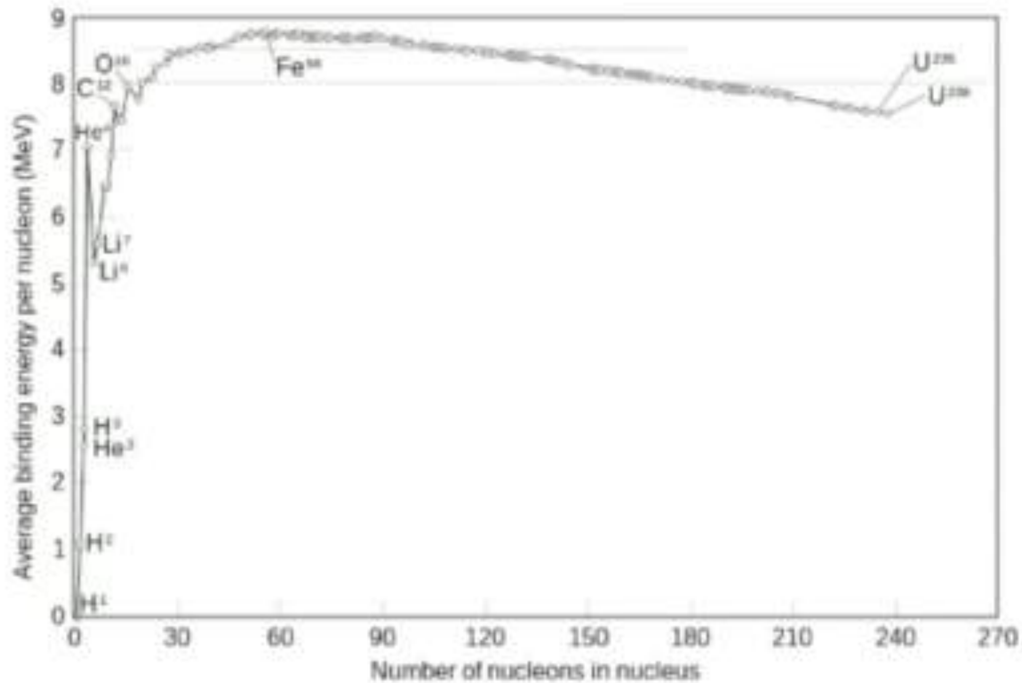
Name of Process	Fuel	Products	Temperature
Hydrogen-Burning	H	He	60×10^6 °K
Helium-Burning	He	C, O	200×10^6 °K
Carbon-Burning	C	O, Ne, Na, Mg	800×10^6 °K
Neon-Burning	Ne	O, Mg	1500×10^6 °K
Oxygen-Burning	O	Mg to S	2000×10^6 °K
Silicon-Burning	Mg to S	Elements near FE	3000×10^6 °K

Is the universe made of iron?



So what happens beyond iron?

- capture of particles requires energy
- capture of charged particles very unlikely
- neutrons still can be captured



- iron from the earlier burning processes exposed to the neutron flux
- two processes possible:
  - slow neutron capture: s-process
  - rapid neutron capture: r-process

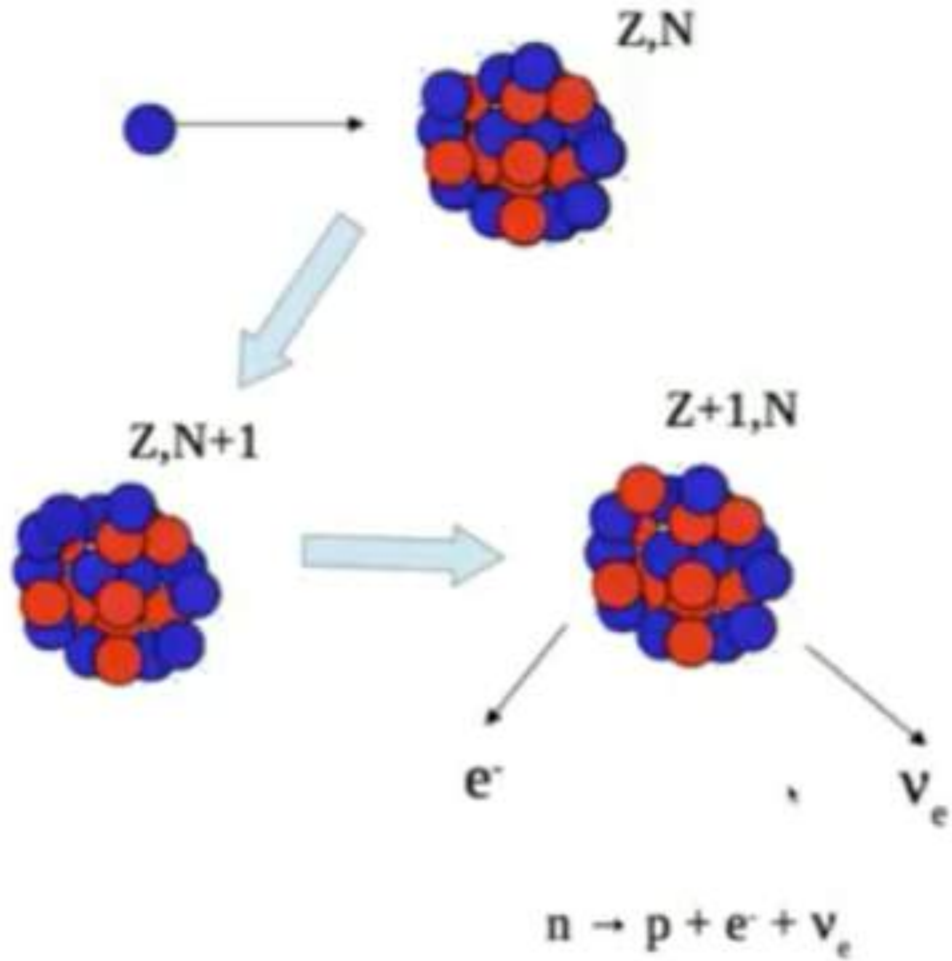
Supernova Explosion

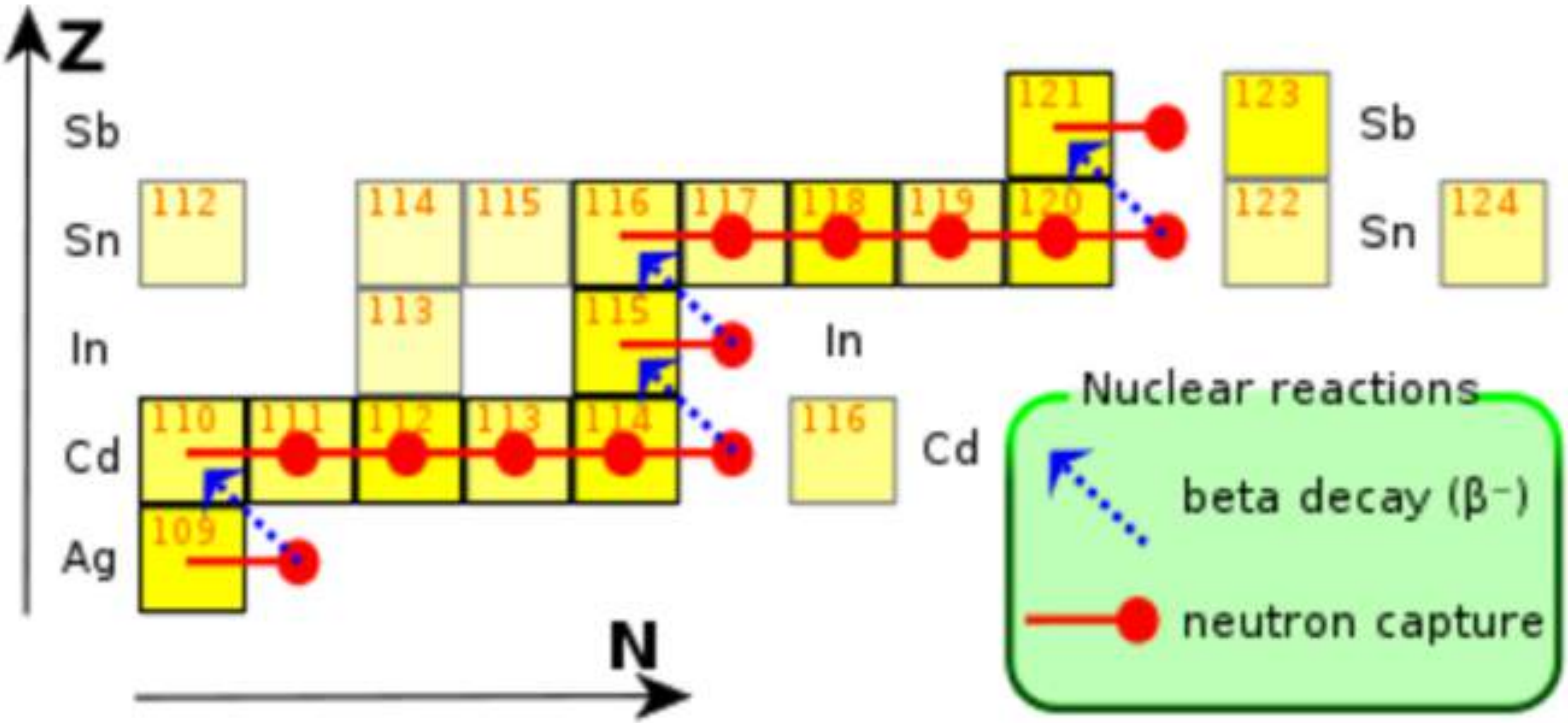
s-process – slow neutron capture

What does it mean 'slow'?

Nucleus half-life – life time of a nucleus before it decays

→ 'slow' = time until a neutron is captured is longer than the half-life of the nucleus





Z
Sb
Sn
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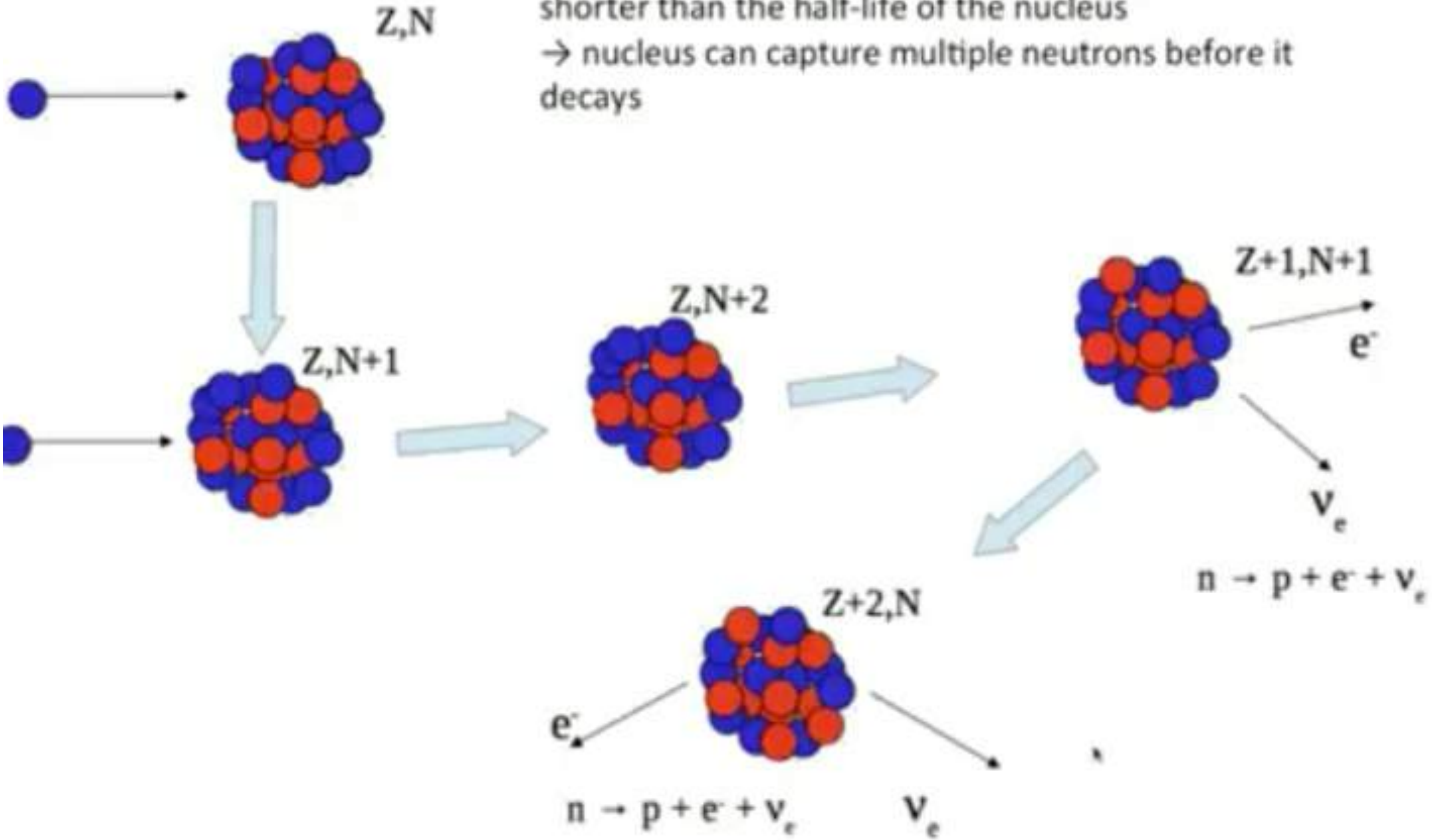
111
112
113
114
116
109
Sb
Sn
In
Cd
N
Nuclear reactions
beta decay (β⁻)
neutron capture

r-process – rapid neutron capture

→ 'rapid' = time until a neutron is captured is much shorter than the half-life of the nucleus
→ nucleus can capture multiple neutrons before it decays



r-process nucleosynthesis:

rapid neutron addition

beta decay does not keep pace with n addition

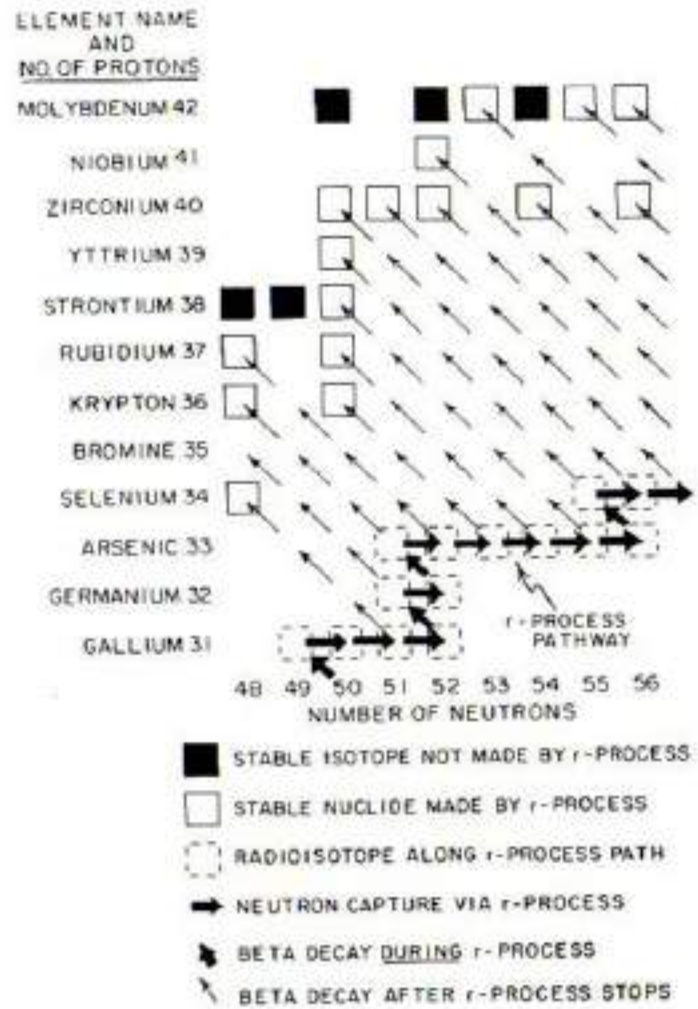
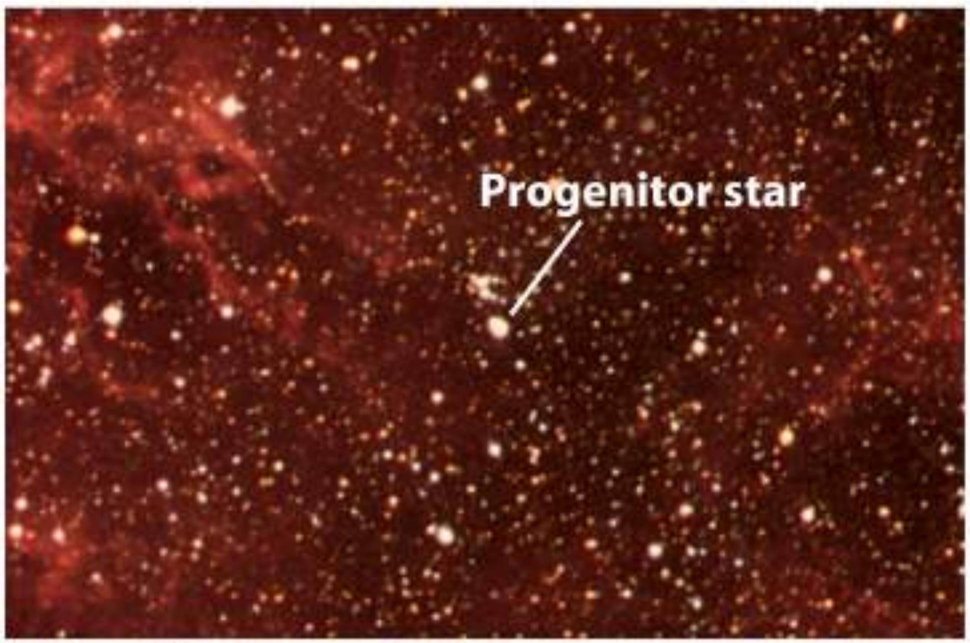


Figure 2-7. A segment of the r-process pathway: Rapid-fire neutron bombardment adds neutrons until a nuclide cannot hold any more. Only then does the nuclide undergo beta decay to become the next heavier element. This process—neutron capture to saturation followed by beta decay—is repeated over and over again, producing successively heavier elements. The r-process buildup occurs during the explosion that destroys the red giant. Hence it ends abruptly. The neutron flux stops and the highly radioactive isotopes on the r-process pathway emit beta particles one after another until stability is achieved. Note that in the case of those isobars for which two stable nuclides exist, only the neutron-rich nuclide of the pair is produced by the r-process.

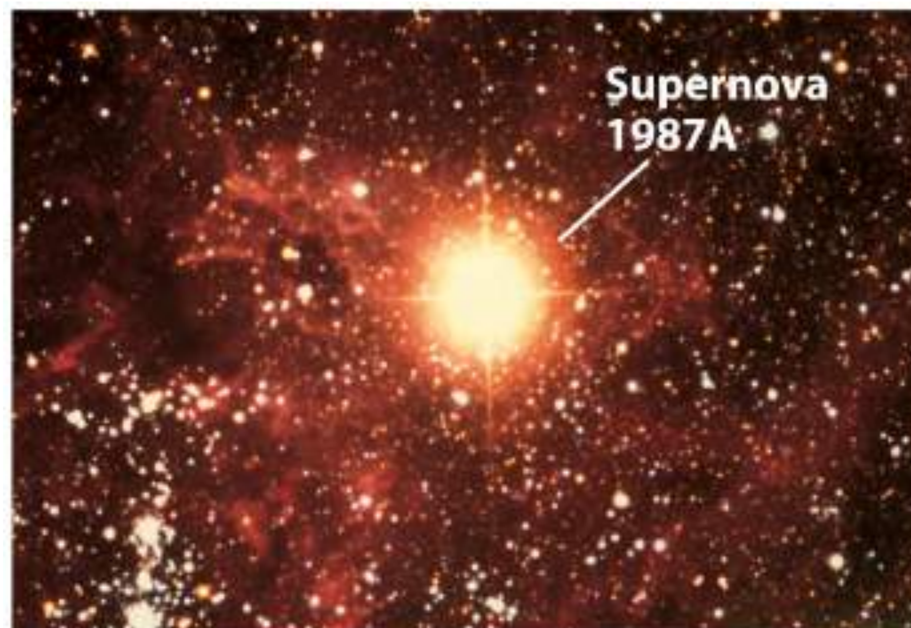
Supernova Explosion

End for high mass star comes as it tries to fuse core Fe into heavier elements– and finds this absorbs energy

STAR COLLAPSES & EXPLODES AS SUPERNOVA

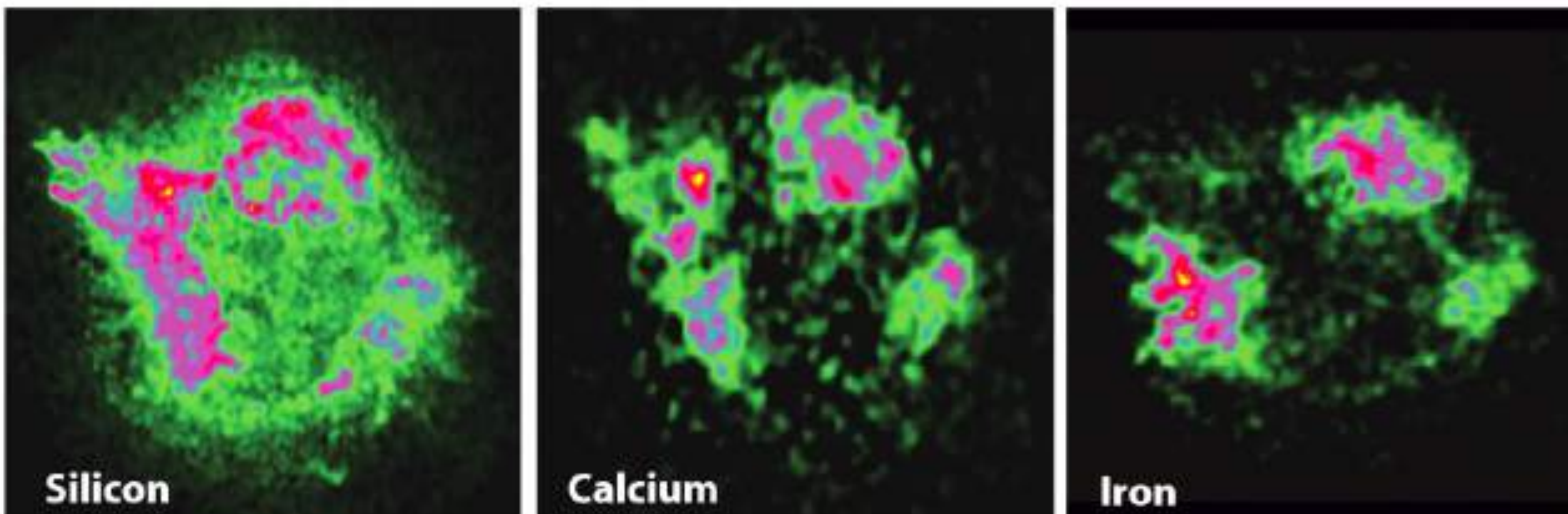


Before the star exploded



After the star exploded

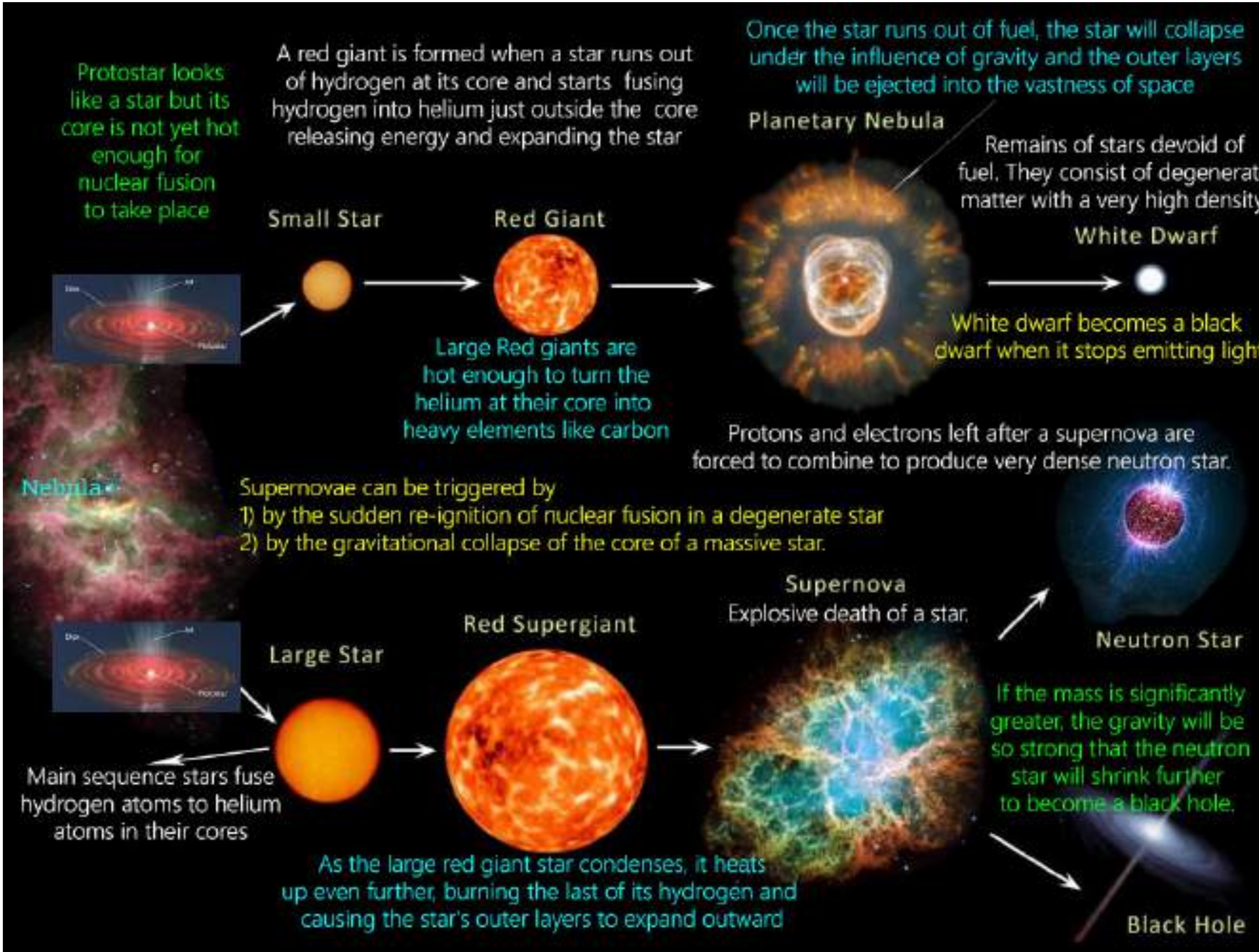
Supernova remnants



Material was ejected in "blobs" from the supernova that produced the Cassiopeia A supernova remnant

Element (H-Fe) factory "stars", supernova explosion along with s-and r-process continued to produce the building blocks of our universe (hydrogen to uranium)

Life cycle of a star



Summary of nucleosynthesis processes

process	main products	comment
H-burning	^{4}He	main seq.
He-burning	^{12}C, ^{16}O	Red Giant
C-O-Ne-Si burning	^{20}Ne, ^{28}Si, ^{32}Si, up to ^{56}Fe	Supergiants
s-process	many elements	Red Giants, Supergiants
r-process	many heavy elements	Supernova

Formation of Solar System

4.57 billions years ago

The Nebular Theory

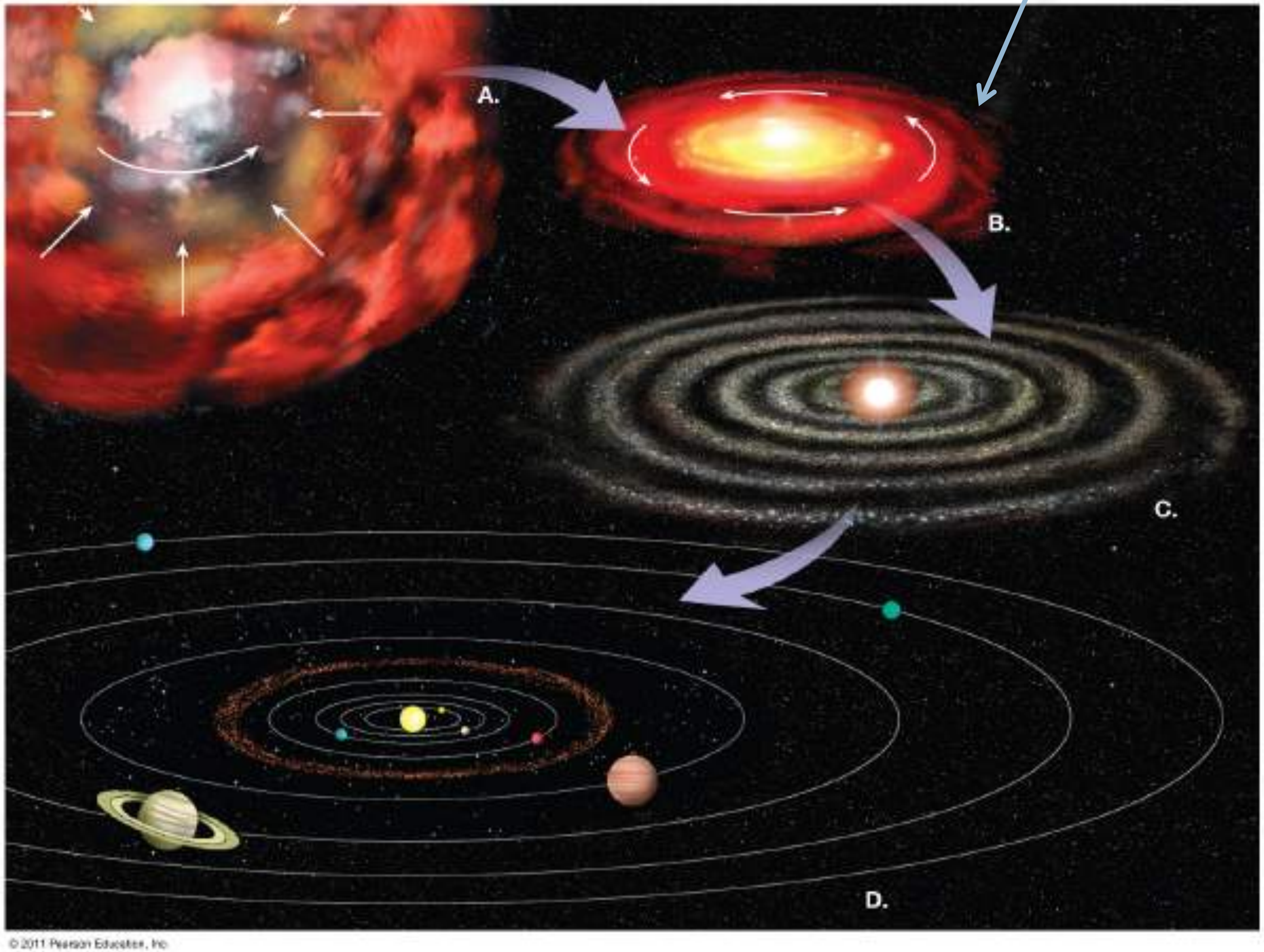
1. Cosmic cloud formed from dust of previous Supernovae

2. Gravity pulls particle closer and increase rotation

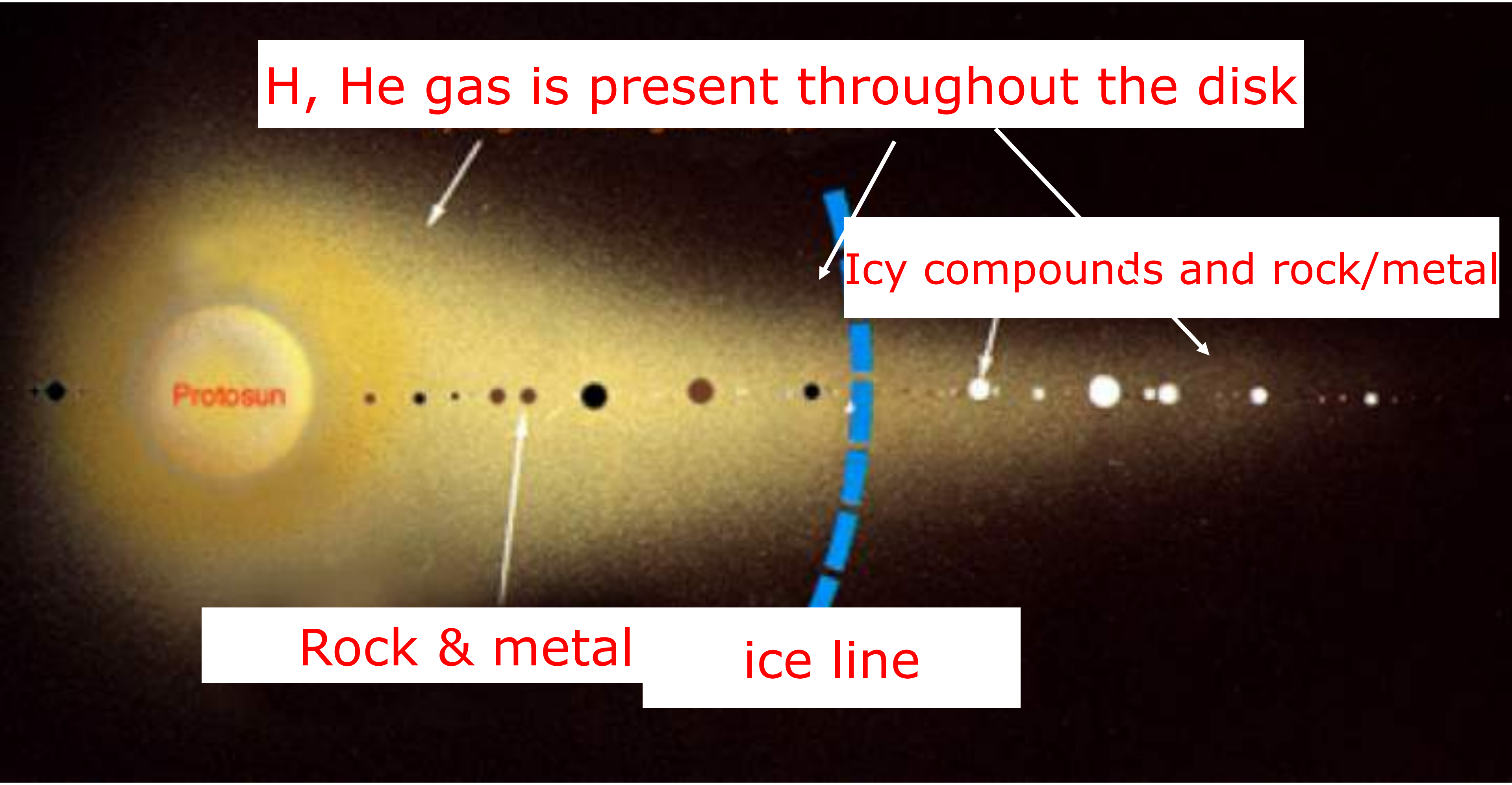
3. Nuclear reaction begins ~ 5 billion years ago at the centre of the cloud due to high concentration of material

4. Remaining particle continues to come closer and accretion took place

5. Eventually larger particles accreted and formed 'planets'



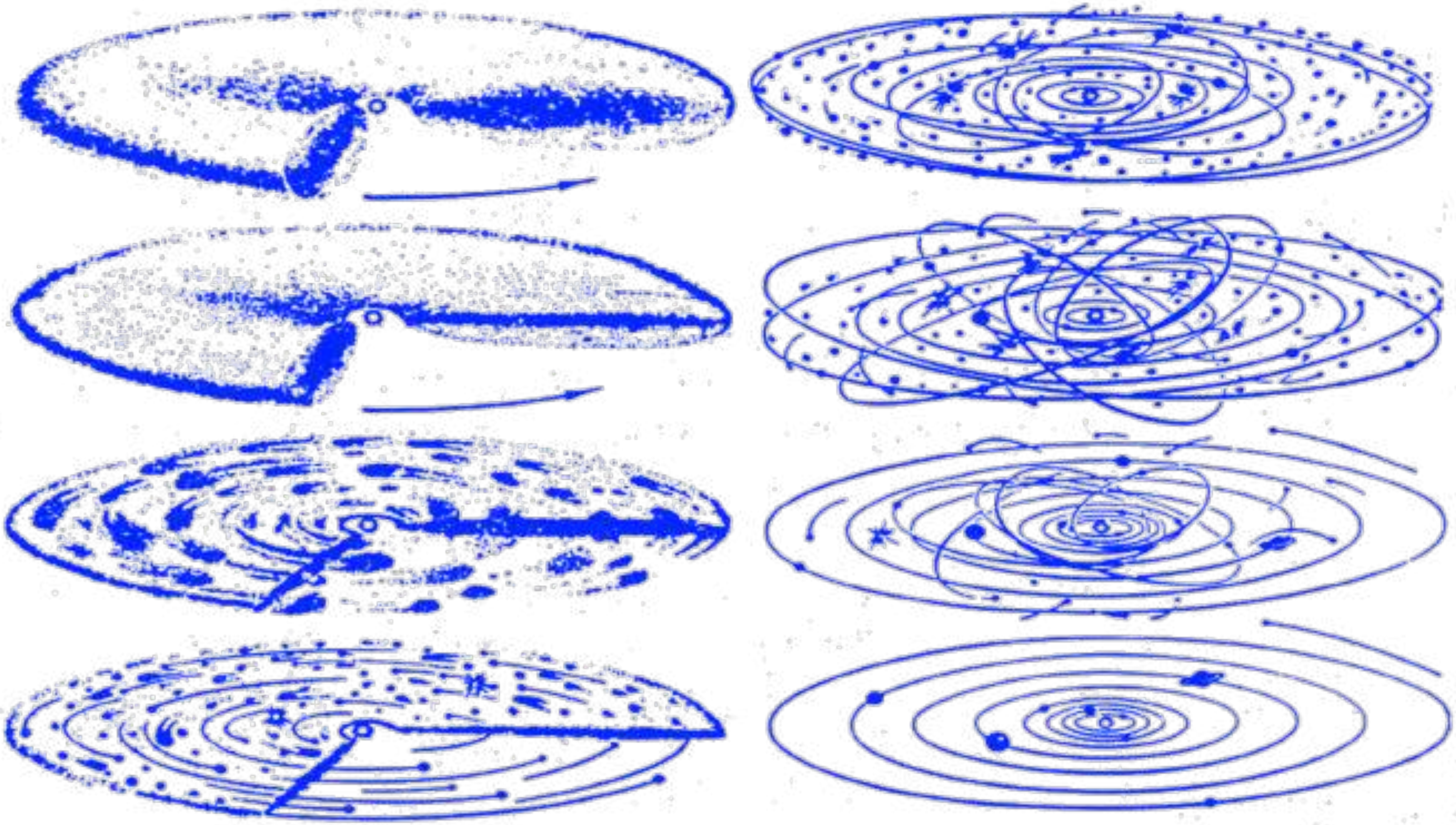
Formation of Solar System



Condensation: gas becomes solid

Terrestrial planets form by accretion of solids

Dust >rocks >planetesimals >embryos >planets



Planet formation: Terrerstrial vs. giant planets

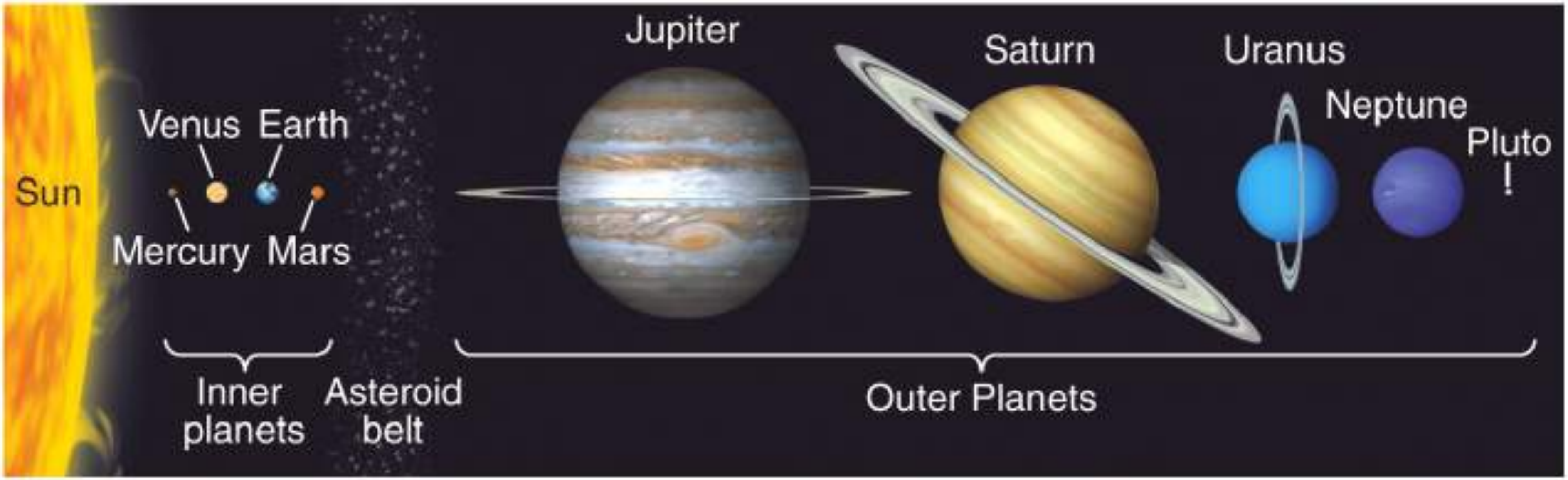
Giant ("jovian")

1. Lots of solids in the disk (cold > 5 AU)
2. Cores form from ice, rock and metal
3. Grow large, quickly (~1 million years)
4. Big enough to trap H and He gas from disk

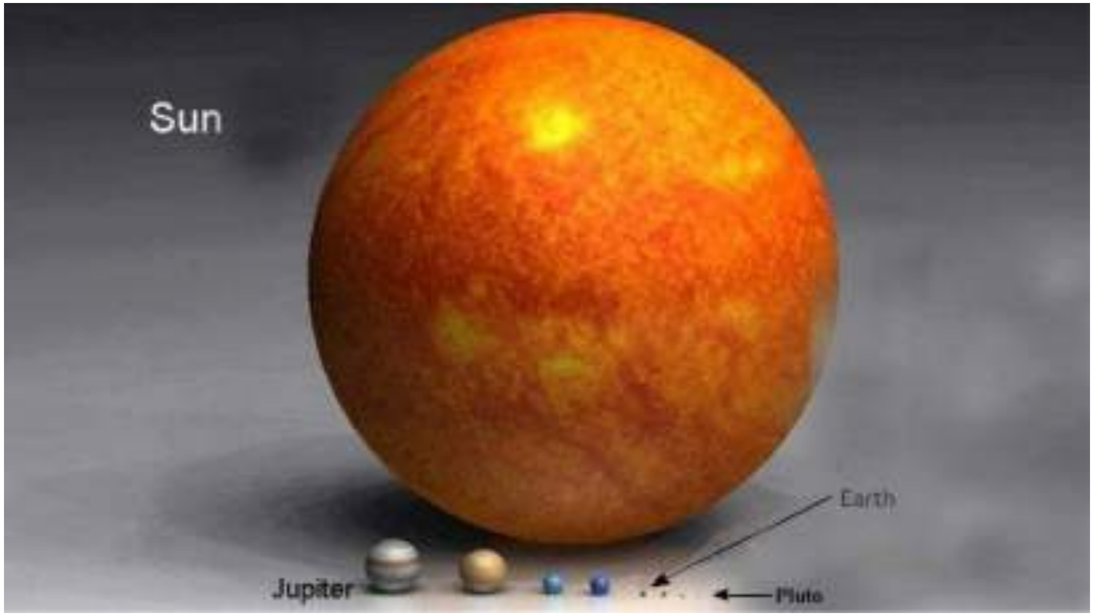
Terrestrial ("earth like")

1. Very little solid material in disk at 1 AU
2. Form from rock and metal only
3. Grow slowly (~100 million years)
4. Too small to trap any gas from disk

Solar System



Sizes of the planets relative to Sun



Sun-planet distance
(relative to Earth: AU)

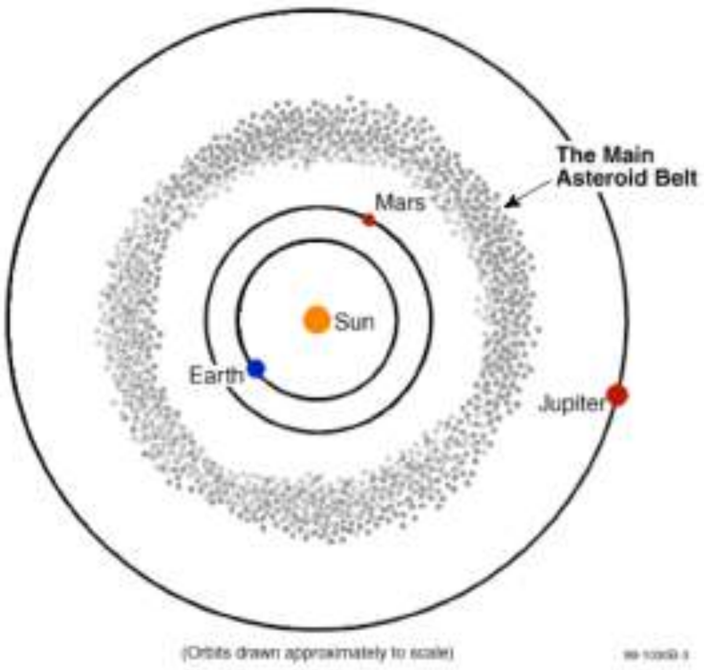
Mercury	0.4 AU
Venus	0.7
Earth	1.0
Mars	1.5
Jupiter	5.2
Saturn	9.5
Uranus	19
Neptune	30

1 AU = 150 million km

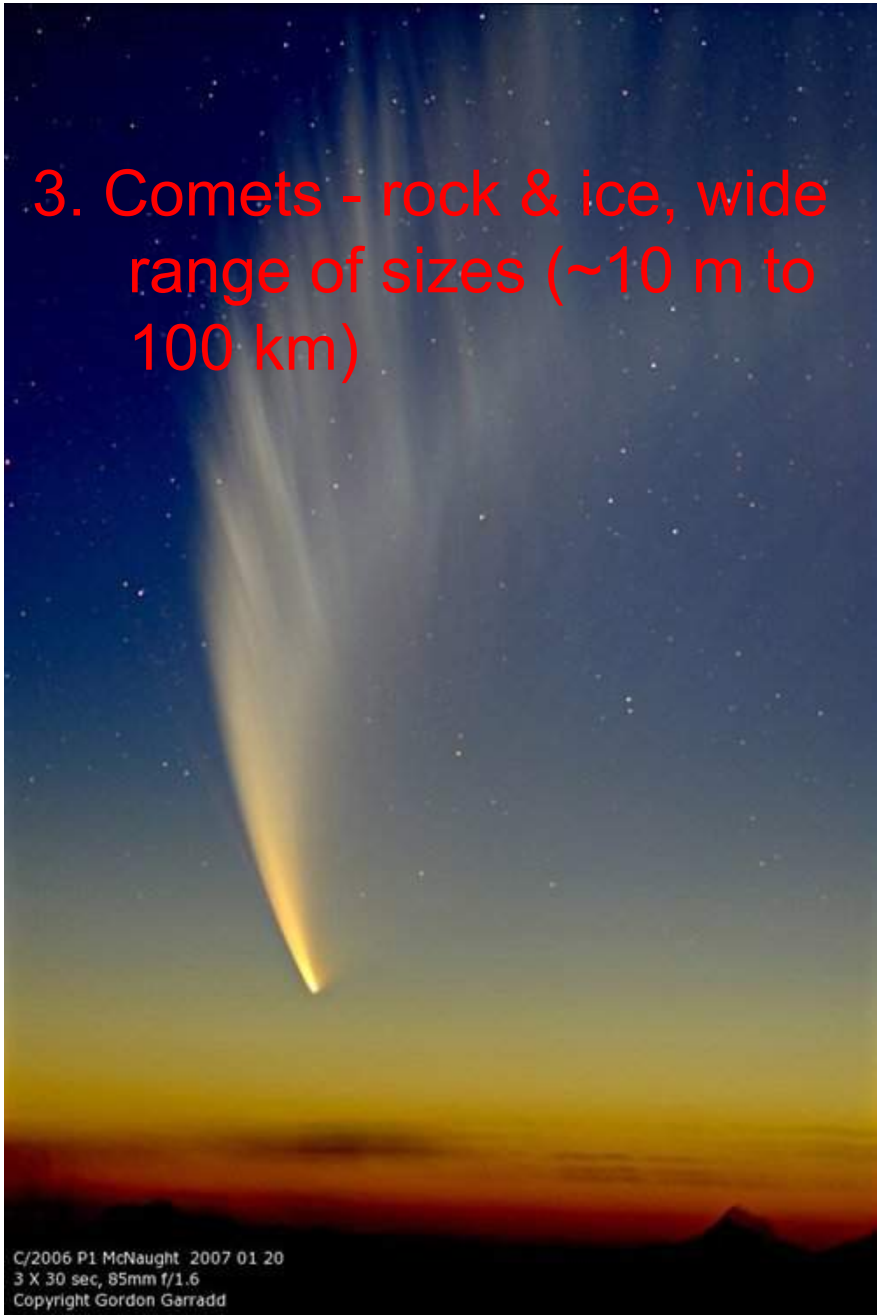
Other residents of the solar system

1. Moons - orbit planets, some are larger than Mercury

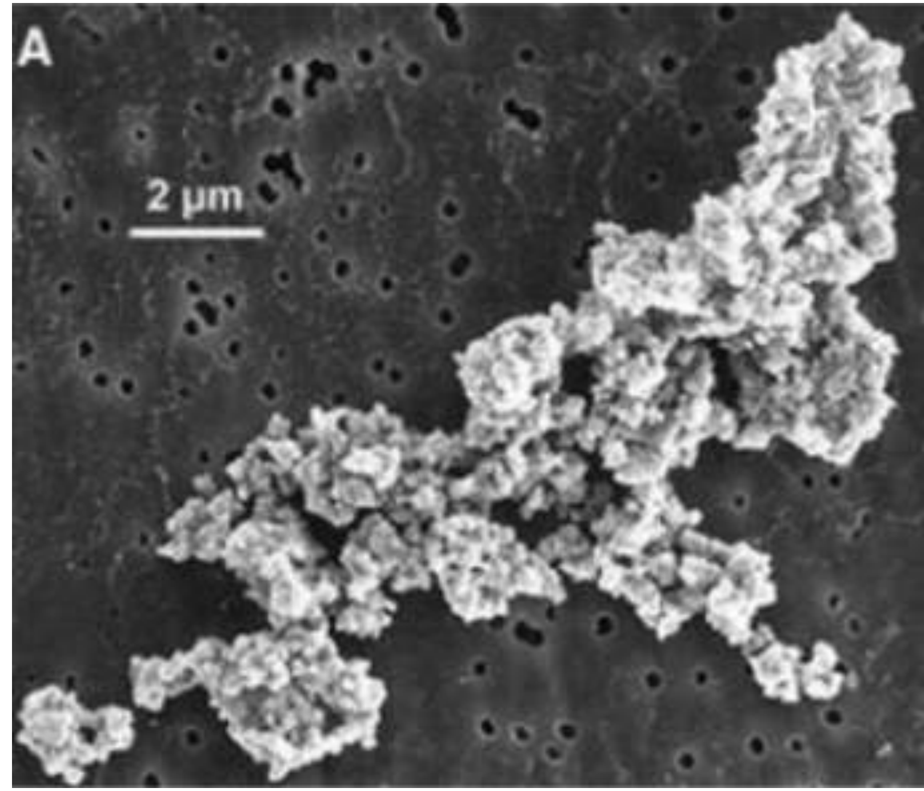
2. Asteroids - rocky, d < 1000 km, orbit the sun



Other residents of the solar system



3. Comets - rock & ice, wide range of sizes (~10 m to 100 km)



4. Meteoroids - small fragments of asteroids that enter earth’s atmosphere (dust to boulder sized)

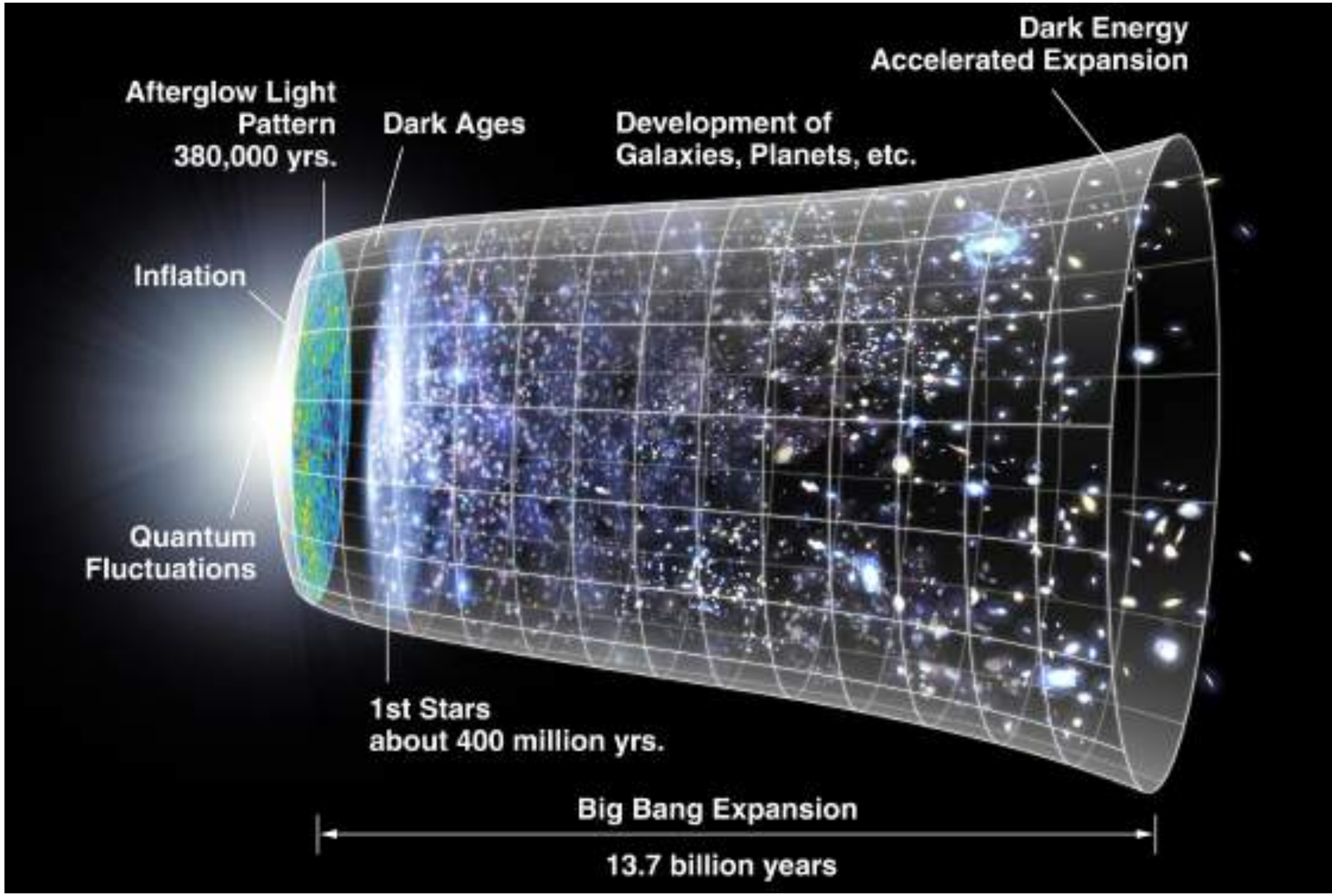
Fundamentals of Earth Sciences (ESO 213A)

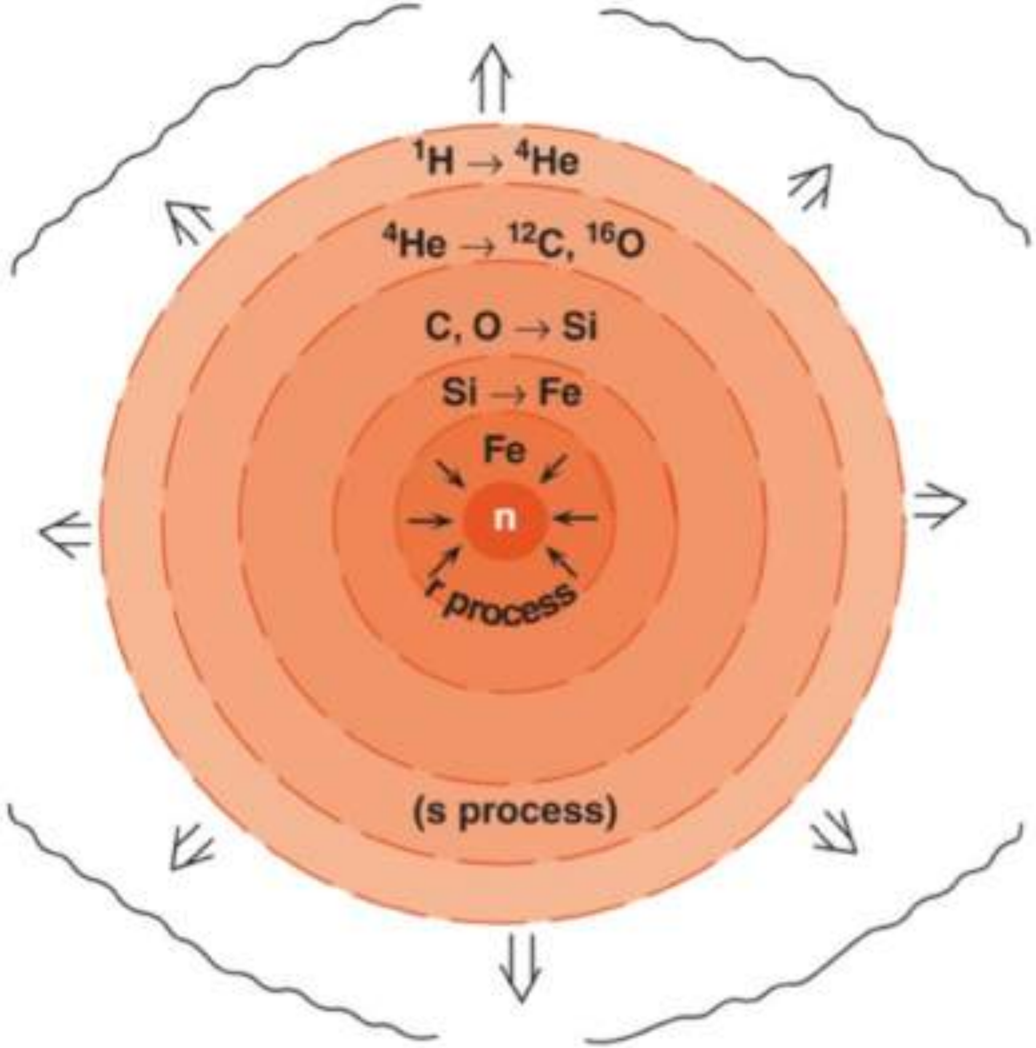
Dibakar Ghosal
Department of Earth Sciences

Lecture 3: Origin of Earth, Moon and Atmosphere

Last Class: Review

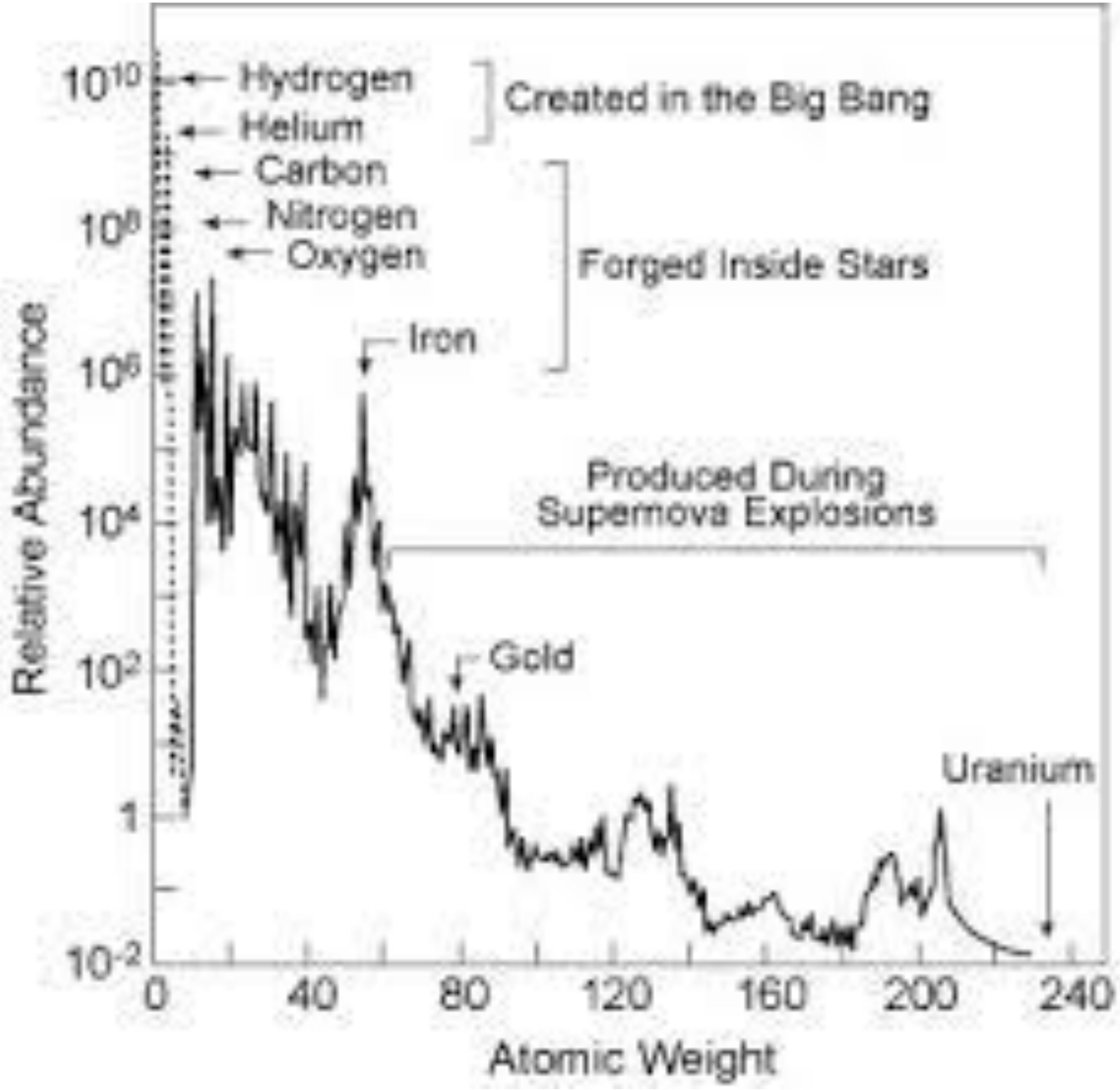
- Big Bang Theory (13.7 billions of years ago)
- Nucleosynthesis (BigBang or Primordial and Stellar)
- Supernova Explosion
- Origin of our Solar System (4.57 billions of years ago)





Gravity & Fusion

Stellar Nucleosynthesis && Neutron capture (s-r) processes



Formation of Solar System

4.57 billions years ago

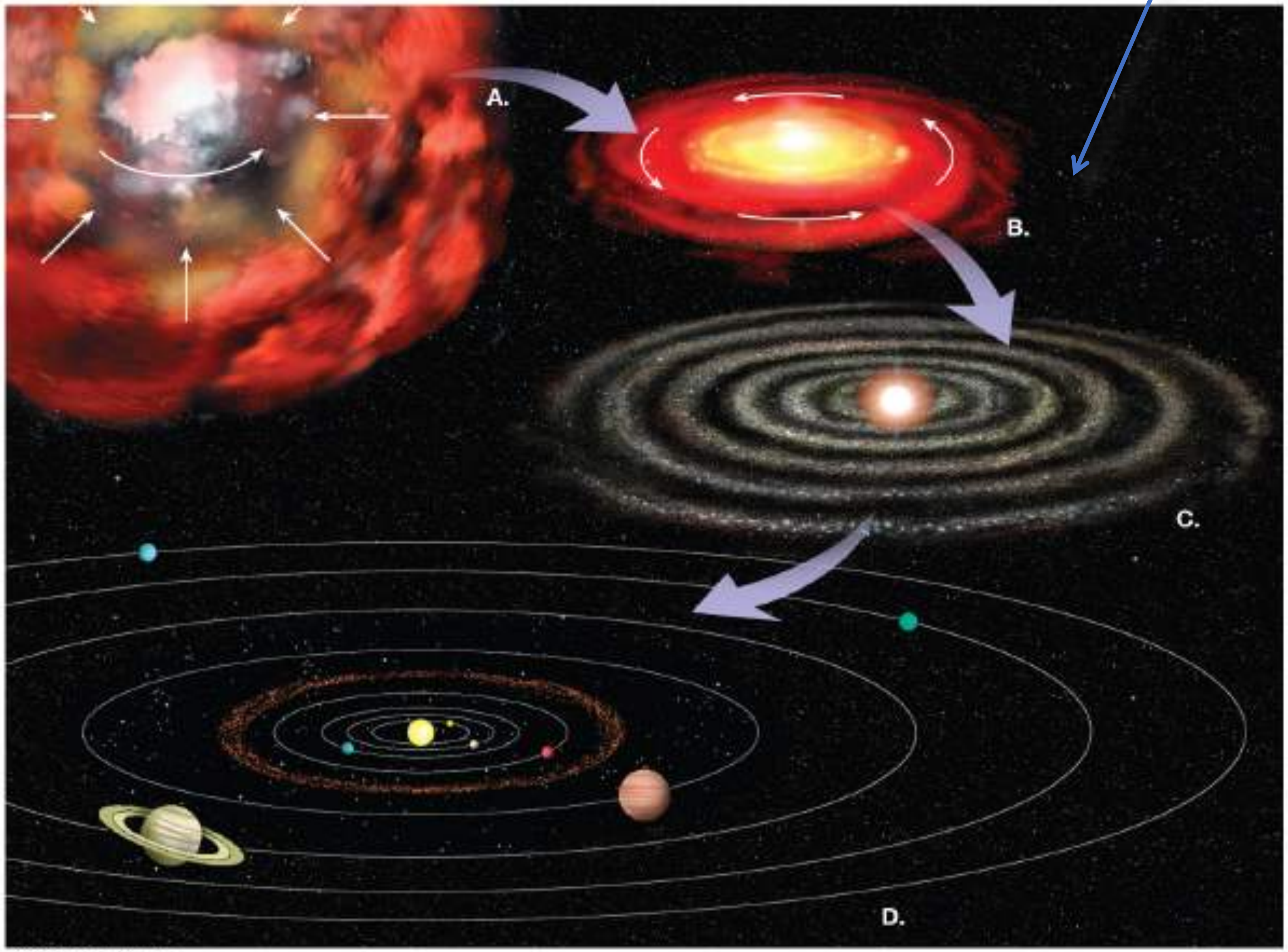
1. Cosmic cloud formed from dust of previous Supernovae

2. Gravity pulls particle closer and increase rotation

3. Nuclear reaction begins ~ 5 billion years ago at the centre of the cloud due to high concentration of material

4. Remaining particle continues to come closer and **accretion** took place

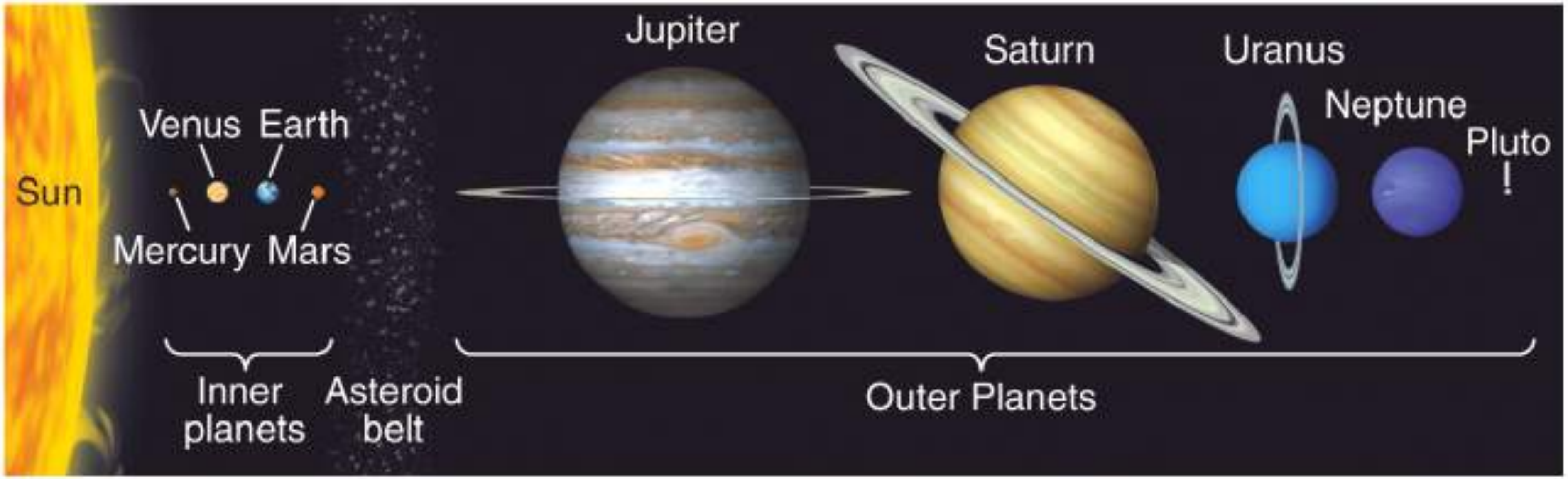
5. Eventually larger particles accreted and formed 'planets'



The Nebular Theory

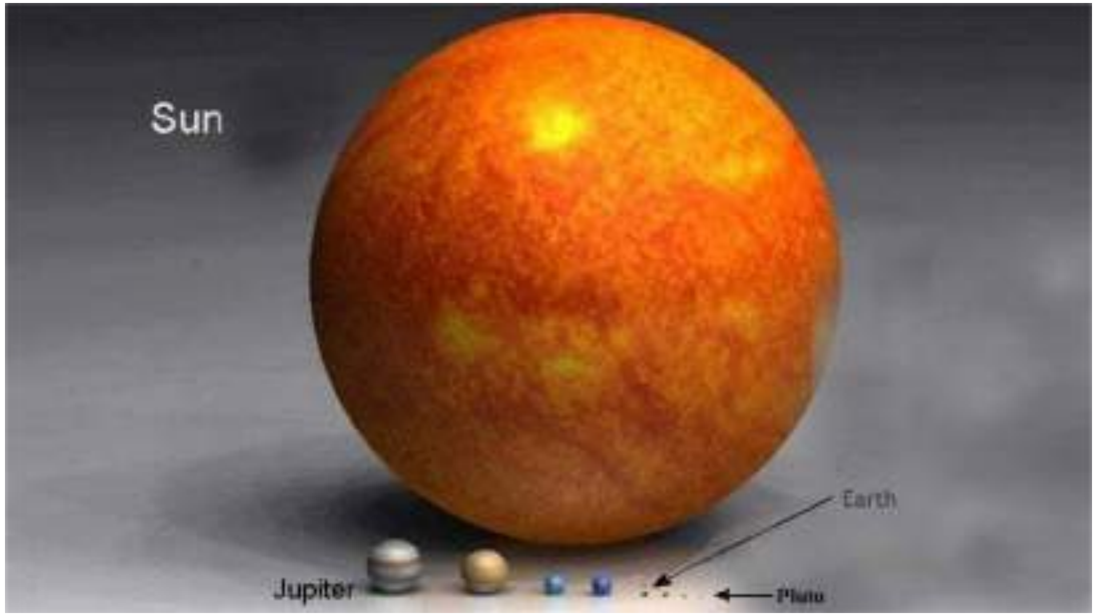
Dust >rocks >planetesimals >embryos >planets

Today's Solar System



'Pluto is a dwarf planet'
- By IAU in 2006

Sizes of the planets relative to Sun



Sun-planet distance
(relative to Earth: AU)

Mercury	0.4 AU
Venus	0.7
Earth	1.0
Mars	1.5
Jupiter	5.2
Saturn	9.5
Uranus	19
Neptune	30

1 AU = 150 million km

Two different types of planets in Solar system:

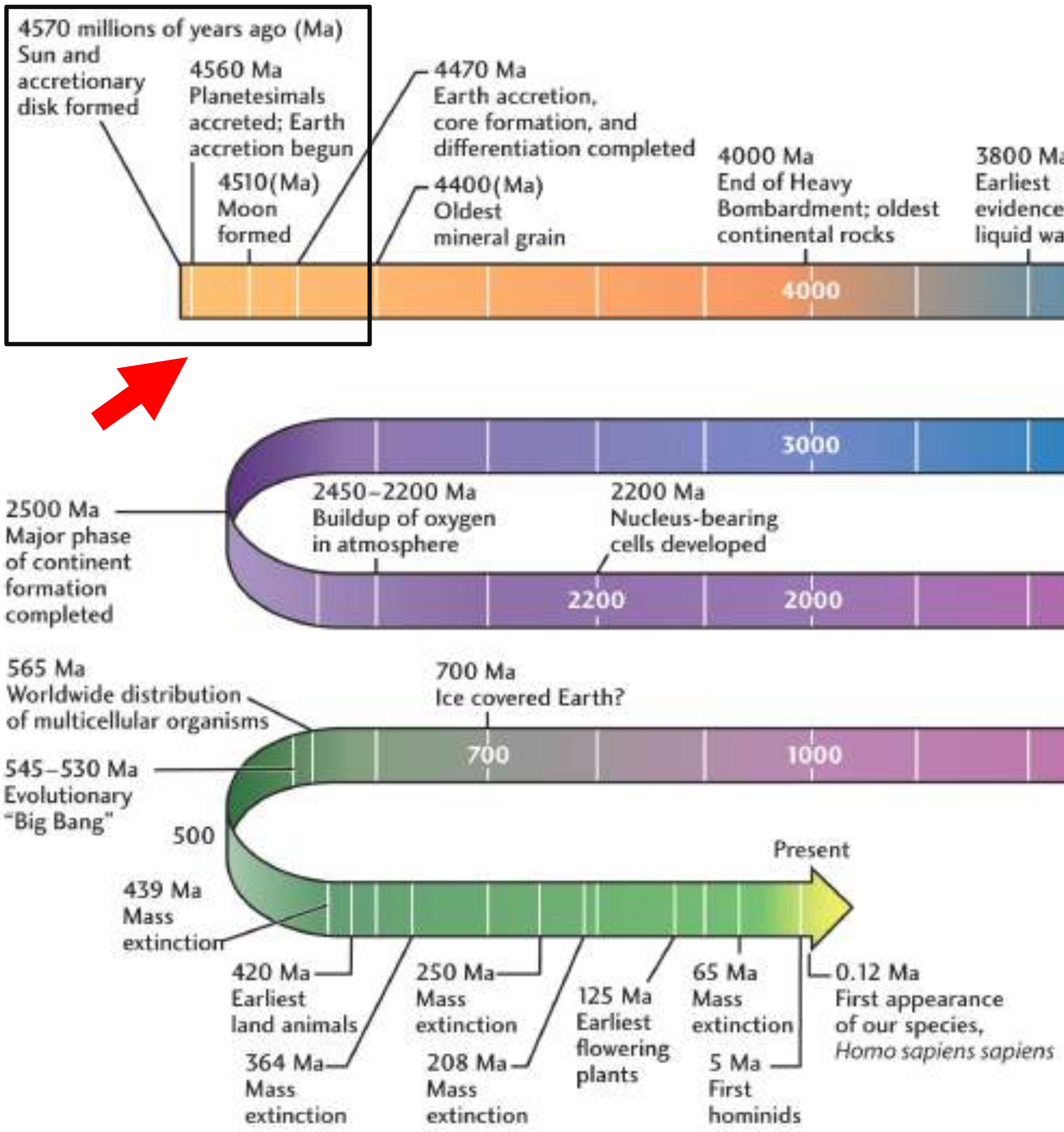
1. Terrestrial planet:

Mercury, Venus, Earth, Mars
(Small rocky, dense, closer to Sun)

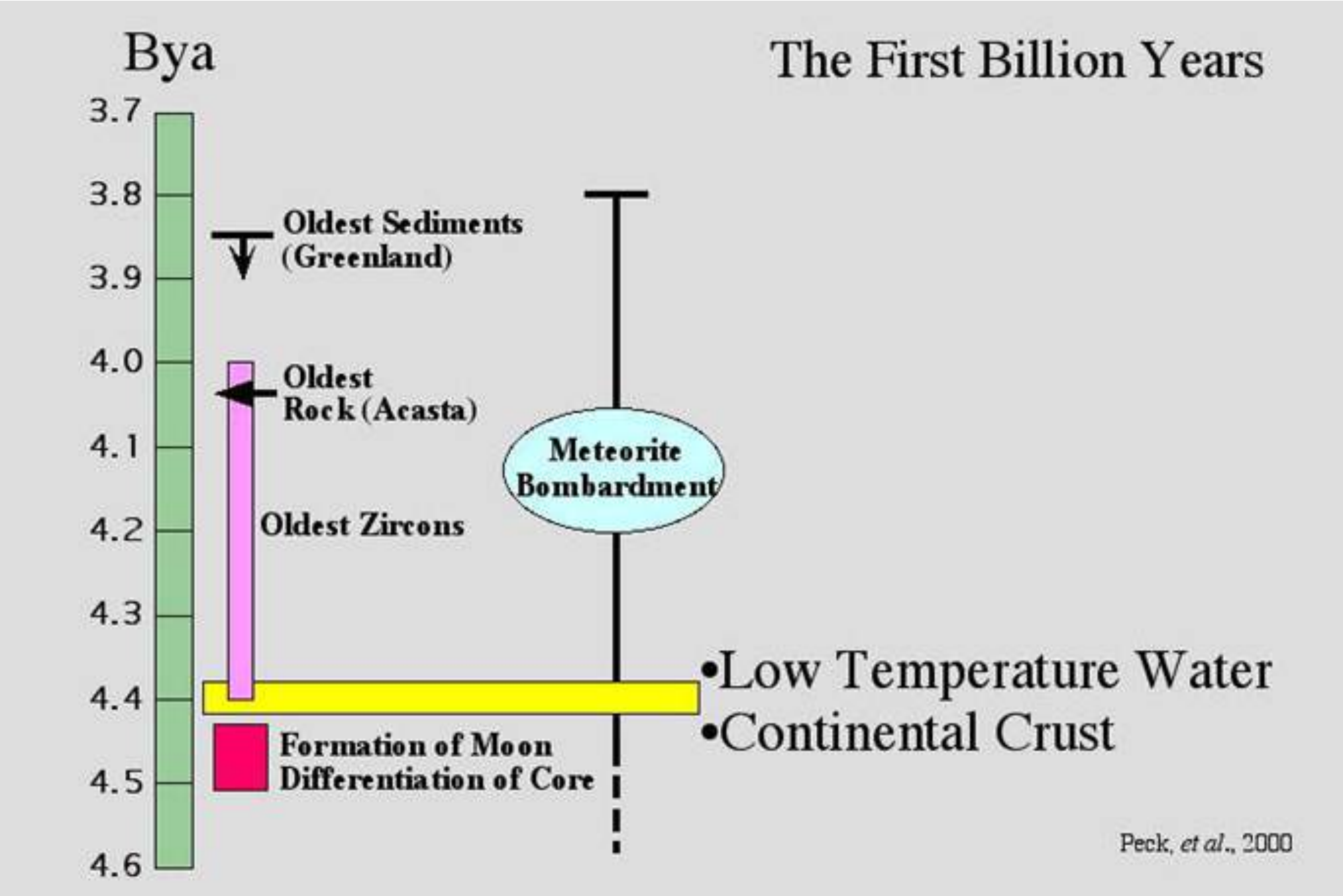
2. Jovian planets

Jupiter, Saturn, Uranus, Neptune
(larger, more gaseous, less dense, away from Sun)

Geologic Time Scale



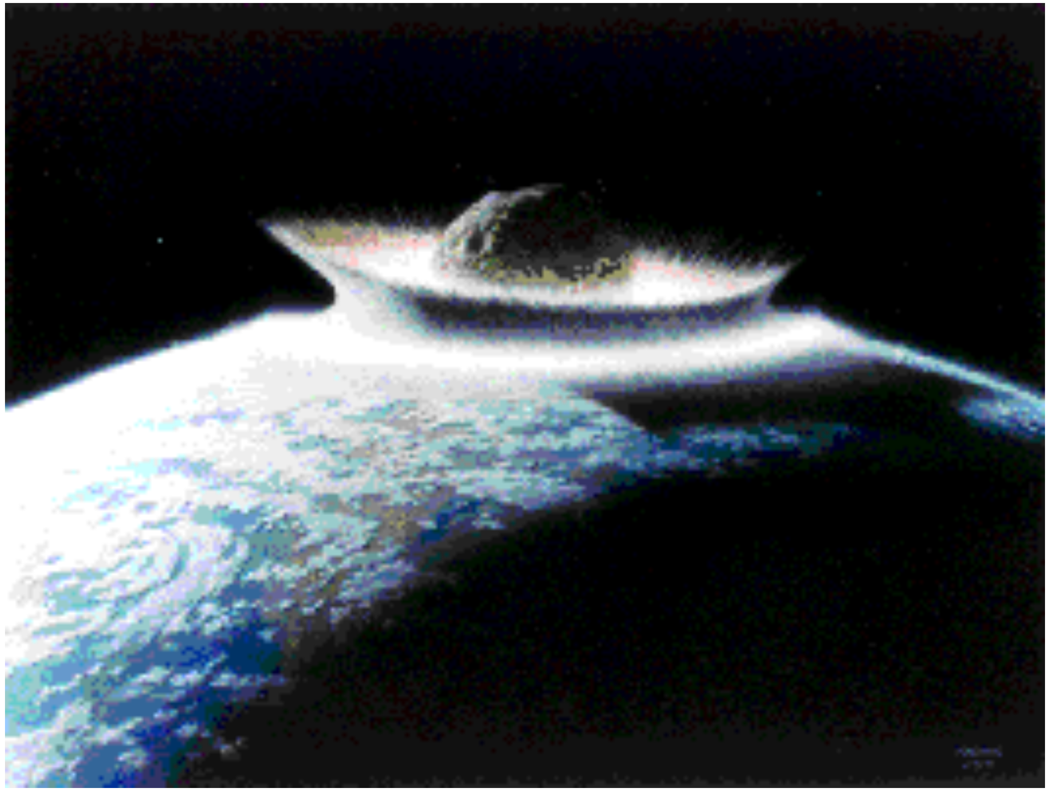
Connecting the dots: From planet formation to early Earth
Computational astrophysics meets field geology!

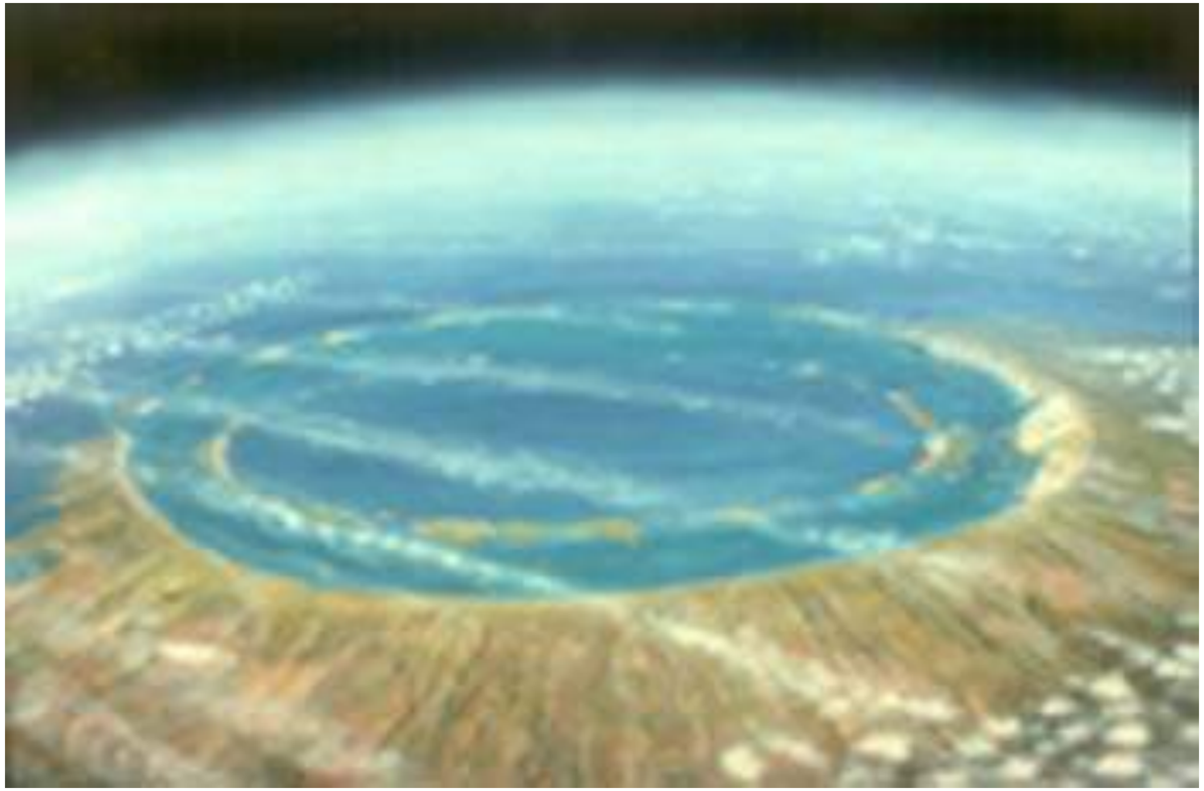


Bombardment From Space

For the first 50 million years of its existence, the surface of the Earth was repeatedly pulverized by asteroids and comets of all sizes

One of these collisions formed the Moon





Chelyabinsk meteor entered Earth's atmosphere over the southern Ural region in Russia on 15 February 2013

Formation of the Moon

Giant Impact Hypothesis predicts that around 50 million years after the initial creation of Earth, a planet about the size of Mars collided with Earth

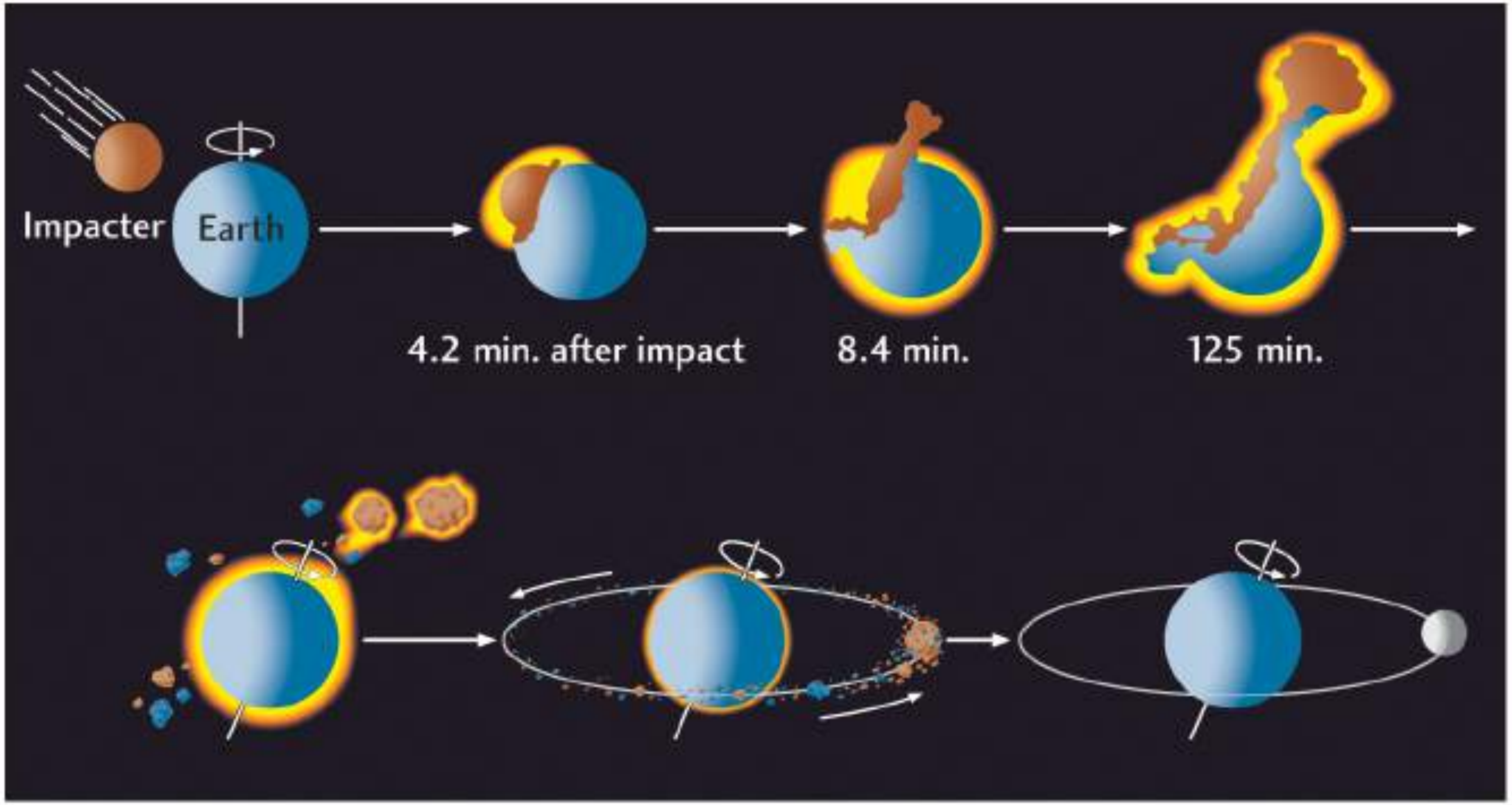
This idea was first proposed about 30 years ago, but it took calculations by modern high-speed computers to prove the feasibility

Why Moon Formation is Important?

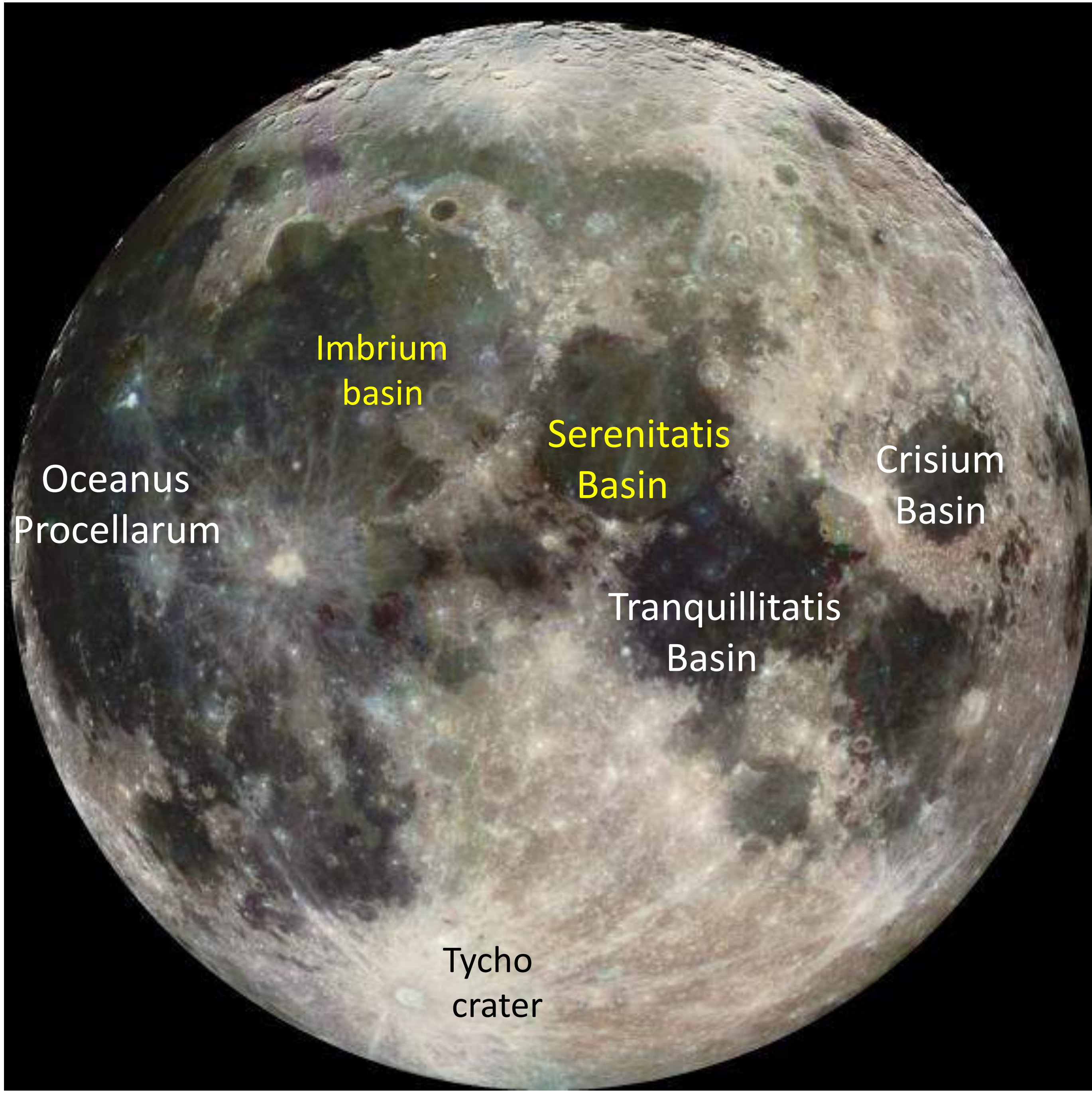
Formation of the Moon

This collision had to be very spectacular!

A considerable amount of material was blown off into space, but most fell back onto the Earth



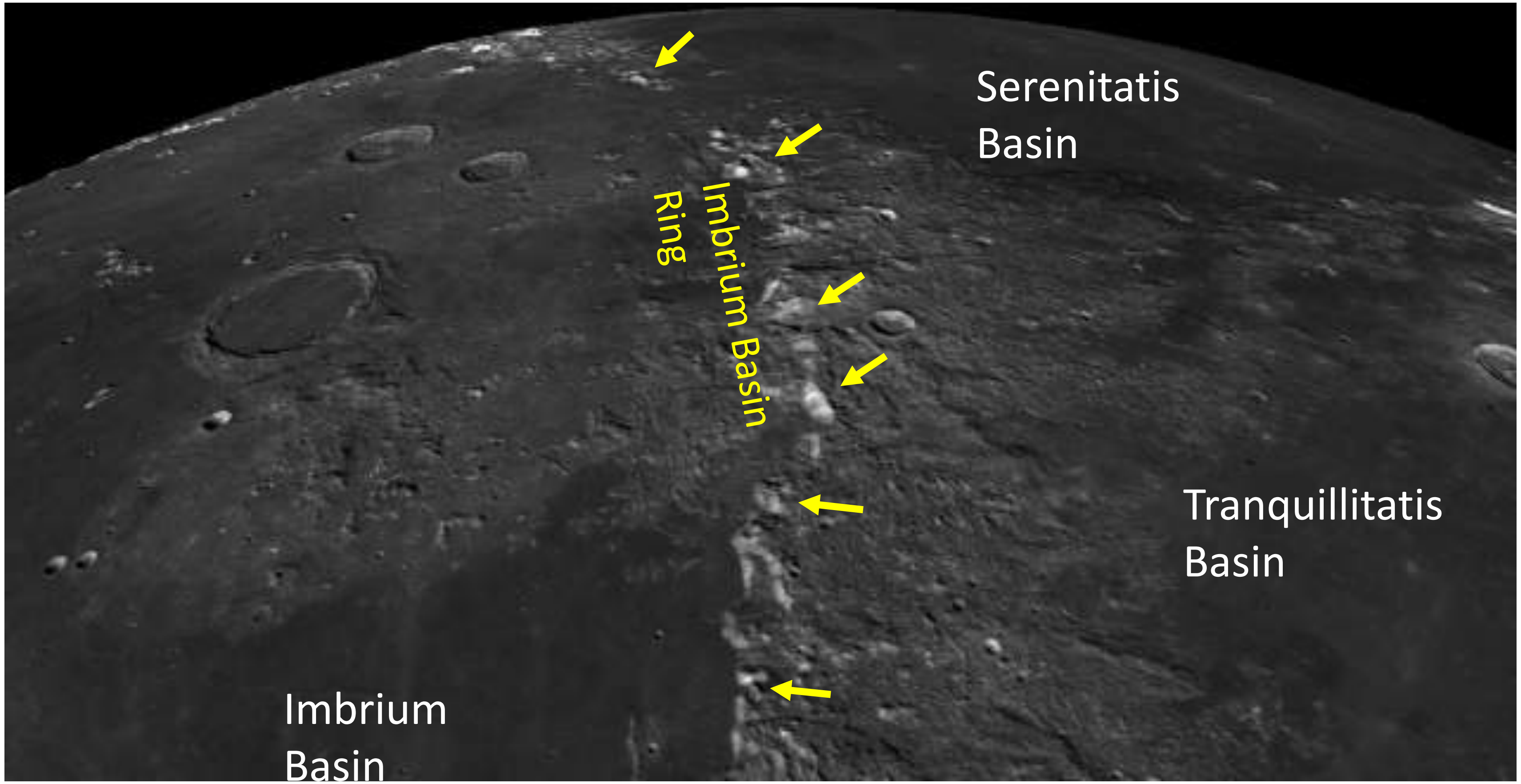
Moon from Galileo spacecraft. The distinct bright ray crater at the bottom of the image is the <u>Tycho impact crater</u>. <u>The dark areas are lava rock filled impact basins</u>: Oceanus Procellarum (more than 2,500 km), Mare Imbrium (diameter of 1145 km), Mare Serenitatis (diameter 674 km) and Mare Tranquillitatis (diameter 873 km), and Mare Crisium (diameter 556 km). This picture contains images through the Violet, 756 nm, 968 nm filters.



Lunar Impact *Basins*

Both Earth and Moon were struck by numerous large asteroids and comets in their early history. These impacts produced deep basins up to 2500 km across surrounded by high rings of mountains on the Moon and are visible to the human eye as prominent circular structures.

A view of the mountains that surround the Imbrium impact basin. Lava flow observed both side of the ridge.

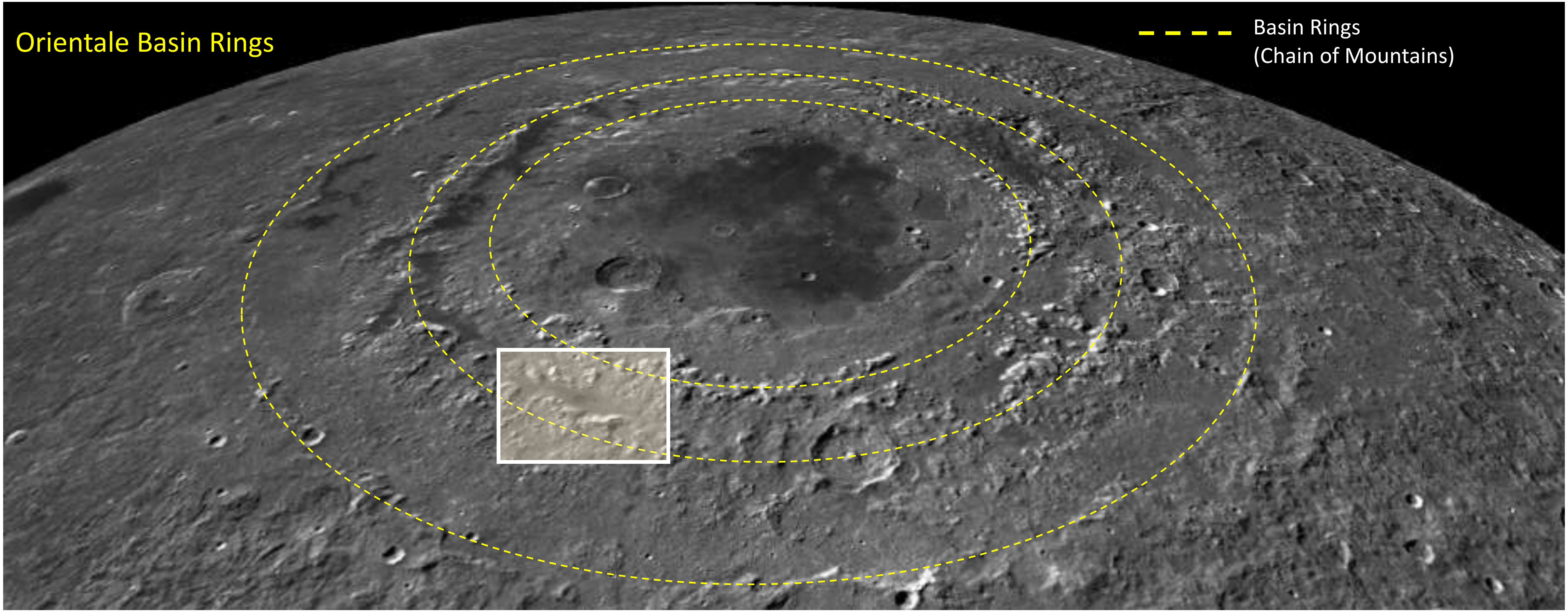


Courtesy of Prof. D. Dhingra

Big, frequent impacts until 3.8 billion years ago

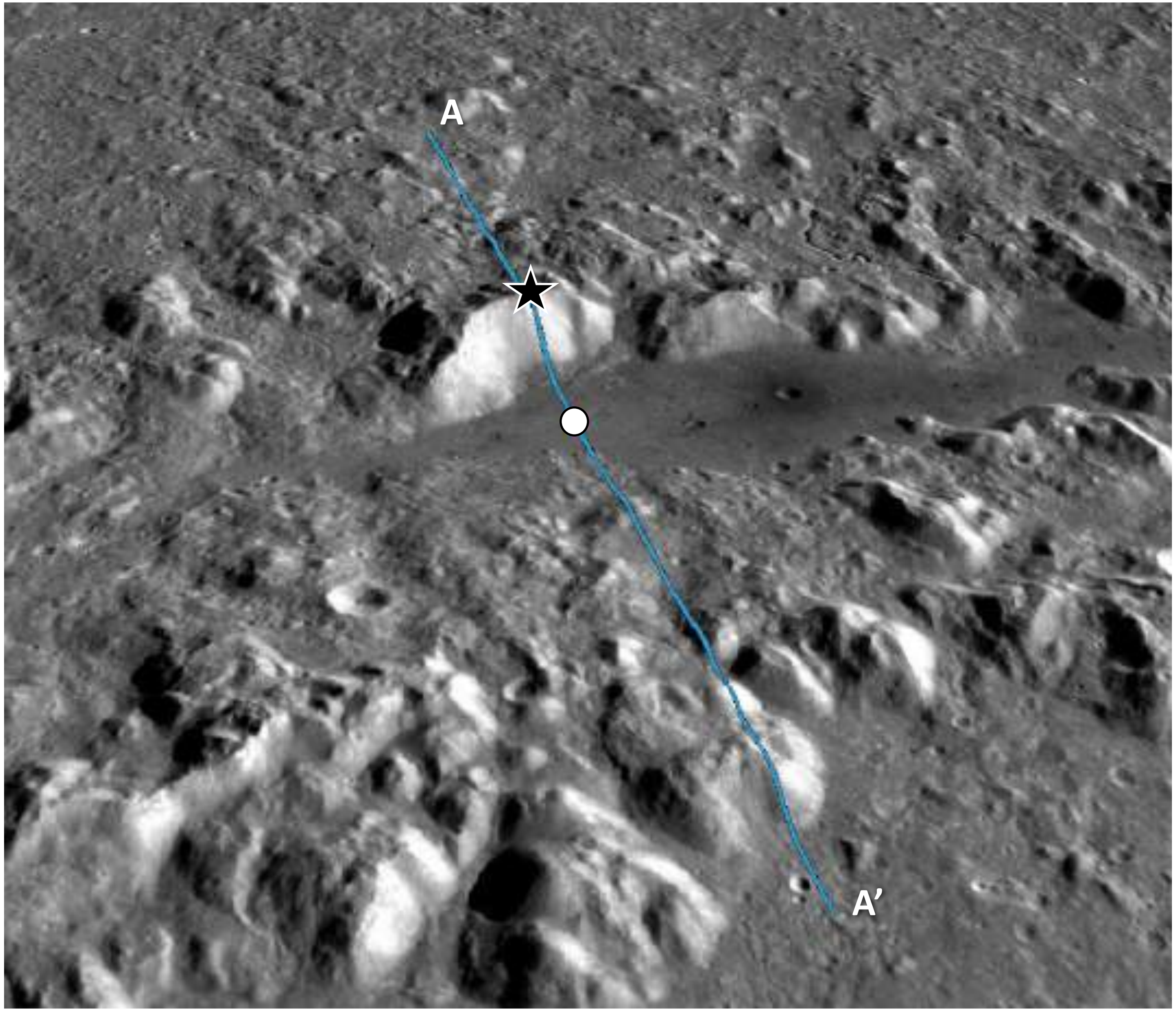
Impact events continue on all moons and planets today

Lunar Impact *Basins*



Courtesy of Prof. D. Dhingra

Three mountain rings surround the Orientale impact basin. Diameter of the outer ring is ~900 km. <u>Both the Imbrium and the Orientale impacts occurred around 3.8 billion years ago.</u>



Courtesy of Prof. D. Dhingra

How high are the basin rings?

Height of mountain: 5.4 km !

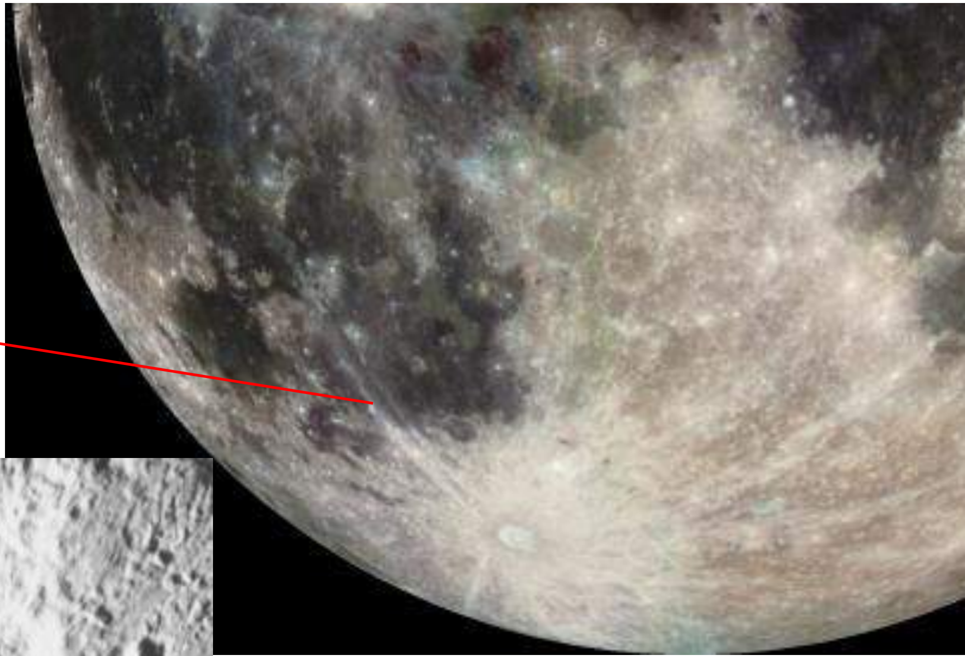
Magma Ocean Rocks

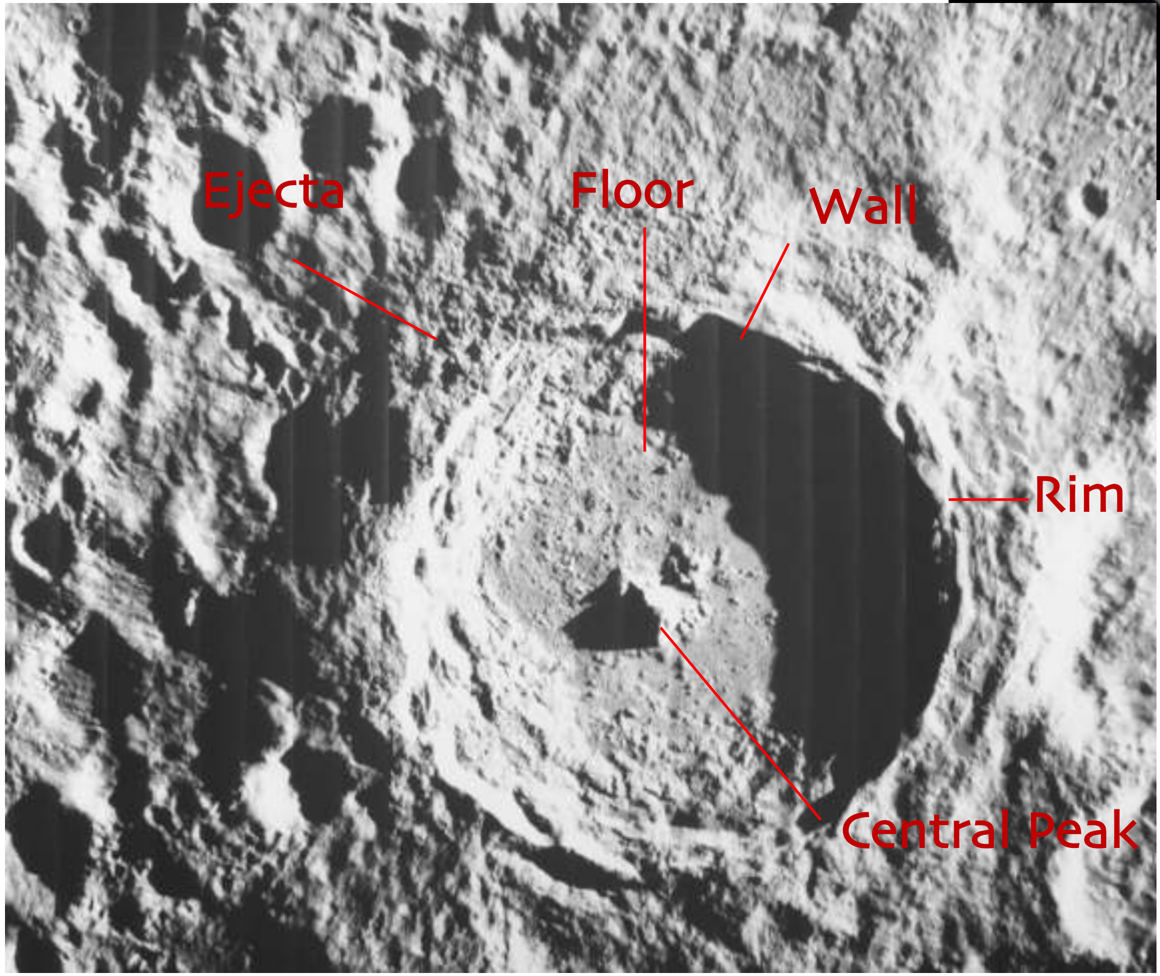
These are two examples of rocks that crystallized from the lunar magma ocean. Both are made primarily of the mineral plagioclase, which gives the lunar highlands its light gray color. The troctolite also contains some greenish olivine grains (troctolite may be later intrusion).

60025
Anorthosite
4.44-4.51 Ga
95% Plag Feld (anorthite)
Magma Ocean!
No Water!

76535
Troctolite
4.2-4.3 Ga

This image clearly shows both the central peak and terracing in the walls of Tycho. Tycho is in the lunar highlands, and the terrain surrounding the crater is quite rugged. Multispectral images obtained by the Clementine spacecraft show that the central peak has a different composition than the surrounding material, presumably because the central peak is composed of material that originated at greater depths in the Moon's crust. *(Lunar Orbiter image V-125M.)*





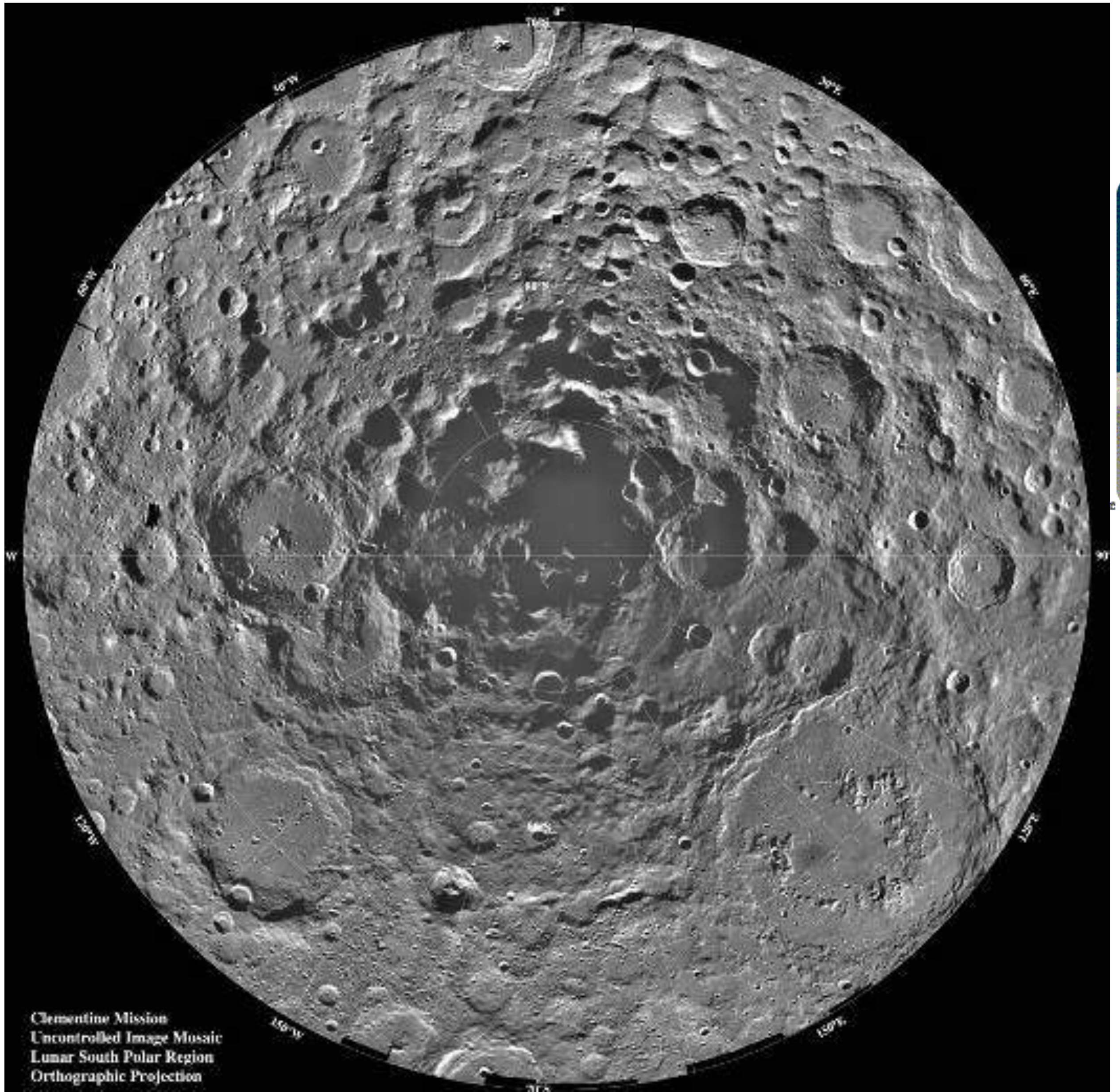
Tycho Crater

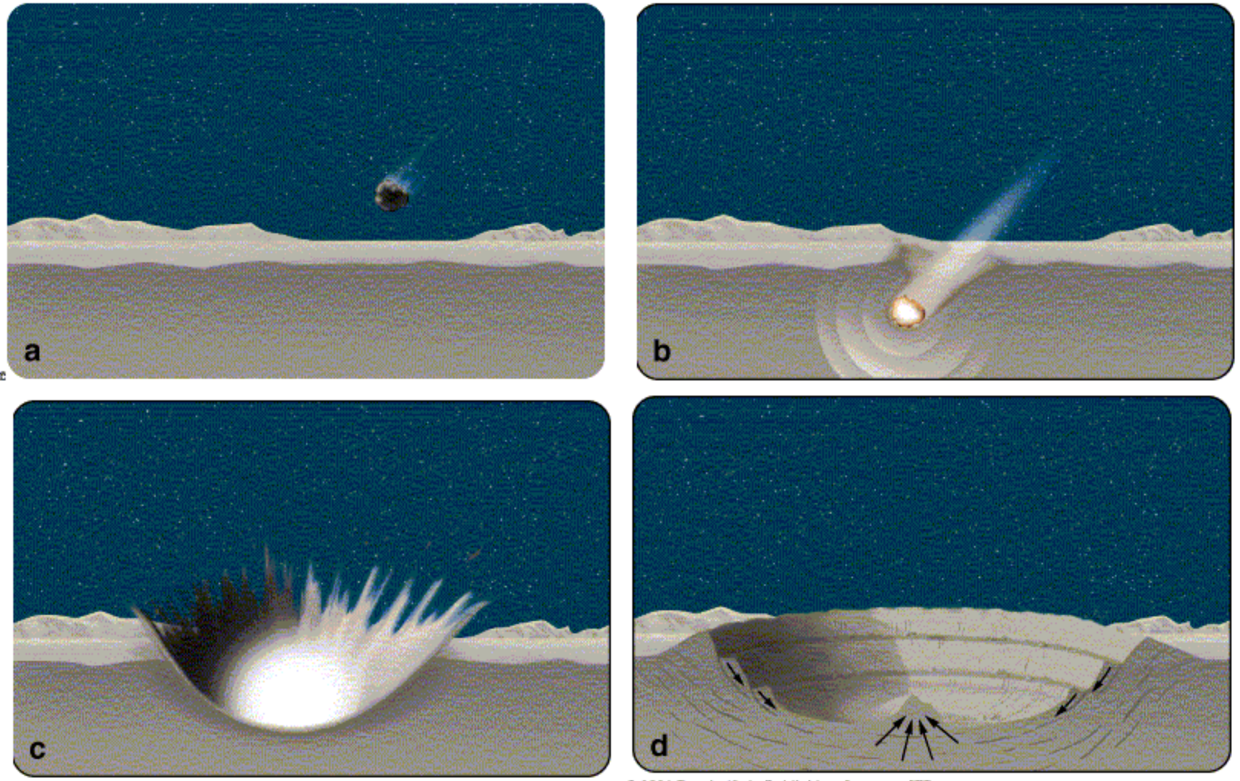
Young – 100 MY

85 kilometers diameter

Fresh (rays) = young

Impacts …"the most fundamental process on the terrestrial planets…" *Eugene and Carolyn Shoemaker*





Lunar Volcanism
Portions of the Moon's interior remained hot enough to produce magma for more than a billion years after it formed. Molten rock flowed onto the lunar surface through cracks in the crust, spreading out and filling the low regions in the impact basins. The lava cooled quickly, forming the fine-grained, dark rocks — basalt — sampled during the Apollo missions. The dark areas seen on the Moon are basaltic lava plains 4.2 to 1 billion. Volcanism in circular Mare Imbrium (left image). At right, shadows reveal the edges of a long lava flow from the lower left to the upper right of the image. The volcanism in Mare Imbrium occurred about 3.3 billion years ago (7 am on our clock). Because of its small size, the Moon cooled quickly and was mostly dead volcanically by 3 billion years ago, although limited volcanism in isolated regions is thought to have occurred as recently as 1 to 2 billion years ago.

Moon Becomes Geologically Inactive
Lunar volcanism decreased significantly by 3 billion years ago and ceased completely by about 1 billion years ago as the interior of this small body cooled.

Lunar Geologic History
Mare Volcanism

Mare Imbrium

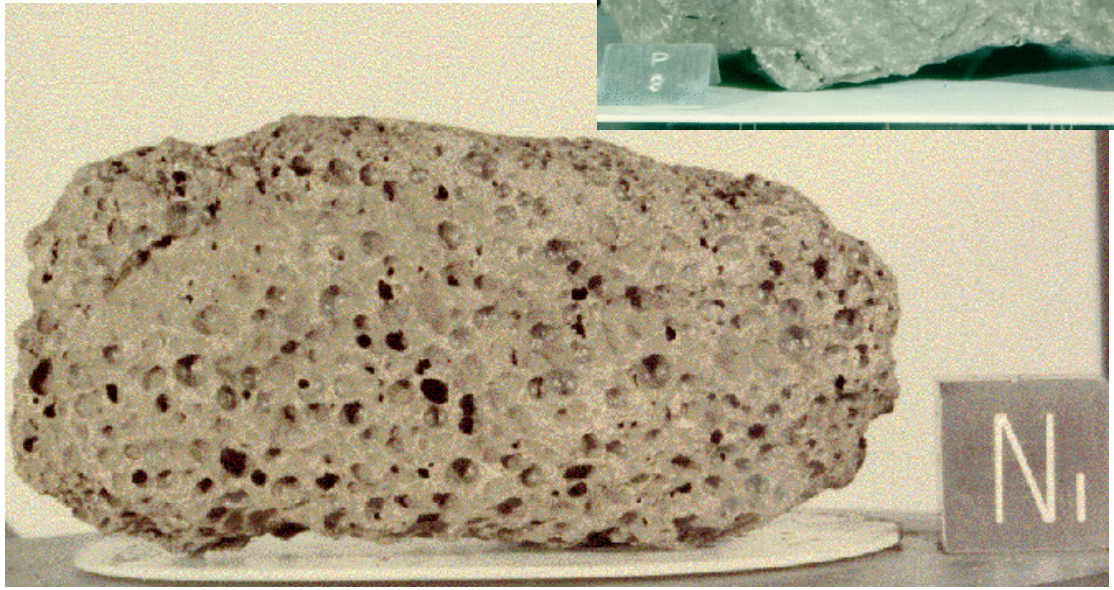
SW Mare Imbrium

Volcanism *after* impacts – most before 3 Ga (to 1 Ga)

Lunar Basalts

These rocks are typical of lunar volcanic rocks. Collected on Apollo 15, both are 3.3 billion year old basalts, similar to those produced by volcanos such as Hawaii on Earth. The lower image (sample 15016) contained some type of gas, possibly carbon monoxide, which formed the round holes known as vesicles.

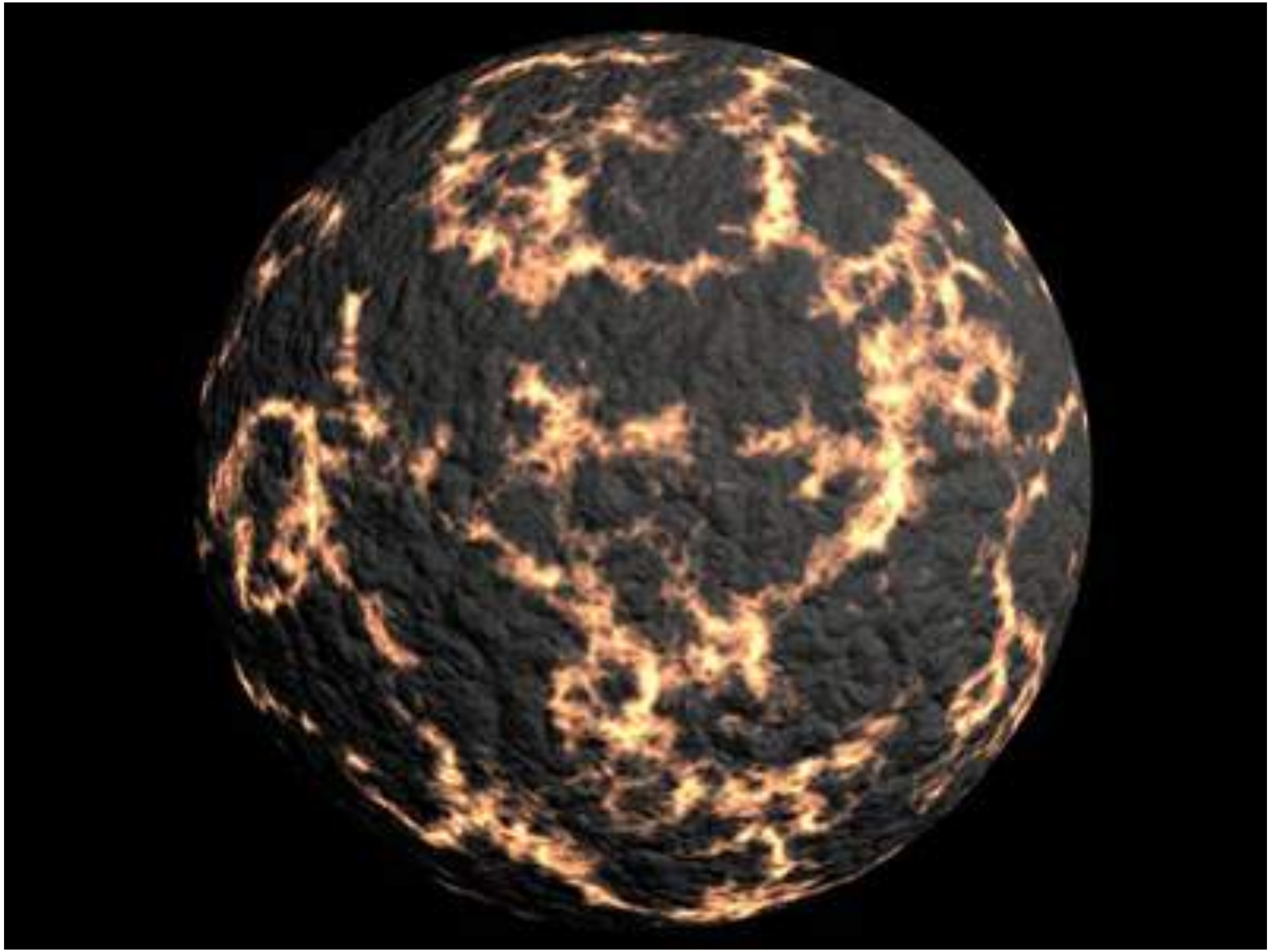
15555



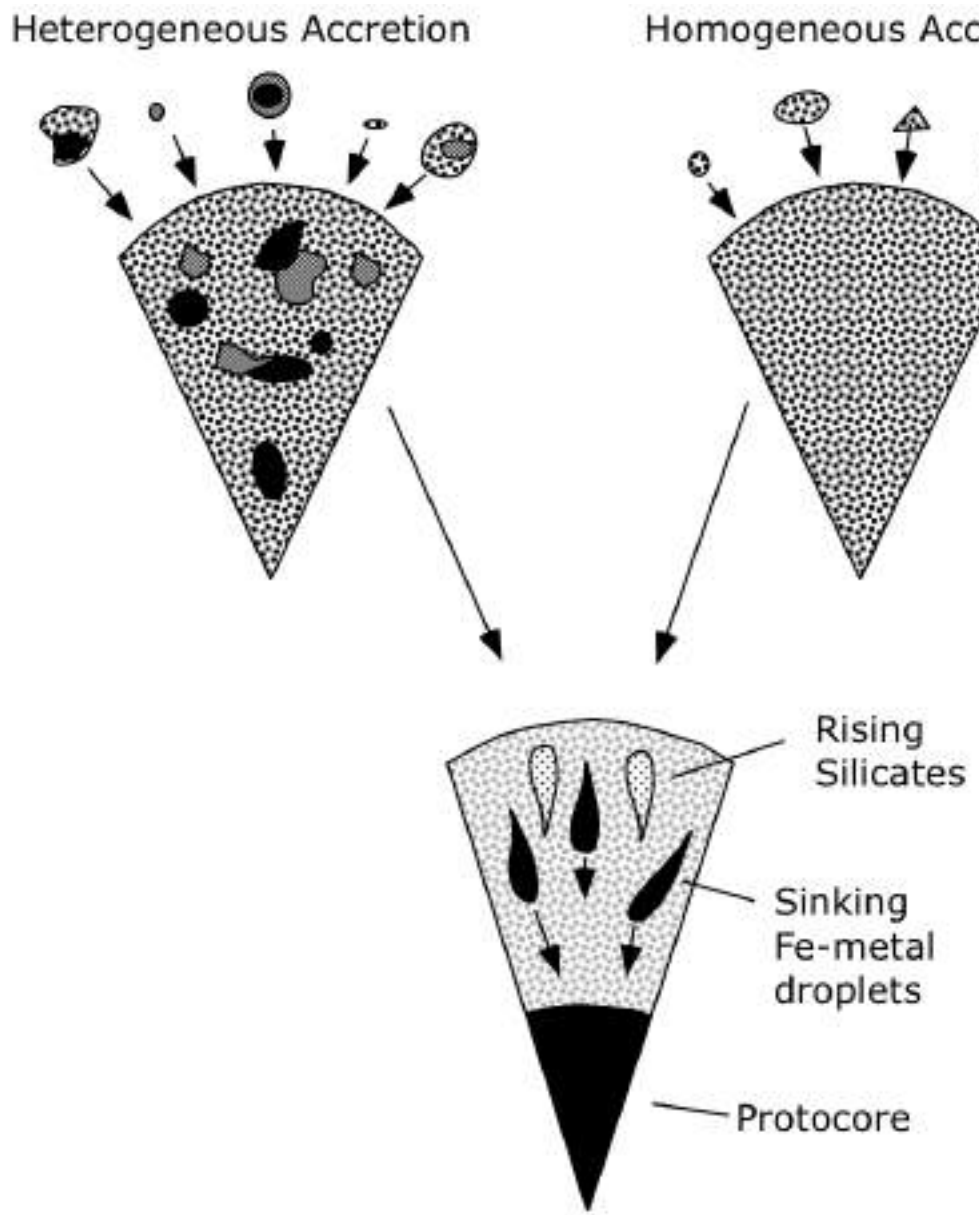
3.3 Ga

15016

The Early Earth Heats Up (Magma Ocean)



Origin of the Earth’s Internal Layering



Origin of the earth by accretion of planet-forming materials.

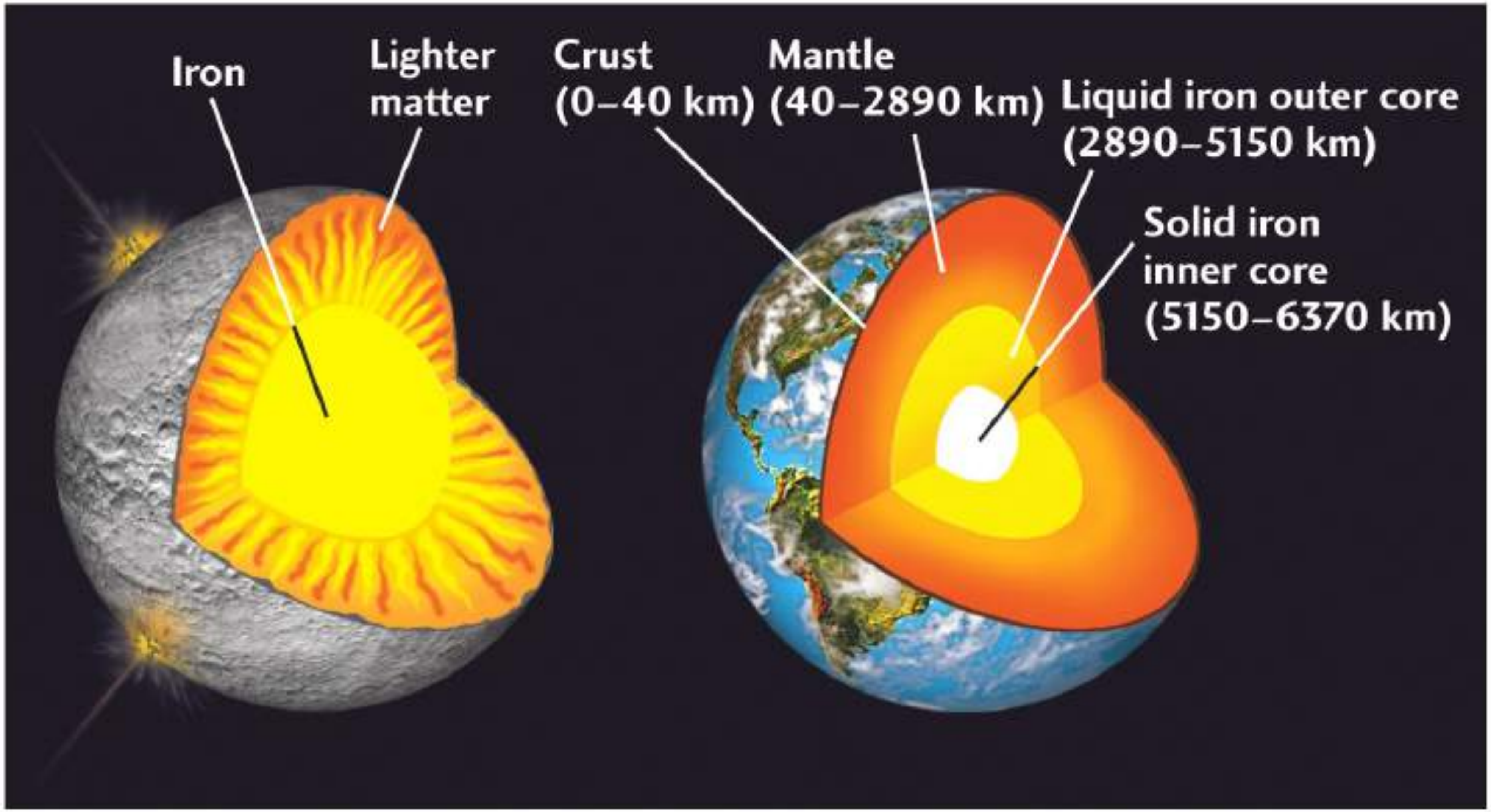
Terrestrial (inner) planets undergo differentiation process that includes melting and separation into layers

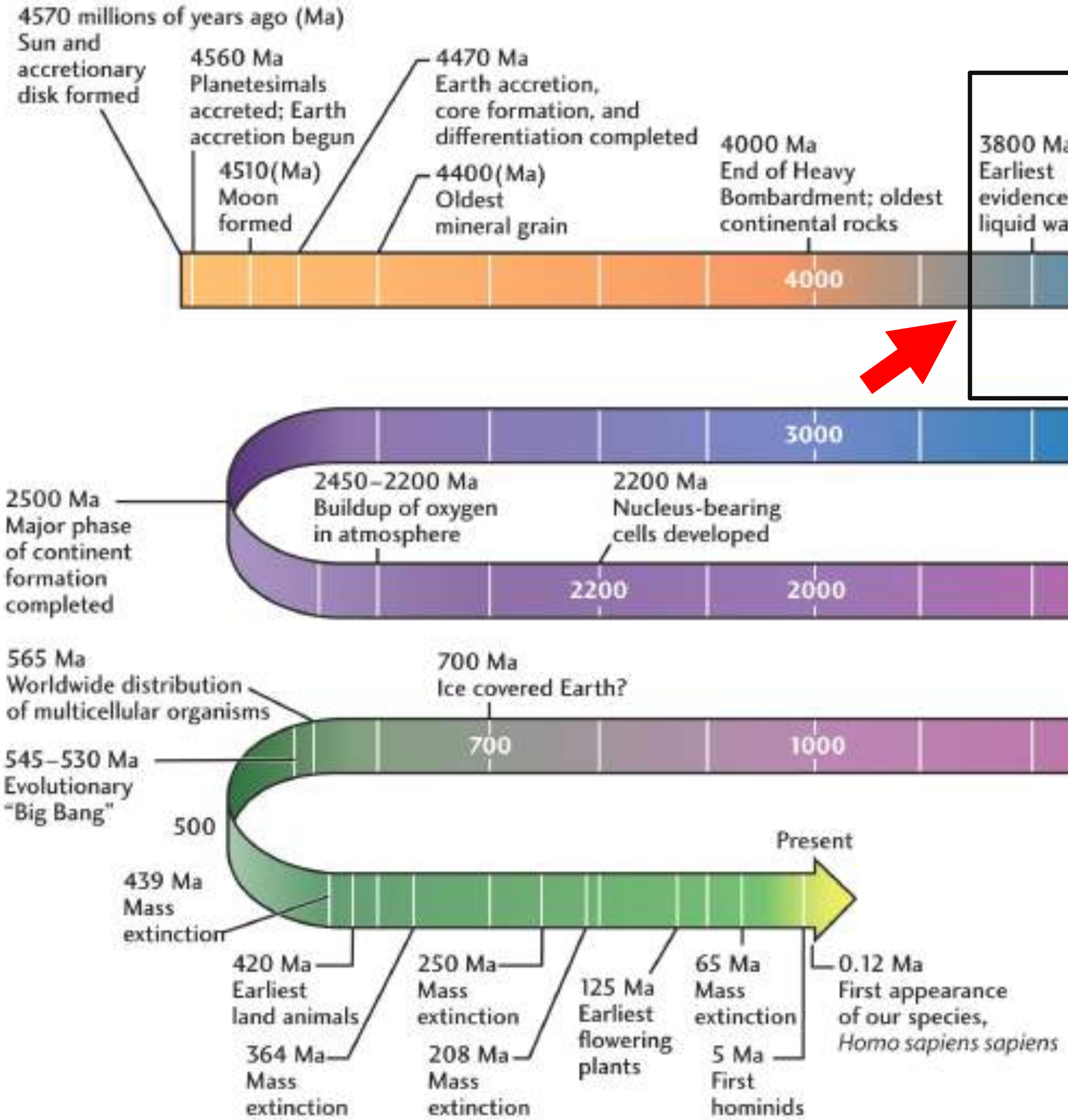
As rocks undergo collision during accretion phase and produce heat causing melting and eventually forms different layers

Denser material sinks to centre of the planet and lighter ones rises to surface

Global Chemical Differentiation

This global chemical differential was completed by ~4.3 billion years ago, and the Earth had developed a inner and outer core, a mantle and crust

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4560 Ma Planetesimals accreted; Earth accretion begun
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4400(Ma) Oldest mineral grain
4000 Ma End of Heavy Bombardment; oldest continental rocks
4000
3800 Ma Earliest evidence for liquid water
3500 Ma Earliest evidence for life
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2500 Ma Major phase of continent formation completed
2450–2200 Ma Buildup of oxygen in atmosphere
2200 Ma Nucleus-bearing cells developed
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545–530 Ma Evolutionary "Big Bang"
500
Present
439 Ma Mass extinction
420 Ma Earliest land animals
364 Ma Mass extinction
250 Ma Mass extinction
208 Ma Mass extinction
125 Ma Earliest flowering plants
65 Ma Mass extinction
5 Ma First hominids
0.12 Ma First appearance of our species, *Homo sapiens sapiens*

The Evolving Atmosphere

Right after its creation, the Earth is thought to have had a thin atmosphere composed primarily of helium (He) and hydrogen (H) gases

The Earths gravity could not hold these light gases and they easily escaped into outer space

Today, H and He are very rare in our atmosphere

The Evolving Atmosphere

For the next several hundred million years, volcanic out-gassing began to create a thicker atmosphere composed of a wide variety of gases mostly

composed of CO_2, H_2O and NH_3

The released gases were probably similar to those created by modern volcanic eruptions

Creating the Oceans

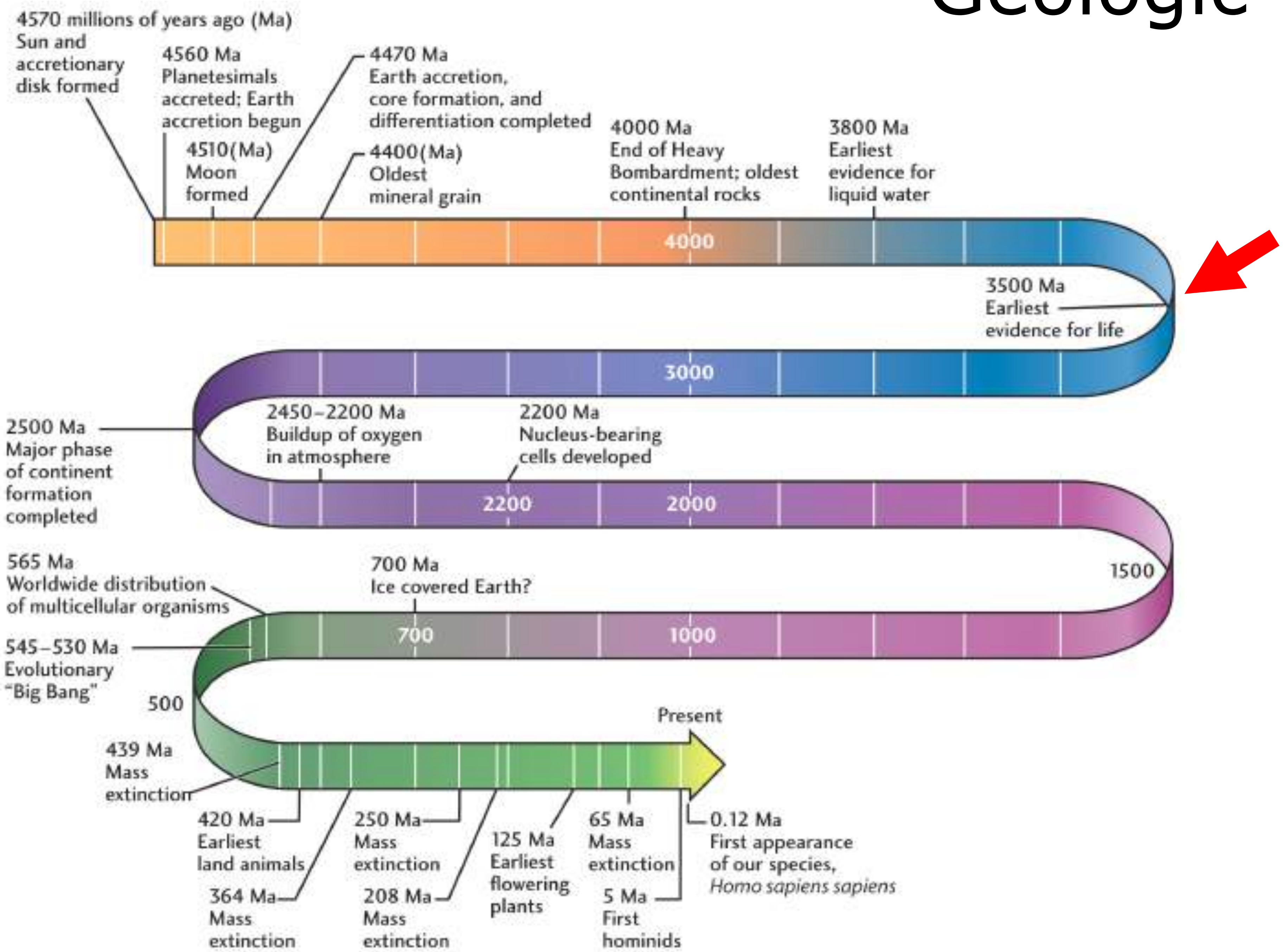
By 3.5 billion years ago, when the Earth was a billion years old, it had a thick atmosphere composed of CO_2, methane, water vapor and other volcanic gases

Earth cooled with time.

It is hypothesized that water vapor escaping from the interior of the Earth via countless volcanic eruptions produced rain for millions of years and eventually created oceans (this took hundreds of millions of years)

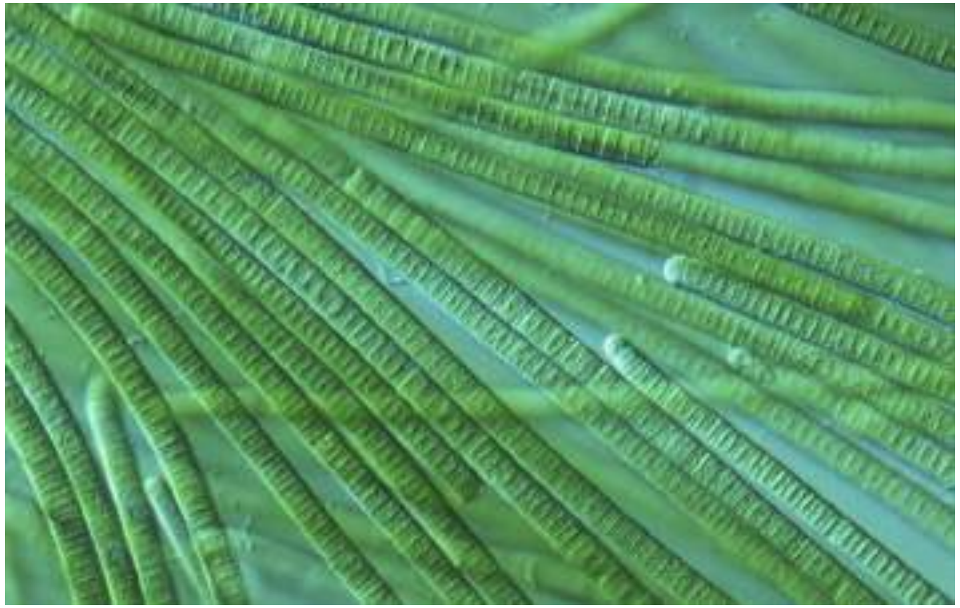
But O_2 is still Missing!

Geologic Time

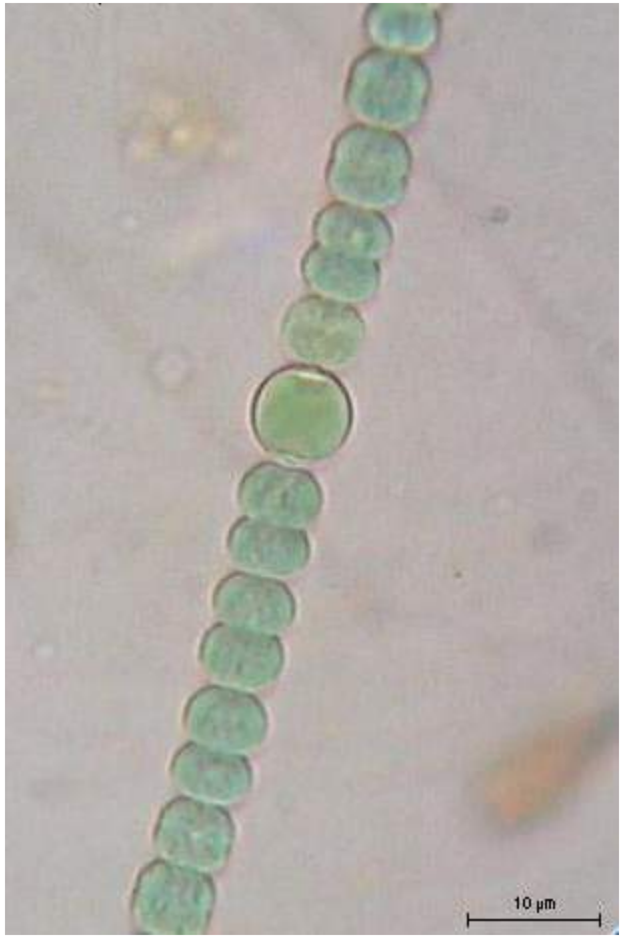


Cyanobacteria

Cyanobacteria, commonly called blue-green algae, is a phylum of bacteria that obtain their energy through photosynthesis



This was the first life on Earth



<u>CO_2 and N_2 dissolved into Oceans and Cyanobacteria developed in oceans which started photosynthesis using sunlight, H_2O and CO_2.</u>

Evidence of Early Life

The 3.5 billion year old fossilized algae mats, which are called stromatolites, are considered to be the earliest known life on earth. Stromatolites are formed in shallow seas or lagoons when millions of cyanobacteria (a primitive type of bacteria) live together in a colony.

Stromatolites are mound like bio-accretionary structures. Microbial mats by Cyanobacteria developed on top surfaces of stromatolitic deposits and then was trapped by cycle of sedimentation. Eventually another layer of microbial mat developed on top of the earlier layer and again was trapped by sedimentation. Thus stromatolites grew preserving history.

Banded Iron Formations (BIF)

How do we know that there was no oxygen in the early Earth atmosphere?

It is hypothesized that the banded iron layers were formed in sea water as the result of free oxygen released by photosynthetic cyanobacteria combining with dissolved iron in the oceans to form insoluble iron oxides, which precipitated out, forming a thin layer on the seafloor

The structures consist of repeated thin layers of iron oxides, either magnetite or hematite, alternating with bands of iron-poor shale and chert

Banded Iron Formations (BIF)

<u>BIFs are primarily found in very old sedimentary rocks, ranging from over 3 to 1.8 billion years in age</u>

Iron rich basalt leached iron into <u>acidic</u> ocean formed due to dissolved CO_2. Photosynthesis of Cyanobacteria produced free oxygen which oxidized iron (Fe^{+2} and Fe^{+3}) to produce red iron (III) oxide (Fe_2O_3) on the ocean floor

Banded Iron Formations

Water must have been replenished with fresh, Iron enriched ocean water cyclically, leading to fresh deposition of BIF

<u>BIF indicates seasonality</u> with iron-rich layers and also <u>indicates possibility of a period of more sunlight availability</u> with increasing photosynthesis, alternating with iron poor layers with low availability of sunlight with less photosynthesis

Oxygen Evolution in the Atmosphere

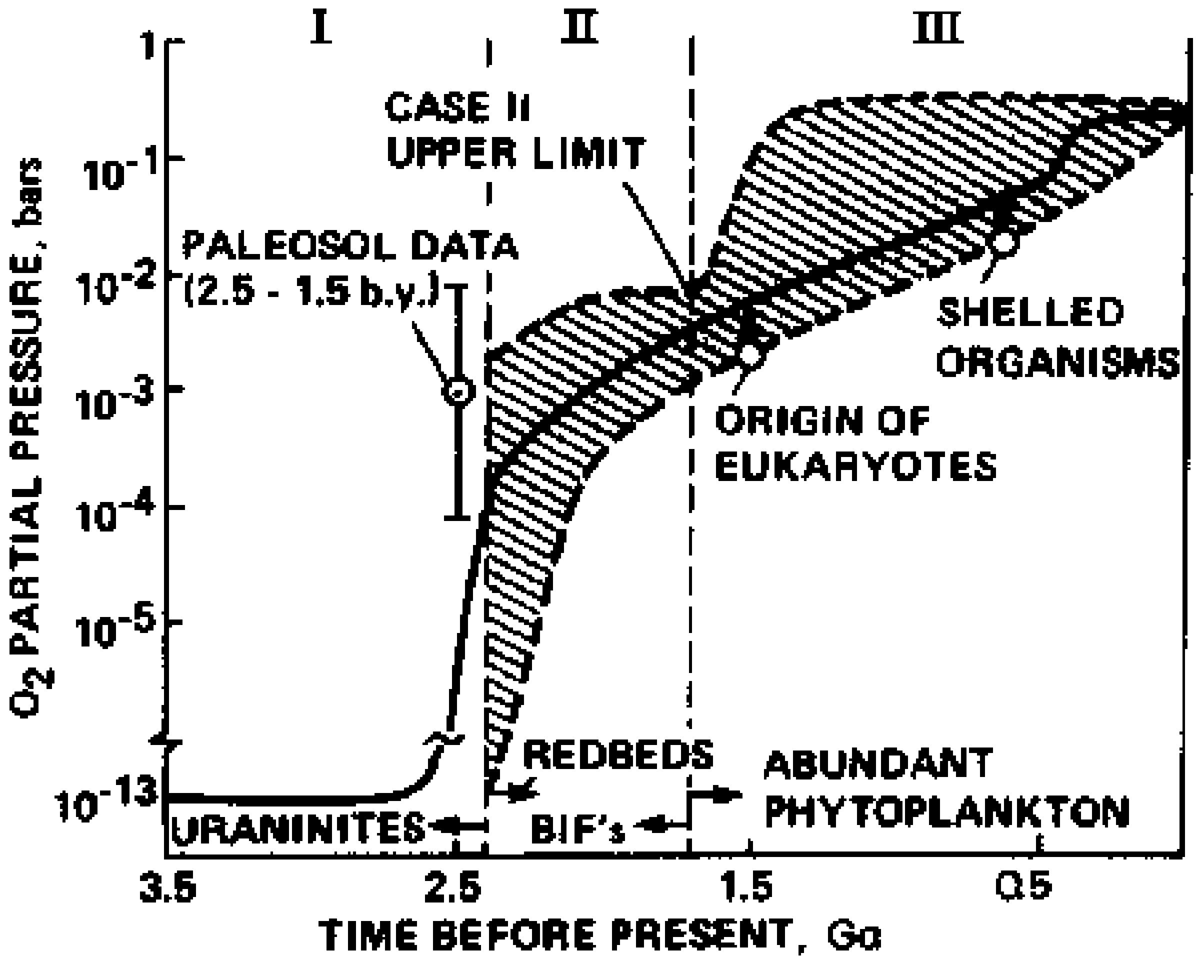


Fig. 7. Estimated change in pO_2 over geologic time. Again, the solid curve is a best guess, and the shaded area represents the range of uncertainty. The point labelled 'paleosol data' is derived from the results of Holland and Zbinden (1986), assuming that $pCO_2 = 0.05$ bar.

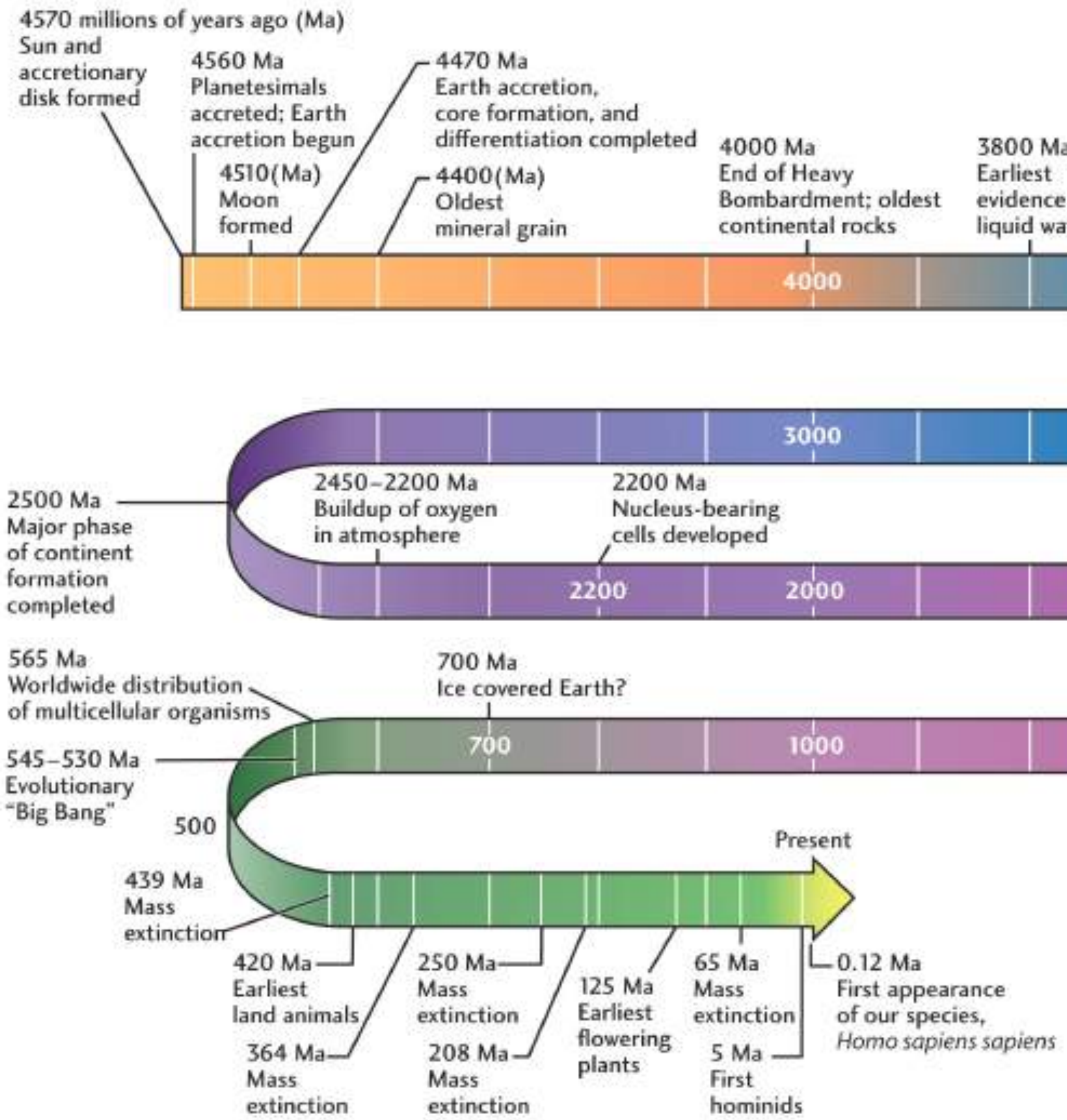
Kasting 1987

Cyanobacteria were considered to be the source of oxygen and was responsible for BIF precipitation between 3.5-1.8 Ba.

Free O_2 released into ocean participated in Fe oxidation until all Fe was depleted

<u>Increasing O_2 production eventually released into atmosphere and the environment shifted to</u>

<u>irreversible oxidizing state from a reducing state</u>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4000 Ma
End of Heavy Bombardment; oldest continental rocks
3800 Ma
Earliest evidence for liquid water
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3500 Ma
Earliest evidence for life
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2500 Ma
Major phase of continent formation completed
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Buildup of oxygen in atmosphere
2200 Ma
Nucleus-bearing cells developed
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565 Ma
Worldwide distribution of multicellular organisms
700 Ma
Ice covered Earth?
700
1000
545–530 Ma
Evolutionary "Big Bang"
500
Present
439 Ma
Mass extinction
420 Ma
Earliest land animals
364 Ma
Mass extinction
250 Ma
Mass extinction
208 Ma
Mass extinction
125 Ma
Earliest flowering plants
65 Ma
Mass extinction
5 Ma
First hominids
0.12 Ma
First appearance of our species, *Homo sapiens sapiens*

FUNDAMENTALS OF EARTH SCIENCES
(ESO 213A)

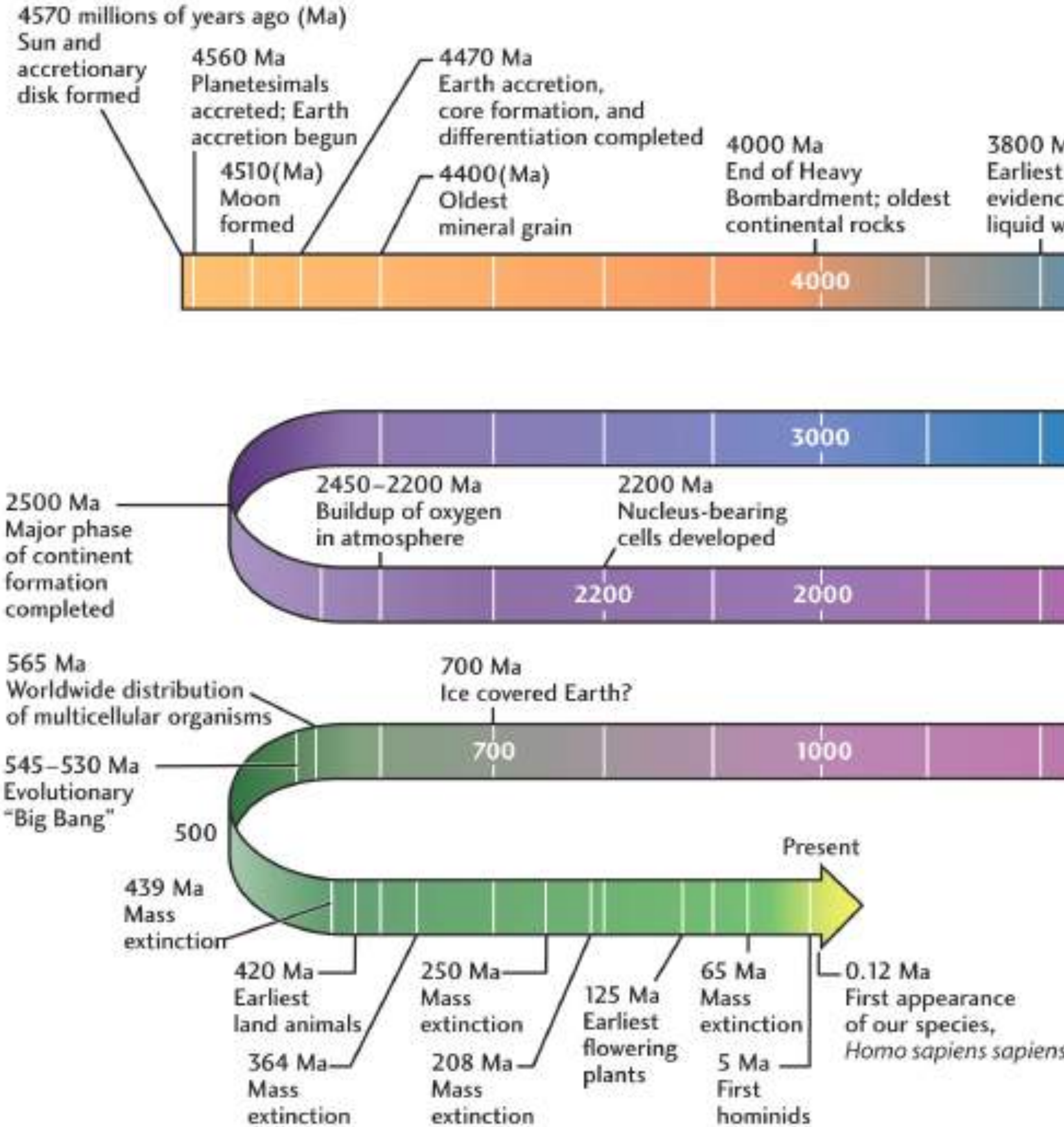
DIBAKAR GHOSAL
DEPARTMENT OF EARTH SCIENCES

Topic: Internal structure of Earth

Previous Class: Earth, Moon and Atmosphere

Last Class: Review

- Origin of our Solar System (4.57 Ba)
- Origin of Earth (4.56 Ba)
- Origin of Moon (4.51 Ba)
- Internal Layering (4.47 Ba)
- Water (3.8 Ba)
- Oxygen(3.5 Ba)
- BIF (~3.0 Ba)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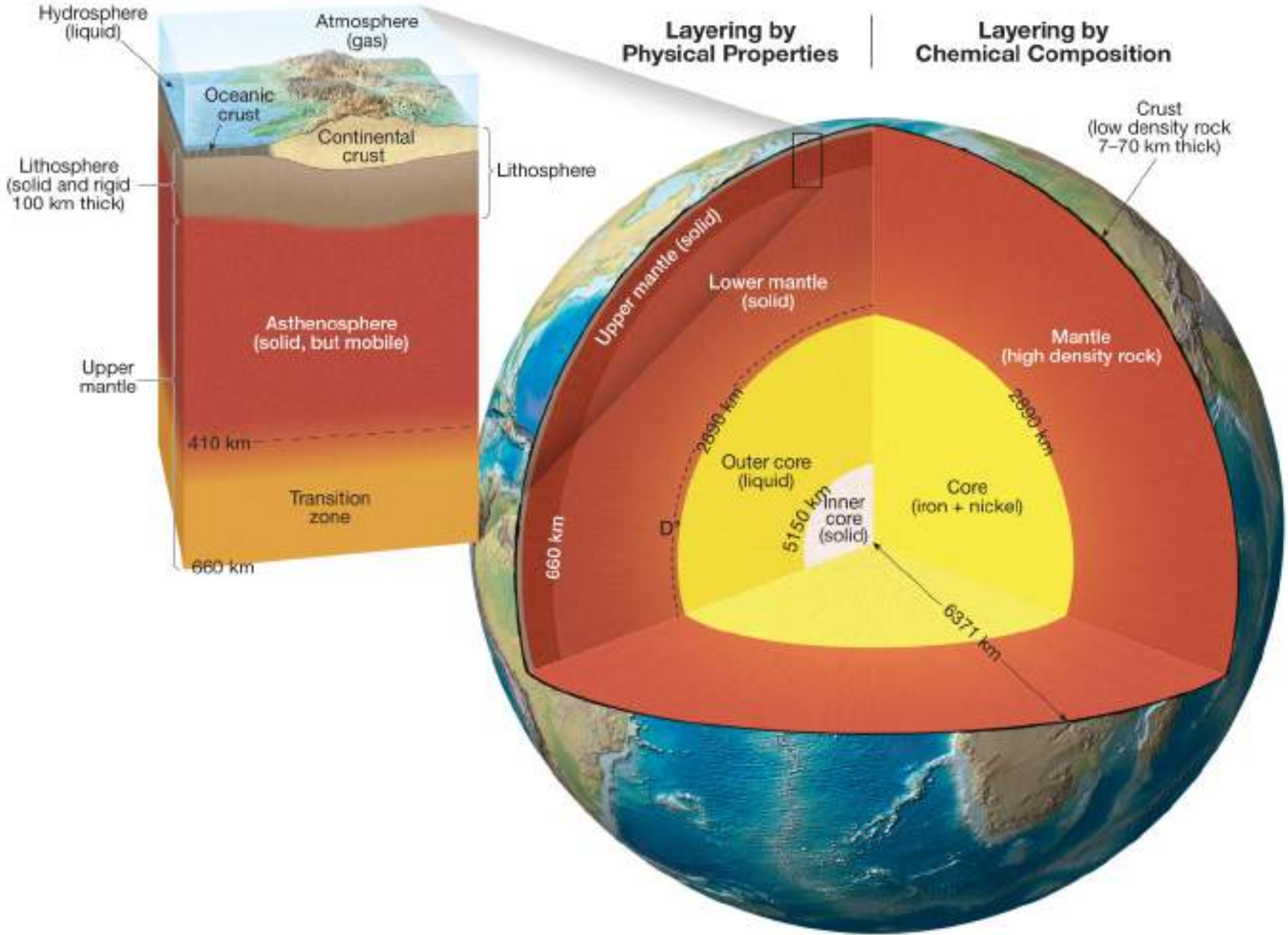
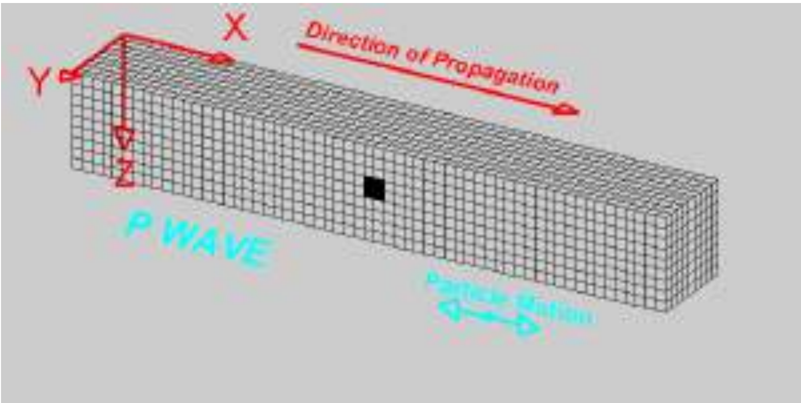
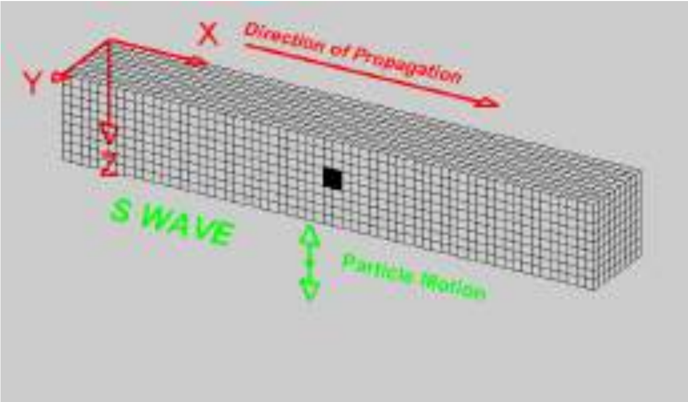
Earth's Layered Structure



Probing Earth's Interior

- *Most of our knowledge of Earth's interior comes from the study of earthquake waves.*
  - **Travel times of P (compressional) and S (shear) waves through the Earth vary depending on the properties of the materials. P waves travel faster than do S waves. S waves cannot travel through liquids**





$$v_p = \sqrt{\frac{\kappa + 4\mu/3}{\rho}}$$

$$v_s = \sqrt{\frac{\mu}{\rho}}$$

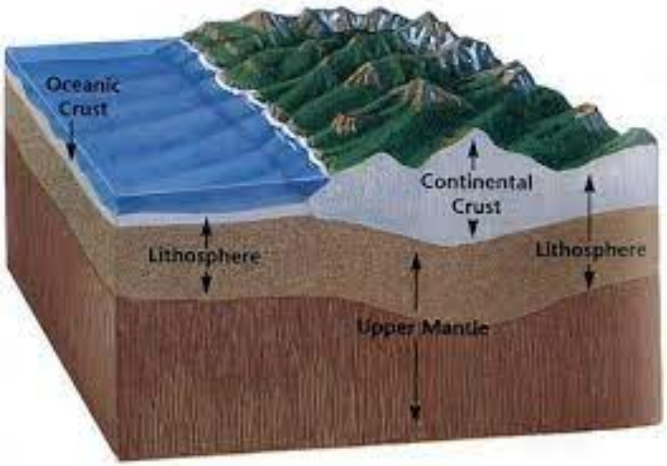
Earth's Layers

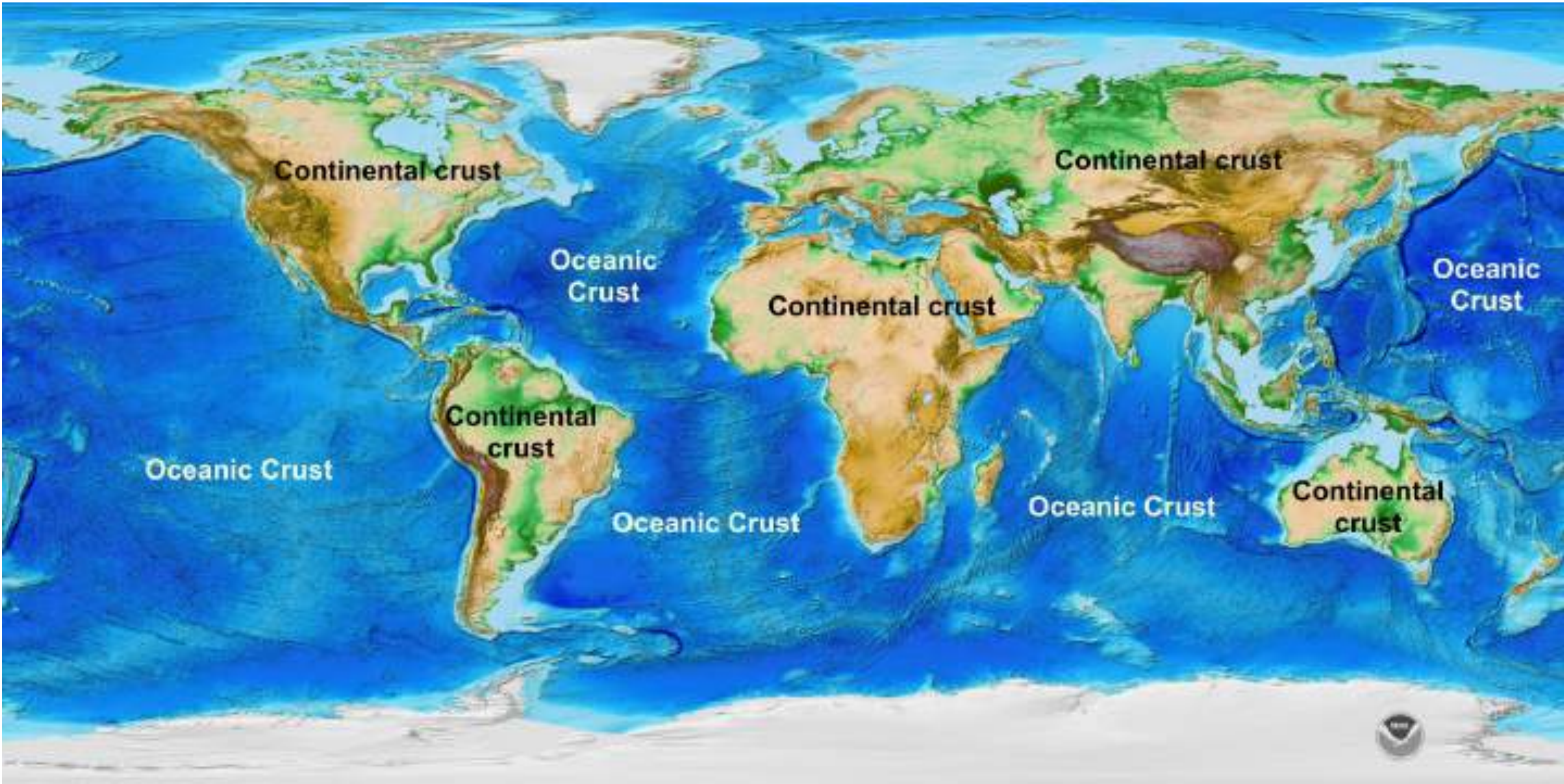
Crust: *1. oceanic* - P wave = 5 – 7 km/s

- density = 3 g/cm³

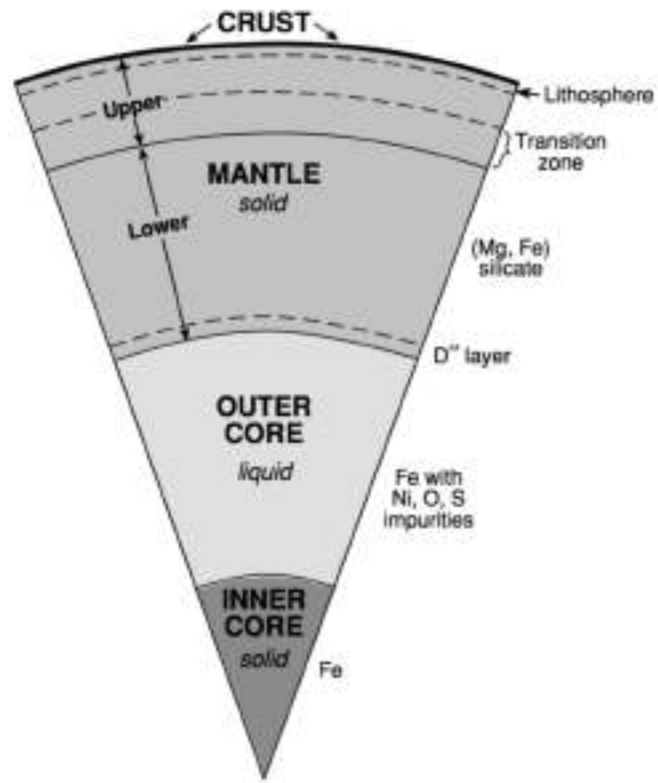
2. continental - seismic velocities vary

- density = 2.7 g/cm³ (buoyant)





Earth's Layers



Crust: *1. oceanic* - P wave = 5 – 7 km/s

- density = 3 g/cm³

***2. continental* - seismic velocities vary**

***- density = 2.7 g/cm³* (buoyant)**

Mantle: - 82 % of Earth's volume, ~ 2900 km thick

- between Moho (base of crust) and the liquid core

- silicate minerals rich in Fe and Mg

- density = between 3.3 and 5.6 g/cm³

Core: - at the mantle-core boundary

» P wave velocities drop from ~13.7 km/s to 8.1 km/s

» S wave velocities drop from ~7.3 km/s to 0 km/s

- density = 9.9 g/cm³

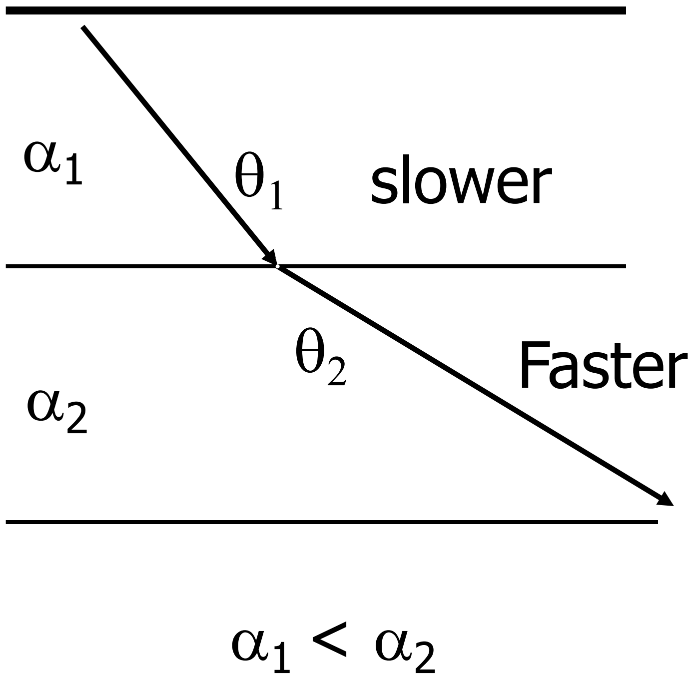
Probing Earth's Interior

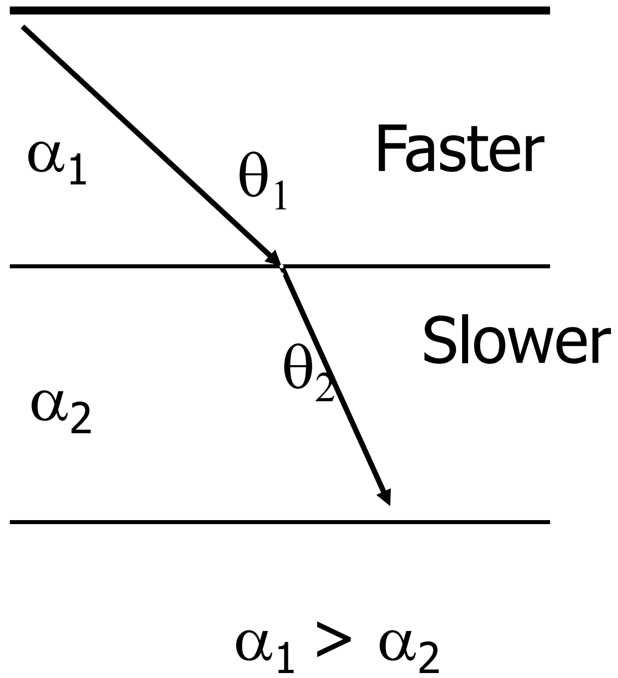
- The speed of seismic waves
  - Velocity (speed) depends on the *stiffness* and *compressibility* of the intervening material → information about the composition and temperature
  - Faster in more rigid (stiff) and less compressible rocks
  - Increases with depth (pressure increases and squeezes the rock into a more compact, rigid material) → strongly curved paths

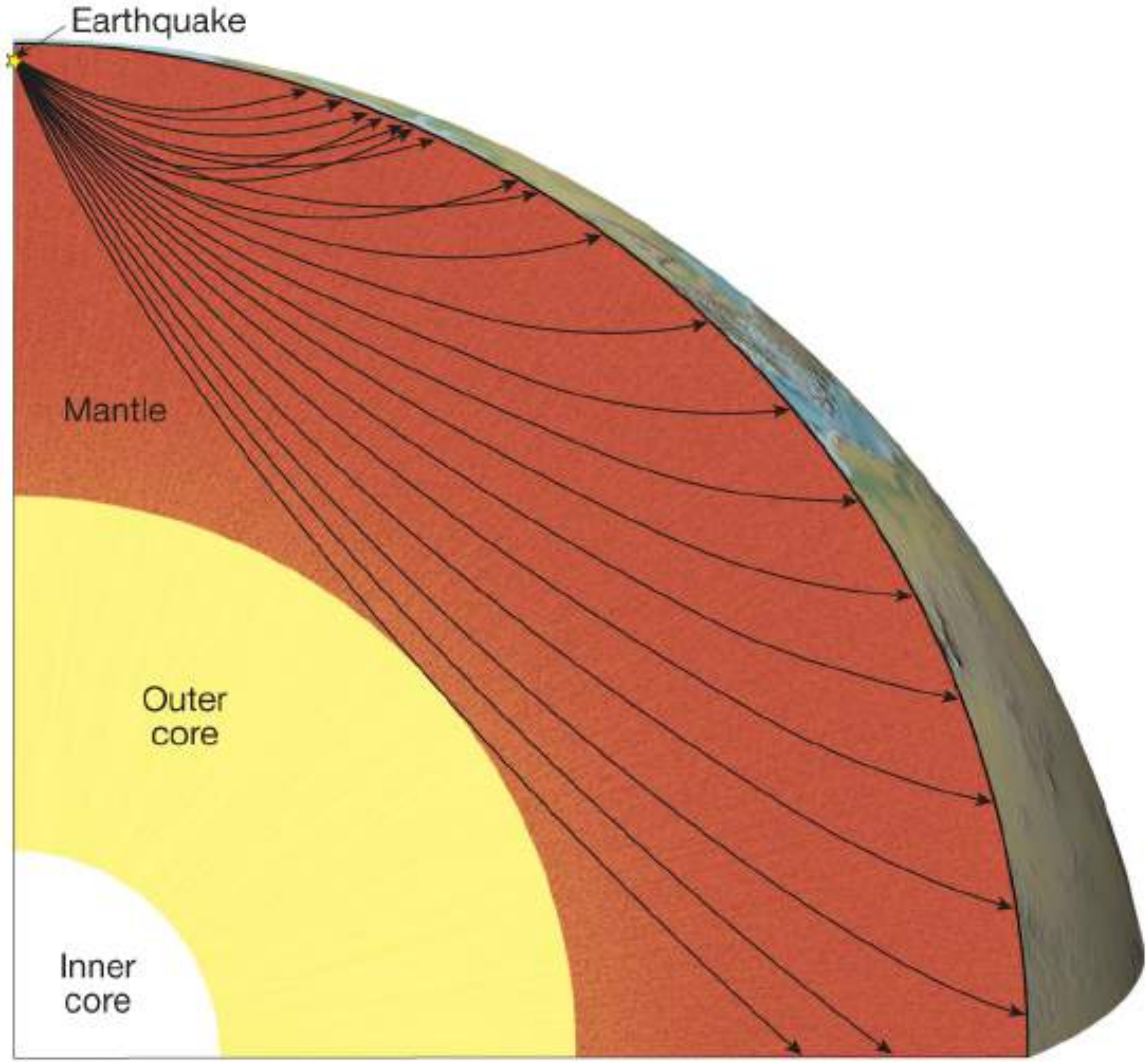
Ray Paths in a Layered Medium

$\sin\theta_1 / \alpha_1 = \sin\theta_2 / \alpha_2 = s_1 \sin\theta_1 = s_2 \sin\theta_2$

$\alpha =$ velocity of seismic energy in the layer

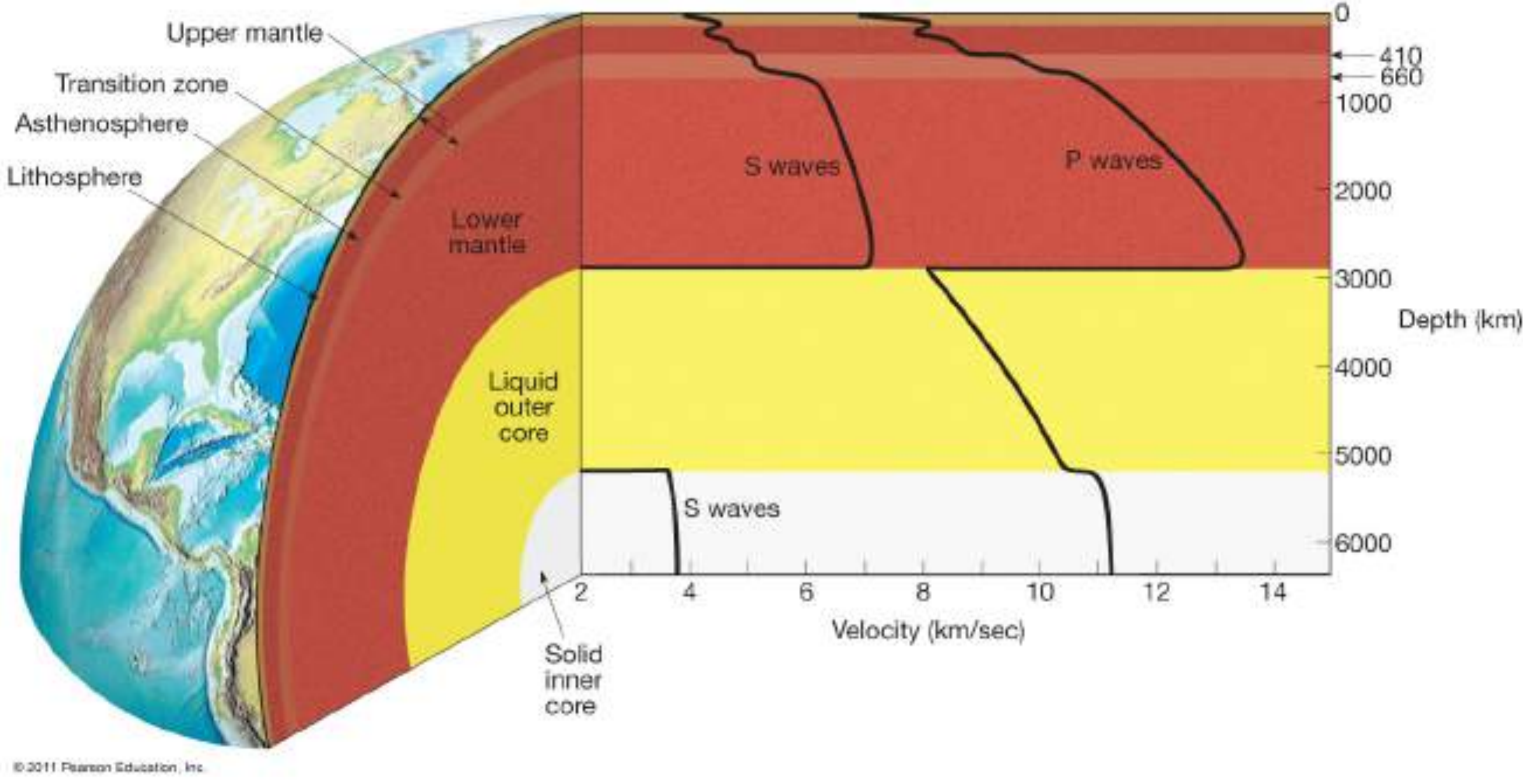





Earthquake
Mantle
Outer core
Inner core

Seismic Waves and Earth's Structure

- **Abrupt changes in seismic-wave velocities that occur at particular depths helped seismologists to conclude that Earth must be composed of distinct shells.**

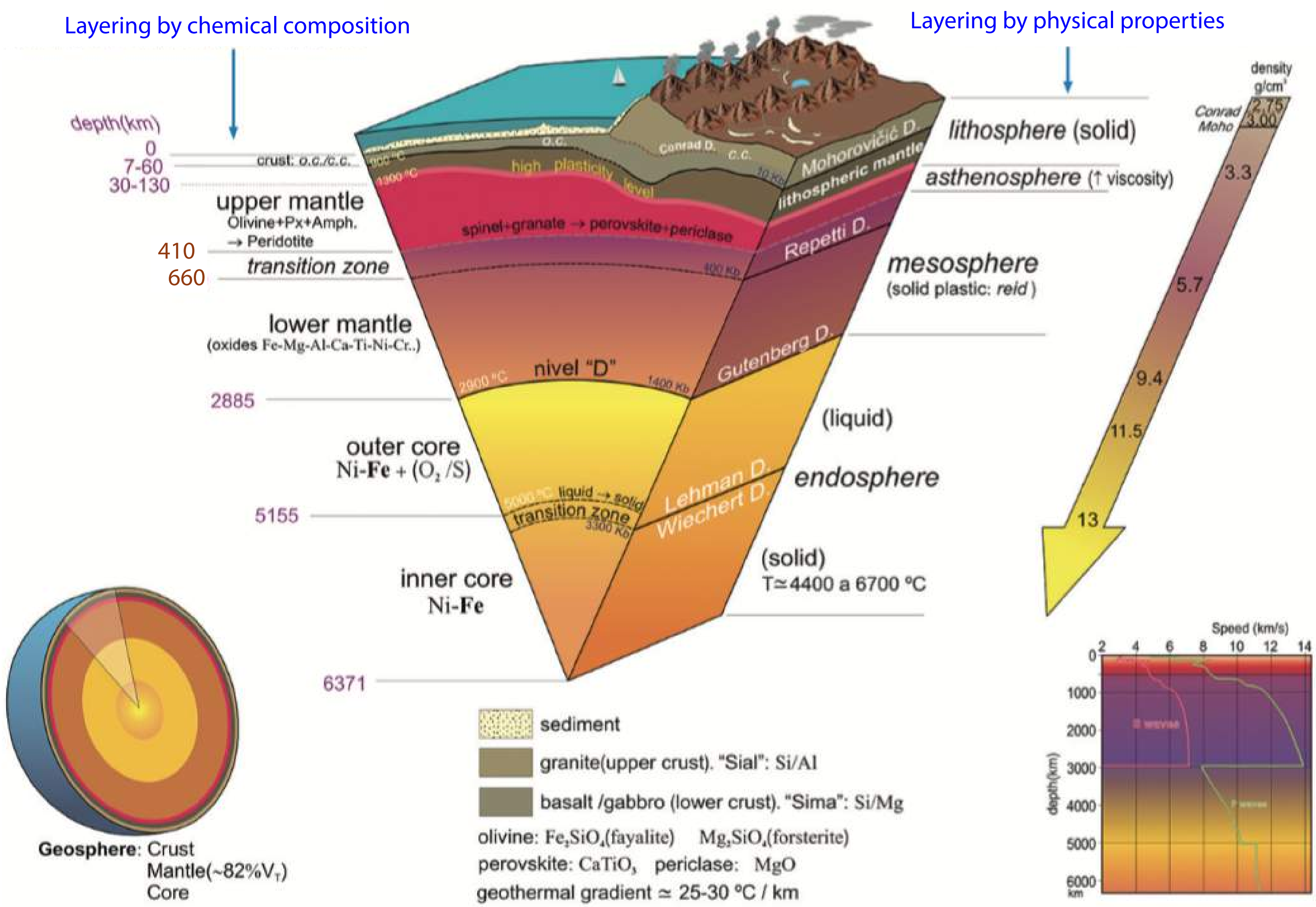


I. Layers are defined by composition.

Earth's Layers

Three principal compositional layers

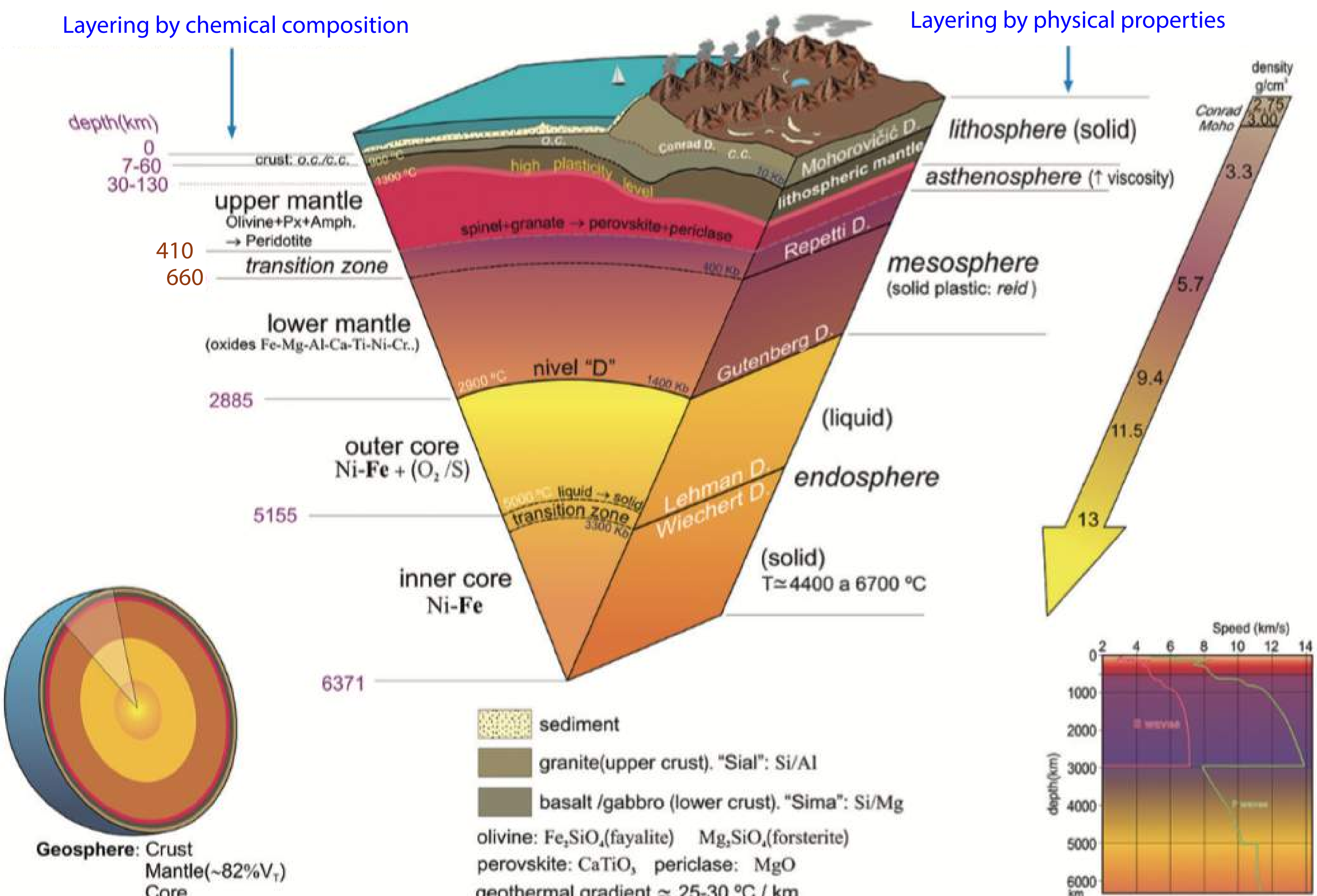
1. **Crust is the comparatively thin outer skin that ranges from 7 kilometers at the oceanic ridges to 70 kilometers in some mountain belts**
2. **Mantle is a solid rocky (silica-rich) shell that extends to a depth of about 2900 kilometers**
3. **Core is an iron-rich sphere having a radius of about 3500 kilometers**



modified after Gervilla et al., 2019

Discovering Earth´s Major Boundaries

- *The crust-mantle boundary*
- **The Moho (Mohorovicic) discontinuity**
  - **Discovered in 1909 by Andrija Mohorovičić**
  - **Identified by an abrupt change in the velocity of P waves at the base of continents (from ~6 km/s to 8 km/s)**

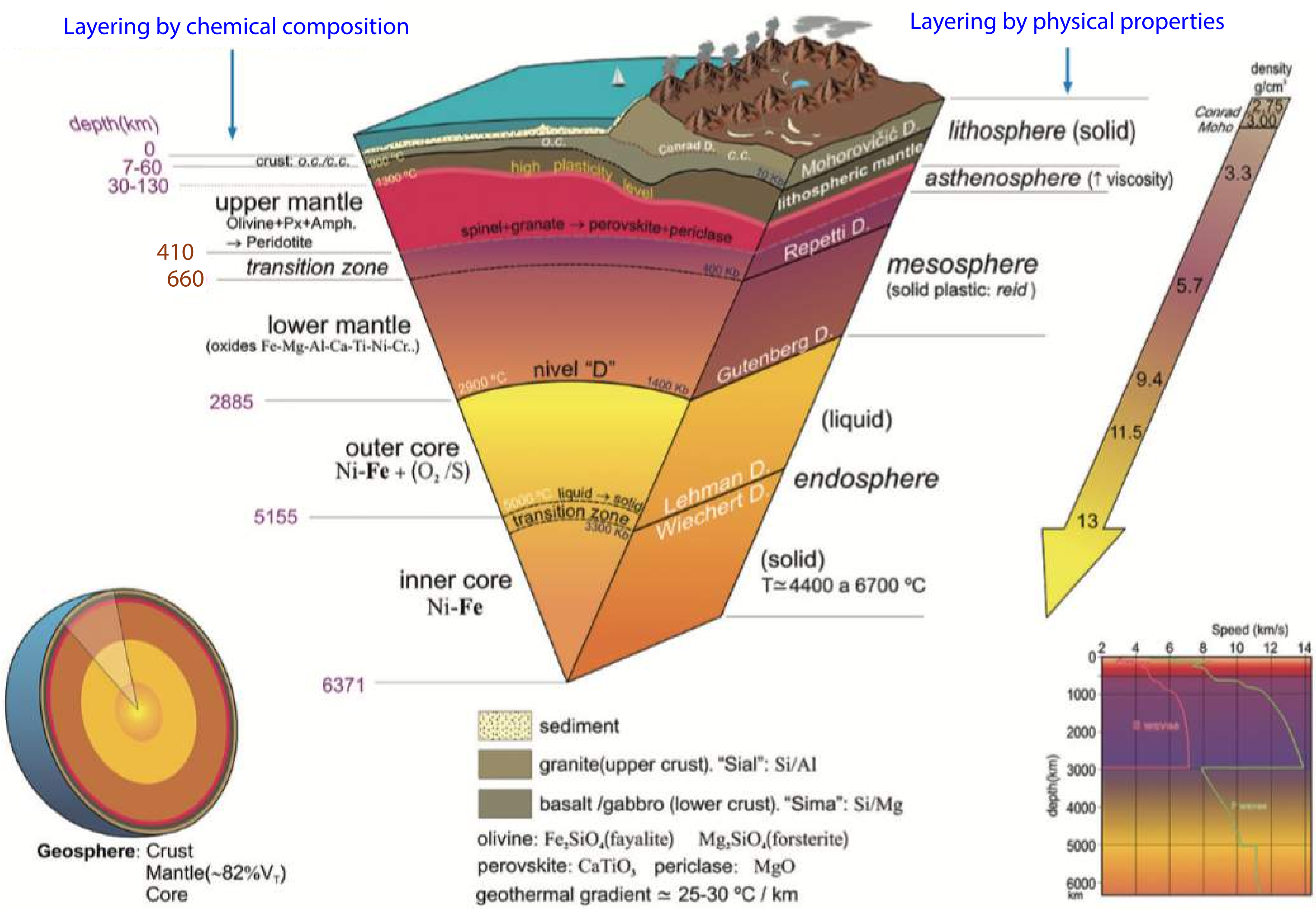


modified after Gervilla et al., 2019

Discovering Earth's Major Boundaries

The mantle-core boundary

- **Discovered in 1906 by Richard Oldham (Gutenberg Discontinuity)**
- **Based on the observation that P waves die out at 100 degrees from the earthquake and reappear at about 140 degrees**
- **35 degree-wide belt is named the P-wave shadow zone.**



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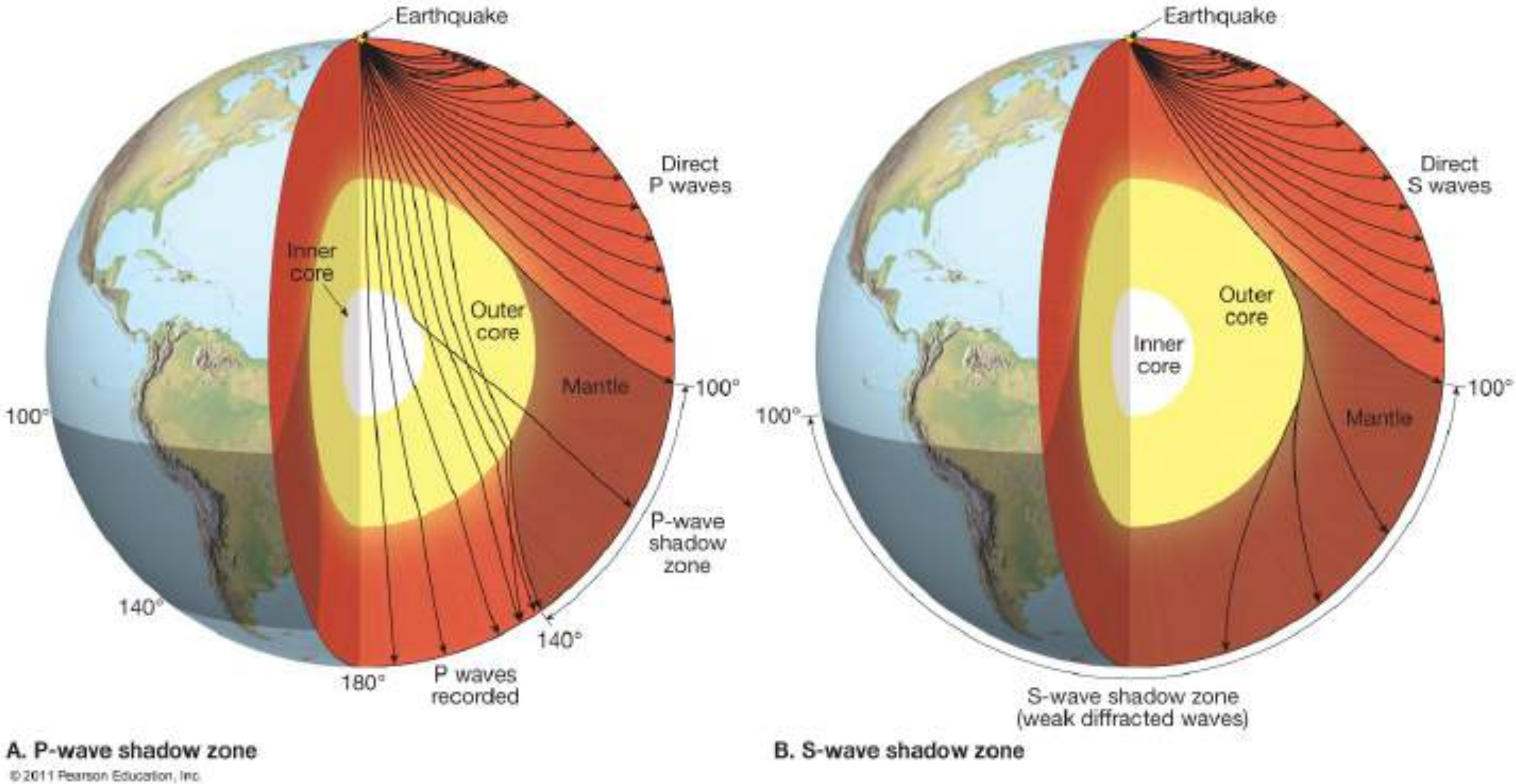
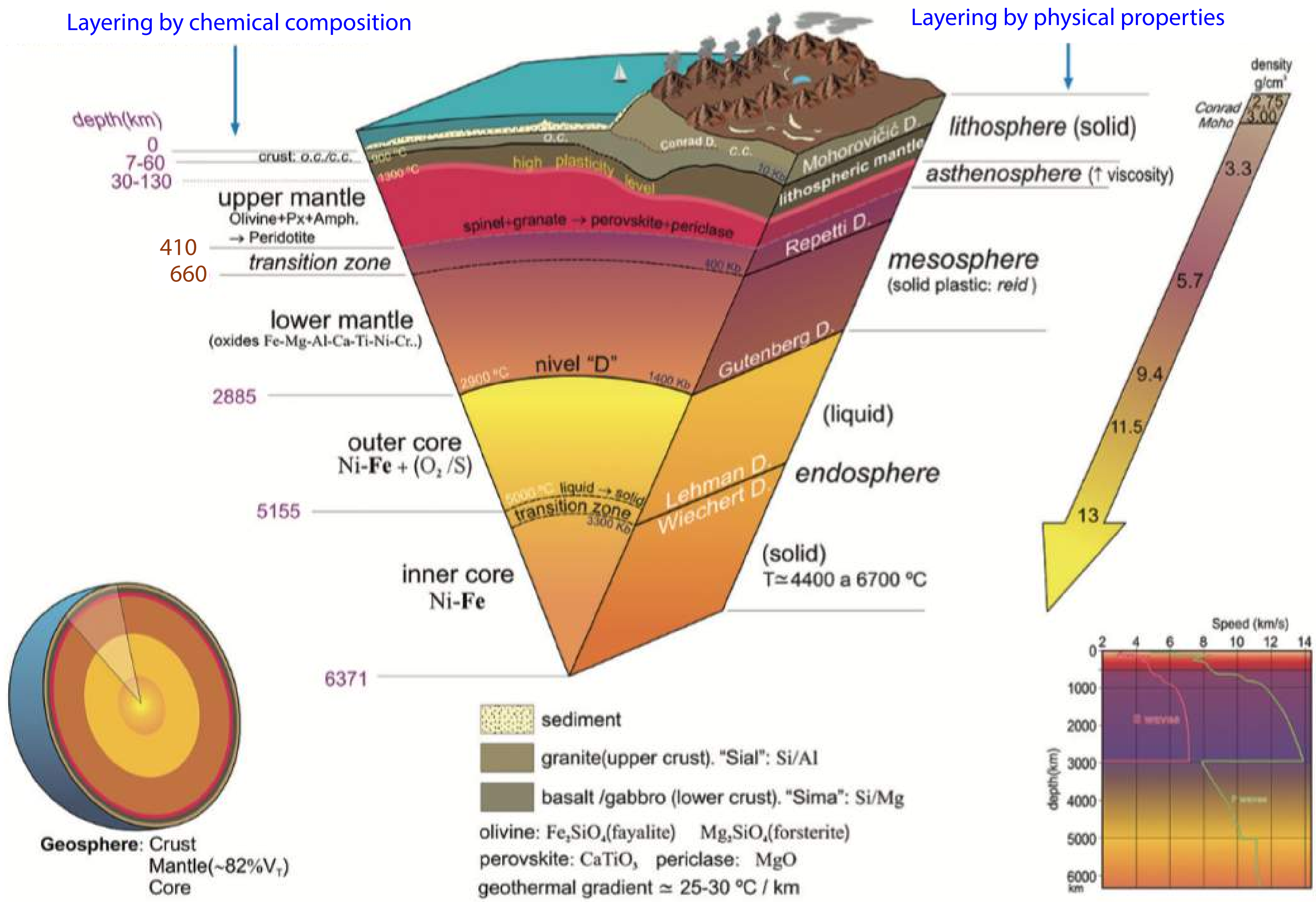
Shadow zones



Earth's Layers

II. Layers are defined by physical properties.

- With increasing depth, Earth's interior is characterized by gradual increases in temperature, pressure, and density.
- Depending on the temperature and depth, a particular Earth material may behave like a brittle solid, deform in a plastic–like manner, or melt and become liquid.
- Main layers of Earth's interior are based on physical properties and hence, mechanical strength.



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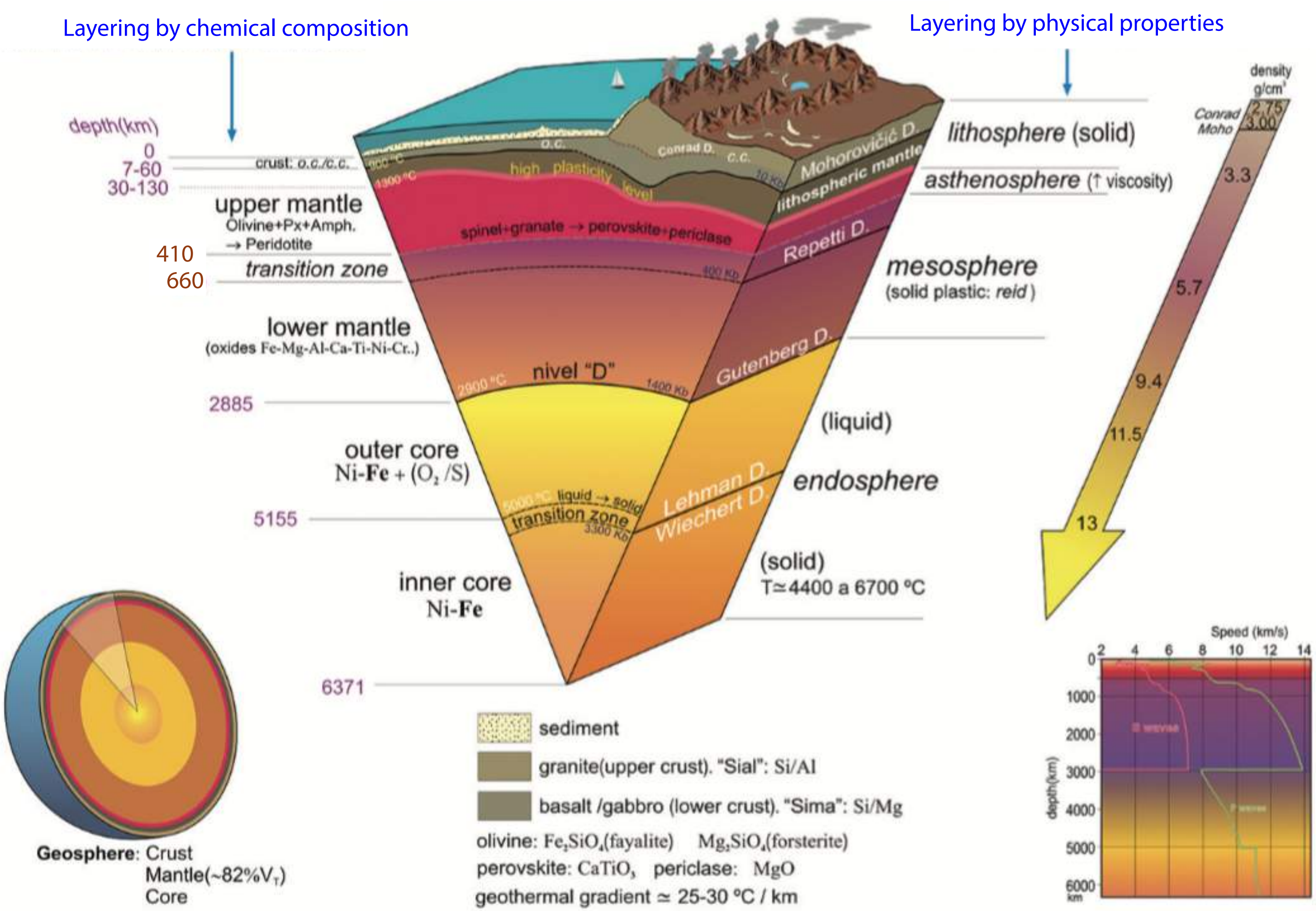
Gervilla et al., 2019

I. The Upper Mantle (Moho → 660 km)

Earth's Structure

- **A. Lithosphere (sphere of rock)**
  - **Earth's outermost layer**
  - **Consists of the crust and uppermost mantle**
  - **Relatively cool, rigid shell**
  - **Averages about 100 kilometers in thickness, but may be 250 kilometers or more thick beneath th older portions of the continents.**



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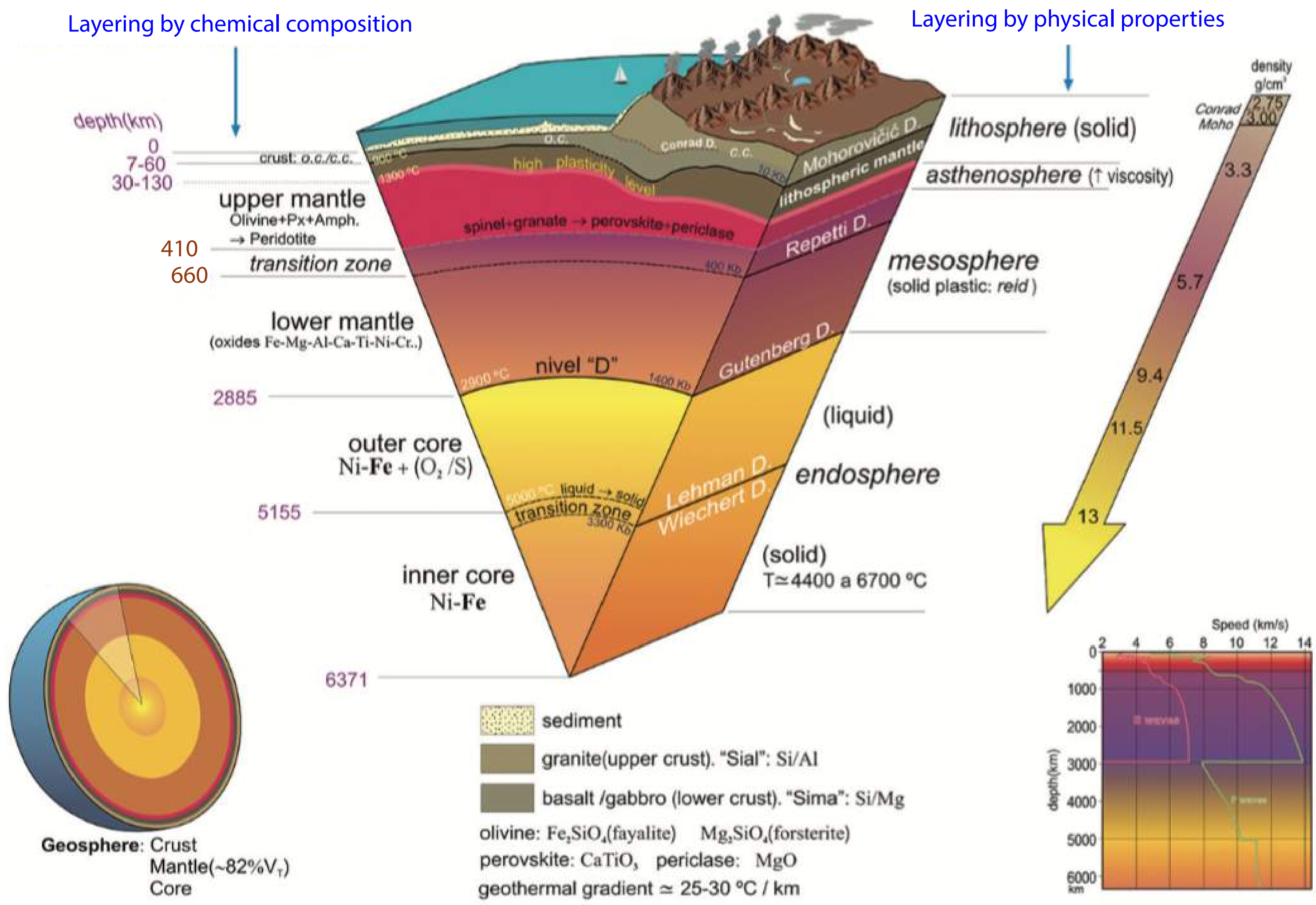
The Upper Mantle

Earth's Structure

- B. Asthenosphere (weak sphere)
  - Beneath the lithosphere, in the upper mantle to a depth of about ~410 kilometers
  - A small amount of melting in the upper portion mechanically detaches the lithosphere from the layer below, allowing the lithosphere to move independently of the asthenosphere.



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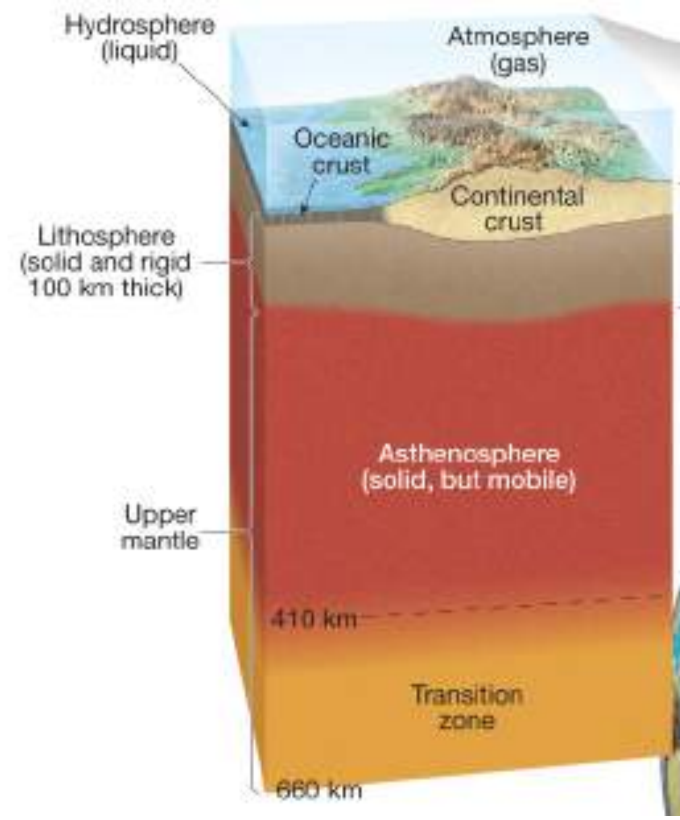
Earth's Structure

The Upper Mantle

- C. Transition Zone (410 – 660 km)
  - Beneath the asthenosphere, in the upper mantle, to a depth of about 660 kilometers
  - Top of TZ identified by sudden increase in density from 3.5 to 3.7 g/cm^3
  - Change in mineral phase:

    Olivine → β-spinel → Ringwoodite



PERIDOTITE – mainly olivine and pyroxene

Earth's Structure

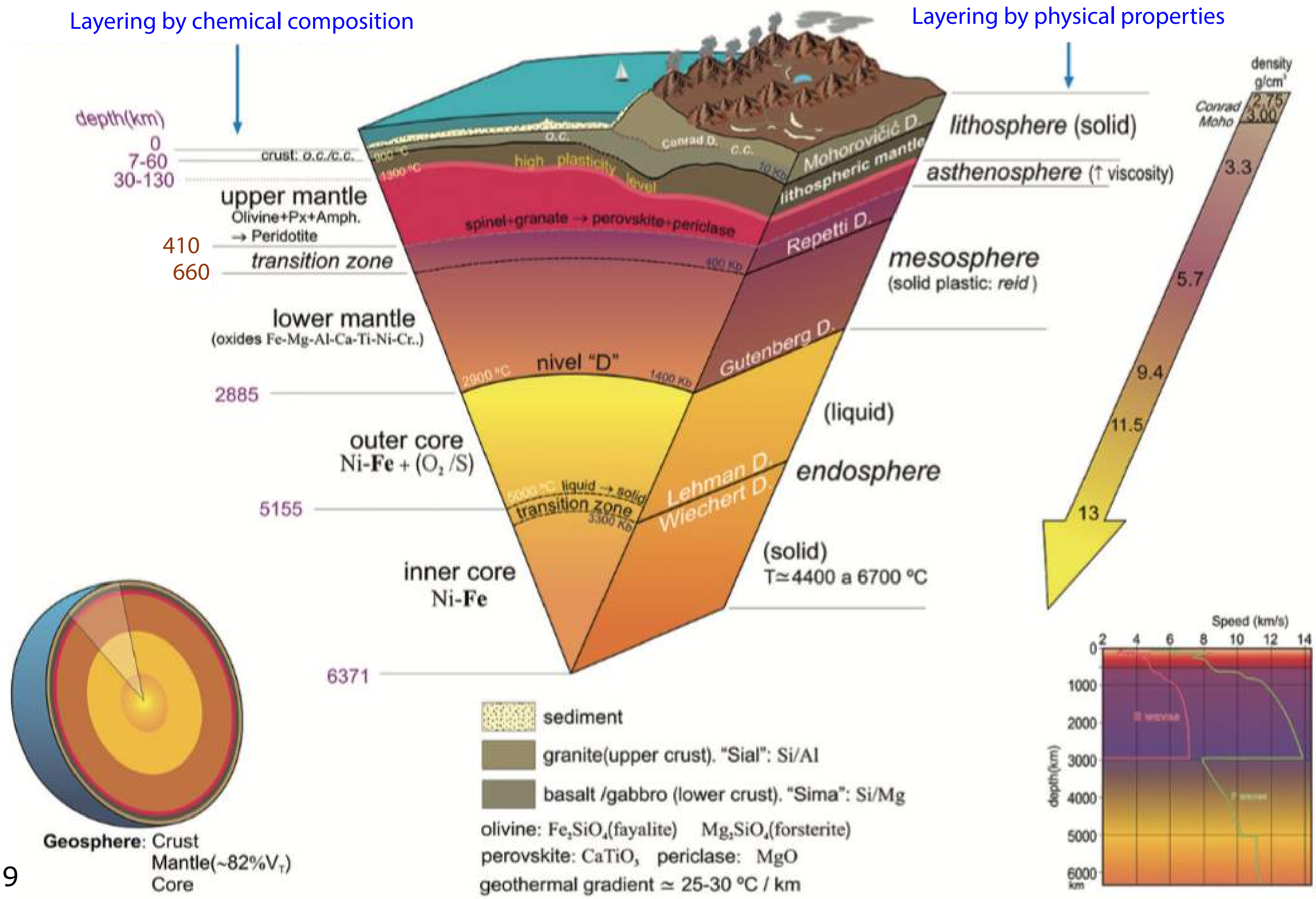
II. The Lower Mantle (Mesosphere)

Rigid layer between the depths of 660 kilometers and 2900 kilometers

Largest by volume (56%)

Rocks are very hot and capable of very gradual flow

Olivine and Pyroxene→ Perovskite



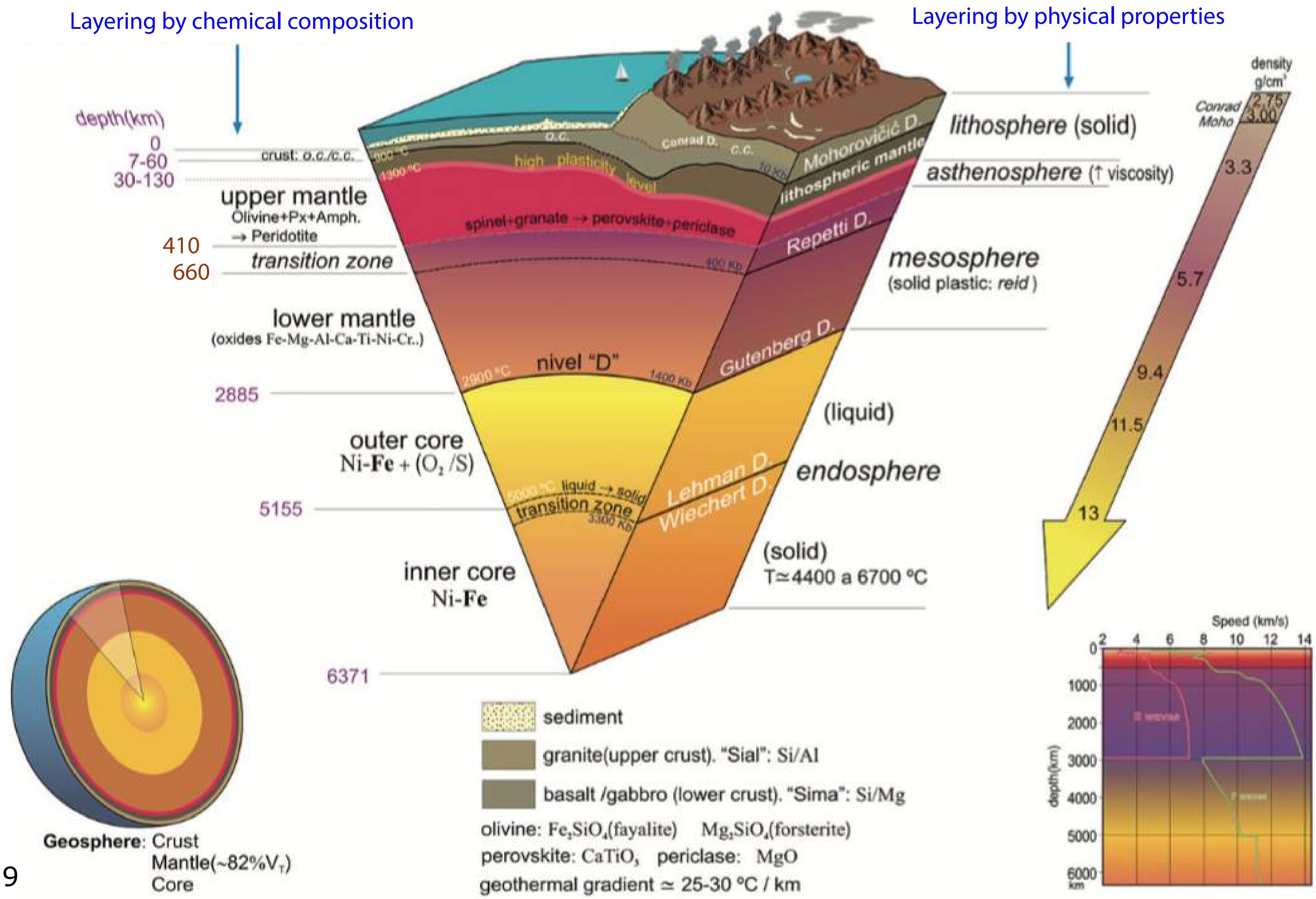
modified after
Gervilla et al., 2019

III. The D” Layer

Earth’s Structure

Boundary layer between the rocky mantle and the liquid outer core

- **“Graveyard” of some subducted oceanic lithosphere and “birthplace” of some mantle plumes**



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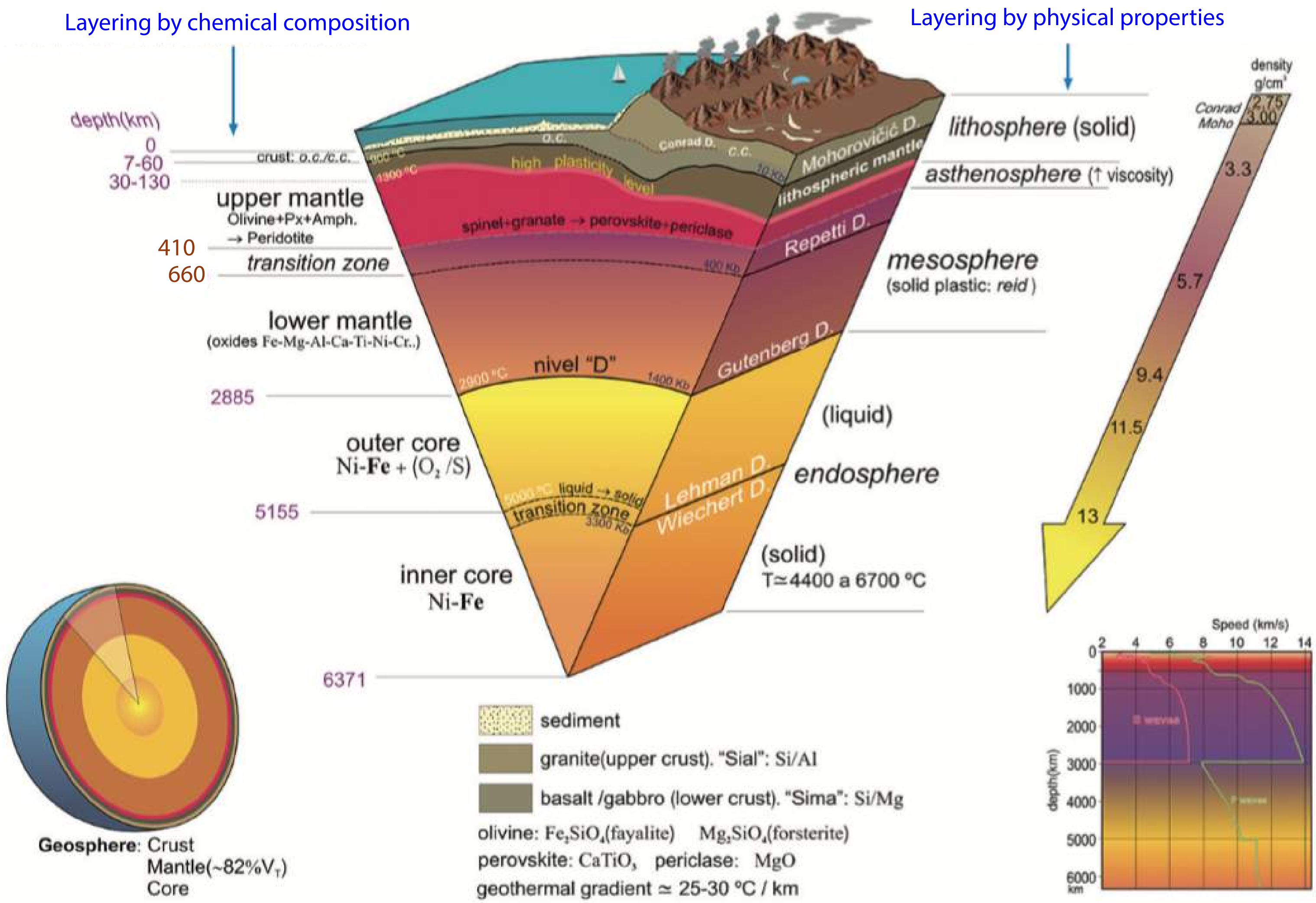
Gervilla et al., 2019

IV. The Outer Core

Earth's Structure

- Composed mostly of an iron-nickel alloy
- Lower amounts of S, O, Si, H Liquid layer
- Density of ~ 9.9 g/cm^3
- Around 2300 kilometers
- A convective flow within generates Earth's magnetic field



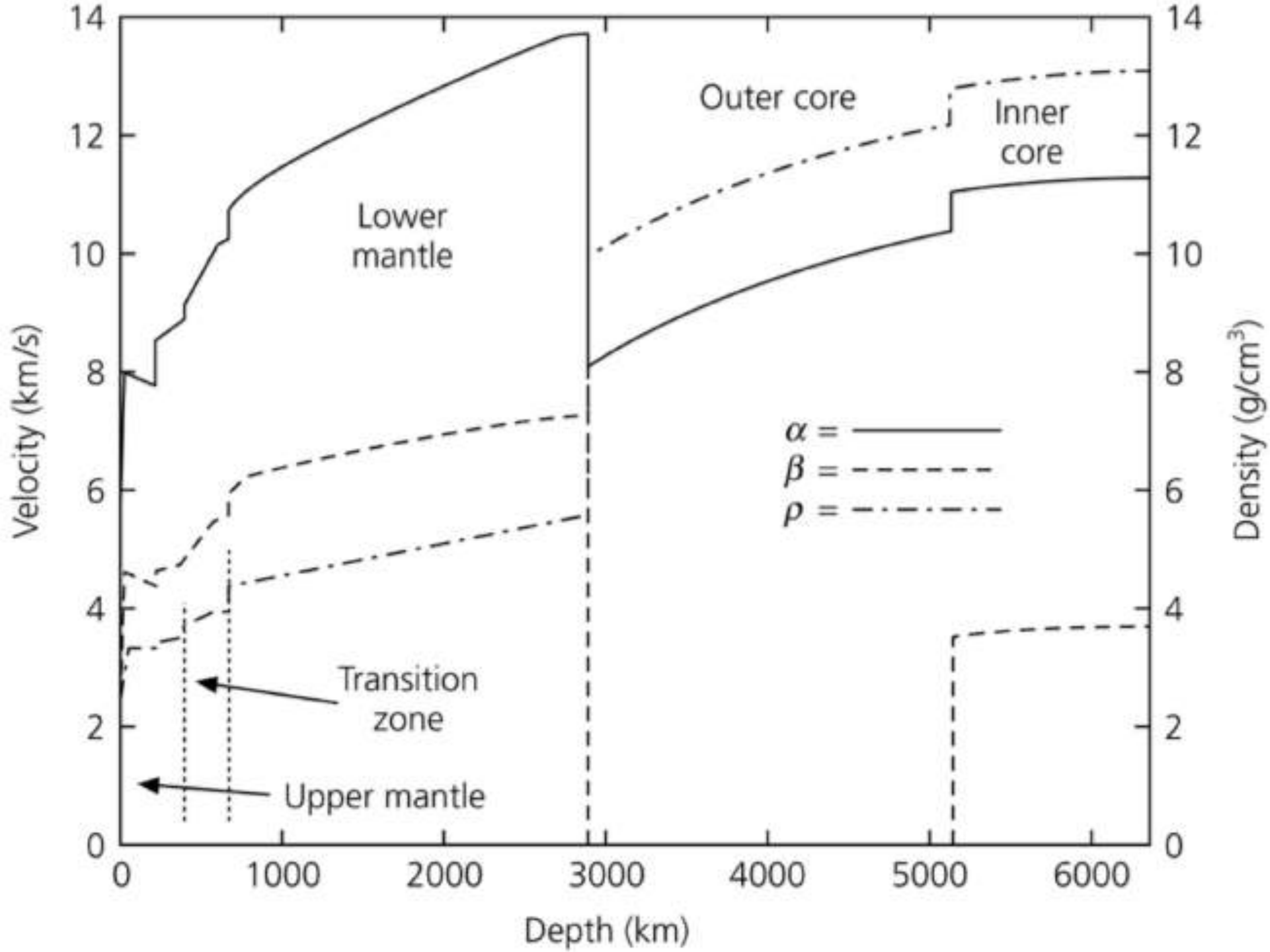
modified after
Gervilla et al., 2019

Earth's Structure

IV. The Inner Core

- Sphere of Fe with a radius of around 1200 kilometers
- Stronger than the outer core
- Behaves like a solid
- Did not exist early in Earth's history
- Started to form as Earth cooled and Fe began to crystallize at the center
- P waves passing through the inner core show increased velocity, suggesting that the inner core is solid

Figure 3.8-4: Preliminary Reference Earth Model.



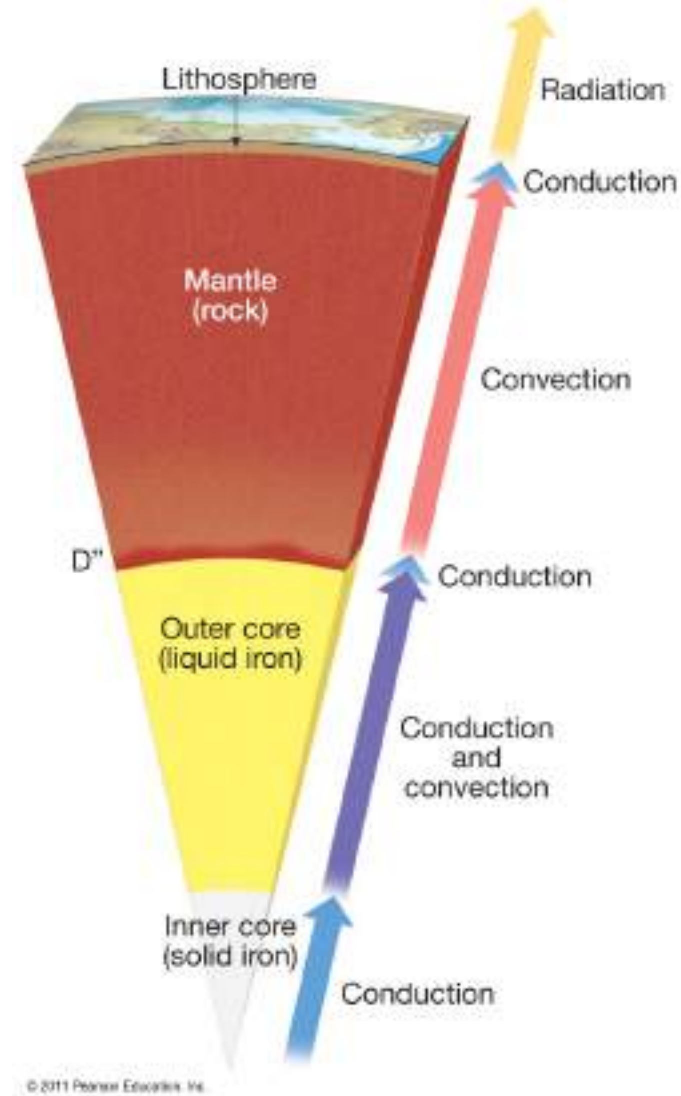
Earth's Temperature

Major processes that have contributed to Earth's internal heat

- **Heat emitted by radioactive decay of isotopes of uranium (U), thorium (Th), potassium (K), aluminum (Al), calcium (Ca), etc.**
- **Heat released as iron crystallized to form the solid inner core**
- **Heat released by collisions of countless planetesimals ("baby planets") during the formation of Earth (kinetic energy → thermal energy)**

Earth's Temperature

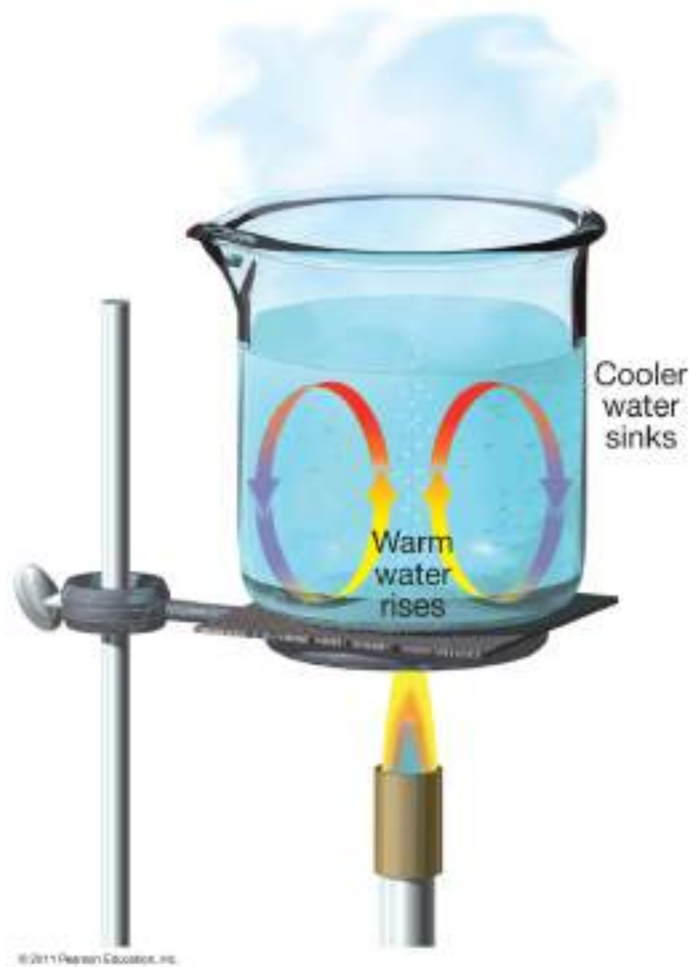
- Heat flow
  - Two main processes operate within Earth's interior:
  - *Convection*: the *transfer of heat by moving material* in a fluid-like manner in which hot materials displace those that are cooler (or vice-versa)
  - *Conduction*: the *flow of heat through a material*



Earth's Temperature

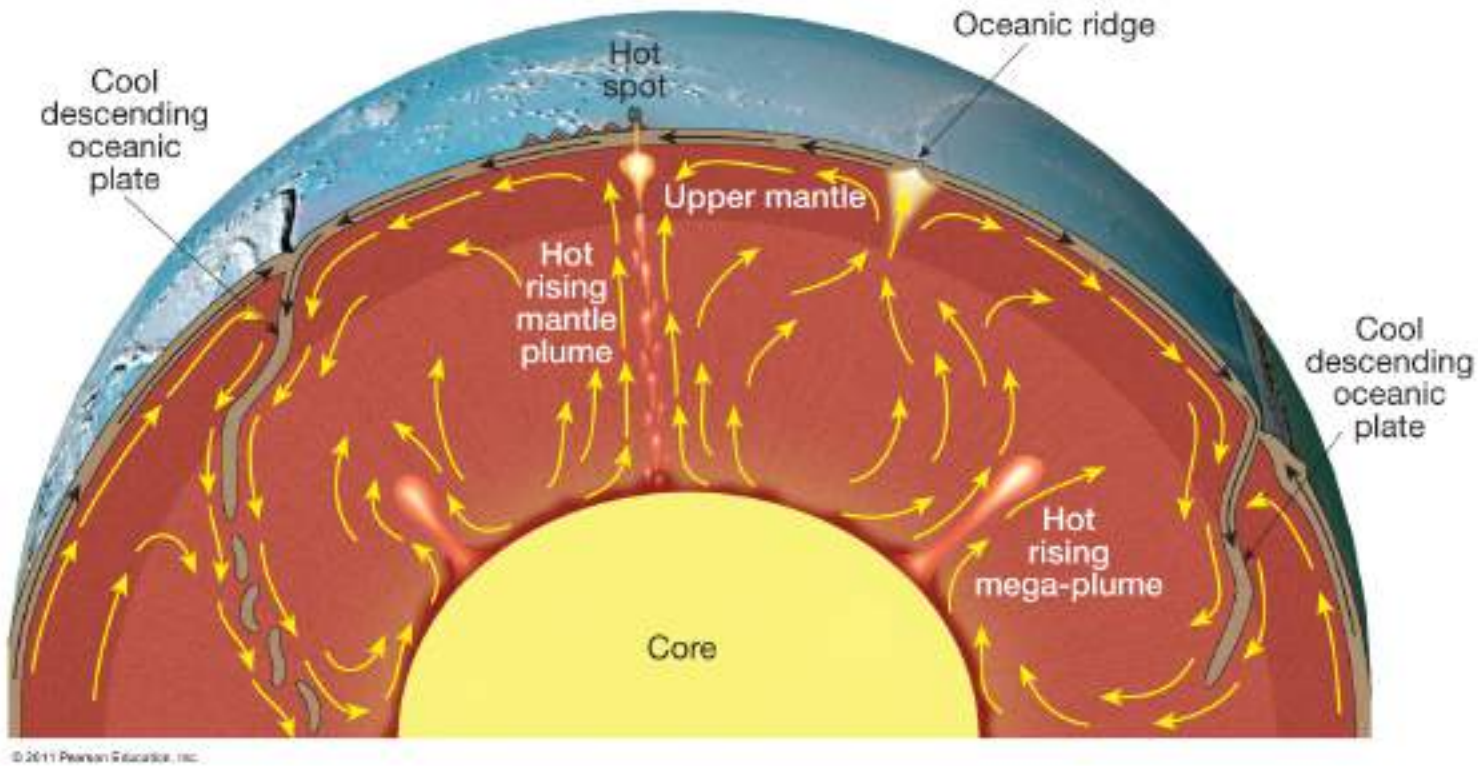
I. Convection

- Gravity is the driving force for convection, leading to gravity induced buoyancy
- Materials must also be weak enough to flow
- Resistance to flow = viscosity



Earth's Internal Heat Engine

- **Mantle convection**
  - **Important process in Earth's interior**
  - **Provides the force that propels the rigid lithospheric plates across the globe.**



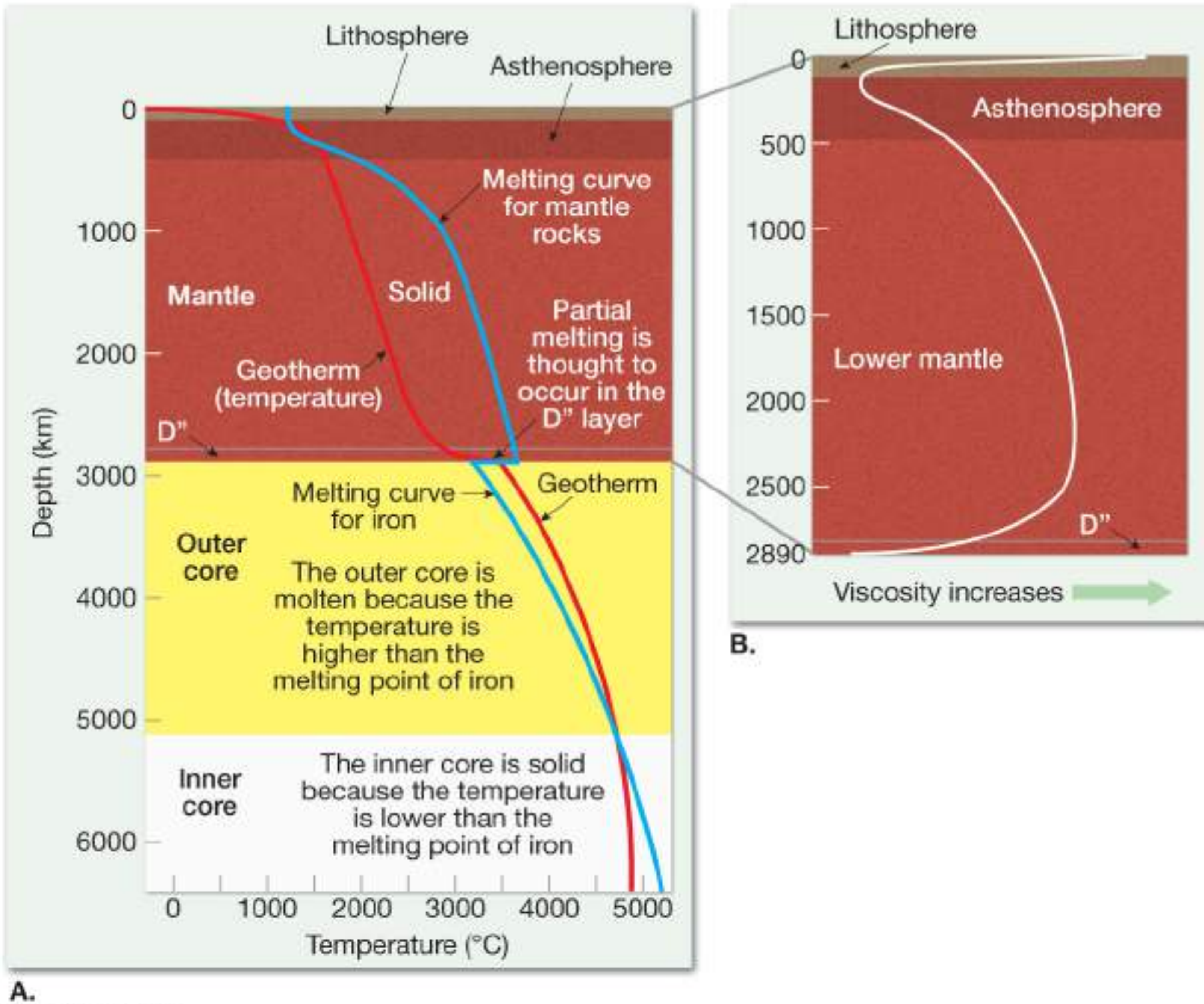
Earth's Temperature

II. Conduction

- Occurs much more quickly in metals than rocky substances
- Not an efficient way to move heat through most of Earth
- However, important mechanism in the core, D" layer, and lithosphere

Earth's Temperature Profile

- **Earth's temperature gradually increases with an increase in depth at a rate known as the geothermal gradient.**
  - **Varies considerably from place to place**
  - **Averages between about 20 ° and 30 °C / km in the crust (rate of increase is much less in the mantle and core)**

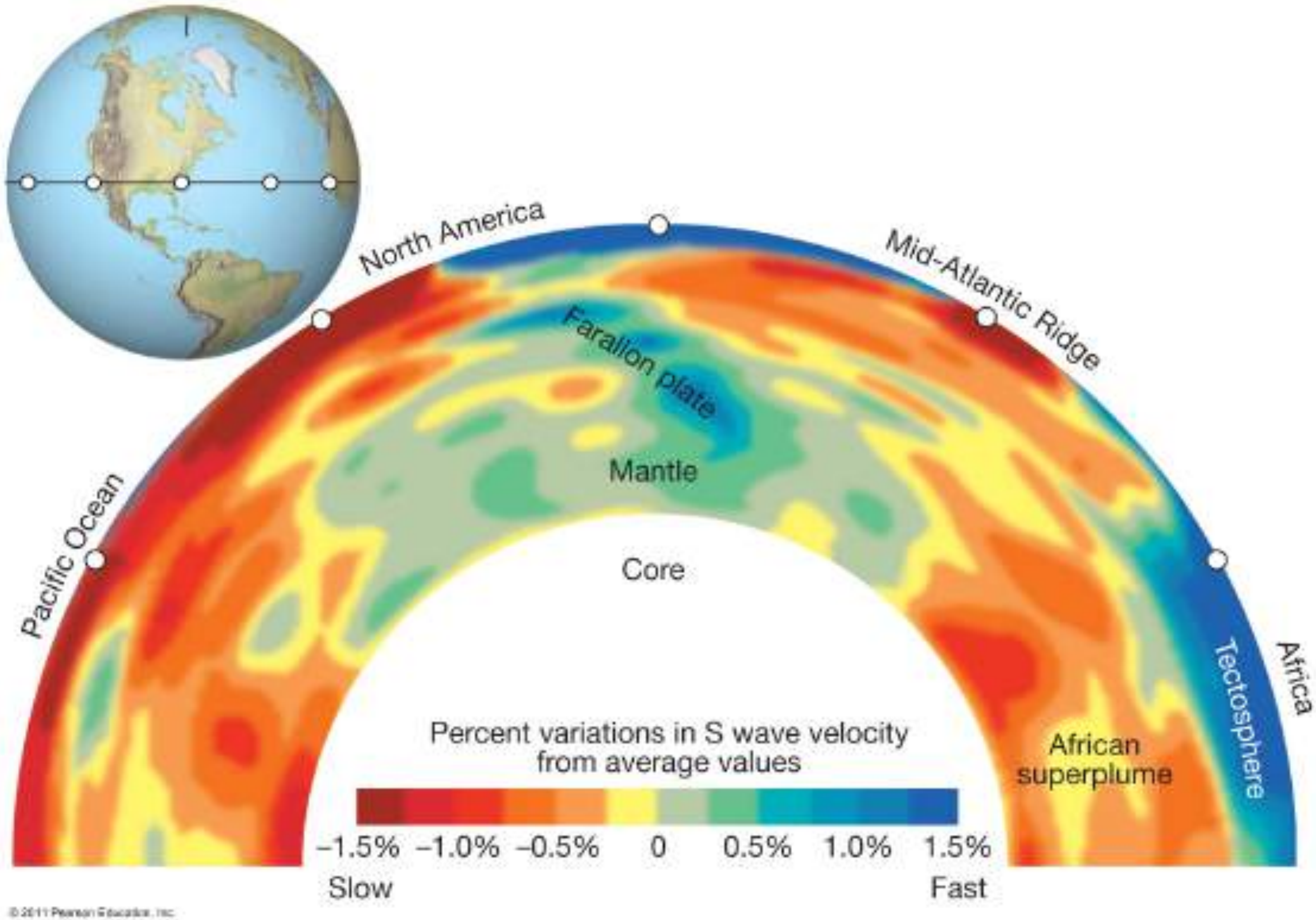


Lithosphere
Asthenosphere
0
1000
2000
3000
4000
5000
6000
Depth (km)
Melting curve for mantle rocks
Mantle
Solid
Partial melting is thought to occur in the D" layer
Geotherm (temperature)
D"
Melting curve for iron
Geotherm
Outer core
The outer core is molten because the temperature is higher than the melting point of iron
Inner core
The inner core is solid because the temperature is lower than the melting point of iron
0
1000
2000
3000
4000
5000
Temperature (°C)
Lithosphere
0
Asthenosphere
500
1000
1500
Lower mantle
2000
2500
D"
2890
Viscosity increases
B.
A.

Earth's Three-Dimensional Structure

- Seismic tomography
  - Three-dimensional changes in composition and density in all parts of Earth's interior can be viewed using seismic waves.
    - The continental lithosphere can extend hundreds of kilometers into the mantle.
    - Cold, subducted oceanic lithosphere sinks to the base of the mantle, while mega-plumes rise upward from the core–mantle boundary.

Seismic Tomographic Slice Through the Earth



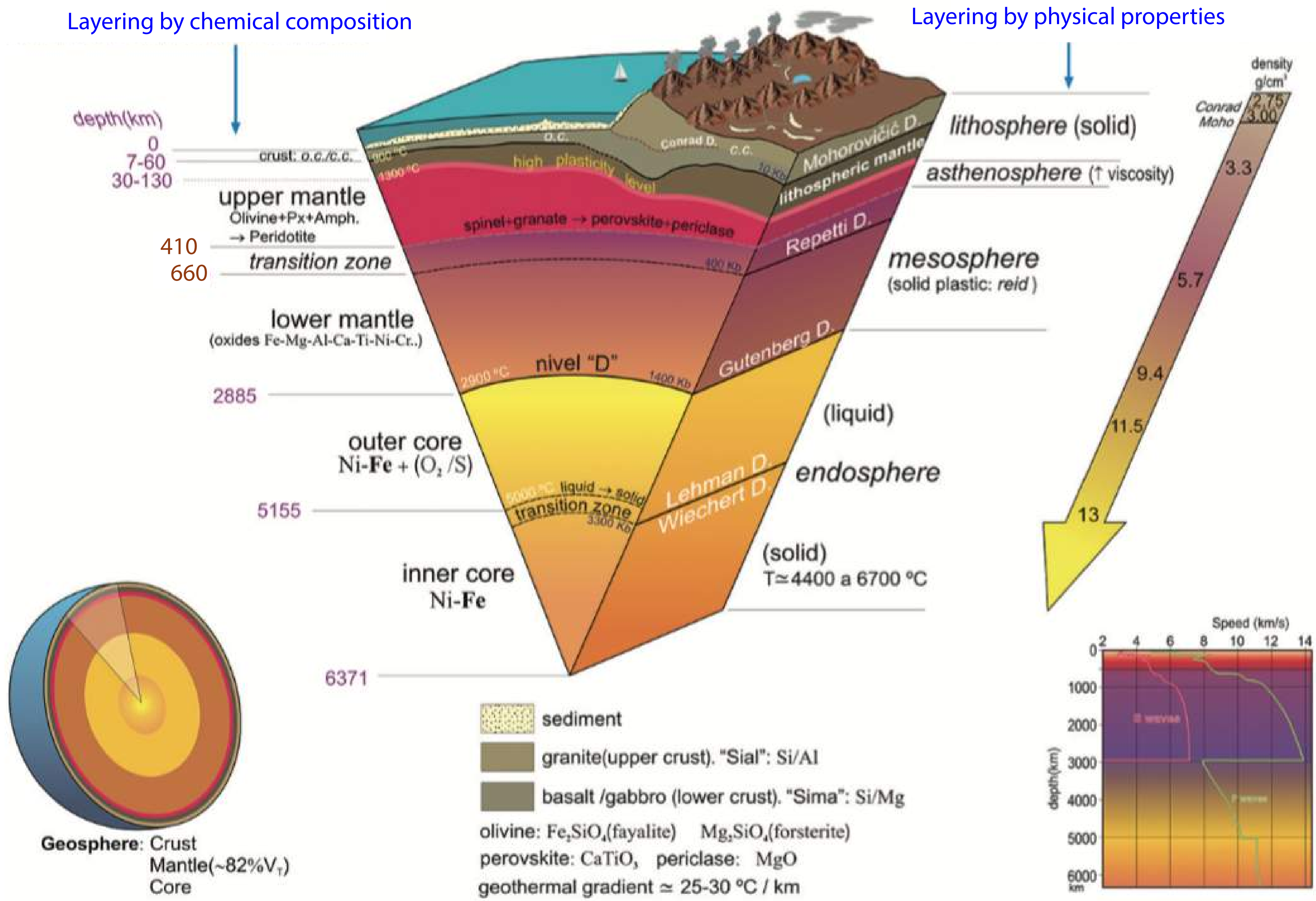
FUNDAMENTALS OF EARTH SCIENCES (ESO 213A)

DIBAKAR GHOSAL
DEPARTMENT OF EARTH SCIENCES

Topic: Plate tectonics

Previous Class: Earth's Internal Structure

Last Class: Review



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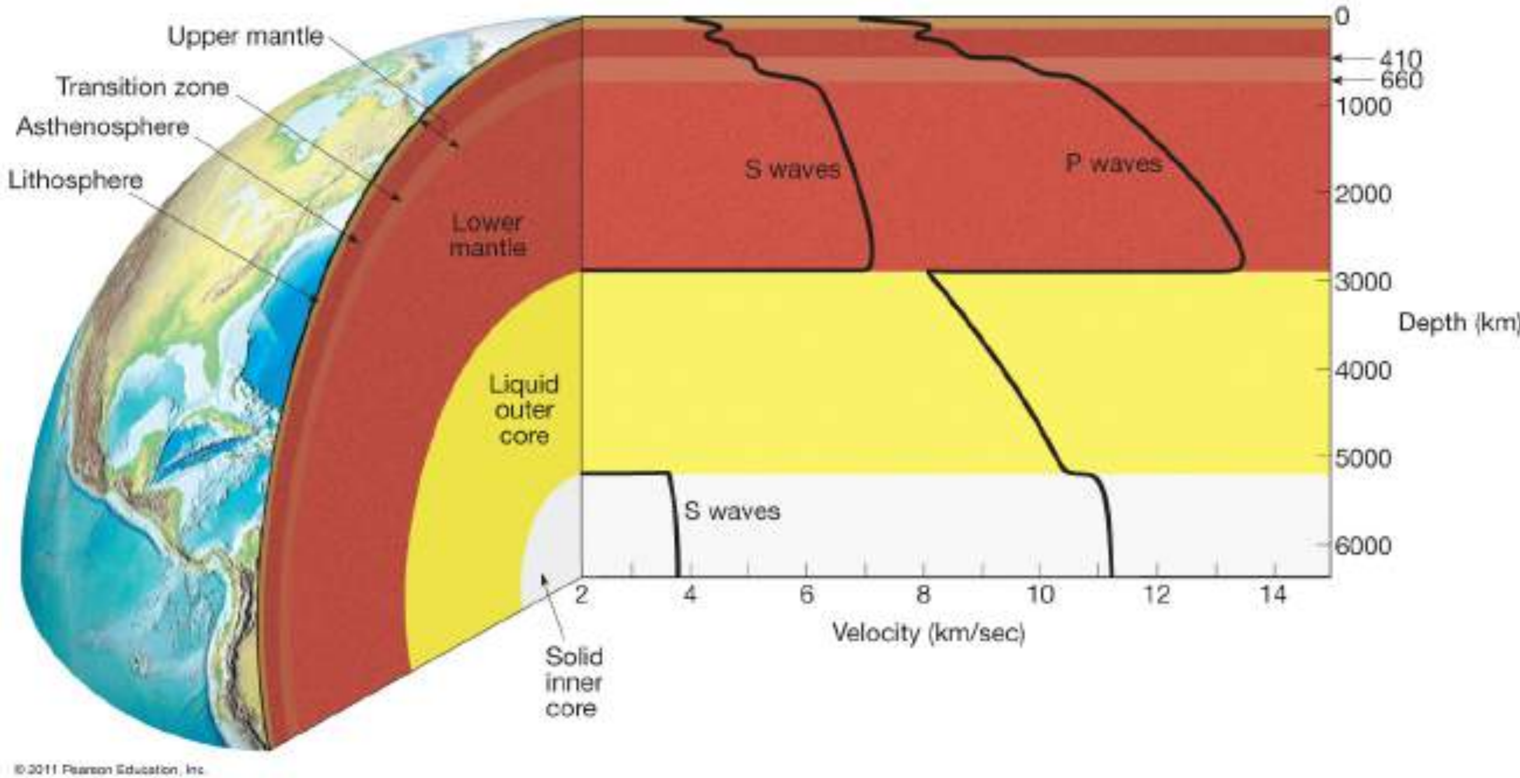

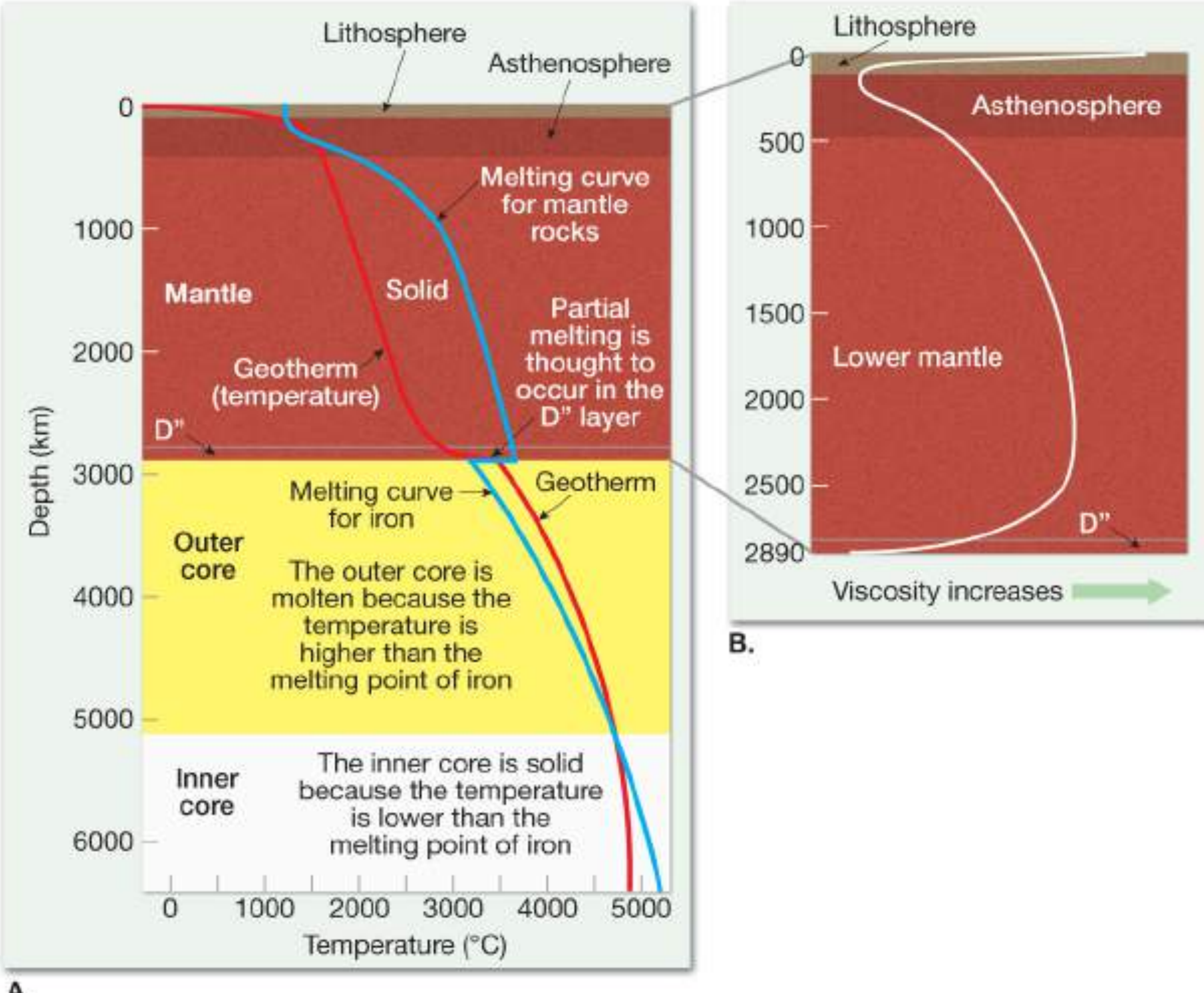

Lithosphere
Asthenosphere
0
1000
2000
3000
4000
5000
6000
Depth (km)
Melting curve for mantle rocks
Mantle
Solid
Partial melting is thought to occur in the D" layer
Geotherm (temperature)
D"
Melting curve for iron
Geotherm
Outer core
The outer core is molten because the temperature is higher than the melting point of iron
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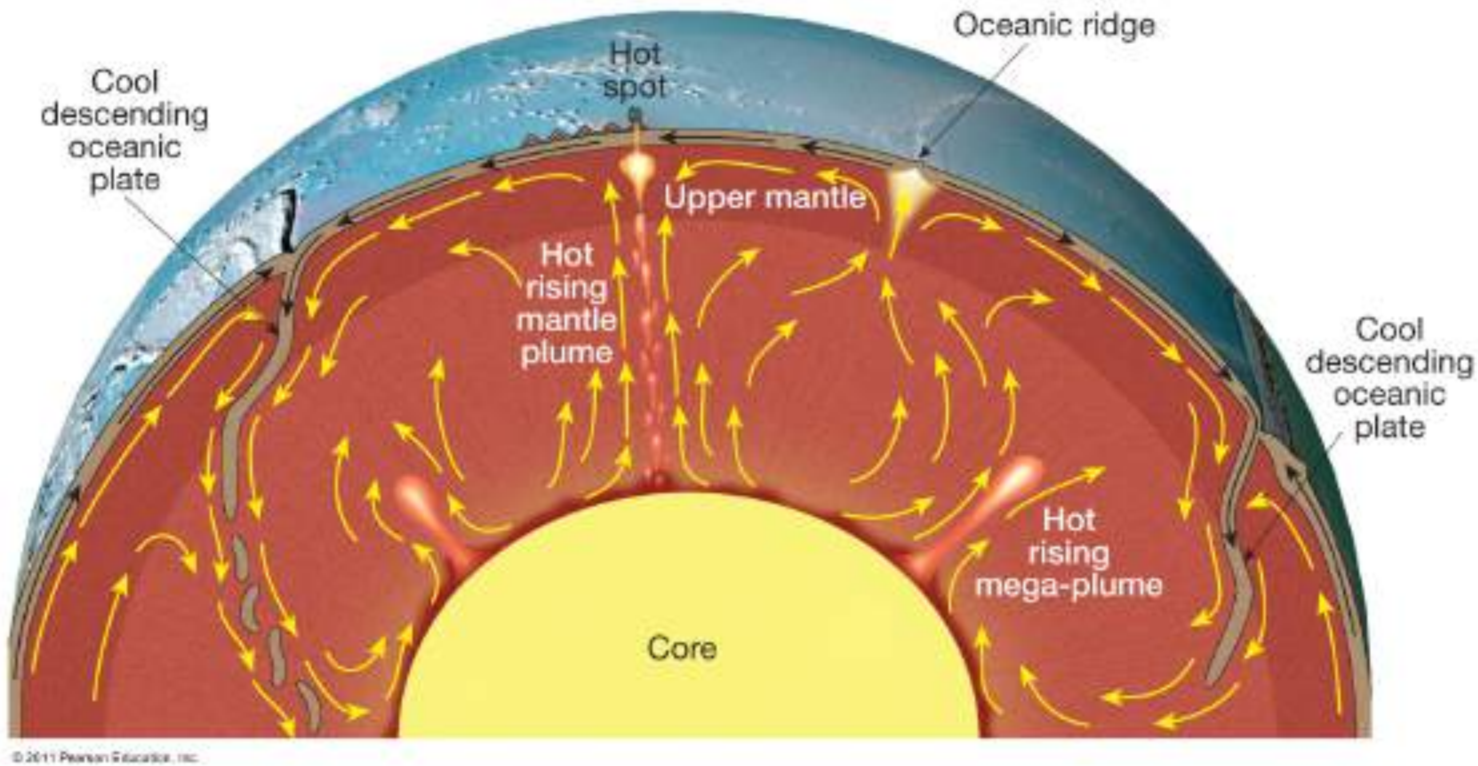
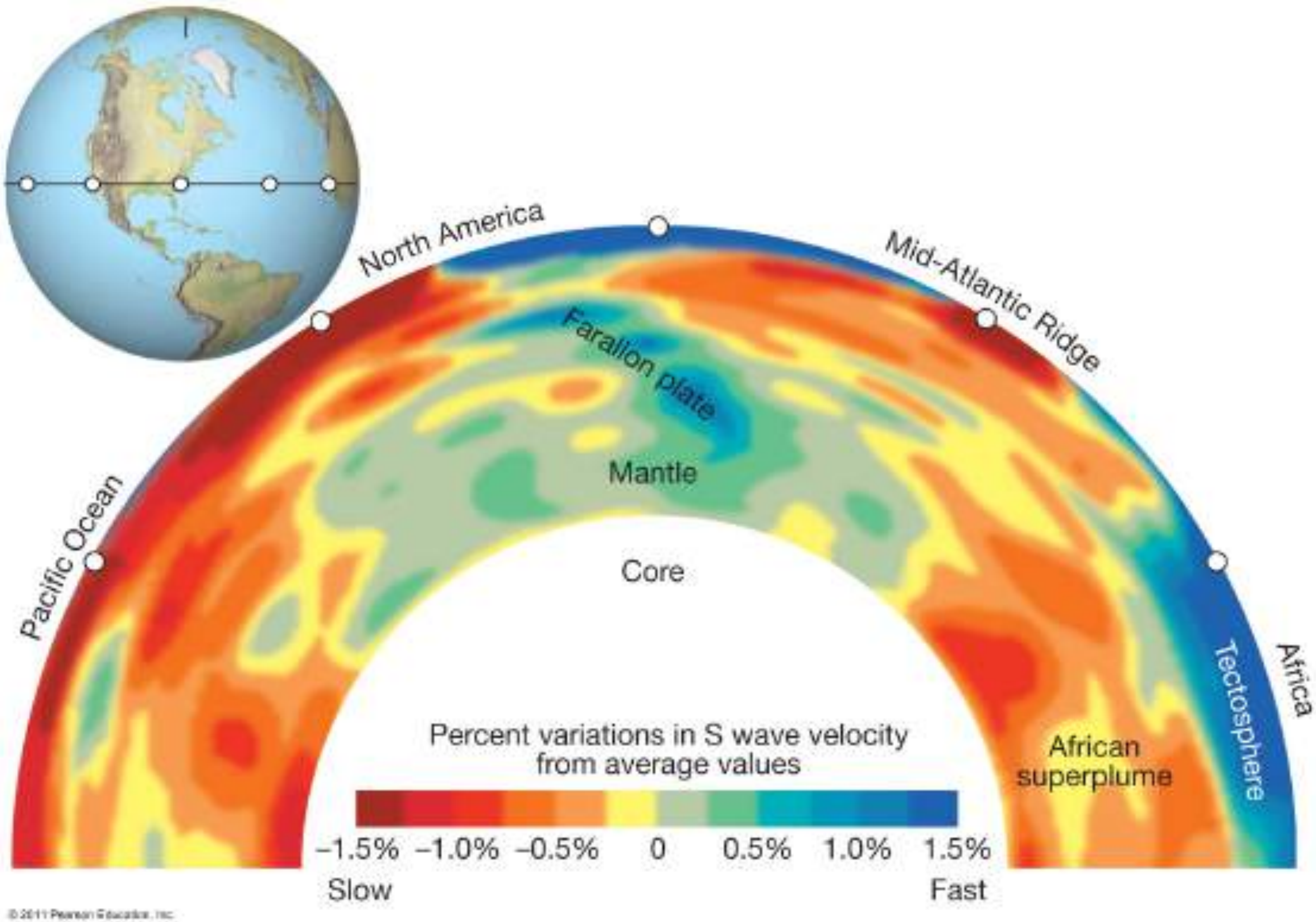
The inner core is solid because the temperature is lower than the melting point of iron
0
1000
2000
3000
4000
5000
Temperature (°C)
A.
Lithosphere
0
Asthenosphere
500
1000
1500
Lower mantle
2000
2500
D"
2890
Viscosity increases
B.

Earth's Internal Heat Engine

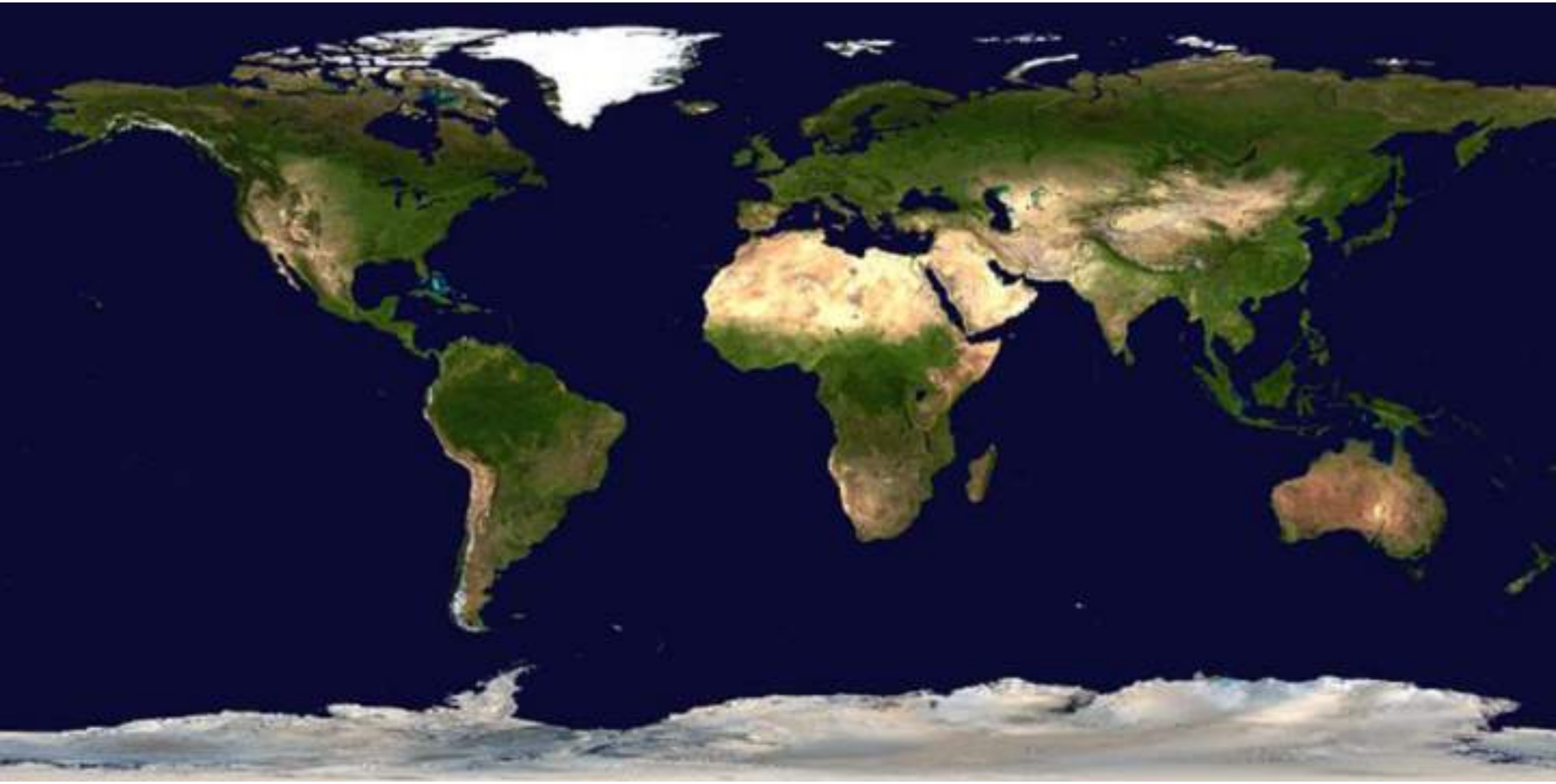
- **Mantle convection**
  - **Important process in Earth's interior**
  - **Provides the force that propels the rigid lithospheric plates across the globe.**



Seismic Tomographic Slice Through the Earth



Present day Earth Surface



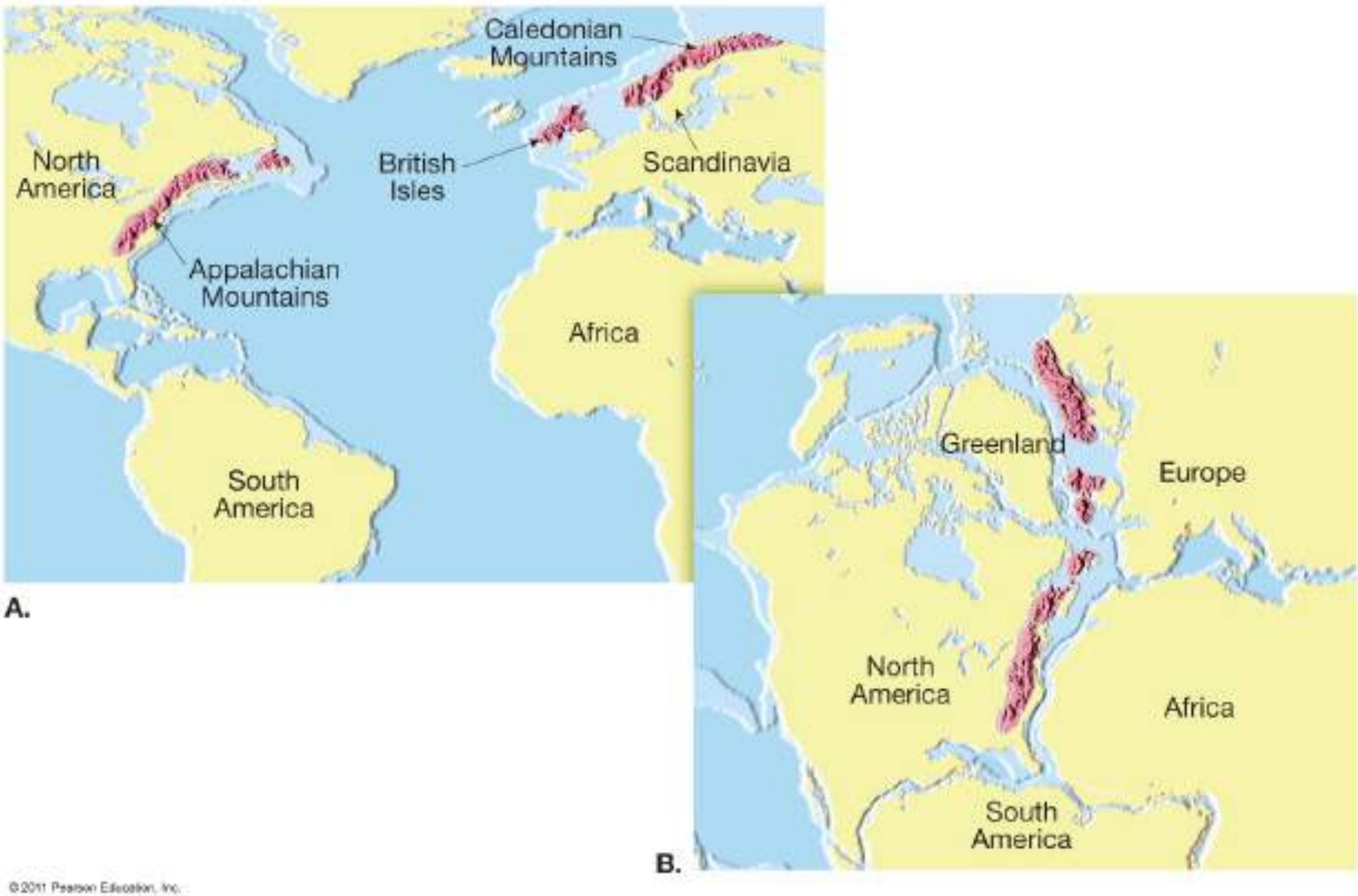
Continental Drift: An Idea Before Its Time

- **Continental drift hypothesis**
  - **Continents "drifted" to present positions**
- **Evidence used in support of continental drift hypothesis:**
  - **Fit of the continents**
  - **Fossil evidence**
  - **Rock type and structural similarities**
  - **Paleoclimatic evidence**

Alfred Wegner

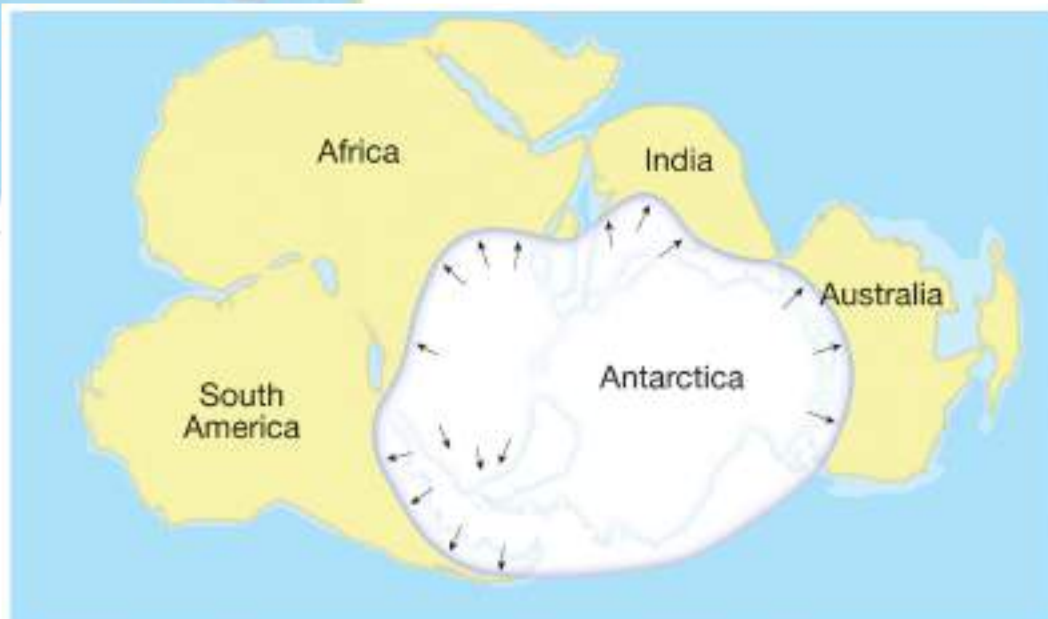
originator of continental drift hypothesis in 1912

Matching Mountain Ranges Fit of the continents




India
Africa
South America
Australia

B.


Africa
India
Australia
Antarctica
South America

C.

Pangaea Approximately 200 Million Years Ago

A. Modern reconstruction of Pangaea

B. Wegener's Pangaea

The Great Debate

- **Objections to the continental drift hypothesis:**
  - **Lack of a mechanism for moving continents**
  - **Wegener incorrectly suggested that continents broke through the ocean crust.**
  - **Strong opposition to the hypothesis from all areas of the scientific community**

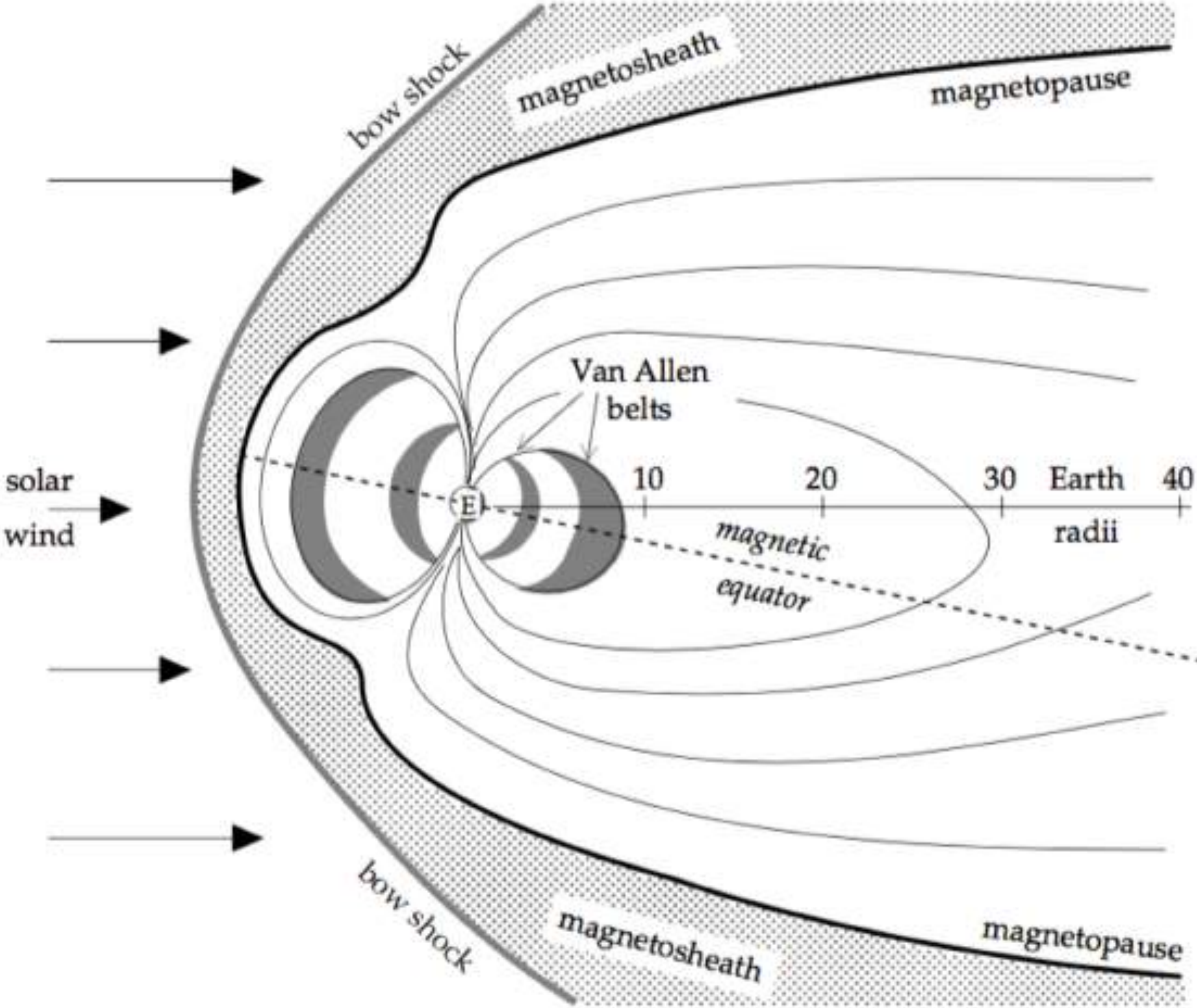
The Great Debate

- **Continental drift and the scientific method**
  - **Wegener's hypothesis was correct in principle, but contained incorrect details.**
  - **A few scientists considered Wegener's ideas plausible and continued the search.**

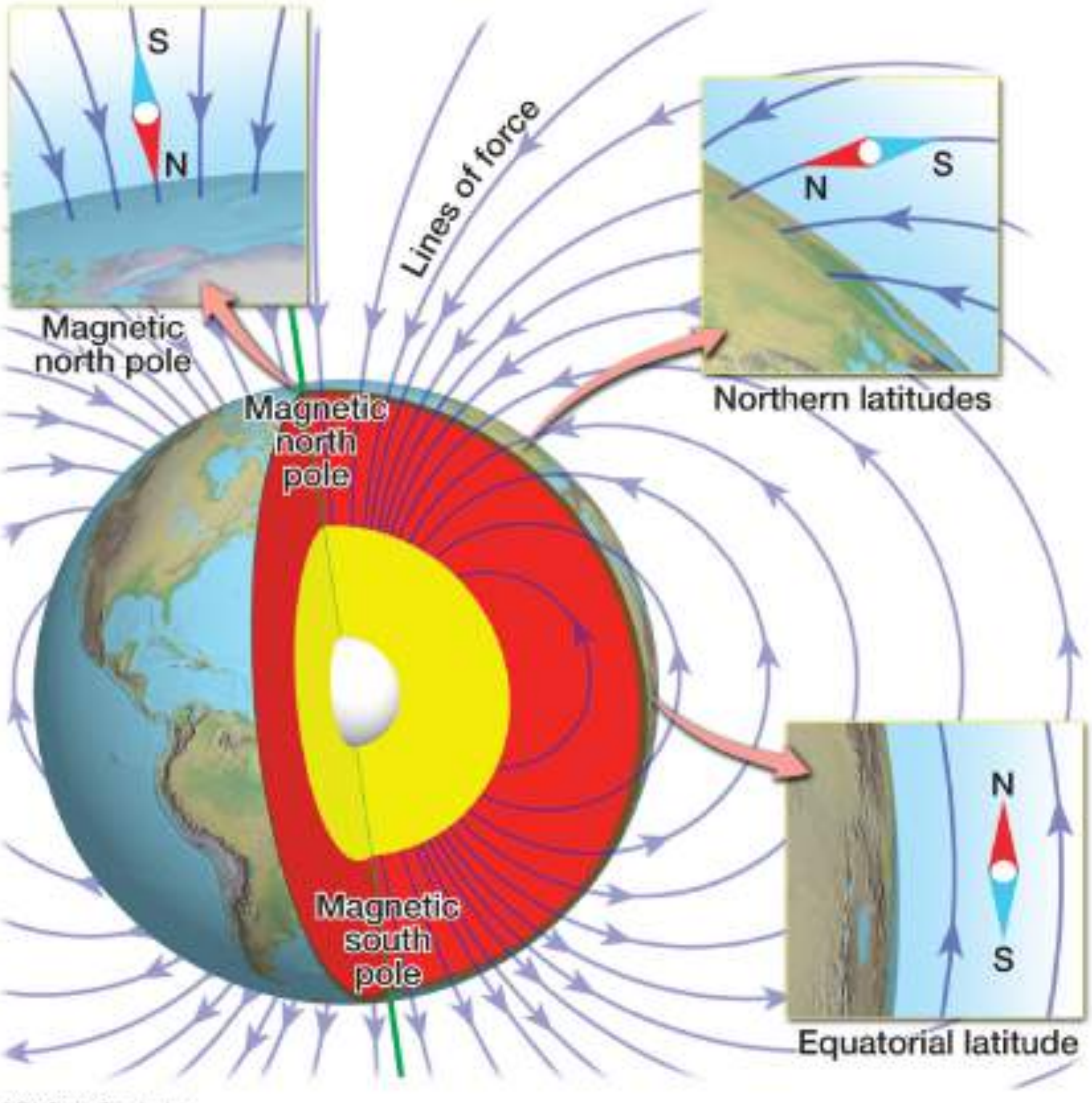
Continental Drift and Paleomagnetism

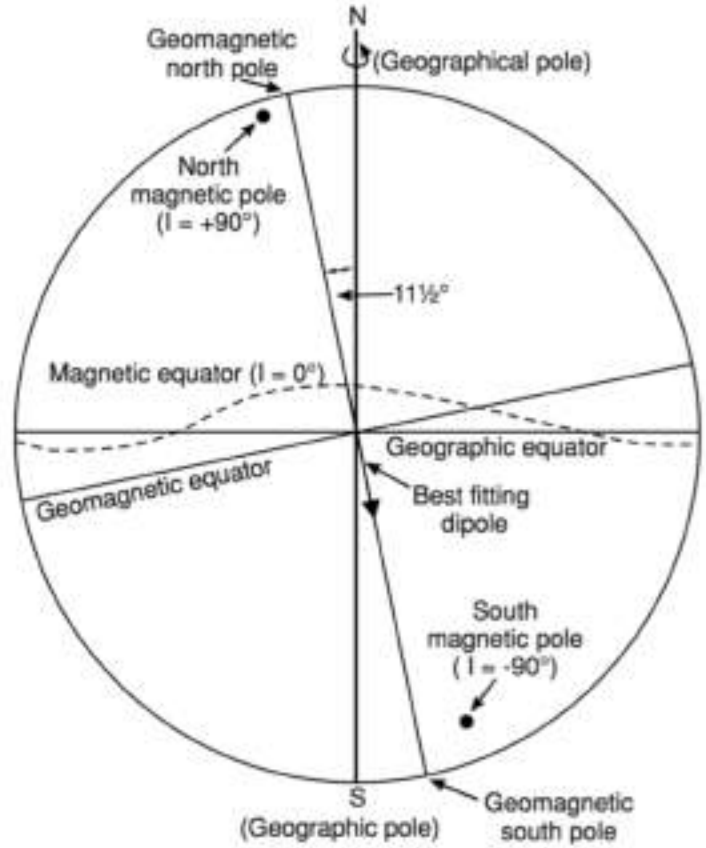
- **A renewed interest in continental drift initially came from rock magnetism.**
- **Magnetized minerals in rocks:**
  - **Show the direction to Earth's magnetic poles**
  - **Provide a means of determining their latitude of origin**

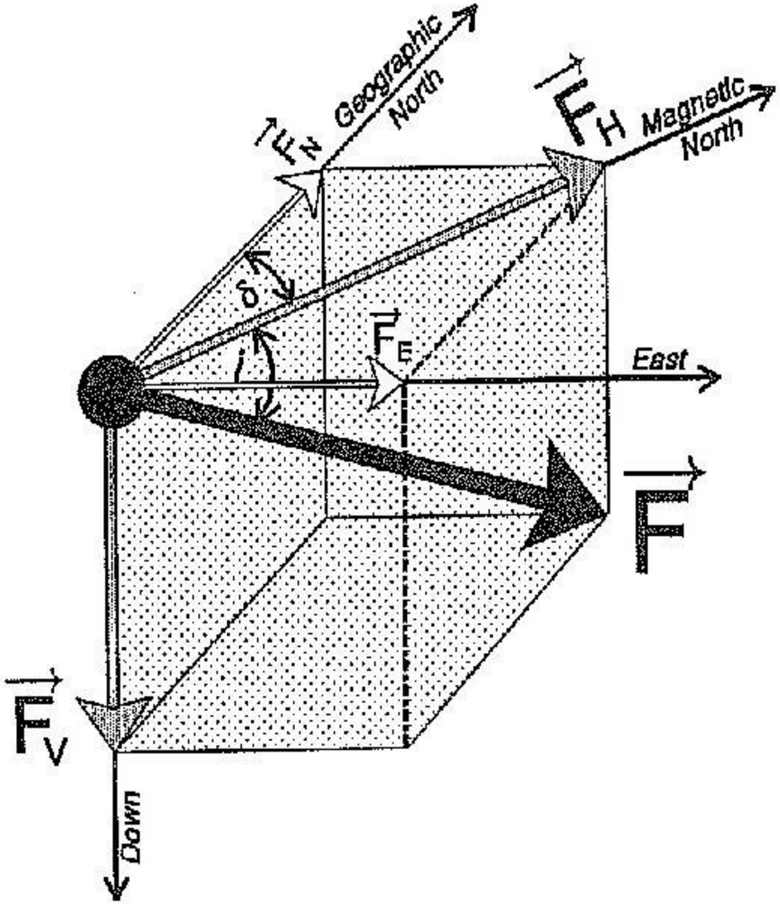
Earth's Magnetic Field

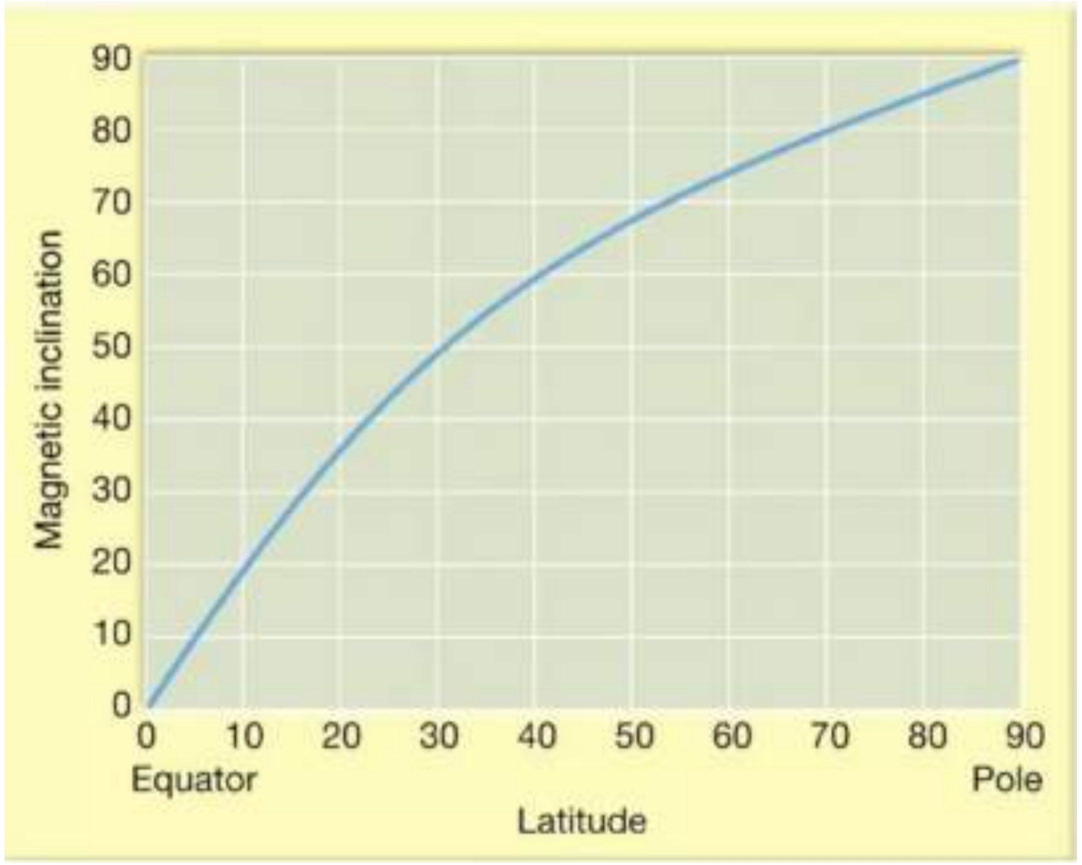


Earth's Magnetic Field









declination : angle of horizontal field with true north

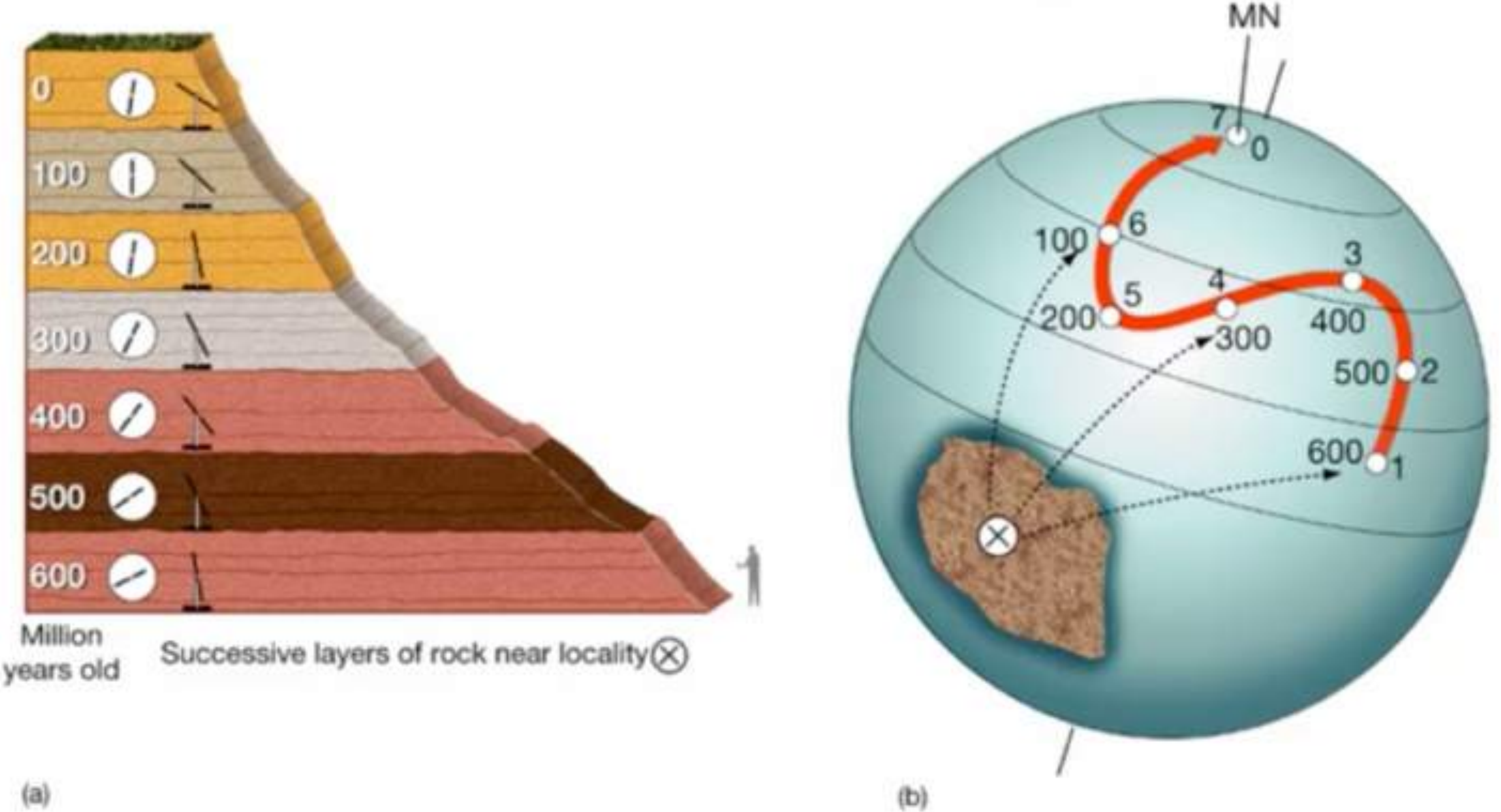
inclination : angle of total magnetic field with horizontal

Magnetized minerals in rocks:

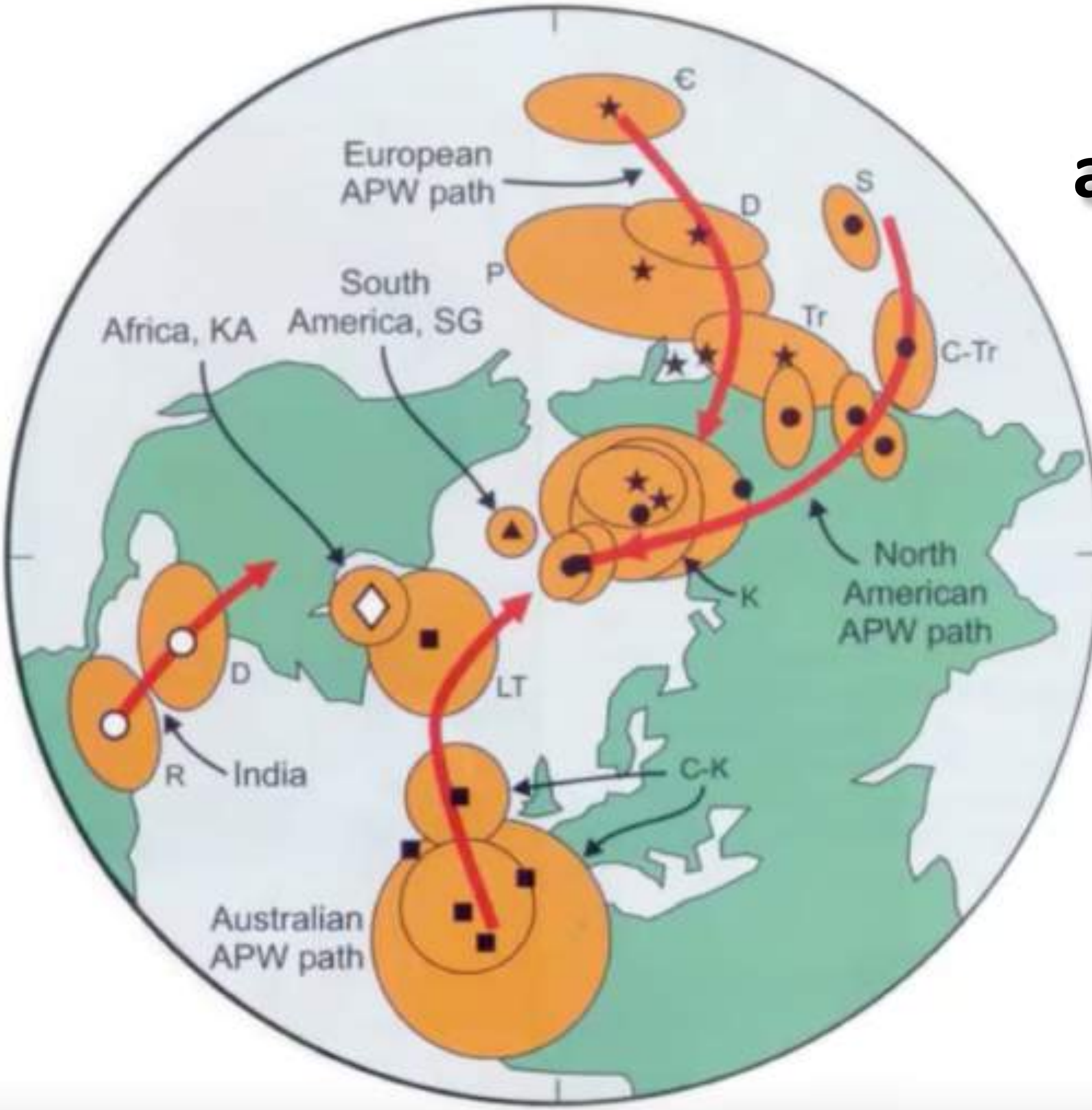
Show the direction to Earth's magnetic poles

Provide a means of determining their latitude of origin

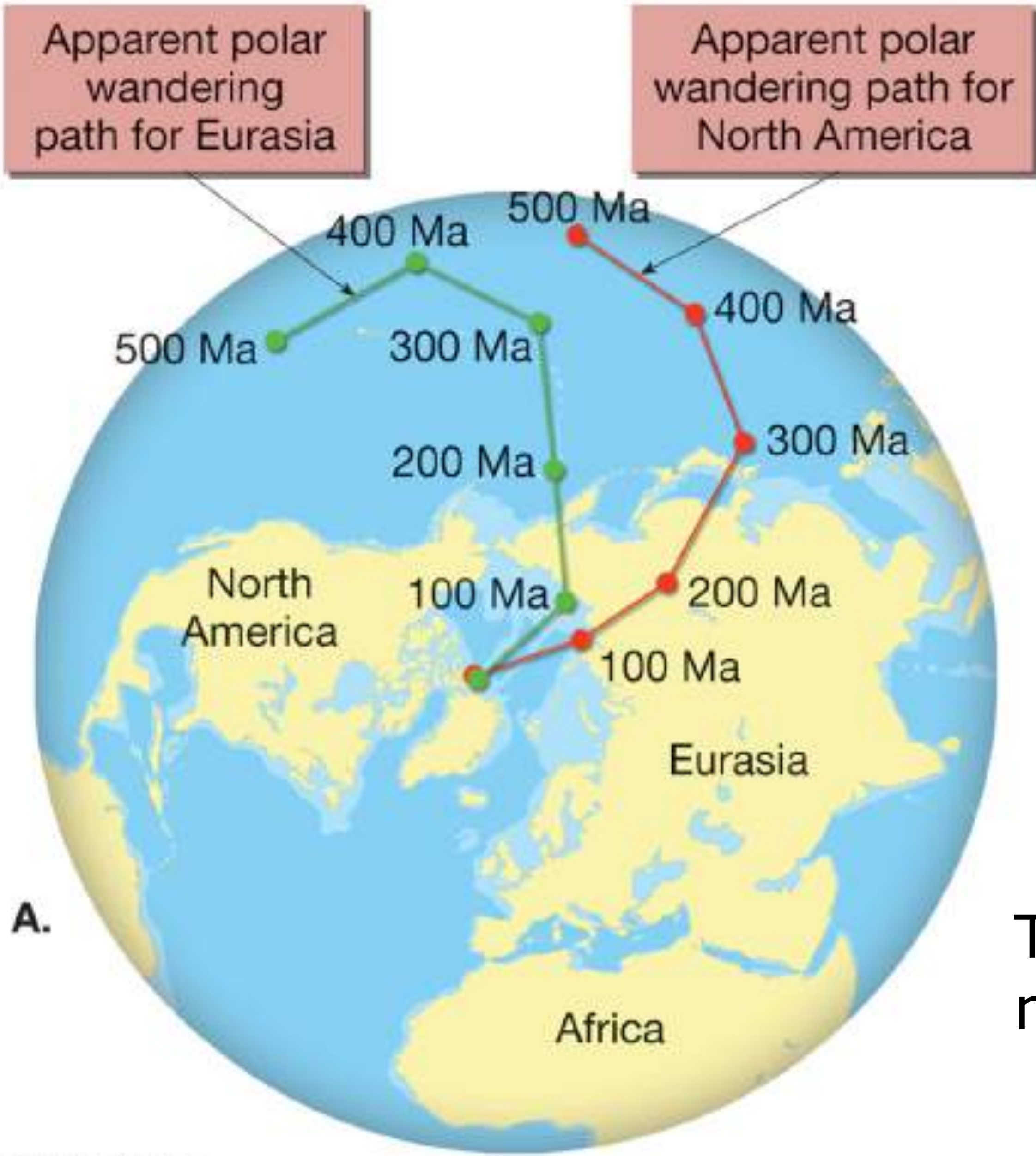
Apparent Polar wandering path



Why apparent?



Polar Wandering Paths for Eurasia and North America



There can’t be so many poles !

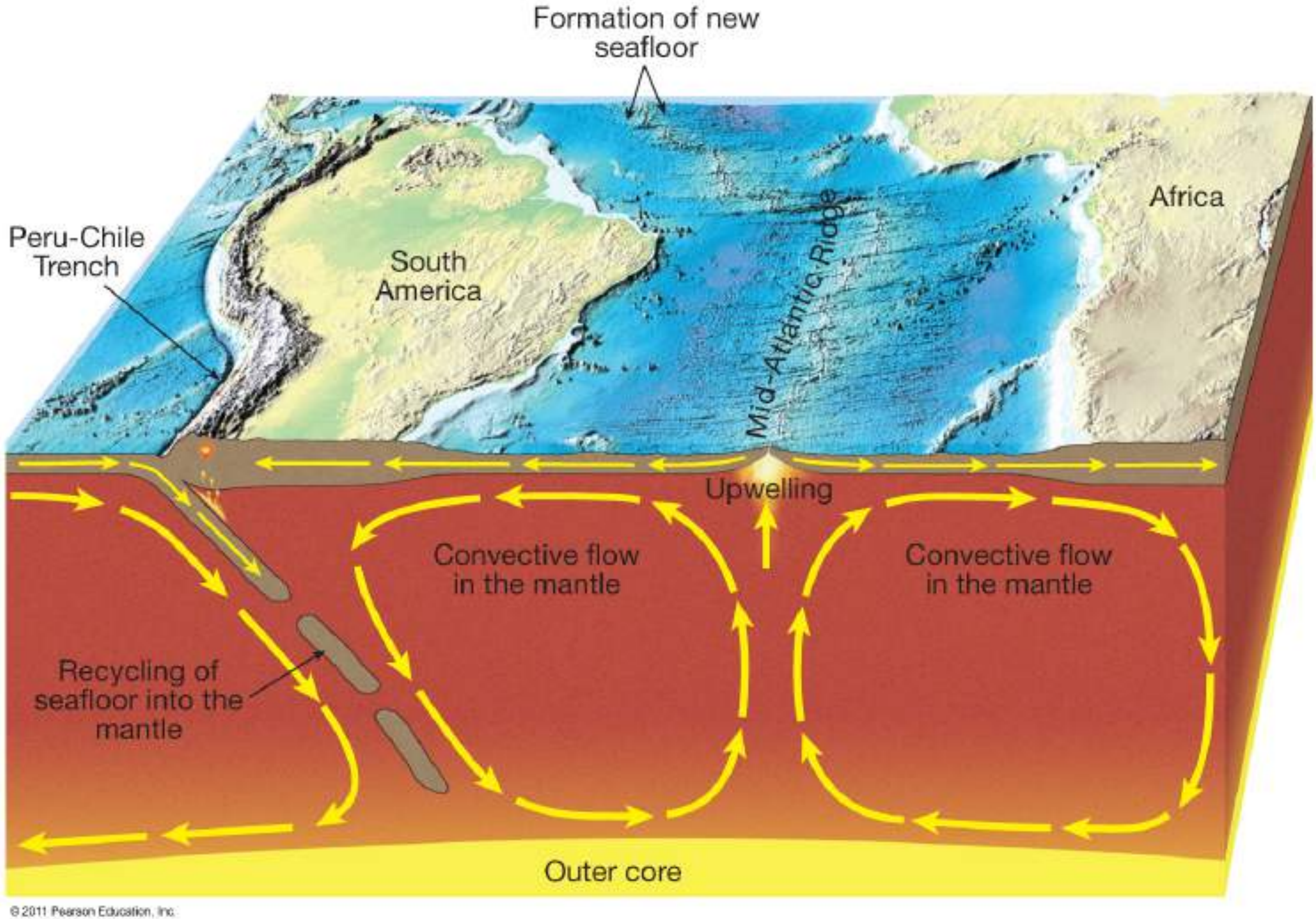
Continental Drift and Paleomagnetism

- **Polar wandering**
  - **The apparent movement of the magnetic poles indicates that the continents have moved.**
  - **It also indicates Europe was much closer to the equator when coal-producing swamps existed.**

A Scientific Revolution Begins

- **During the 1950s and 1960s, technological strides permitted extensive mapping of the ocean floor.**
- **The seafloor spreading hypothesis was proposed by Harry Hess in the early 1960s.**
- **Harry Hammond Hess** was an American geologist and a United States Navy officer in World War II who is considered one of the "founding fathers" of the unifying theory of plate tectonics. He is best known for his theories on sea floor spreading, suggesting that the convection of the Earth's mantle was the driving force behind this process.

Harry Hammond Hess


Formation of new seafloor
Peru-Chile Trench
South America
Africa
Mid-Atlantic Ridge
Upwelling
Convective flow in the mantle
Convective flow in the mantle
Recycling of seafloor into the mantle
Outer core
© 2011 Pearson Education, Inc.

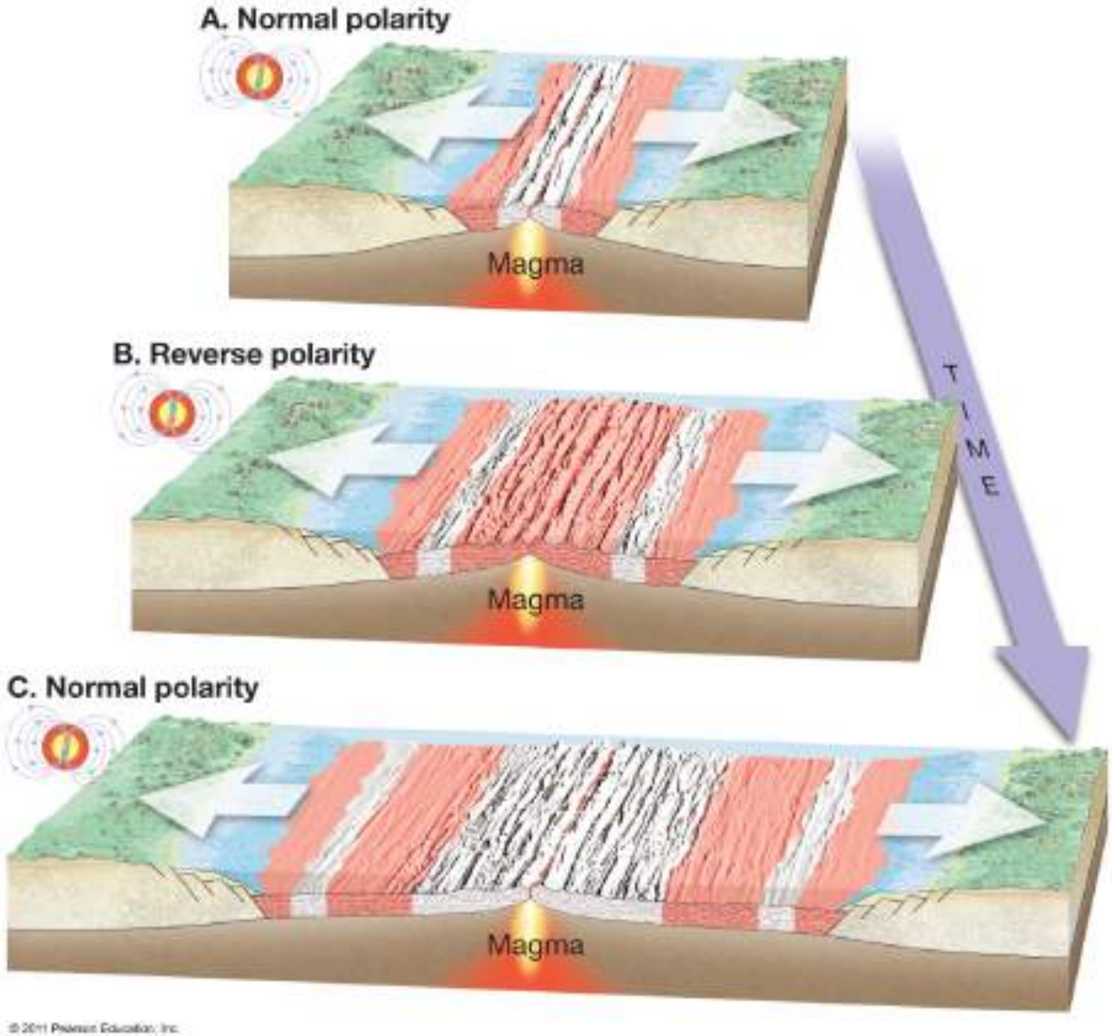
A Scientific Revolution Begins

- **Geomagnetic reversals**
  - **Earth's magnetic field periodically reverses polarity—the north pole becomes the south pole, and vice versa.**
  - **Dates when the polarity of Earth's magnetism changed were determined from lava flows.**

A Scientific Revolution Begins

- Geomagnetic reversals
  - Geomagnetic reversals are recorded in the oceanic crust.
  - In 1963, Vine and Matthews tied the discovery of magnetic stripes in the oceanic crust near ridges to Hess' s concept of seafloor spreading.

Paleomagnetic Reversals Recorded in Oceanic Crust



A Scientific Revolution Begins

- **Geomagnetic reversal**
  - **Paleomagnetism was the most convincing evidence set forth to support the concepts of continental drift and seafloor spreading.**

Plate Tectonics: The New Paradigm

- Earth's major plates
  - Associated with Earth's strong, rigid outer layer:
    - Known as the lithosphere
    - Consists of uppermost mantle and overlying crust
    - Overlies a weaker region in the mantle called the asthenosphere

Plate Tectonics: The New Paradigm

- **Earth's major plates**
  - **Seven major lithospheric plates**
  - **Plates are in motion and are continually changing in shape and size.**
  - **The largest plate is the Pacific plate.**
  - **Several plates include an entire continent plus a large area of seafloor.**

Earth's Tectonic Plates

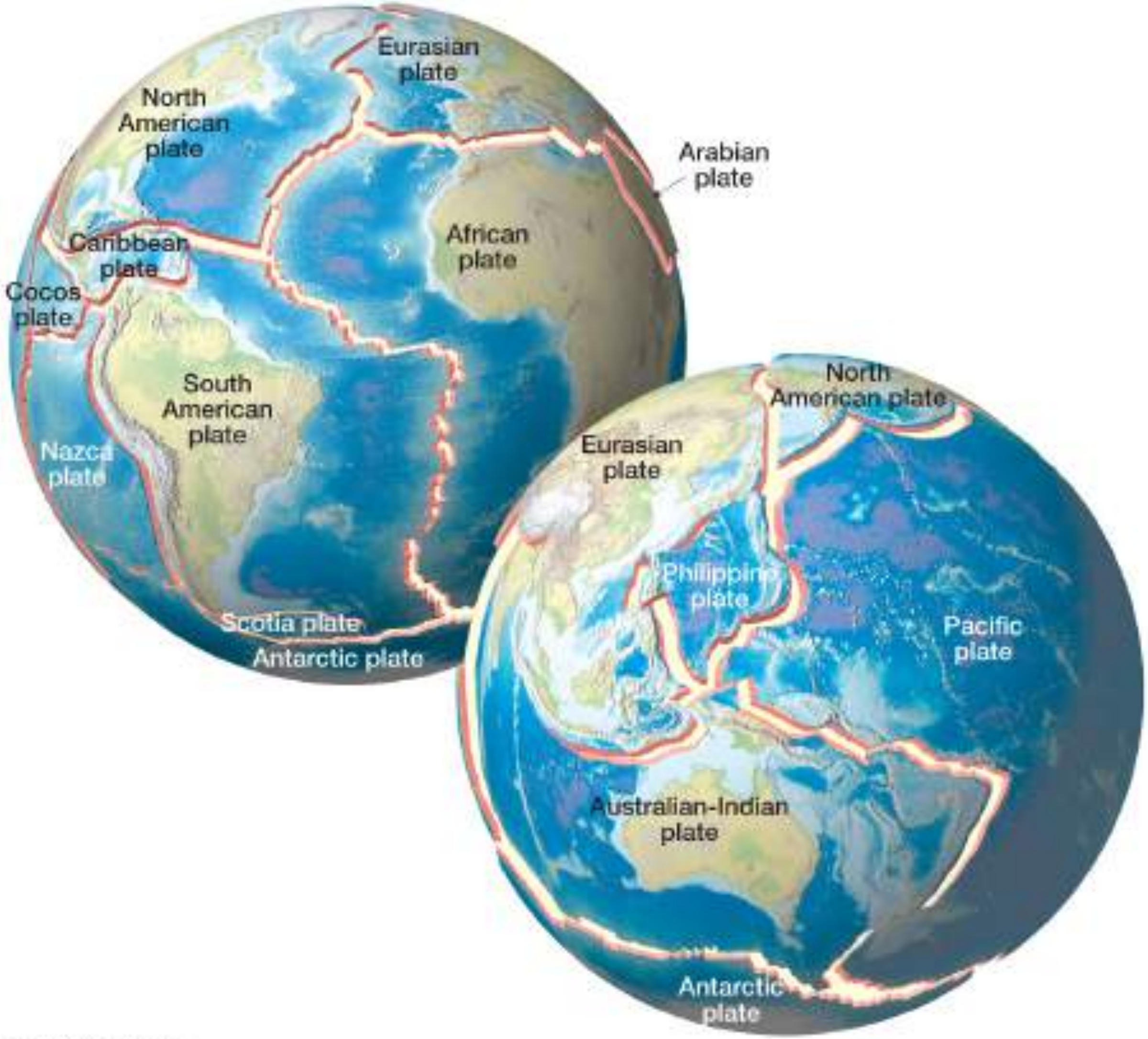


Plate Tectonics: The New Paradigm

- Earth's major plates
  - Plates move relative to each other at a very slow but continuous rate.
    - About 5 centimeters (2 inches) per year
    - Cooler, denser slabs of oceanic lithosphere descend into the mantle.

Plate Tectonics: The New Paradigm

- Plate boundaries
  - Interactions among individual plates occur along their boundaries.
  - Types of plate boundaries:
    - **Divergent plate boundaries (**constructive margins)
    - **Convergent plate boundaries** (destructive margins)
    - **Transform fault boundaries** (conservative margins)

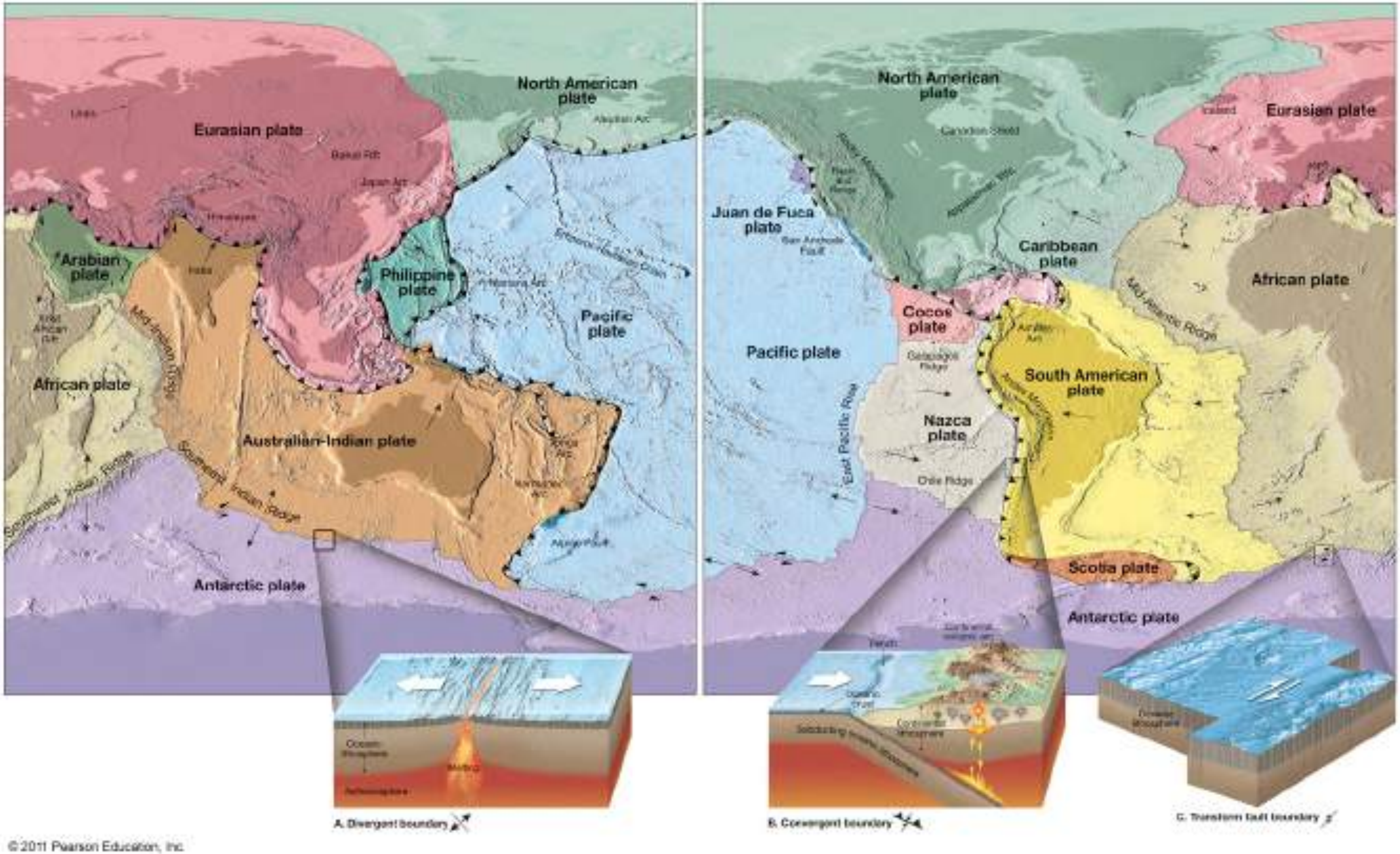

North American plate
Eurasian plate
Arabian plate
Philippine plate
Pacific plate
African plate
Australian-Indian plate
Antarctic plate
Juan de Fuca plate
Caribbean plate
Cocos plate
Nazca plate
South American plate
Scotia plate
Mid-Atlantic Ridge
East Pacific Rise
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Plate Tectonics: The New Paradigm

- **Plate boundaries**
  - **Each plate is bounded by a combination of the three types of boundaries.**
  - **New plate boundaries can be created in response to changing forces.**

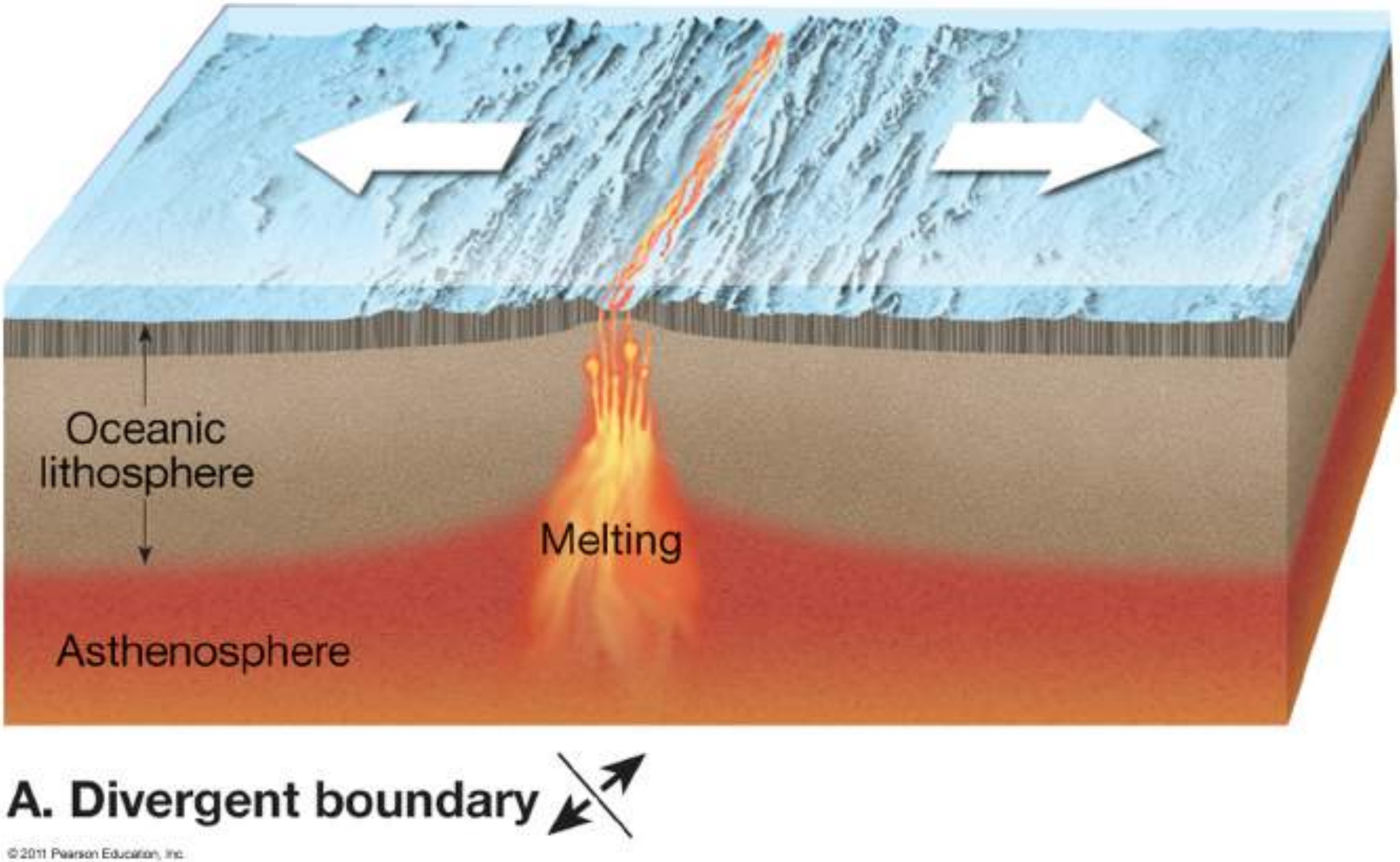
Divergent Plate Boundaries

- Most are located along the crests of oceanic ridges.
- Oceanic ridges and seafloor spreading
    - Along well-developed divergent plate boundaries, the seafloor is elevated, forming oceanic ridges.

Divergent Plate Boundaries

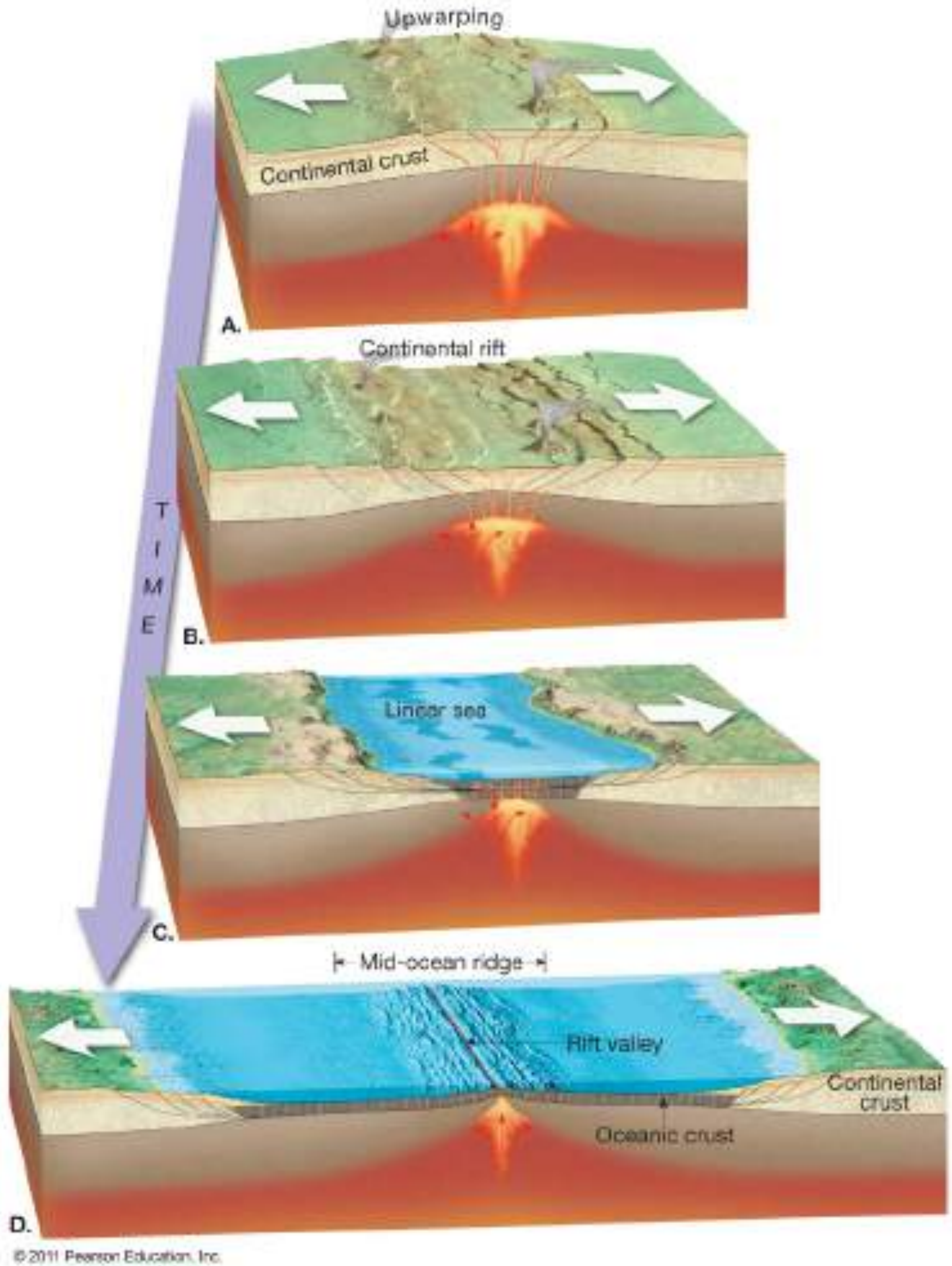
- **Oceanic ridges and seafloor spreading**
  - **Seafloor spreading occurs along the oceanic ridge system.**
- **Spreading rates and ridge topography**
  - **Ridge systems exhibit topographic differences.**
  - **Differences are controlled by spreading rates.**

Divergent Plate Boundary



Divergent Plate Boundaries

- Continental rifting
  - Splits landmasses into two or more smaller segments along a continental rift
  - Examples include:
    - East African Rift Valleys
    - Rhine Valley in Northern Europe
  - Produced by extensional forces



Upwarping
Continental crust
A.
Continental rift
B.
T
I
M
E
Linear sea
C.
Mid-ocean ridge
Rift valley
Continental crust
Oceanic crust
D.
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FUNDAMENTALS OF EARTH SCIENCES (ESO 213A)

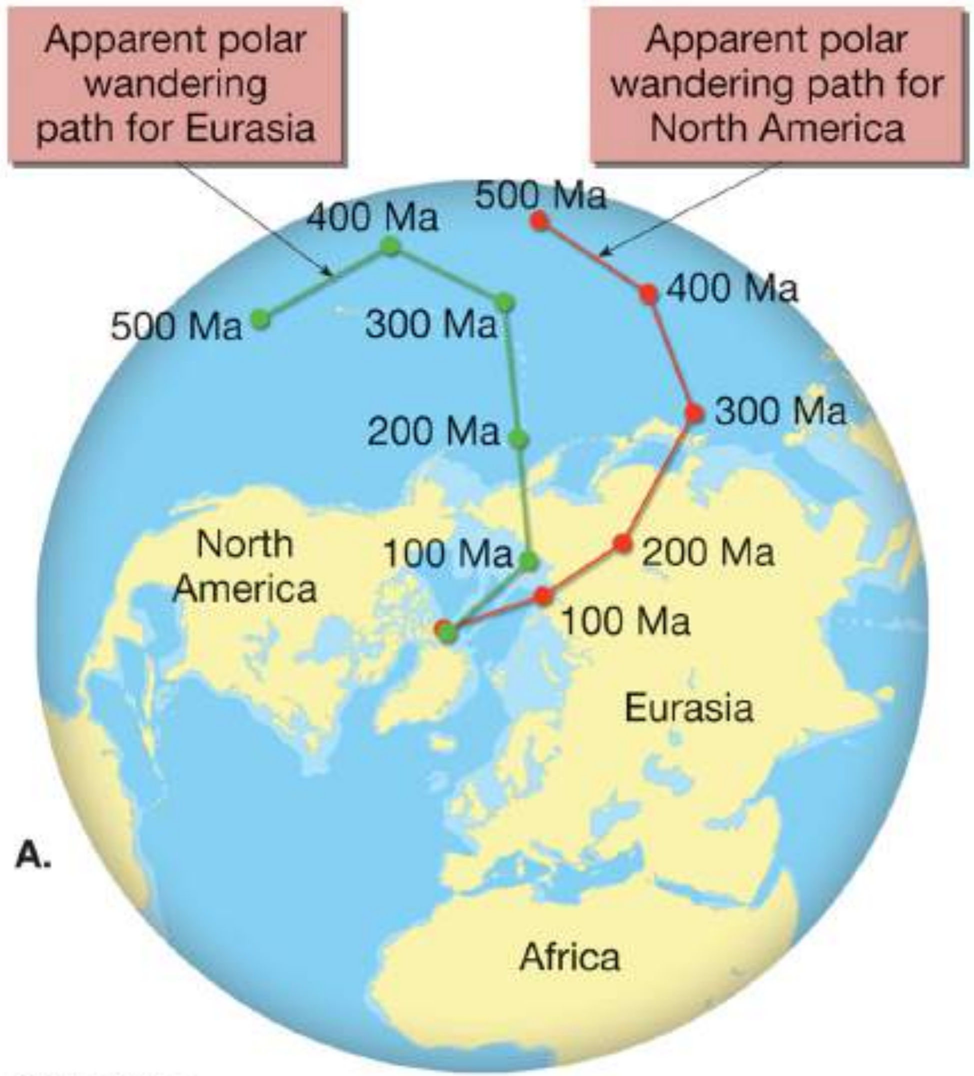
DIBAKAR GHOSAL
DEPARTMENT OF EARTH SCIENCES

Topic: Divergent/Convergent/Transform Plate Boundaries

Previous Class: Plate Tectonics

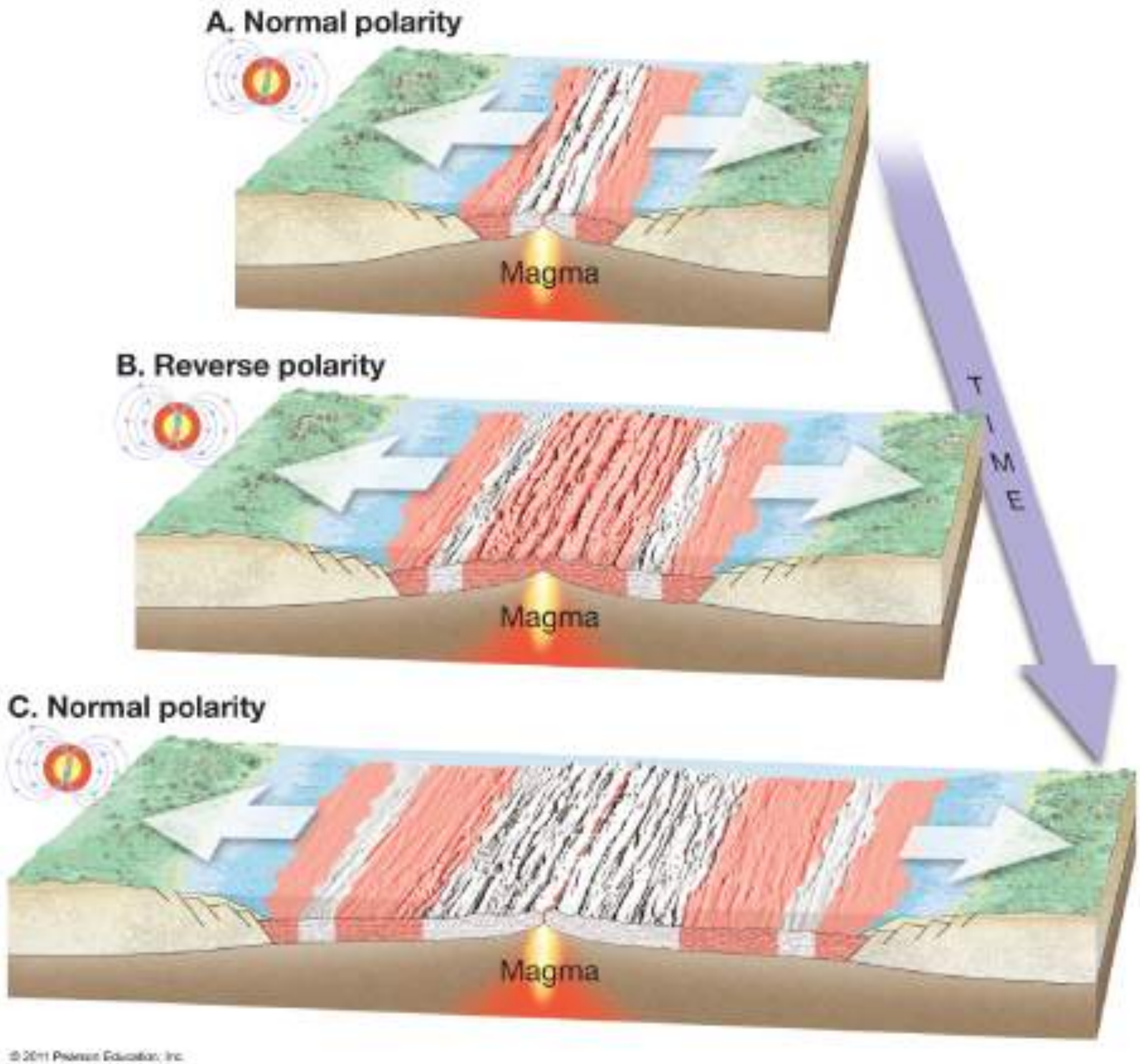
Last Class: Review

Polar Wandering Paths

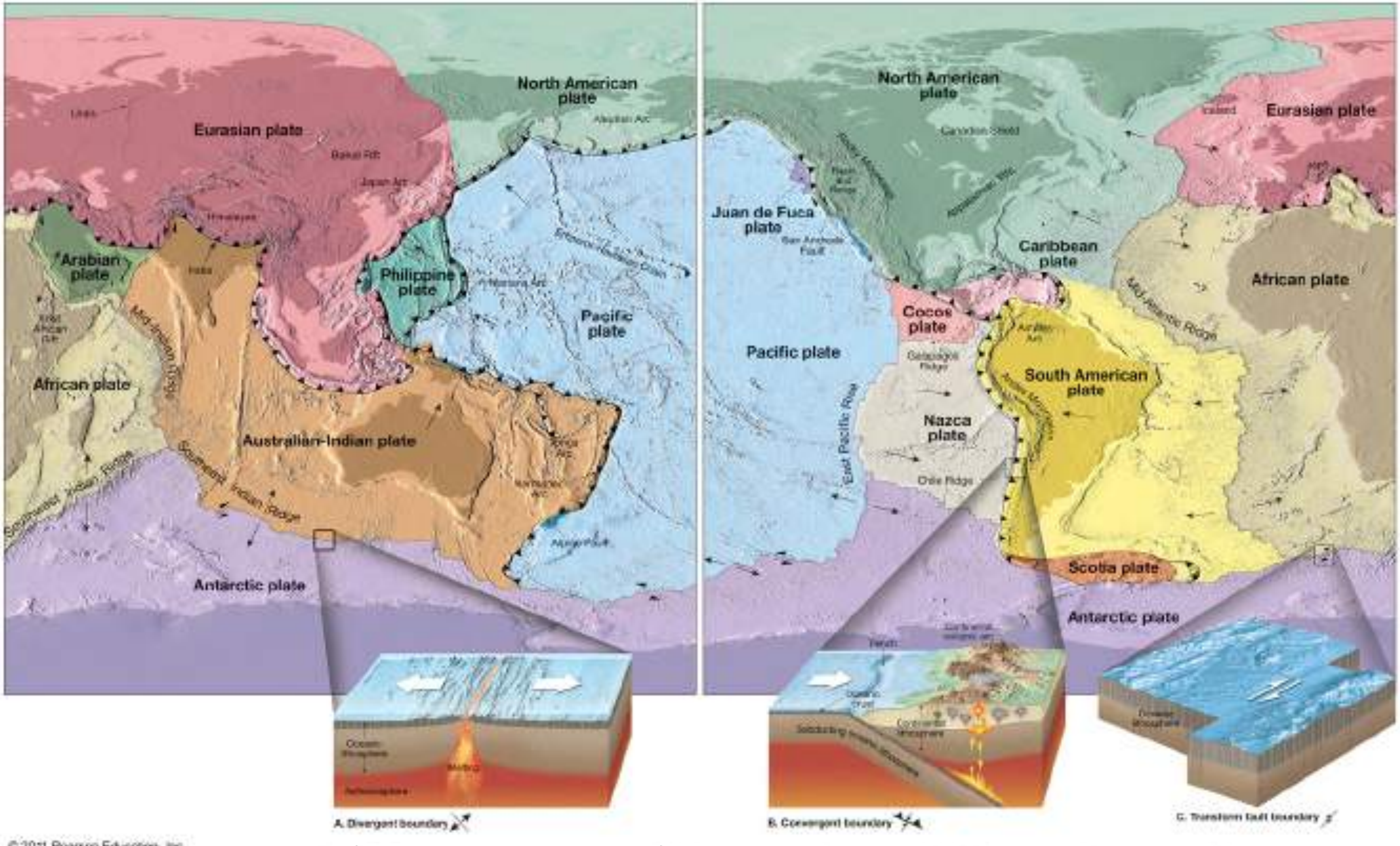


Last Class: Review

Paleomagnetic Reversals Recorded in Oceanic Crust



Last Class: Review



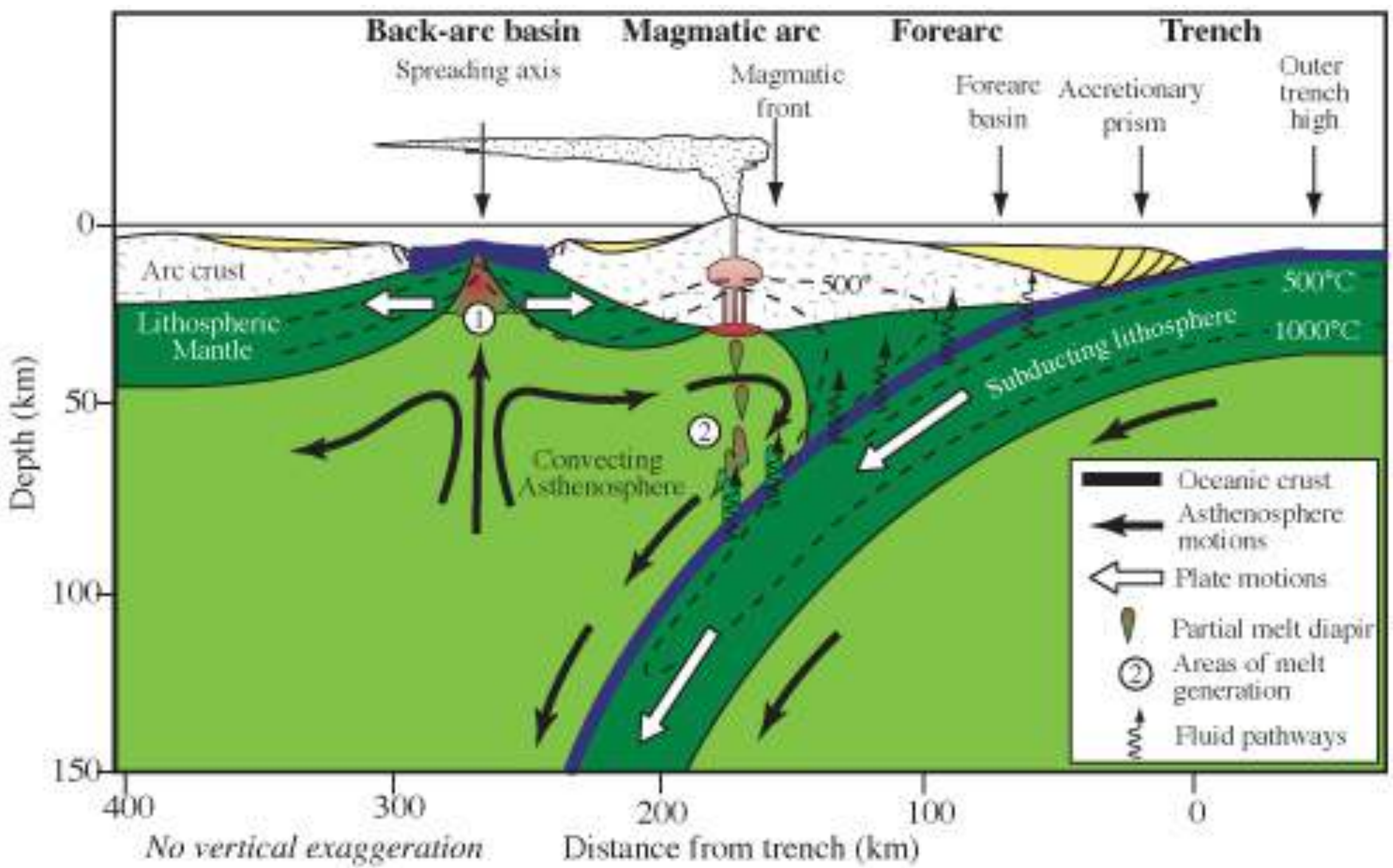
Divergent/Convergent/Transform Plate Boundary

Convergent Plate Boundaries

- **Older portions of oceanic plates are returned to the mantle at these destructive plate margins.**
  - **Surface expression of the descending plate is an ocean trench.**
  - **Also called subduction zones**
  - **Average angle of subduction = 45 degrees.**

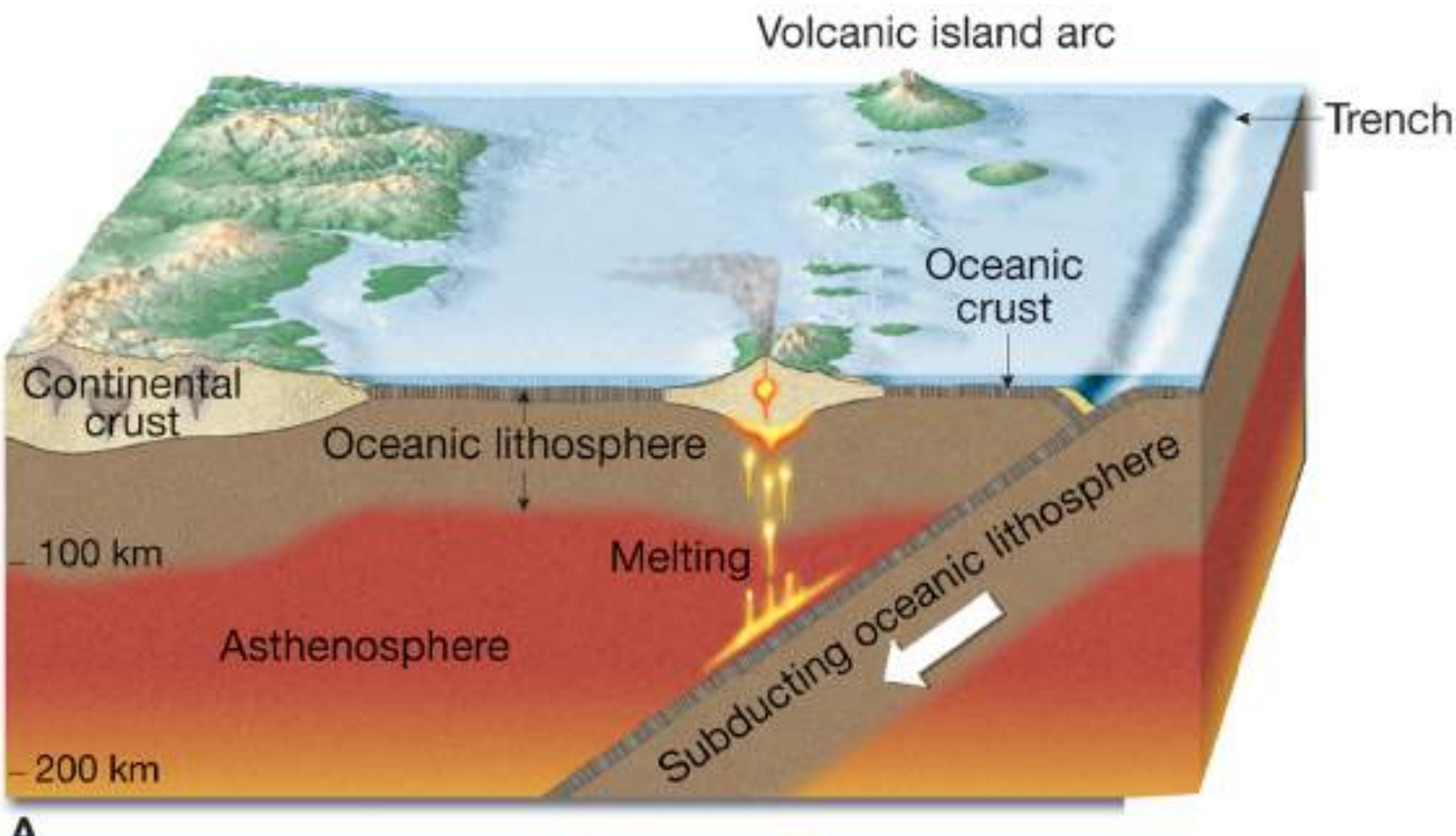
Convergent Plate Boundaries

- **Types of convergent boundaries:**
  - **Oceanic–continental convergence**
    - **The denser oceanic slab sinks into the asthenosphere.**
    - **Along the descending plate, partial melting of mantle rock generates magma.**
    - **The resulting volcanic mountain chain is called a continental volcanic arc. (The Andes and the Cascades are examples.)**



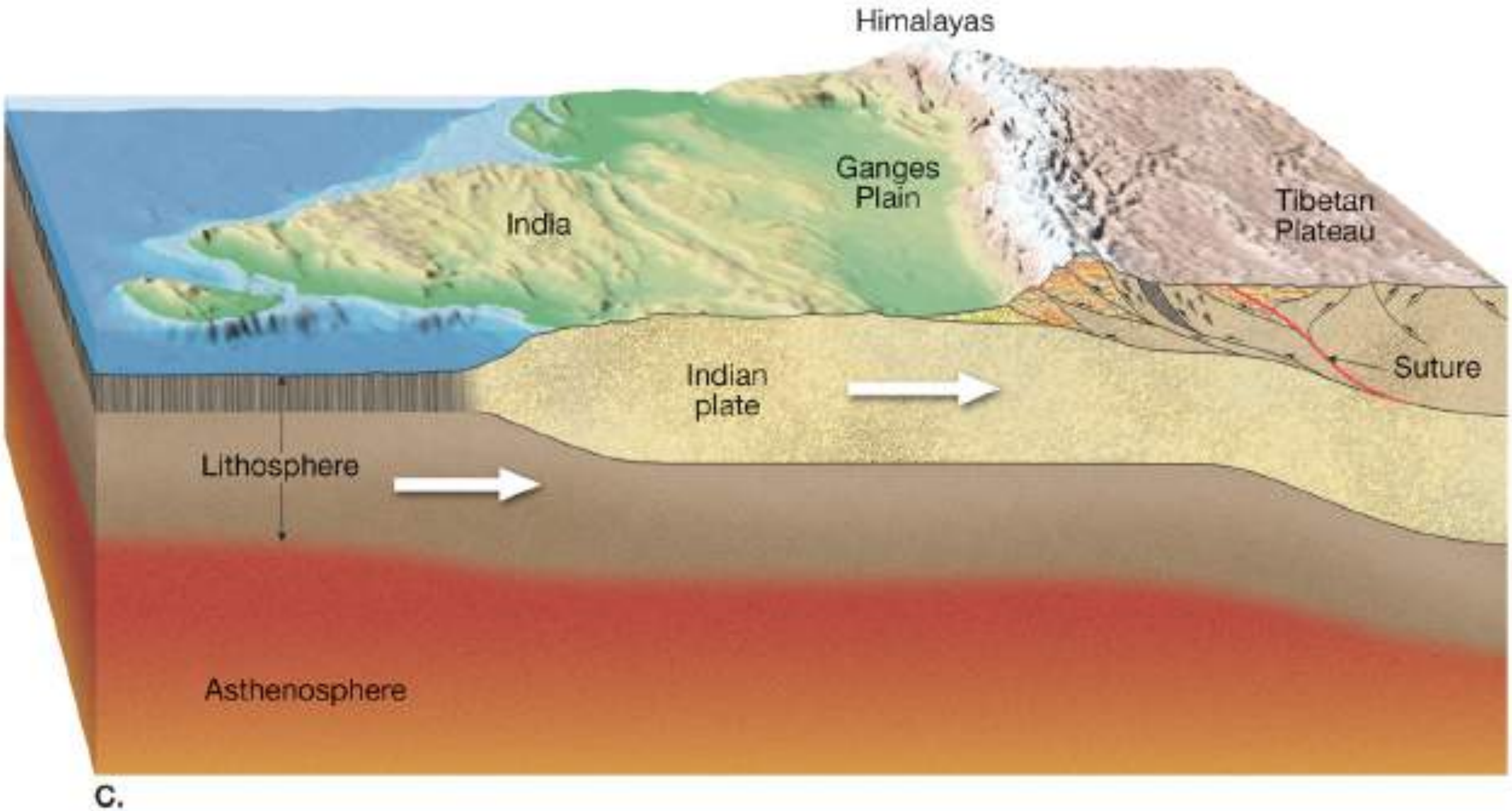
Convergent Plate Boundaries

- Types of convergent boundaries:
  - Oceanic–oceanic convergence
    - When two oceanic slabs converge, one descends beneath the other.
    - Often forms volcanoes on the ocean floor
    - If the volcanoes emerge as islands, a volcanic island arc is formed. (Japan, the Aleutian islands, and the Tonga islands are examples.)



Convergent Plate Boundaries

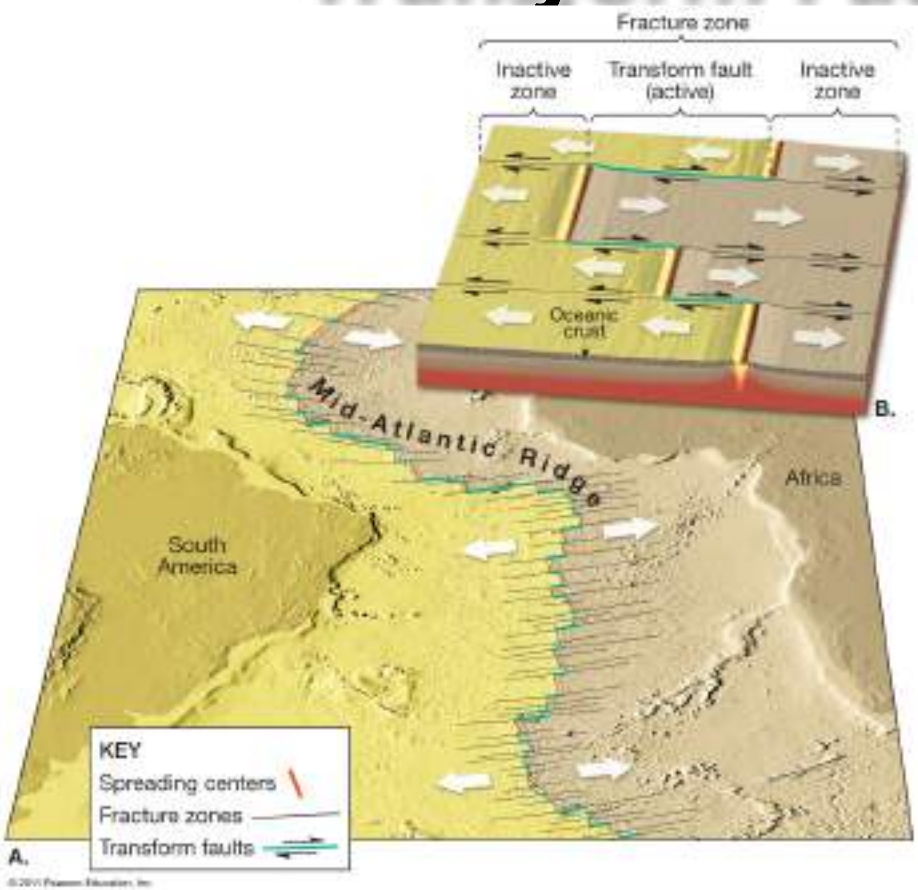
- Types of convergent boundaries:
  - Continental–continental convergence
    - Continued subduction can bring two continents together.
    - Less dense, buoyant continental lithosphere does not subduct.
    - The resulting collision produces mountains. (The Himalayas, the Alps, and the Appalachians are examples.)

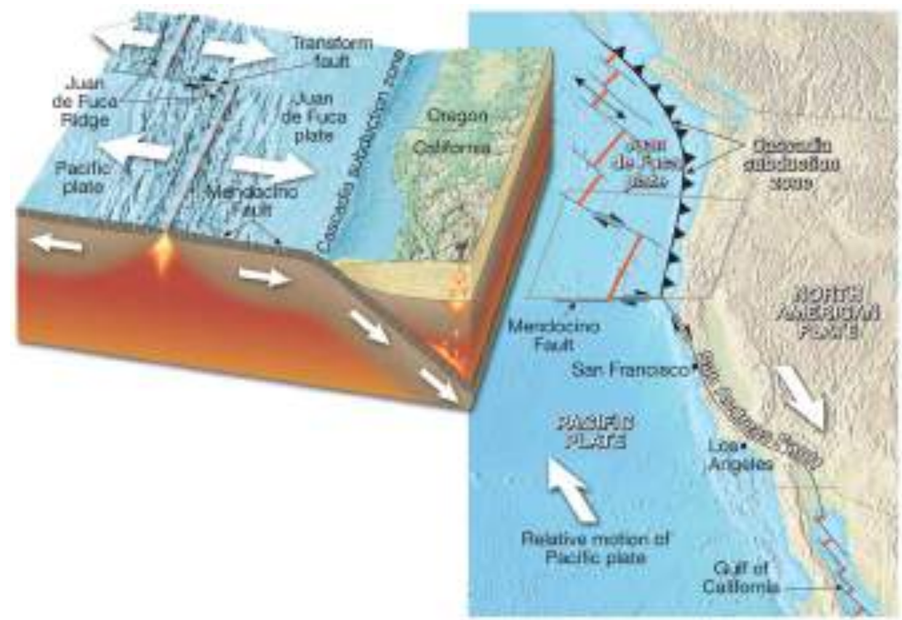


Transform Fault Boundaries

- **Plates slide past one another and no new lithosphere is created or destroyed.**
- **Transform faults**
  - **Mostly join two segments of a mid-ocean ridge (MOR) along breaks in the oceanic crust known as fracture zones.**
  - **A few (the San Andreas fault and Alpine Fault of New Zealand) cut through continental crust.**

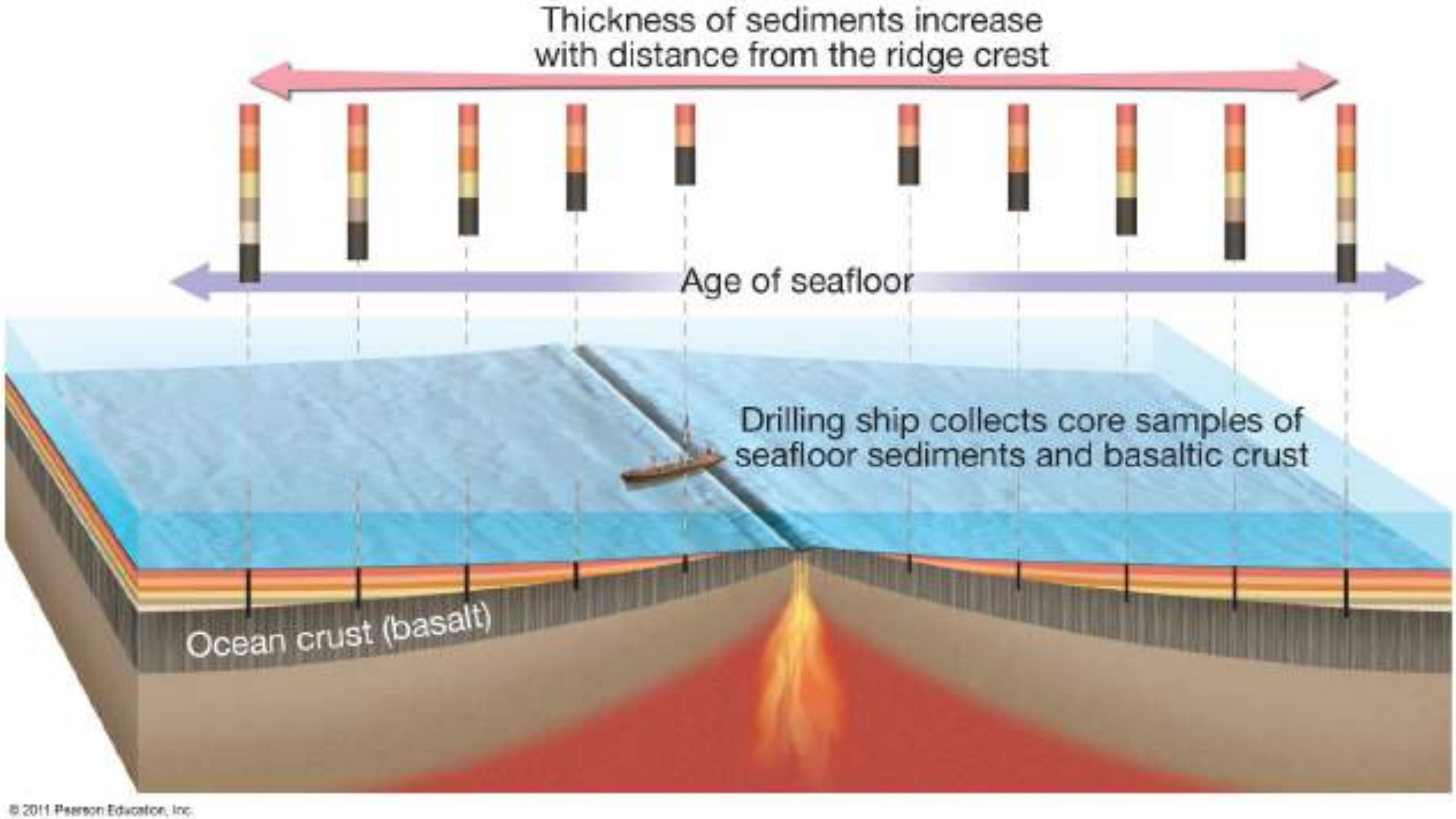
Transform Fault Boundaries





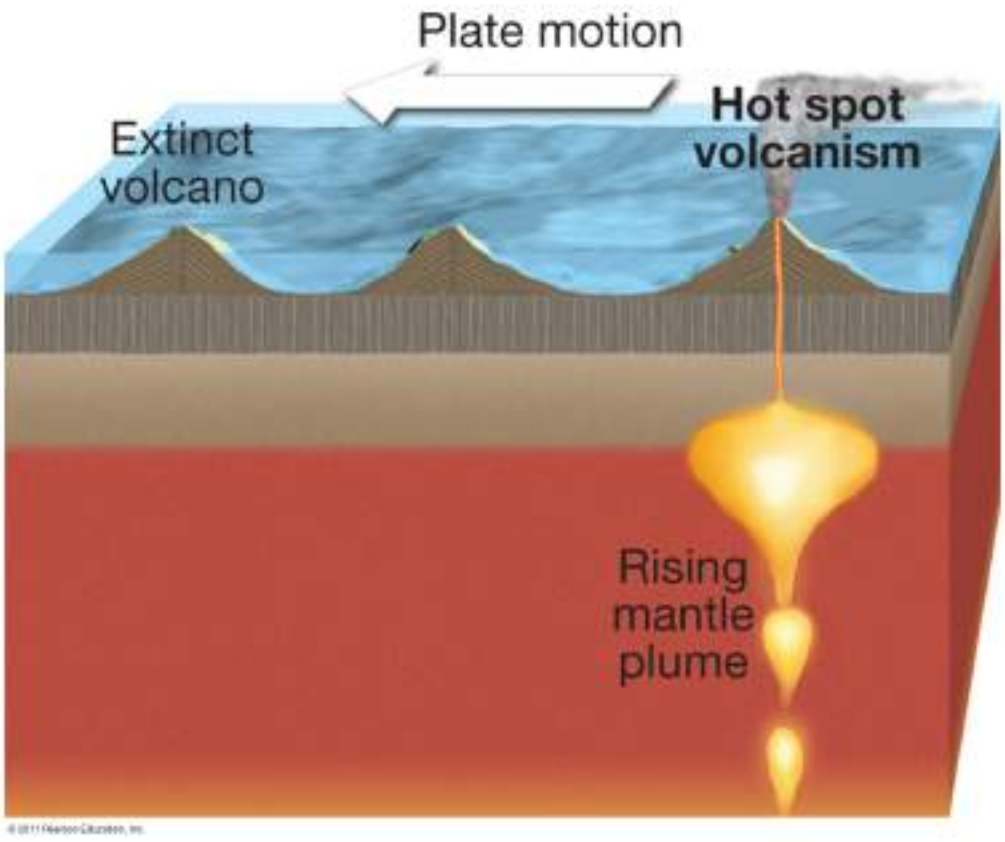
Testing the Plate Tectonics Model

- **Evidence from ocean drilling**
  - **Some of the most convincing evidence has come from drilling directly into ocean-floor sediment.**
    - **Age of deepest sediments**
    - **The thickness of ocean-floor sediments verifies across seafloor spreading.**



Testing the Plate Tectonics Model

- **Hot spots and mantle plumes**
  - **Caused by rising plumes of mantle material**
  - **Volcanoes can form over them (Hawaiian Island chain).**
  - **Mantle plumes**
    - **Long-lived structures**
    - **Some originate at great depth.**



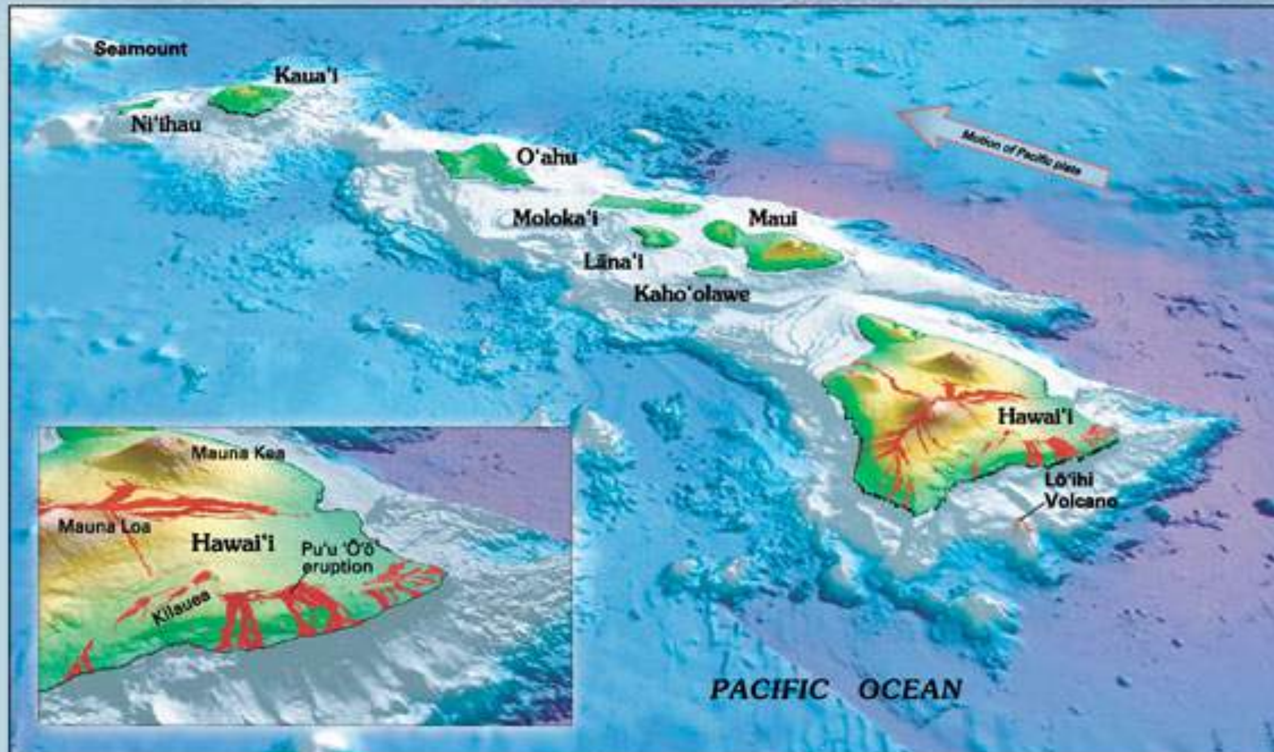


Figure 2.—Oblique view of the principal Hawaiian Islands and (the still submarine) Lō'ihi Volcano. Inset gives a closer view of three of the five volcanoes that form the Island of Hawai'i (historical lava flows are shown in red). The longest duration historical eruption on Kīlauea's east-rift zone at Pu'u 'Ō'ō (inset), which began in January 1983, continues unabated (as of spring 2006). View prepared by Joel E. Robinson (USGS).

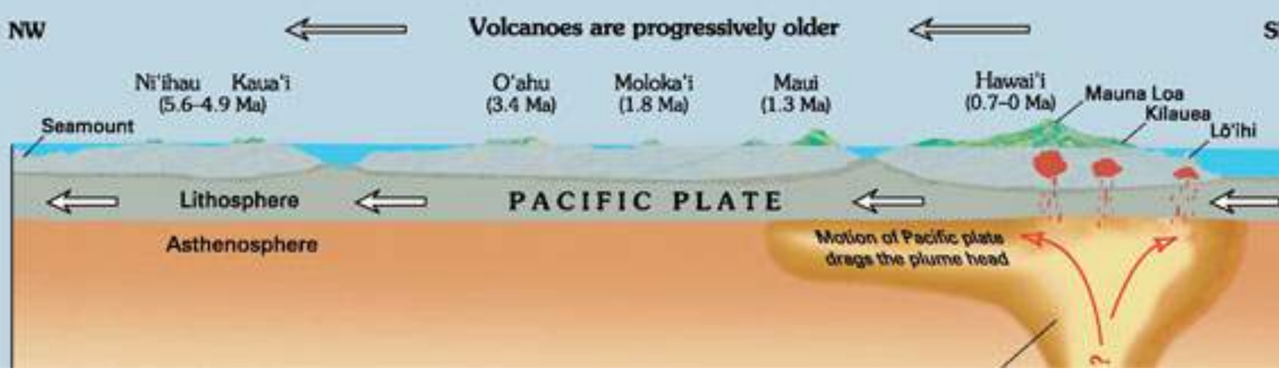
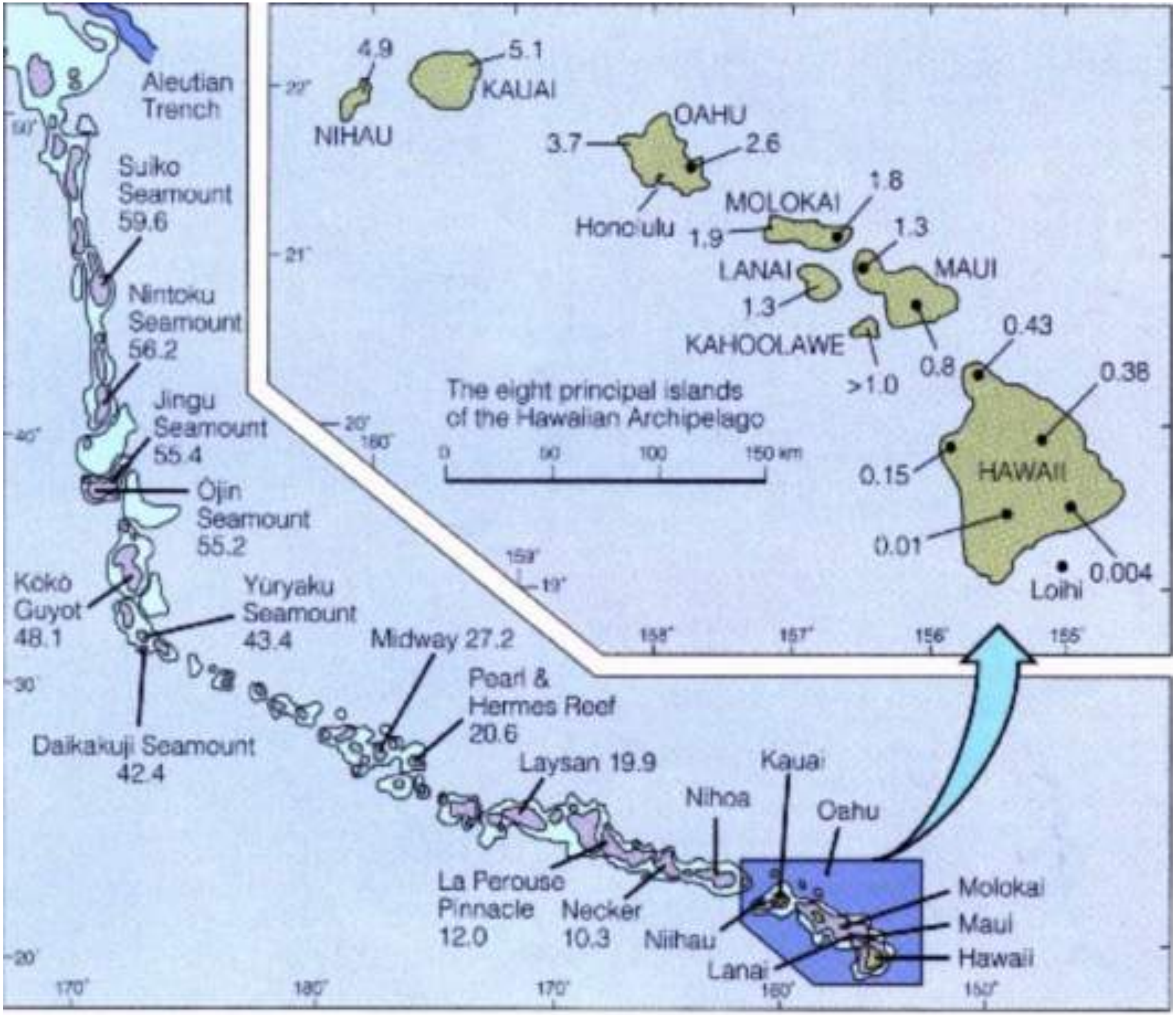


Image courtesy: USGS

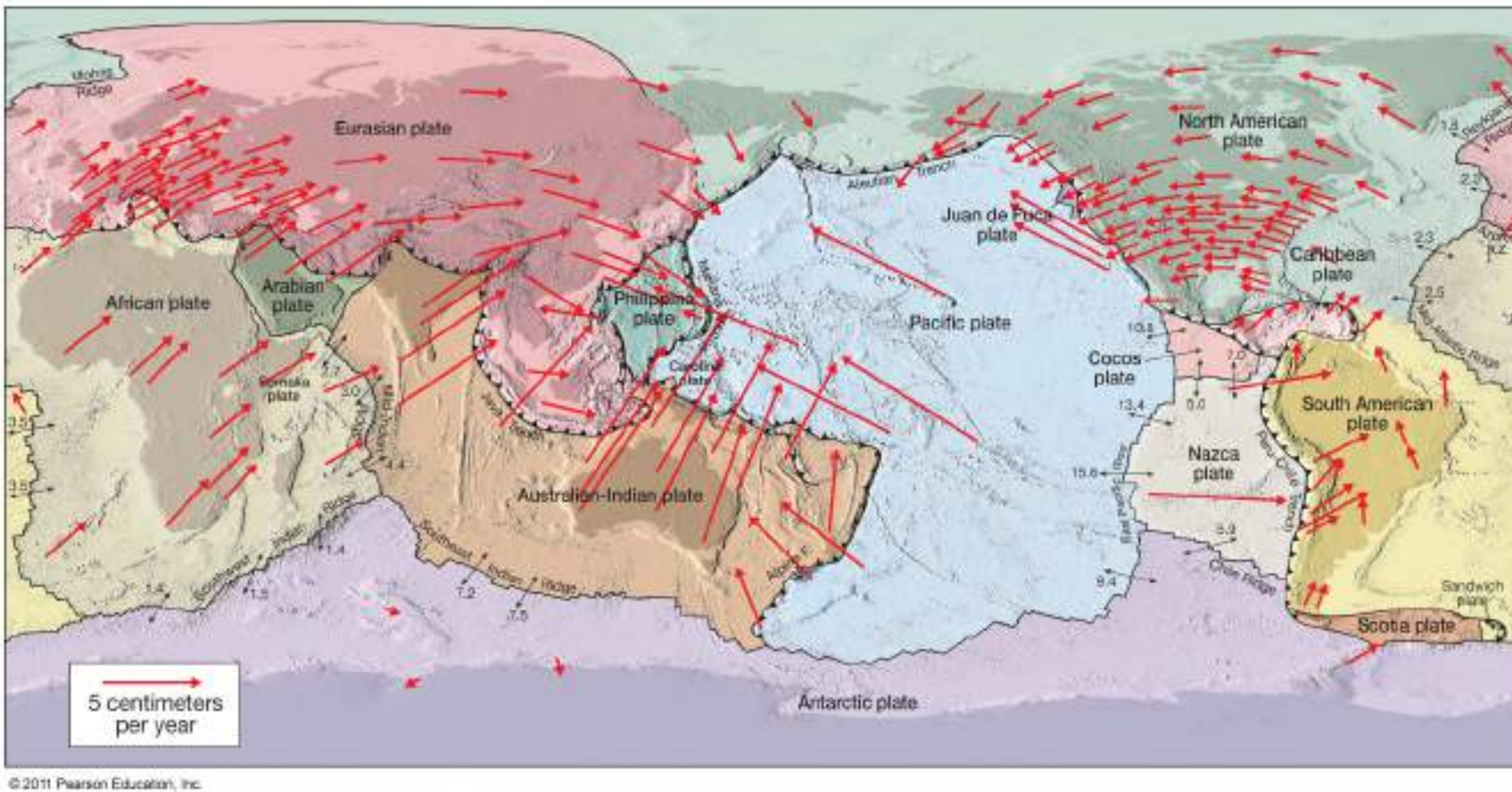


In which direction the plates are moving?

Measuring Plate Motion

- Paleomagnetism and plate motions
  - Paleomagnetism stored in rocks on the ocean floor provides a method for determining plate motions.
  - Both the direction and the rate of spreading can be established.
- Measuring plate velocities from space
  - Accomplished by establishing exact locations on opposite sides of a plate boundary and measuring relative motions
  - Various methods are used:
    - Global Positioning System (GPS)

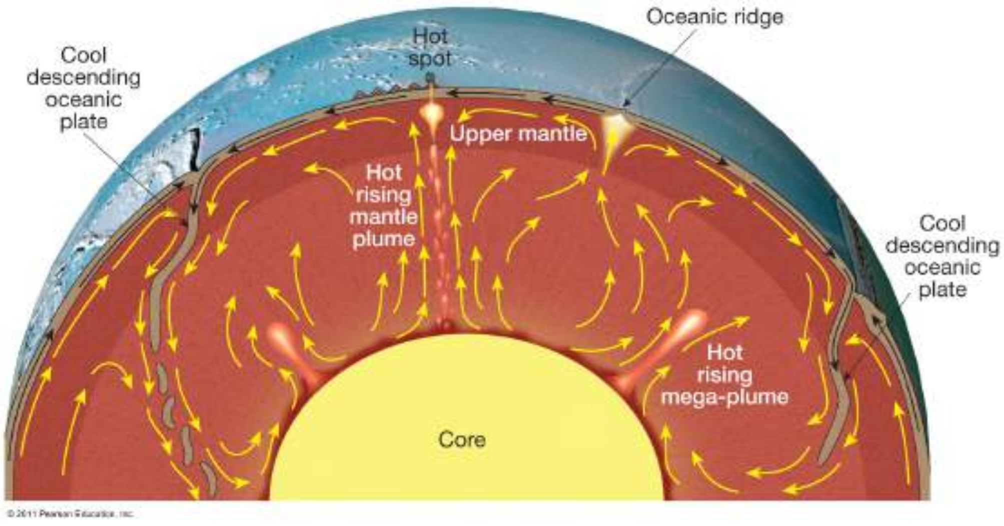
Plate Motions



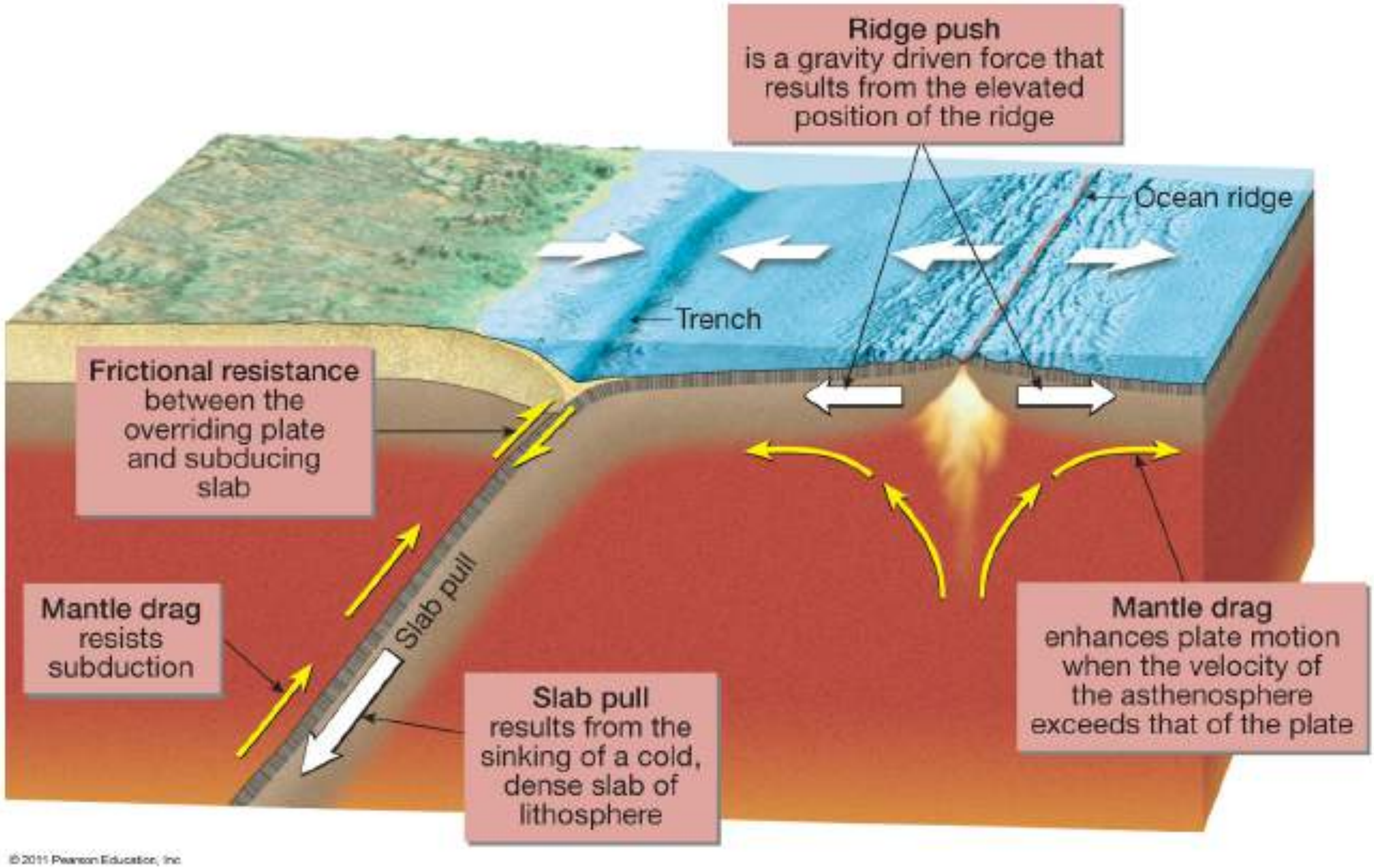
What Drives Plate Motions?

- Researchers agree that convective flow in the mantle is the basic driving force of plate tectonics.

- Driven by three thermal processes:
  - heating at the bottom by heat loss from Earth's core
  - heating from within by decay of radioactive isotopes
  - cooling from top (sinking of cold lithospheric slabs in the mantle)



Forces Driving Plate Motions



Importance of Plate Tectonics

- The theory provides explanations for:
  - Earth's major surface processes
  - Distribution of earthquakes, volcanoes, and mountains
  - Distribution of ancient organisms and mineral deposits

Reconstructed Plate tectonics in geologic past

Questions

1. The volcanoes of Hawaii are localized above a deep mantle hot spot; they are not part of the East Pacific oceanic ridge.
Answer: TRUE / FALSE

2. New oceanic crust and lithosphere are formed at ________.
A) transform boundaries by submarine eruptions
B) convergent boundaries by submarine eruptions
C) divergent boundaries by submarine eruptions

3. The Himalayan Mountains and Tibetan Plateau are still rising today as Eurasia slides beneath the Indian subcontinent.
Answer: TRUE / FALSE

4. Deep ocean trenches are surficial evidence for ________.
A) rifting beneath a continental plate and the beginning of continental drift
B) sinking of oceanic lithosphere into the mantle at a subduction zone
C) rising of hot asthenosphere from deep in the mantle
D) transform faulting between an oceanic plate and a continental plate

5. Hotspot can be used to measure ________ plate motion.

Continental Margins

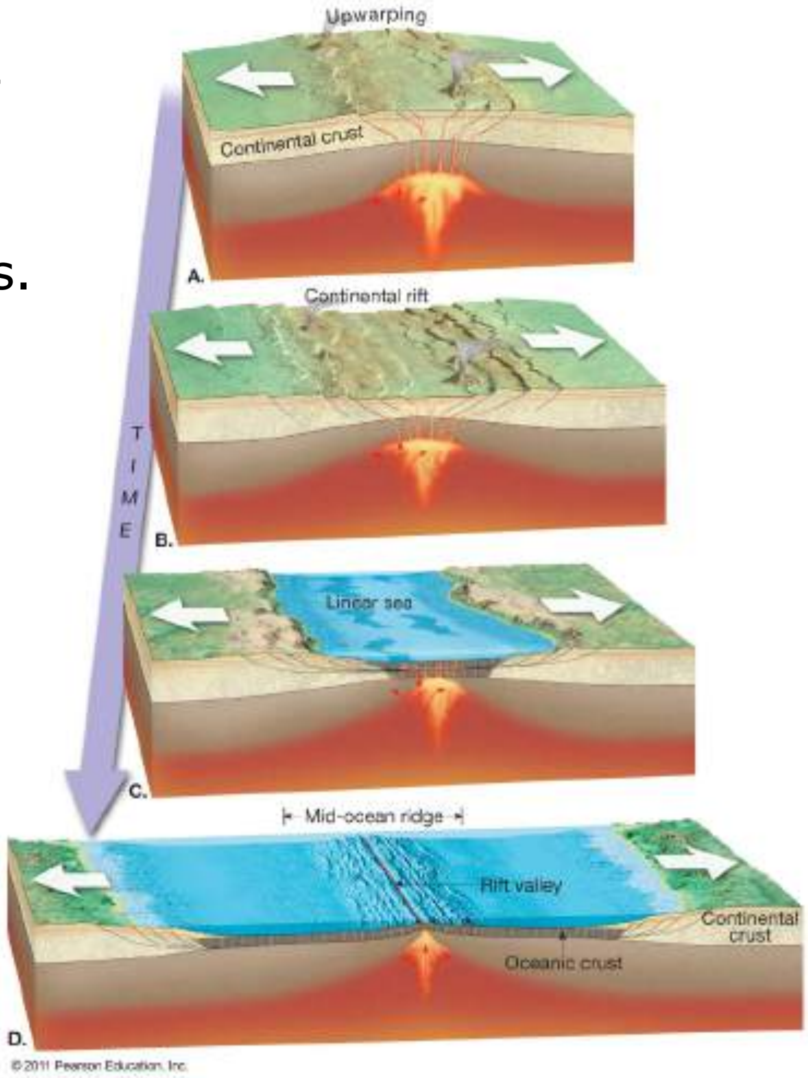
Continental margins are underwater edge of continents. These include continental shelf, slope, rise and abyssal plain. These margins are of two types: passive and active margins.

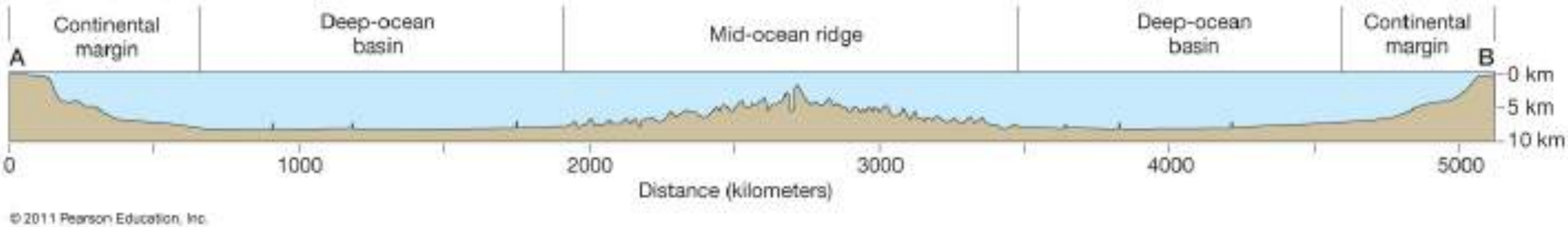
I. **Passive continental margins**

Found along most coastal areas that surround the Atlantic Ocean

Not associated with plate boundaries

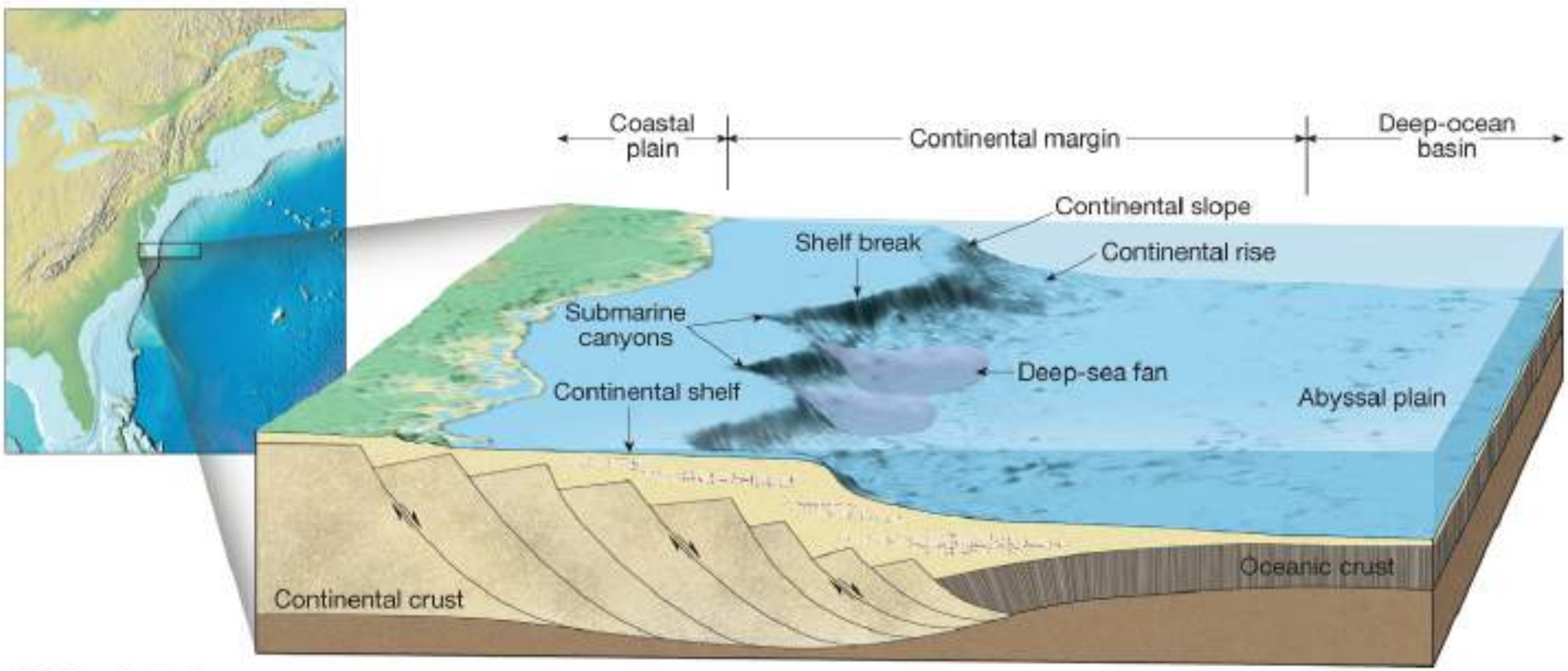
Experience little volcanism and few earthquakes





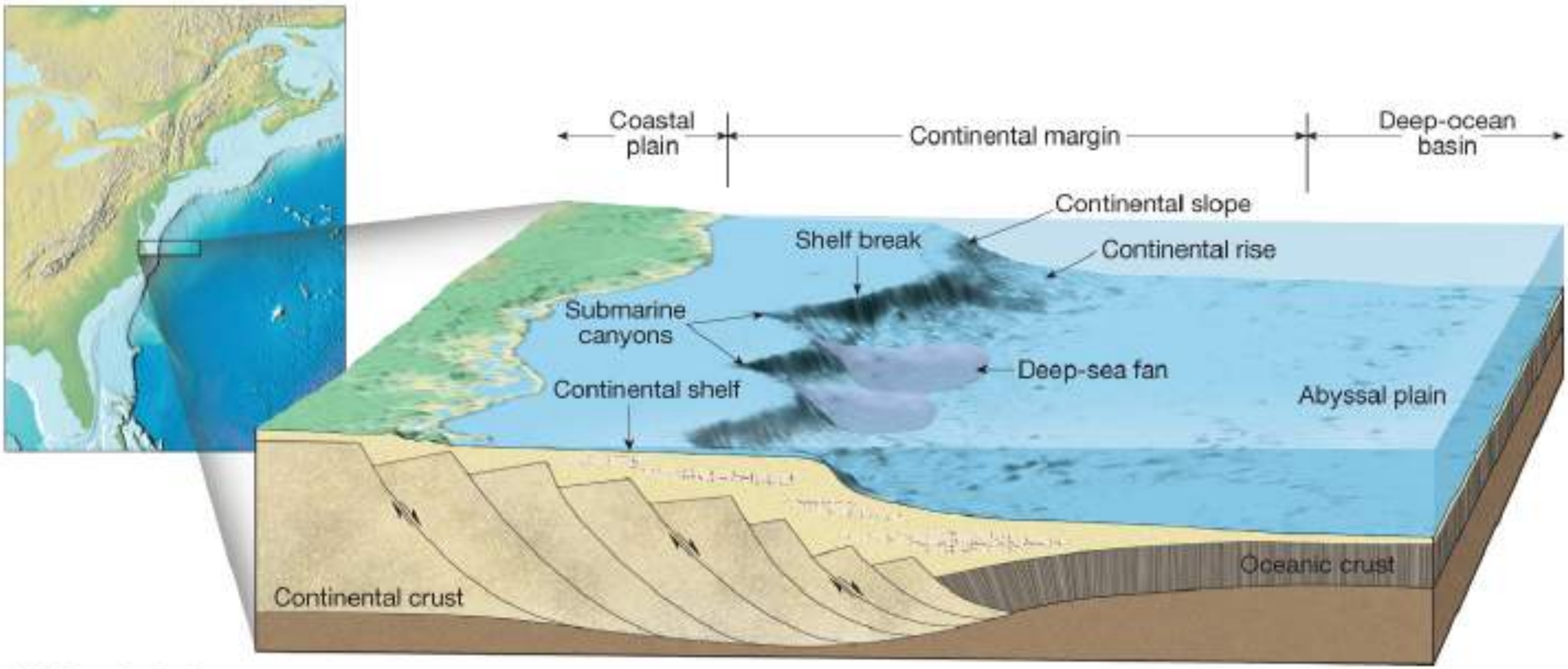
Continental Margins

- Features comprising a passive continental margin
  - Continental shelf
    - Flooded extension of the continent upto shelf
    - Varies greatly in width (average = 80 km)
    - Gently sloping
    - Contains important mineral deposits
    - Some areas are mantled by extensive glacial deposits.



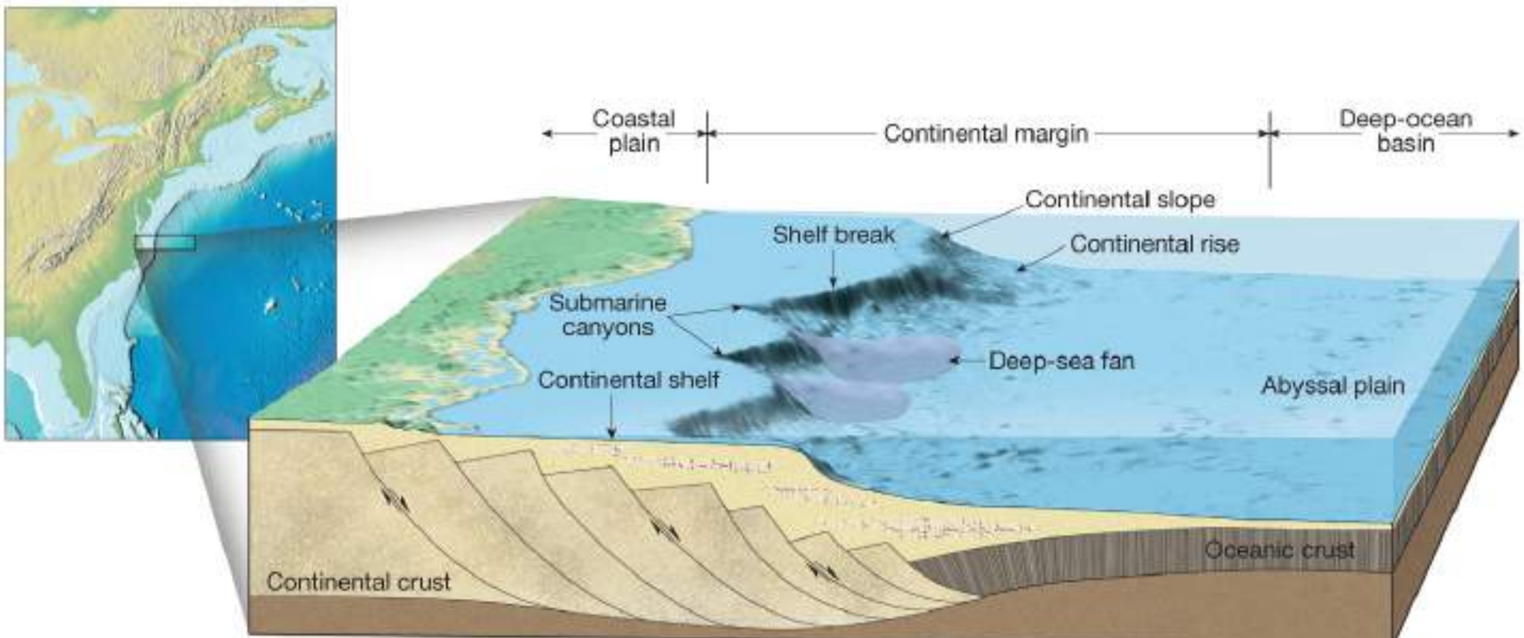
Continental Margins

- Features comprising a passive continental margin
  - Continental slope
    - Marks the seaward edge of the continental shelf
    - Water depth increases rapidly
    - Relatively steep structure (5^{O} – 25^{O})
    - Boundary between continental crust and oceanic crust

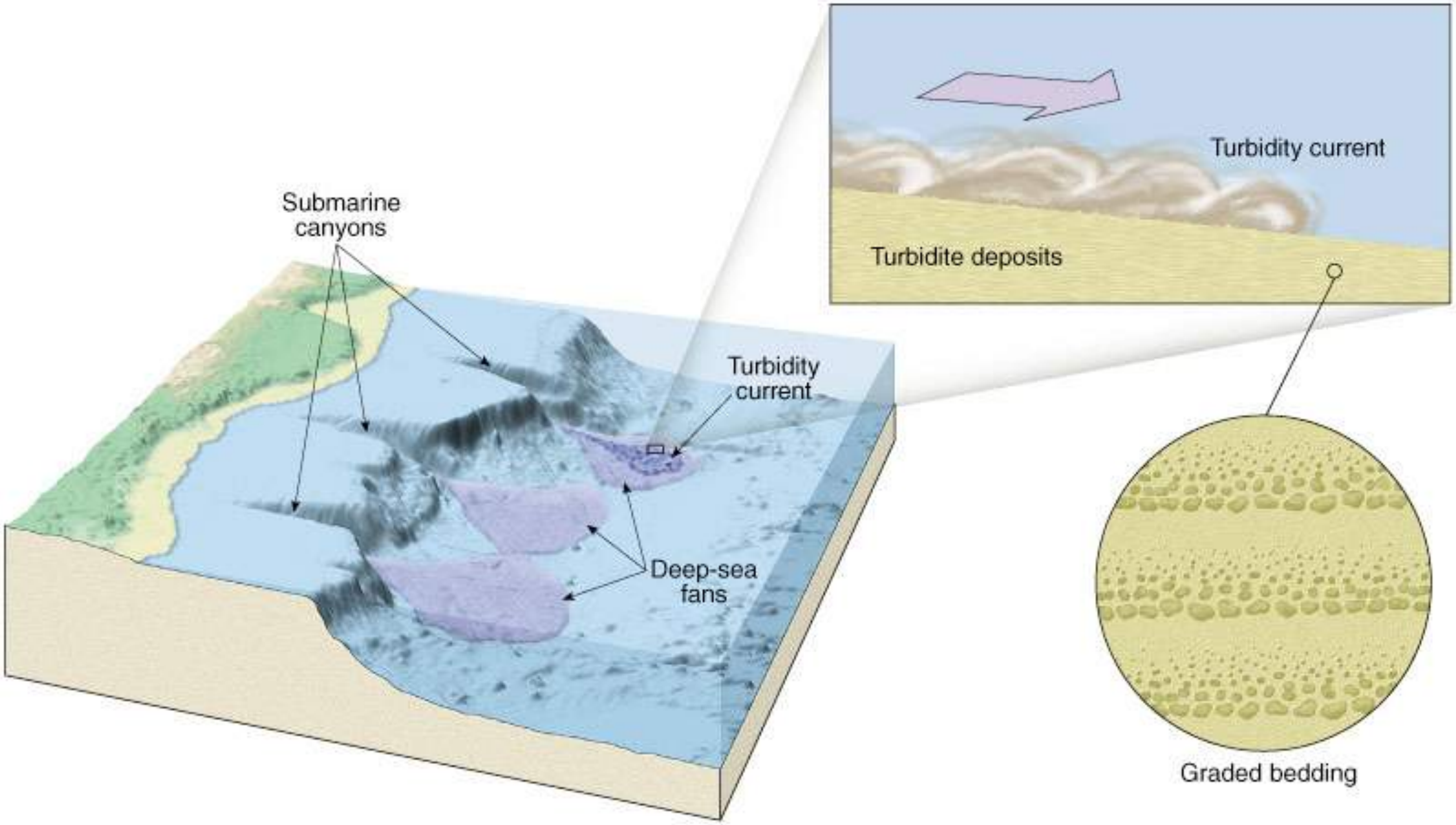


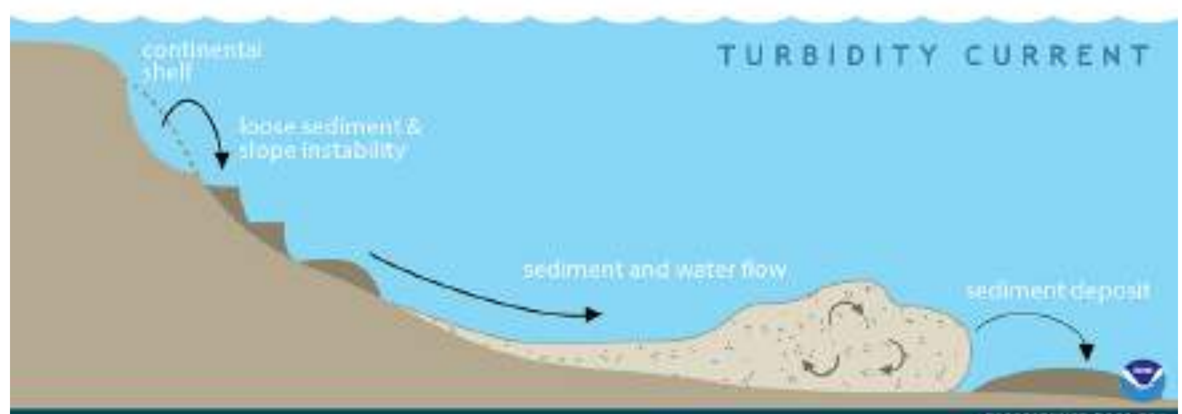
Continental Margins

- Features comprising a passive continental margin
  - Continental rise
    - Sediments become unstable on slope and tumble downward and form continental rise.
    - Found in regions where trenches are absent
    - A continental slope merges into a more gradual incline—the continental rise.
    - Thick accumulation of sediment
    - At the base of the continental slope, turbidity currents deposit sediment that forms deep-sea fans.

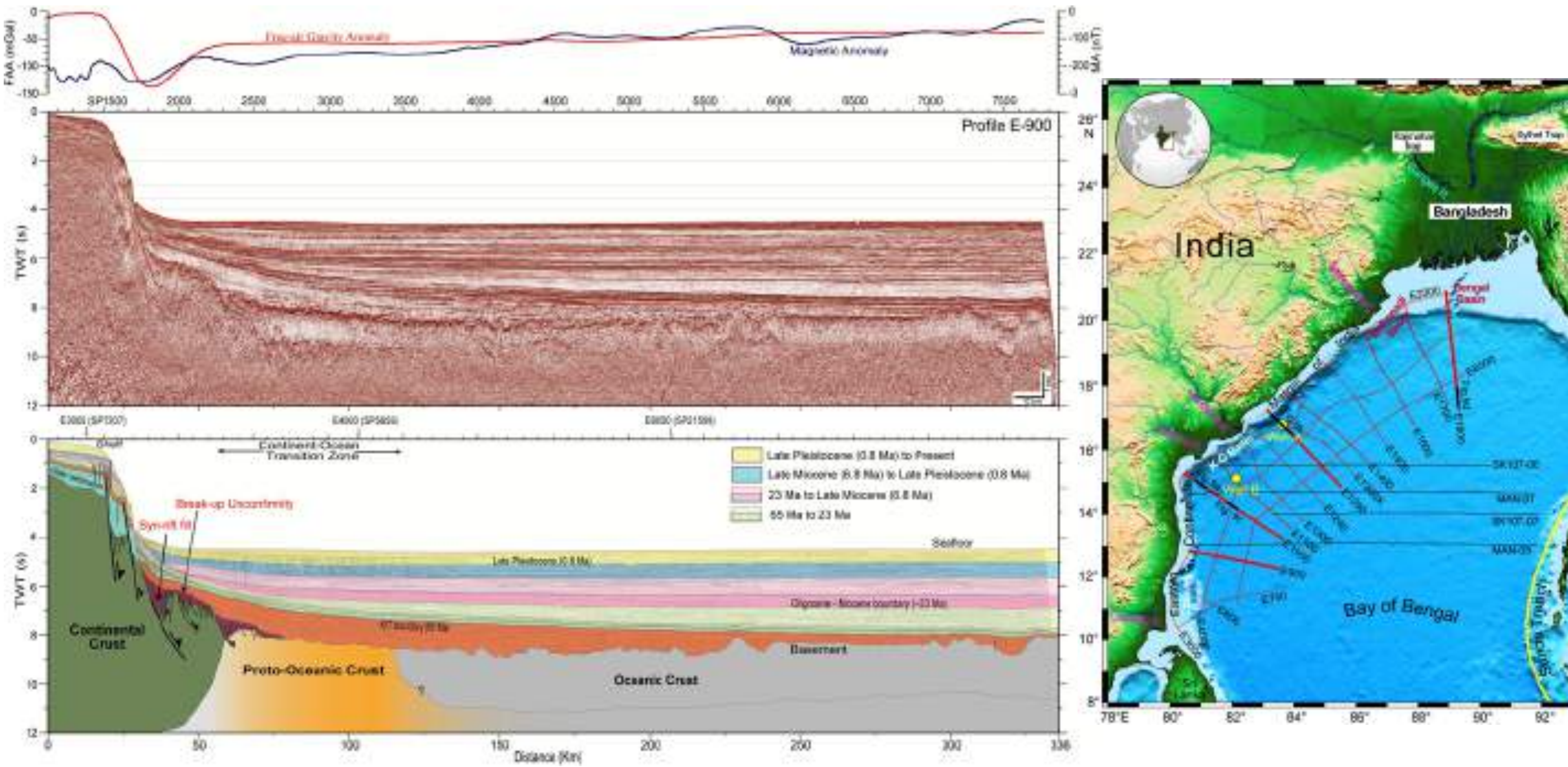


Turbidity current





Passive margin: Krishna-Godavari basin

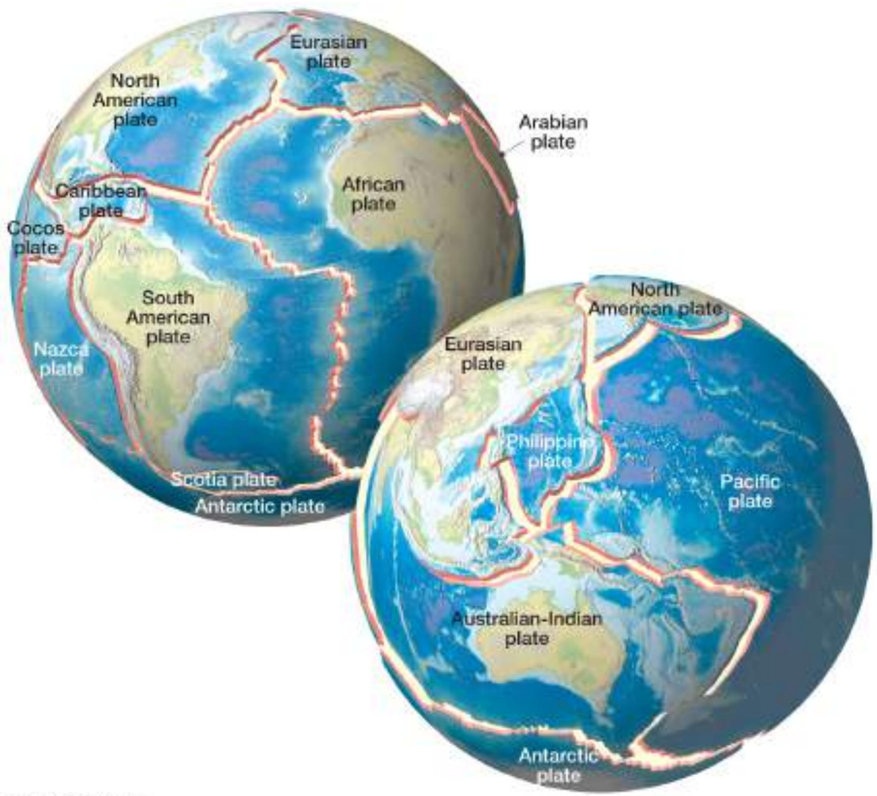


Seismic profile E900 across the offshore Cauvery Basin and adjacent deep-water region. Line drawing of interpreted seismic data together with free-air gravity and magnetic anomaly data are also shown (Ismaiel et al., 2020).

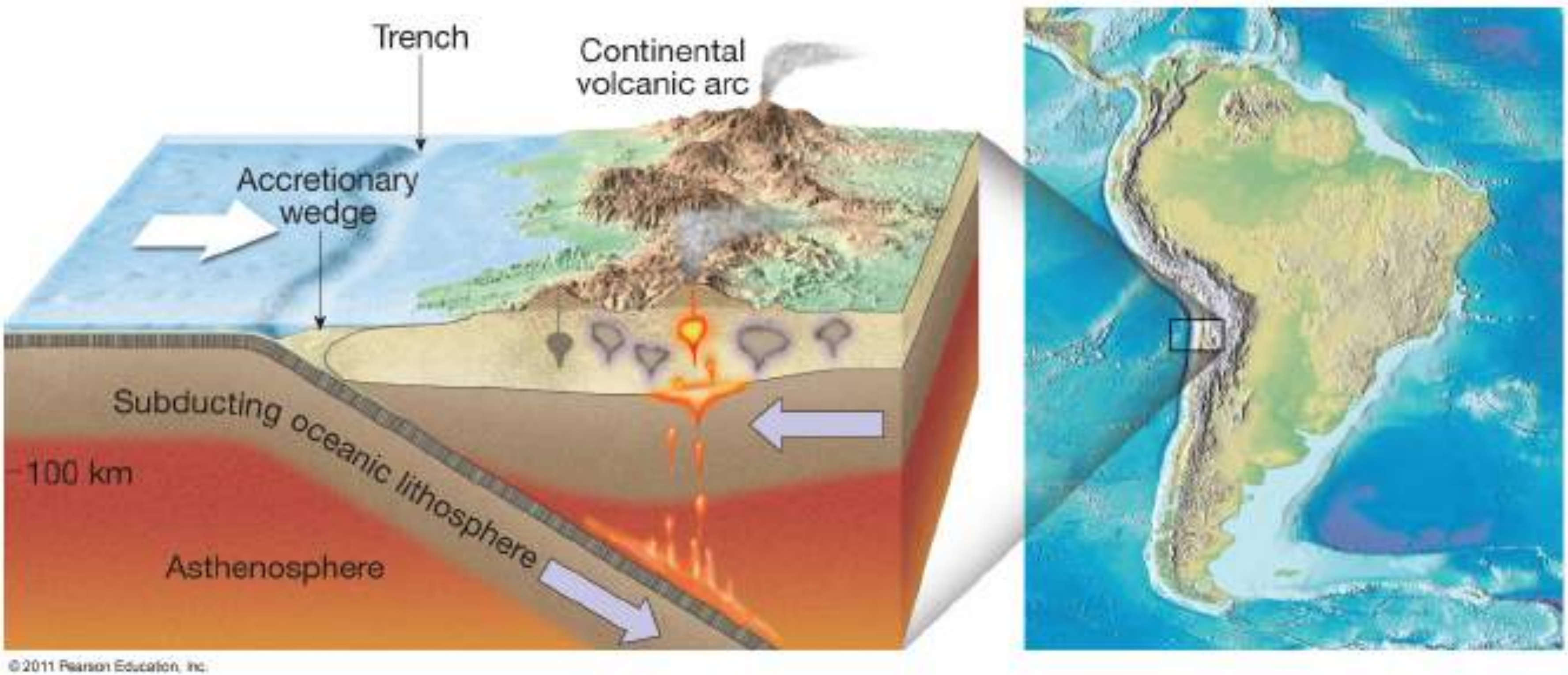
Continental Margins

II. Active continental margins

- The continental slope descends abruptly into a **deep-ocean trench**.
- Located primarily around the Pacific Ocean



An Active Continental Margin



Accumulations of deformed sediment and scraps of ocean crust form accretionary wedges.

Detailed plate boundaries and continental margins

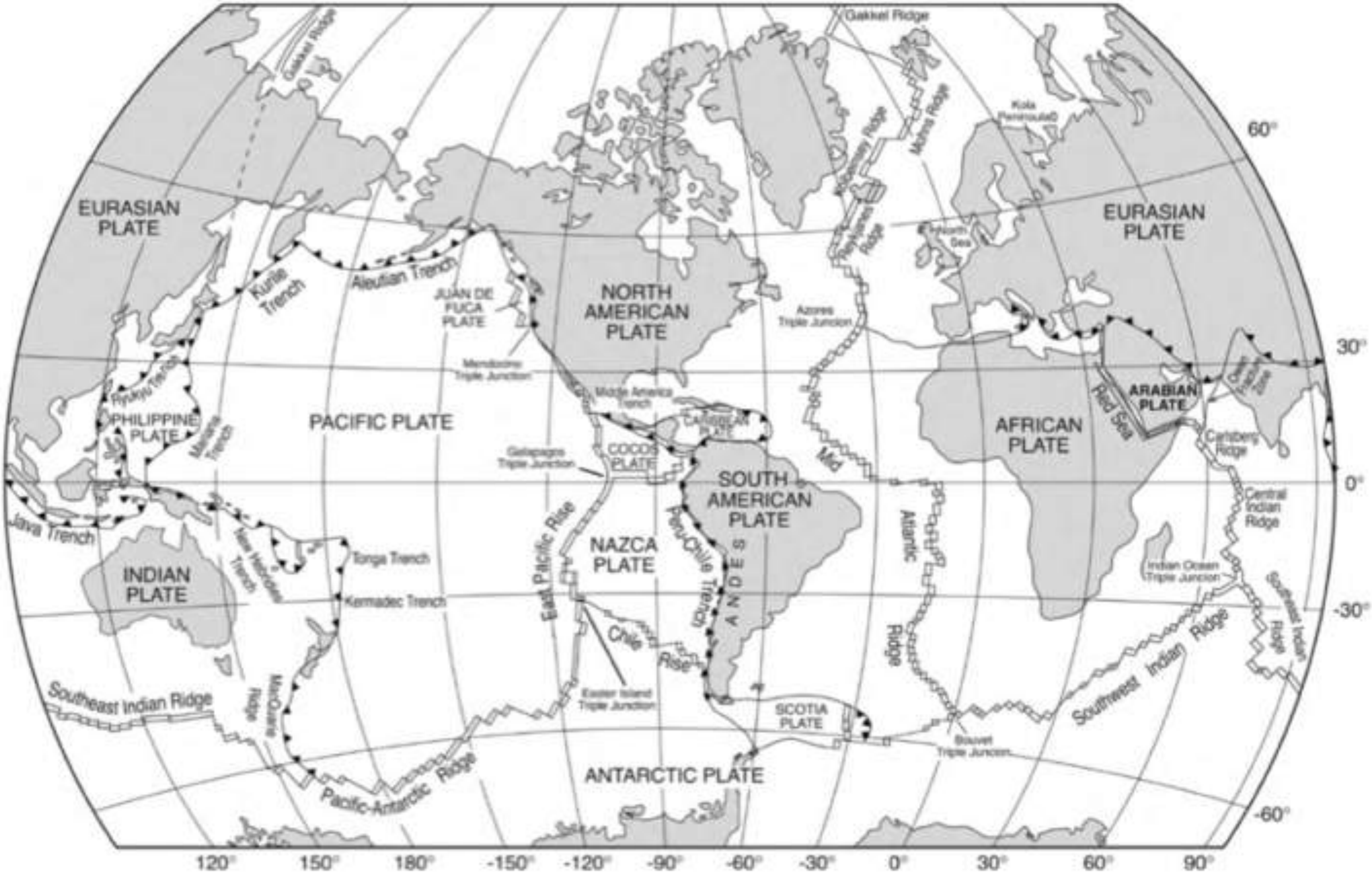


Plate margin seismicity

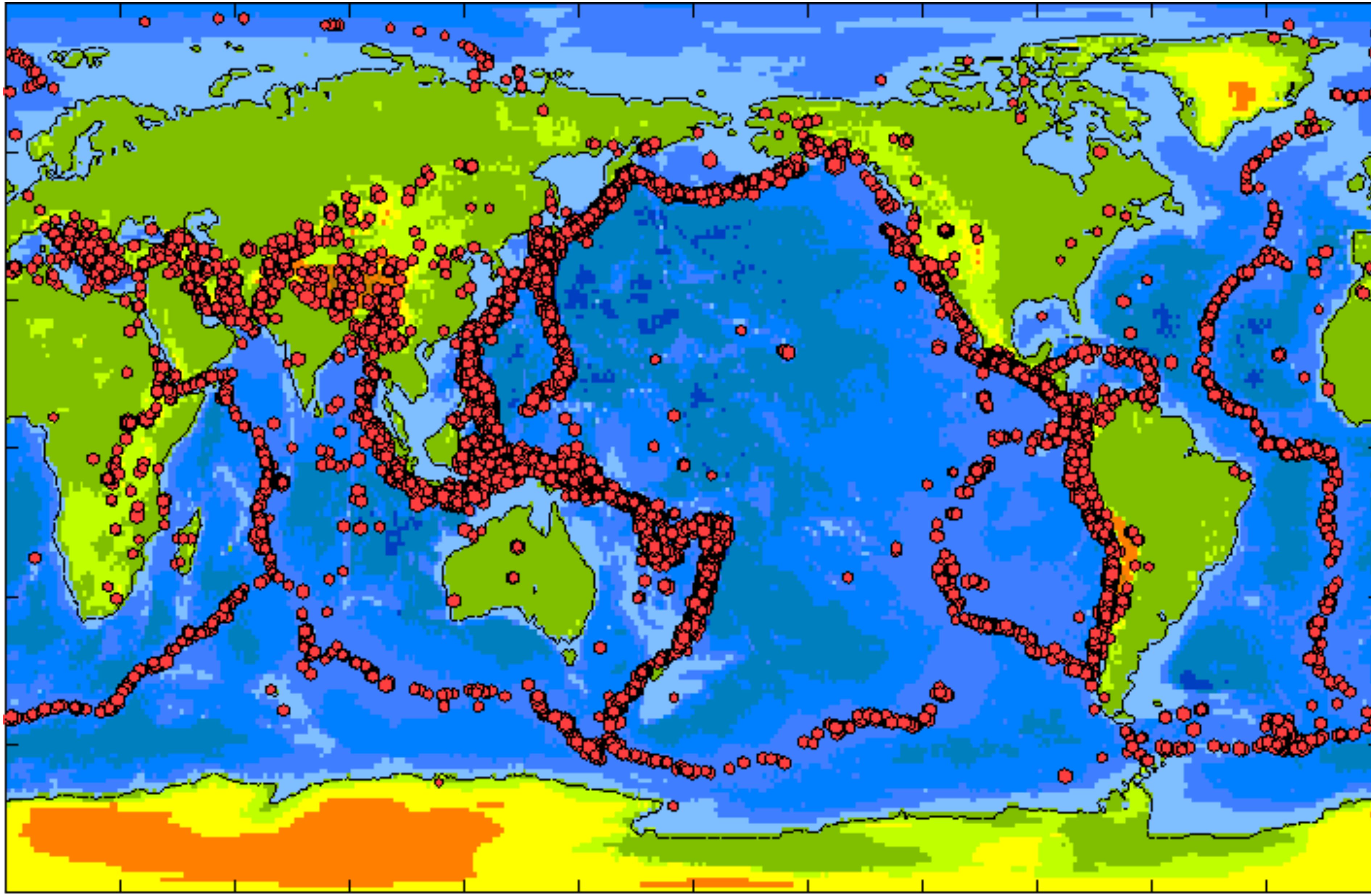
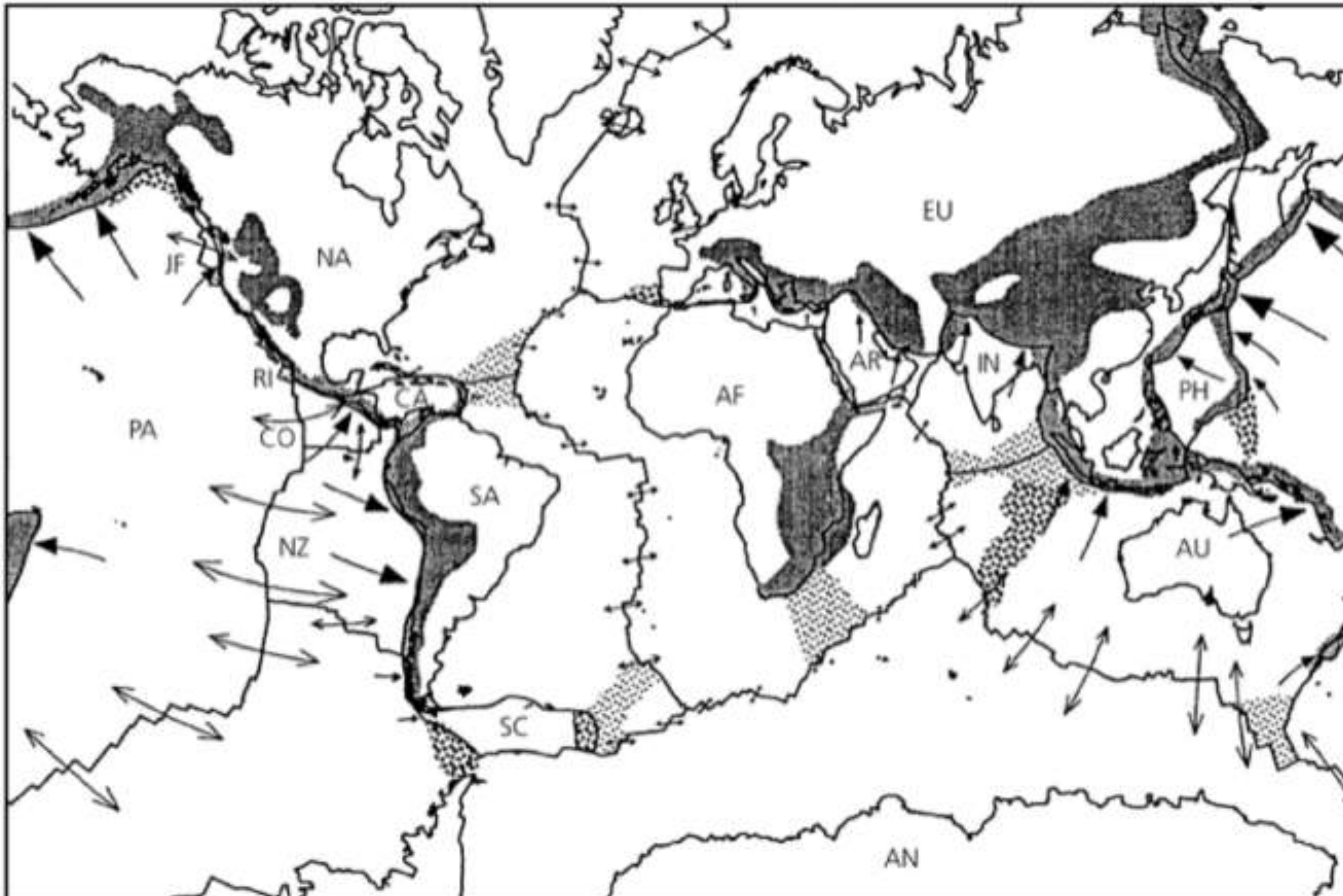
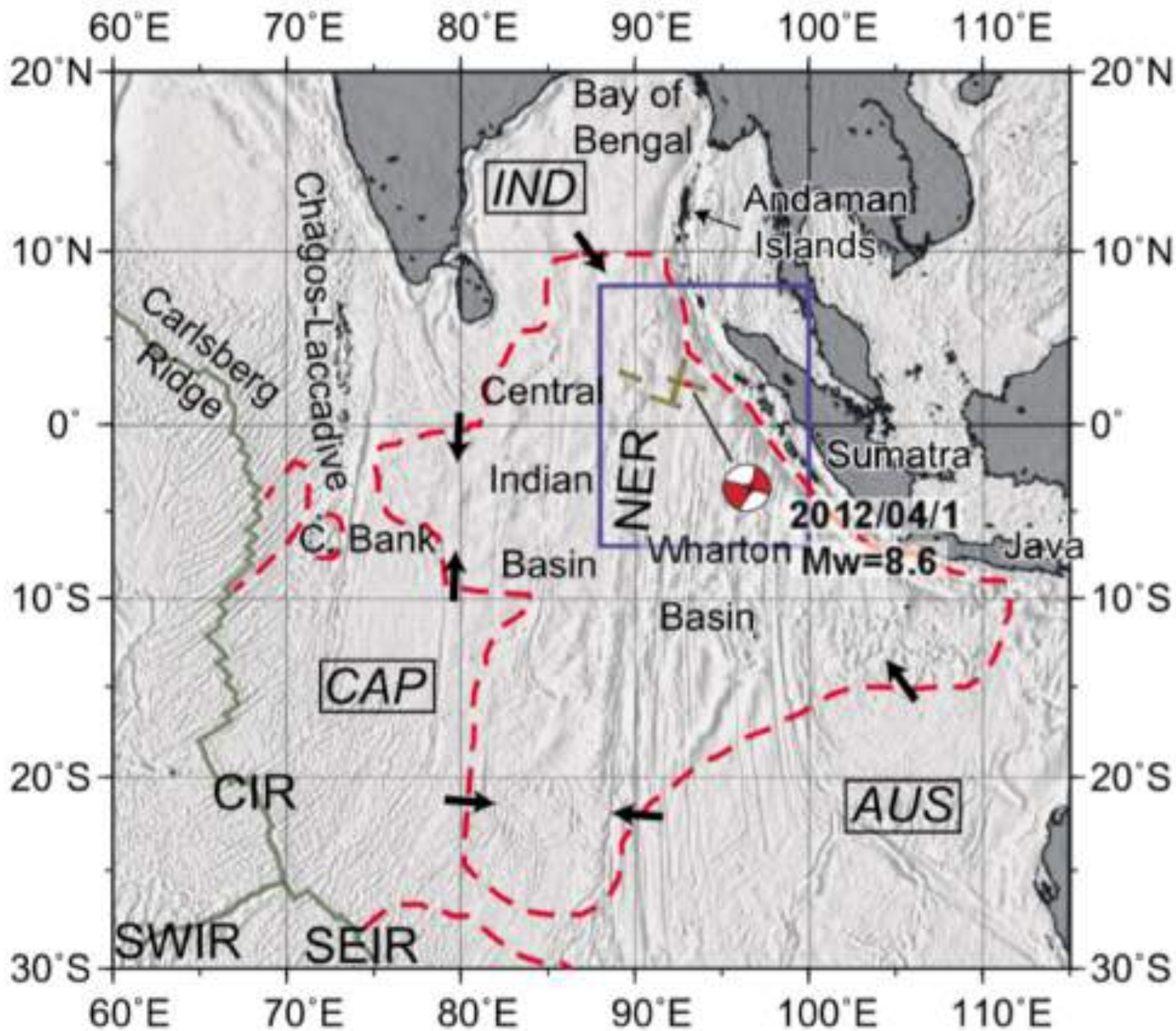


Figure 5.2-4: Relative plate motions and diffuse plate boundary zones.



Diussed plate boundary example

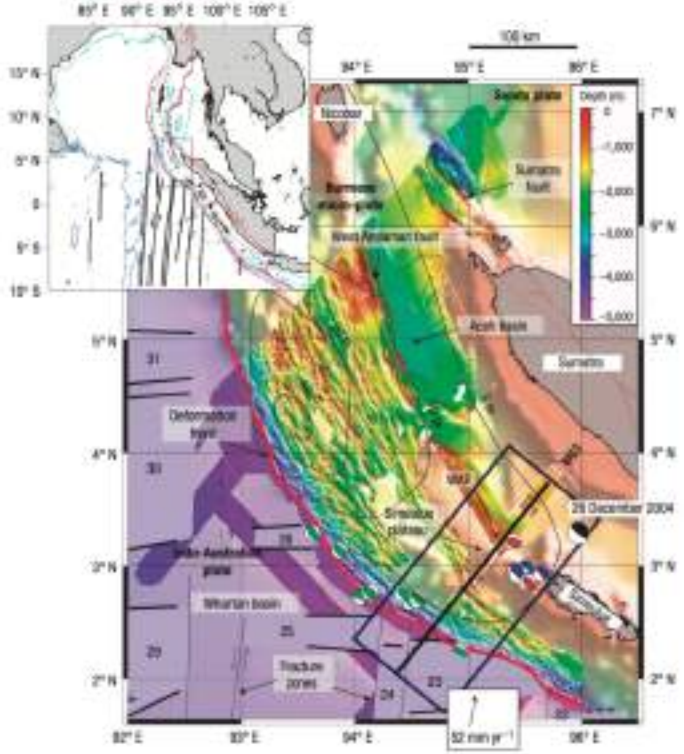


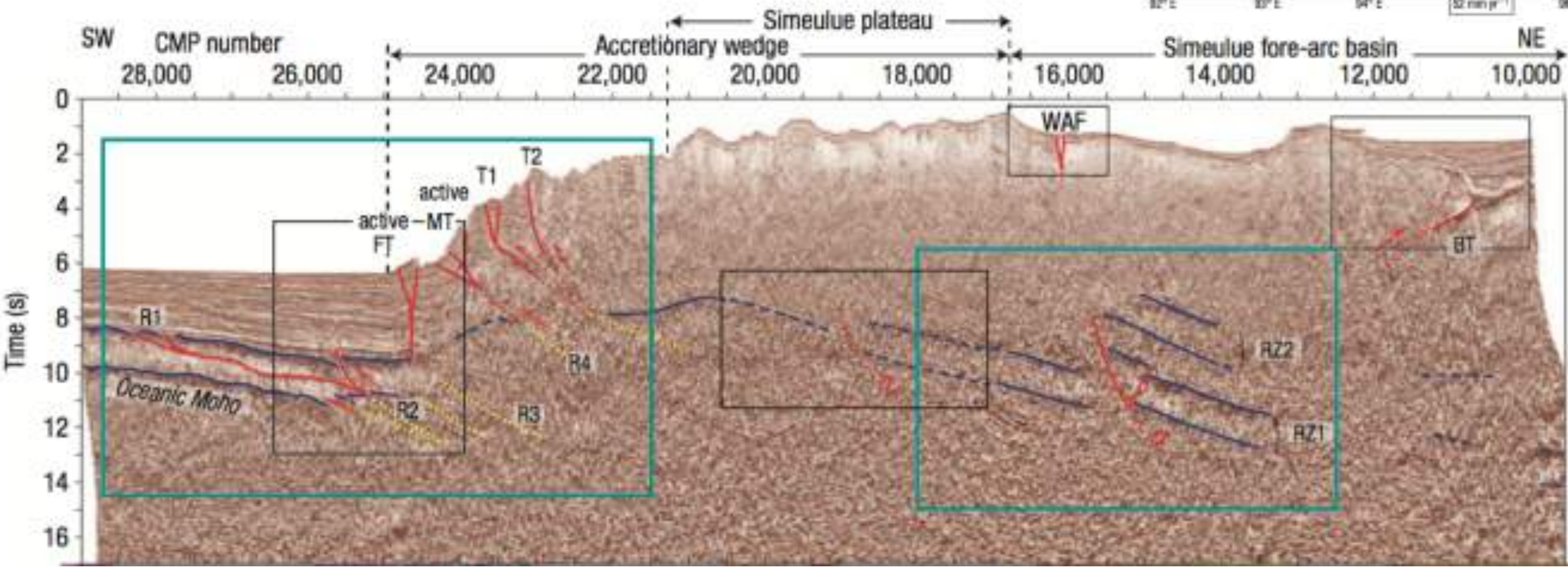
Carton et al., (2014)

Component plates of the Indo-Australian plate (IND: India; AUS: Australia; CAP: Capricorn) and diffuse deformation zones according to Royer and Gordon [1997]. Deformation zones are marked as red dashed contours; active spreading centers (Carlsberg Ridge; SEIR: Southeast Indian Ridge; SWIR: Southwest Indian Ridge; CIR: Central Indian Ridge) are marked as semitransparent green-gray lines. Arrows indicate motion between component plates. Red dot is epicenter location of the 11 April 2012 M_w8.6 great strike-slip earthquake, and bars indicate proposed rupture zone of Yue et al. [2012]. Location of Figure 2 is shown with a blue box. C. Bank: Chagos Bank; NER: Ninety East Ridge.

Examples of Active margins: Sumatra

Seafloor is irregular
Subducting oceanic crust is buckled
Subducting oceanic crust is broken
Thick pile of deposits

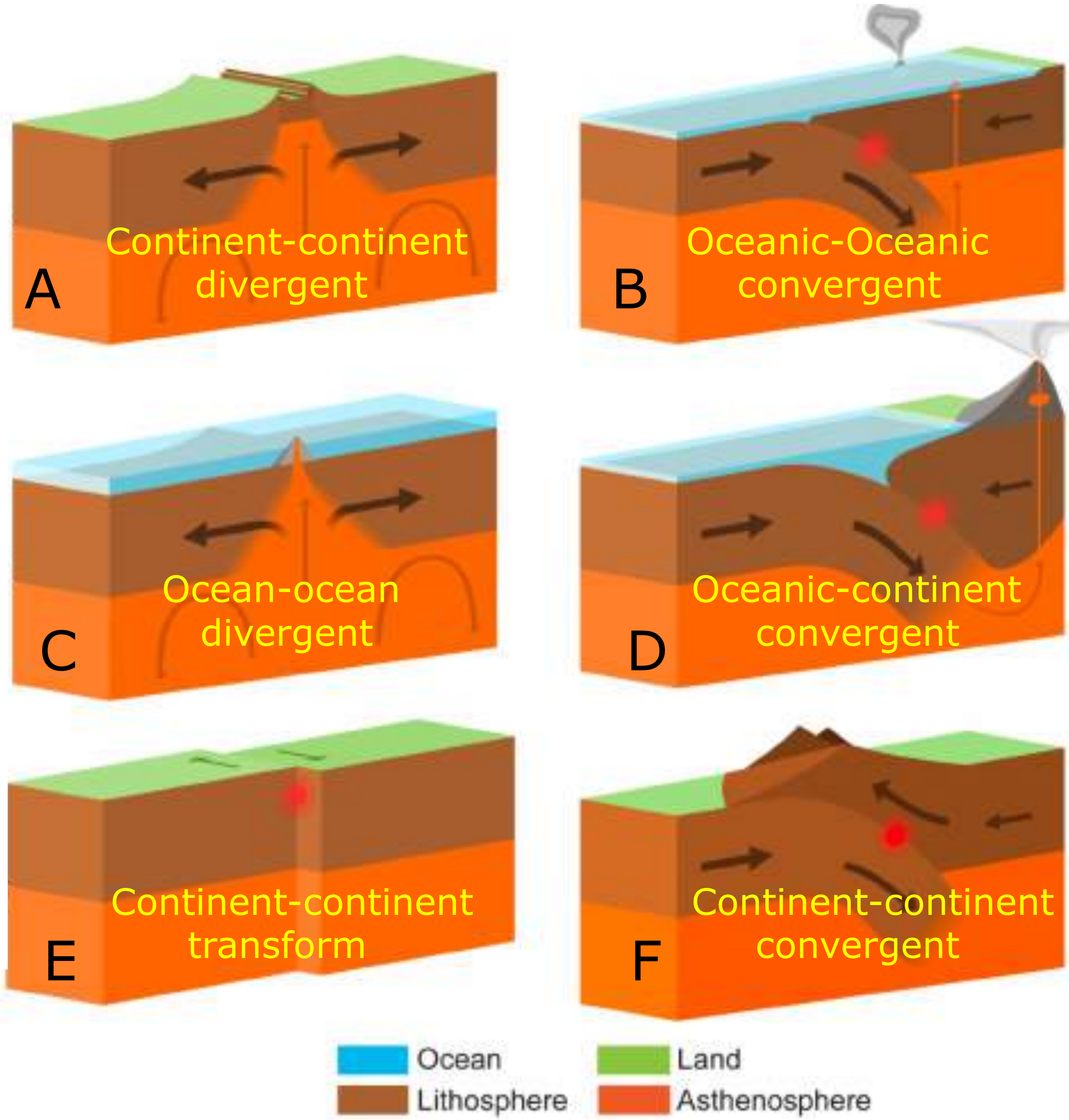




Singh et al., (2008), Nature

Q1: Identify the tectonic setup and different landforms

Q2: Which setup will form the active and passive continental margins?



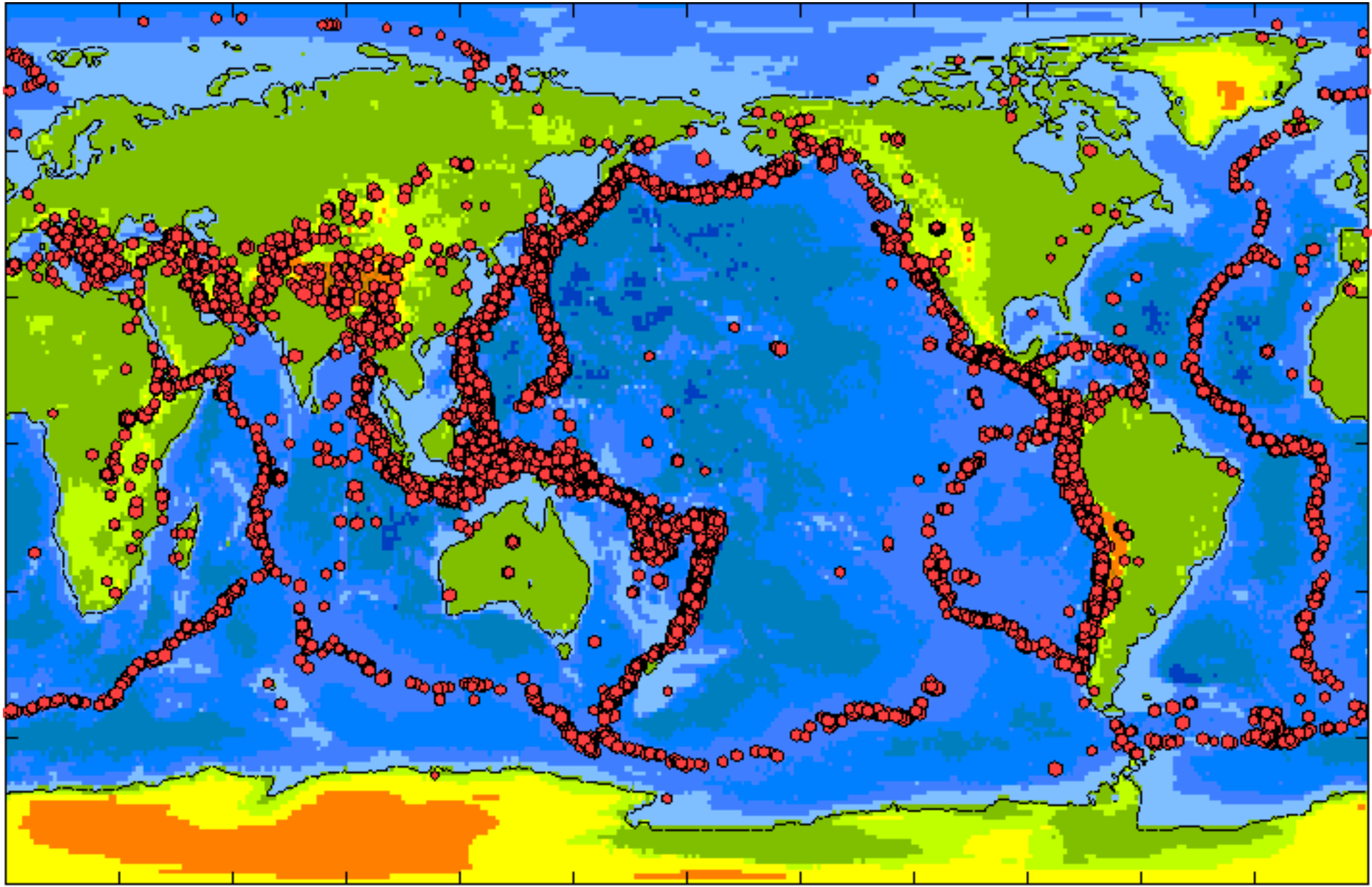
Island arc

Volcanic arc

Mountain building

Plates and plate boundaries do not stay the same for all time !

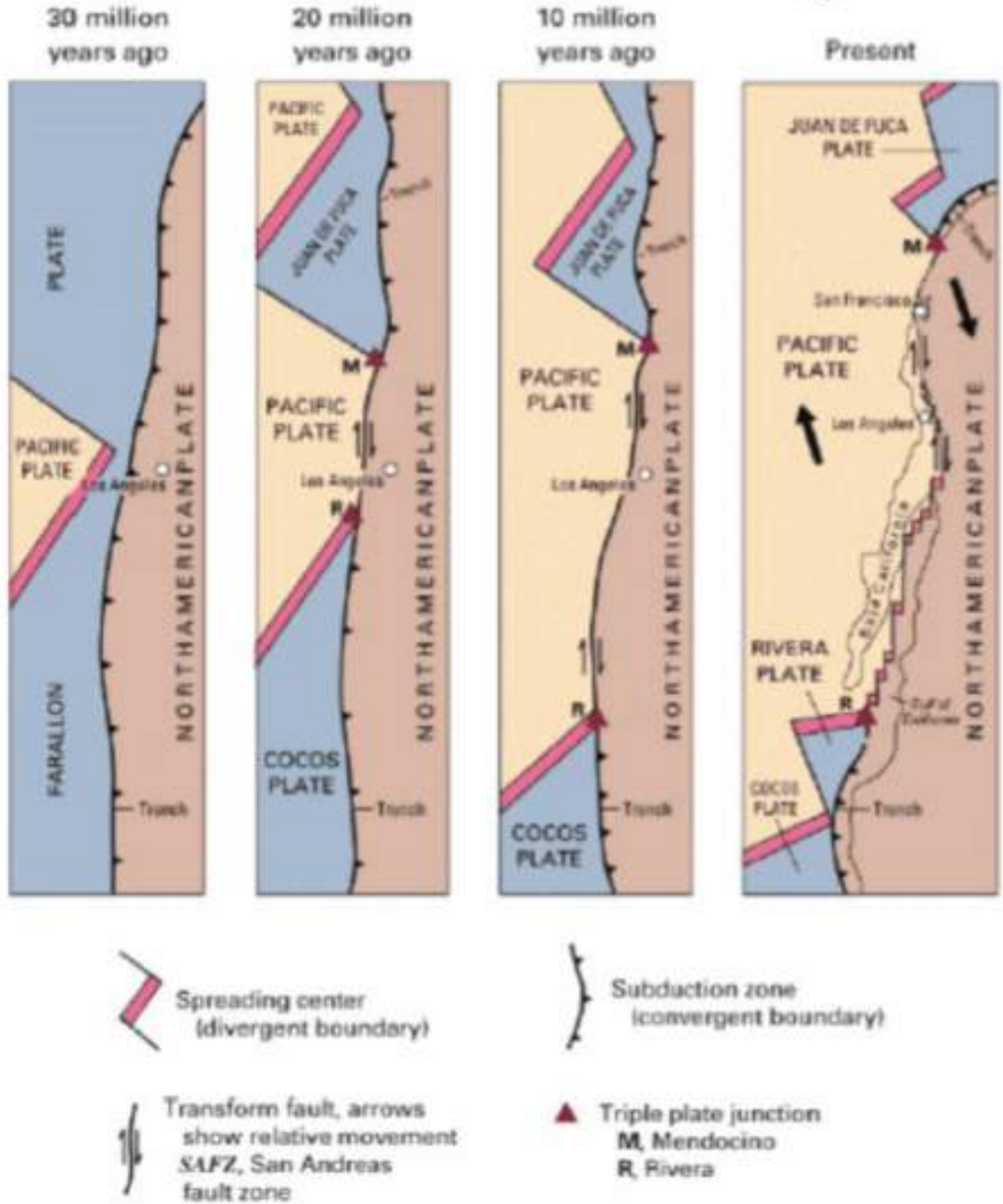
The formation of new plates and destruction of existing plates are the most obvious global reasons why plate boundaries and relative motions change.



Tripple junction:

A *triple junction* is a point at which three plates meet.

They are important as they provide a tool to calculate kinematic evolution of plate boundaries; and their motion cause significant reworking of lithospheric material.



Features of the Deep-Ocean Basin

I. Deep-ocean trench

- **Long, relatively narrow features**
- **Deepest parts of ocean**
- **Most are located in the Pacific Ocean.**
- **Sites where moving lithospheric plates plunge into the mantle**
- **Associated with volcanic activity**
- **Often paralleled by arc-shaped row of active volcanoes (volcanic island arc; continental volcanic arc)**

Earth's Deep-Ocean Trenches

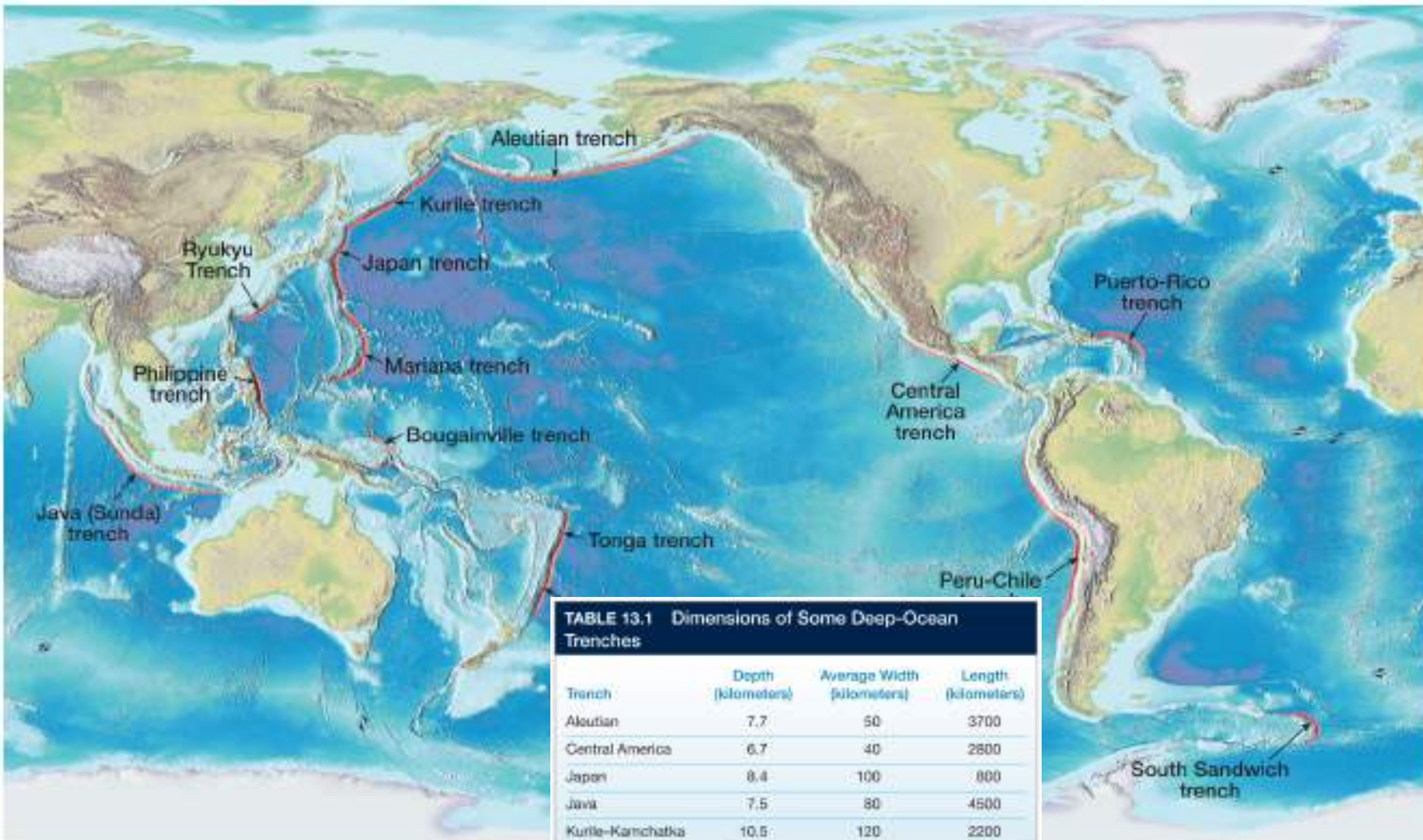


TABLE 13.1 Dimensions of Some Deep-Ocean Trenches

Trench	Depth (kilometers)	Average Width (kilometers)	Length (kilometers)
Aleutian	7.7	50	3700
Central America	6.7	40	2800
Japan	8.4	100	800
Java	7.5	80	4500
Kurile-Kamchatka	10.5	120	2200
Mariana	11.0	70	2550
Peru-Chile	8.1	100	5900
Philippine	10.5	60	1400
Puerto Rico	8.4	120	1550
South Sandwich	8.4	90	1450
Tonga	10.8	55	1400

Features of the Deep-Ocean Basin

II. Abyssal plains

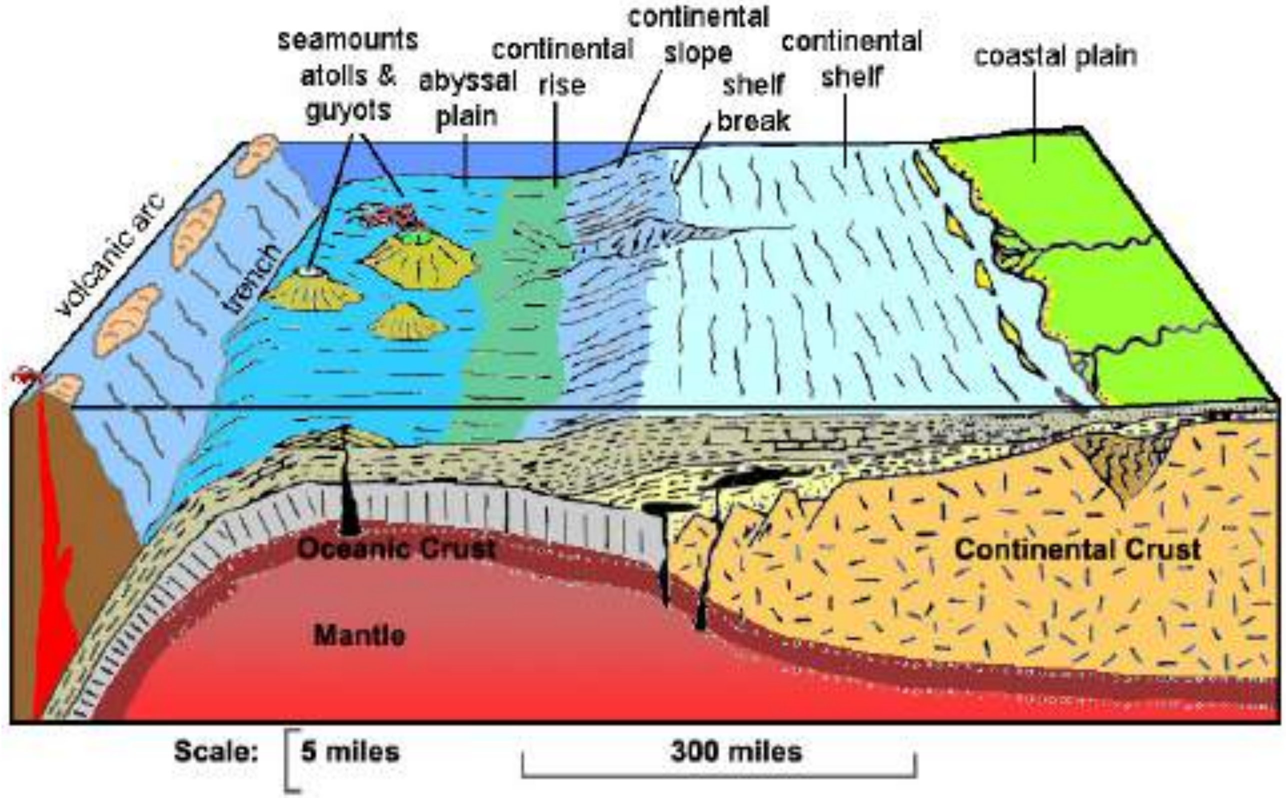
- **Likely the most level places on Earth**
- **Sites of thick accumulations of sediment**
- **Found in all oceans**

•**Seamount:** It is a mountain with pointed summits, rising from the seafloor that **does not reach the surface** of the ocean. Seamounts are volcanic in origin. These can be 3,000-4,500 m tall.

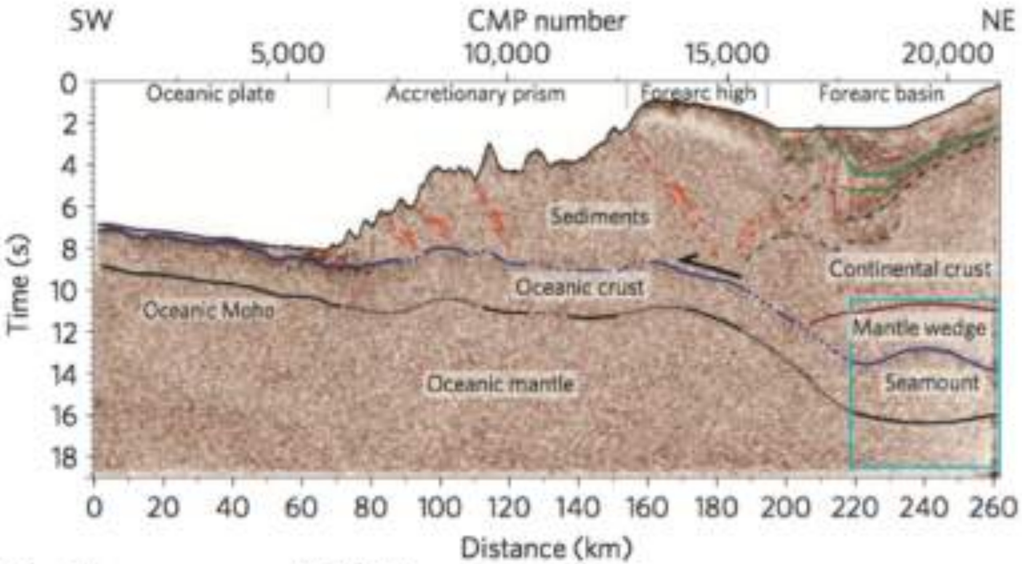
•**Guyots:** The flat topped mountains (seamounts) are known as guyots.

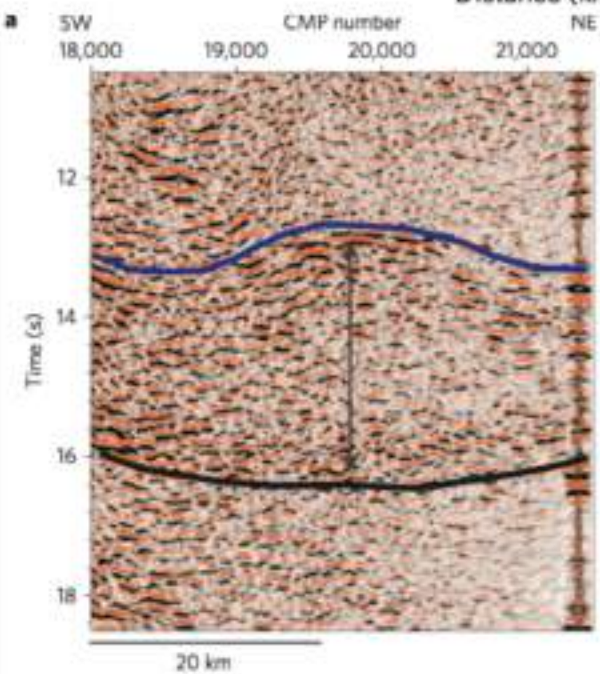
Atoll: These are low islands found in the tropical oceans consisting of coral reefs surrounding a central depression.

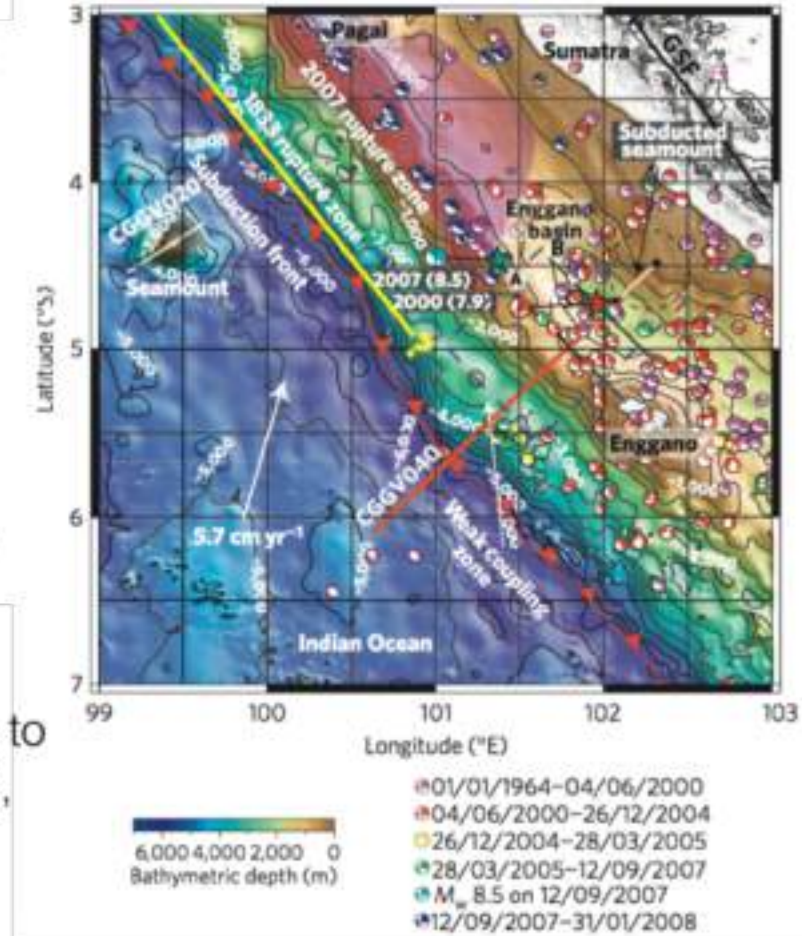
It may be a part of the sea (lagoon), or sometimes form enclosing a body of fresh, brackish, or highly saline water.



Case Study 1: Sumatra-Andaman Subduction system



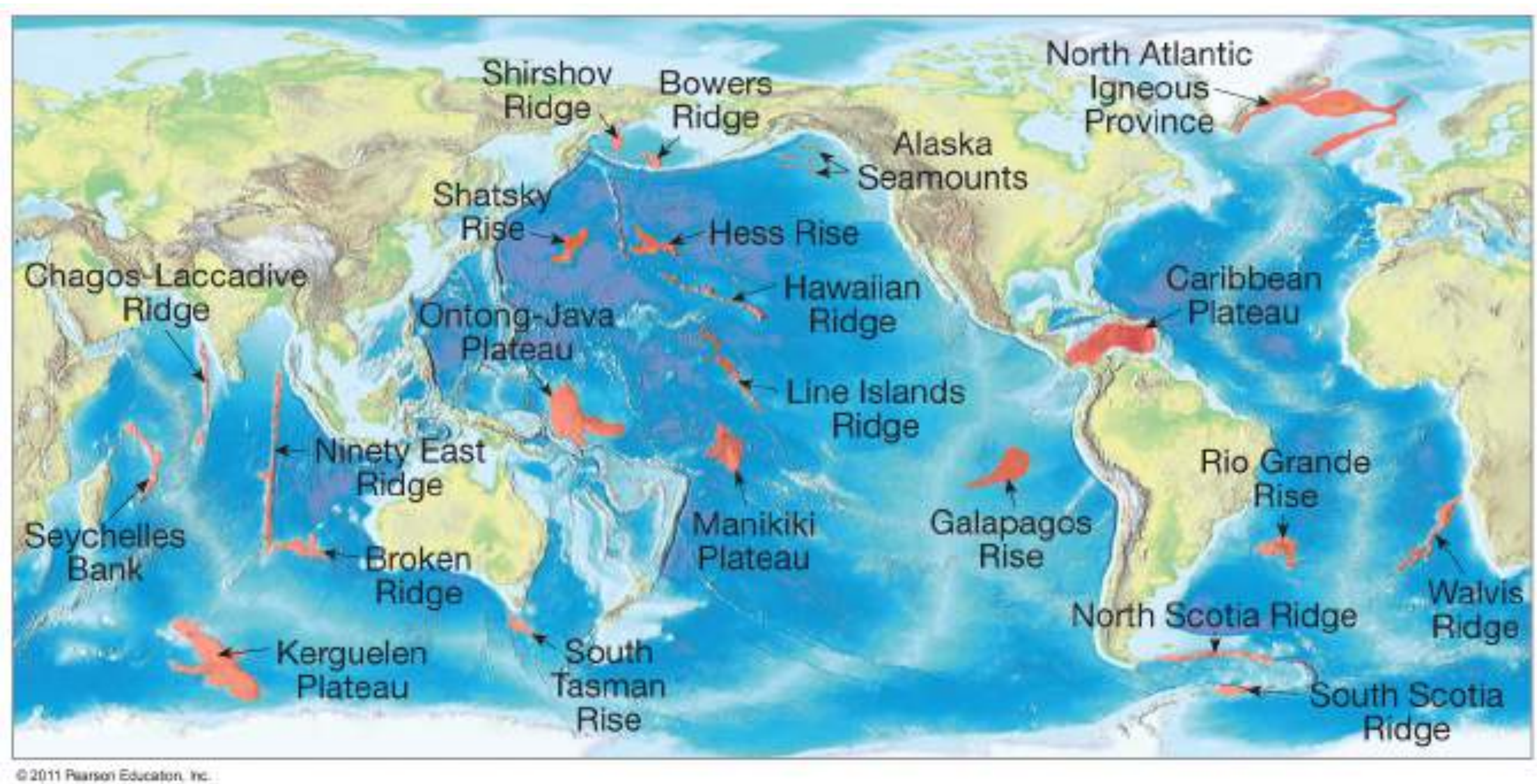




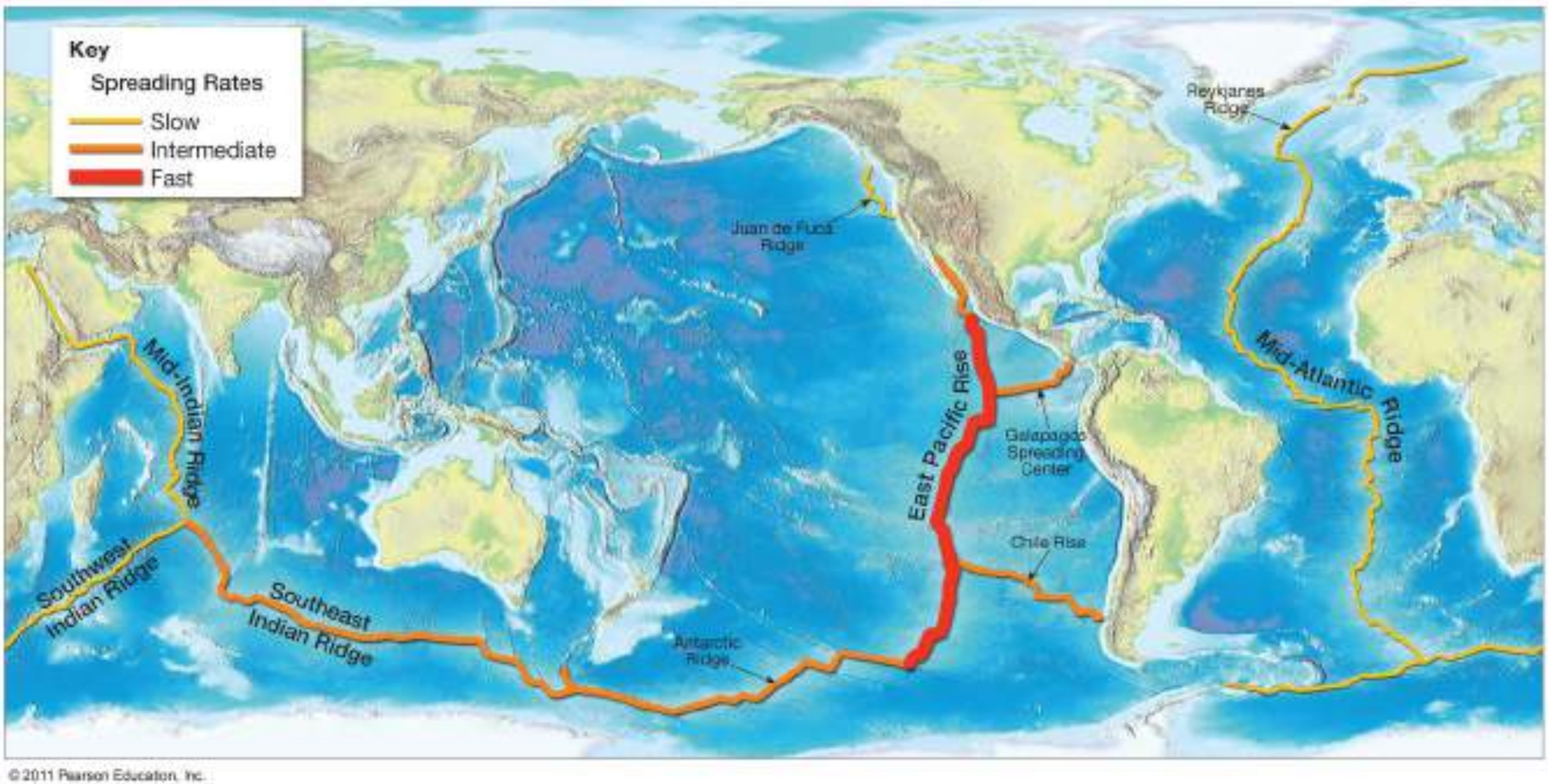
- Seamount subduction links to the plate locking, seismogenesis, crustal erosion
- Evidence of subjected seamount is reported in Sumatra from high-resolution seismic images at 30-40 km depth below forearm mantle, reducing maximum size of the megathrust

Singh et al., (2011)

Distribution of Ocean Plateaus, Hot Spots, and Submerged Crustal Fragments

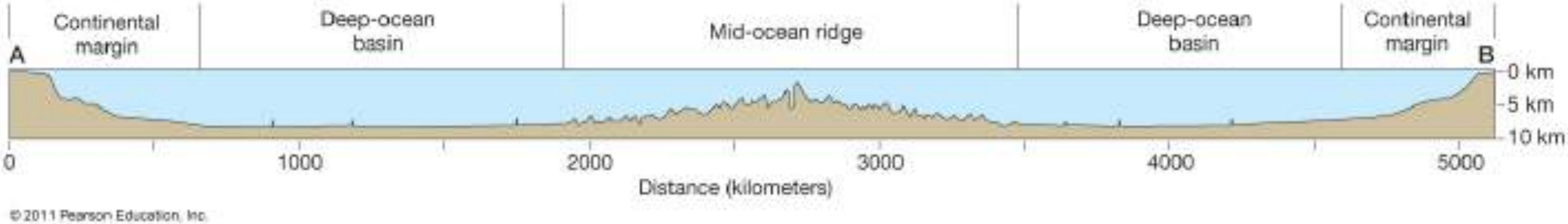


Distribution of the Oceanic Ridge System



Oceanic Ridges and Seafloor Spreading

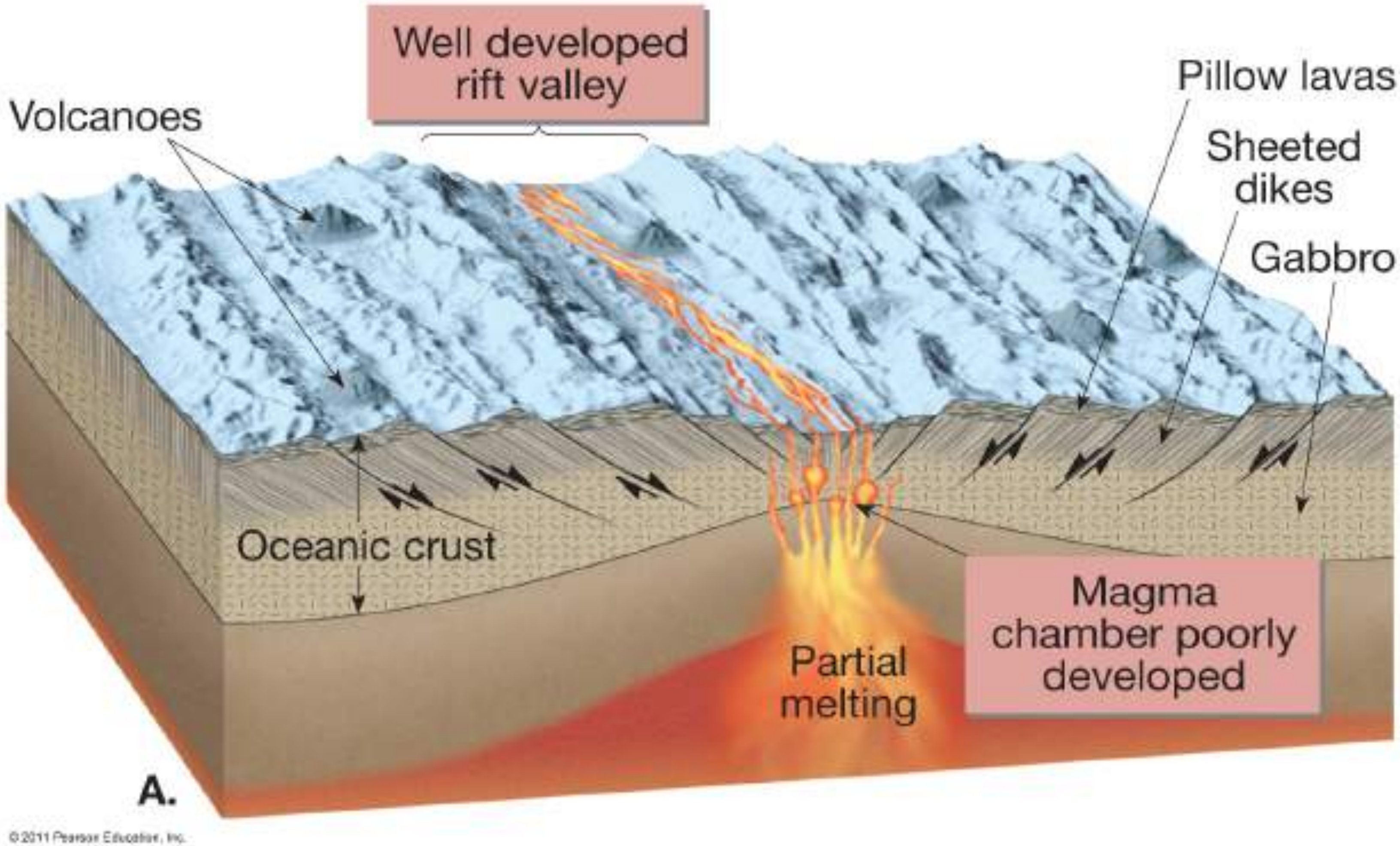
- **Why are oceanic ridges elevated?**
  - **The primary reason is because newly created oceanic lithosphere is hot and occupies more volume than cooler rocks.**
  - **As the basaltic crust travels away from the ridge crest, it is cooled by seawater.**
  - **As the lithosphere moves away, it thermally contracts and becomes more dense.**



Anatomy of the Oceanic Ridge
Oceanic Ridges and Seafloor Spreading

- **Spreading rates and ridge topography**
  - **Ridge systems exhibit topographic differences.**
  - **Topographic differences are controlled by spreading rates.**
    - **At *slow spreading rates* (1 to 5 centimeters per year), a prominent rift valley develops along the ridge crest that is usually 30 to 50 kilometers across and 1500 to 3000 meters deep.**
    - **Mid-Atlantic; Mid-Indian**

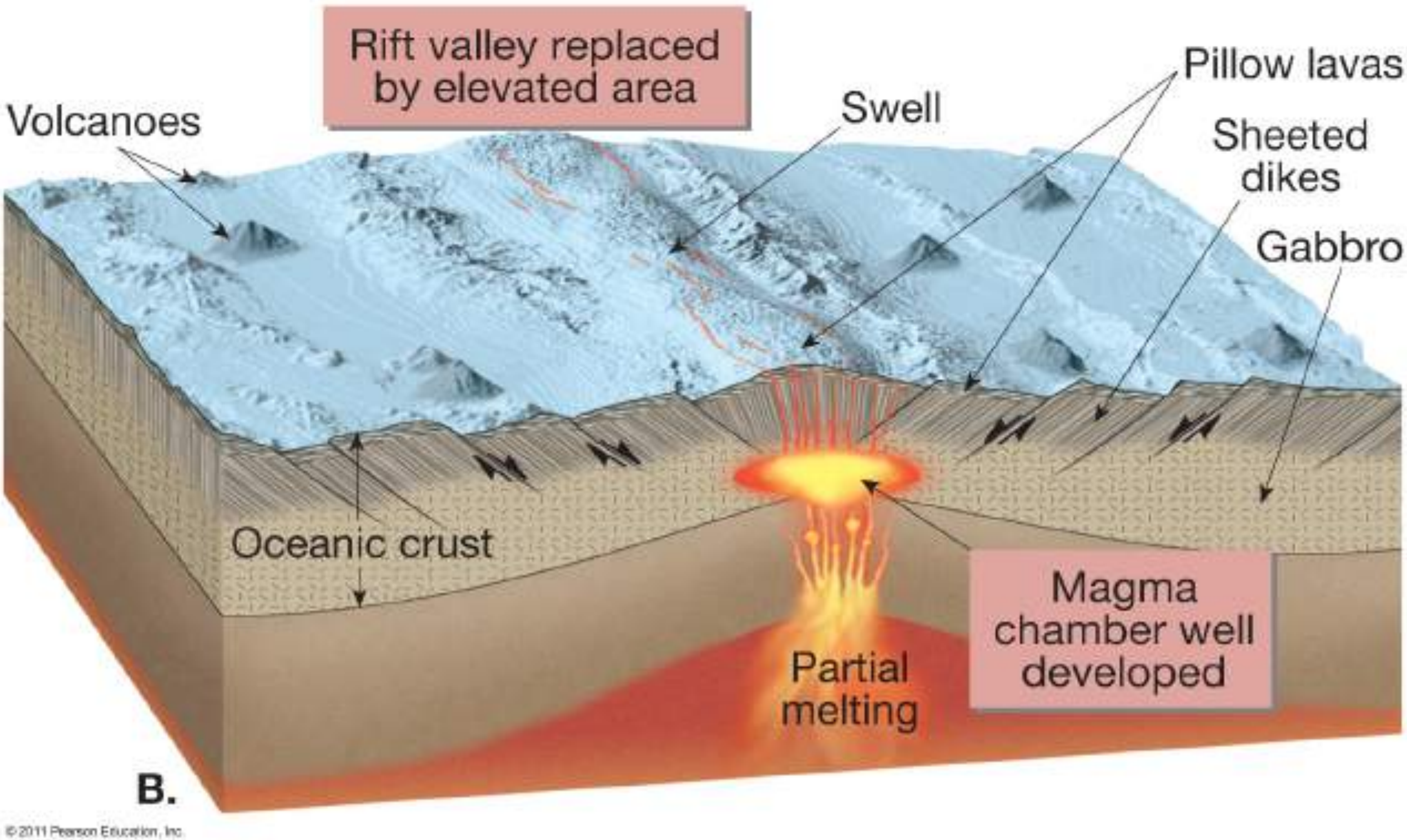
Slow Spreading Oceanic Ridge

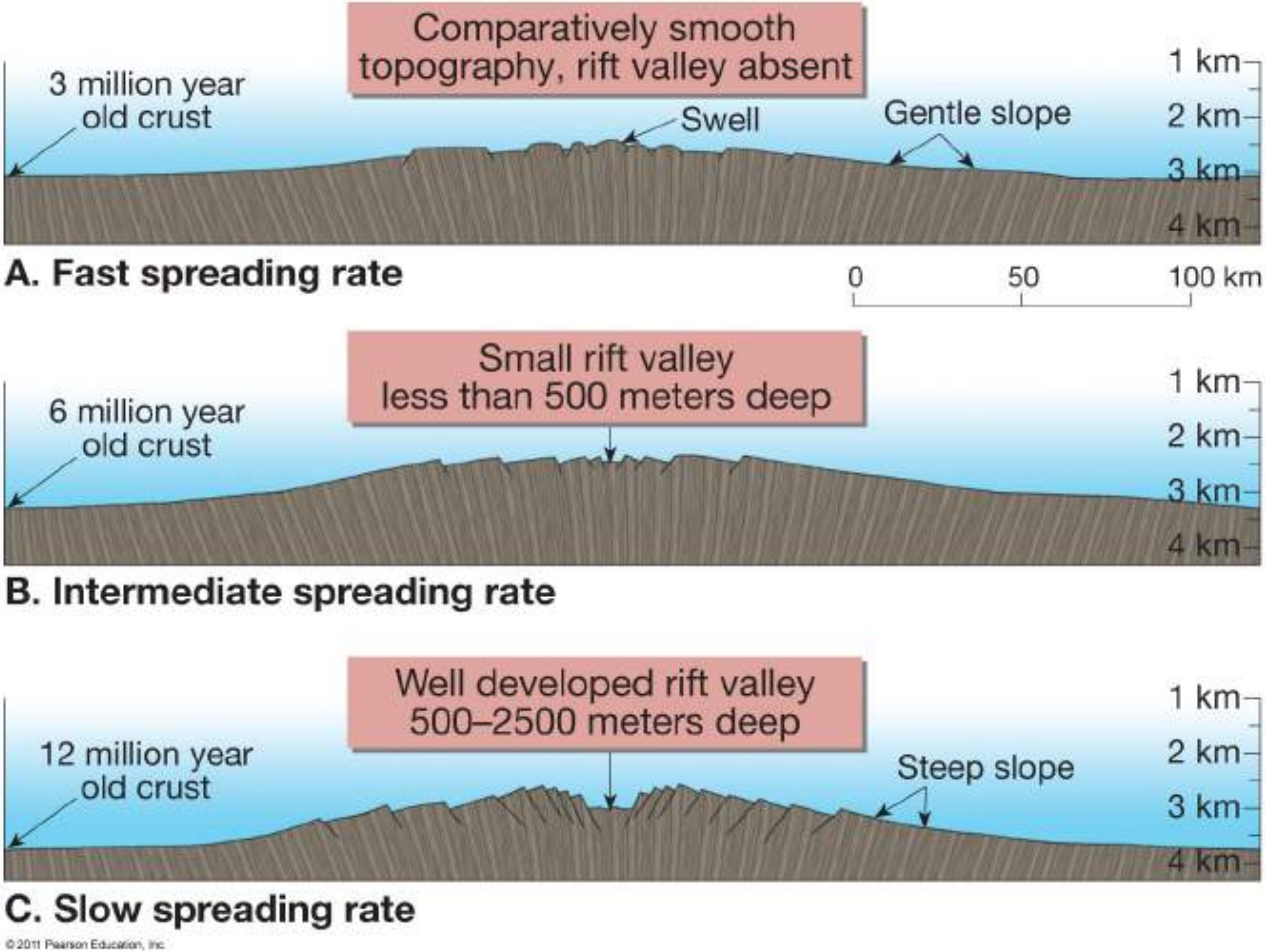


Oceanic Ridges and Seafloor Spreading

- **Spreading rates and ridge topography**
  - **Topographic differences are controlled by spreading rates.**
    - **At *intermediate spreading rates* (5 to 9 centimeters per year), rift valleys that develop are shallow and less than 200 meters deep (e.g., Galapagos Ridge)**
    - **At *spreading rates greater than 9 cm / year*, no median rift valley develops and these areas are usually narrow and extensively faulted (e.g., East Pacific Rise)**

Fast Spreading Oceanic Ridge




Comparatively smooth topography, rift valley absent
3 million year old crust
Swell
Gentle slope
1 km
2 km
3 km
4 km
A. Fast spreading rate
0
50
100 km
Small rift valley less than 500 meters deep
6 million year old crust
1 km
2 km
3 km
4 km
B. Intermediate spreading rate
Well developed rift valley 500–2500 meters deep
12 million year old crust
Steep slope
1 km
2 km
3 km
4 km
C. Slow spreading rate
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Questions

1. The oldest rocks of the oceanic crust are found in deep ocean trenches far away from active, mid-ocean ridges.
Answer: TRUE/ FALSE

2. The boundaries of the Earth's tectonic plates are shown as zones of high seismic activity.
Answer: TRUE / FALSE

3. The ________ lies at the base of the continental slope.
A) offshore shelf
B) off-slope reef
C) continental rift
D) continental rise

4. Spreading rates along the East Pacific Rise are relatively fast with many areas spreading more than 9 centimeters per year.
Answer: TRUE / FALSE

5. Island arc forms in ________ setup
A) Ocean-continent transform
B) Ocean-ocean convergent
C) Continent-continent divergent
D) Ocean-continent subduction

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Magma and Igneous Rocks "Granites"

Previous Class: Divergent/Convergent/Transform Plate Boundaries

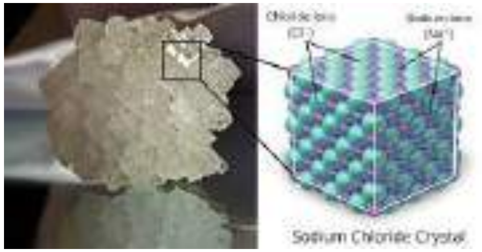
Last Class: Review

1. Convergent/Divergent/ Transform plate boundaries
2. Hot Spots and Mantle plume
3. Drivers of plate movement
4. How do we measure plate Movements
5. Features of continental margins and deep oceans
6. Effect of spreading rate

Minerals and Rocks

- Minerals:
  1. must be naturally formed
  2. must be inorganic
  3. must be a solid
  4. must have a specific chemical composition
  5. must have a characteristic <u>crystal</u> structure

Is ice a mineral??



Is salt a mineral??

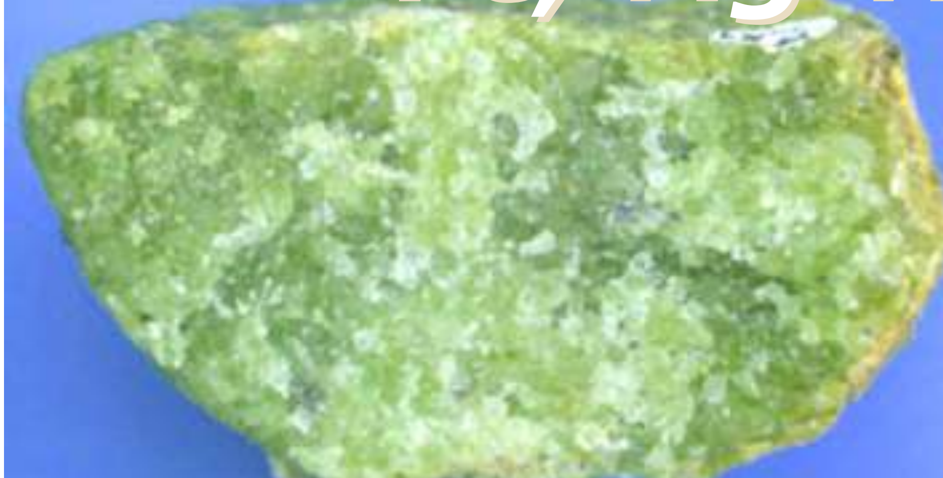
<u>Rocks are mineral assemblages</u>!

Is sugar a mineral??

Common rock forming minerals

1. Silicates (~60% of crust)
-- all contain a $(SiO_4)^{4-}$ in single, chains or sheets or more complex form
-- e.g. Feldspar, Quartz (SiO_2), clay, Biotite, Muscovite
2. Oxides e.g. Hematite (Fe_2O_3), Magnetite (Fe_2O_4)
3. Carbonates e.g. Calcite ($CaCO_3$), Dolomite $(Ca,Mg)_2CO_3$, Aragonite ($CaCO_3$)
4. Sulfates e.g. Gypsum ($CaSO_{4,}$ $2H_2O$), Baryte ($BaSO_4$), Anhydrite ($CaSO_4$)
5. Sulfides e.g. Pyrite (FeS_2), Galena (PbS), Sphalerite ((Zn,Fe)S)

Fe, Mg-rich Silicates



Olivine
$(Fe, Mg)_2SiO_4$

Hornblende
$(Ca, Na)_{2-3}(Mg, Fe, Al)_5(Al, Si)_8O_{22}(OH, F)_2$

Augite
$(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$

Biotite mica
$K(Mg,Fe)_3(AlSi_3O_{10})(F,OH)_2$

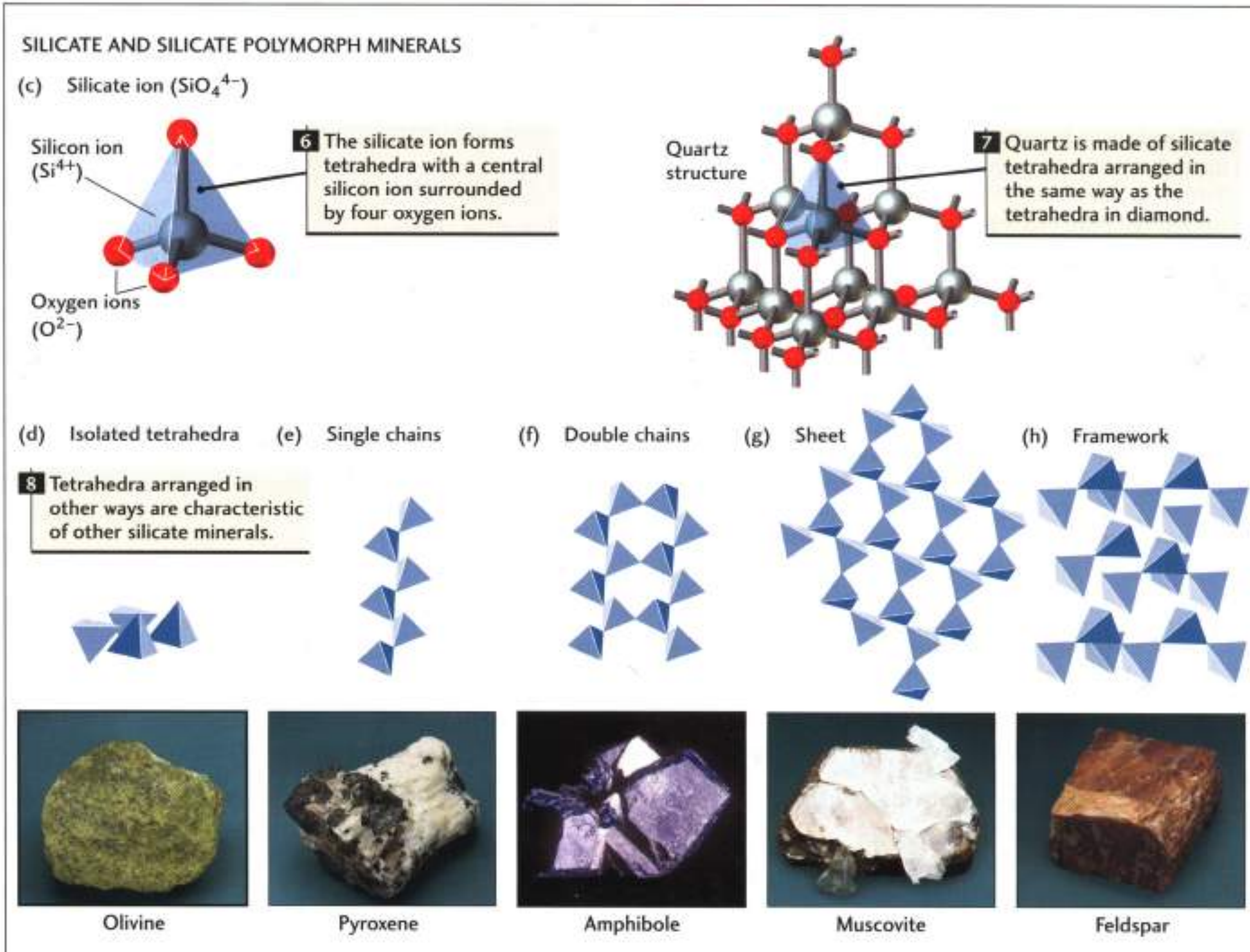
Quartz & Al-rich Silicates

Quartz
SiO_2

Potassium Feldspar (Orthoclase)
$KAlSi_3O_8$

Plagioclase Feldspar
$NaAlSi_3O_8$ to $CaAl_2Si_2O_8$

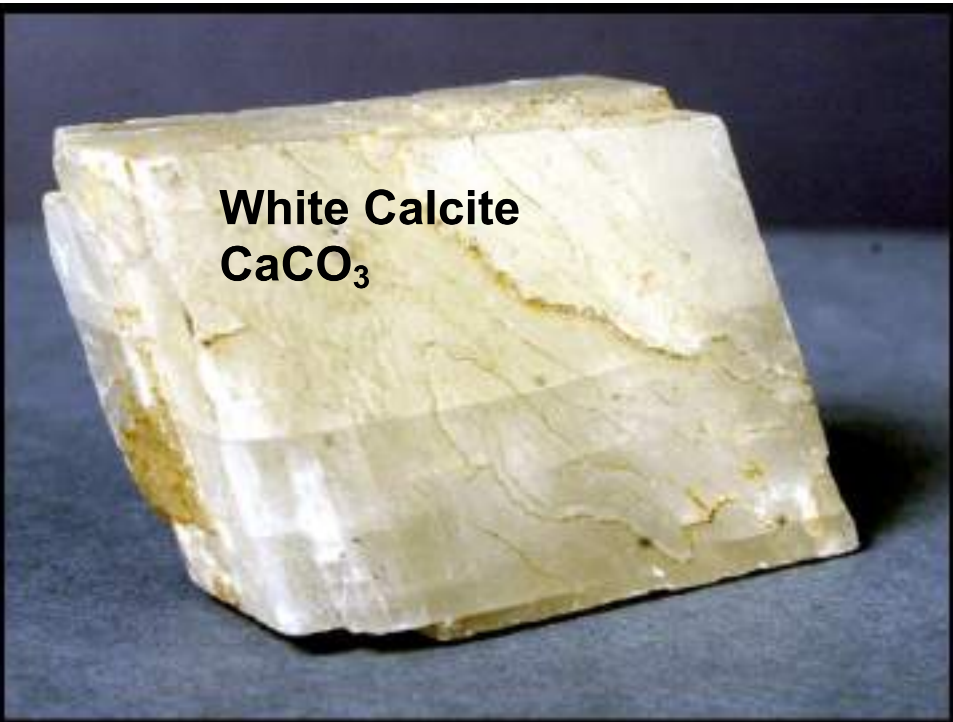
Muscovite
$KAl_2(AlSi_3O_{10})(F,OH)_2$

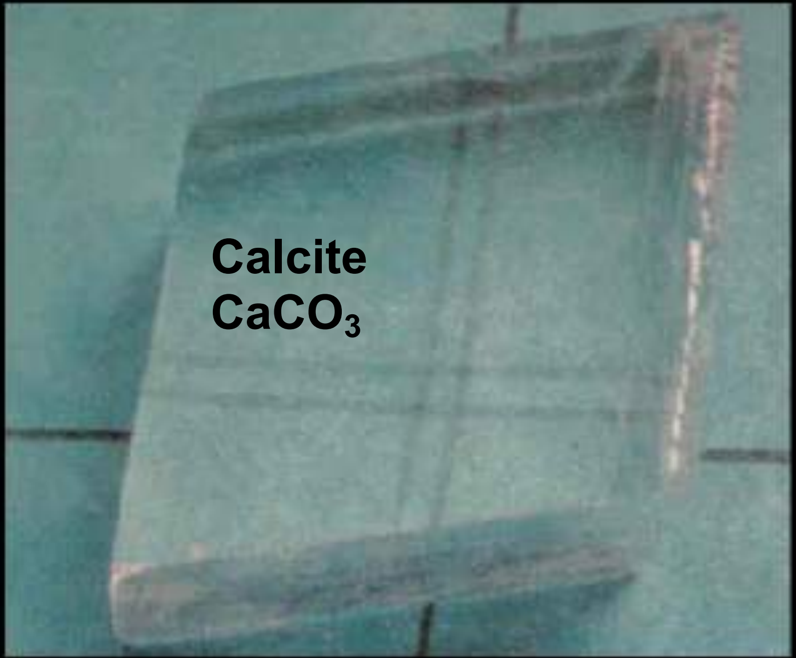


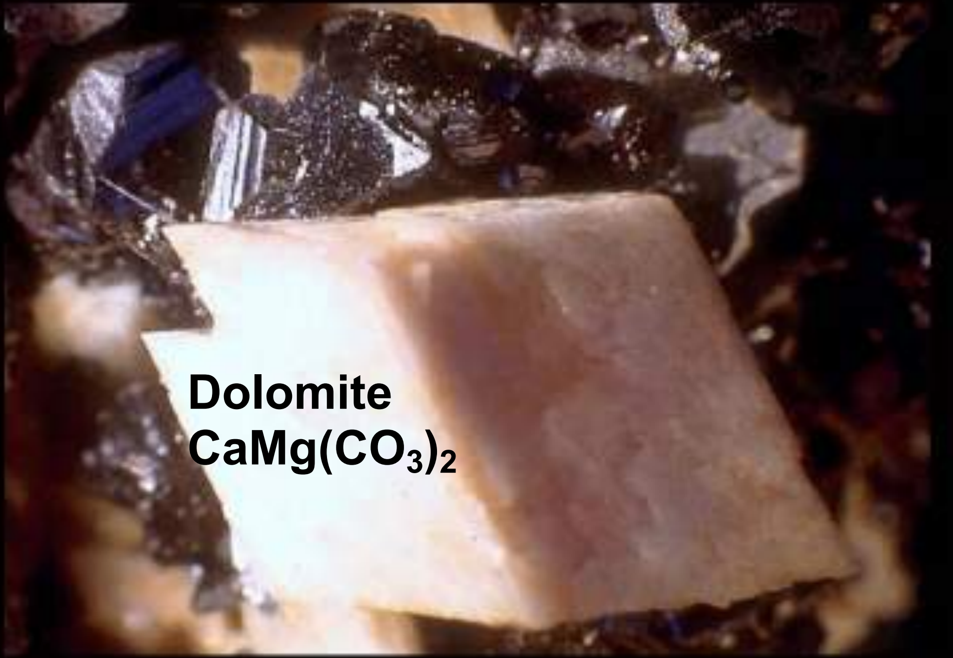
SILICATE AND SILICATE POLYMORPH MINERALS
(c) Silicate ion (SiO_4^{4-})
Silicon ion (Si^{4+})
Oxygen ions (O^{2-})
6 The silicate ion forms tetrahedra with a central silicon ion surrounded by four oxygen ions.
Quartz structure
7 Quartz is made of silicate tetrahedra arranged in the same way as the tetrahedra in diamond.
(d) Isolated tetrahedra
(e) Single chains
(f) Double chains
(g) Sheet
(h) Framework
8 Tetrahedra arranged in other ways are characteristic of other silicate minerals.
Olivine
Pyroxene
Amphibole
Muscovite
Feldspar

Carbonates

note rhombohedral cleavage in all three carbonate samples shown







Sulfides, Sulfates & Halides

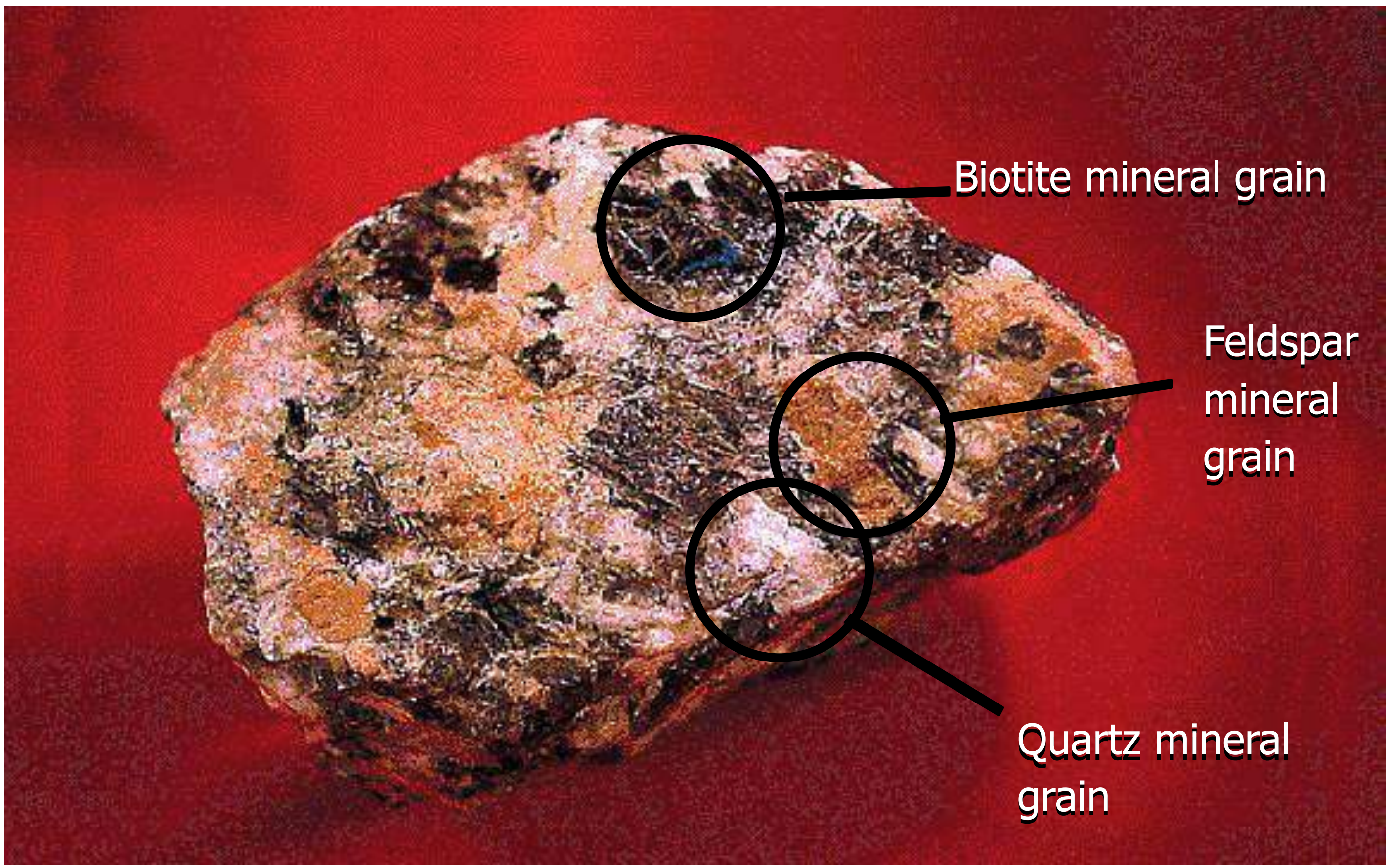
Forms of Gypsum
$CaSO_4.2H_2O$

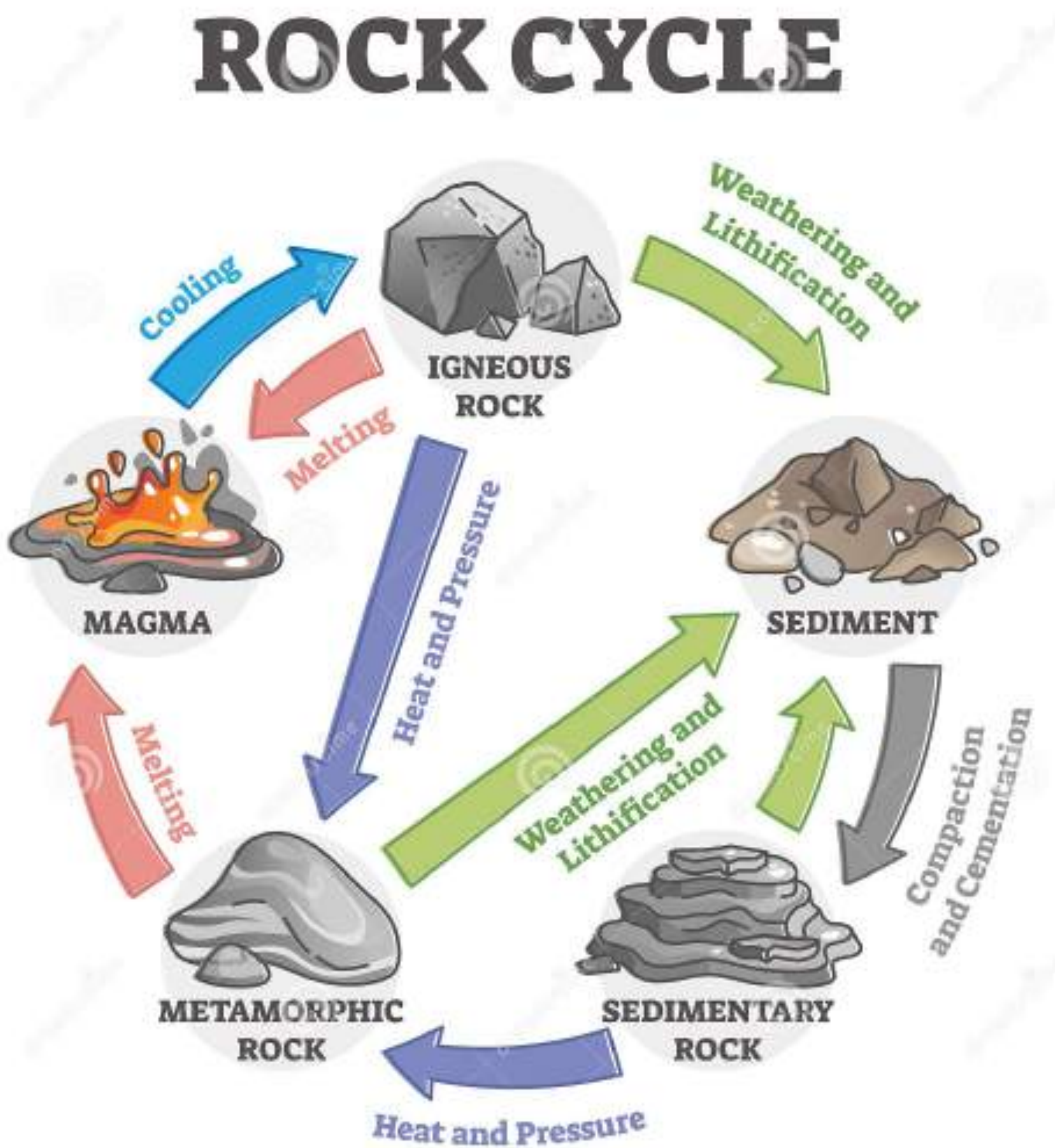
Alabaster

Satin Spar

Where do rocks come from?

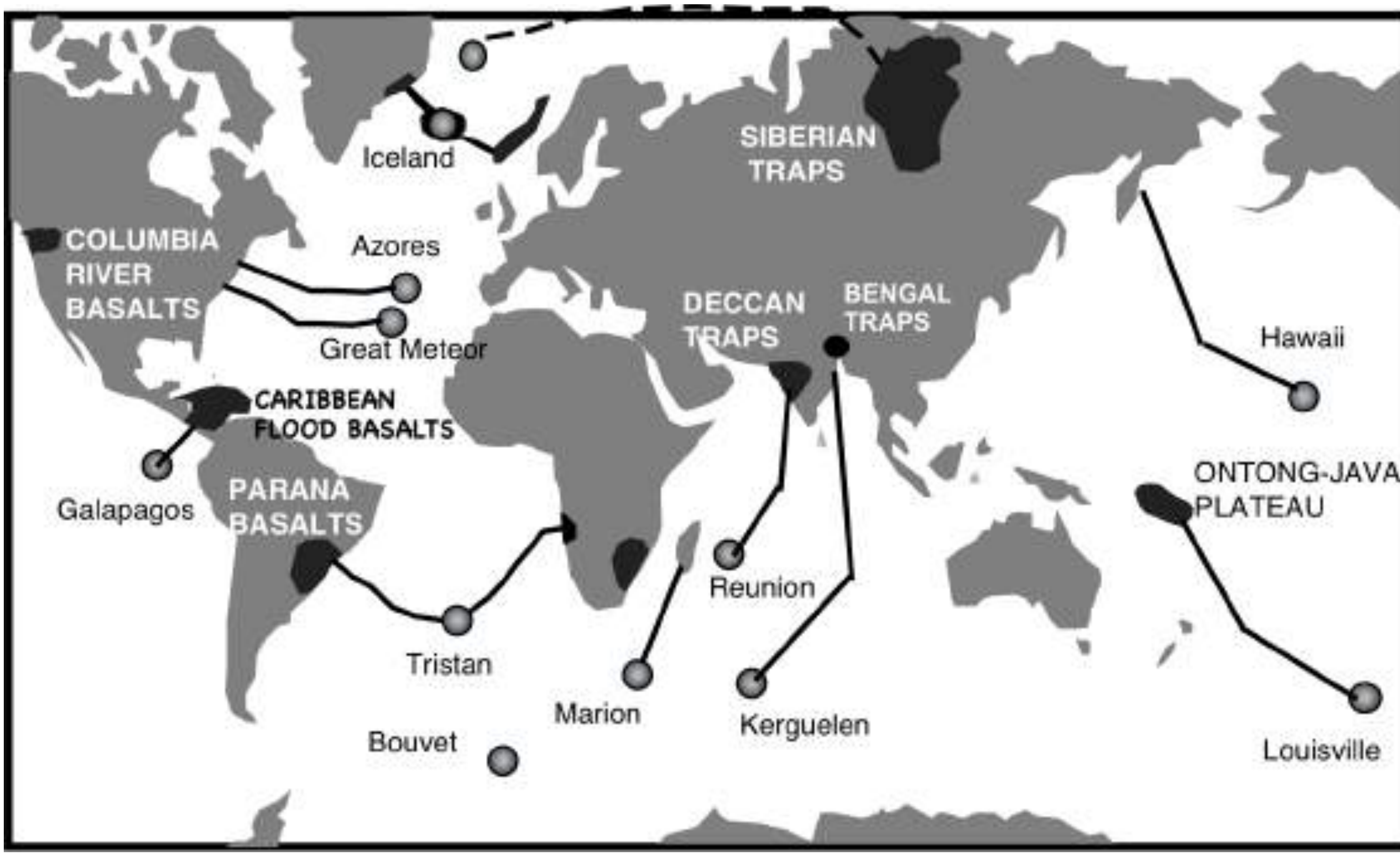
- **Building blocks of all rocks are minerals**
- **Some minerals form as molten rock cools**
- **Some minerals form as chemical precipitates**
- **Some are produced by chemical reactions (weathering)**
- **Some are "manufactured" by living things**




ROCK CYCLE
IGNEOUS ROCK
SEDIMENT
MAGMA
METAMORPHIC ROCK
SEDIMENTARY ROCK
Cooling
Melting
Weathering and Lithification
Heat and Pressure
Melting
Weathering and Lithification
Compaction and Cementation
Heat and Pressure

Igneous rocks

Throughout the earth's geologic past, there have been episodes of massive outpourings of basaltic lavas on the ocean floor and on continents. The large plateaus that were formed by such volcanism have been variously called *flood-basalt provinces* or *large igneous provinces* (LIP)

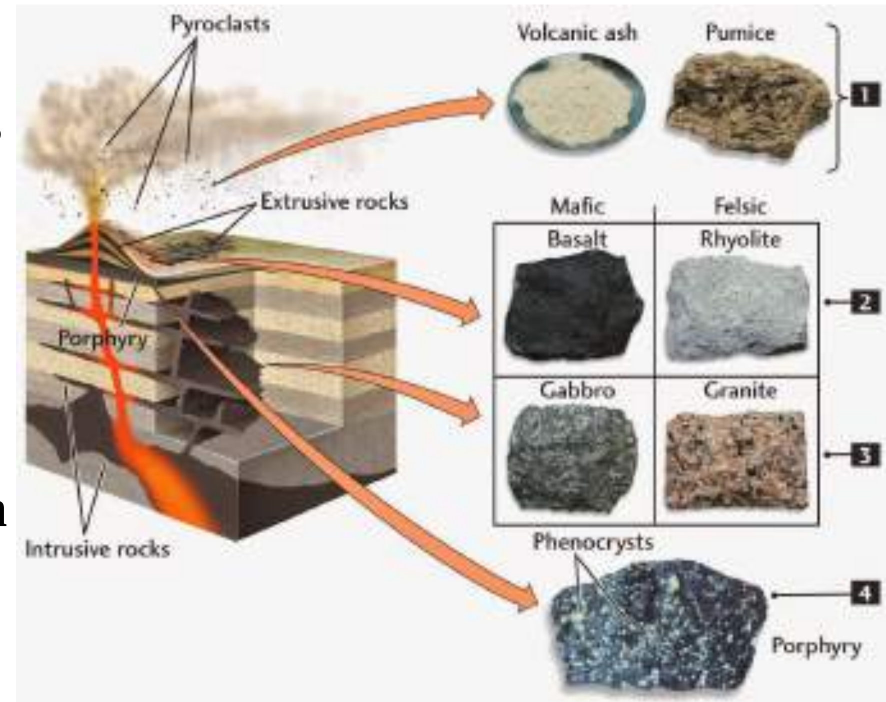


It is believed that episodically large plume "heads" rise from the deep mantle and melt when they reach the base of the lithosphere. Such melts or magmas give rise to large igneous provinces, such as the Deccan Traps of India.

General Characteristics of Magma

- Igneous rocks form as molten rock cools and solidifies.
- General characteristics of magma:

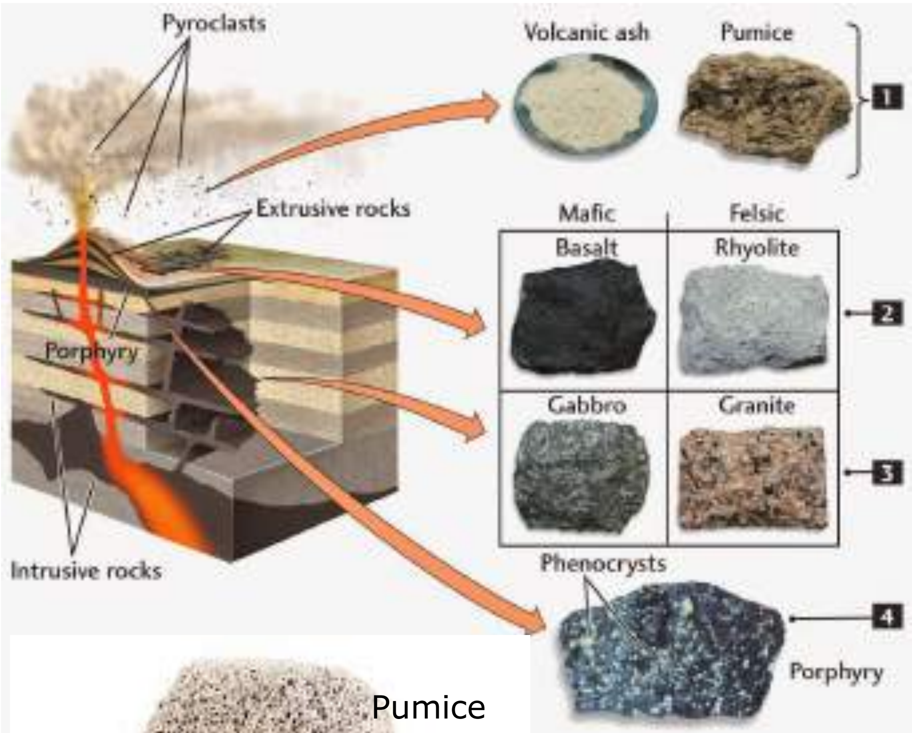
  (Parent material of igneous rocks)
  - Forms from partial melting of rocks inside Earth
  - Magma at surface is called lava.
  - Rocks formed from lava are extrusive, or volcanic rocks.
  - Rocks formed from magma at depth are intrusive, or plutonic rocks.



- The nature of magma
  - Consists of three components:
    1. Liquid portion = melt (ions of Si, O, Al, Na, K, Ca, Mg, Fe etc)
    2. Solids, if any, are silicate minerals.
    3. Volatiles are dissolved gases in the melt, including water vapor (H_2O), carbon dioxide (CO_2), and sulfur dioxide (SO_2).

Igneous Textures

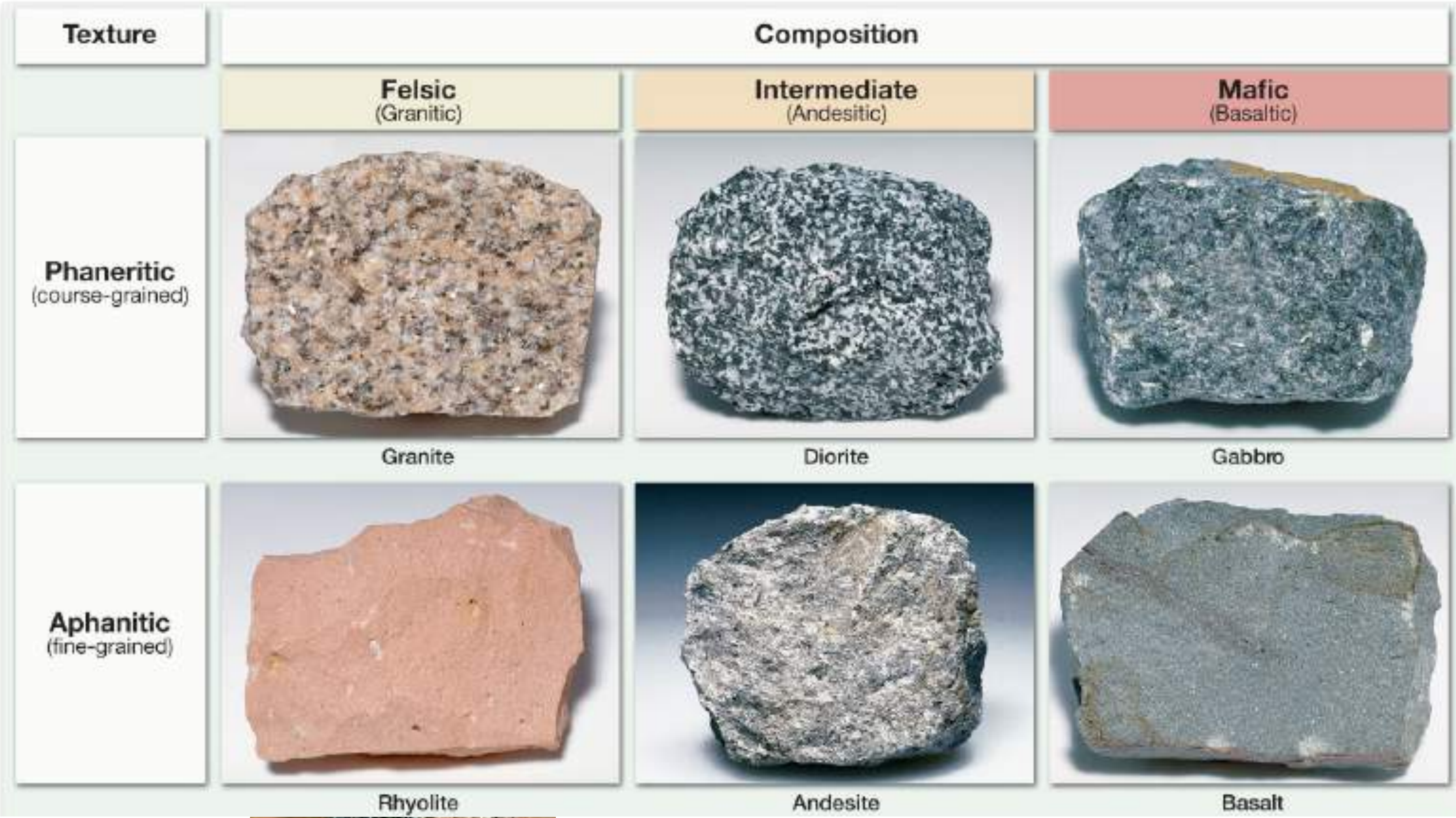
- Texture is the overall appearance of a rock based on the size, shape, and arrangement of interlocking minerals.
- Factors affecting crystal size:
  - Rate of cooling
    - Slow rate = fewer but larger crystals
    - Fast rate = many small crystals
    - Very fast rate forms glass.
- Types of igneous textures
  - Aphanitic (fine-grained) texture
    - Rapid rate of cooling
    - Microscopic crystals
    - May contain vesicles (holes from gas
  - Phaneritic (coarse-grained) texture
    - Slow cooling
    - Large, visible crystals
  - Porphyritic texture (slowly rise before eruption)
  - Vesicular texture (holes/pores due to gas expansion)
  - Glassy texture (Due to very fast cooling)




Pumice


Glassy

Texture examples



Porphyritic granite

Igneous Compositions

- **Igneous rocks are composed primarily of silicate minerals.**
  - **Dark (or ferromagnesian) silicates**
    - **Olivine, pyroxene, amphibole, and biotite mica**
  - **Light (or nonferromagnesian) silicates**
    - **Quartz, muscovite mica, and feldspars**

Granite

- **Granitic composition**
  - **Light-colored silicates**
  - **Termed felsic (*fel*dspar and *si*lica) in composition**
  - **High silica (SiO_2) content**
  - **Major constituent of continental crust**

Basaltic composition

Dark silicates and calcium-rich feldspar

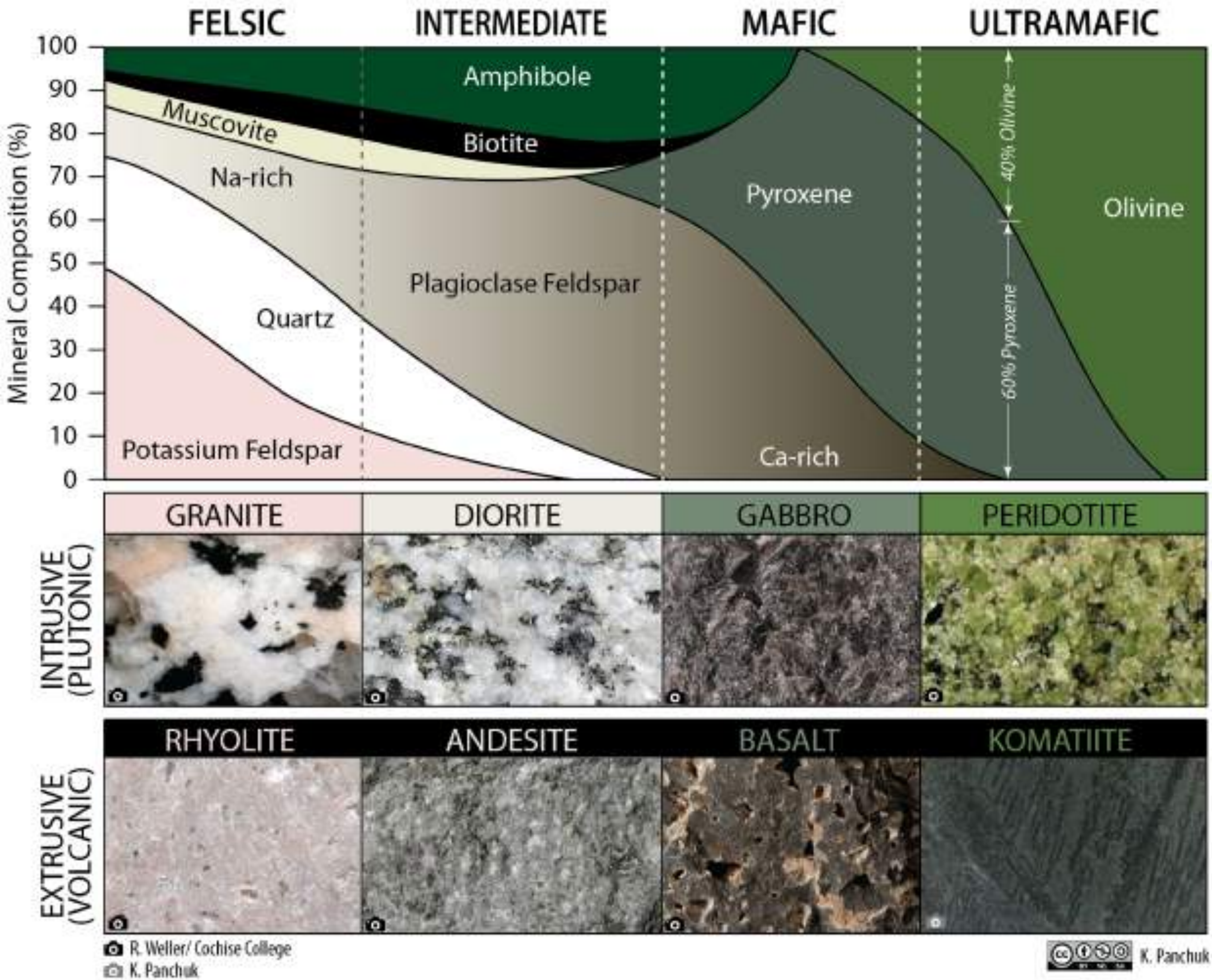
Termed mafic (*ma*gnesium and *fe*rrum, for iron) in composition

Higher density than granitic rocks

Comprise the ocean floor and many volcanic islands

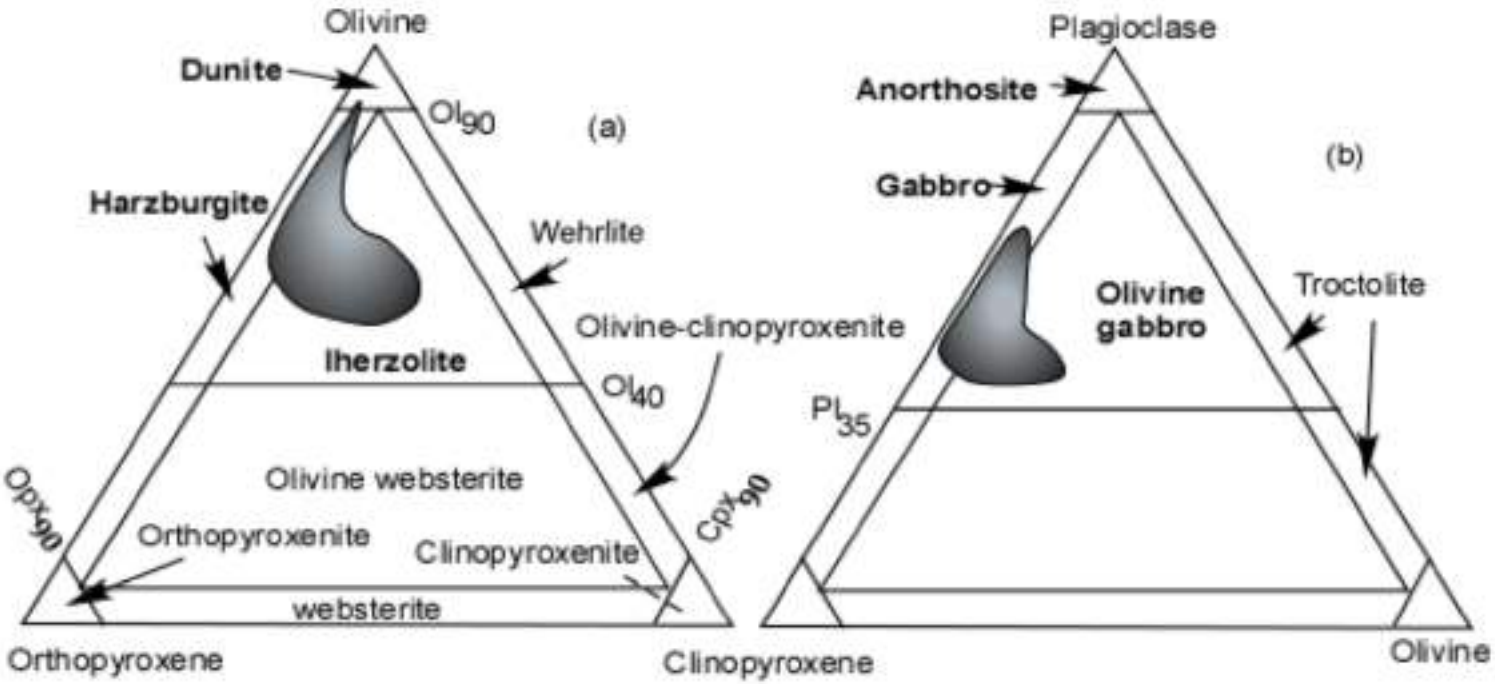
Basalt

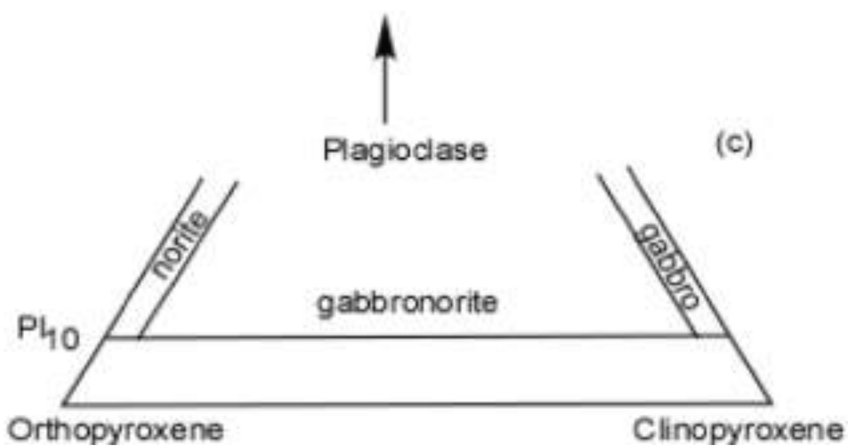
Mineralogy of common igneous rocks



<u>Classifications of Igneous Rocks</u> : Plutonic rocks are classified on the basis of mineralogy and texture

Classification of <u>Mafic and Ultramafic</u> rocks.





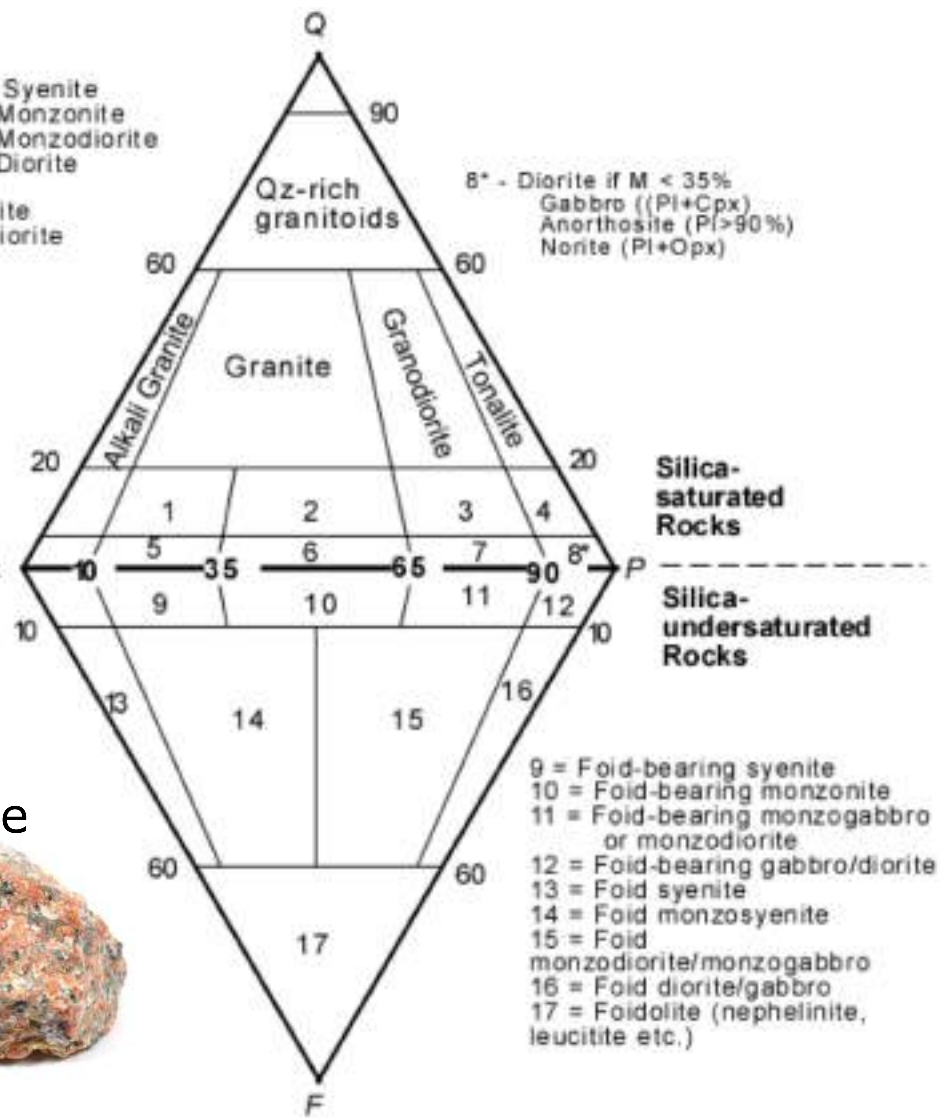
Basalt

Based on IUGS classification

1. Determine percentage of mineral from a rock

2. Plot mineral percentage and name the rock

QAPF classification of felsic plutonic rocks (Phaneritic rocks)



Granite

Q = Quartz, A = Alkali feldspar and albitic plagioclase,
P = Plagioclase
F = Feldspathoids (Foid), M = Mafic minerals

This classification scheme is for plutonic rocks containing <90% M.
For rocks with >90%M, the classification for ultramafic rocks should be used.

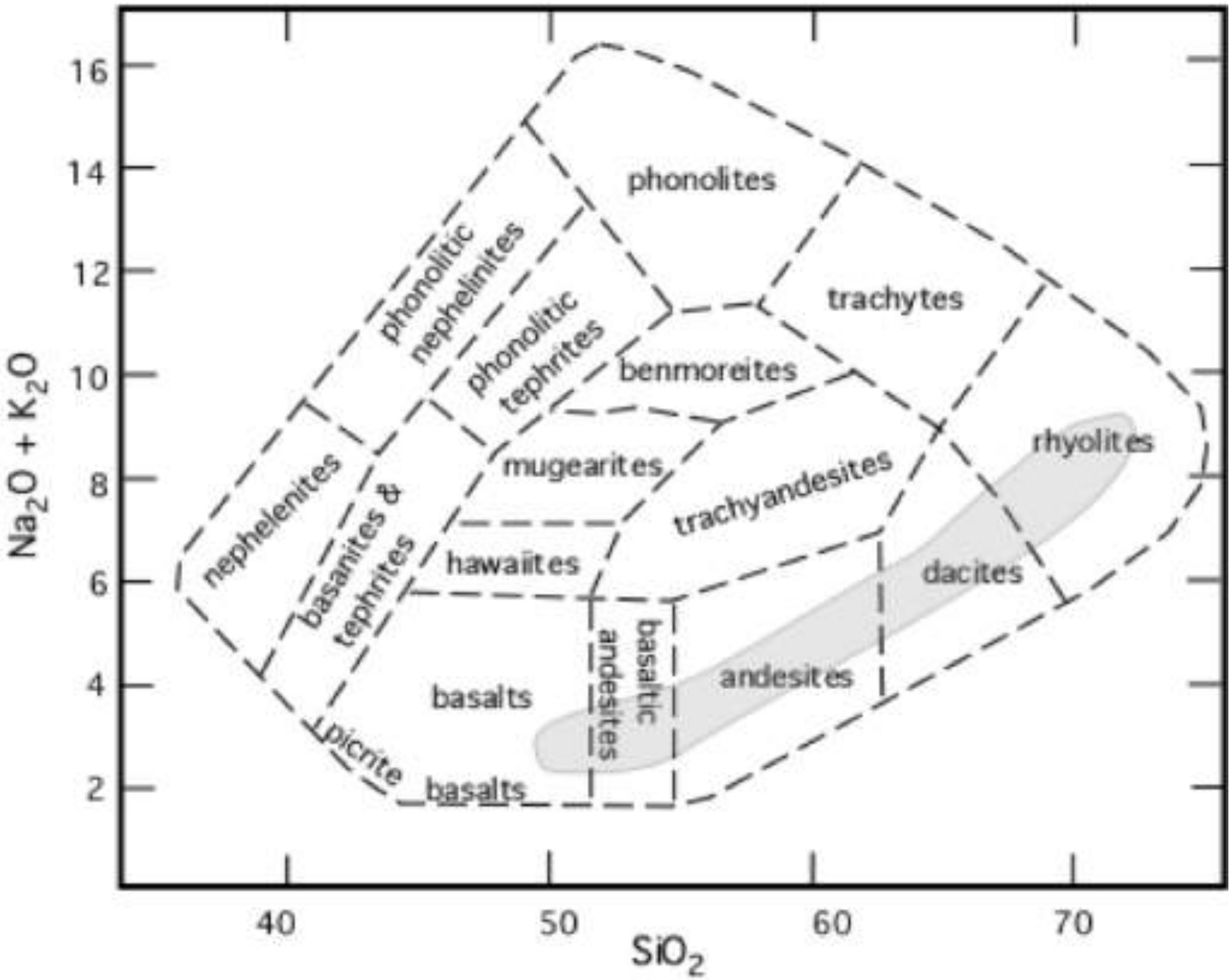
Rocks never contain both Q and F; so they are classified In terms of QAP or FAP

Based on IUGS classification

1. Determine percentage of mineral from a rock

2. Plot mineral percentage On a QAFP diagram to Name the rock

Question: If a rock contains 27% Quartz, 33 % Plagioclase and 20% Alkali feldspar, what will be the name of the rock?



Volcanic rocks can be very fine grained and difficult to classify Using QAPF diagram

Then Geochemical analysis is done keeping alkali % in Y-axis and Silica % in X-axis

If silica % increases Mafic → felsic

<u>Volcanic</u> rocks are classified on the basis of their major element chemistry

Remember!!!!!

Texture	Felsic (light color)	Intermediate	Mafic (dark color)	Ultramafic
Coarse	Granite	Diorite	Gabbro	Peridotite
Fine	Rhyolite	Andesite	Basalt	
Vesi-cular	Pumice		Scoria	
Glassy	Obsidian			
Minerals Present	QUARTZ K-FELDSPAR NA-PLAG	NA-CA PLAG AMPHIBOLE	CA PLAG PYROXENE	PYROXENE OLIVINE

Density →

← **Viscosity**

Questions

Q1: Lava flows are typically finer grained than intrusive igneous rocks. Why?

(a) Intrusive magma is cooler because it is well insulated by the surrounding rock.
(b) Intrusive magma flows onto the Earth's surface and cools very slowly, allowing many small mineral grains to grow.
(c) The extrusive magma cools quickly so the mineral grains do not have time to grow.
(d) The extrusive magma, because it is deep below the surface, cools very slowly, producing very small mineral grains.

Q2: Which of the following rocks is likely to have the most quartz within it and why?

(a) Granite; intrusive rock that formed from cooling of relatively high silica magma.
(b) Rhyolite; extrusive rock that formed from cooling of relatively low silica magma.
(c) Diorite; intrusive rock that formed from the cooling of relatively intermediate silica magma.
(d) Basalt; extrusive rock that formed from cooling of relatively low silica lava.

Q3: Igneous rocks are produced largely by ____.

(a) the changing of a rock from one set of minerals to another
(b) the compaction of metamorphic rocks
(c) the melting of sedimentary rocks
(d) the cooling of magma

Q4: Glassy igneous rocks form when the magma _______.

(a) cools so fast that mineral grains cannot crystallize and grow
(b) cools so slowly that only one mineral is formed
(c) is composed of basalt
(d) cools at an extremely high temperature

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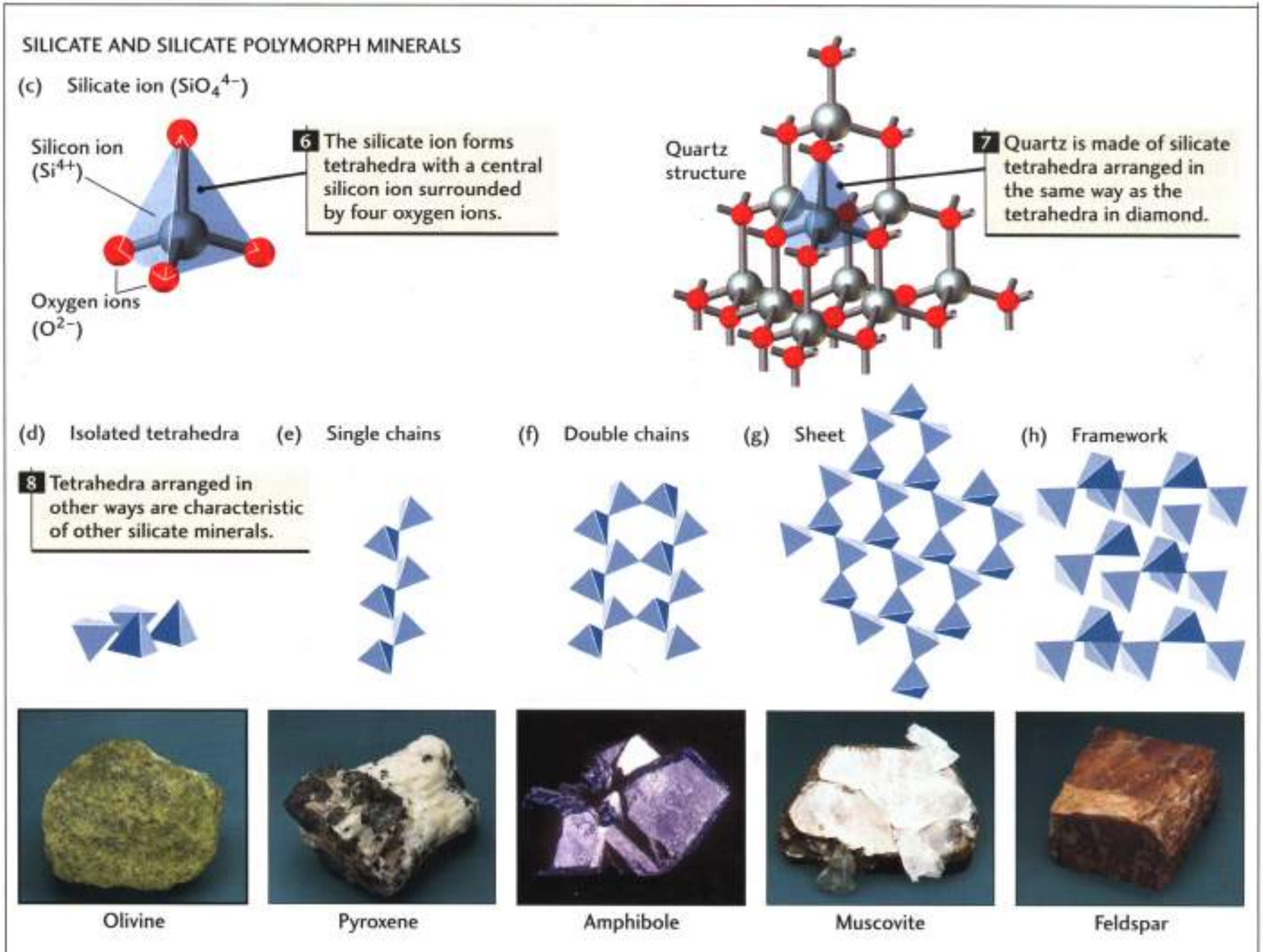
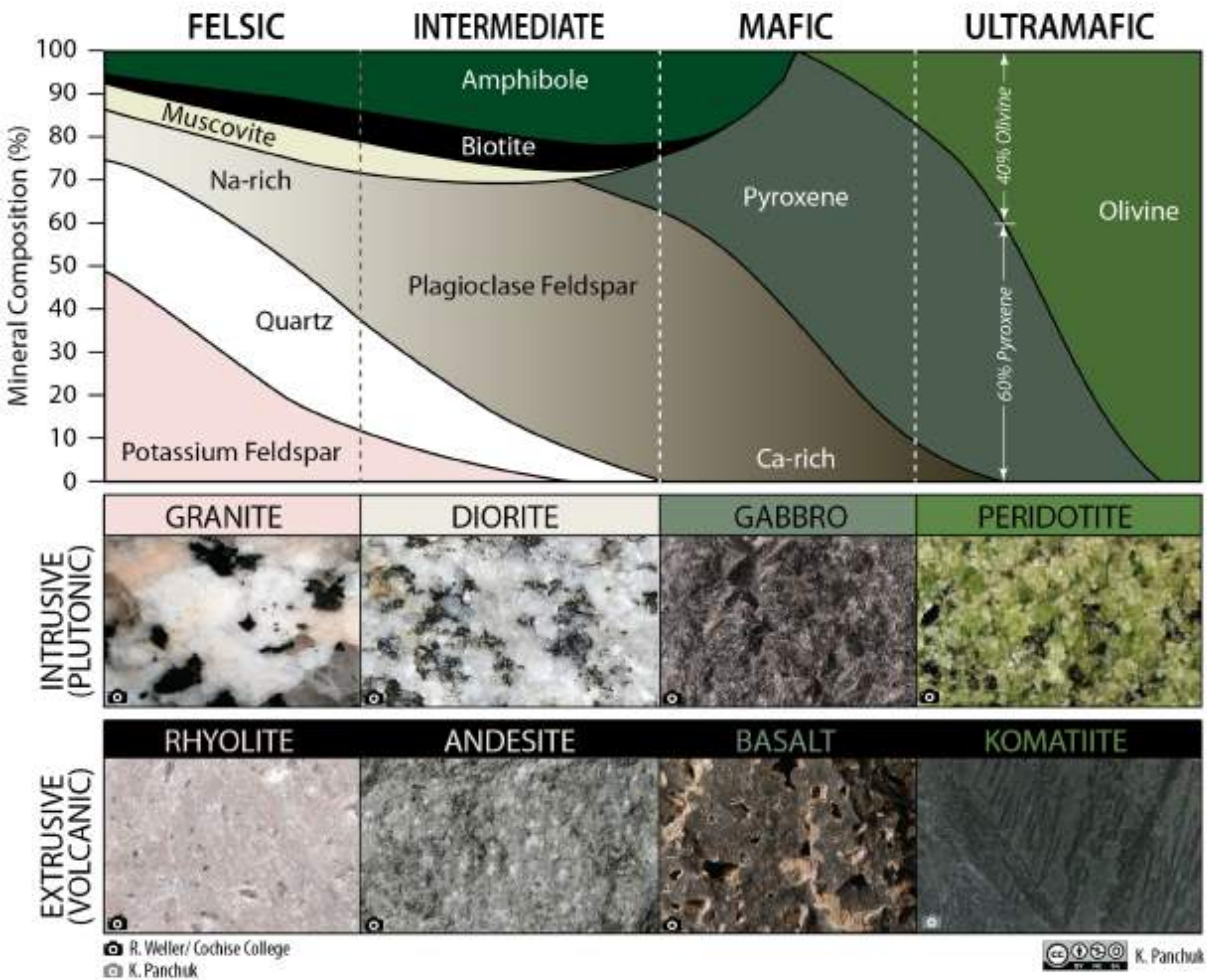
Topic: Magma and Igneous Rocks continued

Previous Class: Magma and Igneous Rocks "Granites"

Review: 1. Silicates



Review: 2. Mineralogy of common igneous rocks



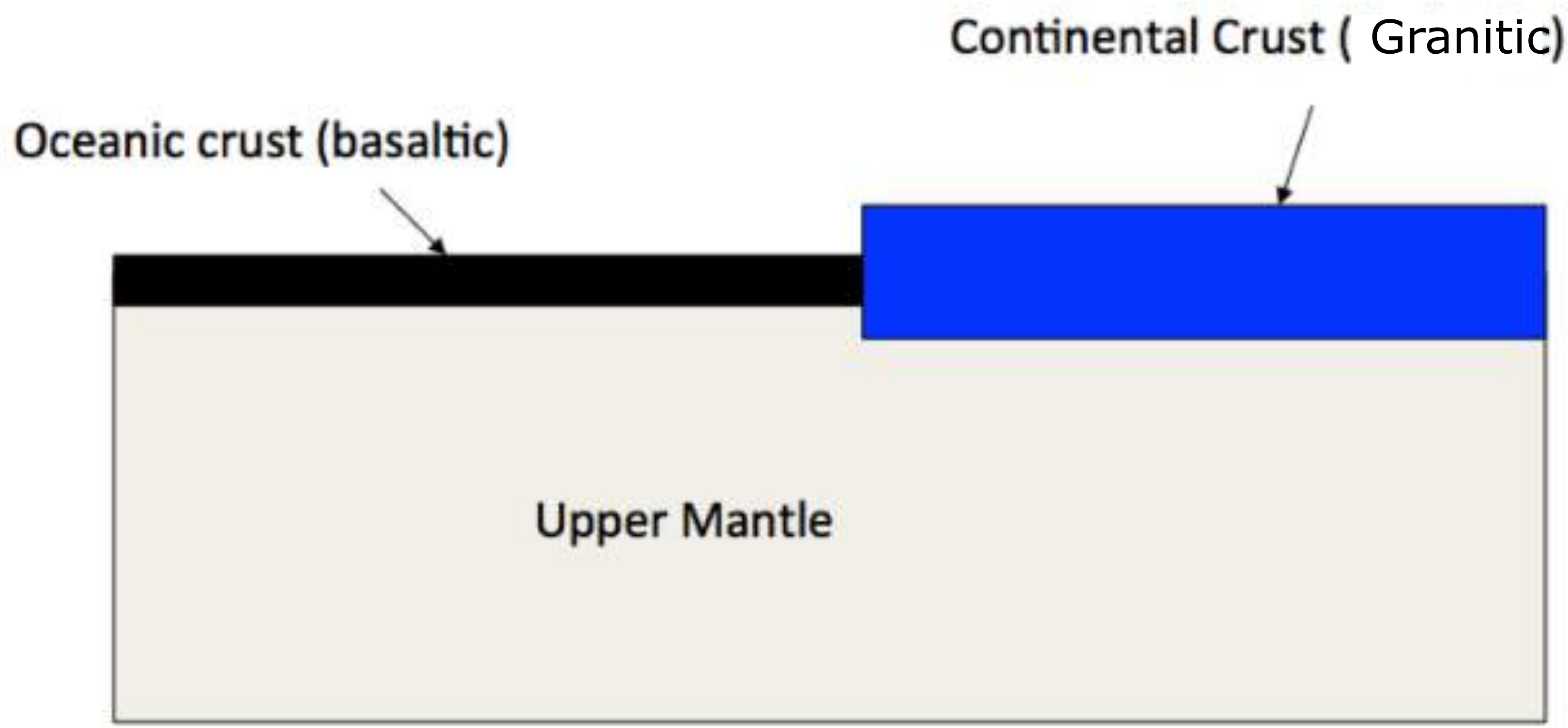
2. Rock nomenclature for mafic and ultramafic, Felsic and Volcanic rocks

Q: How does melt generate? How does magma ascend?

Magma Generation, Segregation, and Evolution

Under favorable thermal conditions, magma may form in the crust or upper mantle. Such magma must somehow segregate from the source rock, and form larger pools that will ascend toward the surface.

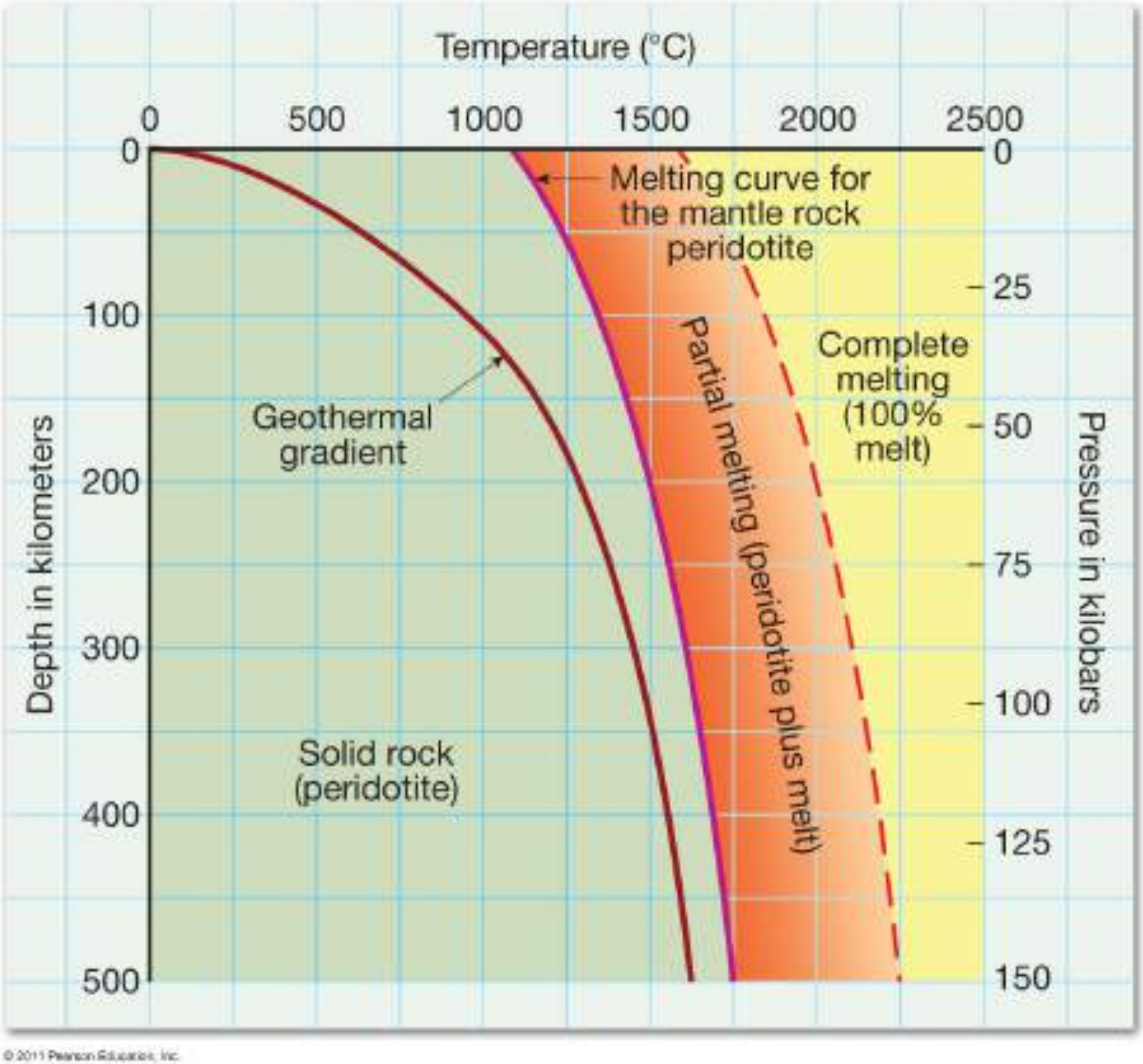
The Sources of Magmas



Origin of Magma

- • Highly debated topic
  • Generating magma from solid rock
- • Produced from partial melting of rocks in the crust and upper mantle
- – Consider the-
  • Role of temperature rise
  • Role of pressure
  • Role of volatiles

Origin of magma



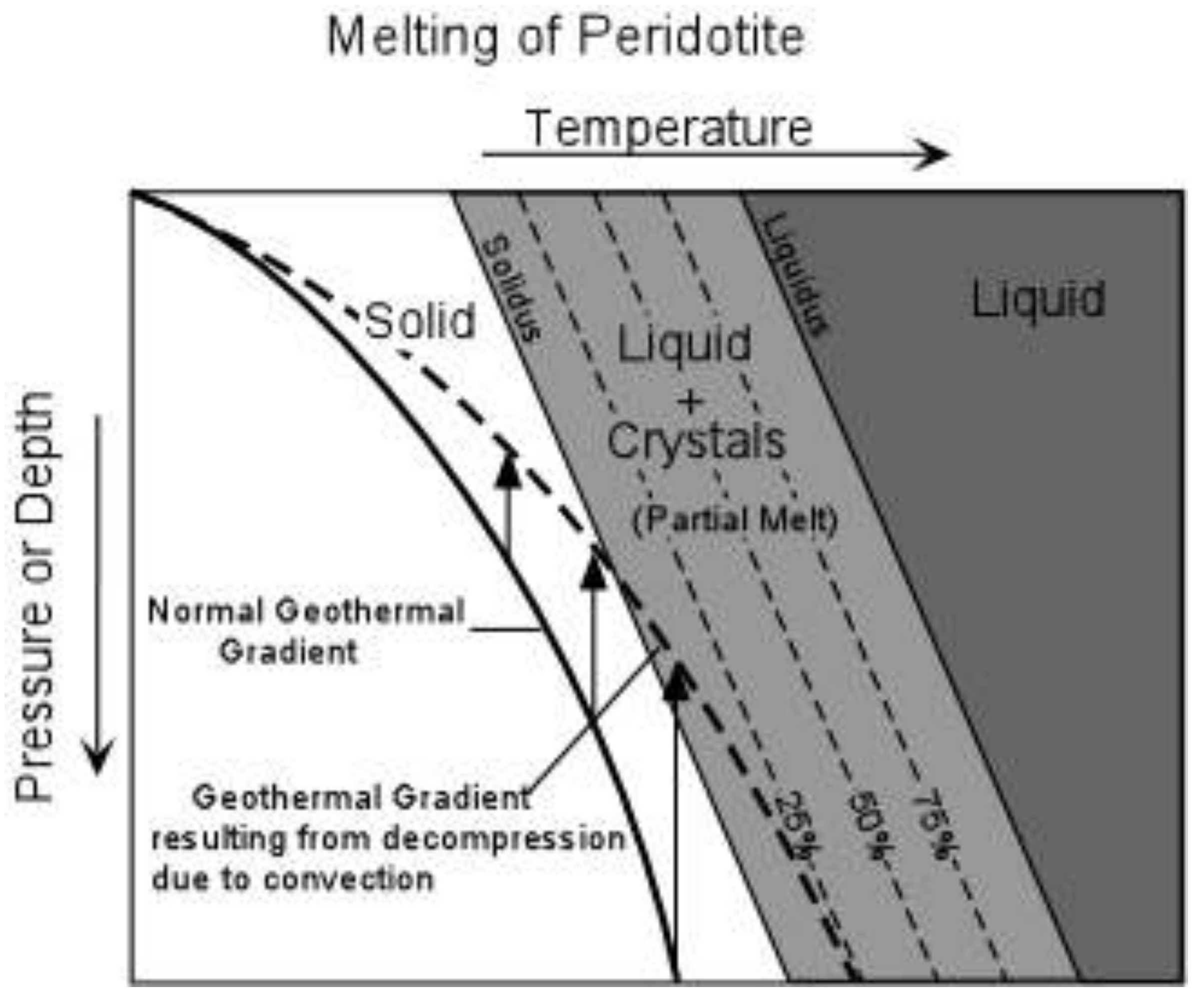
1. Role of temperature

- Temperature increases within Earth's upper crust (called the geothermal gradient) average between 20^{o}C to 30^{o}C per kilometer
- Rocks in the lower crust and upper mantle are near their melting points. Any additional heat (from rocks descending into the mantle or rising heat from the mantle) may induce melting
- In continental settings, basaltic magma often "ponds" beneath crustal rocks, which have a lower density and are already near their melting temperature. The hot basaltic magma may heat the overlying crustal rocks sufficiently to generate a secondary, silica-rich magma.

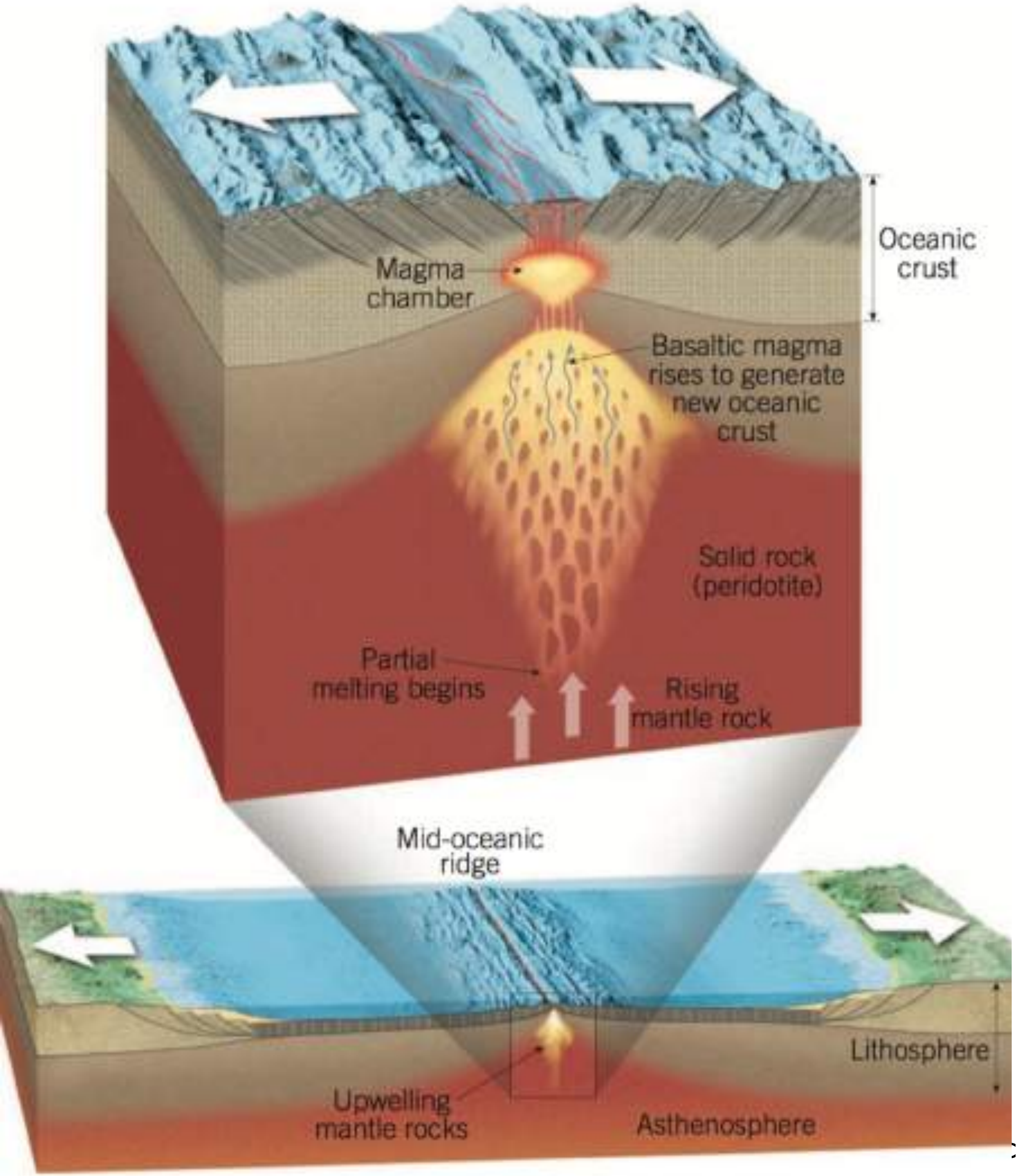
Origin of Magma

2. Role of pressure (Decompression Melting)

- Increases in confining pressure increases a rock's melting temperature.
- When confining pressures drop, decompression melting occurs.



Decompression Melting

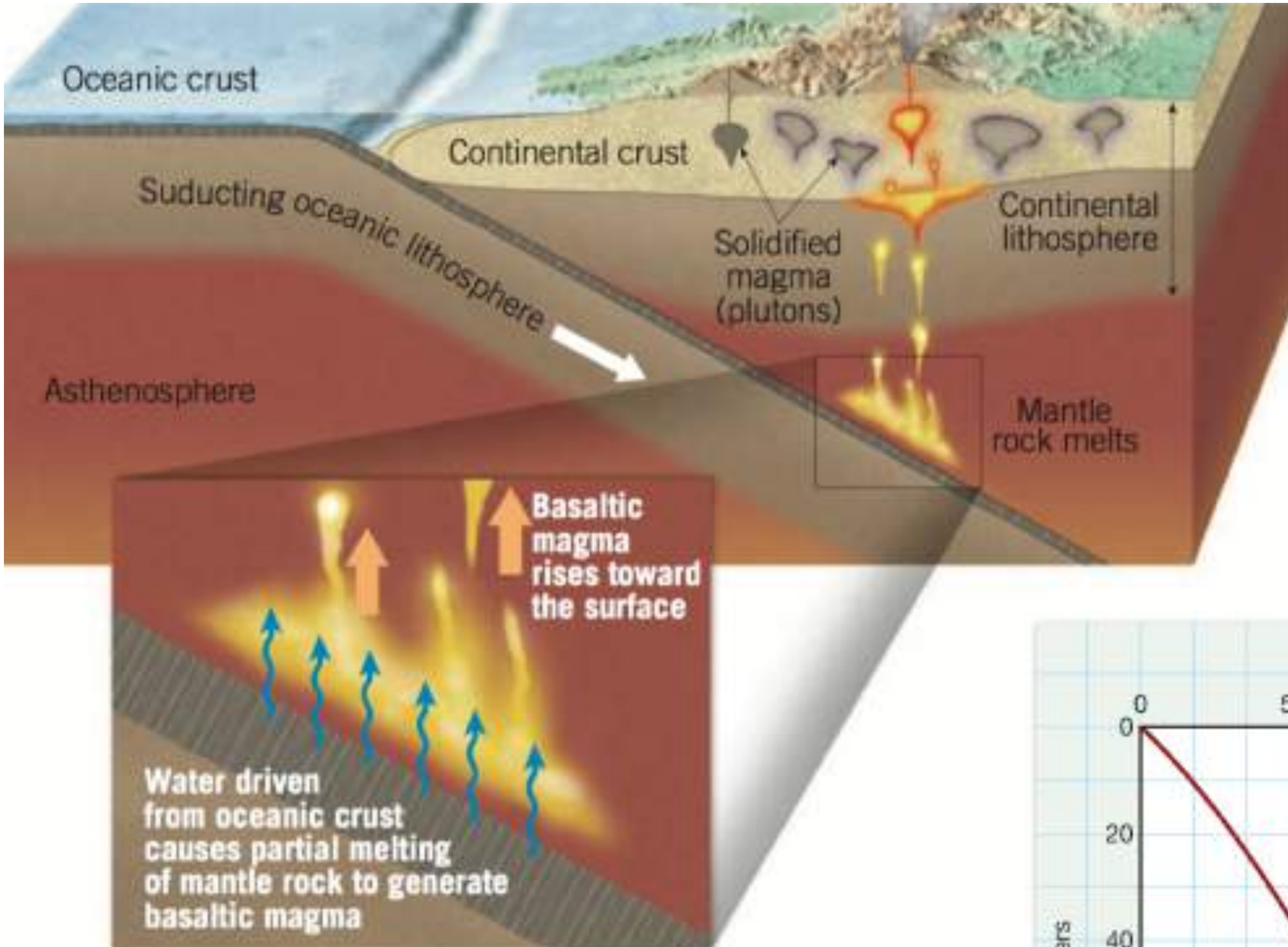


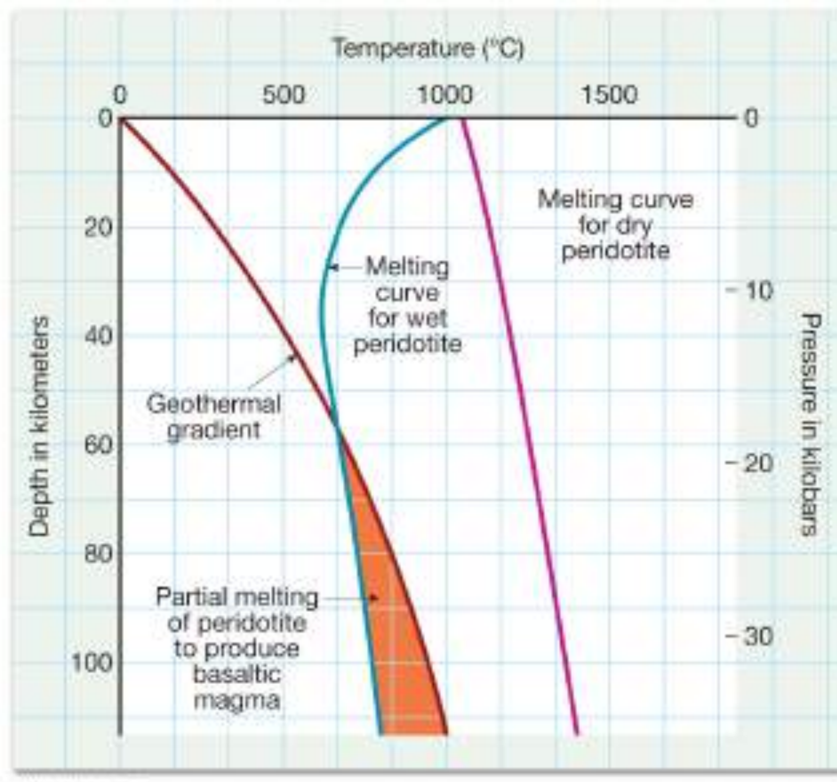
1. As hot mantle rock ascends through convective upwelling, it continually moves into zones of lower and lower pressure. This drop in confining pressure initiates *decompression melting*, in the upper mantle.

2. Decompression melting also occurs when ascending mantle plumes reach the uppermost mantle.

3. Role of volatiles

Volatiles (primarily water) cause melting at lower temperatures. Important factor where oceanic lithosphere descends into the mantle

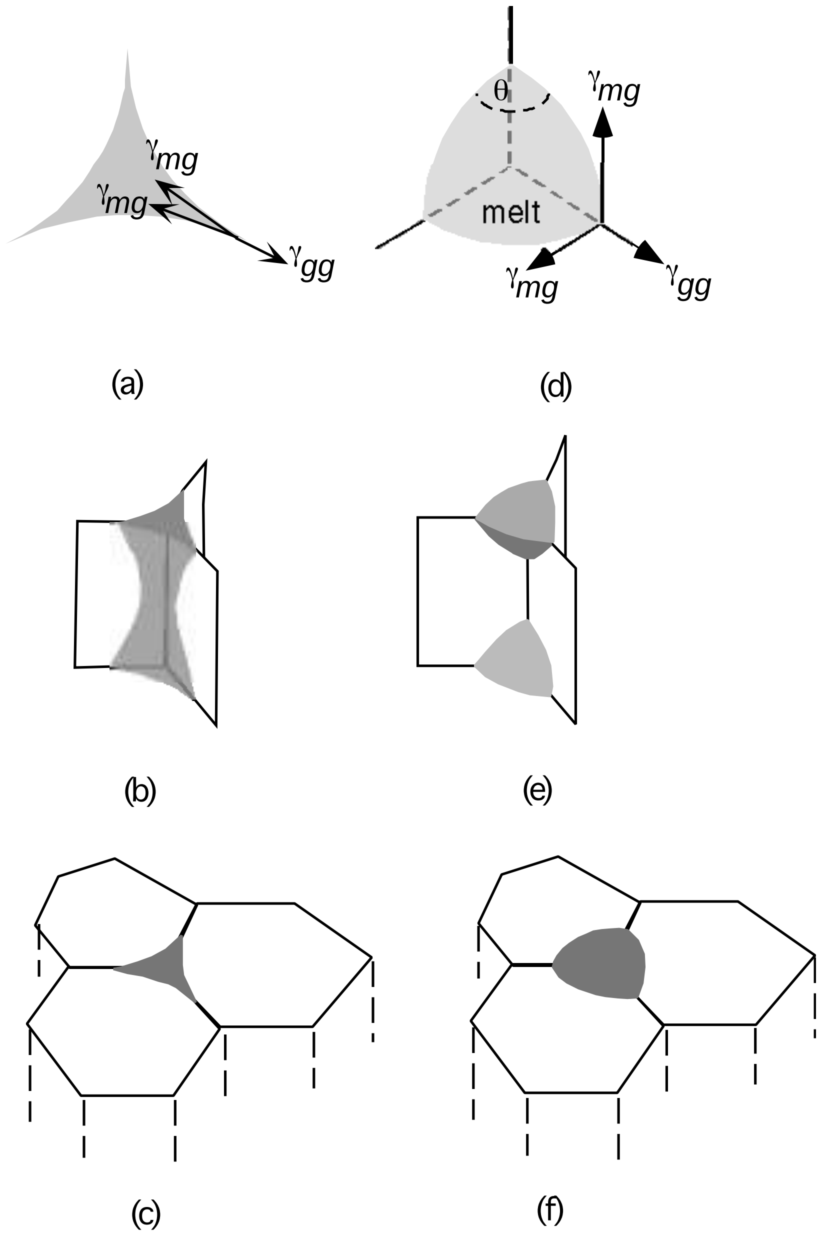




Water lowers the melting temperature of hot mantle rock to trigger partial melting

As an oceanic plate descends into the mantle, water and other volatiles are driven from the subducting crustal rocks into the mantle resulting partial melting of mantle rock and generate basaltic magma. At a depth of about 100 km the wedge of mantle rock is sufficiently hot that the addition of water leads to some melting. Partial melting of the mantle rock peridotite generates hot basaltic magma whose temperatures may exceed 1250° C.

Magma Segregation and Compaction



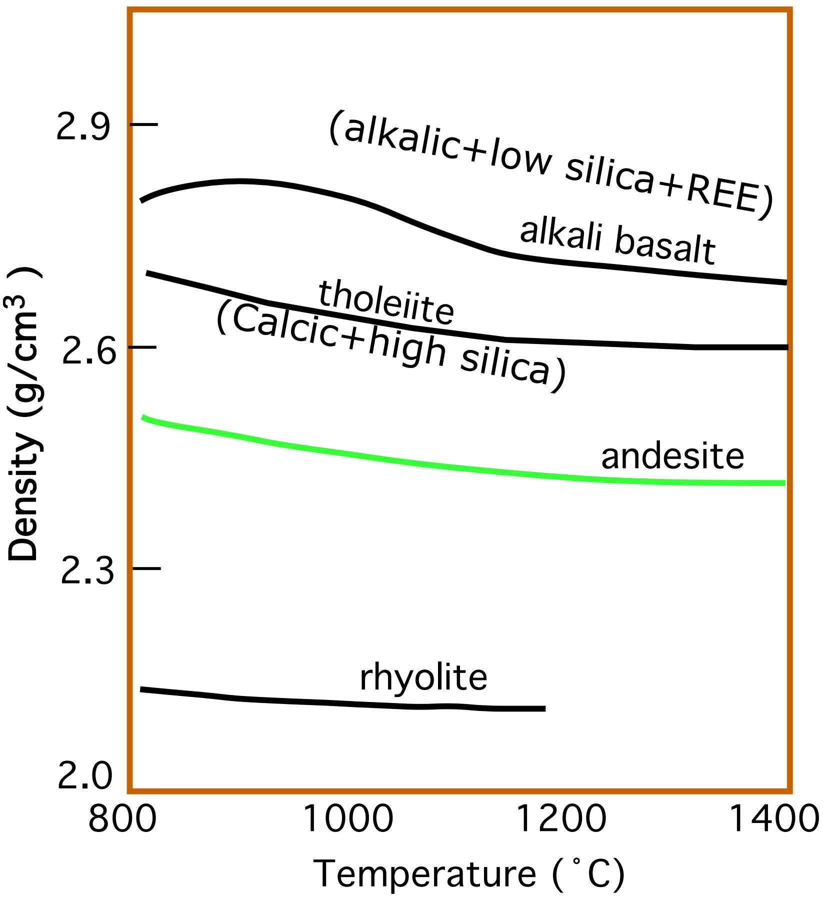
- Melting appears to begin at the intersections ("triple point junctions") of grains of different phases.
- The *dihedral angle* (*q*) between two adjacent solid grains and melt plays an important role in controlling melt distribution in the pore spaces of the rock. If *q* < 60°, then melts in all corners will be interconnected, which allows the melt to escape along grain boundaries even when the melt fraction [i.e, mass of melt /(mass of melt + mass of rock)] is very small.
- Basaltic magmas exhibit this behavior, BUT NOT GRANITE

How magma flows?

Flow of magma through interconnected pores (i.e., porous flow) is governed by *D'Arcy's law:*

$$v = \frac{K}{\mu\phi} \cdot \frac{dP}{dz}$$

where *v* is magma velocity, *K* is permeability, **Φ** is porosity and **μ** is viscosity of the magma. dP/dz is simply the pressure gradient caused largely by the density difference between a magma and the solid residue.



Densities of different magmas have been measured in the laboratory, mostly at atmospheric pressure, and they vary between 2.2 and 3.1 g/cm^3. Density of magma is directly related to the abundance of the mafic (i.e., Mg + Fe) component.

Consider a simple example of buoyant rise of a x magma from a depth of 60 km to the surface. We assume that the wall rock at ~60-40 km is y with a density of 3.3 g/cm^3. The magma's density is assumed to be constant at 2.9 g/cm^3.

$$P = \boldsymbol{\rho} g h$$

where P is pressure (in GPa), **ρ** is density, and g is acceleration due to gravity (assumed to be constant with a value of 980 cm/sec^2).

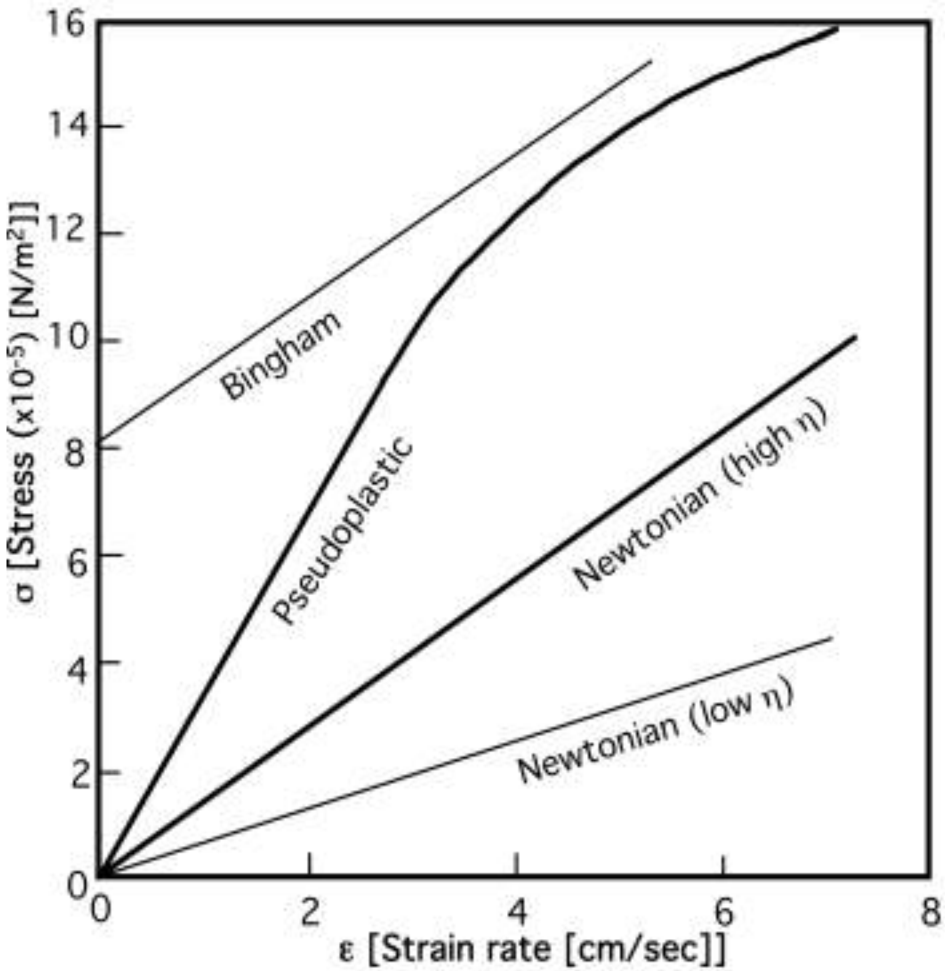
P_{rock} at 60 km = (60,000,00 * 3.3 * 980)/10^{10} = 1.94 GPa

P_{magma} at 60 km = (60,000,00*2.9*980)/10^{10} = 1.70 GPa

Therefore, the pressure difference of 0.24 GPa between the magma and wall rock makes the magma sufficiently buoyant to rise to the surface.

Magma Flow

Viscosity and Density are important factors that determine how fast magma will rise.



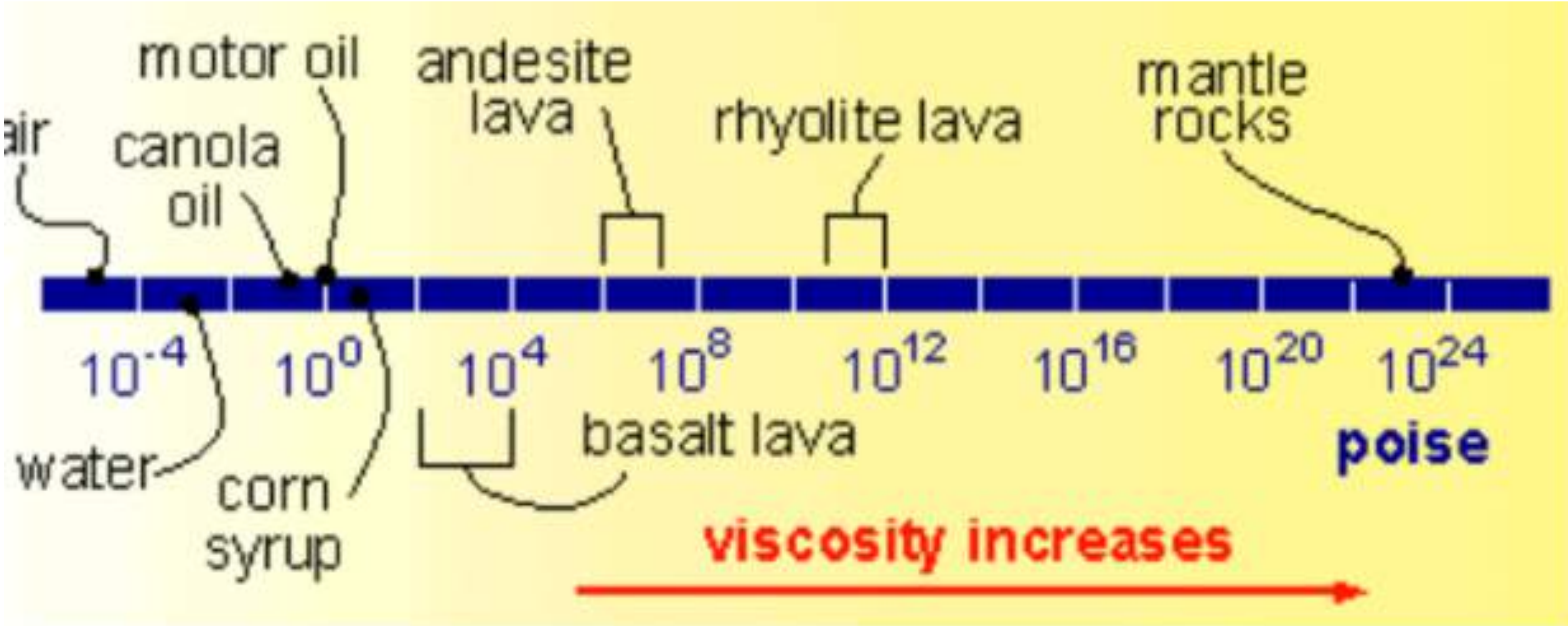
Viscosity (**η**) of a magma is simply defined as its internal resistance to flow and is given as:

$$\eta = \sigma / \varepsilon$$

σ=Shear Stress

ε=Shear Strain rate

- Crystal-free basalt magmas show Newtonian behavior.
- Andesitic magma containing abundant crystals may behave like a *Bingham plastic* - that is, they may possess some finite yield strength and thus flow only when a certain threshold value of stress has been exceeded.
- Rhyolitic magmas exhibit *pseudoplastic* behavior in that it shows a non-linear relationship between stress and strain rate.



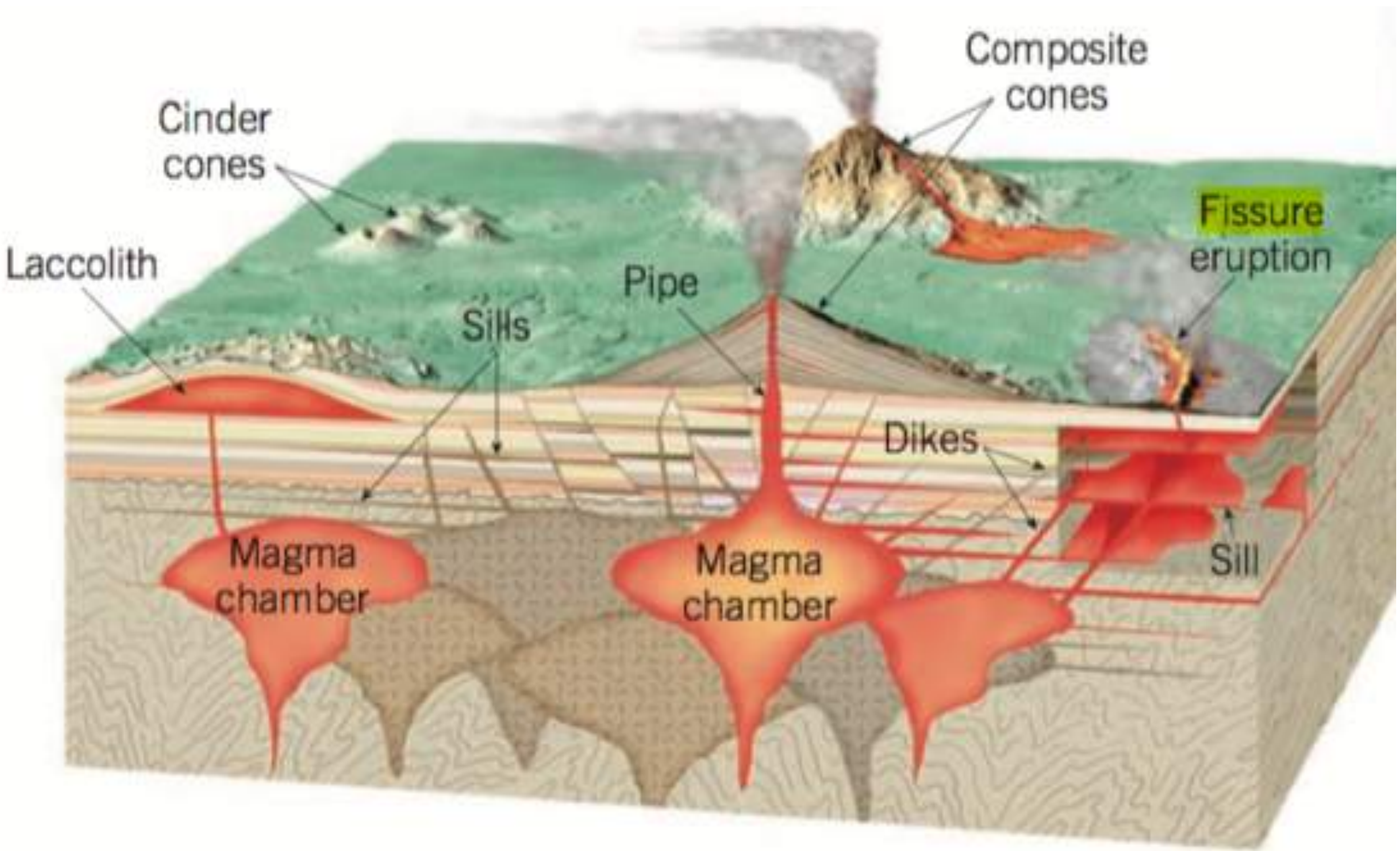
(University of British Columbia)

Factors affecting viscosity

- **Temperature—Hotter magmas are less viscous.**
- **Composition—silica (SiO_2) content**
  - **– Higher silica content = higher viscosity (e.g., felsic lava such as rhyolite).**
- **Dissolved gases**
  - **Gases expand within a magma as it nears Earth's surface due to decreasing pressure.**
  - **The violence of an eruption is related to how easily gases escape from magma.**

The Nature of Volcanic Eruptions

- **In summary, factors affecting viscosity:**
  - **Fluid basaltic lavas generally produce quiet eruptions.**
  - **Highly viscous lavas (rhyolite or andesite) produce more explosive eruptions.**



Why?

Q1: How come oceanic crust is composed of basalt although upper mantle is of peridotite?

Q2: Why do we observe andesitic volcanism at the Subduction zones when the subducting oceanic plates are made up of basalts??

Q3: Why continents are of granitic compositions?

Q4: How come a single volcano extrudes lavas of very different compositions?

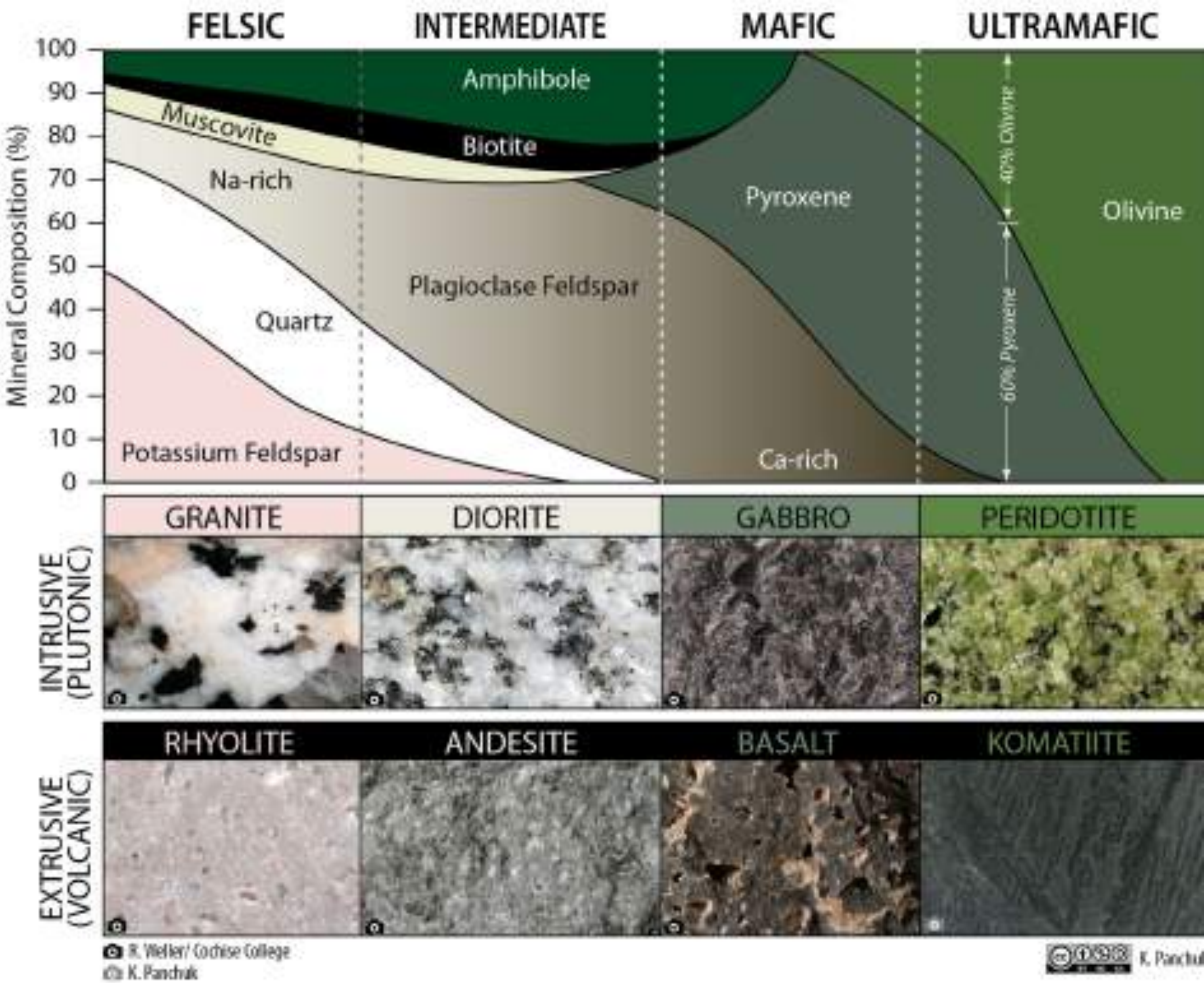
Evolution of Magmas

- **A single volcano may extrude lavas of very different compositions.**

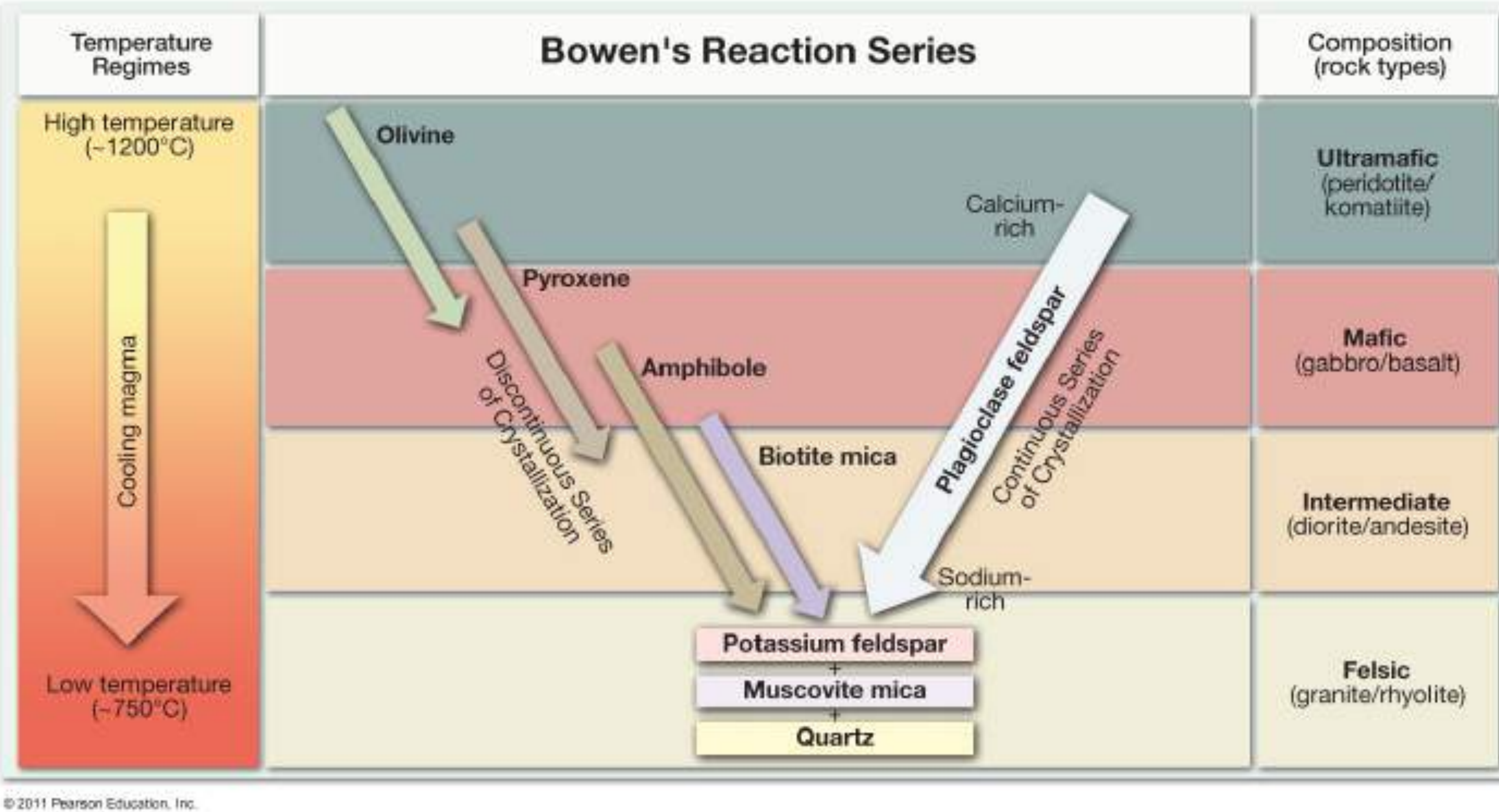
Bowen's reaction series

- **Minerals crystallize in a systematic fashion based on their melting points.**

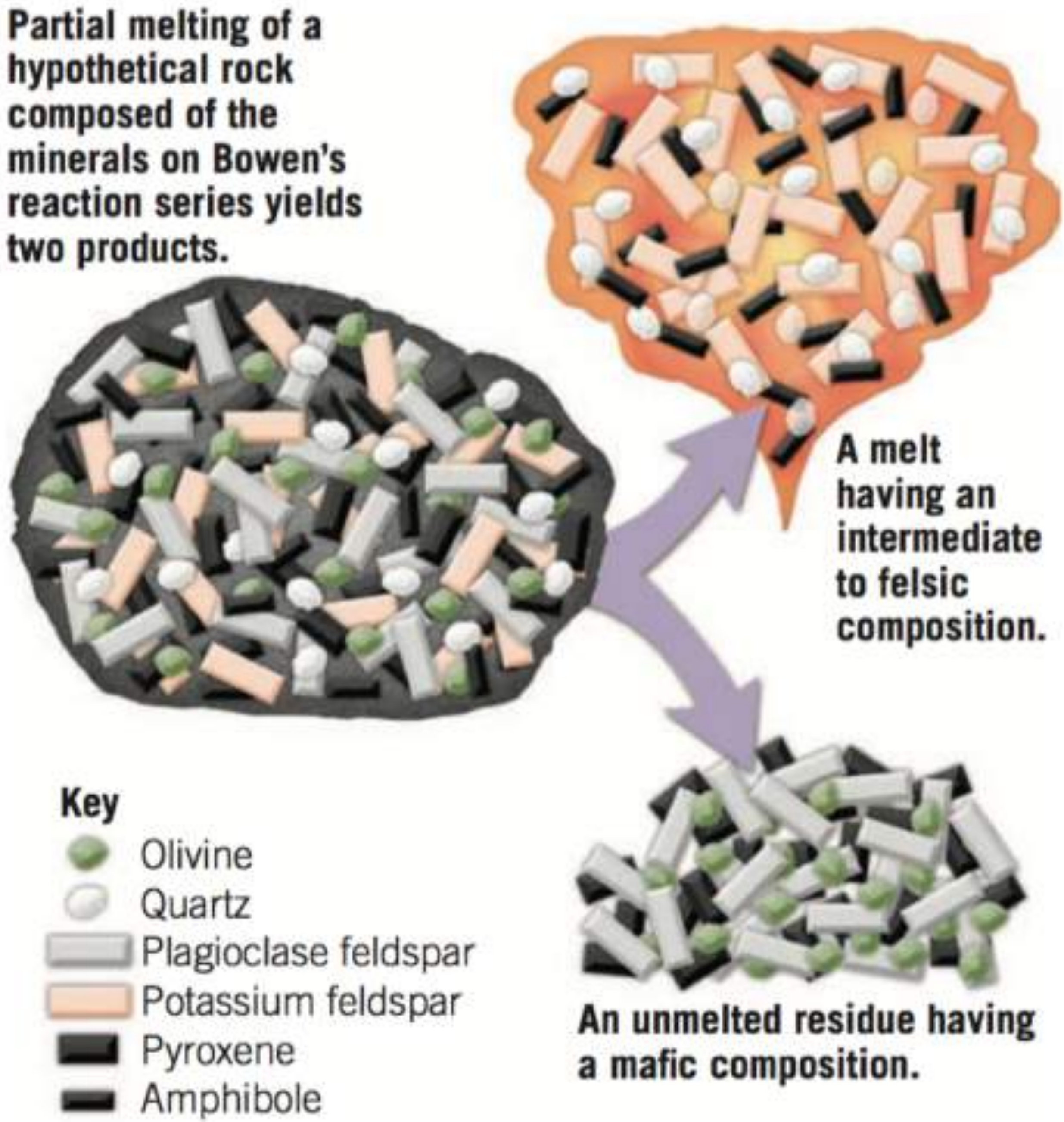
- **During crystallization, the composition of the liquid portion of the magma continually changes.**



Bowen's Reaction Series



This diagram shows the sequence in which minerals crystallize from a mafic magma.

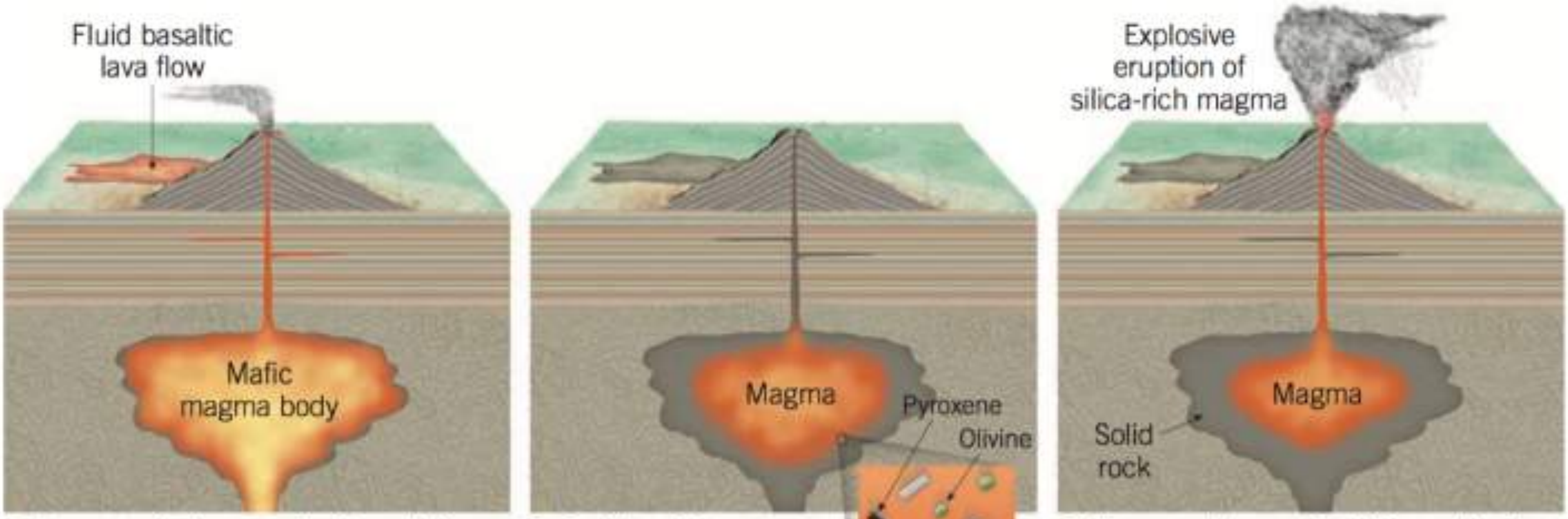


<u>Partial melting generates a magma that is nearer the felsic (granitic) end of the compositional spectrum than the parent rock from which it was derived.</u>

- Partial melting of *ultramafic* rocks yields *mafic (basaltic) magmas*,
- partial melting of *mafic* rocks yields *intermediate (andesitic) magmas*,
- partial melting of *intermediate* rocks yields *felsic (granitic) magmas.*

Magmatic Differentiation and Crystal Settling

The formation of one or more secondary magmas from a single parent magma is called **magmatic differentiation**.



A. A magma having a mafic (basaltic) composition erupts fluid basaltic lavas.

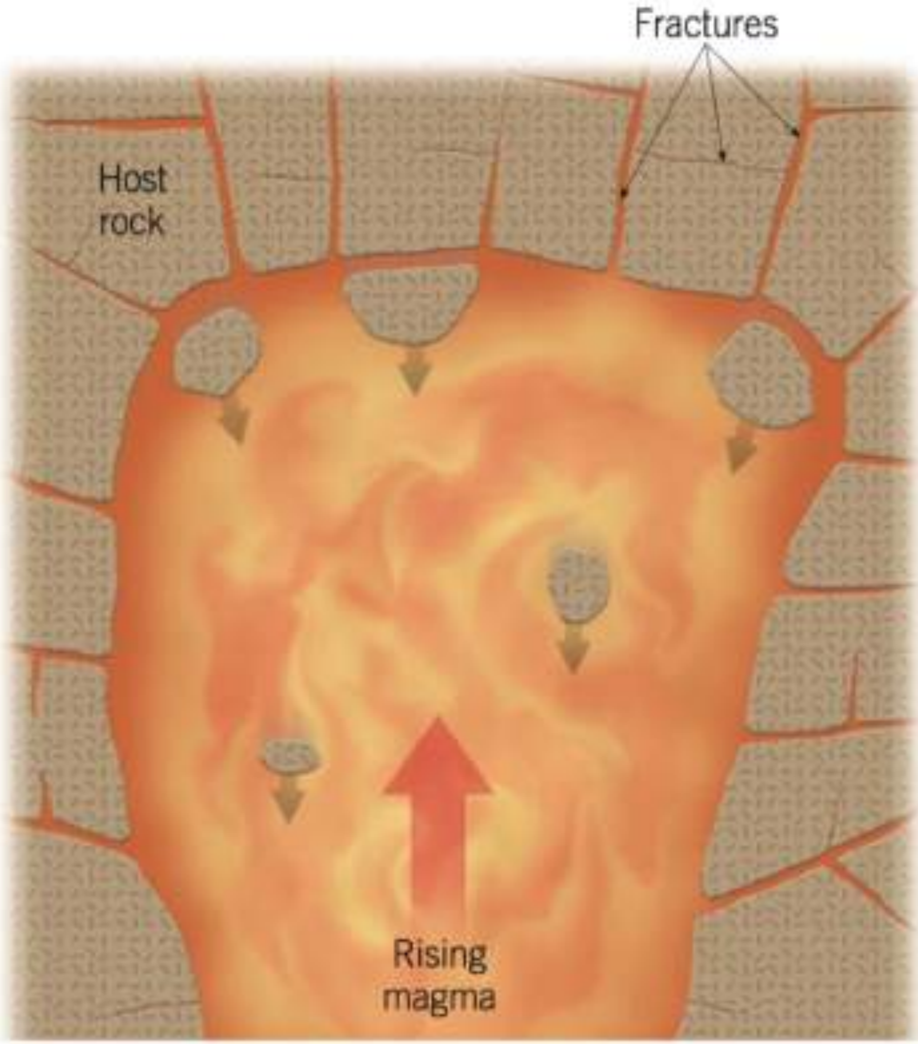
B. Cooling of the magma body causes crystals of olivine, pyroxene, and calcium-rich plagioclase to form and settle out, or crystallize along the magma body's cool margins.

C. The remaining melt will be enriched with silica, and should a subsequent eruption occur, the rocks generated will be more silica-rich and closer to the felsic (granitic) end of the compositional range than the initial magma.

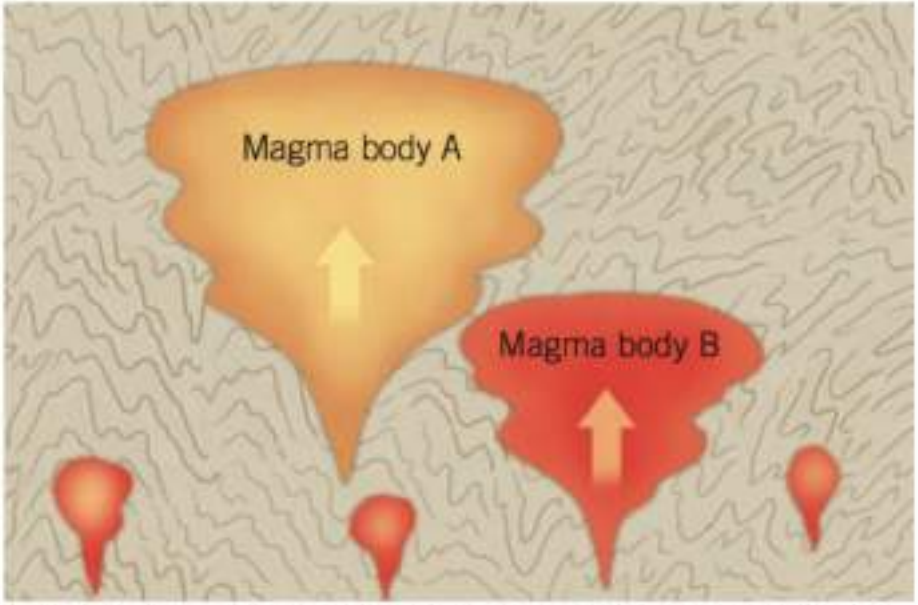
Crystal settling results in a change in the composition of the remaining melt

Illustration of how a magma evolves as the earliest- formed minerals (those richer in iron, magnesium, and calcium) crystallize and settle to the bottom of the magma chamber, leaving the remaining melt richer in sodium, potassium, and silica (SiO_2)

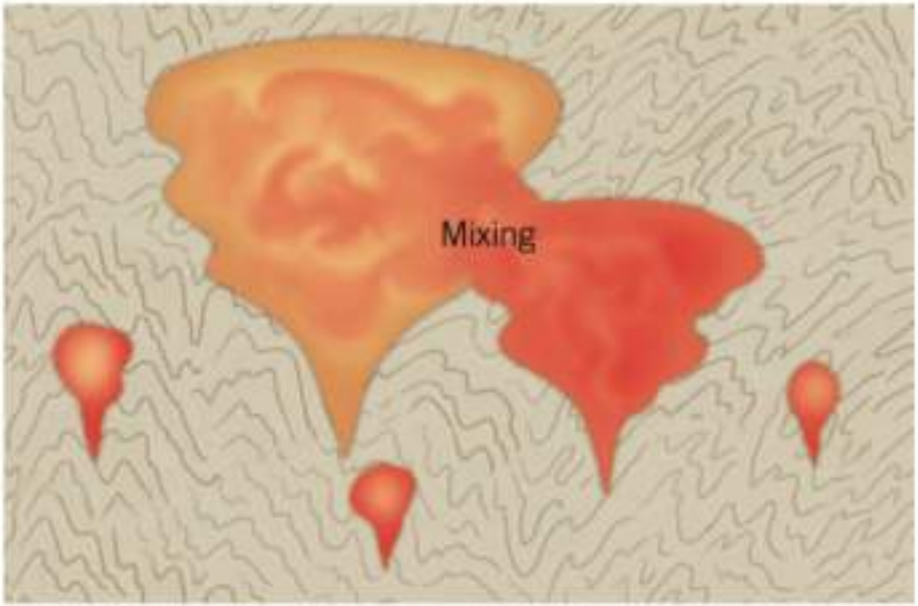
Assimilation and Magma Mixing



As magma rises through Earth's brittle upper crust, it may dislodge and incorporate the surrounding host rocks. Melting of these blocks, a process called *assimilation*, changes the overall composition of the rising magma body.

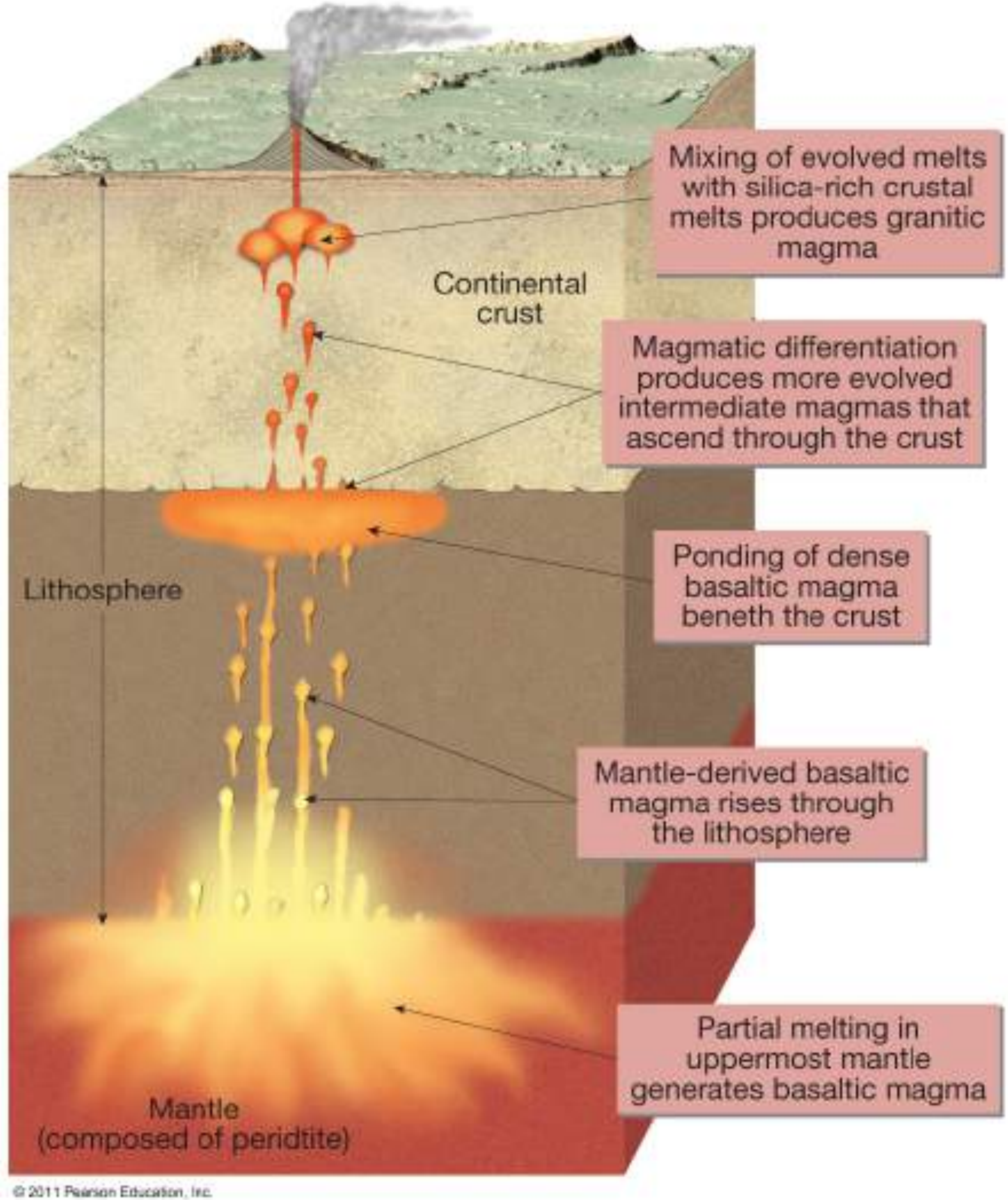


A. During the ascent of two chemically distinct magma bodies, the more buoyant mass may overtake the slower rising body.

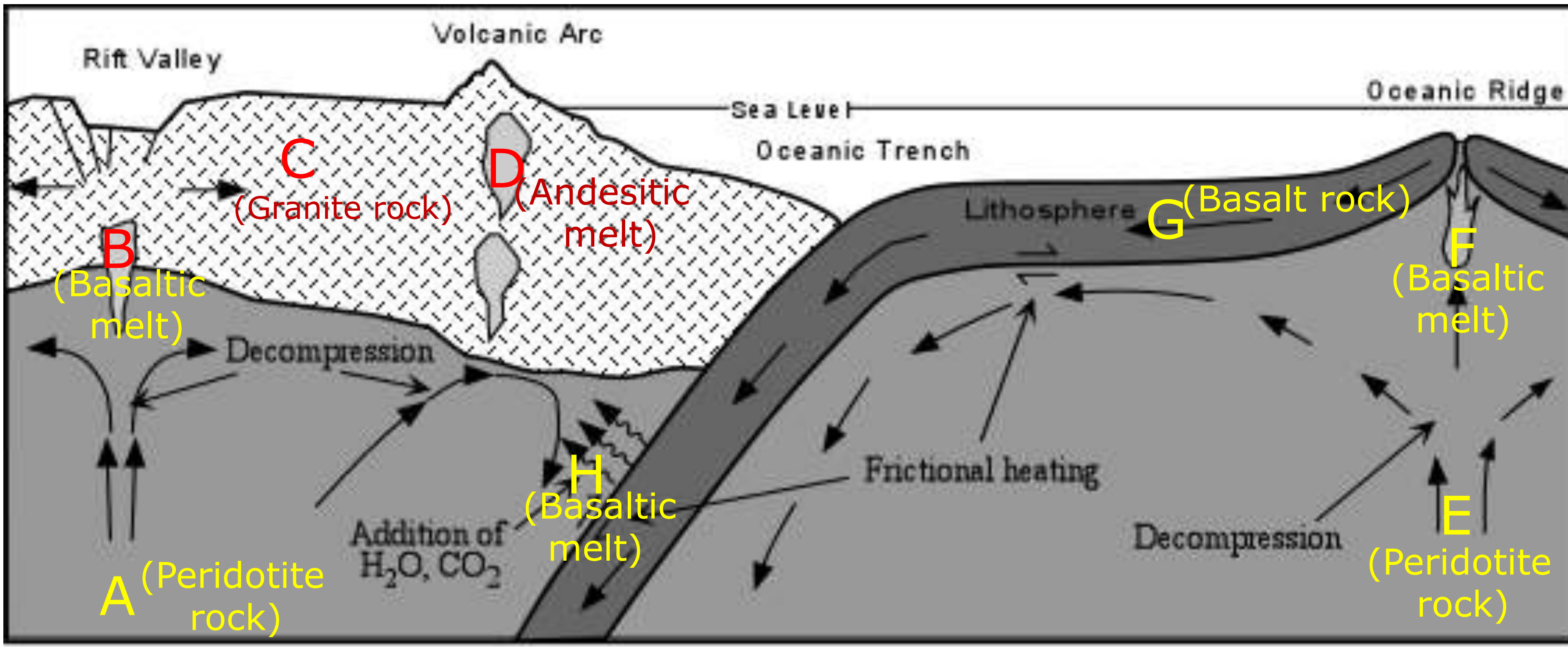


B. Once joined, convective flow will mix the two magmas, generating a mass that is a blend of the two magma bodies.

Granitic magmas are generated by partial melting of continental crust

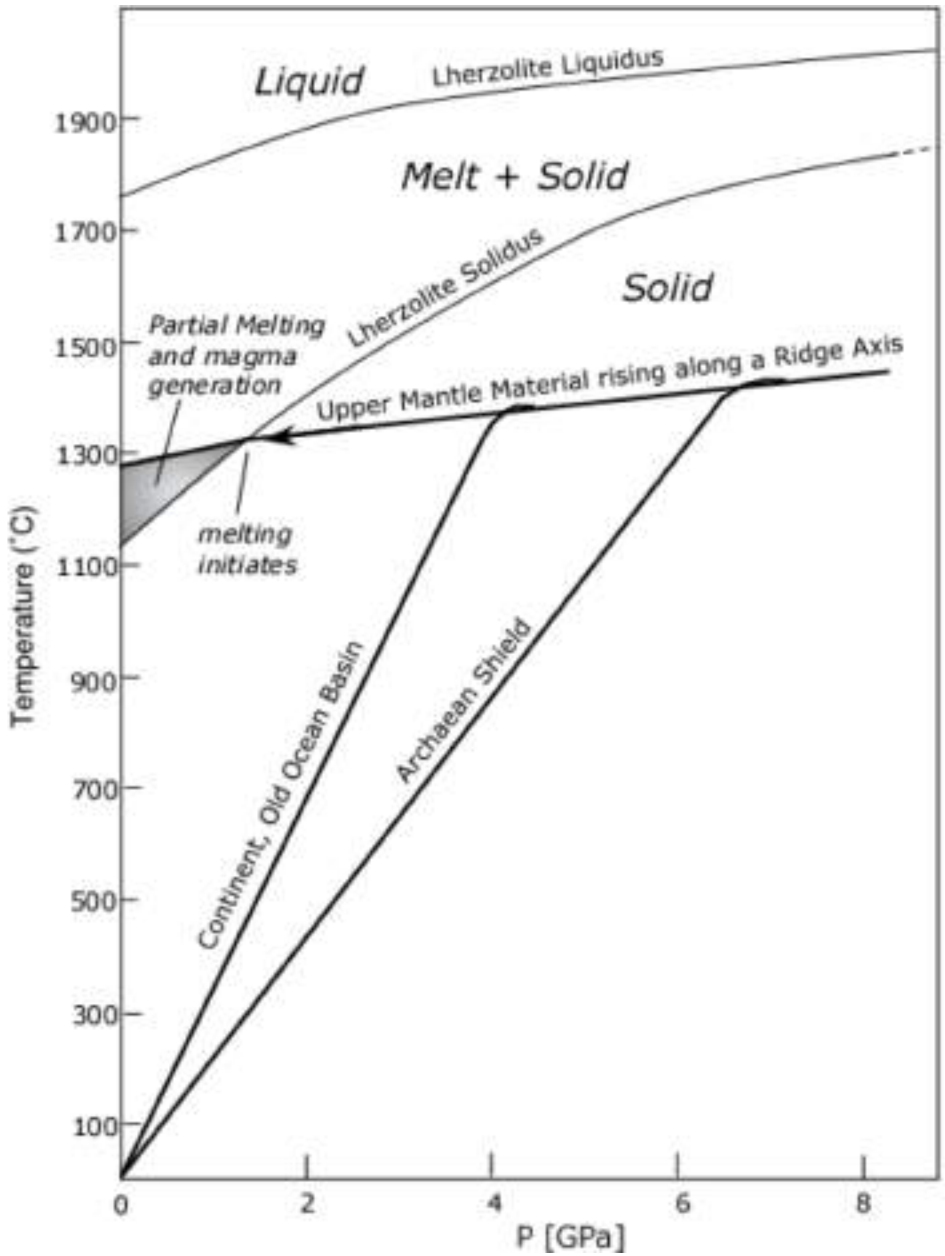


Questions

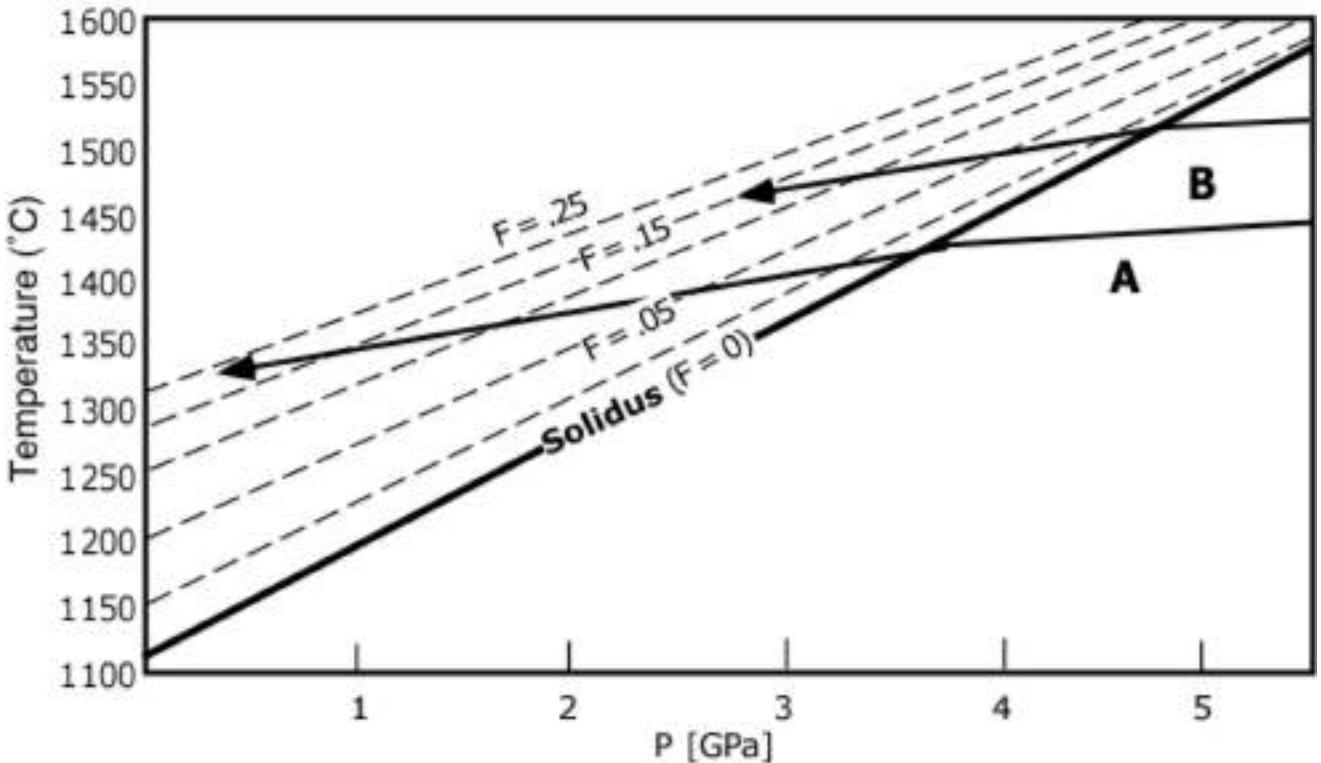


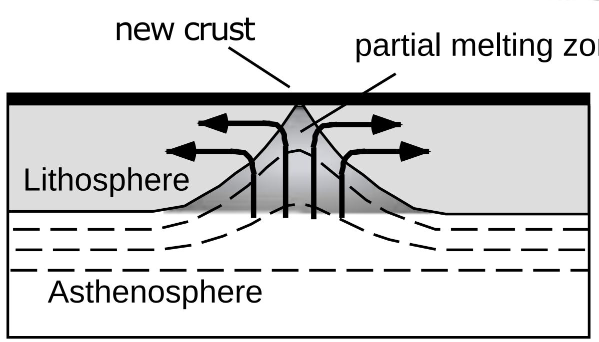
1. Which kind of rocks/melt you expect at A, B, C, D, E, F, G, H?
2. Which one is older: Oceanic/Continental crust?

Evolution of Magmas

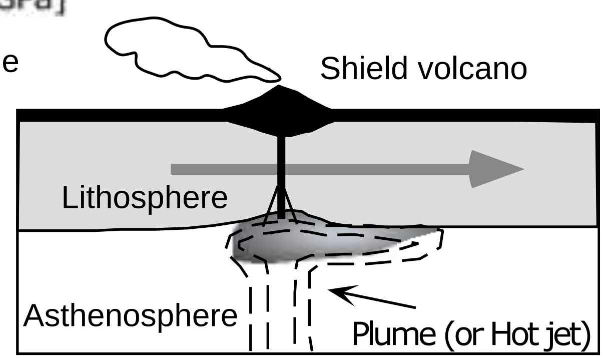


This diagram shows the solidus and liquidus of upper mantle lherzolite, adiabatic ascent path of mantle rock beneath a mid-oceanic ridge (MOR), and geothermal gradients in Archaean shield areas, stable continental platform areas and old (far away from ridge axis) ocean basin (redrawn after McKenzie and Bickle 1988). In this model, the Mid-ocean ridge adiabat represents the path taken by a parcel of mantle rock (asthenosphere) that rises and crosses lherzolite solidus at about 1.8 GPa, at which point it begins to melt. It continues to melt all the way up to the base of the crust. This partially molten region is depicted as the gray area here.





Passive Upwelling of Asthenosphere



Hot Plume impact on a moving Lithosphere

Formation of different kind of Magma

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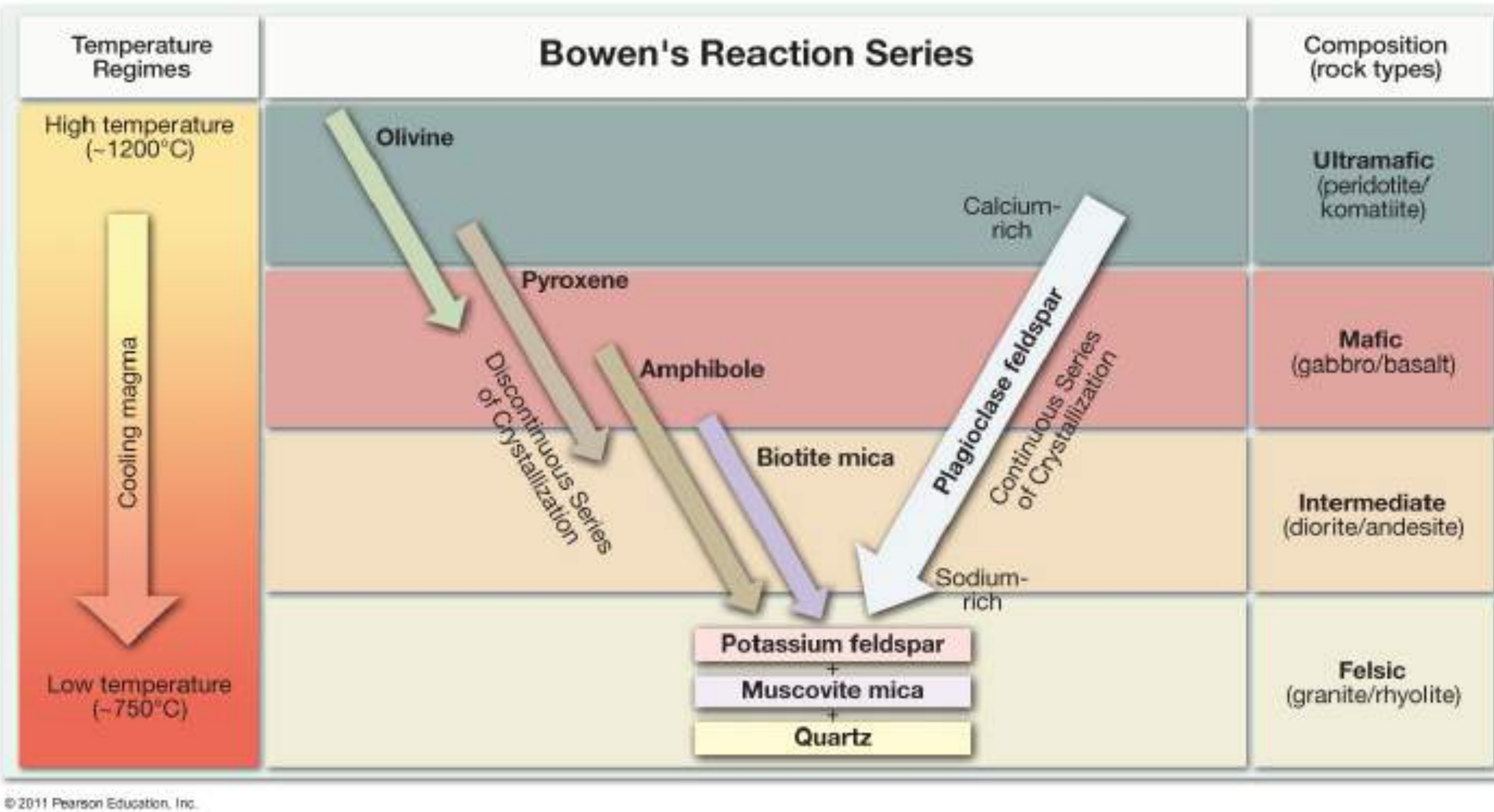
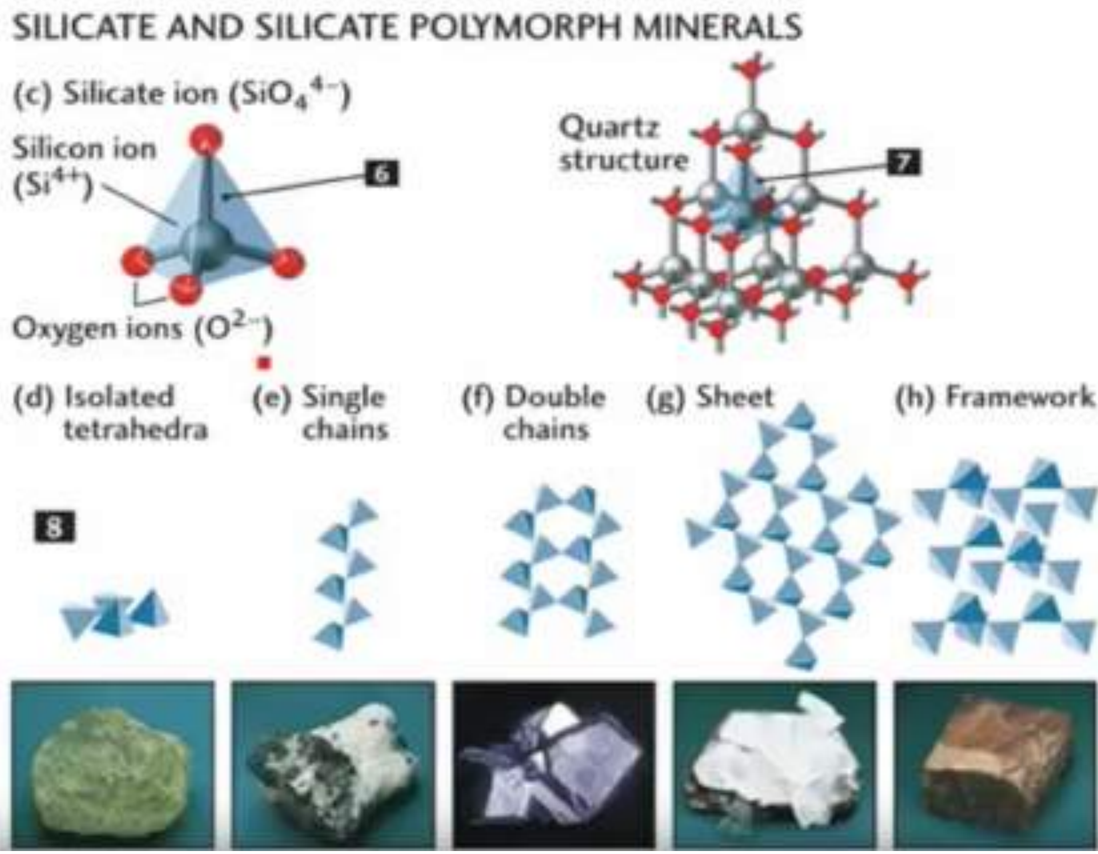
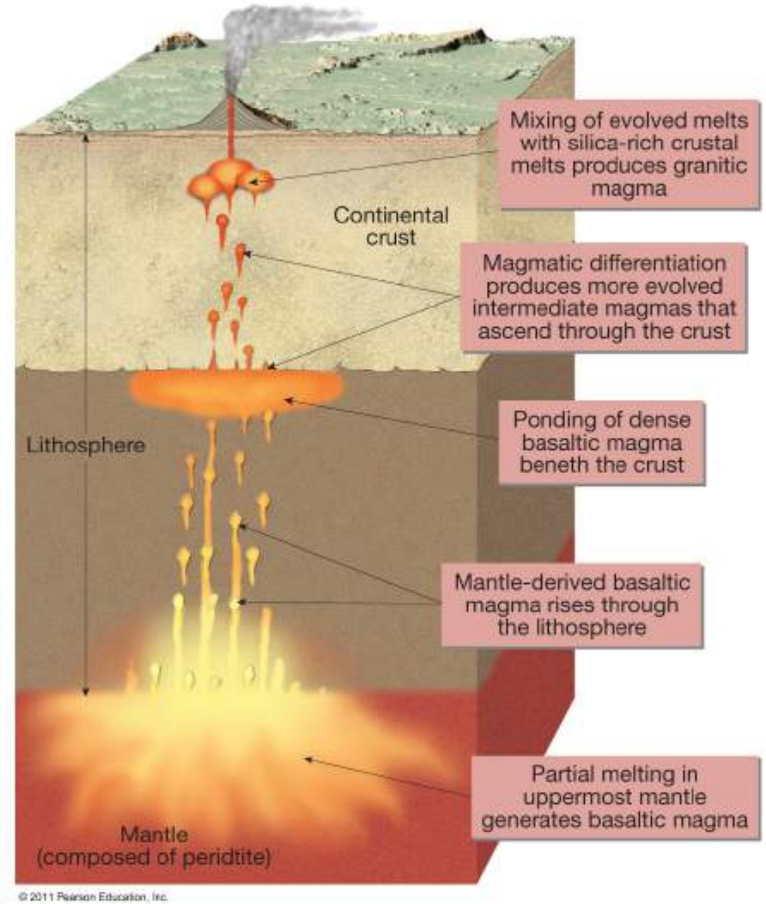
Volcanoes

Bowen’s Reaction Series



Order of crystal formation depends upon silicate structure





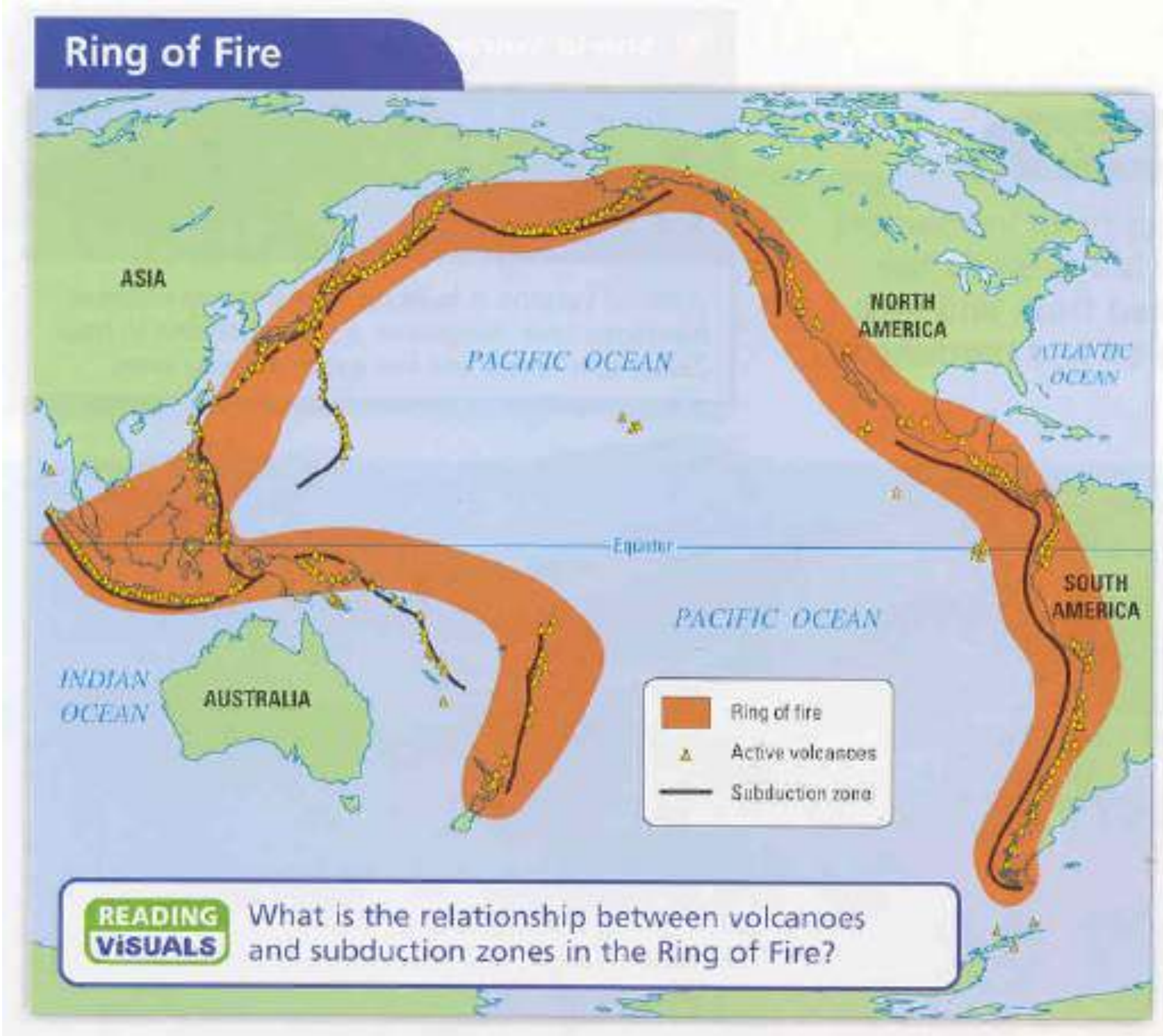
Volcanoes

An opening in Earth's crust through which molten rock, rock fragments, and hot gases erupt.

Where do volcanoes occur?

Most form along plate boundaries ….

1. in subduction zones (one plate sinks under another)
2. over hot spots
3. where plates are pulling apart



Materials Extruded from a Volcano

- 1. Lava flows
  - ~ 90% is basaltic in composition
  - ~ 1% is rhyolitic in composition

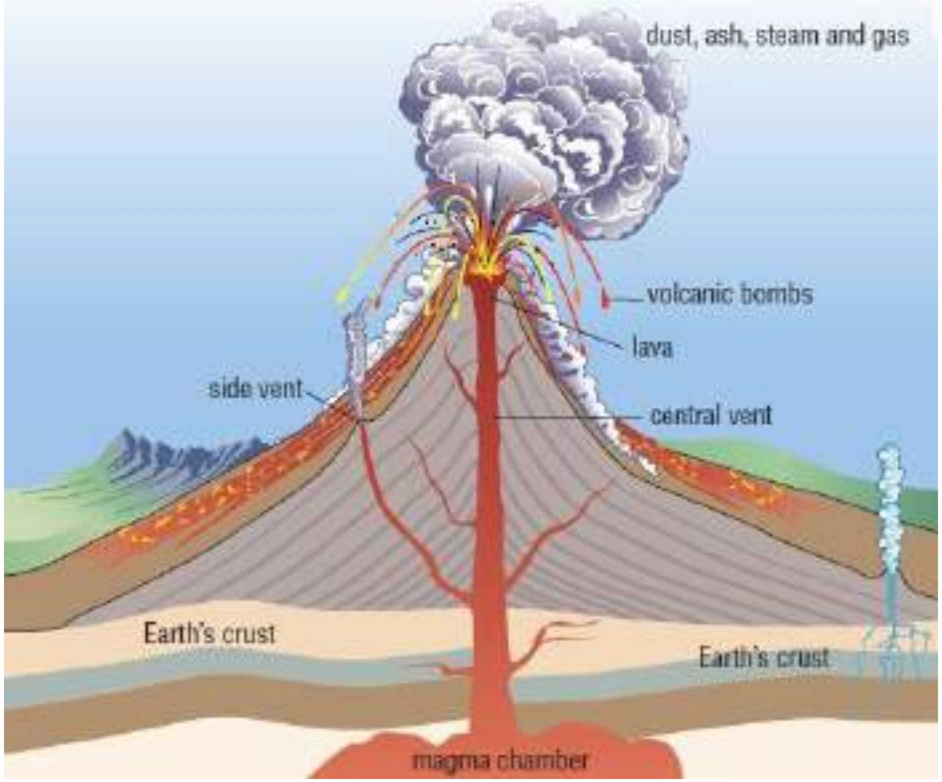
  a) *Aa flows* – rough jagged blocks, sharp edges

  b) *Pahoehoe flows* – smooth surfaces, more fluid

  c) *Lava tubes*

  d) *Block lavas* – common in case of andesitic and rhyolitic magmas

  e) *Pillow lavas* – outpourings of lava on the ocean floor



- Factors affecting viscosity:
  - Fluid basaltic lavas generally produce quiet eruptions.
  - Highly viscous lavas (rhyolite or andesite) produce more explosive eruptions.

A Pahoehoe Lava Flow

B.

Materials Extruded from a Volcano

- 2. Gases (volatiles)
  - ~ 1 to 6 % of the total weight

    ~ 70% water vapor

    ~ 15 % carbon dioxide (CO_2)

    ~ 5% nitrogen (N)

    ~ 5% sulfur dioxide (SO_2)

    ~ 5% chlorine, hydrogen, and argon
  - Natural source of air pollution

1. **Water Vapor:** more water=bigger explosion
2. **Trapped gases (water and CO_2):**

Easy escape (low pressure)=quiet eruption

Difficult to escape (high pressure)=explosive/violent eruption

Materials Extruded from a Volcano

- **3. Pyroclastic materials (fire fragments)**

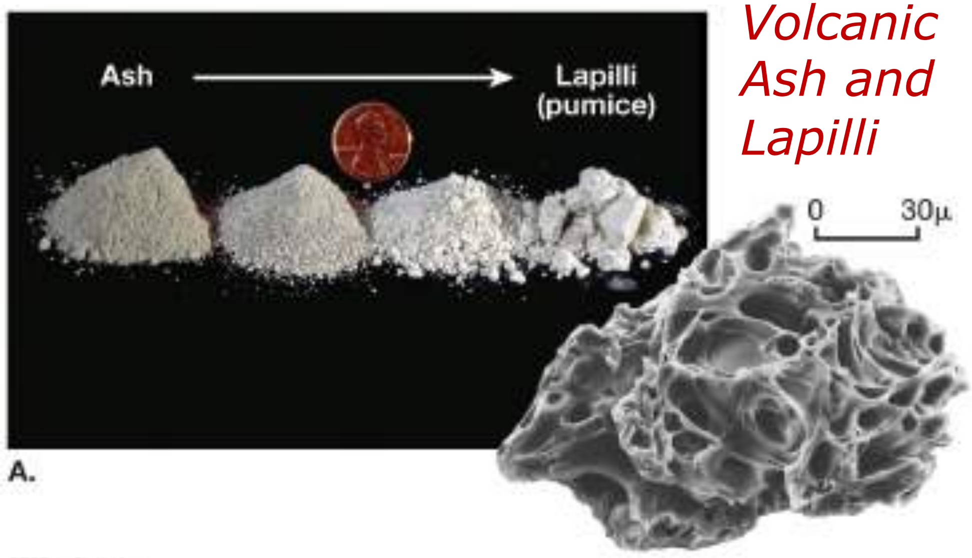
  Types of pyroclastic debris

  - **Ash and dust** - fine, glassy fragments (welded tuff)
  - **Lapilli** (little stones) - walnut-sized material
  - Particles larger than lapilli
    - **Blocks** - hardened or cooled lava
    - **Bombs** - ejected as hot lava

  Vesicular rocks:

  Scoria – vesicular ejecta that is a product of basaltic magma

  Pumice – vesicular ejecta that is a product of andesitic and rhyolitic magmas



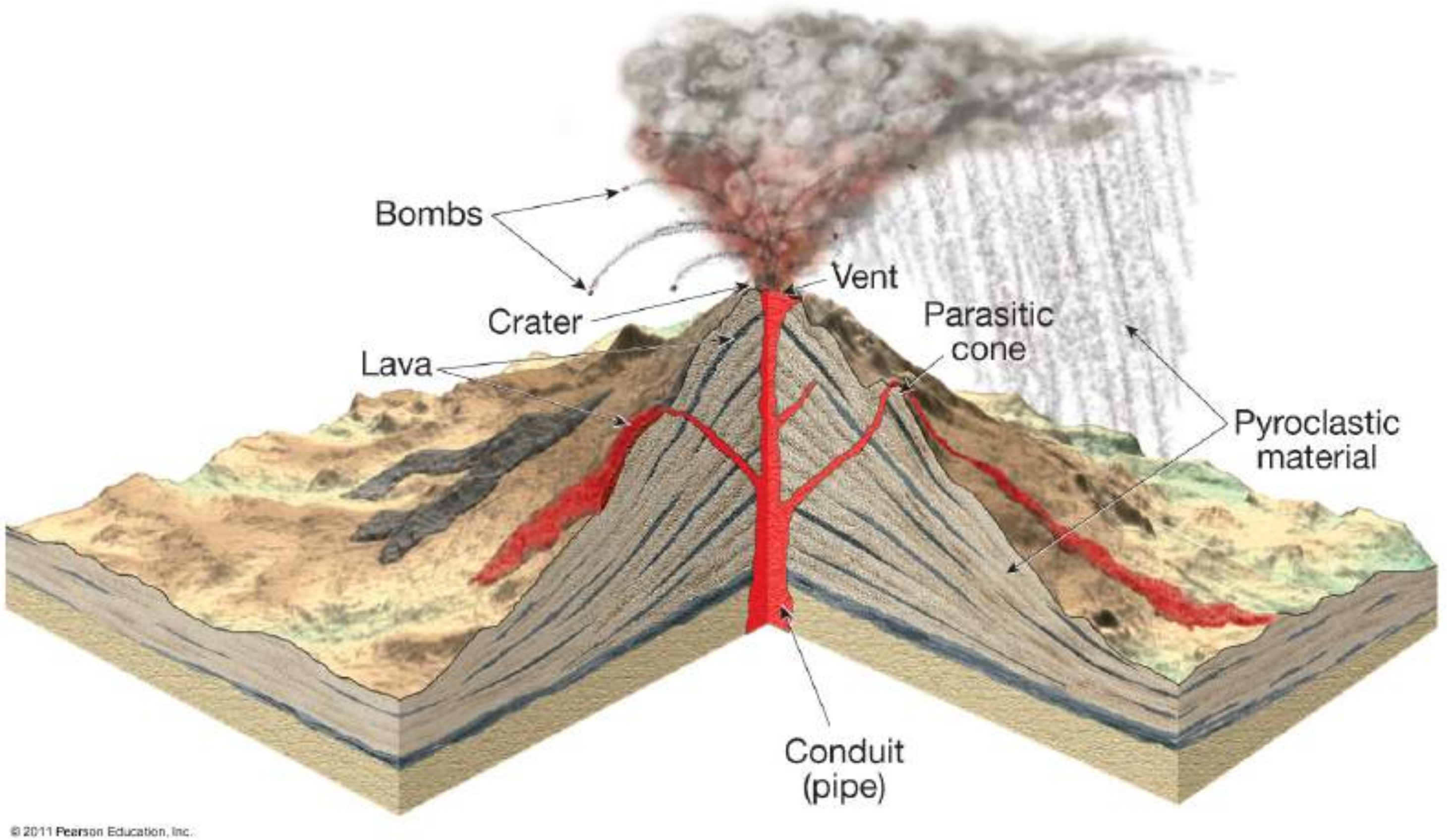
Volcanic Ash and Lapilli

Volcanic Bomb

Volcanoes

General features

- **Crater—A steep-walled depression at the summit, generally less than 1 km in diameter.**
- **Caldera—A summit depression typically greater than 1 km in diameter and produced by a collapse following a massive eruption.**
- **Vent—An opening connected to the magma chamber via a conduit (pipe).**
- **Volcano – successive eruption of lava and pyroclastic material**



Magma Composition

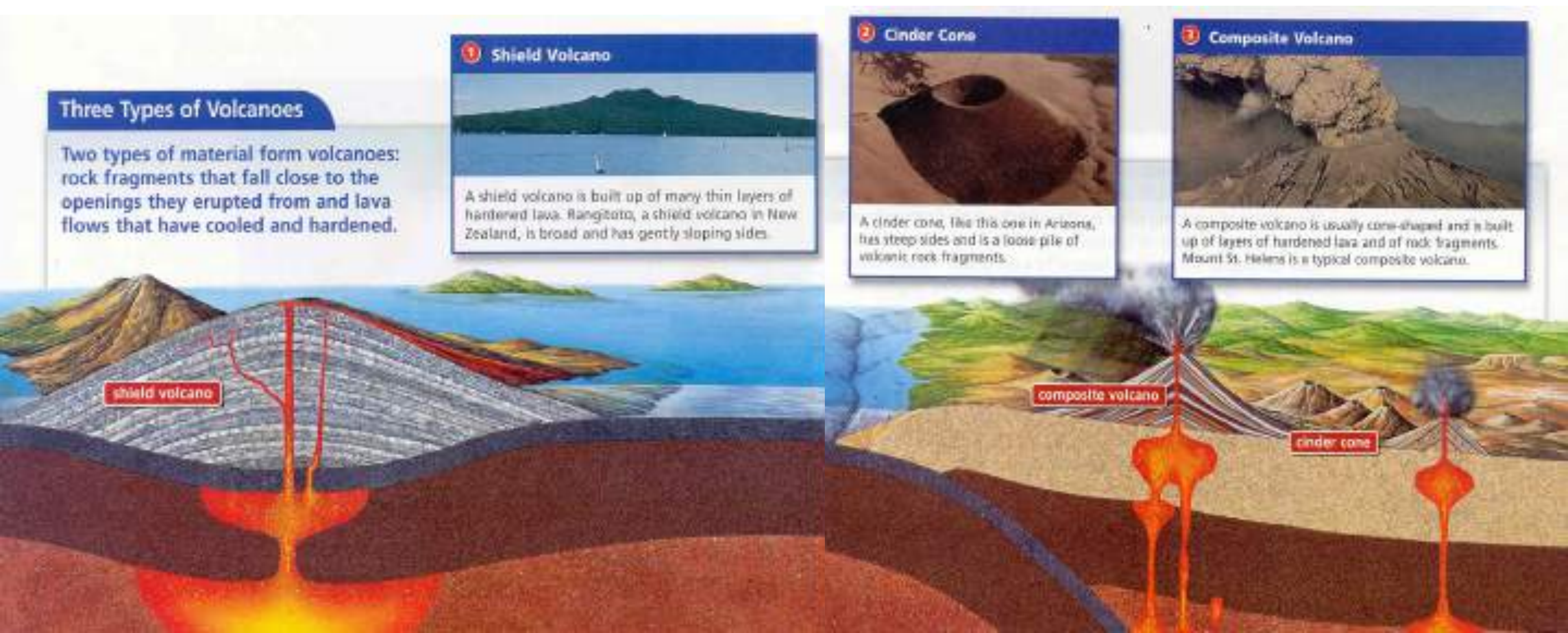
- Basaltic lava
  - Hawaiian Volcanoes, including
    - Kilauea
    - Mona Loa
  - Iceland
    - Heimaey
    - Hekla

- Granitic volcanoes are
  - Yellowstone Caldera
    - It is a super volcano!
  - Katmai, Alaska
    - Last eruted in 1912.

- Andesitic Lava
  - Mount Pelee, Martinique (Famous for the May 8, 1902 eruption which killed 29,000 people and destroyed the city of St. Pierre. This is the largest number of <u>causalities</u> for a volcanic eruption this century).
  - Mayon, Phillipines (It is the most active volcano in the Philippines. Since 1616, Mayon has erupted 47 times.
  - It's 1814 eruption killed 1,600.)

Basic Volcano shapes

The shape and size are determined by the type of magma feeding it.

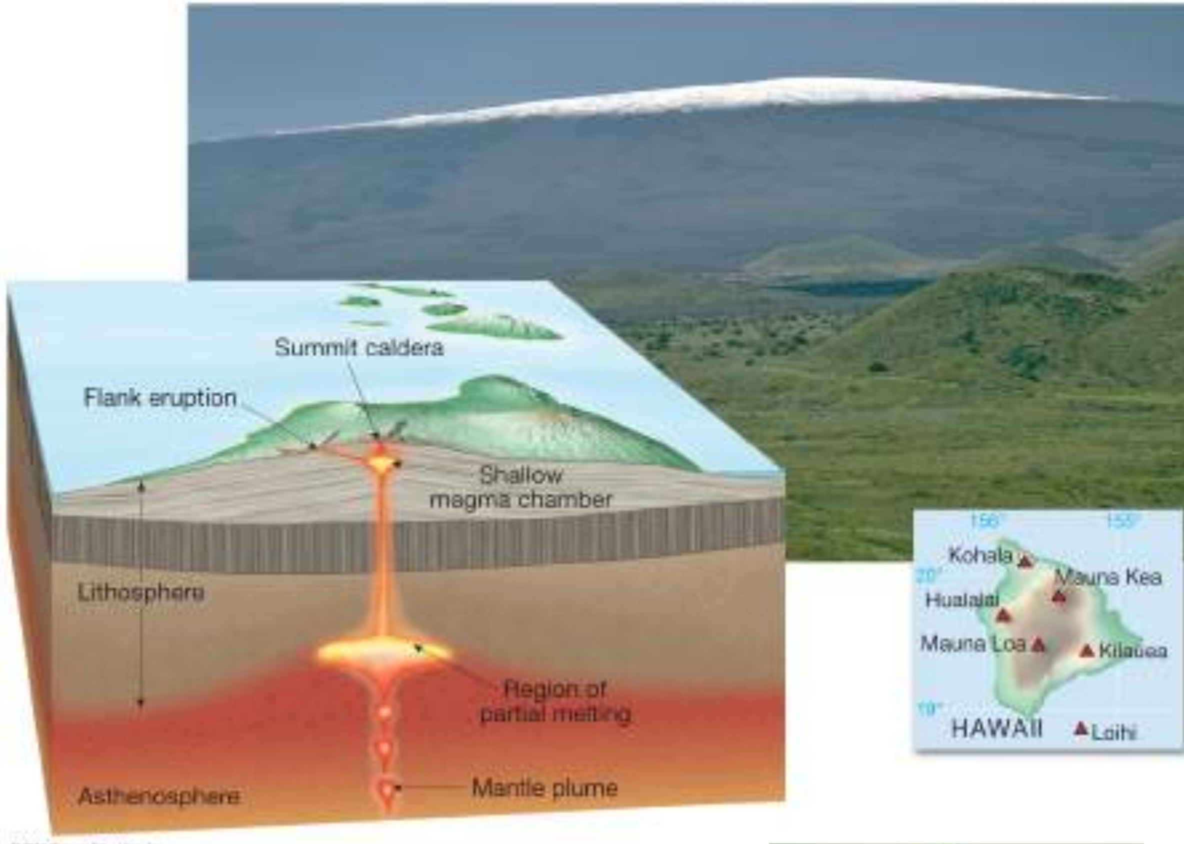


Types of Volcanoes

1. Shield volcano

- Formed by quiet eruptions of slow-moving lava flows
- Basaltic lava builds up in flat layers
- Largest with gently sloping sides
- Broad, slightly dome-shaped
- Generally covers large areas
- Majority begin on the ocean floor as seamounts
- Produced by mild eruptions of large volumes of lava
- Mauna Loa in Hawaii is a good example.

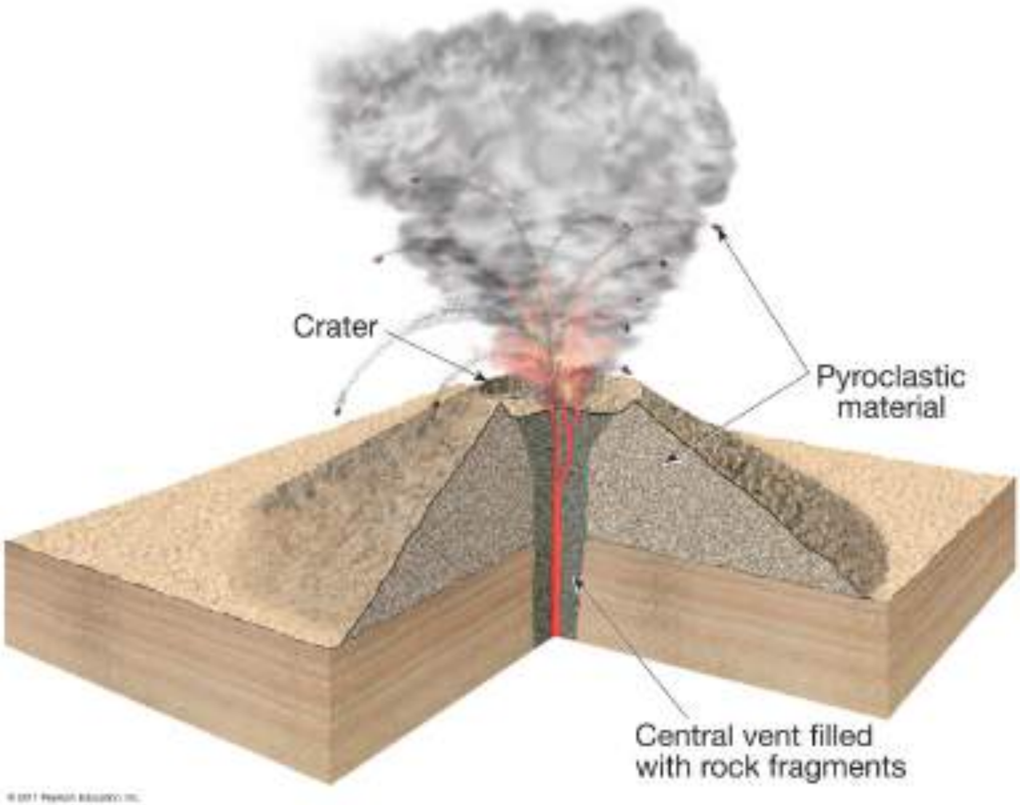
Mauna Loa—A Shield Volcano



Types of Volcanoes

2. Cinder (scoria) cone

- Built from ejected lava (mainly cinder-sized) fragments. Lava cools into different sizes of volcanic material called tephra.
- Steep slope angle (~ 30^{O} – 40^{O})
- Rather small size and usually < 300 m in height
- Frequently occur in groups
- Presence of large, deep craters
- Generally produced by a single, short-live eruptive event (95% - less than 1 year)



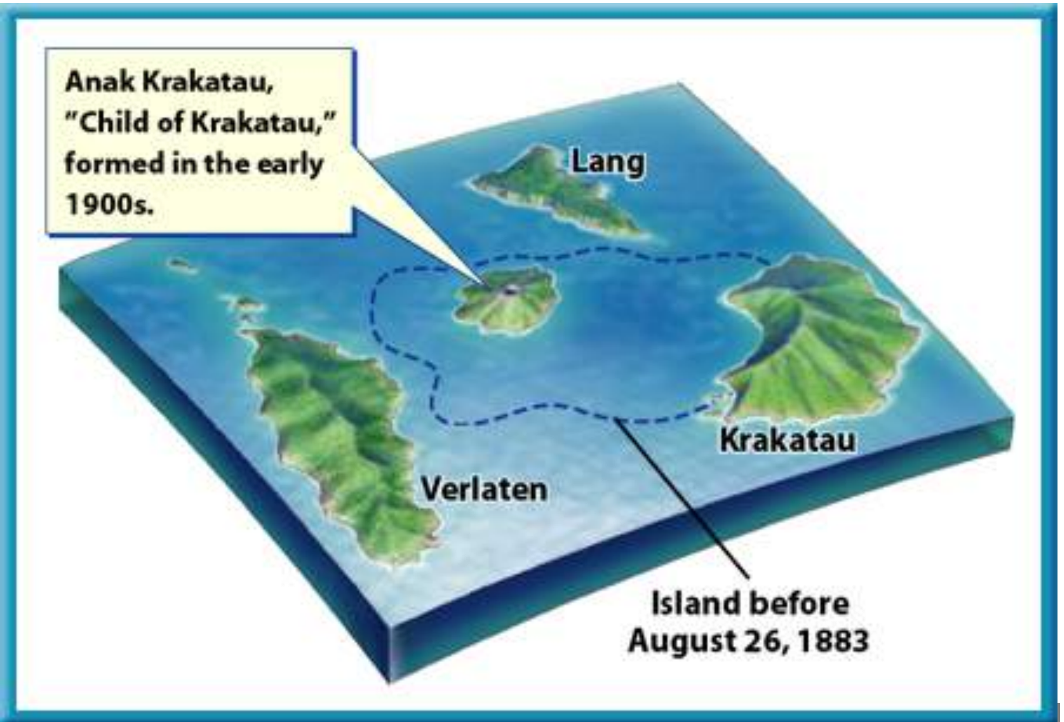
Example: Parícutin Volcano in Mexico

Types of Volcanoes

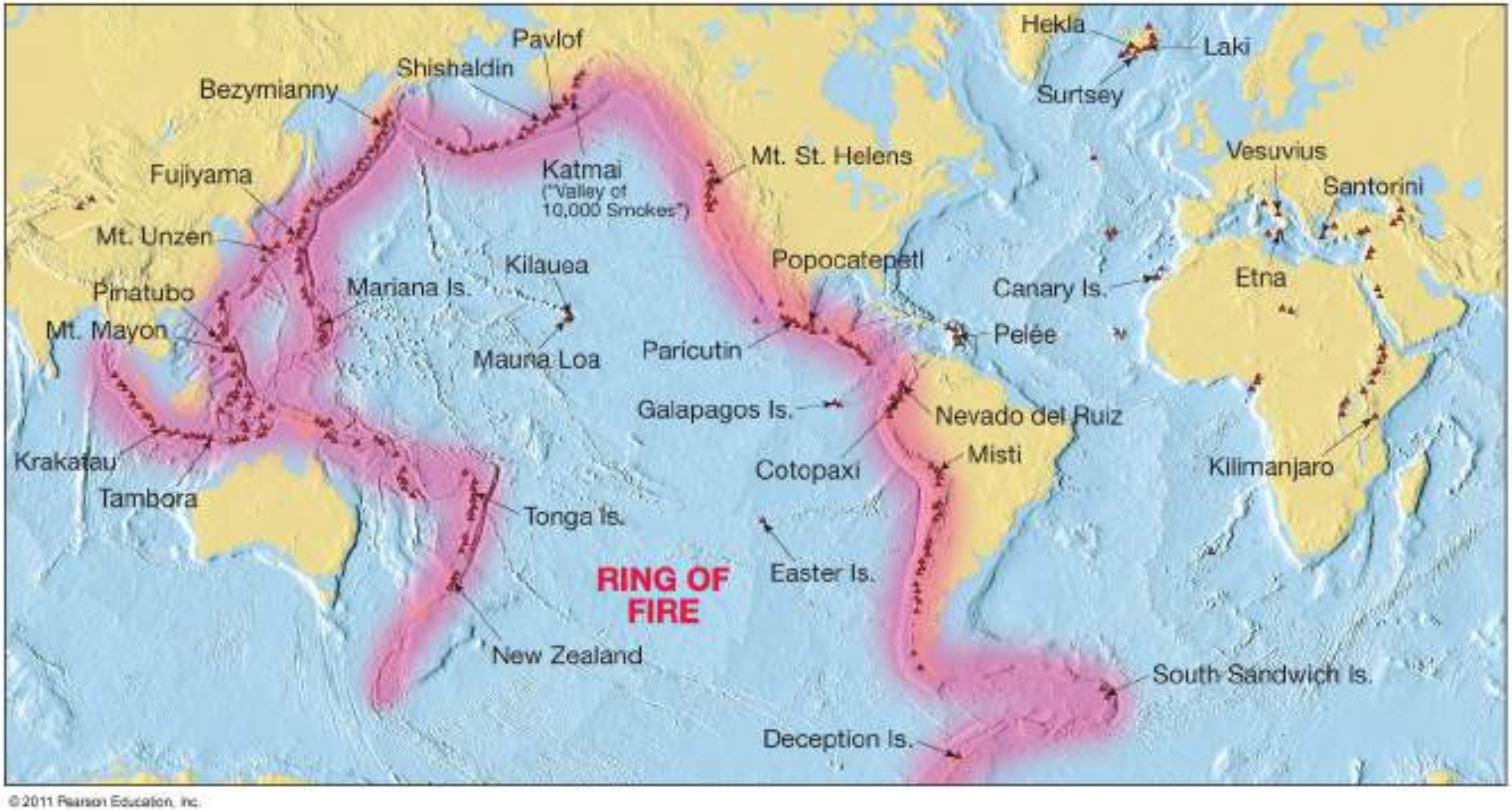
- Composite cone (stratovolcano)
  - Most are located adjacent to the Pacific Ocean (e.g., Mount Fujiyama and Mount St. Helens) (Ring of Fire).
  - Large, classic-shaped volcano (thousands of feet high and several miles wide at base)
  - Composed of interbedded lava flows and layers of pyroclastic debris
  - Associated with *SUBDUCTION ZONES*

Mount Fujiyama—A Composite Volcano

Example of Composite Volcano



- **Krakatau**
  - One of the most violent eruptions in recent times occurred on an island in the Sunda Straits near Indonesia in August of 1883.
  - Krakatau, a volcano on the island, erupted with such force that the island disappeared.
  - Killed 36,000 people most were killed by a giant tsunami and destroyed 160 villages
  - Fine ashes from the eruption were carried by upper level winds as far away as New York City
  - Volcanic dust lowered global temperatures for five years, this caused


Pavlof
Shishaldin
Bezymianny
Fujiyama
Katmai
("Valley of 10,000 Smokes")
Mt. Unzen
Kilauea
Pinatubo
Mariana Is.
Mt. Mayon
Mauna Loa
Krakatau
Tambora
Tonga Is.
New Zealand
RING OF FIRE
Mt. St. Helens
Popocatepetl
Paricutin
Galapagos Is.
Cotopaxi
Easter Is.
Deception Is.
Nevado del Ruiz
Misti
Hekla
Laki
Surtsey
Vesuvius
Santorini
Etna
Canary Is.
Pelée
Kilimanjaro
South Sandwich Is.
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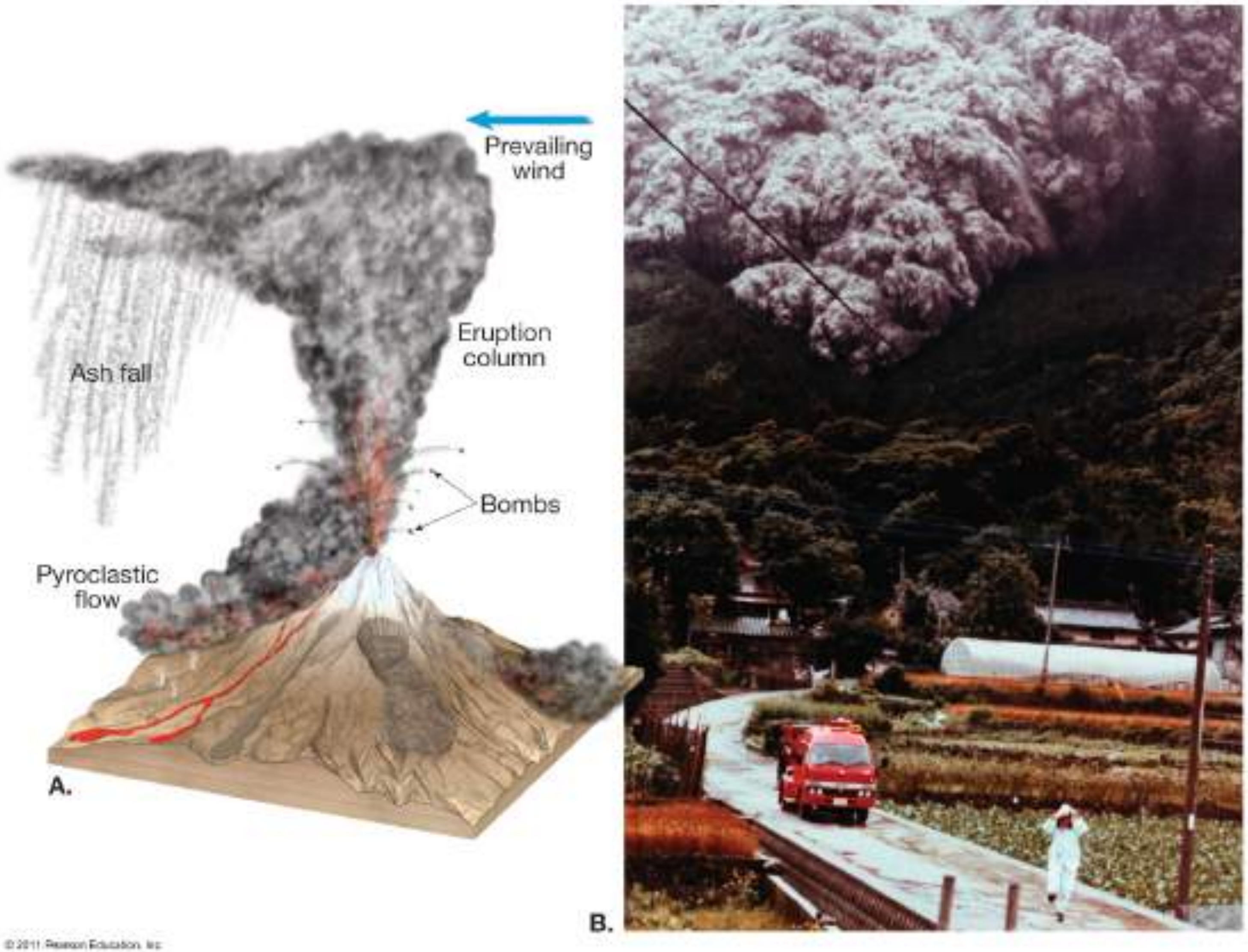
Volcanoes

- Composite cones
  - Most violent type of activity (e.g., Mount Vesuvius)
  - Often produce *nueé ardentes* (glowing avalanches)
    - Fiery pyroclastic flows made of hot gases, infused with ash and other debris
    - Move down the slopes of a volcano at speeds up to 200 km per hour
  - May produce a *lahar*, which is a volcanic mudflow
    - » Volcanic debris becomes saturated with water and rapidly moves down steep volcanic slopes

A Pyroclastic Flow

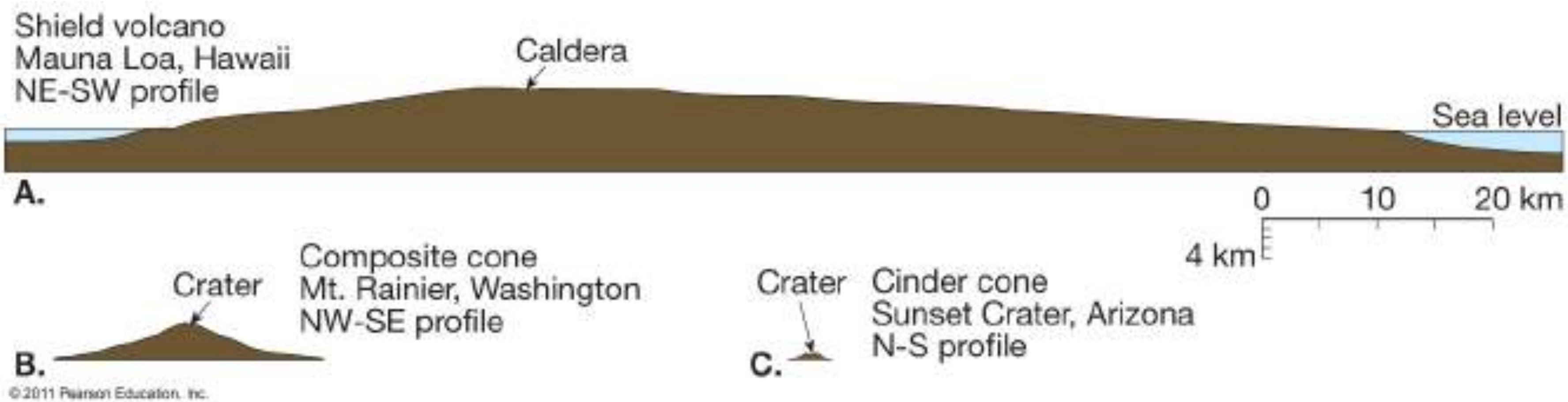


A.

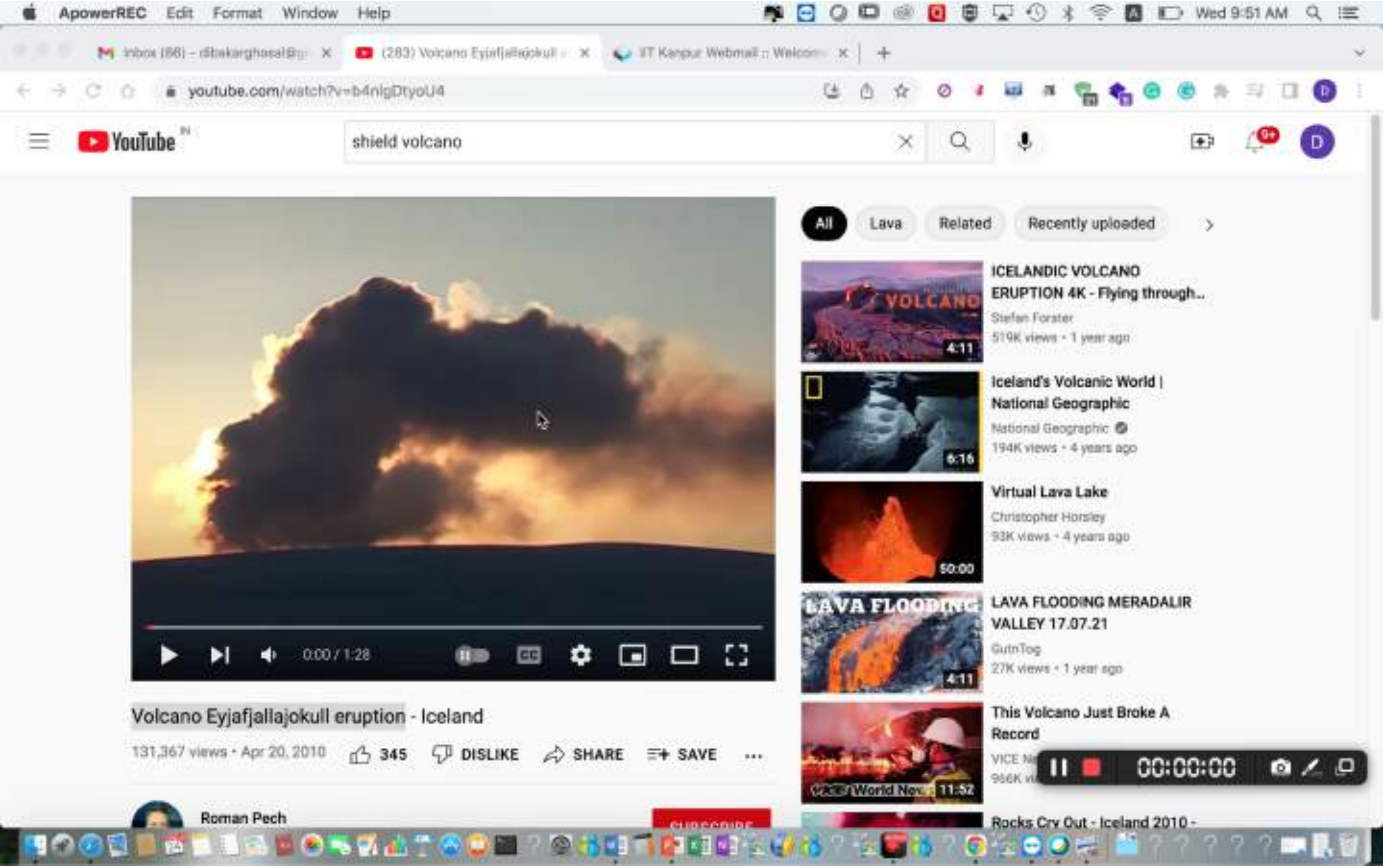
B.

The remains of human victims were quickly buried by falling ash and subsequent rainfall caused the ash to harden. Over the centuries, the remains decomposed which created cavities discovered by nineteenth-century excavators. Casts were then produced by pouring plaster into the voids.

A Size Comparison of the Three Types of Volcanoes



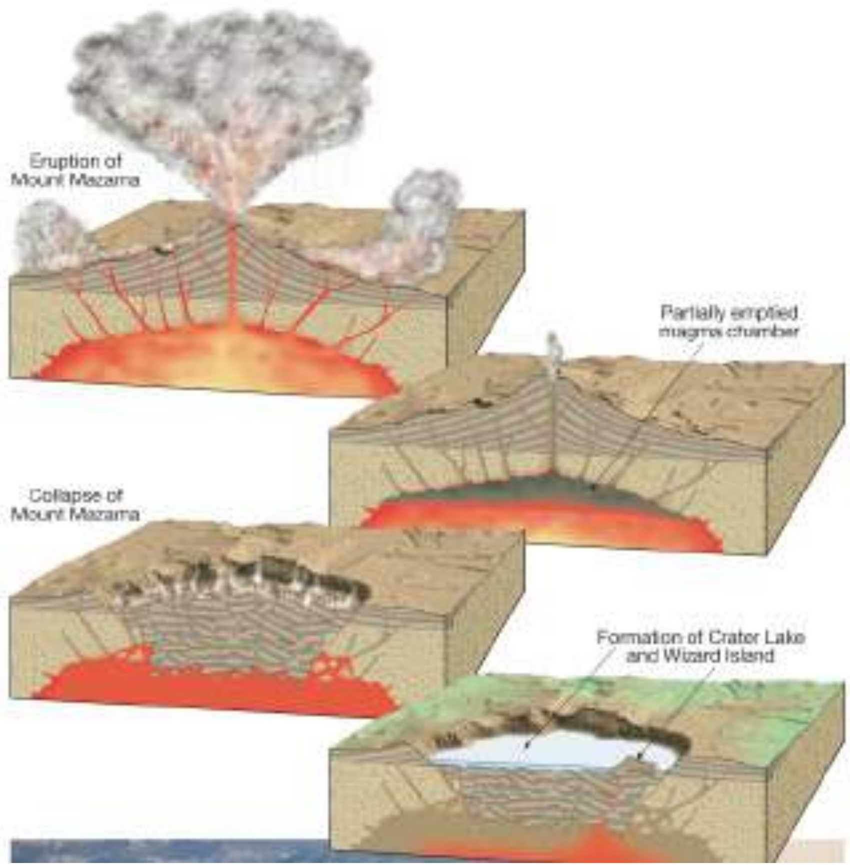
Volcano Eyjafjallajokull (from Iceland)



Other Volcanic Landforms

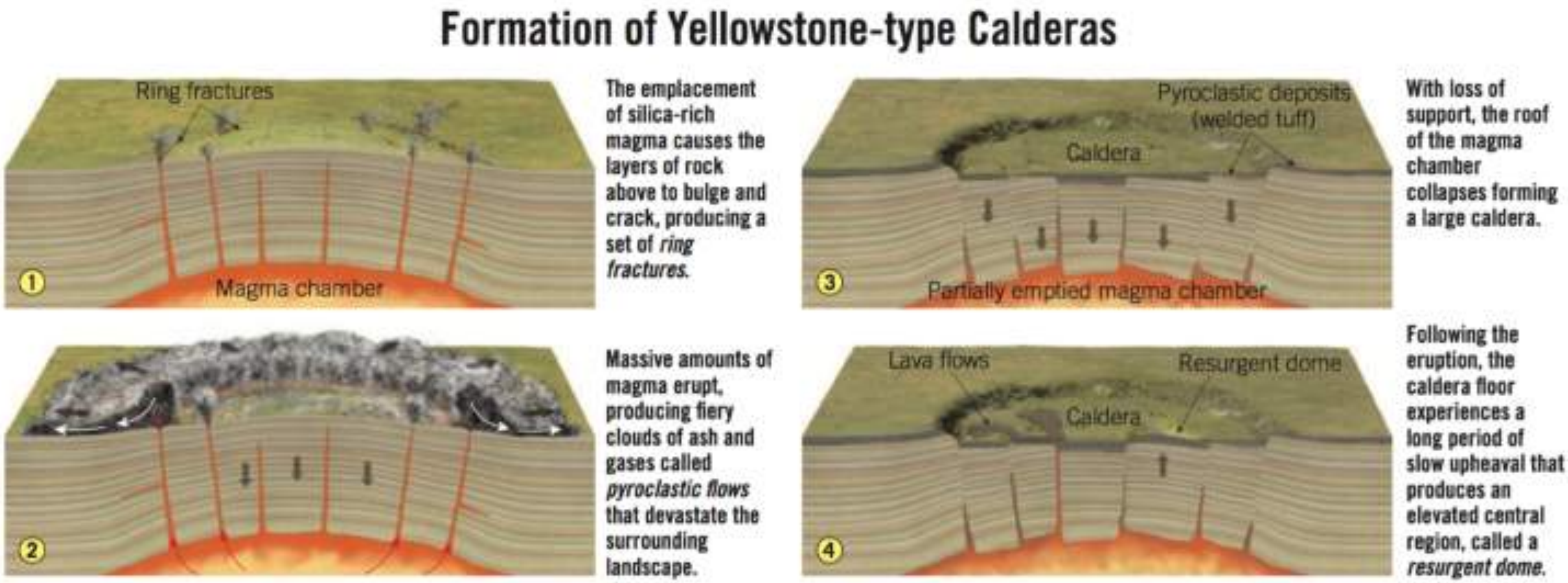
- **1. Calderas**
  - **Steep-walled depressions at the summit**
  - **Size generally exceeds 1 km in diameter**
  - **3 types:**
    - » **Crater Lake-type calderas (collapse of the summit of a composite volcano after an explosive eruption)**
    - » **Hawaiian-type calderas (formed by gradual subsidence as magma drained laterally from the magma chamber)**
    - » **Yellowstone-type calderas (the collapse of a large area, caused by the discharge of colossal volumes of silica-rich pumice and ash along ring fractures)**

Crater Lake—A Caldera in Oregon



- 10 km diameter
- 1175 m deep

Caldera-Yellowstone type



Other Volcanic Landforms

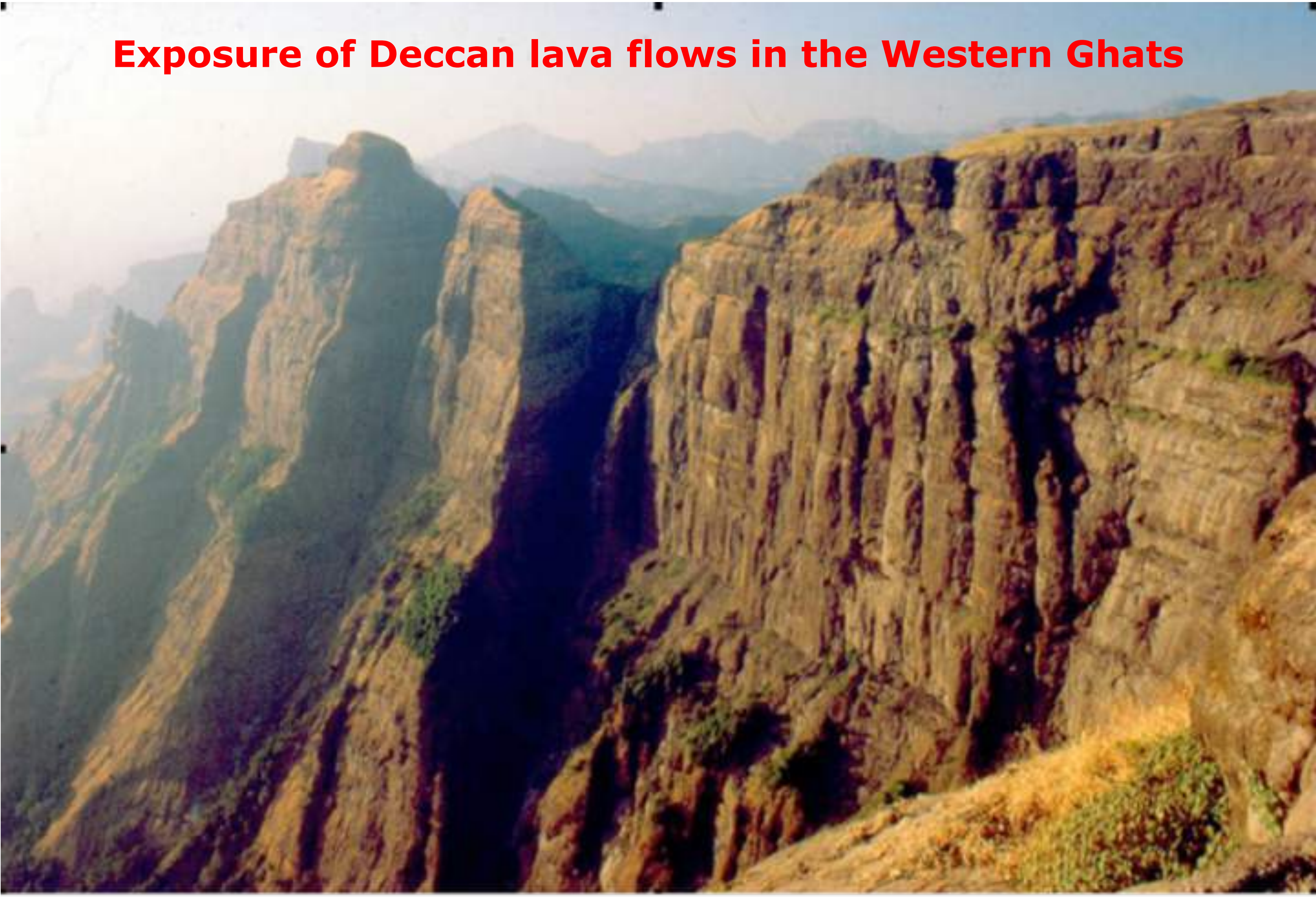
2. Fissure eruptions and basalt plateaus

- **Massive amount of fluid basaltic lava extruded from crustal fractures called fissures**
- **Columbia River Plateau – 200,000 km^2**
- **Deccan Traps – 500, 000 km^2**
- **Ontong-Java Plateau (submarine)**

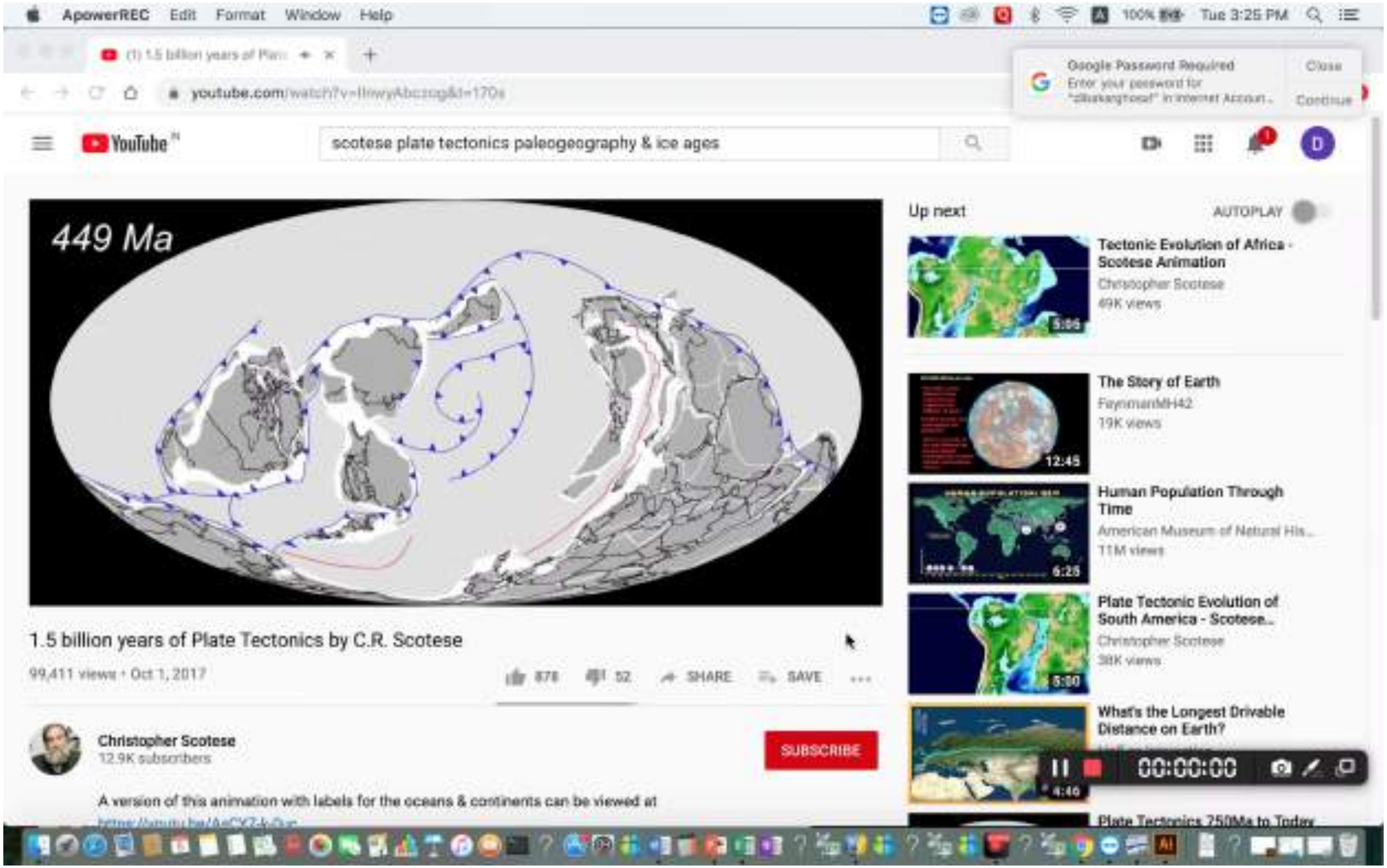
B.

The Columbia River Basalts

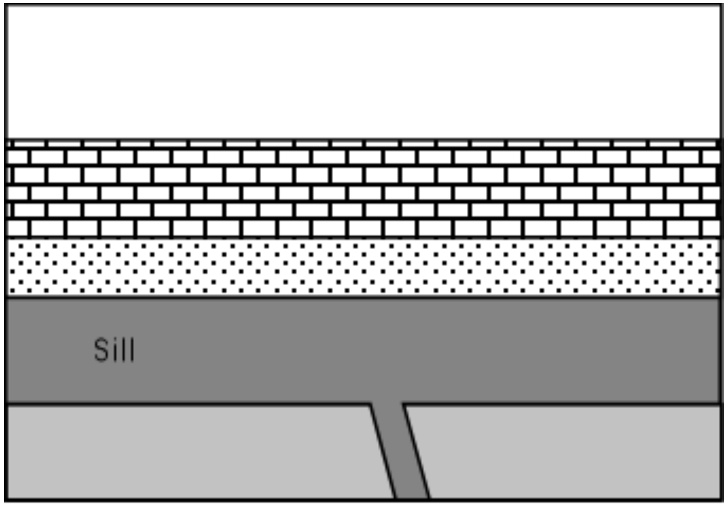
Exposure of Deccan lava flows in the Western Ghats

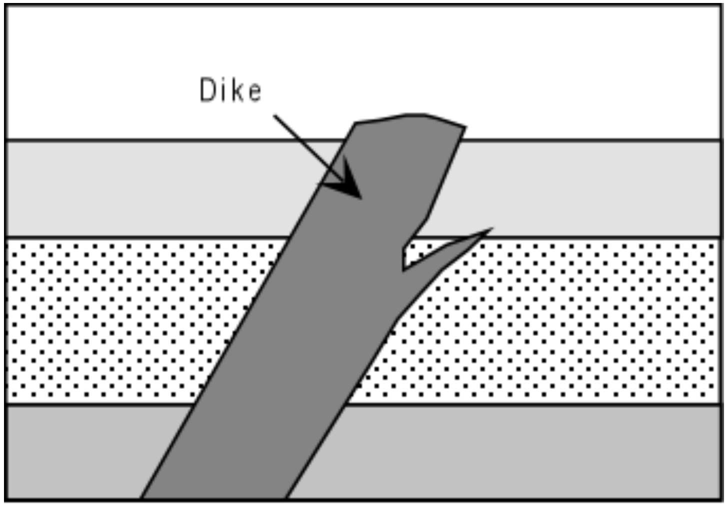


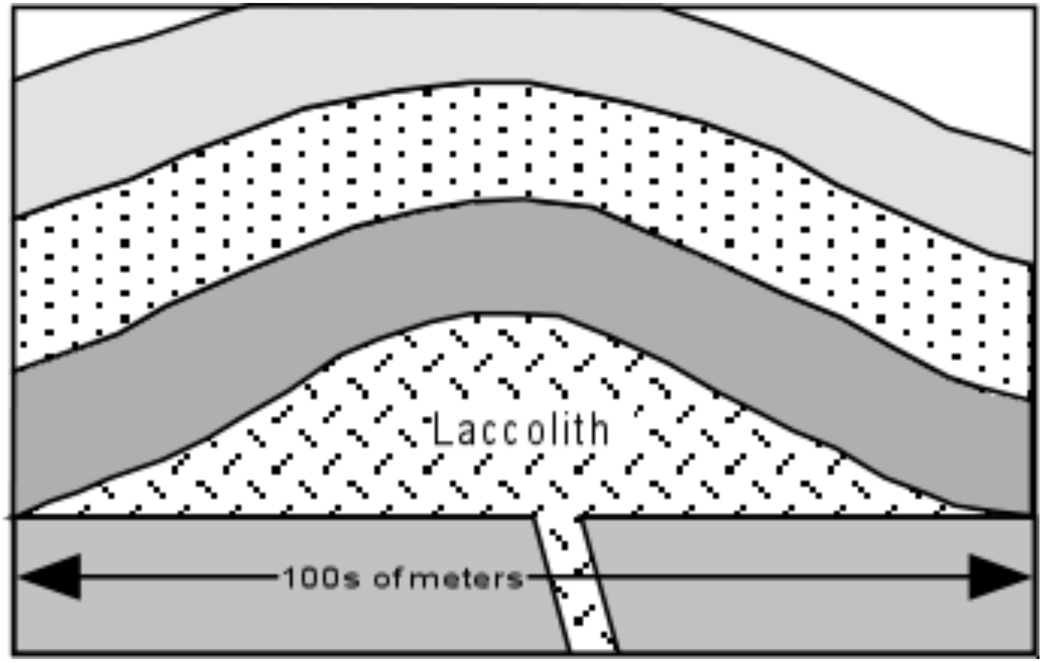
Deccan trap formation



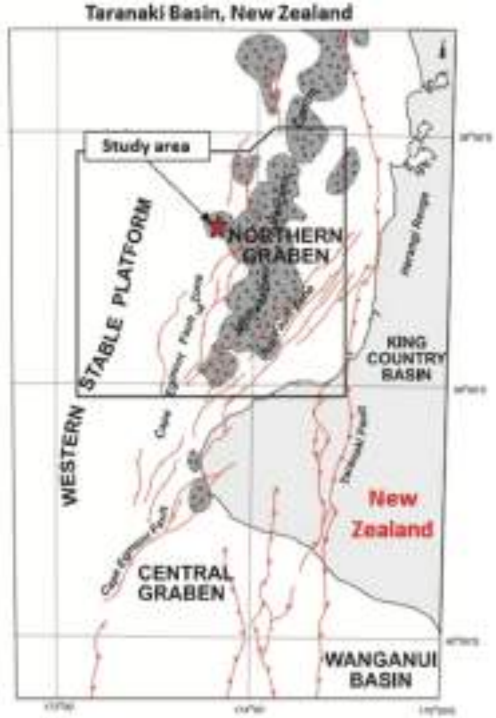
Dike/Sill/Laccolith

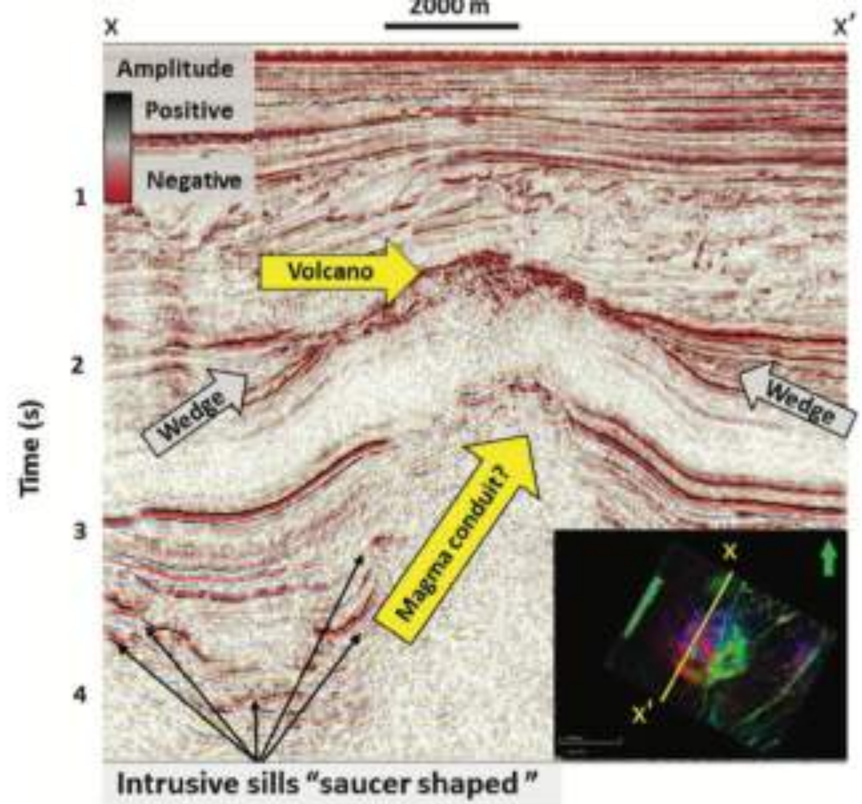


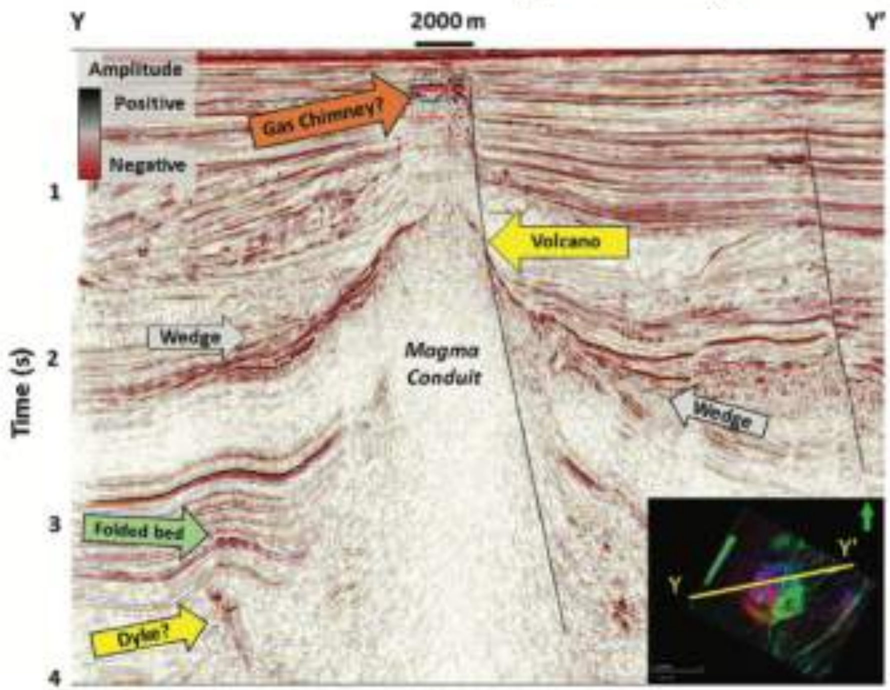


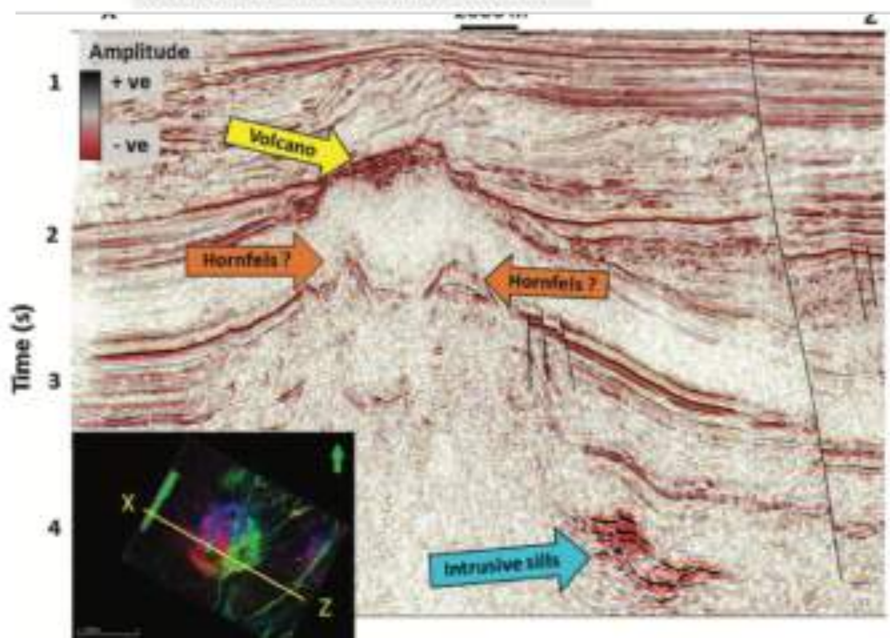


Examples of Submarine buried volcanoes



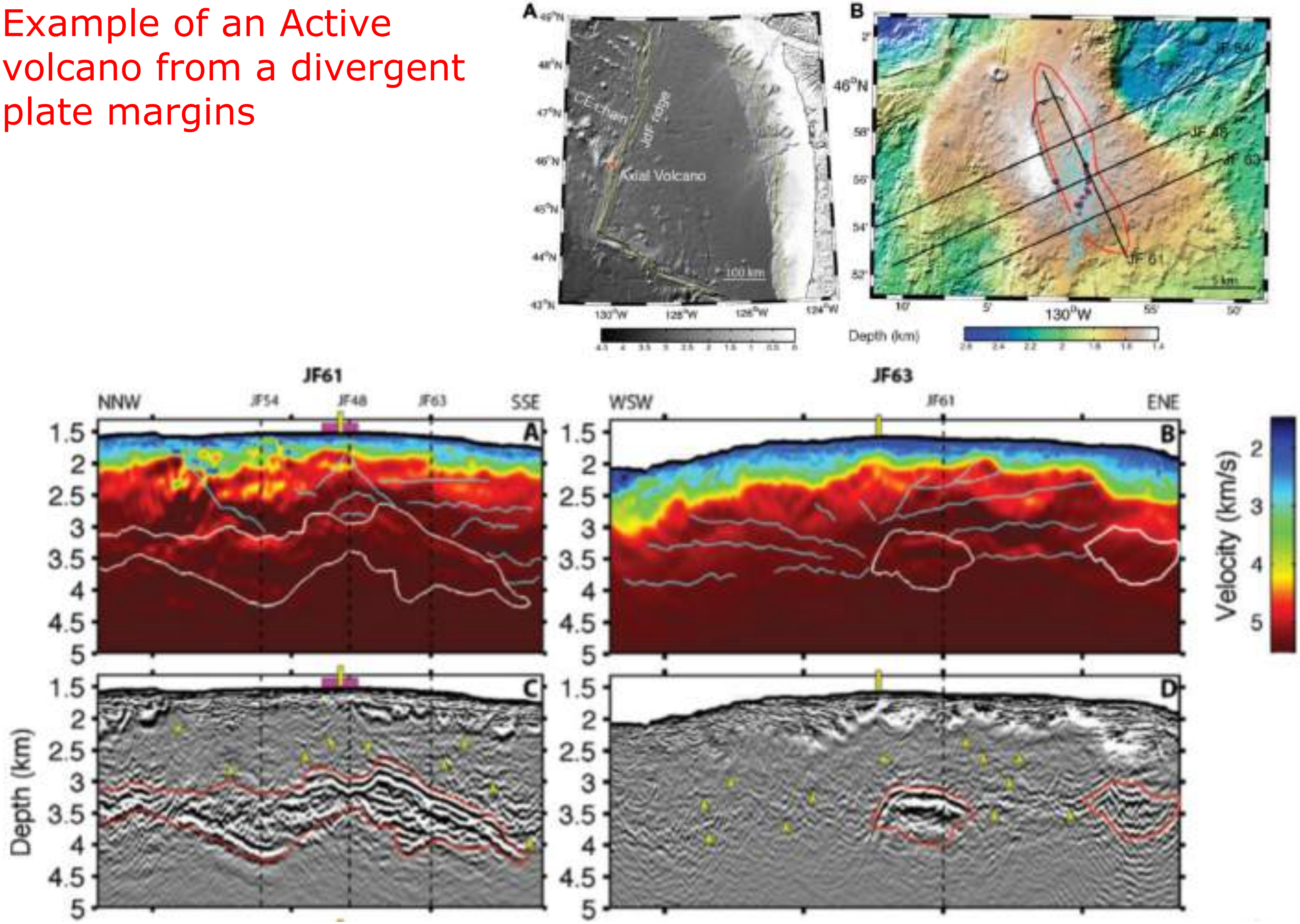






Infante-Paez and Marfurt, (2017)

Example of an Active volcano from a divergent plate margins



Arnulf et al., (2014)

Materials From Volcanic Eruptions Affect Earth		
Land	**Air**	**Water**
Lava	Poisonous Gases*	Hot Springs
Volcanic Ash*	Adds to Acid Rain	Geysers
Landslides (can cause tsunamis)	Haze	Fumaroles
Mudflows	Lower Temperature	Deep -Sea Vents

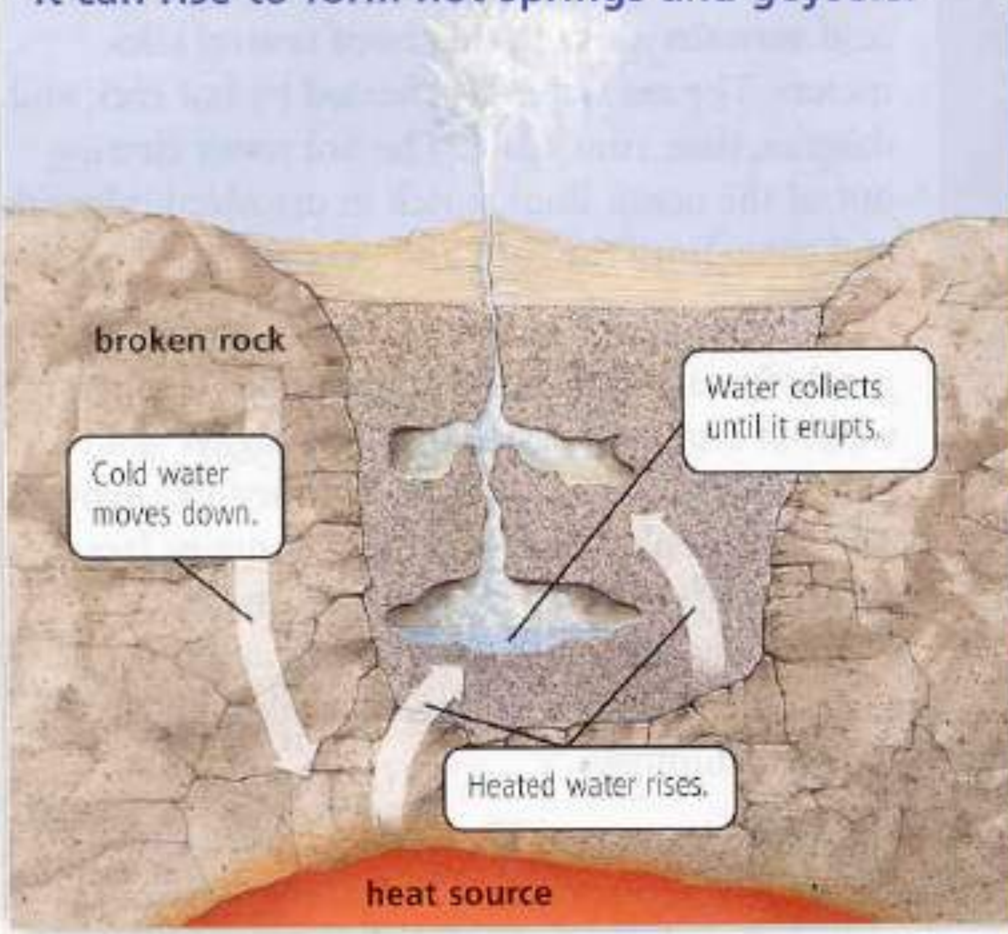
***These can get in the jet stream and affect the weather around the world for months or years**

****There can be benefits: richer farmland and beautiful landscapes**

Volcanoes Affect Earth's Land, Air, and Water

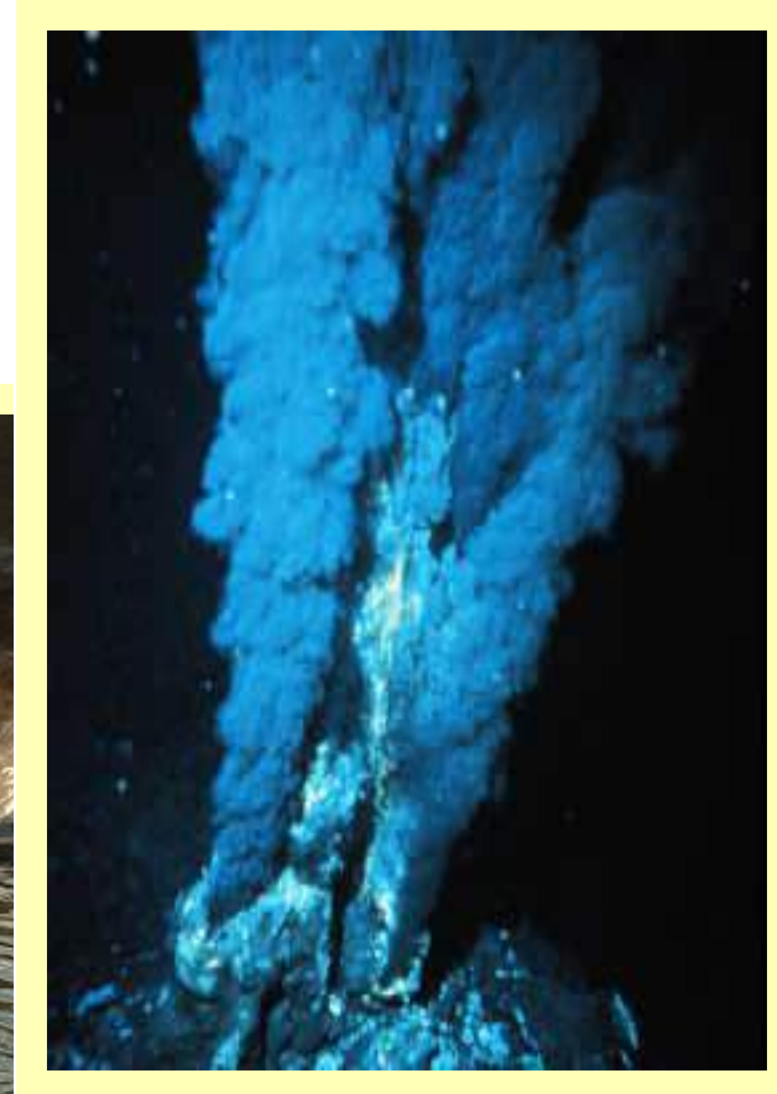
Geysers

Rainwater can sink through cracks in rock. If it is heated within Earth, it can rise to form hot springs and geysers.

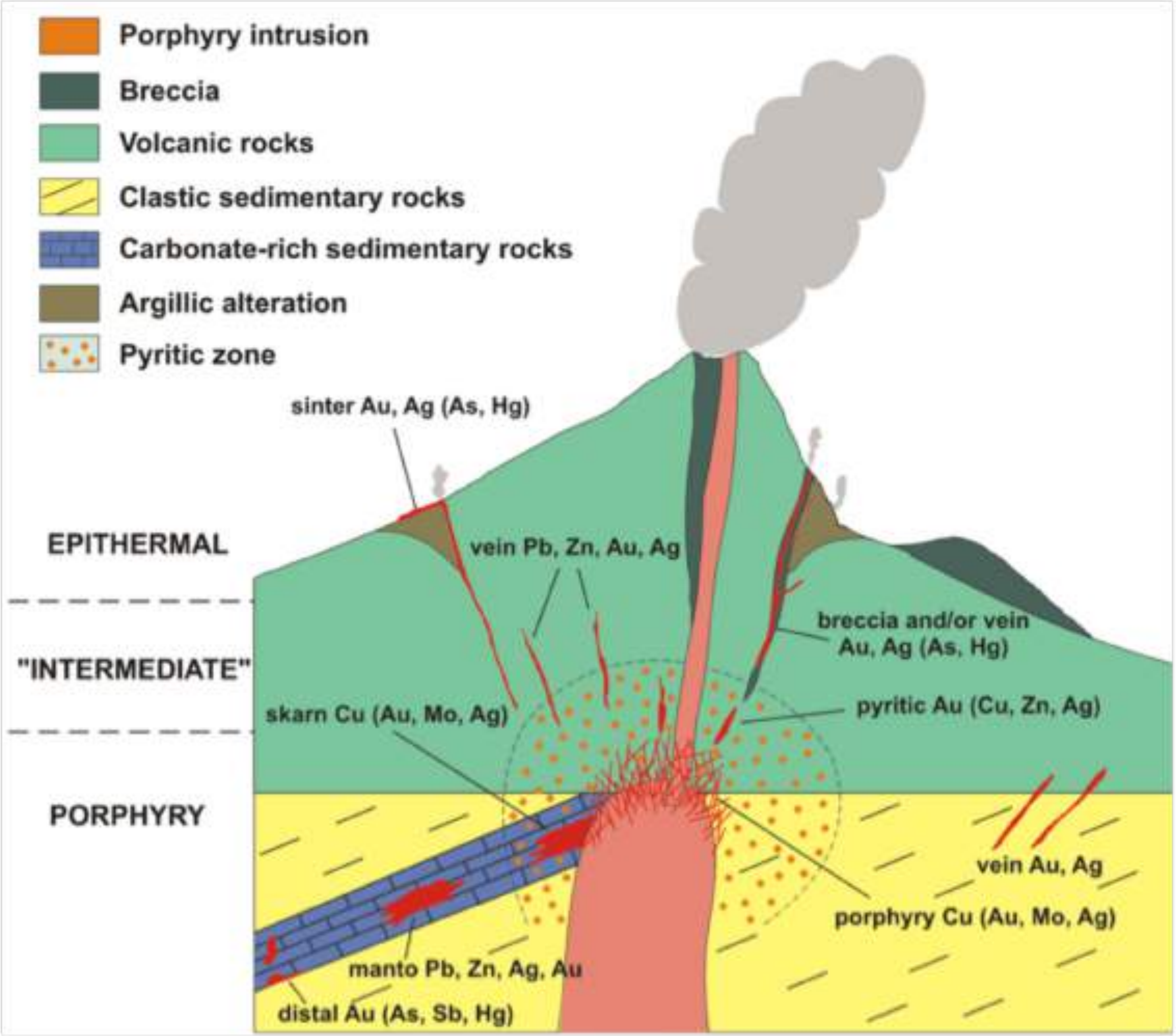


Old Faithful geyser in Yellowstone National Park erupts more often than any other large geyser. Heated water is forced up into the air through a narrow channel.

Deep-Sea Vent



Hot Spring


Porphyry intrusion
Breccia
Volcanic rocks
Clastic sedimentary rocks
Carbonate-rich sedimentary rocks
Argillic alteration
Pyritic zone
sinter Au, Ag (As, Hg)
EPITHERMAL
vein Pb, Zn, Au, Ag
"INTERMEDIATE"
breccia and/or vein
Au, Ag (As, Hg)
skarn Cu (Au, Mo, Ag)
pyritic Au (Cu, Zn, Ag)
PORPHYRY
vein Au, Ag
porphyry Cu (Au, Mo, Ag)
manto Pb, Zn, Ag, Au
distal Au (As, Sb, Hg)

Earth Science current events:

Earthquakes:

http://www.iris.edu/seismon/

Volcanic eruptions:

http://www.swisseduc.ch/stromboli/livecams/index-en.html

Local weather:

http://www.srh.noaa.gov/mfl/

Hurricanes on the way?

http://www.nhc.noaa.gov/

Questions

Q1: ________ is the dominant lava erupted from volcanoes on Hawaii and Iceland.
A) Rhyolite
B) Andesite
C) Peridotite
D) Basalt

Q2: Which of the following is associated with deep mantle hot spots?
A) Vesuvius and the other volcanoes of Italy
B) the volcanoes of Hawaii and the recent activity in Yellowstone National Park
C) the very young cinder cones scattered across the southwestern United States
D) Mt. St. Helens and other volcanoes of the Cascade Mountains

Q3: ________ tend to increase the explosive potential of a magma body beneath a volcano.
A) High viscosity and dissolved gas
B) High viscosity; low dissolved gas content
C) Low silica content, low viscosity
D) Low viscosity; low dissolved gas content

Q4: Which region has the greatest concentration of currently active volcanoes?
A) the coastal plain of western Africa
B) European Russia and Siberia
C) the area surrounding the Red Sea
D) the circum-Pacific area

Q5:Kilauea and Mauna Loa are ________.
A) explosive, rhyolitic volcanoes
B) andesitic stratovolcanoes
C) basaltic shield volcanoes
D) small, basaltic cinder cones

Fundamentals of Earth Sciences (ESO 213A)

Dibakar Ghosal
Department of Earth Sciences

Sedimentary Rocks

Previous Class: Volcanoes

Important Announcements

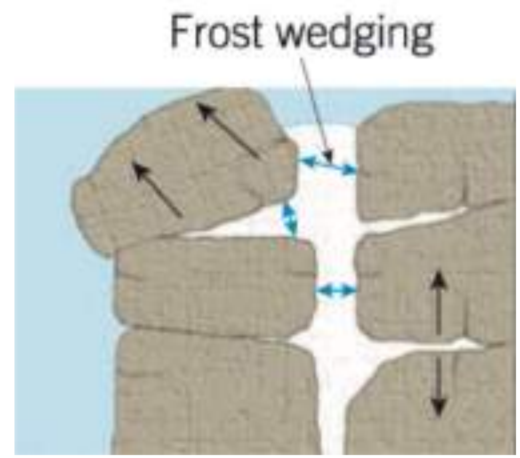
- Quiz 1 will be conducted during normal class hours (11:00 -11:40 AM)
- Date: 2nd September 2022
- Venue: L-16
- Syllabus: Material covered up to 29th August
- Type: MCQ (30 questions/1 mark each/0.25 marks negative marking, you can open notes, books and internet but no discussion)

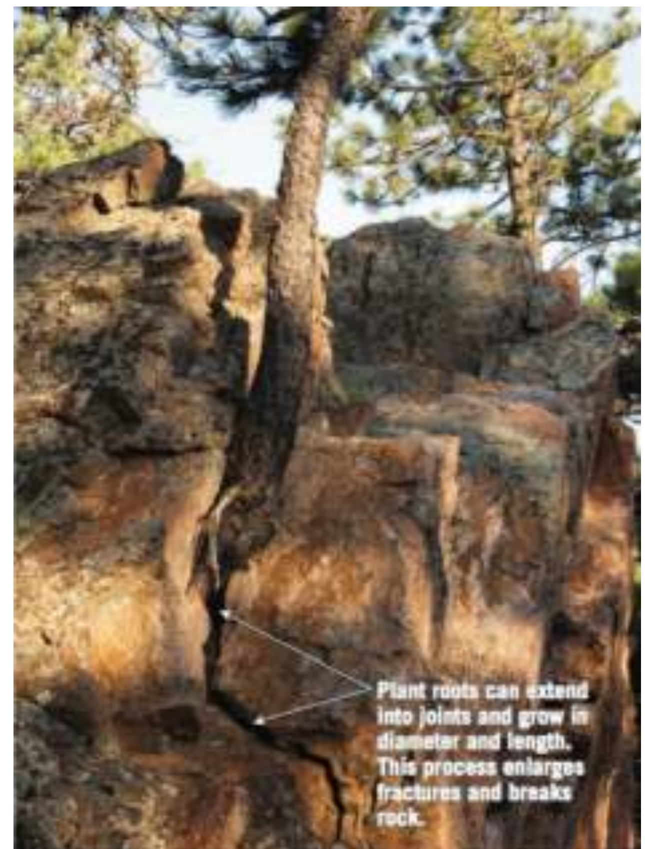
What Is a Sedimentary Rock?

- 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

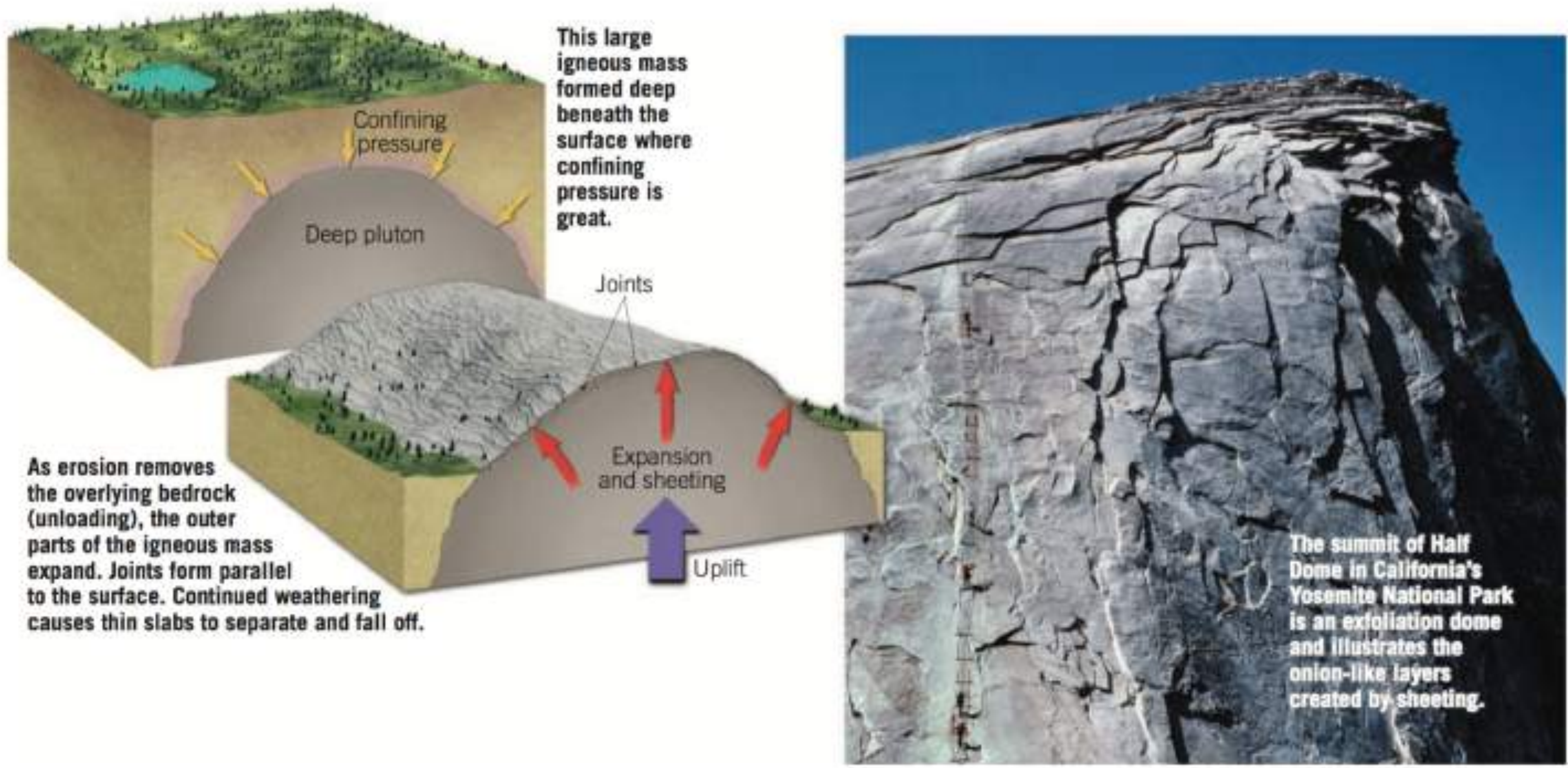
- **Frost wedging:** When liquid water freezes, it expands by 9% and expands cracks producing fragments of rocks
- **Salt crystal growth:** Salty groundwater penetrates pores or crevices. As water evaporates, salt crystals form and grow pushing surrounding grains, opening up of tiny cracks.
- **Biological 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





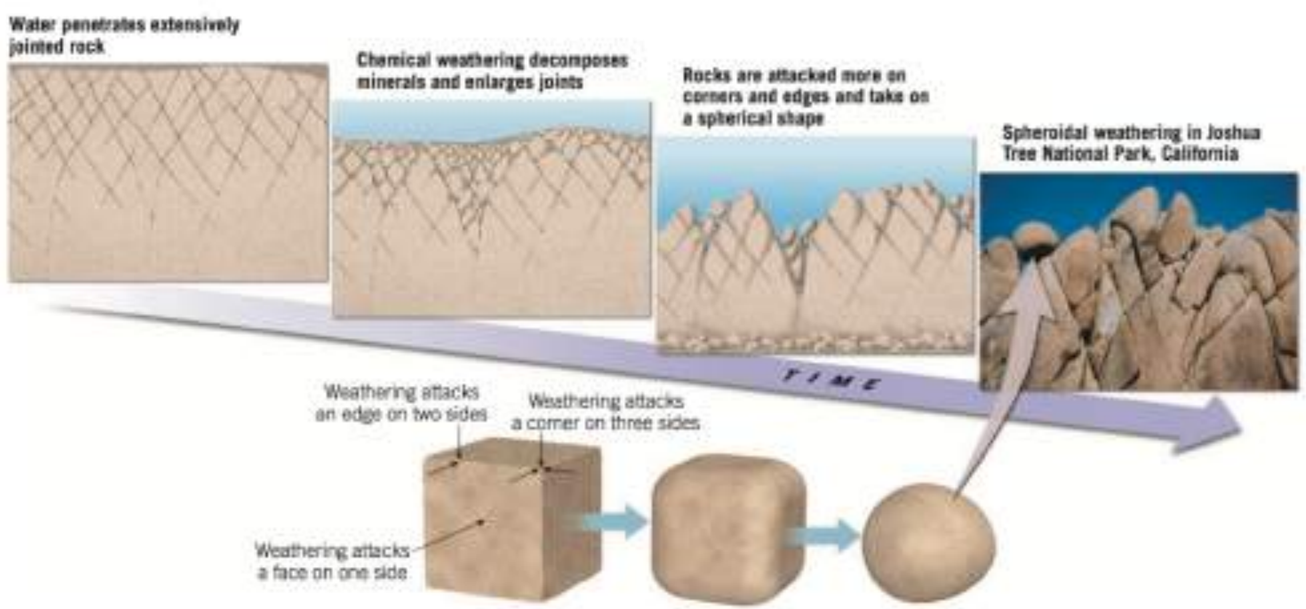
Physical Weathering

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

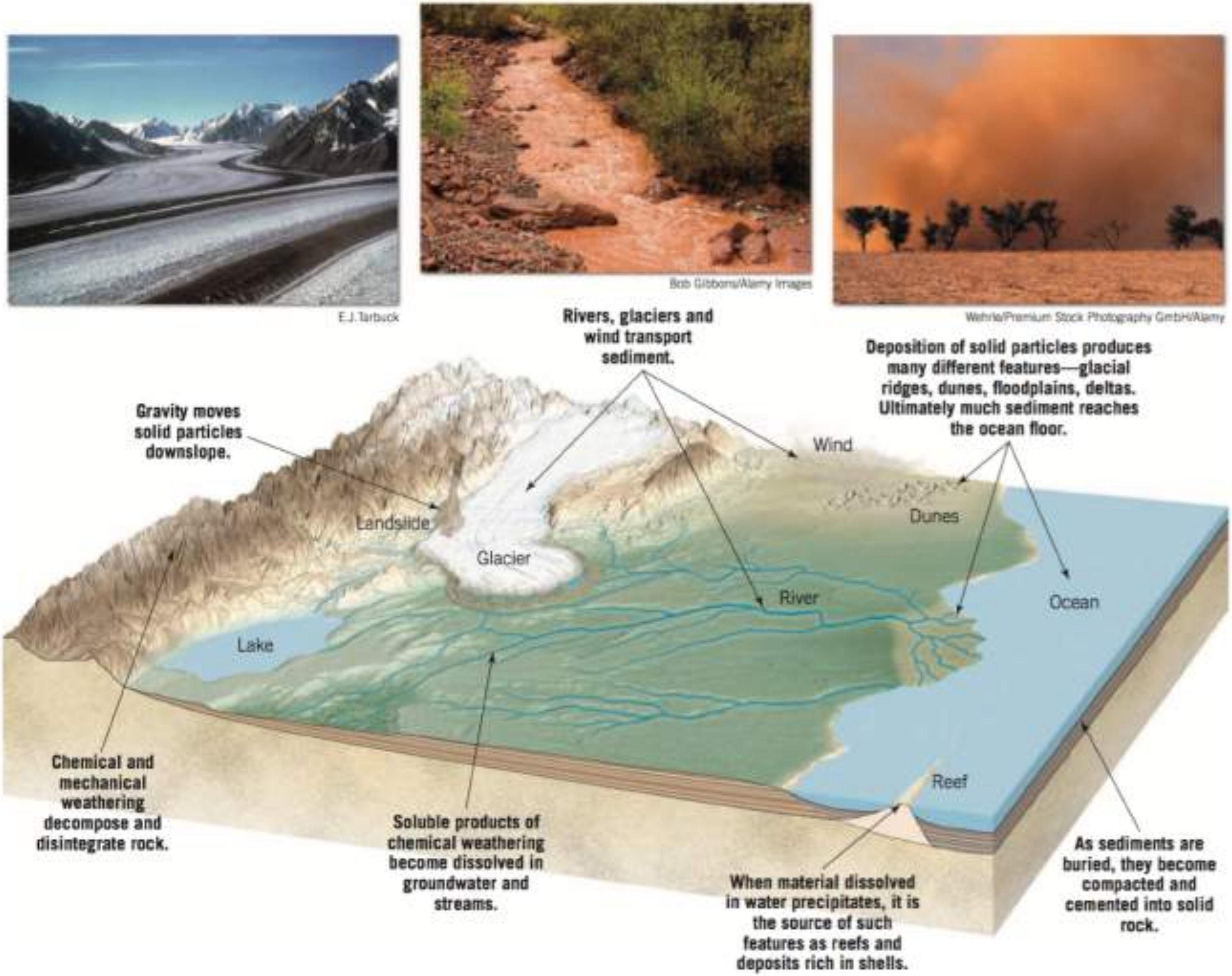
- Many changes occur to sediment after it is deposited.
- Diagenesis—chemical, physical, and biological changes that take place after sediments are deposited
  - Occurs within the upper few kilometers of Earth's crust at temperatures < 150^{O} -200^{O}C

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.

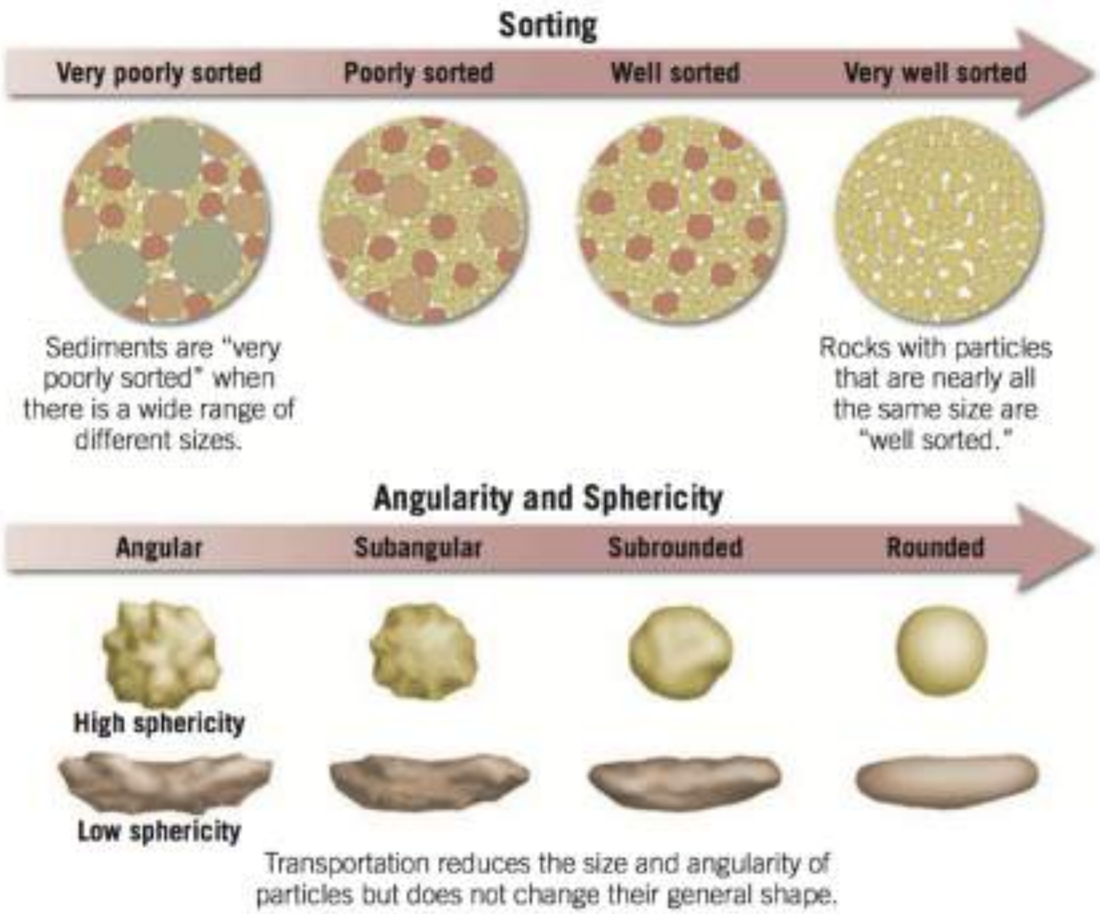
Size Range (millimeters)	Particle Name	Common Name	Detrital Rock
>256	Boulder	Gravel	Conglomerate, Breccia
64–256	Cobble		
4–64	Pebble		
2–4	Granule		
1/16–2	Sand	Sand	Sandstone
1/256–1/16	Silt	Mud	Shale, Mudstone or Siltstone
<1/256	Clay		

Detritial Sedimentary Rocks

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)**

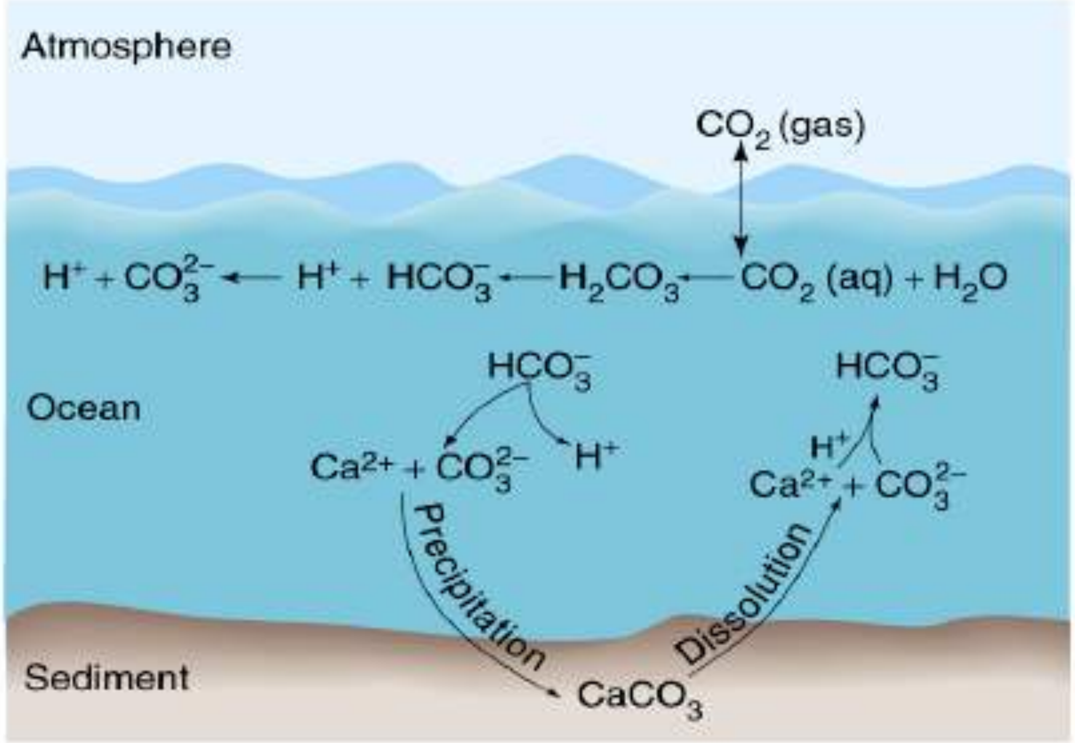
Chemical Sedimentary Rocks

- **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

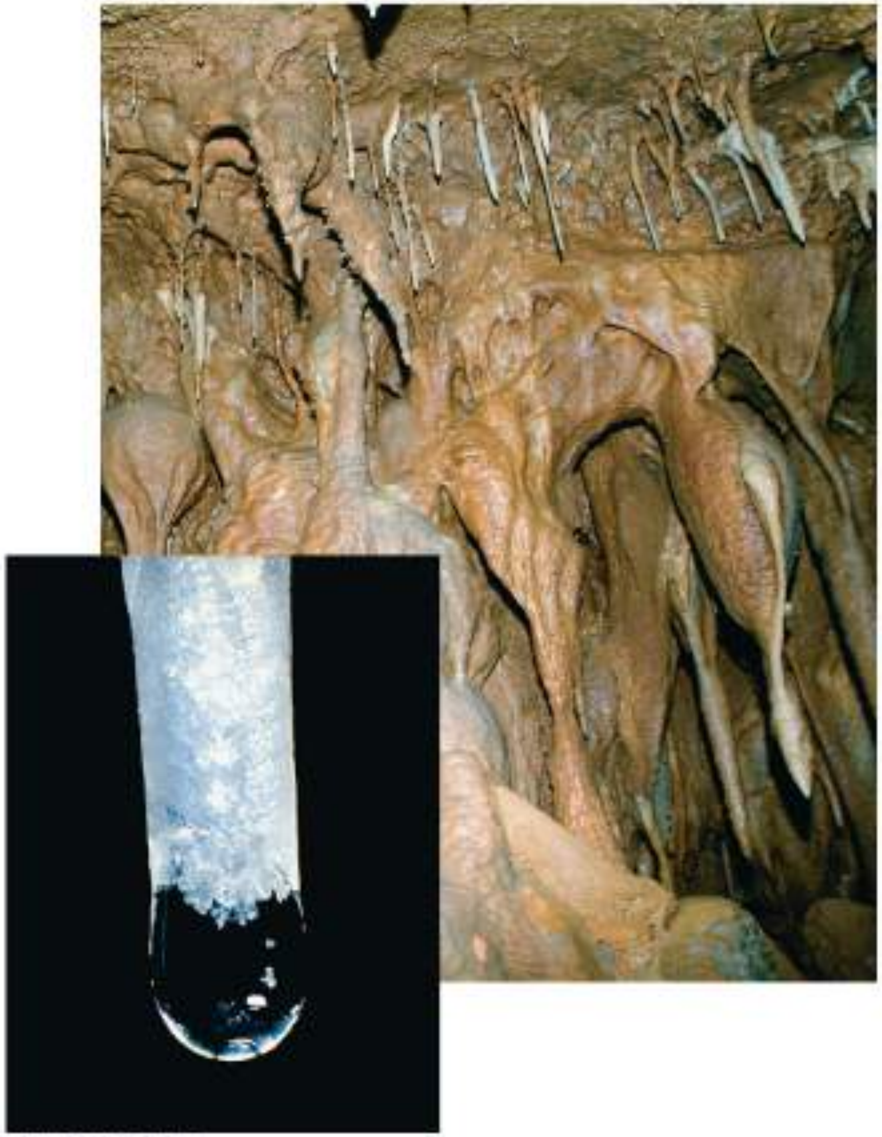
- Oceans can absorb CO_2 from atmosphere without much change in pH
- Keeps ocean pH about same (8.1)
- pH too high, carbonic acid releases H+
- pH too low, bicarbonate combines with H+
- Precipitation/dissolution of calcium carbonate $CaCO_3$ buffers ocean pH



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

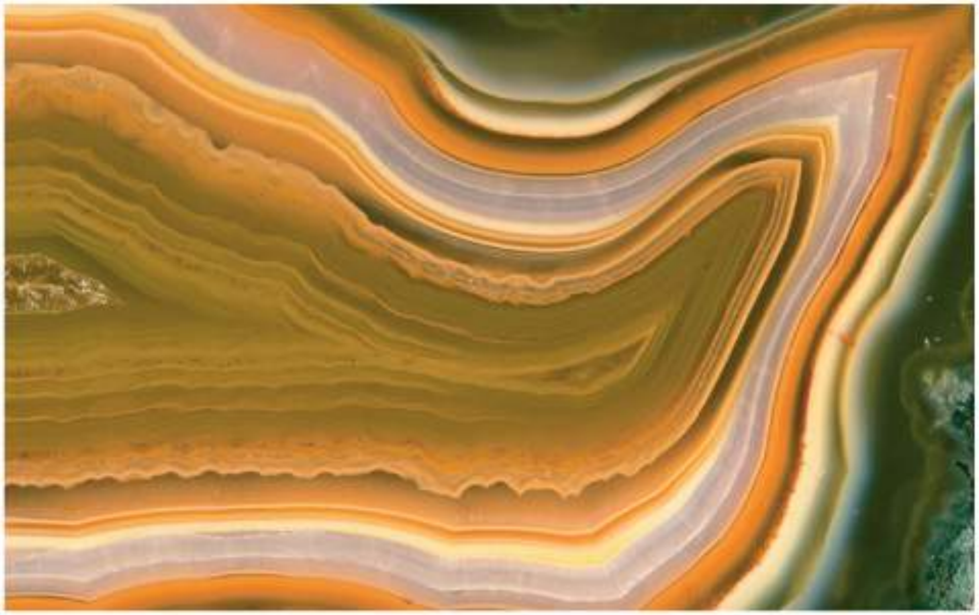
$$Ca(HCO_3)_2(aq) \rightarrow$$

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

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

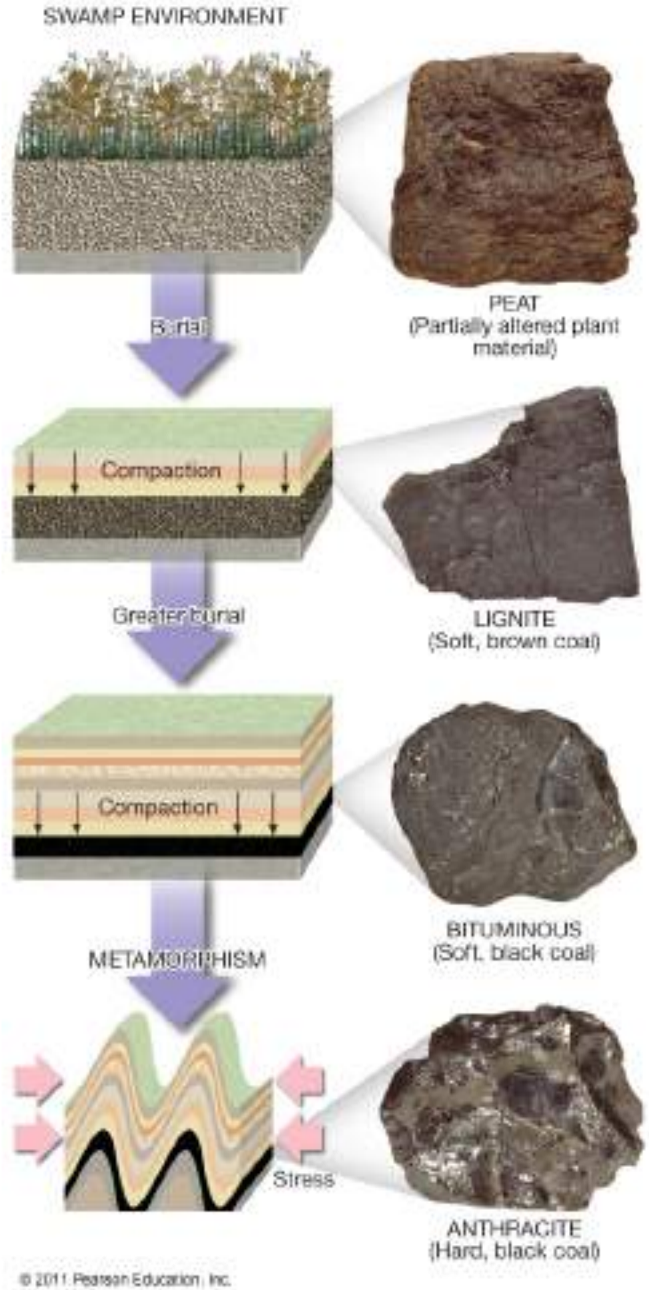
Chemical Sedimentary Rocks

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

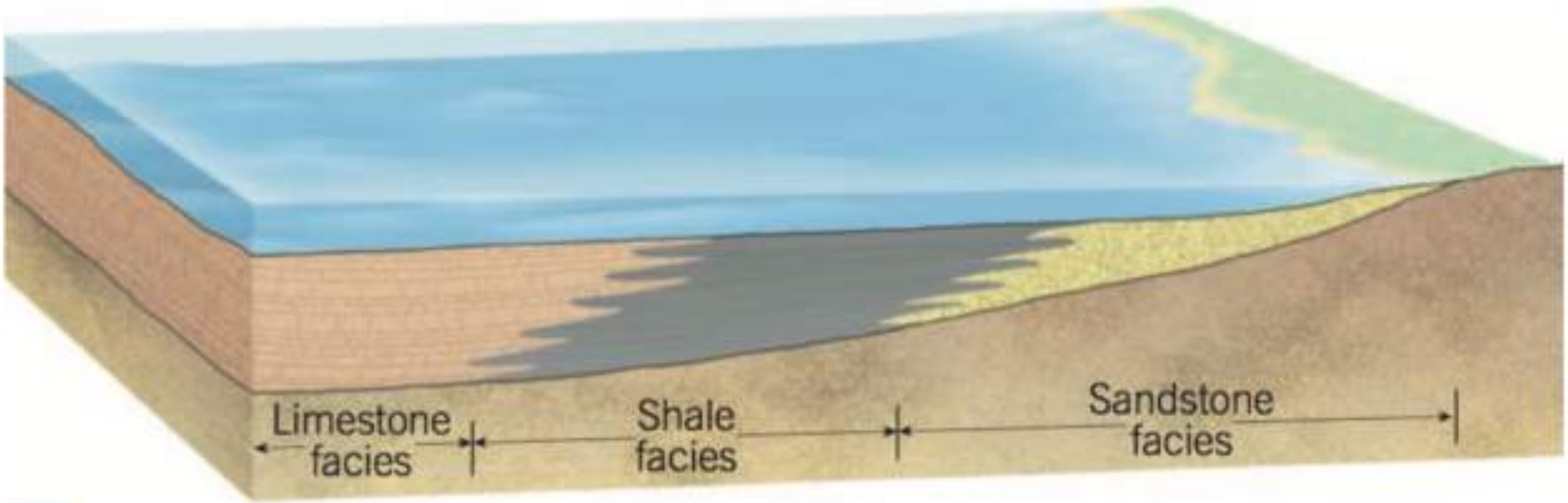
Detrital Sedimentary Rocks

Clastic Texture (particle size)		Sediment Name	Rock Name
Coarse (over 2 mm)		Gravel (Rounded particles)	**Conglomerate**
		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**	
		Travertine	
	Clastic: Visible shells and shell fragments loosely cemented	**Coquina**	**Biochemical Limestone**
	Clastic: Various size shells and shell fragments cemented with calcite cement	**Fossiliferous Limestone**	
	Clastic: Microscopic shells and clay	**Chalk**	
Quartz, SiO_2	Nonclastic: Very fine crystalline	**Chert (light colored) Flint (dark colored)**	
Gypsum $CaSO_4{\bullet}2H_2O$	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**	

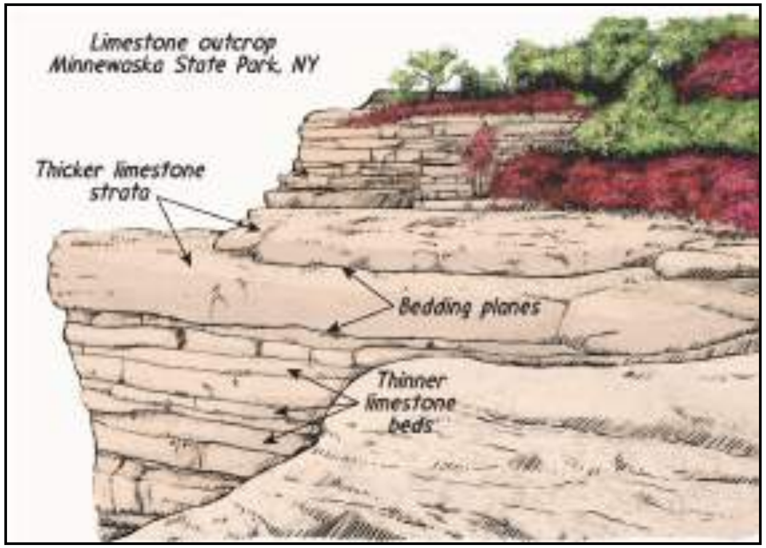
Sedimentary Facies



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.

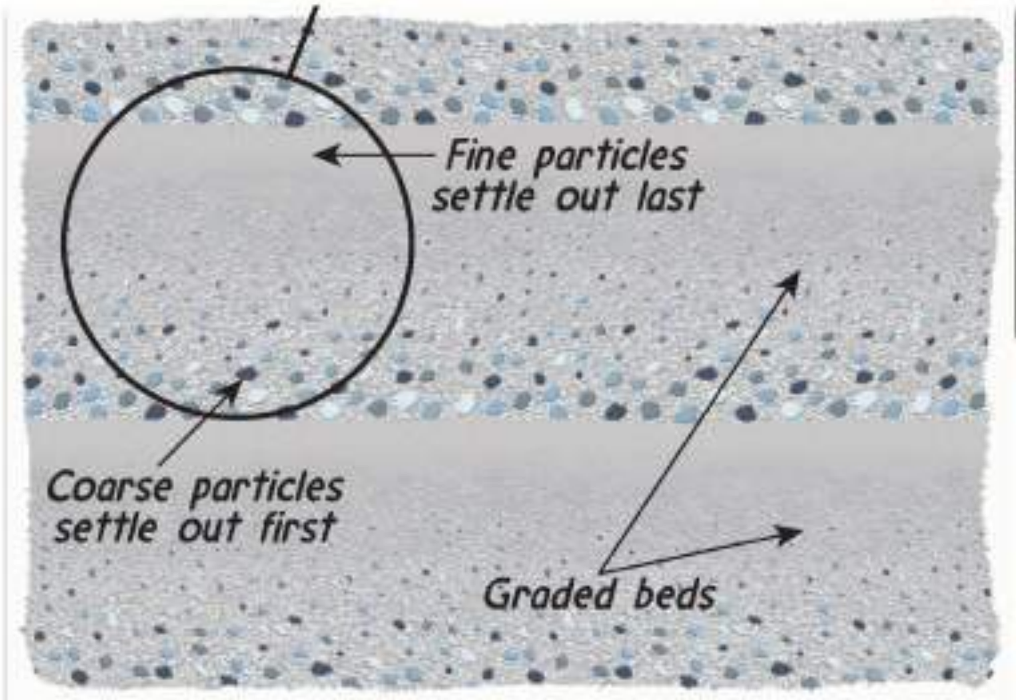
Sedimentary Structures

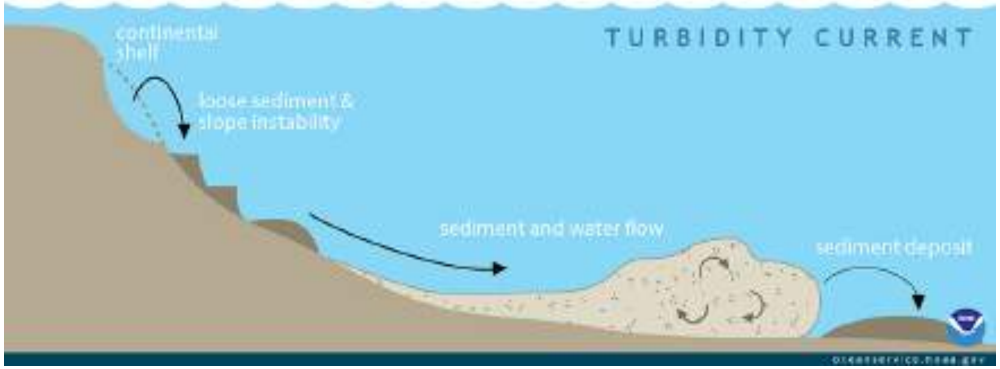
- **Provide information useful in the interpretation of Earth's history**
- **Types of sedimentary structures**
  - ***Strata*, or beds (most characteristic of sedimentary rocks, which form as layer upon layer of sediment accumulates in various depositional environments)**
  - ***Bedding planes* separate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



Sedimentary Structures

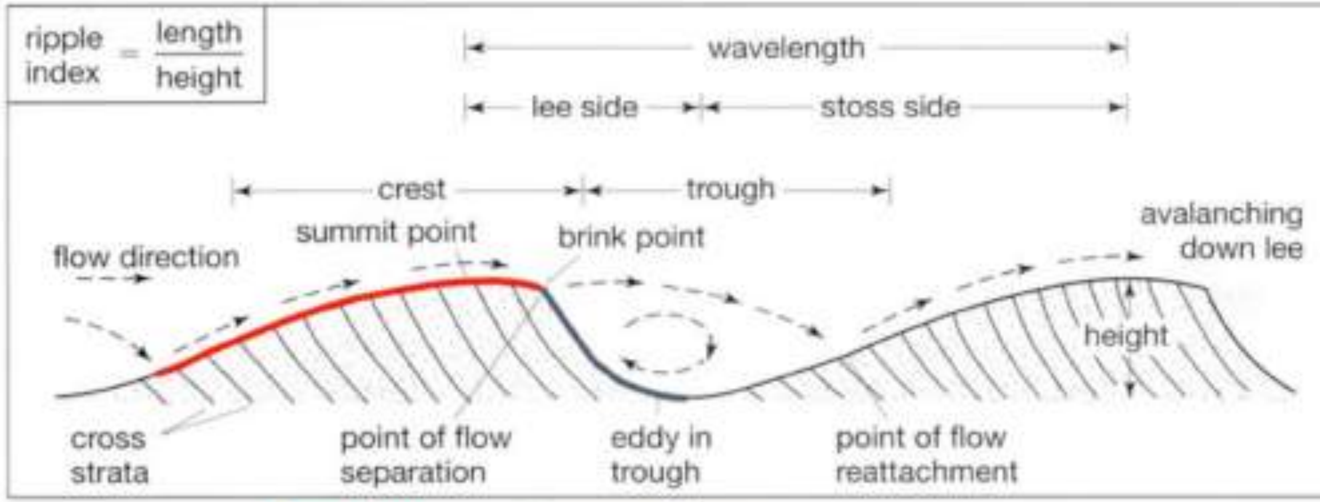
- **Types of sedimentary structures**
  - **Graded beds** **(characteristic of rapid deposition from water containing sediment of different sizes)**





Cross-bedding

(characteristic of sand dunes, river deltas)



Erosion Deposition

B.

Flow Direction

Mode of grain transport

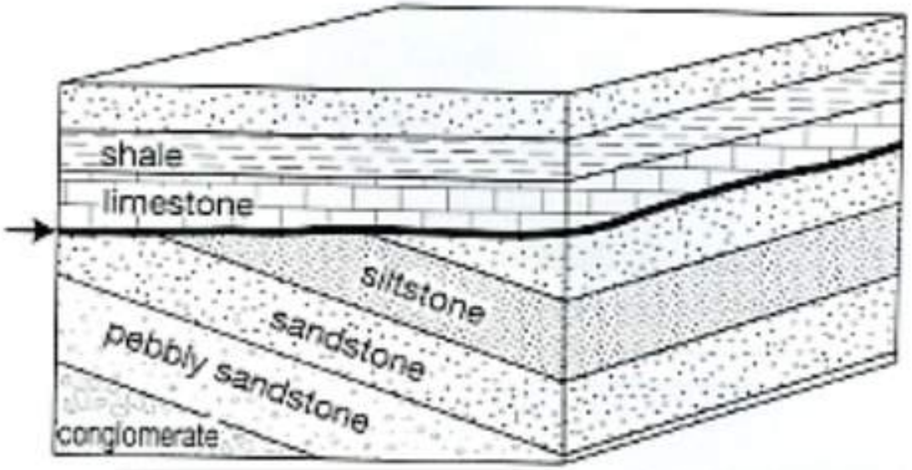
Sedimentary Structures

- **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)**

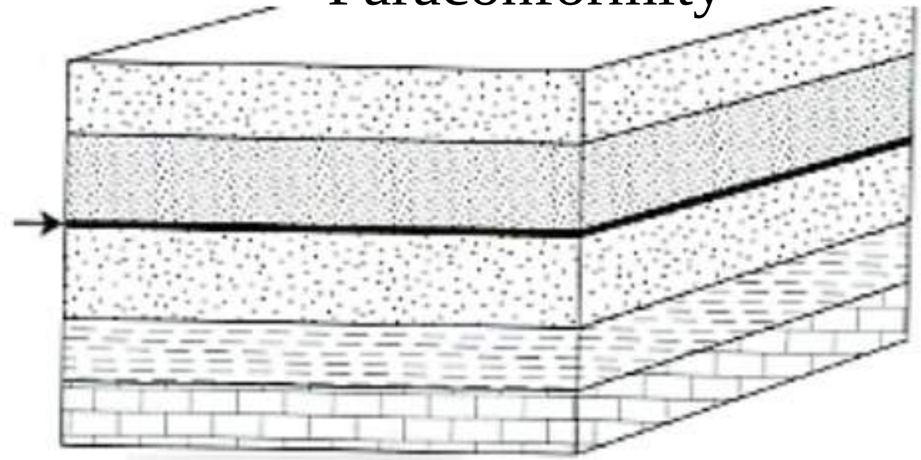
A.

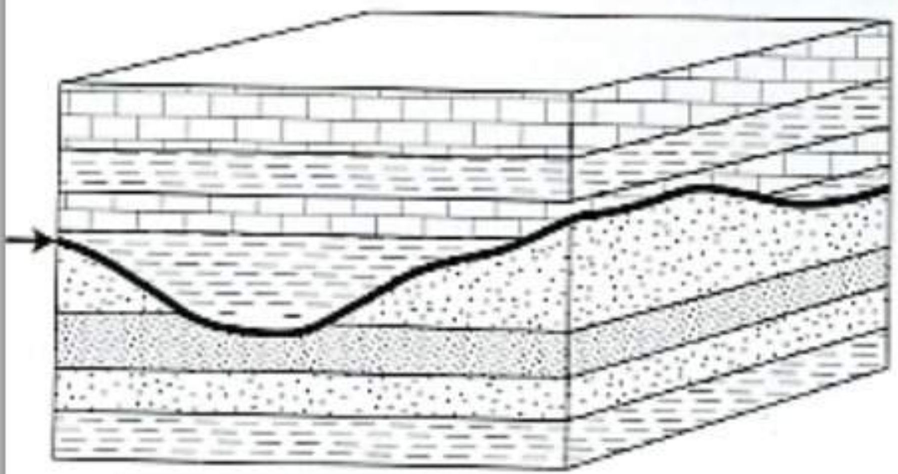
Unconformity

Angular Unconformity

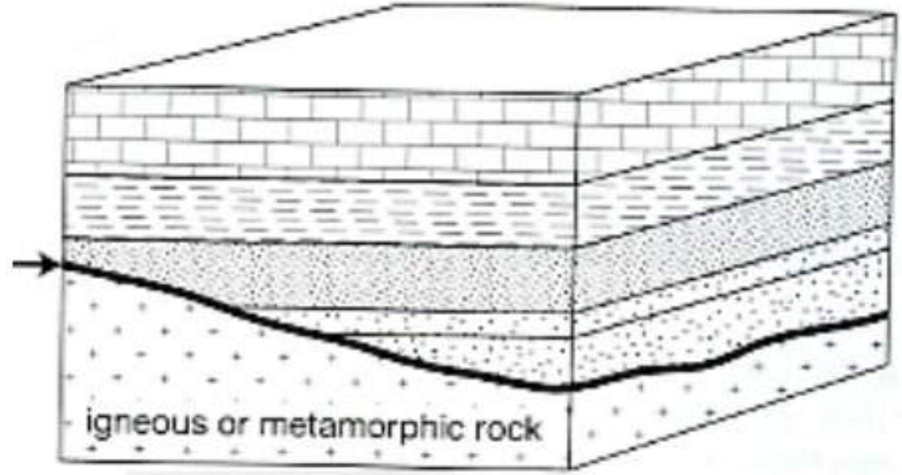


Paraconformity



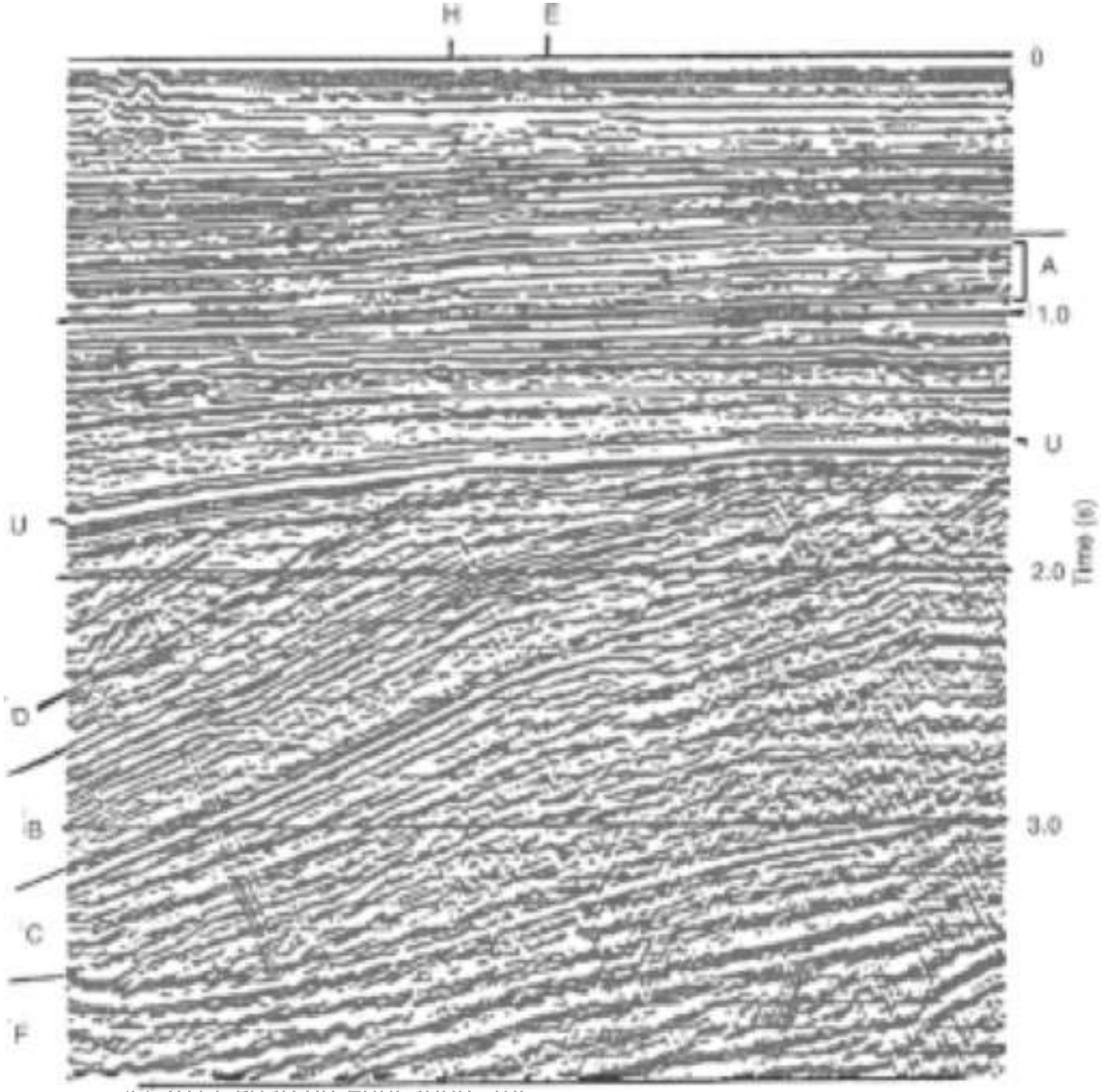


Disconformity



Nonconformity

Example of angular unconformity

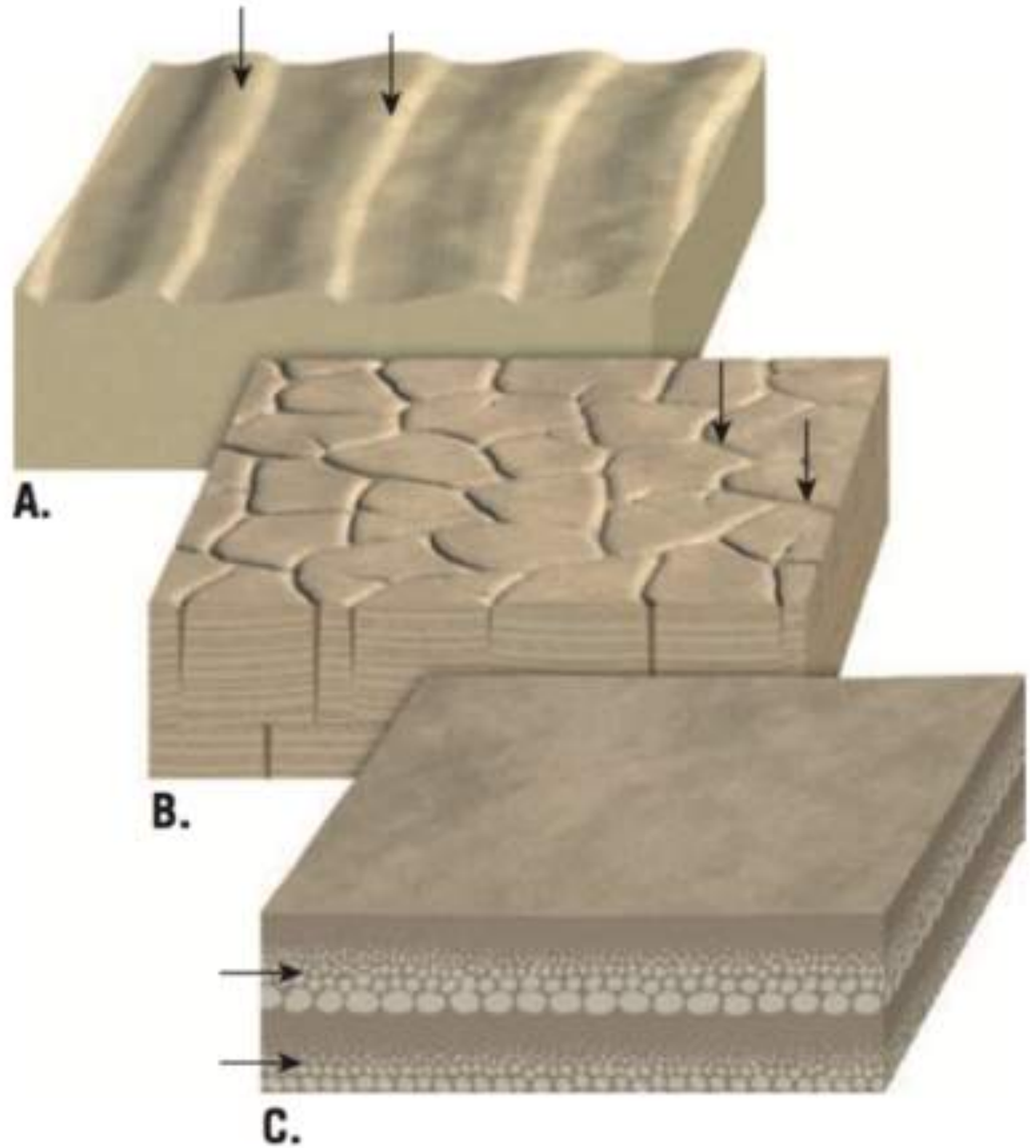


Question

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”

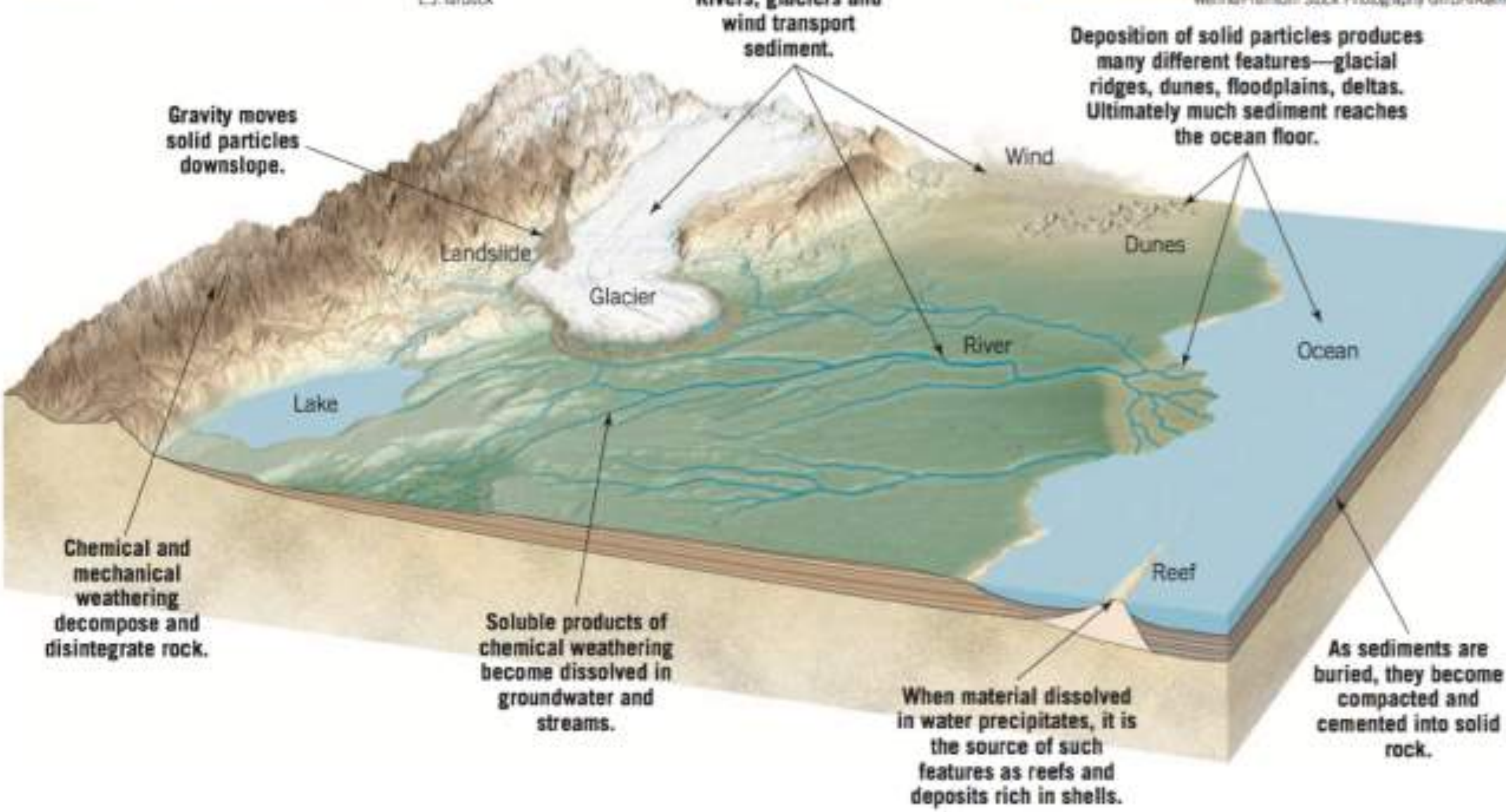
Previous Class: Sedimentary rocks

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

E.J. Tarbuck

Bob Gibbons/Alamy Images

Wehrle/Premium Stock Photography GmbH/Alamy



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**
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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)**	
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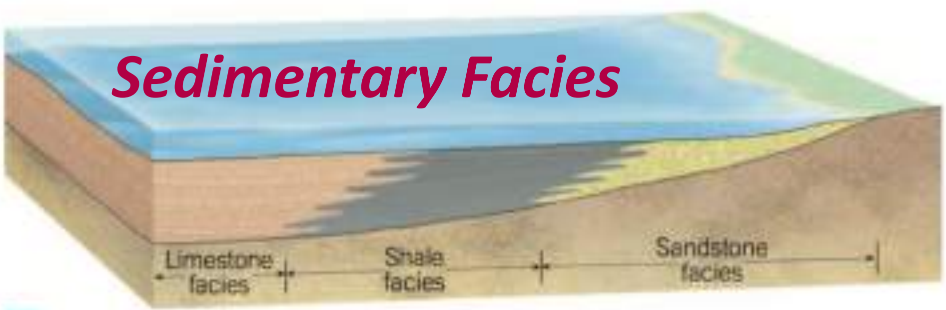
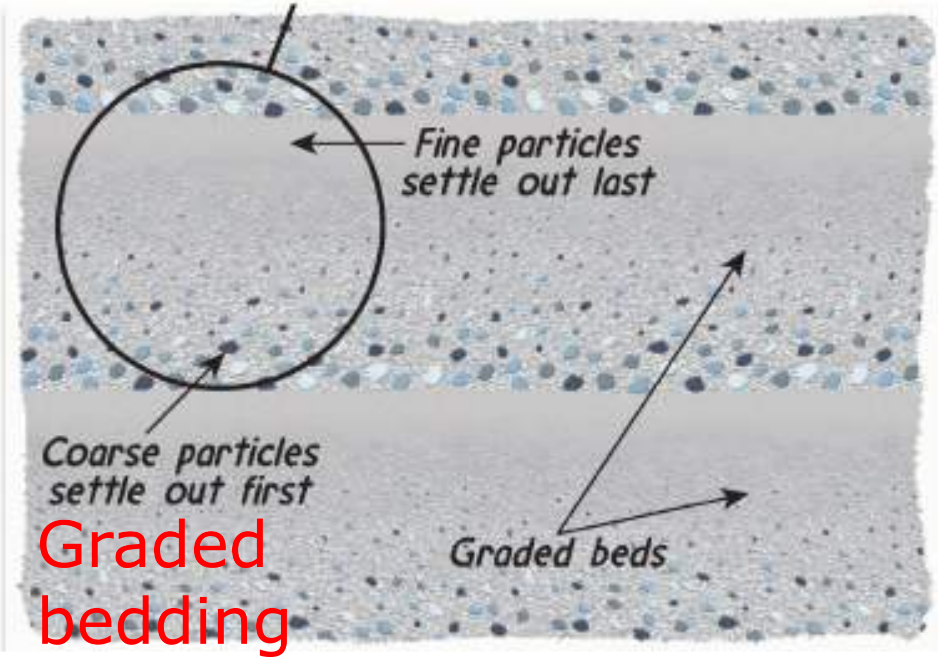
Altered plant fragments	Nonclastic: Fine-grained organic matter	**Bituminous Coal**	




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

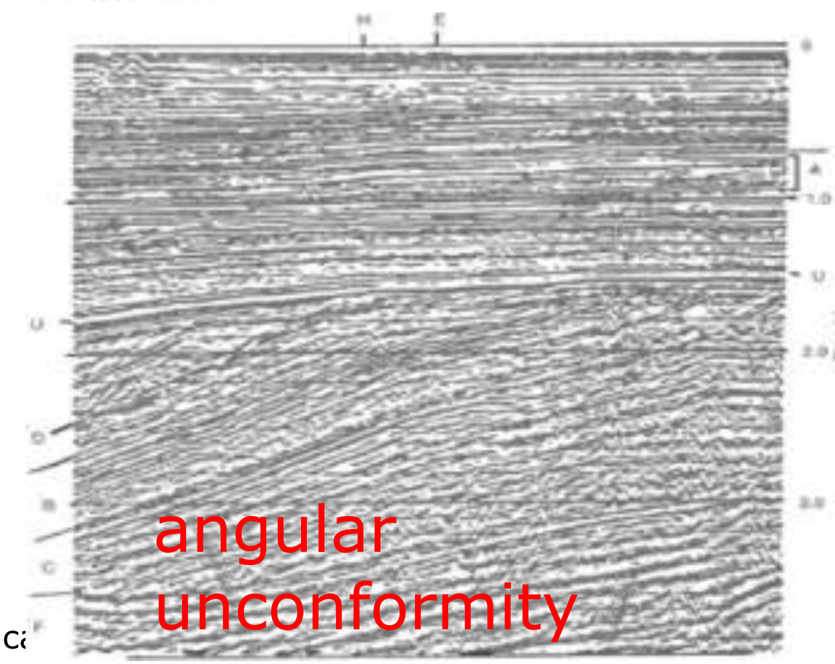

Ripple marks

A.


Cross bedding

B.

son Educa


angular unconformity

Taj Mahal Constructed primarily of marble.

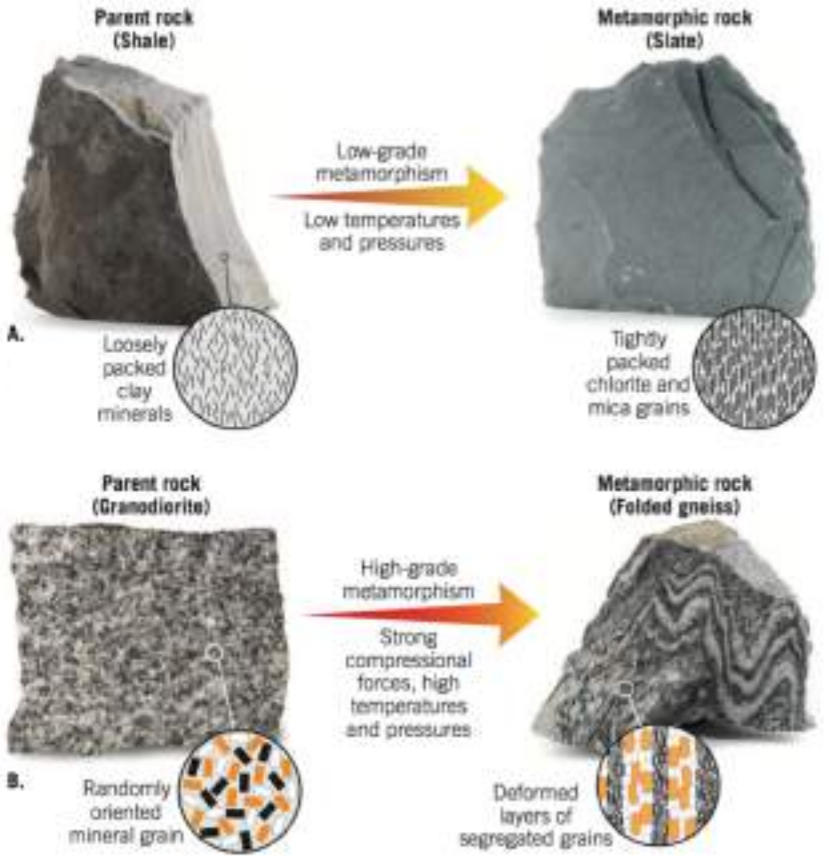
Metamorphic rocks

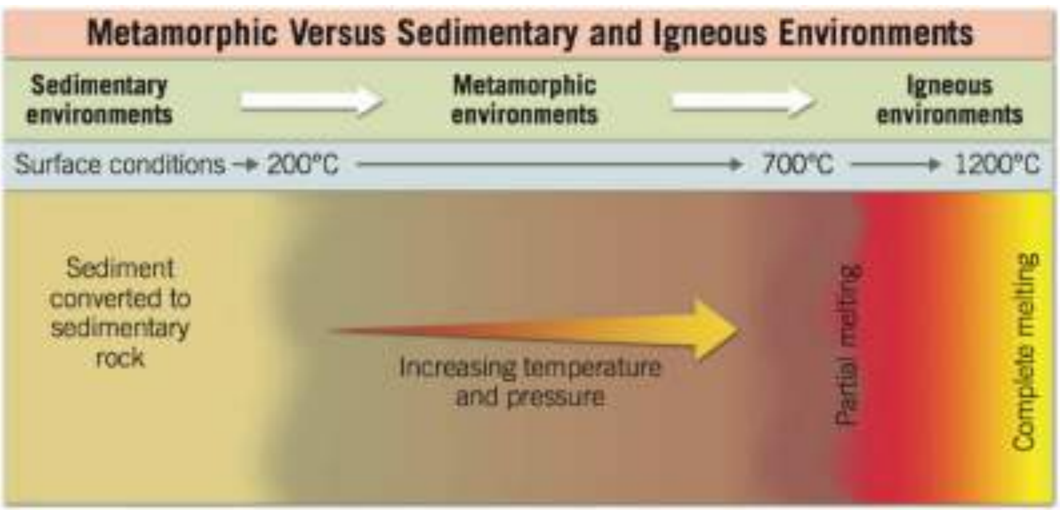
Metamorphism

<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>.**

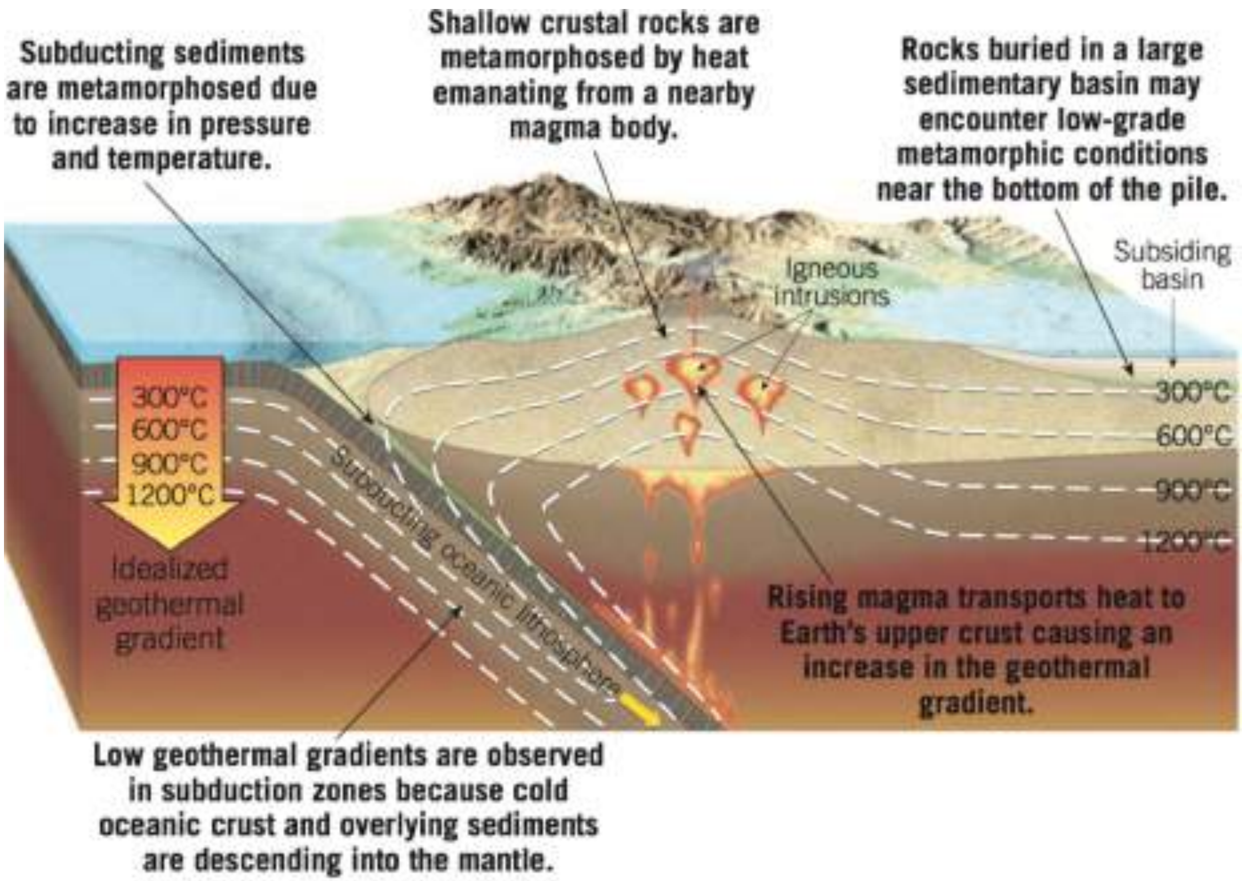




Agents of Metamorphism

I. Heat

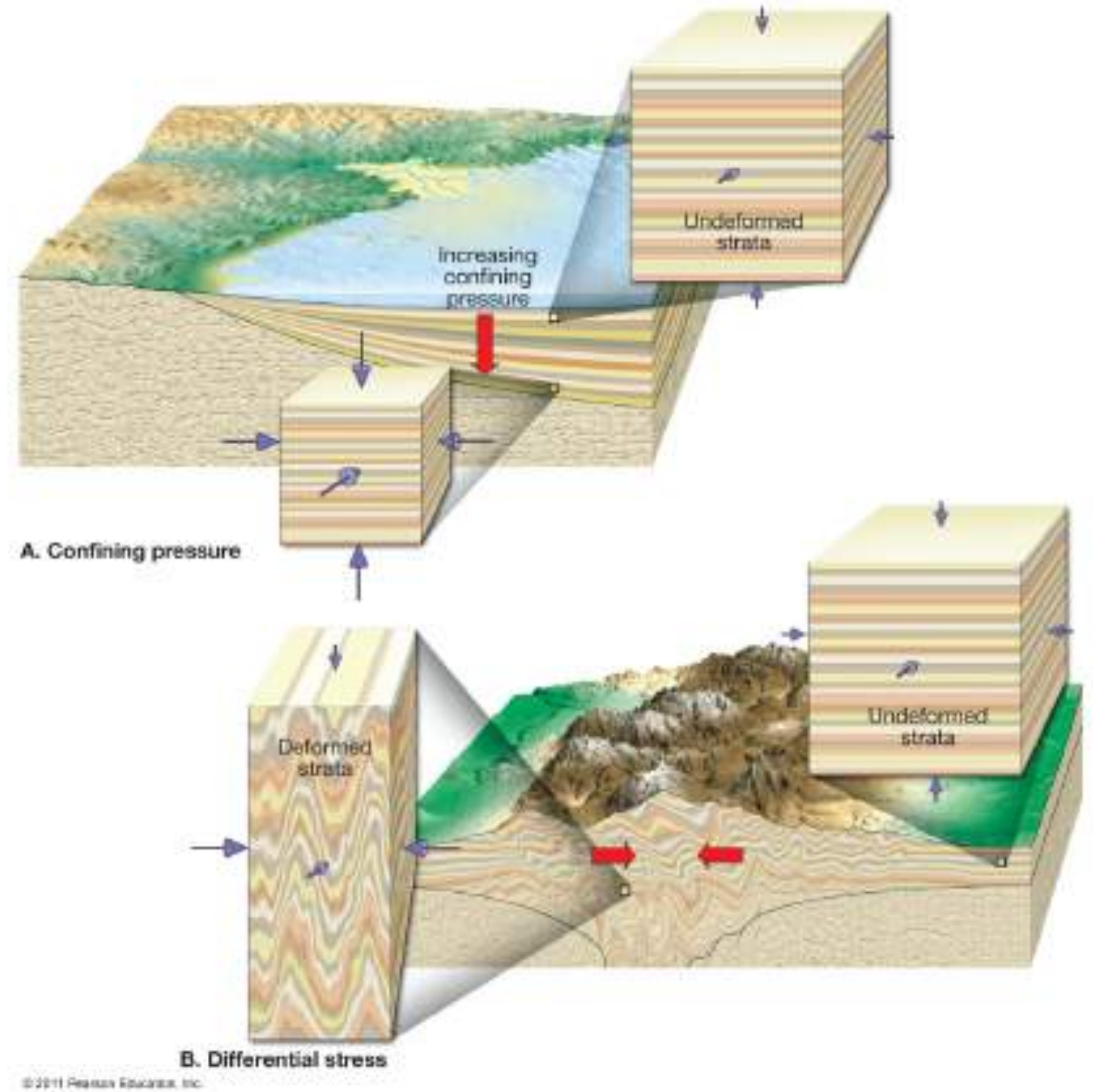
- **Most important agent**
- **Recrystallization results in new, stable minerals.**
- **Two sources of heat:**
  1. **Contact metamorphism—heat from magma**
  2. **An increase in temperature with depth—geothermal gradient**



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

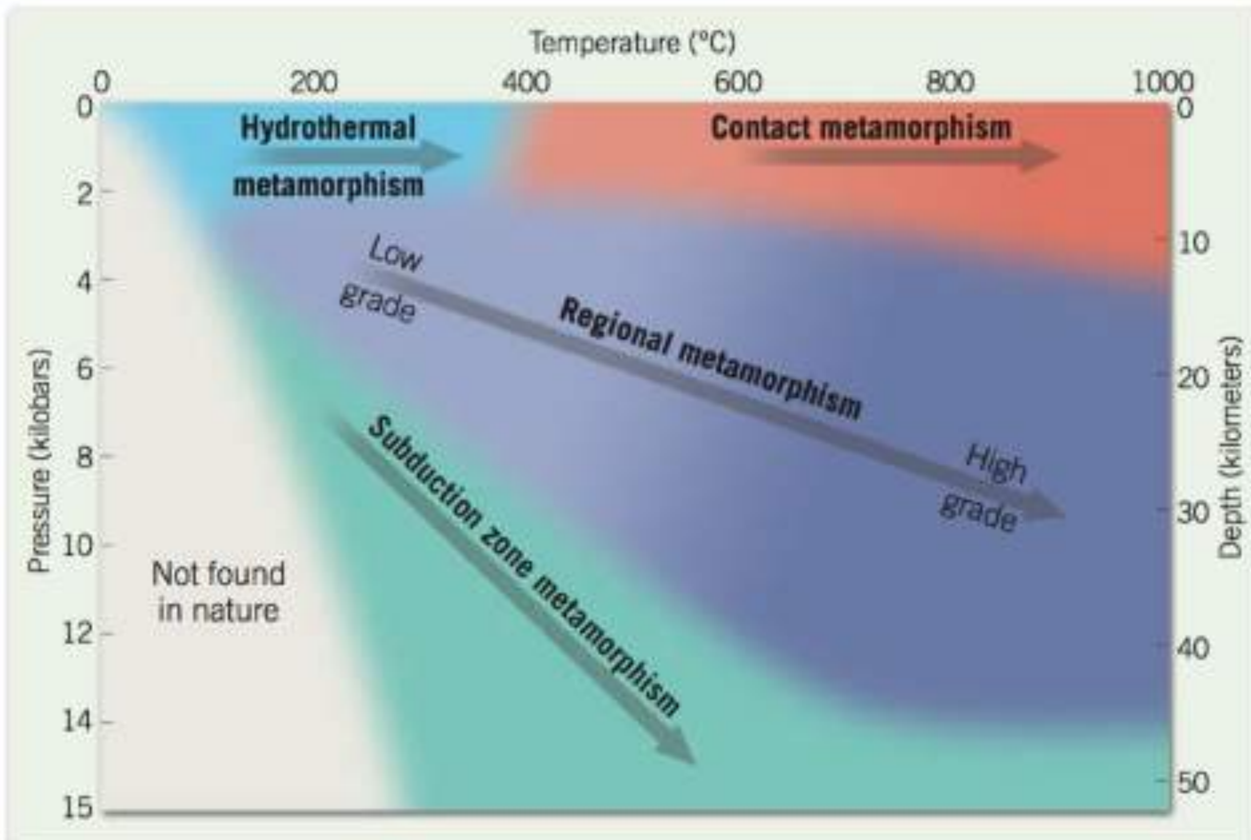
- **Mainly water**
- **Enhances migration of ions**
- **Aids in recrystallization of existing minerals**
- **Sources of fluids**
  - **Pore spaces of sedimentary rocks**
  - **Fractures in igneous rocks**
  - **Hydrated minerals such as clays, micas, amphiboles**

Metasomatism Example

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

Metamorphic settings

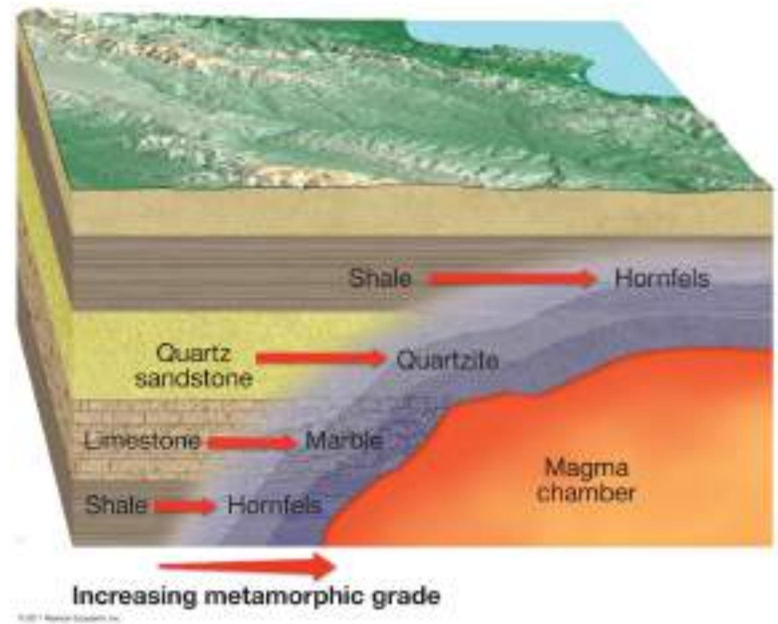
- Contact or thermal metamorphism—driven by a rise in temperature within the host rock
- Hydrothermal metamorphism—chemical alterations from hot, ion-rich water
- Regional metamorphism
  - Occurs during mountain building
  - Produces the greatest volume of metamorphic rock
  - Rocks usually display zones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

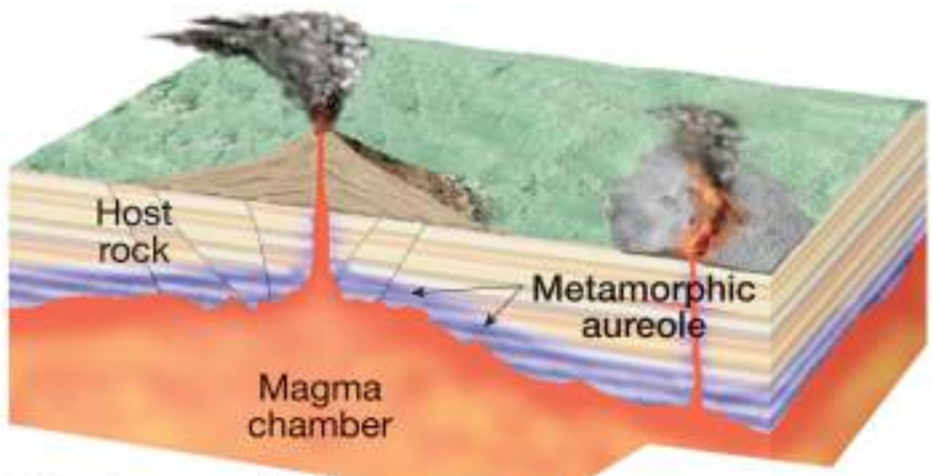


Metamorphic Environments

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.



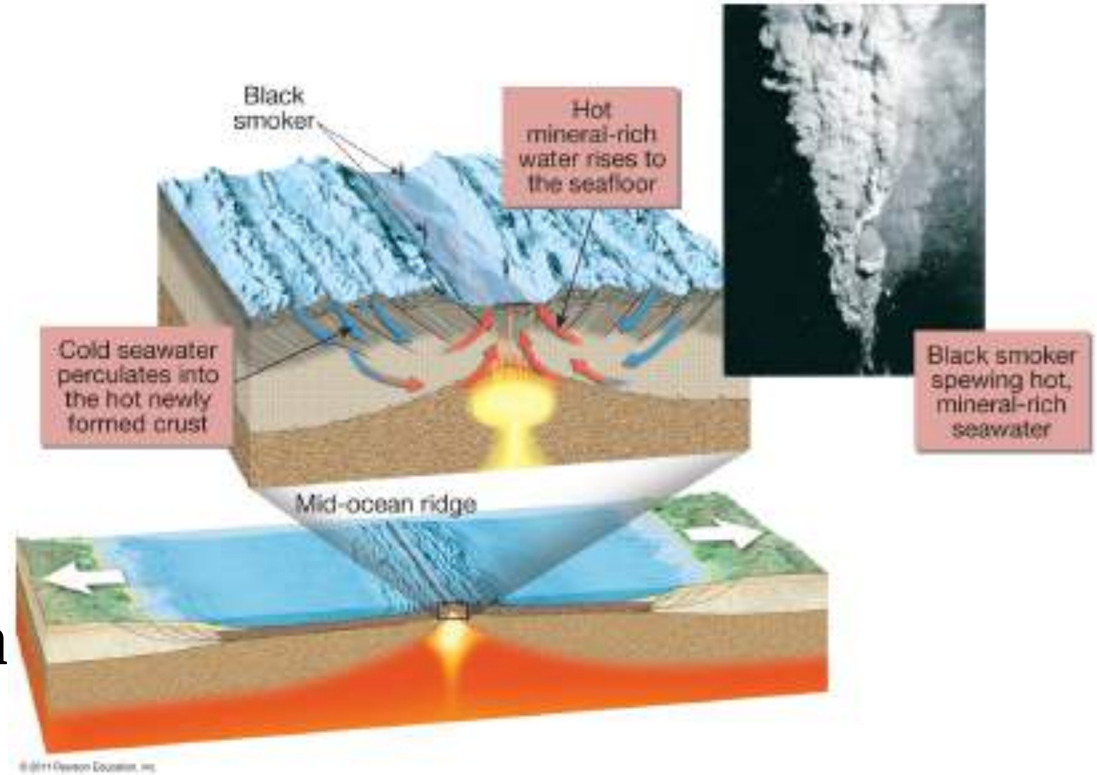


A. Implacement of igneous body and metamorphism

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

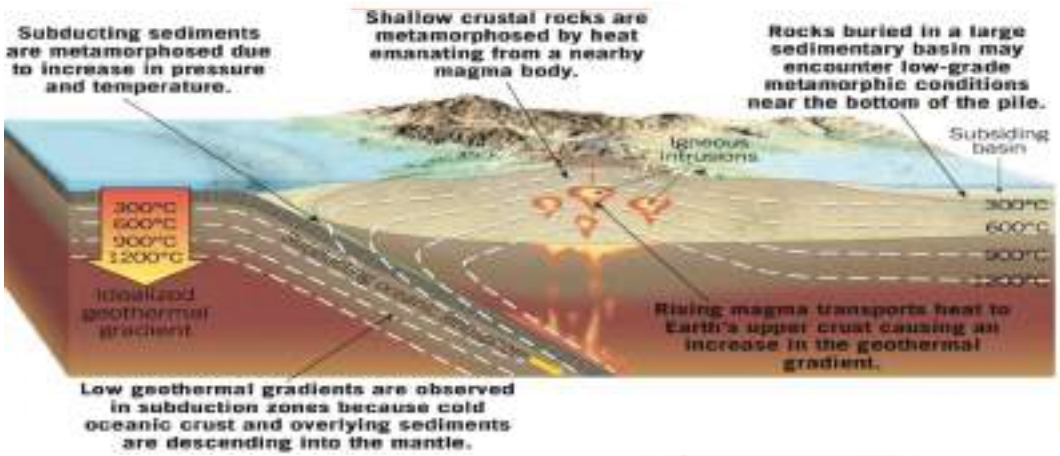


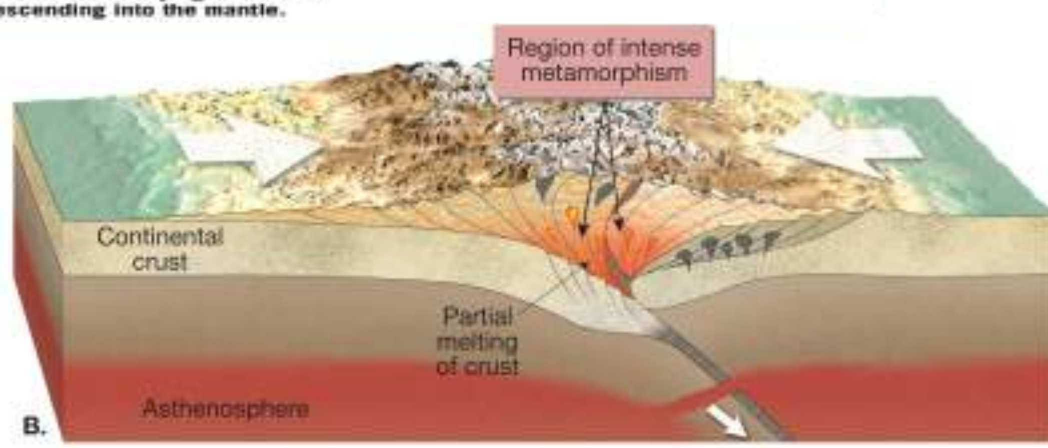
Hydrothermal solutions circulating through the seafloor remove large amounts of metals (Fe, Co, Ni, Ag, Au, Cu) from the newly formed crust.

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

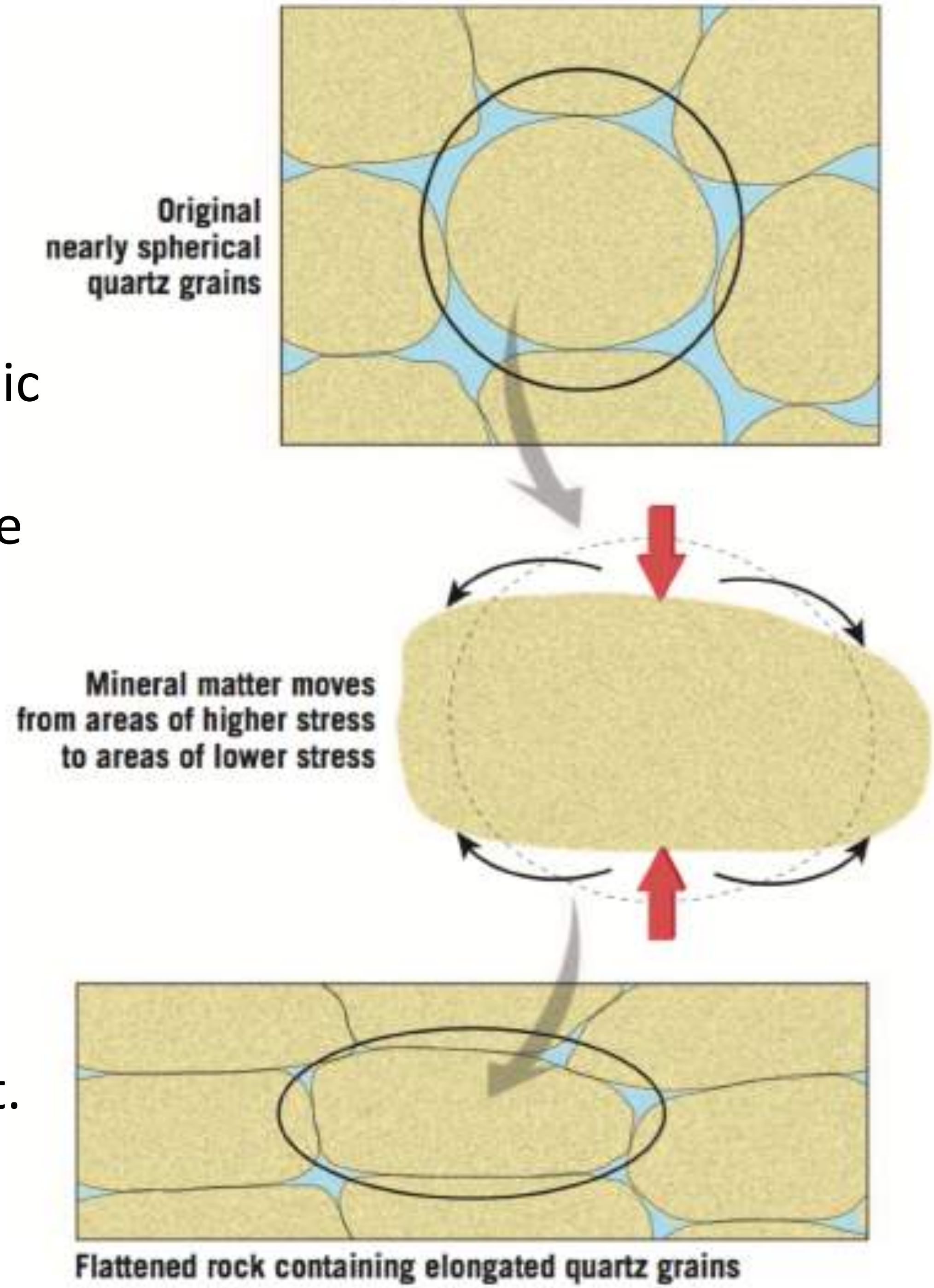
Processes for metamorphism

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.

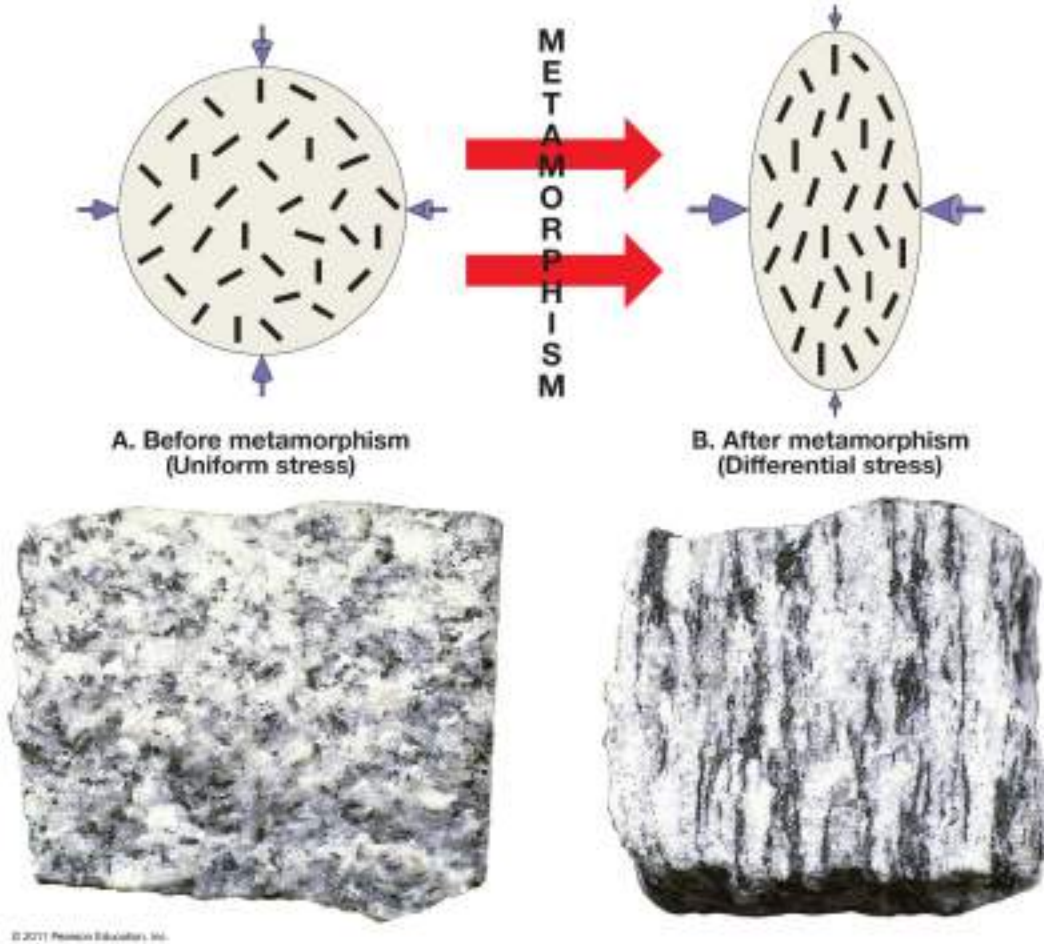
4. **Remobilization:** High P and T can cause certain minerals to breakdown allowing them to diffuse, dissolve and partially melt. The mineral then reprecipitate to low stressed zone.



Metamorphic Textures

Foliation (planner arrangement of minerals in a rock)

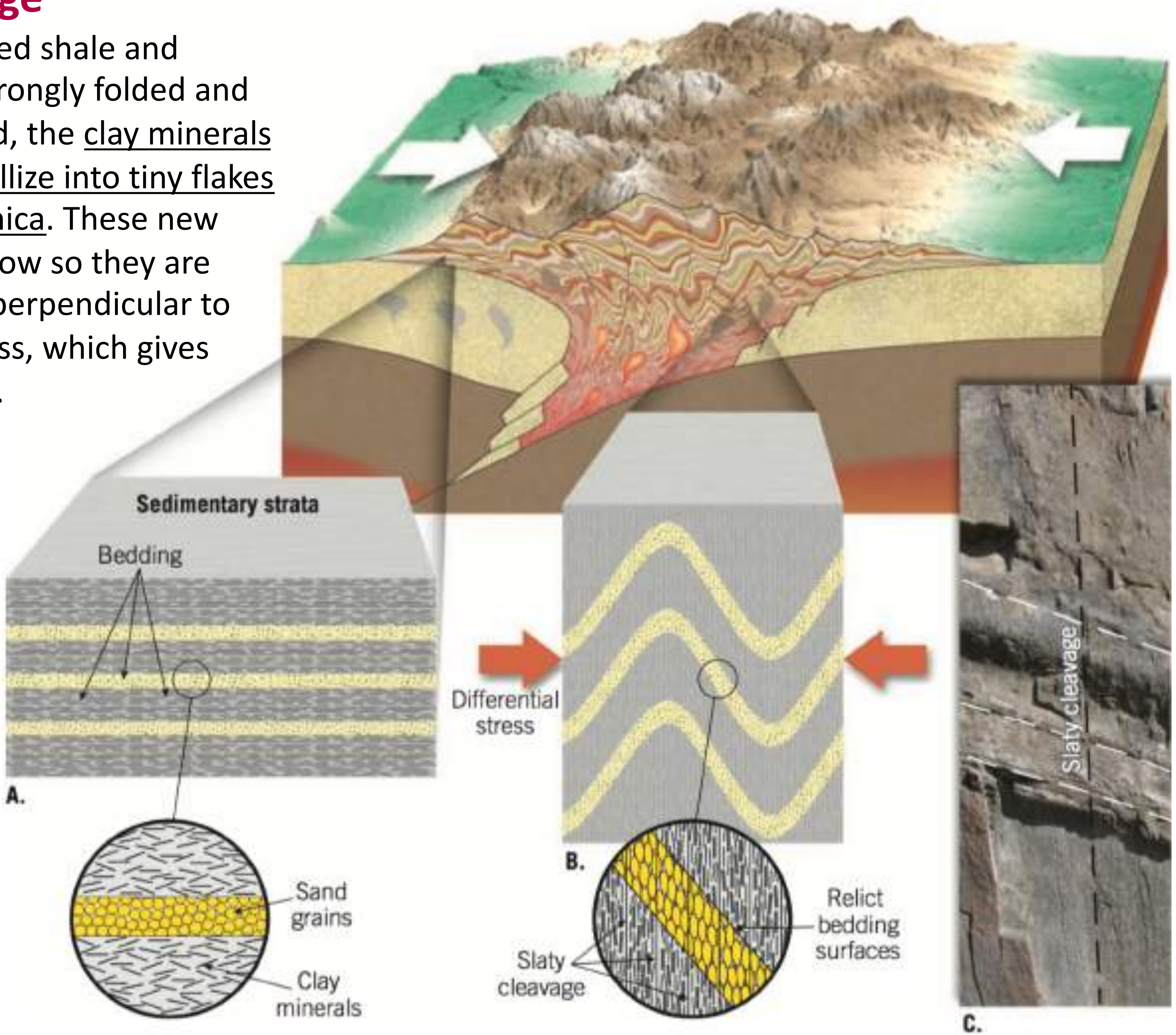
- **Examples of foliations**
  - **Parallel alignment of flattened / platy mineral grains and pebbles**
  - **Parallel alignment of elongated minerals**
  - **Compositional banding (separation of light and dark minerals causes a layered appearance)**
  - **Slaty cleavage where rocks can be easily split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



Foliation Resulting from Directed Stress

Slaty Cleavage

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



Metamorphic Textures

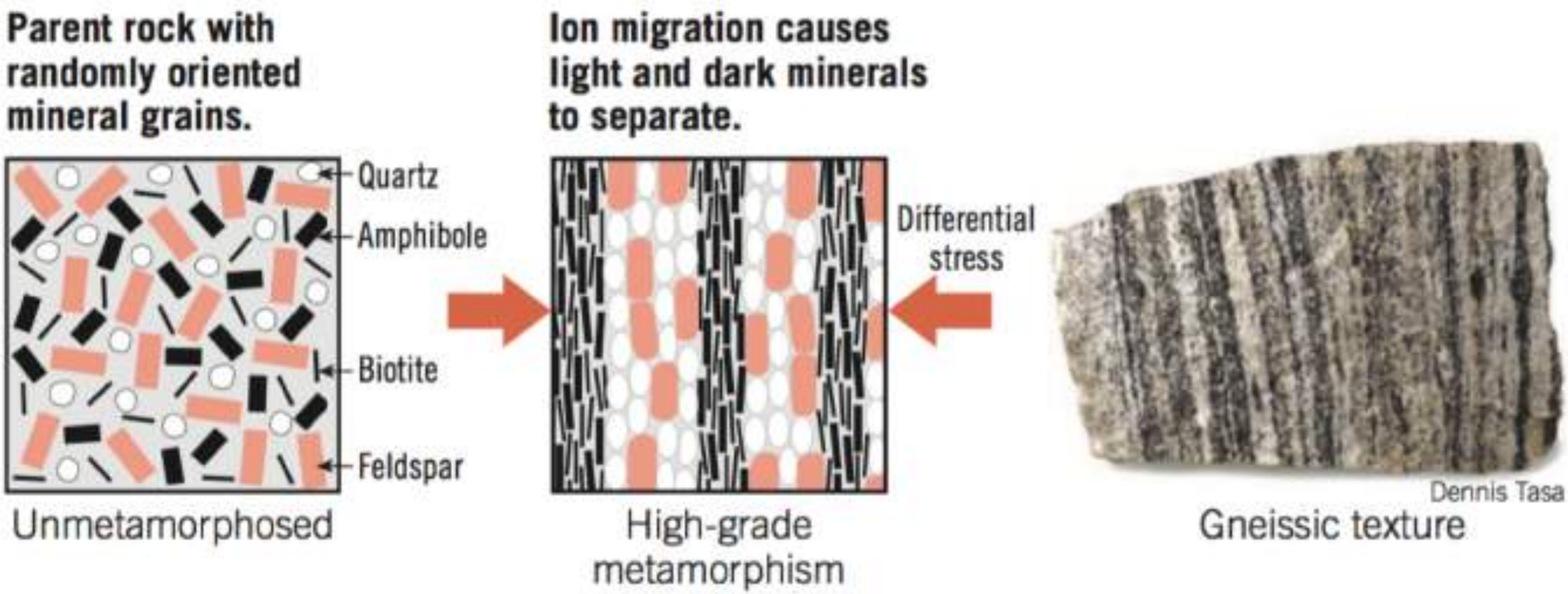
I. Foliated textures

- 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?.

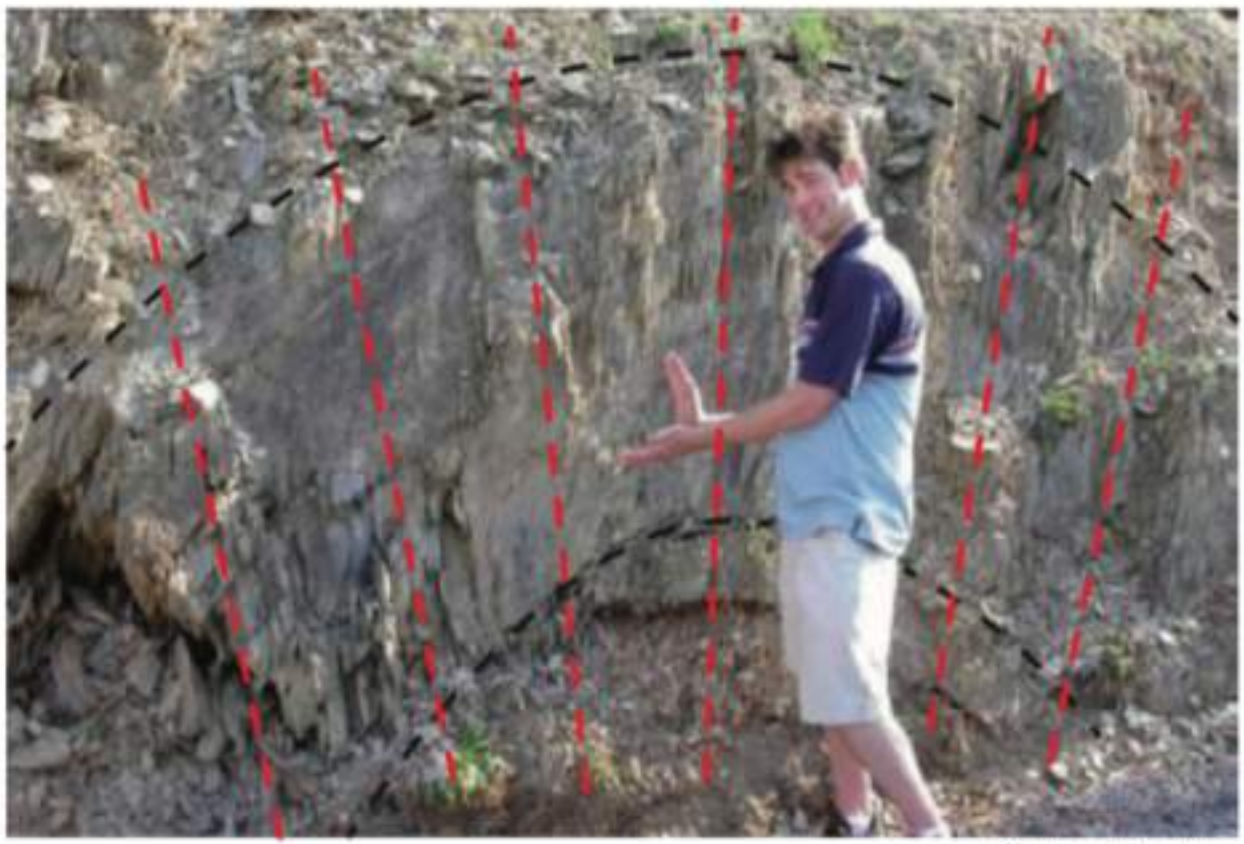
Question 2 Do these rocks appear to have experienced high-grade or low-grade metamorphism?

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?

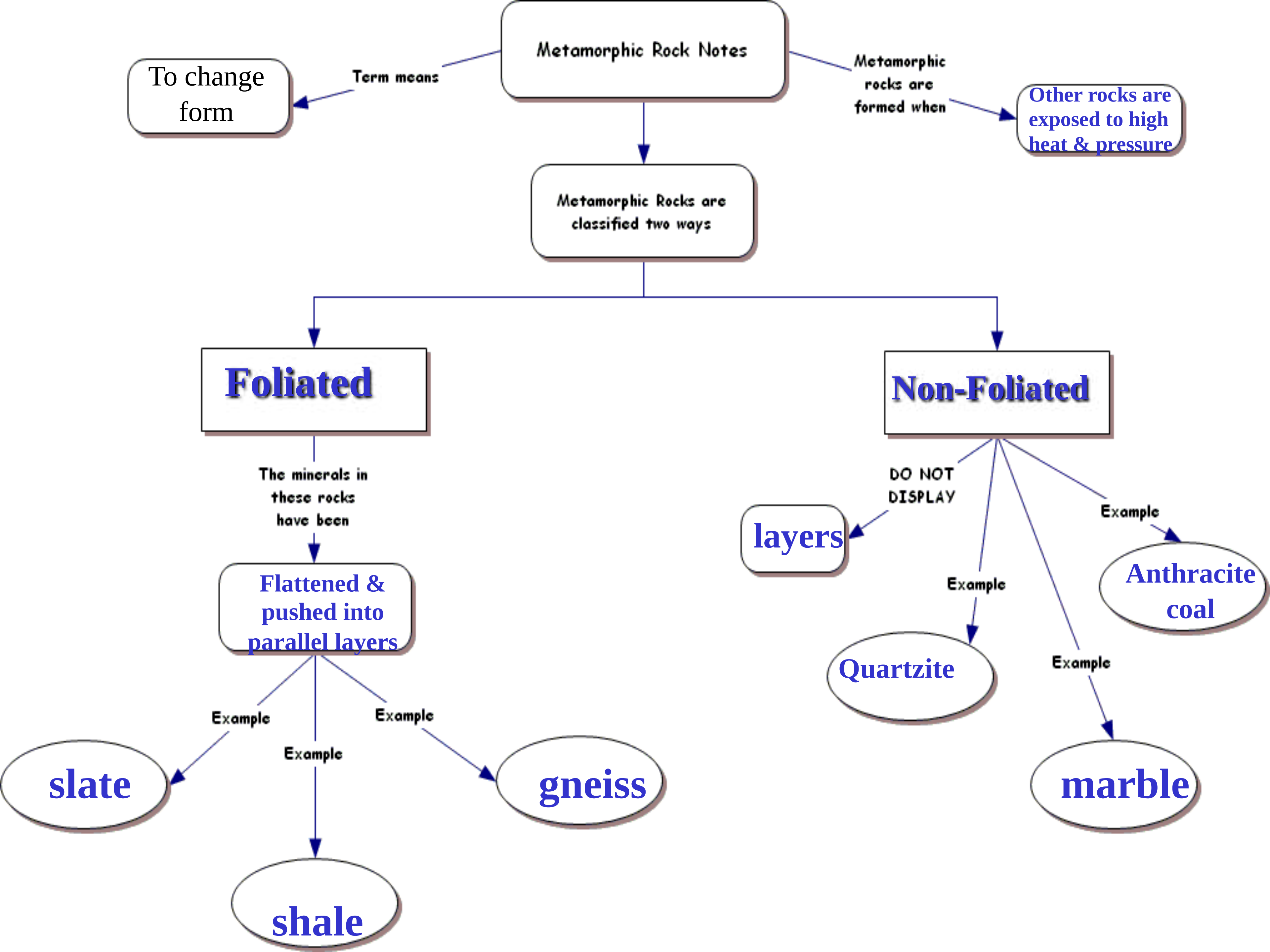


Callan Bentley

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

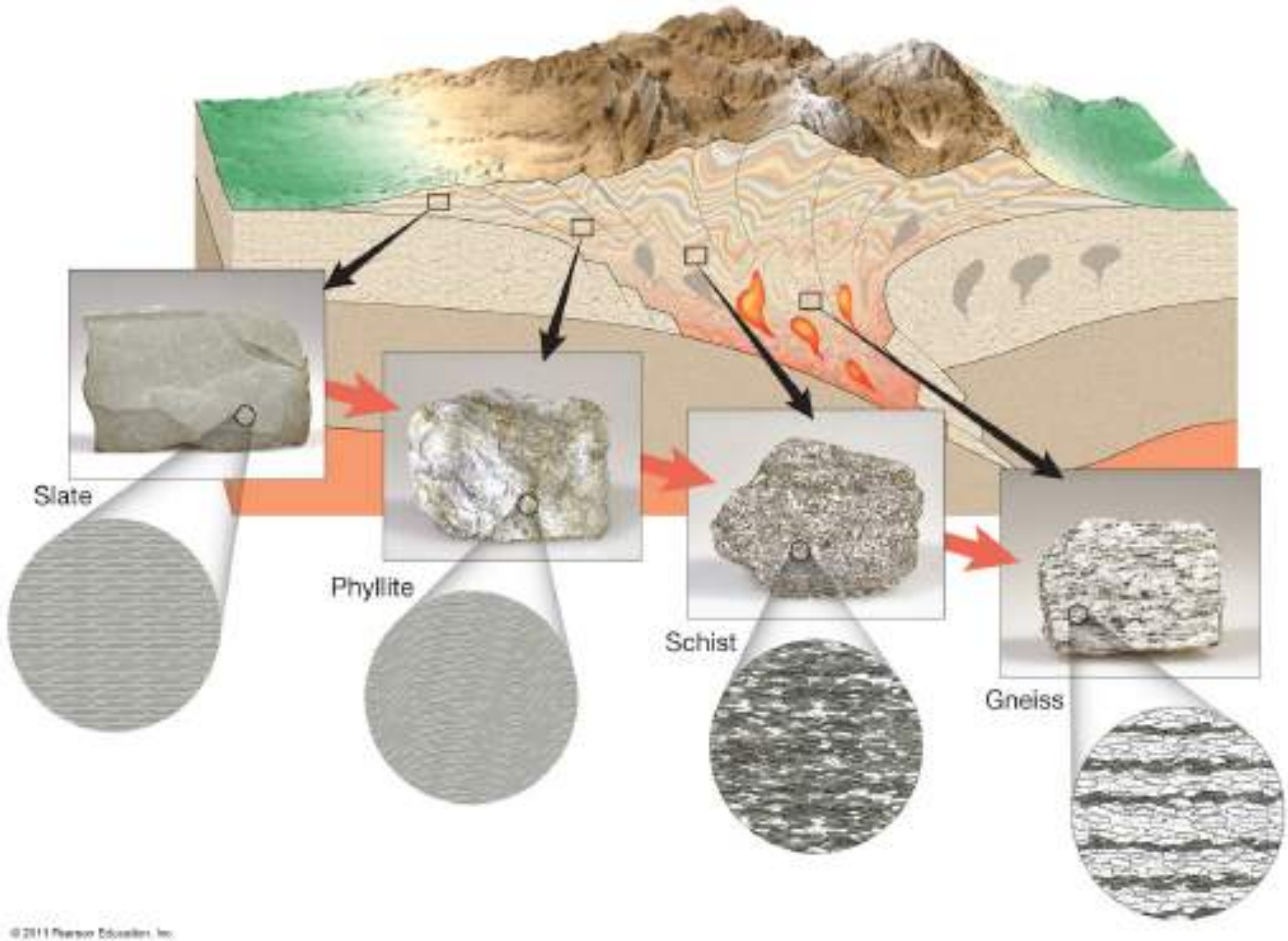
Rock Name		Texture	Grain Size	Comments	Original Parent Rock
Slate	Increasing Metamorphism	Foliated	Very fine	Excellent rock cleavage, smooth dull surfaces	Shale, mudstone, or siltstone
Phyllite		Foliated	Fine	Breaks along wavy surfaces, glossy sheen	Shale, mudstone, or siltstone
Schist		Foliated	Medium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

Metamorphic Zones

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

Starting rock:

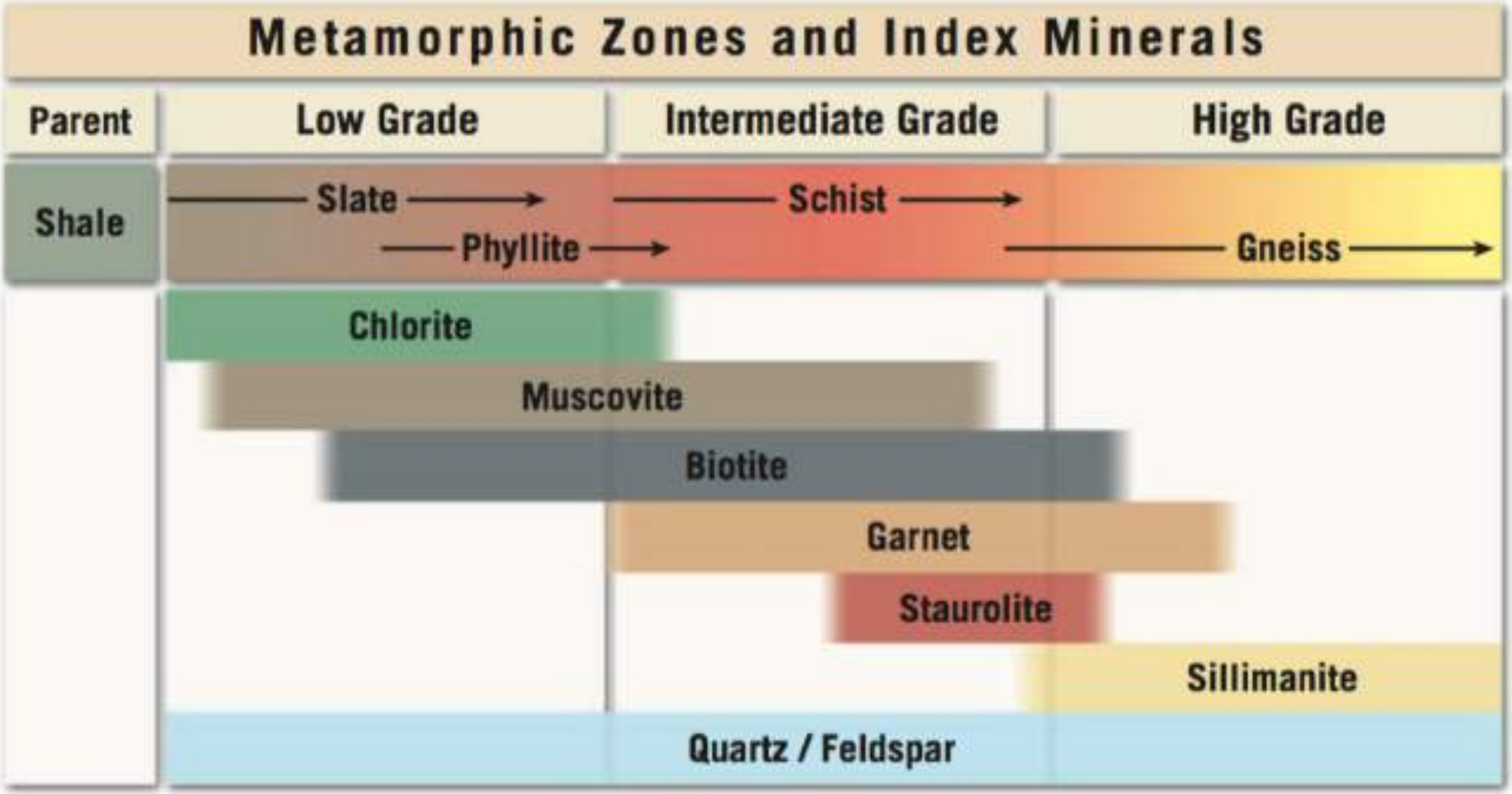
SHALE



Metamorphic Zones

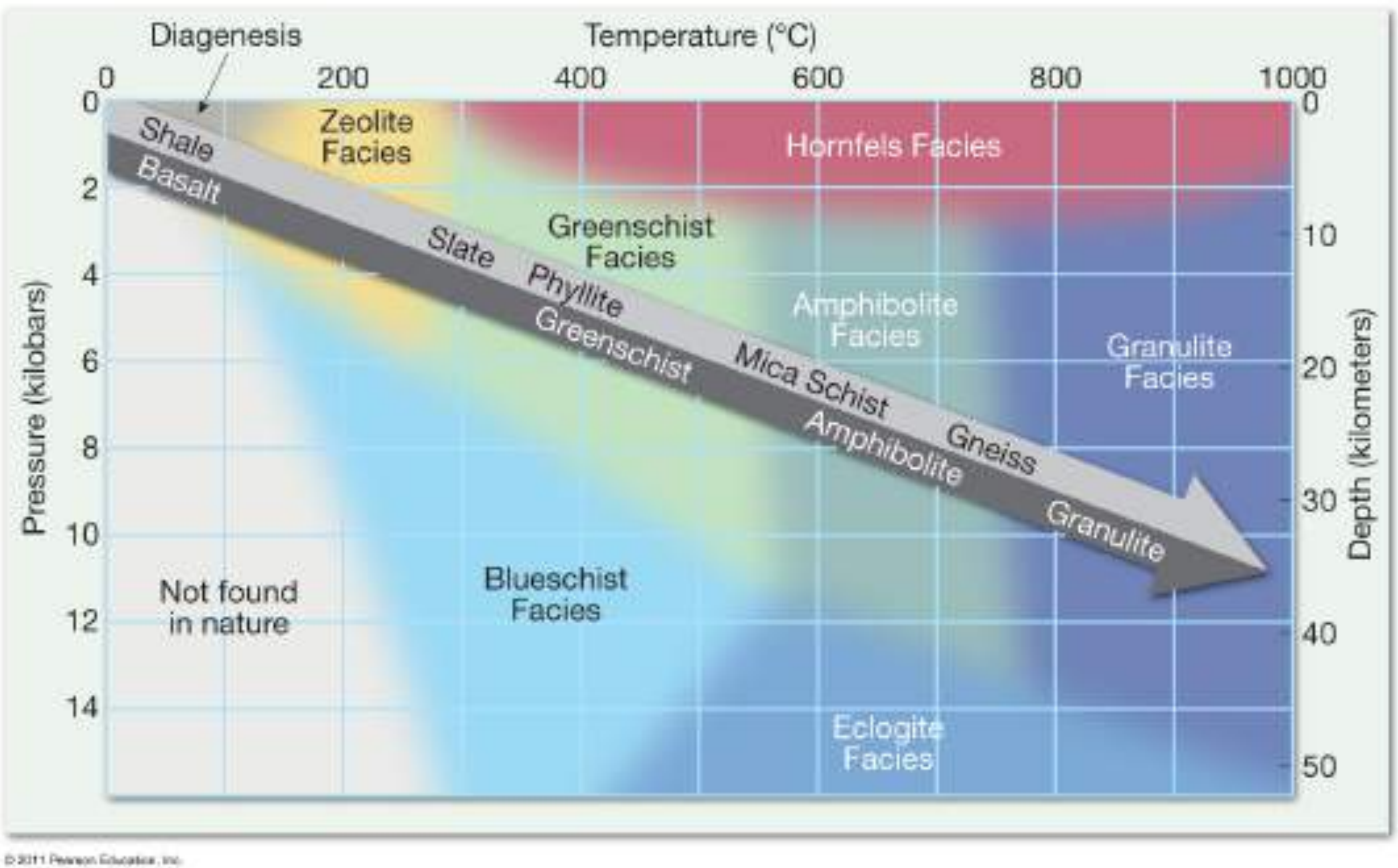
Index minerals and metamorphic grade

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

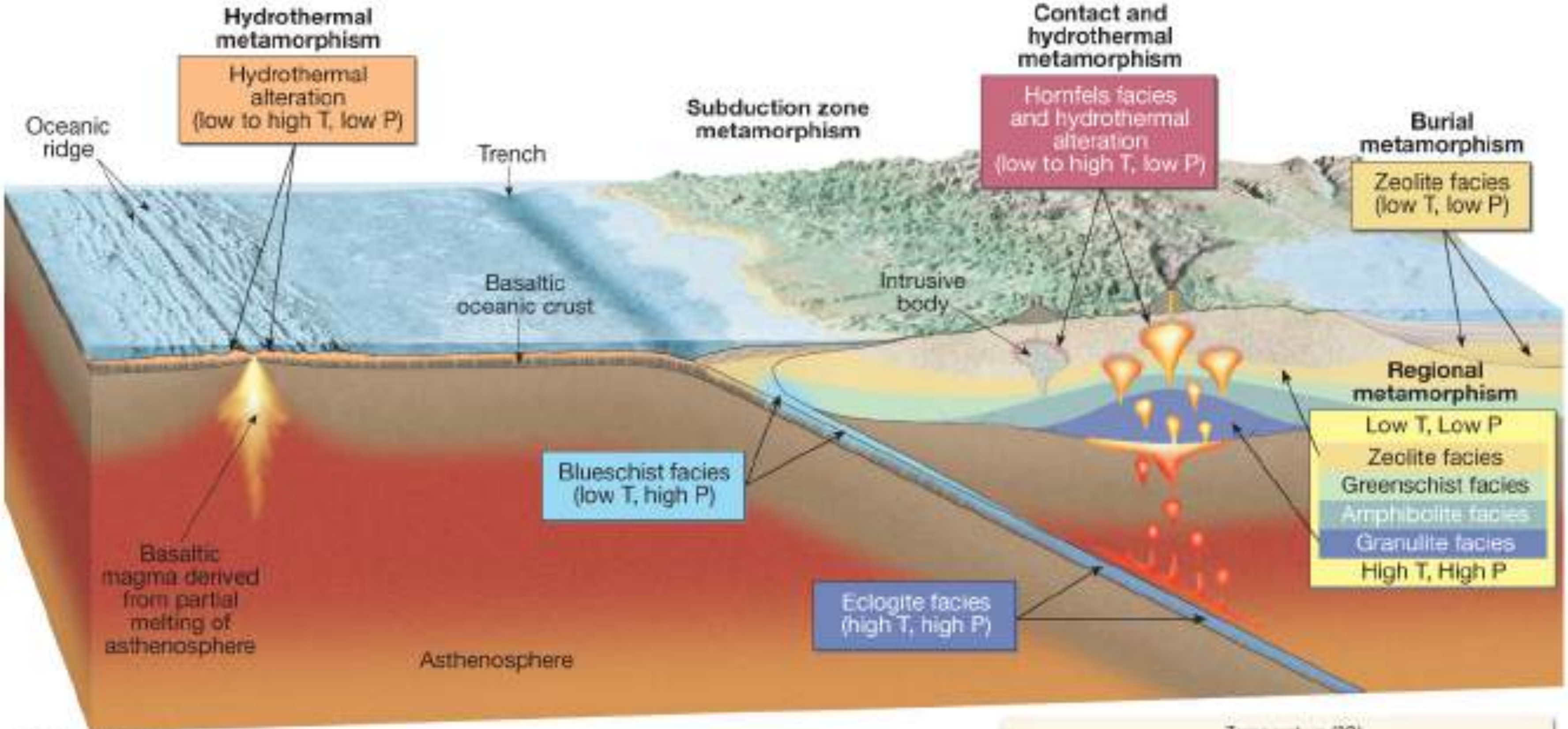


Metamorphic Facies

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

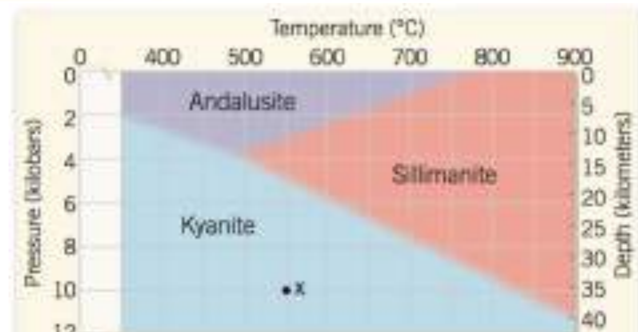


Metamorphic Facies and Plate Tectonics



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

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



A. Andalusite B. Kyanite C. Sillimanite

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?