8th edition of the biennial African School of Fundamental Physics and Applications

12/07/024, Morrocco

Special lecture on the Earth Sciences

Dr Bjorn P. von der Heyden
Stellenbosch University: Department of Earth Sciences (RSA)

Background image from: https://www.lanl.gov/projects/national-security-education-center/space-earth-center/index.php

Bjorn von der Heyden CV

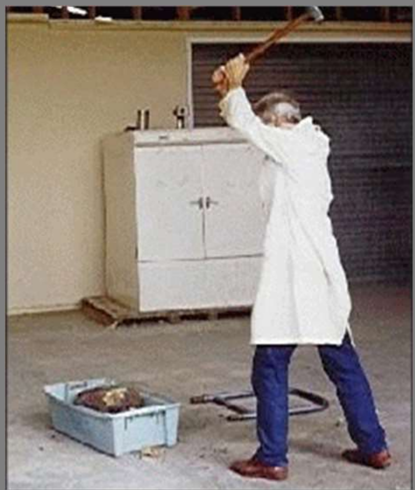
- B.Sc. Applied Earth Science, Stellenbosch University (2008)
- B.Sc. Hons. Geology, Stellenbosch University (2009)
- Ph.D. Geology, Stellenbosch University (2013)
- Professional-in-Training, Exxaro Resources (2013-2015)
- Lecturer/Sen. Lecturer in Economic Geology, Stellenbosch University (2015-present)
- African Rainbow Minerals co-Chair in Geometallurgy (2023-present)
- Lecturer: African School of Fundamental Physics and Applications (2021, 2022, 2024)

Earth Sciences...

What I think I do

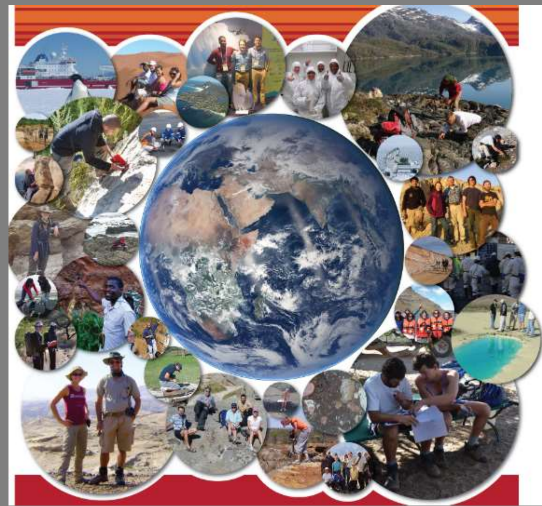
What I other scientists think I do

What my mom thinks I do



What my friends think I do

What rocks think I do



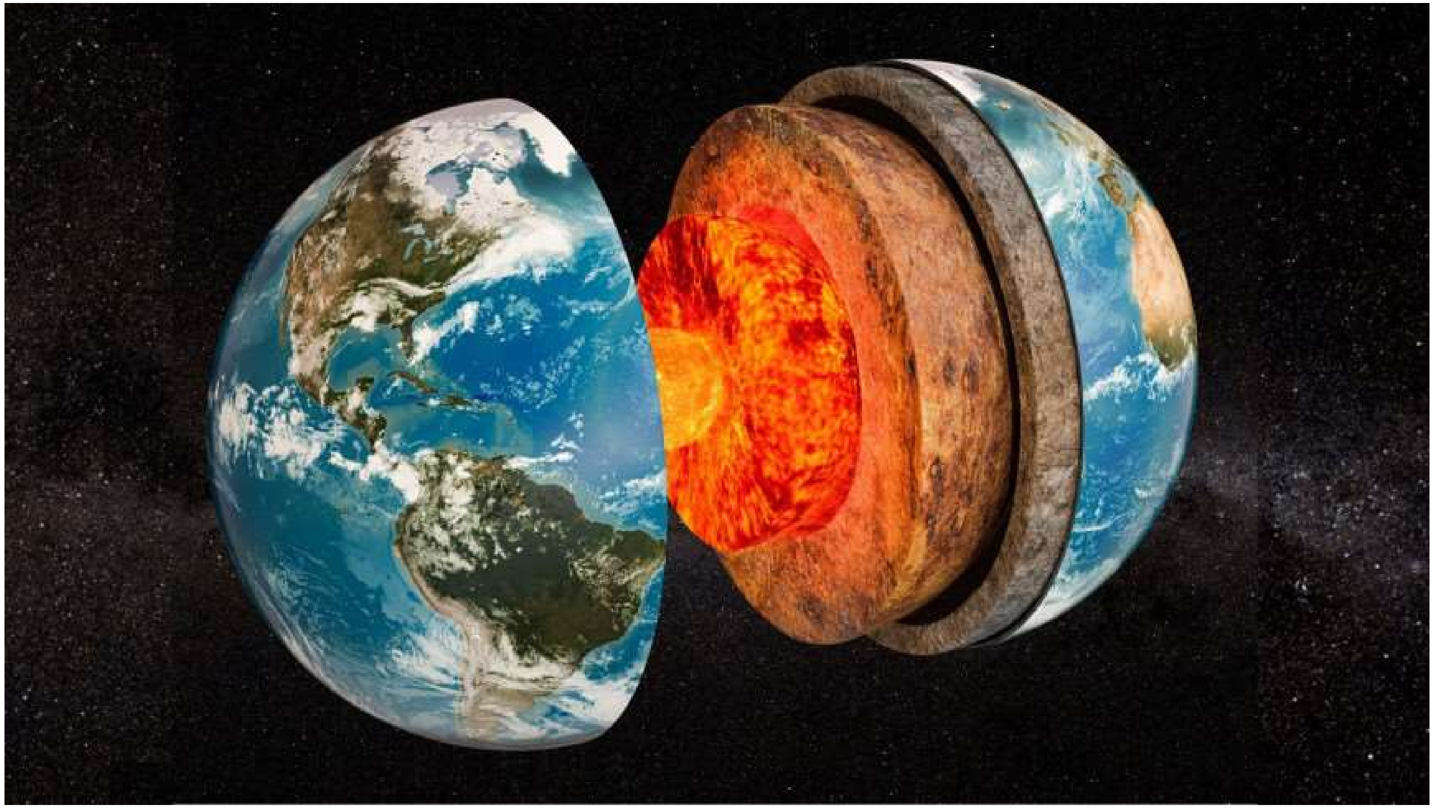
What I actually do

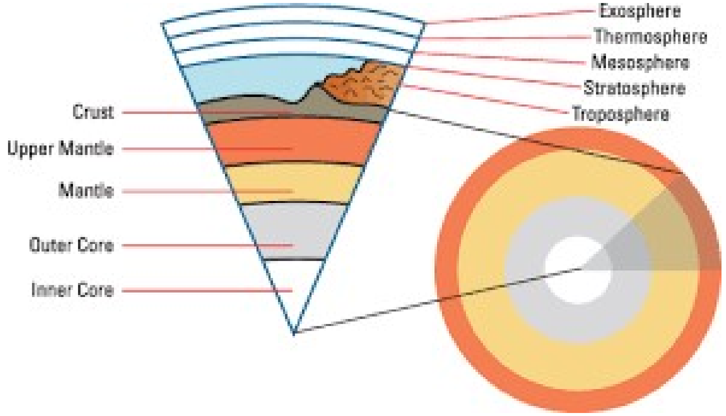
Seminar structure

- Part 1 (4.30 – 5.30 pm)
  - An introduction to the Earth Sciences
  - Fundamental insights into each of the Earth Sciences’ “spheres”
  - Job opportunities in each of the Earth Sciences’ “spheres”

- Part 2 (5.30 pm – 6.30 pm)
  - Selected case studies of PHYSICS application to the Earth Sciences’ “spheres”

What are the Earth Sciences?





But also the:

Hydrosphere Biosphere

Sphere: *realm (world) of something or physical dimensions / area of something, or both of these (Quora.com).*

Image credits: interestingengineering.com; dummies.com; geographyrealm.com

Opportunities for scientists trained in a "systems science"

- Important for students to start thinking about their future career opportunities early. Career choices may be informed by e.g., passion for a specific field, a calling, lucrativeness of that field, ease of promotion to senior roles, etc.
- Besides finding work in applied or technical roles, students trained in the Earth Sciences are also strongly sought after by a diverse array of industries which appreciate systems thinking coupled to a degree of creativity.
- Diversified opportunities in e.g., banking, insurance, logistics etc.

Image credit: https://ceo-insight.com/companies-of-excellence/digital-banking-revolution-and-ics-financial-systems-2/

The “Inner Spheres”

- The earth’s interior is divided into three main zones viz., the crust, the mantle and the core.

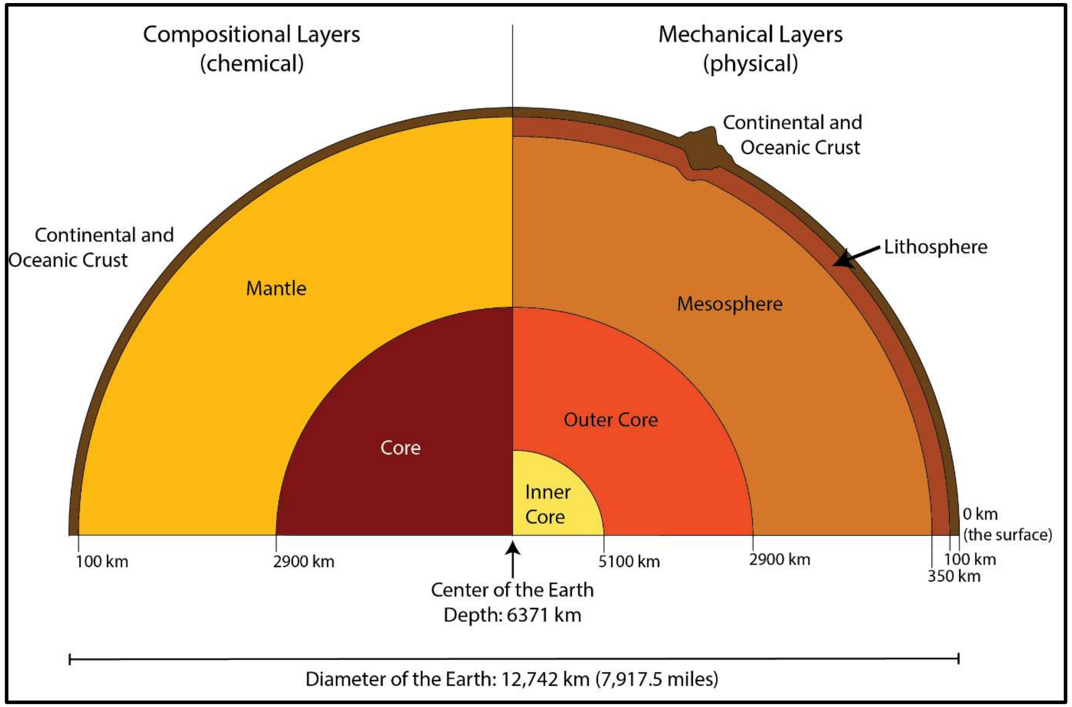


Image credit: Nooreen Meghani, 2016

- **Crust:** 0 -100 km comprising silicate minerals (divided into oceanic (SIMA) and continental crust (SIAL)). Brittle.
- **Mantle:** 100 – 2900 km comprising Fe- and Mg silicates. Based on mechanical properties can be divided into Asthenosphere and Mesosphere. Ductile.
- **Core:** 2900 – 6370 km. Predominantly Fe and Ni metal. Divided into outer core (liquid) and inner core (solid).

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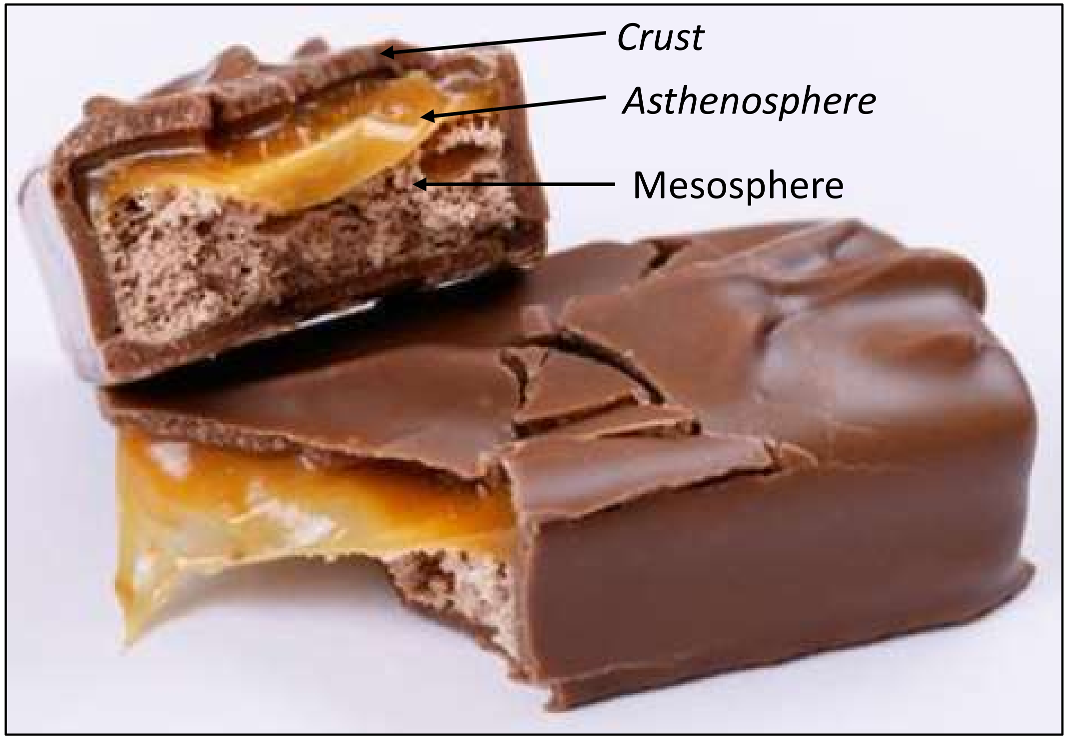

Image credit: Shutterstock

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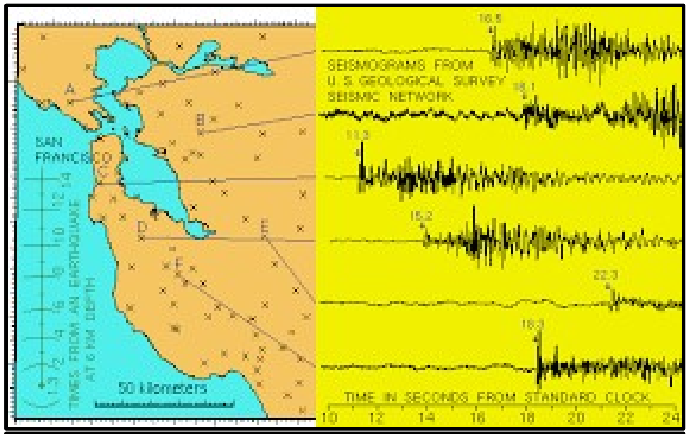
Opportunities for scientists who study the "inner spheres"

Seismology



Kimberlite experts

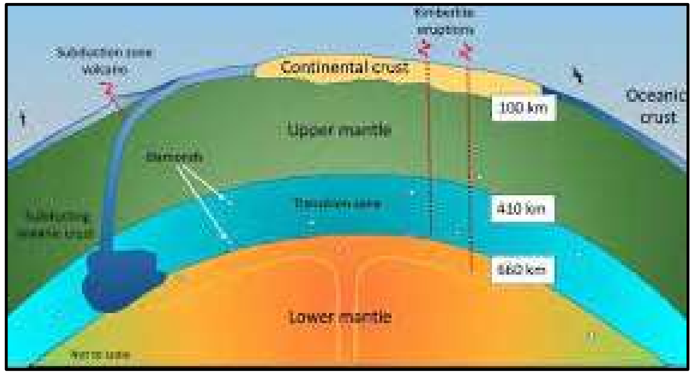


Image credits: USGS.gov; physics.org; geologyscience.com;

The lithosphere

- **First:** what is a rock versus what is a mineral??

The lithosphere

- **First:** what is a rock versus what is a mineral??

- What is a rock?
    - A rock is an aggregate of minerals. The mineral assemblage in each rock determines what type of rock it is. Three broad classes of rocks.

- So what is a mineral?
    - Homogeneous, naturally occurring, inorganic substance with a definable chemical composition and an internal structure characterised by an orderly arrangement of atoms, ions, or molecules in a lattice.

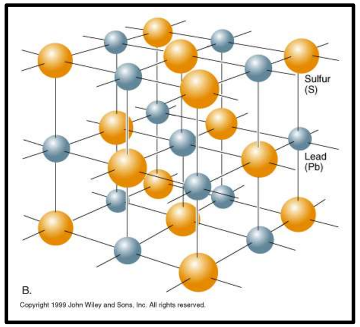
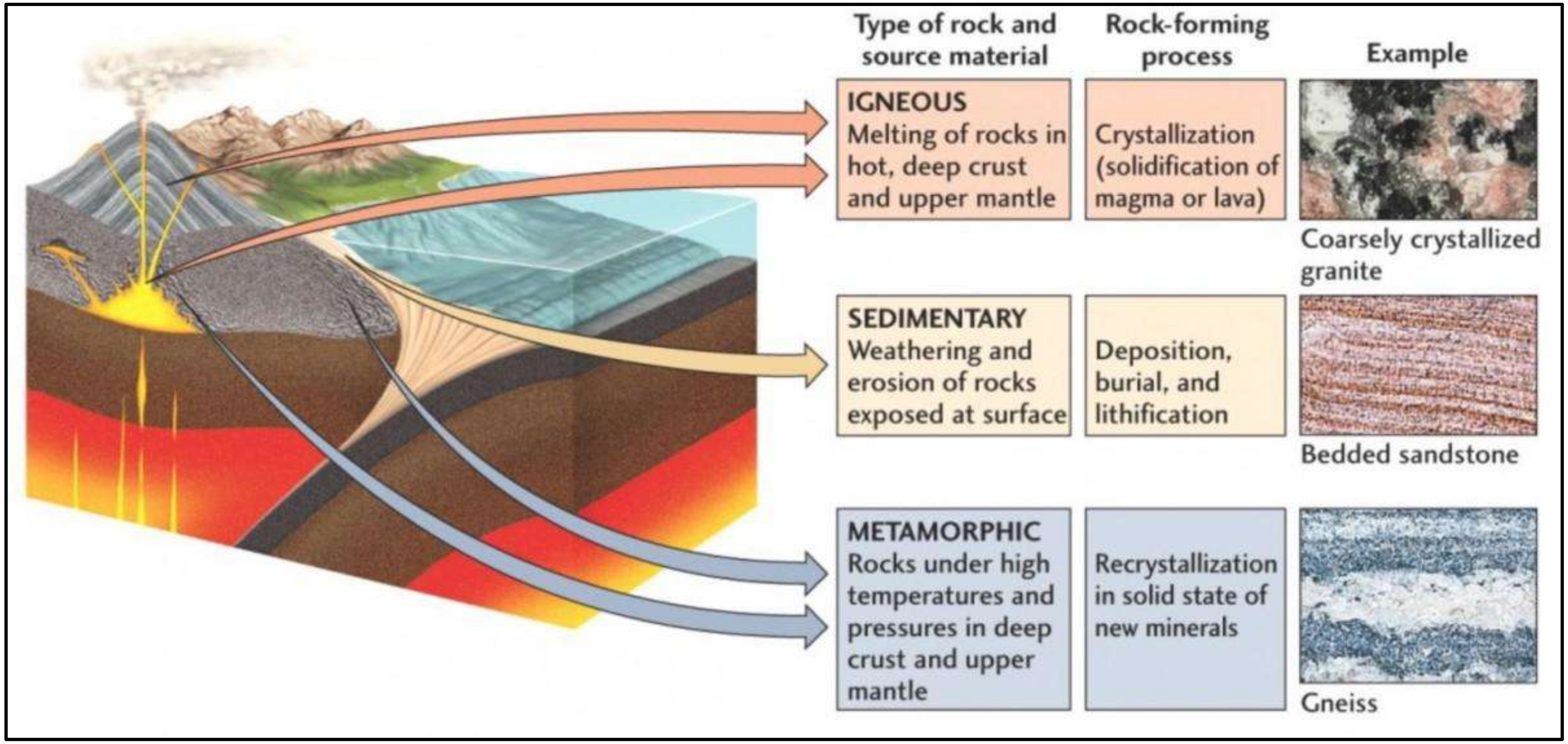


Image credits: alltop.com; geology.com; John Wiley and Sons (1999)

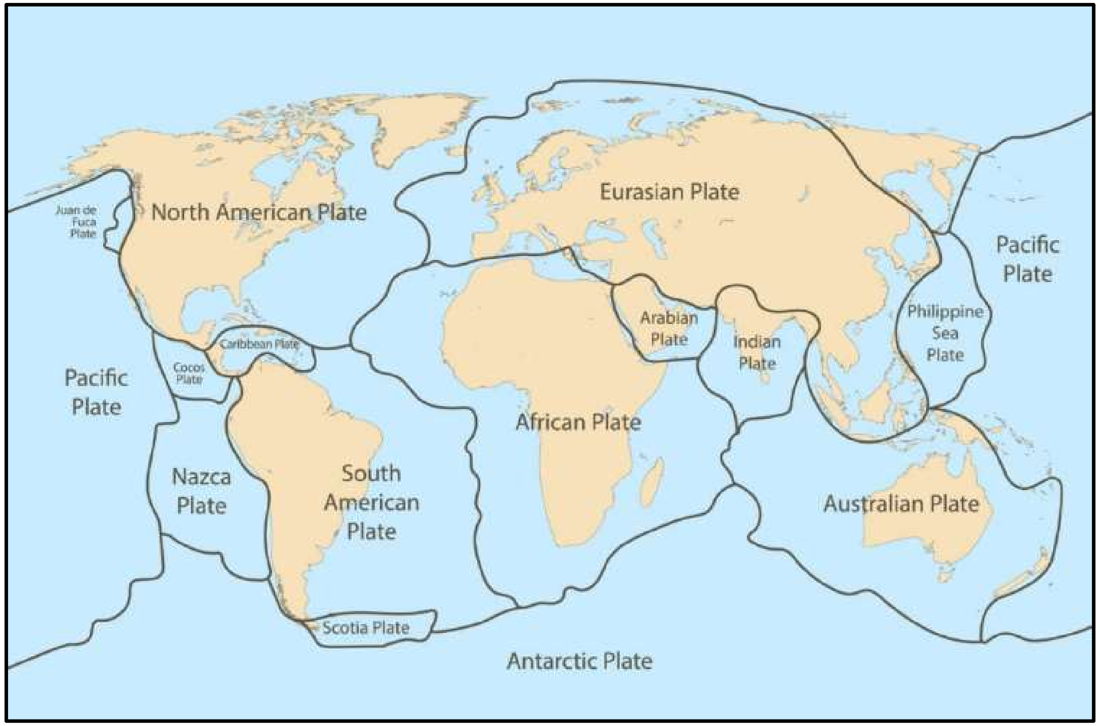
The lithosphere

- The rock cycle gives rise to three main classes of rocks:



The lithosphere

- The rock cycle: governed on a global scale by PLATE TECTONICS



- Theory first presented by Alfred Wegener in 1912.
    - Observations include geometric similarities between South America and Africa, and similarities in rock types and fossil records.
- Earth's rigid lithosphere is separated into seven major plates and eight minor plates.
- These plates 'ride' over the ductile and convecting asthenosphere and move at different rates relative to one another (2 -15 cm / year).
- Interactions at the plate boundaries give rise to e.g., mid-ocean ridges and mountain ranges such as the Himalayas.

Image credits: sciencesparks.com

The lithosphere

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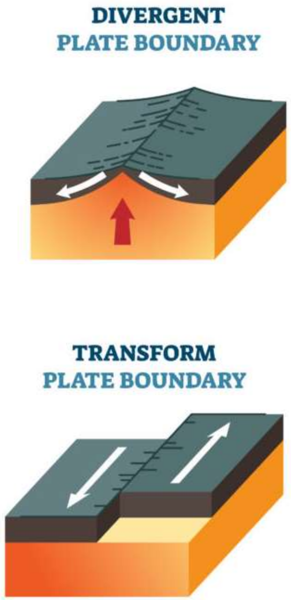
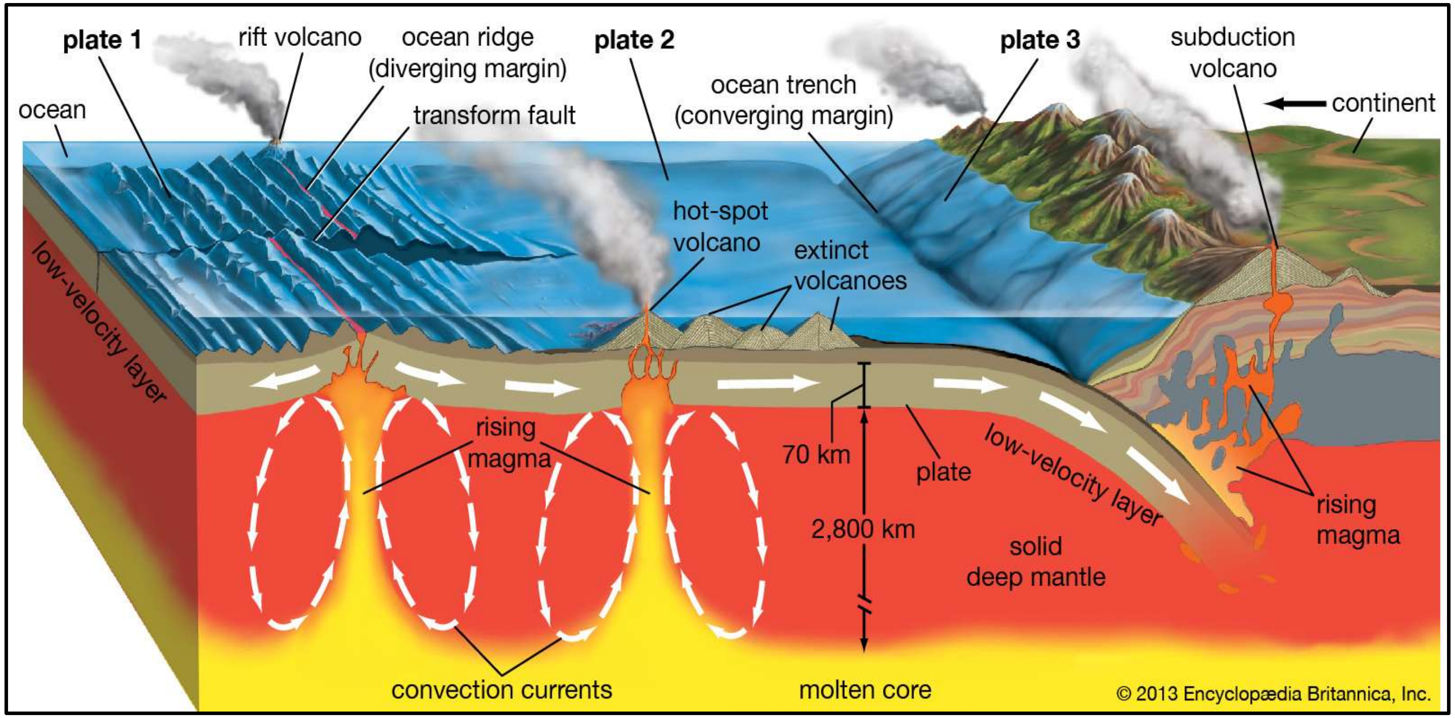




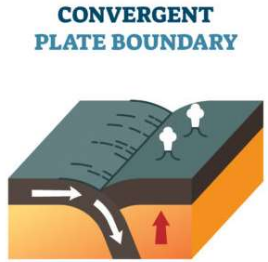


Image credits: sciencesparks.com; britannica.com

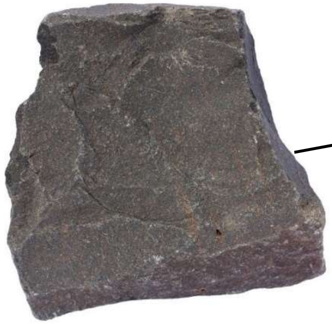
The lithosphere

- Each tectonic environment can be associated with characteristic rock types

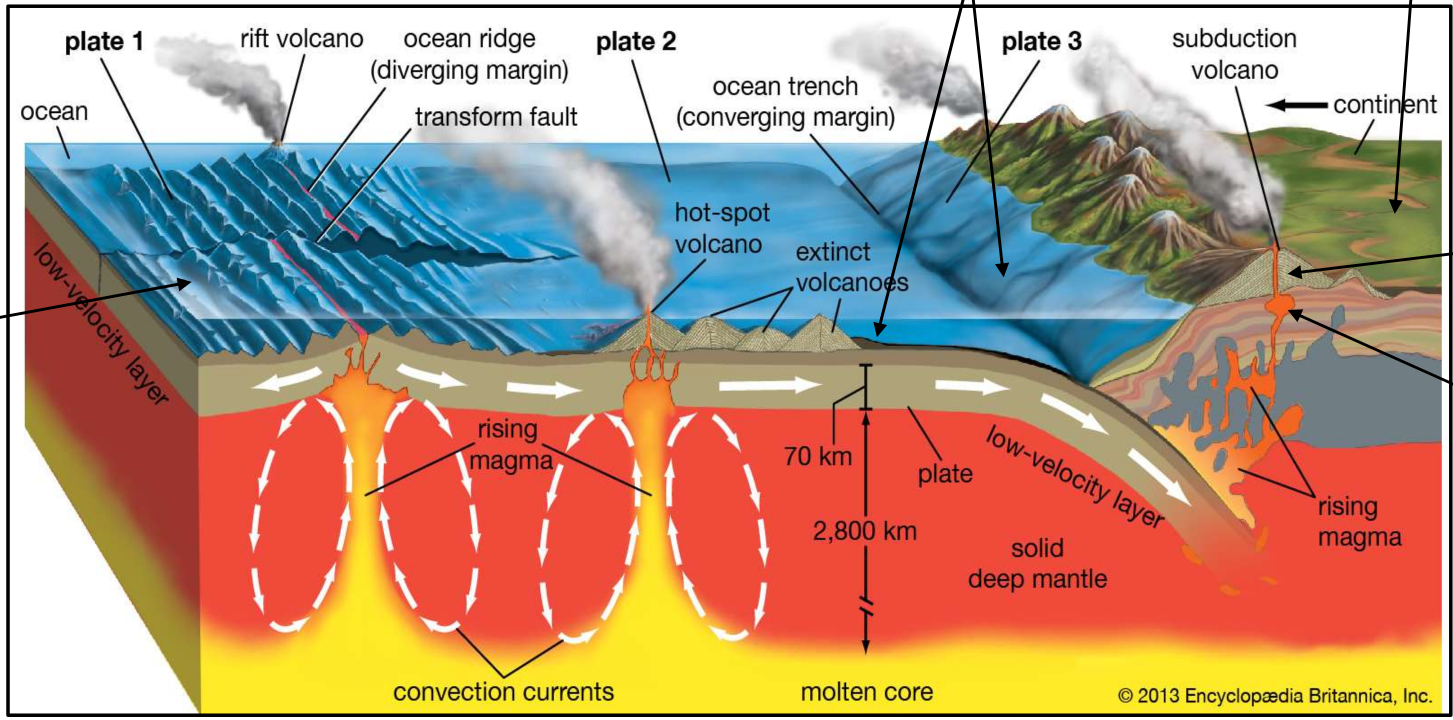
Shale

Sandstone

Rhyolite



Basalt

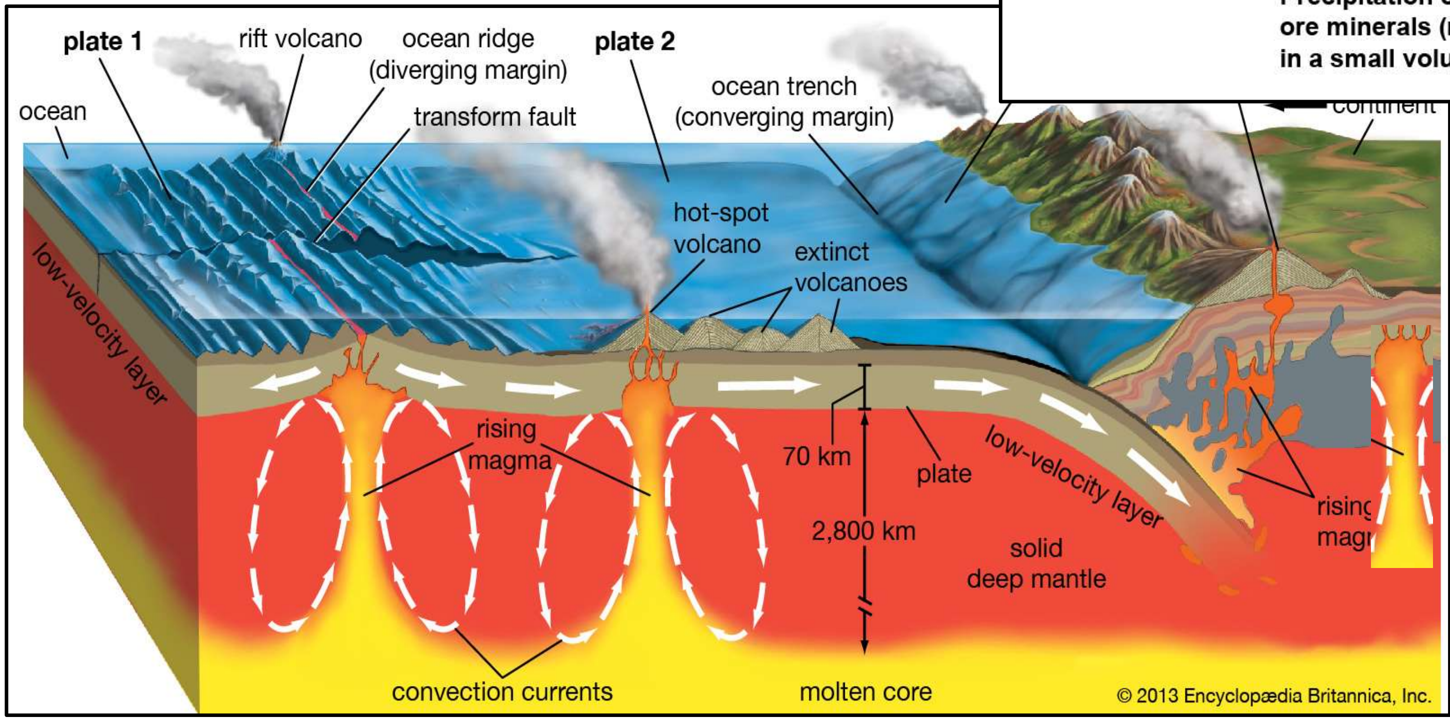


Granite

Image credits: britannica.com; geologylearn.blogspot.com; geology.com; sandatlas.org

The lithosphere

- Each tectonic environment can be associated with characteristic ore deposits



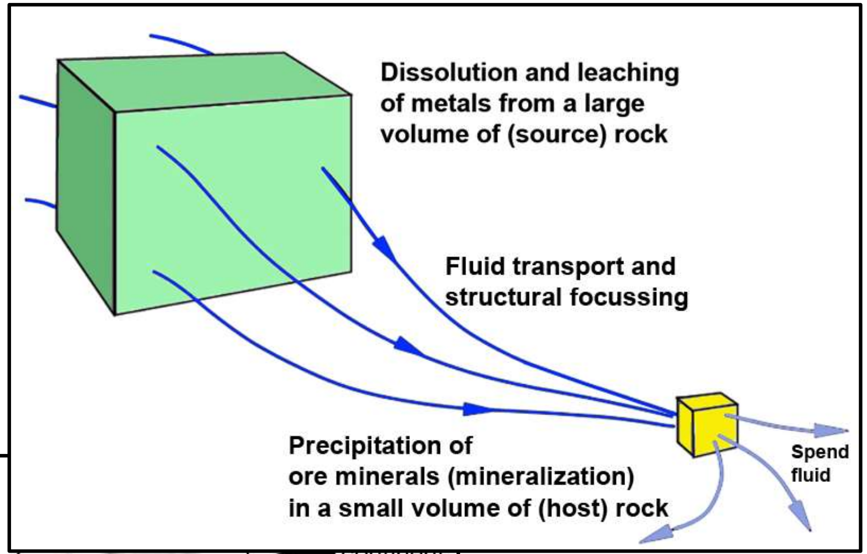


Image credits: britannica.com; isa.org.jm; seg2020.org; bcgoldadventures.com; geologyforinvestors.com; Wikipedia.com

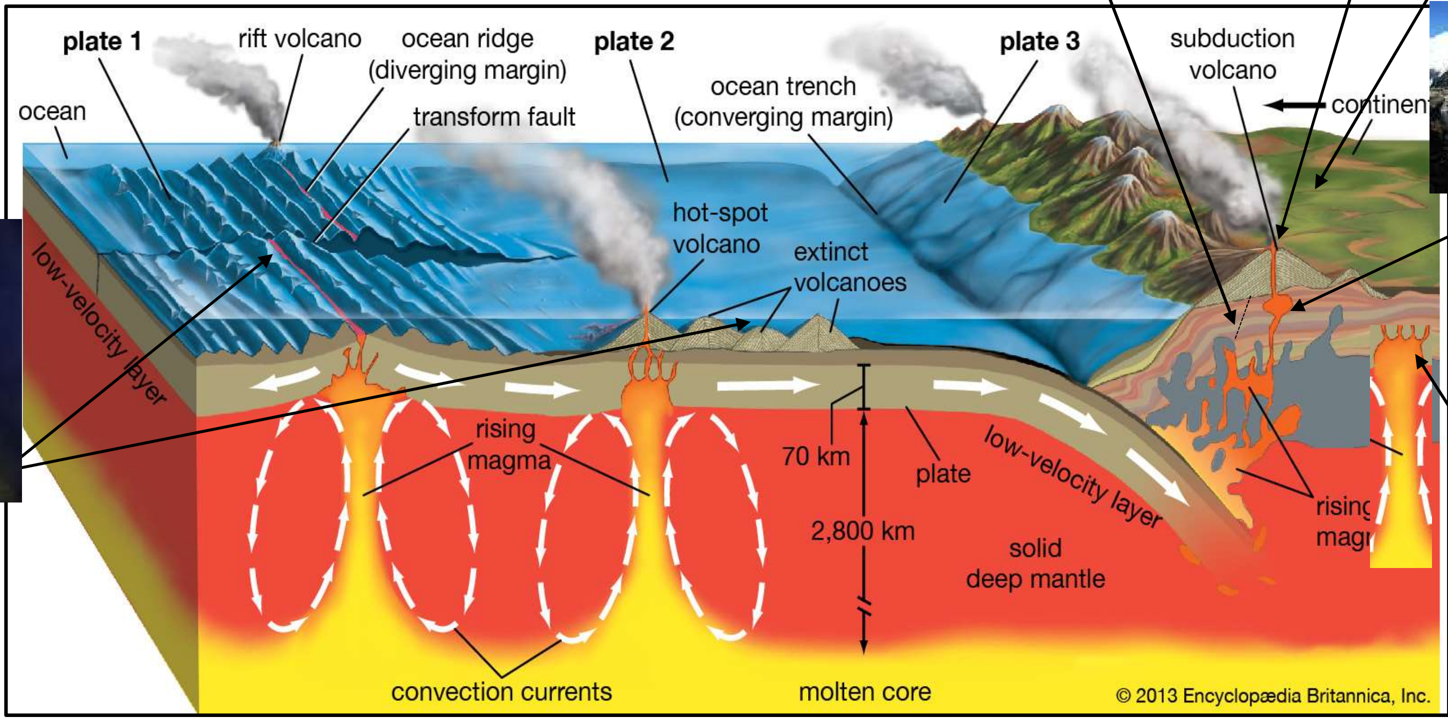
The lithosphere

- Each tectonic environment can be associated with characteristic ore deposits

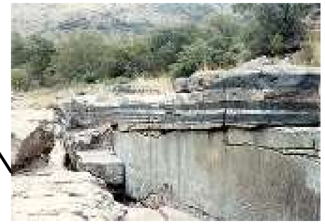
Orogenic Gold
Au

Epithermal systems
Au, Ag, Cu

Surficial deposits
U, Al,



Porphyry deposits
Cu, Mo, Au



Volcanic Massive Sulphide (VMS)
Cu (+-Zn, Pb)

Mafic layered intrusions
PGE, Cr, V, Ni, Cu

Image credits: britannica.com; isa.org.jm; seg2020.org; bcgoldadventures.com; geologyforinvestors.com; Wikipedia.com

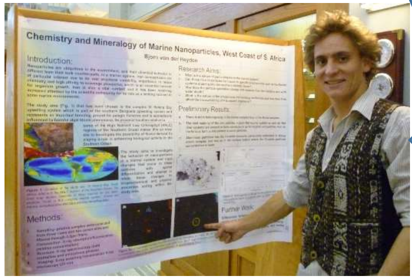
Mining

Commodity analyst

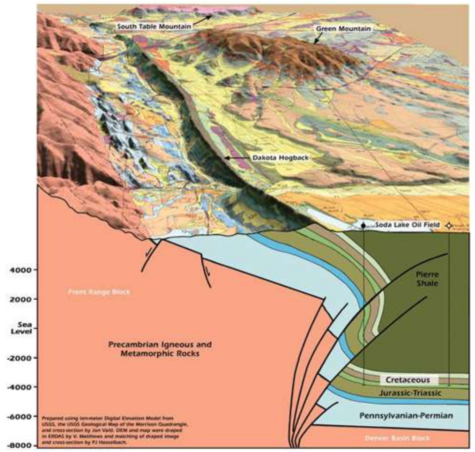
Consultancy

www.salemgroup.com

Engineering Geology



Academia



www.coloradosurvey.org

Mapping/Surveys

Exploration

www.halepaska.com

Ground water exploration/
geohydrology

Palaeontology

**Apologies, image credits not cited.*

The hydrosphere

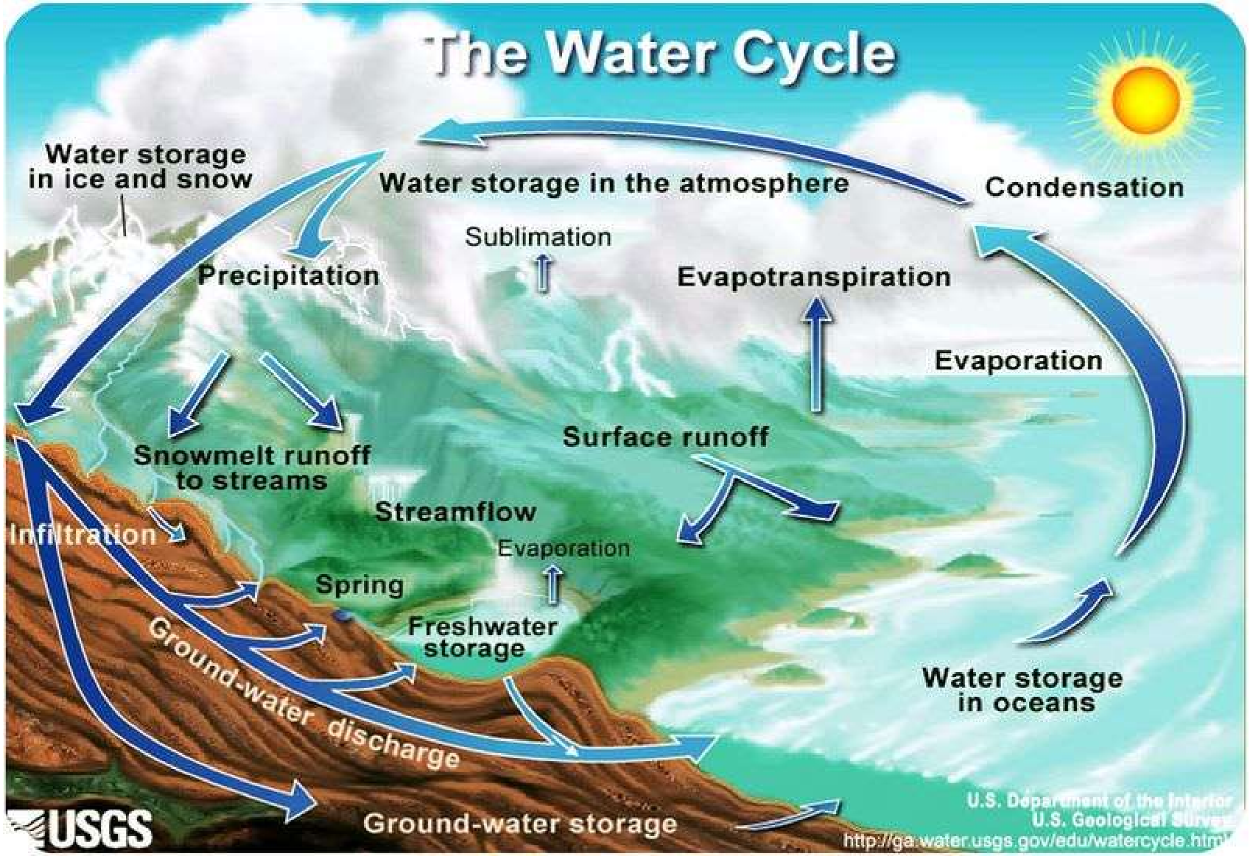
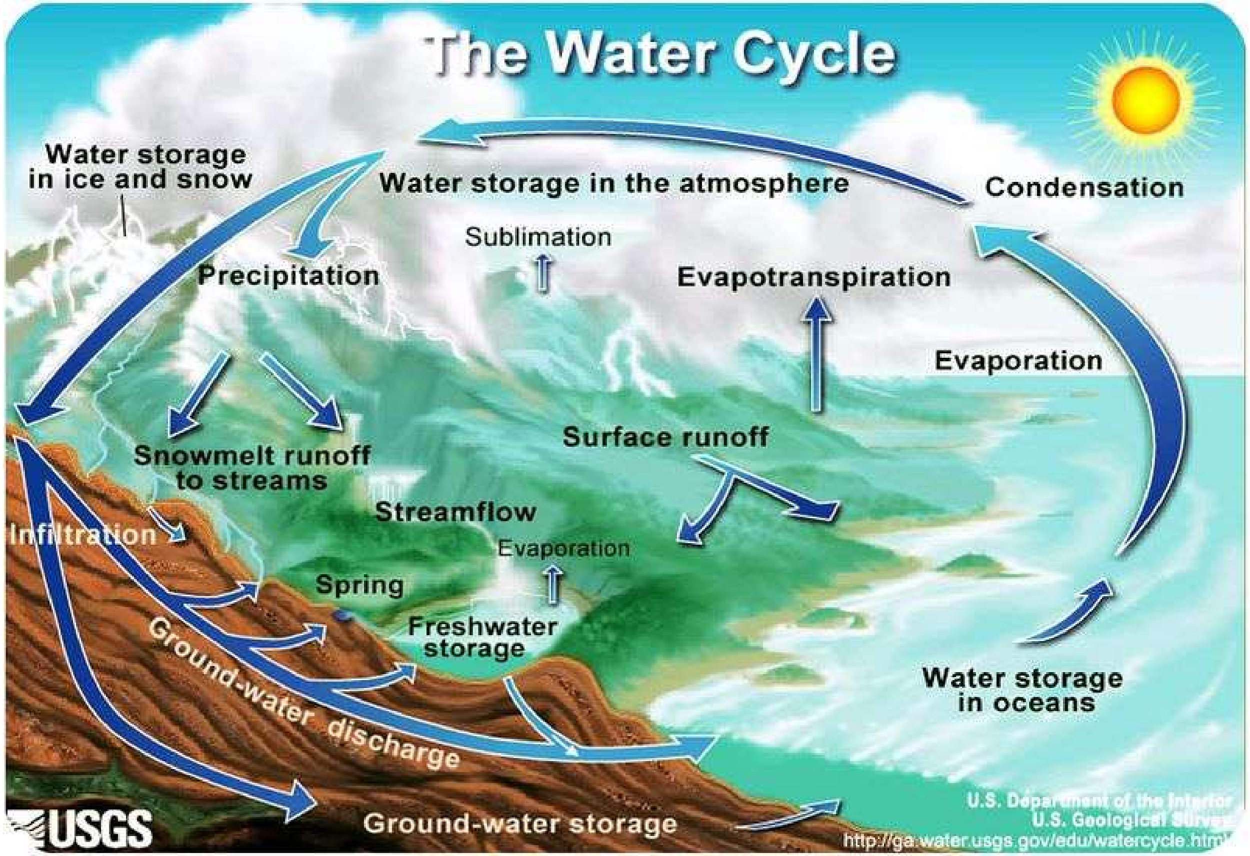


Image credits: USGS

- Water occurs in three states on planet earth, viz. liquid (water), solid (ice) and gas (water vapour).
- 71% of Earth's surface is covered in water; oceans store 96.5% of all water.
- Regarded as a renewable resource, since the hydrological cycle is essentially a closed system.

The hydrosphere



Reservoir	Average residence time
Antarctica	20,000 years
Oceans	3,200 years
Glaciers	20 to 100 years
Seasonal snow cover	2 to 6 months
Soil moisture	1 to 2 months
Groundwater: shallow	100 to 200 years
Groundwater: deep	10,000 years
Lakes (see lake retention time)	50 to 100 years
Rivers	2 to 6 months
Atmosphere	9 days

Image credits: USGS; Table credit: Wikipedia (with external citation)

The pedosphere

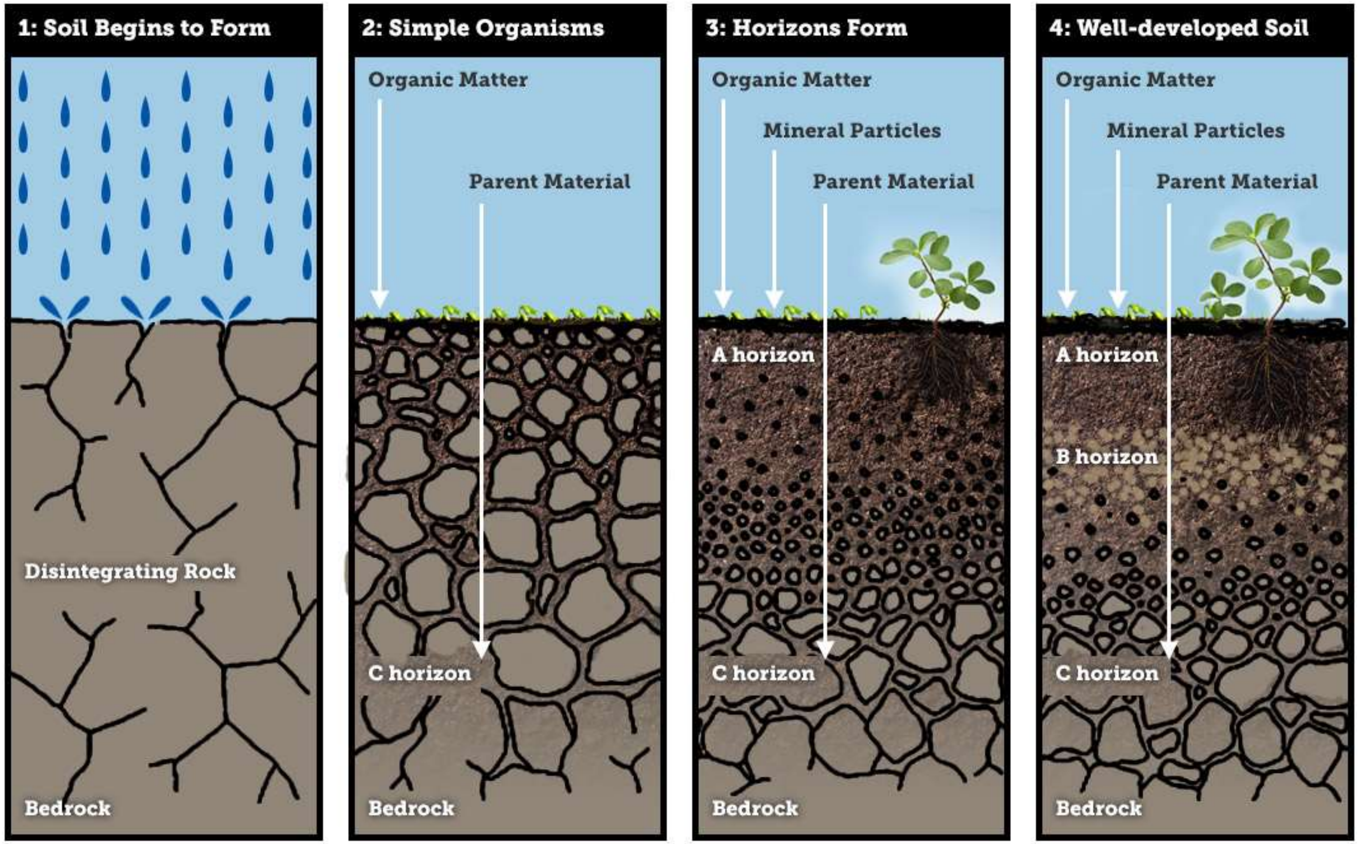
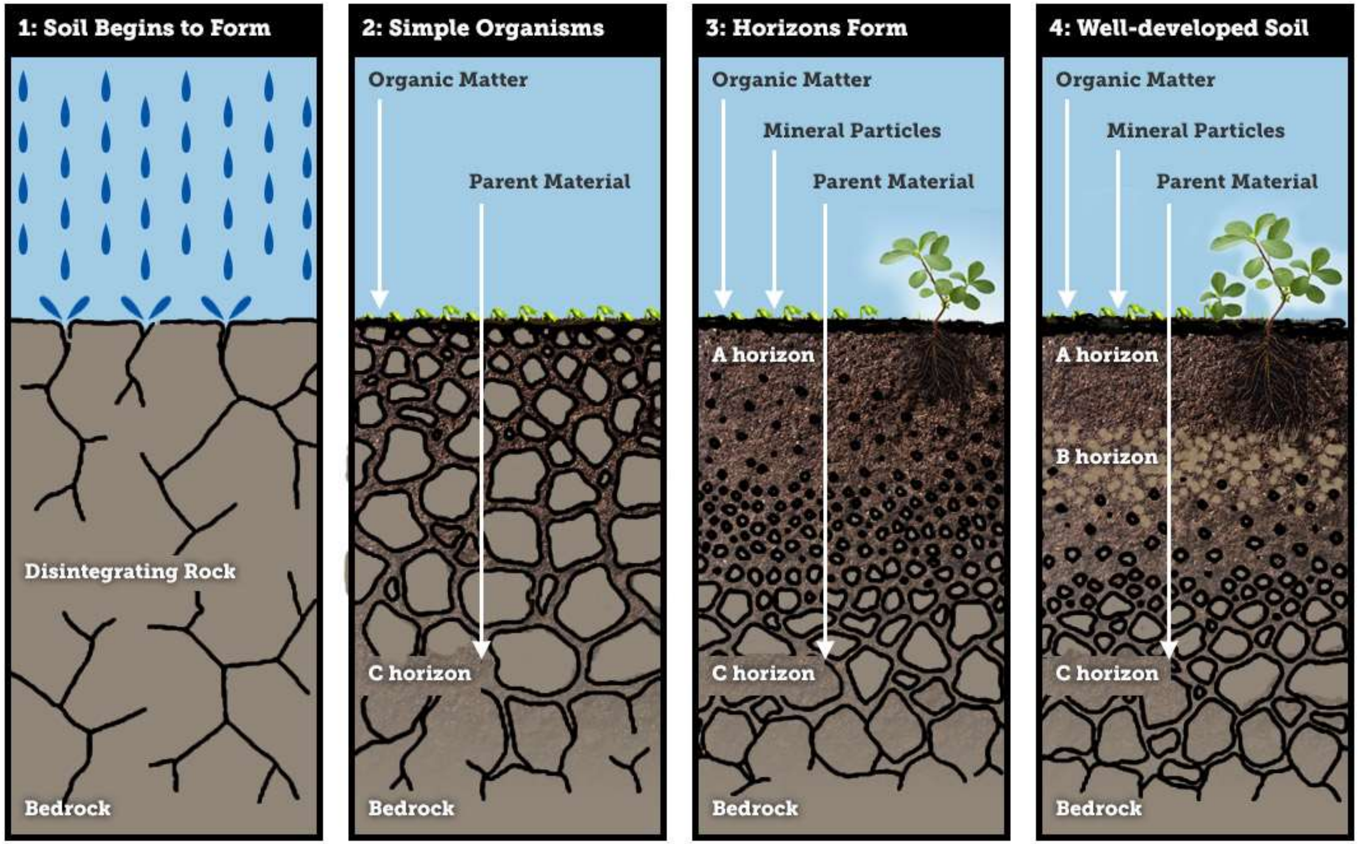


Image credits: socratic.org

- Biogeochemical cycling (action of fluids and microbes) result in rocks breaking down to form a soil profile.
- Dependent on climate, vegetation type, slope, parent rock-type and time.
- O, E, A, B, C, and R horizons commonly defined

The pedosphere

O Horizon: predominantly organic matter
A Horizon: humic material mixed with clay minerals
E Horizon: zone of significant leaching but no organics
B Horizon: zone of accumulation of leached ions
C Horizon: partially weathered parent rock
R Horizon: Regolith, or fresh bedrock



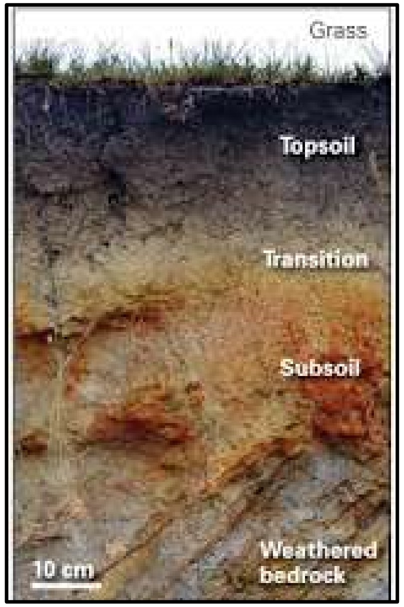
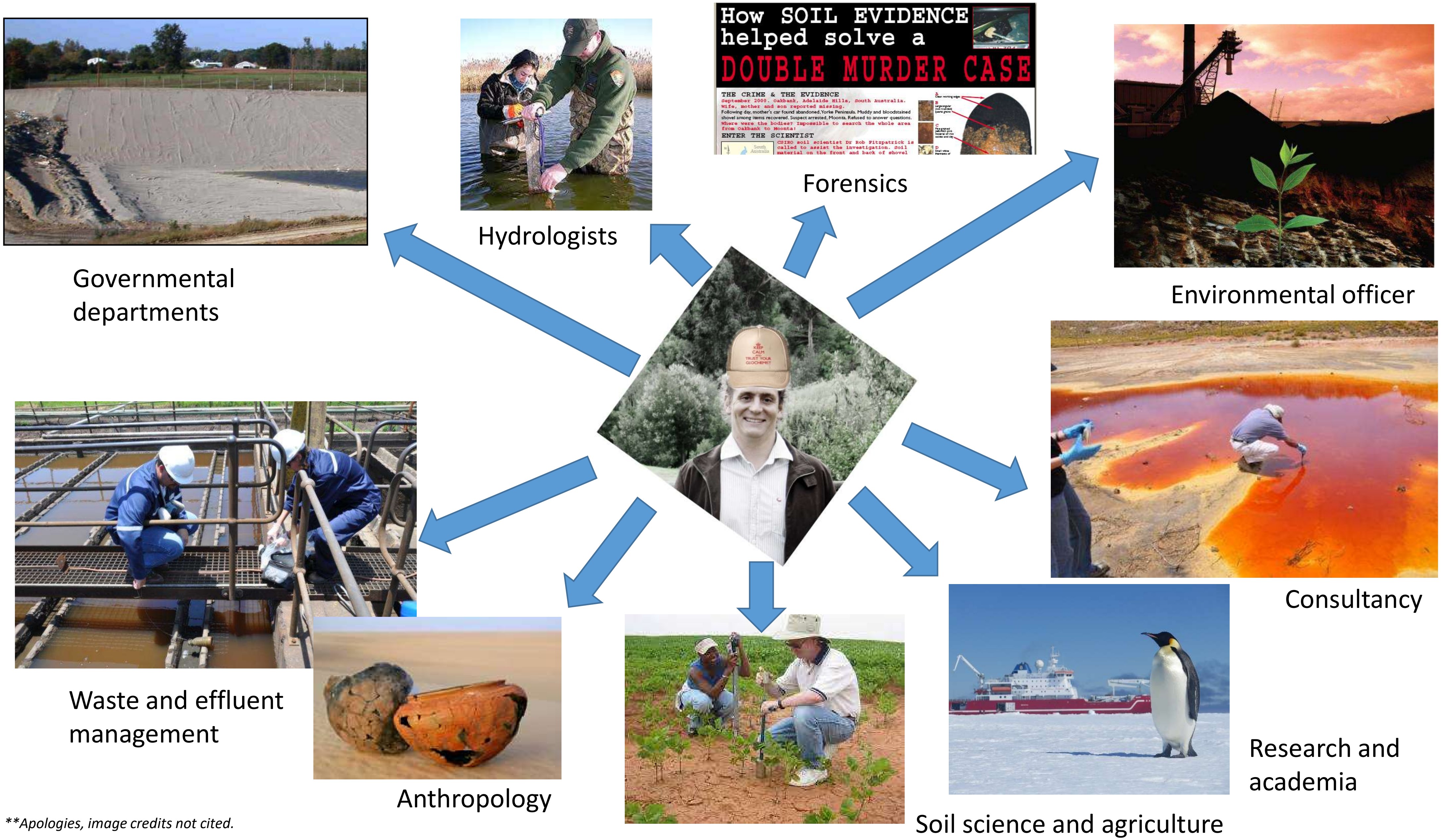


Image credits: geologylearn.blogspot.org; socratic.org



***Apologies, image credits not cited.*

The atmosphere

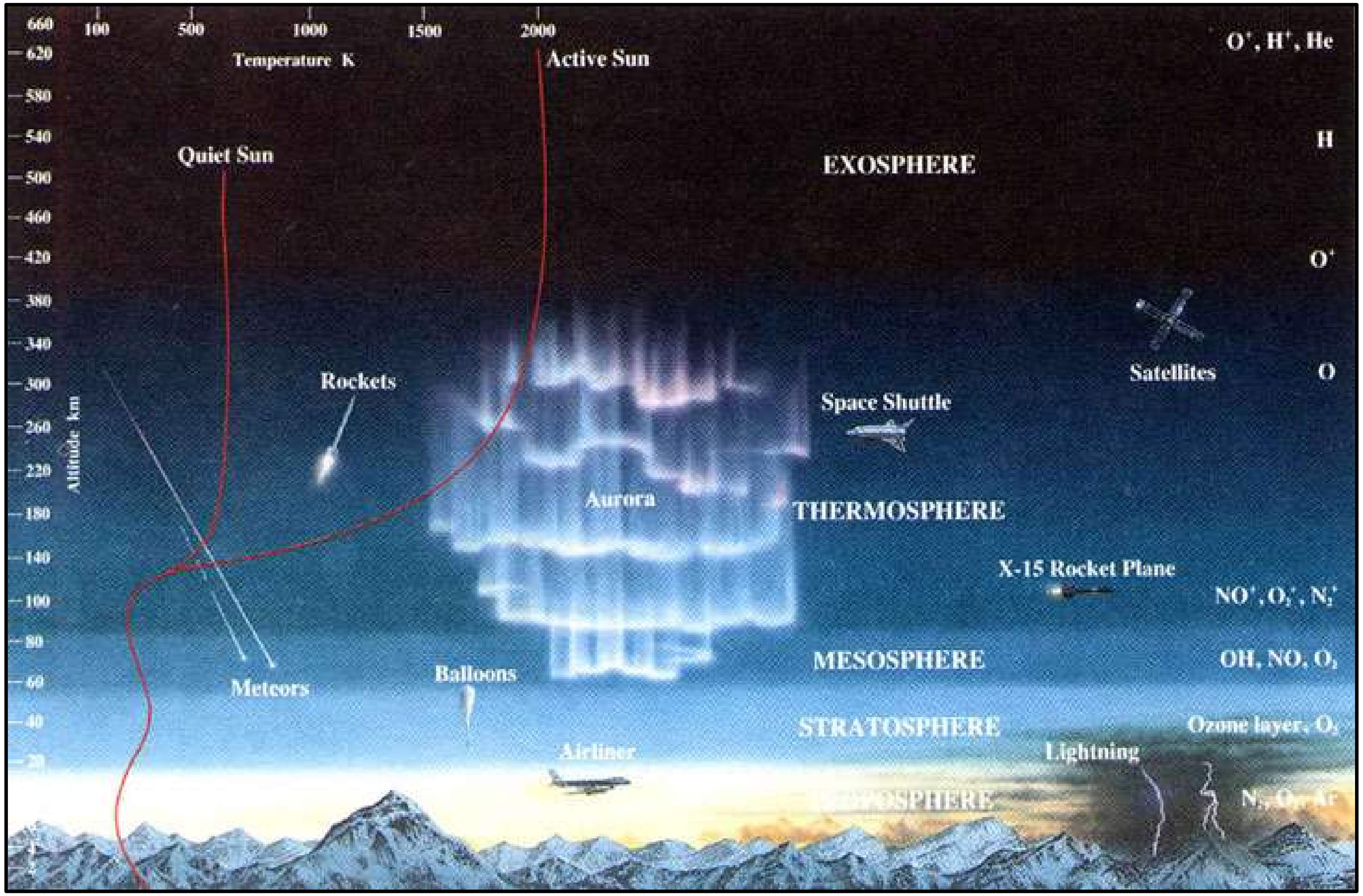


Image credits: Howthingsfly.si.edu.

- **Troposphere:**
  - contains 75% of all air in the atmosphere, and almost all moisture.
  - From surface to the tropopause which is located 7-18 km above earth's surface.
  - Temperature decreases by 6.6°C/km elevation.
- **Stratosphere:**
  - Contains most of earth's ozone
  - Extends from tropopause to ~50 km above earth's surface
  - Temperature increases with elevation due to absorption of UV radiation.

The atmosphere

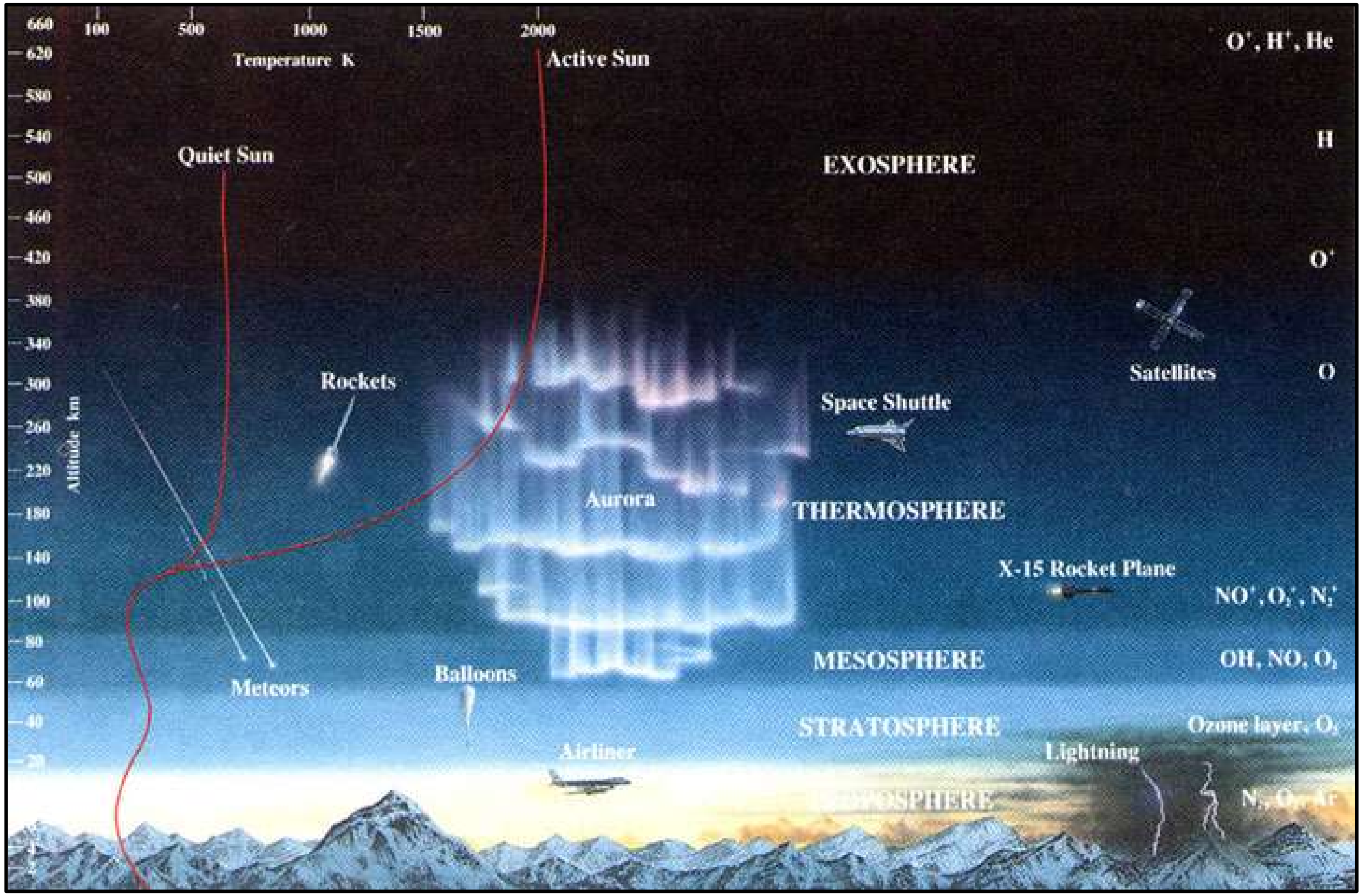


Image credits: Howthingsfly.si.edu.

- **Mesosphere:**
  - Comprises a relatively high concentration of metals (e.g., Fe) from meteor vapourisation.
  - Located between 50 – 85 km above earth's surface.
  - Difficult to study.
  - Temperatures as cold as -90°C.
- **Thermosphere:**
  - Ionic species prevalent due to interactions with X-rays
  - 85-~400 km above earth's surface
  - Temperature increases on account of UV and X-ray absorption
- **Exosphere:**
  - Mainly oxygen and hydrogen atoms following ballistic trajectories (rare collisions due to low concentrations).

Opportunities for scientists who study the earth's atmosphere

Aerosol chemist

Meteorologist

Climate scientist

Planetary scientist

Image credits: sciencephoto.com; career.ireasearchnet.com; phys.org; carnegiestemgirls.org

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Background image from: https://www.lanl.gov/projects/national-security-education-center/space-earth-center/index.php

Seminar structure

Part 2 (5.30 pm – 6.30 pm)

Selected case studies of PHYSICS application to two of the Earth Sciences' "spheres"

- **"Inner-sphere":** Seismic wave propagation and earthquake monitoring
- **Lithosphere:** Formation of orogenic gold deposits

- Each case study will be preceded by a brief recap…

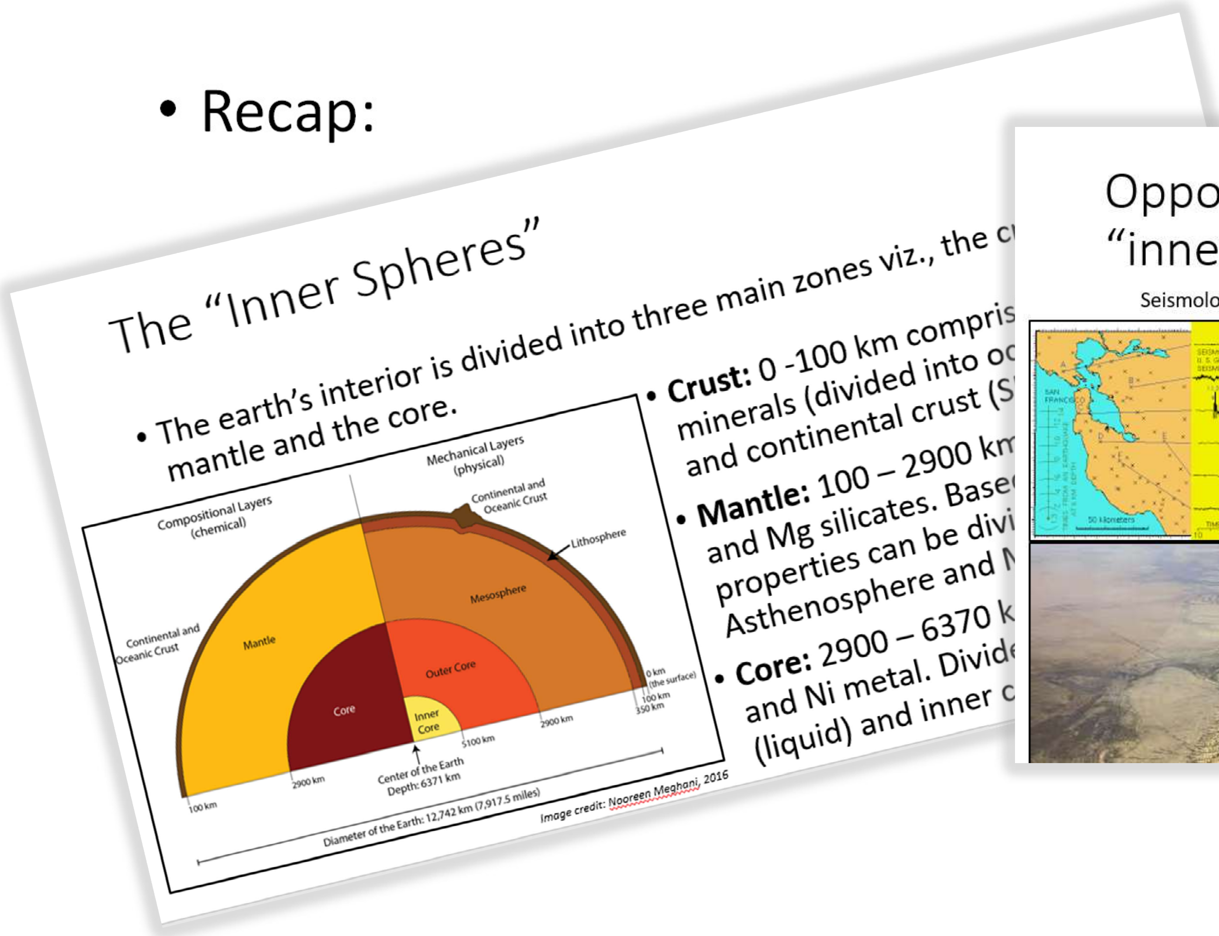
After the seminar, I have left time at the end of this seminar to field any questions related to either of the two sessions.

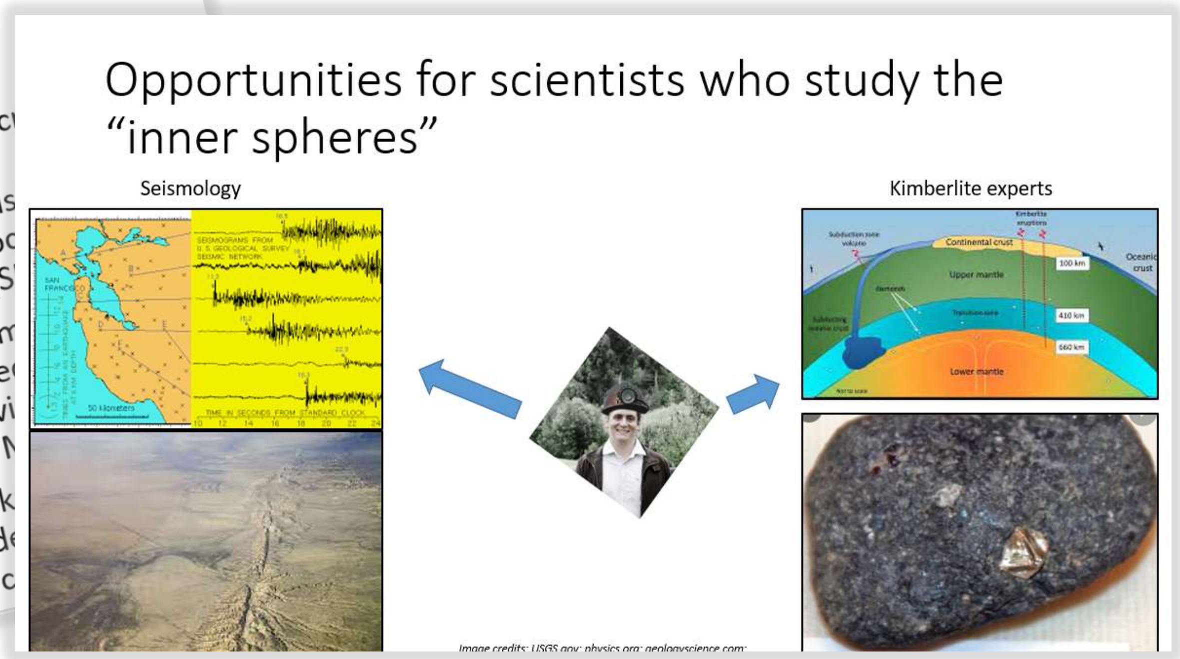
Physics and the Earth Sciences

- As we've already seen, the Earth Sciences can be regarded as being '***Multi-spheric***' – comprising lithosphere, hydrosphere, biosphere, cryosphere, troposphere, stratosphere, and all the way out to the exosphere.
- Broad umbrella term: necessarily an inter-disciplinary field of study.
- A systems science, strongly underpinned by physics and physical principles.
- Sub-disciplines heavily reliant on physics include:
  - hydrogeology, geophysics, geophysical fluid dynamics, atmospheric physics and aeronomy, ocean physics, space physics and astronomy, environmental physics, meteorology, climatology, tectonics, seismology, gravity and magnetism, mineralogy and petrology, geochronology, ecotoxicology, among others...
- **NB: Monitoring instrumentation and analytical techniques.**

“Inner” sphere

- Recap:





“Inner” sphere

CASE STUDY 1: Seismic wave propagation and earthquake monitoring

- Seismic waves are waves of energy that propagate through the earth’s interior and along its surface. These can be initiated by e.g., earthquakes or volcanic eruptions. This branch of seismology is typically referred to as **Earthquake seismology** and the recorded waves provide insight into the earth’s deep interior.

- To study earth’s subsurface, for example during exploration for Earth’s critical ore resources, geophysicists trigger their own seismic waves (using chemical blasts, vibrator trucks, sledge hammers on steel plates, or air-guns (for water media)) to measure the seismic reflections induced by differences in the properties of the underlying rock types. This branch of seismology is typically referred to as **Controlled source seismology** and the recorded waves provide insight into the earth’s upper crust.

Example of controlled source reflection seismology

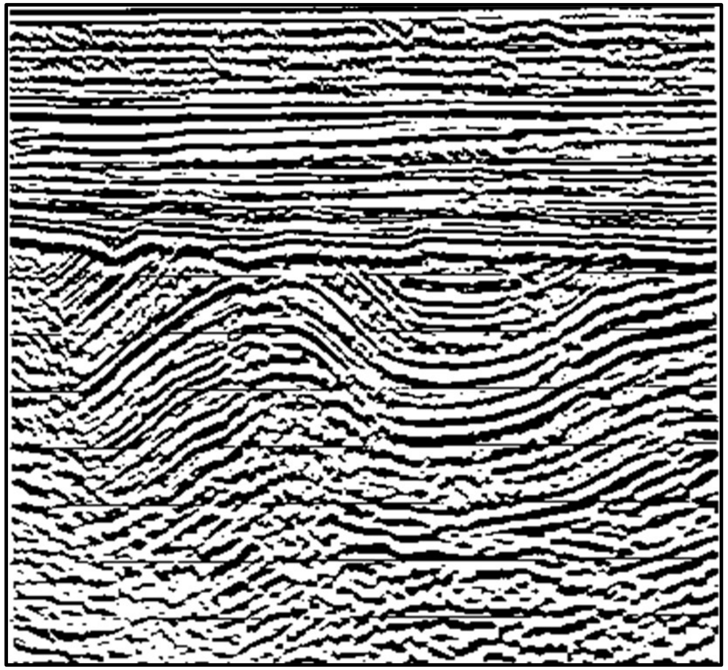


Image credits: Pangea.Stanford.edu

“Inner” sphere

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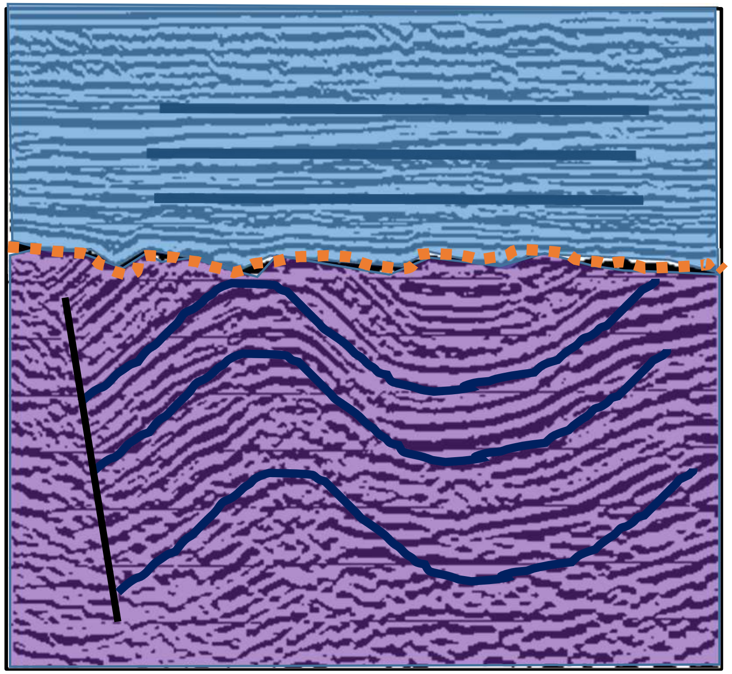


Image credits: Pangea.Stanford.edu

“Inner” sphere

CASE STUDY 1: Seismic wave propagation and earthquake monitoring

Seismic waves can be divided into two key classes:

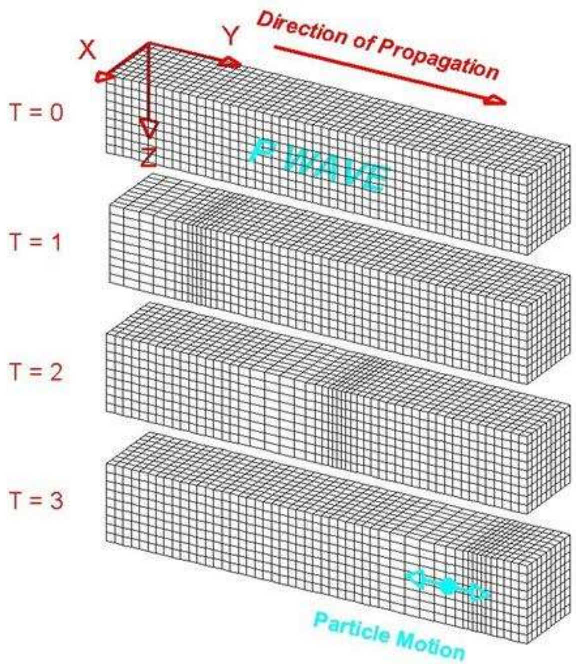
1) **Body waves:** these travel directly through the interior of the earth and are thus first to arrive at a given ‘geophone’ (acoustic listening device).
   - Body waves are divided into P and S waves

2) **Surface waves:** these travel along the surface of the earth, are slower and thus arrive at a given geophone.
   - Surface waves can be divided into Love waves (or L waves) and Rayleigh waves

“Inner” sphere

CASE STUDY 1: Seismic wave propagation and earthquake monitoring

***Types of seismic waves:** Body waves*



P waves:
Fastest body wave, first to arrive at a given location.
Compressional wave: ‘push-pull’ type motion in the same direction in which the wave is moving.

S waves:
Second wave experienced at a given location.
Can only move through solid rock.
Move up and down relative to the direction of wave propagation.

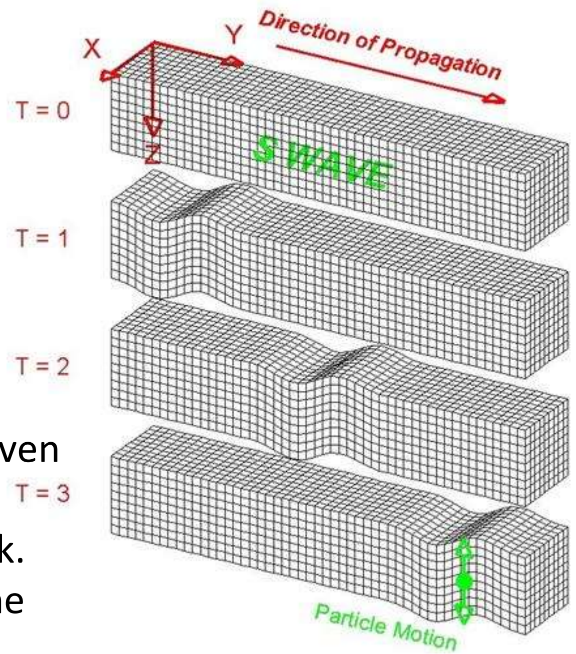
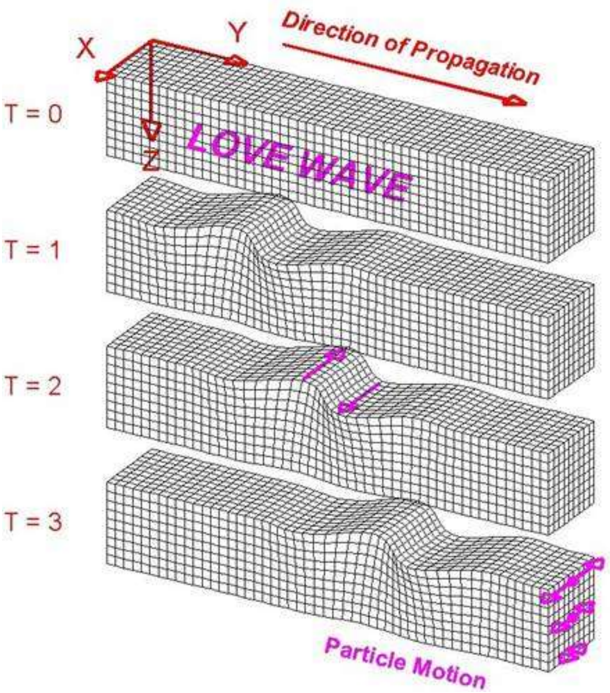


Image credits: geo.mtu.edu

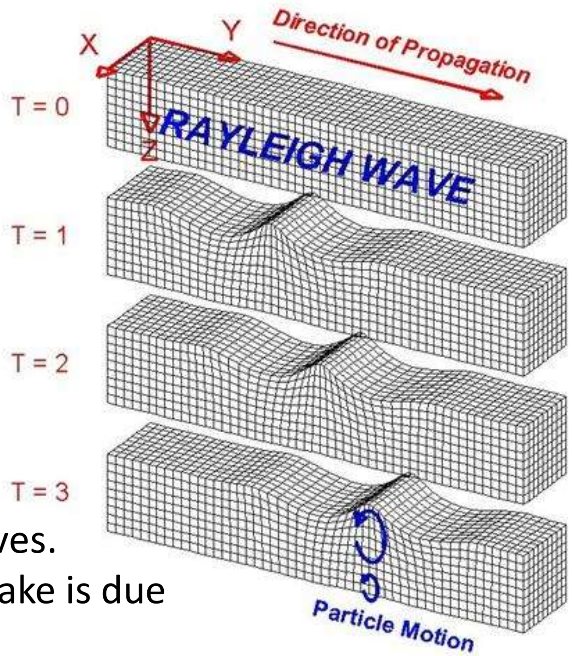
"Inner" sphere

CASE STUDY 1: Seismic wave propagation and earthquake monitoring

Types of seismic waves: *Surface waves*



L waves:
Fastest surface wave, only travels along earths upper crust. Higher amplitude to carry the energy in the confined crust results, therefore larger than body waves (where amplitude disperses as they spread through entire volume of earth's interior).
Horizontal wave, moves the earth's crust from side to side.
Largest recorded waves during an earthquake.

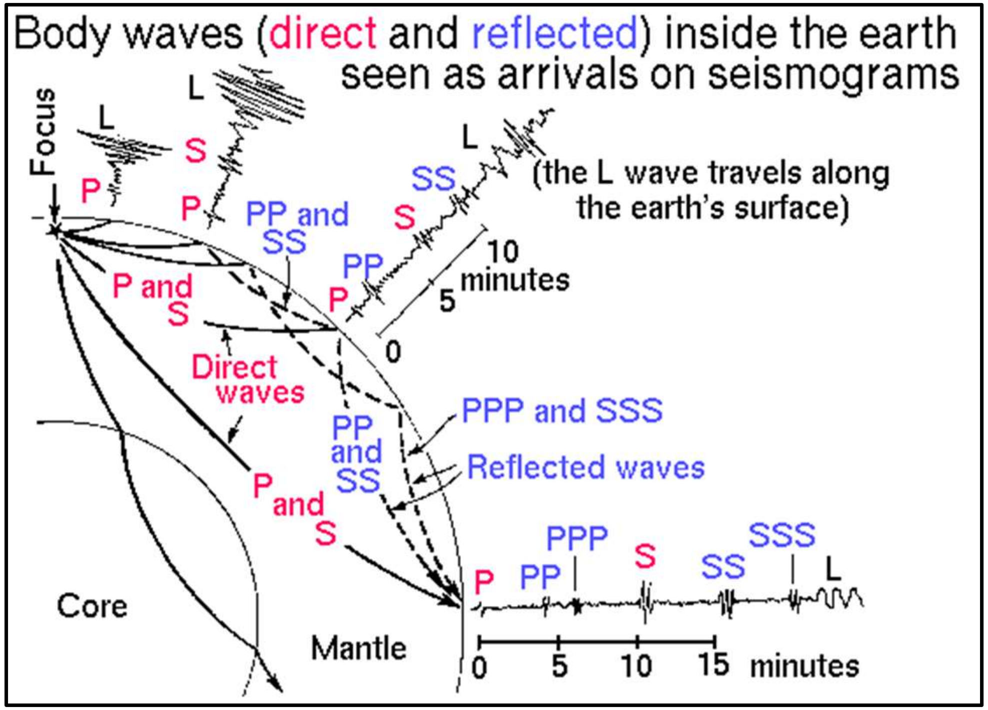


Rayleigh waves:
Moves in a rolling motion, much like ocean waves.
Most of the shaking experienced in an earthquake is due to these waves.

“Inner” sphere

CASE STUDY 1: Seismic wave propagation and earthquake monitoring

Propagation through the earth’s interior



- P waves always first to arrive.
- P waves are able to reflect at the earth surface interface- gives rise to PP and PPP waves.
- Time interval between P wave and subsequently arriving waves (S, L) increases as a function of distance away from the epicenter.
- S waves can’t propagate through the earth’s molten outer core- gives rise to a S-wave ‘shadow zone’ on the opposite side of the earth.

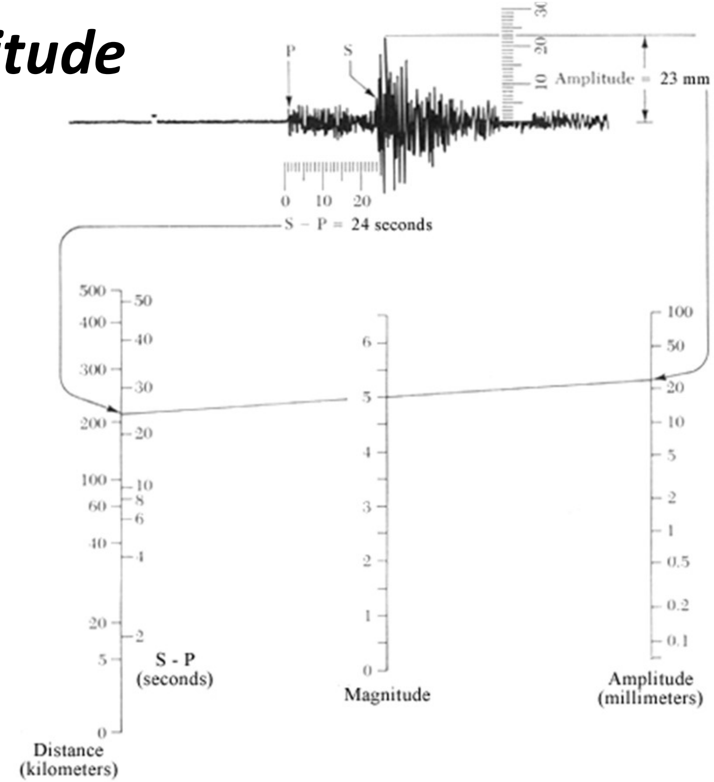
Image credits: USGS.gov

“Inner” sphere

CASE STUDY 1: Seismic wave propagation and earthquake monitoring

Determining earthquake’s epicenter and magnitude

- **Time interval between P wave and subsequently arriving waves (S, L) increases as a function of distance away from the epicenter.**
  - By knowing the rate at which the respective waves propagate, this time difference can be used to calculate a distance from the epicenter.
  - Triangulation of this distance determination (from e.g., three geophones) enables that the approximate epicenter can be pin-pointed.
- Measuring the L-wave peak amplitude and plotting this along with the distance parameter (calculated above), allows for a graphic determination of the earthquake’s magnitude (Richter scale)



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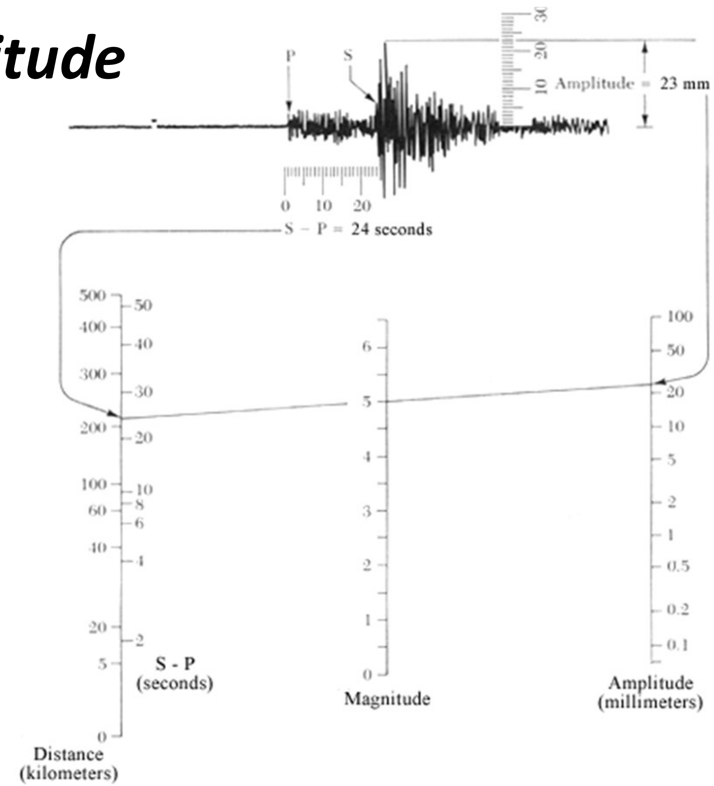
“Inner” sphere

CASE STUDY 1: Seismic wave propagation and earthquake monitoring

Determining earthquake’s epicenter and magnitude

- **The time difference between the arrival for the P wave and the arrival of the S wave is 24 s. How far away is the epicenter from this specific geophone? Assume P waves travel at 8.1 km/s and S waves travel at 4.5 km/s.**

Speed = distance / time



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“Inner” sphere

CASE STUDY 1: Seismic wave propagation and earthquake monitoring

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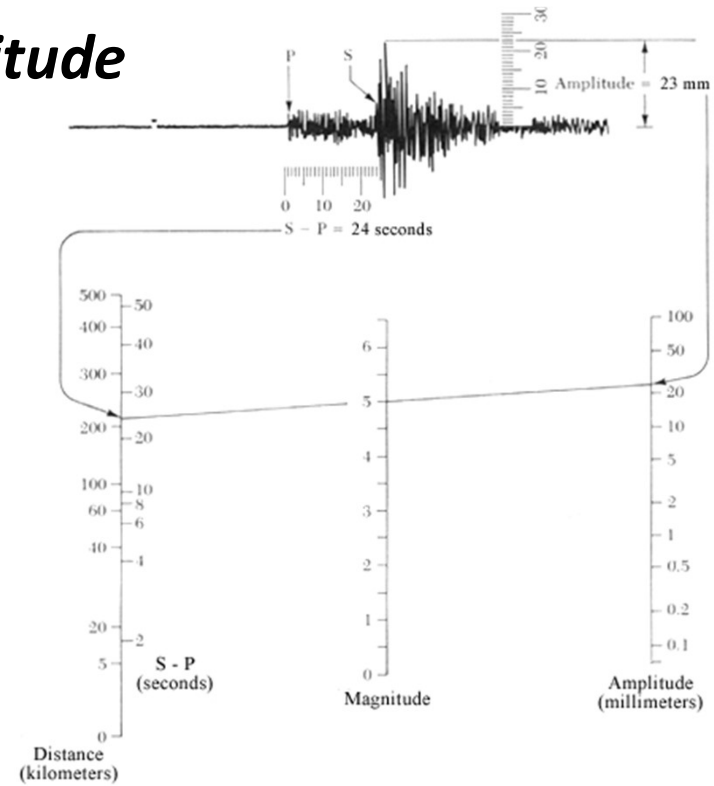
Speed = distance / time;
Therefore time = distance / speed
$t_2 – t_1 = 24$ s
$d_2/s_2 – d_1/s_1 = 24$ s



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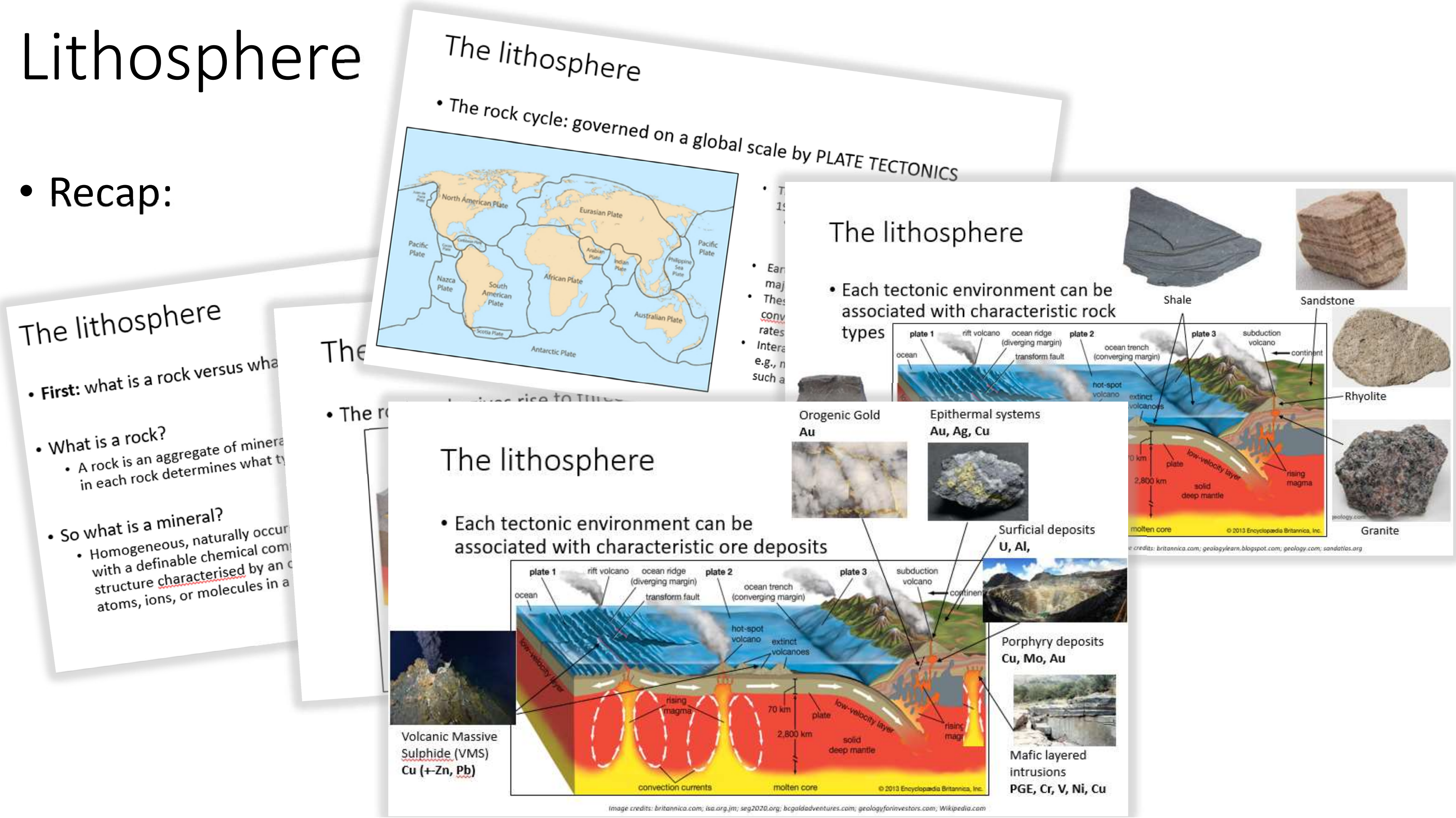
Lithosphere

- Recap:

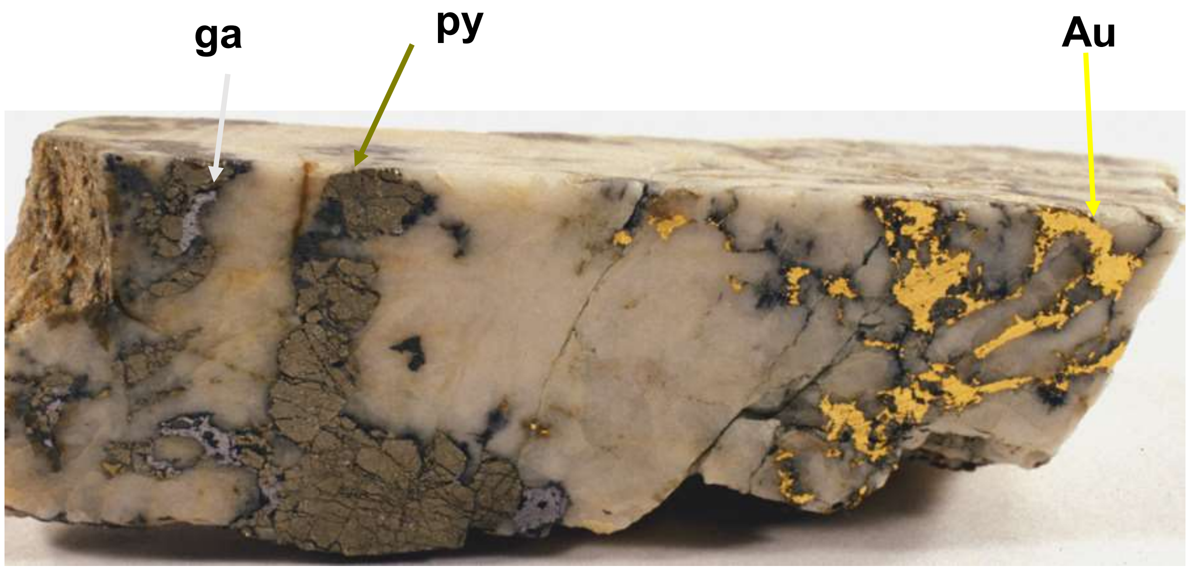


Lithosphere

CASE STUDY 2: The formation of orogenic gold deposits

Gold background:
Uses: jewelry, currency (wealth protection and financial exchange), electronics and technological applications, dentistry, Olympic Gold medals.

Gold mineralogy:
- Native gold: can contain up to 20% Ag (electrum)
- Calaverite ($AuTe_2$): 44 % Au
- Sylvanite $(Au,Ag)Te_4$: 25-27 % Au
- Nagyagite ($Pb_5Au(Te,Sb)_4S_{5-8}$): 6-13 % Au
- Trace amounts in pyrite and arsenopyrite (‘invisible’ or ‘solid solution’ Au)



Lithosphere

CASE STUDY 2: The formation of orogenic gold deposits

Overview:

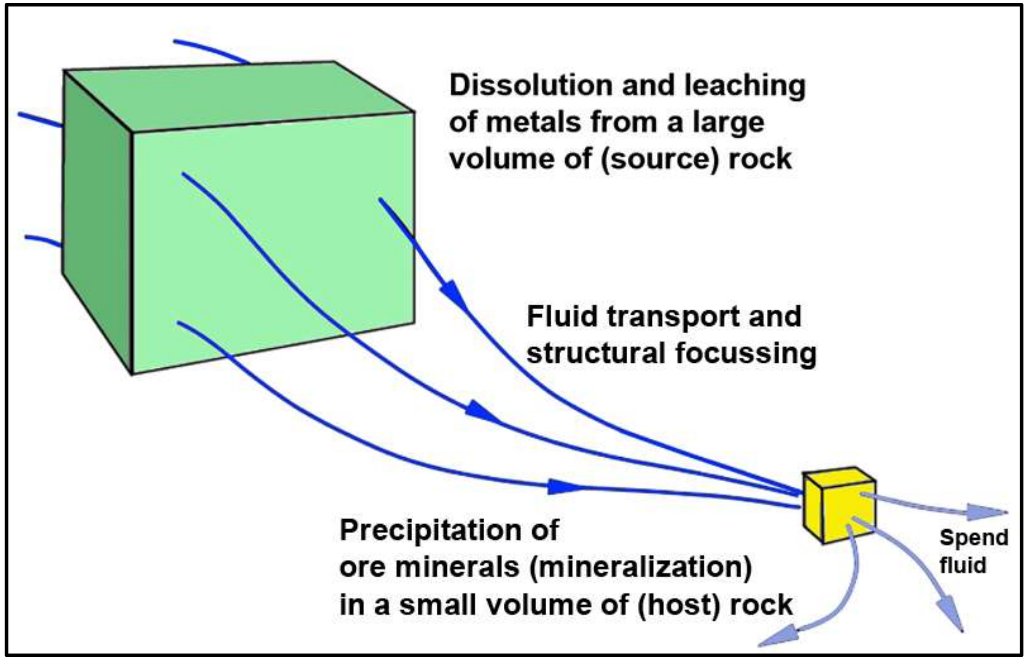
Fluid source: Likely to be devolatilisation during prograde metamorphism. Other possibilities include magmatic fluids and devolatilisation of an external (subducting slab)

Metal source: Likely to have leached from the background levels present in the metamorphosing rocks.

Transport: Fluid migration along structural corridors under pressure differentials due to the evolving orogeny. Fluid buoyancy also important.

Trap: Can be chemical or structural (physical)

Source-Transport-Trap model

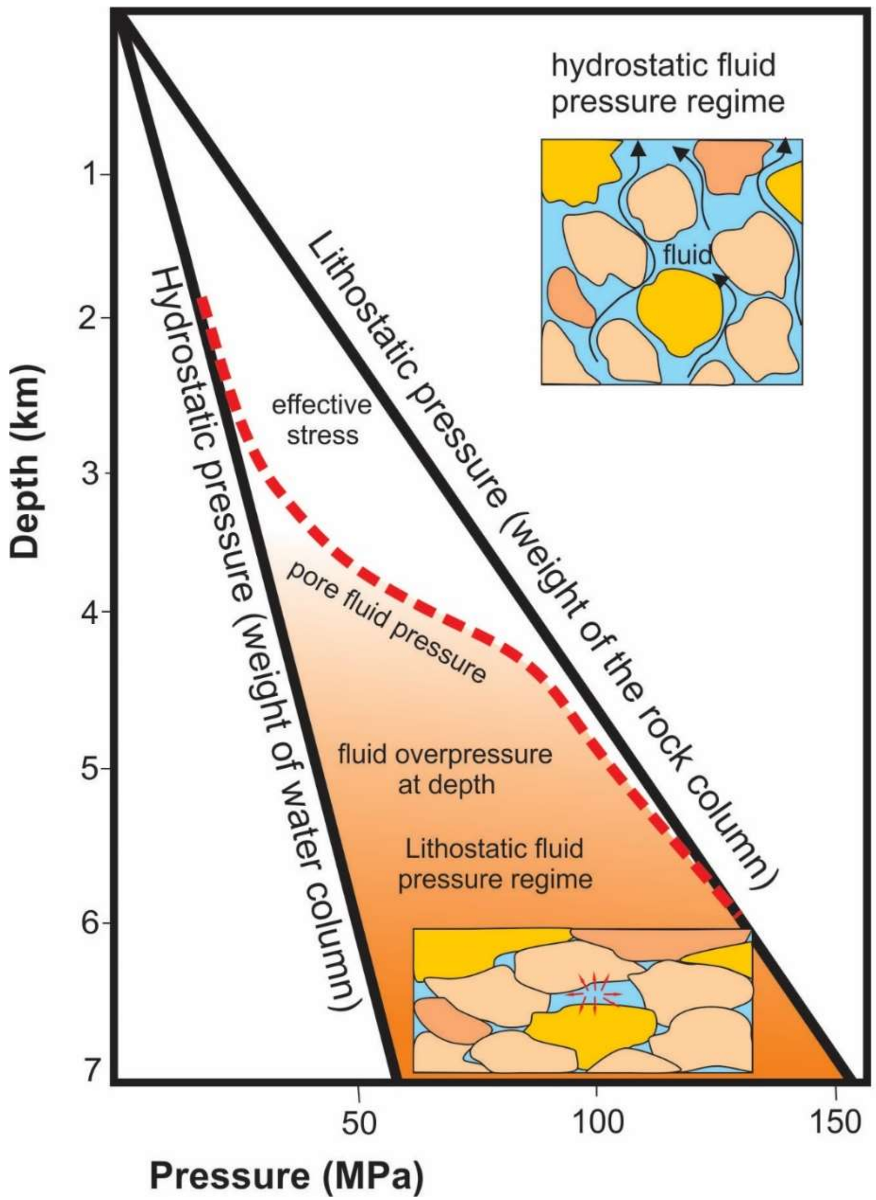


Lithosphere

CASE STUDY 2: The formation of orogenic gold deposits

Trap: The 'Fault-valve' model

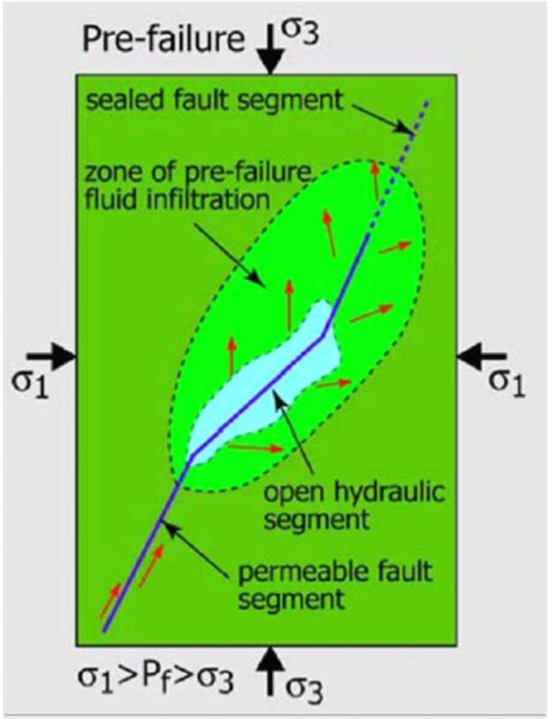
- In upper levels of the earth's crust, **lithostatic pressure gradient** differs to **the hydrostatic pressure gradient** due to the difference in density between fluid (~1 g.cm^{-3}) and rock (~2.6 g.cm^{-3})
- At deeper levels, the hydrostatic pressure gradient is **governed by the confining pressure** of the surrounding rocks. Therefore, it follows the lithostatic pressure gradient.
- In the fault-valve model, external forcings of fluid allow the fluid pressure **to exceed the lithostatic pressure gradient + the tensile strength** of the rocks, leading to fault failure or rupture.

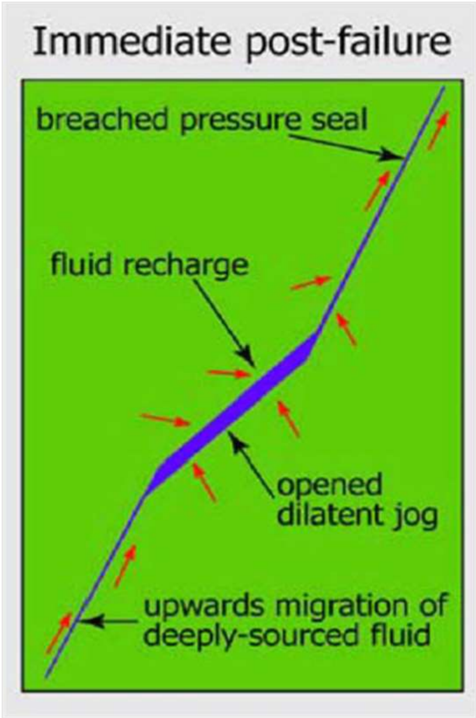


Lithosphere

CASE STUDY 2: The formation of orogenic gold deposits

<u>Trap:</u> The 'Fault-valve' model





- Pre-failure, the hanging wall fault segment is sealed.
- Post-failure, the hanging wall fault segment is breached (open)
- Foot wall fault segment is open (permeable)
- In the open dilatent jog fluid pressure drops to below lithostatic values ($P_f < \delta 3$).
- Fluids to drain back from wallrocks around fault into open dilatent jog and discharge upwards along fault plane.
- Fluid recharge from deep source

Lithosphere

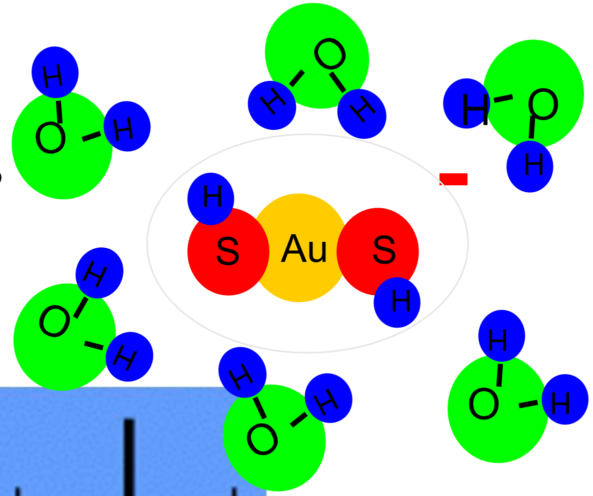
CASE STUDY 2: The formation of orogenic gold deposits

<u>Trap:</u> Textures and features

- Understanding the distribution of structural features (faults) provides insight into the regional stress fields and tectonic framework during ore formation.
- It further enables informed exploration efforts for mineralized structures elsewhere in the belt.
- From a safety perspective, it is crucial that rock engineers have an understanding of these features and their impacts on rock stability.

Lithosphere

CASE STUDY 2: The formation of orogenic gold deposits

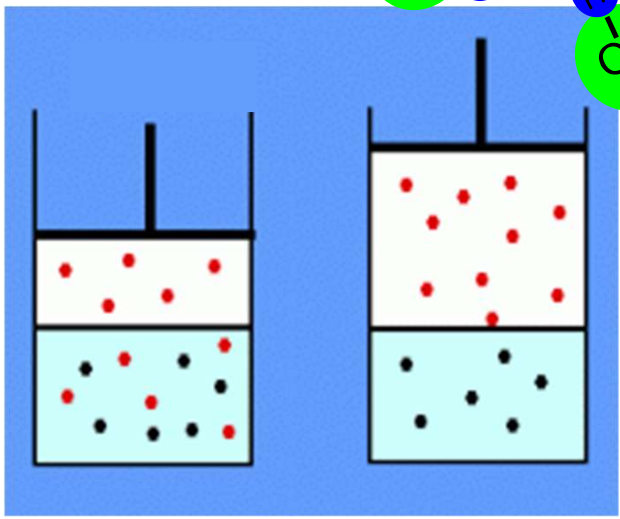


Trap: Gold precipitation due to pressure drops

- Pressure decreases lead to increases in metal solubility (i.e., works in an opposite sense to temperature)
- However, decreases in pressure also lead to boiling and effervescence phenomena:

-Boiling:

Results in residual concentration of solutes
Volatiles partition to gas phase
Increases pH of remaining solution (decreases metal-chloride stability)



Boyles Law: $P_1V_1 = P_2V_2$

THANK YOU!!
Questions/Discussion

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Background image from: https://www.lanl.gov/projects/national-security-education-center/space-earth-center/index.php