



6th edition of the biennial African School of Fundamental Physics and Applications

Special lecture on the Earth Sciences

Dr Bjorn P. von der Heyden

Stellenbosch University: Department of Earth Sciences (RSA)

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 in Economic Geology, Stellenbosch University (2015-2019)
- Senior Lecturer in Economic Geology, Stellenbosch University (2020-present)
- Guest lecturer: African School of Fundamental Physics and Applications (2021)



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



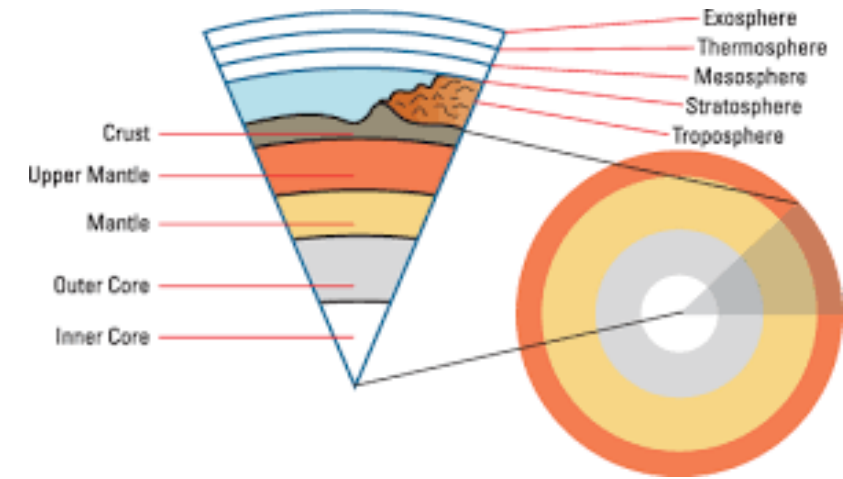
What I actually do

Seminar structure

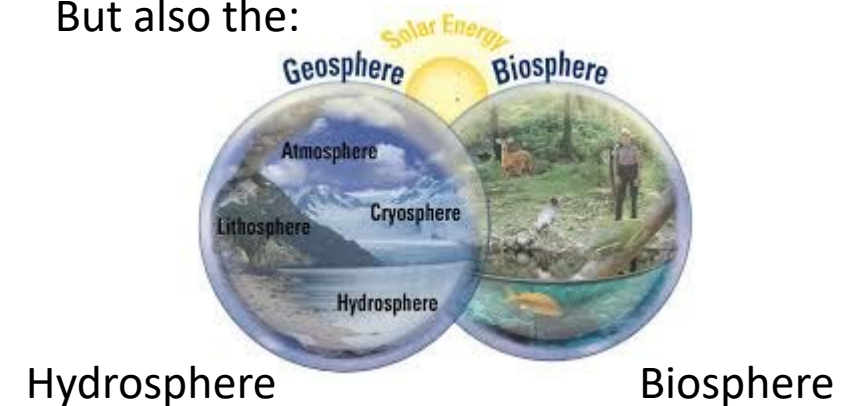
- Part 1 (10.30 – 11.30 am)
 - An introduction to the Earth Sciences
 - Fundamental insights into each of the Earth Sciences' "spheres"
 - Job opportunities in each of the Earth Sciences' "spheres"
- Part 2 (12 noon – 1.00 pm)
 - Selected case studies of PHYSICS application to each of the Earth Sciences' "spheres"

The two parts of the seminar are separated by a short 30 minute break. You are encouraged to use this time to get some fresh air or to partake in the Science in the City mini series — Episode 11: A device to detect male infertility.

What are the Earth Sciences?



But also the:



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

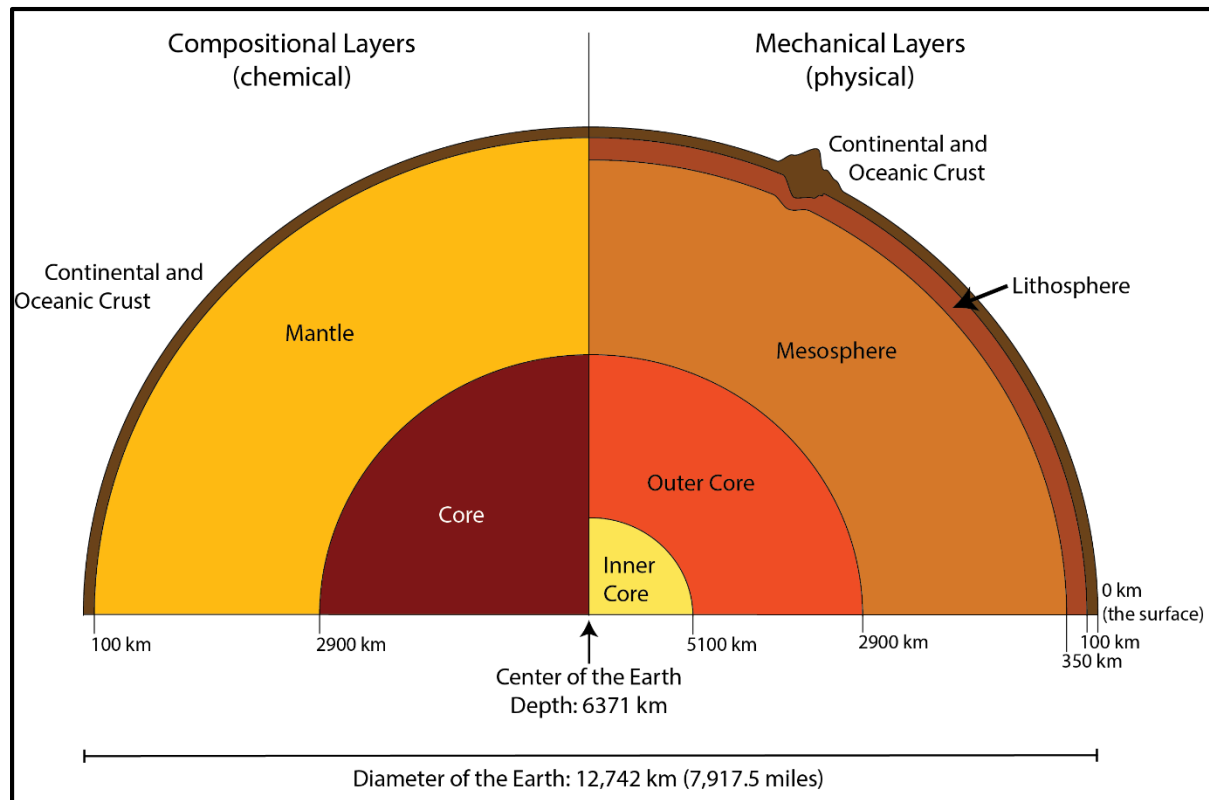
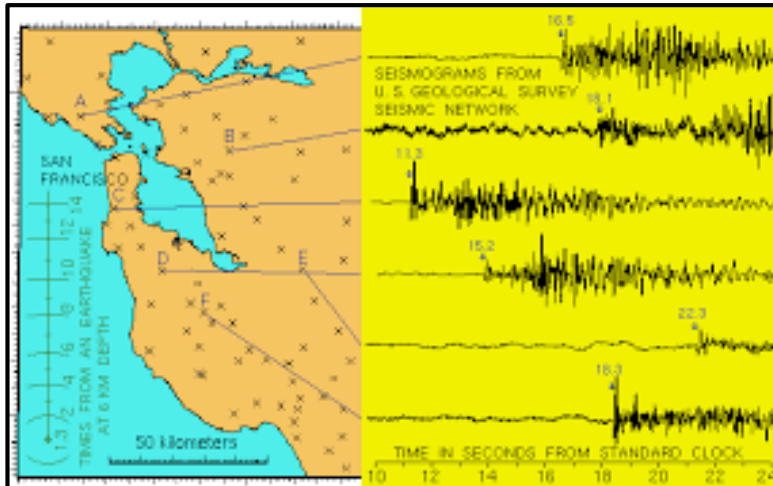


Image credit: Nooreen Meghani, 2016

- **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).

Opportunities for scientists who study the “inner spheres”

Seismology



Kimberlite experts

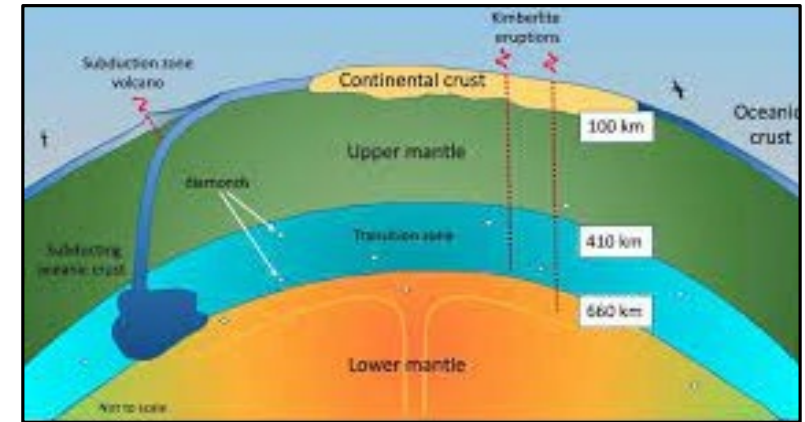


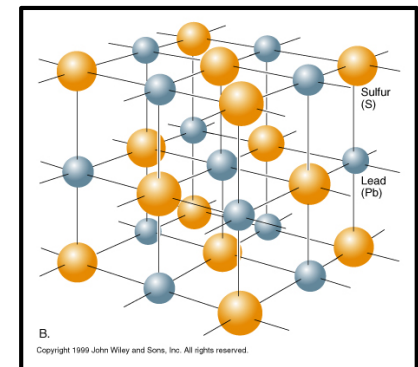
Image credits: USGS.gov; physics.org; geologyscience.com;

The lithosphere

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

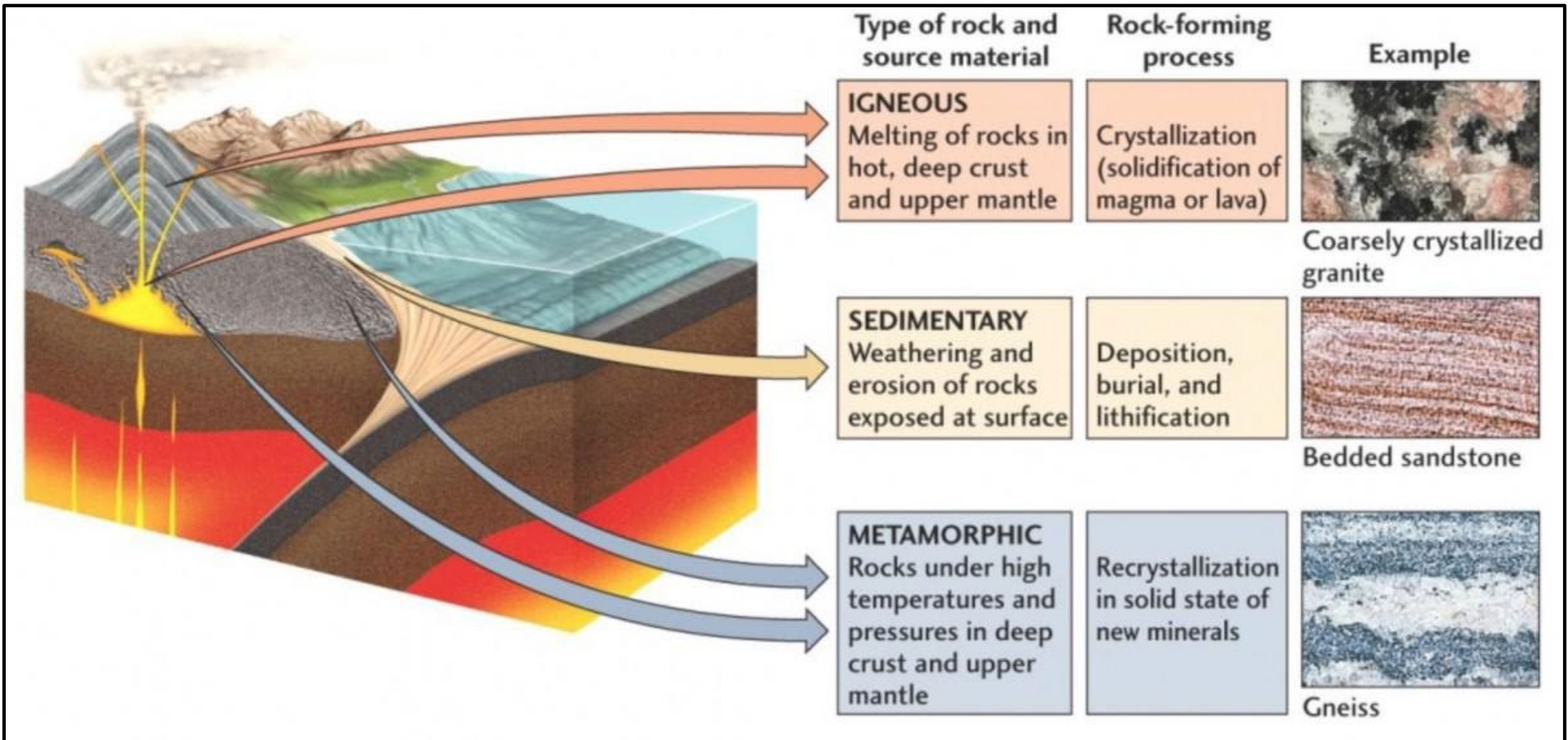
The lithosphere

- **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.
- 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.



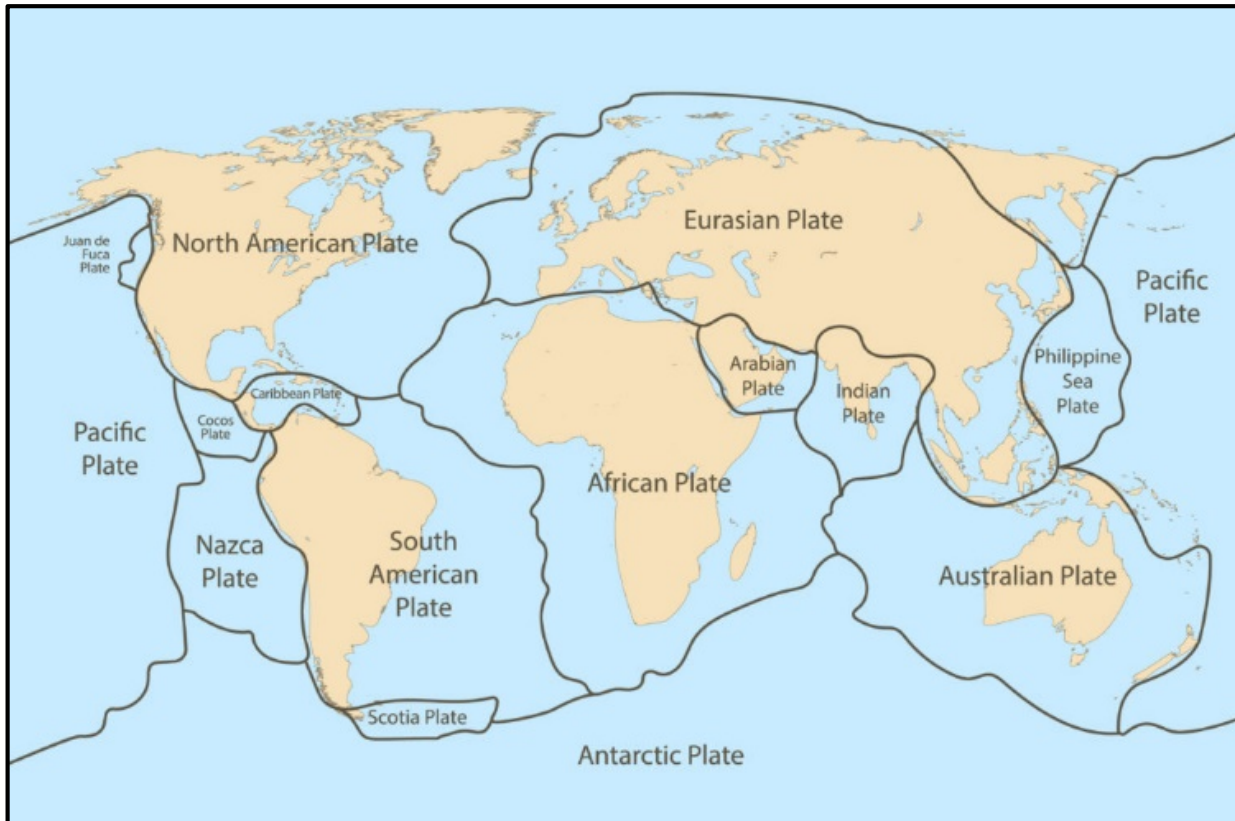
The lithosphere

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



The lithosphere

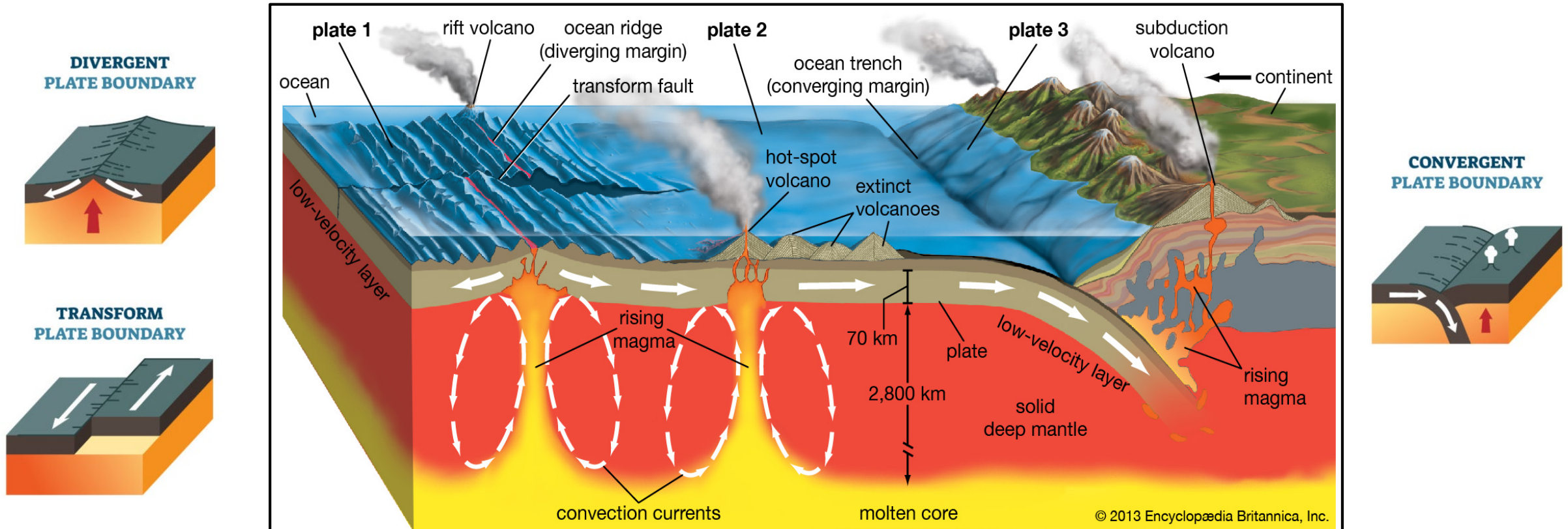
- The rock cycle: governed on a global scale by PLATE TECTONICS



- 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.

The lithosphere

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



The lithosphere

- Each tectonic environment can be associated with characteristic rock types



Basalt



Shale



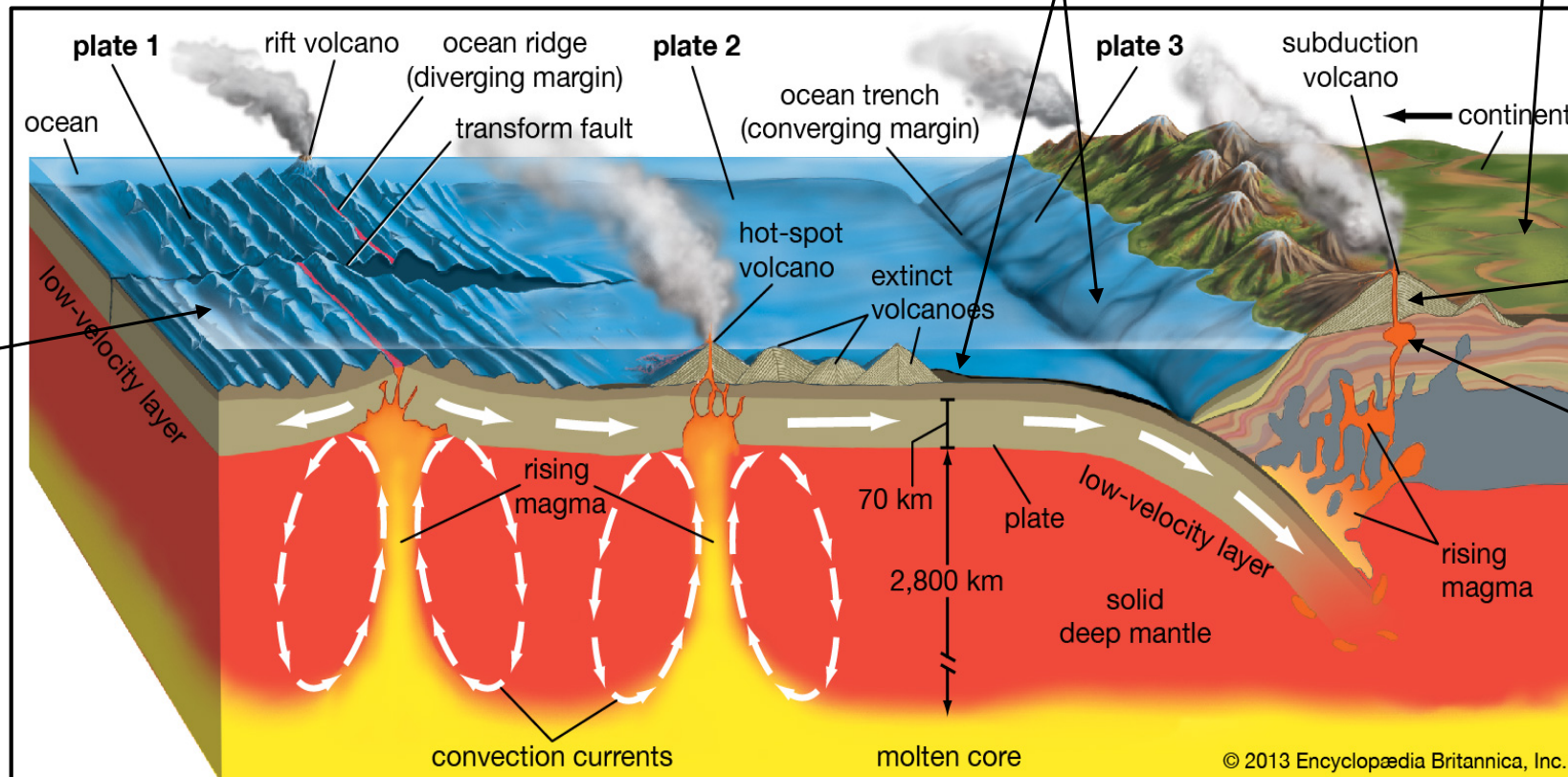
Sandstone



Rhyolite

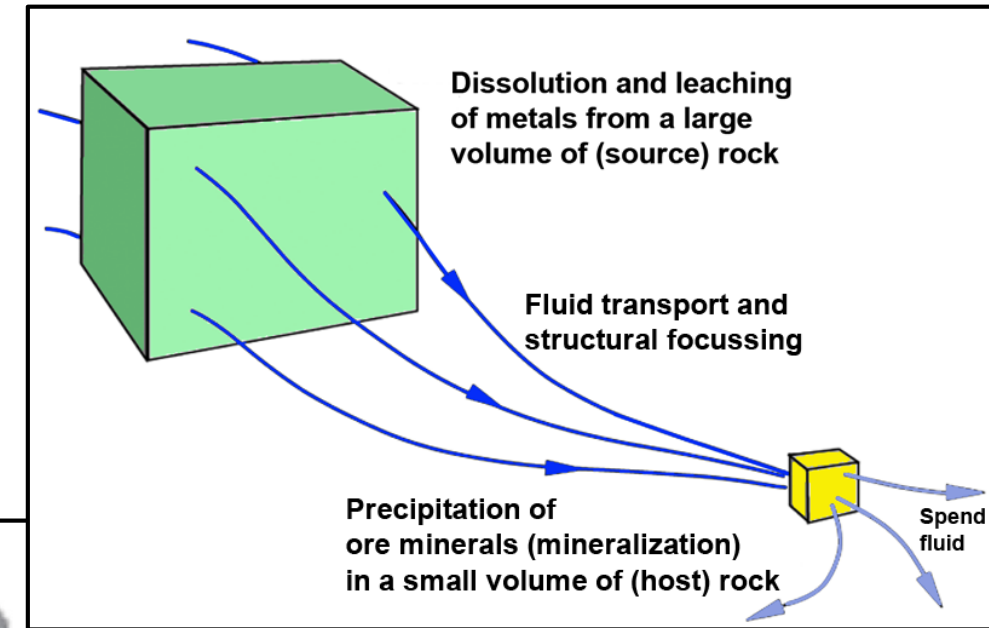
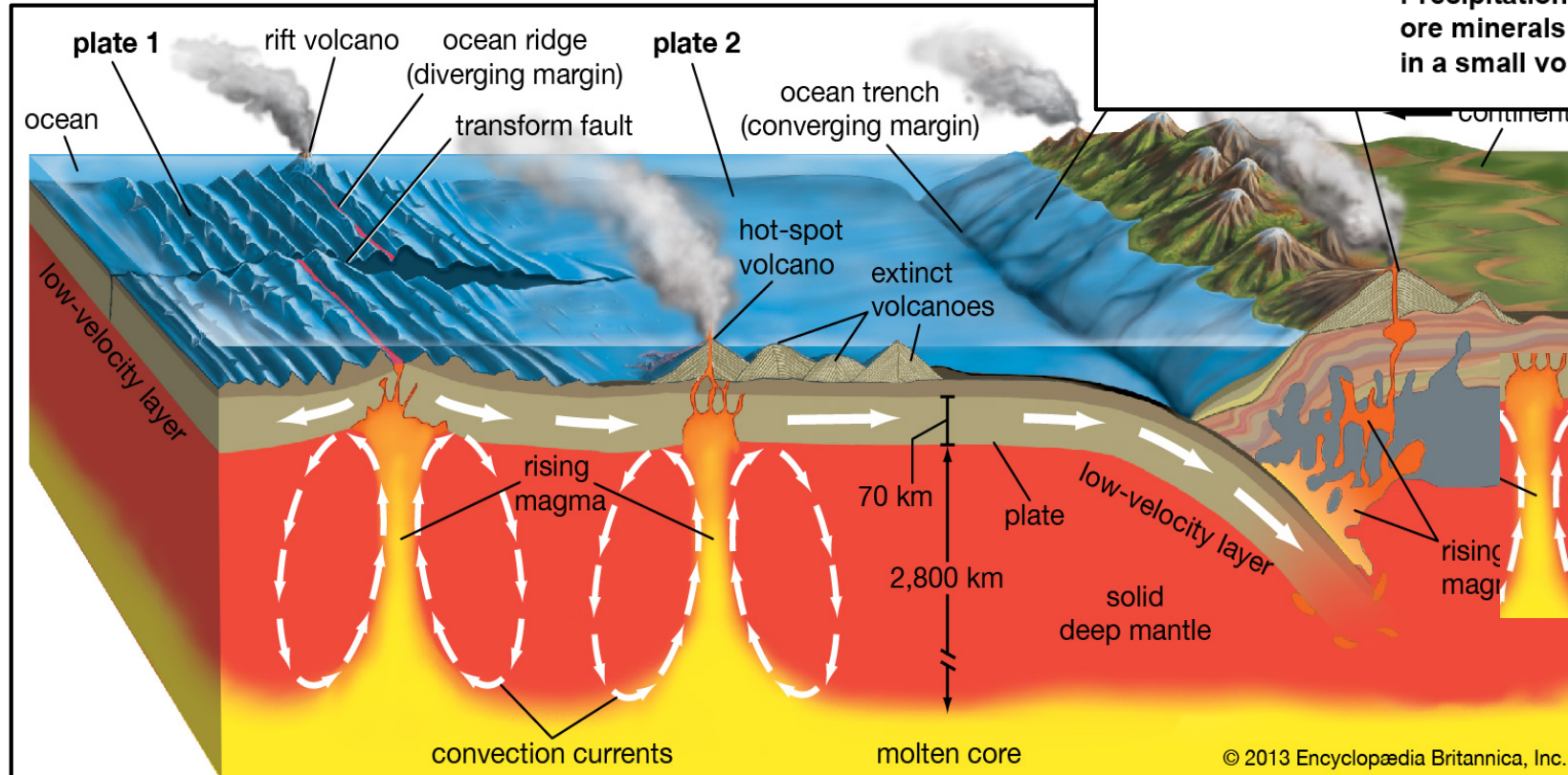


Granite



The lithosphere

- Each tectonic environment can be associated with characteristic ore deposits



The lithosphere

- Each tectonic environment can be associated with characteristic ore deposits

Orogenic Gold
Au



Epithermal systems
Au, Ag, Cu



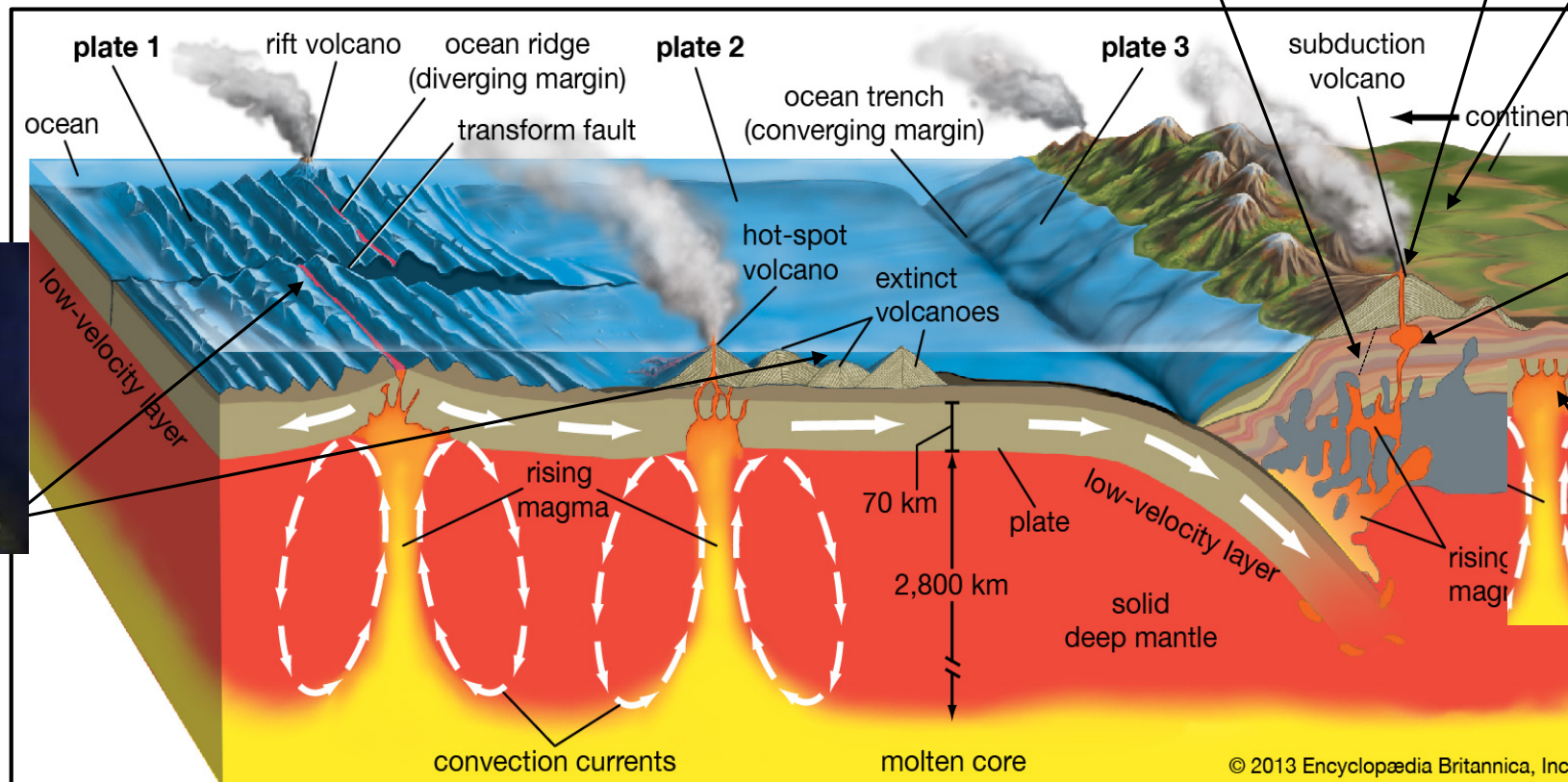
Surficial deposits
U, Al,



Porphyry deposits
Cu, Mo, Au



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



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





Mining



Commodity analyst

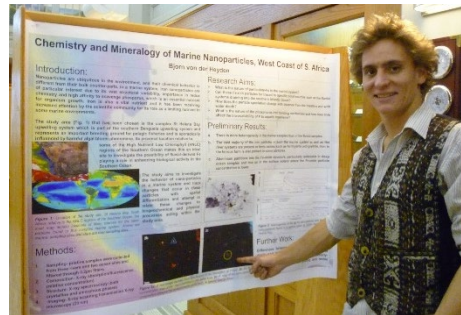


Consultancy



www.salemgroup.com

Engineering Geology



Academia



Exploration

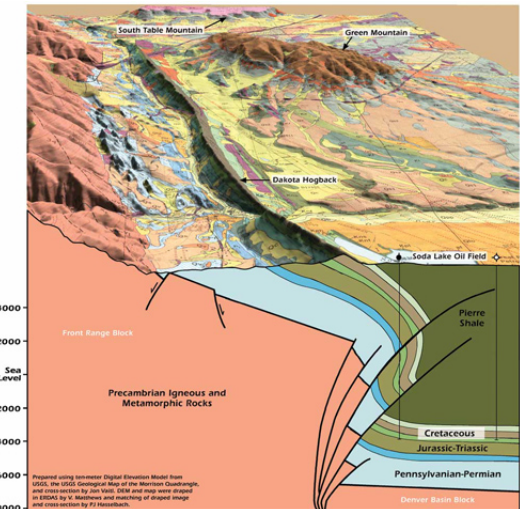


www.halepaska.com

Ground water exploration/
geohydrology



Palaeontology

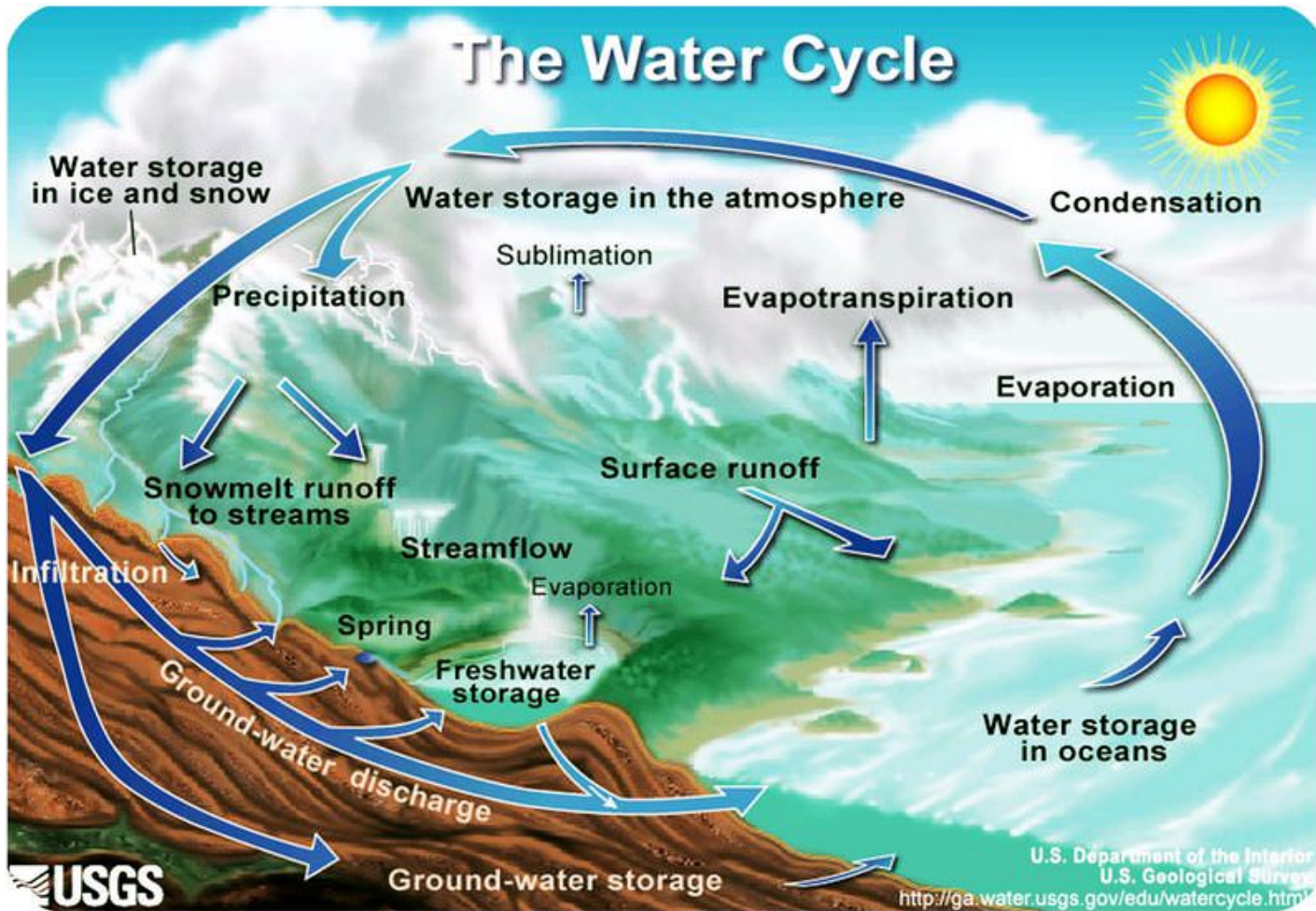


www.coloradosurvey.org

Mapping/Surveys

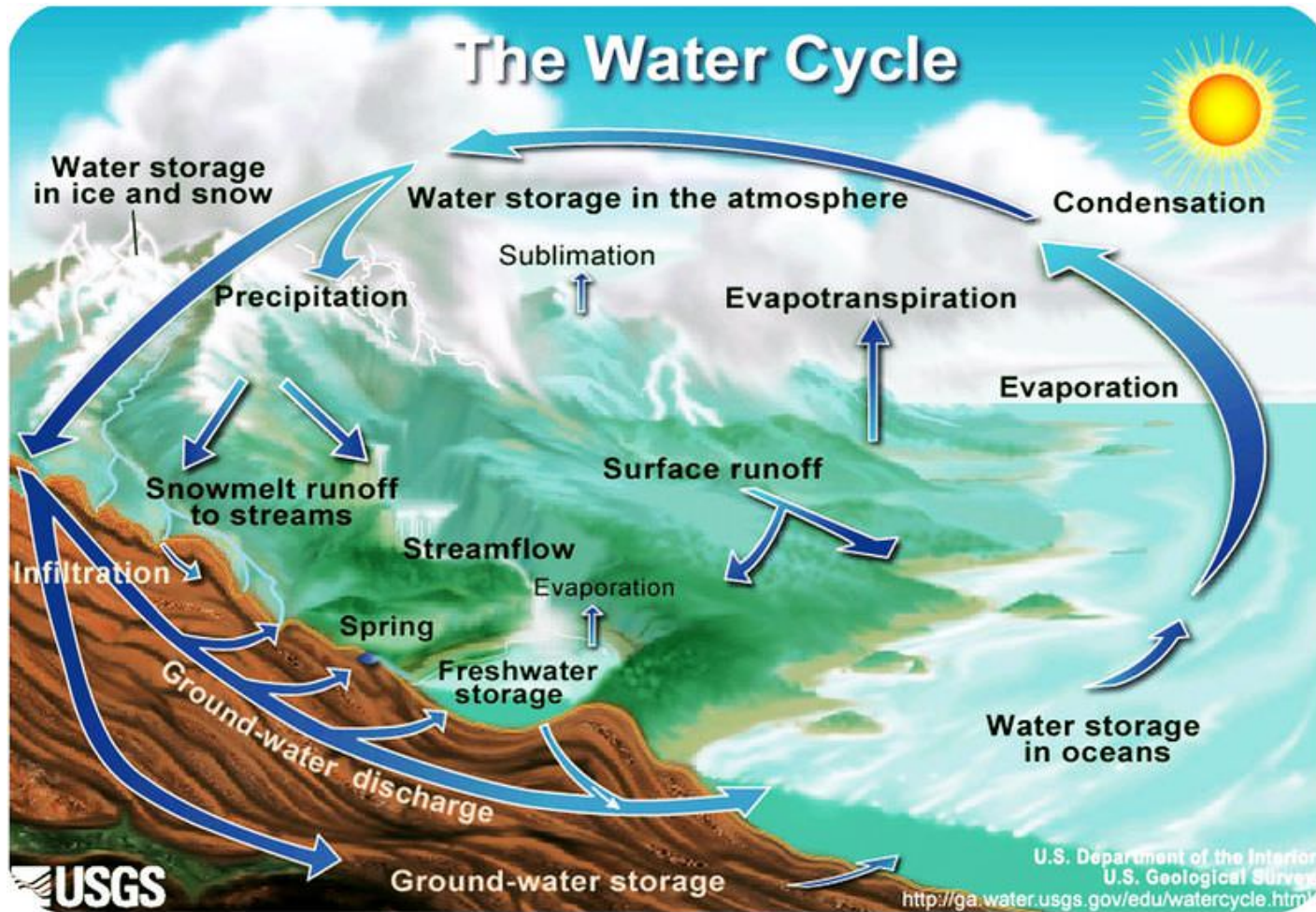
***Apologies, image credits not cited.*

The hydrosphere



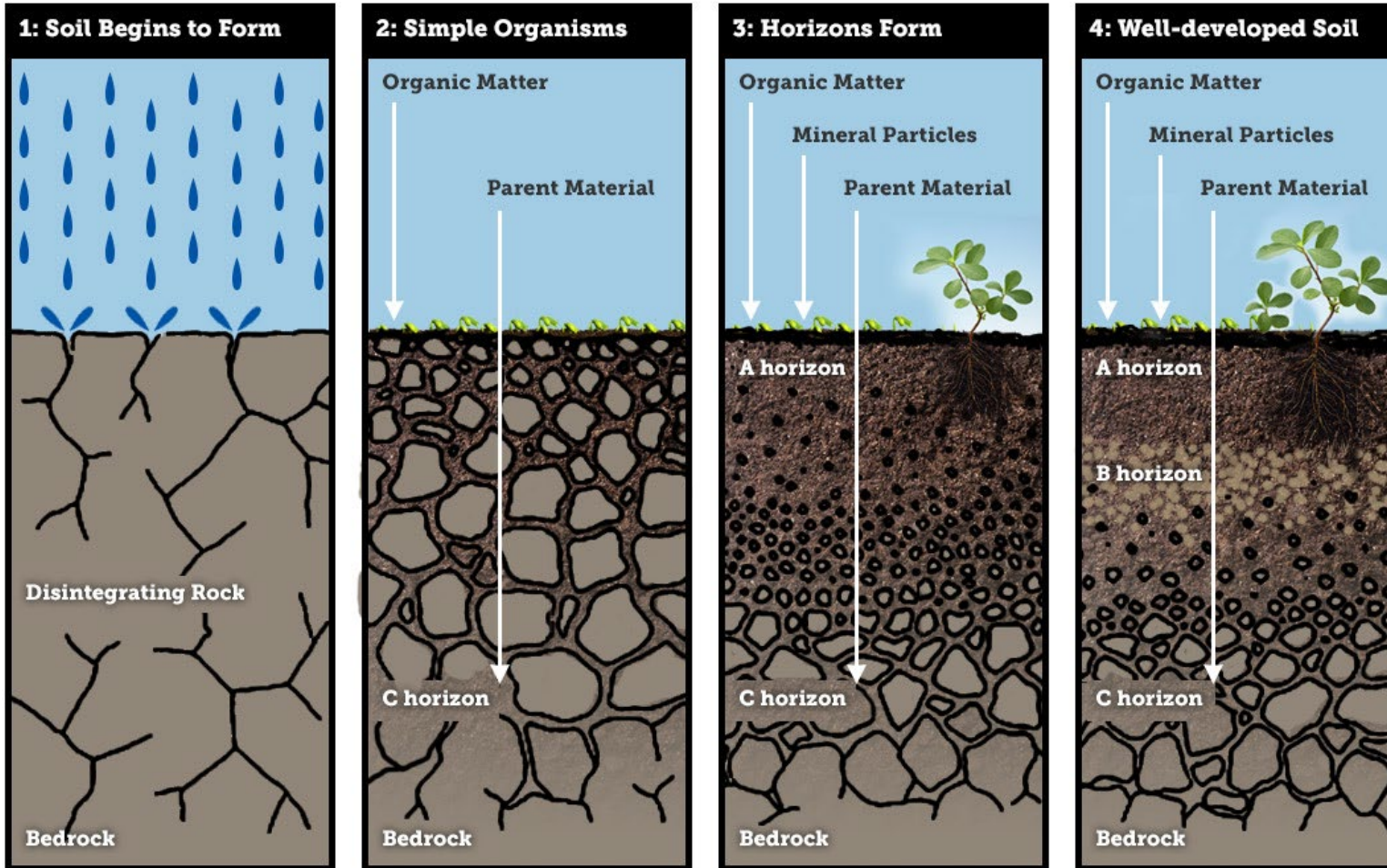
- Water occurs in three states on planet earth, viz. liquid (water), solid (ice) and gas (water vapour).
- 71% of Earth's surface is covered in water; oceans store 96.5% of all water.
- Regarded as a renewable resource, since the hydrological cycle is essentially a closed system.

The hydrosphere



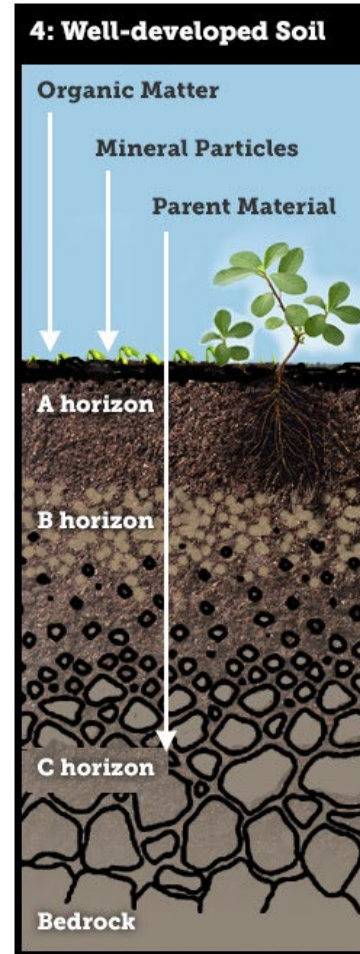
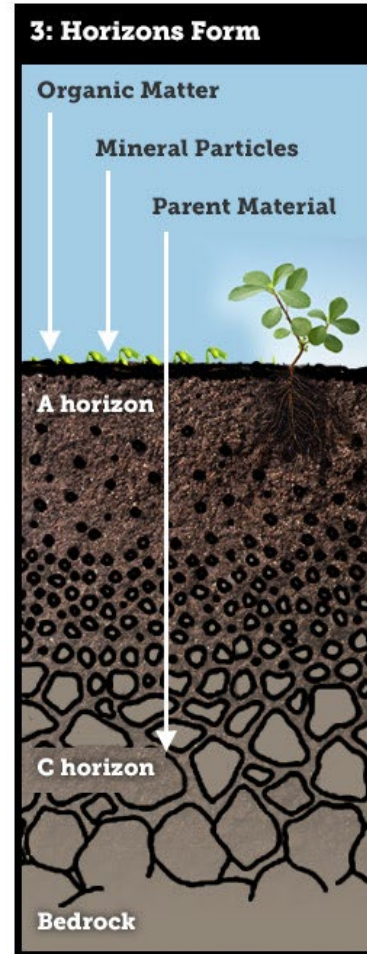
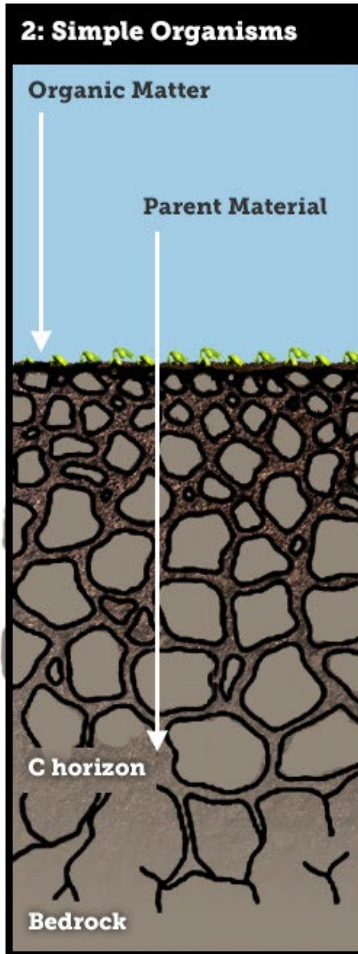
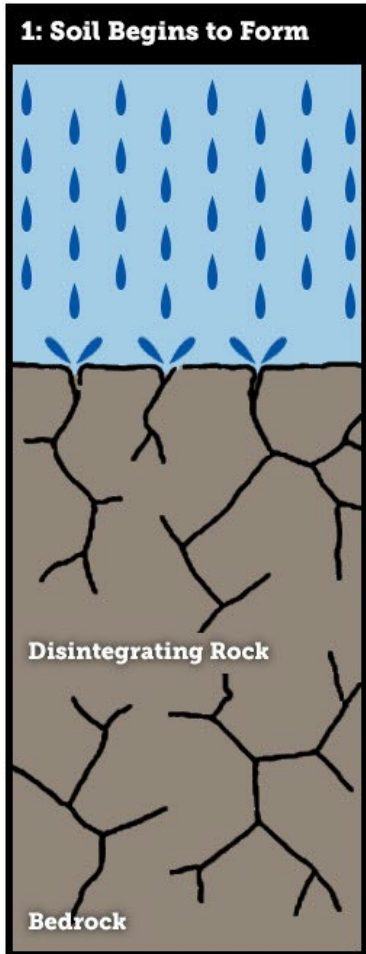
Reservoir	Average residence time
Antarctica	20,000 years
Oceans	3,200 years
Glaciers	20 to 100 years
Seasonal snow cover	2 to 6 months
Soil moisture	1 to 2 months
Groundwater: shallow	100 to 200 years
Groundwater: deep	10,000 years
Lakes (see lake retention time)	50 to 100 years
Rivers	2 to 6 months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

The pedosphere

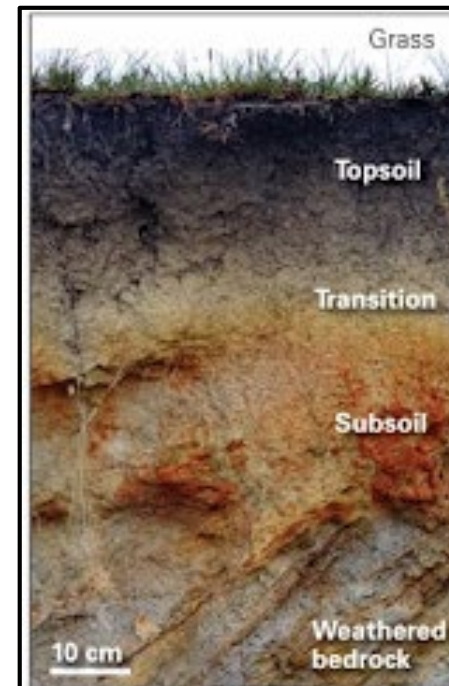


- Biogeochemical cycling (action of fluids and microbes) result in rocks breaking down to form a soil profile.
- Dependent on climate, vegetation type, slope, parent rock-type and time.
- O, E, A, B, C, and R horizons commonly defined

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





Governmental departments



Hydrologists



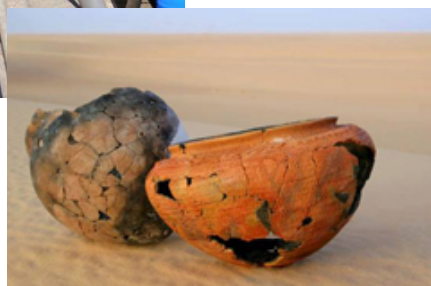
Forensics



Environmental officer



Waste and effluent management



Anthropology



Soil science and agriculture



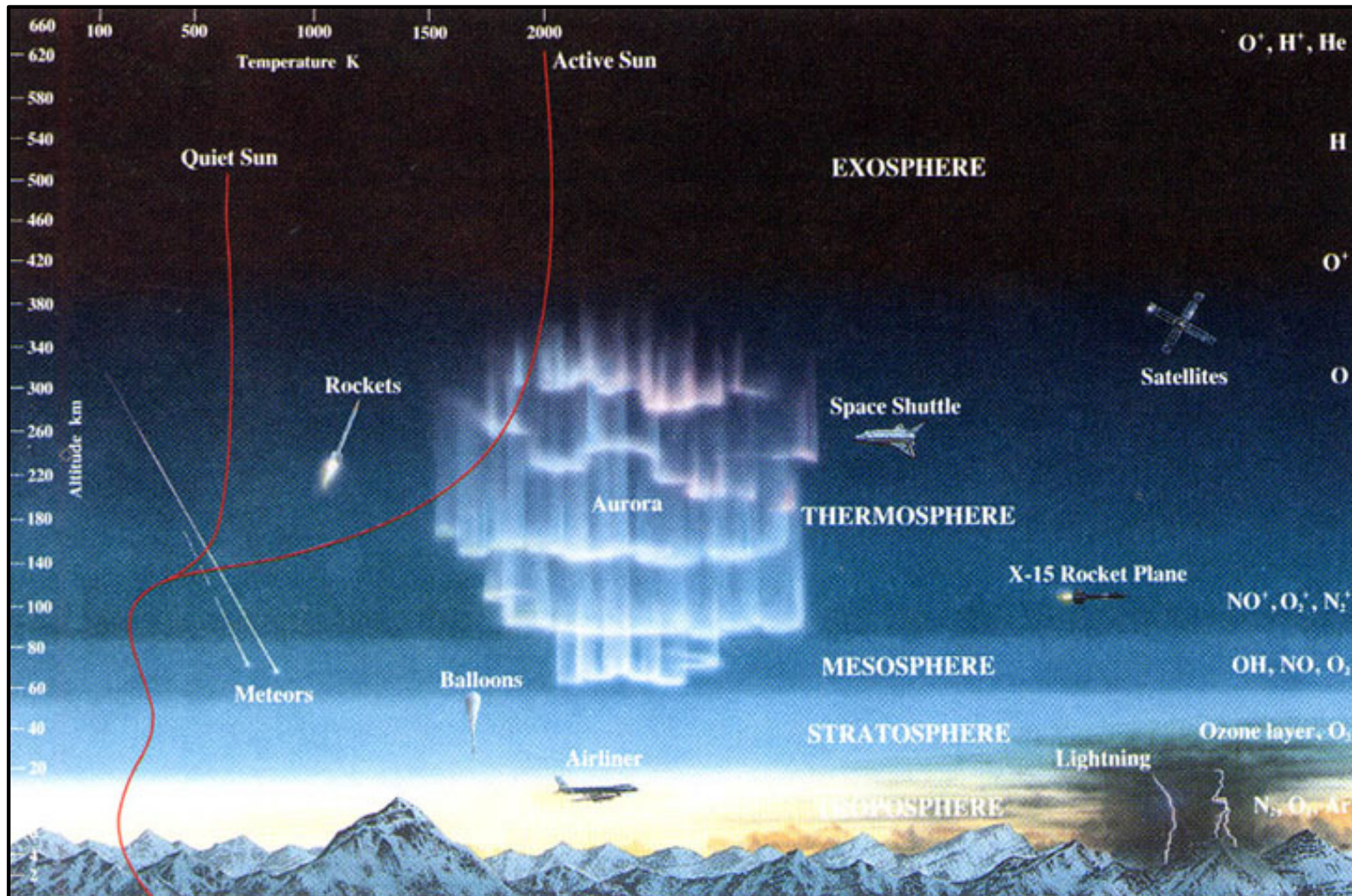
Research and academia



Consultancy



The atmosphere



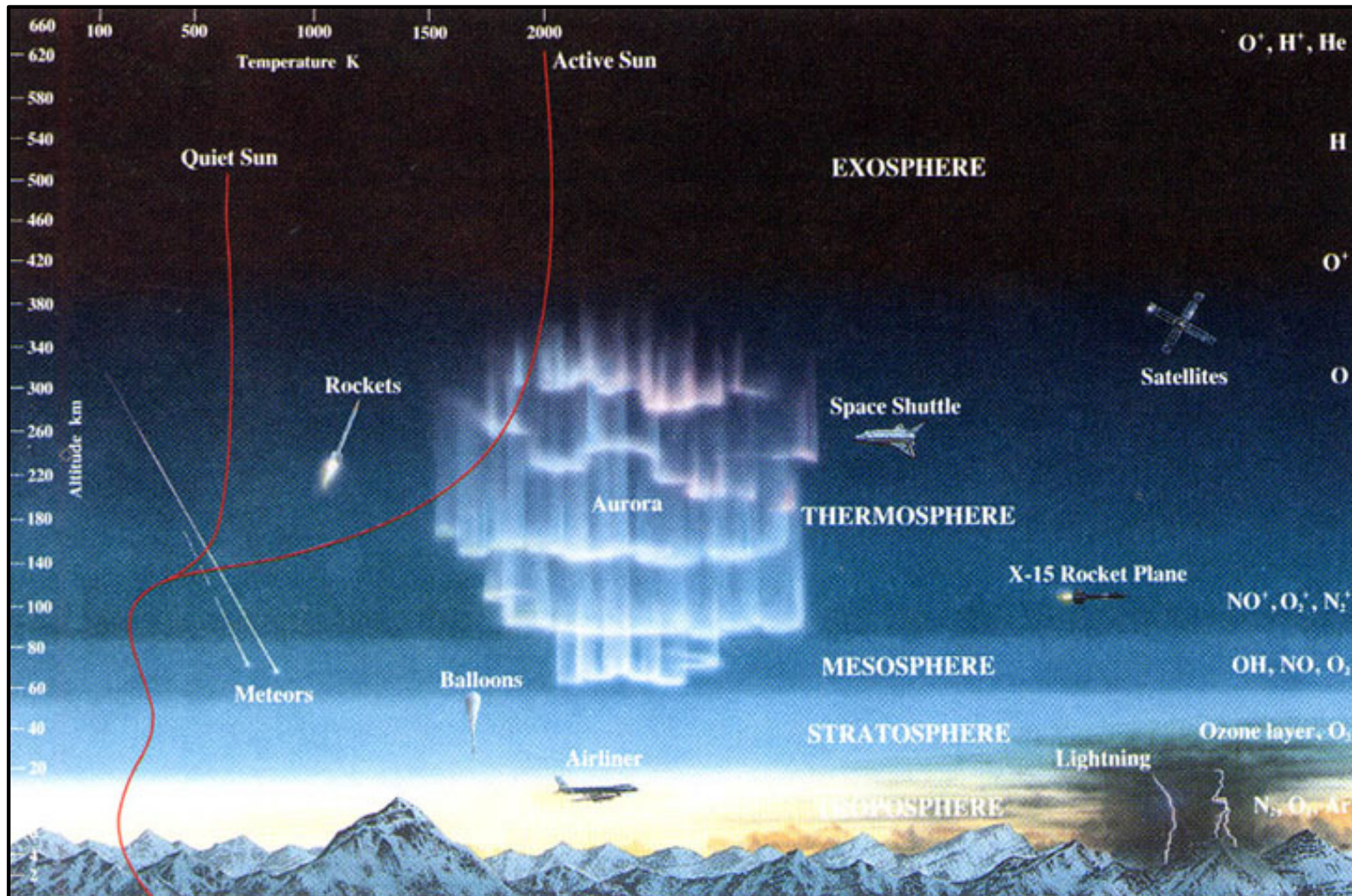
- **Troposphere:**

- 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



- **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



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Seminar structure

Part 2 (12 noon – 1.00 pm)

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

- **"Innersphere"**: 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. Should we require further discussion, I will happily meet further in the Gather Town online meeting space.

Physics and the Earth Sciences

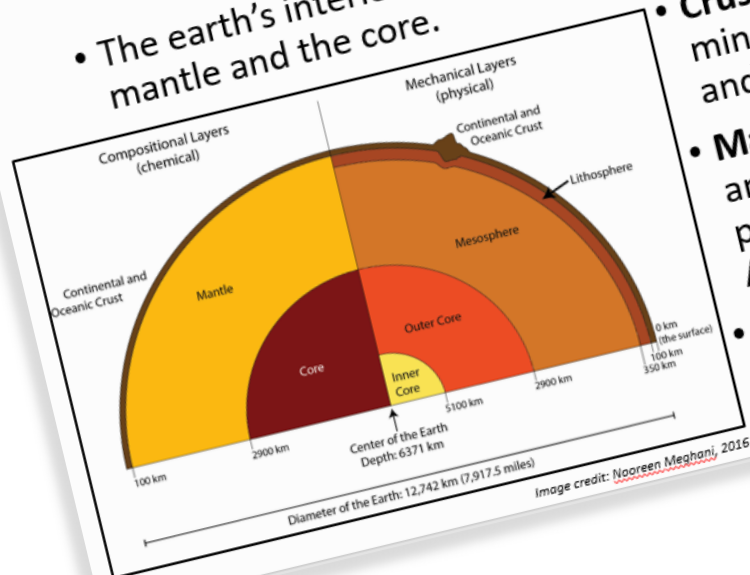
- As we've already seen, the Earth Sciences can be regarded as being '**Multi-spheric**' – comprising lithosphere, hydrosphere, biosphere, cryosphere, troposphere, stratosphere, and all the way out to the exosphere.
- Broad umbrella term: necessarily an inter-disciplinary field of study.
- A systems 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:

The “Inner Spheres”

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



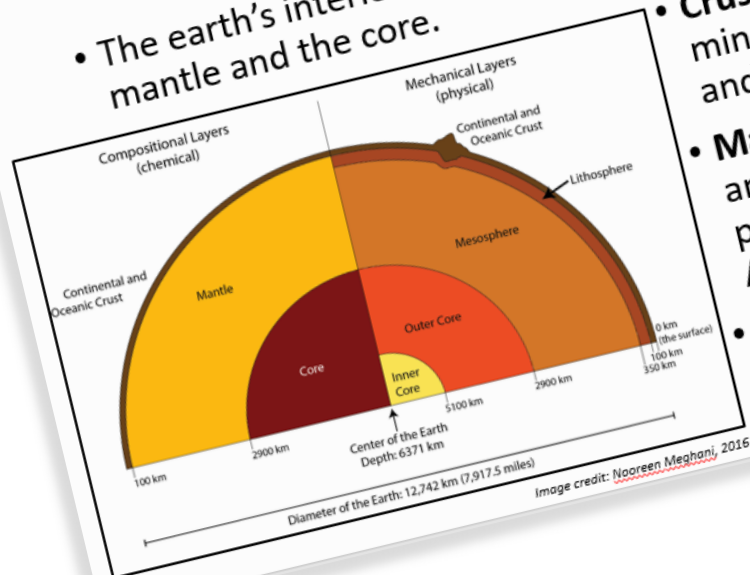
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“Inner” sphere

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The “Inner Spheres”

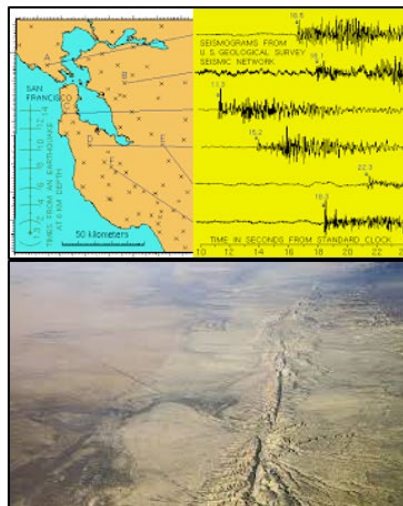
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- Crust:** 0 -100 km comprising minerals (divided into oceanic and continental crust (Sial and Sima))
- Mantle:** 100 – 2900 km comprising silicates. Basic properties can be divided into the Asthenosphere and Mesosphere
- Core:** 2900 – 6370 km comprising iron and Ni metal. Divided into the liquid (outer) and inner (solid) core

Opportunities for scientists who study the “inner spheres”

Seismology



Kimberlite experts



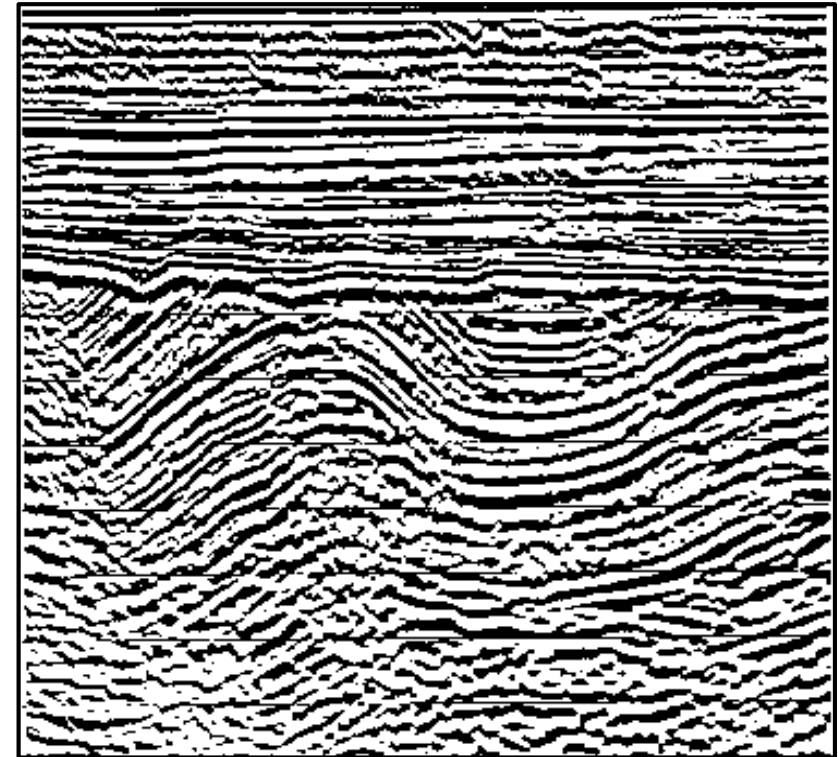
Image credits: USGS.gov; physics.nyu.edu; nasa.gov

“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 airguns (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

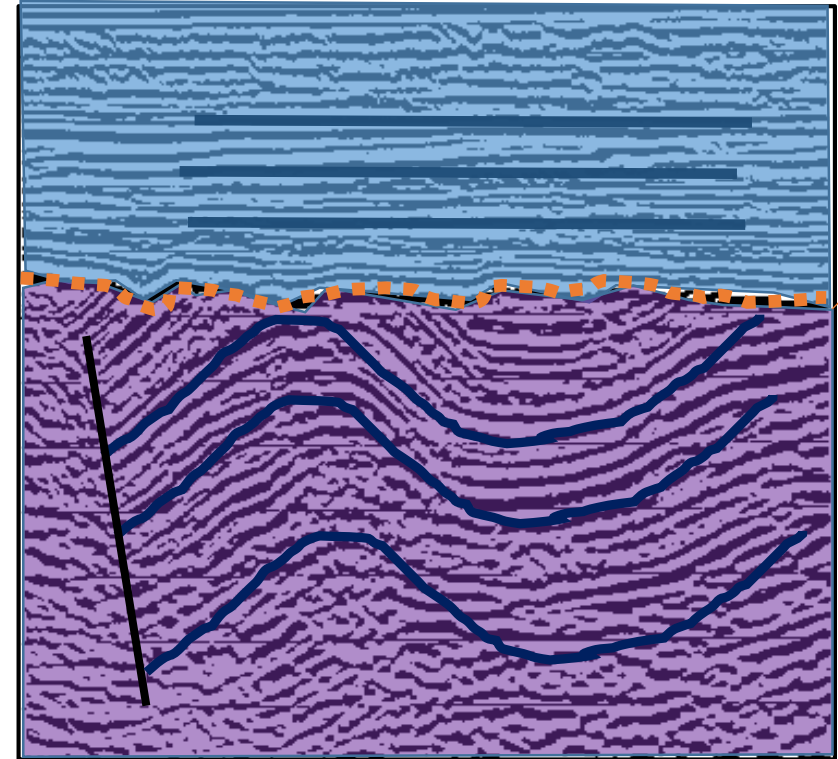


“Inner” sphere

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Example of controlled source reflection seismology



“Inner” sphere

CASE STUDY 1: Seismic wave propagation and earthquake monitoring

Seismic waves can be divided into two key classes:

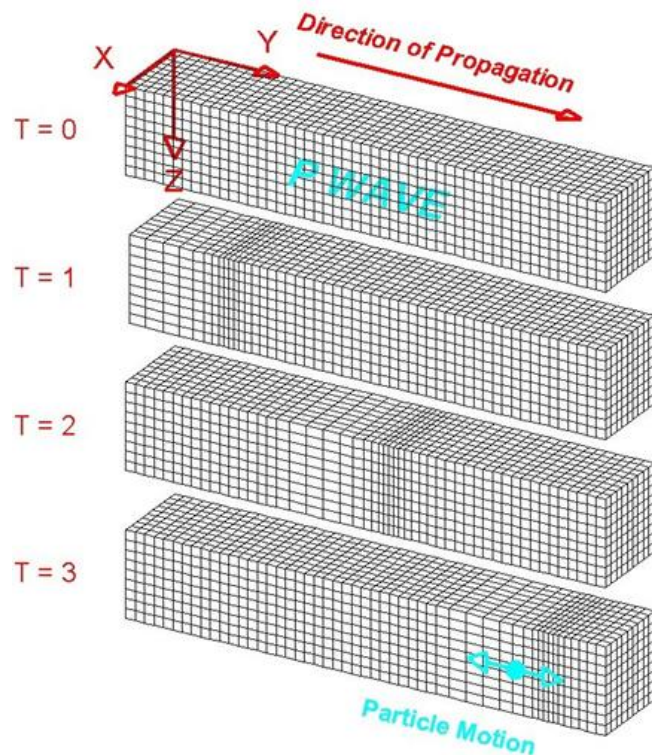
- 1) Body waves:** these travel directly through the interior of the earth and are thus first to arrive at a given ‘geophone’ (acoustic listening device).
 - Body waves are divided into P and S waves

- 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

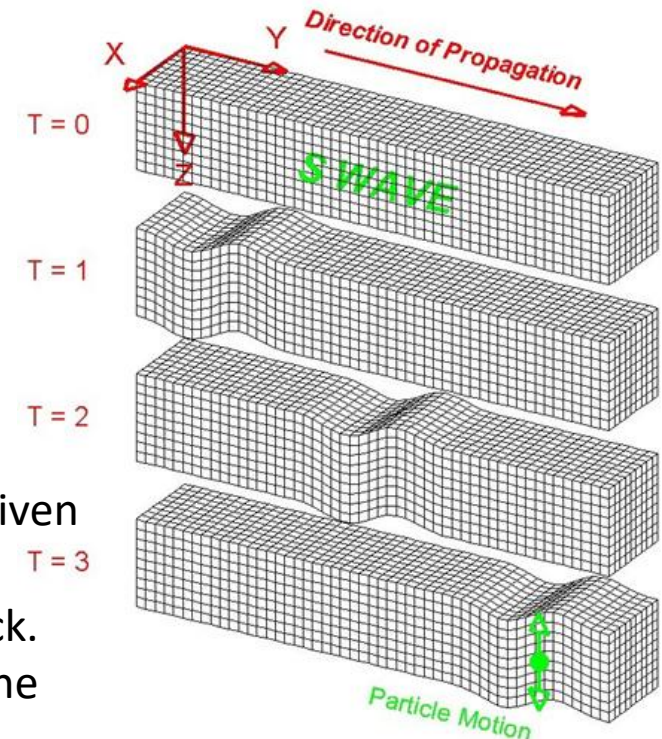


P waves:

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:

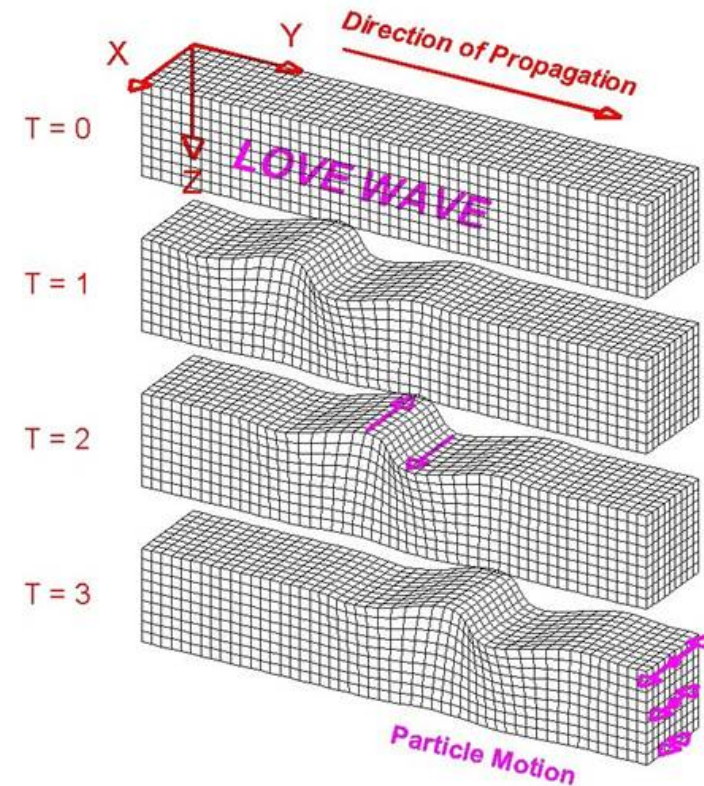
Second wave experienced at a given location.
Can only move through solid rock.
Move up and down relative to the direction of wave propagation.



“Inner” sphere

CASE STUDY 1: Seismic wave propagation and earthquake monitoring

Types of seismic waves: Surface waves



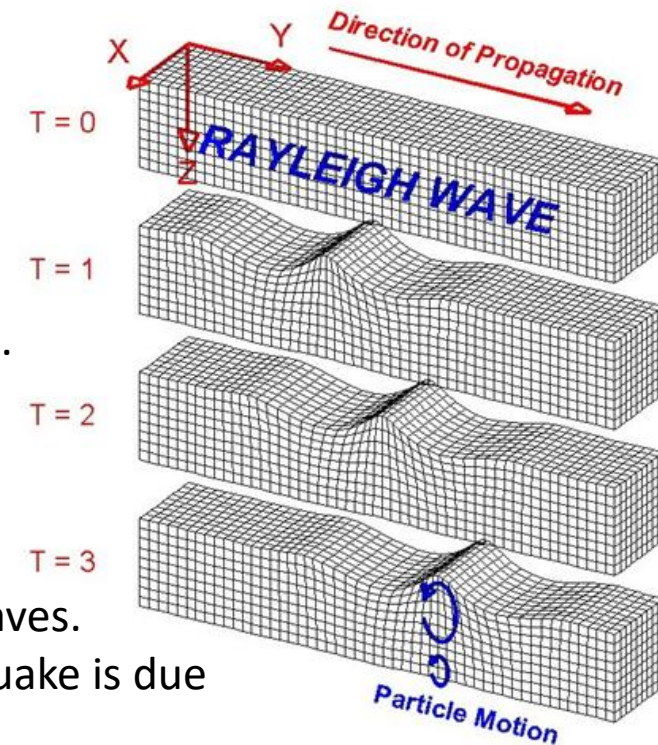
L waves:

Fastest surface wave, only travels along earth's 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:

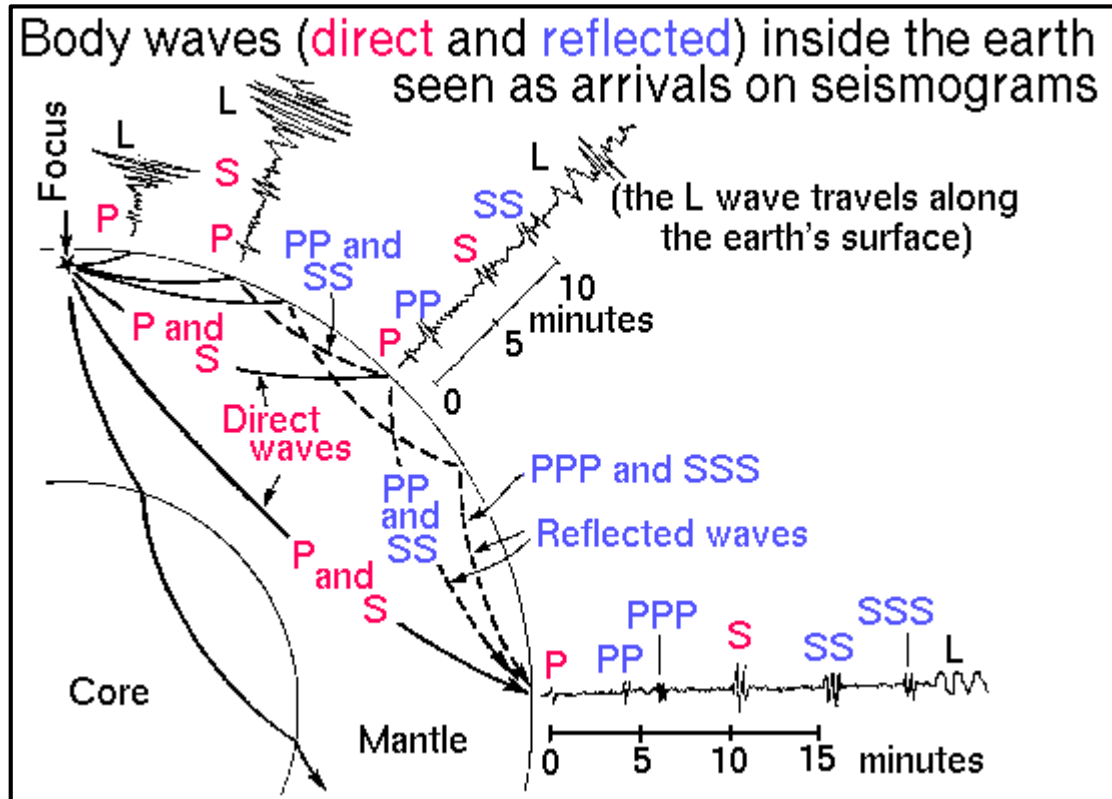
Moves in a rolling motion, much like ocean waves. Most of the shaking experienced in an earthquake is due to these waves.



“Inner” sphere

CASE STUDY 1: Seismic wave propagation and earthquake monitoring

Propagation through the earth's interior



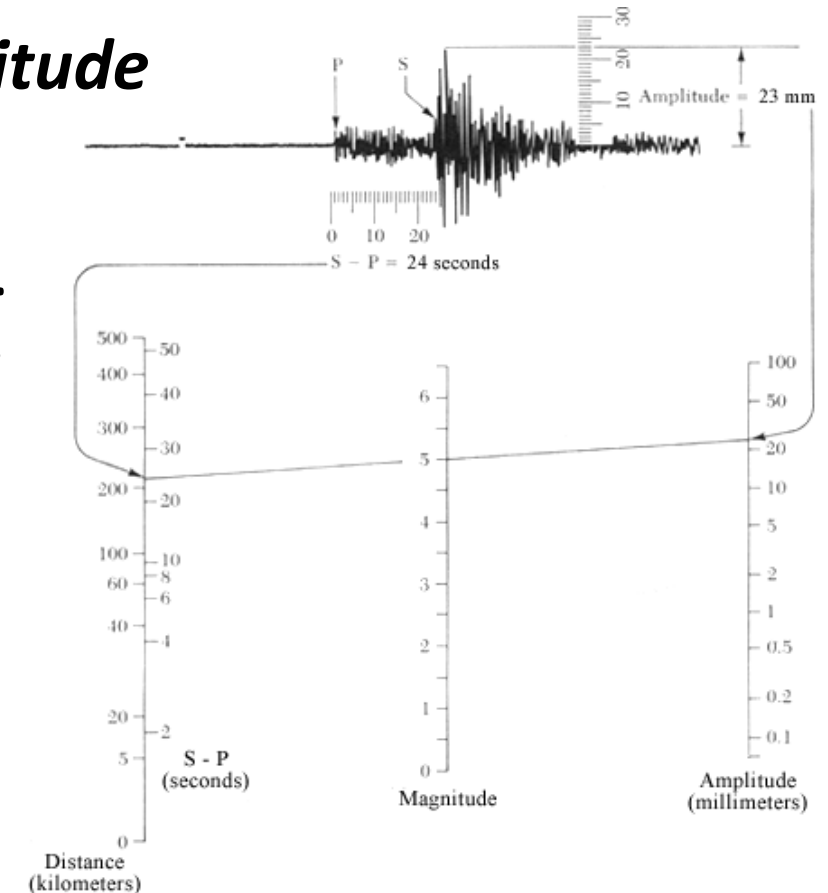
- P waves always first to arrive.
- P waves are able to reflect at the earth surface interface- gives rise to PP and PPP waves.
- Time interval between P wave and subsequently arriving waves (S, L) increases as a function of distance away from the epicenter.
- S waves can't propagate through the earth's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

“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)



Lithosphere

- Recap:

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.
- So what is a mineral?
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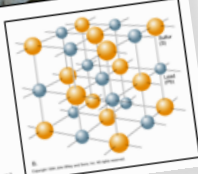




image credits: alltop.com; geology.com; John Wiley and Sons (1999)

Lithosphere

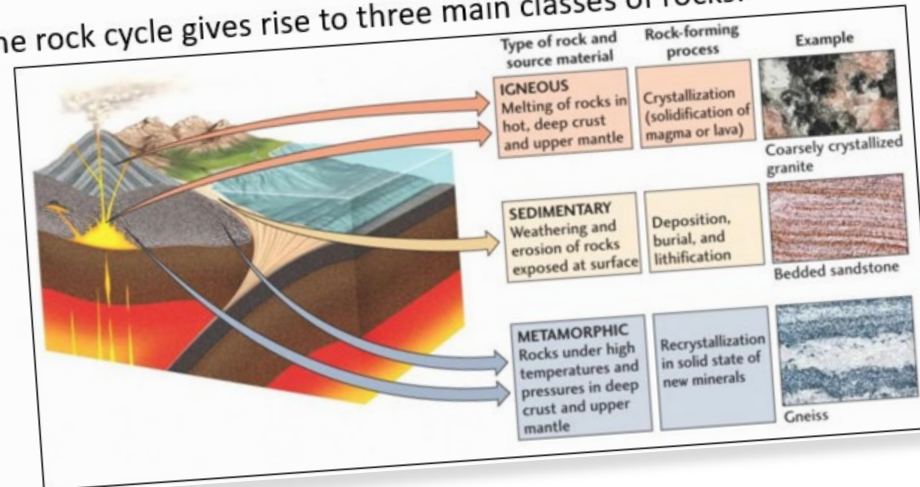
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The lithosphere

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



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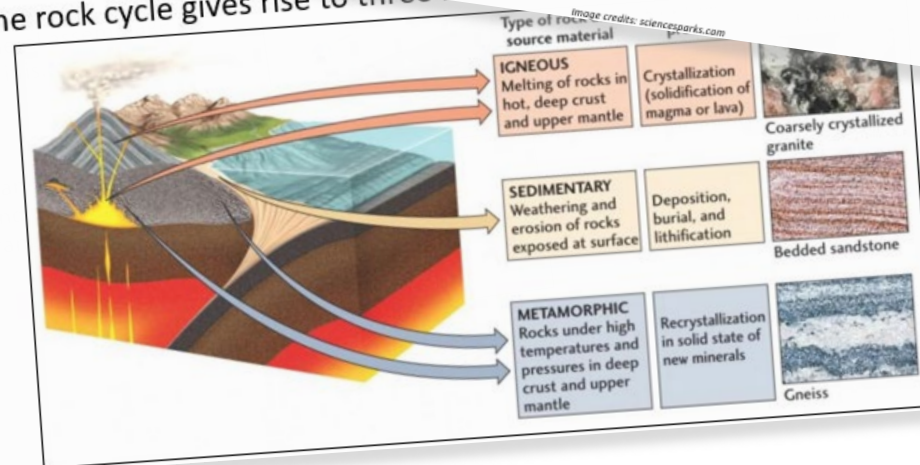
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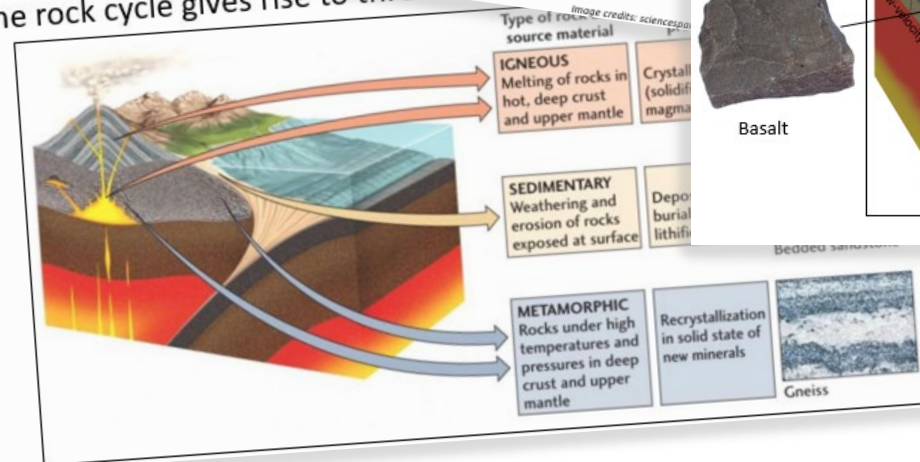
The lithosphere

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The

- The rock cycle gives rise to three types of rocks



The lithosphere

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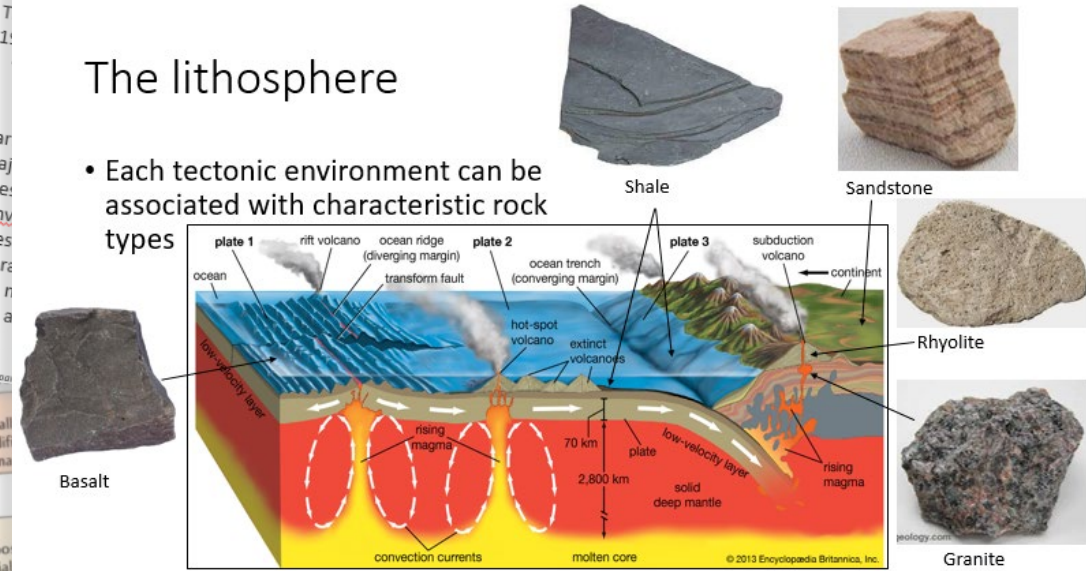


Image credits: britannica.com; geologylearn.blogspot.com; geology.com; sandtlas.org

Lithosphere

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- So what is a mineral?
 - Homogeneous, naturally occurring solid with a definable chemical composition and a crystal structure characterised by an ordered arrangement of atoms, ions, or molecules in a repeating pattern.

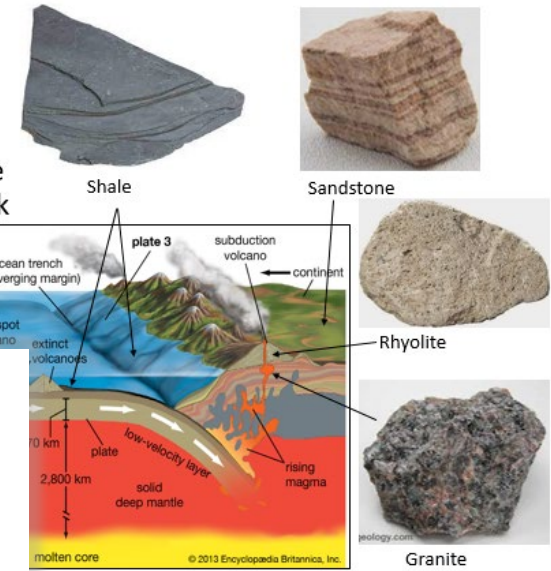
The lithosphere

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



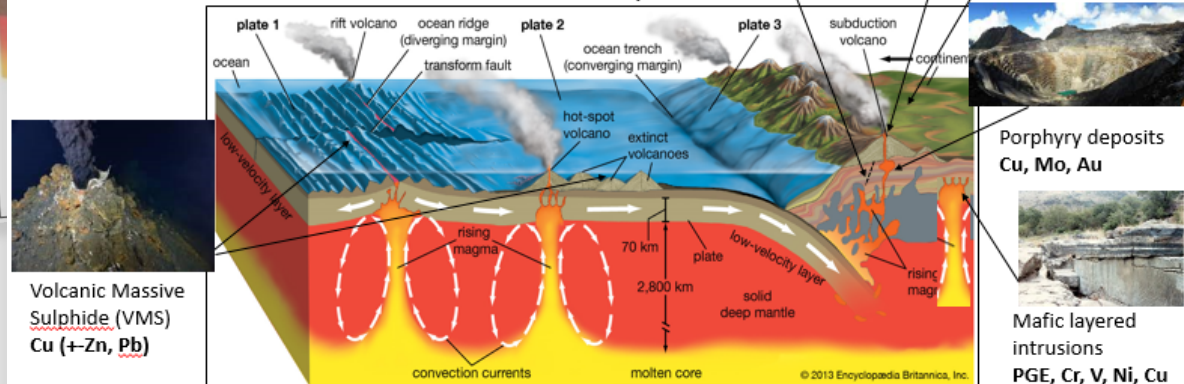
The lithosphere

- Each tectonic environment can be associated with characteristic rock types



The lithosphere

- Each tectonic environment can be associated with characteristic ore deposits



Lithosphere

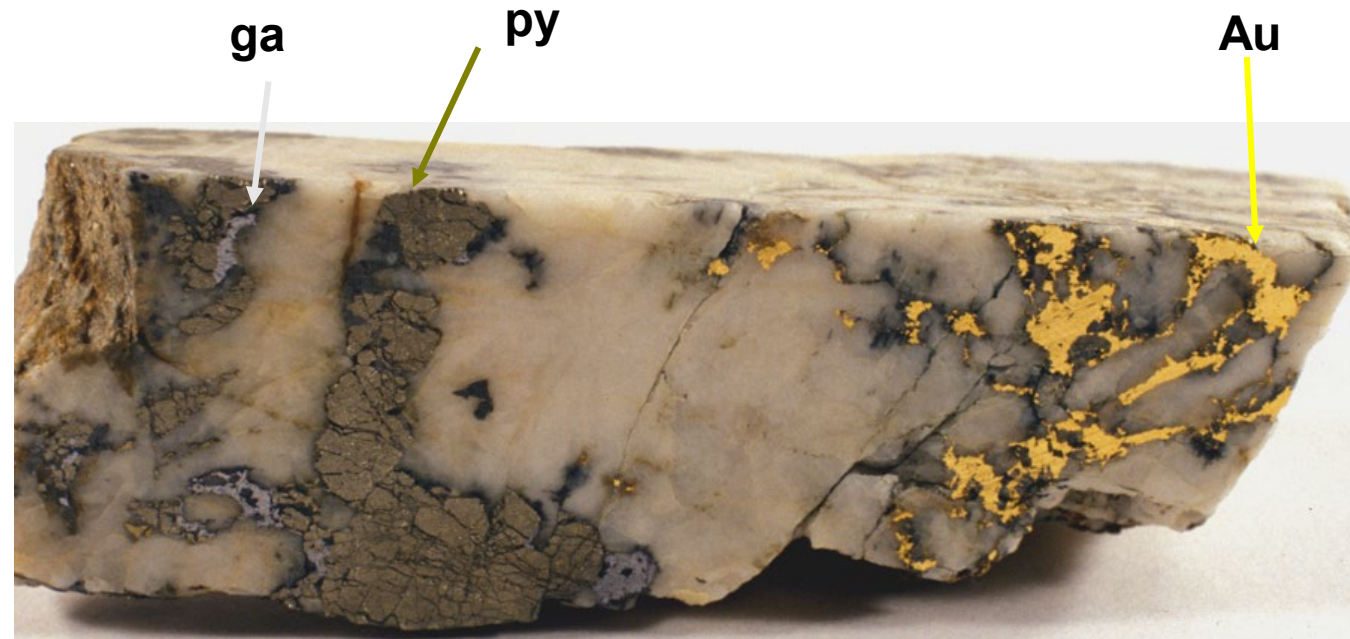
CASE STUDY 2: The formation of orogenic gold deposits

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,AgTe_4): 25-27 % Au
- Nagyagite ($\text{Pb}_5\text{Au(Te,Sb)}_4\text{S}_{5-8}$): 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:

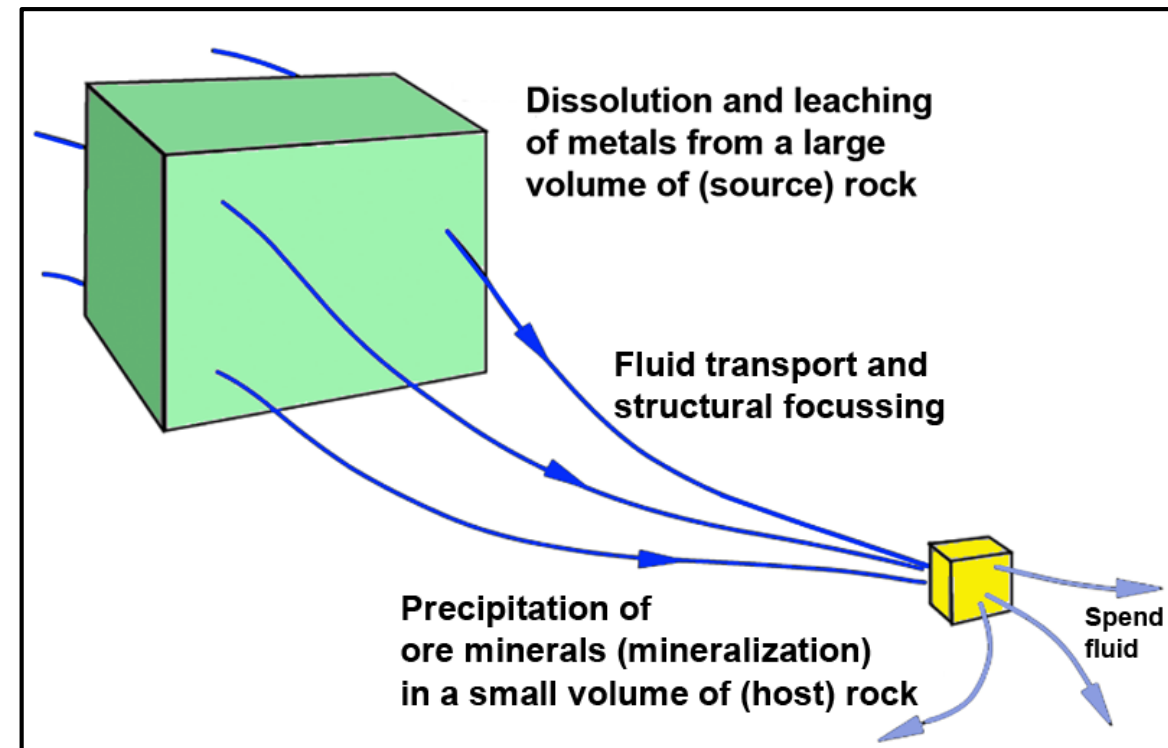
Fluid source: Likely to be devolatilisation during prograde metamorphism. Other possibilities include magmatic fluids and devolatilisation of an external (subducting slab)

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

Fluid source:

Concept of metamorphic facies:

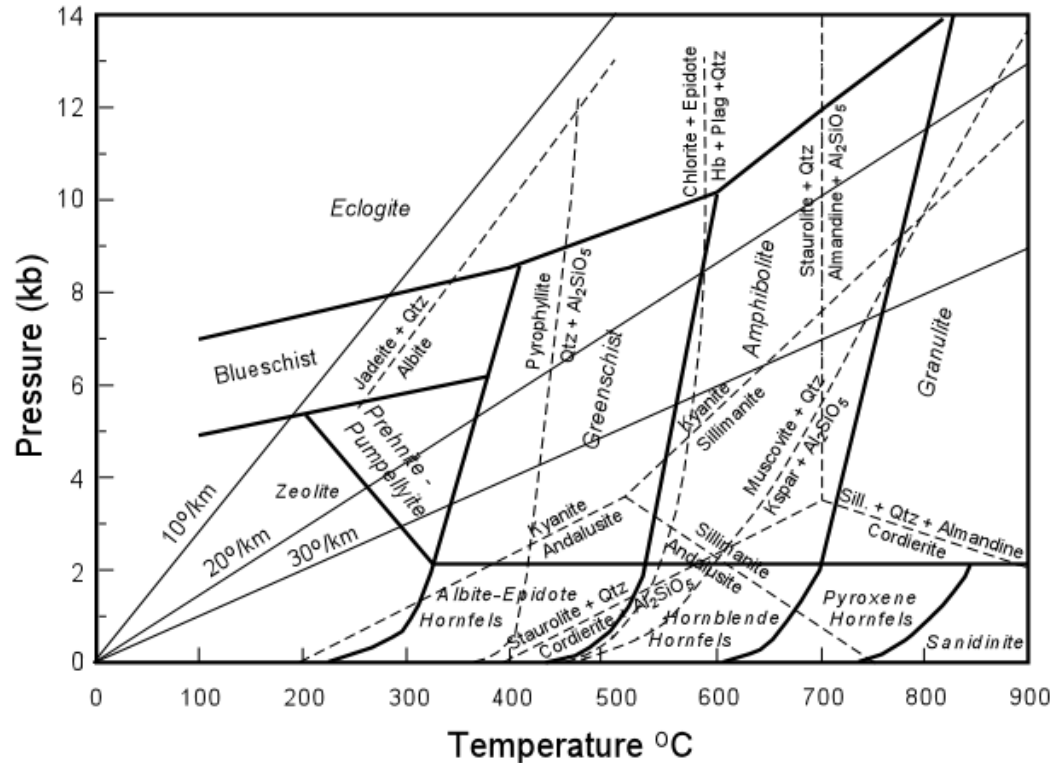
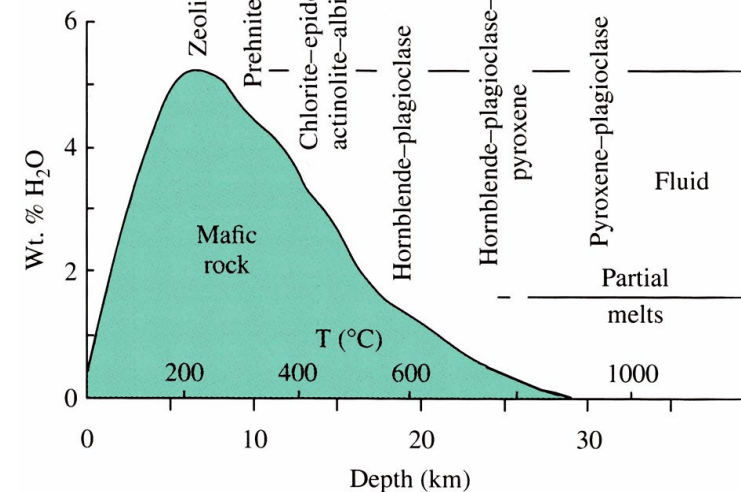
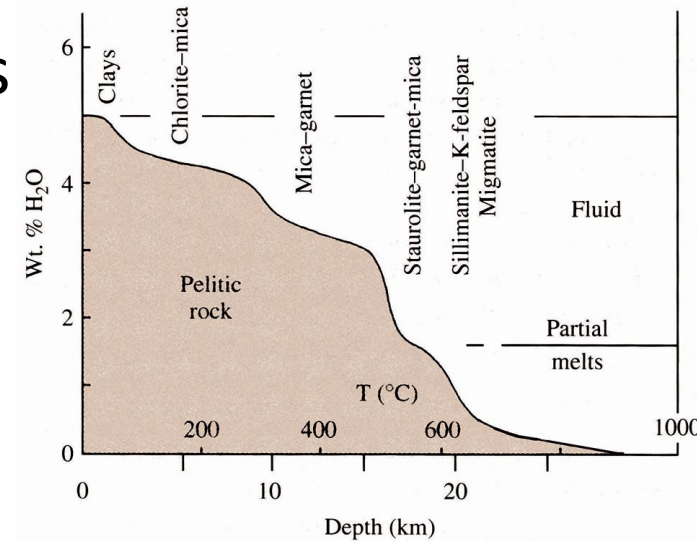


Image credits: tulane.edu; Best (2003)

Fluid production during prograde metamorphism:



Lithosphere

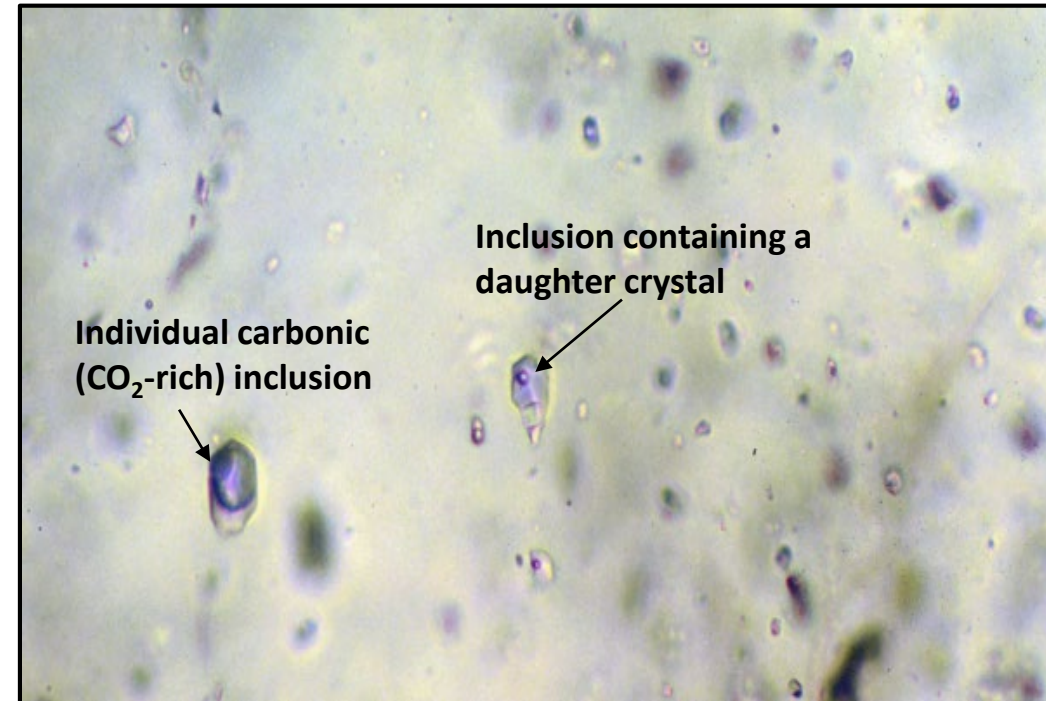
CASE STUDY 2: The formation of orogenic gold deposits

Fluid source:

Fluid characteristics:

- Aqueous-carbonic fluids
- Reduced (near or below the magnetite-hematite buffer)
- Near-neutral pH (~5.5)
- Low salinity (3-7 wt.% NaCl equil.)
- CO₂-rich (5 – 20 mole %)
- H₂S, HS⁻ -bearing (0.1- 0.36 mol%)
- T ~ 200 – 650 °C
- P ~ 1 – 5 kbar
- Variable isotope systematics due to complex geochemical and wall-rock interactions

Fluid inclusion micro-analysis

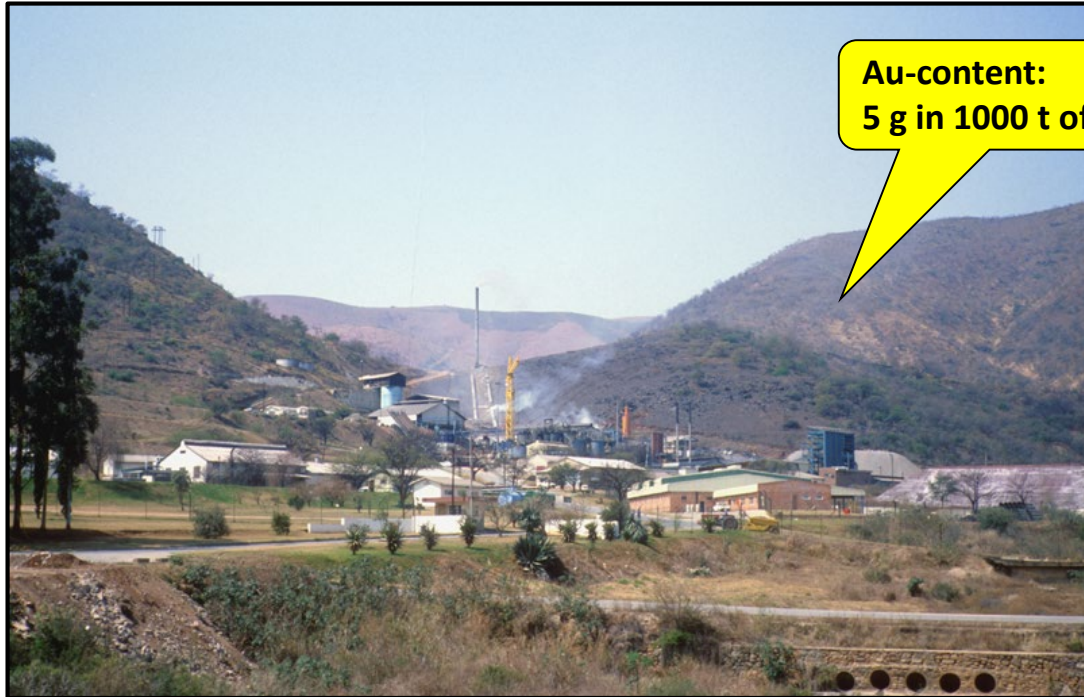


Fluid inclusions range in size from smaller than 5 µm to greater than 60 µm. Studied using microthermometry, Raman spectroscopy, sXRF, LA-ICP-MS

Lithosphere

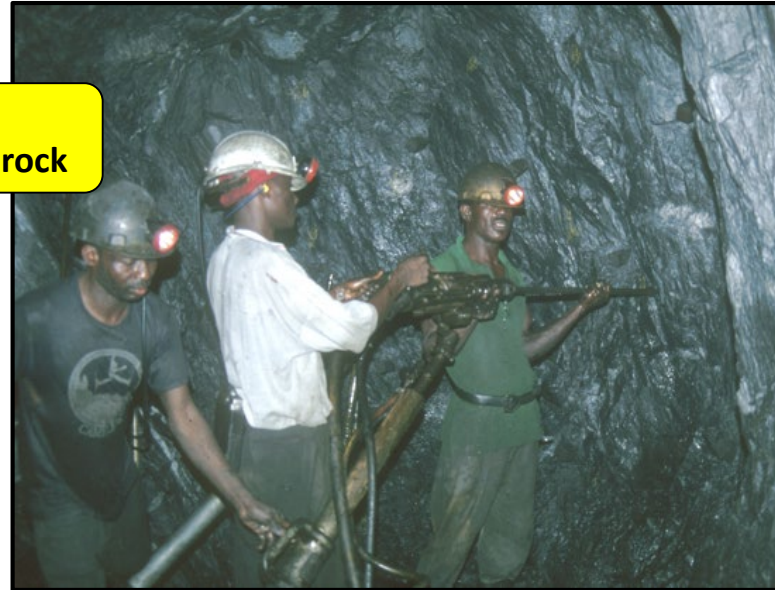
CASE STUDY 2: The formation of orogenic gold deposits

Metal source:



Au-content:
5 g in 1000 t of rock

Fairview Au Mine, Barberton Mountain Land, South Africa



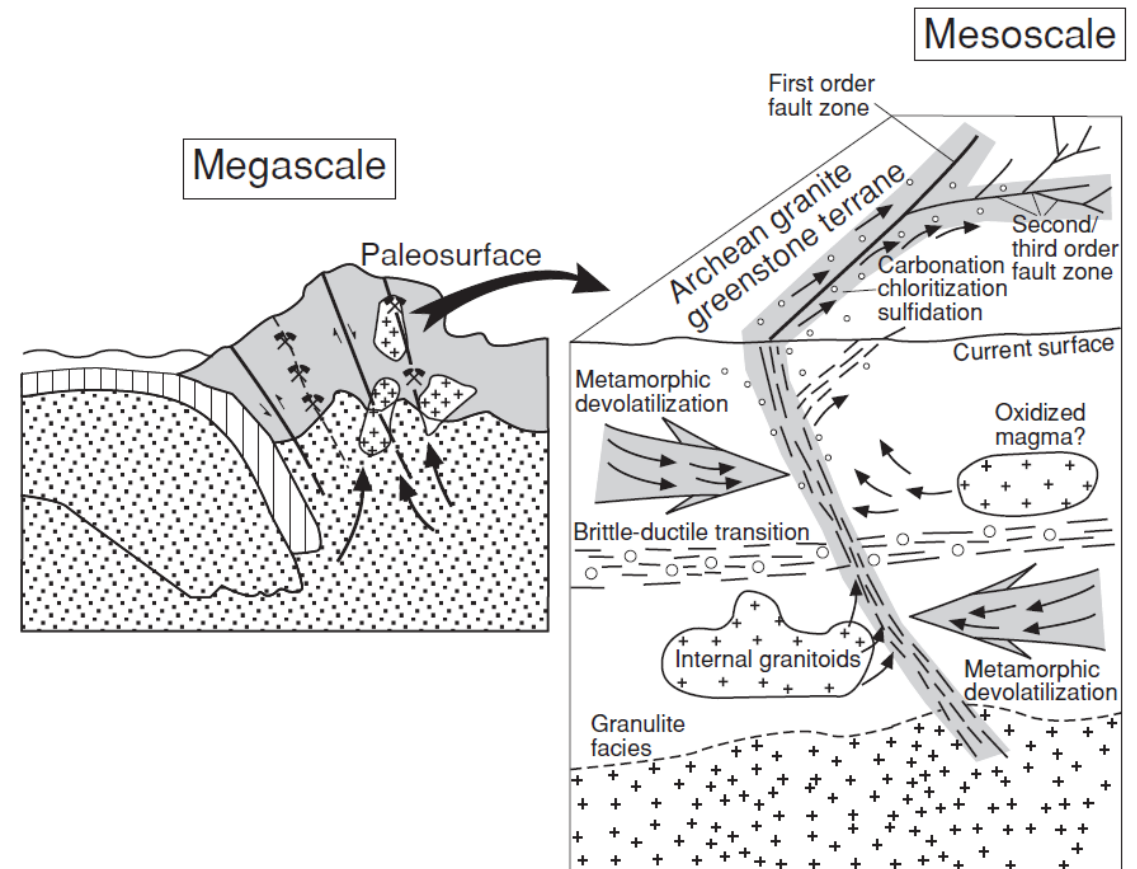
Au-content:
8 g in 1 t of ore

Lithosphere

CASE STUDY 2: The formation of orogenic gold deposits

Transport:

- Gold only deposits that are associated with convergent plate margins.
- Metamorphism results in fluid production that gets focused along major structural discontinuities (e.g., major transcurrent strike-slip faults).
- Ore shoots can have many forms that are related to the wide variety of second and third-order structures that can develop in strike-slip fault systems.
- Mineralisation may be sporadic or continuous. Orogenic Au deposits form at depths between 3 – 20 km

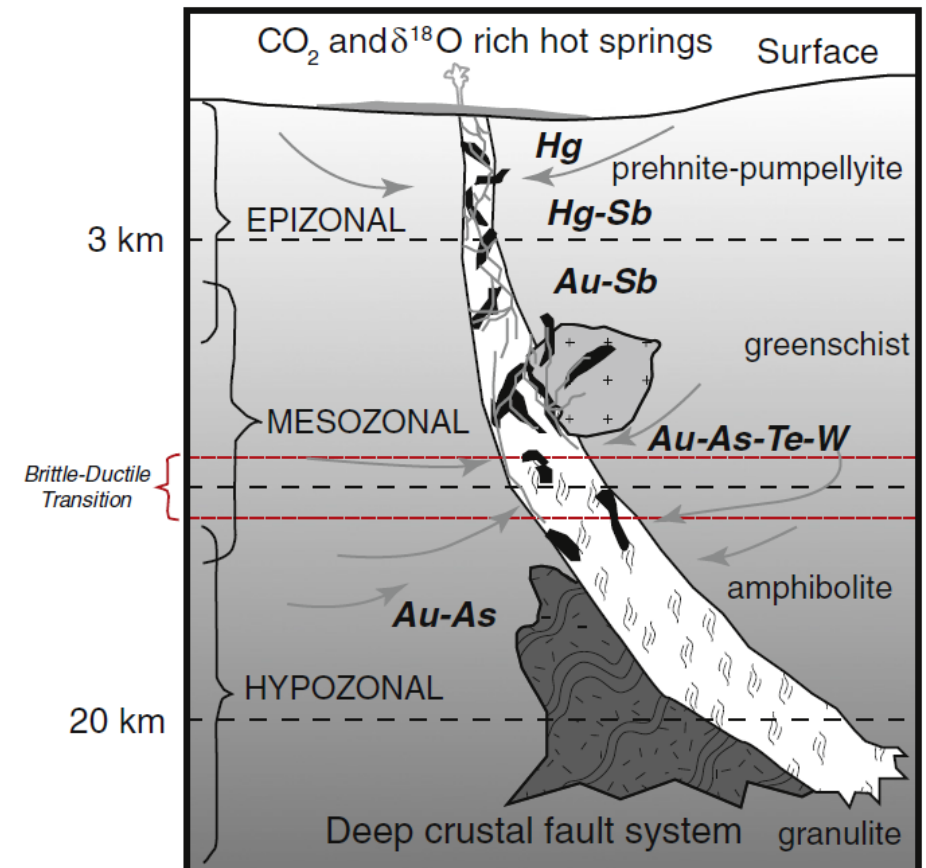


Lithosphere

CASE STUDY 2: The formation of orogenic gold deposits

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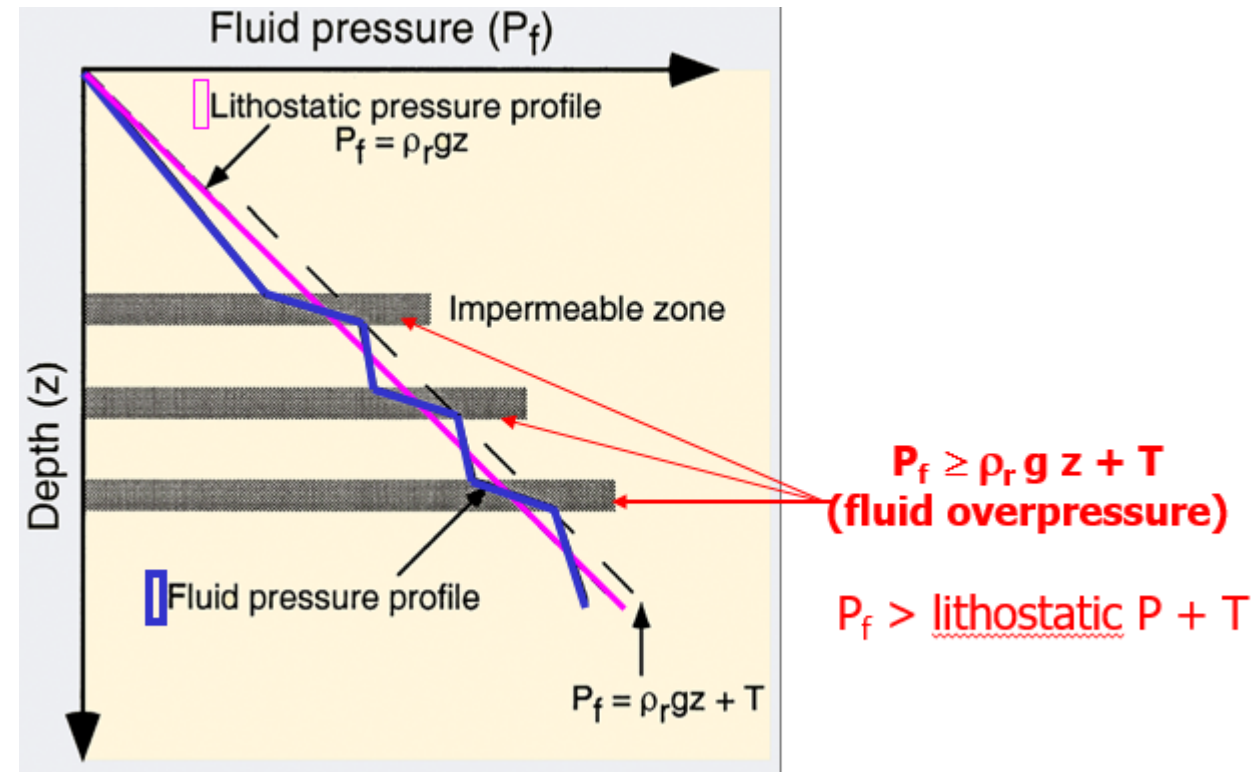


Lithosphere

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 ($\sim 1 \text{ g.cm}^{-3}$) and rock ($\sim 2.6 \text{ g.cm}^{-3}$)
- 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.

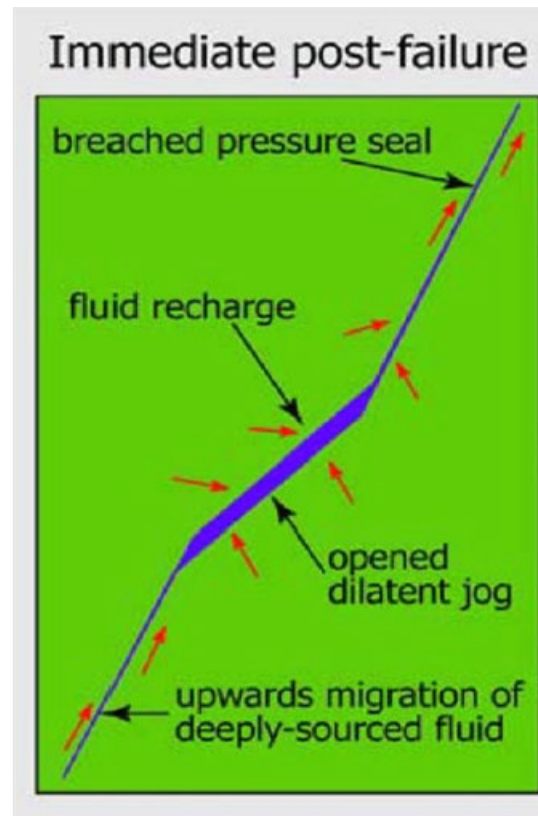
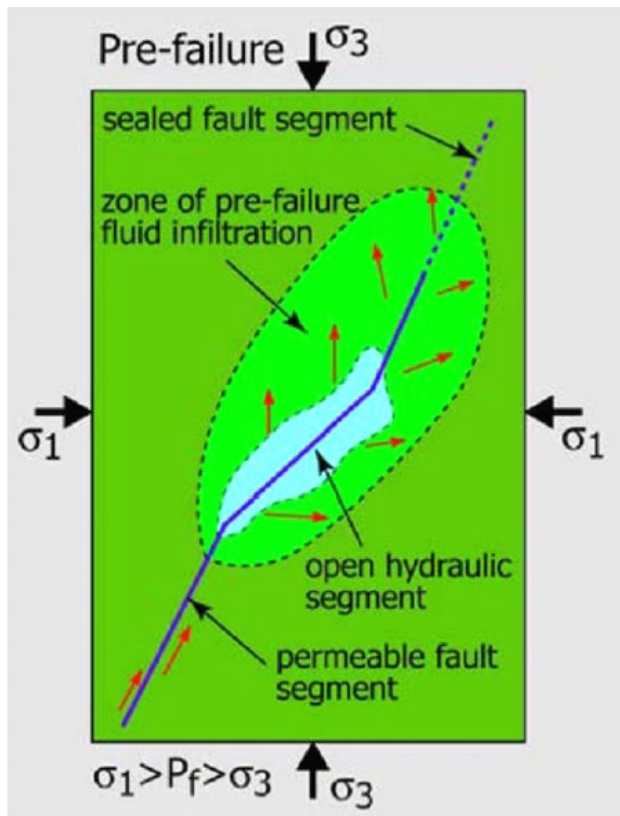


P_f = fluid pressure; ρ_r = density of rock overburden; g = gravitational acceleration; z = depth; T = tensile strength

Lithosphere

CASE STUDY 2: The formation of orogenic gold deposits

Trap: 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 dilatant jog fluid pressure drops to below lithostatic values ($P_f < \delta_3$).
- Fluids to drain back from wallrocks around fault into open dilatant jog and discharge upwards along fault plane.
- Fluid recharge from deep source

Lithosphere

CASE STUDY 2: The formation of orogenic gold deposits

Trap: 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

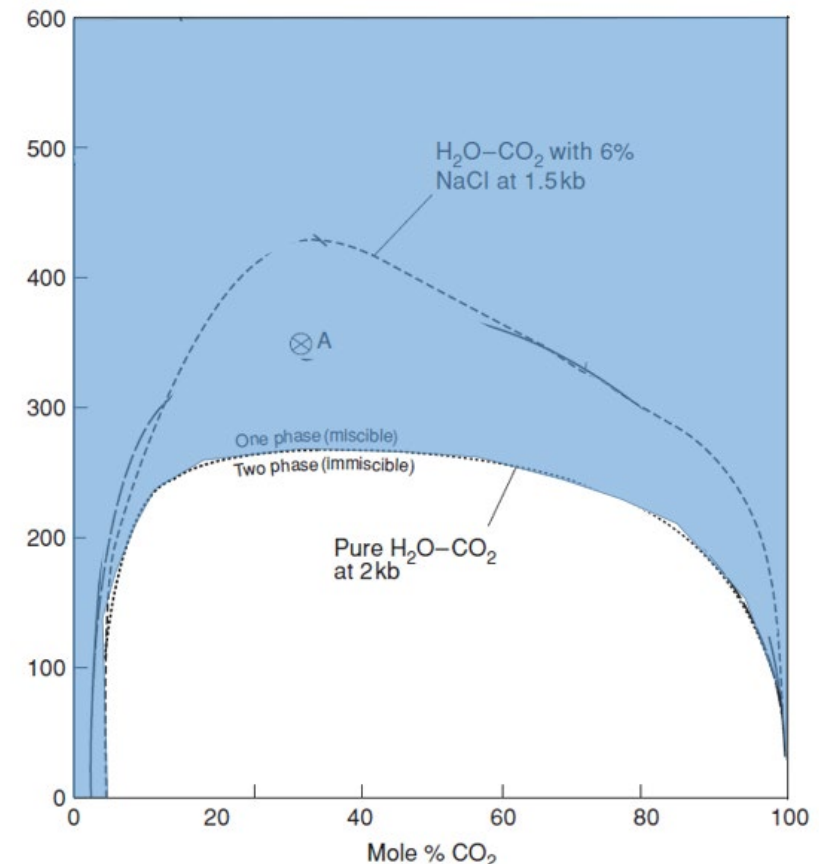
CASE STUDY 2: The formation of orogenic gold deposits

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:

-Effervescence:

Decreases in pressure act to move the solvus to higher temperatures. Immiscibility of H_2O and CO_2 will result in significant changes to the fluid properties leading to deposition of both ore (e.g., Au) and gangue minerals



Lithosphere

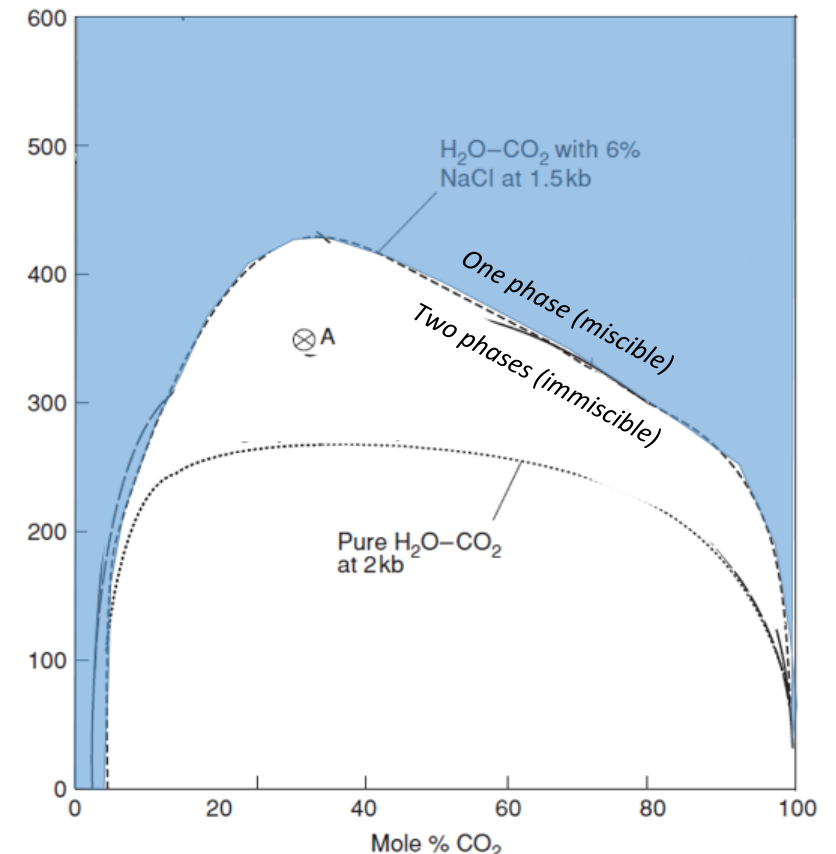
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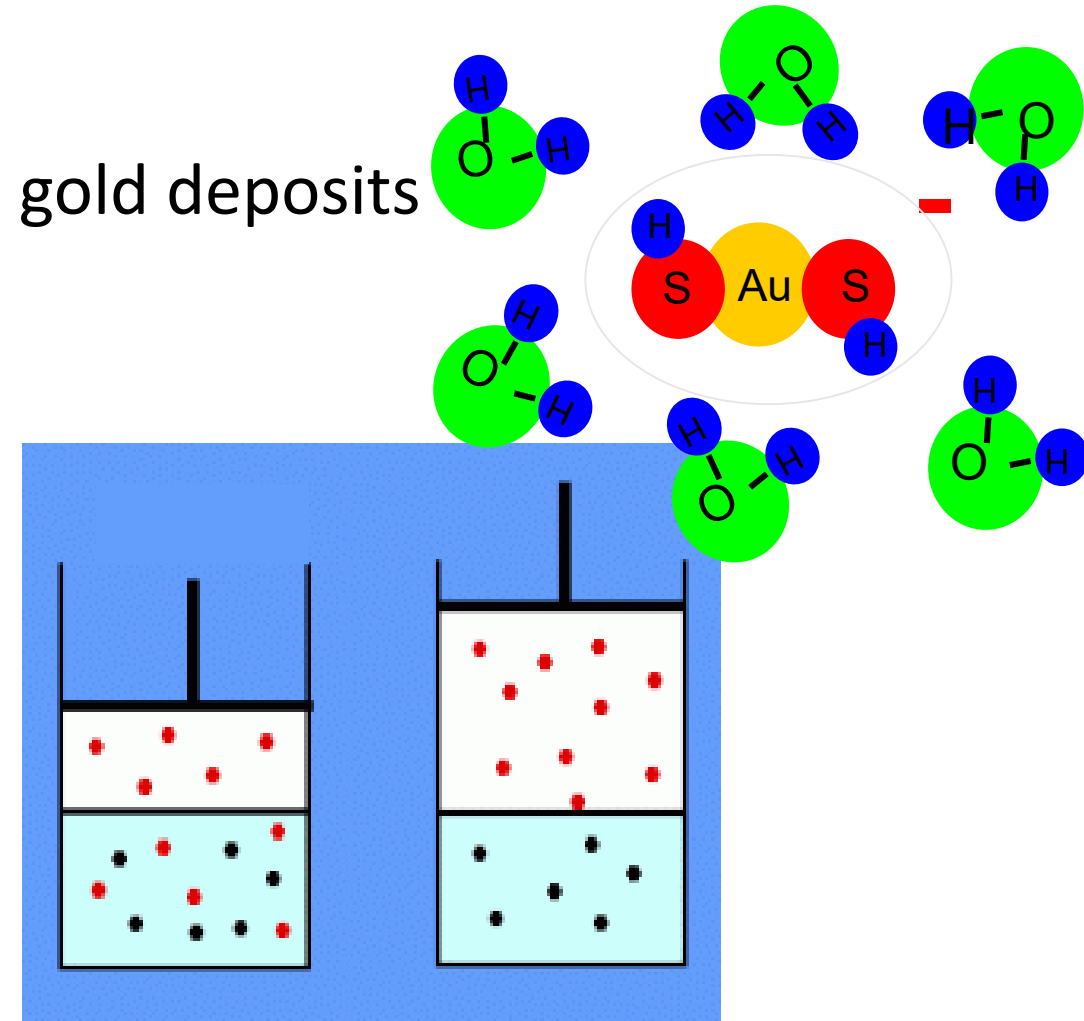
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- However, decreases in pressure also lead to boiling and effervescence phenomena:

-Boiling:

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



Boyles Law: $P_1 V_1 = P_2 V_2$



THANK YOU!!

Questions/Discussion

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