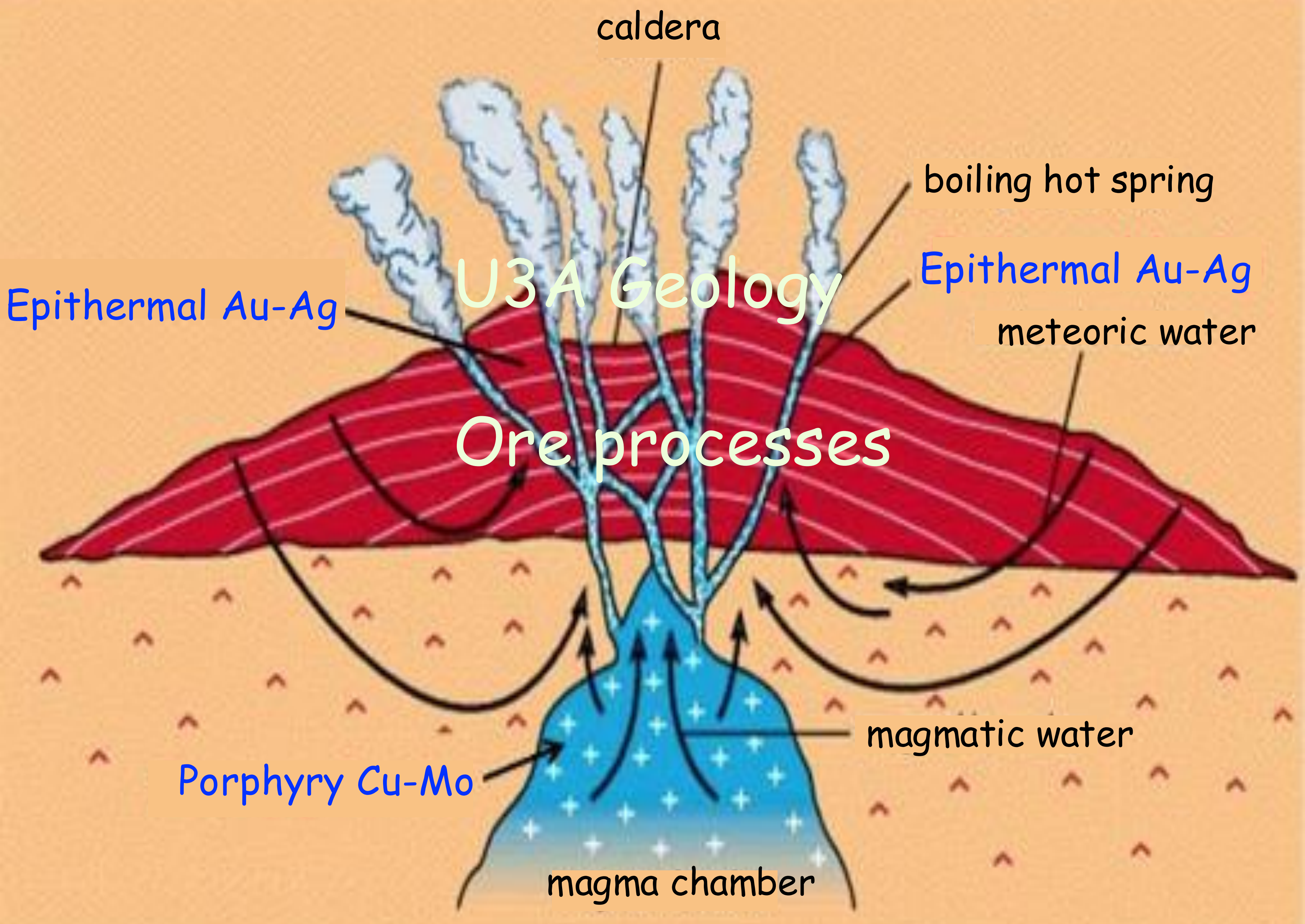
U3A Geology

Ore processes



Introduction

- Ore genesis can arise through a diversity of processes that produce enhancements of commodities toform ore deposits
- often more than one process contributes to the formation of an individual deposit

Ore-forming processes

1. Magmatic concentration*
2. Hydrothermal processes*
3. Contact metasomatism*
4. Sedimentation
5. Volcanic-exhalative processes*
6. Metamorphism
7. Oxidation and supergene enrichment *
8. Weathering (residual deposits)*
9. Evaporation
10. Mechanical concentration*

Magmatic concentration

- Crystallisation of ore minerals will commence when their concentrations exceed their solubilities

- magmatic deposits can form through magmatic crystallisation or through magmatic segregation

- magmatic crystallisation → normal crystallisation

- magmatic segregation (orthomagmatic deposit)
  - (1) Fractional crystallisation
  - (2) Liquid immiscibility (liquidation)

- mineralisation may occur at an early stage prior to formation of silicates or may crystallise from residual fluids

Magmatic crystallisation

- Magmatic crystallisation: the precipitation of ore minerals as major/minor constituents of igneous rocks during *normal crystallisation.*
  - Diamond deposits in kimberlite pipes
  - REE minerals in carbonatites
- normally occur in “unusual” rock types
- ore minerals form either as disseminated grains or as segregations
- crystallisation of ore minerals will commence when their concentrations exceed their solubilities

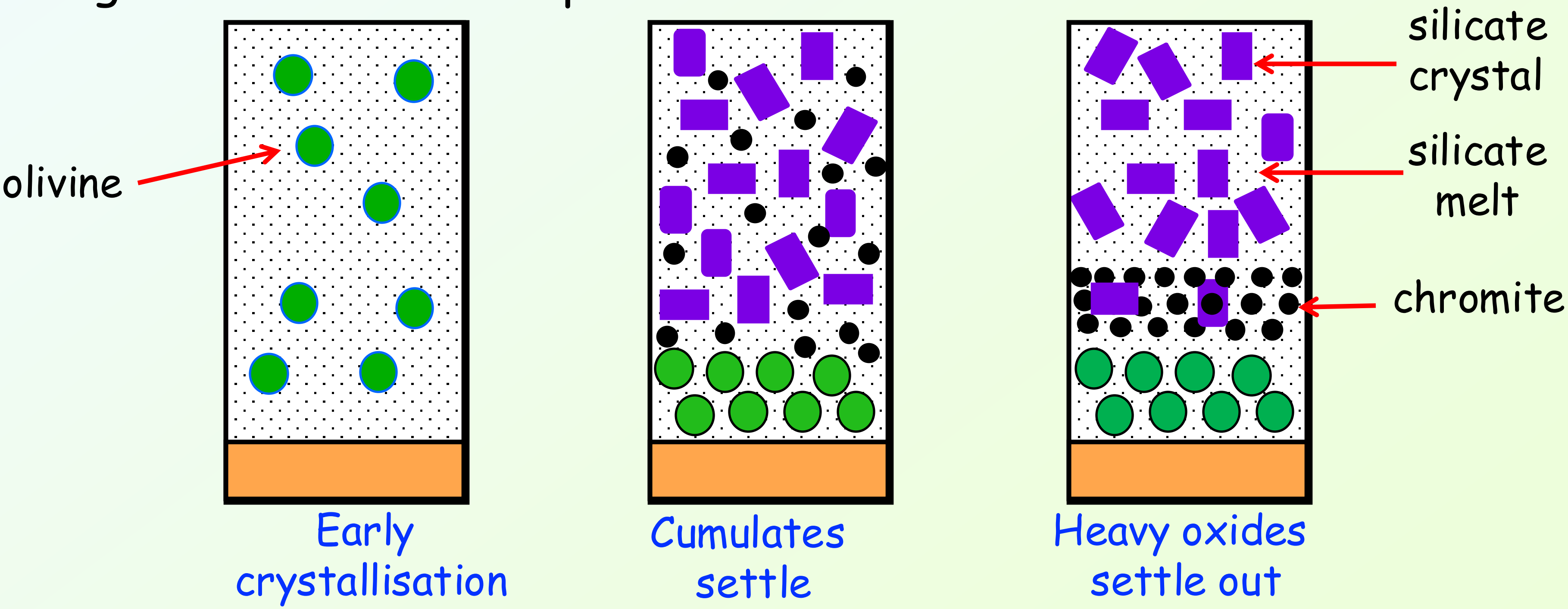
Magmatic segregation

- Magmatic segregation: formed from direct crystallisation of ore minerals from a magma with subsequent separation from the remaining melt
- orthomagmatic deposits form either through crystal fractionation or as a consequence of liquid immiscibility (liquation)
- fractional crystallisation is generally confined to plutonic rocks, whereas liquation may be associated with plutonic or volcanic rocks

Fractional crystallisation

Fractional crystallisation: the process by which early formed crystals are effectively removed from the parent melt

- the term cumulates apply to rocks formed by this process
- normally occur in layered mafic-ultramafic complex
- commonly rhythmic → multiple magma pulses
- e.g. the Bushveld complex intrusion



Liquation

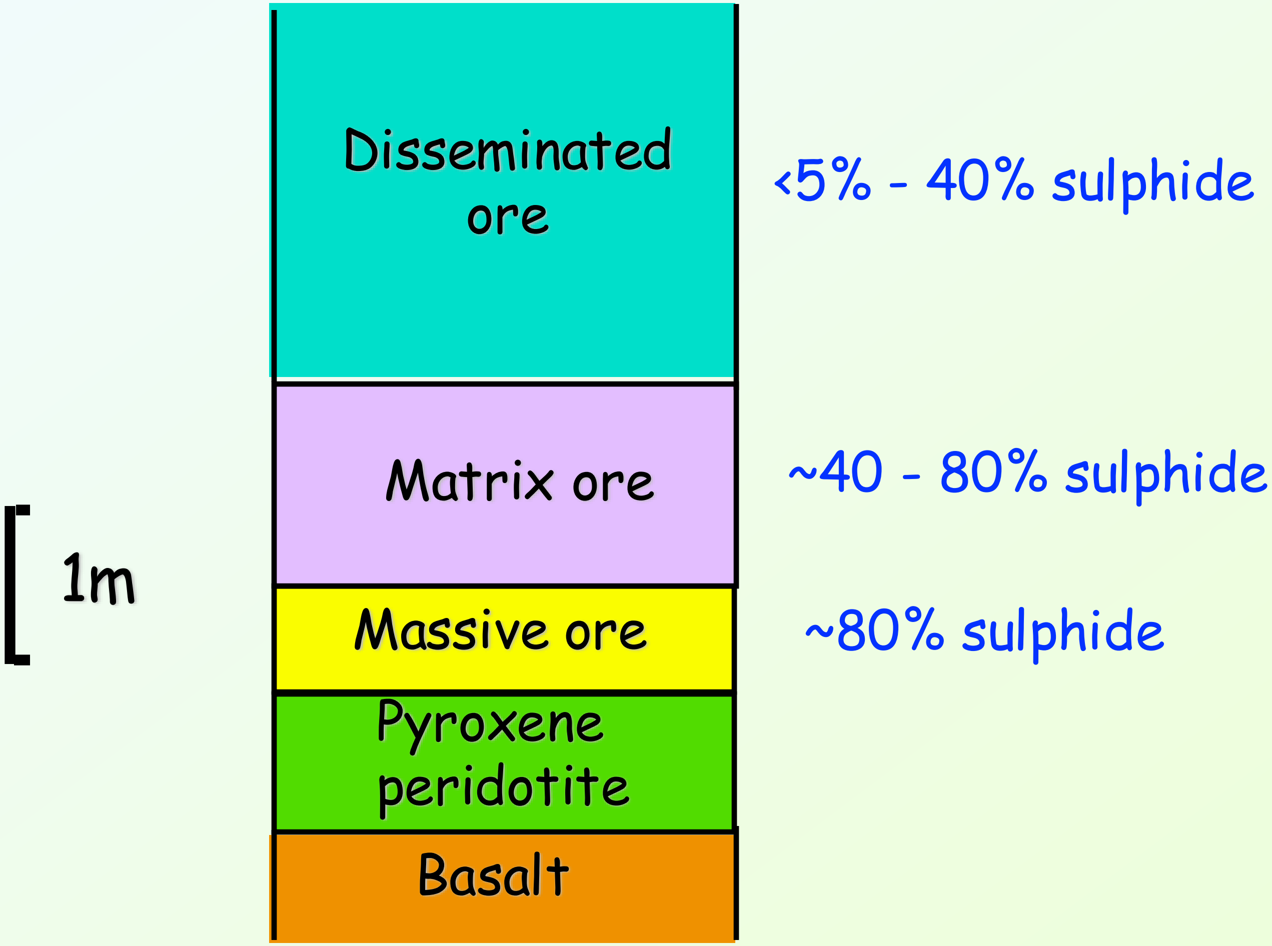
Liquation results from liquid immiscibility

- Sulphur saturation
- commonly associated with mafic-ultramafic magmas
- in mixed silicate –sulphide magma, two liquids tend to segregate in much the same way as water and oil do
- Pyrrhotite-pentlandite-chalcopyite (Ni-Cu ores)

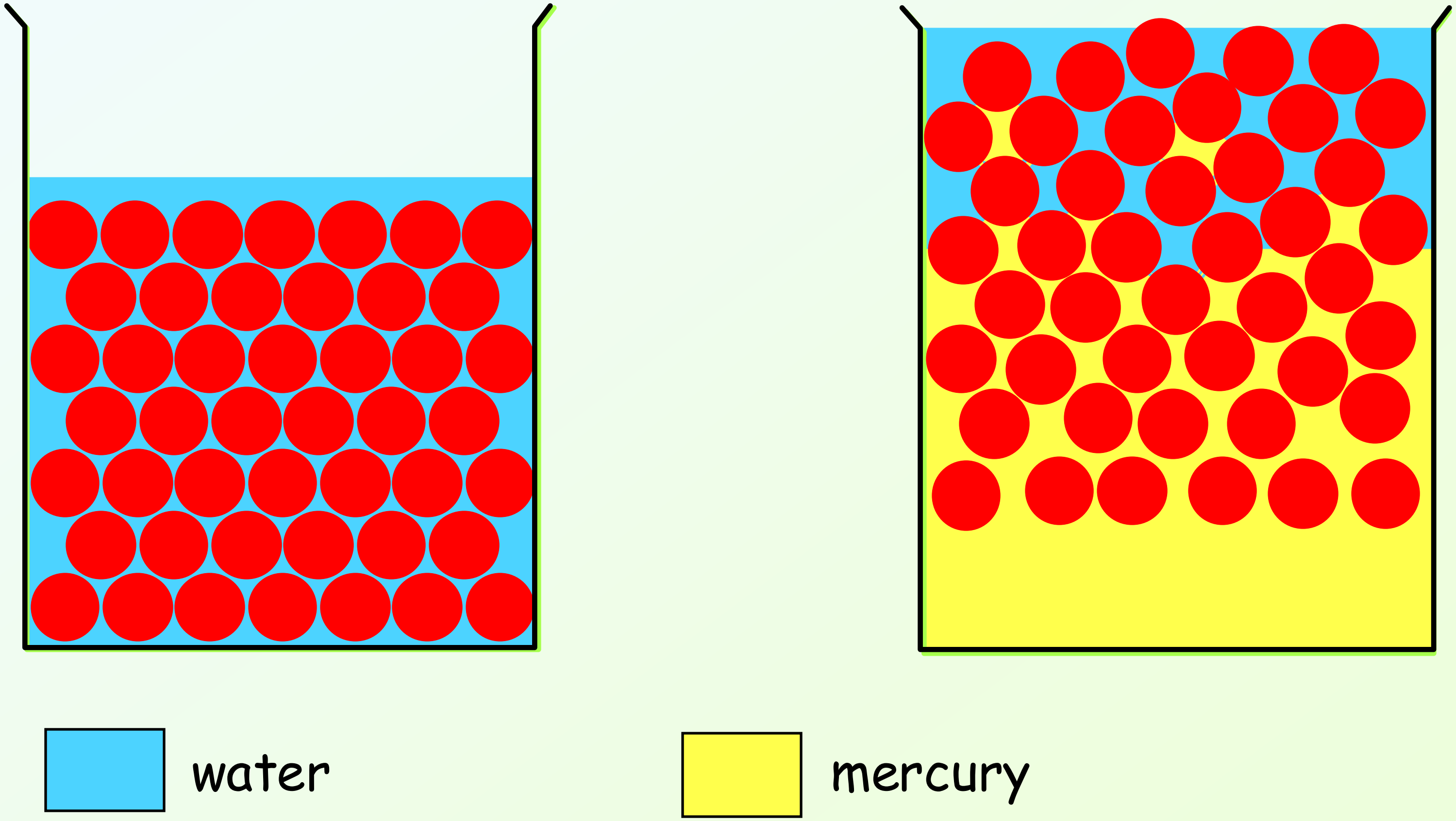
Two types of segregation:

- Batch equilibrium: accumulation in a single phase
- Fractional segregation: continuous process involving the settling of small amounts of immiscible sulphides with further crystallisation of silicate minerals → blebby sulphide texture

Vertical zonation of a nickel sulphide ore body formed through liquation eg. Mariners mine, WA



Billiard ball model illustrating the formation of Fe-Ni-Cu sulphide deposits (Naldret 1973)



Hydrothermal processes

Hydrothermal processes: involve hot, aqueous (saline) solutions that can range in *T* from 50°C – 600°C depending on origin of fluids

- many mineralisation processes involve hydrothermal solutions e.g. vein deposits, volcanic exhalative deposits, skarns, greisens
- wide spectrum of physical (*T*, *P*) and chemical properties
- Fluid inclusions: commonly saline and contain a number of metals and non-metal complexes
- important in igneous, sedimentary & supergene environments

Formation of hydrothermal deposits

(1) Source of metal bearing fluid (MBF) (fluid source, metal source)

(2) transport and focusing of MBF (transport means, channel ways)

(3) trap (deposition mechanism, site)

(4) Precipitating mechanism e.g. decrease in temperature/pressure, change in pH, oxidation state, boiling

Sources of MBF

1. Sub-surface meteoric water
2. sea water
3. deeply penetrating meteoric water
4. metamorphic water (dehydration reactions)
5. magmatic water

Sources of hydrothermal solutions

- Most hydrothermal solutions are derived from crystallising magma
- fluids evolve as crystallisation proceeds
- elements incompatible with silicate minerals in intrusion partition to melt → enriched in residual magmatic fluids
- this model accounts for the fluid, metals and other elements and the heat engine to drive mineralising system
- solutions move via fractures and other channel ways to cooler parts of the crust where they crystallise

Magmatic water & mineralisation

Water content in felsic magmas is normally between 2.5 and 6.5 wt % (Burnham 1979).

- provides MBF (water, metals, ligands)
- one cubic kilometre of magma with 3 wt% water can produce 100 Mt of water
- in addition to water there are other volatile components present in late stage magmatic fluids e.g. H_2S, HCl, HF, CO_2, SO_2
- intrusion → heat source to drive convection and transportation

Metal complexing

- Sulphides and metals have low solubilities in water
- metals are transported in hydrothermal solutions as complex ions to transport sufficient metal for ore deposition
- most important ligands: Cl^-, HS^- and OH^-
- bisulphide complexes most stable at near neutral pH at high temperature

Rock permeability

- Fluids moving from their origin to the site of deposition require a plumbing system
- types of openings hydrothermal solutions pass through can be divided into primary and induced openings

primary	induced
pore spaces	fissures
crystal lattices	shear zones
vesicles	saddle reefs
cooling cracks	volcanic pipes
igneous breccia	tectonic breccia
bedding planes	solution cavities

Contact metamorphism

- Most magmas do not reach the surface but are emplaced within the Earth's crust
- as they cool and crystallise, late stage fluids evolve that may permeate the enclosing rocks → metasomatism
- effects of igneous intrusion can be classified into two processes:
  - (1) contact metamorphic – effect of heat alone
  - (2) contact metasomatism – effects of heat plus constituents from the magma
- as a consequence of contact metasomatism, carbonate rocks are most susceptible to reaction with fluids

Contact metamorphism

Contact metamorphism: involves heat alone eg. in an impure sandstone containing quartz and calcite

$$\underset{\text{quartz}}{SiO_2} + \underset{\text{calcite}}{CaCO_3} \rightarrow \underset{\text{wollastonite}}{CaSiO_3} + CO_2$$

Contact metasomatism: involves the effects of heat plus constituents from the magma

$$\underset{\text{quartz}}{2SiO_2} + \underset{\text{calcite}}{CaCO_3} + FeCl_{2(aq)} + H_2O \rightarrow \underset{\text{diopside}}{CaFeSi_2O_6} + CO_2 + 2HCl$$

Contact metasomatism

- Metasomatic fluids may transport metallic and non-metallic elements that are precipitated within the contact aureole
- temperatures of formation of metasomatic deposits are 300-800°C
- magmatic constituents consist chiefly of metals (e.g. Cu, Zn, Pb,W, Sn), silica, sulphur, boron, chlorine, fluorine, sodium and potassium
- most contact metasomatic deposits are associated with granitoids produce rocks such as skarns and greisens
- contact metasomatic deposits commonly form above flanks of intrusions and around cupolas

Metasomatic mineral deposits

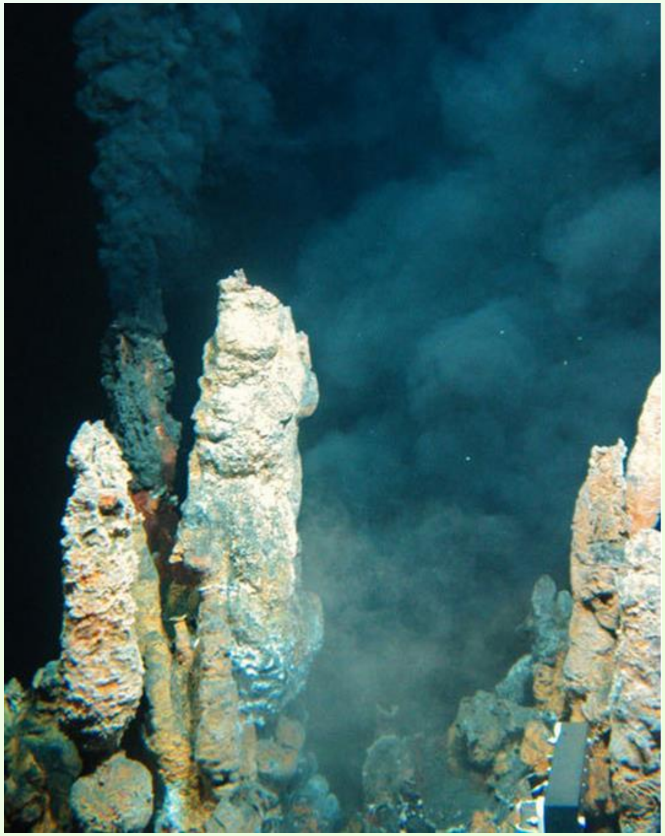
- There are two basic stages in contact metasomatism:

  Stage 1 – recrystallisation and recombination with or without constituents from the magma → forms silicates and Fe oxides

  Stage 2 – formation of sulphides e.g. pyrite, arsenopyrite, molybdenite, sphalerite, chalcopyrite and galena
- metasomatic ore bodies are generally of comparatively small size and contain up to a few 10s of thousands of tonnes of ore
- ores tend to have coarse textures with ore minerals magnetite, scheelite, cassiterite and sulphides most common
- gangue minerals include garnet, actinolite, wollastonite, vesuvianite, fluorite, chlorite and micas

Volcanic-exhalative deposits

Volcanic-exhalative deposits are syngenetic, sedimentary sulphide deposits formed on the sea floor by precipitation of material from hydrothermal vents called 'black smokers'

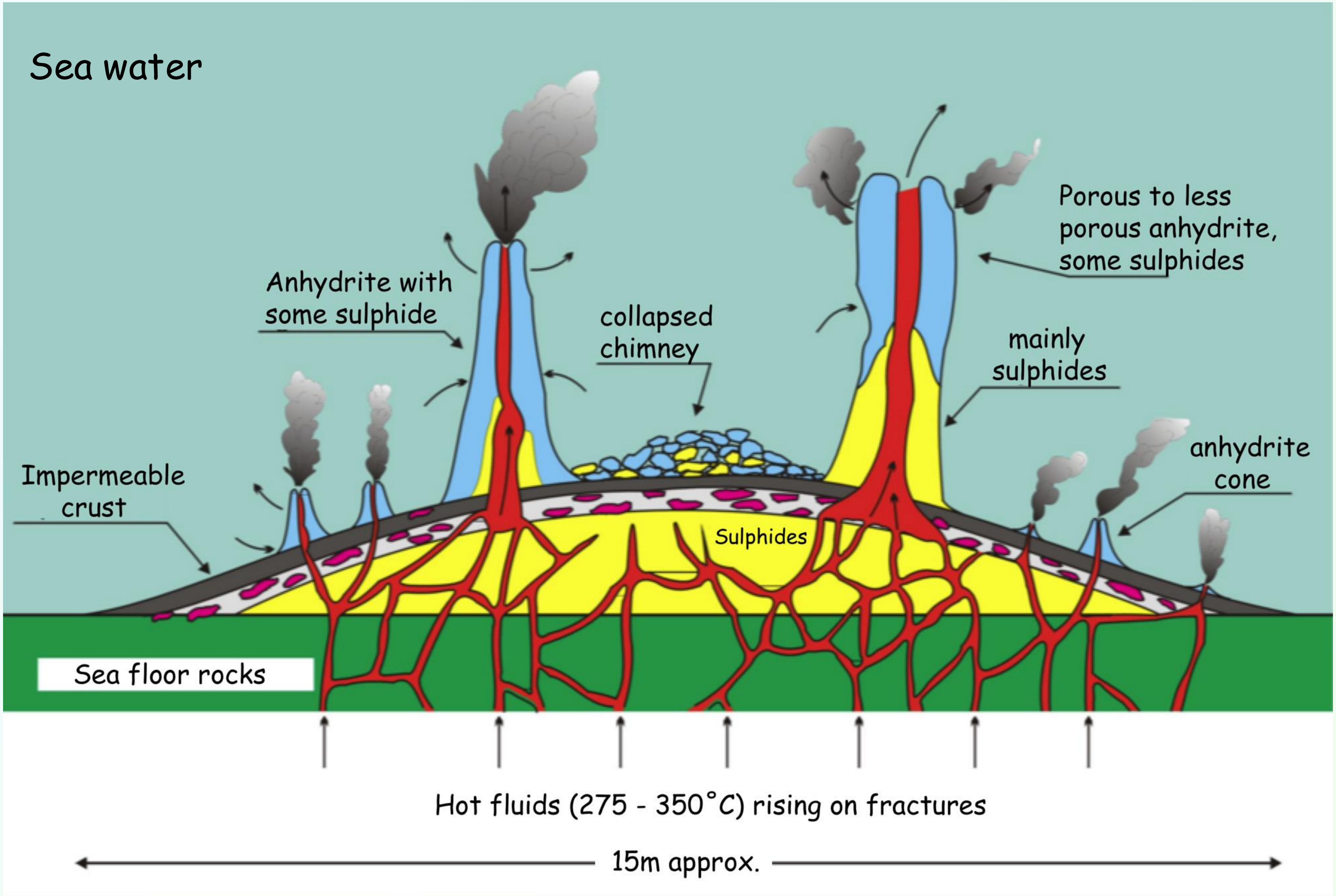


Black smoker,
East Pacific rise

Volcanic-exhalative processes

- Hydrothermal vents are located along seafloor spreading centres
- black smokers are plumes of hydrothermal fluids that may emanate from chimney-like vents
- chimneys normally stand on mounds of massive sulphides
- hydrothermal fluids passing through walls of chimney move rapidly from high temp. (>300°C), acidic (pH ~3.5) to that of normal seawater (2°C and pH ~7.8) and oxidised ($H_2S \ll SO_4$)
- black colour of smokers is due to fine-grained metal sulphide particles

Formation of VMS chimneys and sulphide mounds on the seafloor (After Barnes 1988)



Types of exhalative deposits

- Sedimentary exhalative (SEDEX) deposits

  → pyrite + variable Pb-Zn-Cu-(barite)

- Volcanic massive sulphide (VMS) deposits

  → basic to acid volcanics

- Cyprus types: related to basic volcanics → Cu-pyrite bodies

- Kuroko deposits: related to felsic volcanics

  → Cu-Pb-Zn±Au±Ag ores.

Sedimentary exhalative (SEDEX) deposits

- Sedex deposits → formed through the interaction of metalliferous hydrothermal fluids with sediments on the sea floor
- most common primary minerals formed include pyrite, galena, sphalerite and barite
- deposits commonly hosted in shale and other fine-grained sediments
- often hosted in organic rich horizons within sedimentary basins
- sometimes associated with hydrothermal vent systems → black smokers

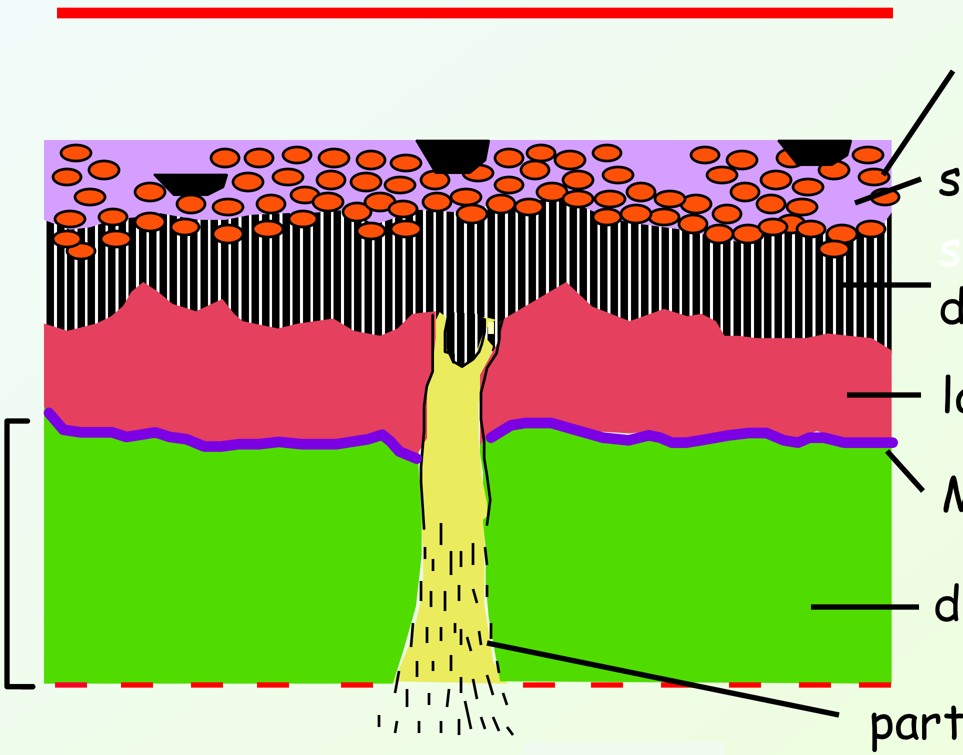
Volcanic massive sulphide (VMS) deposits

- Volcanic massive sulphide (VMS) deposits are a type of mineral deposit that often forms on the sea floor as a result of volcanic and hydrothermal activity
- hosted by volcanic and sedimentary rocks
- characterised by hydrothermal vents on seafloor
- deposits typically composed of metal sulphides Cu, Zn, Pb,Au and Ag
- deposits are typically small to medium-sized and occur in belts often in association with submarine volcanic rocks and hydrothermal vents

Cyprus-type deposits

Cupriferous pyrite volcanic-exhalative deposits associated with basic volcanics are referred to as Cyprus types.

Position of oceanic ridge



Basaltic pillow lavas
and tuffs

sediments

sheeted complex of
dolerite dykes

layered gabbroic rocks

Moho discontinuity

Mantle

depleted mantle

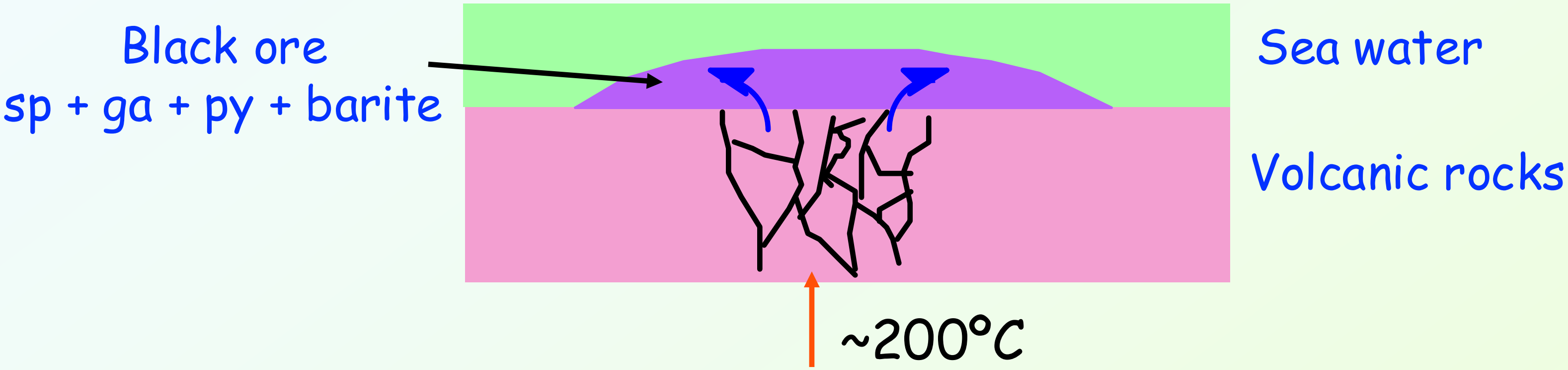
Primitive mantle

partial melting in rising column
produces basaltic magma

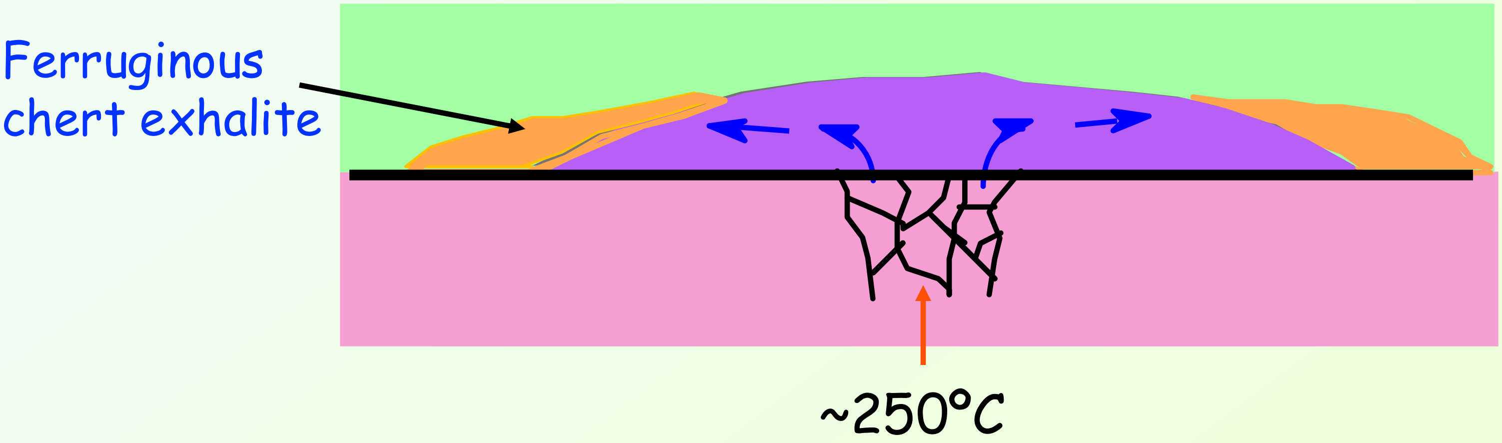
Formation of Kuroko-type deposits

Stage 1 Precipitation of fine-grained "black ore" (sphalerite, galena, pyrite, tetrahedrite, barite & minor chalcopyrite)

Mixing of hydrothermal solutions & seawater (~200°C)

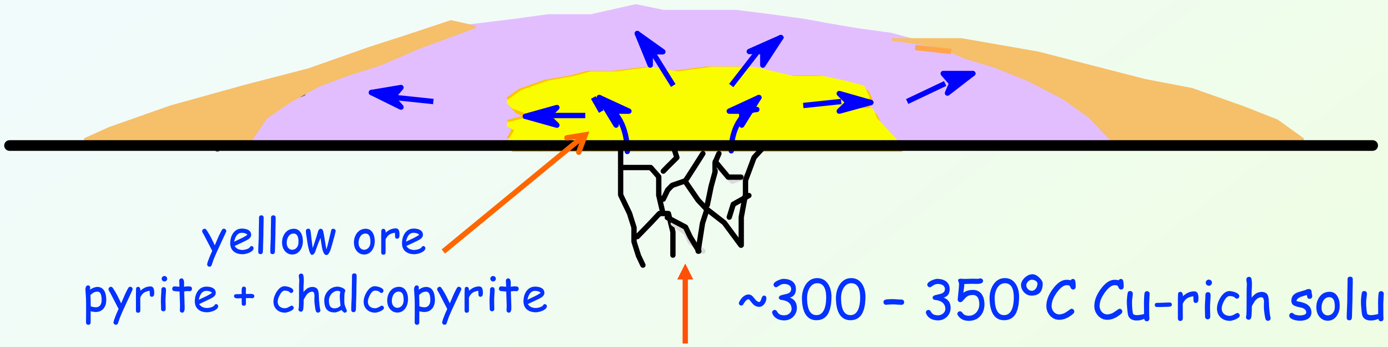


Stage 2 Recrystallisation and grain growth at base of evolving mound by hotter solutions (~250°C)



Formation of Kuroko-type deposits

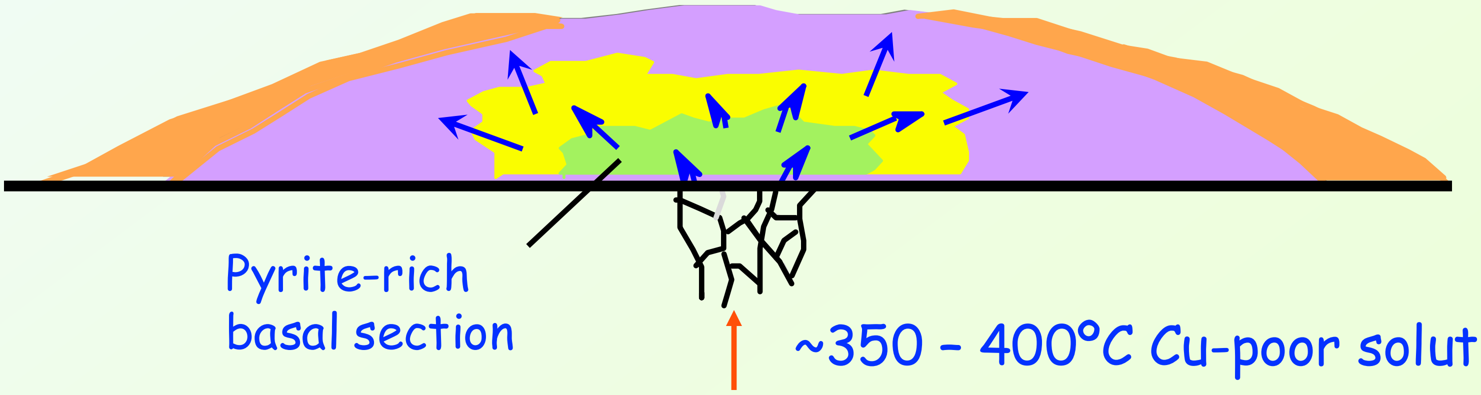
Stage 3 Influx of hotter (~300°C) Cu-rich solutions which replace earlier formed minerals. Yellow ore (chalcopyrite) forms in lower part of the deposit



yellow ore
pyrite + chalcopyrite

~300 – 350°C Cu-rich solutions

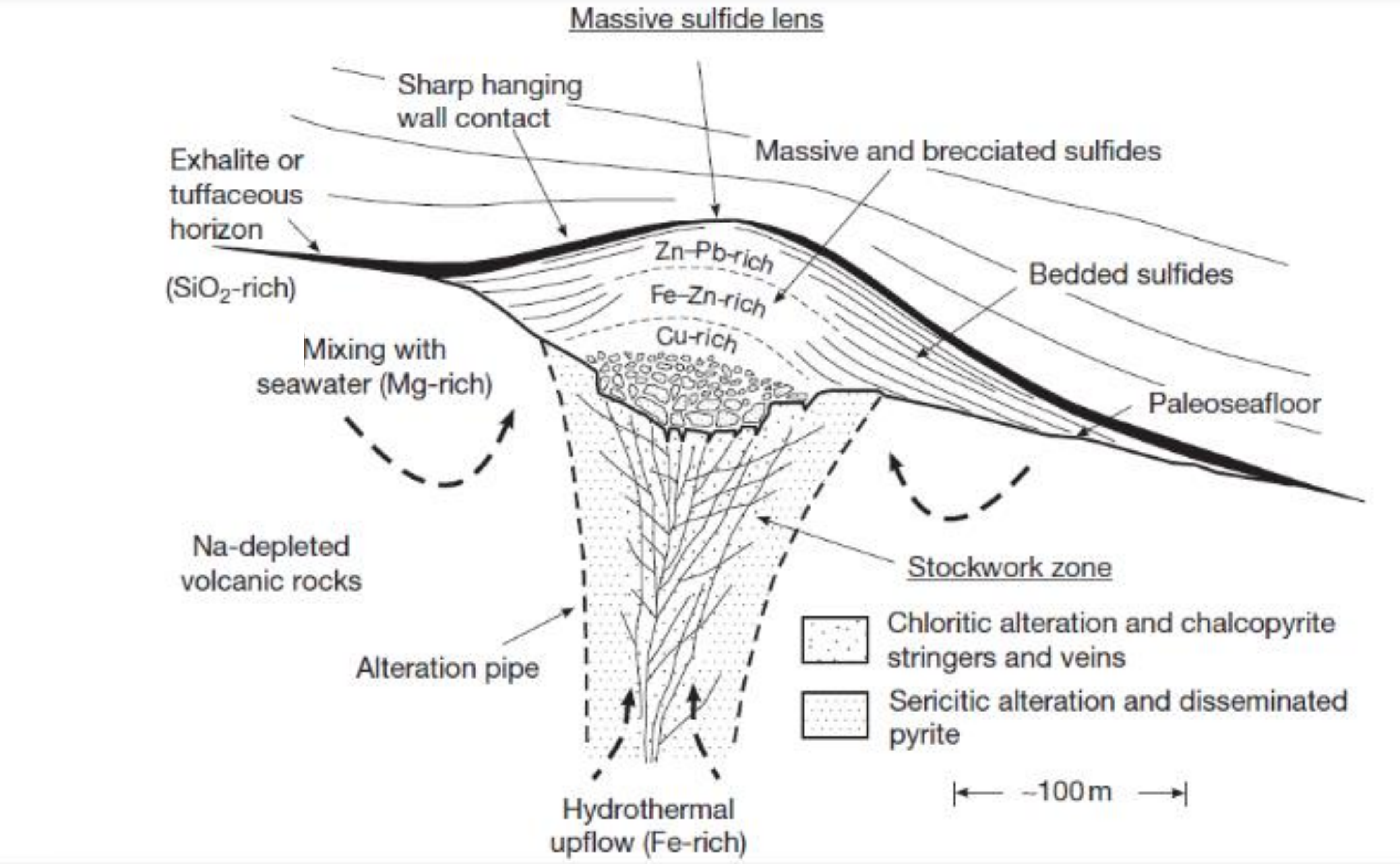
Stage 4 Still hotter Cu-undersaturated solutions then dissolve some chalcopyrite to form pyrite-rich bases



Pyrite-rich
basal section

~350 – 400°C Cu-poor solutions

VMS model (Hannington 2023)



Supergene enrichment and residual deposits

- The near surface environment is dominated by weathering processes and groundwater action

- weathering processes and groundwater action can lead to supergene enrichment of ore and residual deposits

- chemical weathering removes soluble material leaving behind lateritic soils and residual deposits

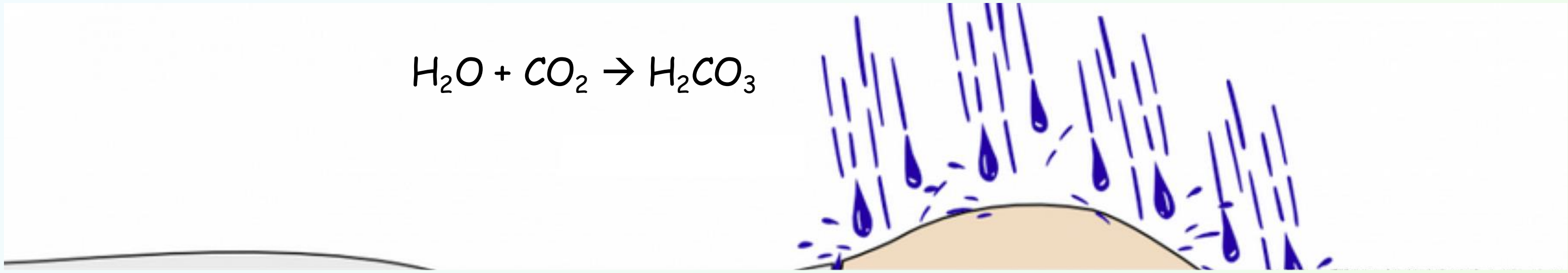
- leaching of some elements down to the water table produces supergene enrichment

Supergene enrichment

- When ore deposits are exposed to the oxidation zone, they are weathered along with the rocks that host them
- an ore deposit is oxidised and leached of many of its valuable elements down to the water table e.g. Cu, Au
- if downward percolating solutions penetrate the water table, their metallic content may be precipitated to deposit supergene sulphide enrichment
- the weathering profile is zoned:

  Gossan → leached → enriched → primary
- enhances grade on primary mineralisation

Oxidation and supergene enrichment



$H_2O + CO_2 \rightarrow H_2CO_3$

limonite $Fe(OH)_3$

$2CuSO_{4(aq)} + 2Na_2CO_{3(aq)} \rightarrow Cu_2(CO_3)(OH)_2 + 2NaSO_{4(aq)} + CO_2$

$2Cu_3(CO_3)_2(OH)_2 + H_20 \rightarrow 3Cu_2(CO_3)(OH)_2 + CO_2$

$5FeS_2 + 14CuSO_4 + 12H_2O \rightarrow 7Cu_2S + 5FeSO_4 + 12H_2SO_4$

$CuFeS_2 + CuSO_4 \rightarrow 2CuS + FeSO_4$

native copper Cu
malachite $Cu_2(CO_3)(OH)_2$
azurite $Cu_3(CO_3)_2(OH)_2$
cuprite Cu_2O
chrysocolla $CuSiO_3.H_2O$

chalcocite Cu_2S

covellite CuS

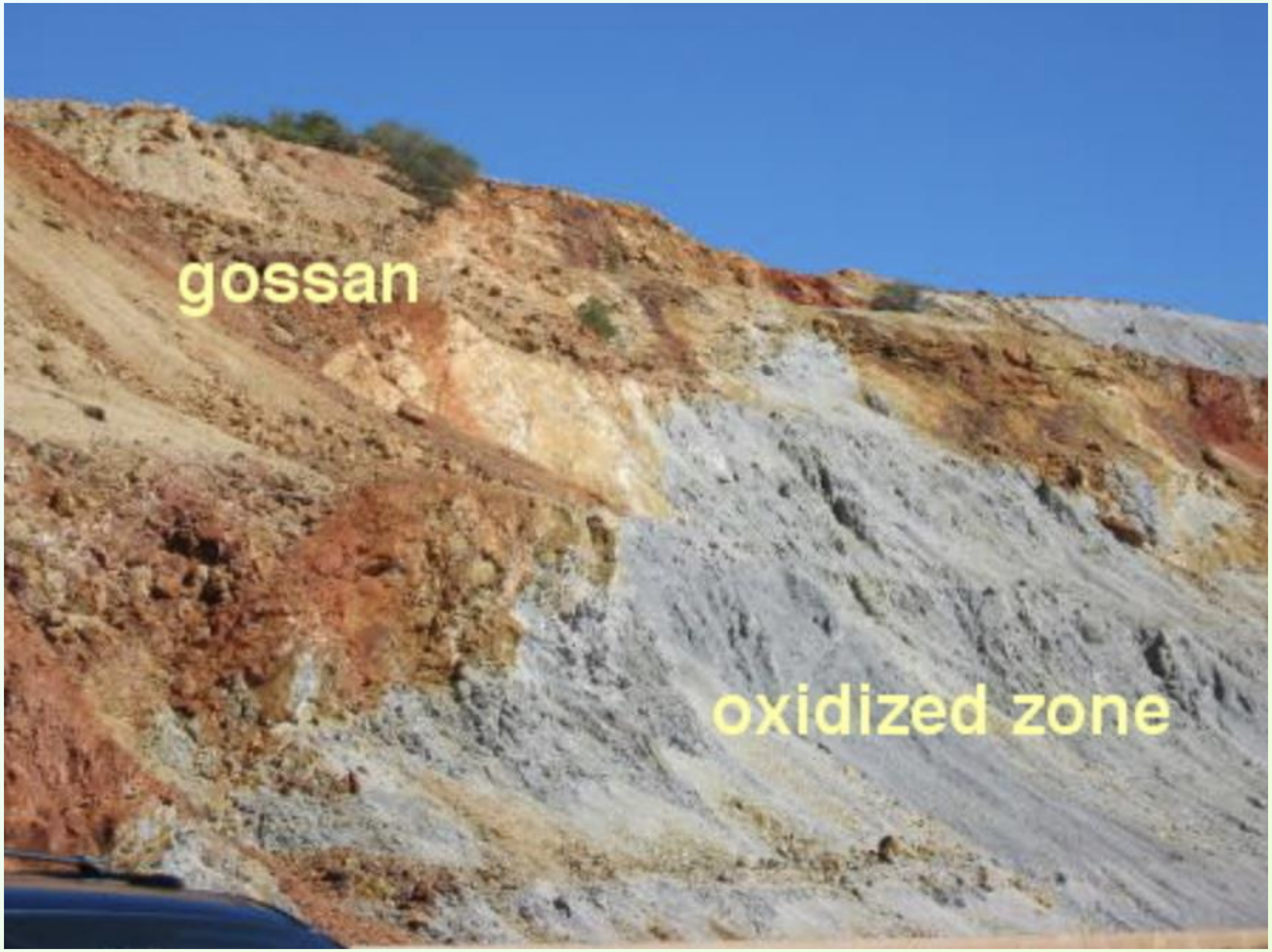
bornite Cu_5FeS_4

chalcopyrite $CuFeS_2$

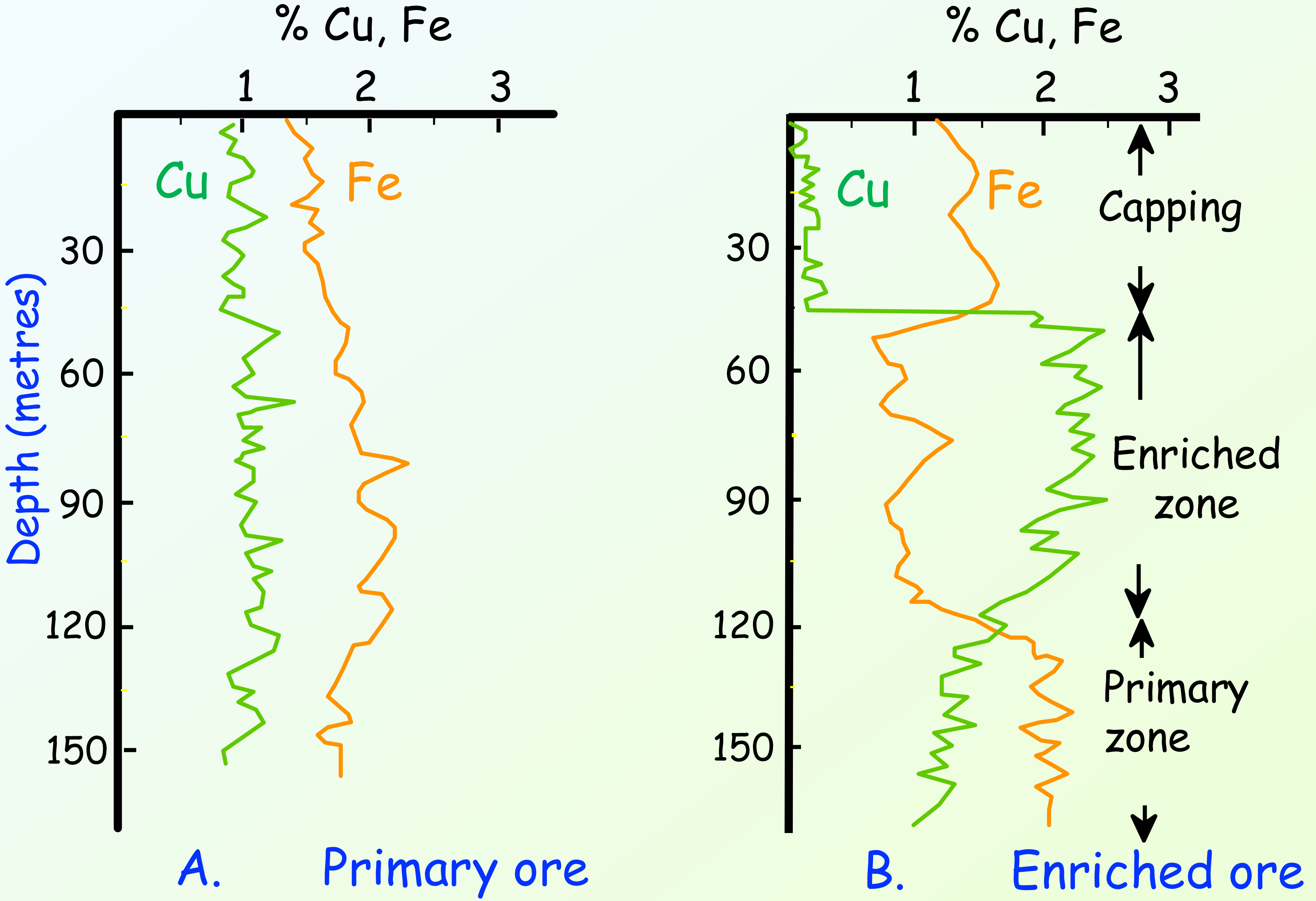
Gossan

- In the zone of extreme oxidisation of a sulphide orebody, gossan may form overlying residual deposits
- extreme leaching and textural modification
- cellular mass of limonite (Fe.OH.nH_2O) and gangue minerals
- other minerals in gossans
    - Pb sulphate and carbonate: anglesite & cerussite
    - Zn carbonate and silicate: smithsonite, willemite
    - Cu carbonates and silicate: malachite, azurite, chrysocolla
    - native silver and native gold

Gossan



Drillhole assays of Cu & Fe vs depth in primary & supergene enriched ore (after Jensen 1981)



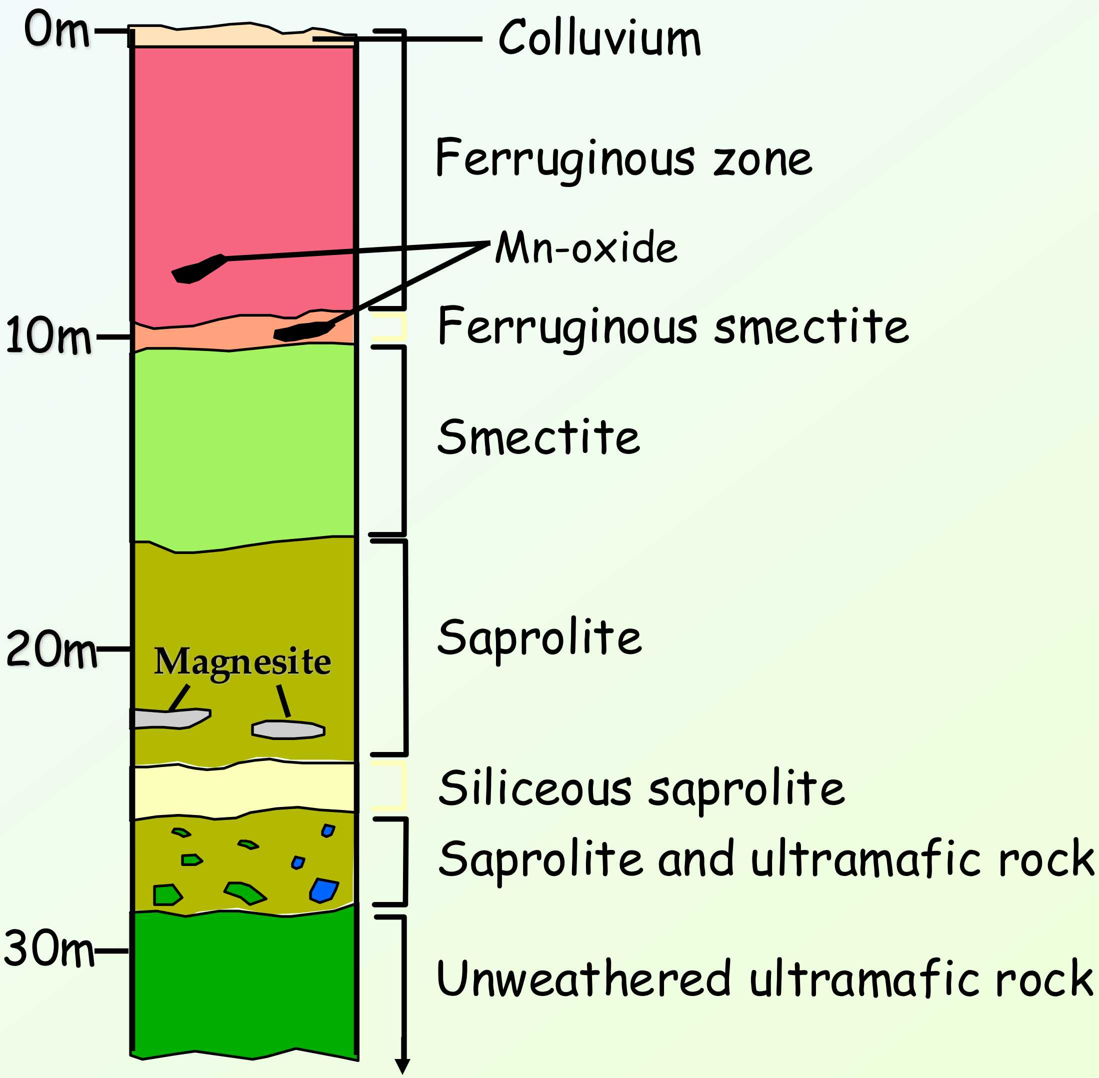
Residual deposits

- Weathering and groundwater action can lead to the formation of residual ore deposits
- the leaching of mobile components can result in the insitu enrichment of inert components and form residual deposits
- tropical climates and high rainfall → intense weathering
- formation of laterites (Fe and Al hydroxides) that have very low solubility in upper weathered zone, depletion in mobile elements e.g. K, Na, Ca, Mg, Si
- economic deposits:
  e.g. bauxite, nickel, phosphate, tin and gold

Residual Ni deposits

- Residual Ni deposits form from the intense weathering of ultrabasic rocks such as peridotites and serpentinites
- these rocks contain up to 0.25% Ni
- during laterisation, Ni is dissolved and reprecipitated on to Fe or forms oxides or garnierite below the laterite
- grades of potentially economic deposits range from 1 to 3% Ni
- most of the ore occurs in the smectite and upper saprolite zones

Residual deposits of nickel



Generalised lateritic profile from Murrin Murrin South,WA
(Fazakerley and Monti 1998)

Mechanical concentration

- Gravity separation of heavy minerals from light minerals by action of air or water, the heavy minerals form placer deposits

- the formation of placer deposits occurs in two stages:

  (1) release of minerals from their host rocks

  (2) concentration of minerals

- Ore minerals:

  - High S.G.

  - chemical resistance to weathering

  - durability (hard or ductile)

  - ore deposit: Au, Pt, Sn, zircon, ilmenite, rutile and monazite.

Mechanical concentration in water

- Process of mechanical concentration depends on differences in S.G., size and shape of particles interacting with moving fluid
- in water, heavier minerals sink more rapidly than lighter ones of the same size
- shape of particle affects its settling → flaky particle will have larger specific surface area than spherical particle→ sink more slowly
- S.G. is accentuated in water c.f. air e.g. ratio of S.G. of gold (S.G. = 19) to quartz (S.G. = 2.6) in air is 7.3 whereas in water it is (19 - 1)/(2.6 - 1) = 11.2

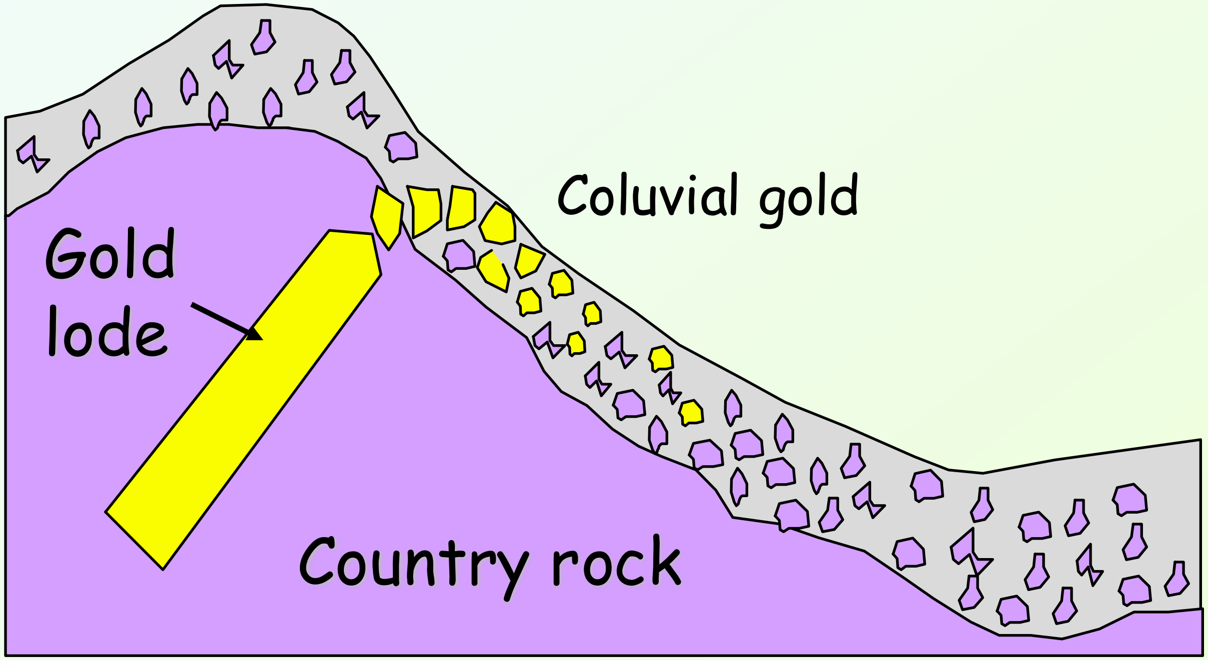
Placer deposits

- **Colluvial placer**: formed without stream action, gravity and slope wash
- **Alluvial (stream) placer**: formed with stream action, most important e.g. gold, platinum, tin, titanium, zirconium
- **Beach placer**: along shorelines by concentrating wave and current action e.g. heavy mineral deposits zircon, titanium minerals (ilmenite, rutile)
- **Eolian placer**: wind (rare)

Coluvial placer deposits

- Formed when material released from a lode moves downslope under the influence of gravity and slope wash

- light material is preferentially transported



Alluvial placer deposits

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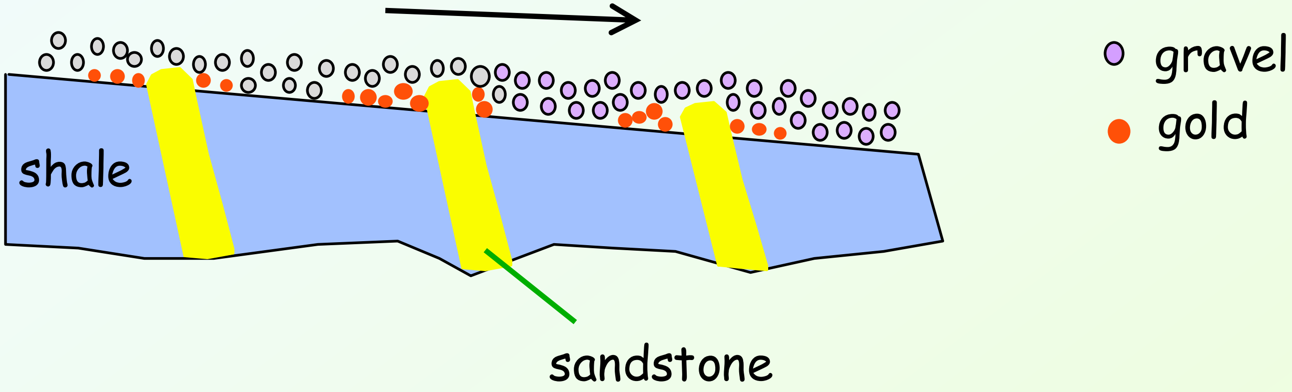

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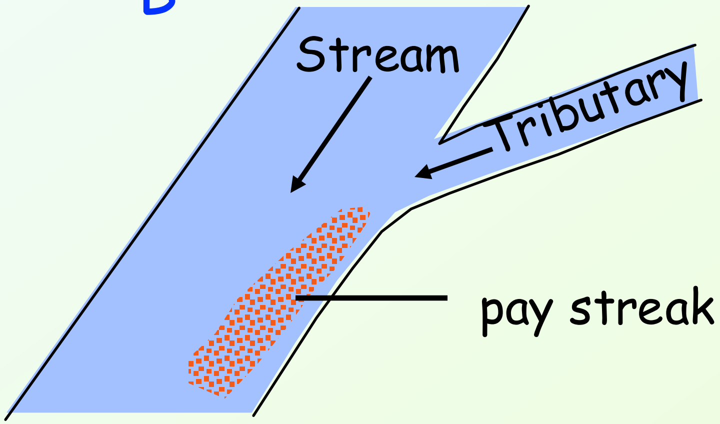

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