U3A
The geology of copper (2)

Cu deposits

Types of deposits

(1) Porphyry Cu

(2) Stratiform Cu

(I) Volcanic-hosted massive sulphide (VMS) deposits

(II) Sediment-hosted copper deposits

(3) Iron oxide-Cu-Au ±U (IOCG) deposits

(4) Cu skarn

(5) Lake Superior deposits

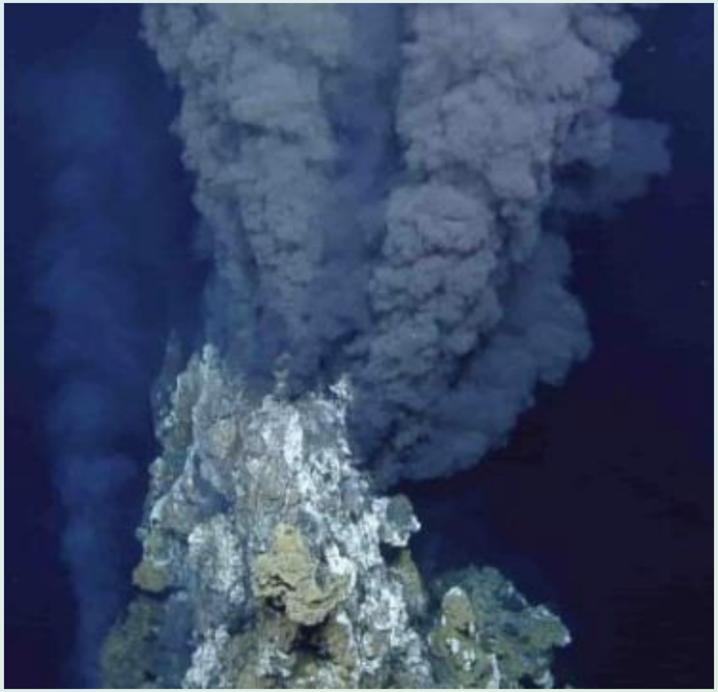
There are two distinct types of ore:

(1) sulphide ore*

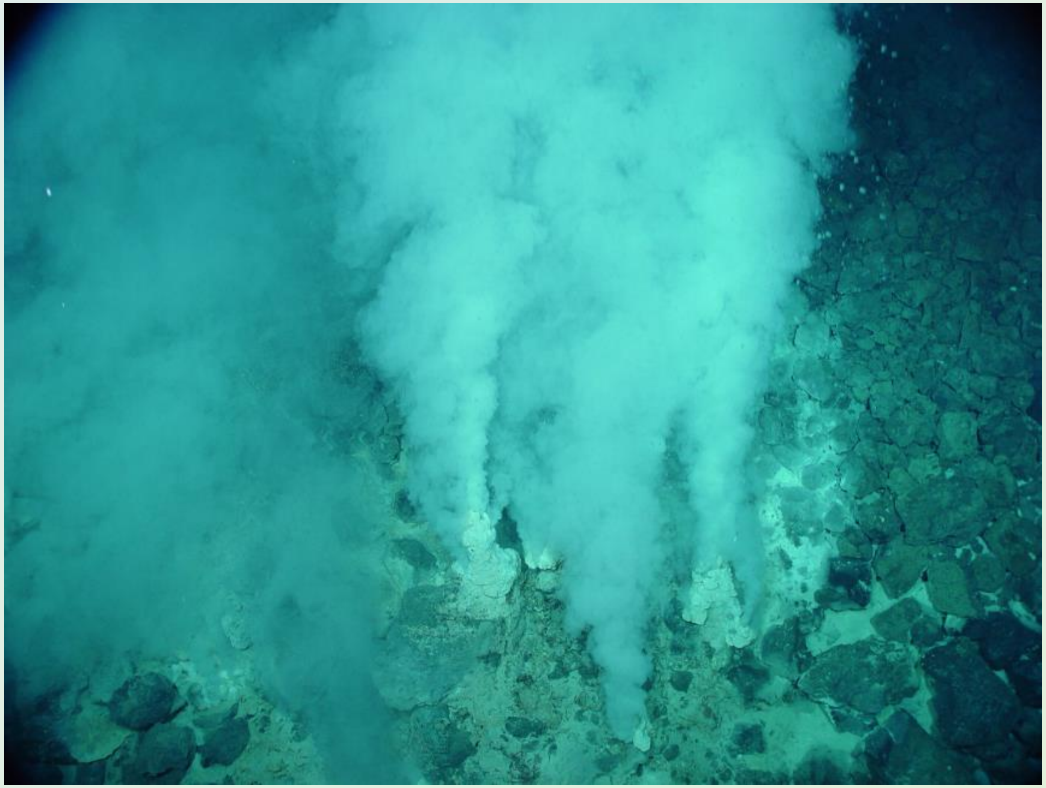
(2) oxide ore

Submarine-exhalative processes

Submarine-exhalative deposits are syngenetic*, sedimentary and volcano-sedimentary metal sulphide deposits formed on the sea floor by chemical precipitation of material from hydrothermal vents called 'black or white smokers'



Black smoker East Pacific



White smokers, Marianas Trench

Submarine exhalative processes

- Geological processes form VMS deposits at depth in the ocean and are associated with volcanic and/or sedimentary rocks
- where Earth's crust is thin due to faulting or tectonic plate separation → magma in upper mantle softens crust → moves up towards the surface → early beginning of a volcano
- heated crust cracks → draws seawater into the crust along fissures
- seawater becomes super heated and endowed with minerals*
- black and white smokers exhale a mineral-rich plume that spreads out over the seafloor → precipitates minerals → create VMS deposits

Volcanic Massive Sulphide (VMS) deposits

- VMS deposits are one of the richest sources of metals (Zn, Pb, Cu, Ag, Au)
- global VMS deposits account for:

  22% Zn

  9.7% Pb

  6% Cu

  8.7% Ag

  2.2% Au

- formed in clusters along ancient submarine volcanic zones
- forming current day on seafloor around volcanoes along many ocean ridges, back arc basins and forearc rifts*

VMS deposit characteristics

- Lenticular, sheet-like stratiform bodies developed at interface between volcanic units or between volcanics and sediment

- deposits are generally small, 80% in the range (0.1 – 10Mt), high grade

- Three classes of deposit:

  (1) Zn – Pb – Cu

  (2) Zn – Cu

  (3) Cu

- rhyolite → dominant host rock for Pb-Zn ores, mafic volcanics host most copper class deposits

- Main ore minerals: galena, sphalerite, chalcopyrite*

  Minor ore minerals: bornite, arsenopyrite, magnetite, tetrahedrite -tennantite, gold, silver

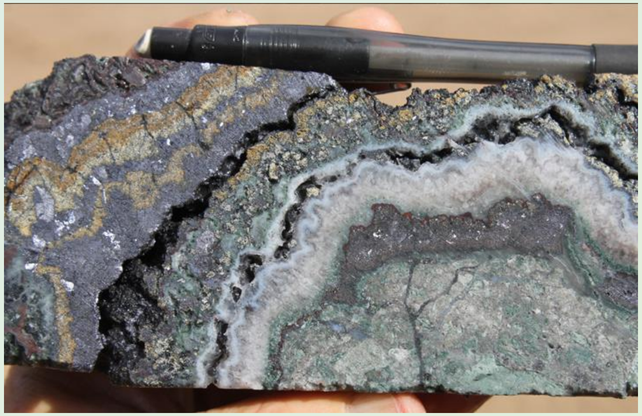
How big can a VMS deposit get?

- Current resource and historical production figures from 904 VMS deposits around the world averages ~7Million tonnes
- average grade → 1.7% Cu, 3.1% Zn and 0.7% Pb
- a few giant mineral deposits (>30Mt) and several Cu-rich and Zn-rich

Mineralogical features of VMS deposits

Mineralisation features

- pyrite is normally the major sulphide plus sphalerite, galena, chalcopyrite ± tetrahedrite, arsenopyrite, minor gold and silver
- Zn-Pb massive sulphide lenses are stratiform
- Cu-rich stringer zones normally crosscutting
- chlorite, sericite, quartz, barite, carbonate are major gangue minerals
- Textures: colloform banding, recrystallised granular, breccia, graded bedding
- vertical zonation of Cu → Pb, Zn → Ba*



Colloform banding

Alteration features

- some deposits have chlorite-sericite zoned alteration pipes below massive sulphides
- intense alteration mainly confined to the footwall

Cp + py + qtz vein in jasper, Gecko mine,Tennant Creek, NT

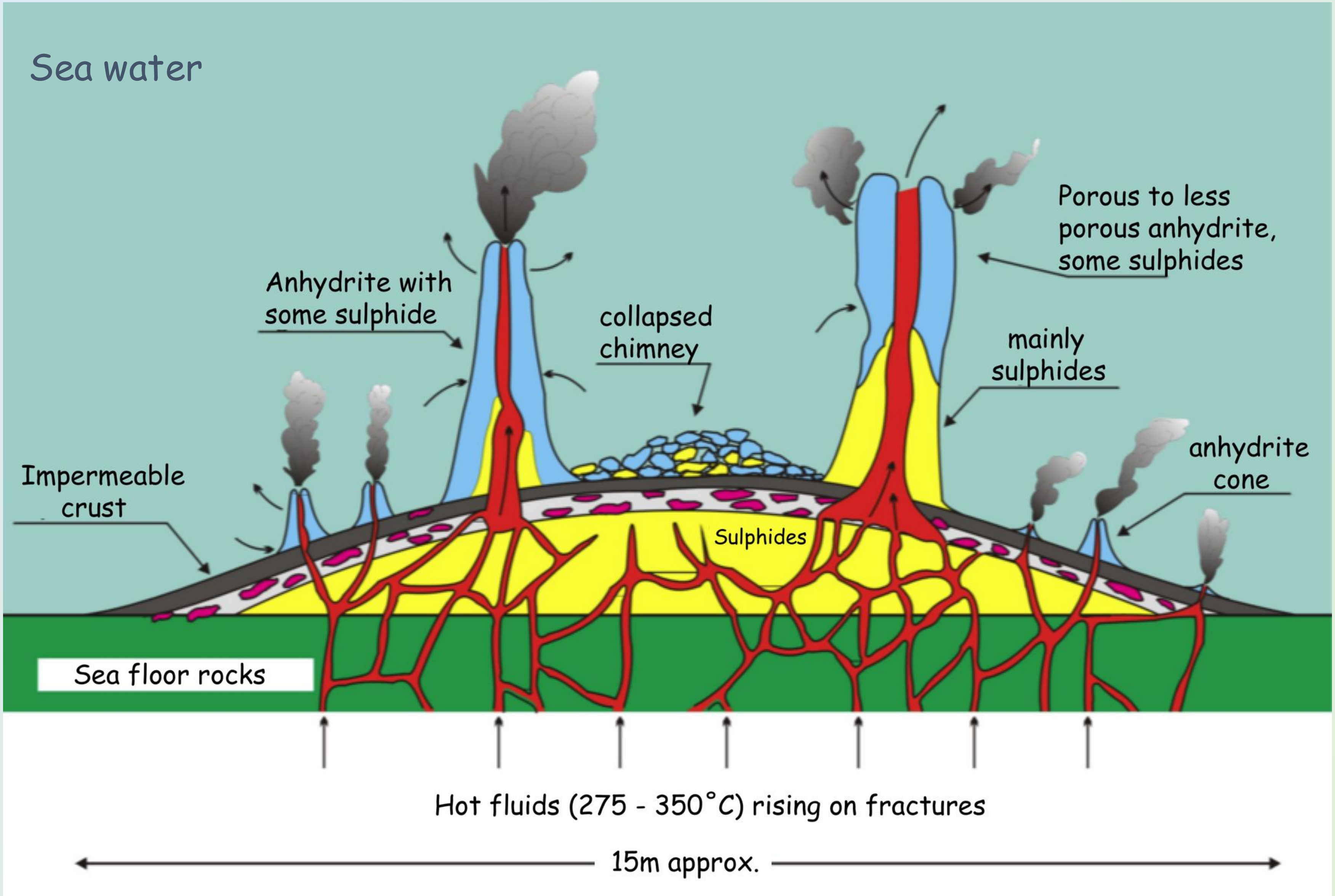
Genesis of VMS deposits

- Formed through interaction of hot sulphurous plumes and seawater
- exhalative vents commonly form chimneys on the seafloor
- chimney growth commences with precipitation of anhydrite ($CaSO_4$)
- hydrothermal fluid passes out through porous chimney walls

Hydrothermal fluid:	Temp. >300°C
	pH ~3.5
	Reduced ($H_2S \gg SO_4$)
Seawater:	Temp. 2°C
	pH ~7.8
	Oxidised ($H_2S \ll SO_4$)

- As chimney grows upwards lower part thickens → sulphides precipitate
- unstable chimneys collapse → debris accumulates on seafloor together with chemical precipitates

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



Conditions of formation

Fluid chemistry

- ore fluids 200 – 350°C, 2-10 wt % NaCl
- pH varies 3 to 5.5
- reduced conditions in ore fluid with $H_2S > SO_4$

$$H_2S + 2O_2 \rightarrow SO_4^{2-} + 2H^+$$

Environments of deposition

- seawater depths of 800-4000 metres are necessary
- sulphide mounds develop above hydrothermal vents

VMS ore minerals

galena (PbS)

sphalerite (ZnS)

gold

chalcopyrite ($CuFeS_2$)

Types of VMS deposits (After Hutchison 1980)

Type	Volcanic rocks	Depositional environment
Besshi Cu-Zn±Au±Ag	Intraplate basalts	Deep marine sedimentation
Cyprus Cu (±Zn)±Au	Ophiolites, tholeiitic basalts	Deep marine
Kuroko Cu-Zn-Pb±Au±Ag	Tholeiitic basalts, calc-alkaline lavas	Explosive volcanism, shallow marine
Primitive Cu-Zn±Au±Ag	Basalt to rhyolite lavas	Marine <1km water depth

Location of some major VMS deposits in Australia

- There are ~30 significant VMS deposits in Australia ranging from Archaean to Permian in age
- most of the VMS deposits occur within Palaeozoic volcanic belts of Eastern Australia

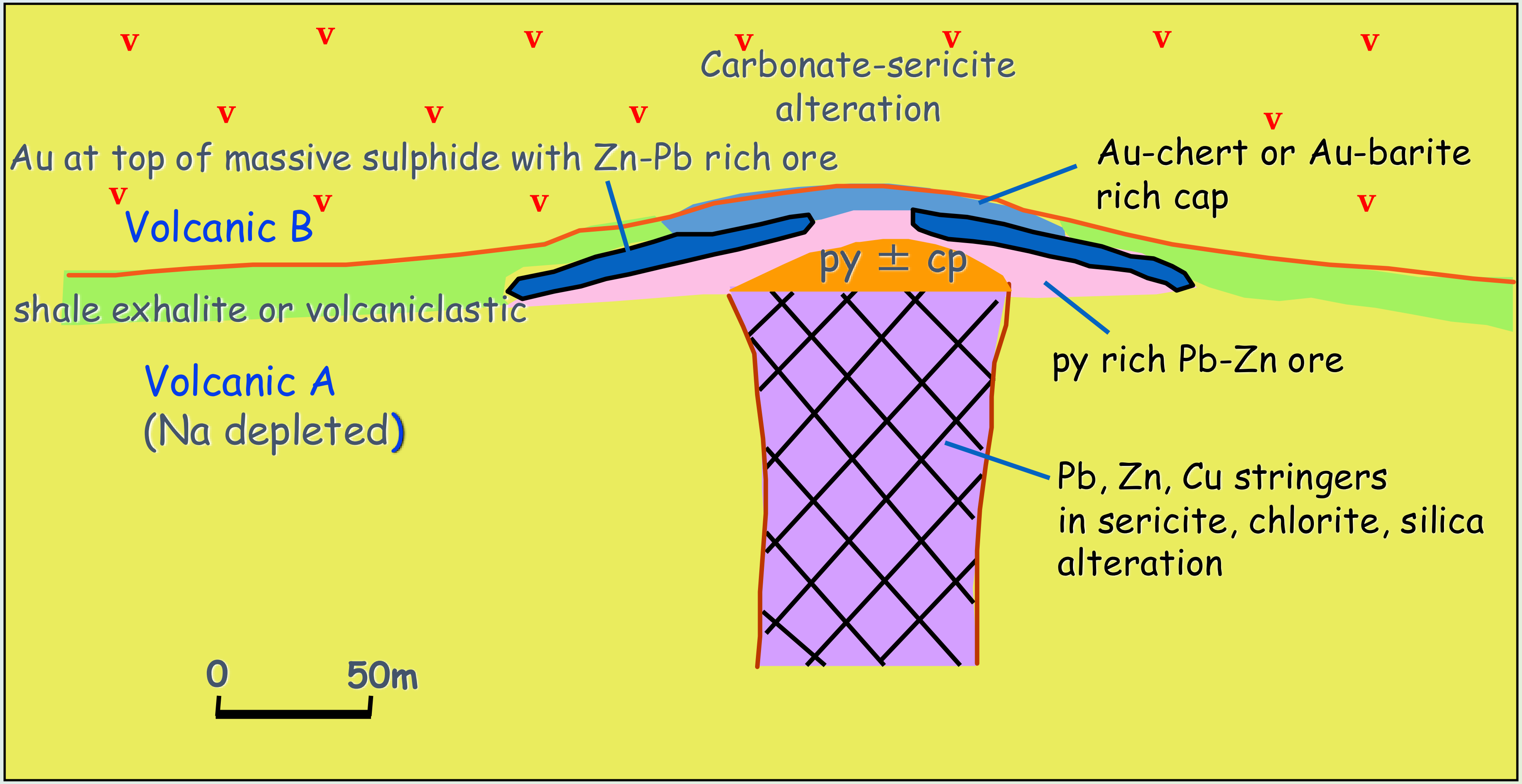
Morphology of Australian VMS deposits

1. Lens and blanket deposits with subordinate stringer zone*
   e.g. Rosebery, Woodlawn (Zn-Pb-Cu)

2. Mound deposits with well-developed stringer zone
   e.g. Hellyer (Zn-Pb-Cu)

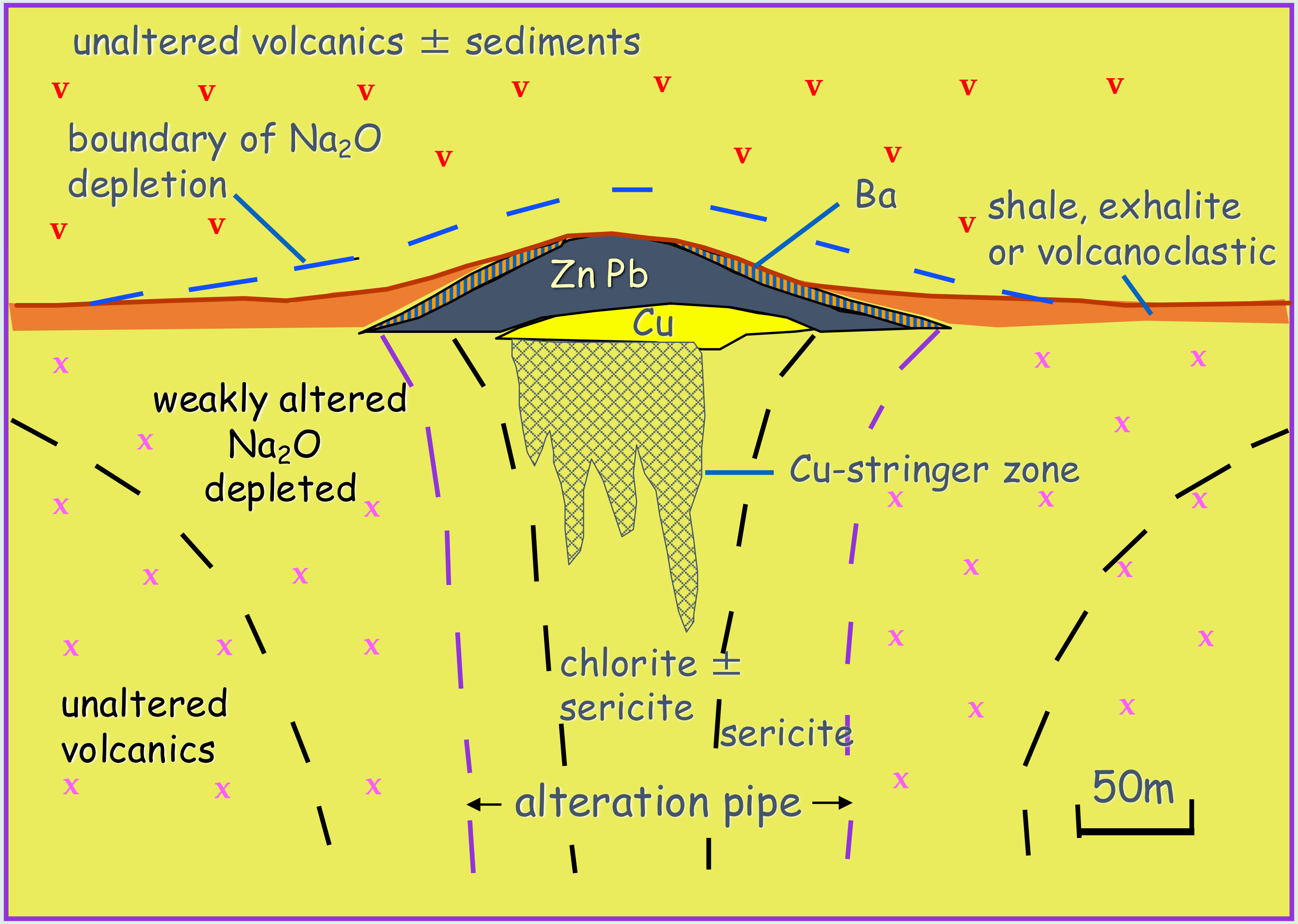
3. Pipe and stringer deposits with little or no stratiform, Zn-rich sulphide lenses e.g. Mt Lyell (chalcopyrite + pyrite)

Model for Zn-Au-(Pb-Ag-Ba) polymetallic VMS deposits eg. Rosebery
(After Large 1987)

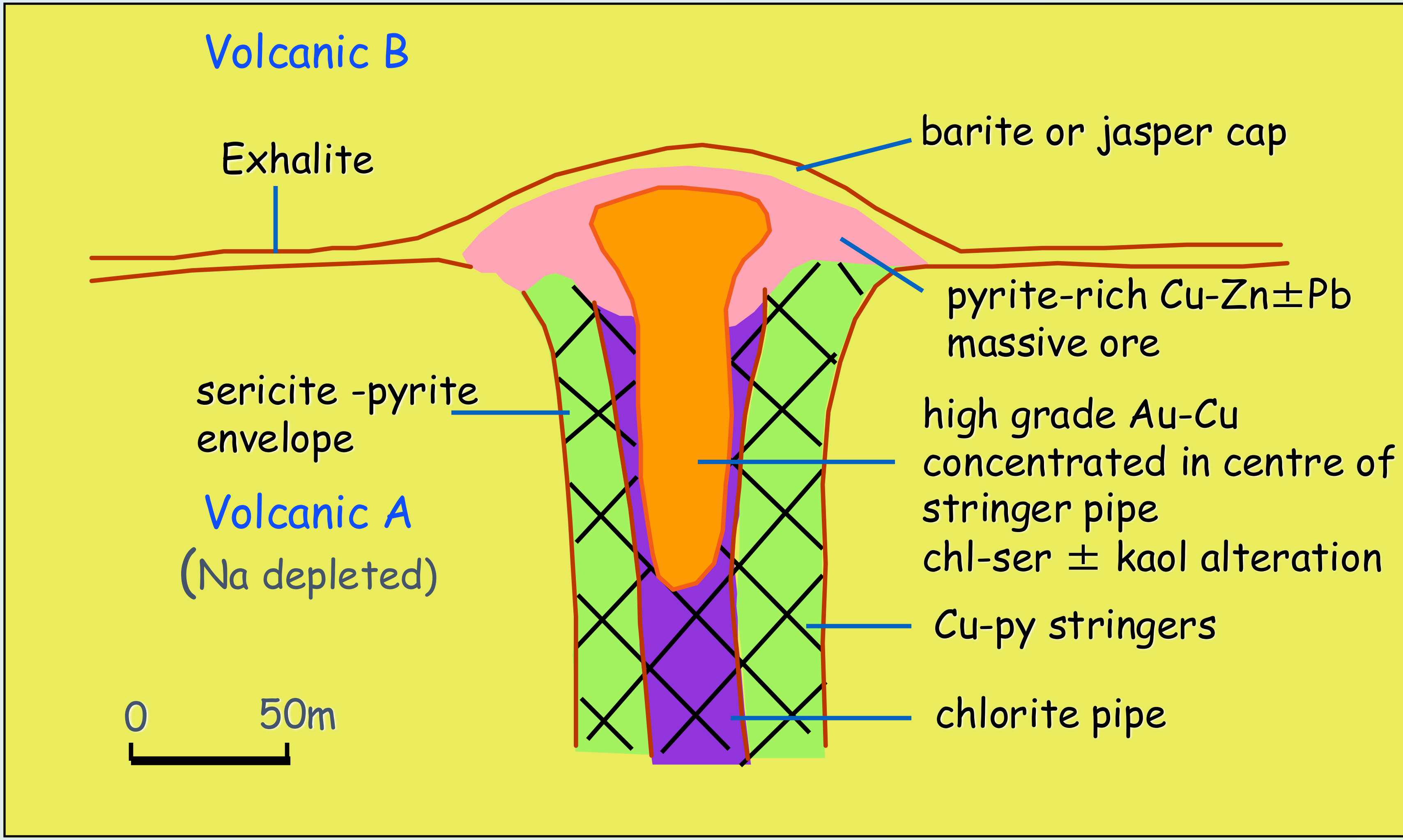


Typical mound style deposit e.g. Hellyer

(After Large and Gemmell 1992)



Model for Cu-Au-rich VMS deposits eg. Mt Morgan (After Large 1987)



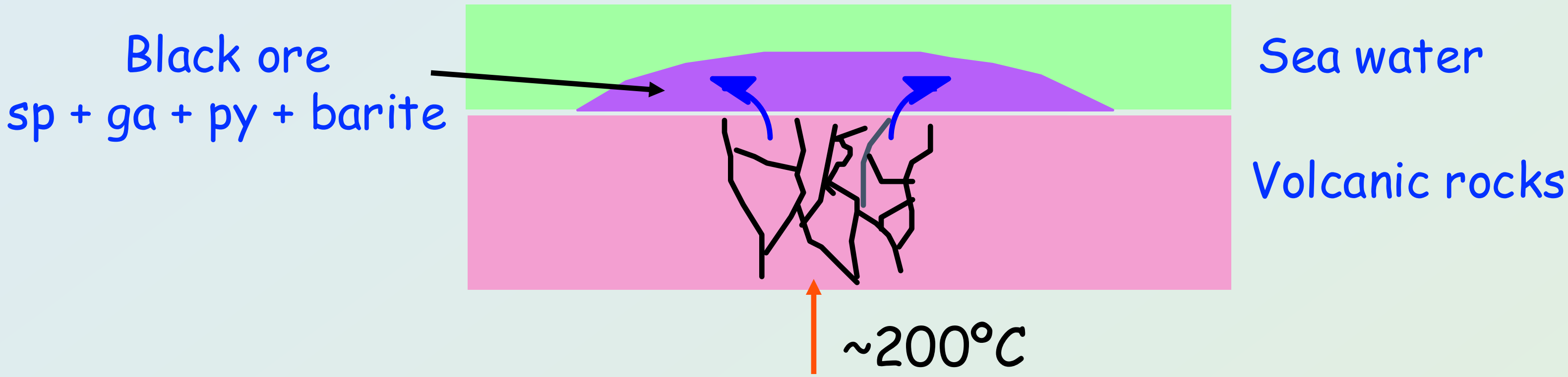
Deposit stratigraphy (Kuroko Type)

Hanging wall	Upper volcanics or sedimentary formations
	Ferruginous chert* zone- hematite, quartz (chert)
	Barite ore zone
	Kuroko or black ore zone -sphalerite-galena -barite
	Oko or yellow ore zone - chalcopyrite, pyrite
	Siliceous ore zone - cupriferous, siliceous, disseminated and/or stockwork ore
Footwall	Silicified rhyolite and pyroclastic rocks

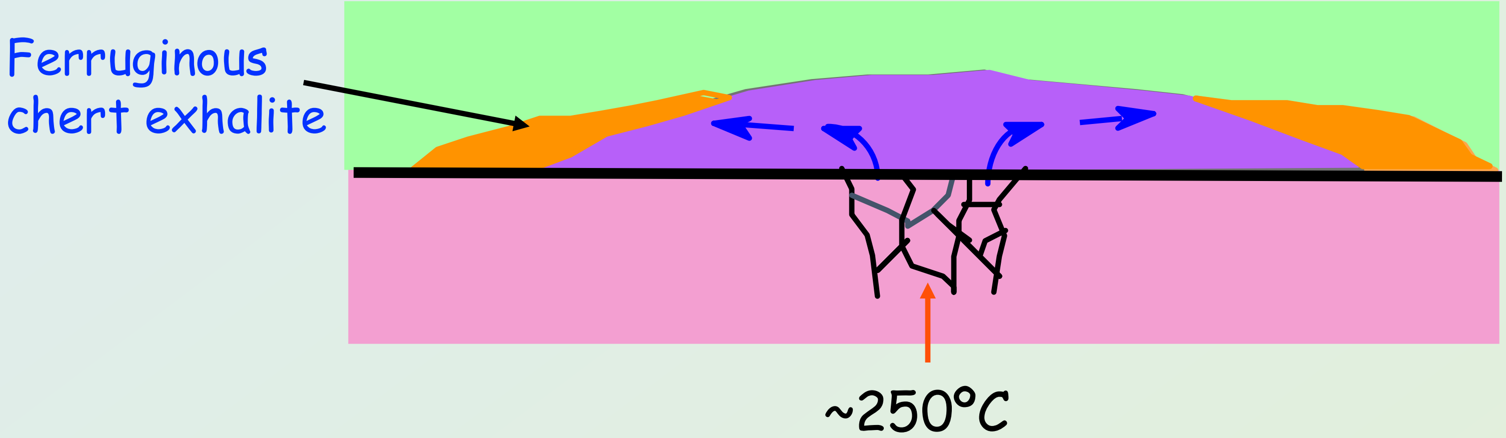
Formation of Kuroko-type deposits

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

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

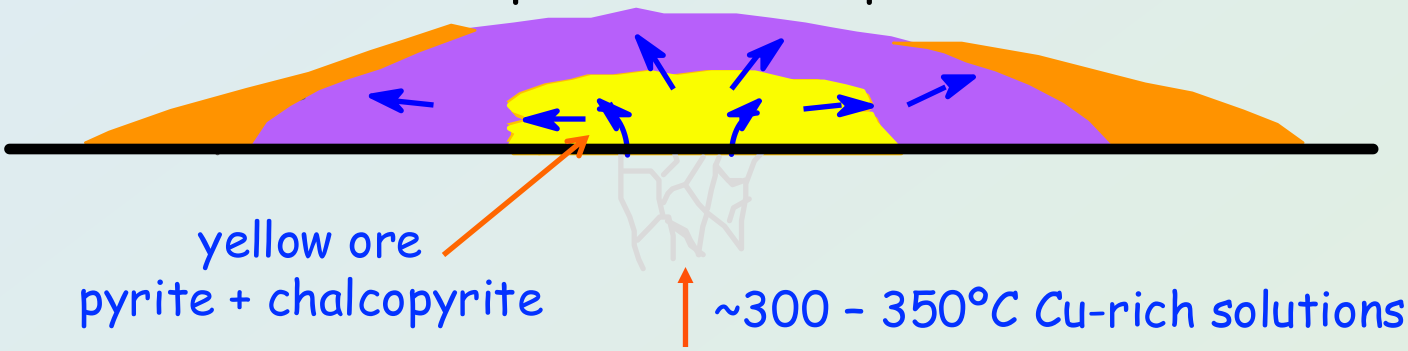


Stage 2 Recrystallisation and grain growth at base of evolving mound by hotter solutions (~250°C)

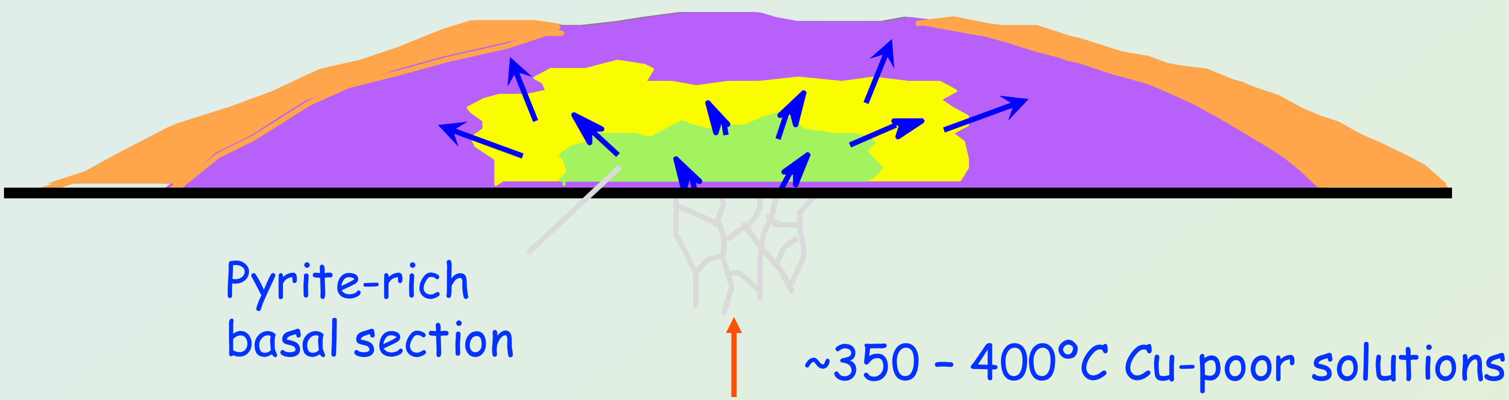


Formation of Kuroko-type deposits

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



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



Sediment-hosted Cu deposits

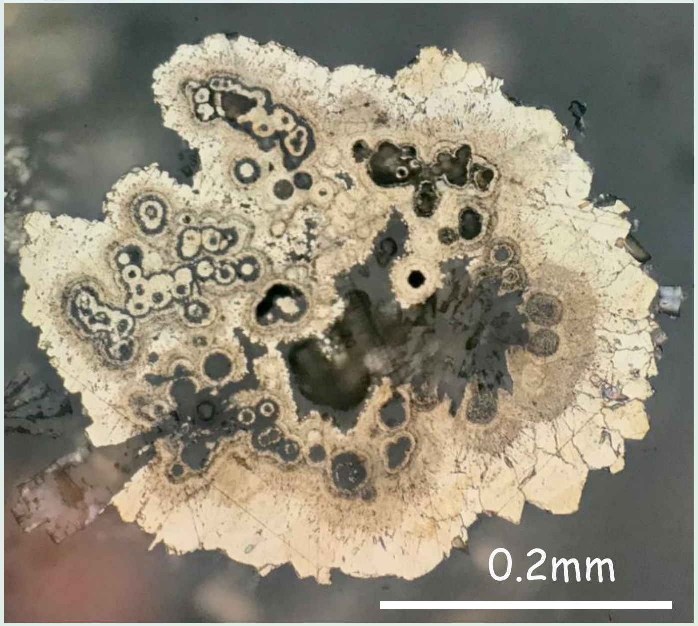
- Second most important Cu deposits after porphyry Cu deposits
  account for 20% of world's Cu production
- deposits are stratiform or stratabound
- epigenetic and diagenetic*
- host rocks are of two types:
  - (1) calcareous or dolomitic siltstones, organic-rich shales
  - (2) high energy sandstones, arkoses and conglomerates of continental origin
- deposits may be extremely large (up to 100s Mt)
- major regions: European Kupferschiefer, Central African Copperbelt

Sediment-hosted Cu deposits

- Host rocks deposited within intracontinental rifts and continental margins
- deposits are lensoid to stratiform in shape and may show layers of different composition*
- Ore minerals: chalcocite, bornite, chalcopyrite, native copper, hematite, galena, sphalerite
- Cu grades typically 1 - 5wt%. Co and Ag important in some deposits
- chalcocite forms near the oxidized source of copper, pyrite occurs near the reduced rocks. Native Cu forms in deposits deficient in S

Texture /structures

- Minerals are finely disseminated
- framboidal or colloform pyrite is common*
- Cu minerals replace pyrite and cluster around carbonaceous fragments
- Fe-calcite and chlorite occur in alteration. Trace elements As, Cd, Hg and Ni are elevated in many deposits



Colloform pyrite

Framboidal pyrite

Genesis of deposits

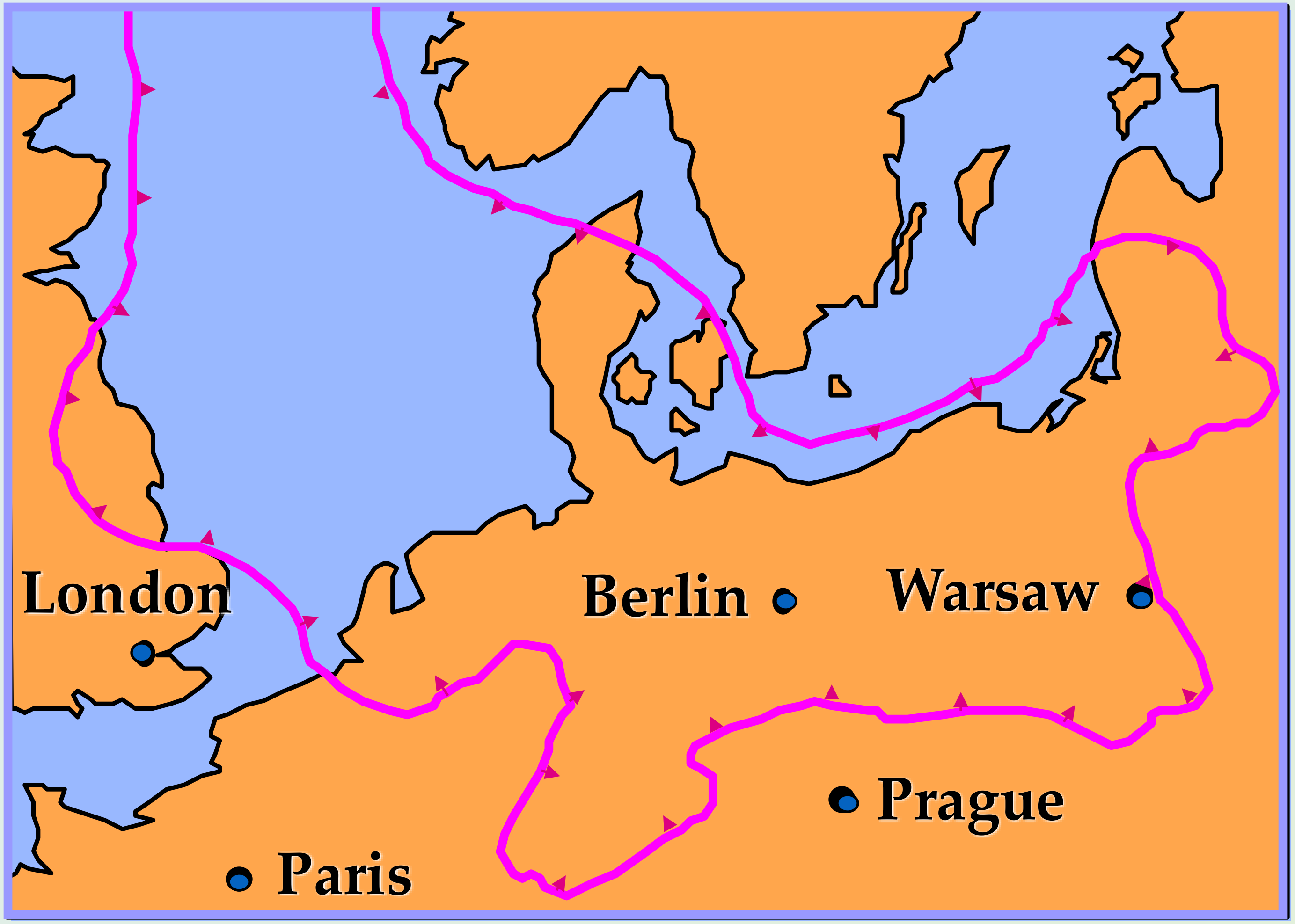
- Deposits formed by fluid mixing in permeable sedimentary rocks
- two contrasting fluids are involved:
  (1) oxidising brine carrying Cu as a chloride complex
  (2) reduced fluid commonly formed in the presence of anaerobic sulphate-reducing bacteria
- for a deposit to form there must be:
  (1) an oxidising source rock (must contain ferromagnesian minerals)
  (2) a source of brine to mobilise Cu (interbedded evaporites)
  (3) a source of reduced fluid to precipitate Cu (organic-rich shales)
  (4) favourable conditions for fluid mixing (permeable host rock)

Kupferschiefer

- The Kupferscheifer is an extensive sedimentary unit in central Europe comprising black shales, bituminous marls, mudstones and limestones*
- Kupferschiefer underlies ~600,000km^2 of Europe (Germany, Poland, Holland, England)
- it hosts large volumes of important Cu deposits
- deposits can be extremely large e.g. 2600Mt at Lublin, Poland
- the deposits have been mined for nearly 1000years
- although anomalously high in base metals, ore grades only occur locally

Extent of the Late Permian Zechstein sea in Central Europe (After Evans 1993)

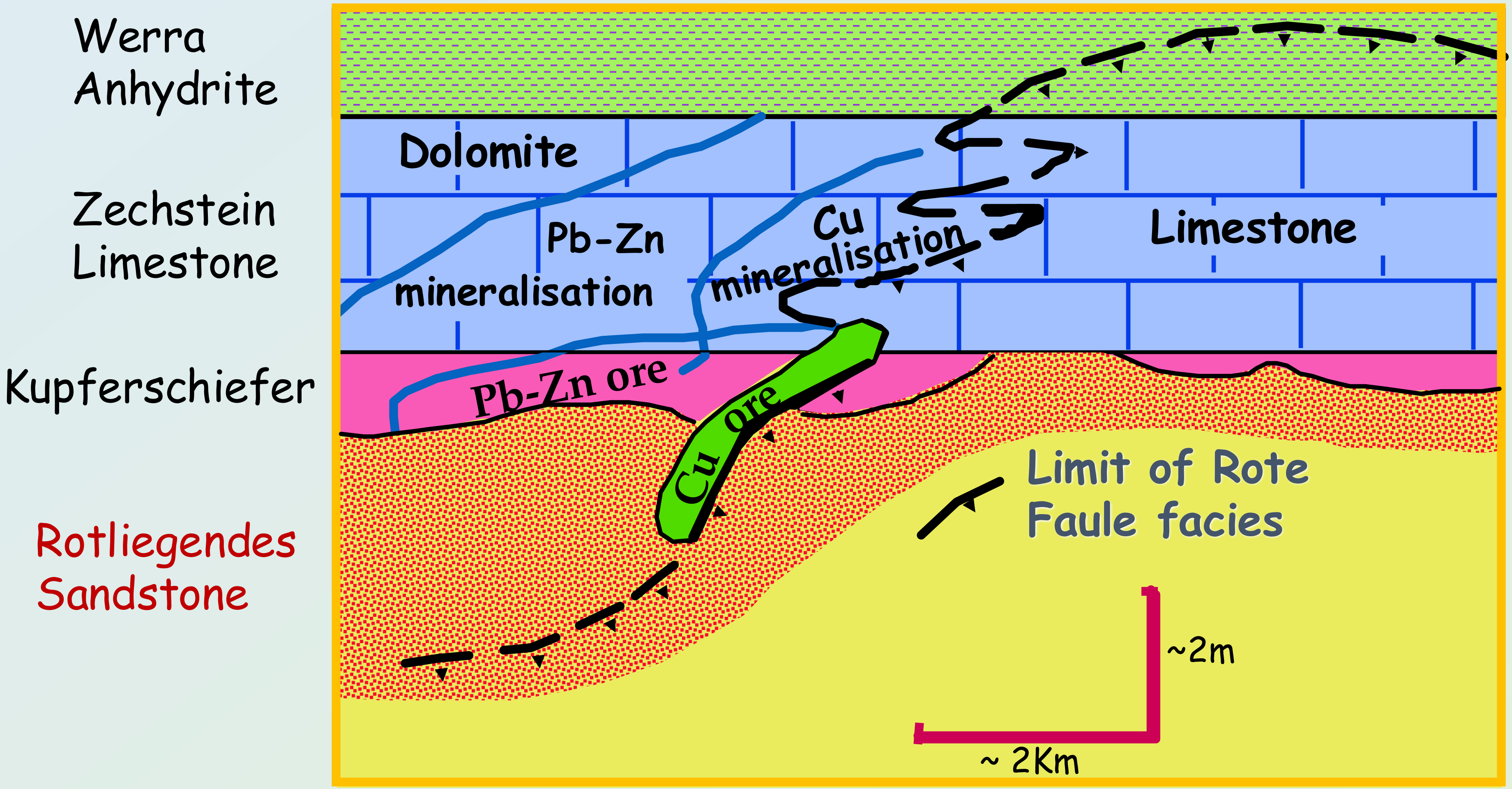
Kupfershiefer was deposited in a deep enclosed basin covered by the Zechstein Sea



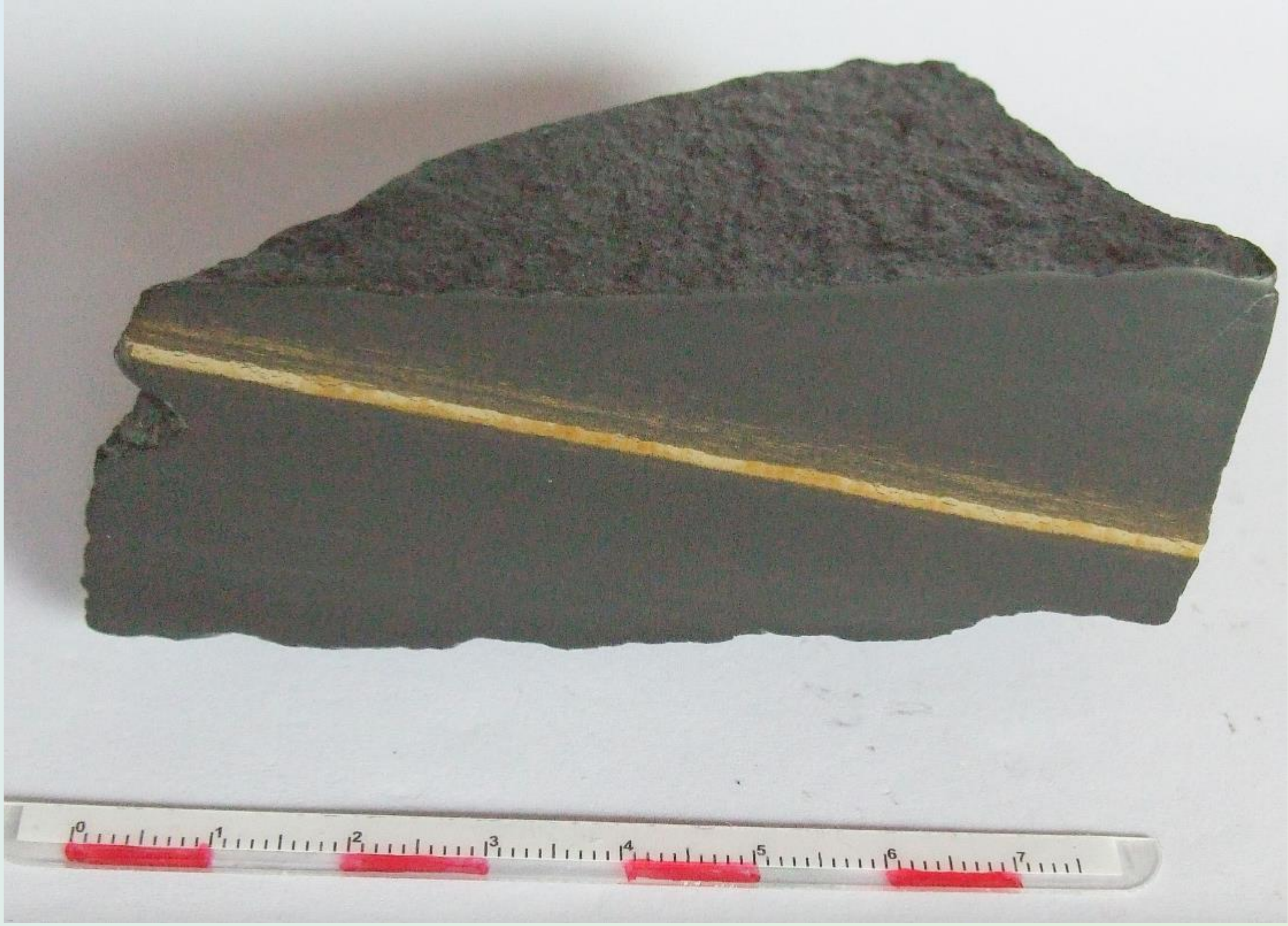
Kupferschiefer copper deposits

- Kupferschiefer → Late Permian age → transgressive marine clays, carbonate, organic material
- underlying sandstones and conglomerates are non-marine
- overlying rocks are limestones and evaporites
- environment of deposition: intertidal (sabkha)
- mineralisation occurs in the Kupferschiefer, underlying sandstone and overlying limestone
- ore minerals: hematite, bornite, chalcocite, chalcopyrite, galena, sphalerite
- mineralisation post dates sedimentation

Diagrammatic section through Kupferschiefer orebodies
(After Brown 1978)



Kupferschiefer shale



Kupferschiefer shale sample with chalcopyrite vein

Rote Faule facies

- Rote Faule – hematitic footwall alteration zone → overprints all other units
- formed by ascending brines interacting with pre-ore pyrite
- Cu mineralisation lies directly above the Rote Faule fluid front
- highest Cu grades are closest to Rote Faule front

Rote Faule alteration (splotchy hematite replacing pyrite)

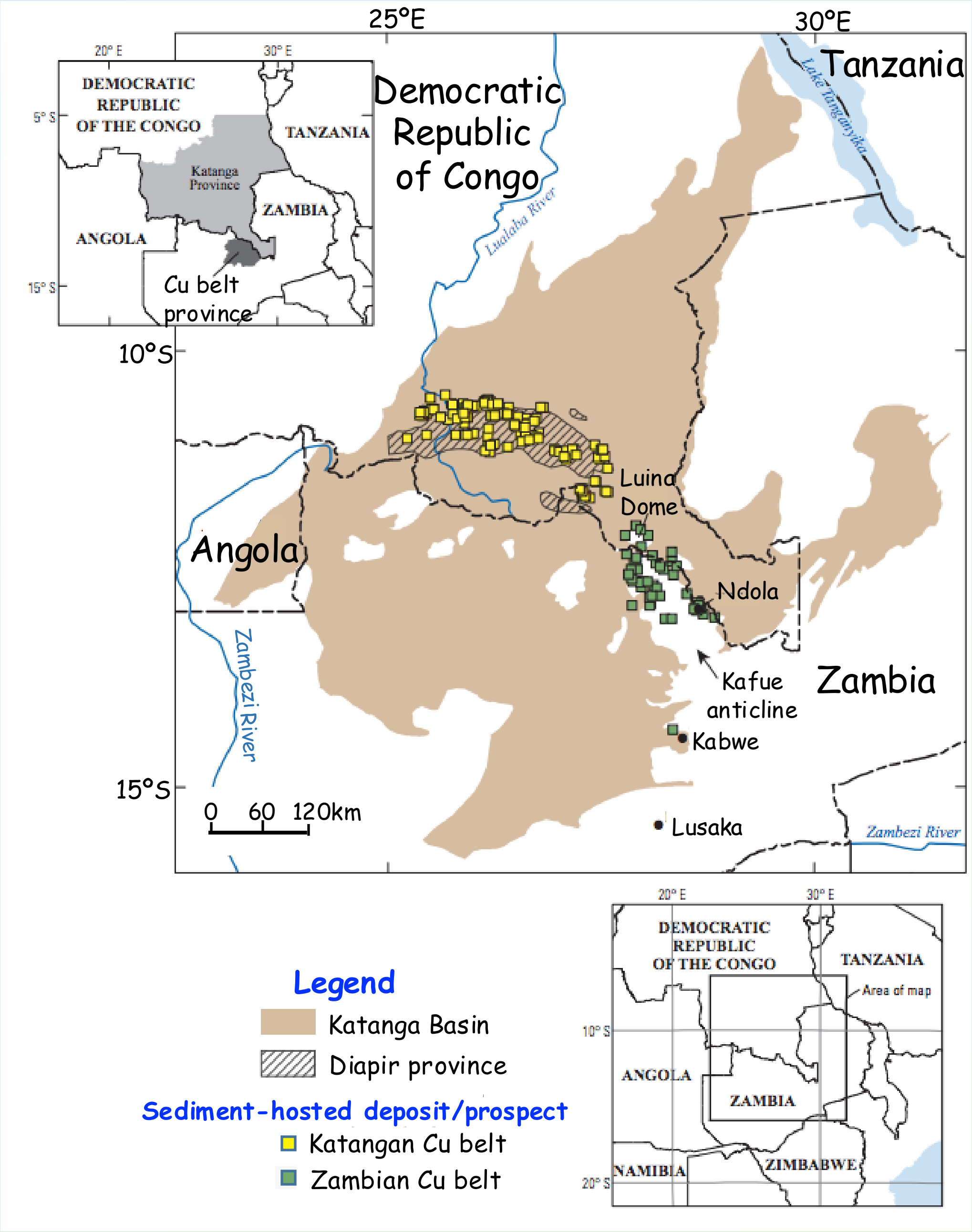
Genesis of Kupferschiefer

- Cu and associated elements → added after sedimentation
- ore genesis closely related to processes responsible for Rote Faule facies
- organic-rich Kupferschiefer produced framboidal pyrite
- sediment compaction caused partial basin de-watering and mobilisation of metalliferous brines
- these brines were oxidising partially replacing pyrite with hematite
- Kupferschiefer acted as hydrodynamic and geochemical barrier that slowed or stopped the ascending fluid flow

Central African Cu belt (CAB)

- The CAB sits on the border region between northern Zambia and the southern Democratic Republic of Congo
- largest and most highly mineralised sediment-hosted Cu province in the world
- many large deposits in the CAB have spatial relationship with mafic magmatism
- the CAB is divided into the Zambian Cu belt and the Katanga Cu belt
- CAB hosts >5 billion tonnes of Cu ore at grades up to 4% Cu
- mineralisation is hosted by the Neoproterozoic Katanga Group sediments deposited in a rift basin*

Central African Cu belt (CAB)



CAB characteristics

- Cu deposits consist of fine-grained Cu and Cu-Fe sulphides that form stratabound to stratiform disseminations in siliclastic or dolomitic sedimentary rocks
- major ore minerals are chalcopyrite and bornite
- ore minerals occur as cements, replacements and less commonly in veinlets

Genesis

Oxidised Cu-Co brines move up fault structures into overlying reduced facies

(1) Reaction with hydrocarbons, anhydrite → Cu-sulphides and gangue

(2) reaction with existing py and Cu-sulphides → Cu-sulphides with higher Cu:S ratio (chalcocite, covellite)*

Katangan Basin

- Katangan basin began as a continental rift and evolved into a collision -related foreland basin

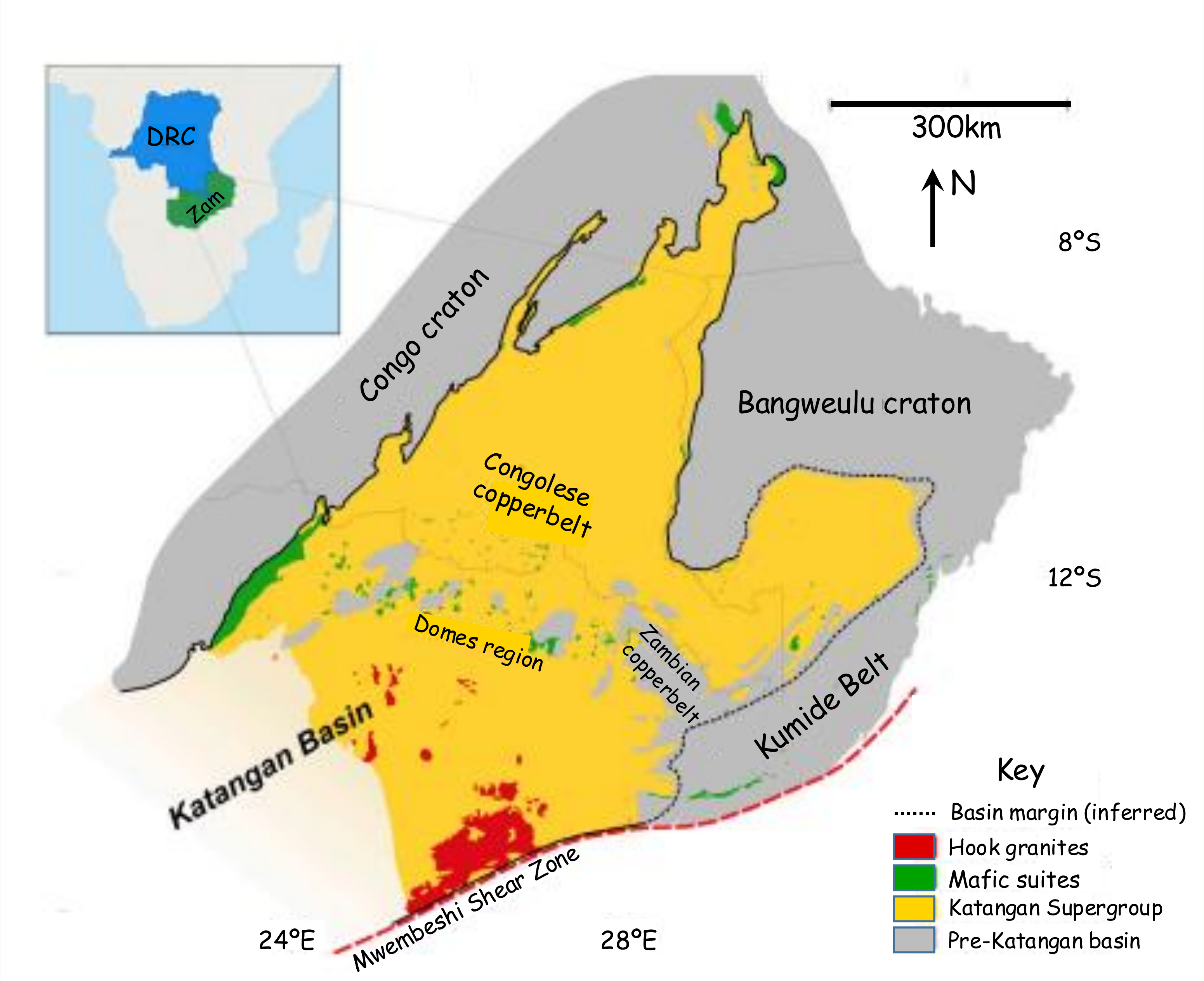
- Katangan Supergroup - Neoproterozoic sequence (5-10km thick) containing rich stratiform Cu-Co deposits → overlies Nchanga Granite

- Kundelunga Group – glacial metasediments and cap carbonates
  Nguba Group – carbonates and carbon-rich shales
  Roan Group – siliclastic and dolomitic, conglomerates, sandstones and shales, mafic igneous rocks

  Top ↑ Bottom

- red beds of Roan Group overlie pre-Katangan basement rocks and are in turn overlain by strata deposited in a reducing environment

Katangan Basin



CAB Cu mineralisation

Chalcopyrite, malachite and azurite in oxidised zone (Katangan Cu belt)

Fe oxide-Cu-Au ± U (IOCG) deposits

- Diverse group of deposits associated with Fe-oxide
- Williams (2005) defined these deposits from the following characteristics:
  (1) Cu with or without Au as an economic mineral
  (2) hydrothermal ore styles and strong structural controls
  (3) abundant magnetite and/or hematite
  (4) Fe-oxides with Fe/Ti > than those in most igneous rocks
  (5) no direct spatial relations with intrusive igneous rocks
- deposits are located along high to low-angle faults that are splays off major crustal-scale faults
- not formed by magmatic processes

Olympic Dam, SA

- Gawler Craton in SA hosts some of the world's most significant Fe oxide-Cu-Au-U deposits e.g. Olympic Dam, Prominent Hill, Carrapateena
- Olympic Dam breccia-hosted Cu-U-Au-Ag deposit is located on the eastern edge of the Archaean to Mesoproterozoic Gawler Craton
- Olympic Dam is the fifth largest Cu, largest U and one of the largest Au deposits in the world
- total resource is 10.4 billion tonnes with grades:

  0.77% Cu

  230ppm U_2O_6

  0.32g/t Au

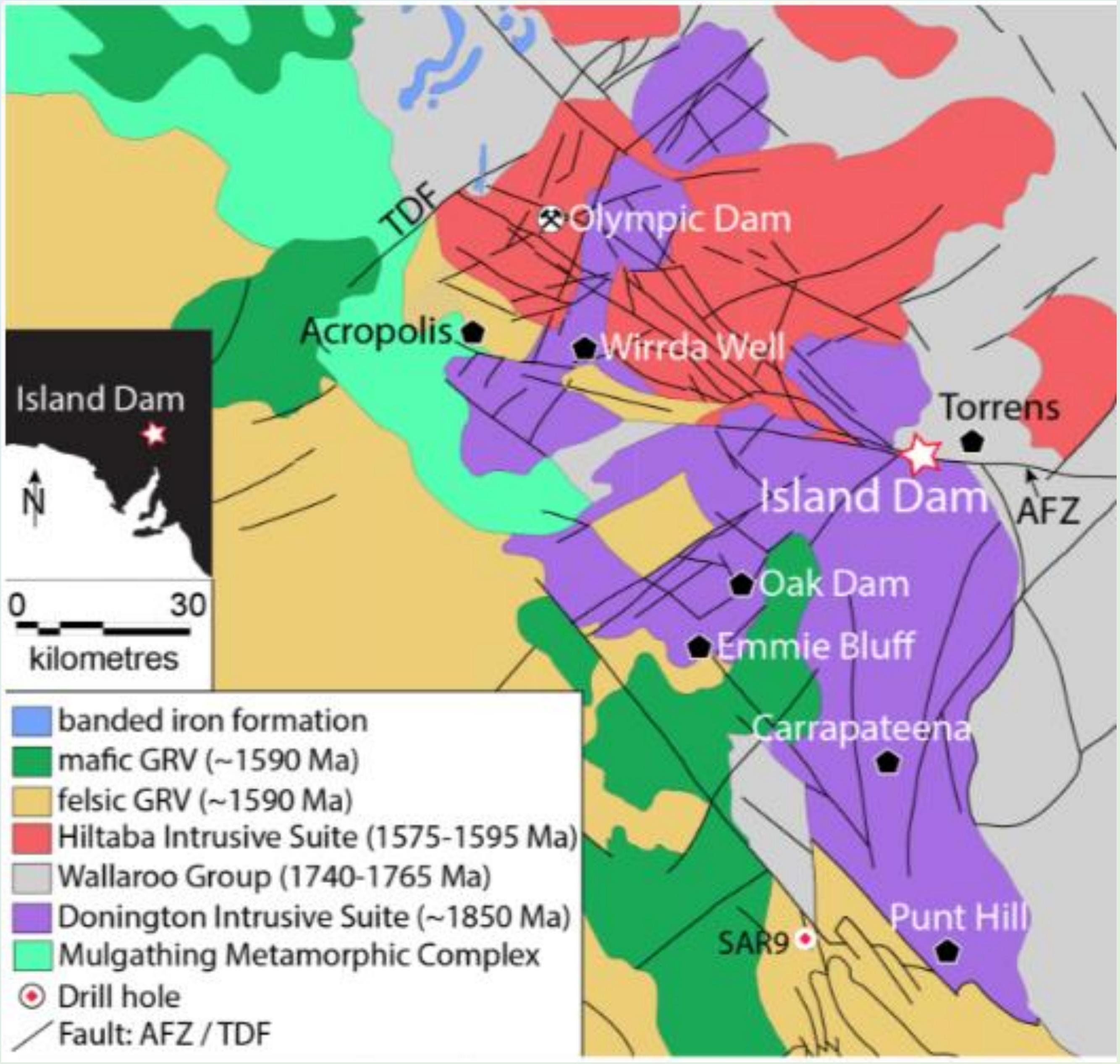
  1.3g/t Ag

Olympic Dam –Regional Geology

Regional Geology

- Mesoproterozoic succession → dominated by the ~1590Ma, Gawler Large Igneous Province
- Gawler Large Igneous Province includes Gawler Range Volcanics
  - Upper Gawler Range Volcanics: 3 large rhyolite lavas
  - Lower Gawler Range Volcanics: mafic and felsic lavas, felsic ignimbrites
- Gawler igneous province also includes granite intrusions of the Hiltaba suite

Olympic Dam


TDF
Olympic Dam
Acropolis
Wirrda Well
Torrens
Island Dam
AFZ
Oak Dam
Emmie Bluff
Carrapateena
Punt Hill
SAR9
Island Dam
N
0
30
kilometres
banded iron formation
mafic GRV (~1590 Ma)
felsic GRV (~1590 Ma)
Hiltaba Intrusive Suite (1575-1595 Ma)
Wallaroo Group (1740-1765 Ma)
Donington Intrusive Suite (~1850 Ma)
Mulgathing Metamorphic Complex
Drill hole
Fault: AFZ / TDF

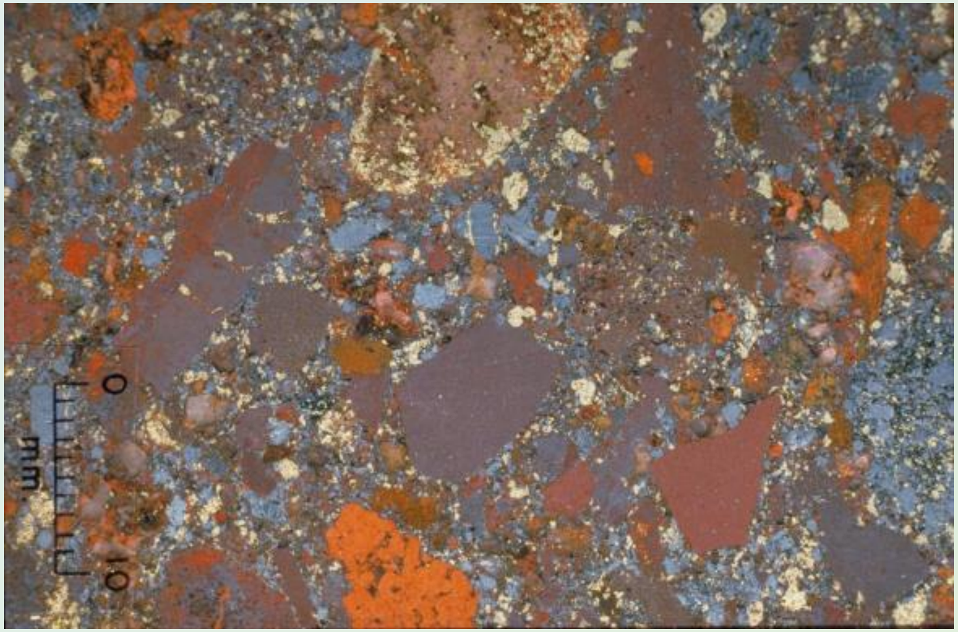
Olympic Dam ore deposit setting

- Mineralisation is hosted within the Olympic Dam Breccia Complex within the Roxby Downs Granite (component of the Hiltaba Suite)
- flat-lying, post brecciation, Neoproterozoic to Cambrian cover rocks (~350m thick) overlie the deposit
- the deposit is located at the junction of regional scale NW and ENE faults and fault splays
- rocks hosting mineralisation include the Roxby Downs Granite, felsic lavas, mafic-ultramafic lavas, dykes and sills
- rocks are weakly to intensely brecciated by tectonic, magmatic and hydrothermal processes
- clasts invariably are replaced by Fe oxide

Olympic Dam mineralisation

- Dominant sulphides within the Olympic Dam deposit are, chalcocite, chalcopyrite, bornite and pyrite
- lesser concentrations of sphalerite, galena, molybdenite, tennantite-tetrahedrite and trace native Cu
- sulphides typically occur as disseminated grains in breccia matrix
- U occurs mainly in fine-grained particles of uraninite (UO_2), coffinite {$U(SiO_4)(OH)_4$} and brannerite {$(U, Ca, Y, Ce)(Ti, Fe)_2O_6$}
- Au occurs on the edge of barren, hematite-quartz-barite-breccia. Rare nuggets and bonanza veins occur in hematite-rich, gold-dominant zones

Olympic Dam breccias



Steps in evolution of deposit

(1) A large intrusive is emplaced at a shallow level in the crust

(2) the intrusive heats the rock above

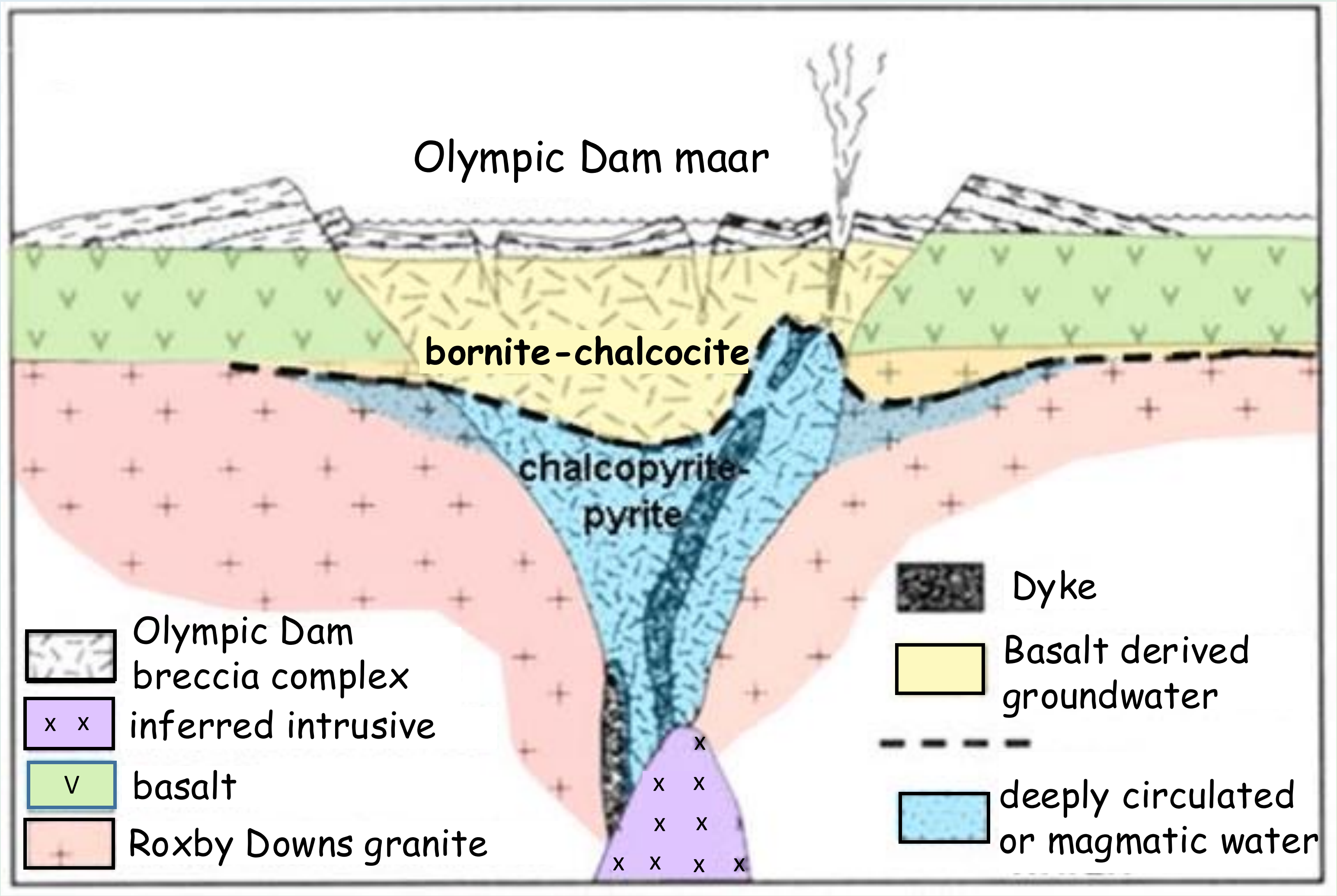
(3) cold brine cools the rock quickly and it shatters and causes miniature steam explosions and cracks throughout → massive breccia created

(4) brine dissolves iron from volcanic debris and fractured basalt and flows into breccia below depositing hematite and magnetite. This creates a chemical "trap"

(5) brine dissolves less soluble metals (Cu and Au) from volcanic debris. upwells and Au, Cu and other metals precipitate when they contact iron oxides.

(6) system cools, and over time almost all metals above water table are leached by residual salt and are deposited at the water table creating supergene Cu and Au

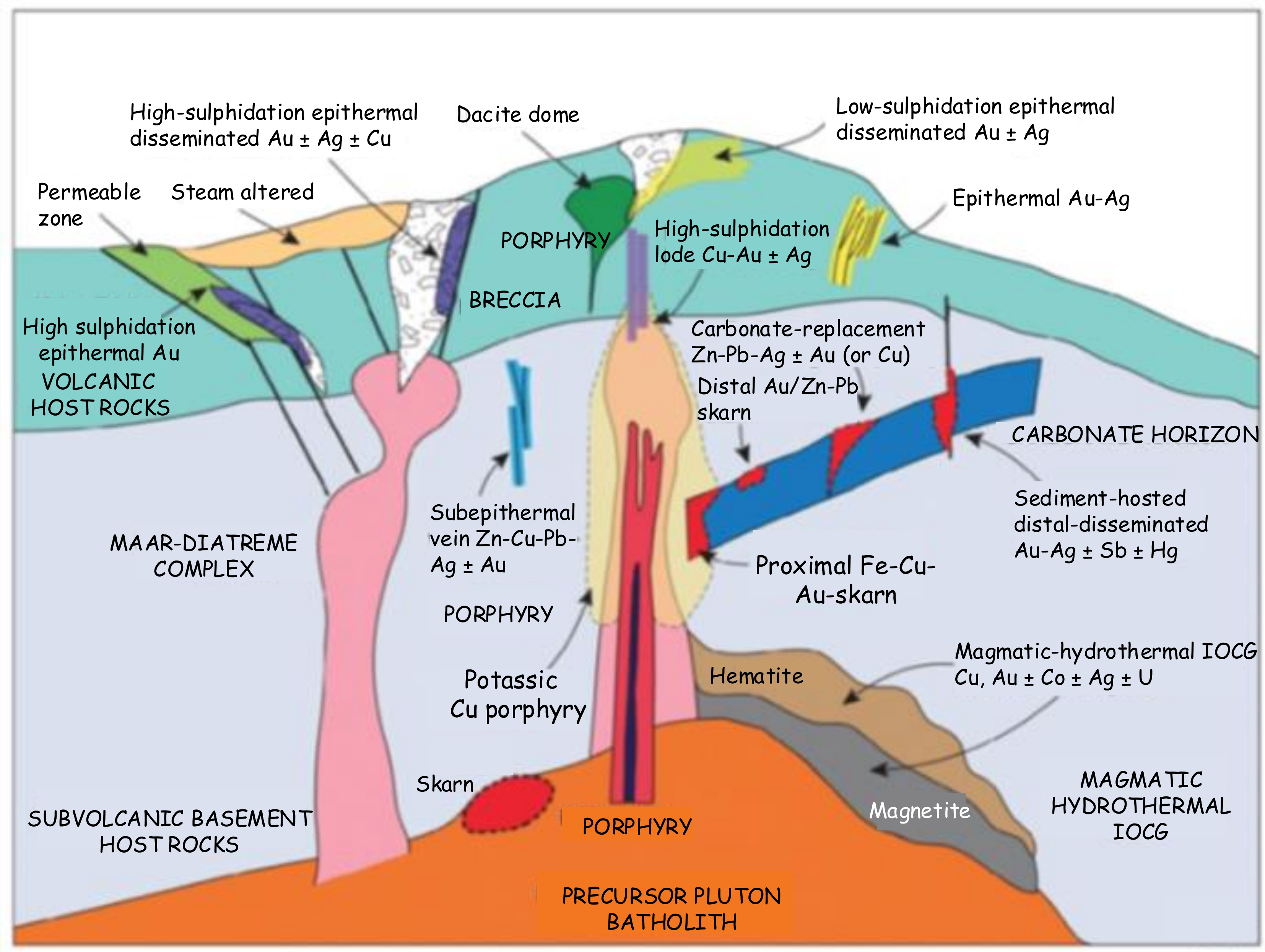
Mineralisation model



Cu skarns

- Cu skarns are metasomatic deposits that form predominantly in marble or meta-dolomite during contact metamorphism
- occur adjacent to felsic plutons in shallow geothermal systems
- most Cu skarns are associated with granodiorite or monzogranite intrusions
- silicate minerals occurring in skarns include andradite $\{Ca_2Fe_2(SiO_4)_3\}$, diopside ($CaMgSi_2O_6$), vesuvianite, wollastonite ($CaSiO_4$), actinolite $\{Ca_2(Mg, Fe)_5Si_6O_{22}(OH)_2\}$ and epidote$\{Ca_2FeAl_2(Si_2O_7)(SiO_4)(O,OH)_2\}$
- chalcopyrite most common Cu ore mineral, chalcocite and bornite are the dominant sulphides in some Cu skarns

Cu skarn in porphyry Cu deposit



Superior Cu deposits

- Economic Cu mineralisation of Mesoproterozoic age (~1100Ma) occurs around Lake Superior in North America
- the Cu occurs in a thick sequence of NW dipping sandstones, conglomerate, ash beds and flood basalts
- the Cu mineralisation is unusual because it occurs in its native form rather than in Cu oxides or Cu sulphides
- native Cu deposits originate in fissures, steeply dipping veins or in the top portion of lavas and conglomerate beds
- the lava series is at least 4,500m thick and consists of several hundred flood basalt flows

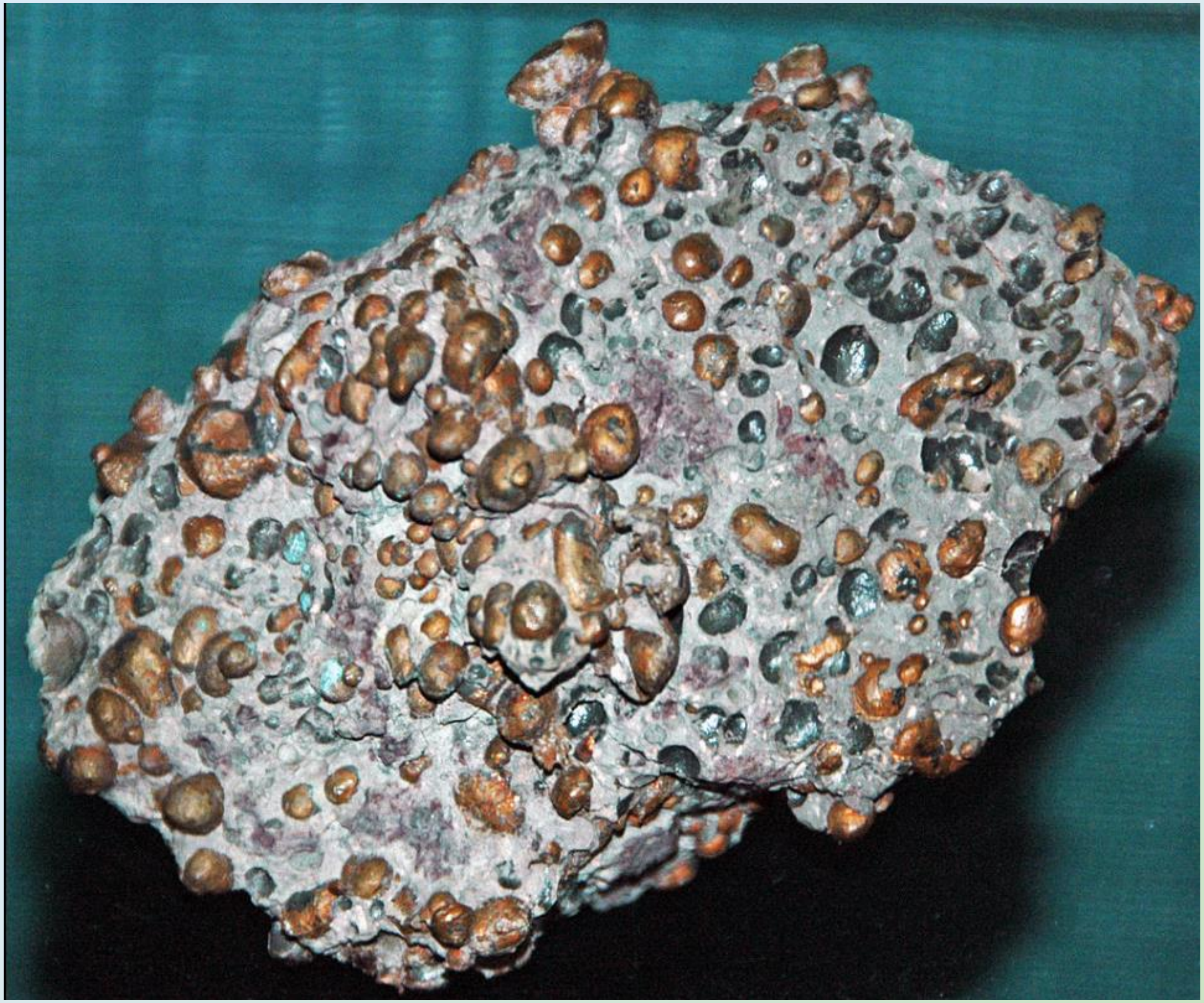
Superior Cu deposits

- The mineralisation was formed by metamorphic fluids that circulated through a network of faults and fissures

- faults and fissures developed during late rift compression and were responsible for leaching and re-deposition of native Cu in the volcanic dominated rocks

- subsequent to the compression event, the area was subject to erosion, exposing Cu to a long period of downward percolating groundwaters before burial
- after burial under a thick Phanerozoic sedimentary sequence, further erosion by Pleistocene continental glaciers removed much of the cover rocks

Lake Superior native Cu deposits



Cupriferous amygdaloidal basalt, Wolverine mine, Kearsage, Michigan