EARTH 471
Mineral Deposits

Metallogeny and ore deposit models

"*There's gold in them hills*"
– An old prospector's saying

Ore deposit:

A volume/mass or aggregate of mineral substance that can be exploited with a profit.

The exploitability is a function of the tonnage, grade, mining (method of extraction), environmental engineering, metallurgy (granulometry, inclusions) and the location of the deposit.

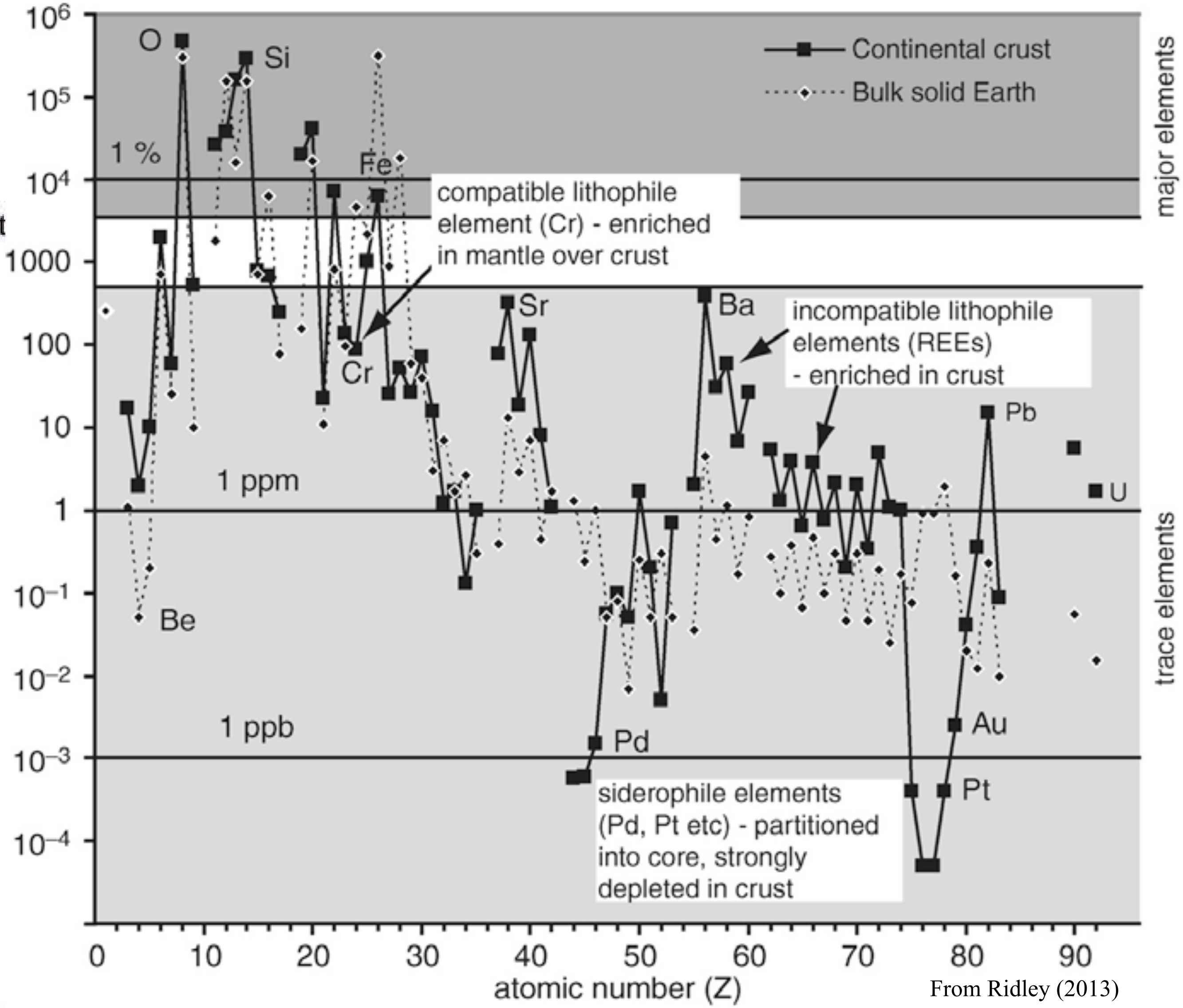
The absolute and relative importance of these factors can vary with the economic, social, political and technological context.

Concentration of elements in the crust and bulk solid earth

Quick conversion chart

1%	10,000 ppm	10000 g/t
0.1%	1,000 ppm	1000 g/t
0.01%	100 ppm	100 g/t
0.001%	10 ppm	10 g/t
0.0001%	1 ppm	1 g/t

In ore geology:
'Grade' = concentration



From Ridley (2013)

Ore grades vs average upper crustal abundance

Ore deposit: A volume/mass or aggregate of mineral substance that can be exploited with a <u>profit</u>. The exploitability is a function of the tonnage, <u>**grade**</u>, mining method…

Enrichment factor (or Clarke of concentration): amount of enrichment required to make a mineral deposit economic

Metal	Clarke = average concentration in upper crust	Grade in typical ore	Clarke of concentration = enrichment factor average crust → ore
Al	8%	30%	4
Fe	5% wt%	60%	12
Ti	5700 ppm	5%	10
Mn	950	5%	50
Cr	100	5%	500
Li	20	1%	500
U	3	0.1%	300
Sn	2	1%	5000
W	1.5	0.3%	2000
Ni	75	1%	100
Zn	70	10%	1000
Cu	55	1%	200
Pb	12	10%	10 000
Mo	1.5	0.3%	2000
Ag	0.1	100	1000
Hg	0.1	1%	100 000
Au	0.004	5	1200
Pt	0.002	5	2500

From Ridley (2013)

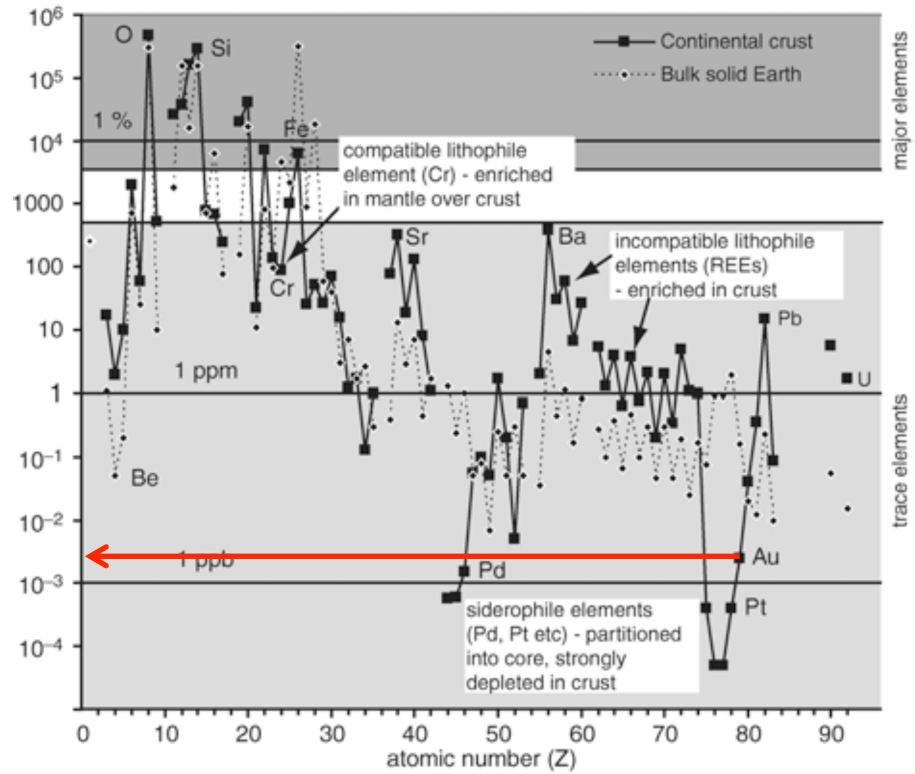
Case study: gold in the crust

Metal	Clarke = average concentration in upper crust	Grade in typical ore	Clarke of concentration = enrichment factor average crust → ore
Au	0.004	5	1200

- 1 km^3 of continental crust at ~2750 kg m^{-3} = ~2.75 x10^{12} kg
- ~2.75 x10^{12} kg x 0.004 ppm Au = 11,000 kg Au
- 32.15 troy oz / kg
- = ~350,000 troy oz Au
- @ $1200/oz = $420 M !!!

However, the costs to mine and process the ore are much much more.

Au needs to be concentrated!



From Ridley (2013)

In general, **1 g / ton (or 1 ppm)** can be mined (open pit) at a marginal profit.

We need to understand how elements of economic importance are concentrated:

(1) Behaviour of elements in the Earth

- What minerals are they found in?
- Why are some elements found together?

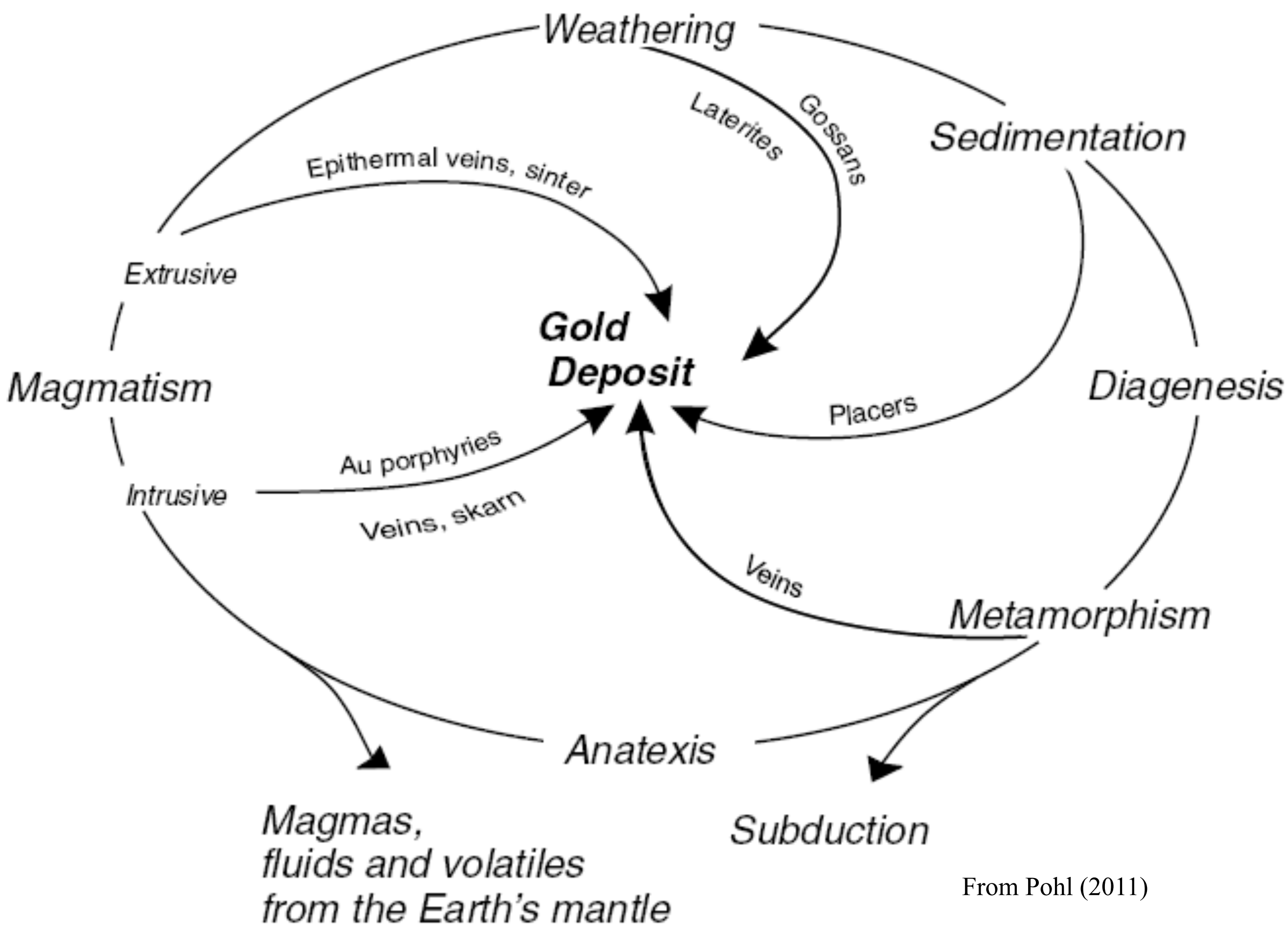
(2) Processes that concentrate the elements

- What geological processes can concentrate elements?
- Why are some elements found in particular regions and not others?

(3) How do I get rich and retire?

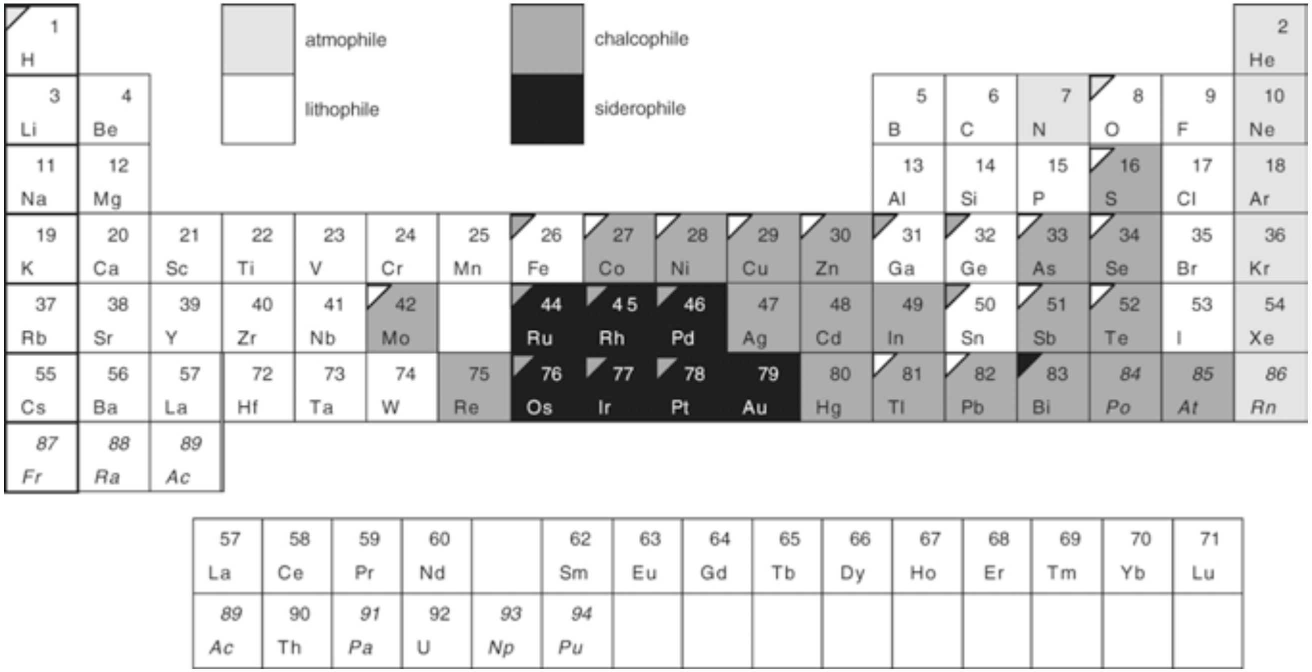
Answering these questions will be the focus of the next few weeks.

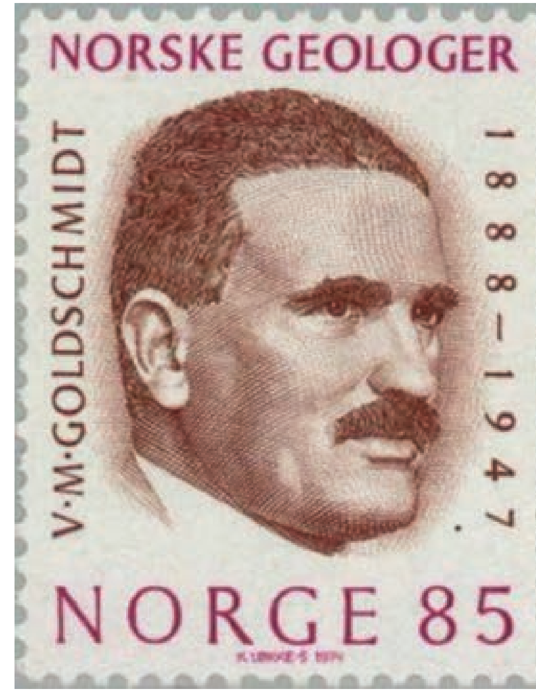
Metallogeny: the study of the genesis of mineral deposits, with emphasis on their relationships in space and time to geological features of the Earth's crust



From Pohl (2011)

Goldschmidt classification of elements

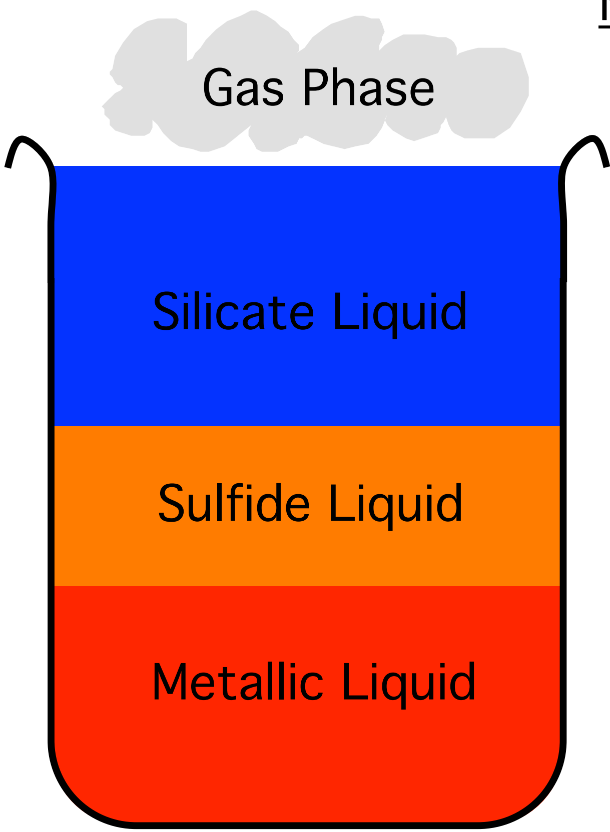




While studying meteorites and ore smelting samples in the 1930’s, Victor Goldschmidt—father of Geochemistry—classified the elements into categories.

In the classification scheme of Goldschmidt, elements are divided according to how they partition between coexisting silicate liquid, sulfide liquid, metallic liquid, and gas phase…defined by examining ore smelting, slags and meteorites

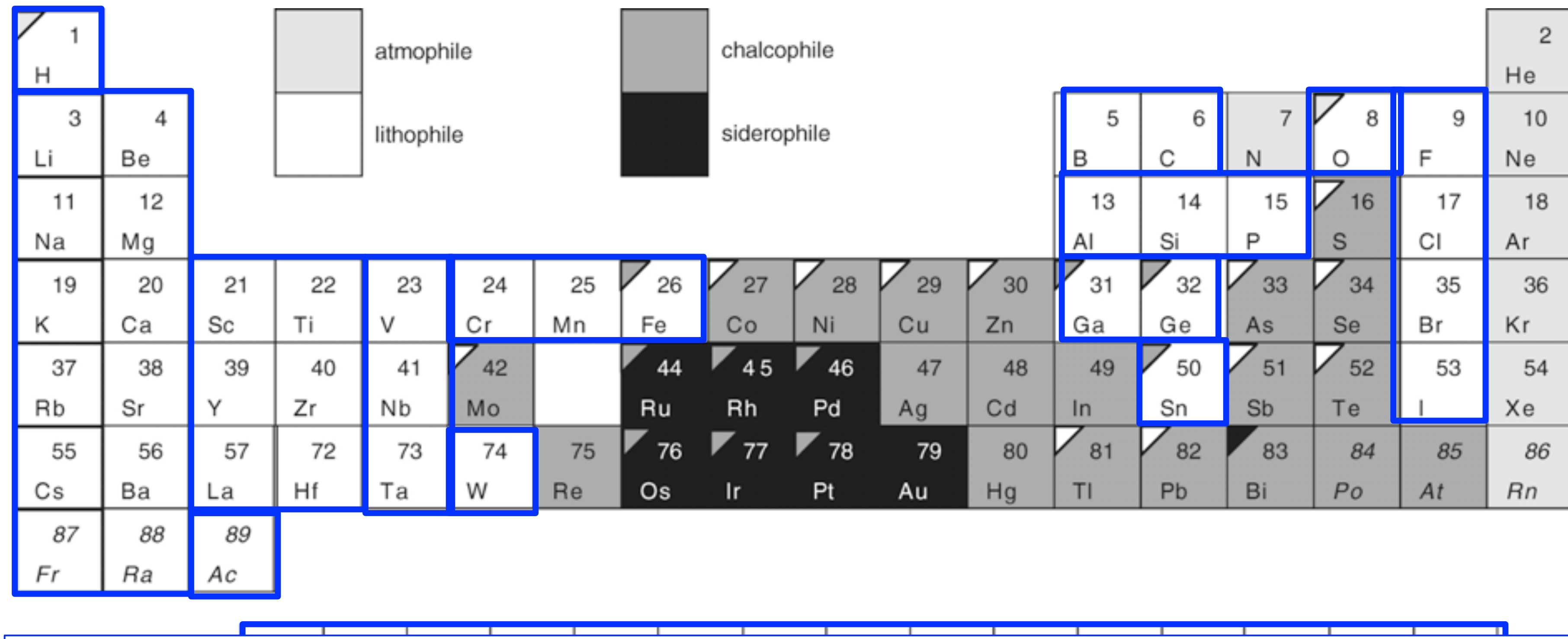
Melting a chondrite gives 3 immiscible liquids plus vapor:



← Atmophile	H, He, N, Noble gases
← Lithophile	Alkalis, Alkaline Earths, Halogens, B, O, Al, Si, Sc, Ti, V, Cr, Mn, Y, Zr, Nb, W, Lanthanides, Hf, Ta, Th, U
← Chalcophile	Cu, Zn, Ga, Ag, Cd, In, Hg, Tl, As, S, Sb, Se, Pb, Bi, Te, Mo (in crust)
← Siderophile	Fe, Co, Ni, Ru, Rh, Pd, Os, Ir, Pt, Mo, Re, Au, C, P, Ge, Sn

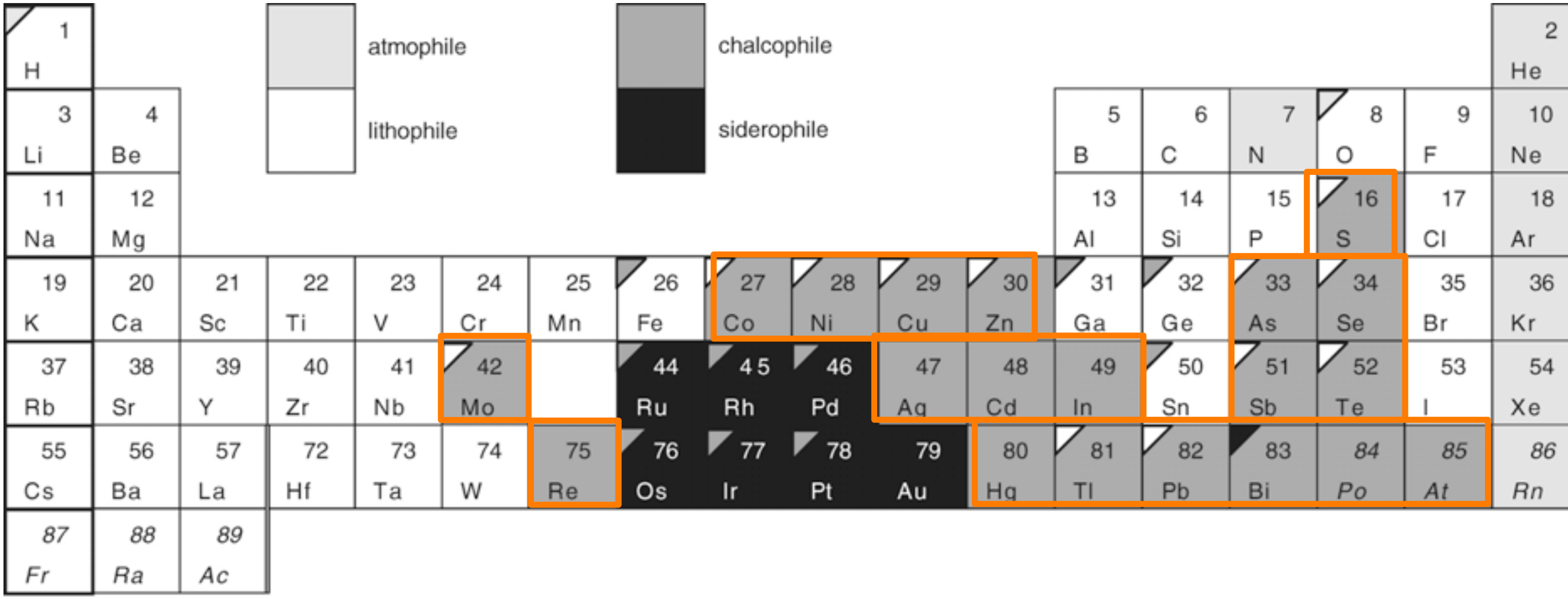
Slide modified from P. Candela (2014)

Goldschmidt classification of elements



Lithophile: "rock-loving"
- Enriched in the crust and lithosphere relative the solar system
- Affinity for oxygen, associated with Si
- Therefore, preferably occur as oxides and silicates

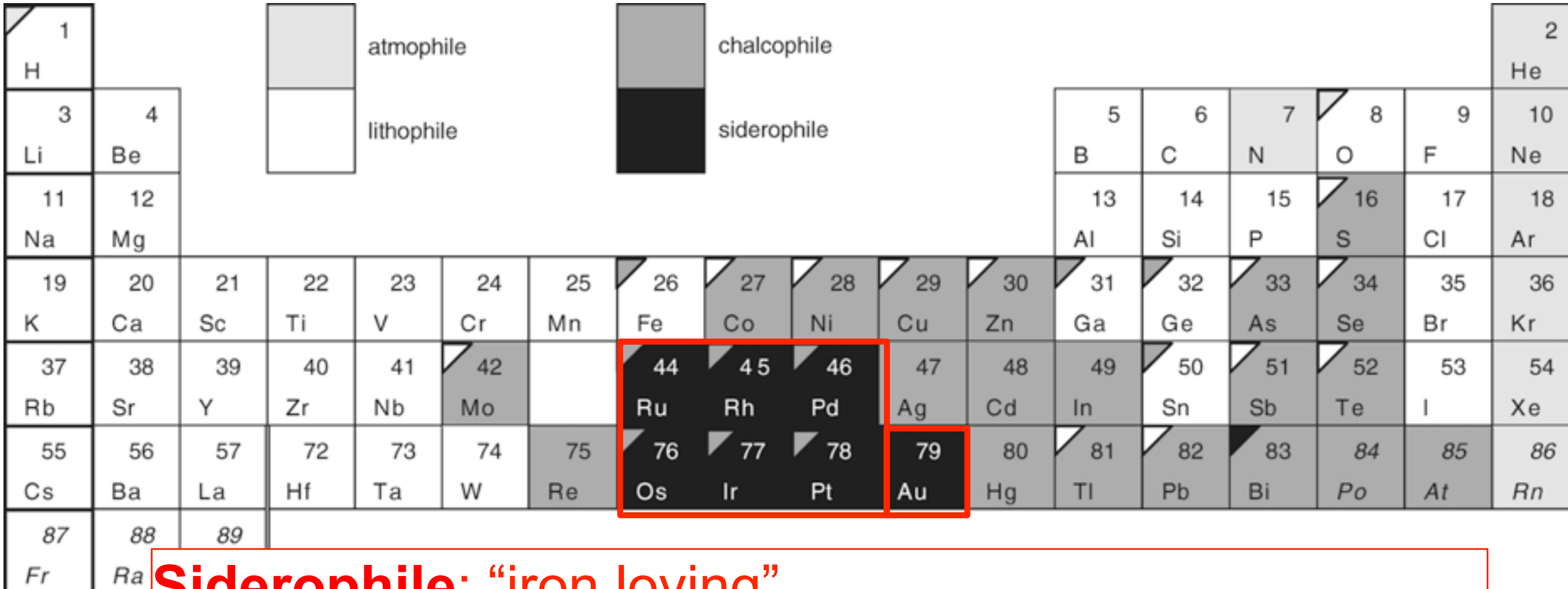
Goldschmidt classification of elements



Chalcophile: "ore loving" or "sufur loving"

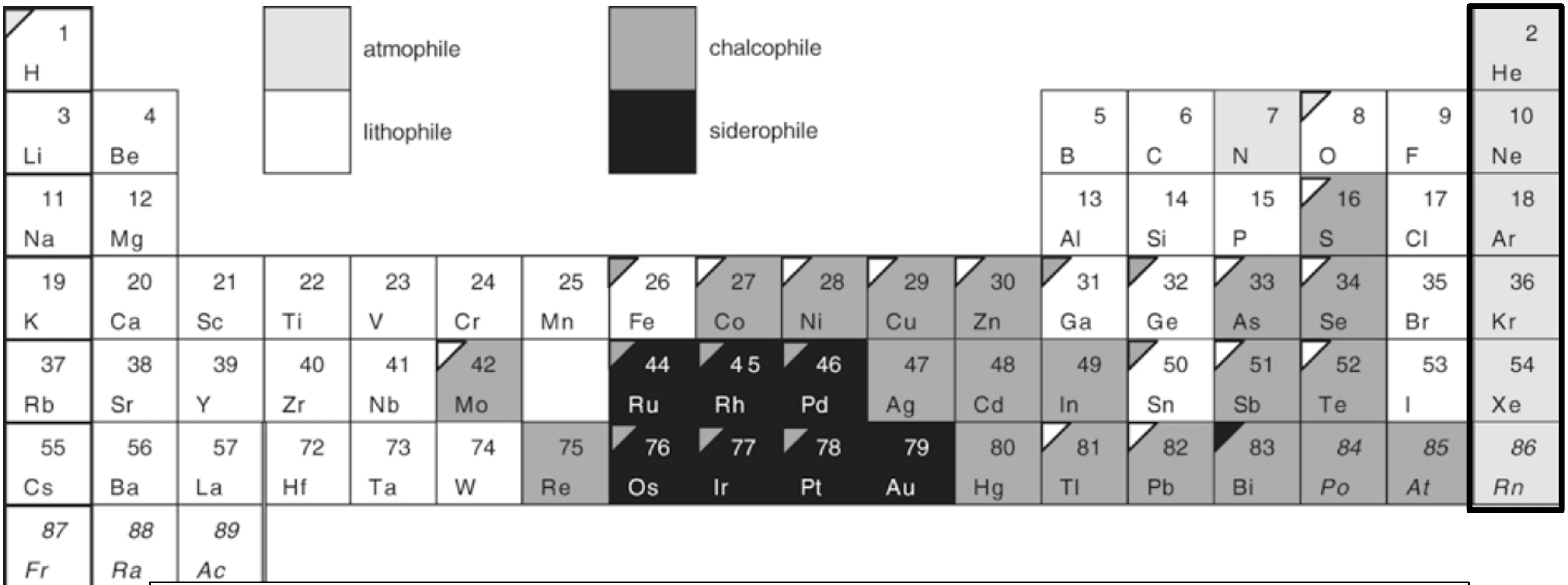
- Relatively depleted in crust relative to solar system
- Low affinity for oxygen
- Preferably occur as sulfide minerals

Goldschmidt classification of elements



Siderophile: "iron loving"
- Essentially no affinity for oxygen
- Preferably occur as alloys
- Concentrated in Earth's core
- Generally form metallic bonds with native iron

Goldschmidt classification of elements



Atmophile: “gas-loving”
- Generally occur in the atmosphere
- Depleted on Earth due to loss from atmosphere during the formation of Earth

Extraction of elements from ore material

Ore deposit: A volume/mass or aggregate of mineral substance that can be exploited with a profit. The exploitability is a function of the tonnage, grade, mining (method of extraction)…

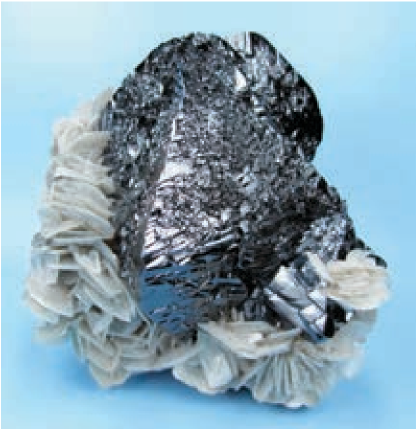
Visible Gold, Dumagami Mine (Dube et al., 2007)

Siderophile elements: rare but easy to extract (alloys or native metals)

Chalcophile elements: less abundant than lithophile elements, but sulfides are easier to break down than oxides

Molybdenite (MoS_2), Molly Hill Mine, Quebec, Wiki

Lithophile elements: abundant but hard to extract from their host oxide/silicate minerals

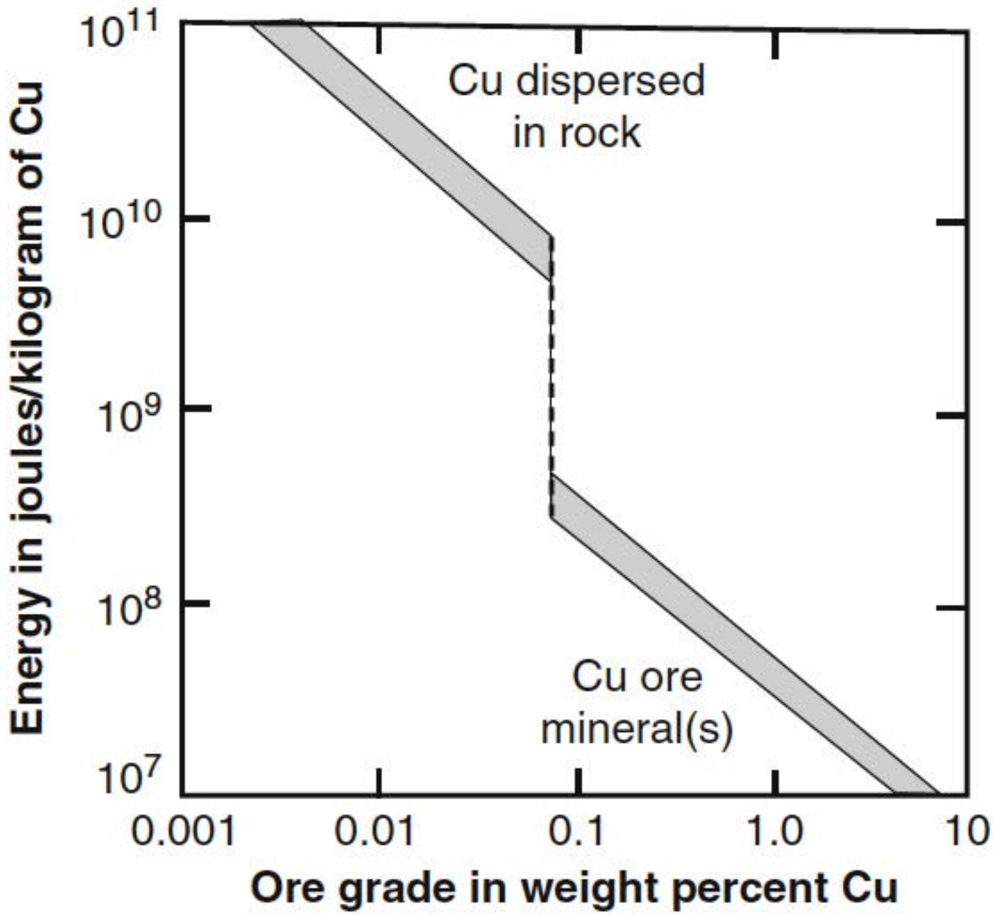


Cassiterite (SnO_2), Xuebaoding, Sichuan, China, Wiki

Extraction of element from ore

Ore deposit: A volume/mass or aggregate of mineral substance that can be exploited with a profit. The exploitability is a function of the tonnage, grade, mining (method of extraction)…

Energy required to extract a metal such as copper from a host mineral as a function of the metal concentration in the host mineral (e.g., copper sulfide versus copper dispersed in a silicate mineral)
– from Ernst (2010)



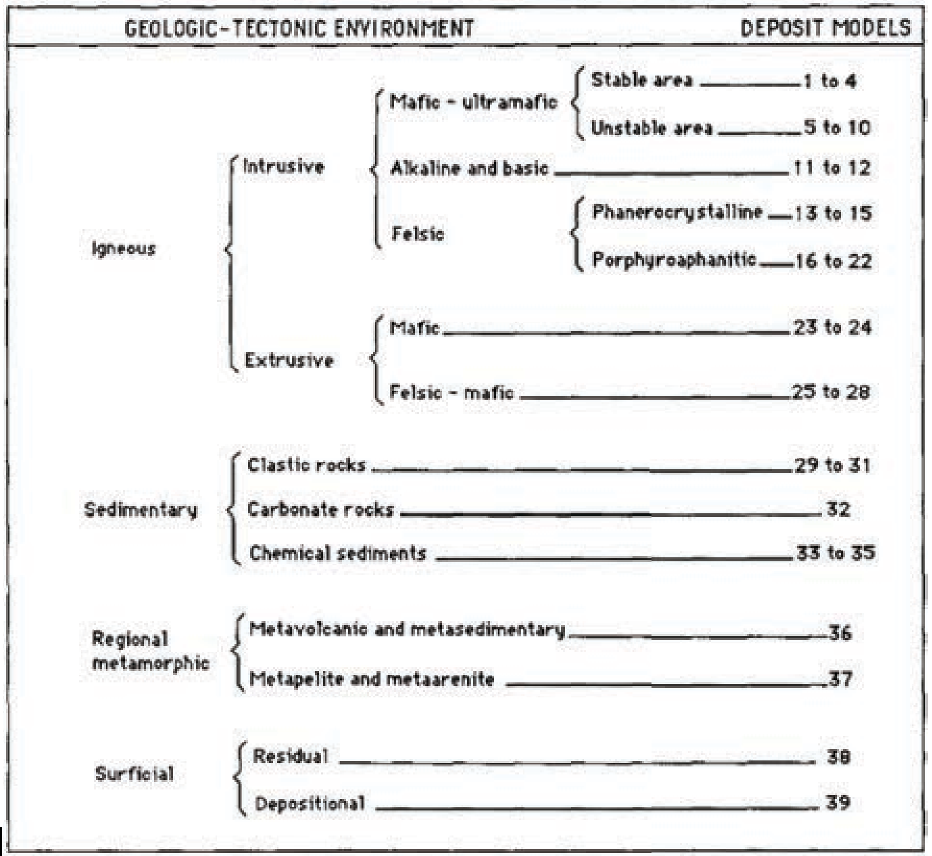
Classification of ore deposits

"Ever since Agricola first classified ore deposits, successive writers have attempted classification of mineral deposits, none of which has obtained unanimous endorsement"

– *Jensen and Bateman, (1979)*

USGS: currently has 85 mineral deposit models

Mineral deposit model: systematically arranged information describing the essential attributes (properties) of a class of mineral deposits. The model may be empirical (descriptive), in which instance the various attributes are recognized as essential even though their relationships are unknown; or it may be theoretical (genetic), in which instance the attributes are interrelated through some fundamental concept.



Cox and Singer, 1992, USGS, Bulletin 1693

Classification of ore deposits – two main types

"An ore deposit model is a conceptual and/or empirical standard, embodying both the descriptive features of the deposit type, and an explanation of these features in terms of geological processes."

– *Hodgson, 1993*

Descriptive models:

- Based on observations
- Cannot not wrong, but can be misunderstood
- Do not explain the genesis (formation) of the deposit

Genetic models:

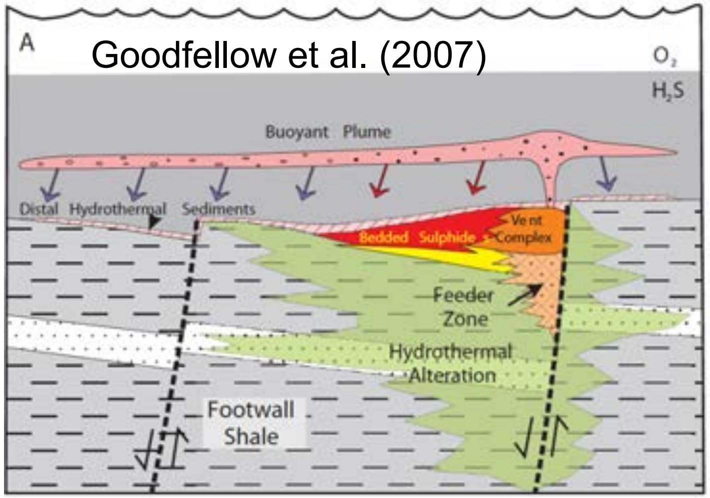
- Aim to understand the processes that led to mineralization
- Used to predict the location of undiscovered mineral deposits
- Can be wrong…

Descriptive model terminology:

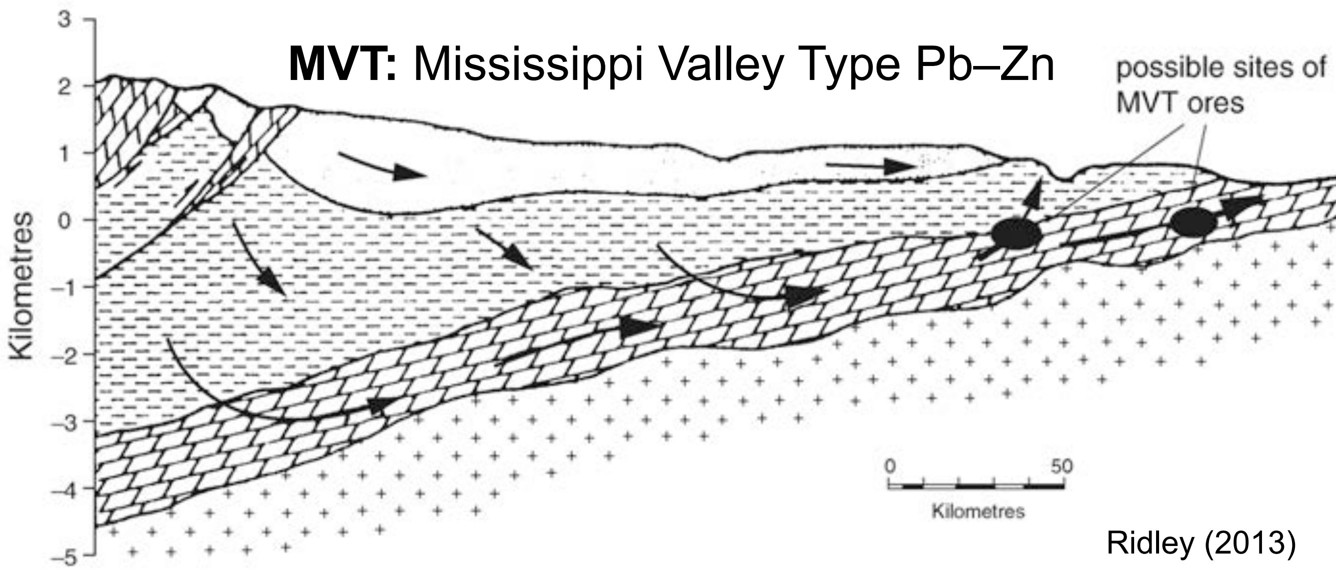
Strataform: Ore body which in three dimensions has the form of a sediment bed

Stratabound: Ore body that is enclosed within a specific part of the stratigraphic column

SEDEX: sedimentary exhalative



MVT: Mississippi Valley Type Pb–Zn



Ridley (2013)

Descriptive model terminology – shape

Oval deposit

Pipe shaped

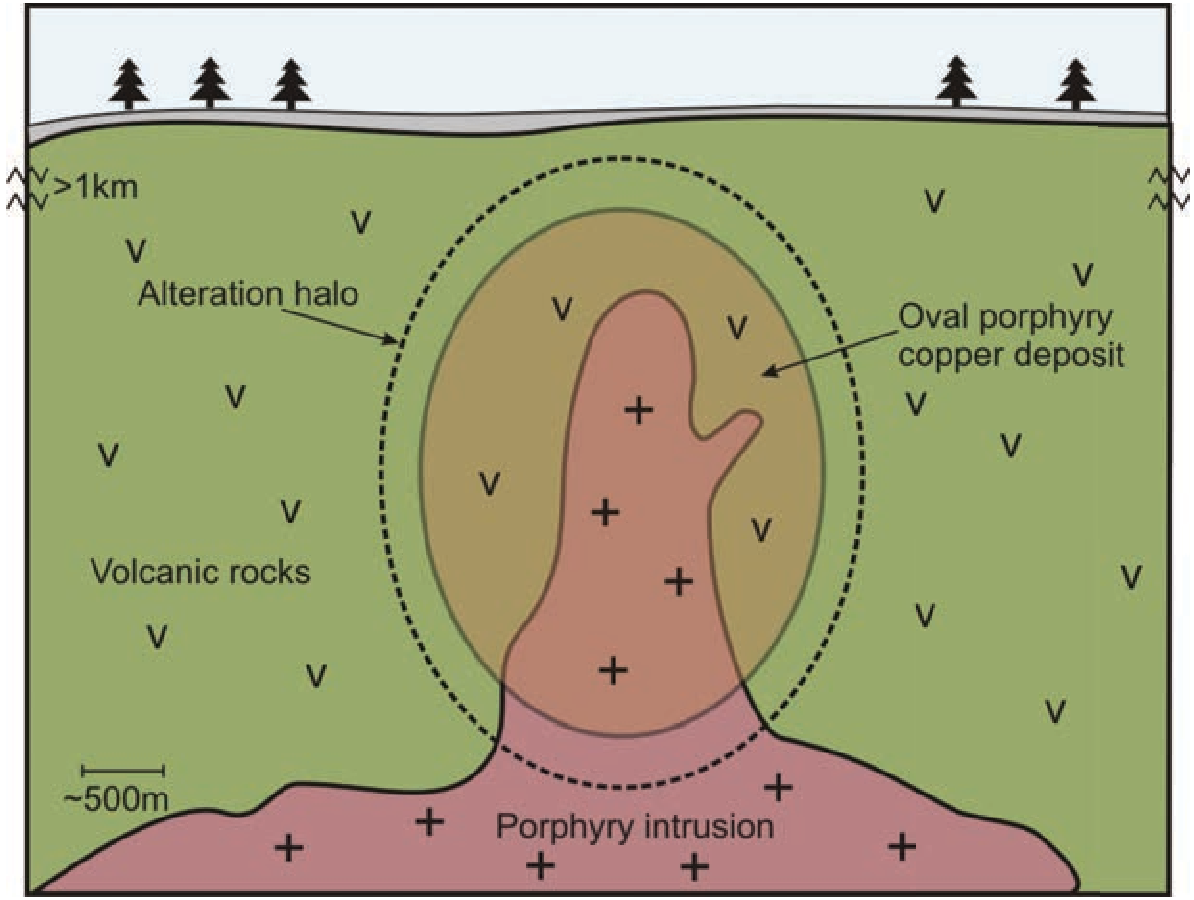
Lens shaped

Tabular/planar

Manto

Chimney

Porphyry Cu: oval-shaped mineralization around intrusion



MEME textbook

Descriptive model terminology – shape

Oval deposit

Pipe shaped

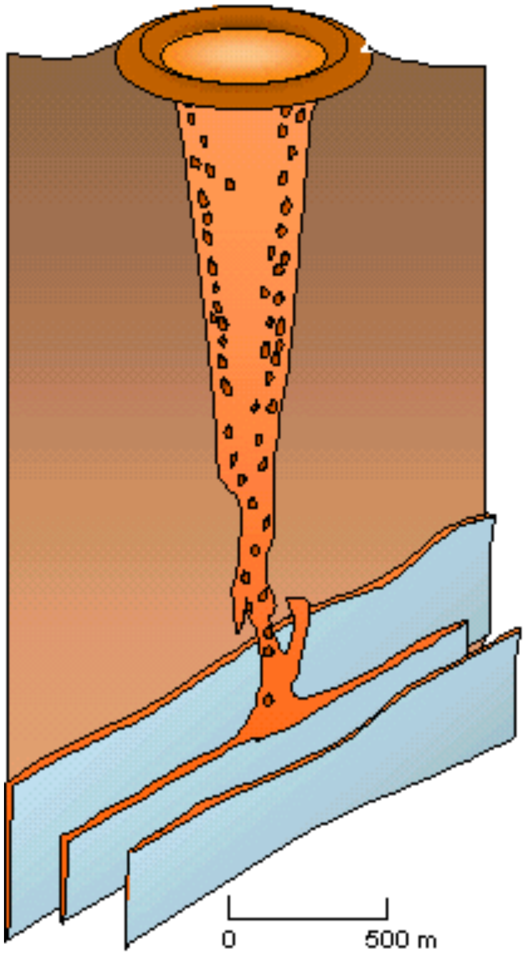
Lens shaped

Tabular/planar

Manto

Chimney

Diamond: pipe-shaped kimberlite intrusion



MEME textbook

Descriptive model terminology – shape

Oval deposit

Pipe shaped

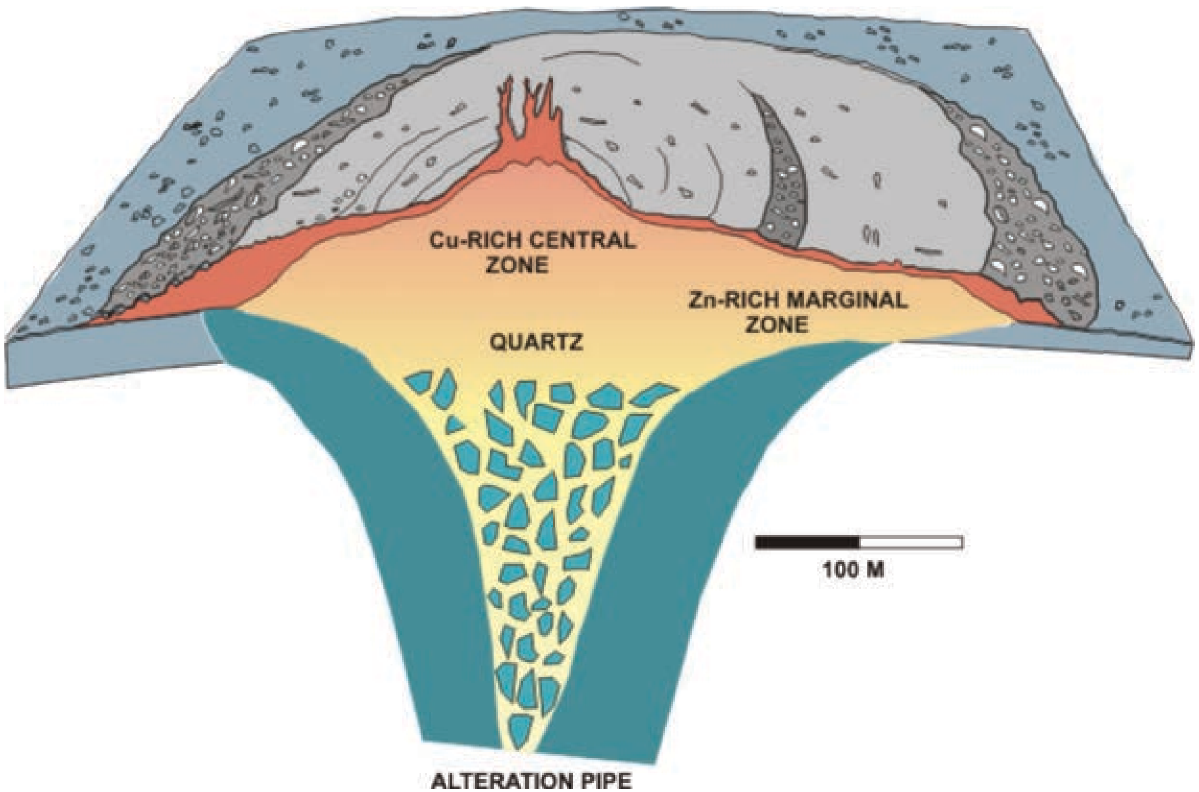
Lens shaped

Tabular/planar

Manto

Chimney

VMS: volcanogenic massive sulphide



MEME textbook

Descriptive model terminology – shape

Oval deposit

Pipe shaped

Lens shaped

Tabular/planar

Manto

Chimney

Gold-bearing quartz veins (Minita Deposit, El Salvador)

MEME textbook

Descriptive model terminology – shape

Oval deposit

Pipe shaped

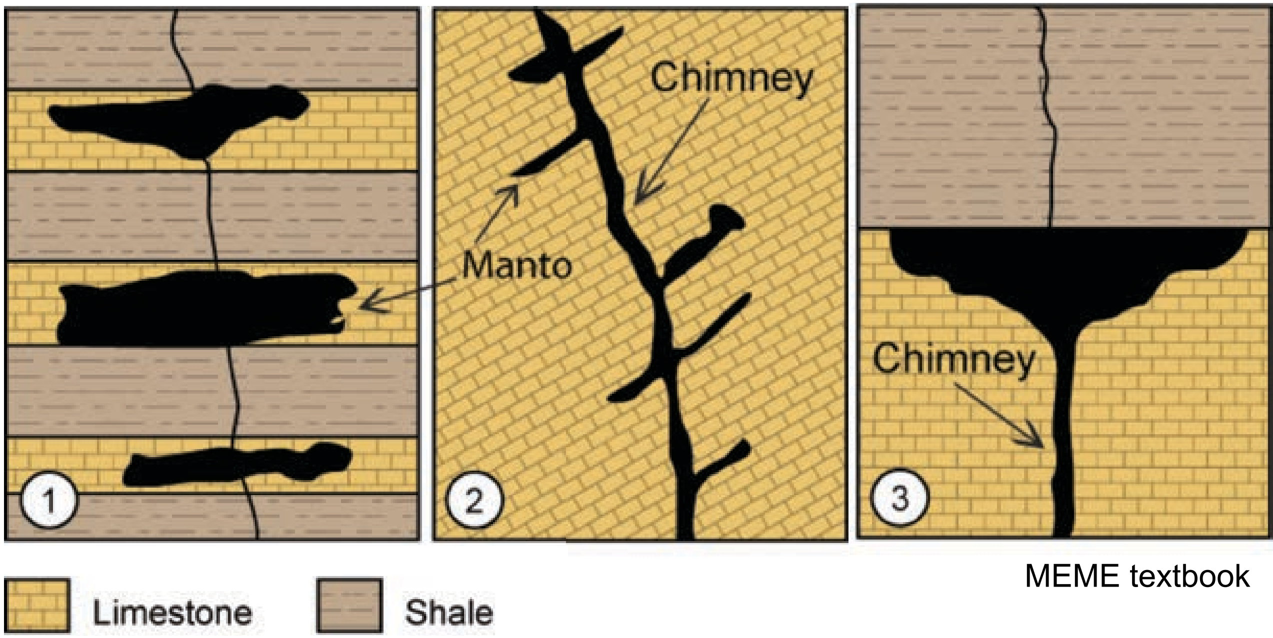
Lens shaped

Tabular/planar

Manto

Chimney

MVT: Mississippi Valley Type Pb–Zn



MEME textbook

Descriptive terminology: size

Giant: ore body containing metal equivalent to that in 10^{11} t of average crust (Ridley, 2013)

Super-giant: ore body containing metal equivalent to that in 10^{12} t of average crust (Ridley, 2013)

World class: Ore deposit that is within the top 10% of deposits by contained metal in its type

Laznicka (2010)

Table 2.2. Terminology of metal accumulations (deposits, districts) based on tonnage accumulation index (tai), exemplified by Cu (Cu clarke=25 ppm)

Magnitude term	Tai: lower threshold	Corresponding Cu tonnage
Supergiant (deposit)		
high supergiant	6.6×10^{12}	165 mt (unknown)
mid supergiant	3.3×10^{12}	82.5 mt
low supergiant	1×10^{12}	25 mt
Giant (deposit)		
high giant	6.6×10^{11}	16.5 mt
mid giant	3.3×10^{11}	8.25 mt
low giant	1×10^{11}	2.5 mt
Large (deposit)	1×10^{10}	250 kt
Medium (deposit)	1×10^{9}	25 kt
Small (deposit)	1×10^{8}	2,500 t
Very small (deposit)	1×10^{7}	250 t

Descriptive terminology: size

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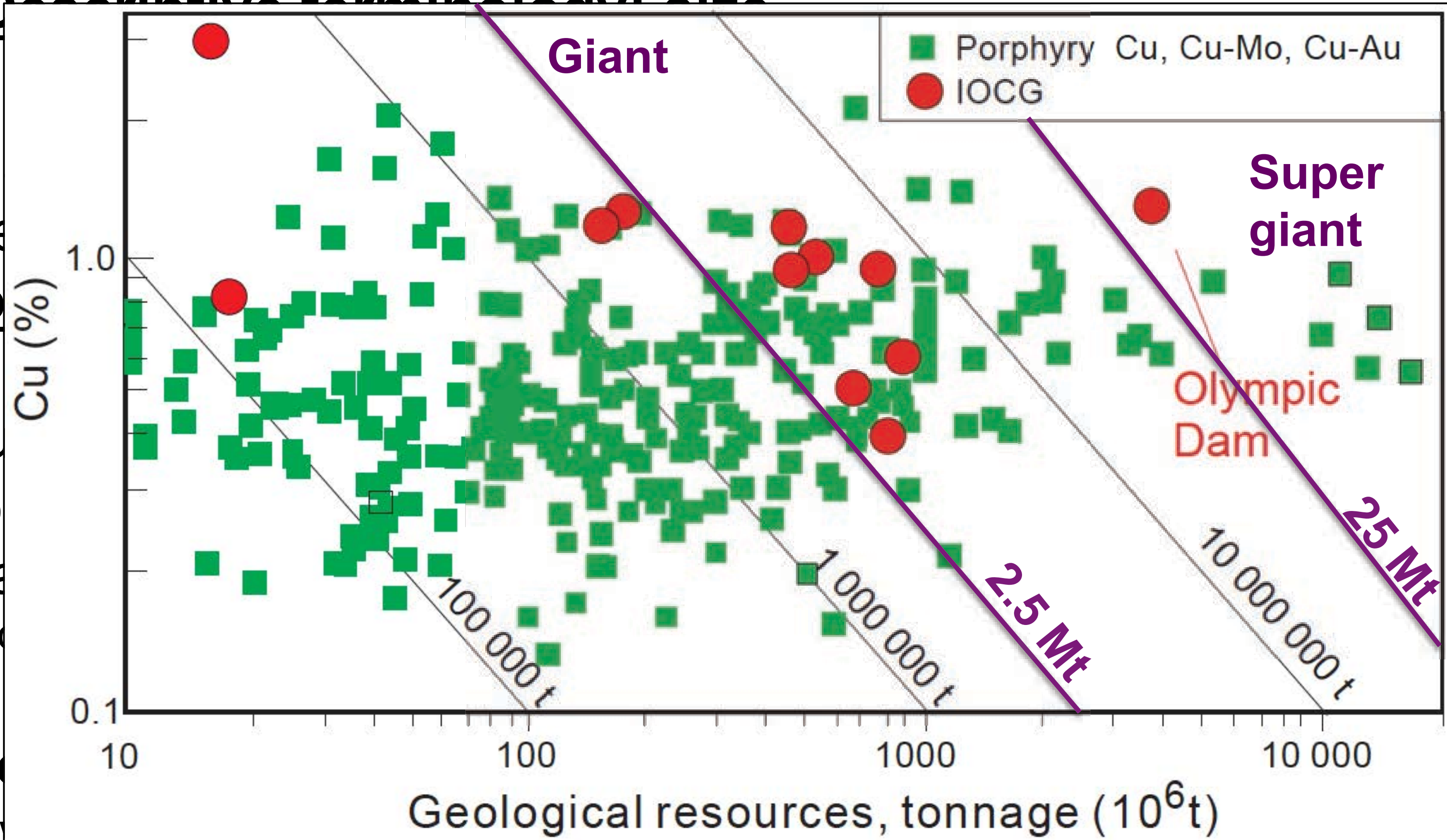


FIGURE 3. Cu grade versus tonnage plot of the geological resources of iron oxide copper-gold (IOCG) deposits and porphyry Cu based on Kirkham and Sinclair (1996).

From Corriveau et al. (2007)

Ore deposits can be classified according to:

1. Element or mineral extracted (e.g. Cu, Au, rutile)
2. **Nature of the ore (e.g. net textured, disseminated)**
3. Host-rock type (e.g. ultramafic intrusive, carbonates)
4. Tectonic setting (e.g. back-arc, Proterozoic intracratonic basins)
5. Genetic process of enrichment (hydrothermal, magmatic)

Nature of the ore:

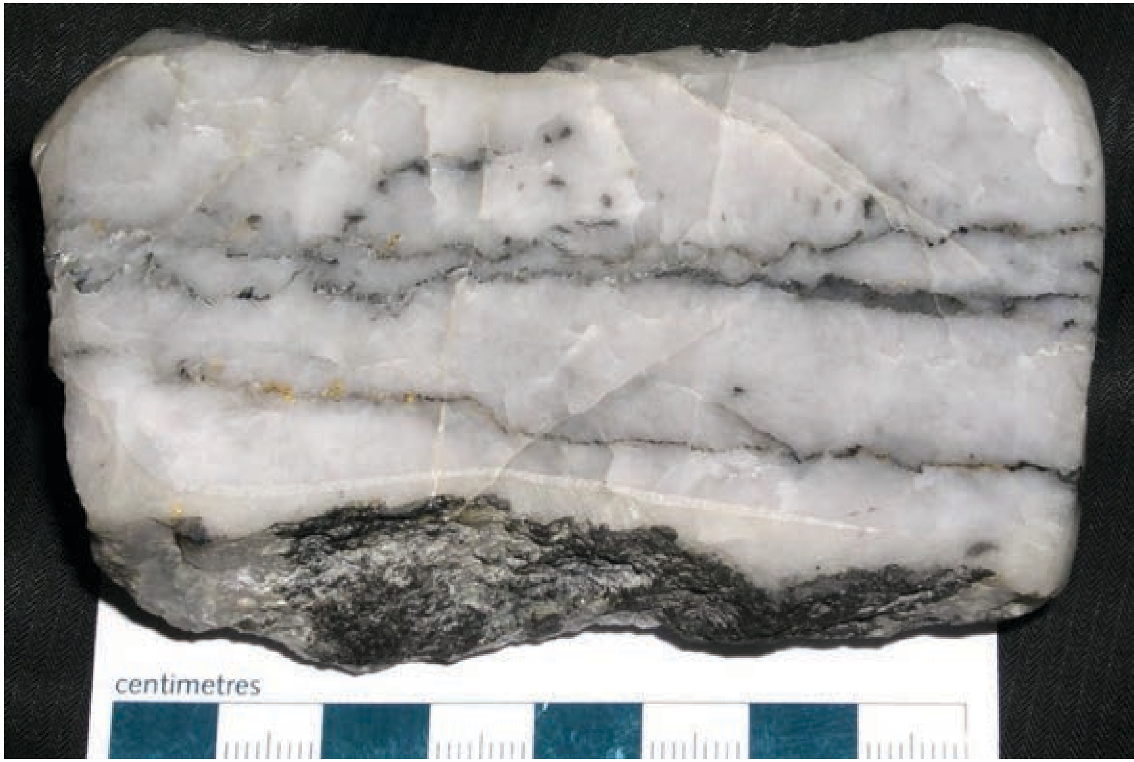
- **Vein**
- Lode
- Stockwork
- Disseminated
- Stringer
- Breccia
- Net textured
- Massive

Quartz vein with thin streaks of molybdenite
Merrill Island deposit, Chibougamau district, Quebec
Porphyry Copper

Planar body of mineralized rock with sharp boundaries against non-mineralized rock

Nature of the ore:

- Vein
- **Lode**
- Stockwork
- Disseminated
- Stringer
- Breccia
- Net textured
- Massive



Native gold
Hoyle Pond Mine, Timmins, Ontario
Mesoarchean lode gold
(http://www.turnstone.ca/rom78hoy.htm)

Planar body of ore of finite thickness (e.g. vein or shear zone)

Nature of the ore:

- Vein
- Lode
- **Stockwork**
- Disseminated
- Stringer
- Breccia
- Net textured
- Massive

Stockwork of wolframite-bearing fractures and quartz veinlets
Mount Pleasant, New Brunswick
Porphyry W–Mo

Set of veins that form a 3 dimensional network (stockwork can refer to the rock body containing the veins)

Nature of the ore:

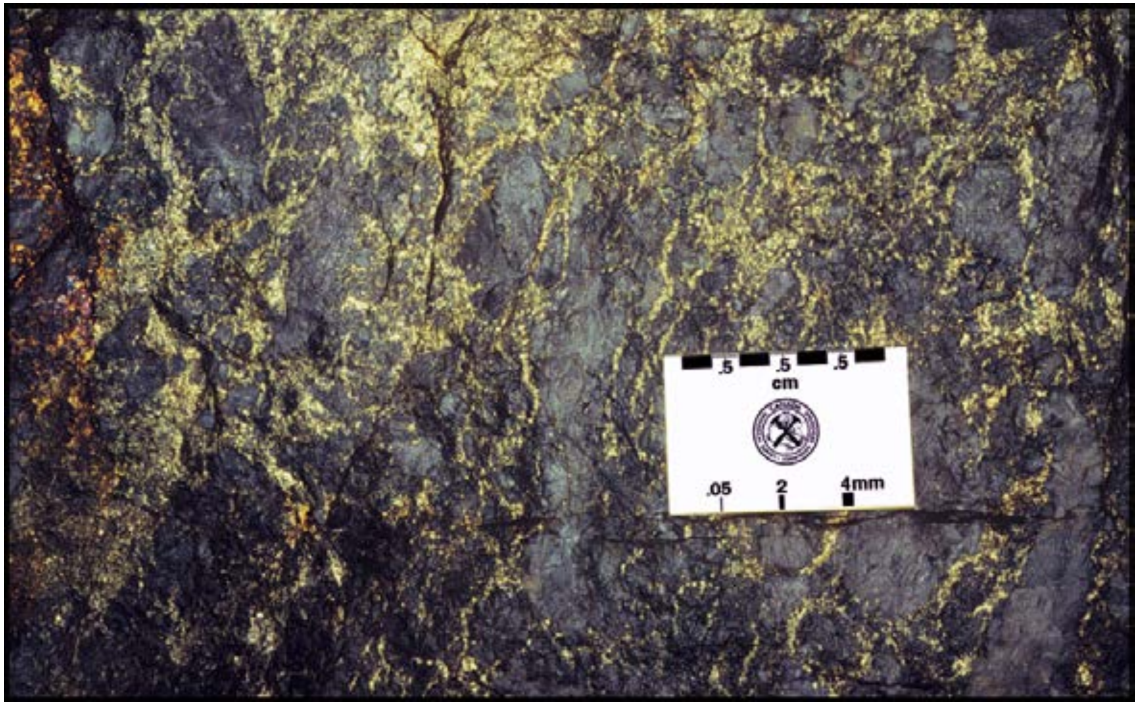
- Vein
- Lode
- Stockwork
- **Disseminated**
- Stringer
- Breccia
- Net textured
- Massive

Chalcopyrite and bornite disseminated
Don Rouyn deposit, Quebec
Archean Porphyry Cu

Fine-grained ore minerals uniformly distributed

Nature of the ore:

- Vein
- Lode
- Stockwork
- Disseminated
- **Stringer**
- Breccia
- Net textured
- Massive

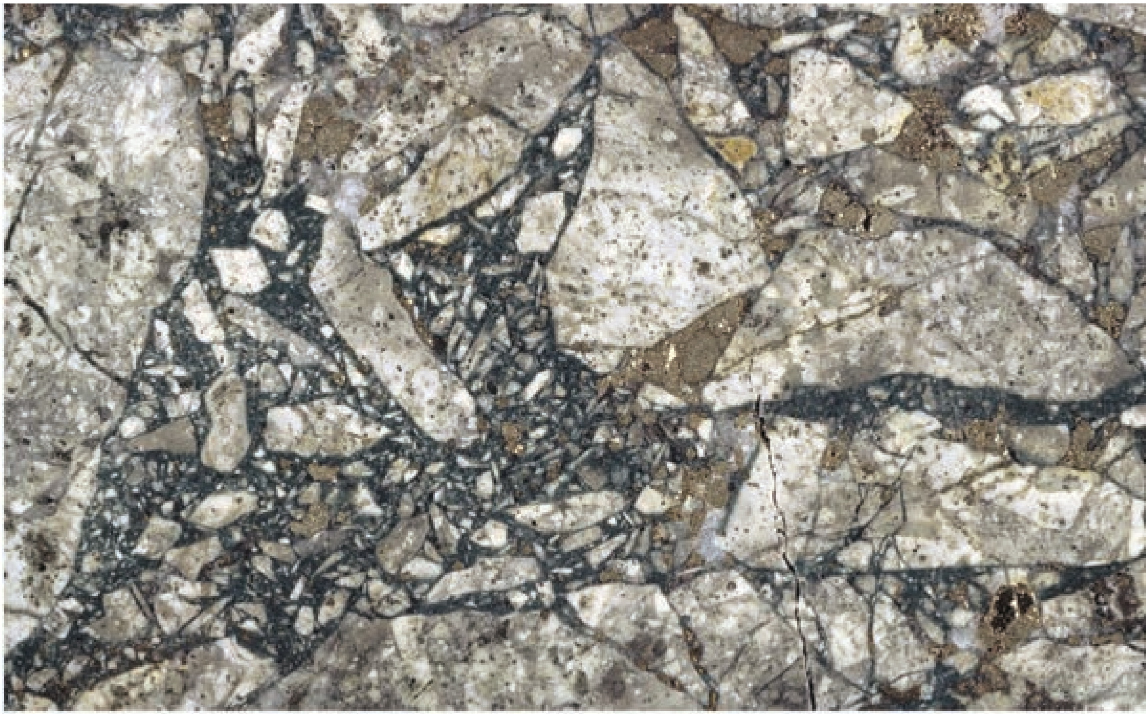


Kidd Creek, Ontario
VMS deposit
Stringers of bornite and chalcopyrite

Discontinuous approximately planar veinlets of ore minerals

Nature of the ore:

- Vein
- Lode
- Stockwork
- Disseminated
- Stringer
- **Breccia**
- Net textured
- Massive



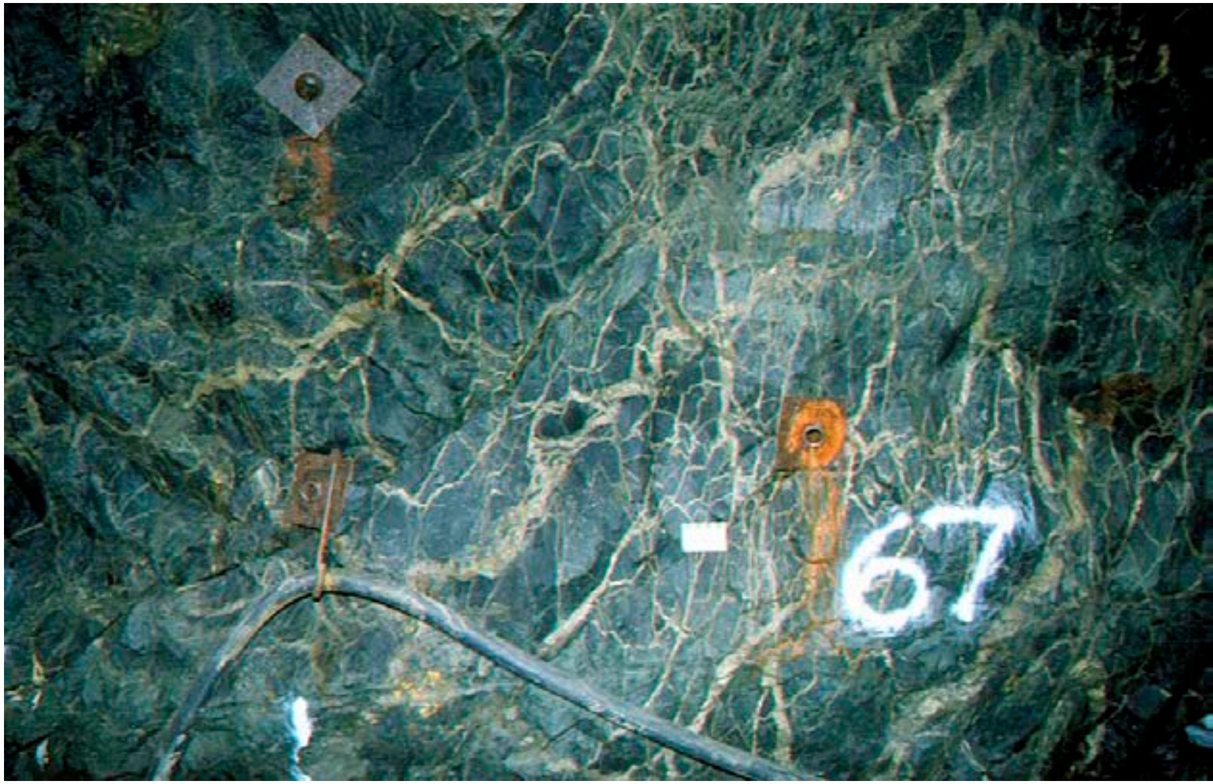
Cuajone mine, Peru

Porphyry Copper

Broken fragments of rock cemented together by a fine-grained matrix

Nature of the ore:

- Vein
- Lode
- Stockwork
- Disseminated
- Stringer
- Breccia
- **Net textured**
- Massive

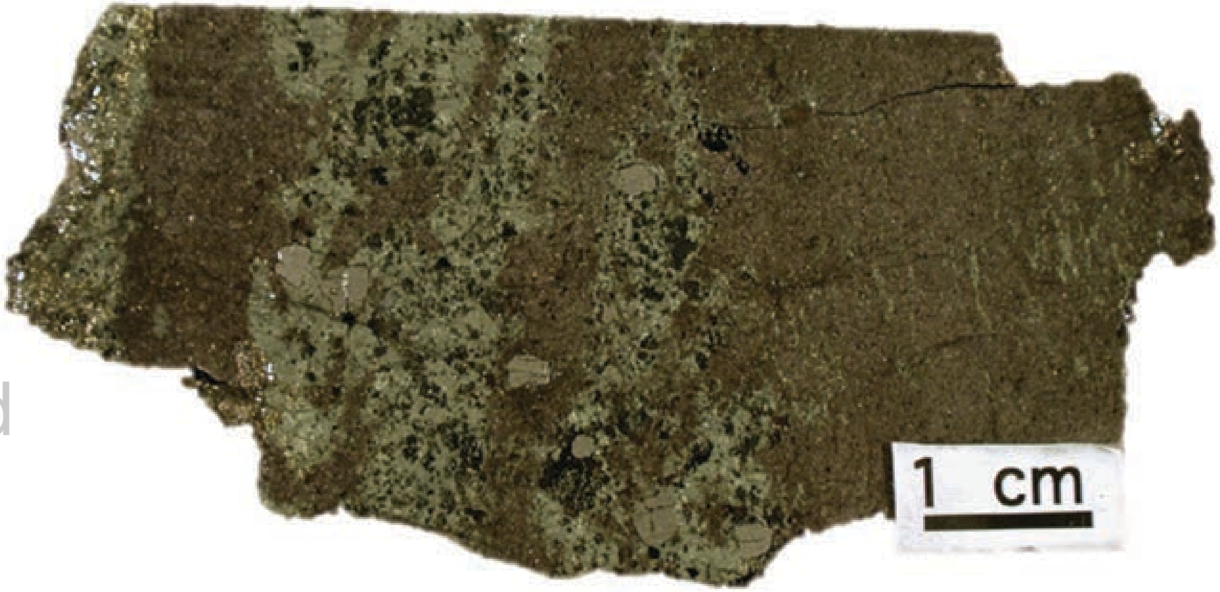


Pyrrhotite-pyrite-chalcopyrite vein network
Windy Craggy, B.C.
VMS

Veinlets of ore minerals that are variably orientated

Nature of the ore:

- Vein
- Lode
- Stockwork
- Disseminated
- Stringer
- Breccia
- Net textured
- **Massive**



Massive sulphide with interbanded pyrrhotite, chalcopyrite and late pyrite porphyroblasts
Flin Flon
VMS

Ore comprised of roughly 50–100% ore minerals

Ore deposits can be classified according to:

1. Element or mineral extracted (e.g. Cu, Au, rutile)
2. Nature of the ore (e.g. net textured, disseminated)
3. Host-rock type (e.g. ultramafic intrusive, carbonates)
4. Tectonic setting (e.g. back-arc, Proterozoic intracratonic basins)
5. **<u>Genetic</u> process of enrichment (hydrothermal, magmatic, sedimentary)**

Genesis of Iron–oxide–copper–gold deposits: case study

Origin of the supergiant Olympic Dam Cu-U-Au-Ag deposit, South Australia: Was a sedimentary basin involved?

Jocelyn McPhie[1], Vadim S. Kamenetsky[1], Isabelle Chambefort[1], Kathy Ehrig[2], and Nicholas Green[2]
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ABSTRACT

The supergiant Olympic Dam Cu-U-Au-Ag ore deposit of South Australia occurs in a tectonic-hydrothermal breccia complex that is surrounded by Mesoproterozoic granite. The breccia is composed mainly of granite clasts and minor amounts of Mesoproterozoic volcanic clasts. Very thick (>350 m) sections of bedded sedimentary facies that occur in the breccia complex include laminated to very thin planar mudstone beds, thin to medium internally graded sandstone beds, and thick conglomerate beds. The bedded sedimentary facies extend

Exploration drilling in the past 10 yr (626 km of diamond drill core) has greatly extended our knowledge of the architecture of the host succession. Here we propose an alternative to the widely accepted maar-diatreme setting of ore formation. We suggest that OD formed beneath and partly within a sedimentary basin. Our

Geology, August 2011; v. 39; no. 8; p. 795–798; doi:10.1130/G31952.1; 4 figures.

Genesis of Iron–oxide–copper–gold deposits: case study

Origin of the supergiant Olympic Dam Cu-U-Au-Ag deposit, South Australia: Was a sedimentary basin involved?

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doi:10.1130/G33040C.1

The fluorine link between a supergiant ore deposit and a silicic large igneous province

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I welcome the description by McPhie et al. (2011) of the major role played by fluorine in the genesis of mineral deposits at Olympic Dam (Australia), and more broadly in the Gawler Range Volcanics. It is important to recall that intrusive granitic rocks with 1%–2% fluorine (F) are a characteristic of much of the European Hercynian province, associated with tin mineralization in particular (e.g., Stein and Hannah, 1990; Aiuppa et al., 2009). Extensive brecciation and greisening (wall-rock alteration of granite to produce a topaz-quartz-mica assemblage) is commonly associated with these mineral deposits.

In their description of Olympic Dam, McPhie et al. claim in their discussion that dissolution of rock fragments is due to the action of hy-mas lead to topaz saturation and precipitation, as observed in the south-western England topaz granites (Pichavant and Manning, 1984). High F contents in high-Ca magmas will lead to fluorite precipitation (in contrast to southwestern England, where fluorite is hydrothermal; Manning and Exley, 1984). In their discussion, McPhie et al. speculate that HF was involved in rock dissolution during brecciation, without presenting unambiguous supporting evidence, and this speculation is repeated in the abstract. Given the widely observed experimental evidence that reaction with fluoride in solution gives a quartz + topaz product, and the field evidence that this reaction takes place (topaz greisens are common in tin mineralized granites), at the very least one would expect to see topaz as a product of reaction with an HF-rich fluid, and also the formation of a quartz-rich reaction product. I remain to be convinced that dissolution during brecciation described in this interesting paper could be attributed primarily to reaction with HF, as is proposed.

Genesis of Iron–oxide–copper–gold deposits: case study

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The fluorine link between a supergiant ore deposit and a silicic large igneous province

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The fluorine link between a supergiant ore deposit and a silicic large igneous province

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Manning (2012) has challenged our suggestion that dissolution by hydrofluoric acid (HF) contributed to the formation of the Olympic Dam breccia complex (McPhie et al., 2011b). Manning has summarized the outcome of considerable experimental and other research on HF-granite

Genetic models require concentrating elements of economic interest, three components:

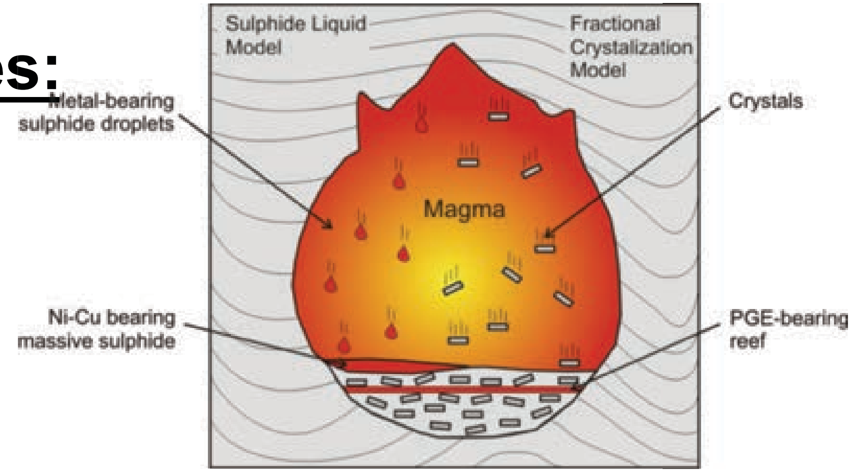
1. Source of metals
   - Earth's crust or mantle

2. Transportation mechanism
   - Magmas, hydrothermal fluids, surface waters

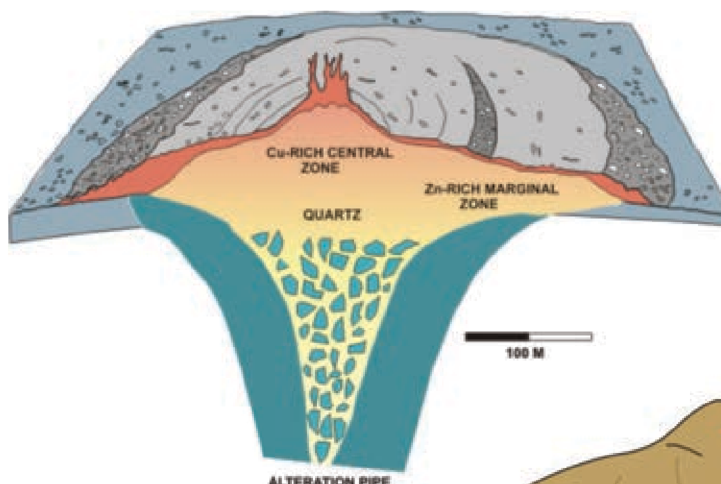
3. Trap
   - Need to concentrate the metals while allowing the discharge of the depleted fluid/magma
   - Think of a water filter, the dissolved elements (Cl^-, Na^+) are precipitated while water still flows through, concentrating these ions in the filter

Three main types of processes:

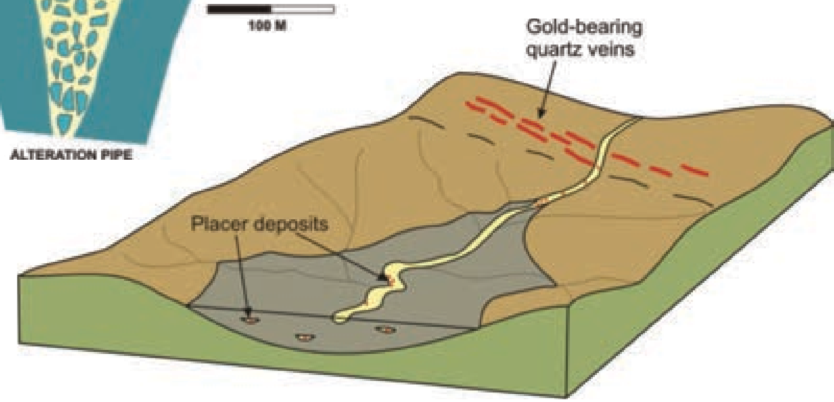
Magmatic



Hydrothermal



Sedimentary



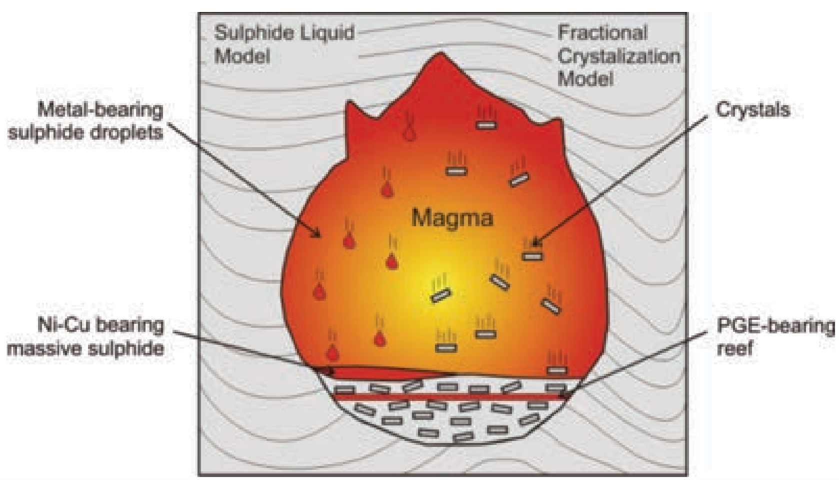
Magmatic processes

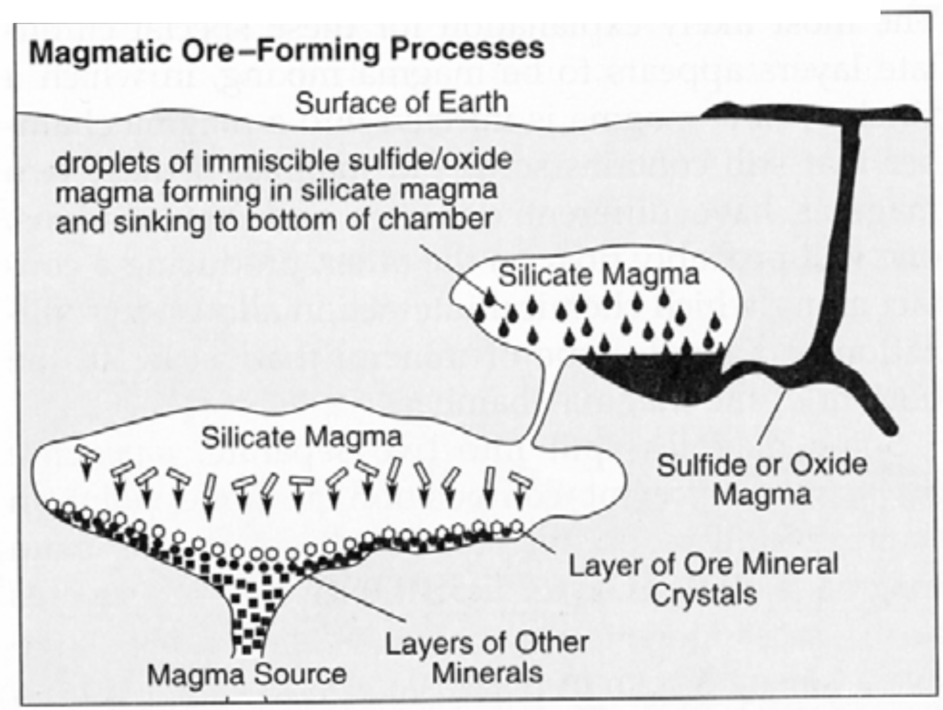
Type of Process	*Types of Deposits Formed/Minerals Concentrated*
Involving Magmas	Crystal fractionation—chromium, vanadium Immiscible magma separation—nickel, copper, cobalt, platinum-group elements

Source: partial melting of the crust or mantle

Transport: magma

Trap: magma chambers and magmatic conduits





Hydrothermal processes

Type of Process	*Types of Deposits Formed/Minerals Concentrated*
Involving Water	Groundwater and related deposits—uranium, sulfur Basinal brines—Mississippi Valley type, sedex Seawater—volcanogenic massive sulfide, sedex Magmatic water—porphyry copper-molybdenum, skarn Metamorphic water—gold, copper

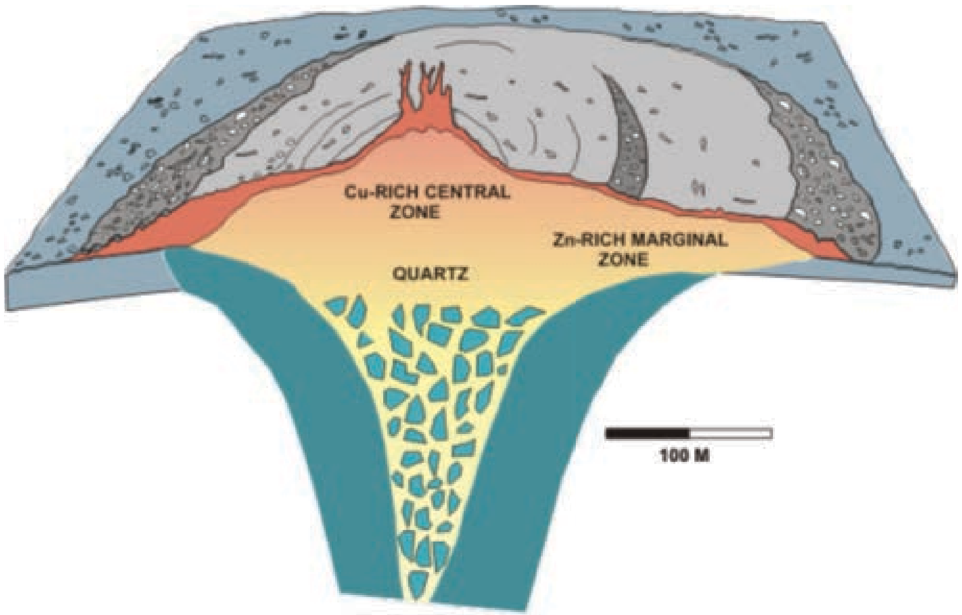
Source: Crust

Transport: Fluid (H_2O and/or CO_2)

Trap: Chemical fronts, veins

Gradients in: T, P, f_{O2}, f_{S2}, X

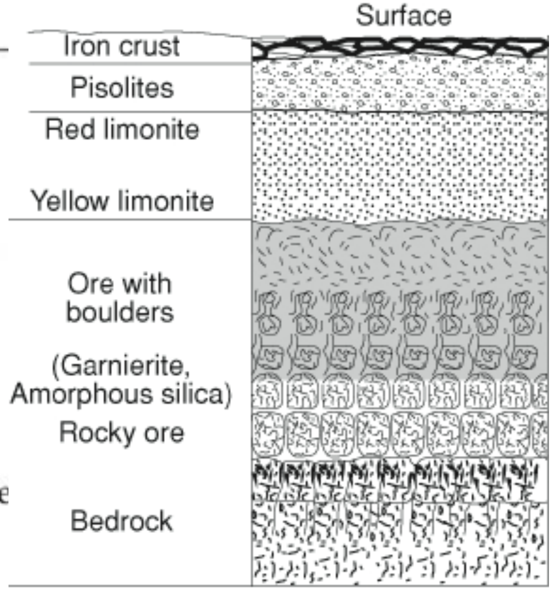
- Cooling (T)
- Boiling (T, P)
- Fluid–rock interaction (f_{O2}, f_{S2}, X)
- Redox (f_{O2})
- Fluid mixing (f_{O2}, f_{S2}, X)



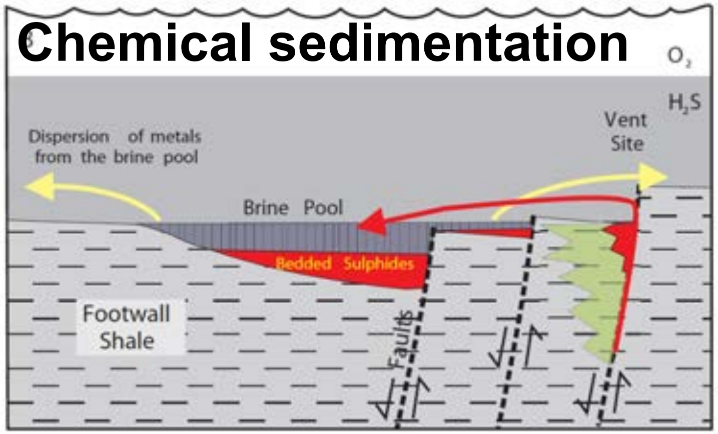
Sedimentary processes

Type of Process	*Types of Deposits Formed/Minerals Concentrated*
Surface Processes	
Weathering	Laterite deposits—nickel, bauxite, gold, clay Soil
Physical Sedimentation	
Flowing water (stream or beach)	Placer deposits—gold, platinum, diamond, ilmenite, rutile, zircon, sand, gravel
Wind	Dune deposits—sand
Chemical Sedimentation	
Precipitation from or in water	Evaporite deposits—halite, sylvite, borax, trona Chemical deposits—iron, volcanogenic massive sulfide deposits, sedex deposits
Organic Sedimentation	
Organic activity or accumulation	Hydrocarbon deposits—oil, natural gas, coal Other deposits—sulfur, phosphate

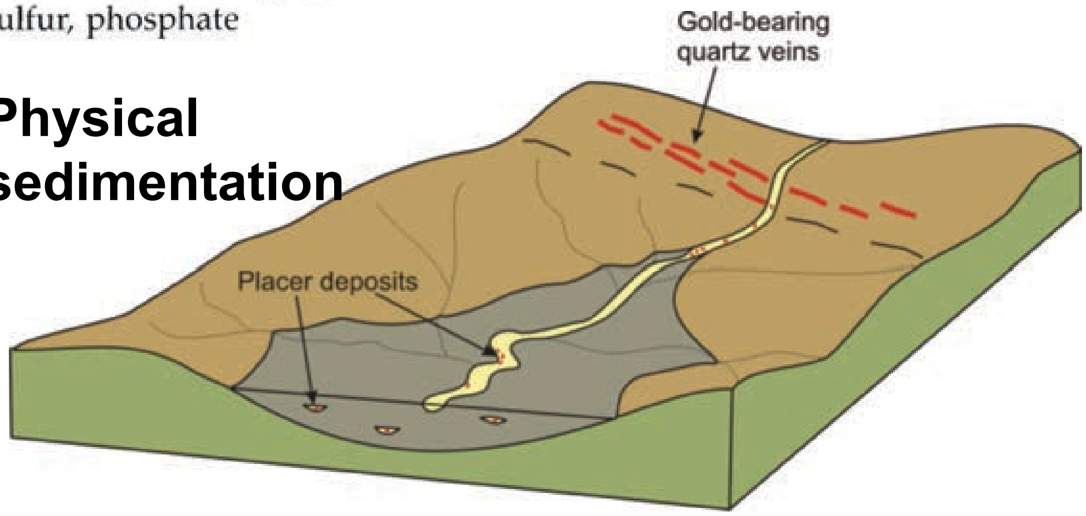
Weathering



Chemical sedimentation



Physical sedimentation



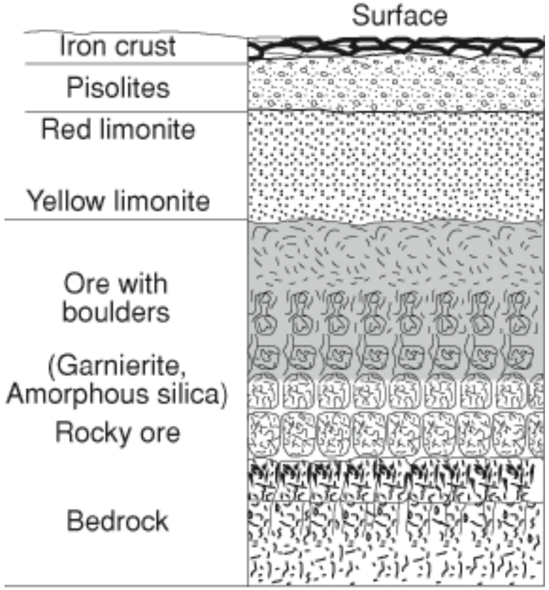
Sedimentary processes

Source: surface rocks, seawater

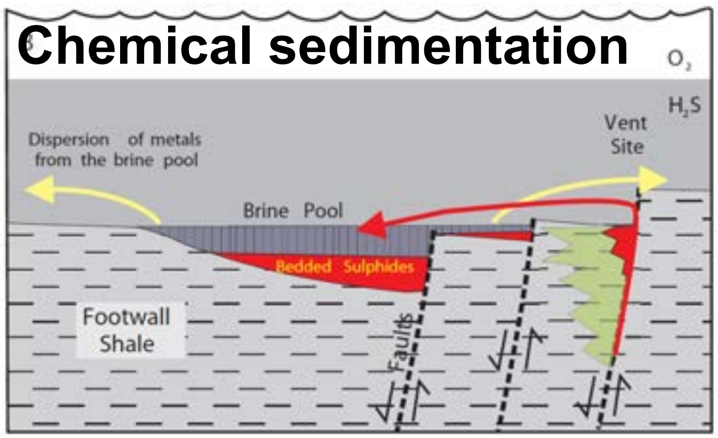
Transport: water, wind

Trap: depositional environments

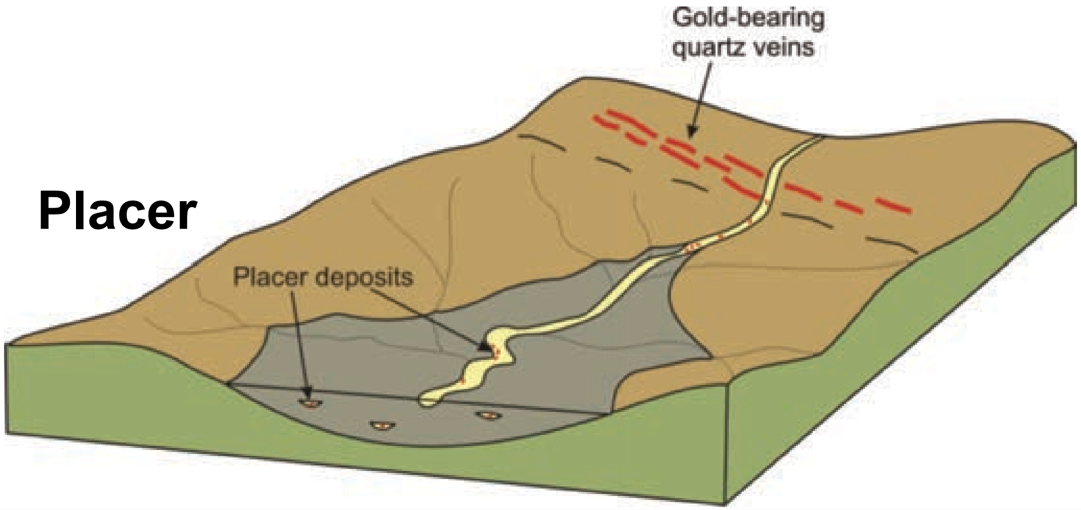
Weathering



Chemical sedimentation



Placer



Other terms used in ore deposit geology:

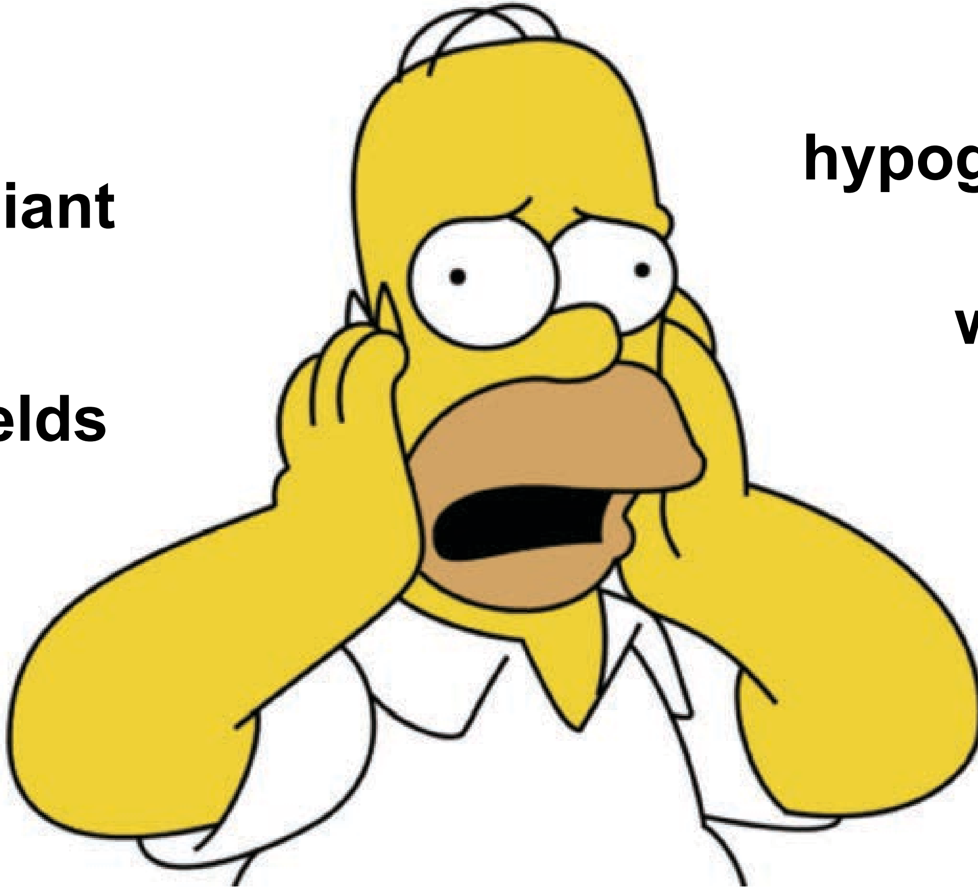
supergene

stratiform

feasibility study

super-giant

hypogene



world class

greenfields

gangue

reserve

brownfields

showing

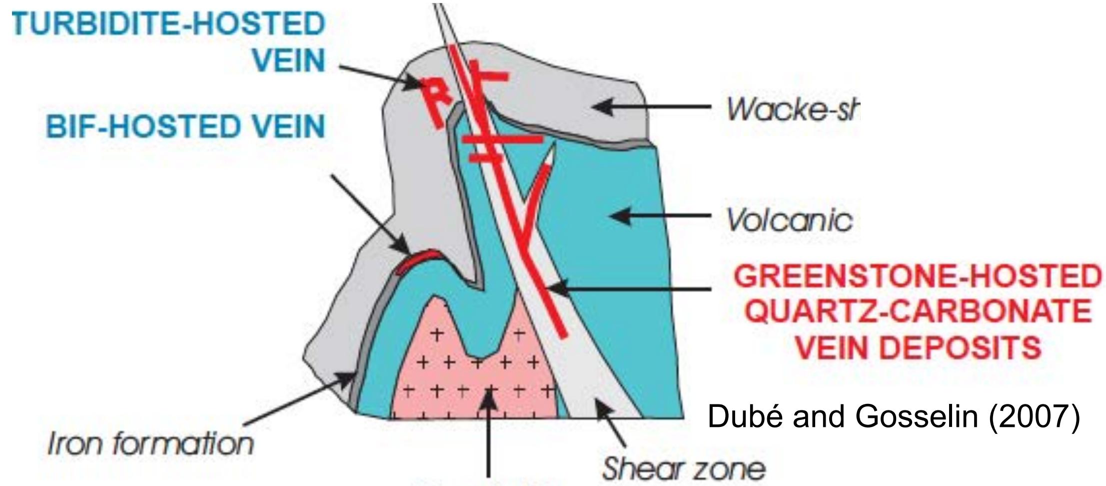
metallotect

Genetic model terminology:

Epigenetic: ore deposits that form after their host rocks

Syngenetic: ore deposits that form at the same time as their host rocks

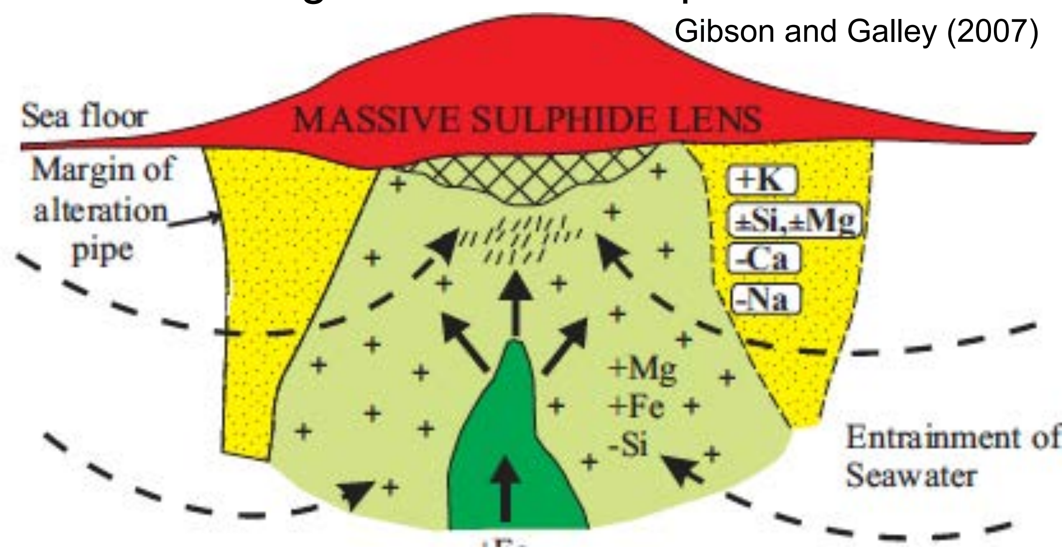
Greenstone Qtz–Carb Vein Au



Dubé and Gosselin (2007)

VMS: volcanogenic massive sulphide

Gibson and Galley (2007)



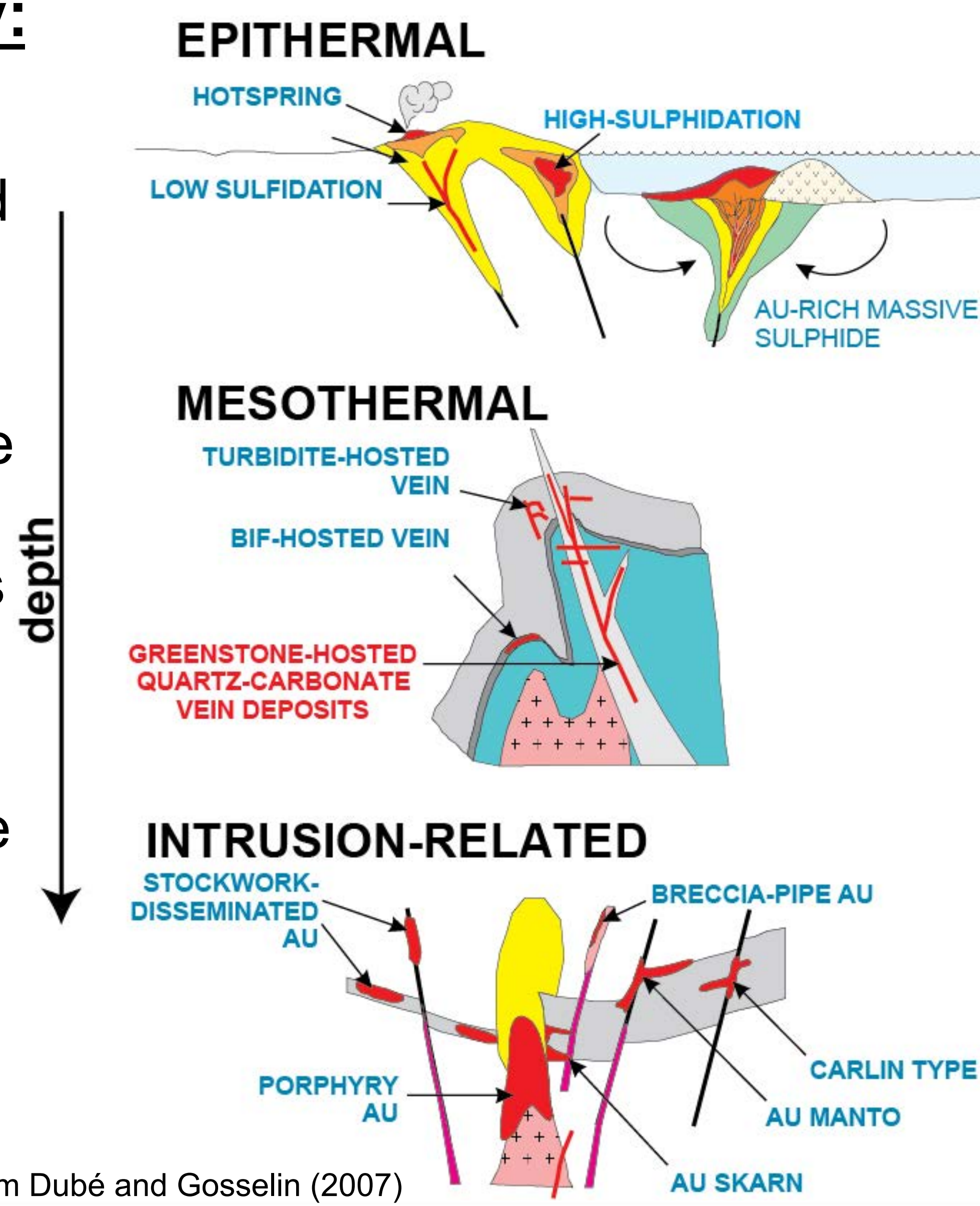
Genetic model terminology:

Epithermal: hydrothermal ore formed at low T (50–200°C) and shallow depths (~0–1.5 km)

Mesothermal: hydrothermal ore formed at intermediate T (200–300°C) and intermediate depths (~1.5–4.5 km)

Hypothermal: hydrothermal ore formed at high T (400–600°C) and great depths (>4.5 km) (a.k.a. **intrusion related**)

Au–Ag hydrothermal deposits

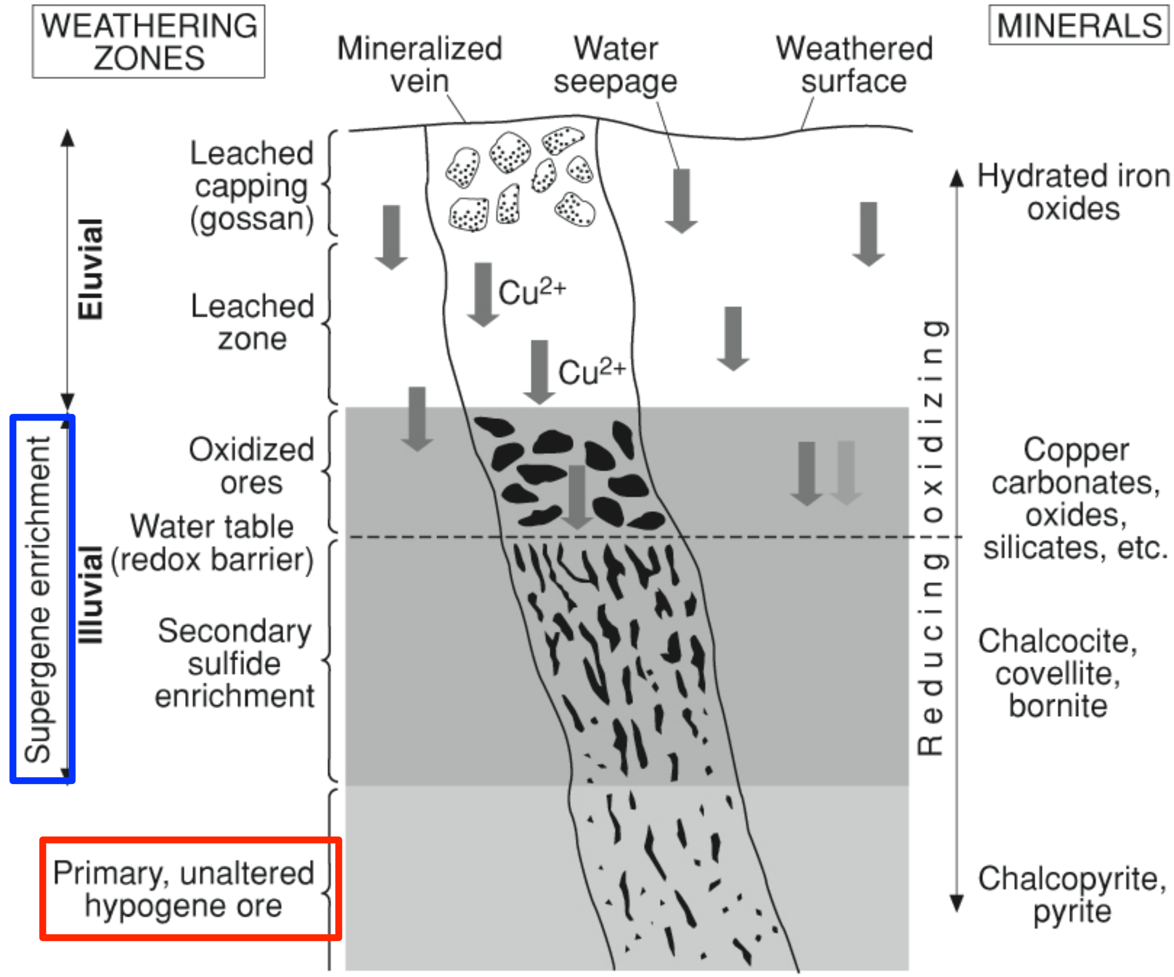


Modified from Dubé and Gosselin (2007)

Genetic model terminology:

Supergene: Ore enrichment formed near the surface (commonly by descending solutions)

Hypogene: formed below the surface of the Earth



Robb (2005)

Terminology in mineral exploration

Mineralization: A general term that can be thought of as "rock of potential interest." As such it usually refers to an area of rock that contains economic minerals or one that has a character that suggests economic minerals might be present.

Showing: A rock occurrence hosting minor in situ mineralization.

Mineral deposit: A mineral occurrence of sufficient size and grade that it might, under favourable circumstances, be considered to have economic potential.

Ore deposit: A volume/mass or aggregate of mineral substance that can be exploited with a profit. The exploitability is a function of the tonnage, grade, mining (method of extraction) and environmental engineering, metallurgy (e.g. inclusions) and the location of the deposit. The absolute and relative importance of these factors can vary with the economic, social, political and technological context.

Some more important definitions

Ore: mineral or mineral aggregate that can be extracted, concentrated and commercialized with a profit. Industrial minerals, chemical substances and energy sources can all be ore.

Gangue: The valueless minerals in an ore; that part of an ore that is not economically desirable but cannot be avoided in mining. It is separated from the ore minerals during concentration.

Mine: Industrial infrastructures/installations to exploit an ore deposit.

A fictional short story:

Bill the prospector discovers **<u>mineralization</u>** near *Happy creek*

He sends a sample to the lab, which determines it has potential economic value: *Happy creek* is now a **<u>showing</u>**

Bill finds more mineralization around the area and convinces a Junior exploration company to buy it. Bill is rich and retires.

The company conducts exploration geology using geophysics, geochemistry and a drilling program. There is quite a lot of mineralization. *Happy Creek* is now a **<u>mineral deposit</u>**.

A fictional short story (continues…):

A major mining company buys *Happy Creek* and the owners of the Junior company are rich and retire.

The major mining company completes a **feasibility study** and they believe they can make a **profit** by mining Happy Creek. It is now an **ore deposit**.

Roads and buildings are constructed and the company starts the mining process. Happy Creek is now a **mine**.

The geologists at the mine now have to separate the **ore** from the **gangue** to maximize profit.

Take home messages:

Elements with similar characteristics behave in a similar manner (siderophile, chalcophile, lithophile and atmophile elements)

Concentration of elements of economic interest occur through 3 main processes:

- Magmatic
- Hydrothermal
- Sedimentary

Descriptive models of ore deposits are based on observations

Genetic models are based on the genesis of the ore deposit and complete models require:

- Source
- Transport mechanism
- Trap