Economic Geology

Base metals and their ore deposit types

Module 4

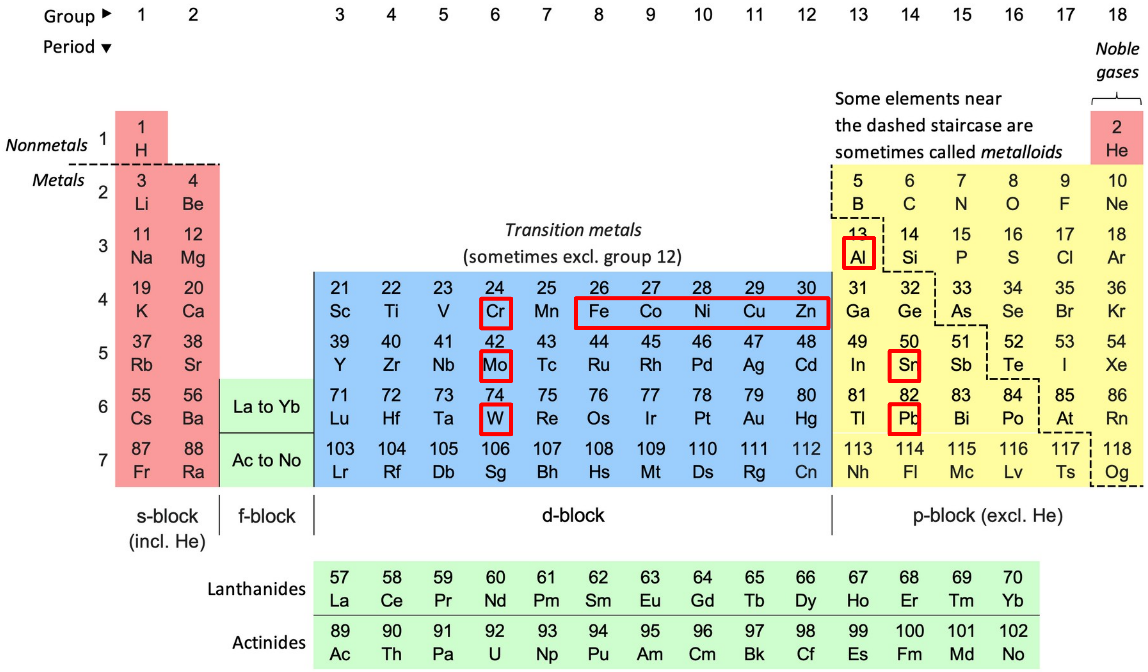
Thomas Ulrich
Institute for Disposal Research

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

Structure of this part

- In the following, different base metals will be discussed in relation to their uses and in which type of ore deposit they can be found.



Base metals

- Nickel, cobalt, (and platinum group elements (Ni-Co-PGE))
- Chromium (Cr)
- Copper and molybdenum (Cu (Mo))
- Lead and zinc (Pb-Zn)
- Iron (Fe)
- Aluminium (Al)
- Tin and tungsten (Sn-W)

Deposit types for base metals

- Magmatic sulphide deposits
- Hydrothermal deposits
- Supergene deposits
- Placer deposits

Ni

Nickel
Ni
28 58.693

- Nickel
- Uses of nickel
- Nickel deposits
  - Magmatic sulphide deposits (together with Cu and PGE)
  - Laterite (supergene) deposits
  - Seafloor Mn-crusts and sulphides

Nickel
Ni
28 58.693

Nickel

- Corrosion resistant silvery metal
- Ore mineral(s): pentlandite $(Fe,Ni)_9S_8$, millerite, garnierite (Ni-clay)

Pentlandite

- Top supplier: Russia, Indonesia, Philippines, Australia, New Caledonia, Brazil
- Reserves: +100 Mio t
- Resources: 300 Mio t (grade of 0.5wt%)

USGS 2022

Nickel uses

Nickel
Ni
28 58.693

- Stainless steel
- Plating
- Alloys
- Batteries

Platinum group elements (PGE)

44 Ru	45 Rh	46 Pd
76 Os	77 Ir	78 Pt

- Among the rarest metals on earth
- Typically tiny minerals (10s-100s μm)
- Magmatic ore deposits with grades of 5-15ppm
- South Africa and Russia
- Used in catalytic converters, jewellery, alloys

Ni-deposits

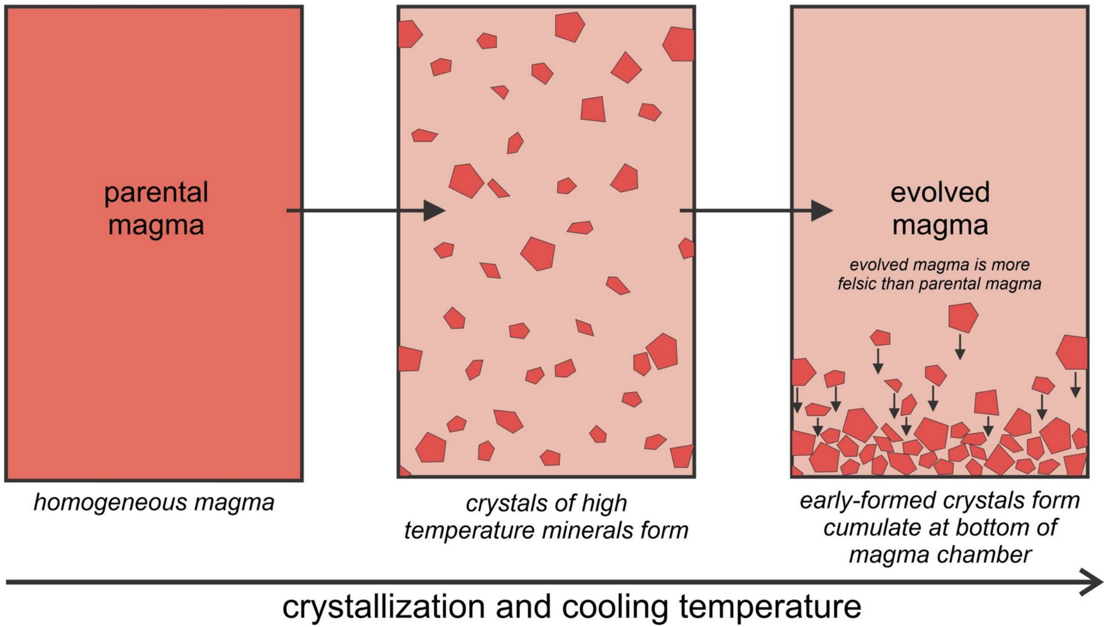
- Magmatic massive sulphide deposits
- Supergene deposits

Magmatic massive sulphide deposits

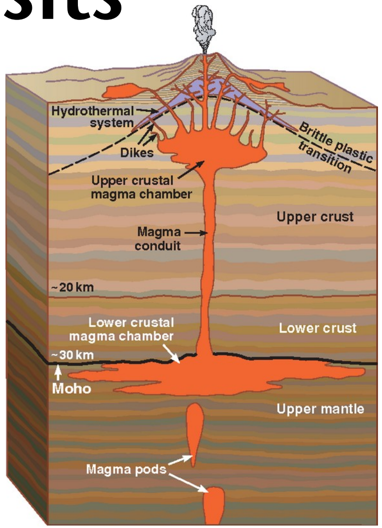
- Occur in mafic layered intrusions.
- Disseminated, net textured to massive sulphide.
- High grade, large tonnage.
- Ore body laterally extensive, but restricted to pods, layers, and lenses

Magmatic massive sulphide deposits

Crystallization in a magma chamber



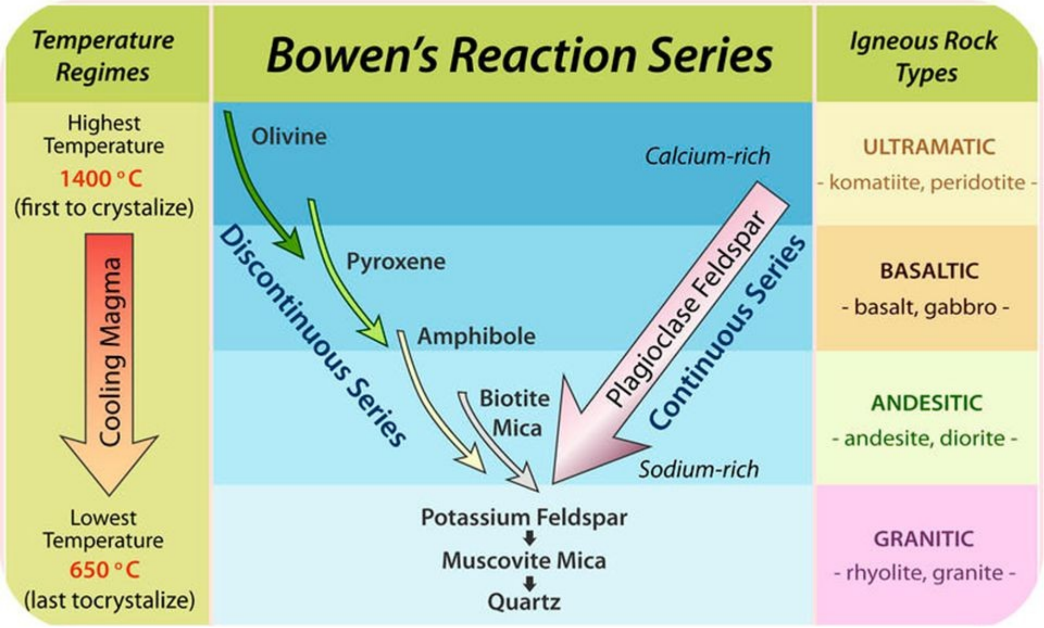
Crystals settle to the bottom of magma chamber



Spera (2004)

Magmatic massive sulphide deposits

Crystallization in a magma chamber (Bowen's reaction series)



Formation of e.g., gabbro or granite

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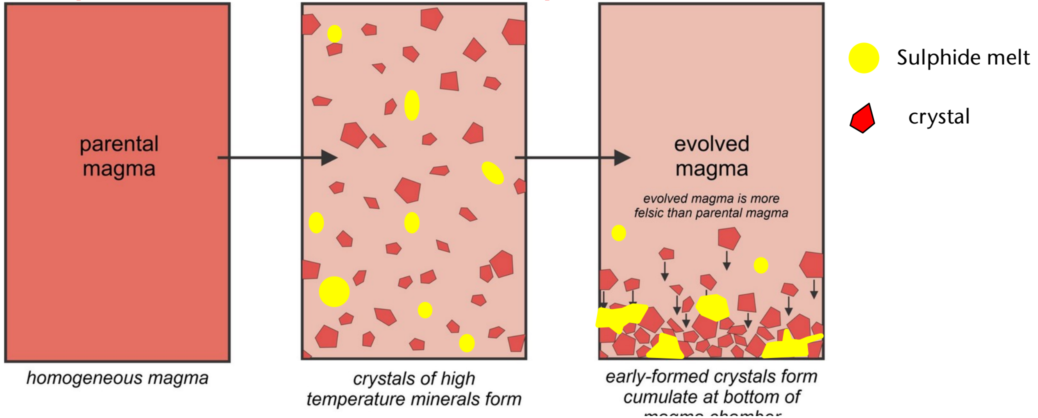
Magmatic massive sulphide deposits

Crystallization in a magma chamber (separation of immiscible melt)

- Key process is to exsolve a sulphide liquid (melt immiscibility)
- Requires saturation of sulphur in silicate melt



- Contaminating silicate melt and adding S from external rocks.
- Magma mixing

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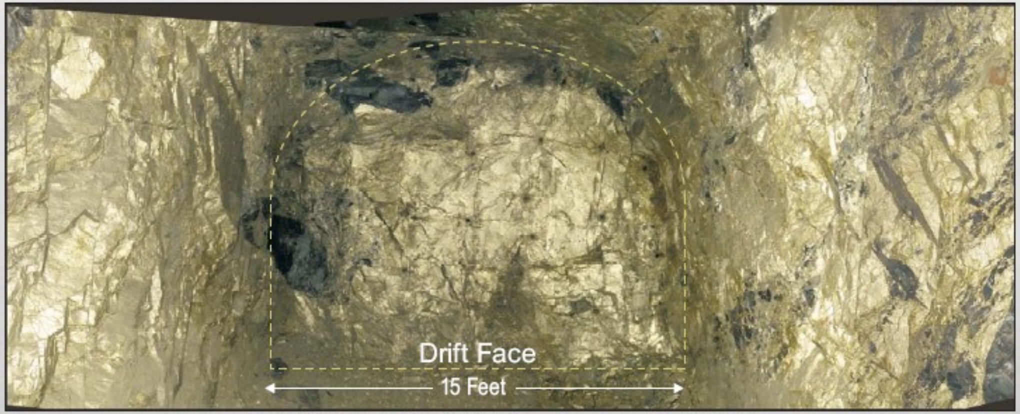
Magmatic massive sulphide deposits

Crystallization in a magma chamber (separation of immiscible melt)

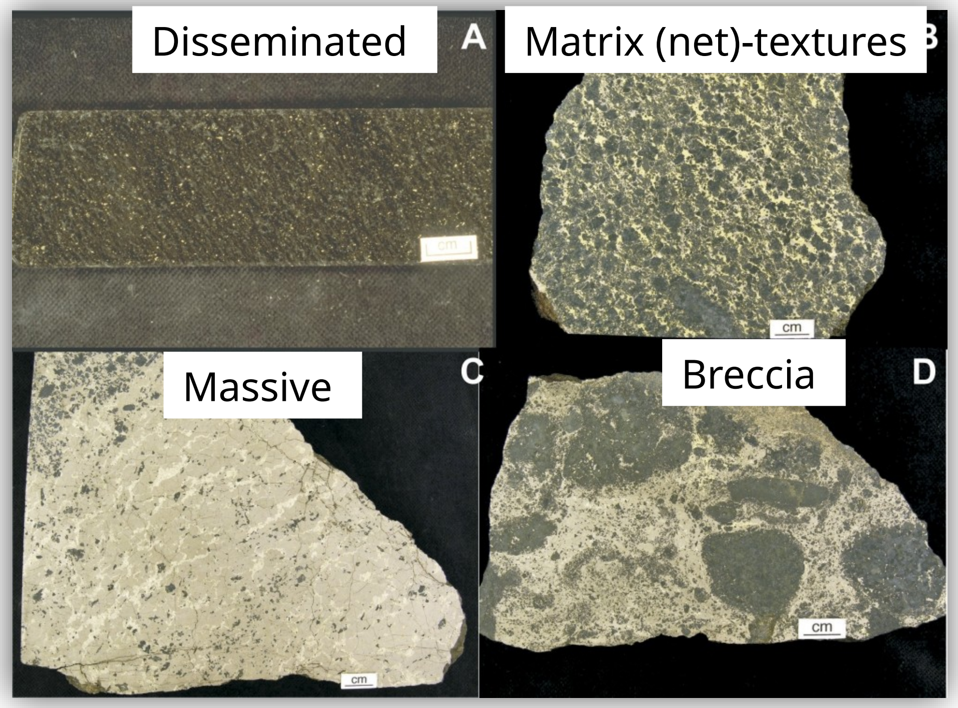
- Metals generally love to go into the sulphide melt (partitioning coefficient)

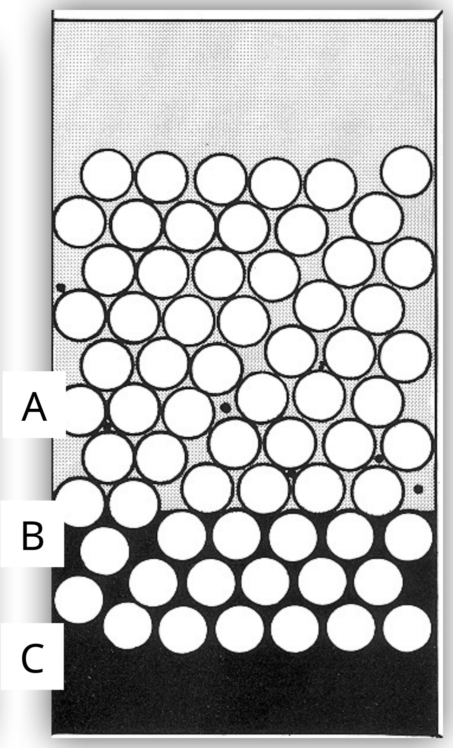


Podolsky Mine - 2450 Level drift intersecting massive Cu-Ni-Pt-Pd-Au mineralization with estimated grade of 20-25% Cu, 1-2% Ni, 0.25-0.75 opt TPM

Sulphide melt is denser and sinks to the bottom of the magma system (massive sulphides).

Rock textures in sulphide deposits





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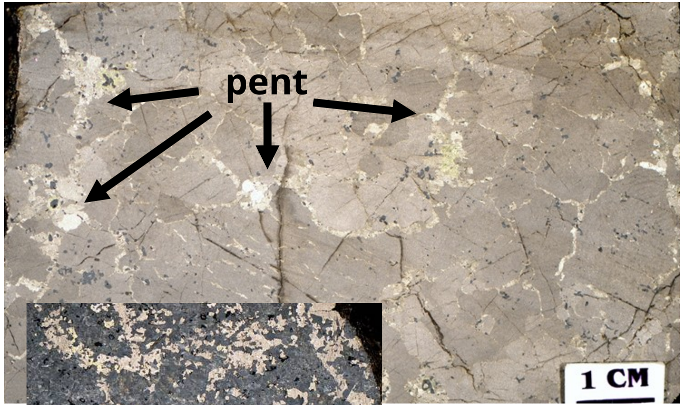
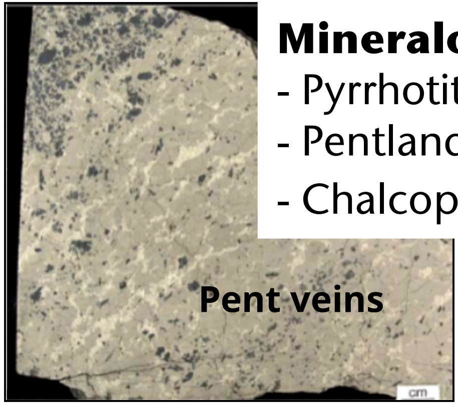




Ore Nature:

- Massive to disseminated sulphides.
- Note textures, especially the nature of the pentlandite in the pyrrhotite rock; this texture is due to exsolution and later mobilization.

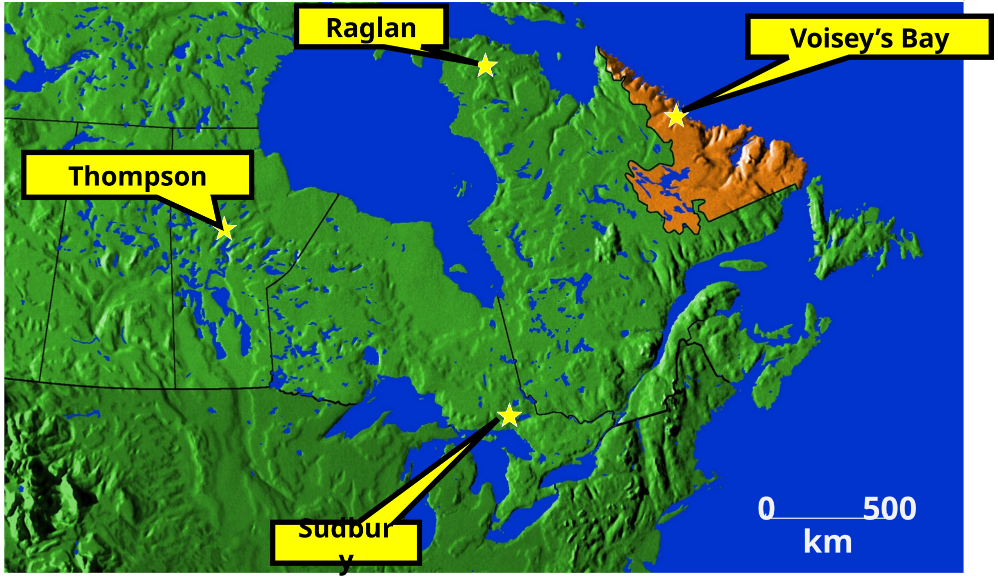
Mineralogy:

- Pyrrhotite (FeS)
- Pentlandite $(Fe,Ni)_9S_8$
- Chalcopyrite ($CuFeS_2$)

- Each of these sulphide droplets was once a much smaller, homogeneous, sulphide melt.
- These blebs represent the end product of accretion of small droplets of sulphide melt.
- The sulphide melt will later crystallize and fractionate, much like a silicate melt, to generate a new composition.

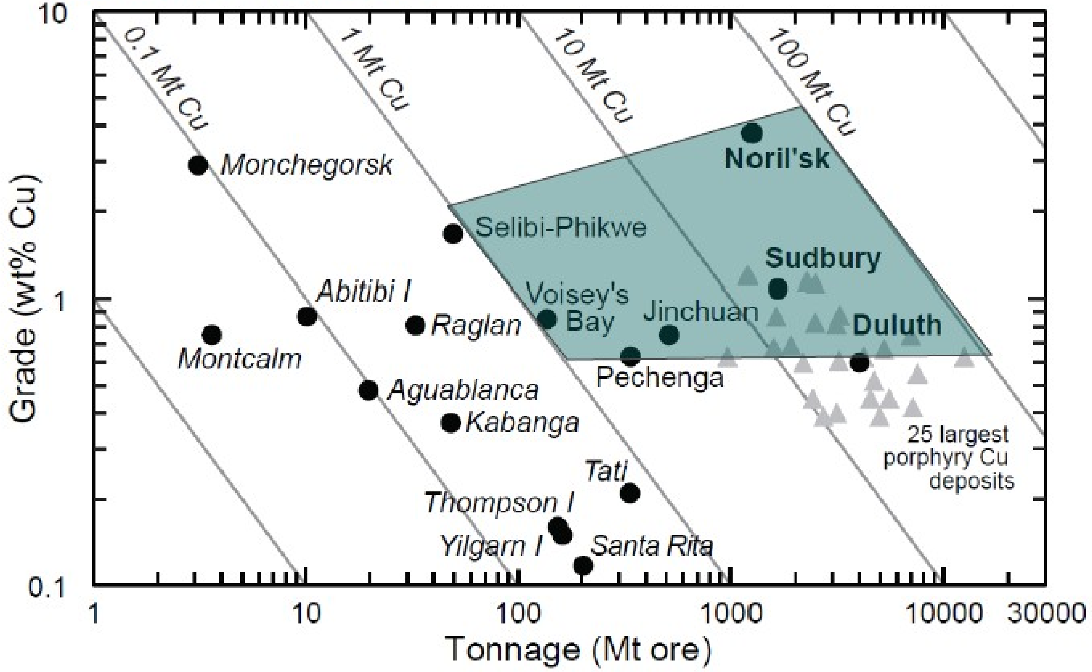
Magmatic Ni deposits, examples

- Sudbury, Canada
- Voisey’s Bay, Canada
- Talnakh, Norilsk, Russia



Cu-rich magmatic Ni-Cu-PGE deposits

Significant Producers

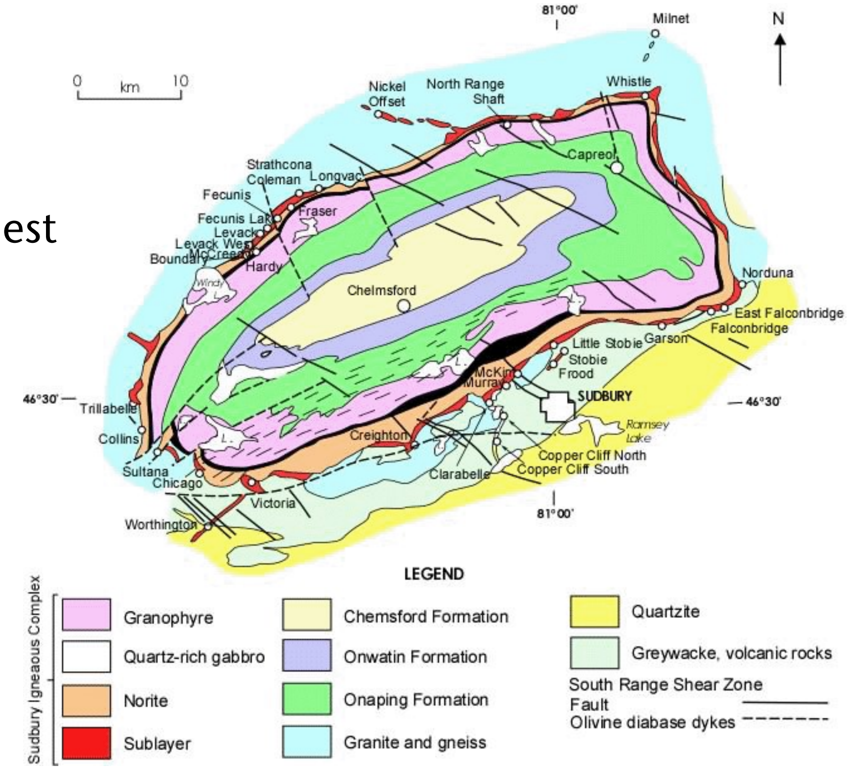


7 SIMEXMIN 2014 Symposium May 14, 2014

VALE

Sudbury Ni-Cu-PGE, Canada

One of the world's largest Ni deposits

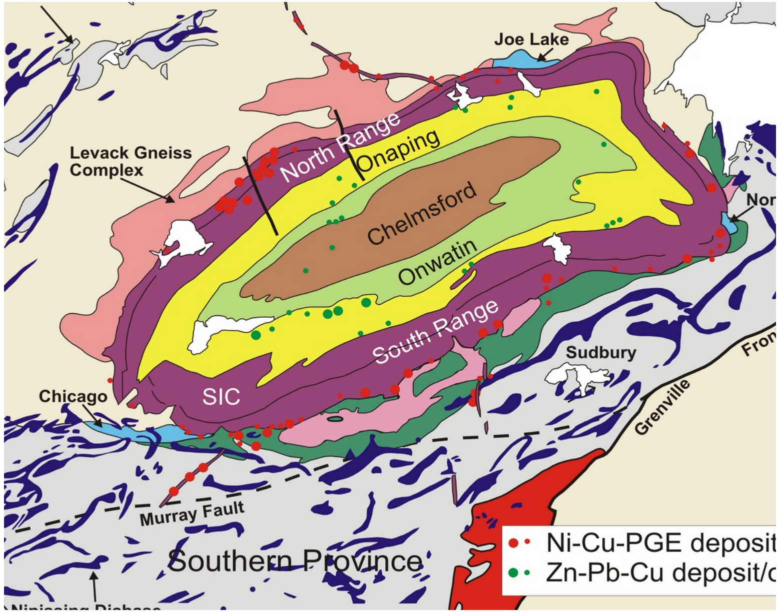


- Largest producer of bedrock Ni for a century.
- Good example of how models for mineral deposit formation have changed through time (hydrothermal to magmatic) and how out-of-the-box thinking has resulted

Impact site for 1.85 Ga bolide which created melt sheet

Sudbury Ni-Cu-PGE, Canada

- Sub-circular structure (due to later defm.).
- Superior Province (2.8 Ga Levack gneiss) in north and Proterozoic (2.4 Ga; Huronian Gp.) rocks to south.
- Structure formed by bolide (10 km) impact at 1.85 Ga.
- Transient crater of 200 km formed with fall back breccia (Onaping Fm.)
- Impact produced a melt sheet (avg. upper crust) due to heating >2000°C that later crystallized to granophyre (60%) at top and norite-gabbro (40%) at the base.
- Breccia bodies produced by shock waves beneath the melt sheet (Sudbury Breccia).
- Magmatic sulphide deposits (Ni-Cu-PGE) formed at base of SIC and in the footwall rocks in variety of settings.



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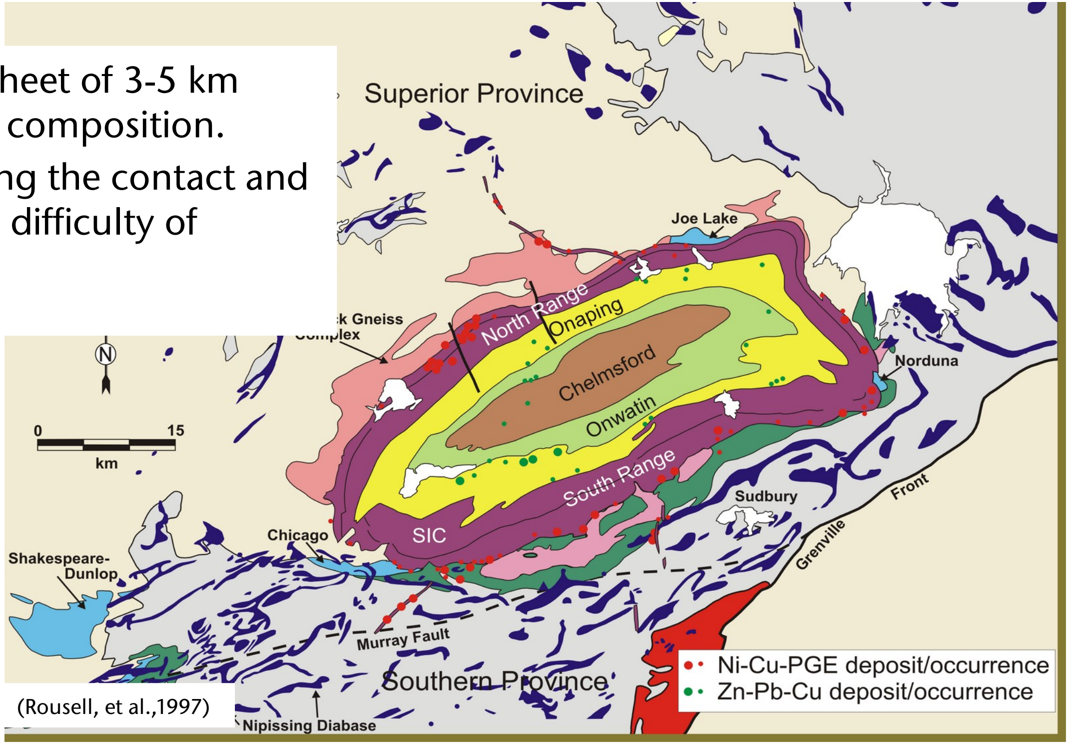
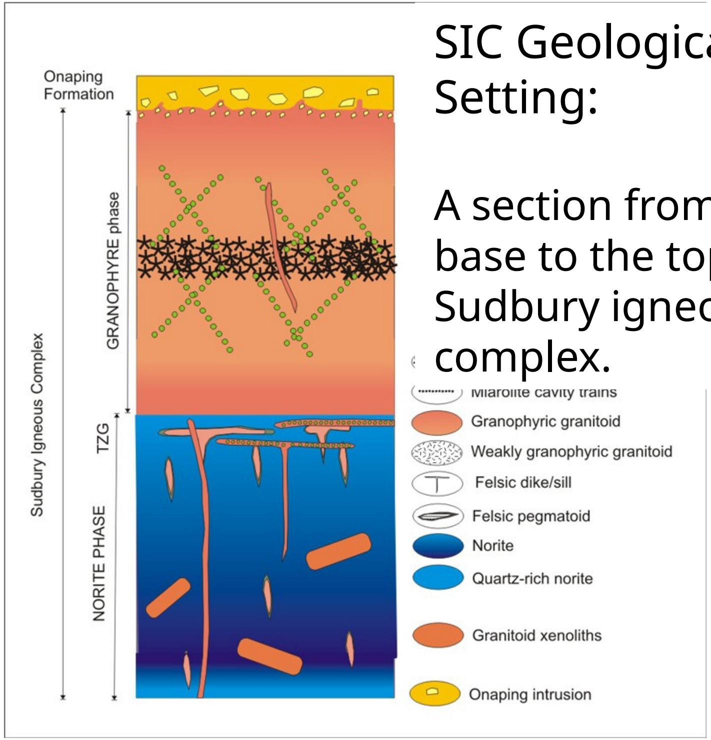
Sudbury Ni-Cu-PGE, Canada

- Bolide generated a melt sheet of 3-5 km thickness of quartz diorite composition.
- Note that deposits are along the contact and none in the middle due to difficulty of exploration and cost.



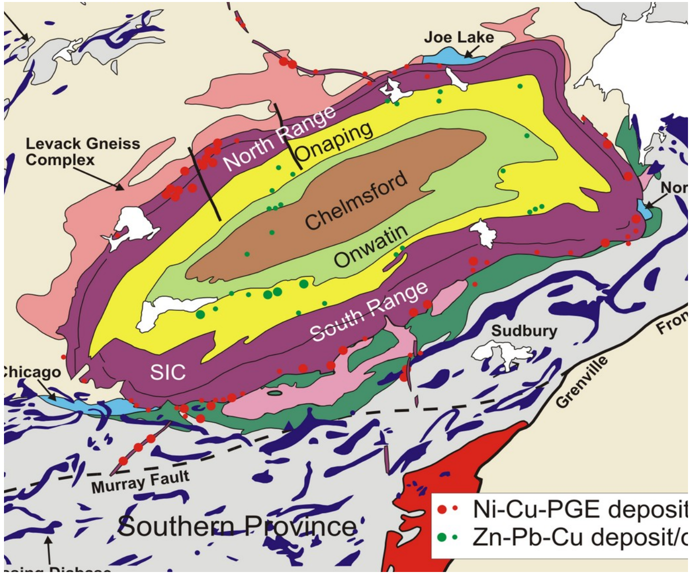
(Rousell, et al.,1997)

Sudbury Ni-Cu-PGE, Canada



SIC Geological Setting:

A section from the base to the top of the Sudbury igneous complex.



- SIC records cooling from top down and bottom up…

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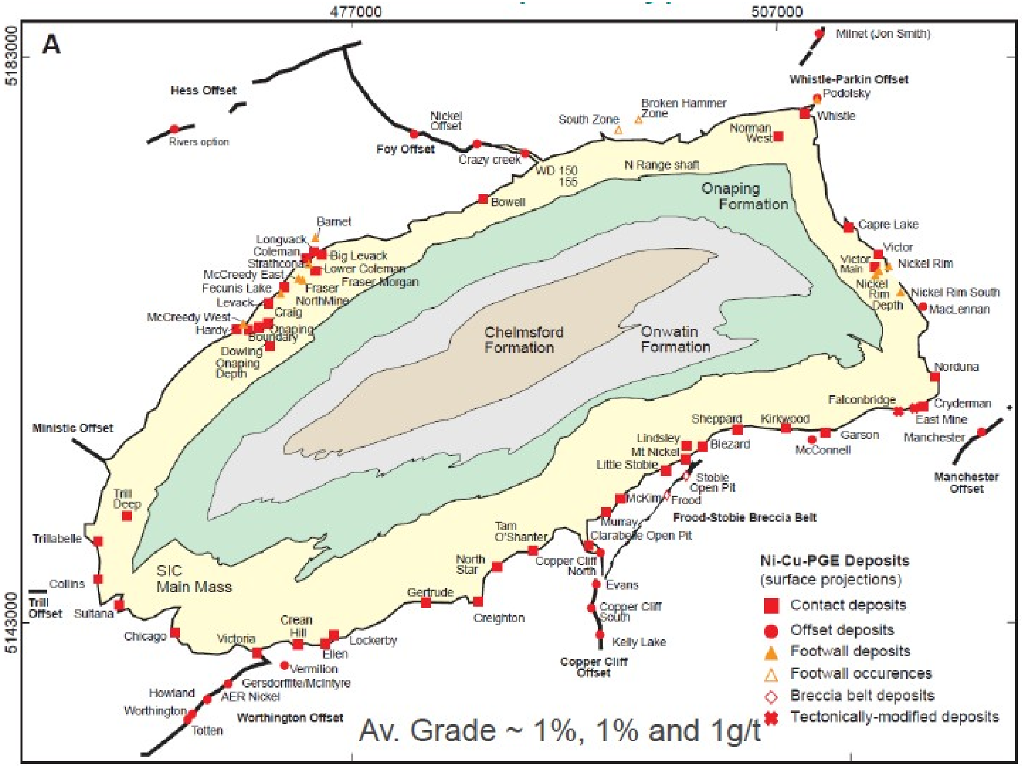
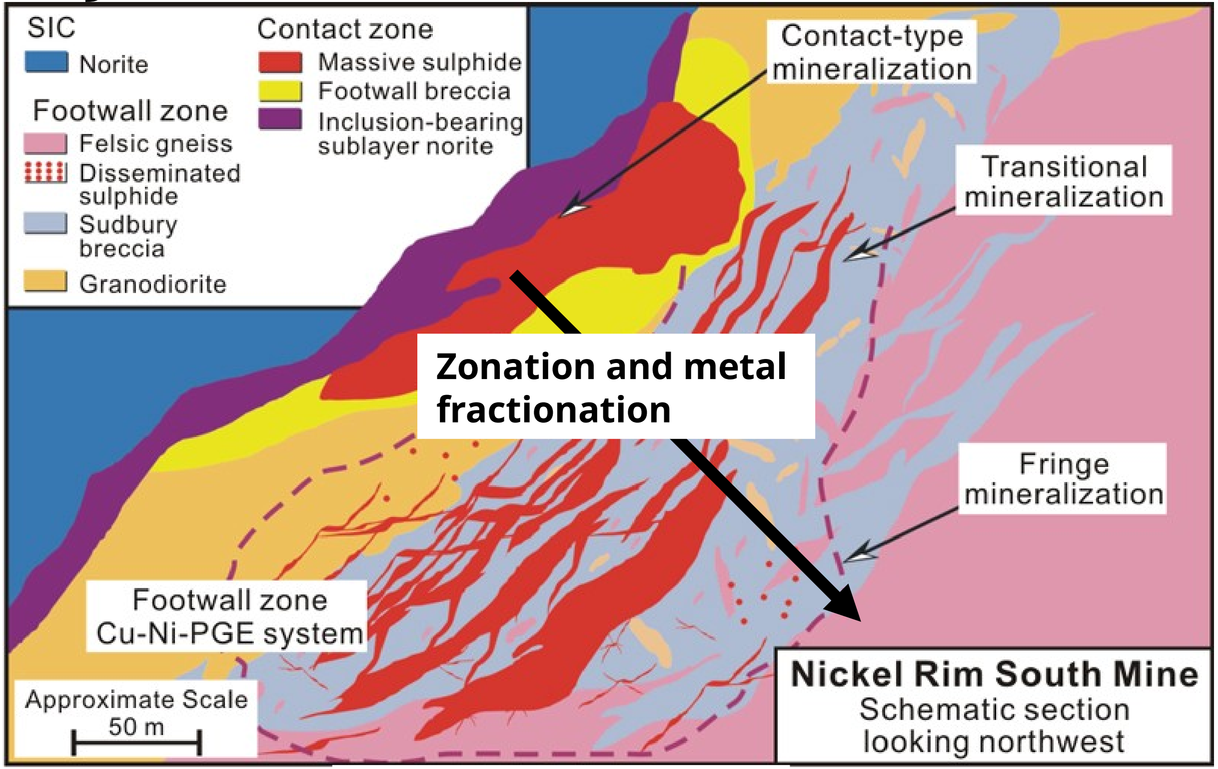
Sudbury Ni-Cu-PGE, Canada

Different types (locations) of deposits

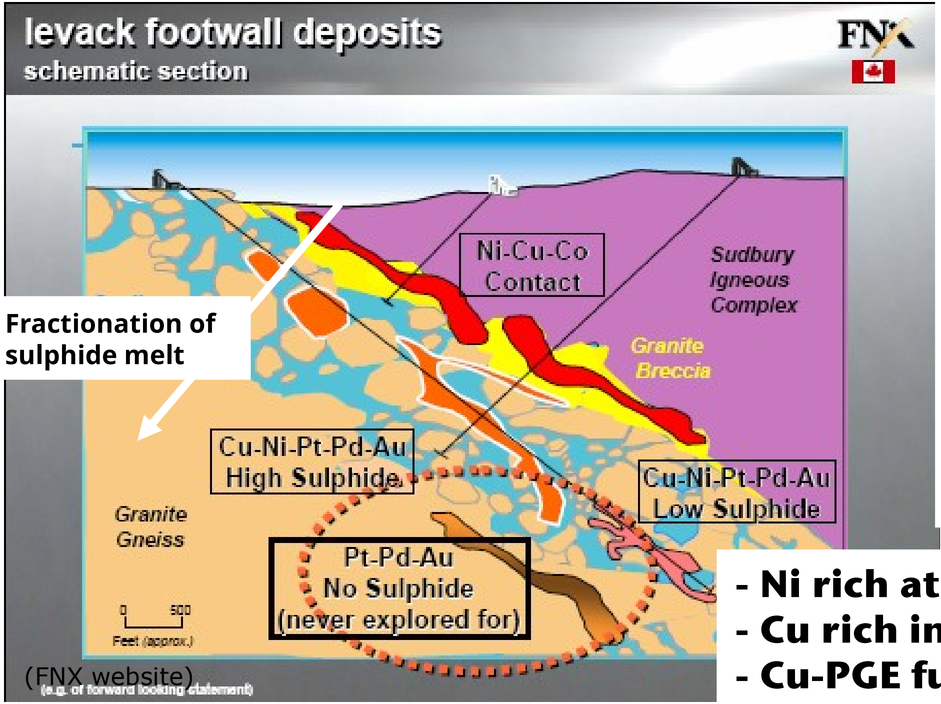


Sudbury Ni-Cu-PGE, Canada



Nickel Rim South (from Ames, GSC website)

Sudbury Ni-Cu-PGE, Canada



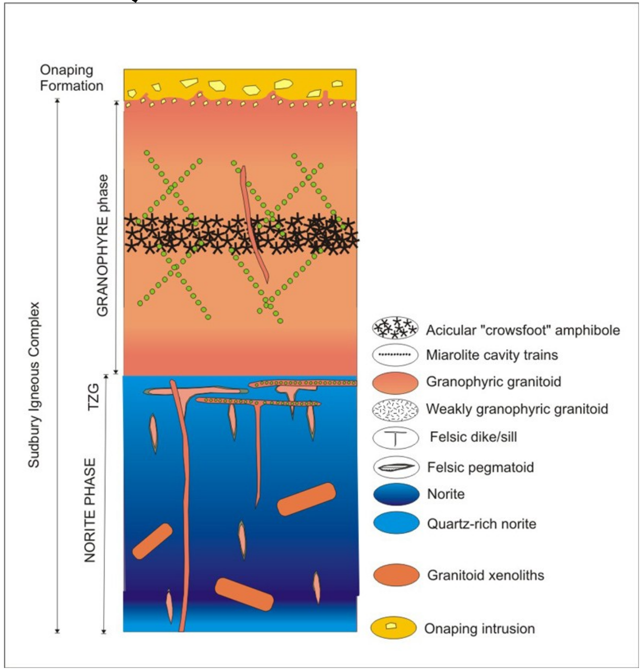
(FNX website)

Fractionation of sulphide melt

- Note the depletion or enrichment trends in the Ni-Cu-PGE ores from top to bottom.
- There is a T gradient from the Ni-rich to the Pt-Pd-Au -rich and sulphide-poor residuum of the fractionated melt.
- **This is a working model, which one MUST use for successful exploration.**

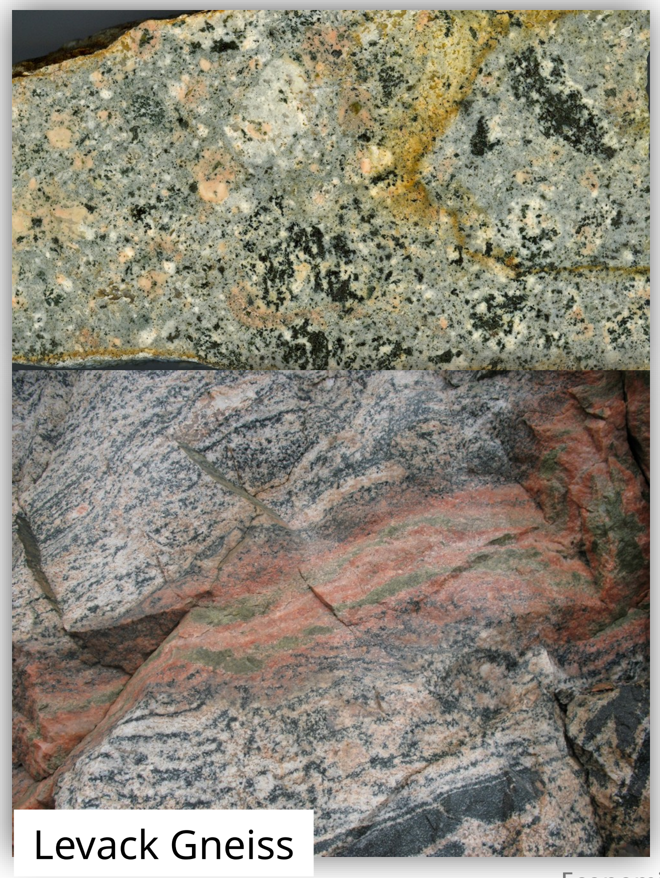
- Ni rich at the base of SIC/contact
- Cu rich into the footwall
- Cu-PGE further into footwall
- Note low sulphide ore furthest away

Sudbury Ni-Cu-PGE, Canada

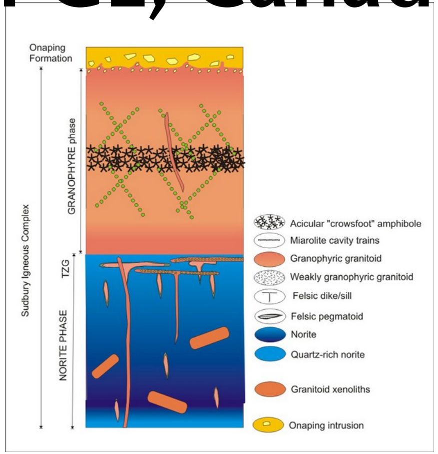


SIC Geological Setting:

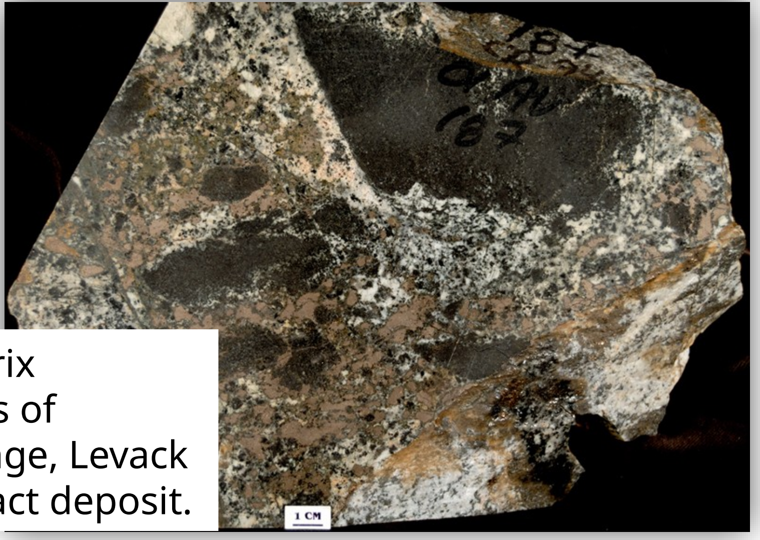
A traverse from the base to the top of the SIC



Sudbury Ni-Cu-PGE, Canada

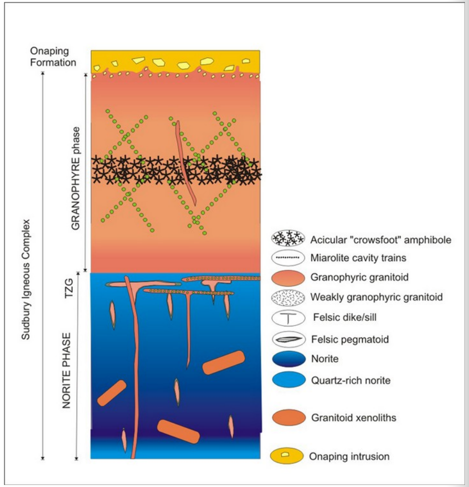


Leucocratic Footwall Breccia; host rock to most of the North Range contact Ni-Cu deposits.

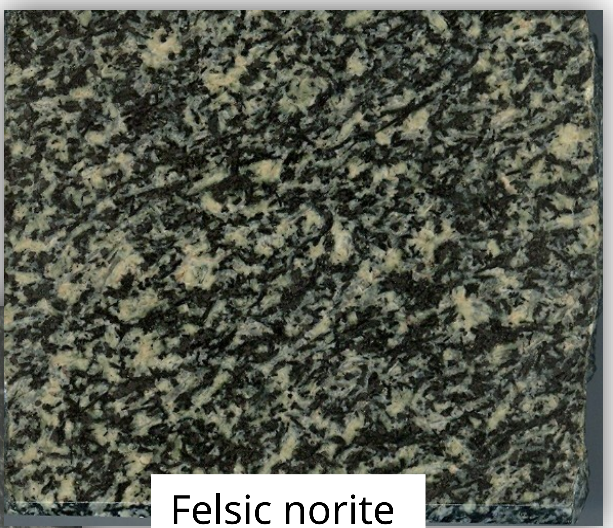


Mineralized Footwall Breccia, a matrix supported rock with lithic fragments of basement rock, from the North Range, Levack embayment; Craig mine Ni-Cu contact deposit.

Sudbury Ni-Cu-PGE, Canada



Sudbury Breccia – matrix of rock flour and melt (?) with fragments



Felsic norite

Mafic norite

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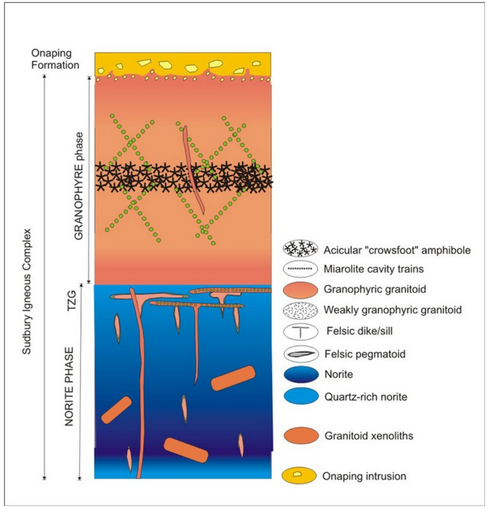
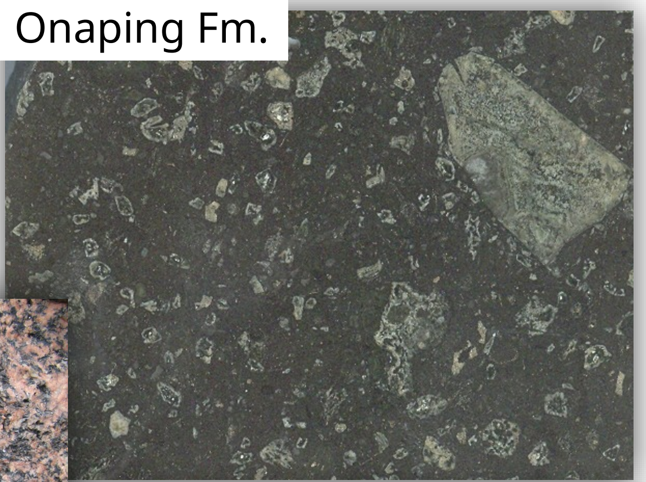
Sudbury Ni-Cu-PGE, Canada



Granophyre

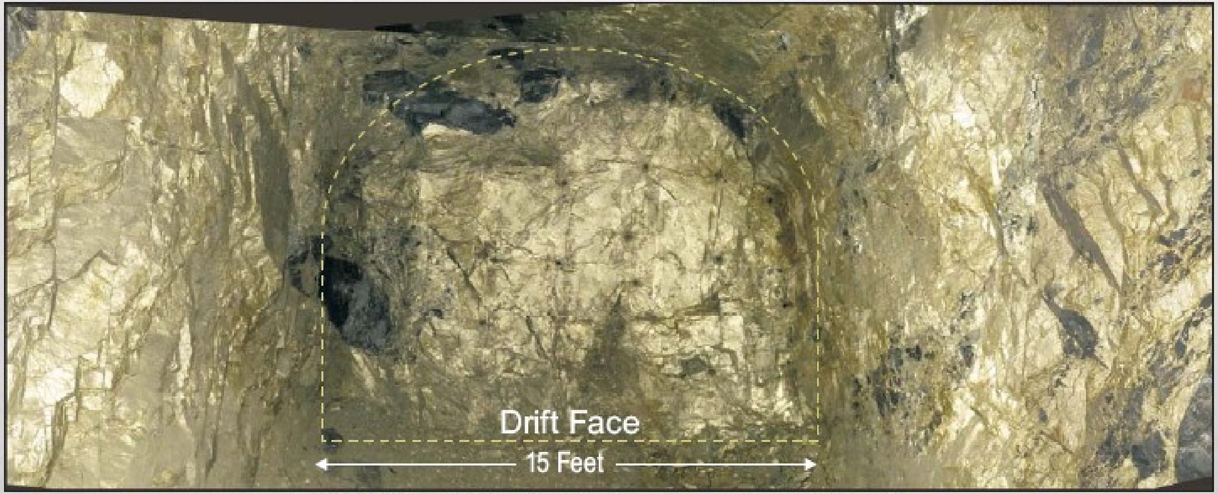
Onaping Fm.



Onaping Fm. (photos, D. Ames GSC)

Sudbury Ni-Cu-PGE, Canada

Podolsky Mine - 2450 Level Active Drift
(FNX Mining Company, Sept 2007)
This is an extreme case of high-grade sulphide ore in Sudbury



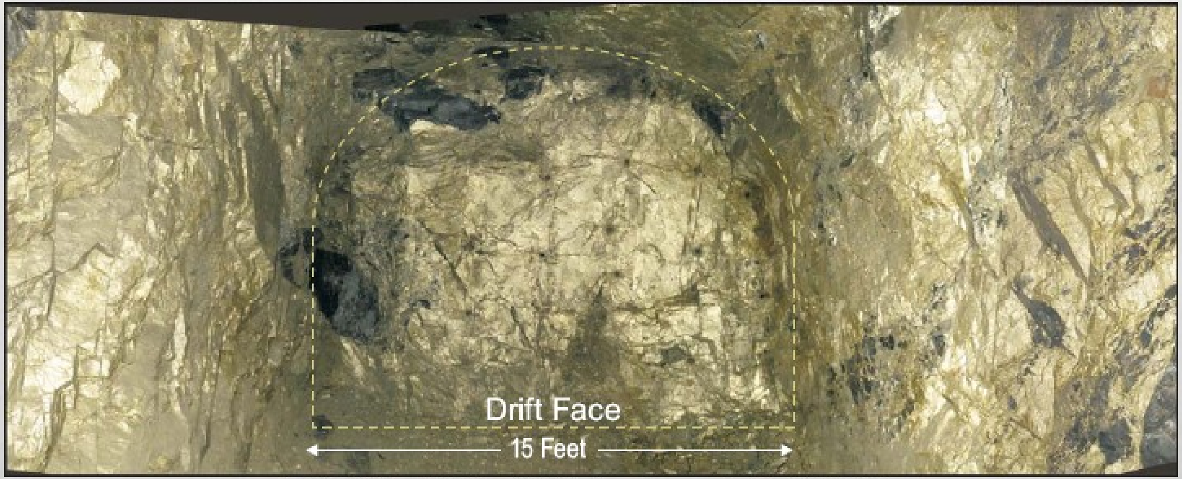
Podolsky Mine - 2450 Level drift intersecting massive Cu-Ni-Pt-Pd-Au mineralization with estimated grade of 20-25% Cu, 1-2% Ni, 0.25-0.75 opt TPM

NI 143-101 indicates a resource for the 2000 deposit of 3.24 Mt of 3.37% Cu, 0.30% Ni and 0.11 oz/t Pt-Pd-Au with inferred resource of 4.86 Mt of 1.16% Cu, 0.15% Ni and 0.04 oz/t Pt-Pd-Au

Sudbury Ni-Cu-PGE, Canada

1. What feature(s) of a sulphide melt will be favorable for its concentration?

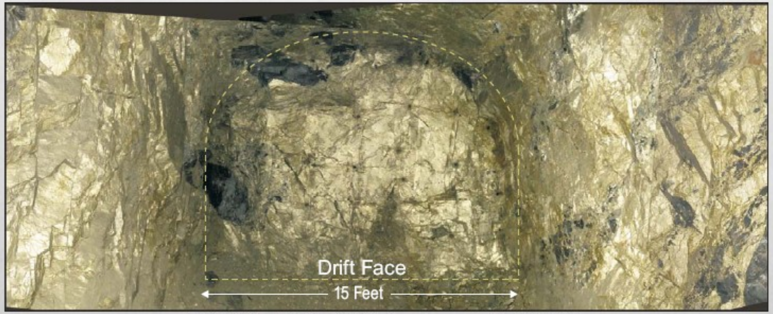
2. Where might you expect to go to find the ore?



Podolsky Mine - 2450 Level drift intersecting massive Cu-Ni-Pt-Pd-Au mineralization with estimated grade of 20-25% Cu, 1-2% Ni, 0.25-0.75 opt TPM

Sudbury Ni-Cu-PGE, Canada

1. The density of sulphide melt favors concentration in depressions
2. The high T of the sulphide melt permits thermal-chemical erosion and generation of traps.
3. Any setting where a change in flow velocity of melt occurs may cause settling of sulphide melt (e.g., Voisey's Bay).

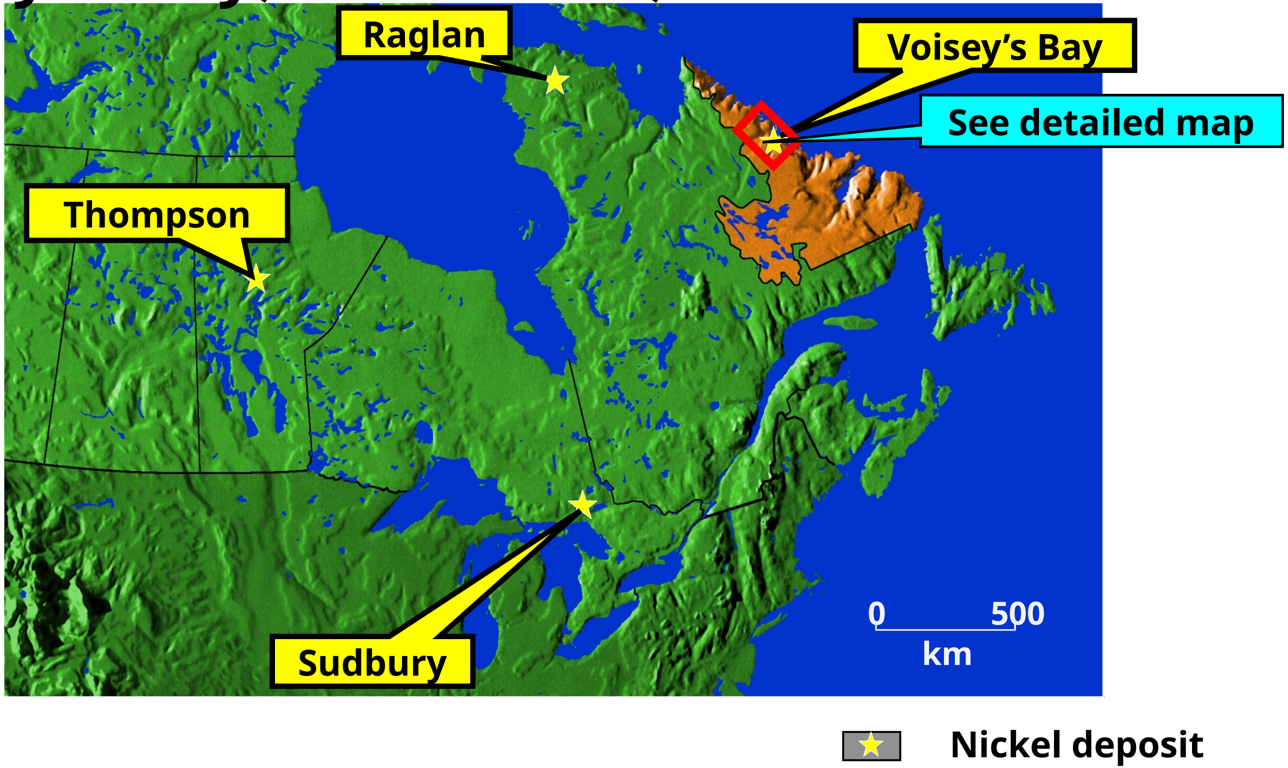


Podolsky Mine - 2450 Level drift intersecting massive Cu-Ni-Pt-Pd-Au mineralization with estimated grade of 20-25% Cu, 1-2% Ni, 0.25-0.75 opt TPM

Voisey's Bay, Ni-Cu-Co, Canada


Peter C. Lightfoot and the staff of VBNC

Voisey's Bay, Ni-Cu-Co, Canada



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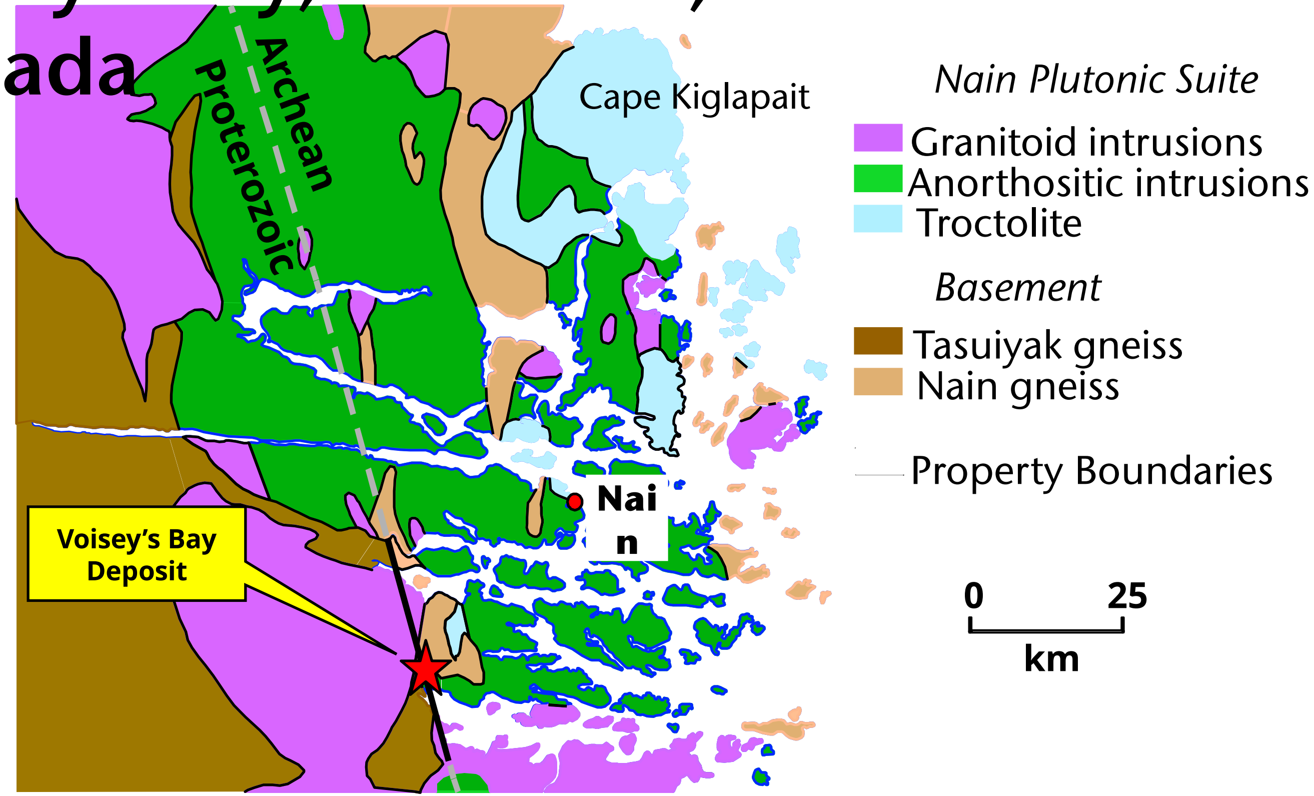
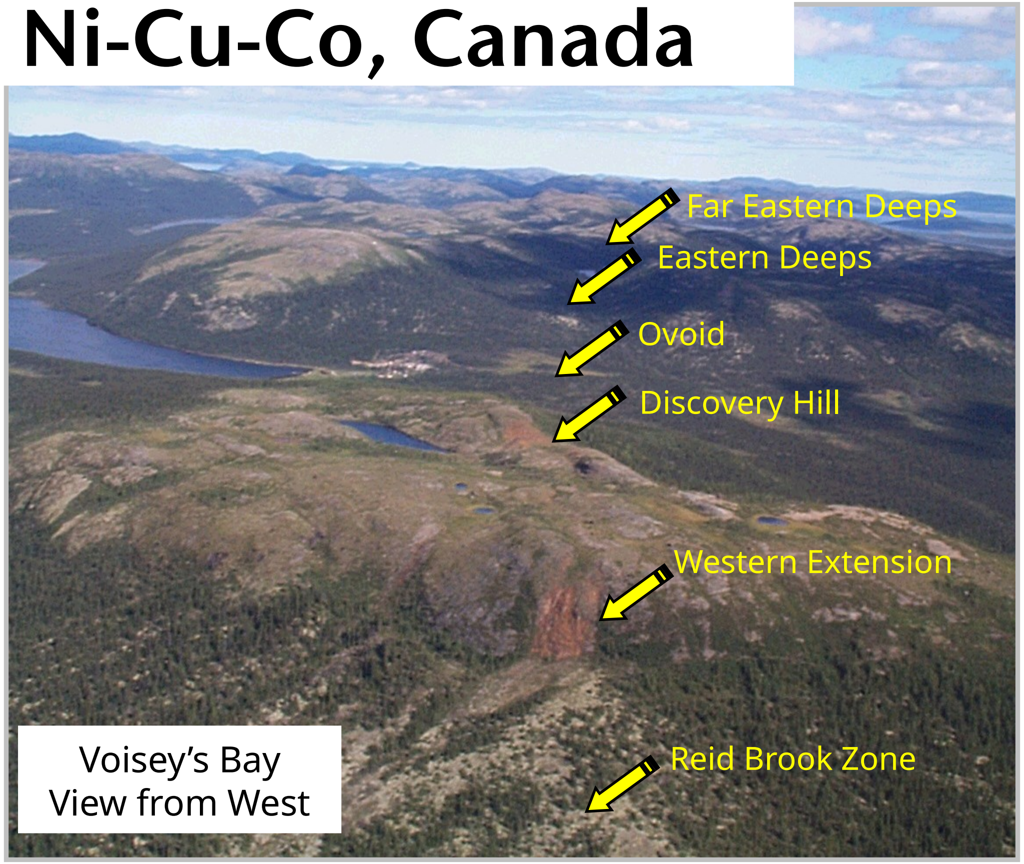
Voisey's Bay, Ni-Cu-Co, Canada



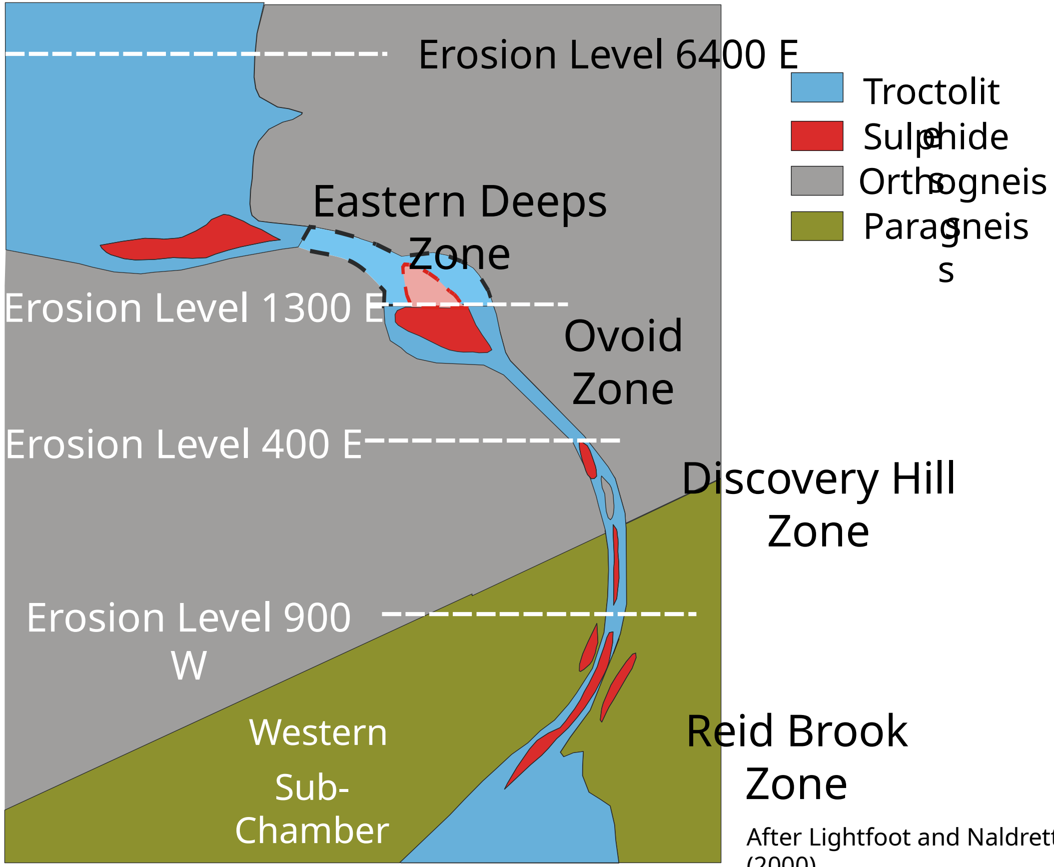
Voisey's Bay, Ni-Cu-Co, Canada

Voisey's Bay, Ni-Cu-Co, Canada

Voisey's Bay, Ni-Cu-Co, Canada



Voisey's Bay, Ni-Cu-Co, Canada



After Lightfoot and Naldrett (2000)

*Supergene Ni deposits

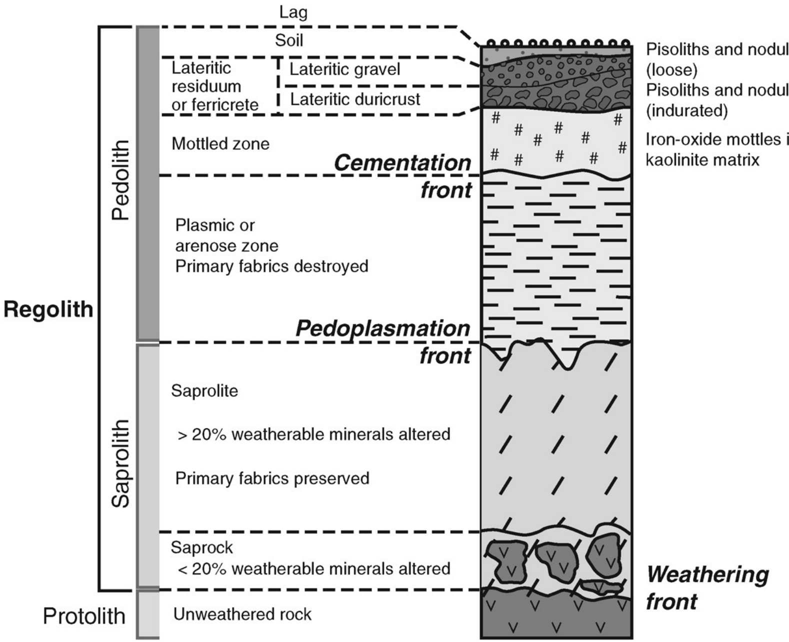
Supergene ore-forming processes

- Ores are formed as a result of weathering and chemical reactions between meteoric water and rock. Type of mineralization depends on the rock to be leached.
- Secondary minerals that are residual and relatively insoluble. The soluble elements are transported away and the insoluble ones become concentrated.
- Orebody laterally extensive, but not thick (10s m).
- High grade, large tonnage.

***Supergene:** genesis at or near Earth surface

Supergene Ni deposits

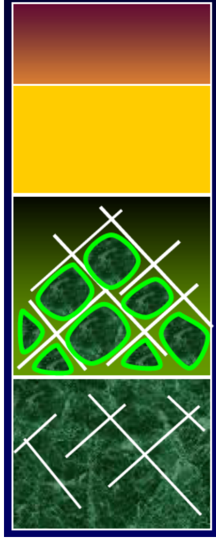
The chemical processes include dissolution, oxidation, hydrolysis and acid hydrolysis.



Humid, warm climates with deep chemical weathering

Supergene Ni deposits

Laterite Zones | **Processes at work**



"Red" Hematite
"Yellow" Limonite

- Acidic environment
- Collapsed profile
- "Soluble" ions leached (Ca, Mg, Si, Na, K)
- "Insoluble" ions concentrated (Cr, Al, Fe)
- Mn, Co show supergene enrichment

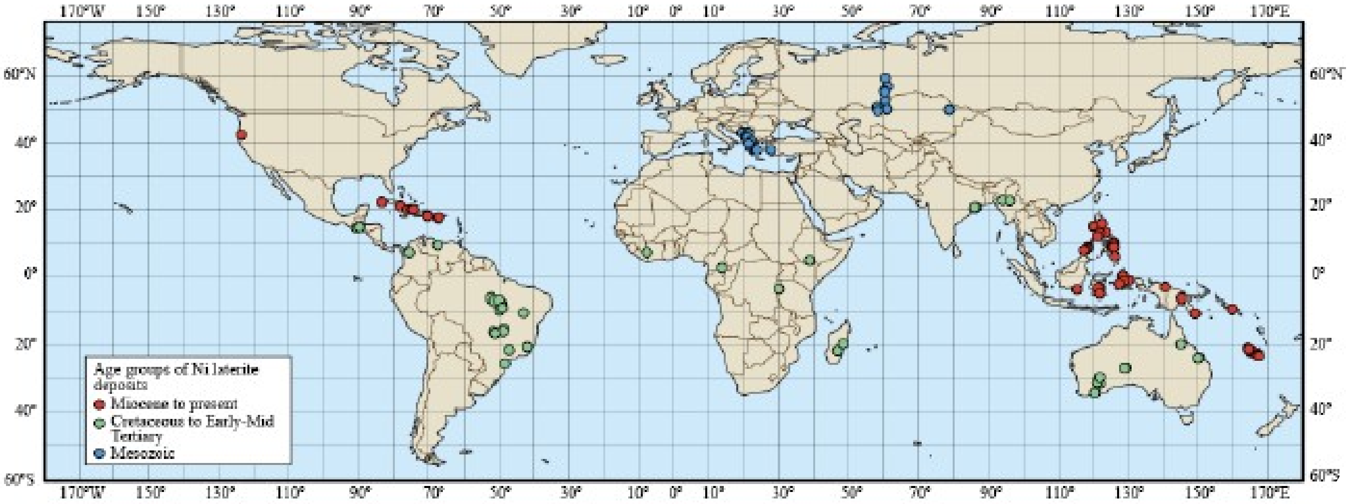
Saprolite zone

- Alkaline environment
- Un-collapsed profile
- Leaching/residual concentration in progress
- Boulder formation
- Ni shows supergene enrichment

Bedrock zone

- Alkaline environment
- Joints / fractures exposed to U/G water
- Chemical attack is just beginning
- Channelways provide removal of dissolveds

Supergene deposits



Berger et al 2011

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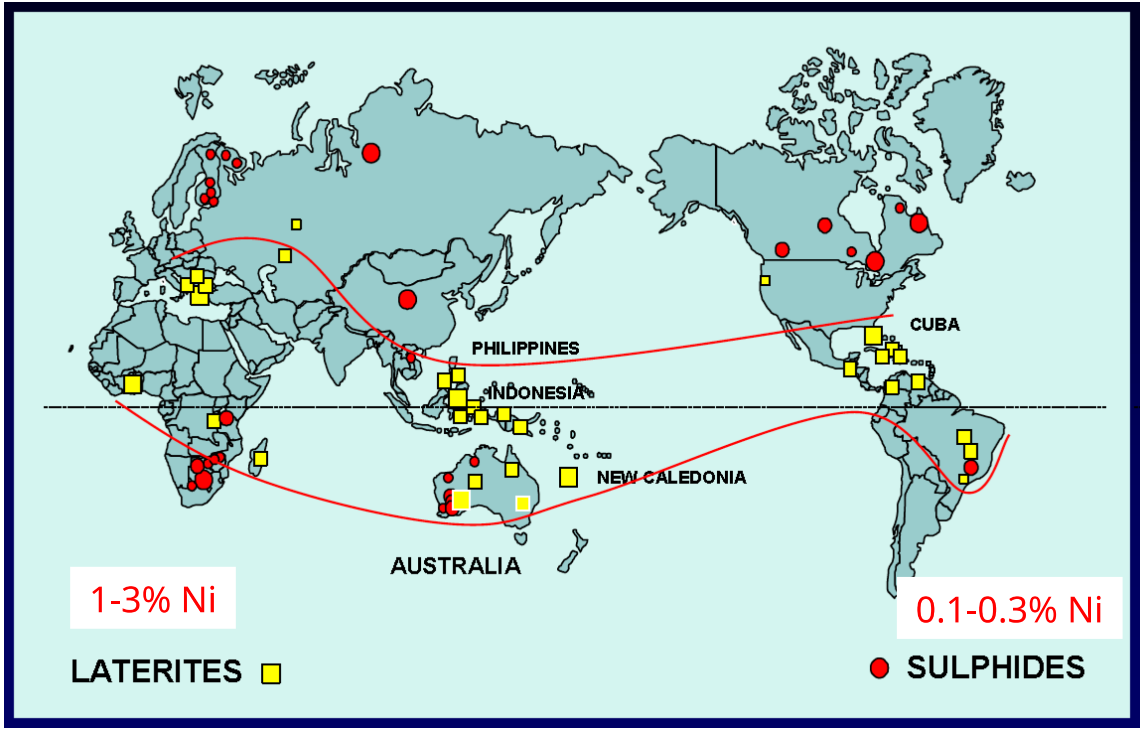
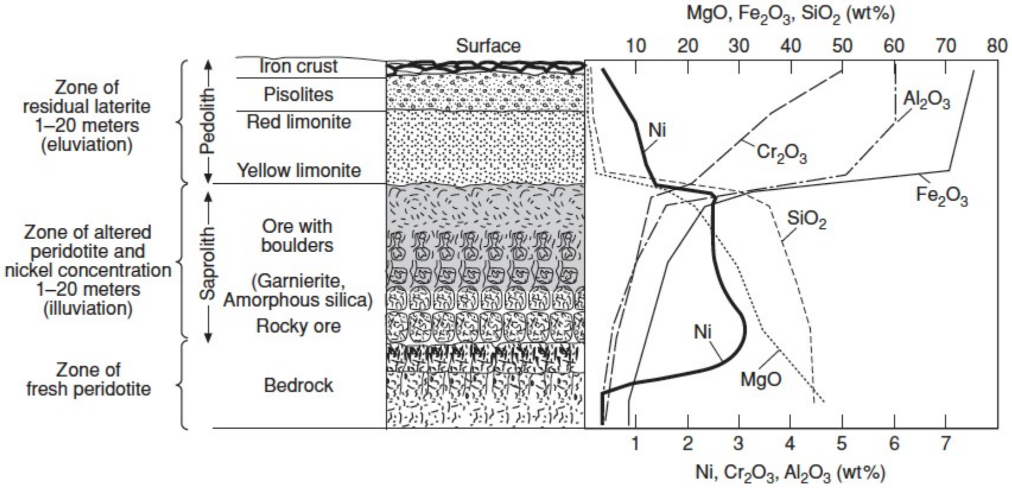
Supergene Ni deposits

Ore grade is typically higher in supergene deposits than the hypogene sulphide deposits.



Supergene Ni deposits

Bedrock was ultramafic and is easily weathered. Up to 90% of the original rock is dissolved. Main minerals olivine and orthopyroxene breakdown due to oxidation (Fe2+-3+ results in charge imbalance, weakness in structure) and hydrolysis.



Ni is insoluble and its original conc. of about 2000ppm becomes enriched 10x in the formation of clays and serpentinite and is moved.

Ni gets removed from uppermost laterite to an underlying saprolite.

Once smectite, serpentinite and talc are formed cation exchange occurs between Mg and Ni. Leads to Ni- clays, Ni-talc, Ni-serpentine **(= garnierite**)

Supergene Ni deposits

Nickel as hydroxide essentially in the goethite-limonite ($Fe_2O_3.nH_2O$) structure. Some Ni adsorbed in Mn-O / Mn-OH.

Nickel as hydro-silicate essentially with the talc-serpentine lattice structure:

Nickel talc: $(Mg,Ni)_3Si_4O_{10}(OH)_2$

Nickel serpentine: $(Mg,Ni)_3Si_2O_5(OH)_4$

Nickel as silicate essentially in the olivine lattice structure, as ionic replacement of Mg and Fe atoms:

Olivine: $(Mg,Fe)_2SiO_4$

Pyroxene: $(Mg,Fe)_2Si_2O_6$

Supergene Ni deposits

	Mafics	Spinels	Clays	Oxides & Hydroxides	Nickel Silicates
Primary igneous minerals	Olivine Pyroxene	Magnetite Chromite			
Hydro-thermal minerals	Serpentine Talc Chlorite	Magnetite			
Secondary Laterite weathering minerals	Serpentine Talc Chlorite		Kaolinite Smectite: (Mont-morillonite) (Nontronite) Illite Mixed Layer	Silica Hematite Goethite Limonite Bauxite Gibbsite	Nepouite Willemsite Pimellite Connarite Falcondite Nimite Noumeite

Contain Ni from primary minerals

Garnerite

Cation exchange (Mg –Ni)

Supergene Ni deposits

Ni laterites

Supergene Ni deposits

Ni laterites

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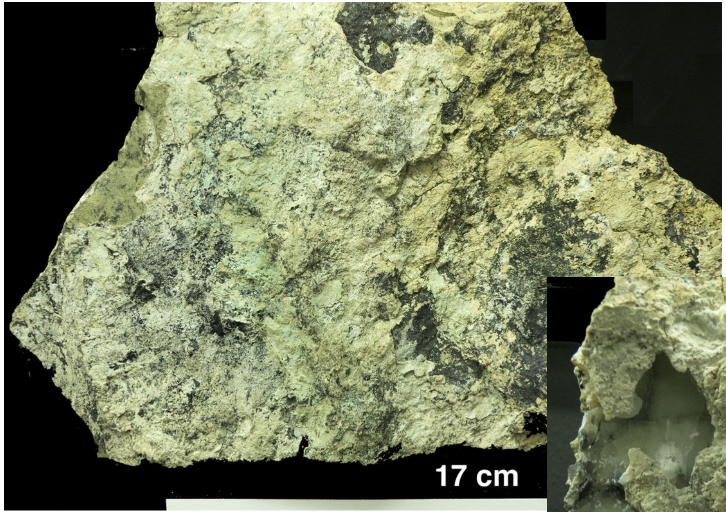
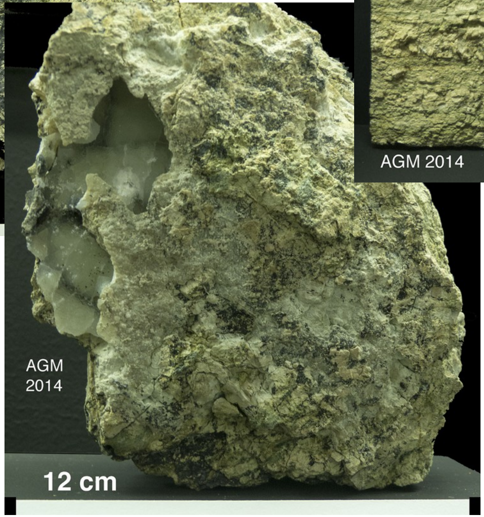
Supergene Ni deposits





Ni laterites

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Institute for Disposal Research

Cr

Chromium
Cr
24 51.996

- Chromium
- Uses of chromium
- Chromite deposits
  - Podiform deposits (ophiolites)
  - Stratiform deposits (layered intrusions)

Chromium

Chromium
Cr
24 51.996

- Cr is hard and silvery
- Ore mineral(s): chromite $FeCr_2O_4$
- Top suppliers: South Africa, Kasachstan, Turkey/India
- Reserves: 570Mio t
- Resources: 12Mrd t

Chromite

USGS 2022

Chromium uses

Chromium
Cr
24 51.996

- Mainly in steel hardening, alloys
- Tanning of leather
- Glass colouring
- Plating

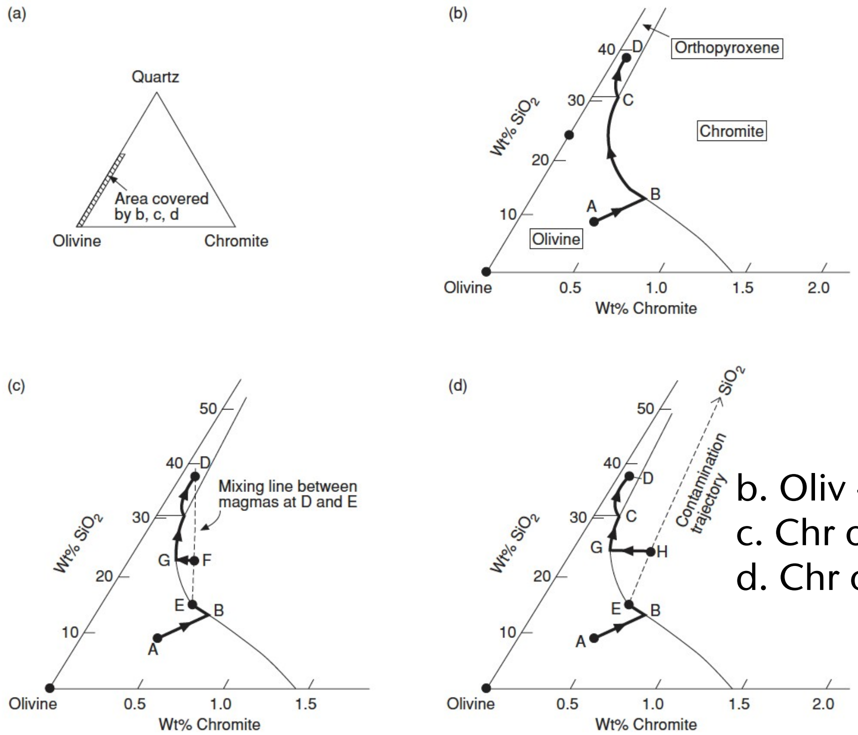
Chromite deposits

- Magmatic deposits, chromite crystallization from a mafic or ultramafic melt.
- Stratiform and podiform types.
- High grade, high tonnage.
- Ore body laterally extensive along thin beds/layers

Chromite deposits

The Irivne model

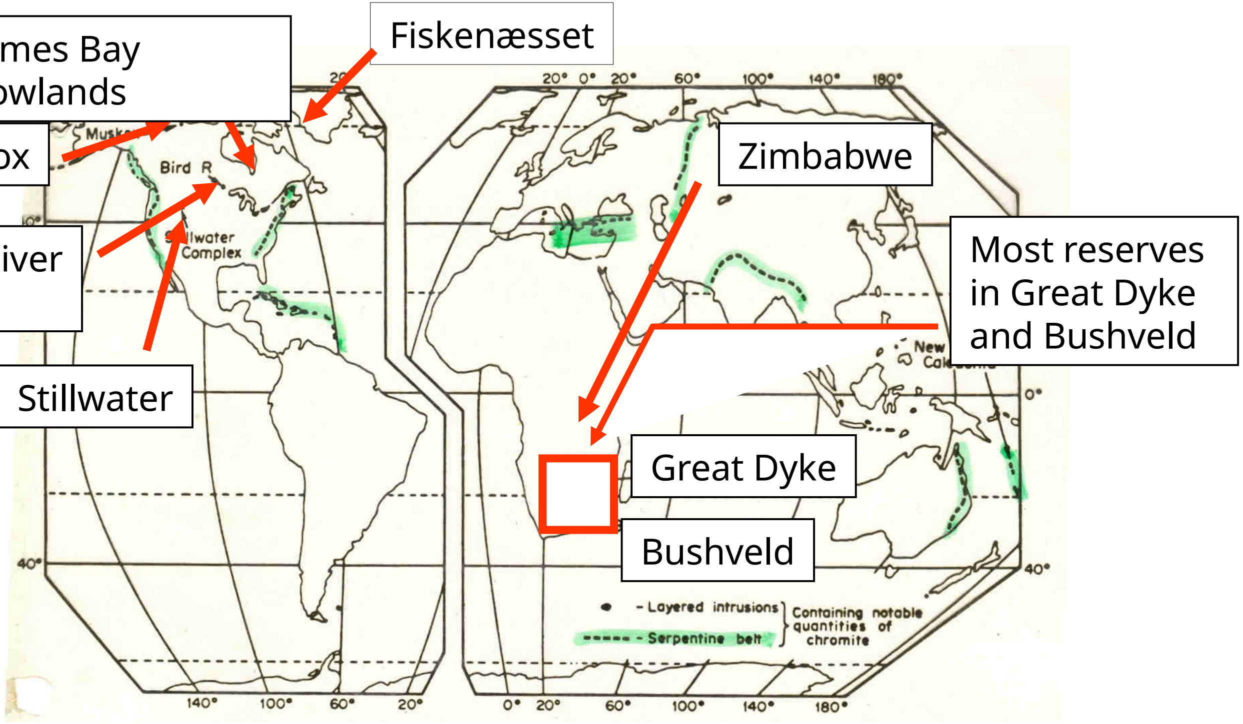
- Magma mixing
- Contamination



b. Oliv + Chr
c. Chr only
d. Chr only

Distribution of major chromite deposits

- Layered intrusions are labeled and the green belts are the Alpine peridotite type (ancient Mountain Belts)



Chromite deposits

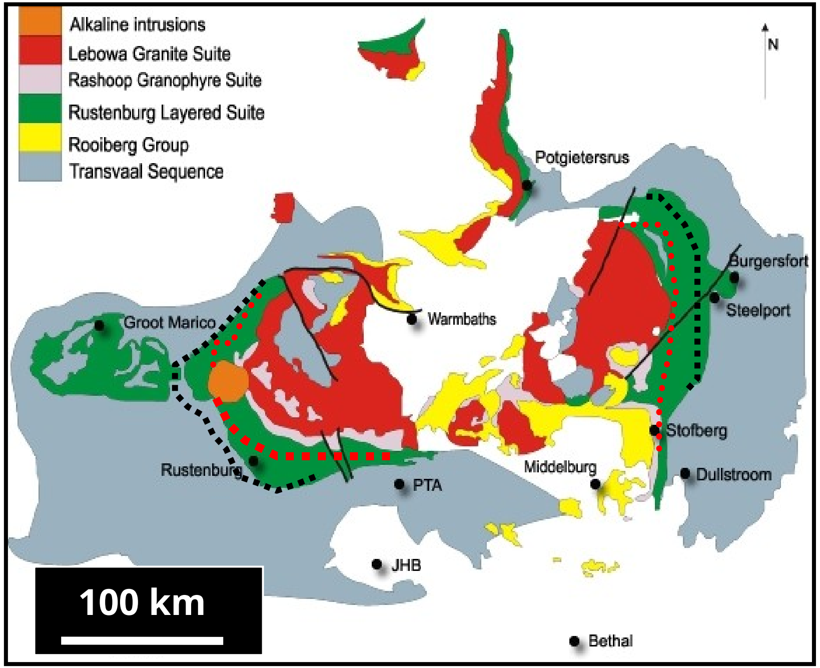
- Cr is only extracted from chromite ($FeCr_2O_4$)
- 75% of the reserves are in South Africa and 23% in Zimbabwe. Lower grade occurrences in Greenland (Fiskenæsset), Canada and Russia.
- Close association to ultrabasic and anorthositic plutons
- 3 types: **stratiform** (Bushveld-type), **podiform** (Alpine-type), or komatiite-related

Chromite deposits

Stratiform Chromite Deposits:

- Monomineralic layers of chromite of cm to 10's m.
- Process extensive in magma chamber – layers 10's km long or 100's km^2.
- Must fit in with evolution of the large layered complexes.
- Thus, chromite is only phase on the liquidus or can separate it from others (e.g., it is heavy and settles).
- The process is repeatable in layered complex since have many chromite seams present in such cases.

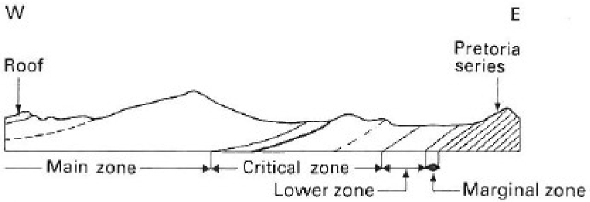
Chromite deposits (Bushveld intrusion)



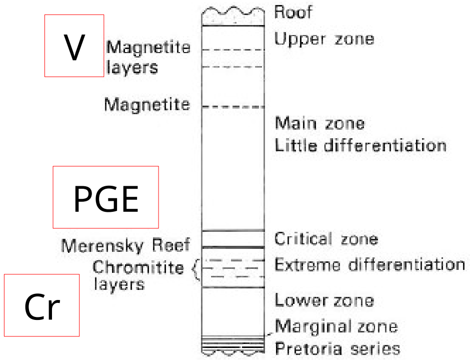
Rustenburg Layered series…hosts Cr, PGE, V mineralization

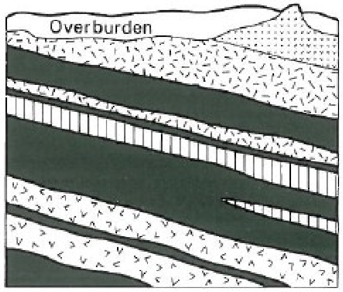
- 2060 Ma
- 240 x 350 Km (66,000 km^2)
- Three large batches of magma – separate lobes
- Maximum of 7 km thickness.
- Cr mineralization shown as dashed lines.
- Average rock composition is gabbroic, whereas for podifrom deposits it is peridotitic (see later)

Chromite deposits (Bushveld intrusion)



Section showing major zones in the Bushveld Complex, north of Steelport. Length of section, 30·5 km. (After Hall, 1932)





Chromitite layers in a section of the Bushveld Complex near Rustenburg.

Mining in the Bushveld area since 1923.

Relatively shallow (300-1400m underground)

Thomas Ulrich
Institute for Disposal Research

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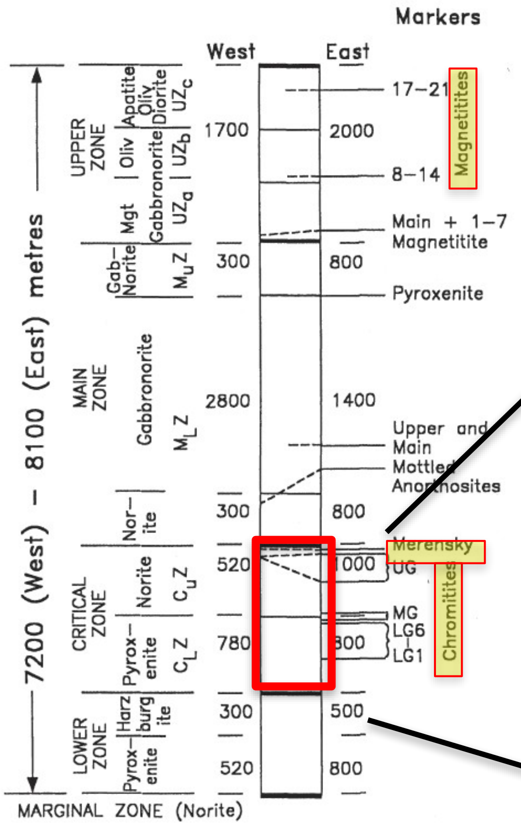
Chromite deposits (Bushveld intrusion)

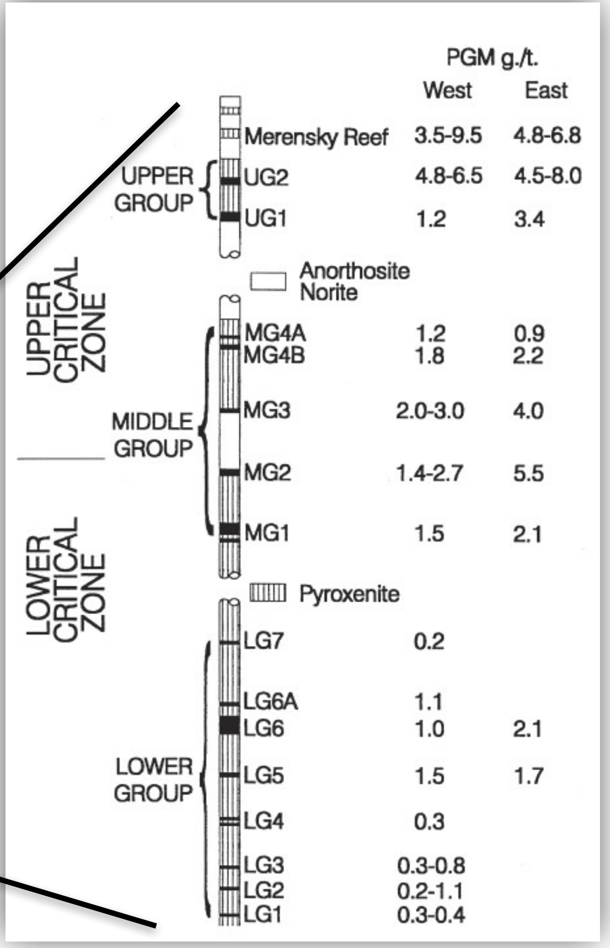
Zone UG1

Chromite layers vary between mm to >1m thick and are laterally extensive (10's km). Several layers stacked on top of each other.

Bushveld stratigraphy



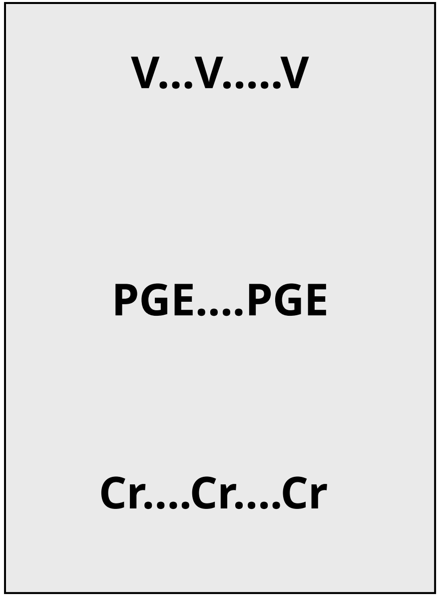
Chromite layers with PGM content



From Cawthorn 1999

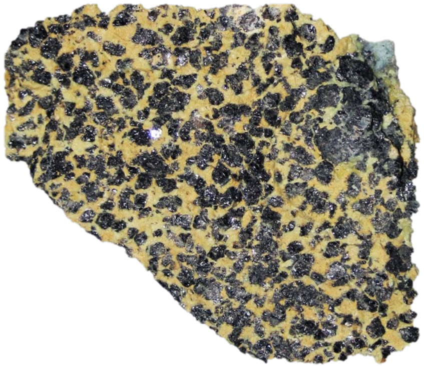
Chromite deposits (Bushveld intrusion)

Nature of layered intrusions and Cr, PGE, V ores



- Large volumes of mafic magma.
- Magma stratifies as crystallization progresses and minerals cumulate with layering developed.
- Mineral composition changes and this is cryptic layering (En in Pyx, An in Plg).
- UM layers at the bottom and more Fe-rich layers at the tops; granophyres overlie the lower mafic part.
- **Ore deposits** - Cr near bottom, PGE’s in middle, and V-rich magnetite towards the top.

Chromite deposits

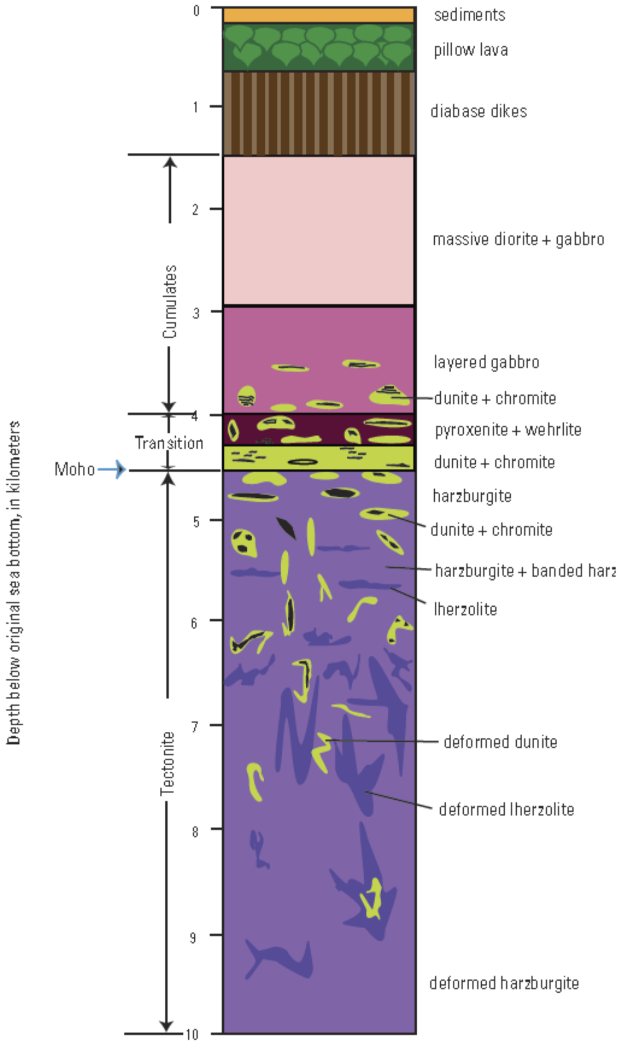

Nodular chromite

Podiform Chromite Deposits:

- Ore as **nodules** of chromite in matrix of serpentinized UM rock – NOT massive chromitite rock.
- Host rocks referred to as "**Alpine-type**" **peridotites** and occur along fault zones (suture zones) in mountain belt. Associated with ultramafic rocks in ophiolites (e.g. Troodos complex, Cyprus).
- Small but important source of refractory grade chromite (>20 % Al_2O_3).

Chromite deposits

- **Ophiolite:** Sequence of oceanic crust that is obducted onto the continental crust
- Generally in ophiolites from marginal basins and not mid-ocean ridges.



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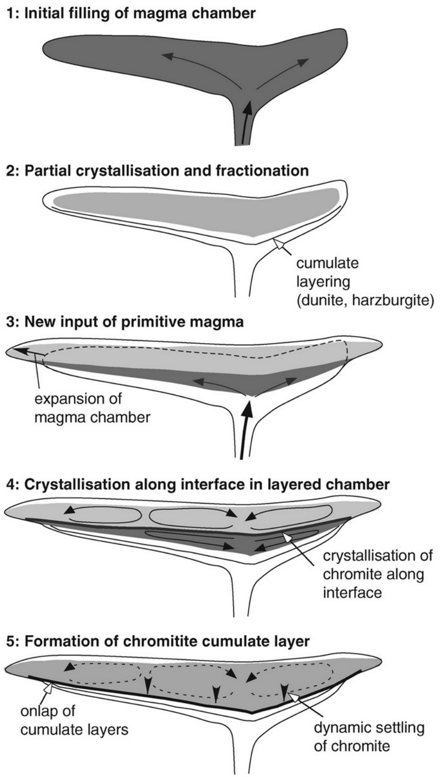
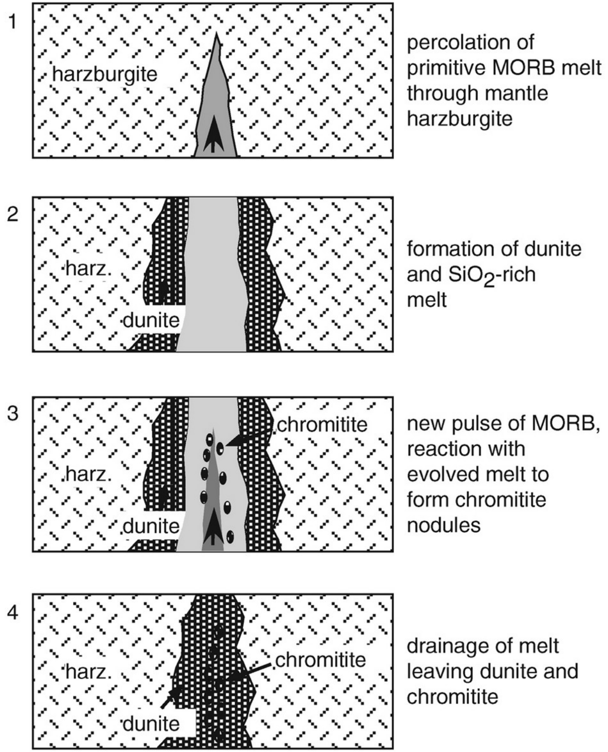
Chromite deposits

Stratiform Cr deposit





Podiform Cr deposit

Cu

Copper
Cu
29 63.546

- Copper
- Uses of copper
- Copper deposits
  - Porphyry Cu-(Mo) deposits
  - Sedimentary Cu deposits (Kupferschiefer)
  - Volcanic massive sulfide deposits (VMS)

Copper

- Reddish metal, easily workable
- Ore mineral(s): chalcopyrite $FeCuS_2$, bornite, chalcocite
- Top supplier: Chile, Peru, China
- Reserves: 890Mio t
- Resources: 2.1Mrd t

chalcopyrite

USGS 2022

Copper uses

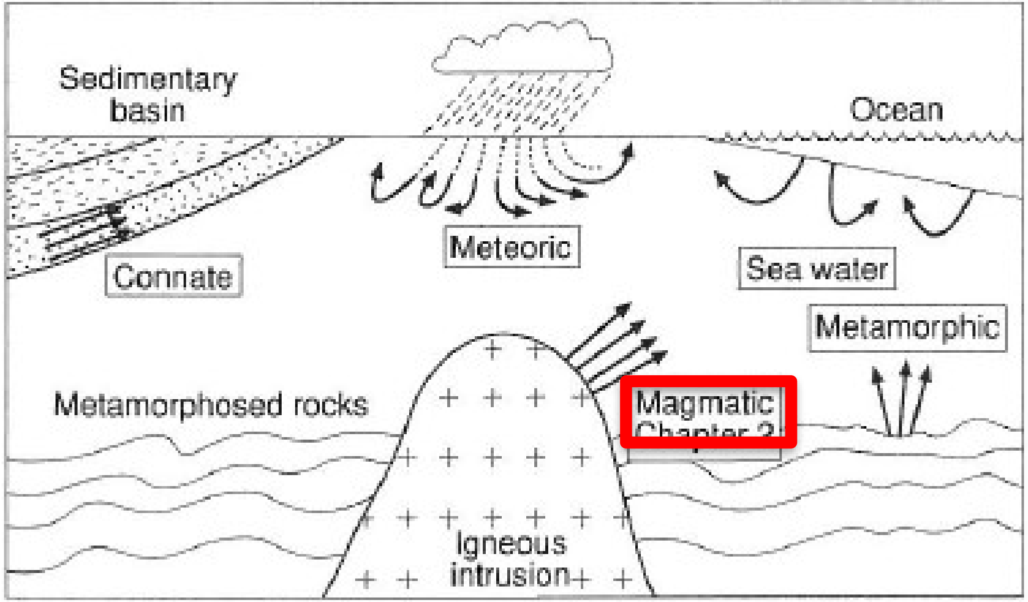
Copper
Cu
29 63.546

- Construction
- Wires
- Electronics

Porphyry Cu-(Mo) deposits

- Magmatic hydrothermal deposits

Fluids exsolved from a magma.



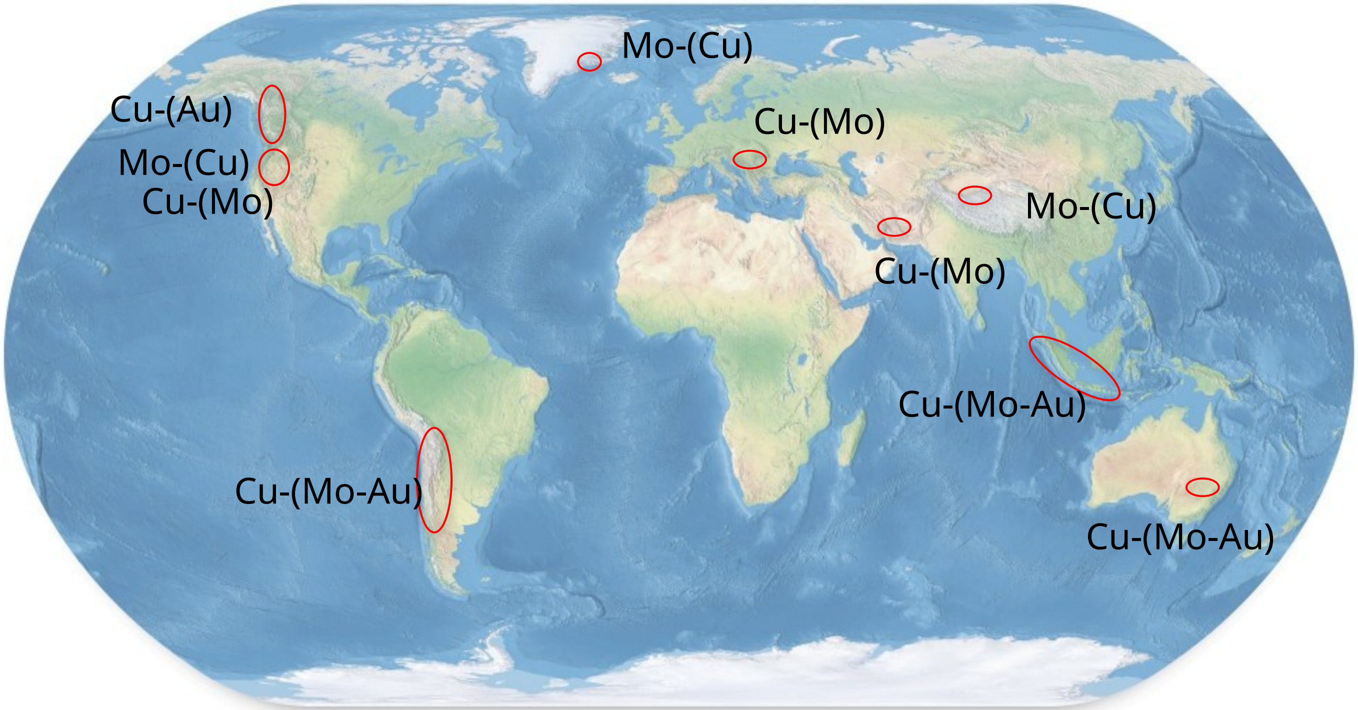
Magmatic-hydrothermal deposits

- Magmatic fluid transporting and dispositioning metals.
- Metals come from a magmatic source.
- Typical alteration types.
- Mineralization in thin veins and disseminated.
- Low grade, high tonnage.
- Ore body concentric (inverted cup)

Thomas Ulrich
Institute for Disposal Research

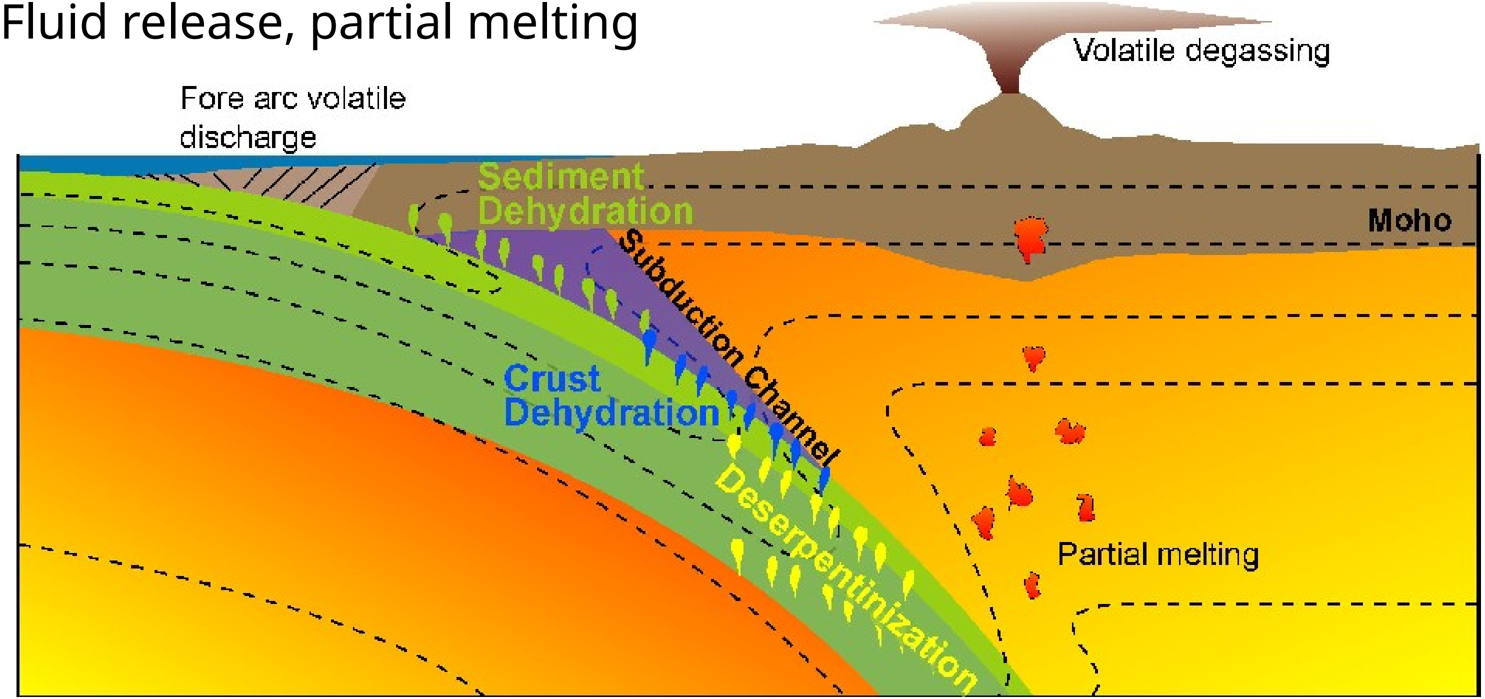
Porphyry type deposits

Two main groups: Cu-(Mo-Au) and Mo-(Cu), others Sn and W

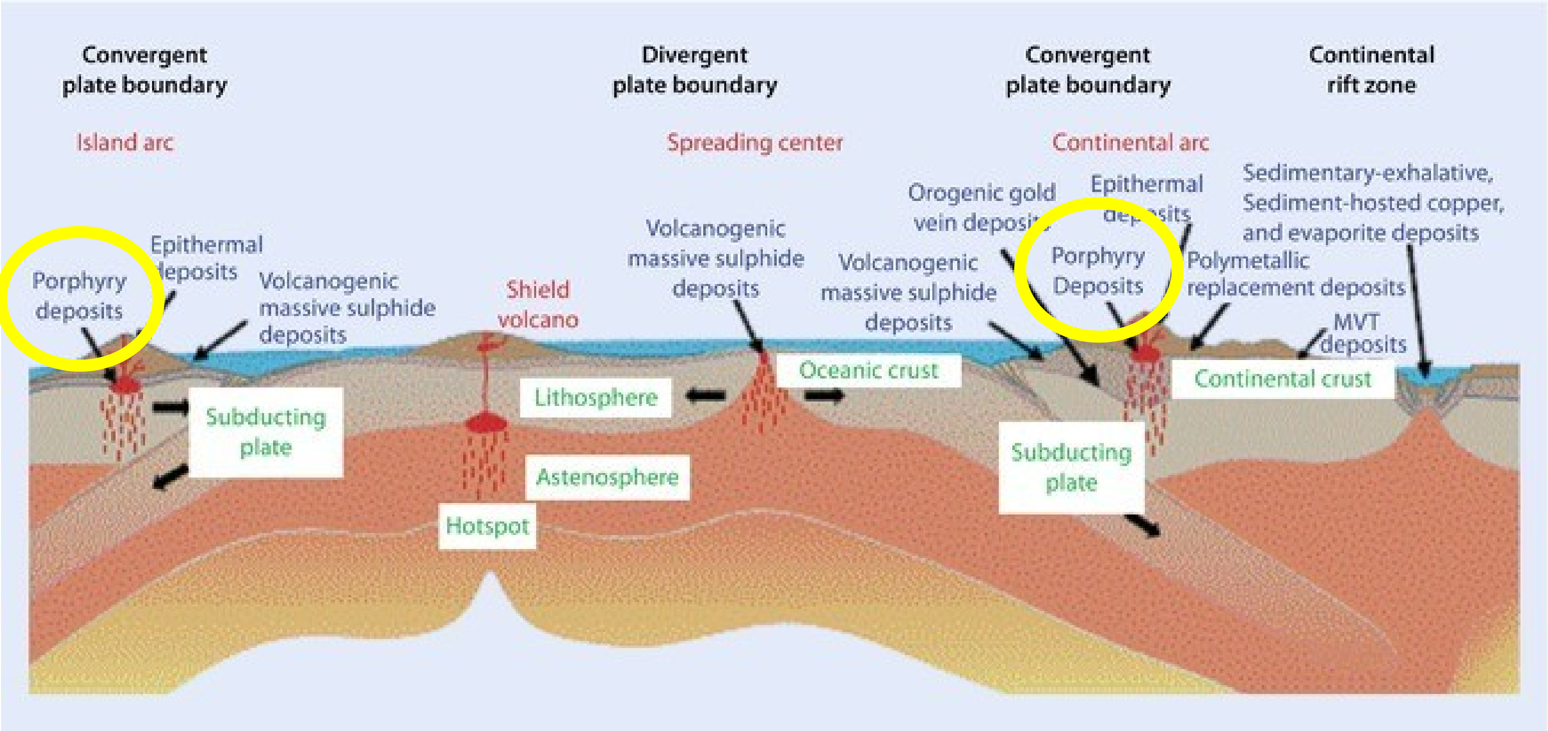


Subduction zones (convergent plates)

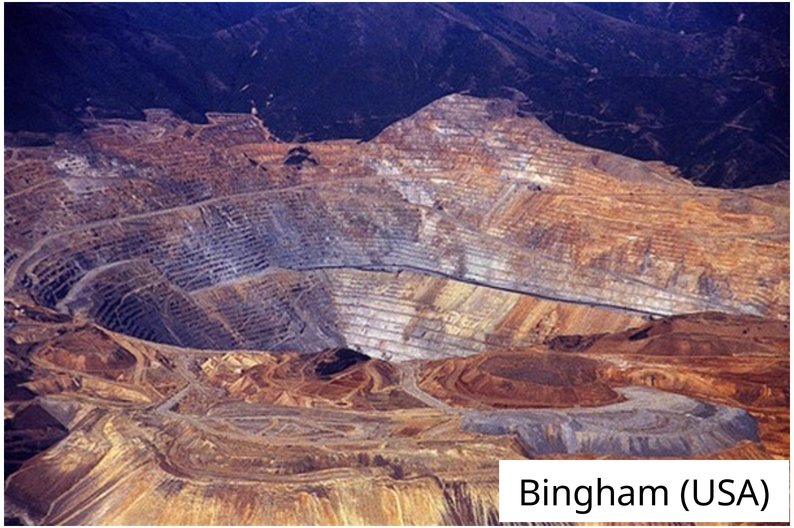
Fluid release, partial melting



Porphyry Cu-(Mo) deposits



Porphyry Cu-(Mo) deposits



Porphyries are low-grade, high tonnage type deposits.
Currently the main Cu supplier.

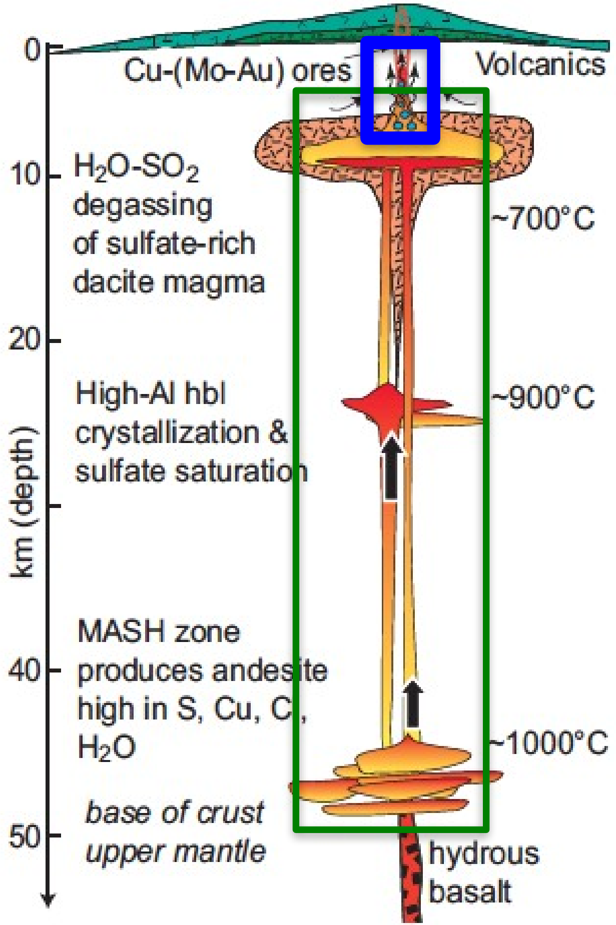
Ore is typically in small veinlets and disseminated.

Porphyry Cu-(Mo) deposits

Magmatic-hydrothermal systems:
Two-stage process

Magmatic processes

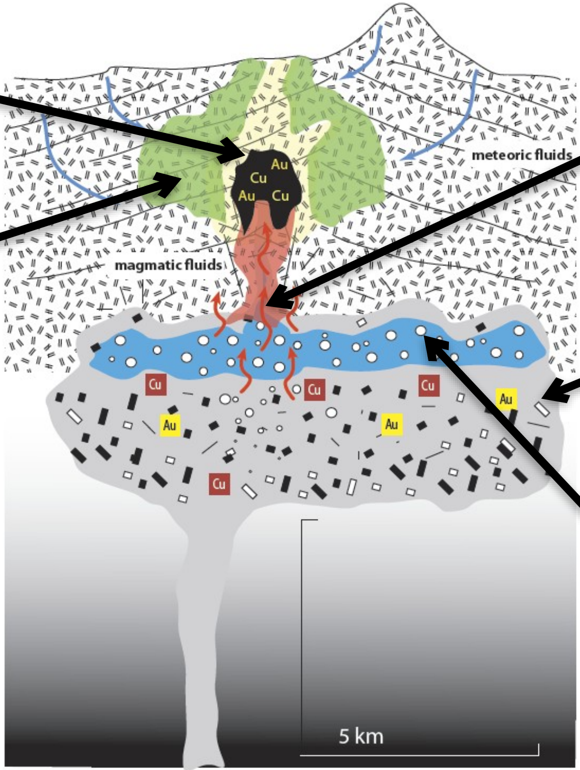
Hydrothermal processes



Porphyry Cu-(Mo) deposits

Metal deposition/ mineralization

Fluid/wall rock interaction (alteration)



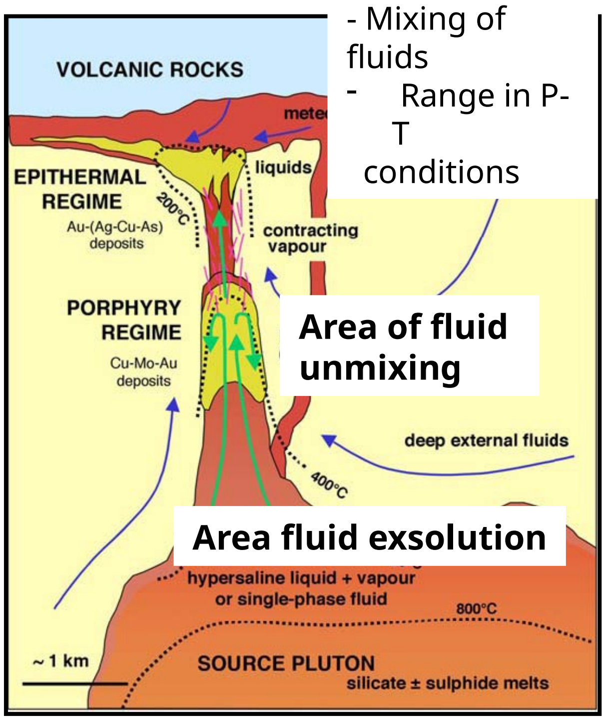
Fluid exsolution and metal transport

The metal source

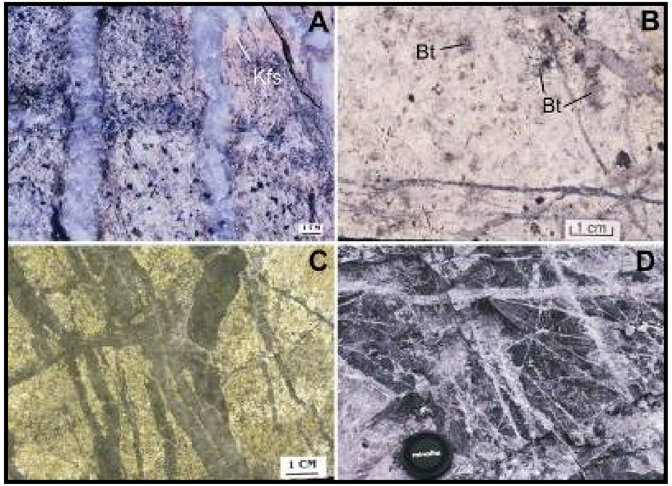
Fluid generation
Crystallization and formation of volatile phases (metal partitioning)

Porphyry Cu-(Mo) deposits

- Long-lived hydrothermal system that forms over range of T (700° to <300°C).
- Multiple, cross-cutting vein systems (see pics. below) reflect brecciation, fracturing.
- High –grade ore forms at <400°C
- Highly variable fluid chemistry (10-70 wt.% NaCl).

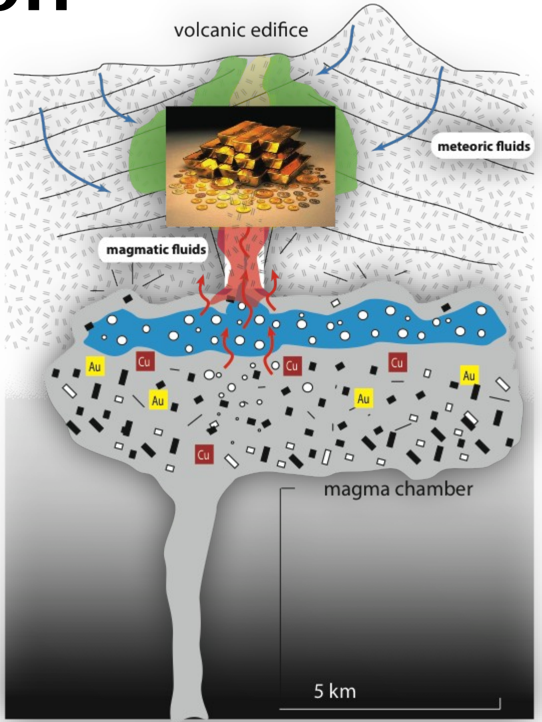


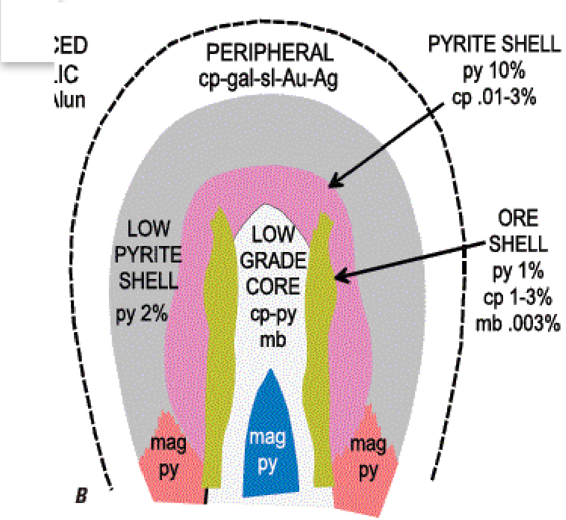
(from Heinrich,2004, Mineral. Deposita)



(from Sinclair, 2007, GAC Volume)

Porphyry Cu-(Mo) deposits: Metal deposition

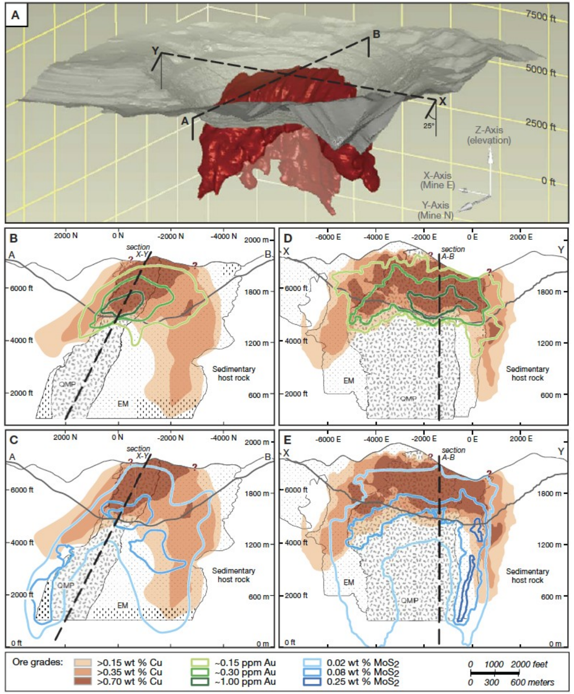




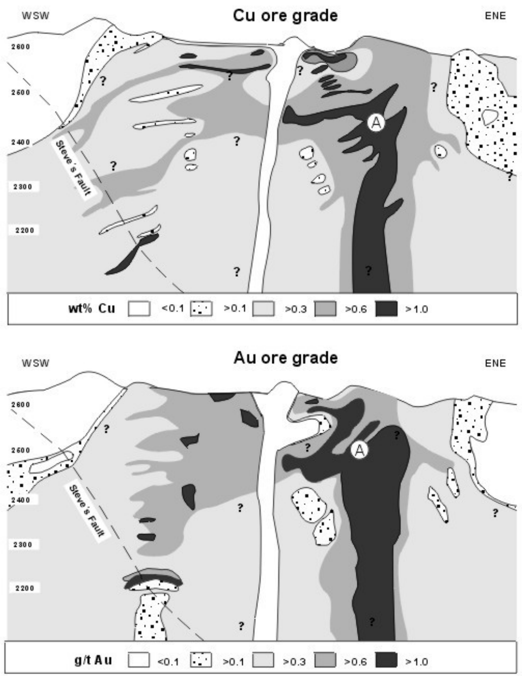
Critical:
Fluid focusing in vein network and precipitation of metals in confined volume

Porphyry Cu-(Mo) deposits: Ore zones

Bingham



Gruen et al 2010

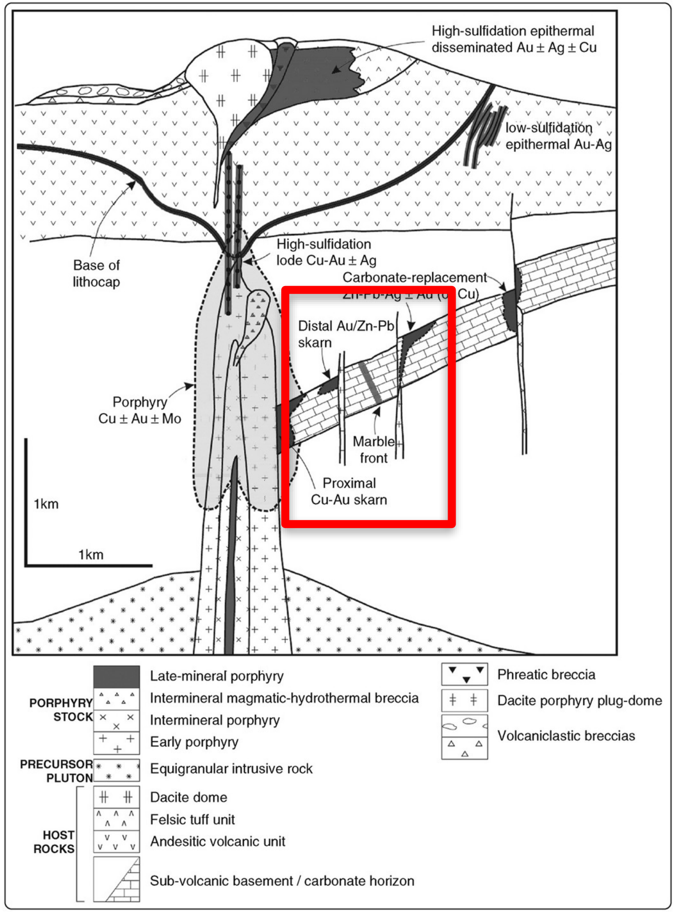


Bajo de la Alumbrera

Ulrich et al 2001

Skarn deposits

- Skarns form when hot, reactive (acidic) fluids interact with a carbonate-rich horizon.



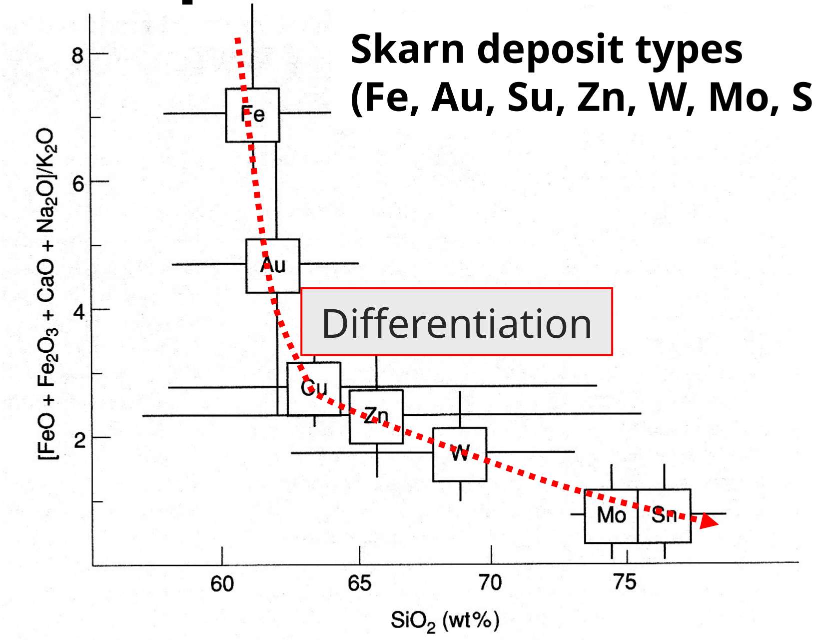
Skarn deposits

- SKARN - Swedish term describing rocks composed of calc-silicate minerals (e.g., Ca-rich garnet, pyroxene, amphibole, epidote) associated with magnetite and chalcopyrite deposits in Sweden

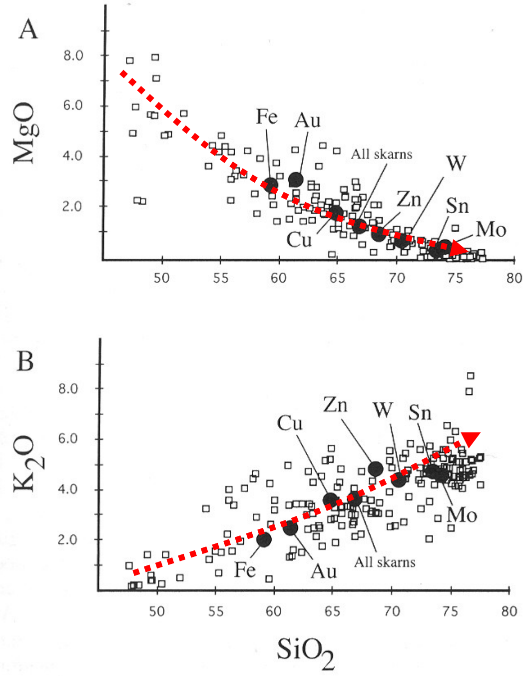
- **MODERN USE** - metasomatic replacement of carbonate rocks (limestone, dolomite) by calc-silicate mineral assemblages during metamorphic processes.

- **MINERAL DEPOSITS** – skarns hosting ore deposits (Sn, W, Zn, Fe, Au) produced by fluid infiltrating from nearby granite or fluids driven by heat of granite (i.e., convecting) and altering the carbonate rocks.

Skarn deposits

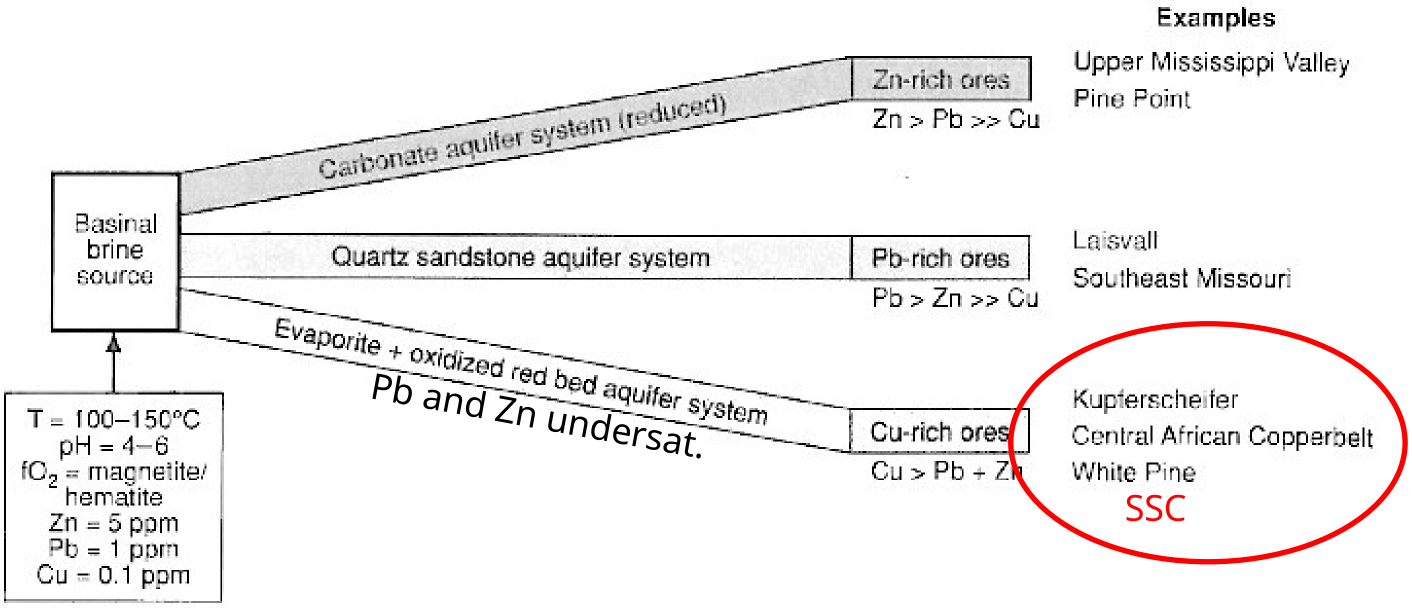


Skarn deposit types (Fe, Au, Su, Zn, W, Mo, Sn)



- Relationship between composition of host intrusion and dominant metal in the skarns – see that there is a strong correlation between the two (after Meinert, 1992).

Sedimentary hydrothermal deposit

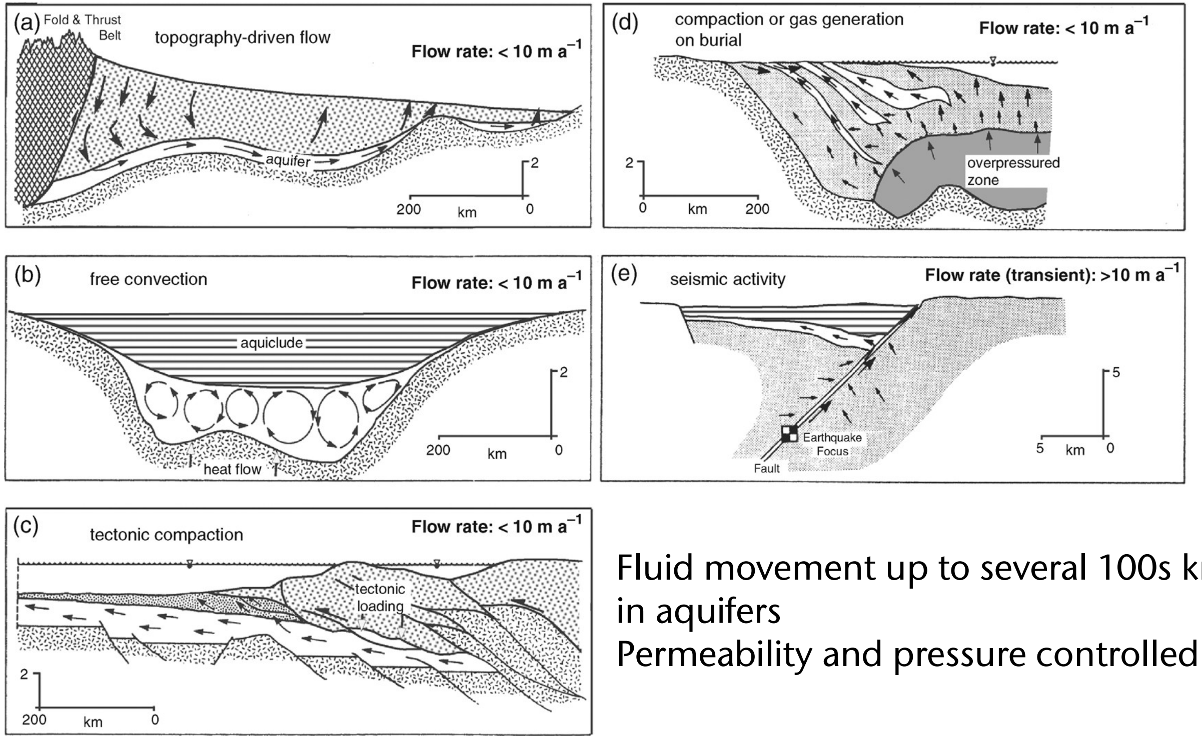


Sedimentary hydrothermal deposit

- Mineralization in large basins. Disseminated, massive, replacement, veins.
- Fluids are basinal brines or connate water.
- Metals leached from sedimentary rocks or underlying basement.
- High grade, high tonnage.
- Ore body laterally extensive in (stacked) lenses

Sedimentary hydrothermal Cu deposit

Fluid flow in sedimentary basins



Fluid movement up to several 100s km in aquifers

Permeability and pressure controlled

Sedimentary hydrothermal Cu deposit

Sediment-hosted Cu is common, but economic deposits very rare, only 3 basins with large deposits.

- Kupferschiefer
- Central African Copperbelt

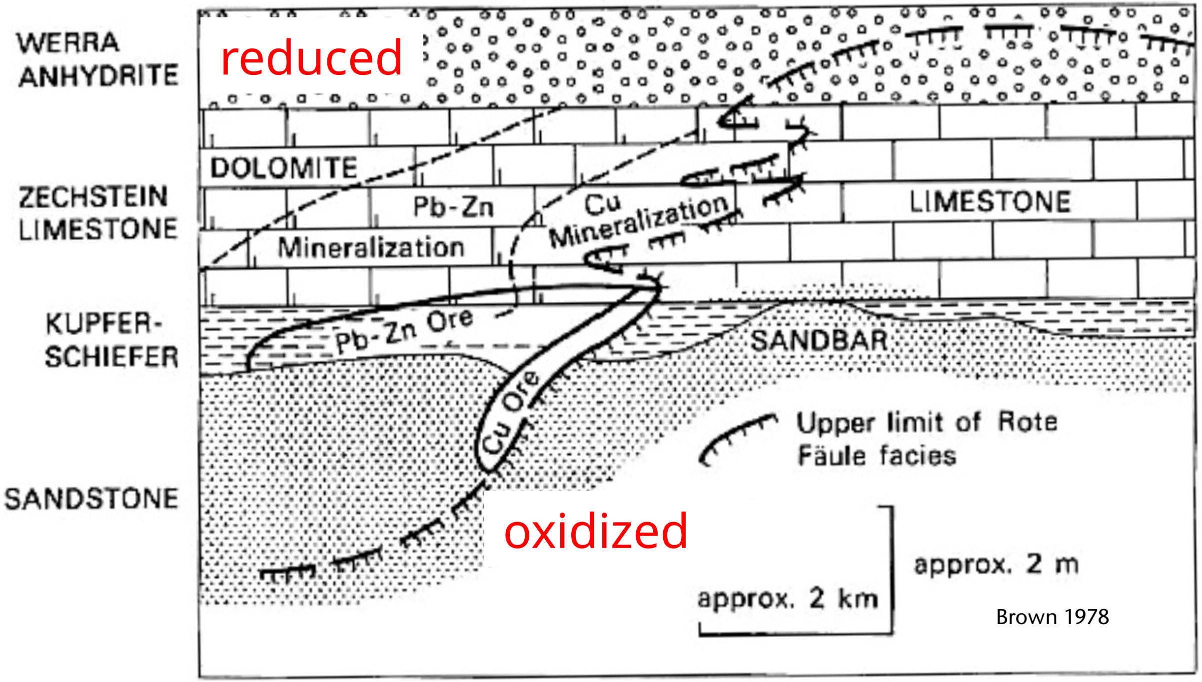
FIG. 1. Map showing worldwide distribution of important and selected sediment-hosted stratiform copper deposits and districts, by age of host rocks. Larger symbols indicate larger tonnage deposits or districts. Data from Table A1.

Sedimentary hydrothermal Cu deposit

- Deposits are typically hosted in intracontinetal rift-related sediment sequences. In sedimentary basin where continental red-bed are overlain by evaporites.
- Early part of sequence is oxidized or gets oxidized during diagenesis and is covered by more reduced shallow marine sequences (shales, carbonates, evaporites)
- Contain other metals such as Ag, Pb, Zn and Co (Central African Copperbelt)

Kupferschiefer

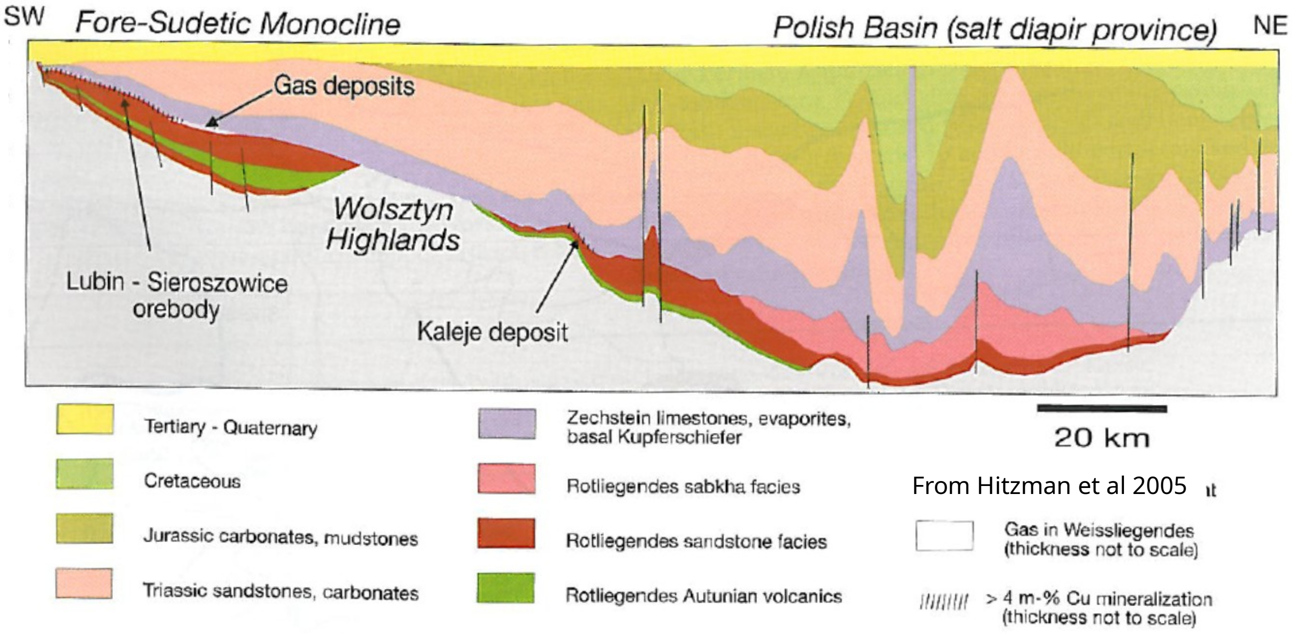
Metal deposition occurs at redox interface either intersecting reduced sediments (organic-rich) or reduced fluids. Commonly replacement textures. Metal deposition associated with reddish zone (‘Rote Fäule’, hematite replacing diagenetic sulfides) transgressing lithologies. General sequence is: **hematite-chalcocite-bornite-chalcopyrite-pyrite**



Rote Fäule alteration and mineralization is not restricted to lithology of the Kupferschiefer shale

Kupferschiefer

Rotliegendes is source region for metals and overlain by Zechstein marine transgression. Inbetween is Kupferschiefer shale. Fluids are derived from downward-migrating Zechstein brines where there is no shale seal. Kupferschiefer only about 1m thick, but very extensive (outline of the Permian sea).

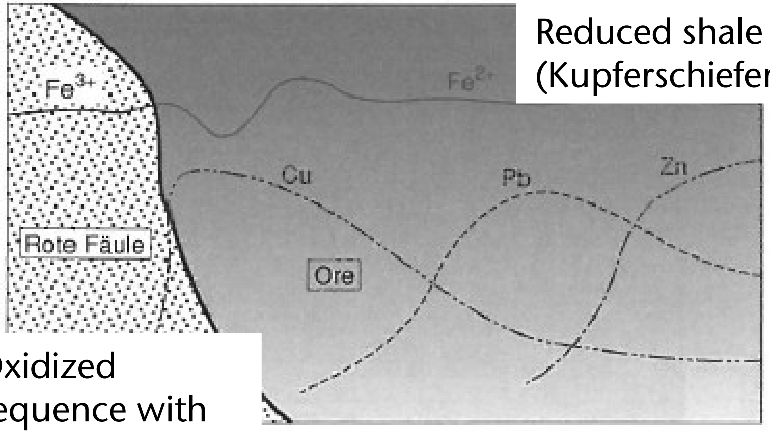


From Hitzman et al 2005

TU Clausthal

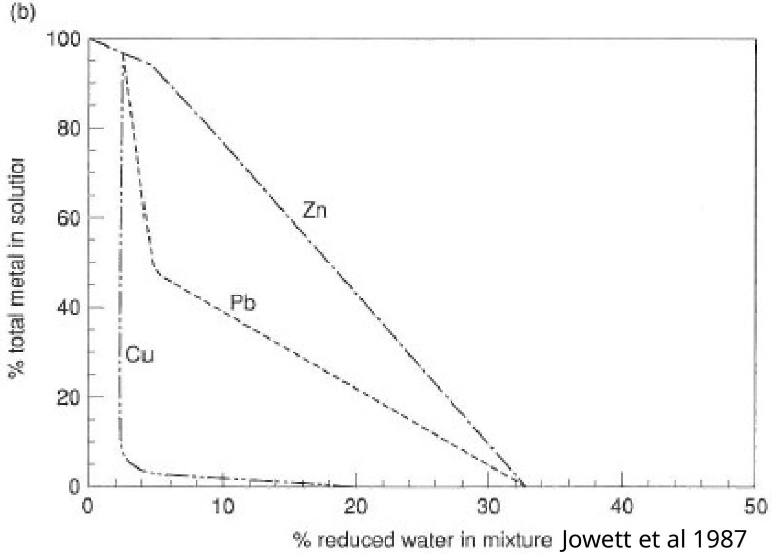
Kupferschiefer

Fluid circulation due to rifting related heat-flow. Interacting with oxidized clastic sequence and evaporite units. Fluids are relatively oxidized and saline (i.e. interacted with evaporites), pH neutral, low T (<150°C). Metals (Cu) leached from detrital minerals from basement erosion.



Reduced shale (Kupferschiefer)

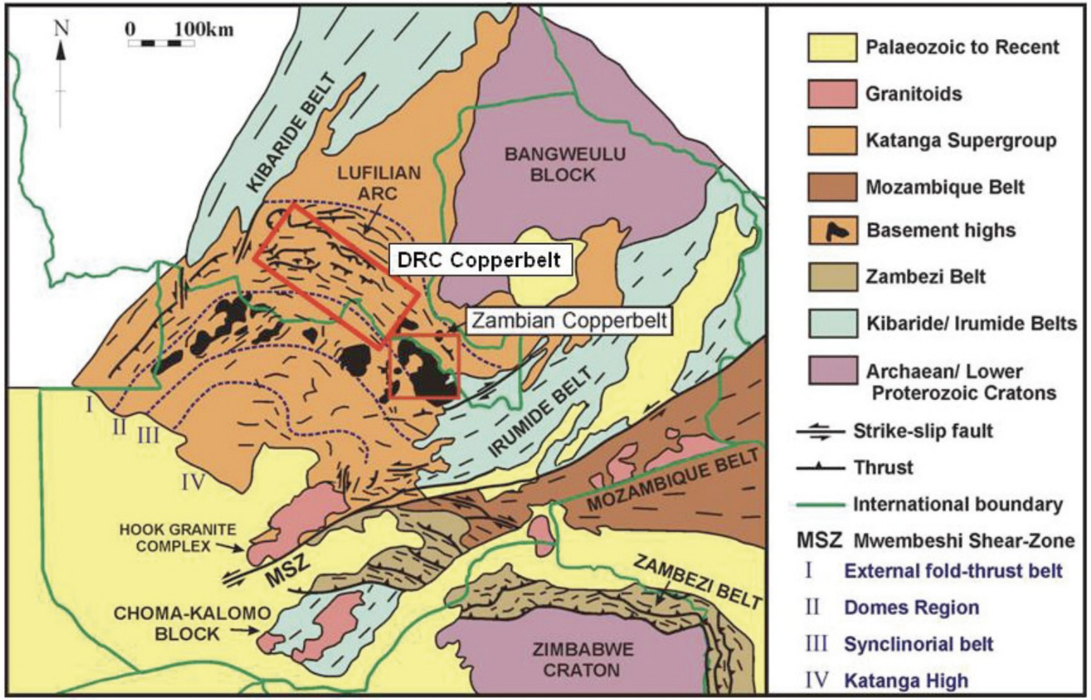
Oxidized sequence with fluids



Jowett et al 1987

Metcalfe et al 1994

Central African Copperbelt

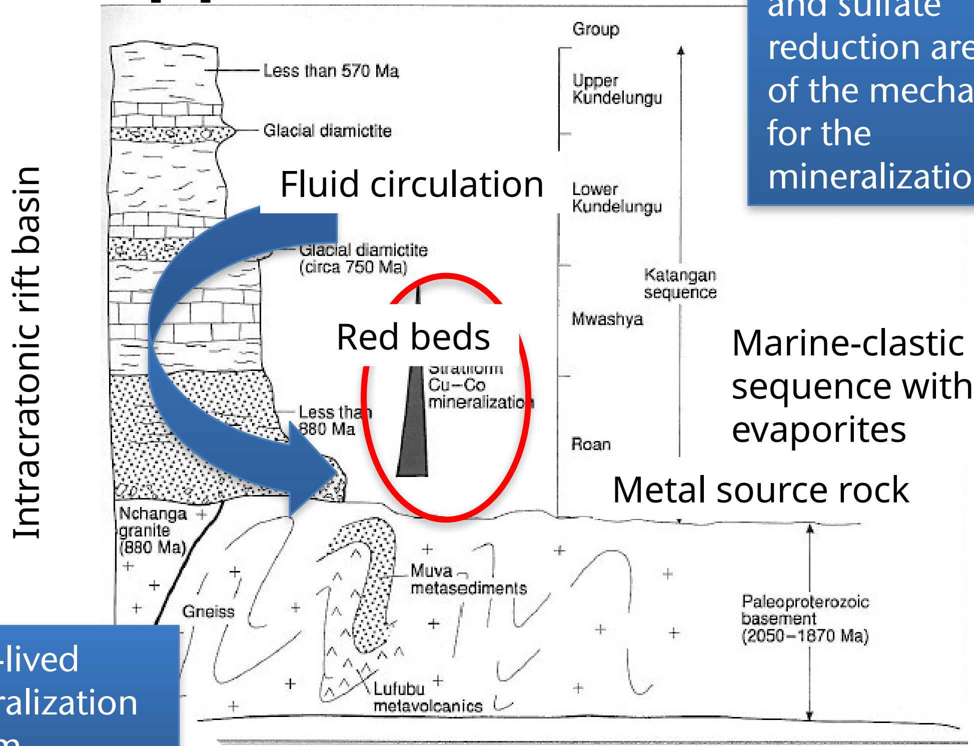


Theron 2013

Central African Copperbelt

Siliciclastic sediments of Roan Fm. Overlying basement is the source of metals.

Fluid interacting with sediments and evaporites in the Rona layer scavenge Cu and Co, but source of fluid and fluid flow in the entire sedimentary sequence.



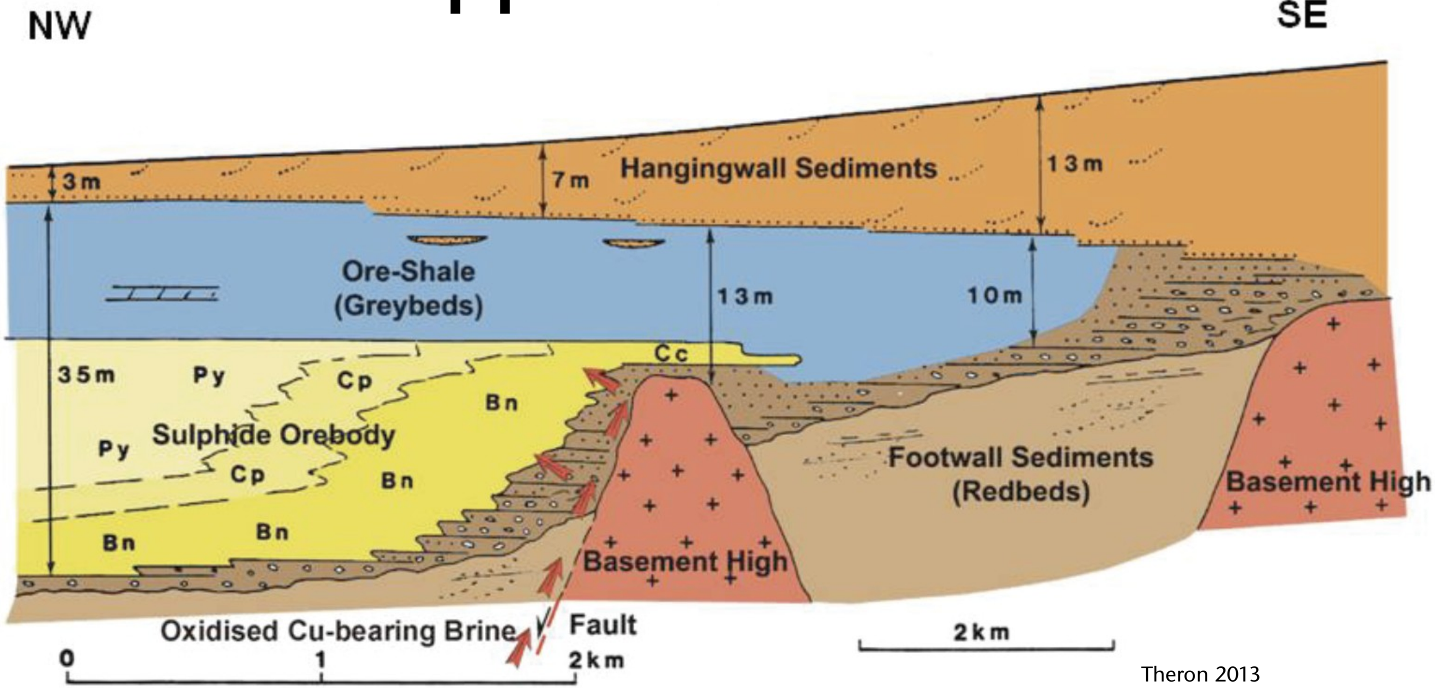
Organic material and sulfate reduction are some of the mechanism for the mineralization

Marine-clastic sequence with former evaporites

Long-lived mineralization system

Central African Copperbelt

Oxidized fluid reacts with a reduced (H_2S-rich) pore fluid.



Theron 2013

Fluids are between 120-180C and 8-18wt NaCl

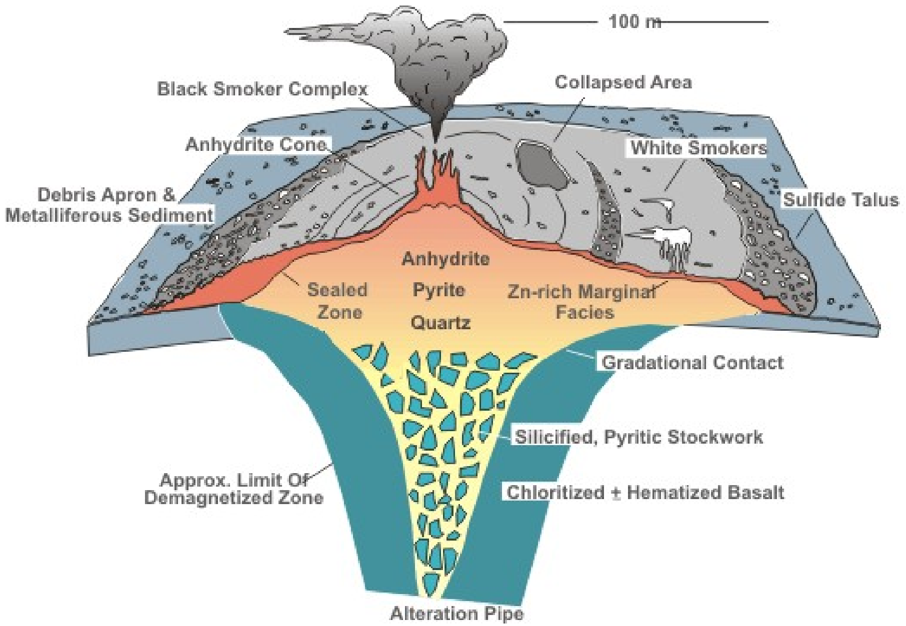
Thomas Ulrich
Institute for Disposal Research

Volcanic massive sulphide deposits (VMS)

- Deposits formed on the sea floor or just below. Fluid is seawater.
- Can be Cu-rich or more Pb-Zn-rich. Depends on the host rock.
- Black smokers are the modern equivalent.
- Minerals: Sphalerite, galena, chalcopyrite, calcite, baryte, anhydrite.
- Mineralization massive, high grade, medium tonnage.
- Ore body in lenses (massive and in veins)

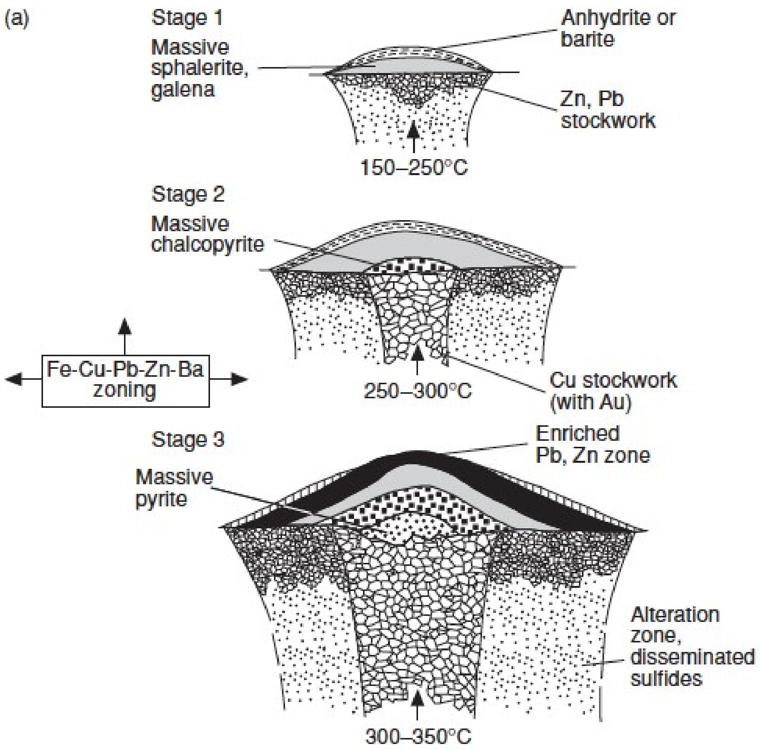
Volcanic massive sulphide deposits (VMS)

- Deposits occurs in clusters - a common heat source and structures.
- Metals are derived via leaching from underlying volcanics, thus underlying rocks determine elemental budgets.
- Presence of thin, but extensive layers of ferruginous chemical sediment from exhalations.

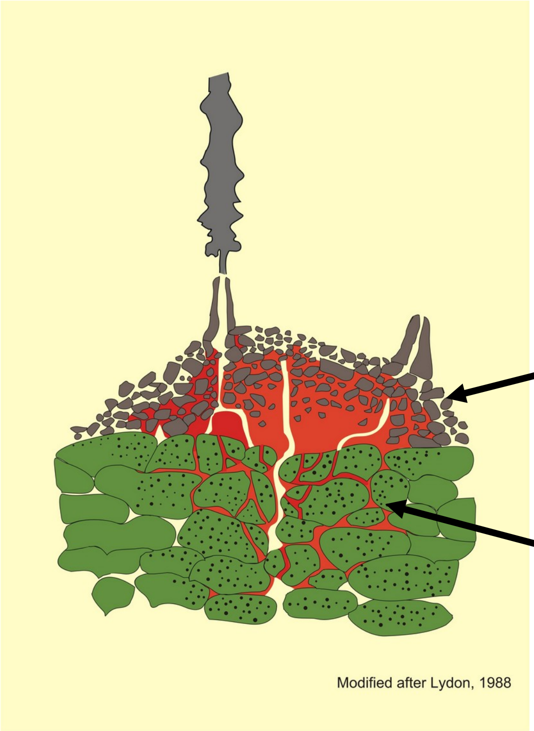


Volcanic massive sulphide deposits (VMS)

Often metal zonation is found. Outer part is Pb-Zn-rich, central part more Cu.



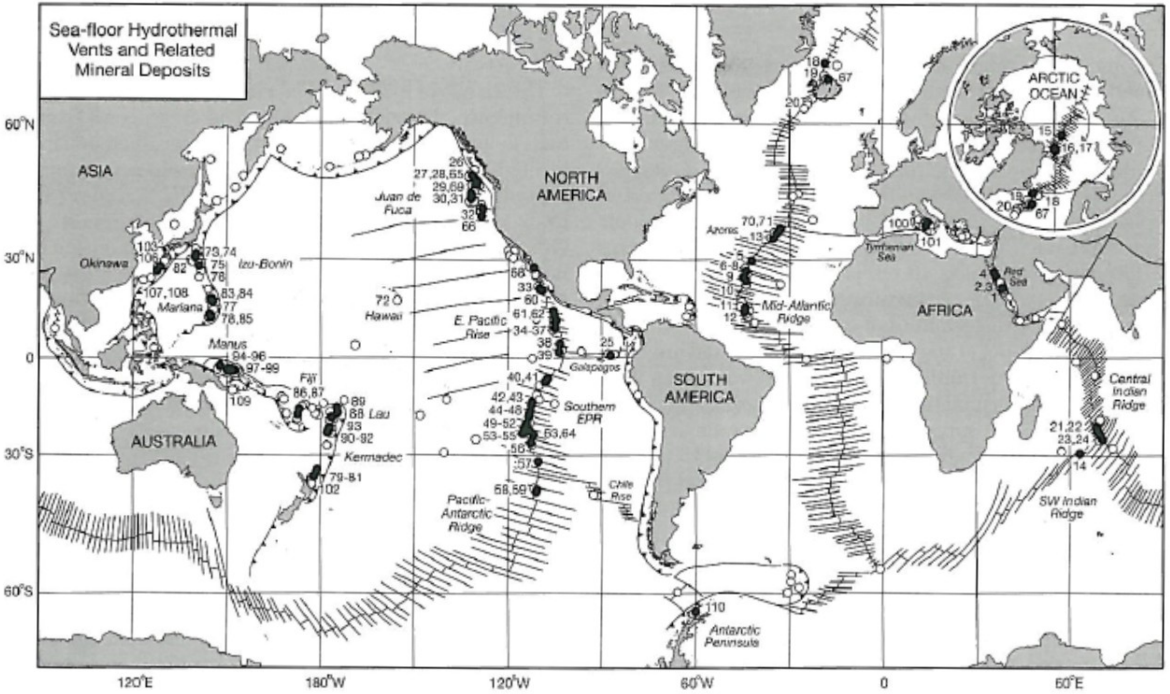
Volcanic massive sulphide deposits (VMS)



Volcanic massive sulphide deposits (VMS)

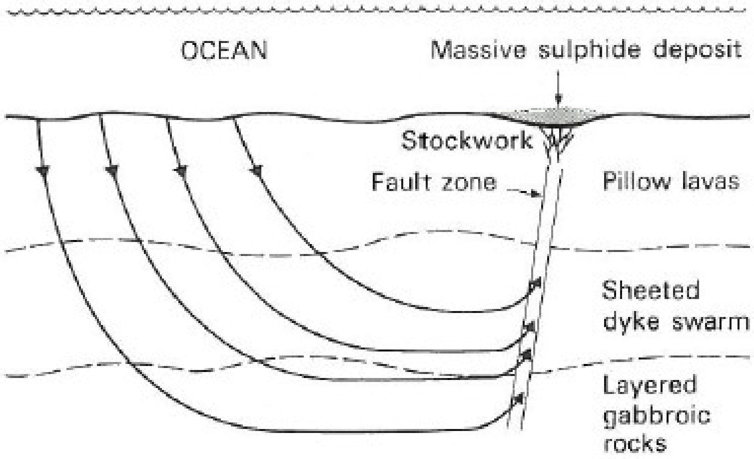
- Cyprus-type: related to mafic volcanics, Cu dominant, oceanic or back-arc spreading
- Besshi-type: related to calc-alkaline volcanism, Zn-Cu dominant, early stage island arc formation
- Kuroko-type: related to more felsic volcanics, Cu-Pb-Zn, late stage island arc formation

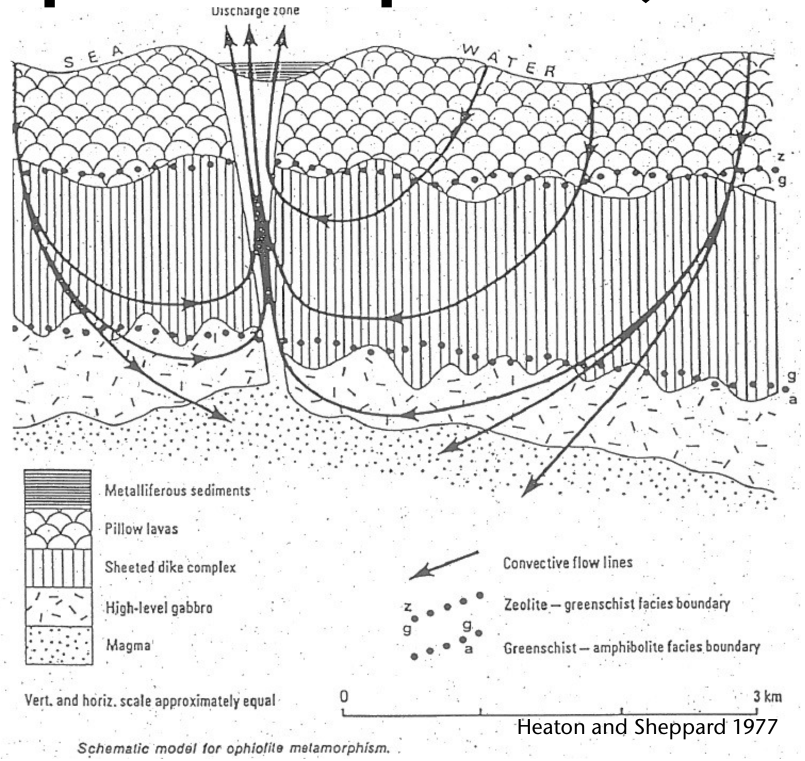
Volcanic massive sulphide deposits (VMS)



https://www.mining.com/web/everything-need-know-vms-deposits/

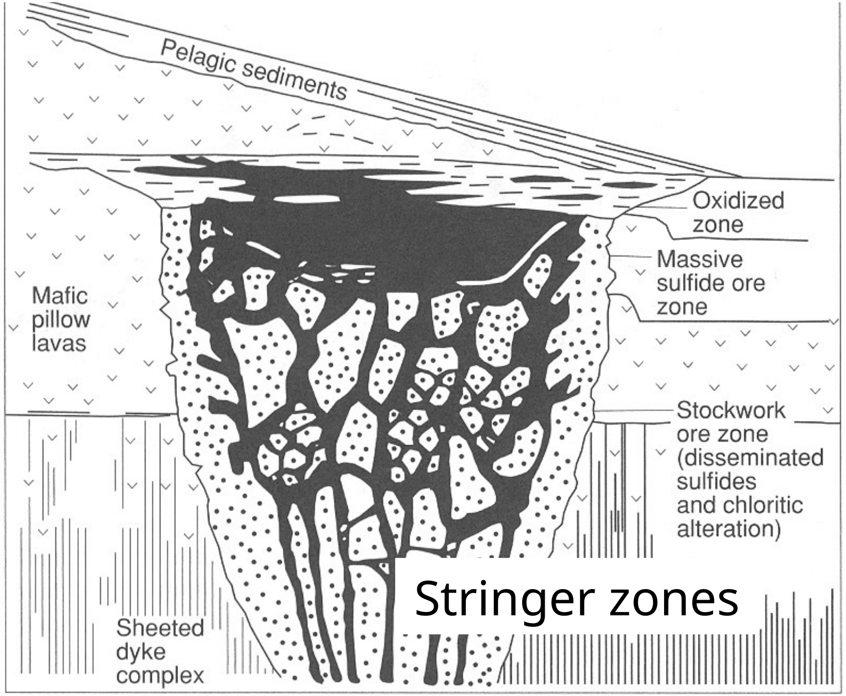
Volcanic massive sulphide deposits (VMS)





Heaton and Sheppard 1977

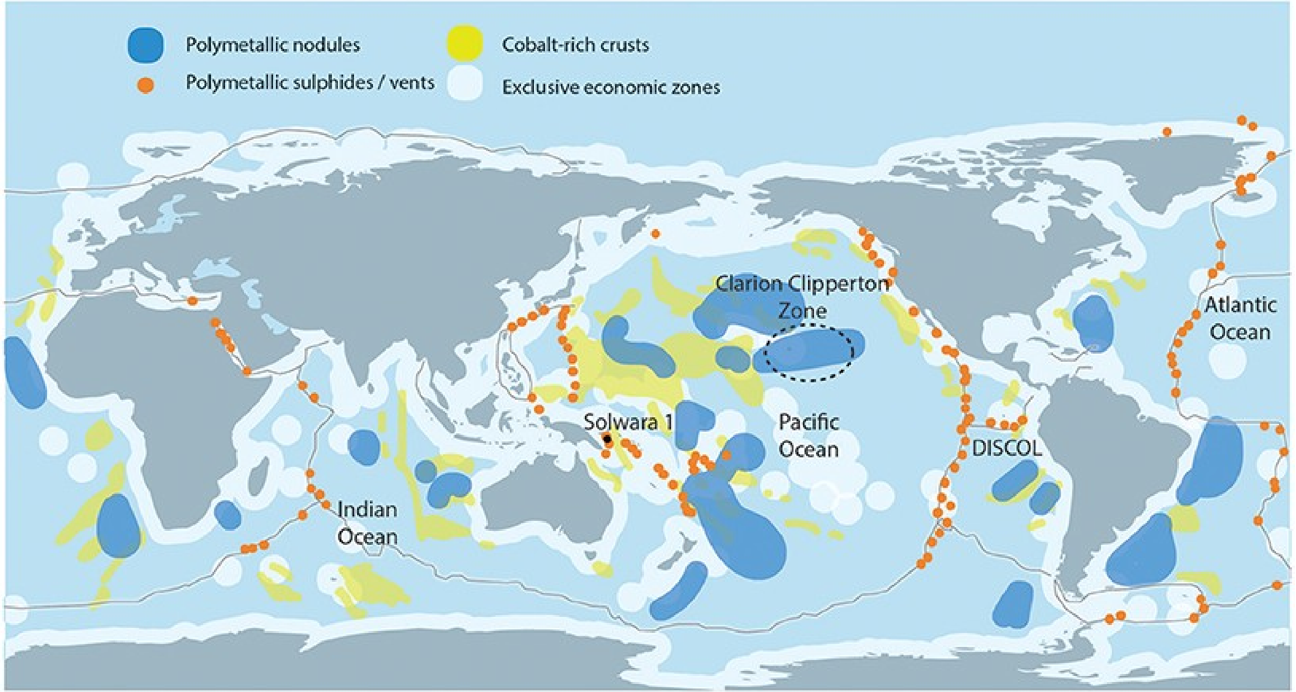
Cyprus Cu (VMS)



(from Robb, 2005)

- Classic model with ophiolitic rocks cut by feeder zone (stringer zone) of silica-sulphides that feeds overlying concordant sulphide zone.
- Note oxidized zone on top (ochre zone) that is a characteristic feature of this deposit type.

Deep sea mining



Hein et al (2013)

Deep sea mining: potential commodities

Resource	Symbol	Uses	References
Copper	Cu	Electricity production/distribution – building wires and telecommunication cables/circuit boards. Transport sector—vehicle brakes, radiators and wiring, copper-nickel alloys are non-corrosive and provide material for the hulls of ships. Ecorys (2012) classes mid-ocean ridge copper deposits as areas of "high" economic interest.	British Geological Survey, 2007 Goonan, 2009 Ecorys, 2012 United States Geological Survey, 2012b
Silver	Ag	Mobile phones, PCs, laptops and batteries currently use the largest volumes of silver, many of the newer uses of silver focus on its antibacterial properties. Silver used domestically in mirrors, jewelery and cutlery. Ecorys (2012) classes mid—ocean ridge silver deposits as areas of "high" economic interest.	Ecorys, 2012
Gold	Au	Predominantly jewelery, although has also been used in electrical products. However, the total amount of material used for electricity is decreasing as base metal-gold alloys are increasingly providing a cheaper alternative to pure gold in electrical products. Ecorys (2012) classes mid—ocean ridge gold deposits as areas of "high" economic interest.	Ecorys, 2012 British Geological Survey, 2007 United States Geological Survey, 2012a
Zinc	Zn	Galvanizing steel or iron to prevent rusting, also commonly used as an alloy in the production of brass and bronze. Zinc is also used in the production of paint, as well as pharmaceutical products as a dietary supplement. Ecorys (2012) classes mid—ocean ridge zinc deposits as areas of "high" economic interest.	British Geological Survey, 2004 Ecorys, 2012
Manganese	Mn	Mainly used in construction industry due to its sulfur fixing, deoxidizing, and alloying properties. It is preferred over other more expensive alternatives. Ecorys (2012) classes manganese crusts and nodules at intraplate seamounts as areas of "low" economic interest.	Ecorys, 2012 Geoscience Australia, 2012 Blöthe et al., 2015

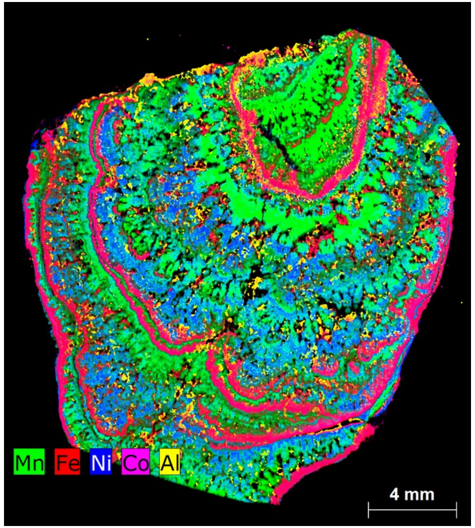
Deep sea mining: potential commodities

Cobalt	Co	Primarily used in production of super alloys with exceptional resistance to high temperatures, for example those used to make aircraft gas turbo engines. Also used in rechargeable batteries—notably lithium-ion batteries used in hybrid electric vehicles. These batteries contain high proportions of cobalt as 60% of the cathode in lithium-ion batteries is composed of lithium-cobalt oxide. Ecorys (2012) classes deep sea and intra plate seamount deposits of cobalt as areas of "moderate" and "low" economic interest, respectively. Cobalt is also found in manganese nodules.	British Geological Survey, 2009 Ecorys, 2012 United States Geological Survey., 2012c
Rare Earth Elements	REEs	Set of 17 elements including the 15 in the lanthanide series, plus scandium and yttrium. Used in the widest group of consumer products of any group of elements and have electronic, optical, magnetic and catalytic applications. Trends suggest that "green"—carbon reducing—technologies such as hybrid and fully electric cars, catalytic convertors, wind turbines and energy efficient lighting are key growth areas for REEs in the future. Demand for rare earth elements is increasing by 5–10% annually. Ecorys (2012) classes intraplate seamount deposits of REEs and yttrium as areas of "low" and "moderate" interest, respectively.	British Geological Survey, 2011 Ernst Young., 2011 Ecorys, 2012MIDAS, 2016
Tin	Sn	Used in the high-tech industry for manufacture of items such as smartphones and laptops in which the metal is used in solder. Also found in tinplate and in compounds that are used to make plastics, ceramics and fire retardants.	Geoscience Australia, 2016
Gas Hydrates		Gas hydrate is a solid ice-like form of water that contains mainly methane gas molecules in its molecular cavities. Methane from gas hydrates may constitute a future source of natural gas. Note that the high methane content of these hydrates and their potential adoption as a fuel resource could make them key sources of Carbon emission. According to the United States Geological Survey, the world's gas hydrates may contain more organic carbon than the world's coal, oil, and other forms of natural gas combined. Estimates of the naturally occurring gas hydrate resource vary from 10,000 trillion cubic feet to more than 100,000 trillion cubic feet of natural gas.	Sloan, 2003 Kretschmer et al., 2015

Some specific information on economic interest in these resources in European waters has been provided where available.

Deep sea mining, license area CCZ

Mn nodules



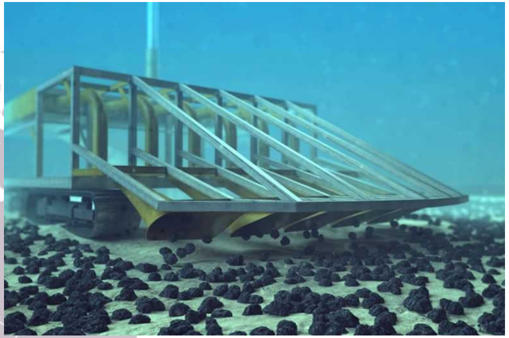
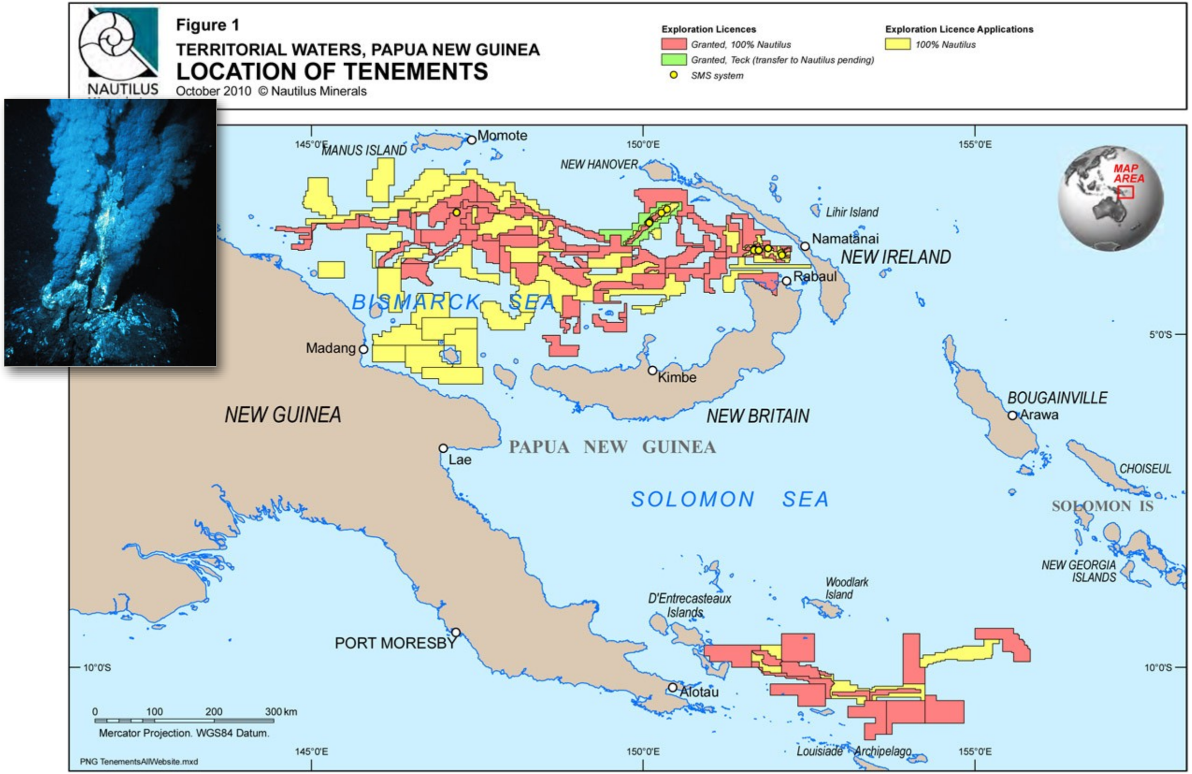


Figure 1. Total area of exploration licenses for manganese nodules in the Clarion-Clipperton Zone (CCZ; ~1.1 million km^2) compared to the area of Europe. Image credit: GEOMAR Helmholtz Center for Ocean Research Kiel.

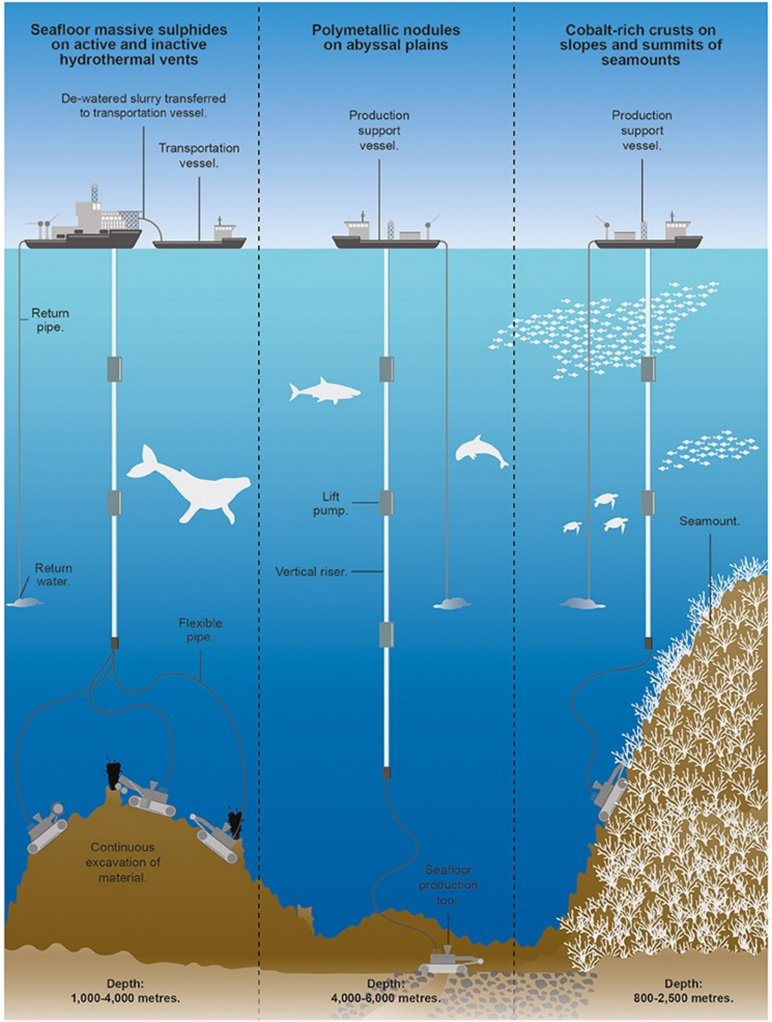
Beaulieu et al 2017

Cu-Au from black smoker chimneys



Deep sea mining

- Possible deposits to be targeted on the seafloor:
  - Volcanic massive sulphide deposits (VMS, black smokers)
  - Polymetallic Mn nodules
  - Mn-Co crusts
  - REE enriched mud (soft sediments)



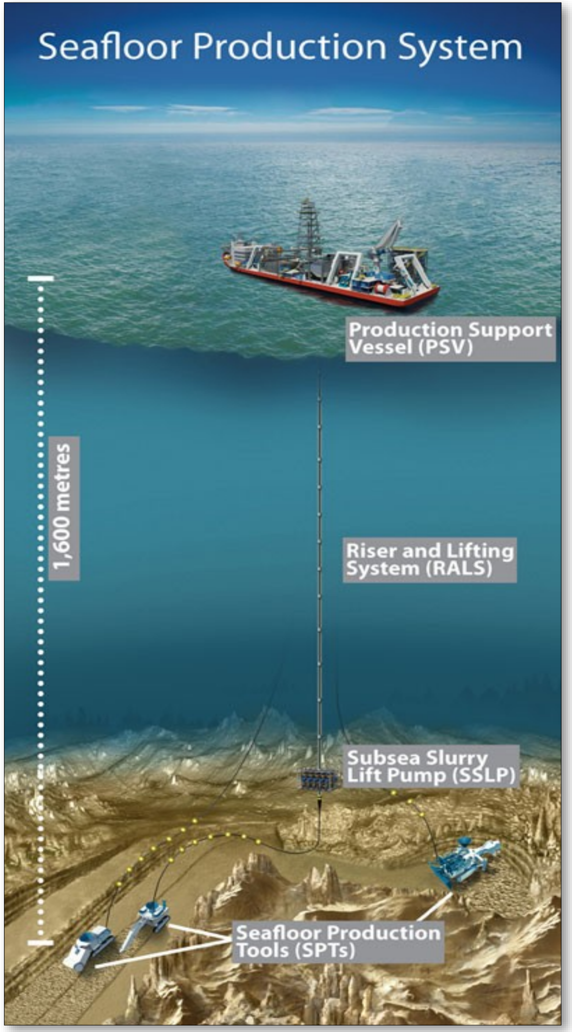
Deep sea mining

Pros:
- 70% of Earth surface is seafloor
- Higher ore grades than land-based deposits, no deep pits
- Reduced social disturbance

Cons:

-unknowns about environmental impact

-legal disputes over land rights outside the 200-mile zone



Exercise 6

Pb and Zn

Lead
Pb
82 207.2

Zinc
Zn
30 65.38

- Lead and Zinc
- Uses of lead and zinc
- Lead-zinc deposits
  - Volcanic massive sulphide deposits (VMS)
  - Sedimentary exhalative deposits (SEDEX)
  - Mississippi Valley-type (MVT)

Lead

Lead	Zinc
Pb	Zn
82 207.2	30 65.38

- Silver-grey metal, relatively soft
- Ore mineral(s): galena, PbS
- Top supplier: China, Australia, USA
- Reserves: 85Mio t
- Resources: 2Mrd t

Galena

USGS 2022

Lead
Pb
82 207.2

Zinc
Zn
30 65.38

Lead uses

- Batteries
- Pigments
- Radiation protection

Zinc

Lead	Zinc
Pb	Zn
82 207.2	30 65.38

- Silver-white metal, tarnished in air
- Ore mineral(s): sphalerite, ZnS
- Top supplier: China, Australia, Peru
- Reserves: 210Mio t
- Resources: 1.9Mrd t


sphalerite

USGS 2022

Lead
Pb
82 207.2

Zinc
Zn
30 65.38

Zinc uses

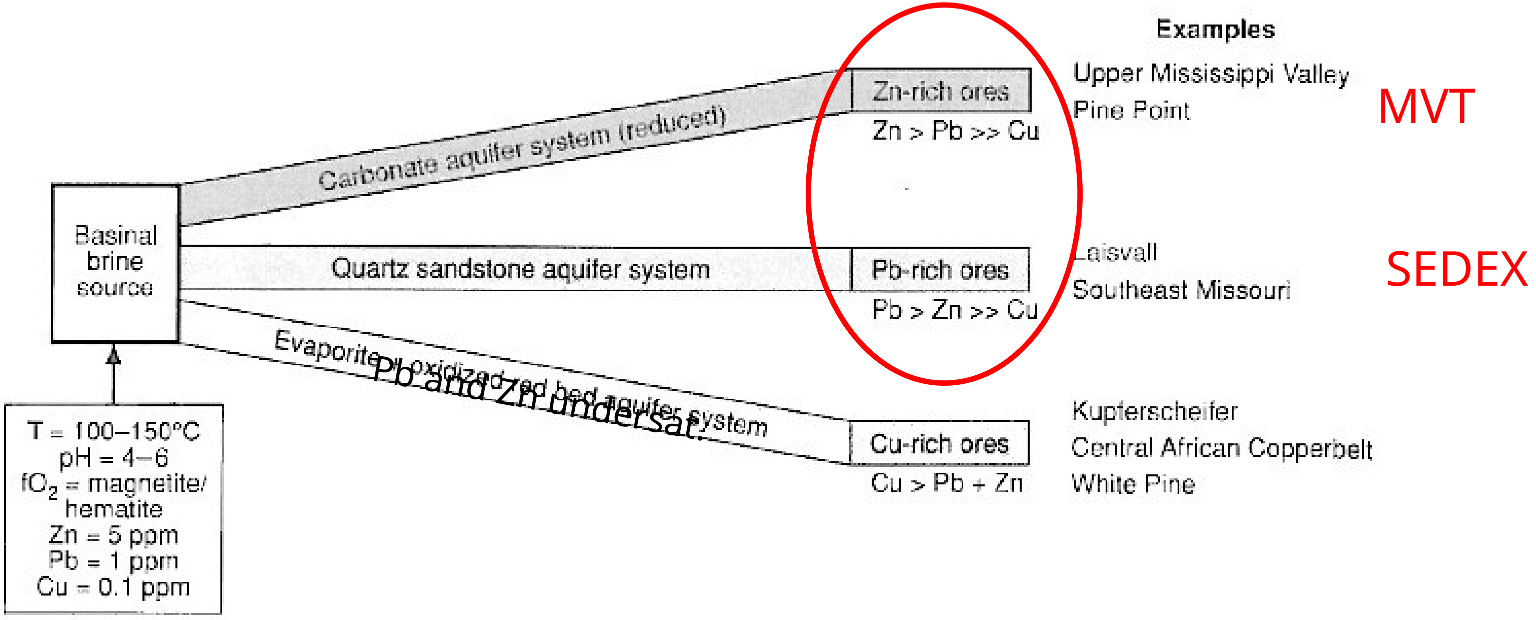
- Galvanisation
- Die-casting
- Alloys
- Paint, plastic, rubber

Sediment-hosted Pb-Zn deposits

There are two types:

- Sedimentary exhalative deposits (SEDEX)
- Mississippi Valley-Type deposits (MVT)

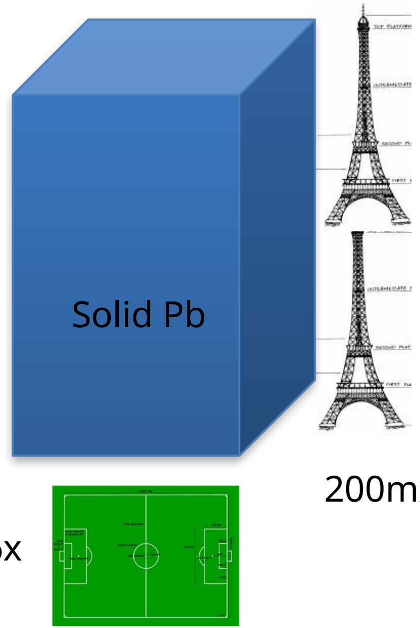
Sedimentary hydrothermal deposit



Sedimentary exhalative Pb-Zn (SEDEX)

SEDEX deposits contain globally more than 50% of the Zn and Pb reserves and make up 25% of the production of these metals

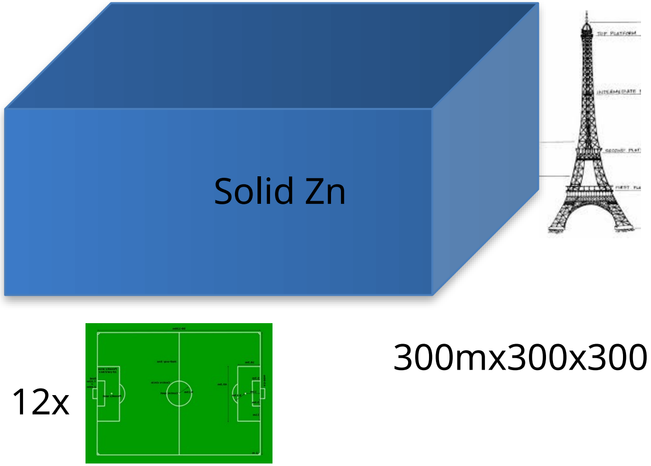
Pb reserves 226Mt*



6x

200mx200x500m

Zn reserves610Mt*



12x

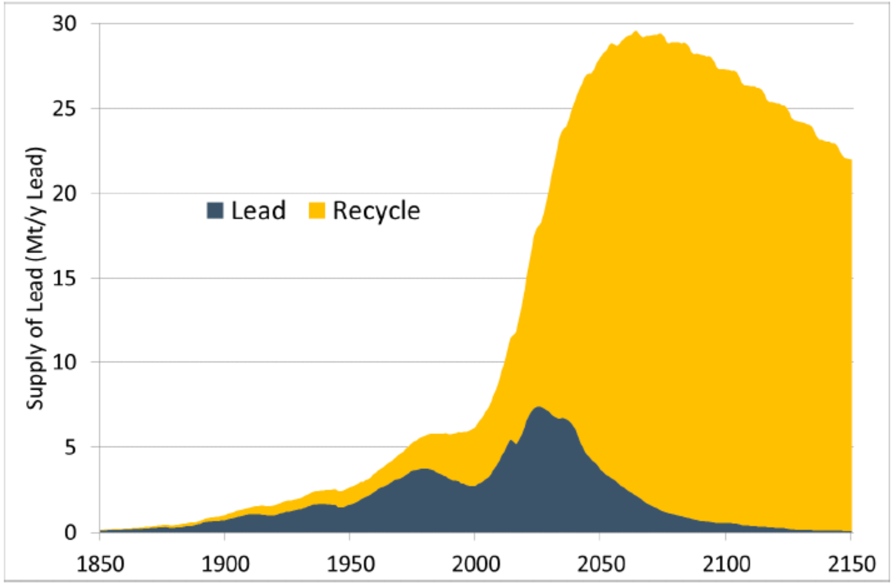
300mx300x300m

*Mudd et al. 2016

Sedimentary exhalative Pb-Zn (SEDEX)

Lead is one of the most effective recycled metal due to organized colleting scheme of car batteries.

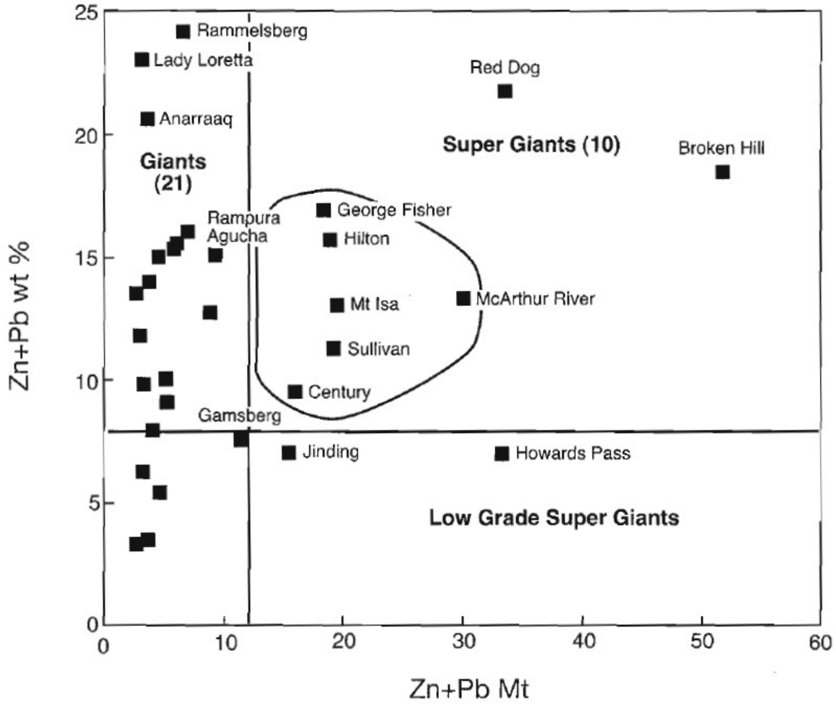
Production of Pb (and prediction)



(a)

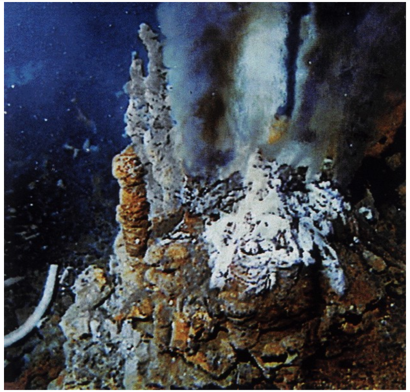
Mohr et al 2018

Sedimentary exhalative Pb-Zn (SEDEX)

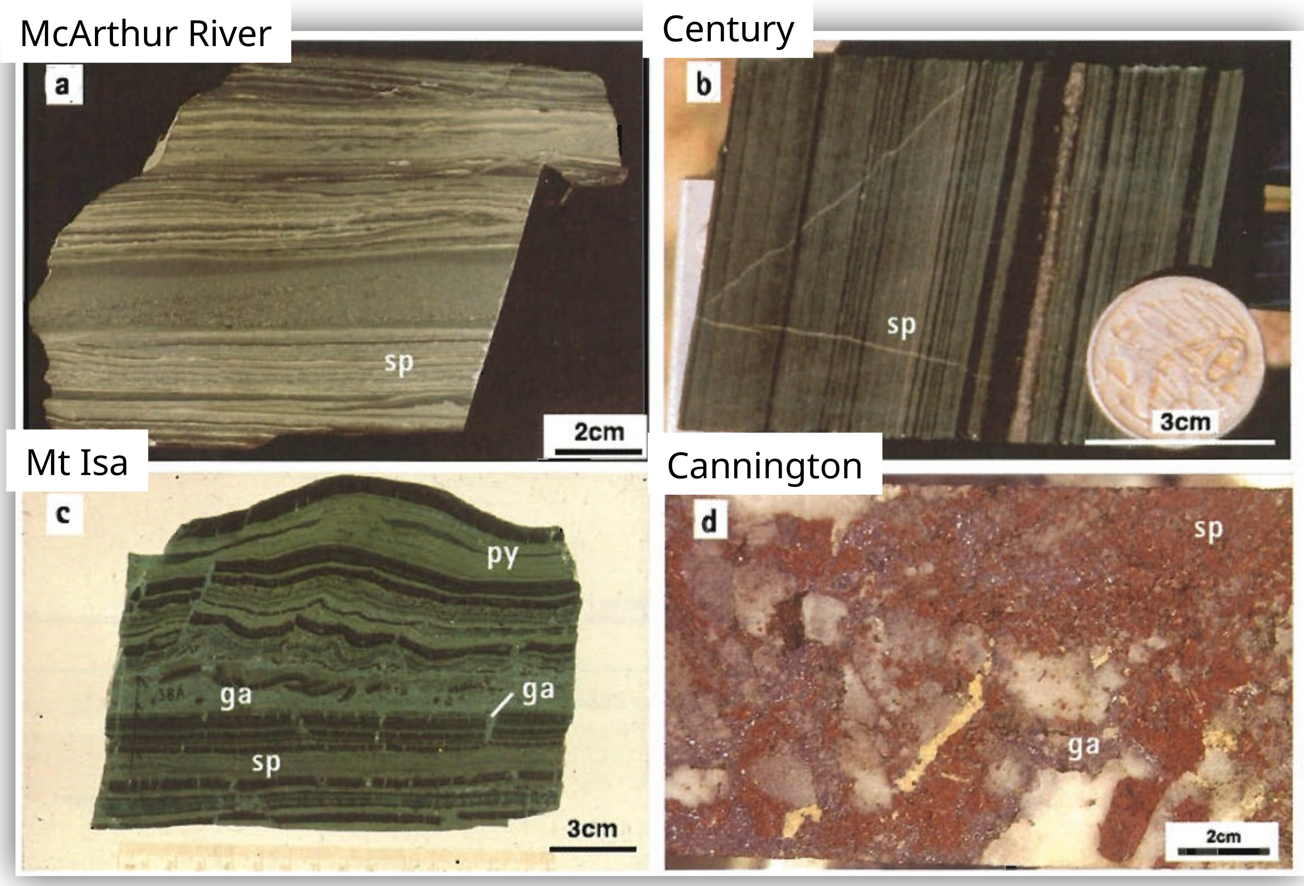


Sedimentary exhalative Pb-Zn (SEDEX)

Similar features to VMS deposits



- Tabular ore body of massive Fe-Zn>Pb (***Sphalerite, Galena***) and Ag (±Cu, Ge). Some are Au-rich.
- Barite and qtz (chert) may be a common gangue.
- Ores interbedded with Fe sulphides (Py, Po) and basinal sedimentary rocks = **SYNGENETIC** origin.
- Contain 50-60% of worlds reserves of Zn-Pb in a few very large deposits (Sullivan, Canada; Red Dog, Alaska; Broken Hill, Mt. Isa, etc. Australia).
- Mineralization can occur from venting of metal-rich fluids into reduced sedimentary basins on continental margin settings, or as replacement beneath the basin floor.


McArthur River
a
sp
2cm
Century
b
sp
3cm
Mt Isa
c
py
ga
ga
sp
3cm
Cannington
d
sp
ga
2cm

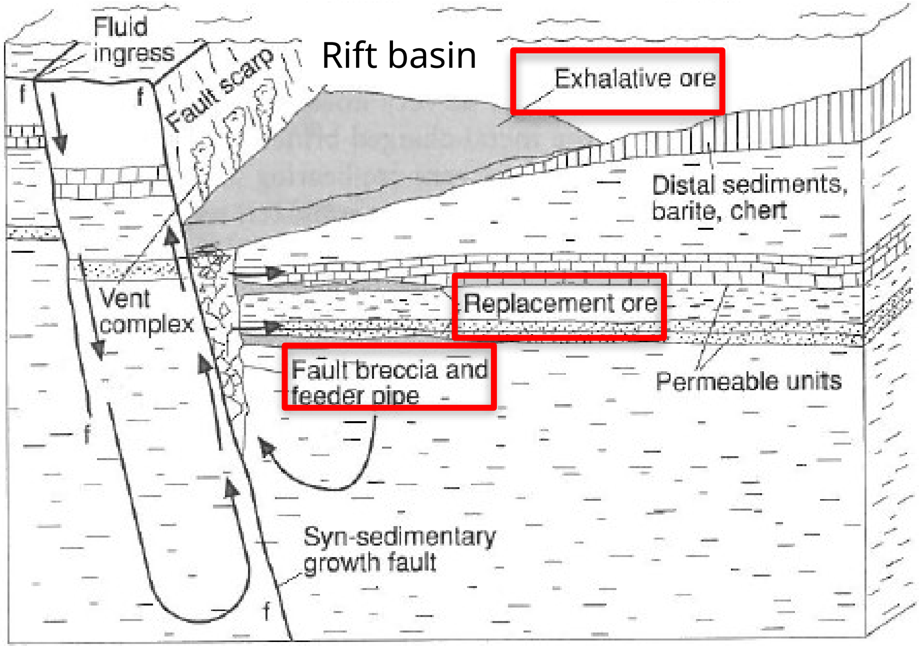
Sedimentary exhalative Pb-Zn (SEDEX)

Fluid inclusion information

- Generally somewhat higher T than MVT deposits (100°-250°C).
- Wide range of salinities (1- to >45wt% NaCl eq.) and temperatures (100° to >400°C) at e.g. Sullivan. Salinity commonly around 5-25wt% NaCl eq.
- The source of the fluids is assumed to be hot basinal brines.
- High T due to high geothermal gradient because of extensional setting and deep fluid circulation.
- High fluid salinity due to density settling of evaporitic brines.

Sedimentary exhalative Pb-Zn (SEDEX)

- Dense brines with metals derived from local sediments.
- Metal deposition due to fluid mixing of brine and cooler, dilute meteoric water subsurface (replacement). Part of fluid can vent on basin floor (exhalative). Therefore it can be syn- and epigenetic.
- Hosted by marine clastic or chemical sediments in rift basins, little or no connection to volcanic rocks.
- Modern analogues could be the Red Sea and Salton Sea systems.

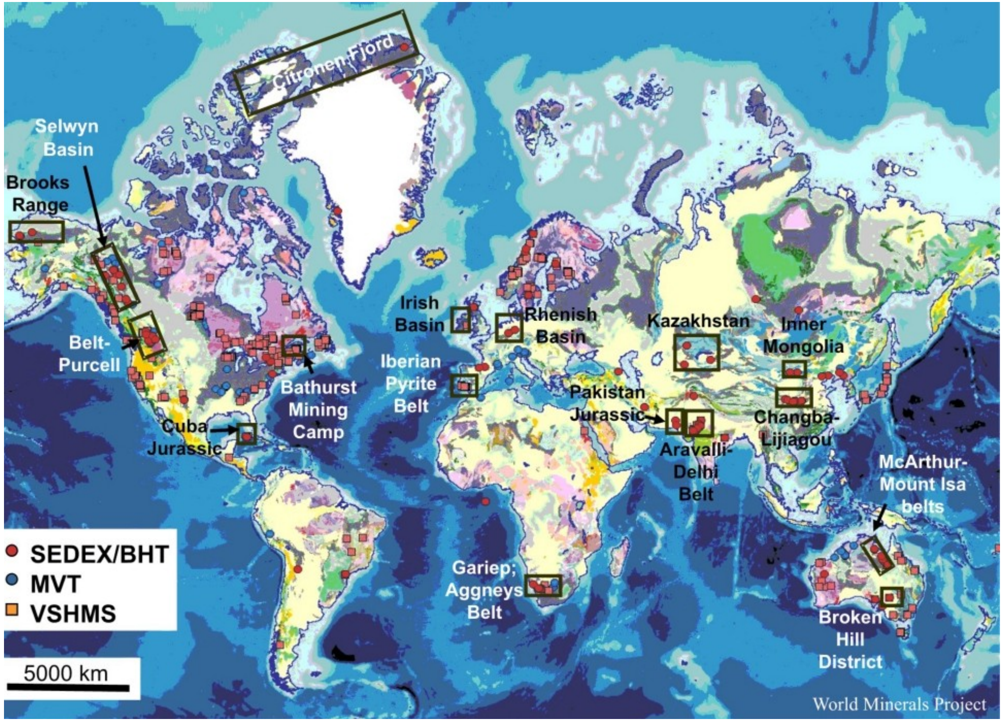


Goodfellow et al 1993 and Misra 2000

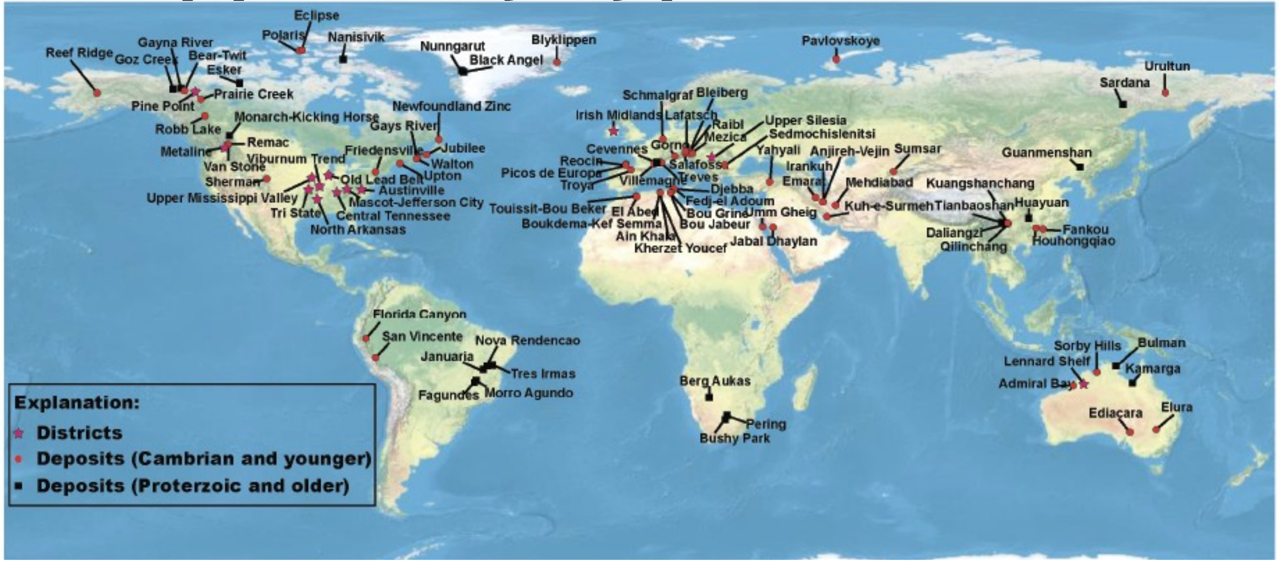
Sedimentary exhalative Pb-Zn (SEDEX)

Global SEDEX Districts:

- Red Dog (Alaska)
- Selwyn Basin (Canada)
- Purcell-Sullivan (Canada, USA)
- Broken Hill, Australia
- McArthur River, Australia



Mississippi Valley-Type Pb-Zn (MVT)

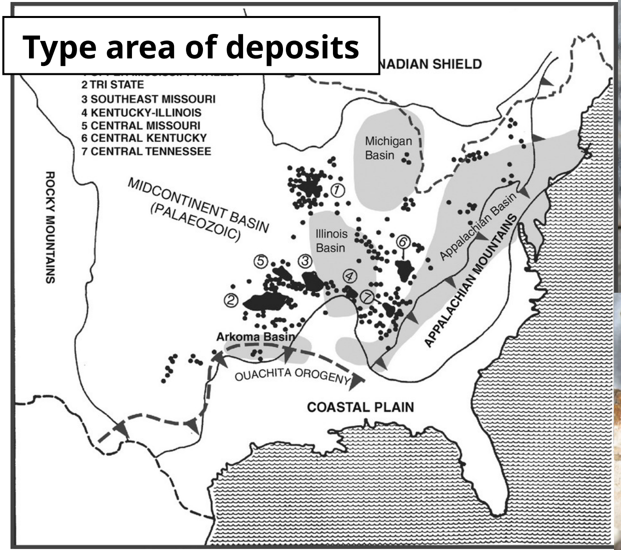


Major deposits/resources: Navan (Ireland), Pavlovskoye (Russia), Admiral Bay (Australia), Buick (USA), Mehdiabad (Iran), Komdok, (N-Korea), Pine Point (Canada)

TU Clausthal

Mississippi Valley-Type Pb-Zn (MVT)

Type area of deposits

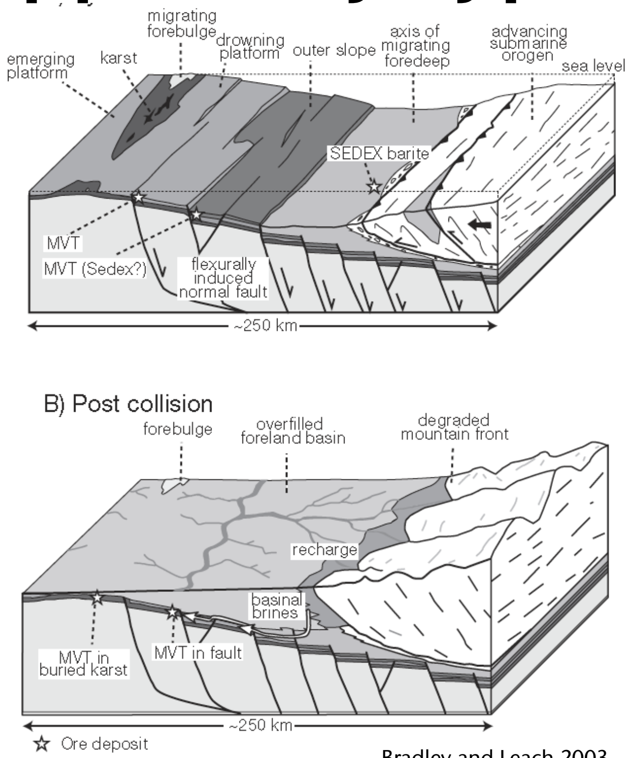


- Refers to deposit type named for Zn-Pb mineralization hosted by carbonate rocks, **EPIGENETIC**.
- Type area is Mississippi area, USA.
- Mineralization often hosted by **dolomitized** carbonates (porosity) formed in reefs, bank settings on paleo-highs, margins of basins.
- Orogenic forelands
- Ore body in lenses, massive sphalerite/galena

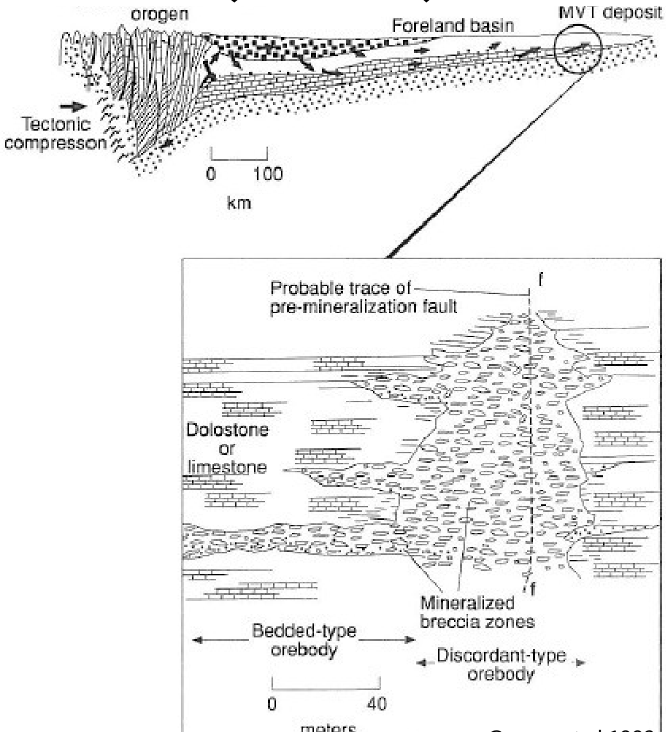
Thomas Ulrich
Institute for Disposal Research

Mississippi Valley-Type Pb-Zn (MVT)

Orogenic foreland basins, fluid flow over 100's km



Bradley and Leach 2003



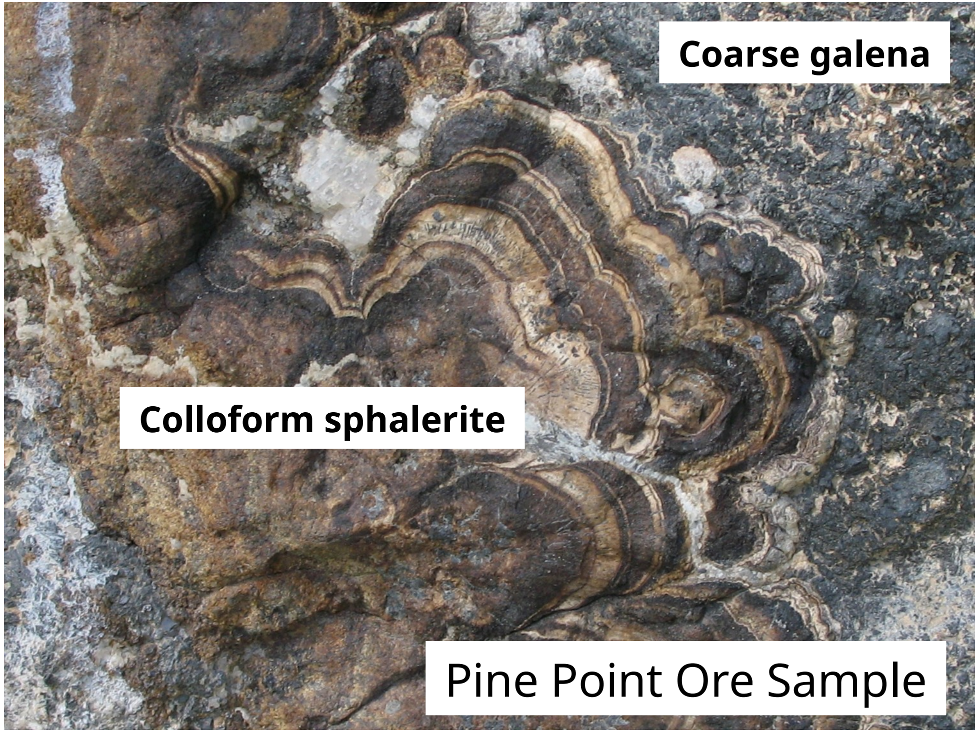
Garven et al 1993

Mississippi Valley-Type Pb-Zn (MVT)

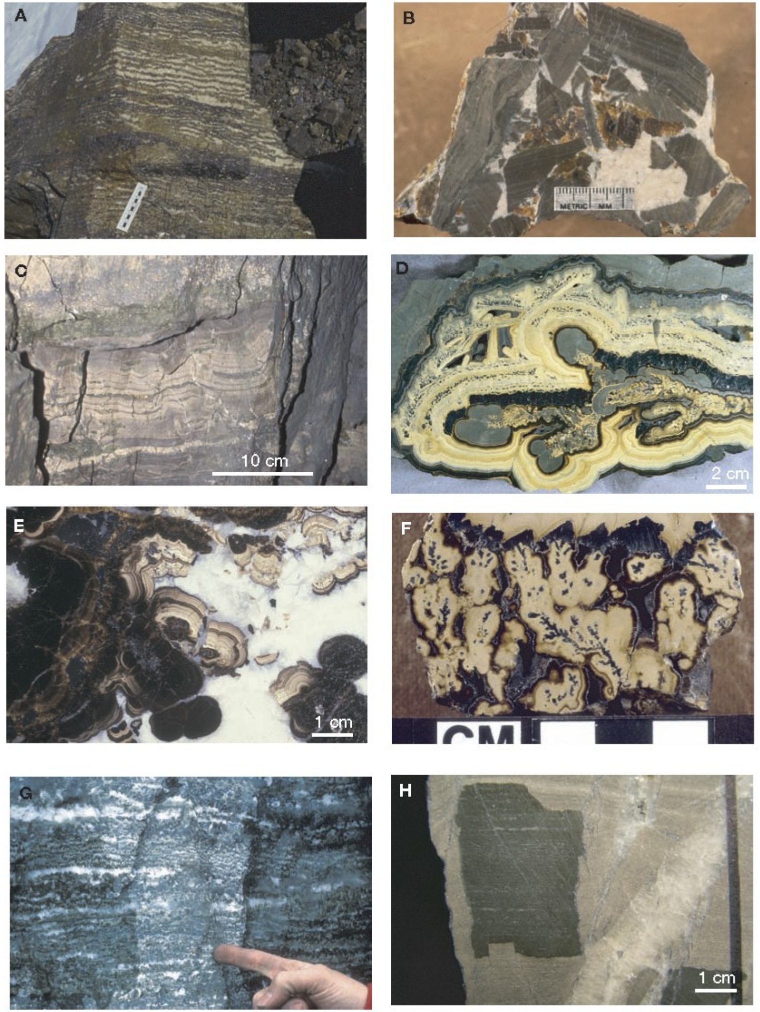

Pine Point ore

- Ore as replacement and cavity filling.
- Host rocks are “dolomitized” carbonate (reefs).
- Generally coarse Gal +/or Sph and colloform Sph. Fluorite and barite can be present.
- Ore body size highly variable and many occur in one district (e.g., Pine Point, N. Canada).
- Fluids are metal-rich basinal brines. 10-30wt% NaCl eq. T $<200^{o}$C.
- Mineralization post dates age of hosts by many Ma – thus, very different to SEDEX and VMS systems.
- Main formation age of MVTs is between Devon and Perm (assimilation of Pangea). Coincides with large-scale contractional events.
- Fluid mixing is one of the most important metal deposition processes.
- Can also contain Ba, F, Cu, Ag, Ge, Co, V)

Mississippi Valley-Type Pb-Zn (MVT)



Mississippi Valley-Type Pb-Zn (MVT)



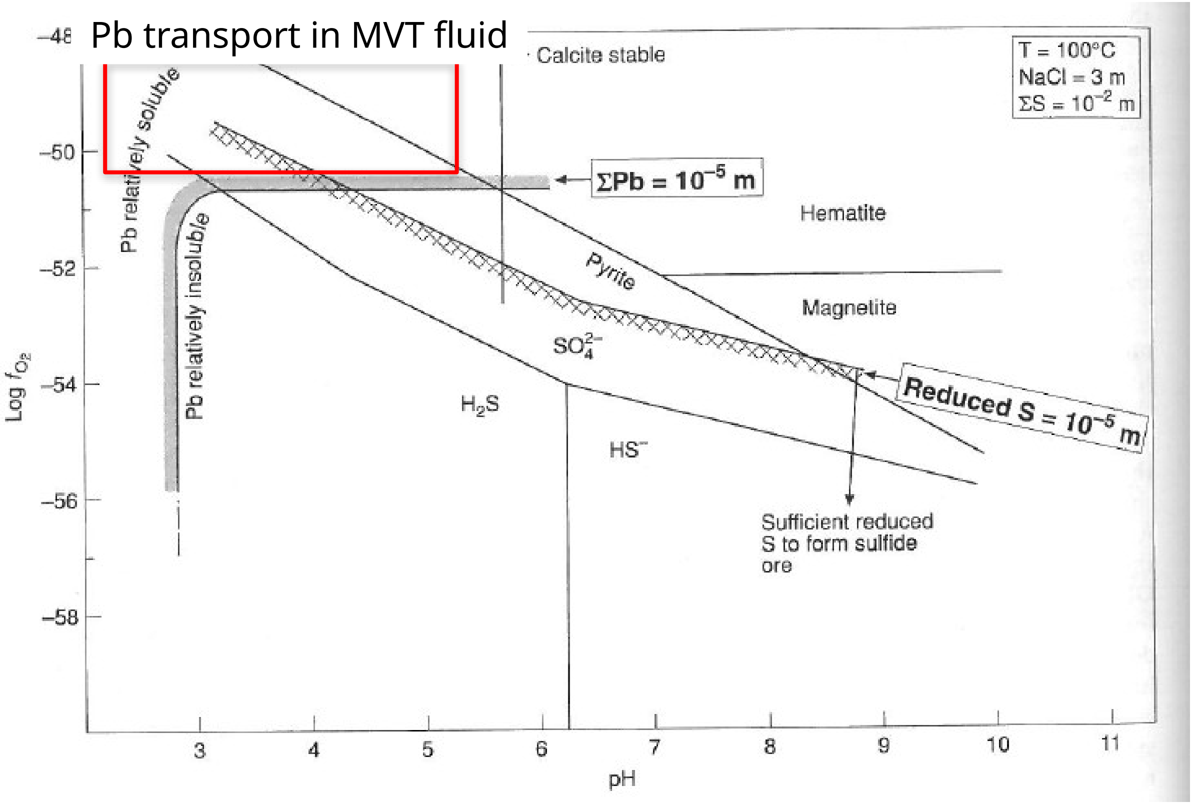
Breccia and replacement textures

Thomas Ulrich
Institute for Disposal Research

Mississippi Valley-Type Pb-Zn (MVT)

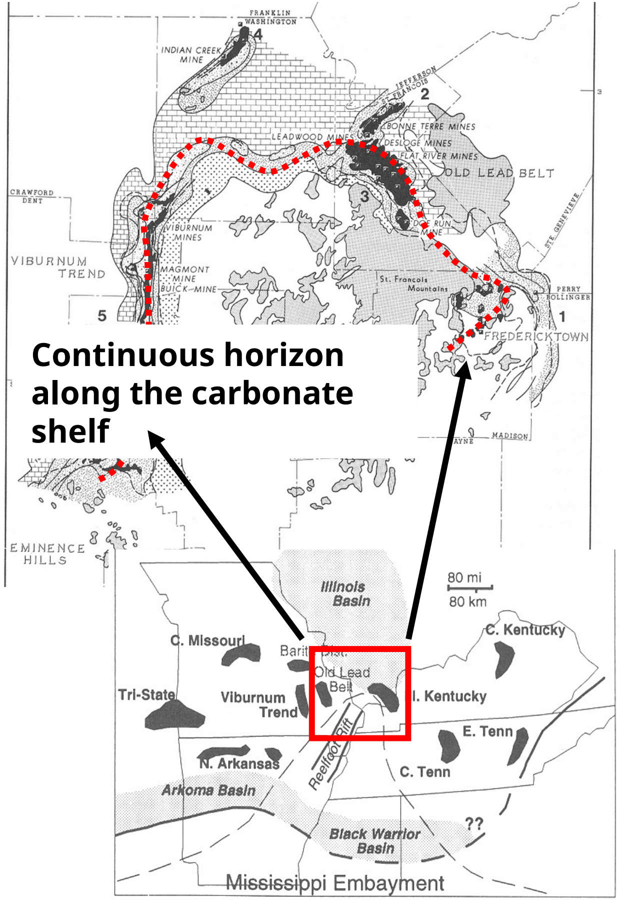
Metal transport as Cl-complexes.
Fluid mixing: reduced sulfur-bearing fluid mixing with a metal-rich fluid. Or S from rocks at depositional site. Temperatures indicate high geotherm or more likely upwelling of deep brines. High-salinity fluids due to evaporite dissolution or evaporated seawater infiltration.

Pb transport in MVT fluid



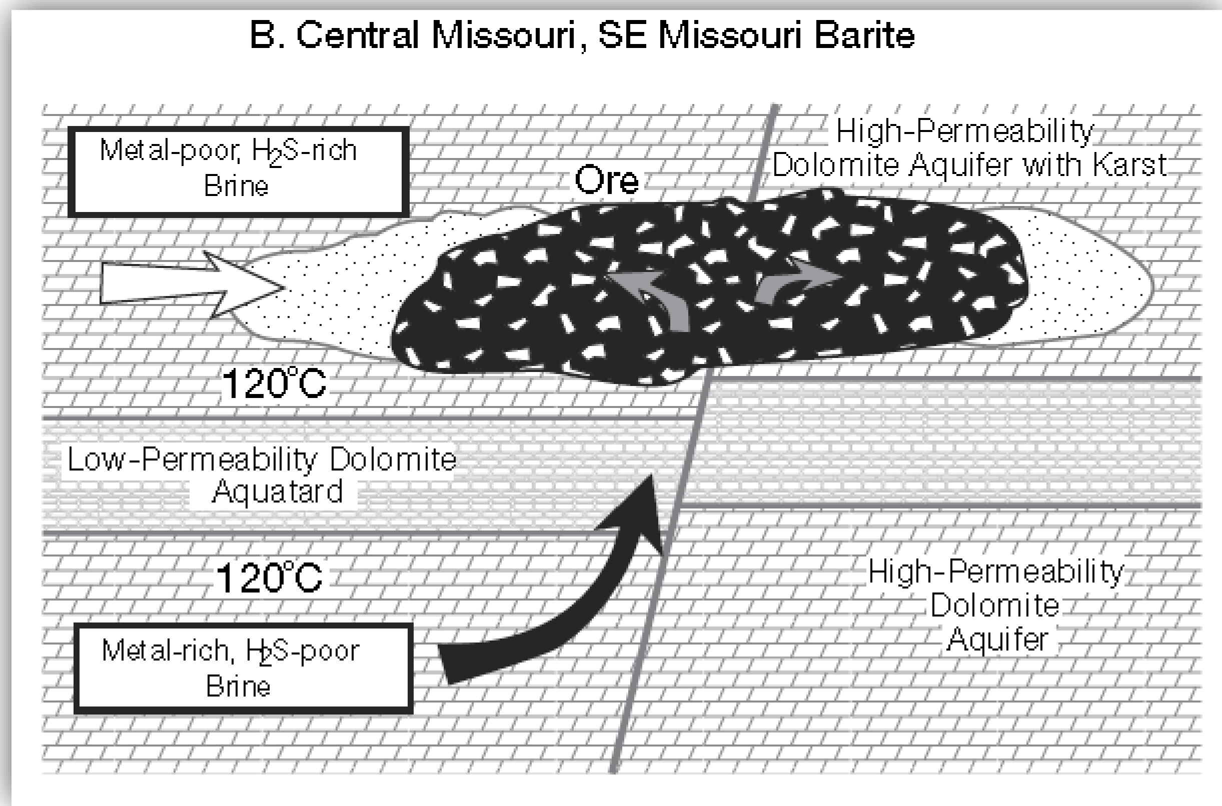
What are the typical conditions of fluid transporting Pb and Zn in MVT (see figure)

Anderson 1975



- Mineralization occurs in similar horizons (strata bound) around the basement uplift area.
- Mining since 1864!
- Exploration concentrated along same stratigraphic horizon – algal carbonate that is dolomitized.
- Common theme to ore bodies is the **dolomitized reef limestone upon basement high with shale aquitard above this unit**.

2. Karst environment



Note relationship to fault

An example of breccia-related mineralization

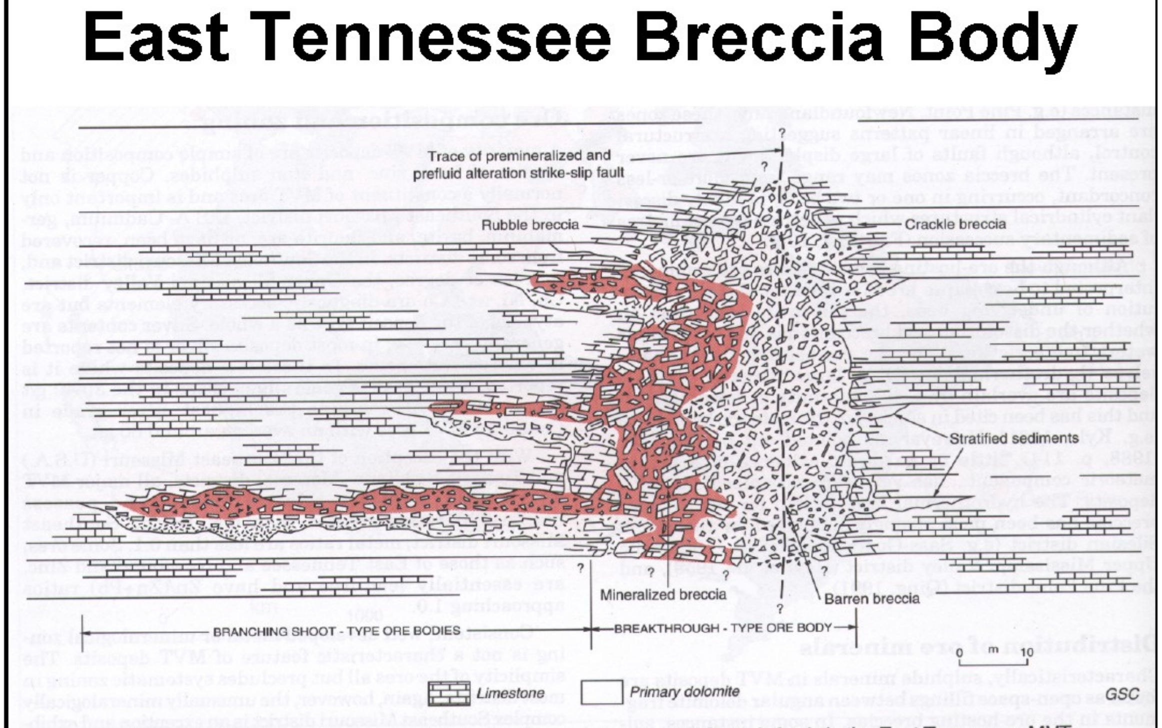
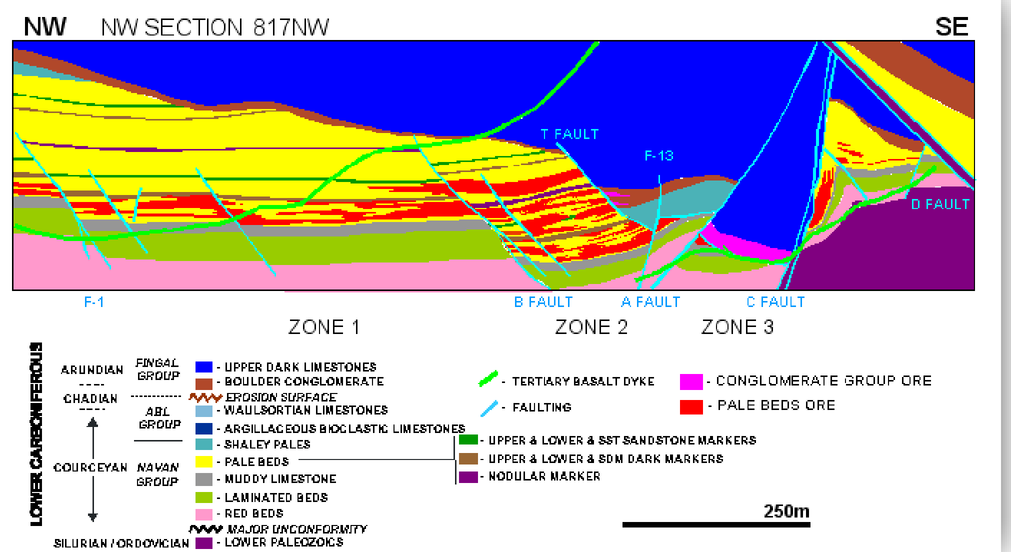


Figure 10-2. Schematic representation of a columnar ore-bearing breccia body in the East Tennessee MVT district (modified from Ohle, 1985).

TU Clausthal

Navan Ore Body in the Northern part of Irish Ore Field:

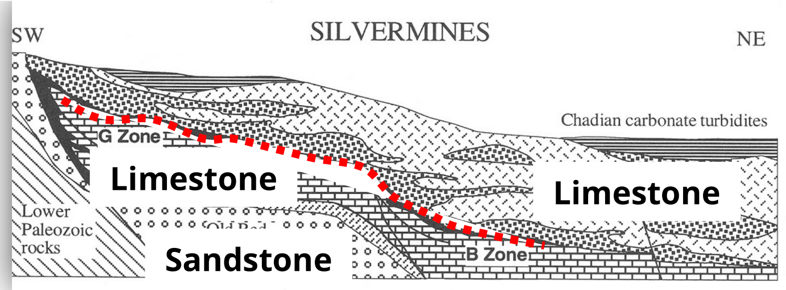
Currently largest MVT deposit in the world

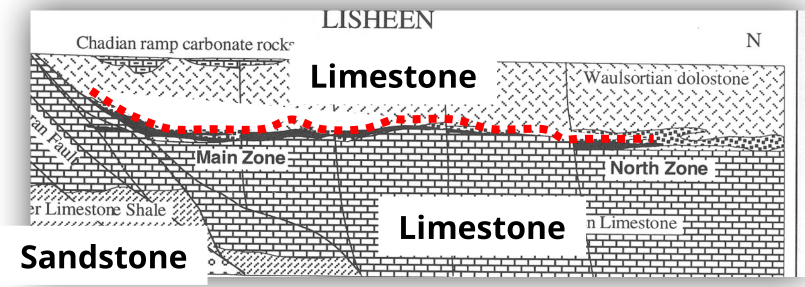


- Massive layered ores as in SEDEX deposits.
- Textures indicate early diagenetic origin – NOT late like in MVTs.
- Boulder bed on top contains fragments of ore – thus an early stage for formation.
- No vent system known.
- Is mineralization like a SEDEX?

Geology of Irish Zn-Pb(-Ba) Deposits:

- Lisheen and Silvermines are other past-current producers.
- Deposits show structural controls and a relationship to dolomitization.





- Faults are fluid zones.
- Clastic sediments (Old Red Sandstone) forms the foot wall.
- Limestone units are dolomitized in the areas of mineralization.
- Ore is along fault and strata bound along zones of dolomitization.
- Ore is syn- to early epigenetic.
- Zn>>Pb

Fe

Iron

Fe

26 55.845

- Iron
- Uses of iron
- Iron deposits
  - Banded iron formation (BIF)
  - Ironstone deposits

Iron

- Shiny, greyish metal, rusts in air
- Ore mineral(s): hematite, Fe_2O_3 magnetite Fe_3O_4
- Top supplier: Australia, Brazil, China
- Reserves: 180Mrd t
- Resources: 800Mrd t

Hematite/magnetite

USGS 2022

Iron
Fe
26 55.845

Iron uses

- Construction
- Steel, alloys
- Cast iron
- Magnets

Iron
Fe
26 55.845

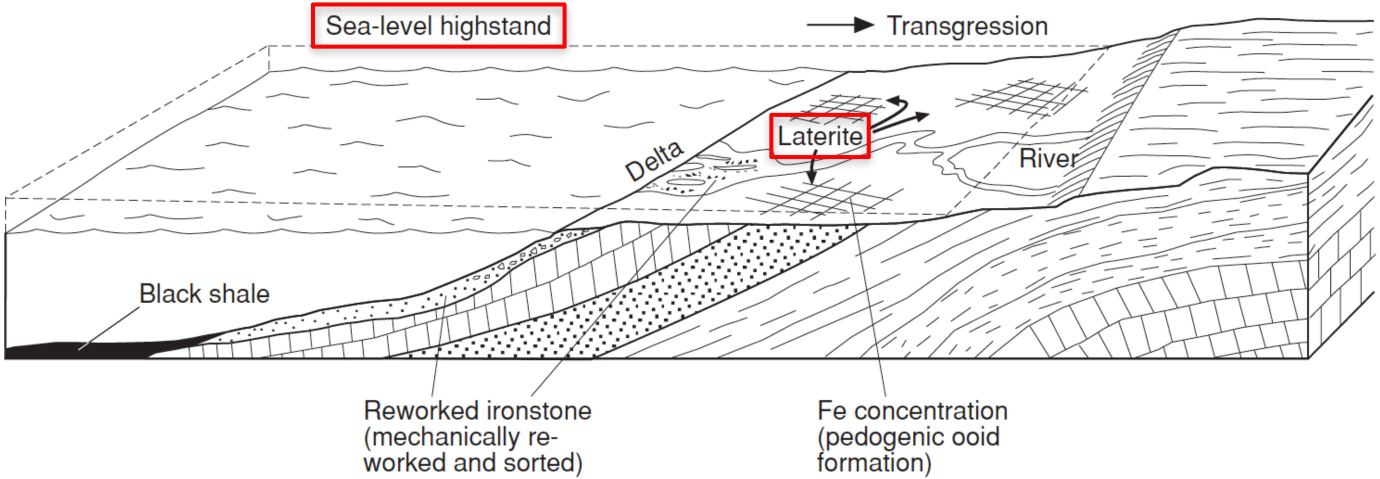
Iron uses

- Ironstone deposits
- Banded Iron Formations (BIF)

Ironstone deposits

Ironstone (hematite, goethite)

Oolites together with Fe-rich silicates (chamosite, glauconite, goethite)



Robb 2005

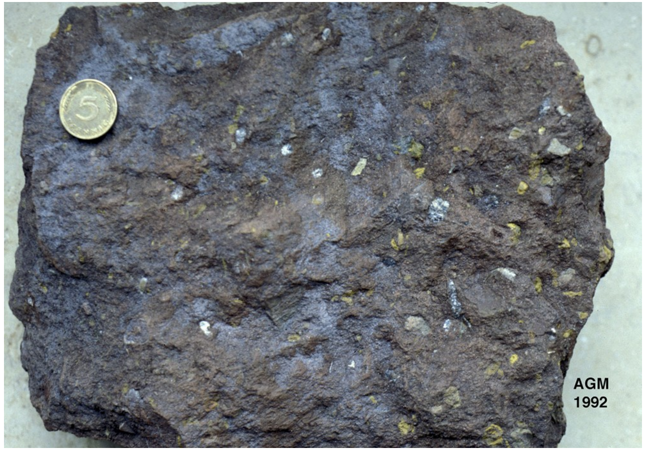
Ironstone deposits

Oolithic and goethite ore

Ironstone deposits

Deposited in river channels and then filled with oxidized/weathered iron from flood basalts.

Miocene



Banded iron formation deposits

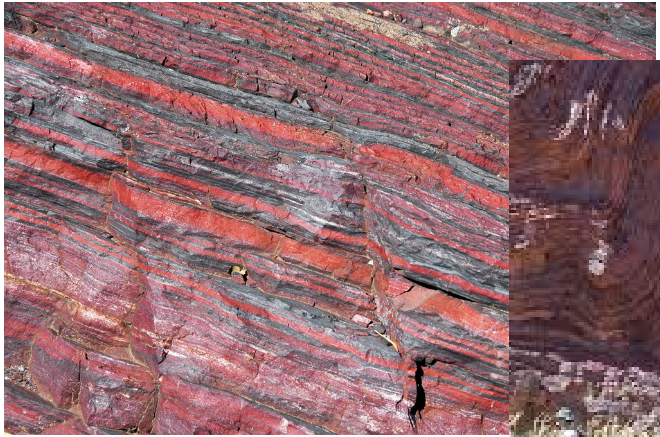
- Cherty iron formations are the global source of iron.
- Formed in 3 main periods: 3.5-3Ga, 2.5-2Ga, 1-0.5Ga
- Basically is a bedded chemical sediment of chert or Fe-rich carbonate and iron-rich layers (hematite/magnetite)
- High grade, high tonnage, ore body laterally extensive and thick

Algoma-type:
Related to volcanic arcs, relatively small, exhalative Fe, mined in the Abitibi greenstone belt, Canada

Superior-type
On stable continental platforms, largest, and most important deposits, lateraly extensive, Fe upwelling

Rapitan-type
Very minor, in glaciogenic sediments, anoxic conditions under ice cap

Banded iron formation deposits



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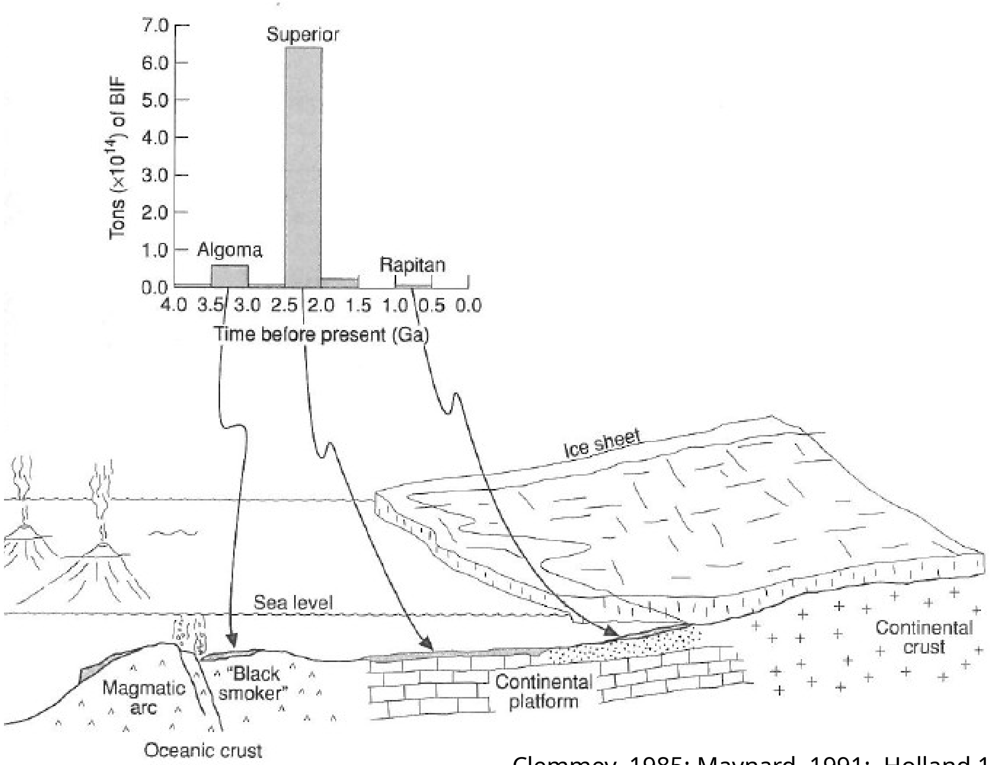
Banded iron formation deposits

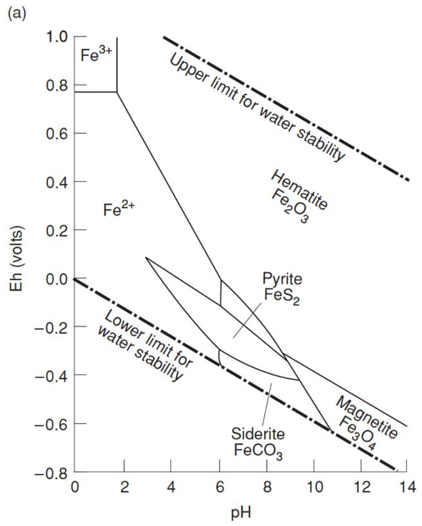
Geological formation settings of the three main types of BIF.



Clemmey, 1985; Maynard, 1991: Holland 1984

Banded iron formation deposits

Banded iron formation (hematite, magnetite) form due to chemical sedimentation of Fe and Si. Hematite is stable over a wide range in Eh-pH and the primary phase in BIF.

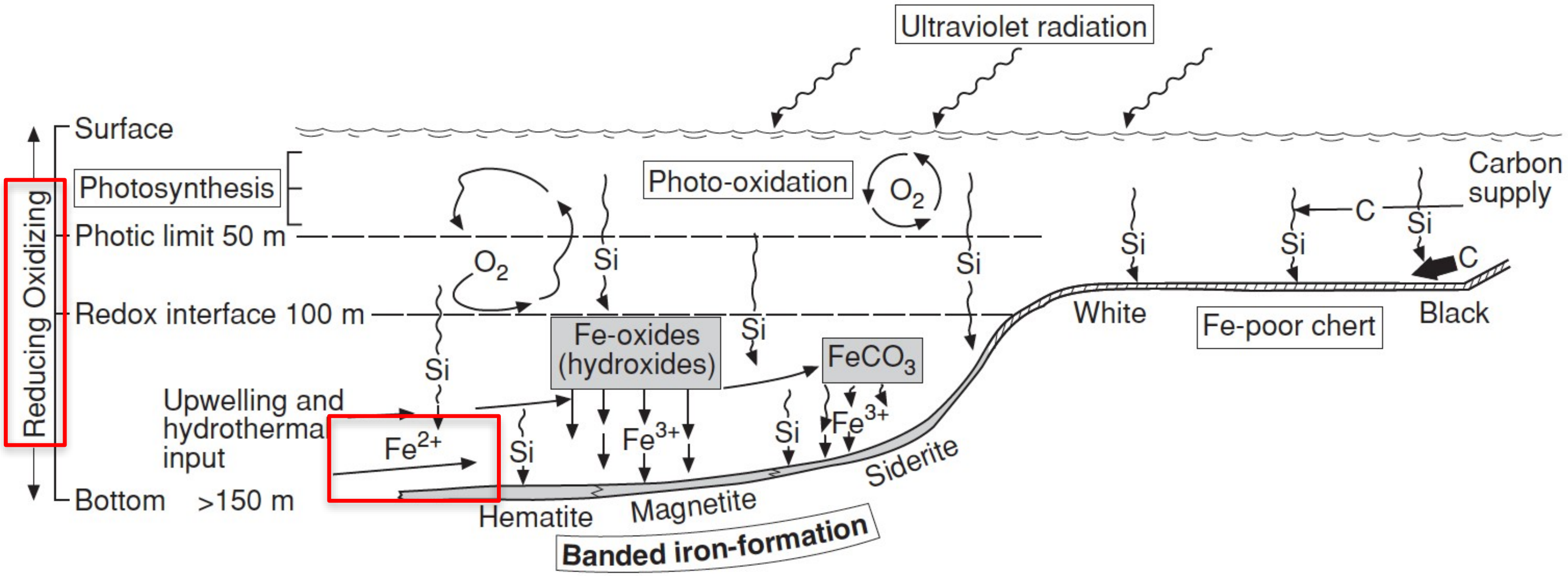


Chemical processes involve:

- oxidation-reduction
- pH
- Climate
- Paleolatitude
- Biological and atmospheric evolution

Banded iron formation deposits

Oxidation of Fe^{2+} due to photosynthesis bacteria

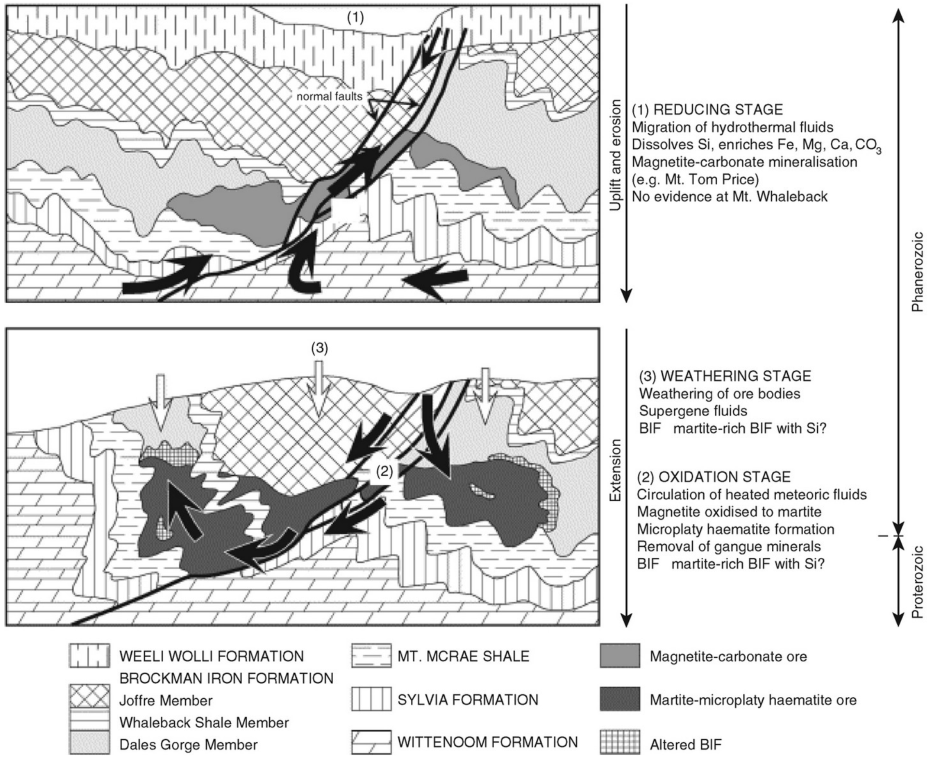


Robb 2005

Banded iron formation deposits: upgrading

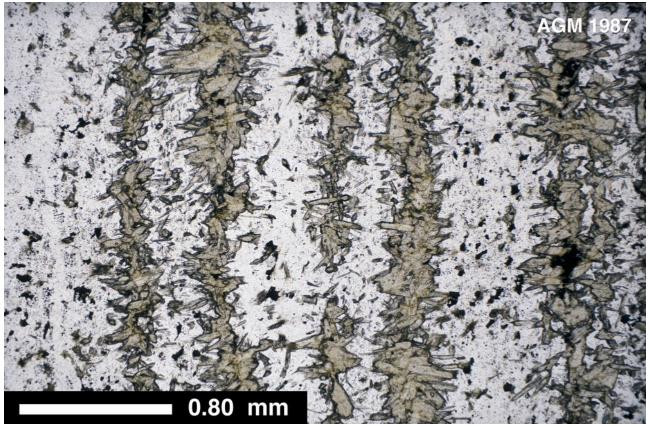
Iron-rich sediments are not rich enough, needs upgrading under epigenetic processes. Economic Fe grades are >30-35wt% Fe.

Either during metamorphism and transformation of iron hydroxides, iron-rich clays to hematite or due to leaching of other components in the sediment (e.g., SiO_2 and replacement by Fe-hydroxides, hypogene and supergene).

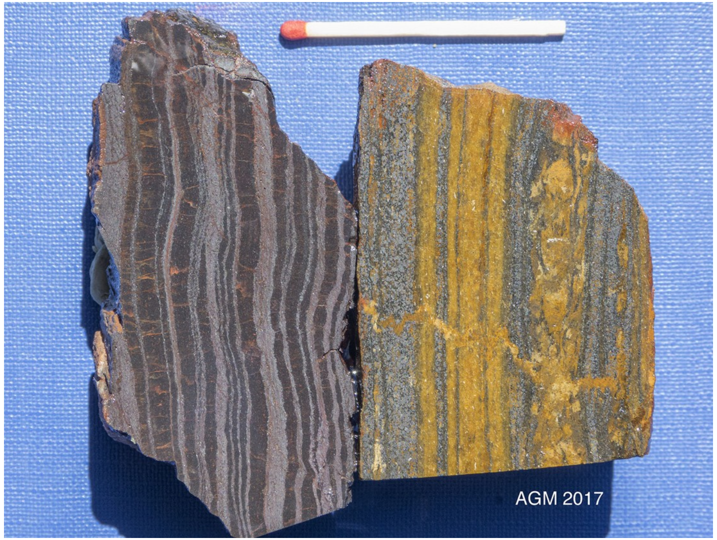


Algoma-Type

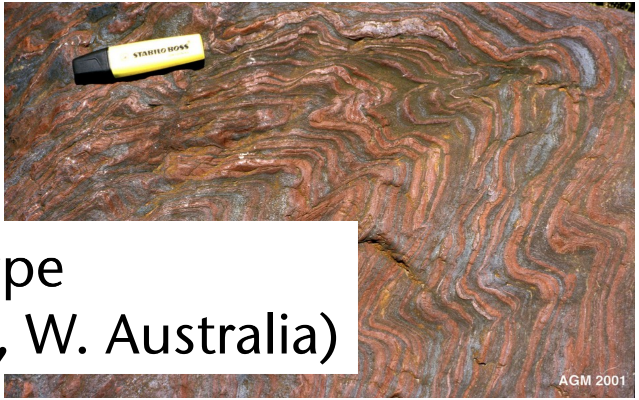
Algoma-Type



Reflected light microscopy



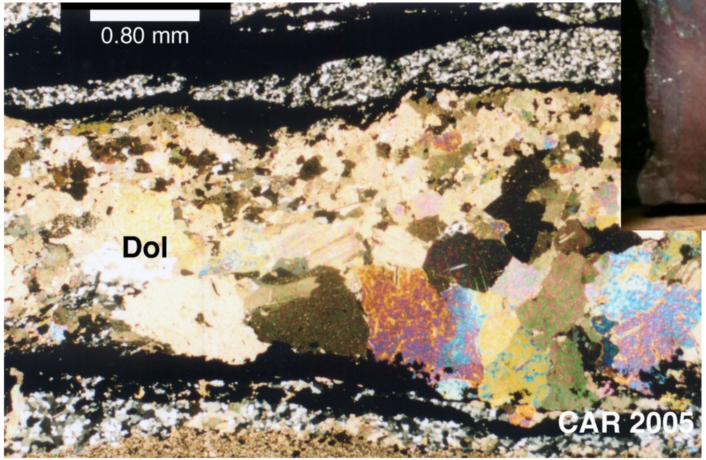
Superior-Type (Hamersley, W. Australia)



Superior-Type (Hamersley, W. Australia)

Superior-Type (Minas, Brazil)

Superior-Type (Minas, Brazil)



Aluminium
Al
13 26.982

Al

- Aluminium
- Uses of aluminium
- Aluminium deposits
  - Bauxite

Aluminium

Aluminium
Al
13 26.982

- Silvery, white metal, soft
- Ore mineral(s): bauxite
- Top supplier: China, India, Canada, Russia
- Reserves: 77Mio t
- Resources: 65Mrd t

Bauxite

USGS 2022

Aluminium uses

Aluminium
Al
13 26.982

- Construction
- Foils
- Aircraft, boats
- Alloys

Aluminium deposits

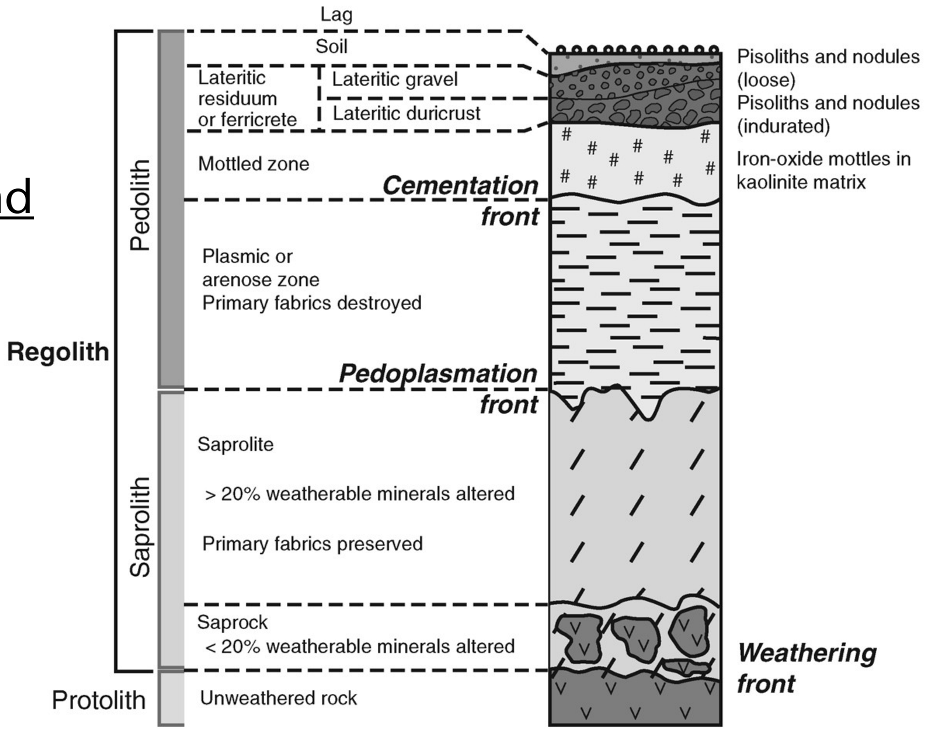
Aluminium
Al
13 26.982

- Supergene enrichment, Bauxite

Supergene enrichment: Bauxite

The chemical processes include <u>dissolution, oxidation, hydrolysis and acid hydrolysis.</u>

Humid, warm climates with deep chemical weathering.



Supergene enrichment: Bauxite

Bauxite is an accumulation of Al due to the leaching of other components such as Si.

Bedrock with more than 12% Al is suitable for bauxite formation.

Fsp-(Si loss) = kaol-(Si loss) = gibbsite

Ore grade is up to 50wt% Al.

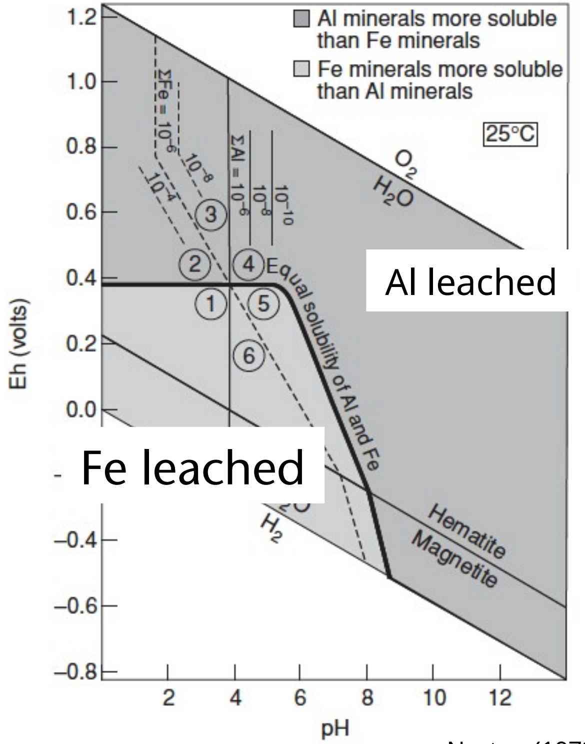
Eh and pH relationship is most important to obtain high-quality bauxite (i.e. low Fe).

Bauxite area in Jamaica

Supergene enrichment: Bauxite

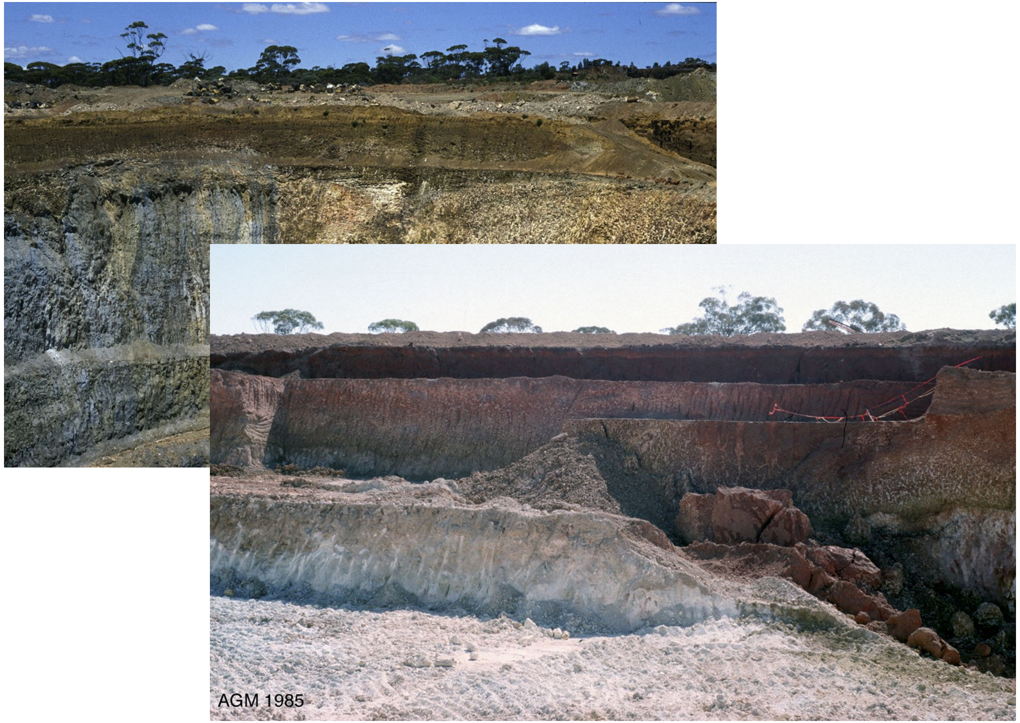
High quality bauxite contains 50wt% Al. Requires that Si and Fe are effectively removed.

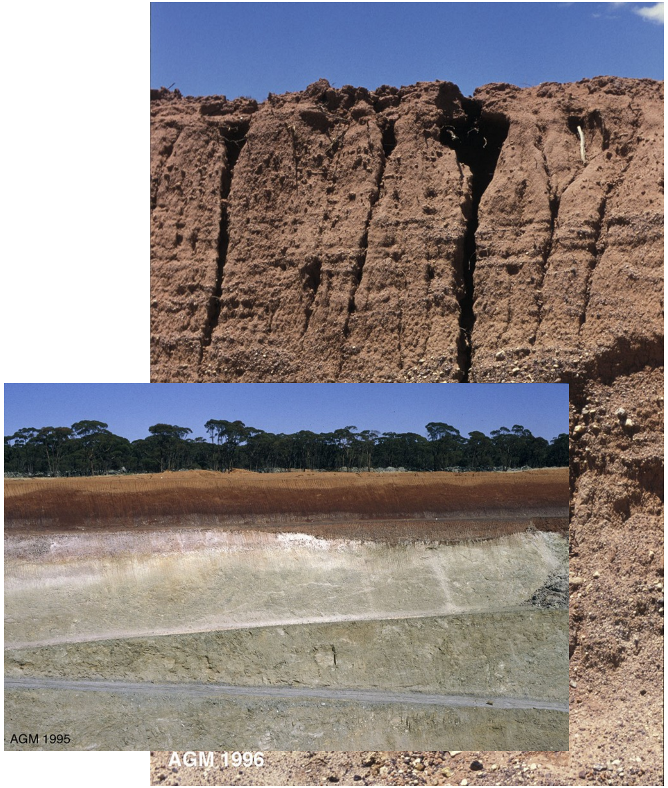
Fe is mobile in reduced state (Fe^{2+}).



Norton (1973)

Supergene enrichment: Bauxite





Supergene enrichment: Bauxite

Sn and W

Tin
Sn
50 118.710

Tungsten
W
74 183.84

- Tin and tungsten
- Uses of tin and tungsten
- Tin and tungsten deposits
  - Intrusion related deposits (granites)
  - Placer deposits

Tin
Sn
50 118.710

Tungsten
W
74 183.84

Tin

- Silvery, soft metal
- Ore mineral(s): cassiterite, SnO
- Top supplier: China, Indonesia, Peru
- Reserves: 4.6Mio t
- Resources: 15.4Mio t

Cassiterite

USGS 2022

Tin uses

Tin
Sn
50 118.710

Tungsten
W
74 183.84

- Alloys (tin cans)
- Glass manufacturing
- Superconducting magnets

Tin
Sn
50 118.710

Tungsten
W
74 183.84

Tungsten

- Silvery, shiny white metal
- Ore mineral(s): wolframite, $(Fe,Mn)WO_4$, scheelite, $CaWO_4$
- Top supplier: China, Russia, Vietnam
- Reserves: 3.8Mio t
- Resources:

Wolframite/scheelite

USGS 2022

Tin
Sn
50 118.710

Tungsten
W
74 183.84

Tungsten uses

- Alloys, high temperature applications
- Cutting/drilling tools
- Light bulbs

Intrusion related ore deposits, granites

Intrusion related ore deposits, granites

- Similar to porphyry Cu systems
- Magmatic-hydrothermal
- Metal source are magmatic (felsic rocks)
- Metal enrichment due to fractionation and then release of hydrothermal fluids.
- Mineralization mainly in veins (mm-cm)
- Low grade, high tonnage.
- Ore body concentric to elongated (veins)

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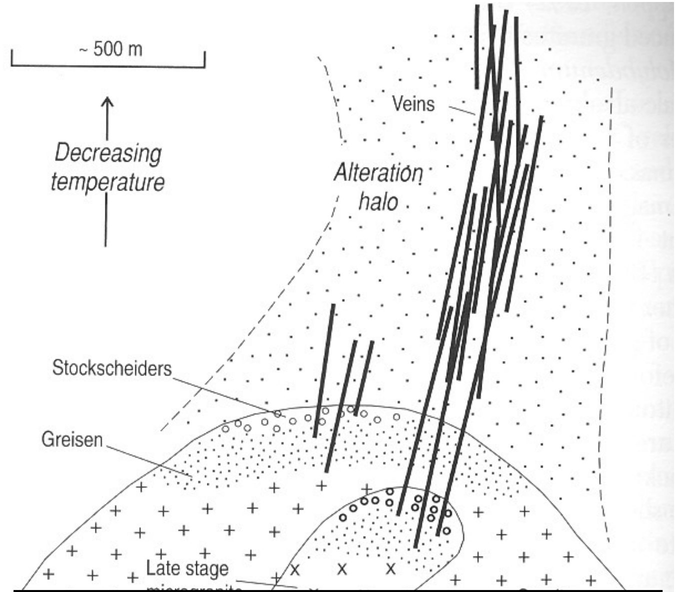
Intrusion related ore deposits, granites



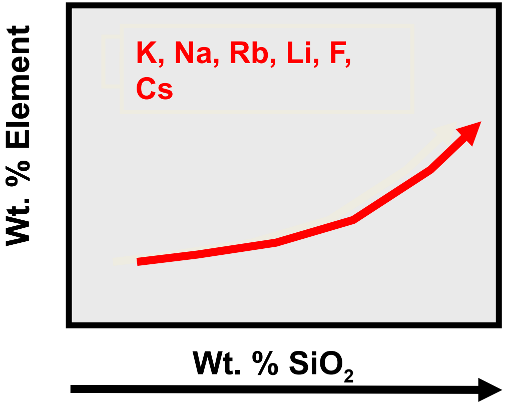
1. Primary enrichment in magma of metals, volatiles

4. Focusing of fluids (ore) into structural sites (veins)

3. Fluids react with granite to form greisens

2. Generation of metal-volatile rich melt

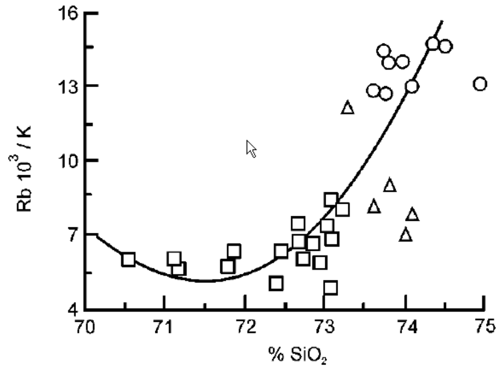
Intrusion related ore deposits, granites

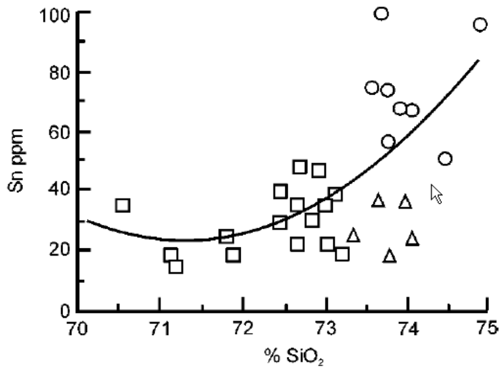


Magma fractionation in granitic systems

- Early removal of Plg-Hbl-Bio enriches melt in elements not compatible in these minerals – Li, Rb, Cs, Ta, Nb, Sn, W, etc.).
- Volatile content increases (H_2O, F, Cl, B).

Intrusion related ore deposits, granites





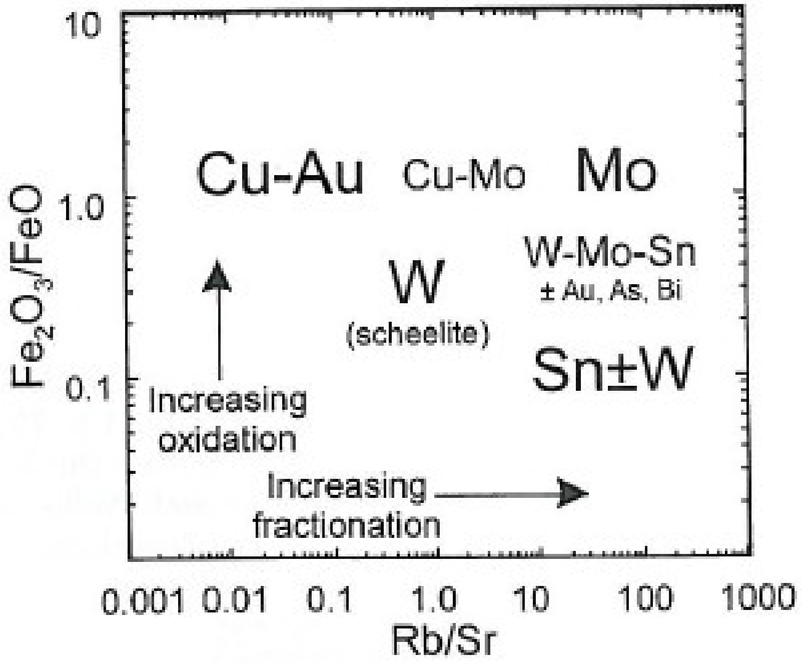
Magma fractionation in granitic systems

- The most evolved rocks are indicated using an index of fractionation, as represented by Rb/K (index of fractionation) values.
- The Sn values are highest, to 100 ppm, in the rocks which are indicated from above to be the most evolved.

(Data from suite of granites in Portugal; Gromes and Neiva, 2002, Chemie de Erde)

Intrusion related ore deposits, granites

- The redox conditions and fractionation of an intrusion control to some degree the metallogeny.
- Oxidized, less fractionated systems are more Cu-Au rich.
- Reduced, but fractionated systems are more Sn-W rich.

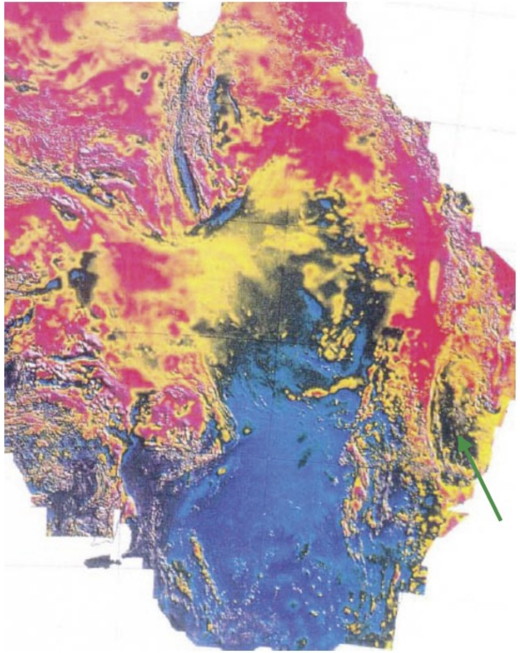


Intrusion related ore deposits, granites

Geophysical signature of granites related to hydrothermal Sn-W deposits

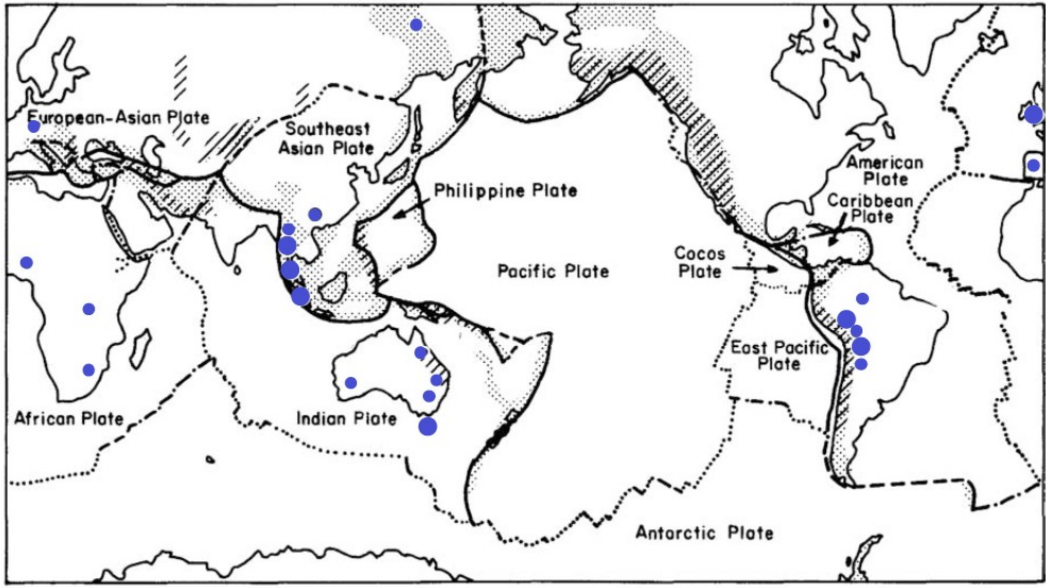
Granites are always reduced
Ilmenite >> magnetite

—> negative aeromagnetic anomalies



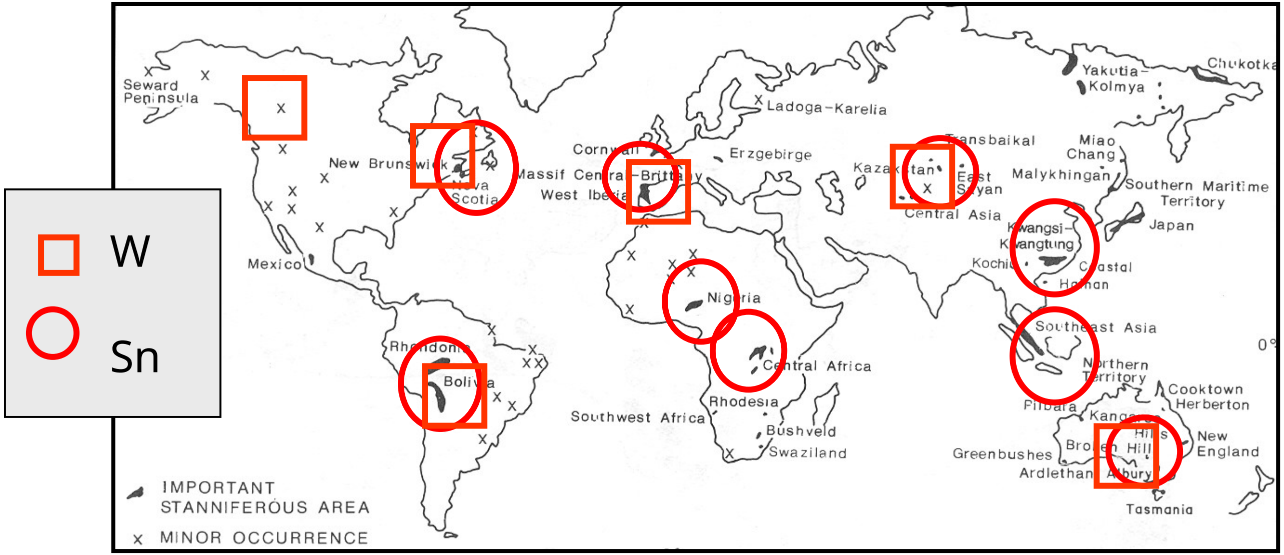
Intrusion related ore deposits, granites

HYDROTHERMAL SN-W (MO) RELATED TO GRANITE INTRUSIONS



Age and tectonic position of Sn-W deposits:
- Palaeozoic (Variscan) to Tertiary.
- Continent-ward of convergent plate margins (Bolivia, Aus)
- Also intracratonic in older provinces (Nigeria; Bushveld)

Intrusion related ore deposits, granites



Important districts in Europe include the **Erzgebirge, Massif Central, Cornwall, Portugal**

Intrusion related ore deposits, granites

Sn-W Minerals of Significance:

Note that scheelite fluoresces blue under UV.

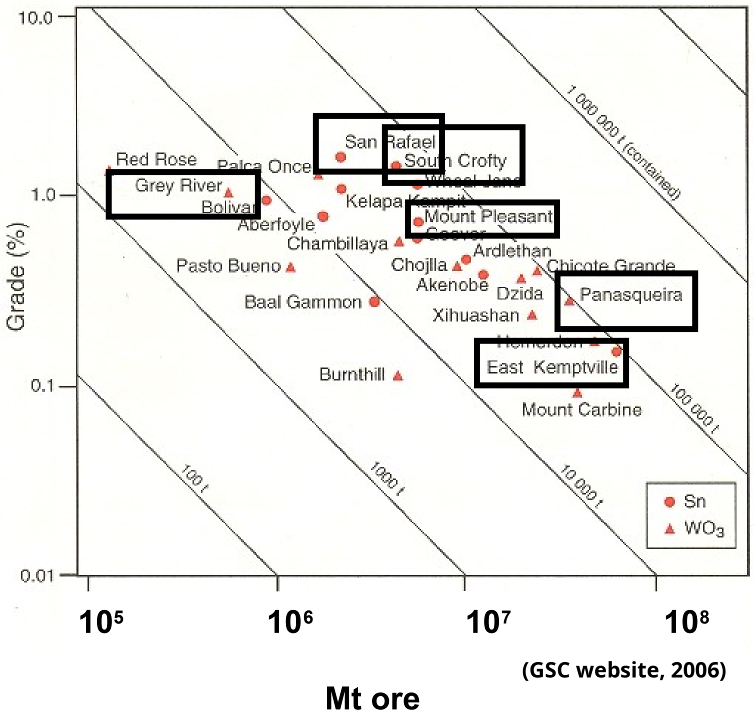
W Minerals

Scheelite - $CaWO_4$
Wolframite - $(Fe, Mn)WO_4$

Sn Minerals

Cassiterite - SnO_2 – dominant phase
Stannite - Cu_2FeSnS_4

Intrusion related ore deposits, granites



(GSC website, 2006)

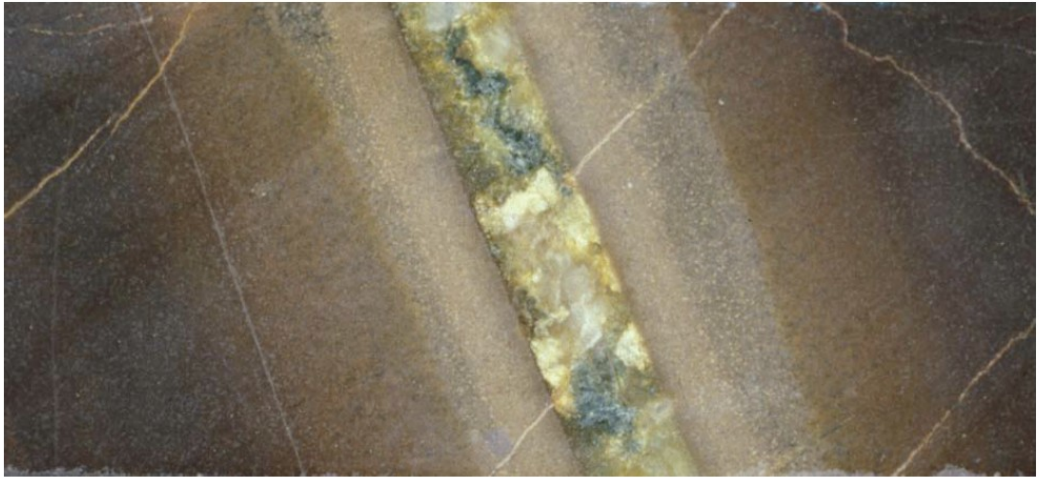
Grade-Tonnage of Sn-W Deposits

- Deposits 0.1-5.0 wt. % Sn, W and tonnage <1-50 Mt.
- Highest grades are vein or skarn deposits, versus greisens that are lower grade.

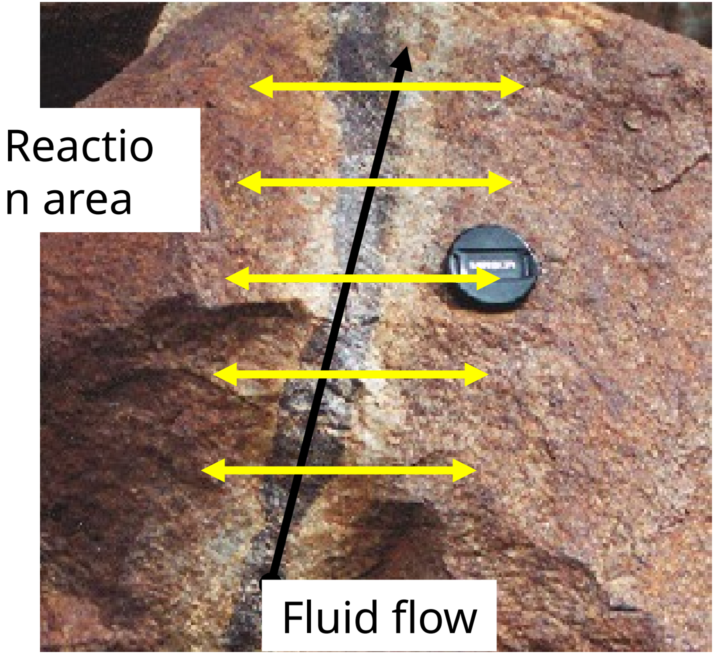
Intrusion related ore deposits, granites

Alteration

- Early albitic alteration in granitoid hosting rocks; pegmatites
- Cassiterite deposition often associated with "phyllic" alteration: feldspars converted to muscovite ± topaz ± chlorite ("greisen").
- Later formation of kaolinite ('china clay' in Cornwall).



Intrusion related ore deposits, granites



Alteration:
Greisen Bodies: Reaction of the fluids with granite or country rock to form greisen (e.g., **quartz, topaz, fluorite, muscovite, tourmaline**).

Placer deposits

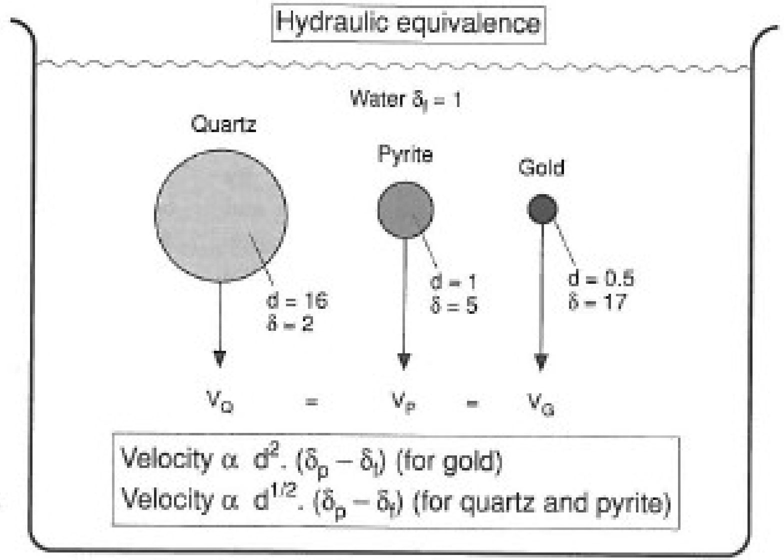
- Sedimentary ore deposit.
- Deposition of ‘heavy’ minerals.
- Fluvial or aeolian transport and sedimentation.
- Cassiterite (SnO_2) is dense and therefore can be enriched in beach sands from where it can be mined.
- High grade, high tonnage.
- Ore body laterally extensive, but restricted to layers

Placer deposits

- Transport and settling of matter in a fluvial system is a complex processes and makes it difficult to predict the formation of 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

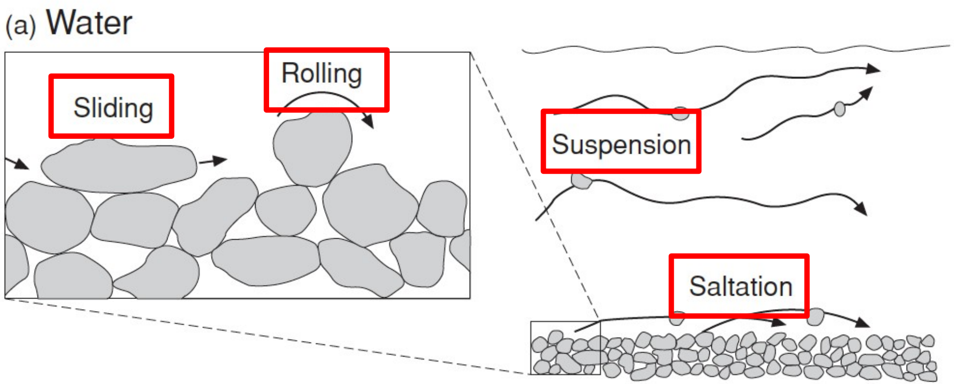


These diameter ratios could lead to a Witswatersrand placer

Placer deposits: Transport modes

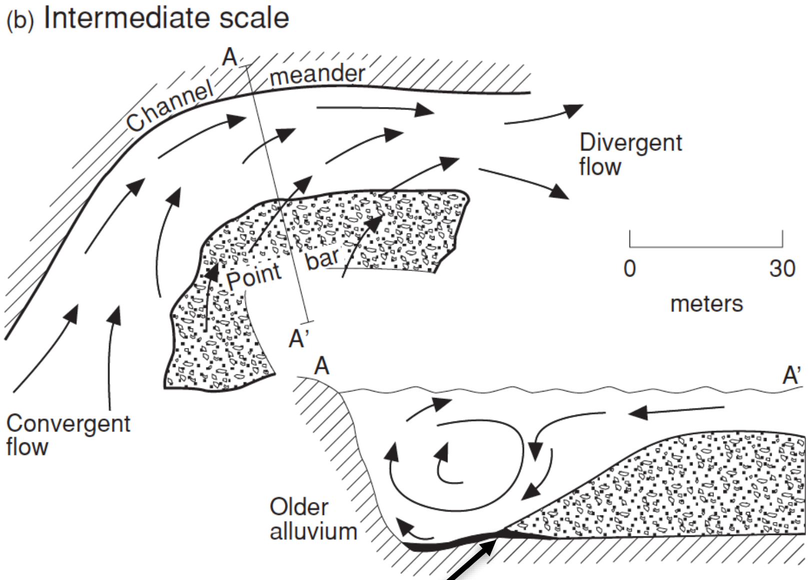
Later entrainment involves the bed load and its remobilization of certain particles.

It has to be considered that larger grains move faster than small once at a given bed roughness (less trapping and shielding).

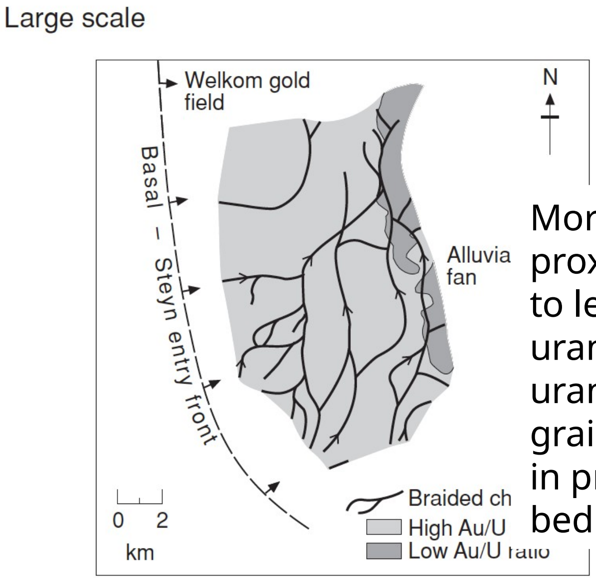


In the formation of placer deposits the flow of the medium is controlling factor (laminar vs. turbulent)

Placer deposits: Transport sorting



Heavy mineral deposition



More dense gold proximal compared to less dense uraninite. Also uraninite larger grains, gold trapped in proximal rough bed.

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Word cloud