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Economic Geology

Ore forming processes

Module 3

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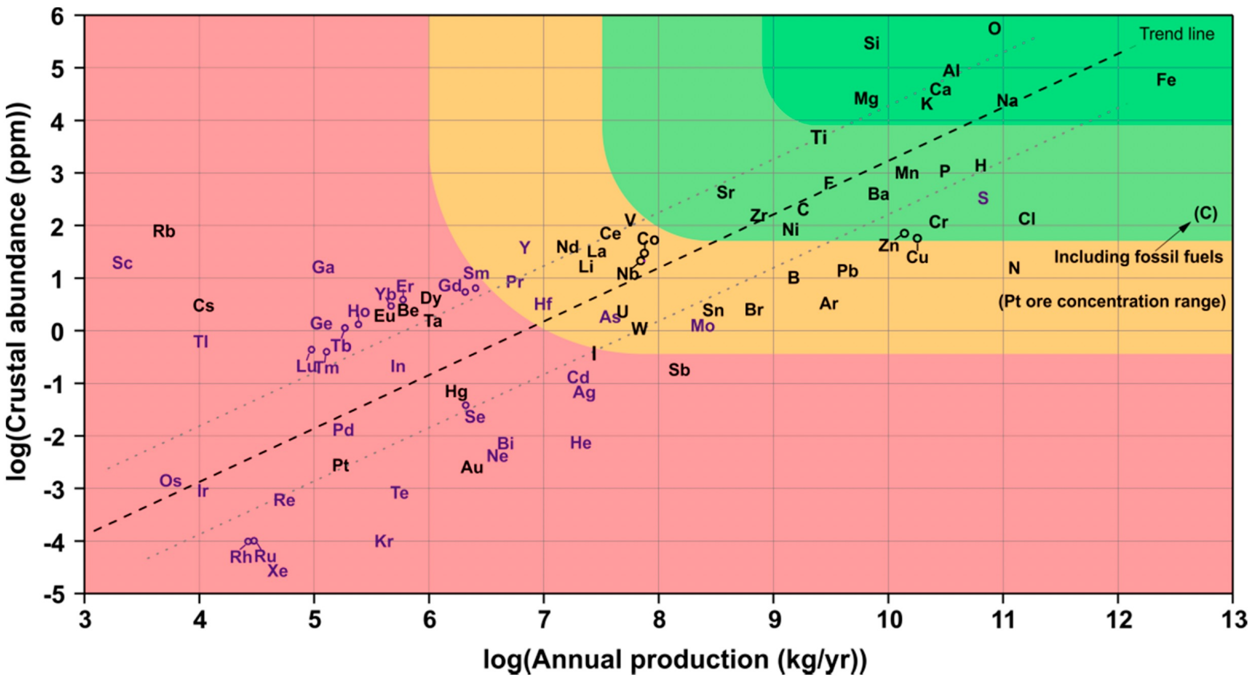
Content and structure

- Module 1: Intro, element abundance, plate tectonics, economics
- Module 2: Minerals, Rock types
- **Module 3: Ore forming processes**
- Module 4: Base metals and their ore deposit types
- Module 5: Precious and rare metals and their ore deposit types
- Module 6: Summary

Enrichment of metals/elements

- To obtain concentrations high enough to form an ore deposit, elements (metals) need to be <u>concentrated in a confined space</u>.



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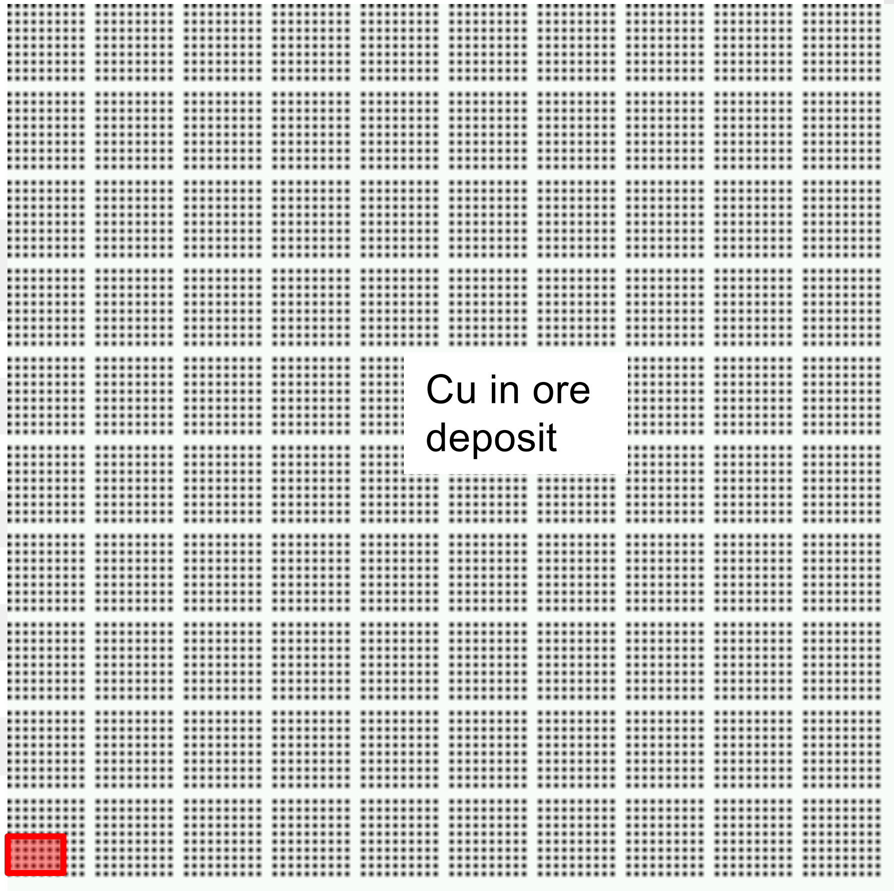
Enrichment of metals

Metal	Typical Background Level	Typical Economic Grade*	Concentration Factor
Copper	40 ppm	10,000 ppm (1%)	250 times
Gold	0.003 ppm	6 ppm (0.006%)	2,000 times
Lead	10 ppm	50,000 ppm (5%	5,000 times
Molybdenum	1 ppm	1,000 ppm (0.1%)	1,000 times
Nickel	25 ppm	20,000 ppm (2%)	800 times
Silver	0.1 ppm	1,000 ppm (0.1%)	10,000 times
Uranium	2 ppm	10,000 ppm (1%)	5,000 times
Zinc	50 ppm	50,000 ppm (5%)	1,000 times



Cu concentration in Earth crust

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Processes to concentrate metals/elements

- Magmatic processes (magma chamber processes)
- Hydrothermal processes (fluids)
- Physical processes (sedimentation)
- Chemical processes (deposition from water)

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Ore forming processes and deposit types

Magmatic deposits

Fractionation: *alkaline intrusions REE, carbonatites, rare metal granites, pegmatites*

Liquid immiscibility: magmatic *massive sulphide Ni-Cu-PGE*

Magma mixing: *massive sulphide Ni-Cu-PGE, chromite deposits*

Assimilation: magmatic *massive sulphide Ni-Cu-PGE, chromite deposits*

Hydrothermal deposits

Magmatic fluids: *porphyry Cu-Mo deposits, skarn, intrusion related veins, Sn-W, epithermal Au-Ag*

Basinal fluids: *SEDEX, MVT, sedimentary Cu, U*

Seawater: *volcanic massive sulphide Cu-Zn-Pb deposits (VMS)*

Metamorphic fluids: *orogenic Au deposits*

Meteoric fluids: *epithermal Au-Ag deposits, Li brines*

Note: mixing of fluids in hydrothermal systems can occur

Sedimentary deposits

Chemical: *evaporites, banded iron formations (BIF), bauxite/laterite, brines*

Physical: *placer deposits*

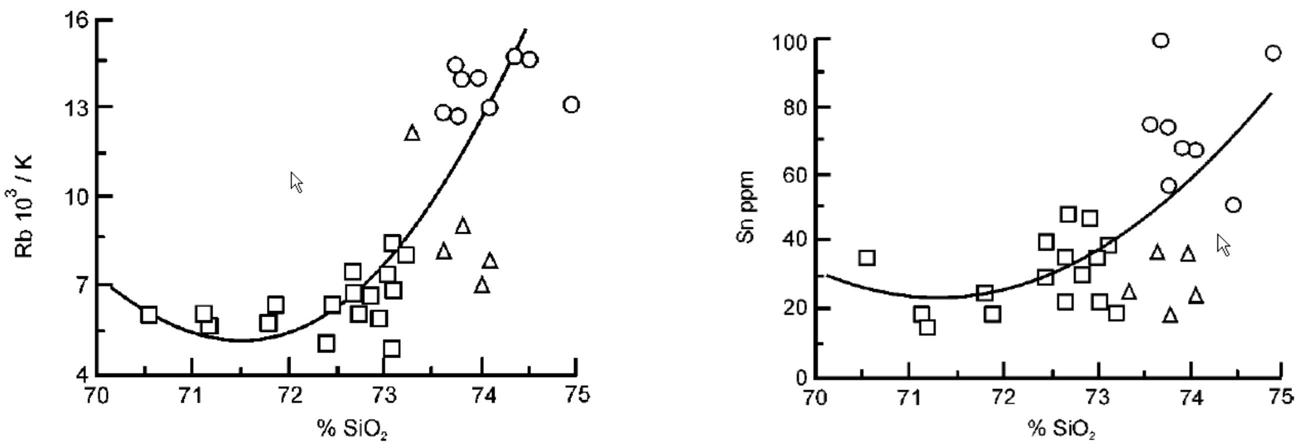
Enrichment of metals (magmatic)

- Crystallization of melt

- Melt immiscibility (sulphide/silicate melt)

Enrichment of metals (Crystallization)

- When a melt crystallizes, certain elements (Li, Sn, Ta, Nb, REE, F...) can be enriched in the melt because they are not entering into minerals (incompatibility).



Fractional crystallization can lead to enrichment of metals

Enrichment of metals (Crystallization)

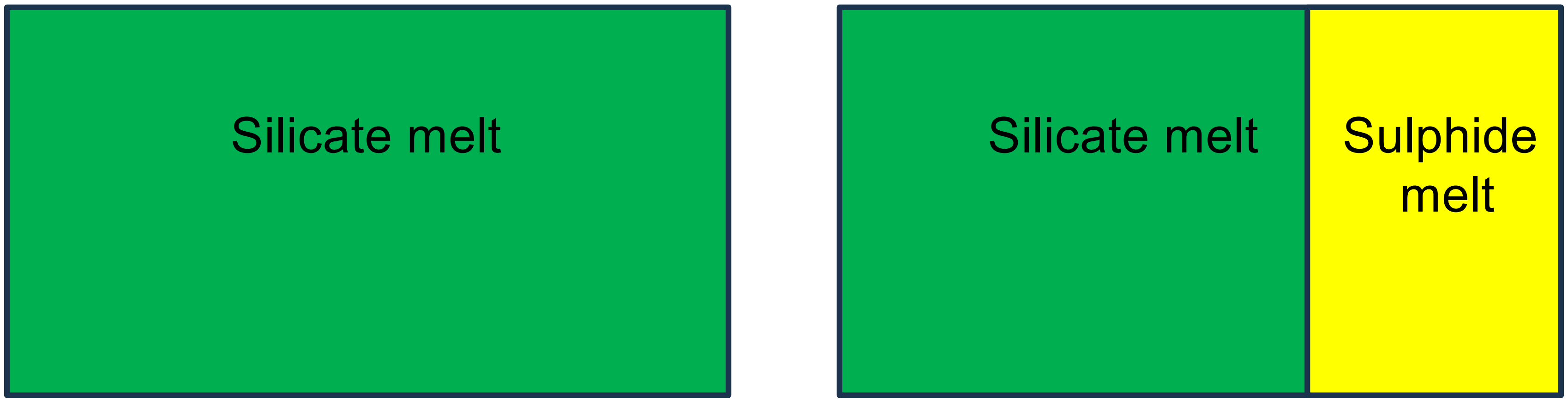
- Examples for highly fractionated systems:

- Pegmatites
- Sn-W granites
- Rare-metal granites (Nb, Ta, REE, Zr, F, Li,...)

Enrichment of metals (Melt immiscibility)

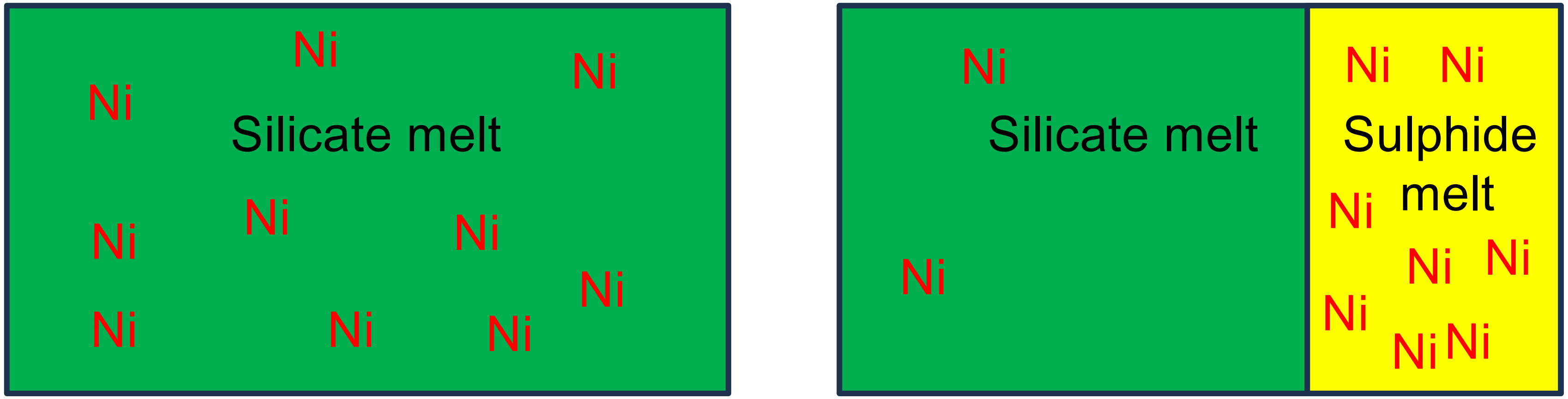
- A sulphide melt exsolves from a silicate melt when the S concentration in the melt increases to a concentration of oversaturation.

Oil and vinegar



Enrichment of metals (Melt immiscibility)

- Metals love the sulphide melt and will be enriched in this melt (Partitioning coefficient, $D^{sulf/silic}$).



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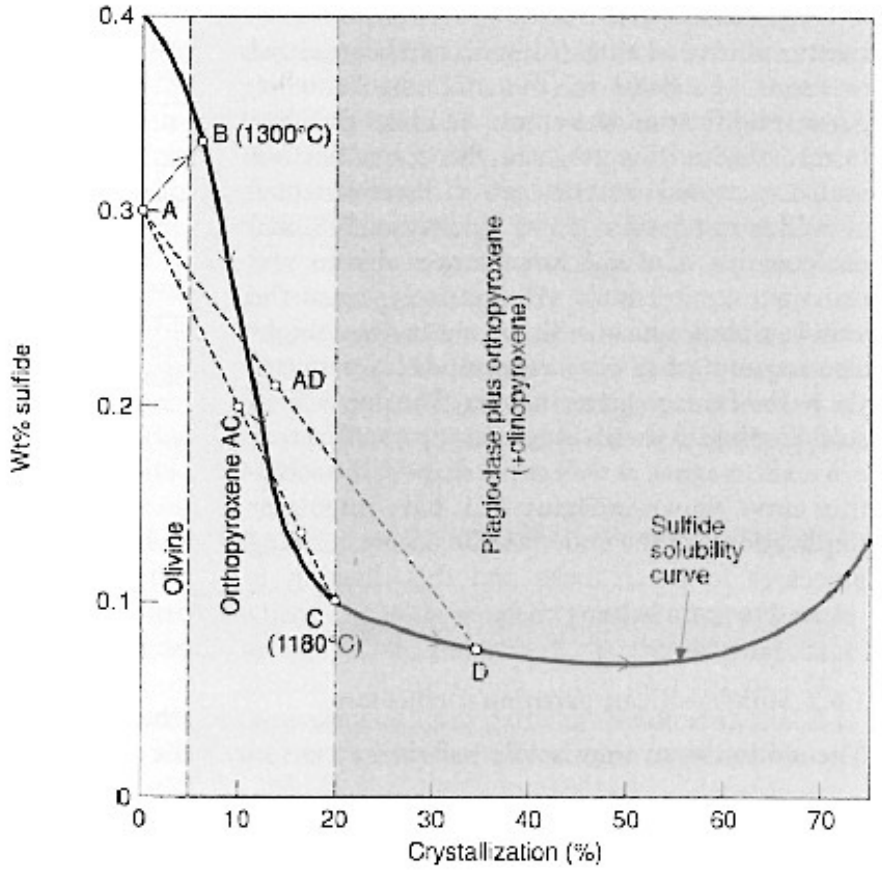
Enrichment of metals (Melt immiscibility)

How to achieve S saturation

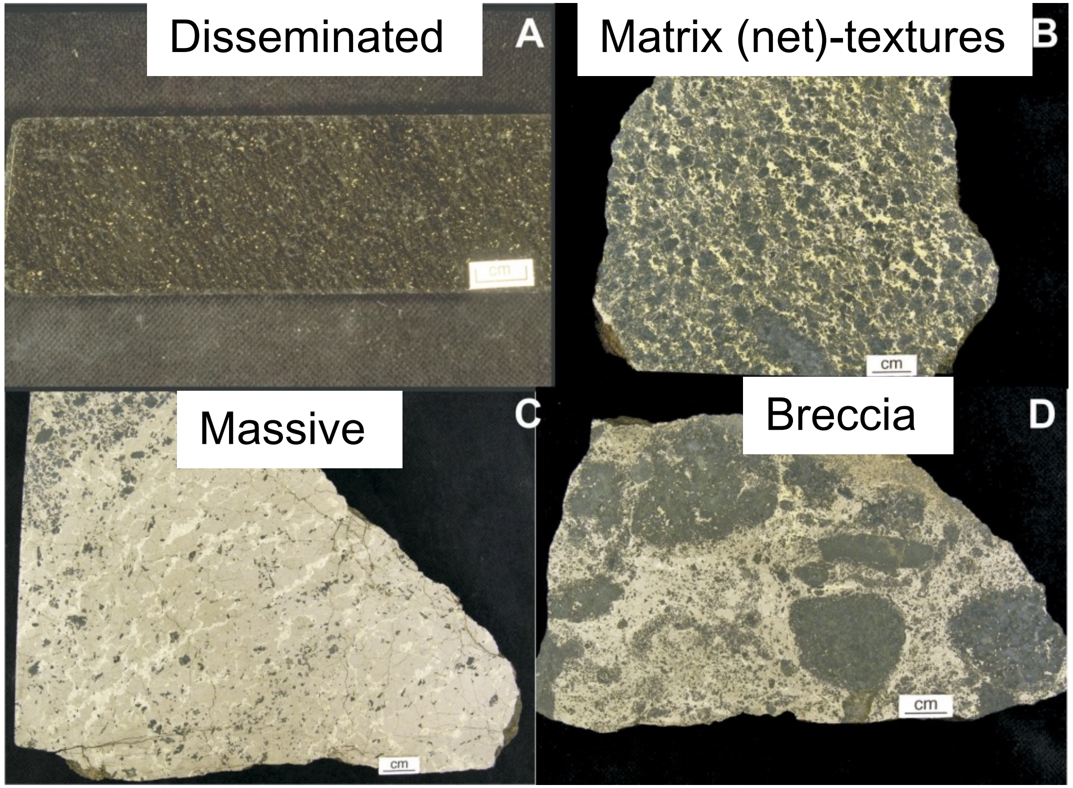
- Sulfur saturation by contamination (adding S).
- Sulfur saturation by magma mixing.

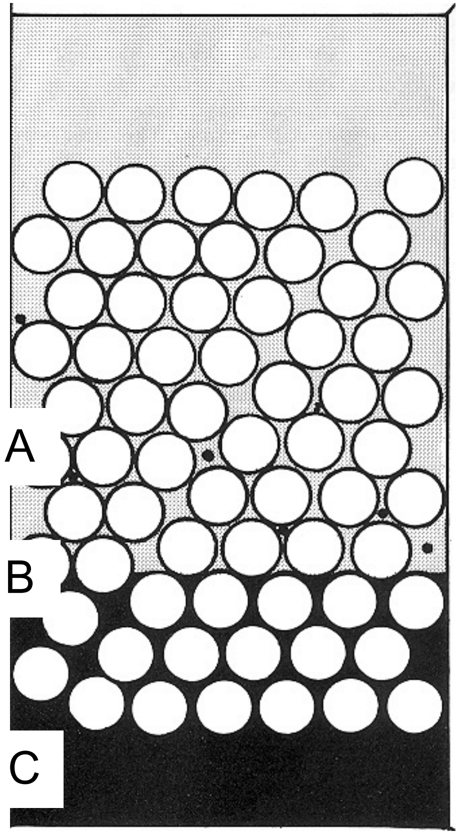


Naldrett and von Grünewaldt 1989

Ni-Sulphide Ore (Textures)

Sulphide melt is typically denser than the silicate melt and tends to accumulate at the bottom of the system.

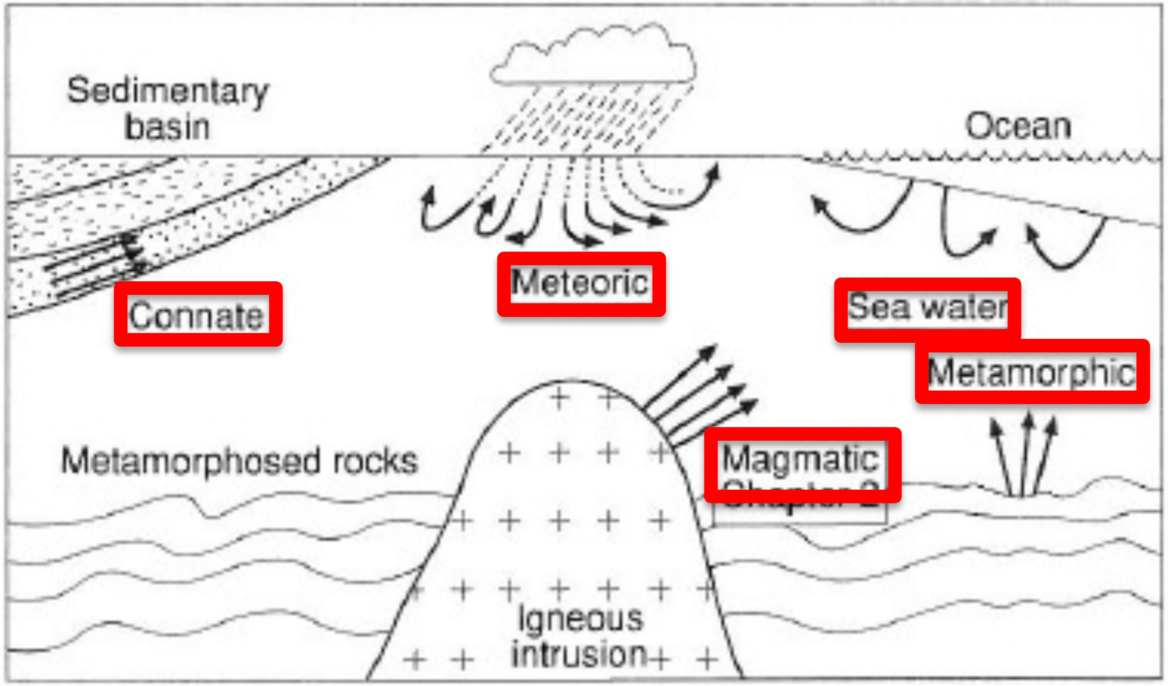




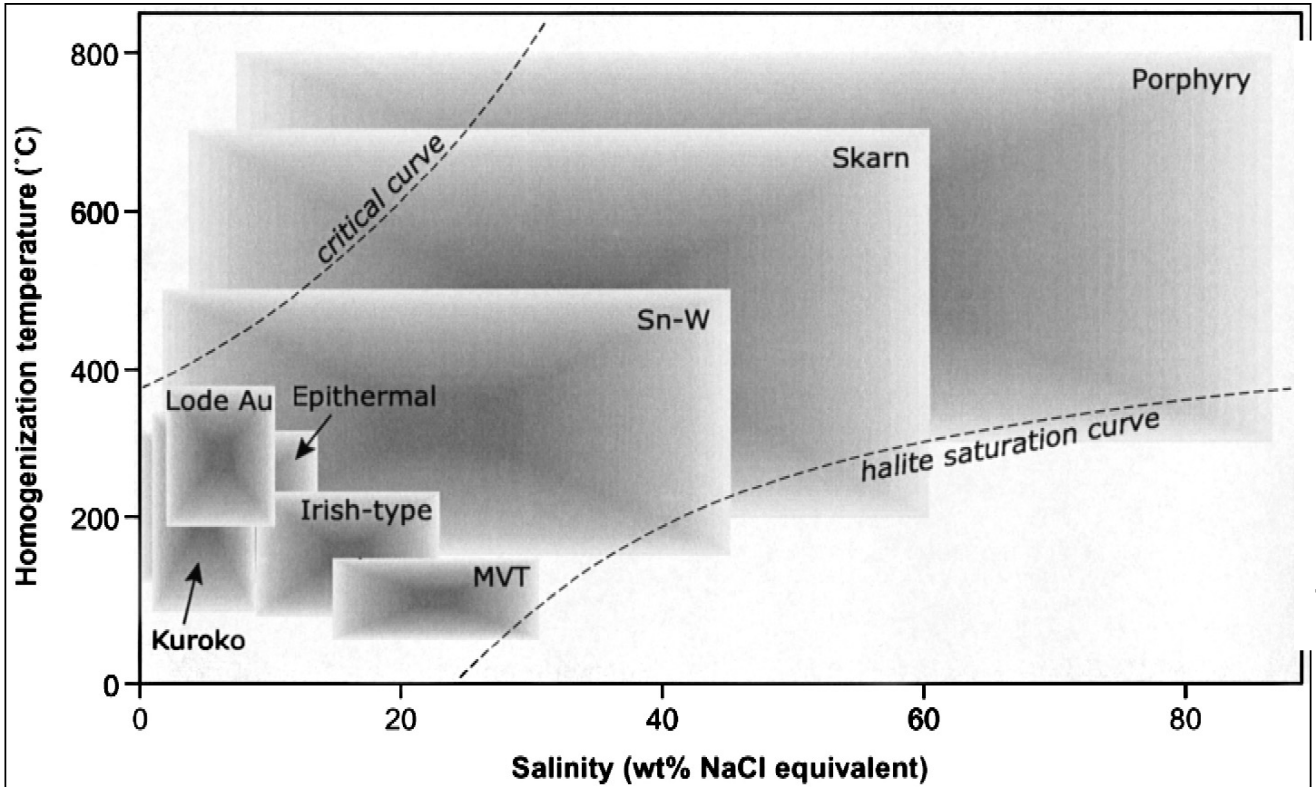
Enrichment of metals (hydrothermal)

Hydrothermal processes play an important role in ore deposit formation. Different fluids can be involved in metal transport.

Different types of fluids



Ore deposits with hydrothermal fluids



(from Wilkinson, Lithos, 2001)

Homog T = minimum T an inclusion homogenizes to

Salinity = wt.% NaCl dissolved in fluid phase

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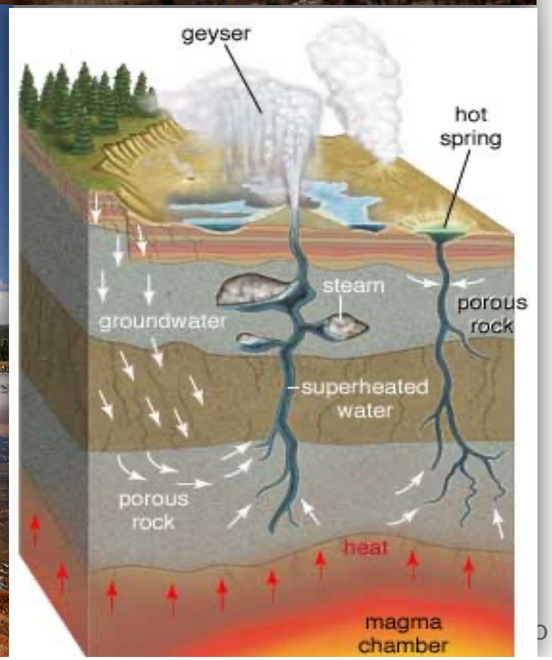
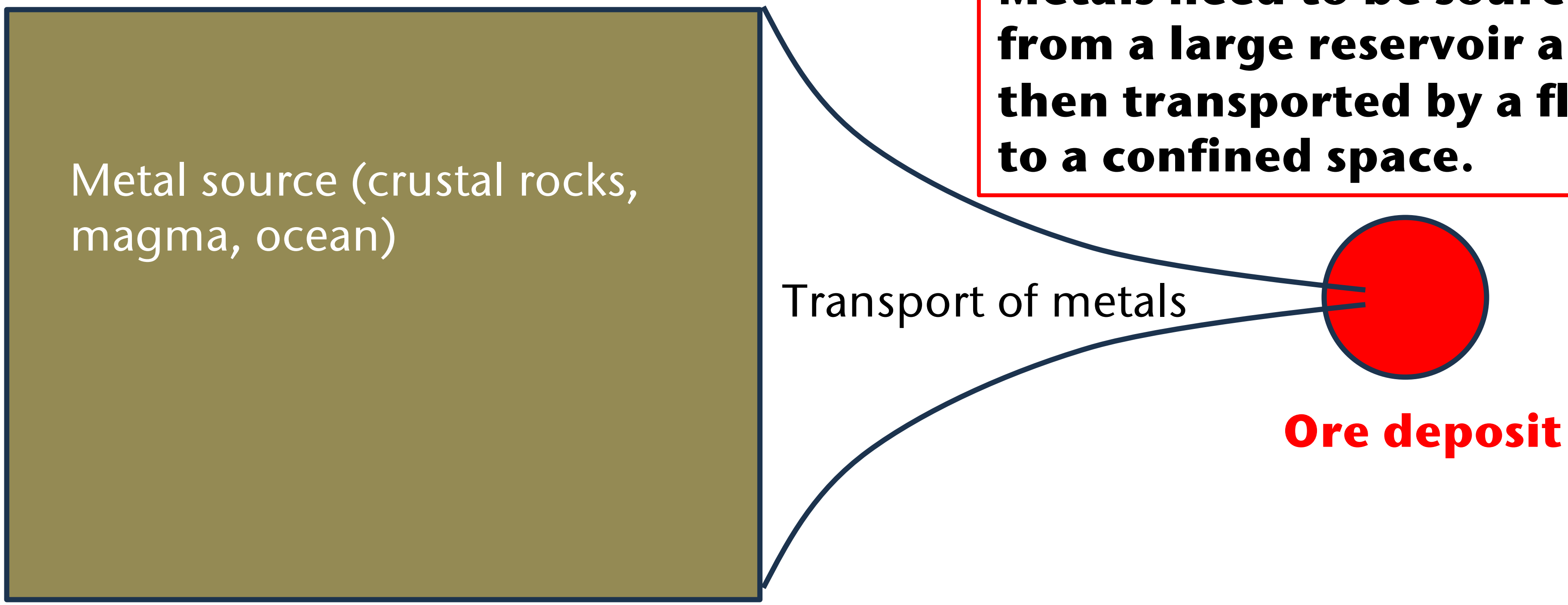
Direct signs of hydrothermal fluids



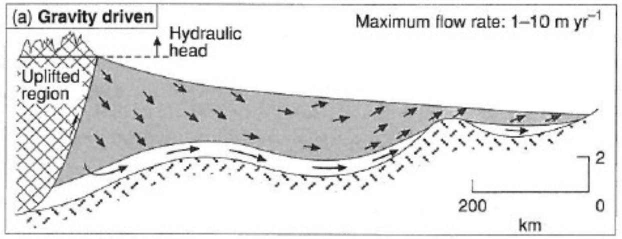
Enrichment of metals (hydrothermal)

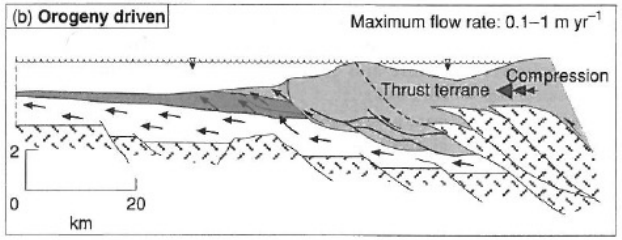
Metals need to be sourced from a large reservoir and then transported by a fluid to a confined space.



Hydrothermal fluid flow in the crust

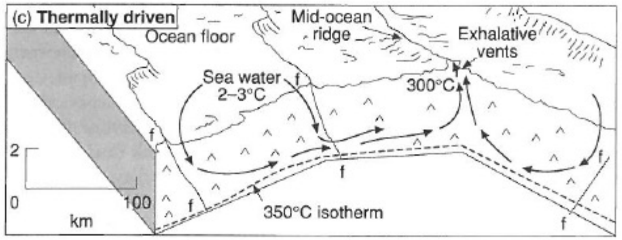
Due to topographic heights during uplift

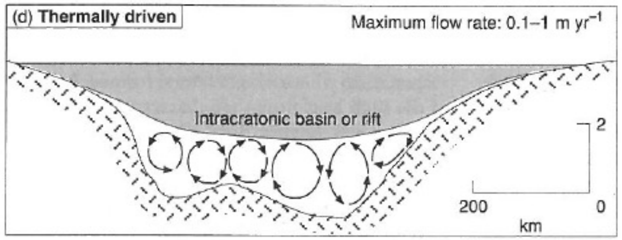




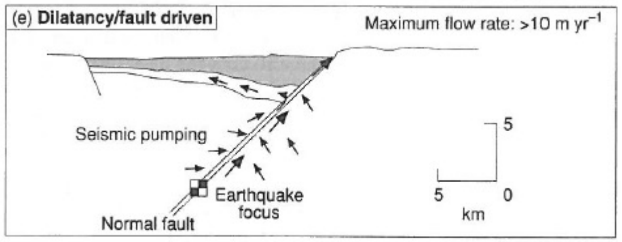
Due to ‘squeezing’ fluids out into thrusts and permeable aquifers

Thermal gradient between seawater and high heat flow in oceanic crust





Deep intercratonic rift basins with elevated heat flow



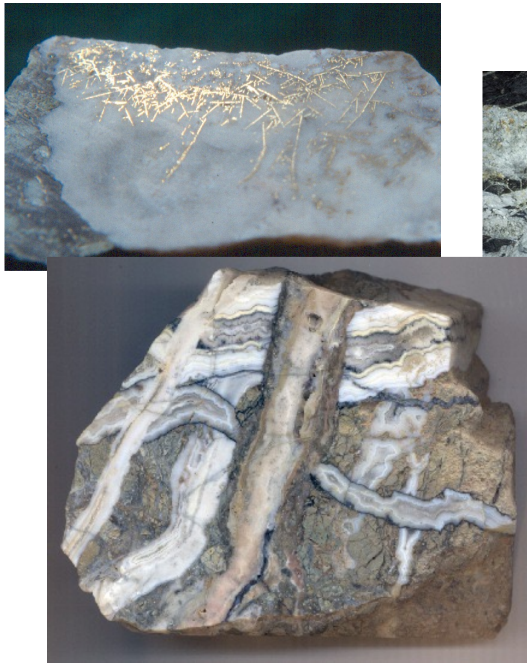
Fault ruptures due to seismic activity

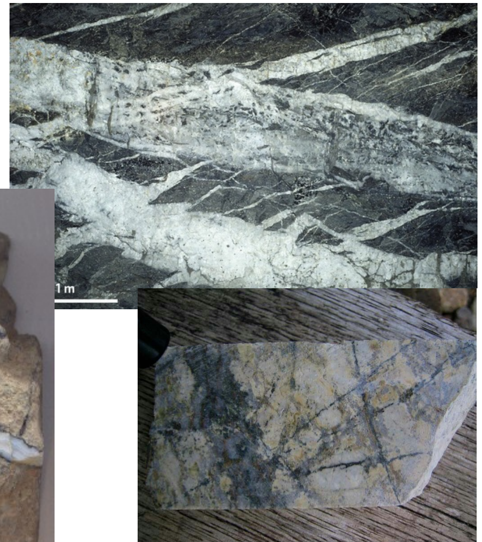
Garven and Raffensperger 1997

Hydrothermal fluid flow in the crust

Fractures and faults are needed to focus the fluid and circulate in the lower crust where rock porosity is minimal. Different scales from crustal to micro scale.

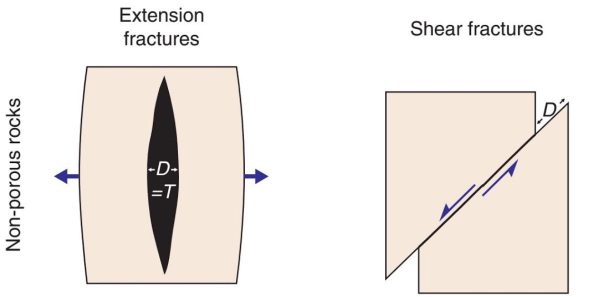
The rapid opening results in a sharp pressure drop, which can lead to ore deposition and fluid boiling. This again leads to mechanical energy and volume expansion that creates further fracturing and brecciating.

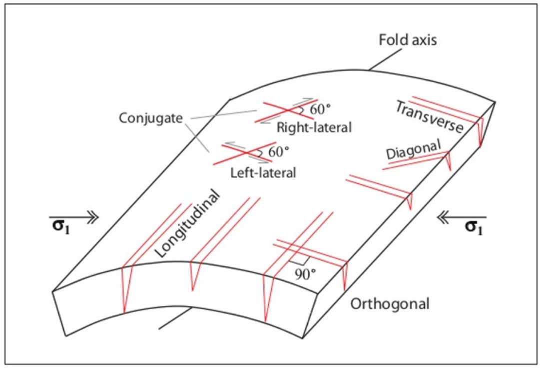


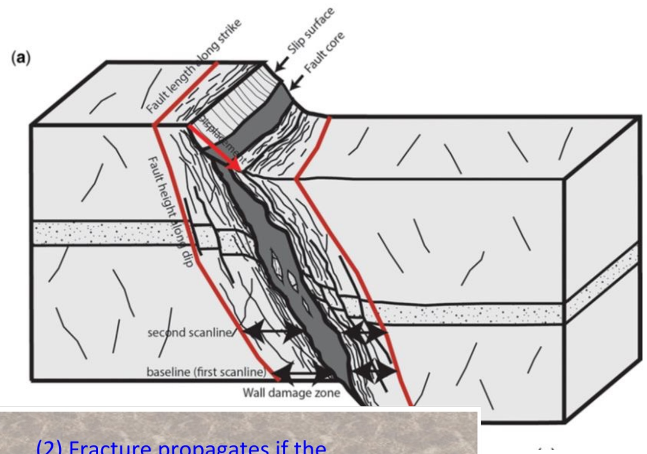


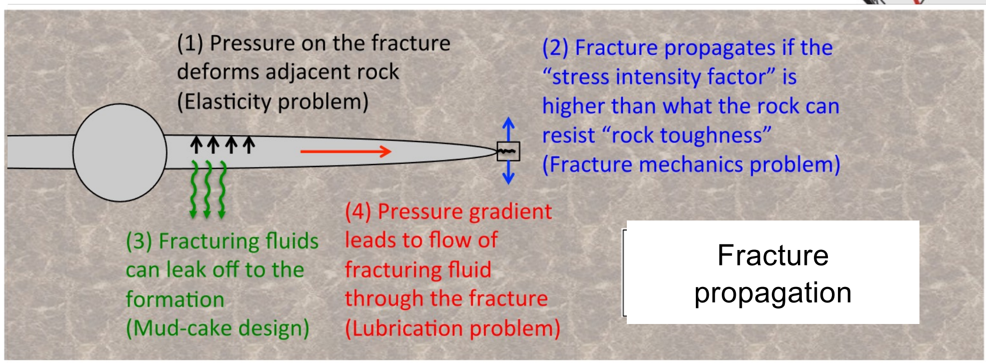
Hydrothermal fluid flow in the crust

The formation of faults and fractures can be due to the strain build-up during plate tectonics and deformation, or fluid (over)pressure.





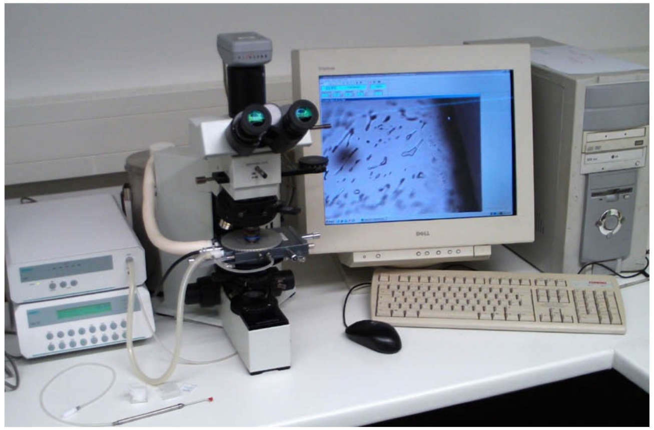




Chemical composition of fluids

Measurements of geothermal waters and volcanic emissions can give an indication of the variability in fluid composition.
Direct analysis of small remnants of fluid trapped in crystals (fluid inclusions).

Fluids range in composition depending where they come from and what elements are dissolved in them. Fluids circulating in rocks under elevated P-T can dissolve part of the rock.

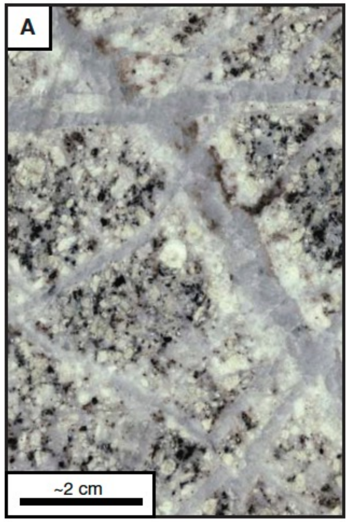


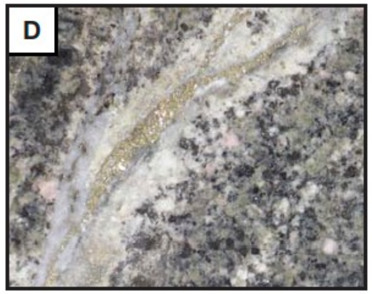
Microthermometry of fluid inclusions

Large range in pH, oxygen fugacity and salinity, partly controls how much metal can be transported in the fluid phase.

Fluid/rock interaction: Alteration

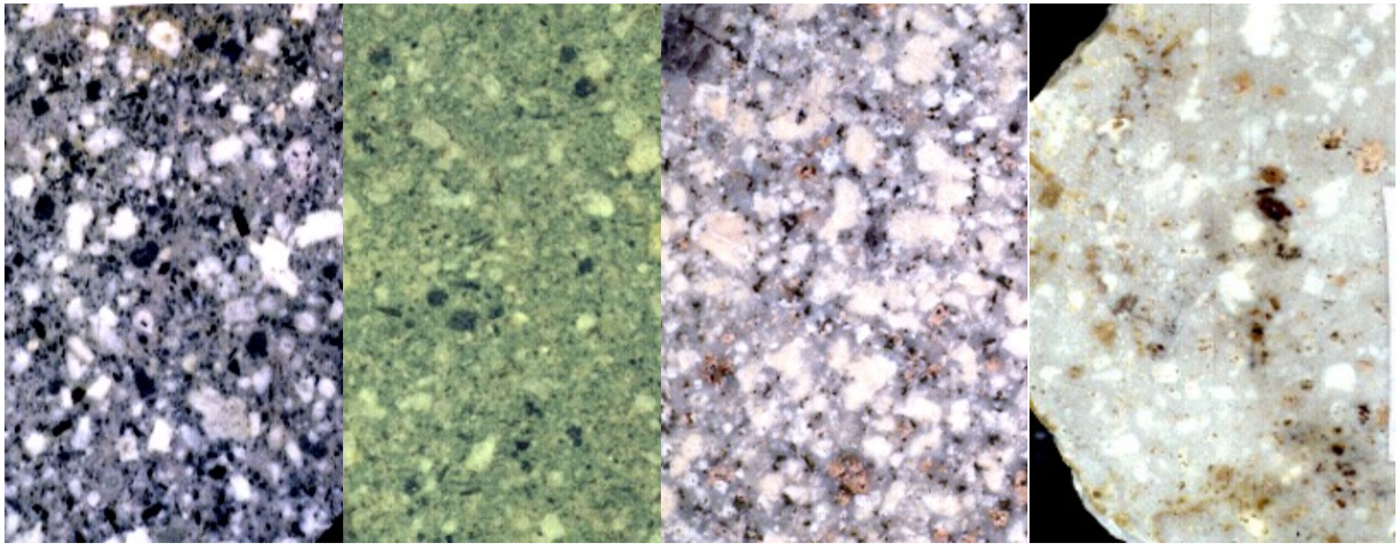
When the fluid circulates through fractures it is in contact with the wall rock. This can lead to chemical reactions and breakdown of minerals and formation of new minerals. This is called **alteration**. This is directly dependent on **fluid and rock composition** and **P-T conditions** and the **fluid/rock ratio**. Other important aspects are ‘reactivity’ and permeability.





Fluid/rock interaction: Alteration

Important alteration types (e.g., Porphyry Cu deposits)



potassic　propylitic　phyllic　argillic

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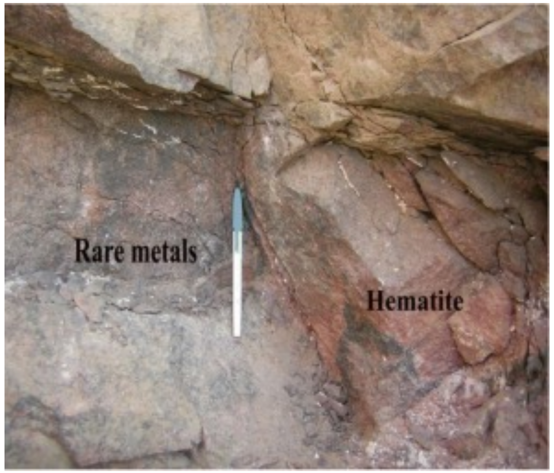
Fluid/rock interaction: Alteration

Important alteration types



Hematitization

Greisen

Silicification

Enrichment of metals (physical)

Physical sedimentation of minerals in fluvial systems and beach environments.

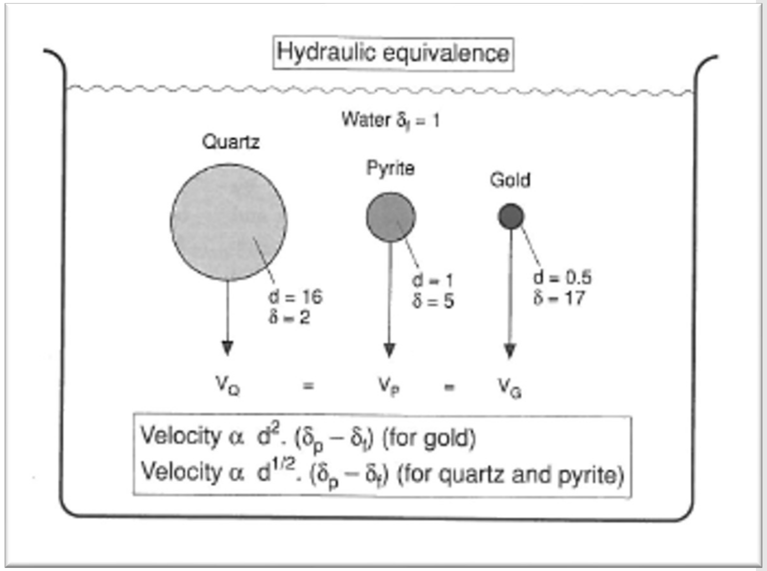
Transport of **mineral grains** and deposition depending on physical principles.

Heavy sand deposits = Placer deposits

Usually the simple Stokes law is not holding up.

Turbulent flow instead of laminar.
Grain-grain contact in systems with >5% solid material.
Grain shapes usually not spherical.

For example Witwatersrand gold grains are too small to have settled together with the quartz grains in the conglomerate.
- Later entrainment



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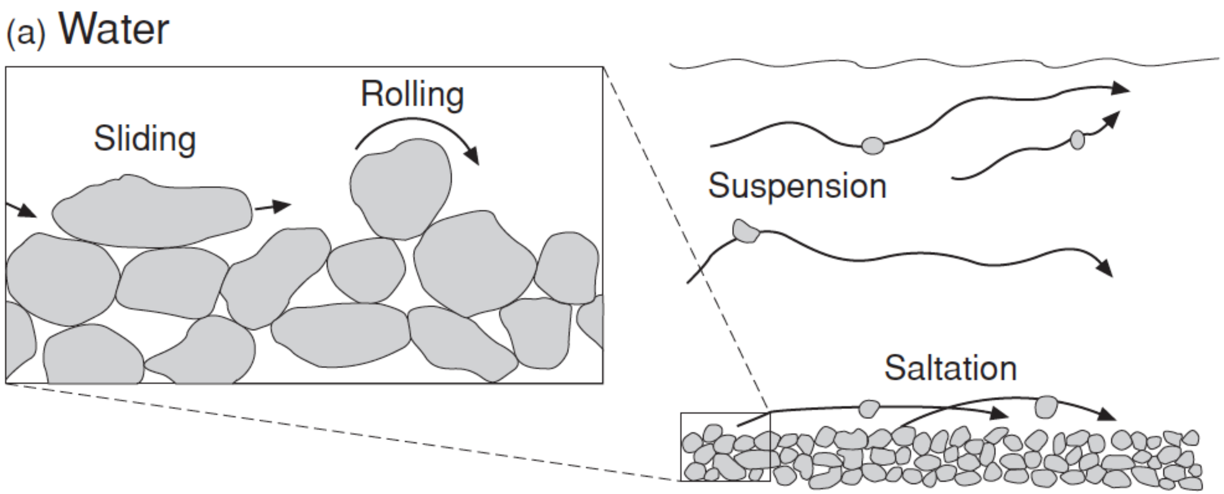
Enrichment of metals (physical)

Fluvial transport of material: Sliding/rolling, Saltation, Suspension

Heavy minerals accumulate, Minerals need to be relatively hard to ‘survive’ the transport.



Enrichment of metals (chemical)

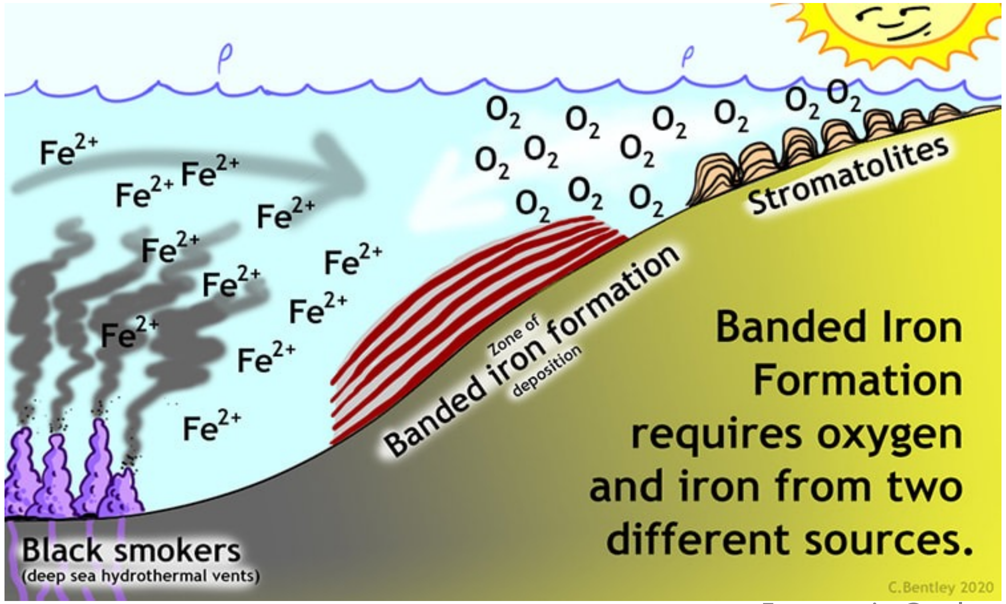
- Precipitation from sea- or groundwater
- Leaching of elements (supergene enrichment)

Precipitation from seawater

Marine to marginal marine environments (e.g. continental shelf and lagoonal settings).
Mostly precipitation of metal(s) from seawater or groundwater due to changes in:

- Eh (oxidation-reduction reaction)
- (pH change)

Origin of the biggest iron mines (banded iron formations).

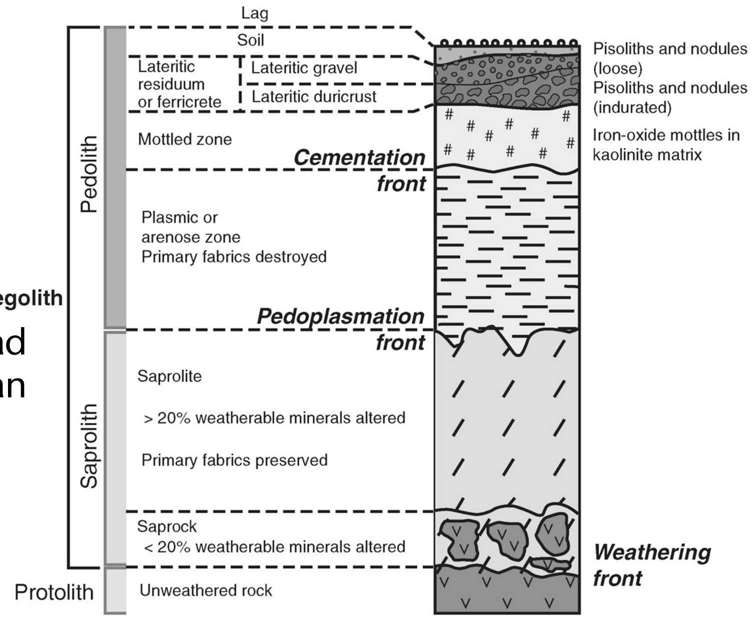


Leaching (supergene enrichment)

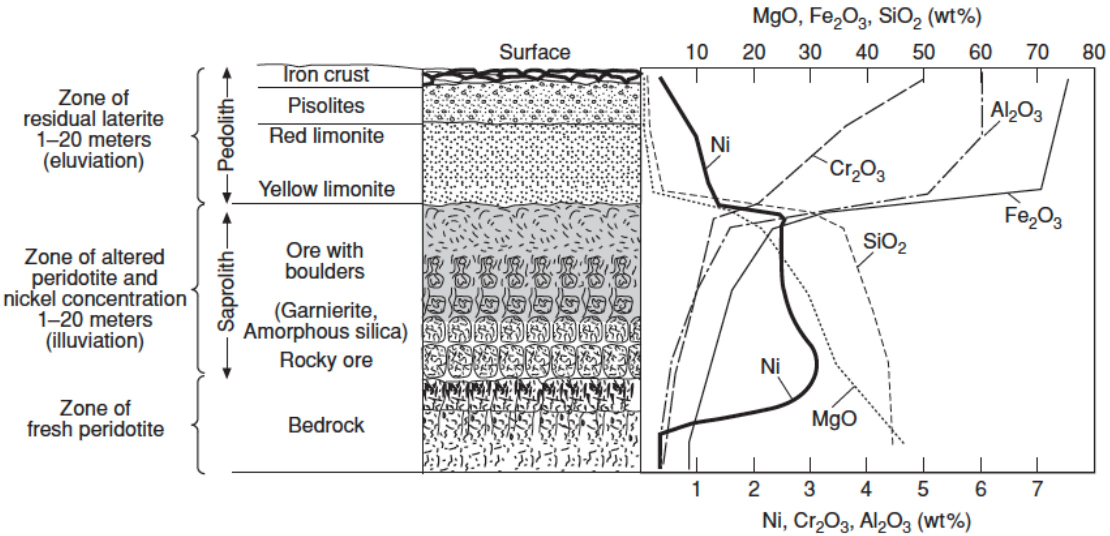
The chemical processes include dissolution, oxidation, hydrolysis and acid hydrolysis. Dissolve and transport certain elements, leave elevated concentrations of metals.

Humid, warm climates with deep chemical weathering. Depending on the rock weathered, there are different metals enriched.

Al-rich rocks, e.g., granite will lead to **bauxite**. (Ultra)mafic rocks can yield **Ni-laterites**.

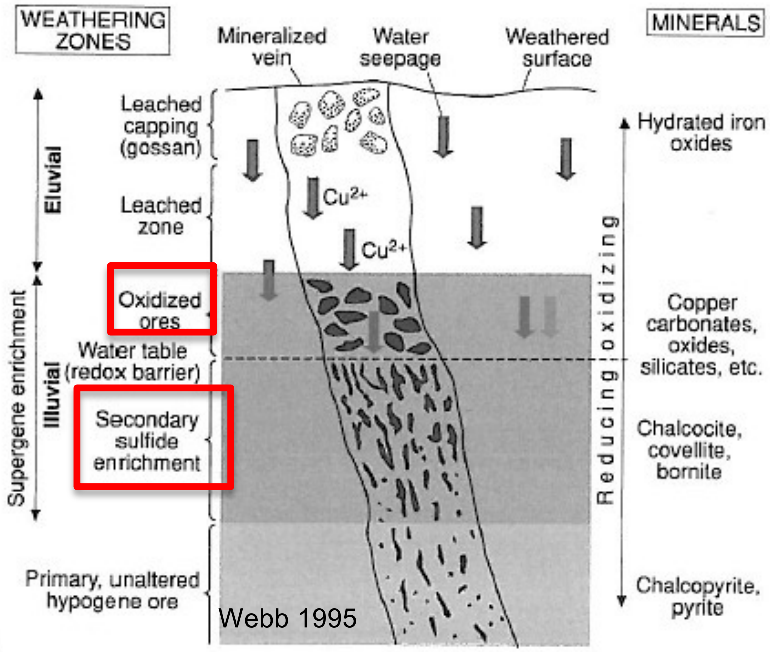


Leaching (supergene enrichment)



Ni is mobilized and deposited deeper in the soil profile

Weathering of sulphides



Chalcopyrite dissolution and mobilization of Cu. Formation of oxides and then secondary sulphides.

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Summary: Module 3

- To form ore deposits there needs to be an enrichment of specific metals.
- Enrichment processes include:

- magmatic processes (extended crystalization, sulphide melt immiscibility).

- hydrothermal processes (metal transport in fluids, fluid rock interaction, alteration).

-physical and chemical processes (deposition of mineral grains, leaching of elements, precipitation from sea water).

- There needs to be a source of metals, a transport medium, and then a confined space for metal deposition.
- Alteration is a sign for hydrothermal fluid flow and can be associated with mineralization.

Test yourself

- What happens to Ni and Cu when a sulphide melt separates from a silicate melt?
- What is alteration?
- List some different fluid types
- How does hydrothermal fluid circulate in the Earth crust?
- Why is supergene enrichment more prevalent in warm and humid regions of the world?
- What properties of minerals are key to form a placer deposit?