

PROCESSOS FORMADORES DE DEPÓSITOS MINERAIS: HIDROTERMALISMO

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CPMTC-IGC-UFMG



AULA SBG

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- ❖ Introdução
 - ❖ Processos formadores de depósitos
 - ❖ Fluidos na Terra
 - ❖ Sistema mineral
 - ❖ Alteração hidrotermal
 - ❖ Fluidos hidrotermais
- Tipos de fluidos e exemplos**

Classificação de depósitos (Lindgren)

- Elementos e/ou mineral
- Rocha hospedeira
- Ambiente tectônico e/ou idade
- Processos genéticos

Introdução

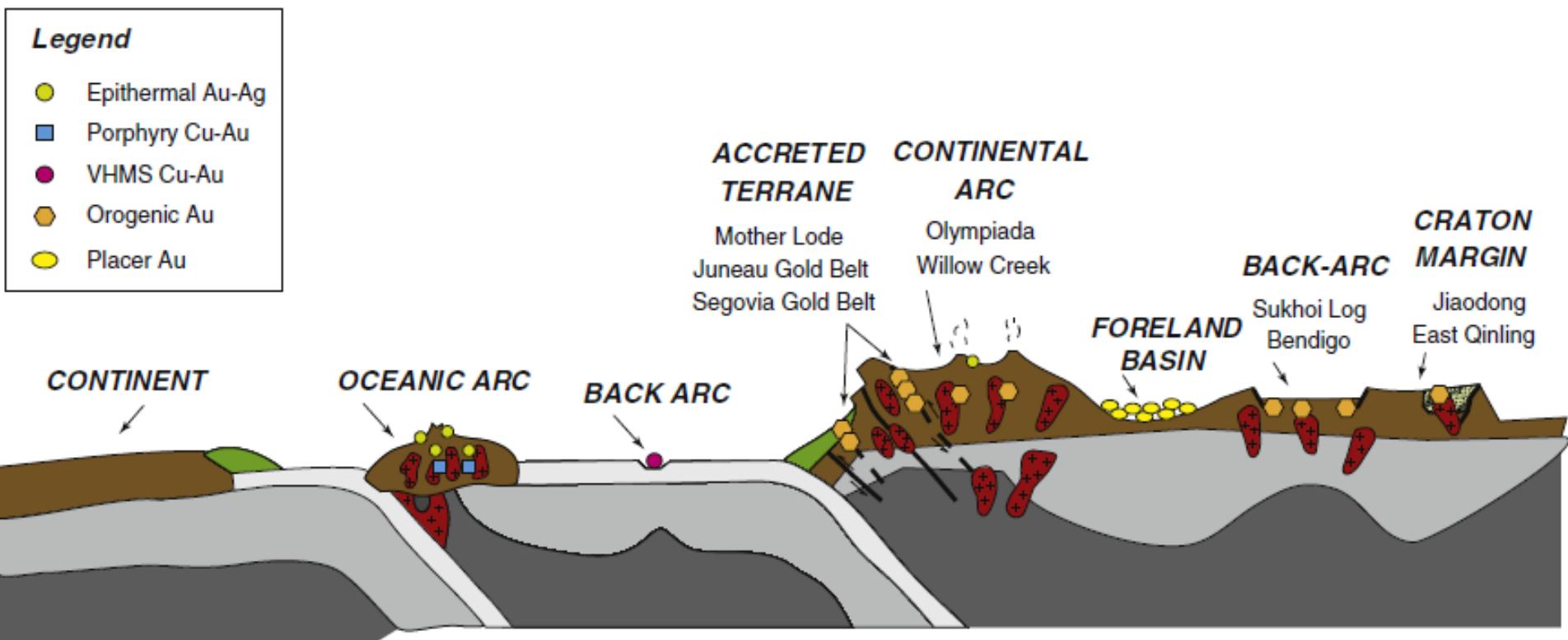


Fig. 1. Tectonic setting of orogenic and other gold deposit types. The orogenic gold deposits may be located in metamorphosed fore-arc and back-arc regions of active continents as well as along the sheared margins to continental arc batholiths. In the case of eastern Asia, orogenic gold deposits are located along the margins of the decrattonized Nor

ORE DEPOSITS CLASSIFICATION

- **magmatic** - concentration as a result of chemical and mineralogical processes in magmas;
- **hydrothermal** - concentration as a result of precipitation from heated aqueous fluids migrating through crustal rocks;
- **sedimentary** - concentration by mechanical or chemical processes at the time of sedimentation;
- **regolith** - enrichment as a result of weathering processes.

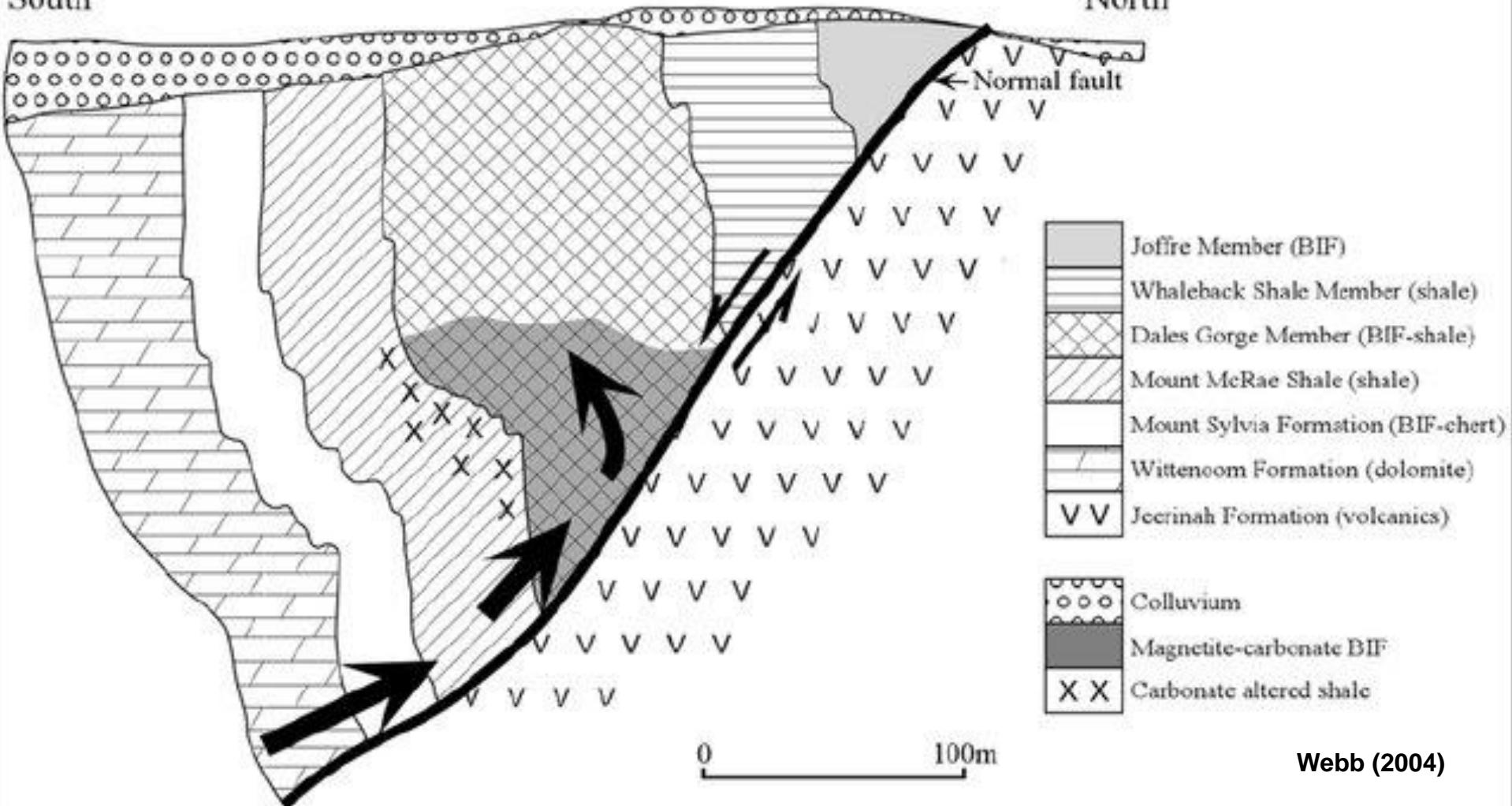
Some Definitions

Supergene - mineral deposit or enrichment formed near the surface, commonly by descending recent meteoric waters; also said of those fluids and of that environment

Hypogene - used to describe mineral deposits formed by ascending solutions from Earths crust or mantle

South

North



Webb (2004)

Magmatic ore deposits

- *small-fraction partial melts*: light rare-earth element (LREE) ores in **carbonatites** Ex. Bayan Obo (ETRL, Nb and Fe – China) Palabora, África do Sul
- *differentiation of a silicate melt*: **chromite deposits** Ex. **Bushveld**
- *immiscible sulfide melt phases*: base-metal Ni-Cu sulfide **deposits** in mafic and ultramafic rocks Ex. Sudbury; Kambalda
- *immiscible sulfide melt phases*: **PGE sulfide deposits**
- Deposits formed through extreme fractionation of magma: **rare-metal pegmatites**
- Ores formed through incorporation of a mineral from depth in the Earth into magma: **diamond deposits** in kimberlites and lamproites

Ore deposits formed in sedimentary environments

Chemical precipitation from surface waters (hydrogene deposits)

Iron ores in ironstones

Sedimentary-rock-hosted Mn deposits

Sedimentary-rock-hosted phosphorus deposits

Ore deposits in clastic sedimentary environments

Heavy-mineral sand deposits on shorelines and
palaeoshorelines

Fluvial placer and palaeoplacer deposits

Hydrothermal ore deposits I: magmatic and orogenic environments

Hydrothermal deposits formed around magmatic centres

- ❖ Porphyry deposits
- ❖ Greisens and related ore deposits
- ❖ Skarn and carbonate-replacement deposits
- ❖ Polymetallic veins and vein fields associated with magmatic centres
- ❖ High-sulfidation epithermal Au-Ag deposits
- ❖ Low-sulfidation epithermal deposits
- ❖ Volcanic-hosted massive sulfide (VHMS) deposits

Syn-orogenic hydrothermal ore deposits without close spatial or temporal relations to magmatism

- Orogenic Au deposits
- Carlin-type gold deposits
- Iron oxide-copper-gold (IOCG) deposits

Hydrothermal ore deposits II: sedimentary environments

Hydrothermal fluids in sedimentary basins

Chemical characteristics of basinal waters

Large-scale fluid flow in sedimentary basins

Base-metal deposits in sedimentary basins

Mississippi Valley-type (MVT) Pb-Zn deposits

SEDEX Pb-Zn-Ag deposits

Kupferschiefer or red-bed copper deposits

Uranium deposits in sedimentary basins

Unconformity-related uranium deposits

Tabular uranium deposits

Roll-front uranium deposits

Supergene ores and supergene overprinting of ores

In situ supergene ores

Bauxite in lateritic weathering profiles
Ni-Co laterite deposits

Supergene ores formed by overprinting of hypogene ores (*supergene-modified*)

Supergene gold ores in lateritic weathering profiles

Supergene copper ores in arid and semi-arid climates

Supergene iron ores

Fluids in the Earth



<https://earthobservatory.nasa.gov/images/565/earth-the-blue-marble>

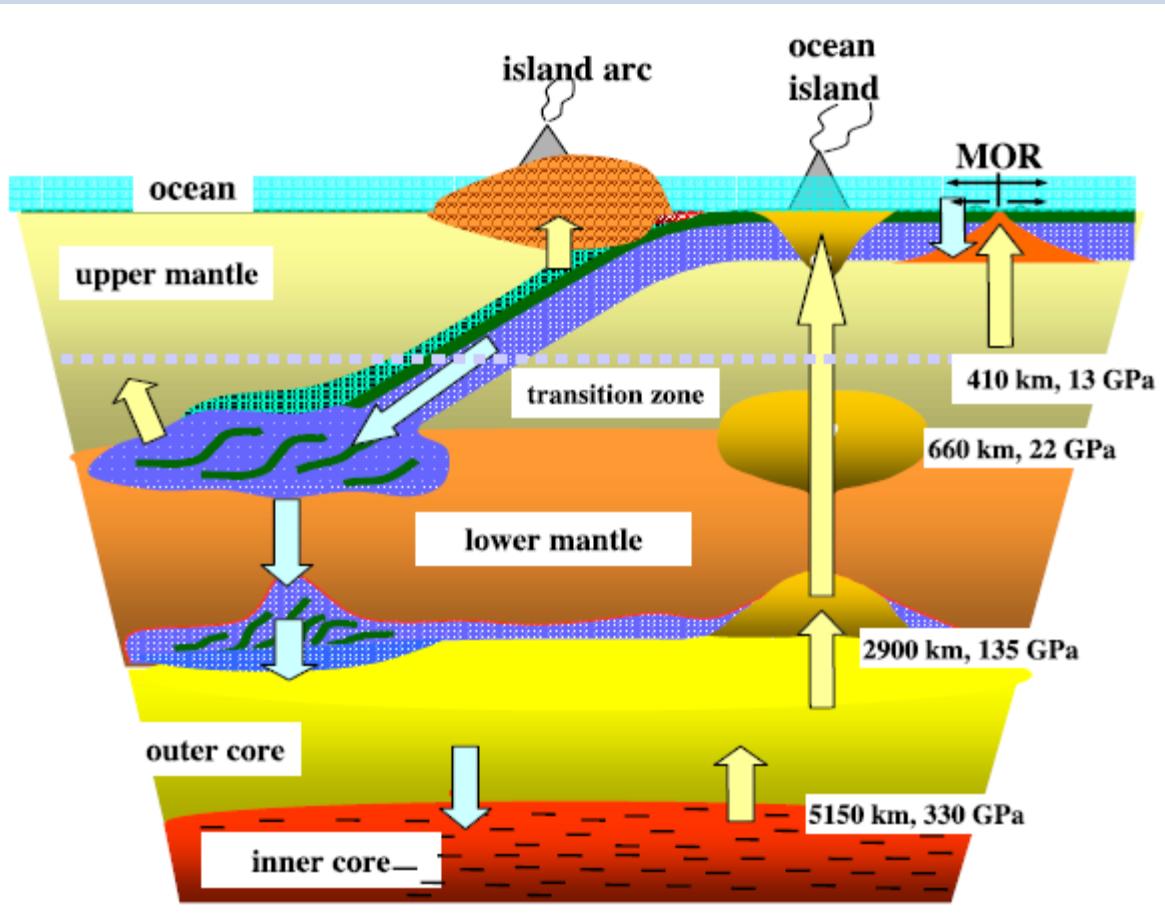
“We all live on this water planet which we have mistakenly chosen to call Earth.”
Anonymous

**Volcanism, both
subaerial and
submarine, is the
major activity
whereby water and
other volatiles are
transferred from the
deep Earth to the
near-surface.**



Fig. An artists impression of what the primitive Earth may have looked like in Eoarchaeon time (>3600 Ma). The Moon would have been closer to the Earth and meteor showers and volcanic activity were more prevalent than today. Hot springs and pillow lavas in thermal areas may have been the breeding grounds for primitive microorganisms and the evolution of life, some associated with stromatolite development in shallow seas.
Geo-artist: Maggie Newman.

Mantle Fluids



Schematic model for global water circulation. The model by Williams and Hemley (2001) is modified in this figure, based on Maruyama et al. (2001) and Ohtani et al. (2004, 2005). Arrows indicate directions of water or hydrogen movement.

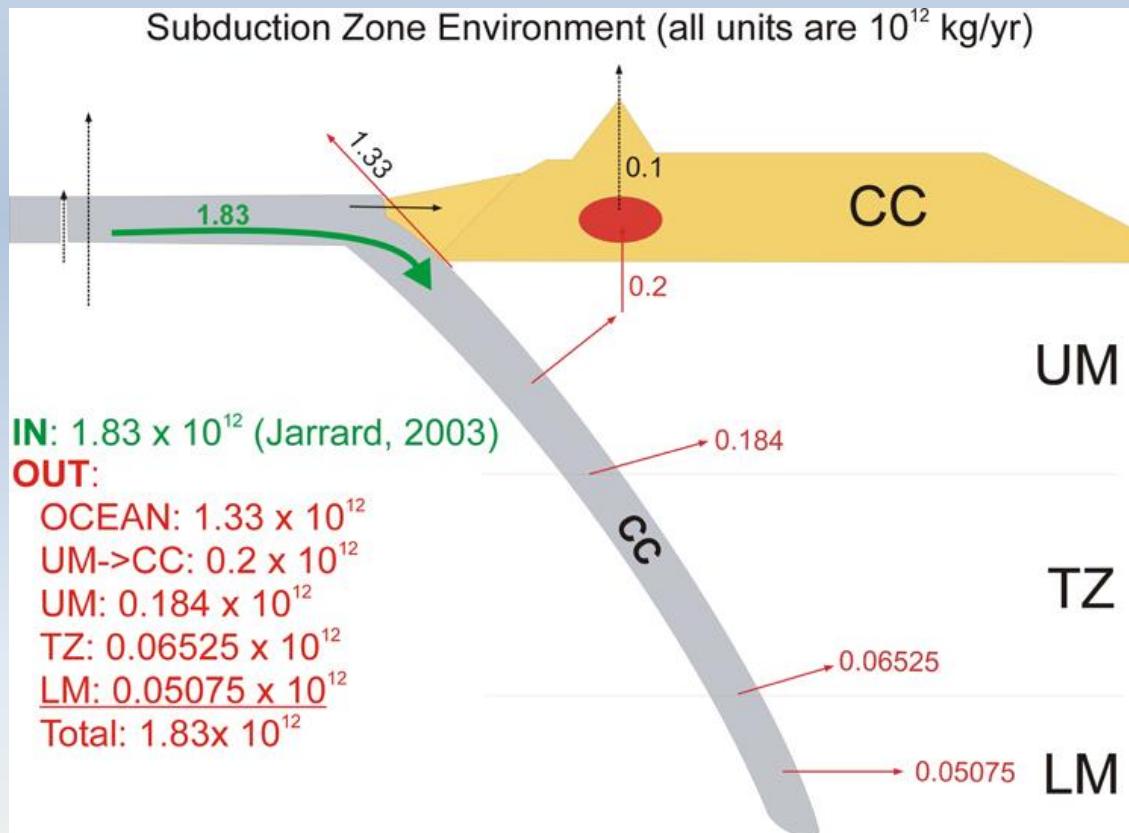
With the exception of the very upper mantle portion, “free” fluids are generally not present in the mantle.

Mantle fluids are either dissolved in silicate melts or occur as defects in nominally anhydrous minerals.

Based on earlier conceptual studies with the goal to develop an internally-consistent, quantitative model describing H_2O reservoirs in the whole-Earth system, fluxes between those reservoirs, and H_2O residence times in the various reservoirs.

Subduction Environment

Summary of H₂O fluxes into subduction zones



- Most water (73%) that enters trench is returned to oceans by updip flow
- About 11% of subducted water is lost to arc magmas
- About 10% of subducted water is incorporated into minerals in the upper mantle
- About 6% of subducted water is transported into the transition zone and lower mantle

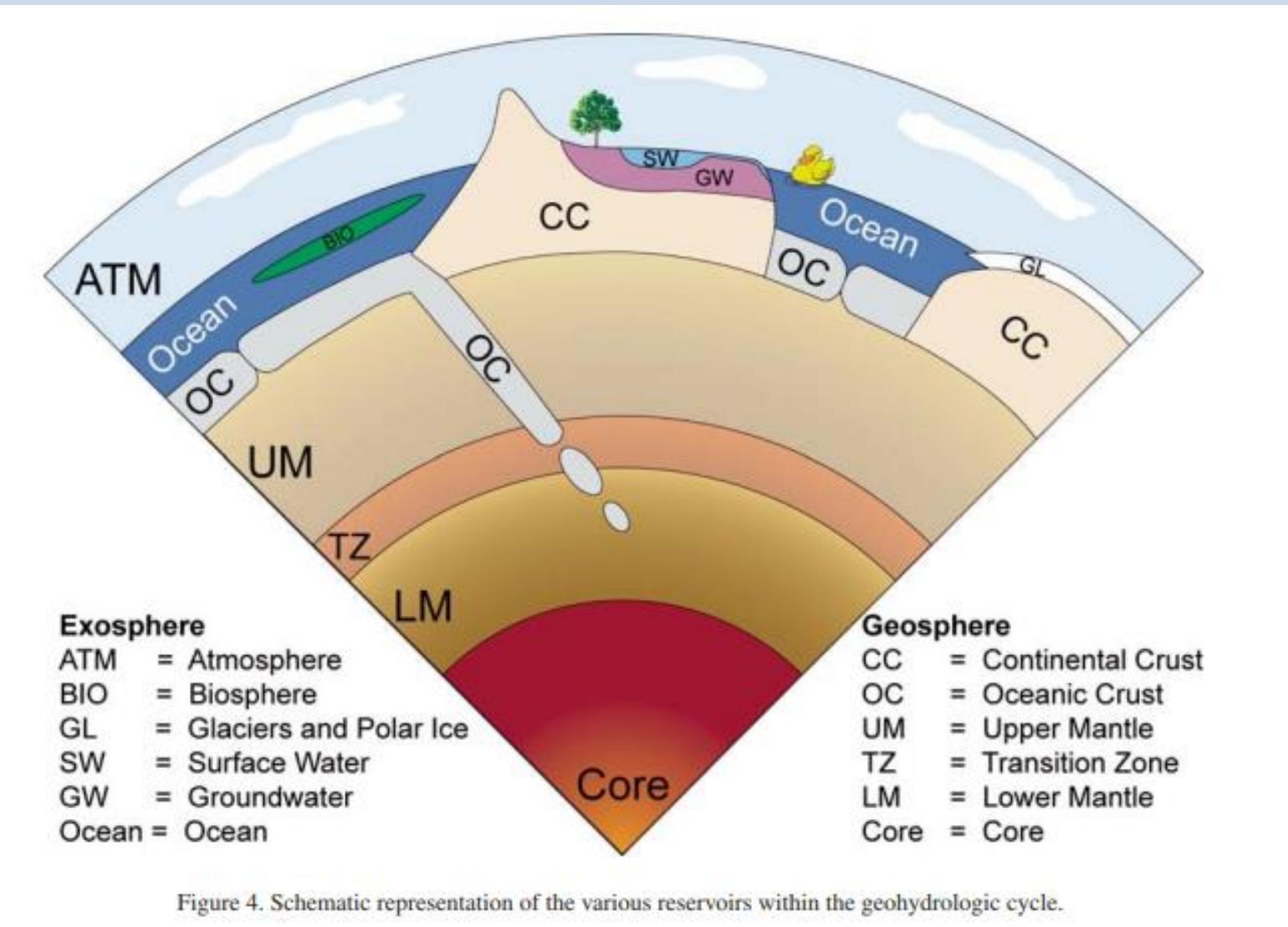
TABLE 1

HYDROUS PHASES EXPECTED IN THE EARTH'S INTERIOR

Name	Formula*	Density g/cm ³	Mg/Si	H ₂ O wt.%
chlorite	Mg ₅ Al ₂ Si ₃ O ₁₀ (OH) ₈	2.6-3.4	1.67	13
serpentine	Mg ₃ Si ₂ O ₅ (OH) ₄	2.55	1.5	14
chondrodite	Mg ₅ Si ₂ O ₈ (OH) ₂	3.06-3.16	2.5	5.3
hydroxylclinohumite	Mg ₉ Si ₄ O ₁₆ (OH) ₂	3.14-3.26	2.25	3
10Å phase	Mg ₃ Si ₄ O ₁₄ H ₆	2.65	0.75	13
phase A	Mg ₇ Si ₂ O ₈ (OH) ₆	2.96	3.5	12
phase B	Mg ₁₂ Si ₄ O ₁₉ (OH) ₂	3.38	3	2.4
superhydrous phase B(= phase C)	Mg ₁₀ Si ₃ O ₁₄ (OH) ₄	3.327	3.3	5.8
phase D(= phase F =phase G)	Mg _{1.14} Si _{1.73} H _{2.81} O ₆	3.5	0.66	14.5~18
phase E	Mg _{2.3} Si _{1.25} H _{2.4} O ₆	2.88	1.84	11.4
wadsleyite	Mg ₂ SiO ₄	3.47	2	≤3
ringwoodite	Mg ₂ SiO ₄	3.47-3.65	2	1.0-2.2
topaz-OH	Al ₂ SiO ₄ (OH) ₂	3.37	-	10
diaspore	AlOOH	2.38	-	15
phase Π	Al ₃ Si ₂ O ₇ (OH) ₃	3.23	-	9
phase EGG	AlSiO ₃ OH	3.84	-	7.5
phase δ	AlOOH	3.533	-	15
lawsonite	CaAl ₂ Si ₂ O ₁₀ H ₄	3.09	-	11.5

* End-member formulas

Fluids in the Earth



Fluids in the Earth

Atmosphere (ATM)

1.3×10^{16} kg

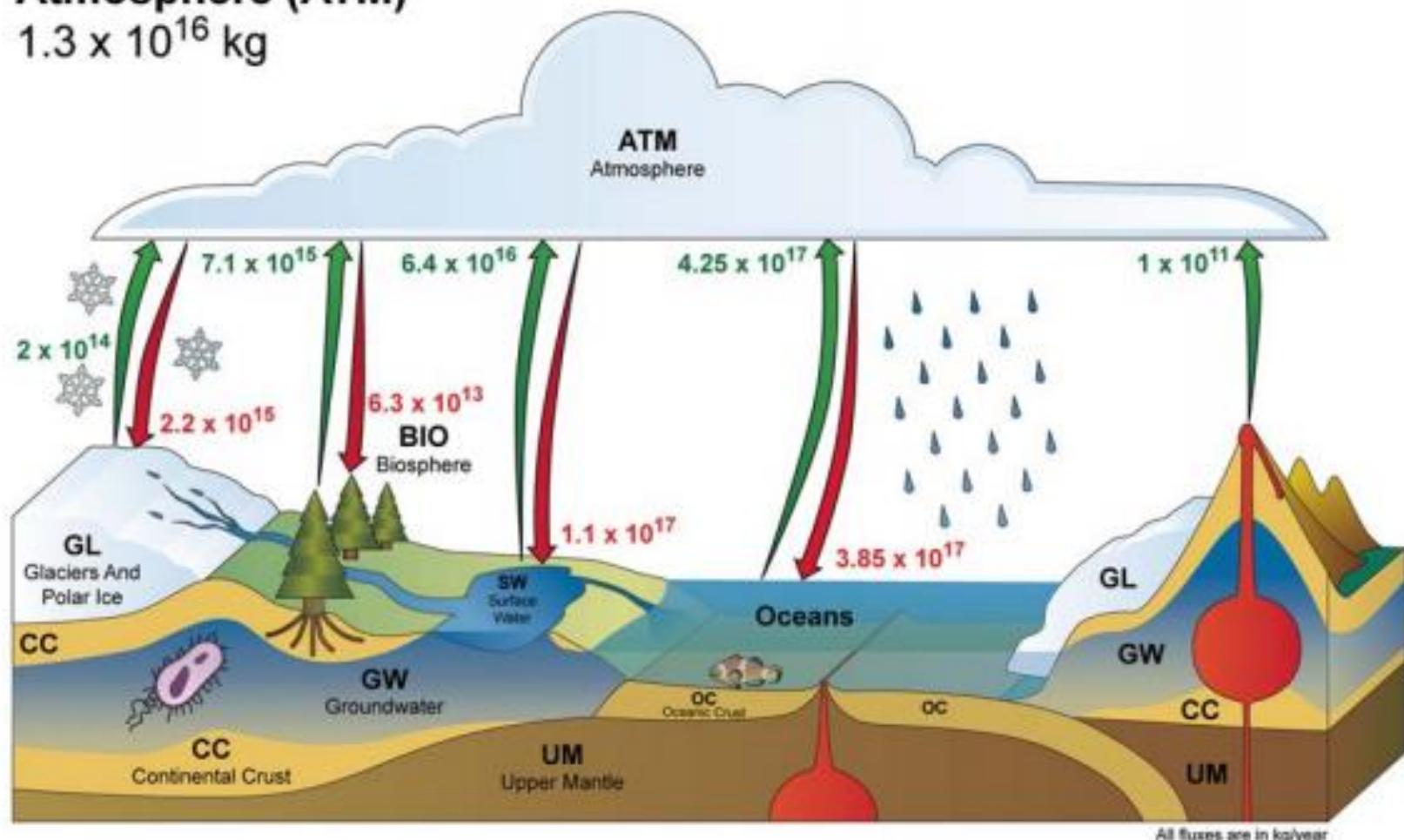
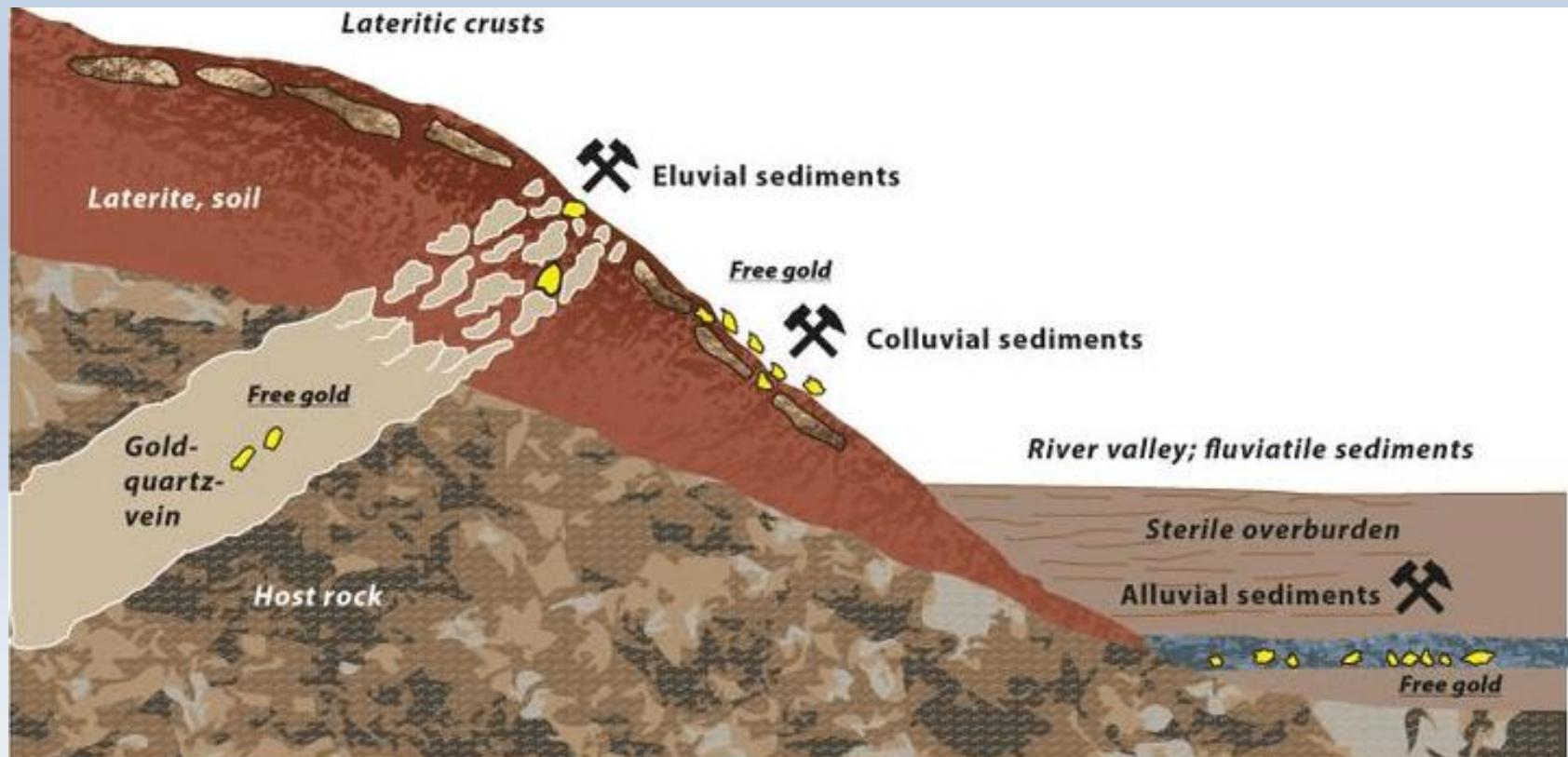


Figure 5. Summary of the fluxes of water between the atmosphere (ATM) and other reservoirs within the geohydrologic cycle. Green arrows represent fluxes into the reservoir, and red arrows represent fluxes out of the reservoir. All fluxes are in kg/yr.

MAIORIA DOS DEPÓSITOS MINERAIS EXISTEM DEVIDO AO IMPORTANTE PAPEL DA ÁGUA CONCENTRANDO E DEPOSITANDO METAIS



Placer deposits

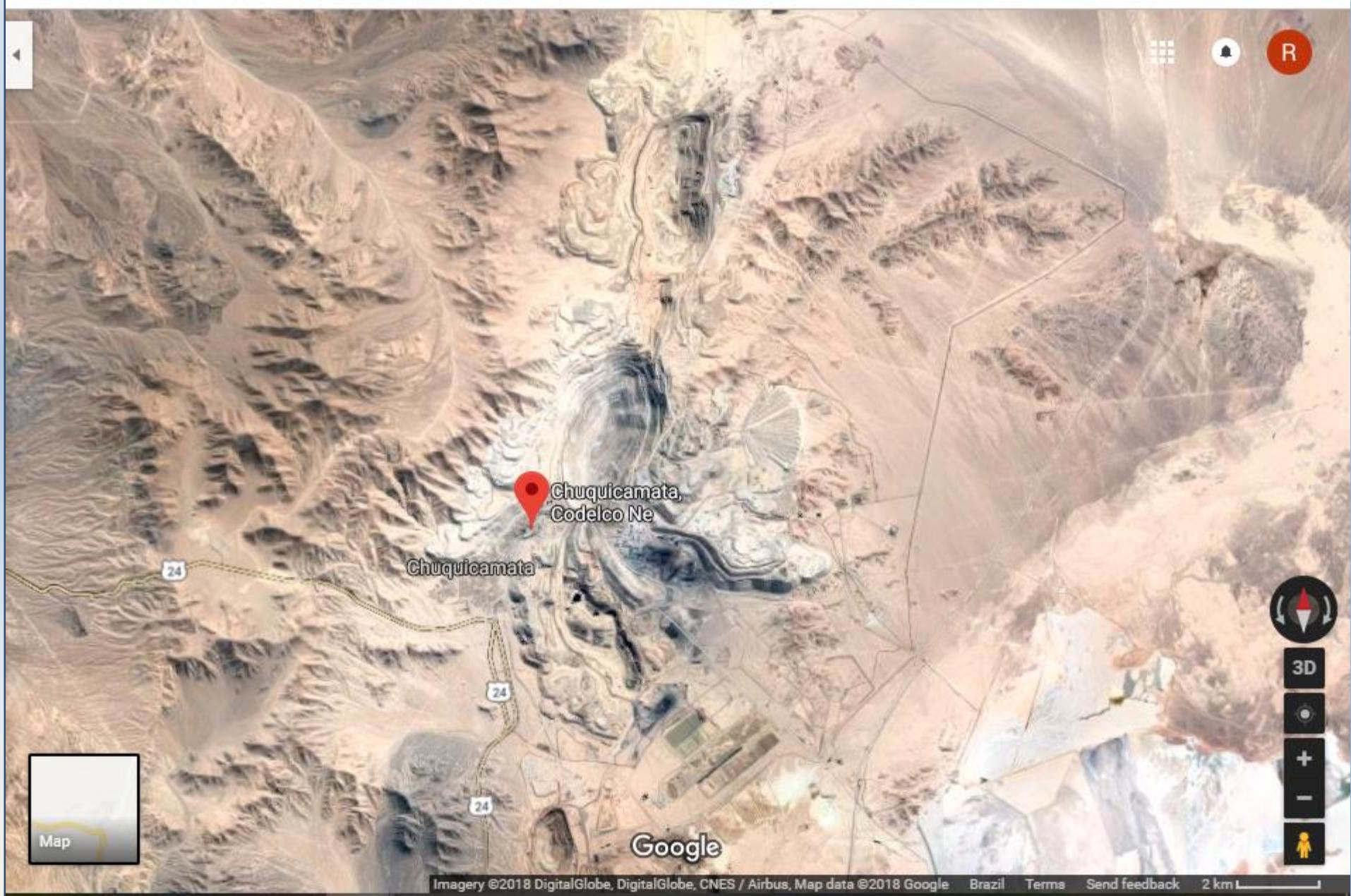
ATM, Surface waters, Oceans

MAIORIA DOS DEPÓSITOS MINERAIS EXISTEM DEVIDO AO IMPORTANTE PAPEL DA ÁGUA CONCENTRANDO E DEPOSITANDO METAIS



Porphyry Cu-Mo-Au deposits

CC, UM, SW, GW, ATM



Chuchicamata, Chile



Butte, EUA

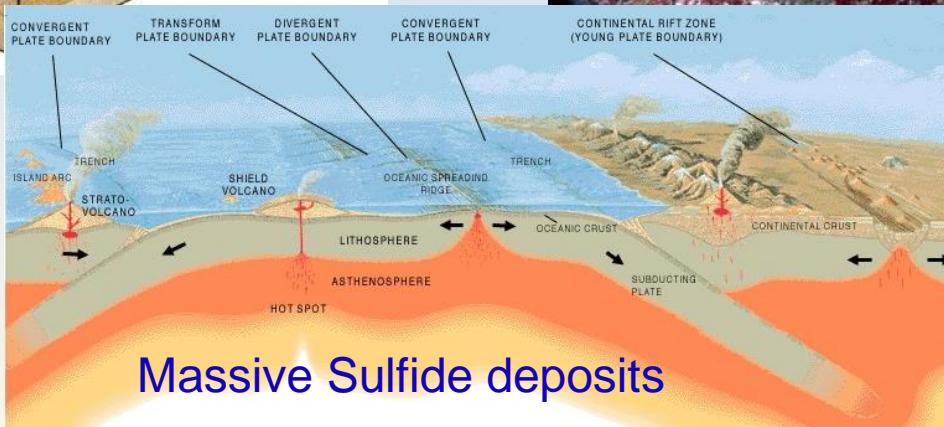
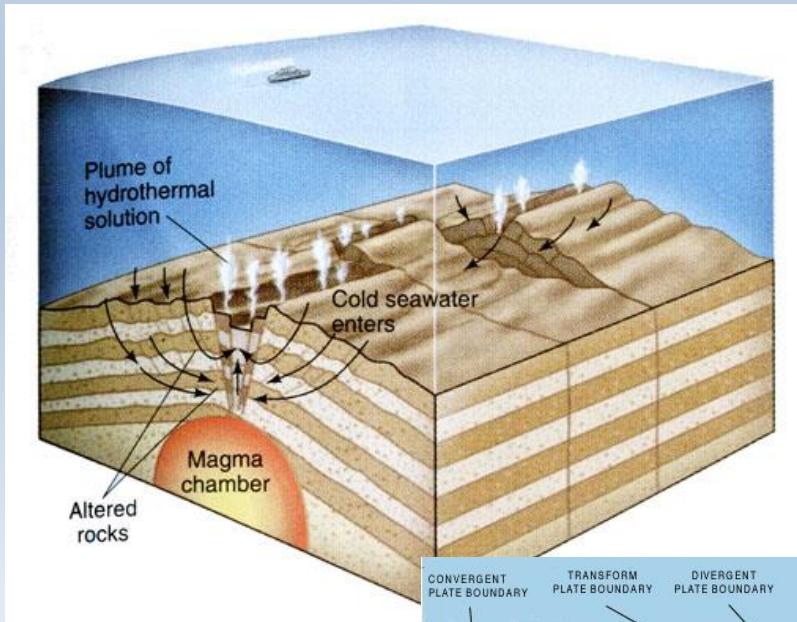


**S11D, Serra Sul,
Carajás**



Mount Whaleback, Western Australia

MAIORIA DOS DEPÓSITOS MINERAIS EXISTEM DEVIDO AO IMPORTANTE PAPEL DA ÁGUA CONCENTRANDO E DEPOSITANDO METAIS



Oceans,
Upper mantle

O que são fluidos hidrotermais?

Qual a fonte do fluido e dos metais?

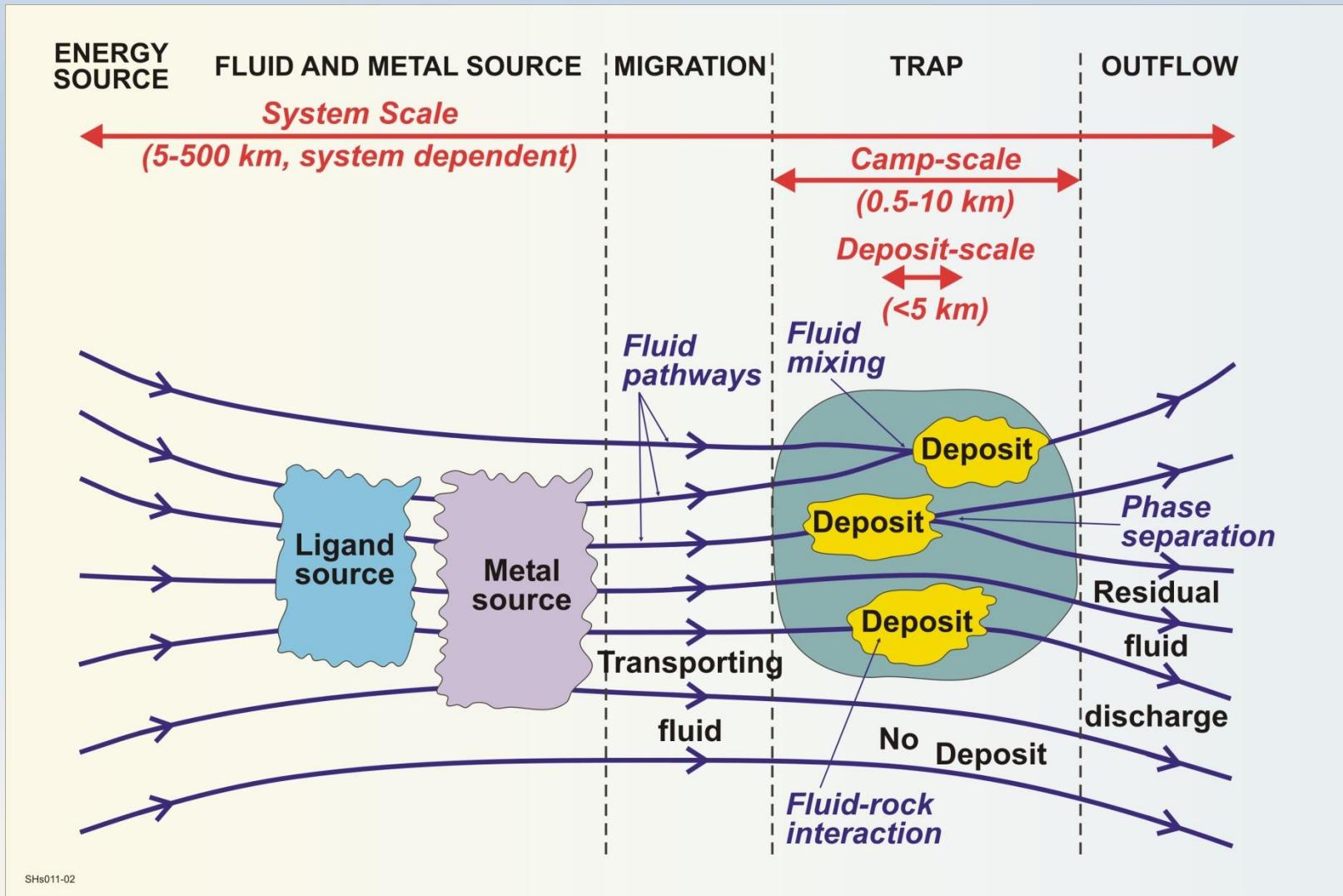
Como são transportados?

Quais os caminhos?

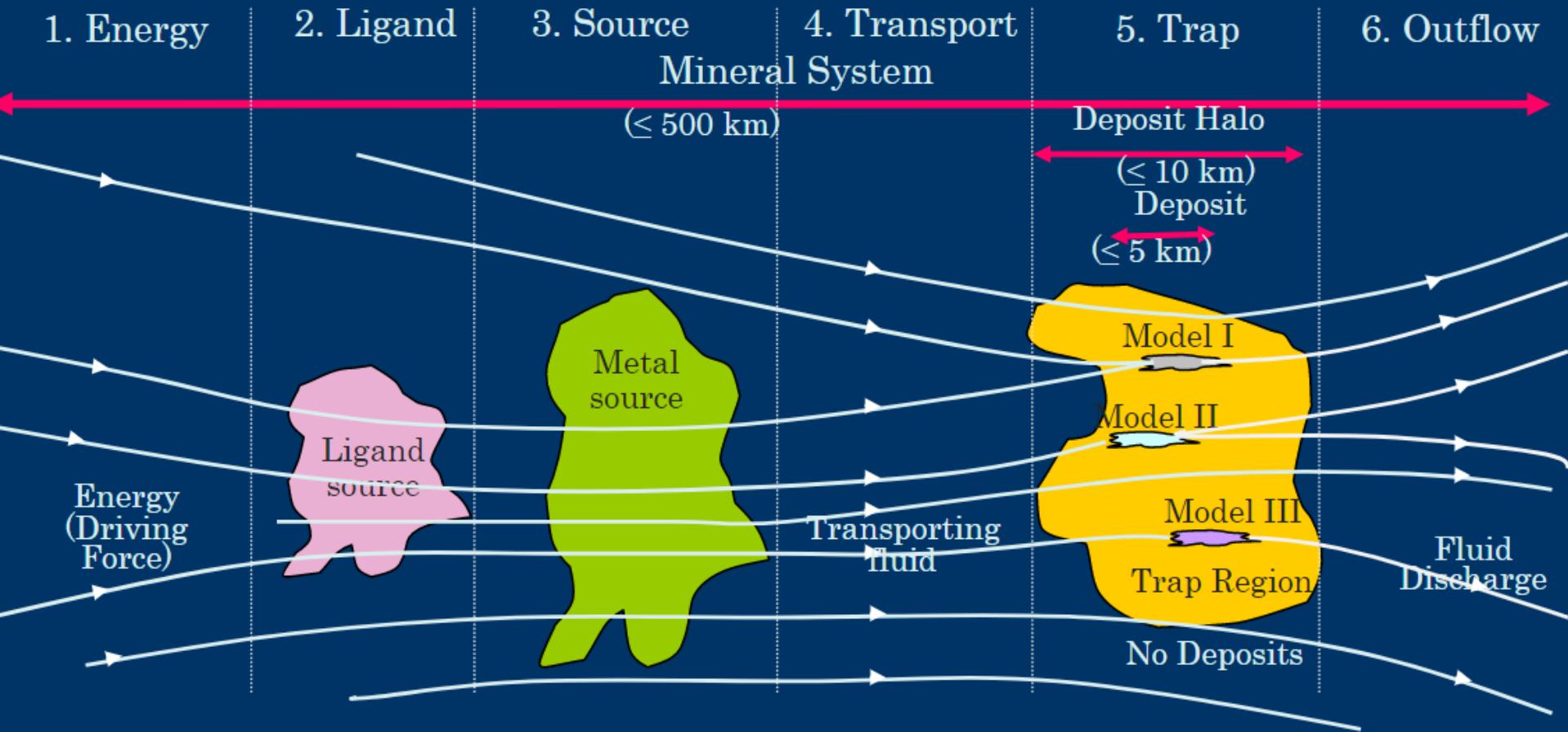
Mecanismos de precipitação?

Preservação

The mineral system concept of ore body formation

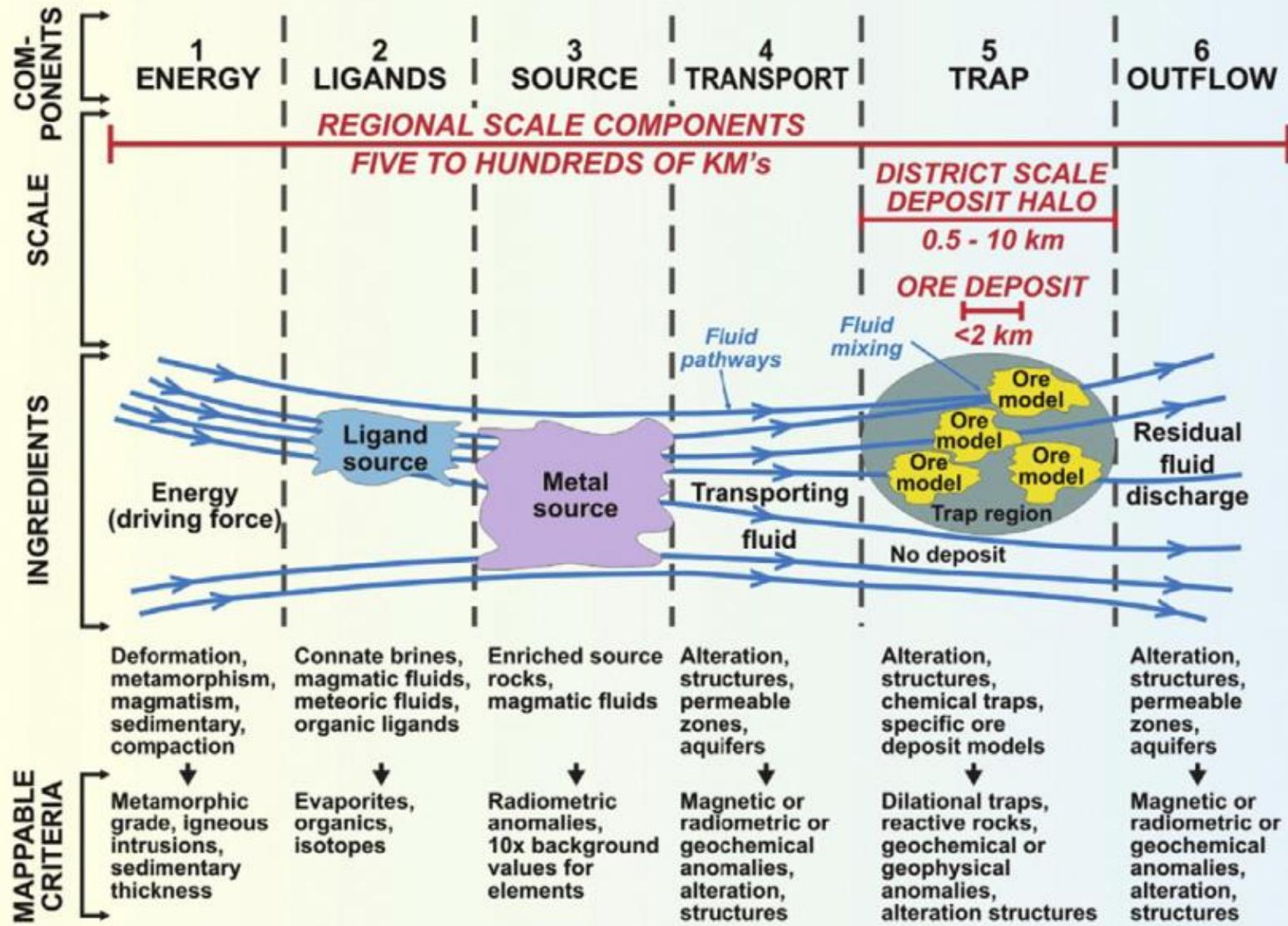


Mineral systems approach (Wyborn et al. 1995)

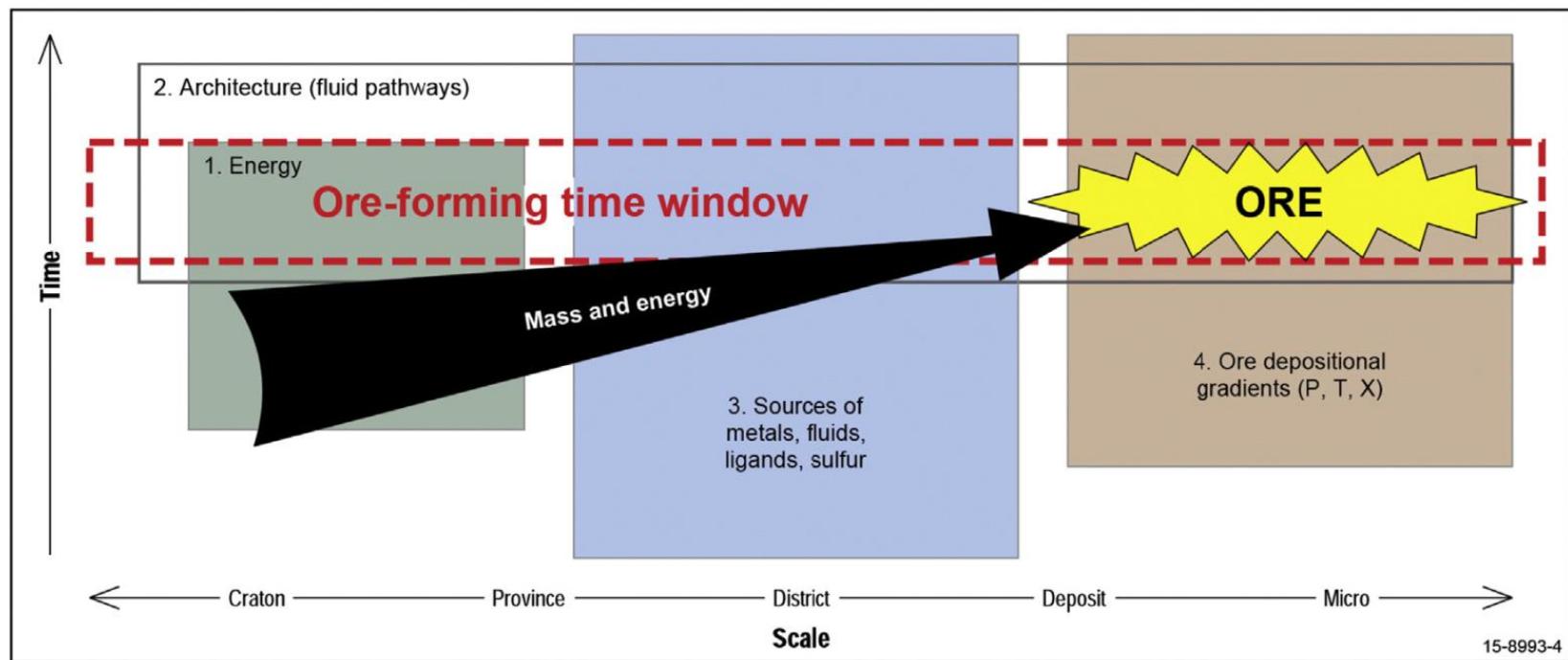


Sistema Mineral

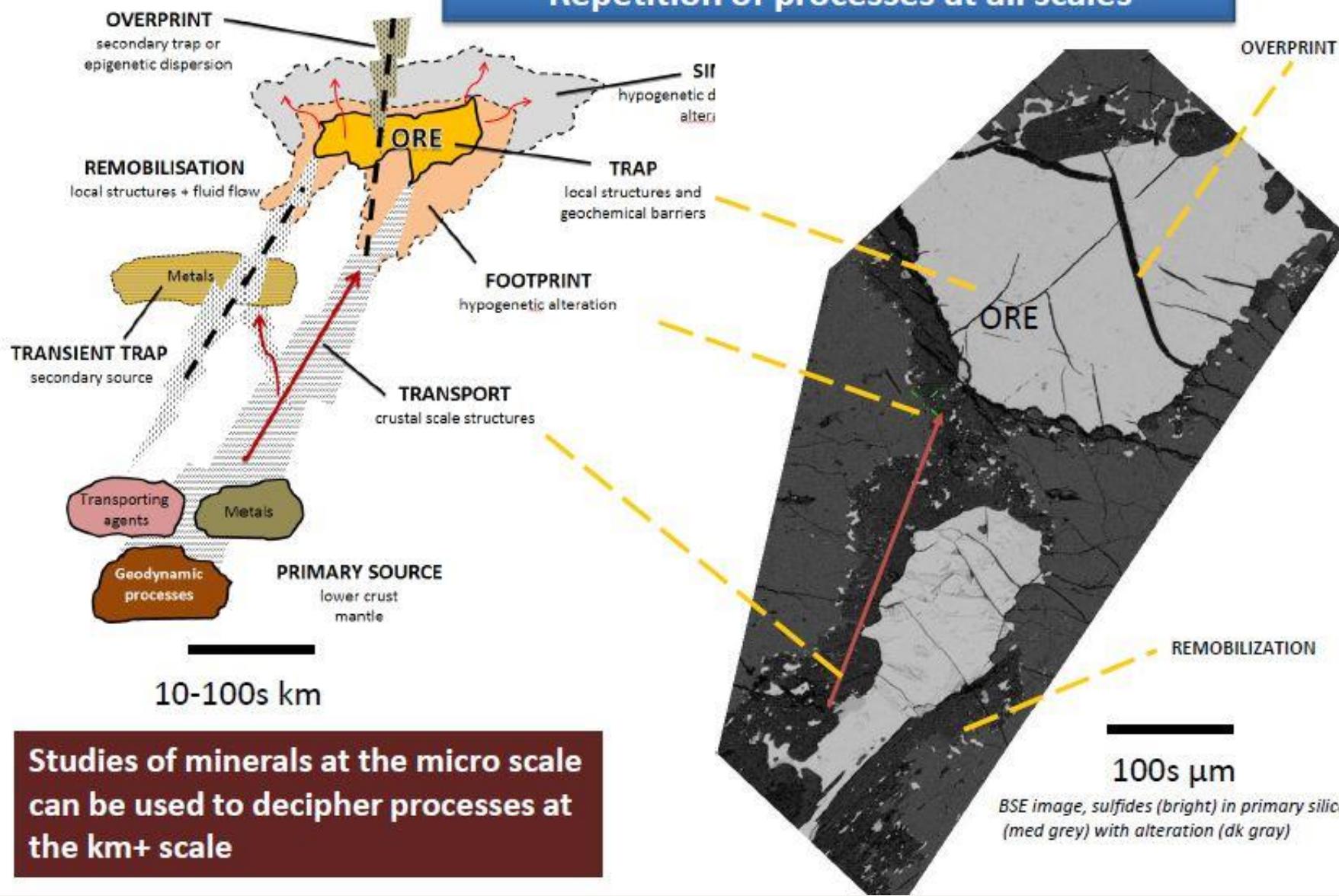
A



Sistema Mineral



Repetition of processes at all scales

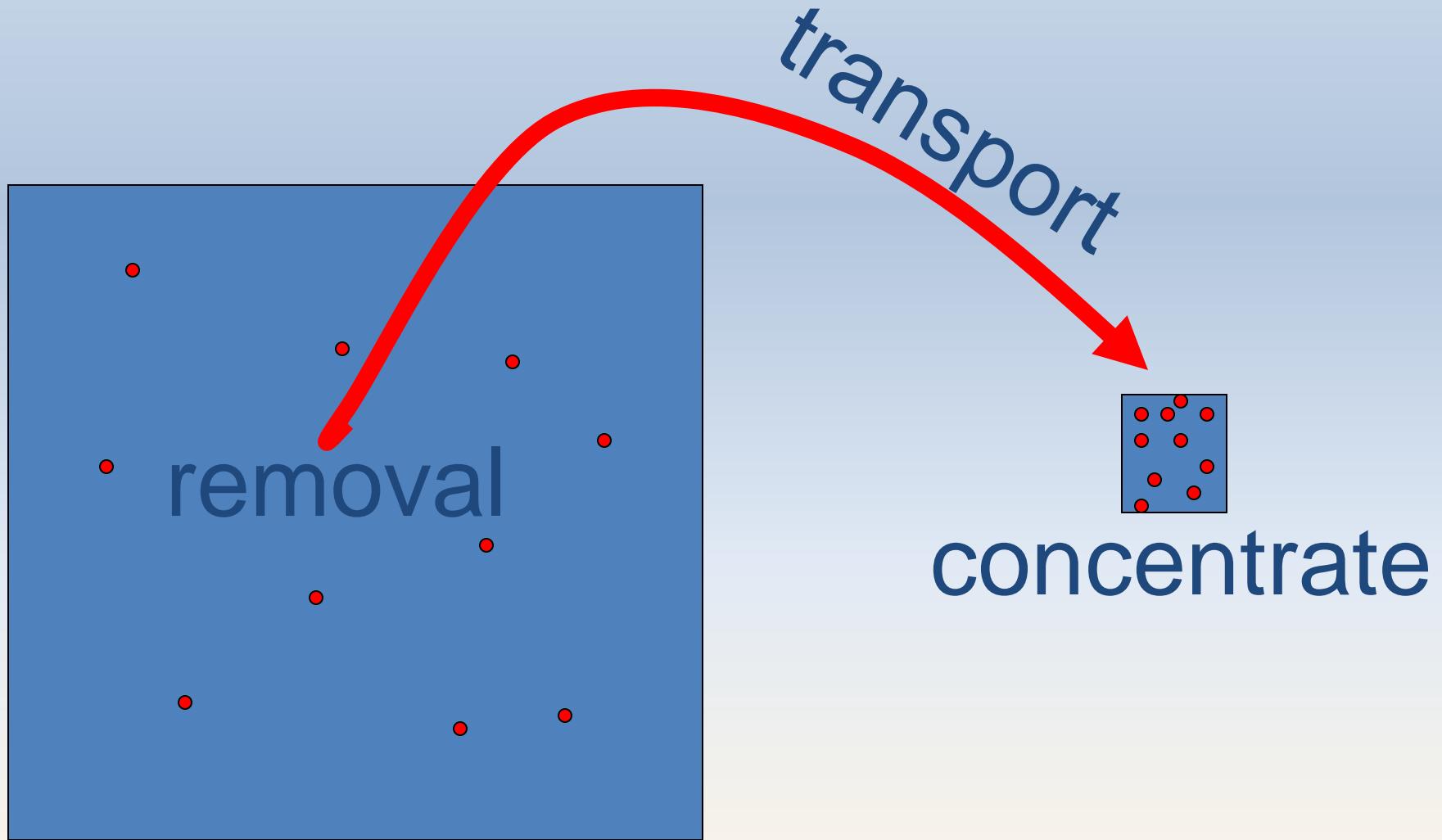


Fluidos Hidrotermais

[*hidro*=água; *termal*=quente]

- São soluções aquosas, quentes, que se movimentam por canais específicos da crosta, ou por uma porção restrita da superfície da crosta, e precipitam uma massa localizada de minerais a partir dos componentes nelas dissolvidos;
- Contêm espécies dissolvidas, principalmente Na^+ , K^+ , Ca^{+2} , Cl , além de $\pm \text{Mg}$, Br , S (reduzido ou não), Sr , e menos Fe , Zn , C (CO_2 , e HCO_3^- ; $\text{N} (\text{NH}_4)$, SiO_2 , etc. → dependendo da fonte e da evolução do próprio fluido;
- Temp de $\sim 32^\circ$ a 360°C (50 to > 500°C), $\sim 2/3$ na faixa de 65° a 121°C ;
- A razão fluido/rocha tem que ser exata: se alta demais → diluição, se baixa demais → volume pequeno de minério.

Formation of ore



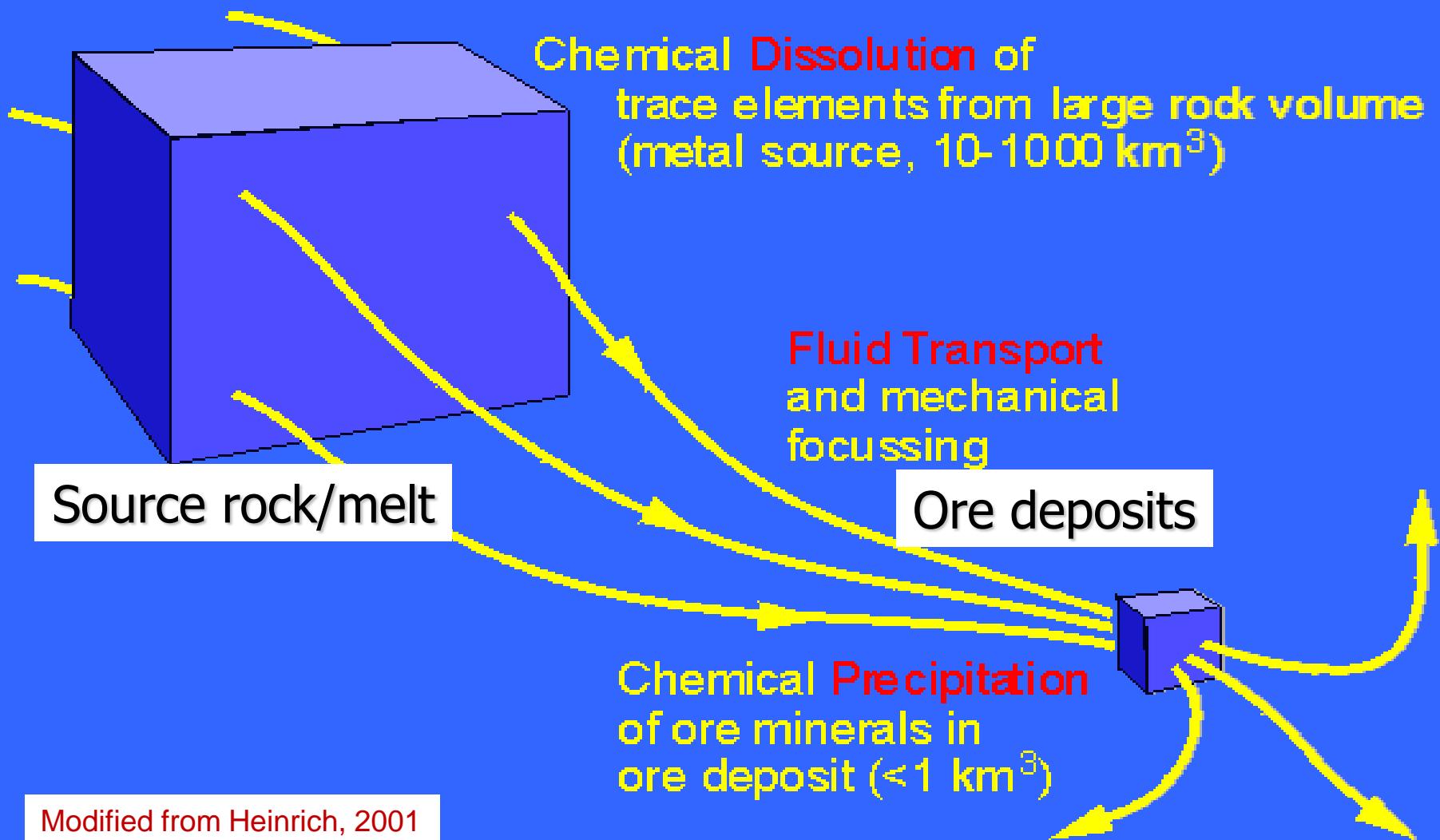
What is an ore deposit?

Table 1.4

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

Concentrations of some economically important metals in average upper crust, and typical **grades** and enrichment factors of ores. Compositions are in ppm, except where indicated. Note that the list gives average grades of ore bodies. In any ore body there will be a range of ore grades, ore will be mined at lower grades than average, and a mine will have internal **cut-off grades** below which rock is considered sub-economic ore or waste (compare Figure 1.2).

From Fluids to Ore Deposits



Se movimentam:

→ Por difusão → em mais de uma direção, com variação mais regular na composição do fluido. Típico de fluido estagnado/ empoçado entre poros e para pequenas variações na T-P. → **minérios de substituição** (*replacement-style ores*)

→ Por infiltração → para grandes distâncias e em uma só direção, com mudanças abruptas. → **precipitação de veios** (e estilo *open-space filling*)

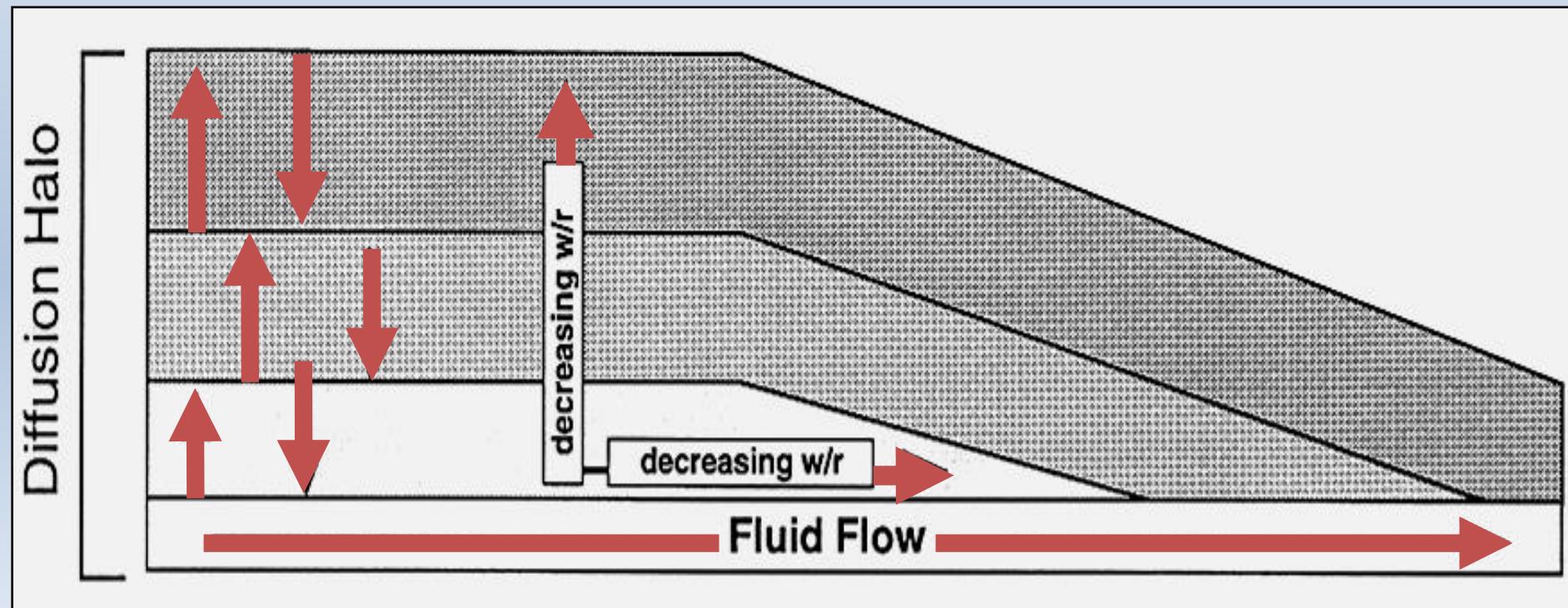
Precipitam por

→ Substituição por reações

→ Precipitação direta do fluido (veios, *vugs* ou cavidades, estilo *open-space filling*)

COMUMENTE AMBOS!

Fluidos Hidrotermais

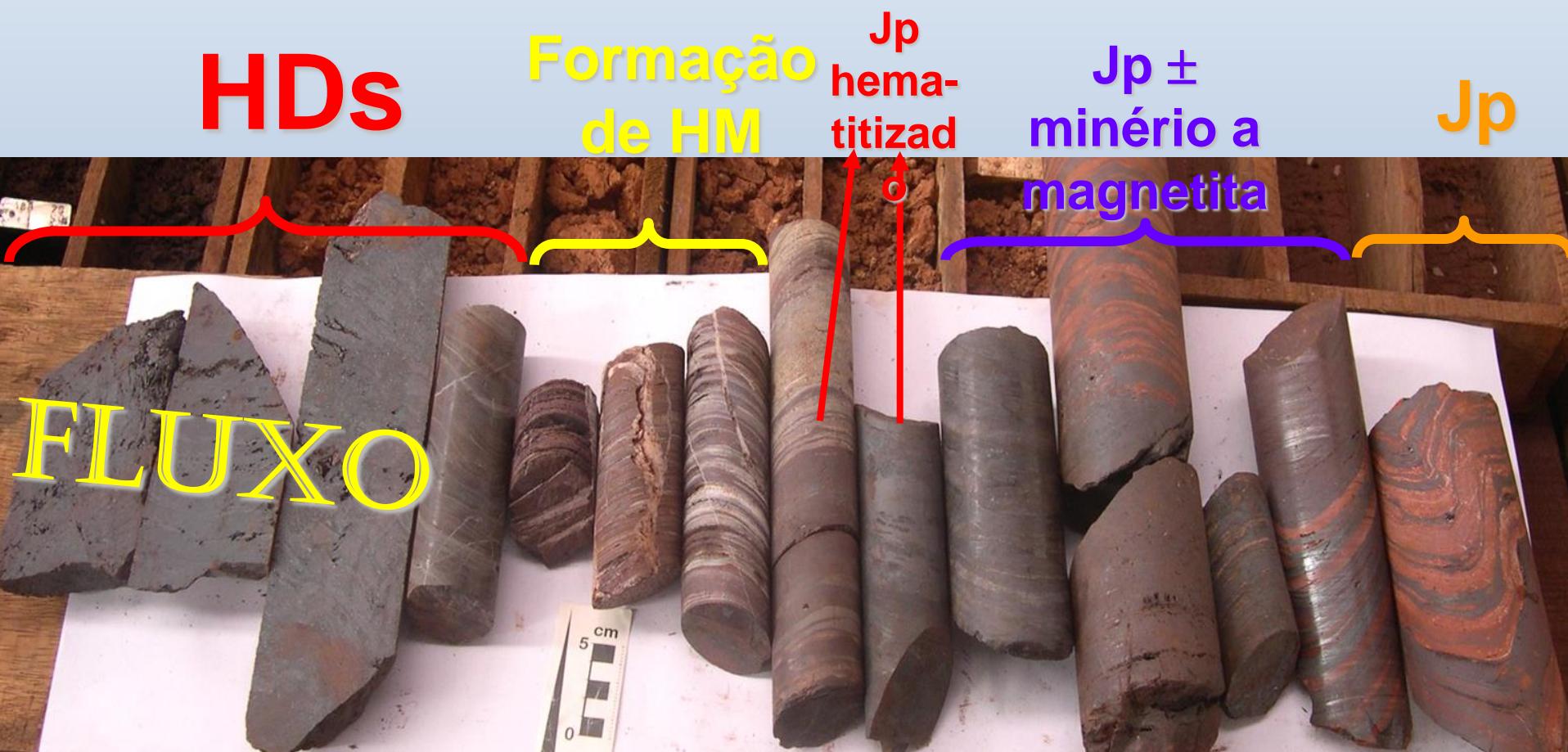


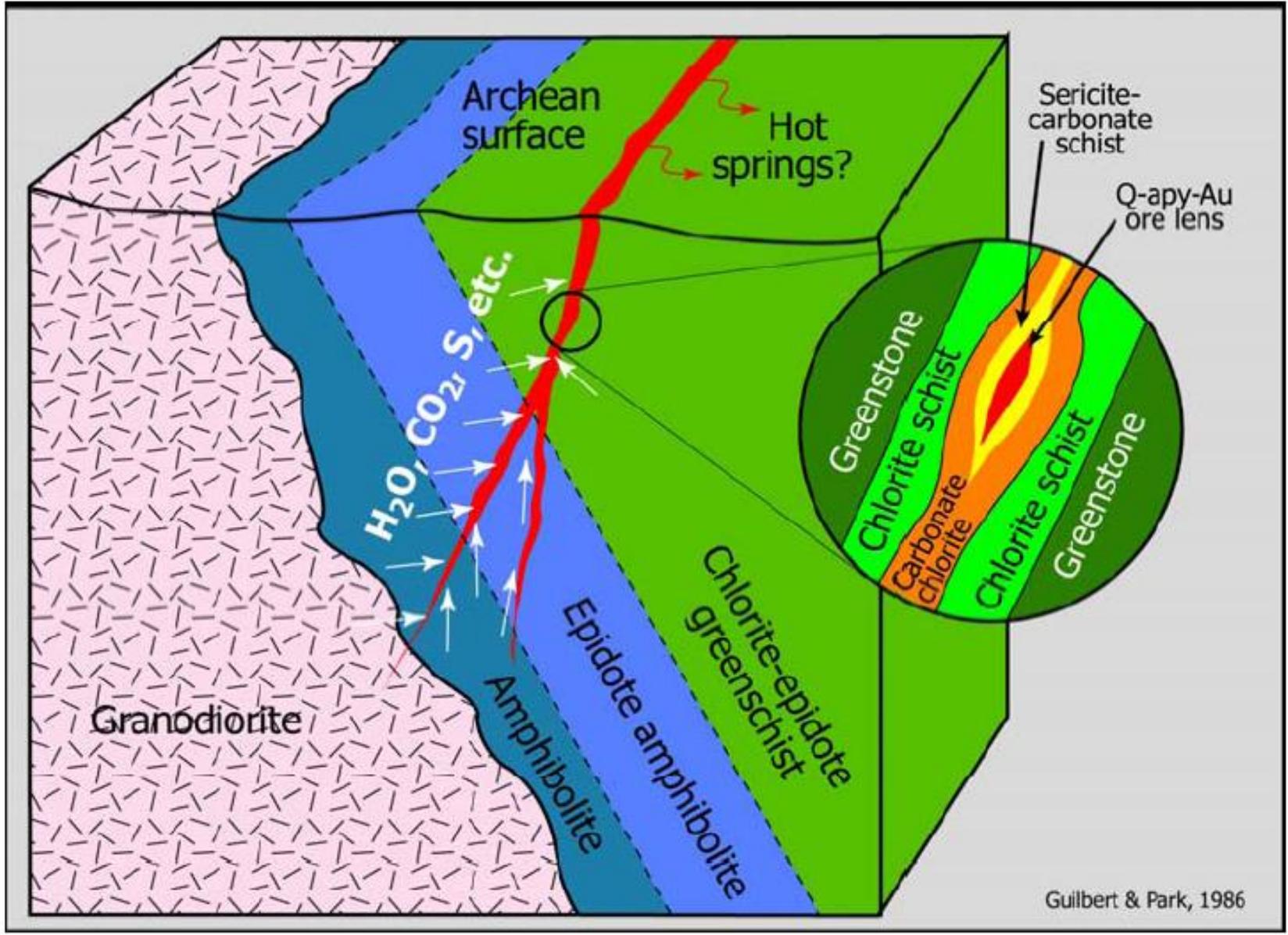
Esquema simplificado mostrando o fluxo de fluido hidrotermal ao longo de uma direção preferencial e sua difusão lateral.



Sunrise Dam, Kalgoorlie

Orogenic gold deposits





- Temperatures ~ 250-400 °C
- Pressure >1-4 kb
- Fluid comp High $CO_2 + H_2O, N_2, CH_4$
- Salinity <5-8 NaCl eq

Orogenic gold deposits

MAFIC-HOSTED VQZ, JAZIDA CUIABÁ



Orogenic gold
deposists

Hidrotermalismo ou Alteração Hidrotermal

- ❖ Conjunto de reações entre um fluido quente e as rochas que o mesmo atravessa, impulsionadas por desequilíbrio qualquer entre esses dois sistemas.
- ❖ É a substituição química dos minerais originais em uma rocha por novos minerais, sendo que o fluido cede os reagentes químicos para a rocha e dela remove os produtos (aquosos) solúveis liberados das reações.
- ❖ O desequilíbrio entre fluido e rocha ou resulta da diferença composicional e química entre os dois, sendo função das fugacidades de voláteis e atividades de componentes químicos em geral, ou de variações físicas, como mudanças de densidade, por exemplo.
- ❖ Ocorre como resposta à variações de temperatura e pressão, e fundamentalmente à de pressão de fluido (P_f).

Hidrotermalismo ou Alteração Hidrotermal

- Composição da rocha hospedeira original
- Composição do fluido original
(f_{O_2} ; pH; P_{vapour} de voláteis; ânions & cátions - salinidade; etc)
- Reatividade fluido-rocha
- T & P (depth) das reações
- Razão fluido/rocha
- Permeabilidade & reologia da rocha
- Estruturas, armadilhas litológicas & químicas/mineralógicas

Ex. fluido interagindo com rocha mafica:

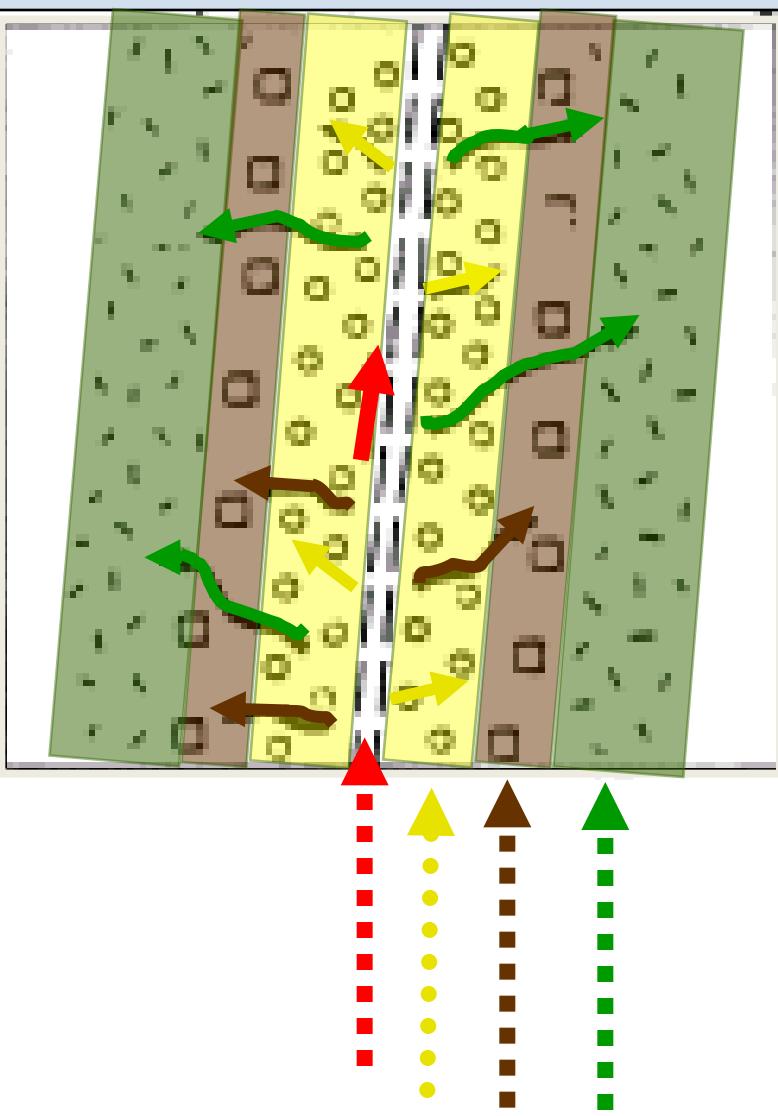
H_2O

$a = 0,8$

CO_2

$a = 0,15$

Sais, S, Au & $a = 0,05$
outros metais

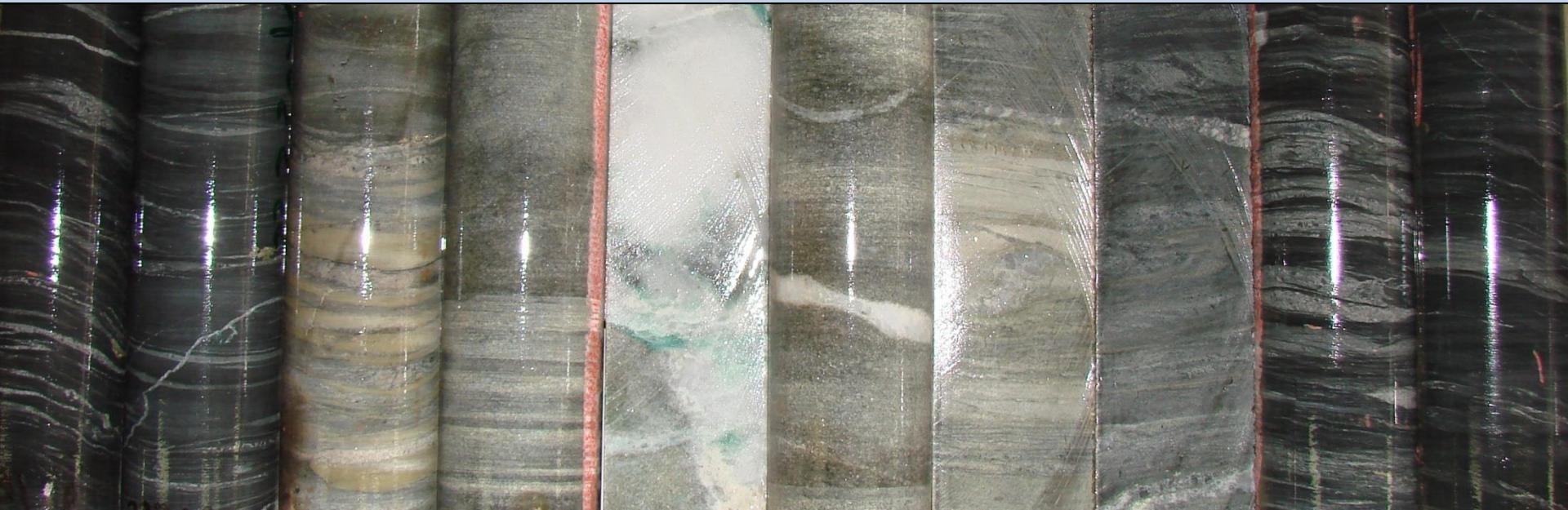


Orogenic gold deposits

Pode envolver mudanças:

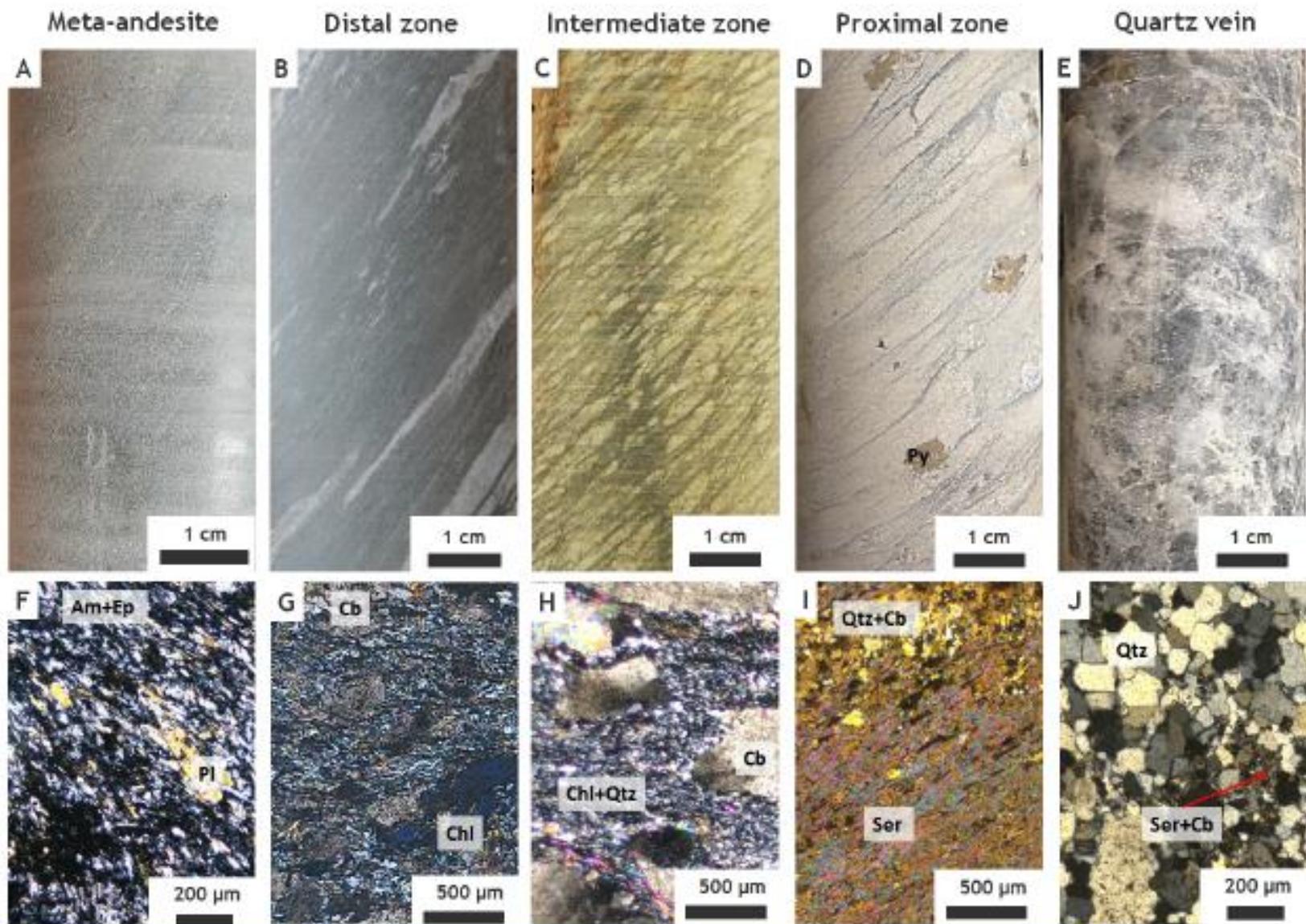
- na cor
- na textura
- na mineralogia
- na química da rocha

Notar a mudança de coloração da rocha entre a zona distal (escura), intermediária (cinza clara) e proximal (amarelada - *bleaching*) de alteração hidrotermal em sequência de rocha metassedimentar.



Córrego do Sítio orogenic gold deposit (Lima, 2012)

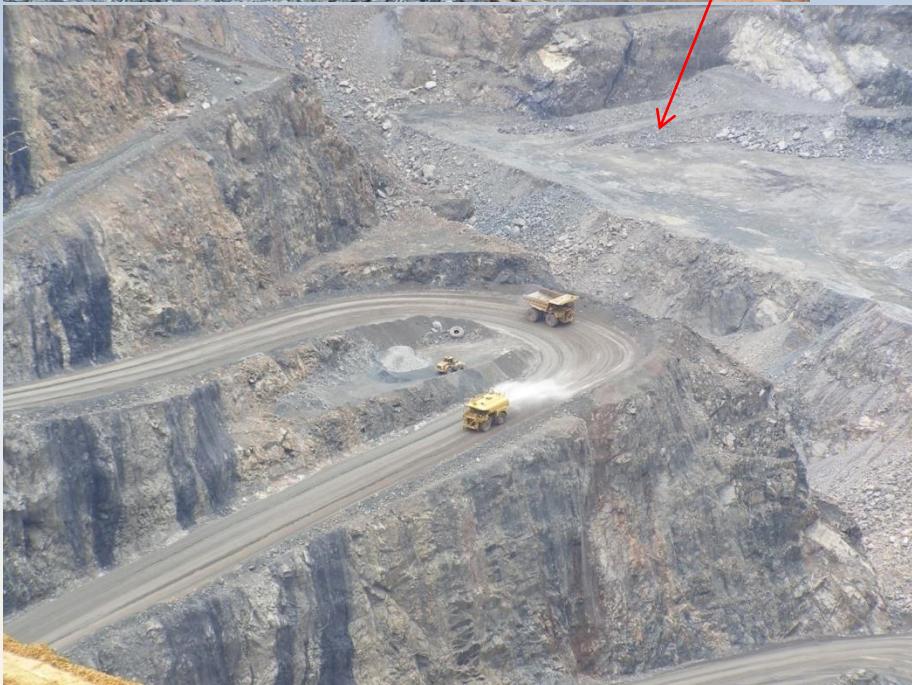
HYDROTHERMAL ALTERATION



VQZ, Cuiaba mine
Vitorino (2017)



Figure 22 Dark-green intermediate and bleached proximal alteration within the Golden Mile Dolerite in the Golden Mile deposit. Red hematite “pigment” visible in the bleached zone. Hematite probably formed after the gold mineralisation; the oxidising retrograde fluids have used only the preexisting fractures and, hence, mostly affected the bleached alteration zones. Note also the brown skeletal leucoxene in unbleached and bleached zones, and the relatively abundant pyrite in the bleached zone.



Superpit, Kalgoorlie

Production: 850,000 ounces of gold every year;

There are over 2,000 ore lodes that occur within the Golden Mile dolerite are found in an area over 5 kilometres in strike and 2 kilometres in width and occur to a depth of over 1 kilometre.

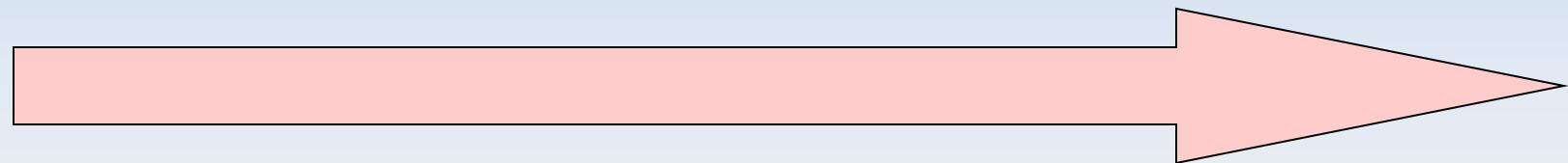
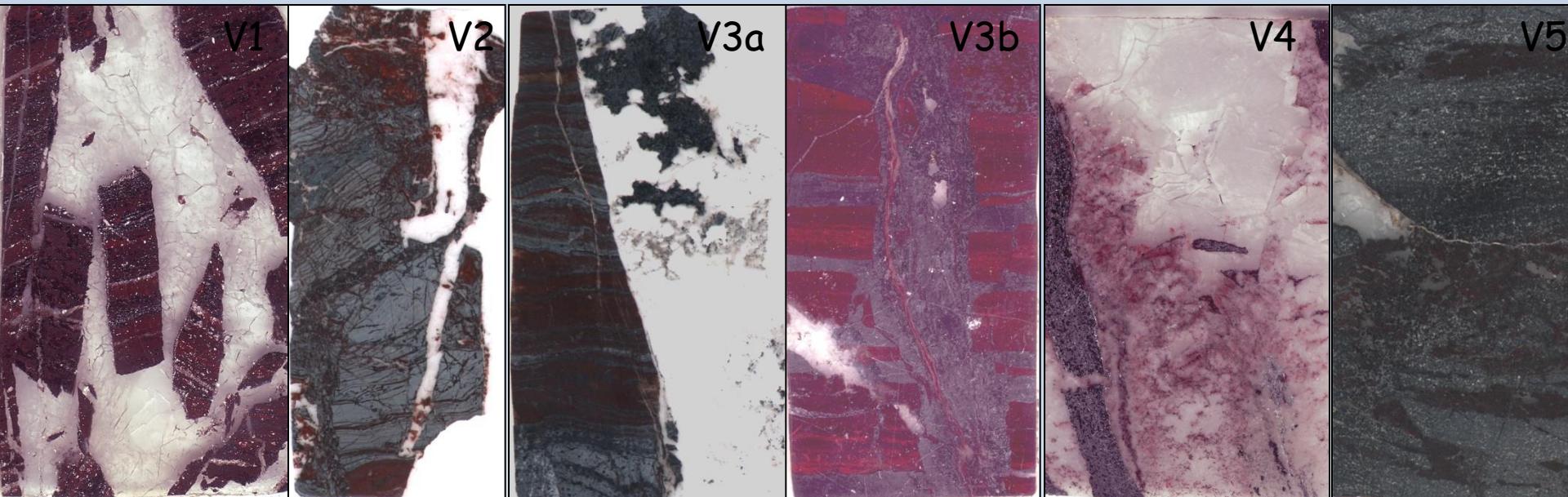
Petrography of Jp to Ore Transitions

~30-35wt% Fe

~35-50wt% Fe

50-65wt% Fe

>65wt% Fe



Distal

Hypogene Alteration

Proximal



Serra Norte, Carajás



**Jaspilitos hidrotermalizados,
mineralizados a Fe**

N5EF523P213 (49)

Rocha encaixante ALTERAÇÃO AVANÇADA – CLORITA & HEMATITA

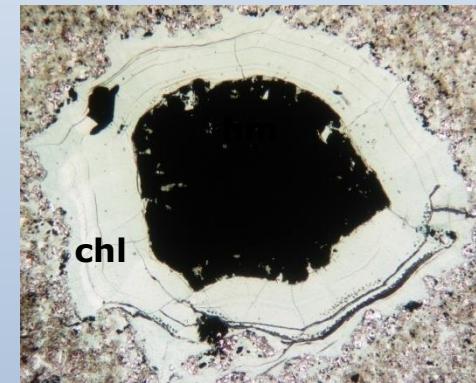
AMYGDALES:
HEMATITE
+
CHLORITE



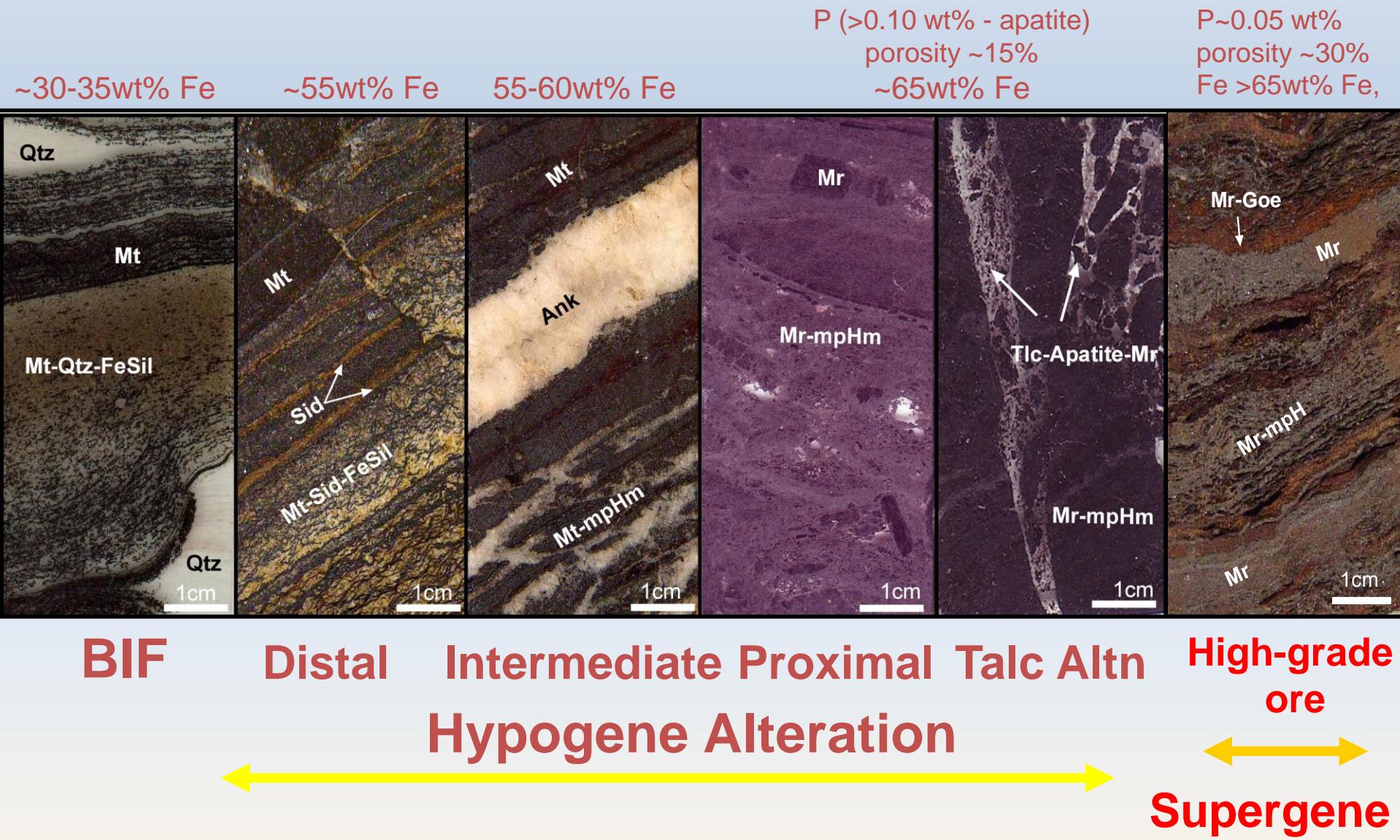
VEIN:
HEMATITE
+
QUARTZ



Zucchetti (2007)

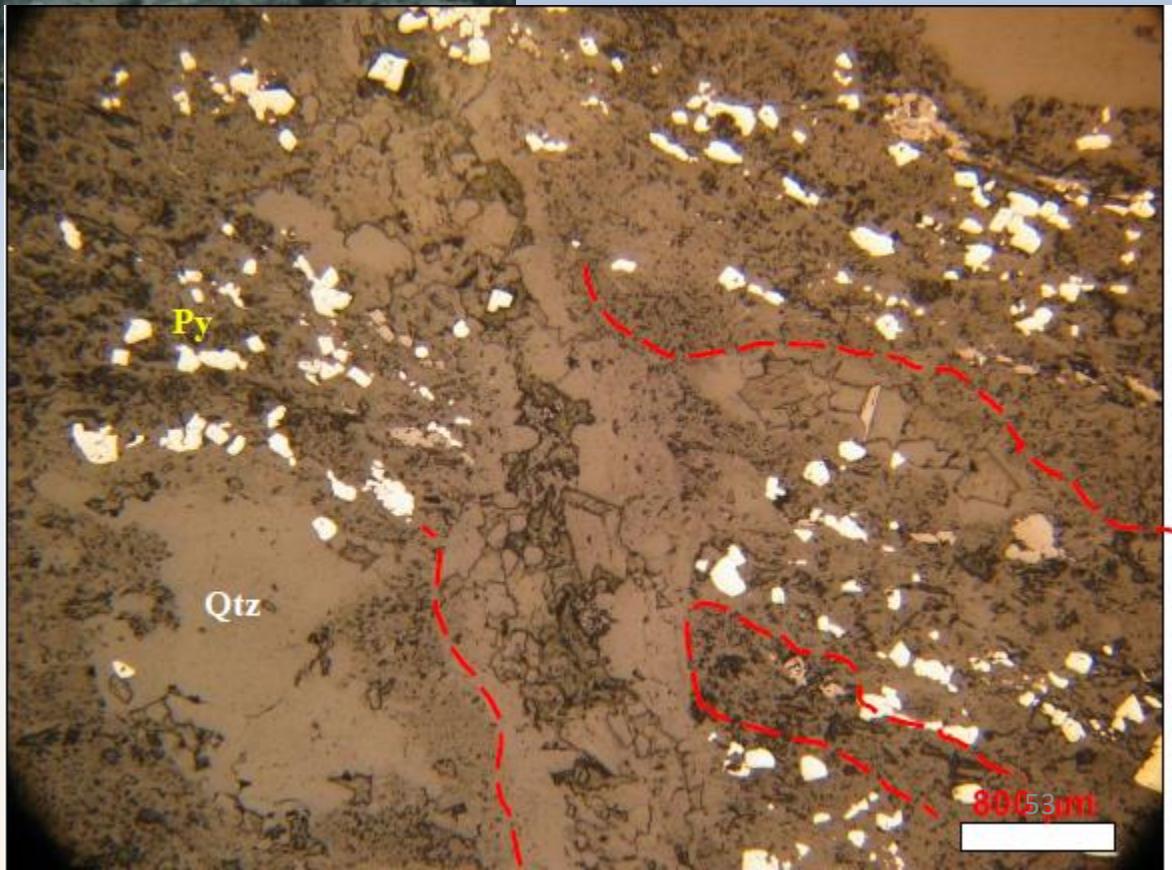
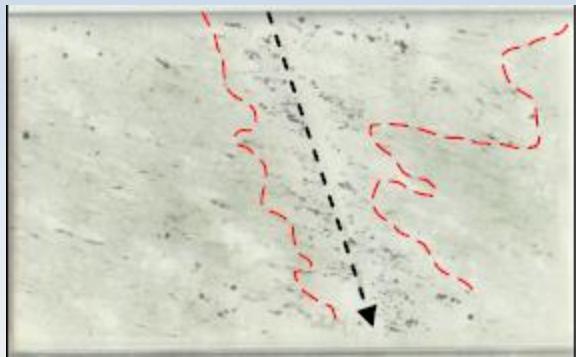


BIF to Ore Transitions – Tom Price



Metadiorite altered to albite-carbonate

Pyrite crystals associated with albite-carbonate halos – veins seem to “feed” rock with pyrite-rich portions.
Reflected light (25X).



Orogenic gold deposits

ARMADILHAS

Cuiabá



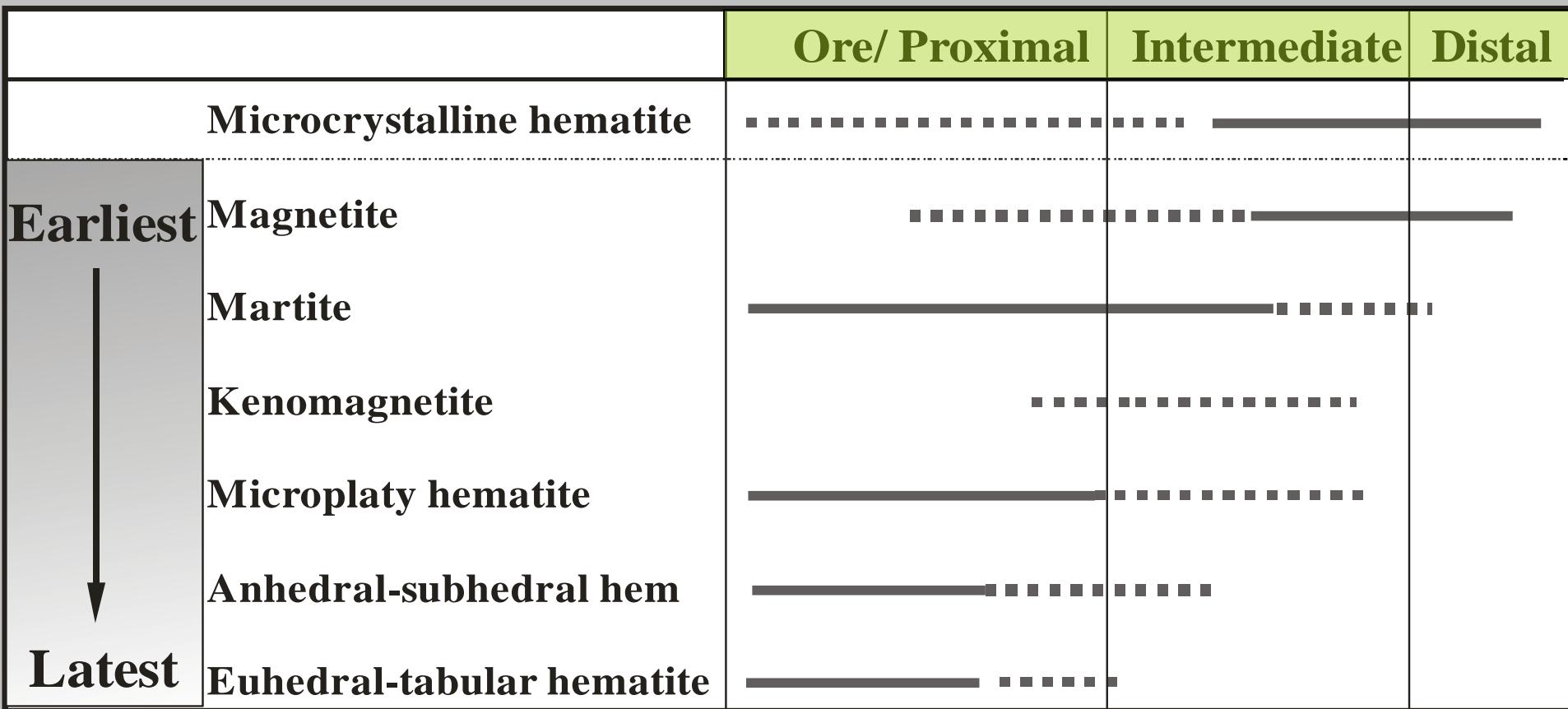
Carbonaceous phyllite
(hanging wall)

Paragenesis and paragenetic sequence

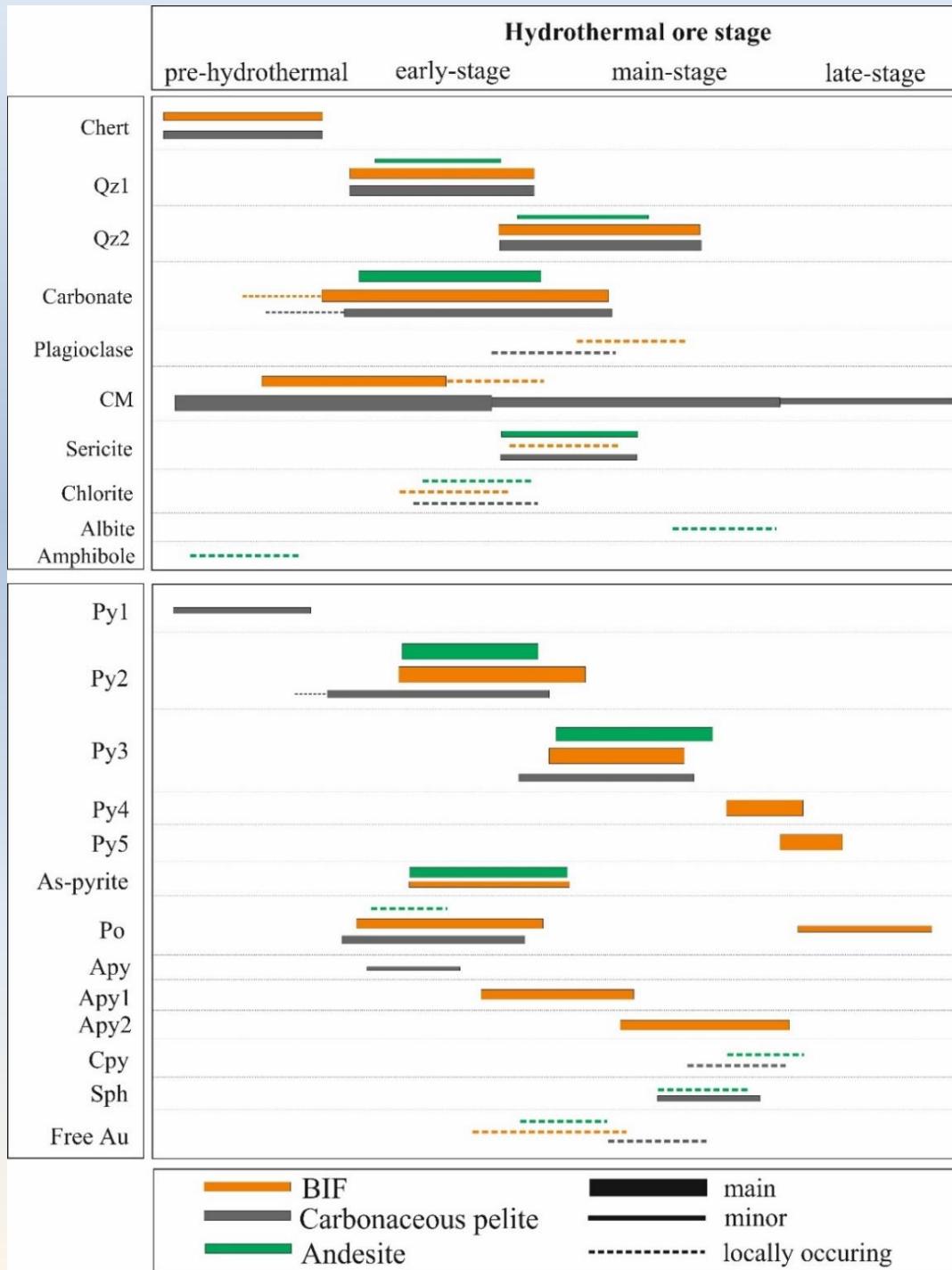
Paragenesis (Greek, “born beside”)

- paragenesis is used to describe any assemblage of ore minerals with or without gangue, formed at the same time and normally in equilibrium
- the chronological order of mineral deposition - the sequence of deposition of minerals, or assemblages - in a rock or ore deposit is known as the paragenetic sequence of a deposit
- Mineral paragenesis is closely related to the concept of mineral zoning

Paragenetic Sequence of Iron Oxides from JPs to high-grade ore



Orogenic gold, Cuiabá mine, QF



IOCG, CARAJÁS

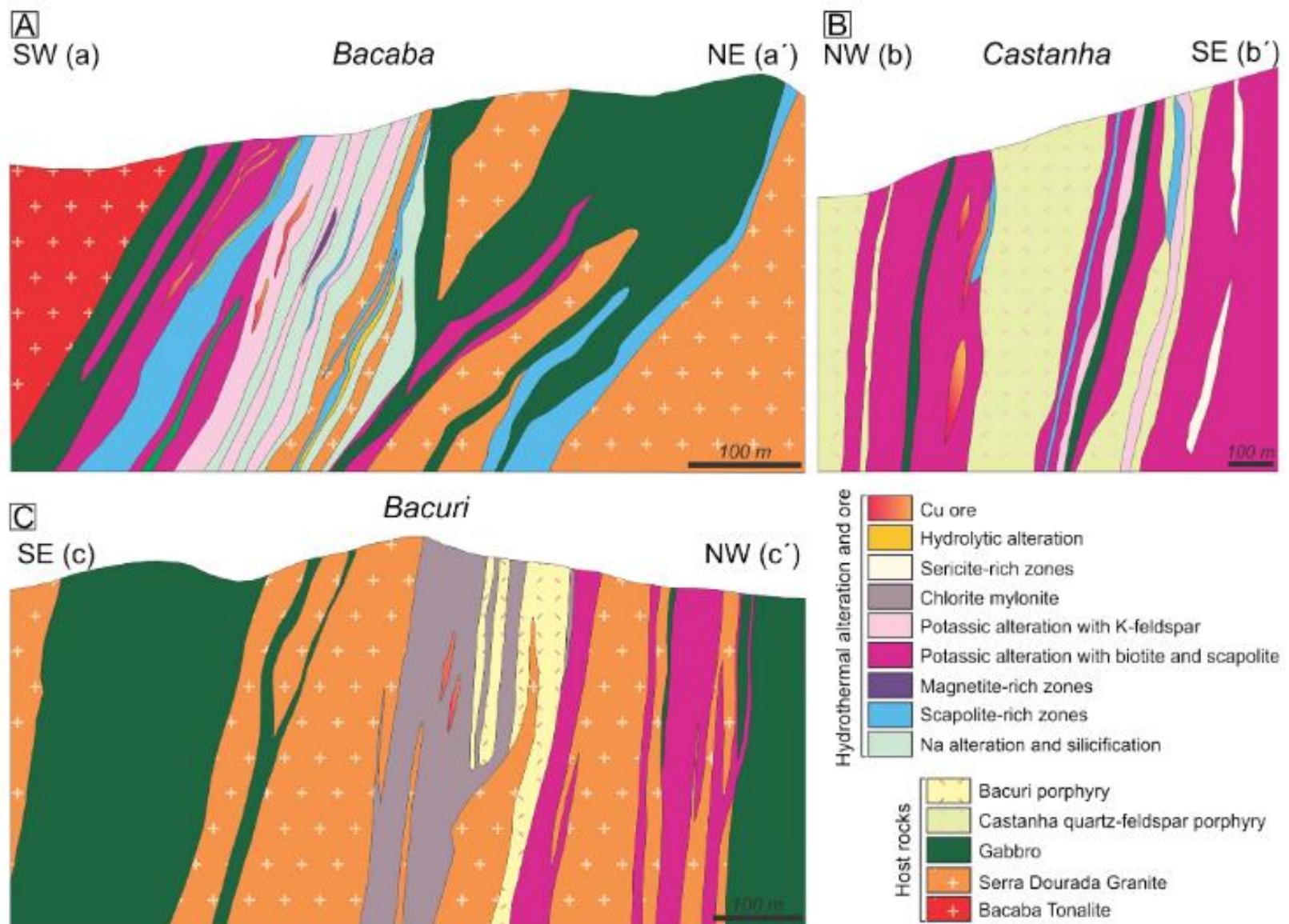


Fig. 5 Simplified cross sections of the **a** Bacaba, **b** Castanha, and **c** Bacuri deposits (modified from Vale, unpublished)

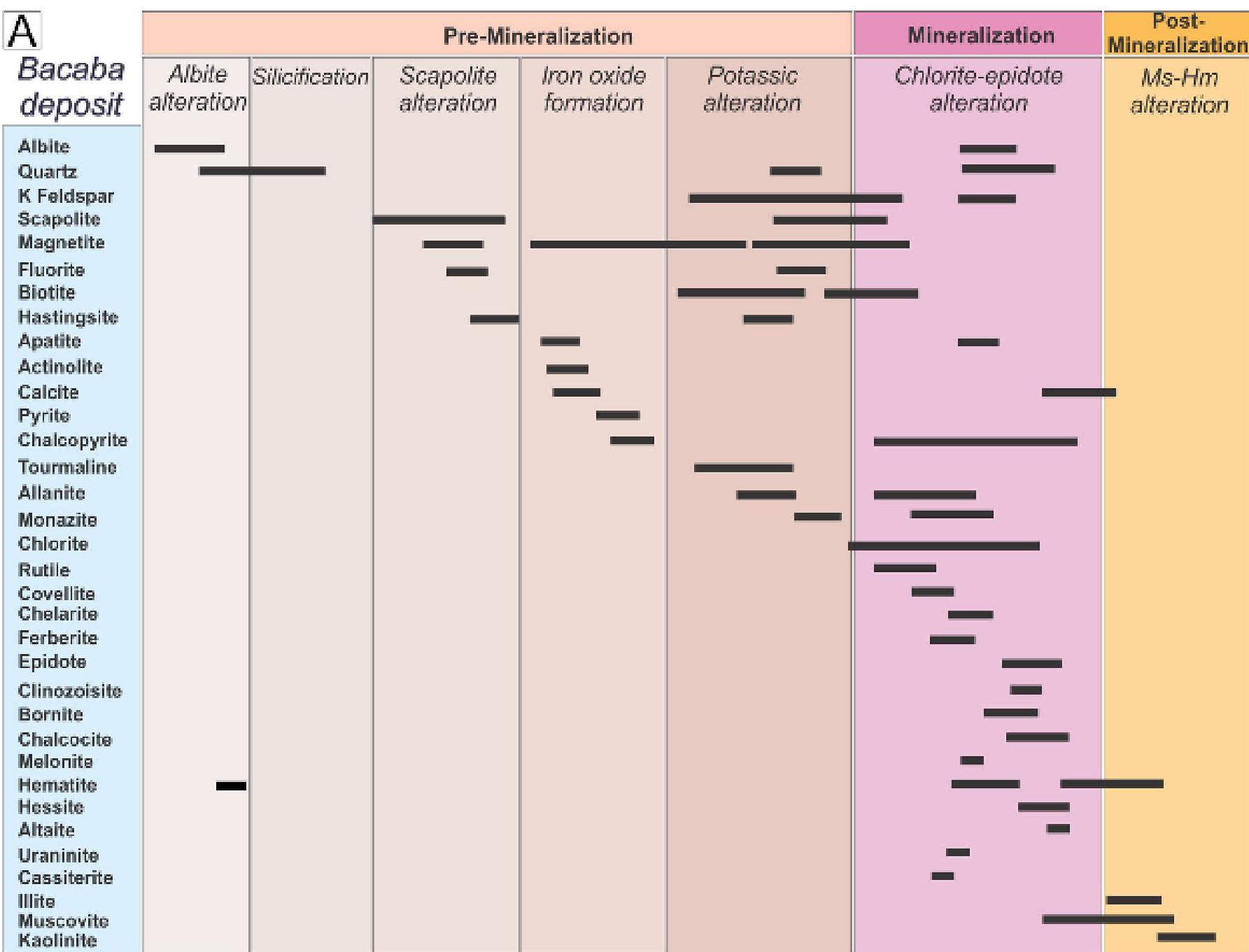
A**Bacaba deposit**

Albite	Albite alteration					
Quartz		Silicification				
K Feldspar			Scapolite alteration			
Scapolite				Iron oxide formation		
Magnetite					Potassic alteration	
Fluorite						Chlorite-epidote alteration
Biotite						
Hastingsite						
Apatite						
Actinolite						
Calcite						
Pyrite						
Chalcopyrite						
Tourmaline						
Allanite						
Monazite						
Chlorite						
Rutile						
Covellite						
Chelarite						
Ferberite						
Epidote						
Clinozoisite						
Bornite						
Chalcocite						
Melonite						
Hematite						
Hessite						
Altaite						
Uraninite						
Cassiterite						
Illite						
Muscovite						
Kaolinite						

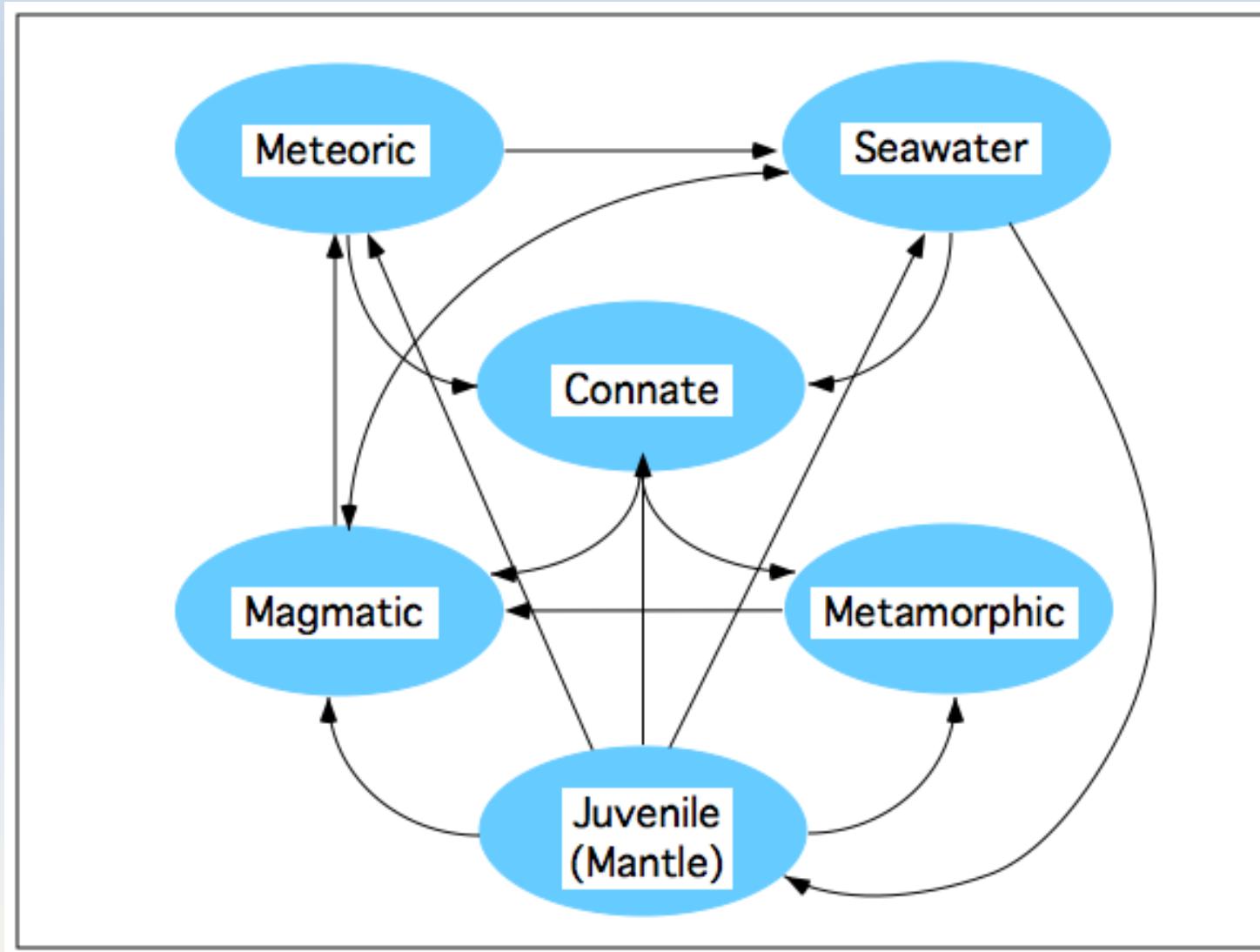
Pre-Mineralization

Mineralization

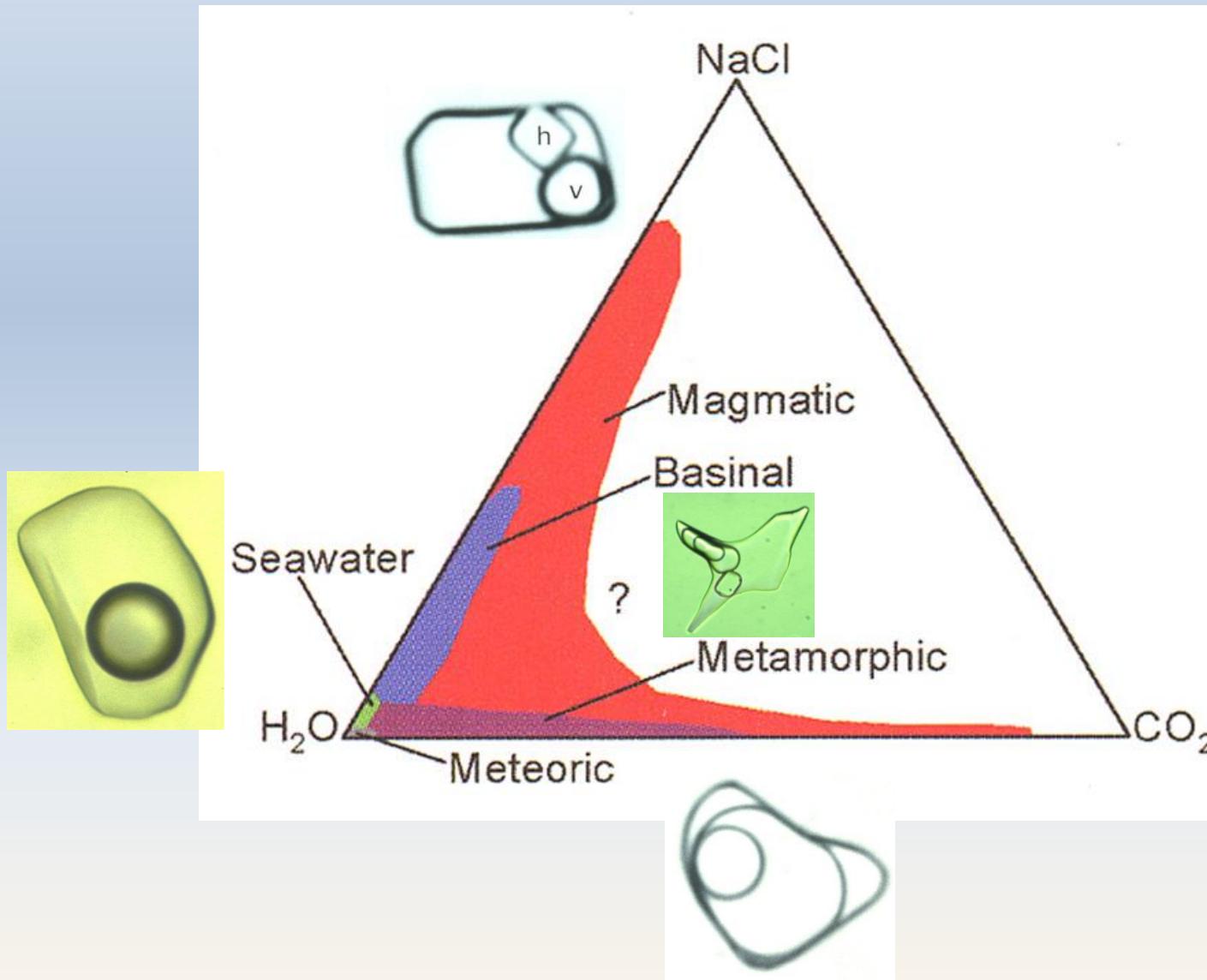
Post-Mineralization



Fluids types in the Earth



Fluids types in the Earth



Fluid inclusions have been widely used to understand behaviour of ore forming fluids and the magmatic immiscibility such as silicate melt, H₂O-CO₂, hydro-saline melt, dense CH₄ and sulphide-metal melt.

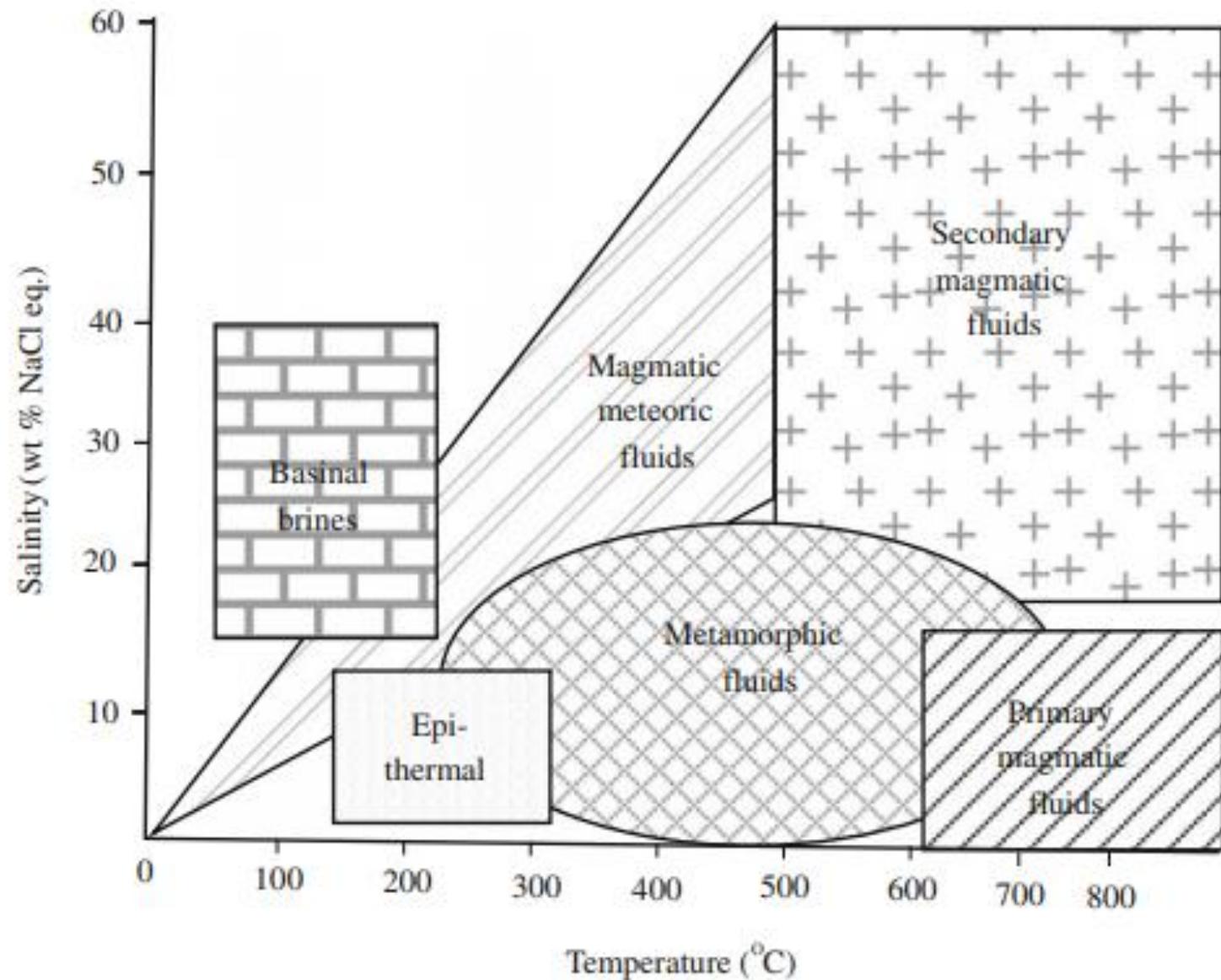


Fig. 5 Diagram showing salinity-temperature range for various hydrothermal fluids (summarised after Beane 1983; Roedder 1984; Bodnar et al. 1985; Lattanzi 1991; Wilkinson 2001 and our own observations.). The boundaries of the various fluids are general and not fixed

Fluid reservoirs

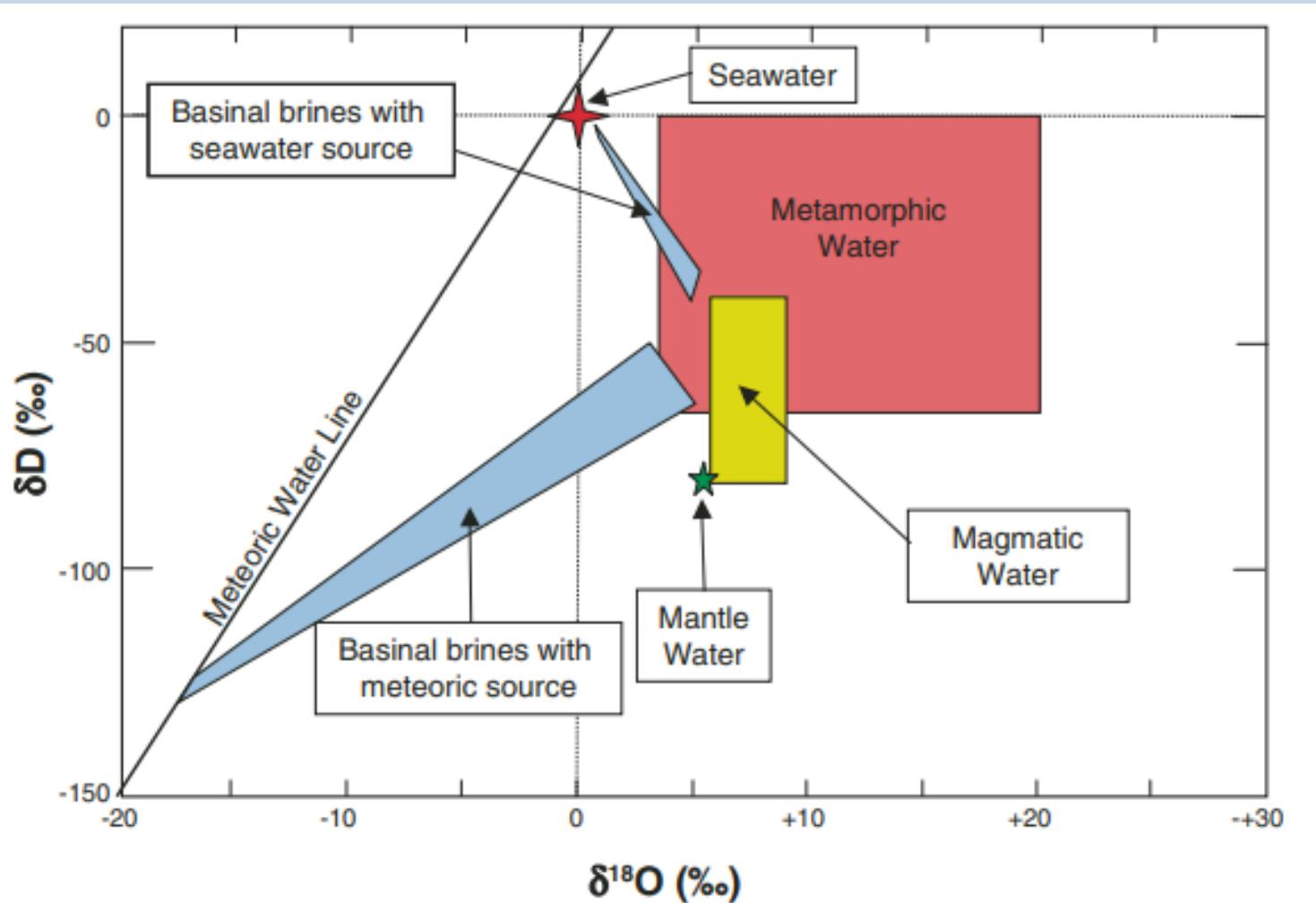
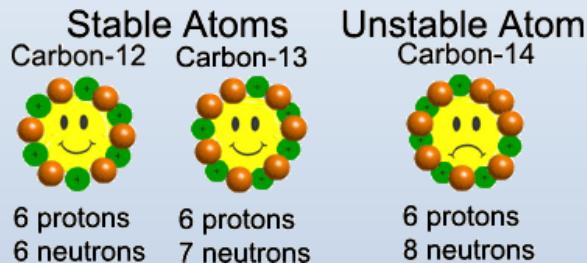


Figure 2. Characterization of the different water reservoirs in and on the Earth based on the oxygen and hydrogen isotopic compositions (modified from Sheppard, 1986).

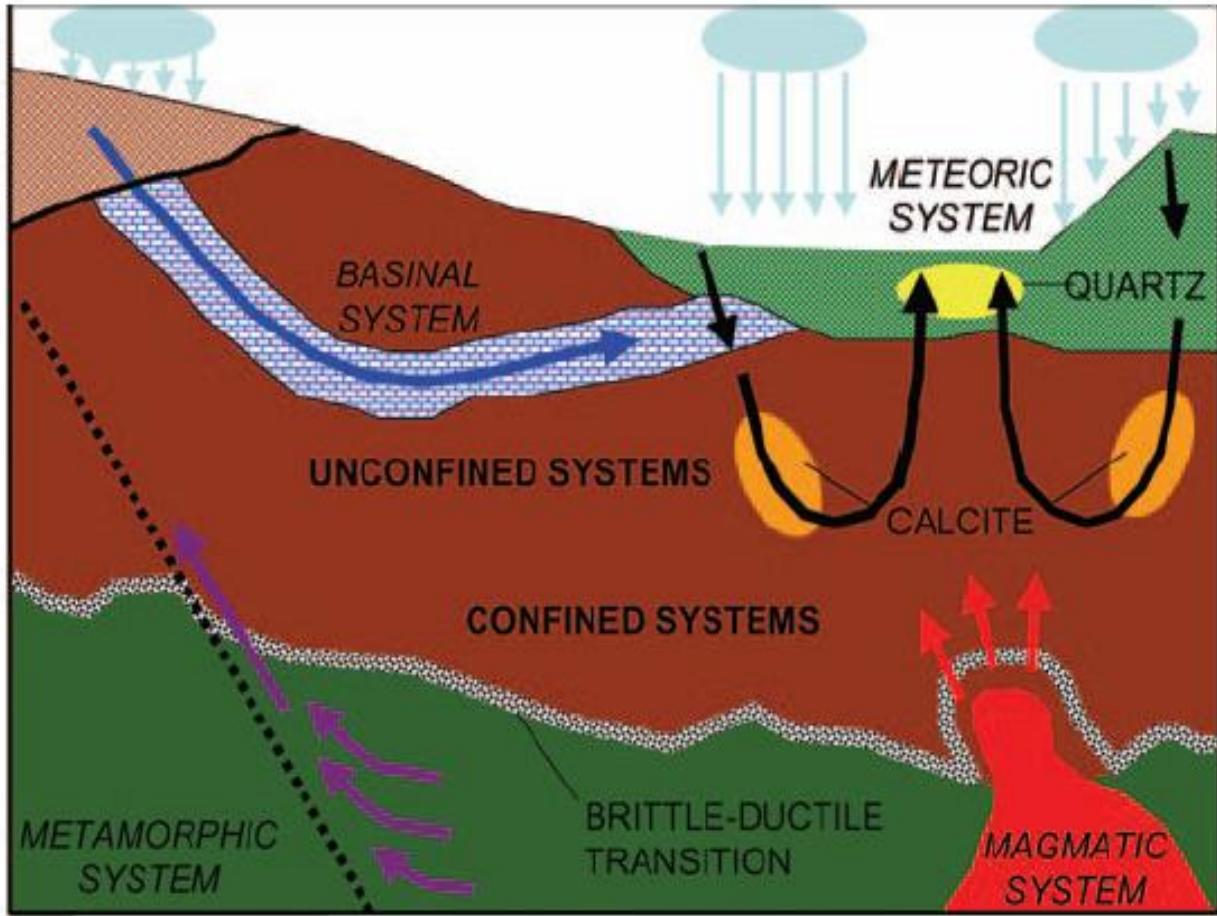
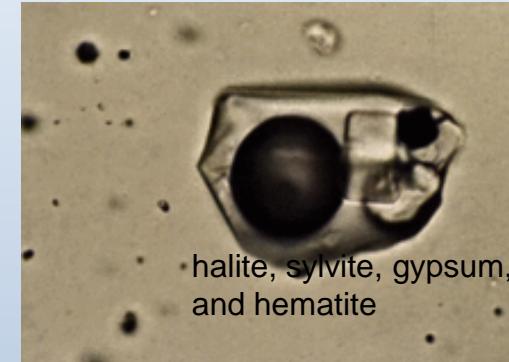


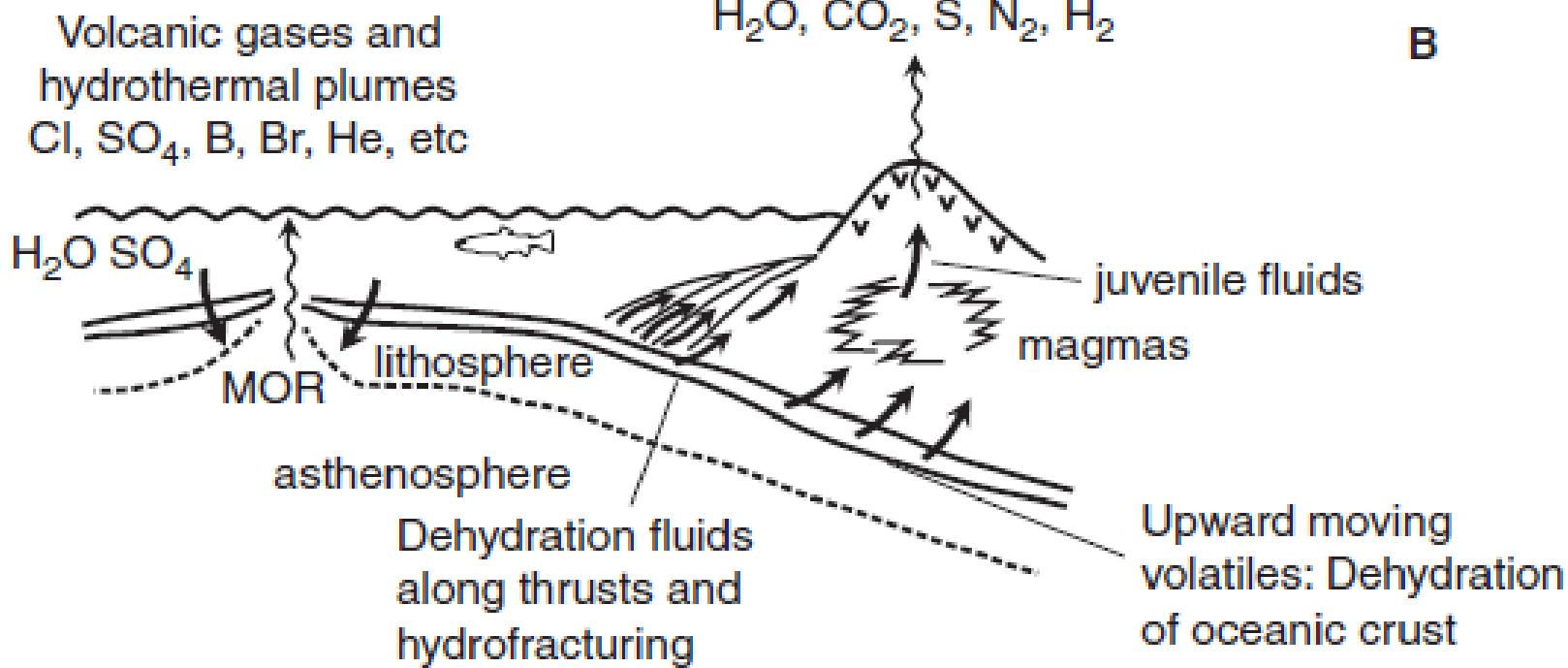
FIGURE 3 Typical hydrothermal systems. Confined magmatic and metamorphic systems are shown below a brittle-ductile transition and a partly confined aquifer is shown in the basinal system. In the unconfined meteoric system, quartz is deposited from cooling water flowing out the top of the system and calcite is deposited from heating recharge water flowing into the sides of the system. Similar flow and depositional patterns would be observed in unconfined seawater hydrothermal systems.

Magmatic fluids

- Volatile magma substances that migrate, carrying differentiation components
- In addition to saline aqueous fluid, the volatiles like H_2S , CO_2 , SO_2 , SO_4 , HCl, B and F, are found as significant ore-depositing agents in magmatic-hydrothermal fluids.
- mobile elements LIL Large ion lithophile such as Li, Be, B, Rb, Cs; also significant quantities of alkalis, alkali earths and volatiles such as: Na, K, Ca, Cl, and CO_2
- metals such as Fe, Cu, Zn
- Water is the principle mobile constituent in all magmas, increases in amount with increasing differentiation and plays an important part in the transportation of many ore components.
- Estimates of water in magmas range from 1 to 15%.



Magmatic fluids



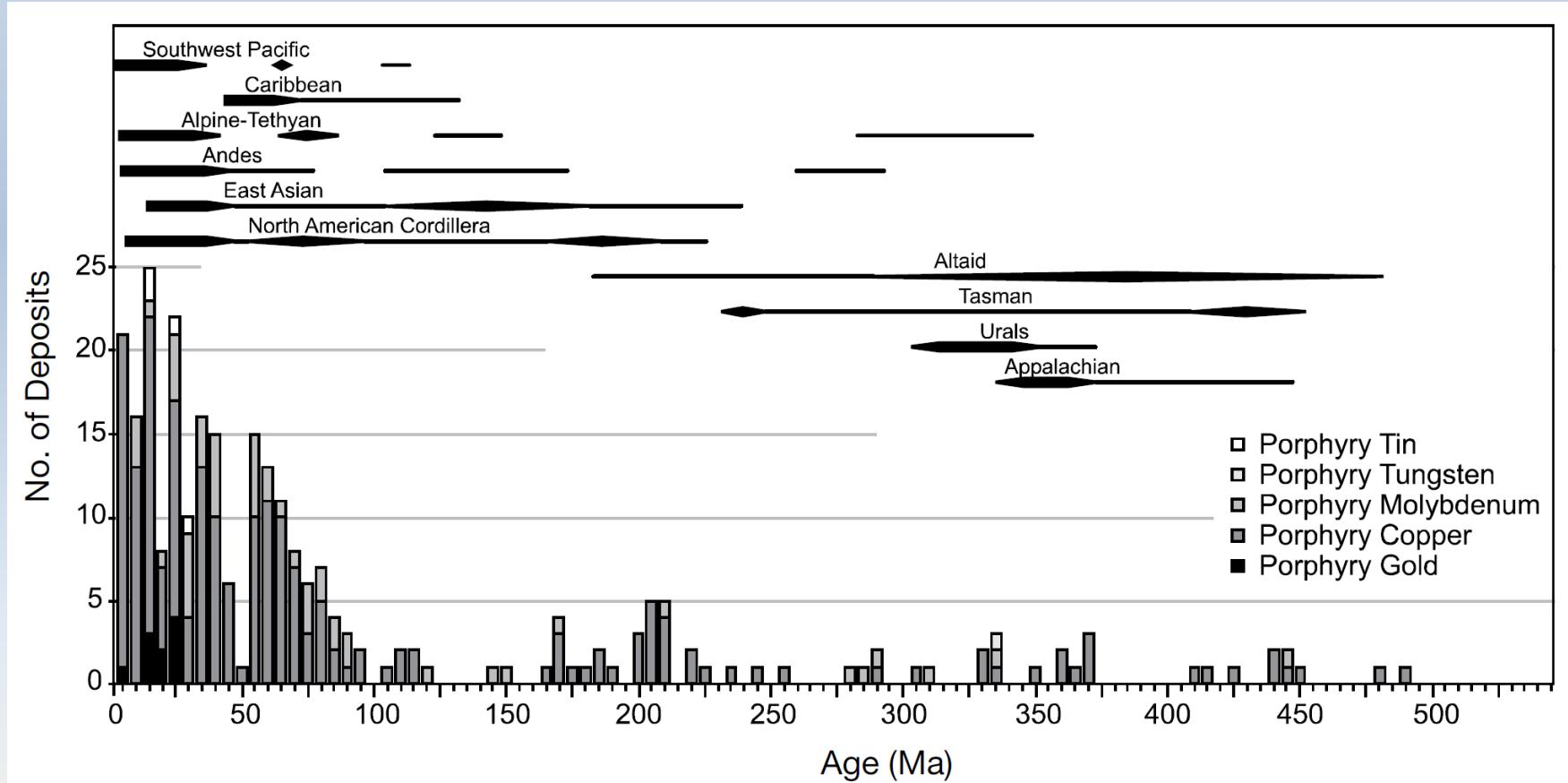
- **Composição determinada:**
 - pelo tipo de magma e sua história de cristalização;
 - pelas relações de T e P durante e depois da separação do magma;
 - pela natureza de outros fluidos que se misturam com esses fluidos à medida que os mesmos se movem e pelas reações decorrentes do contato com rochas encaixantes ou hospedeiras.
- **Mineralização é geralmente associada aos estágios finais de fluidos magmáticos hidrotermais, e pulsos repetitivos podem levar à formação de grandes corpos de minério.**
- **Fluido hidrotermal pode dissolver elementos economicamente úteis ou simplesmente agir como transportador destes.**

DEPÓSITOS PORFIRÍTICOS



Bingham, EUA
Cu, Mo (Au)

Ages of Porphyry style Cu-Mo-Au-Sn-W



Seedorf et al. (2005)

Age distribution of porphyry deposits.

Note that there are Proterozoic and Archean examples of porphyry systems

http://gsc.nrcan.gc.ca/mindep/synth_dep/porph/index_e.php#fig1

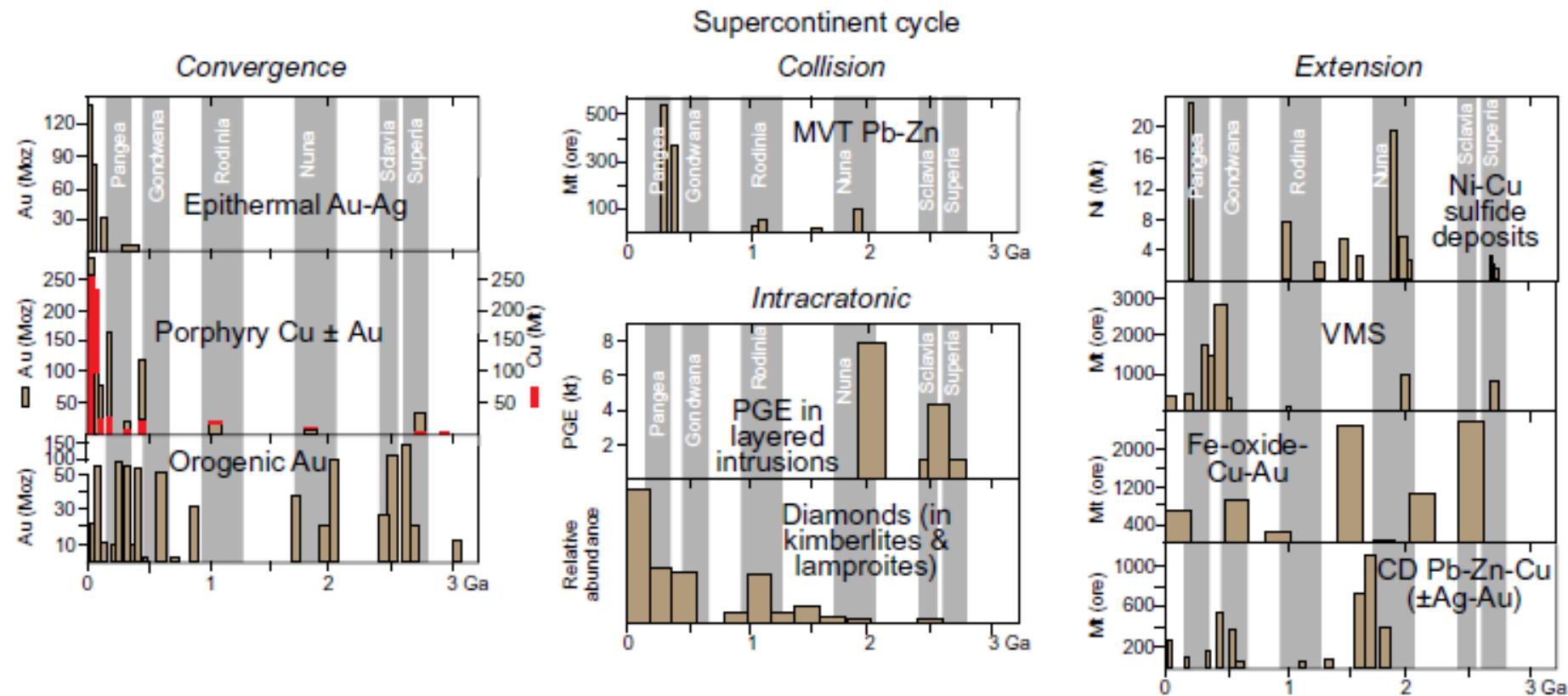


Fig. 3. Diagram showing the temporal distribution of deposit types ascribed to broad geodynamic settings in terms of the supercontinent cycle. Temporal distributions are based on Groves *et al.* (2005b) and references therein. Intracratonic deposit types lie in the interior of continents and generally form after a previous pulse of collisional assembly.

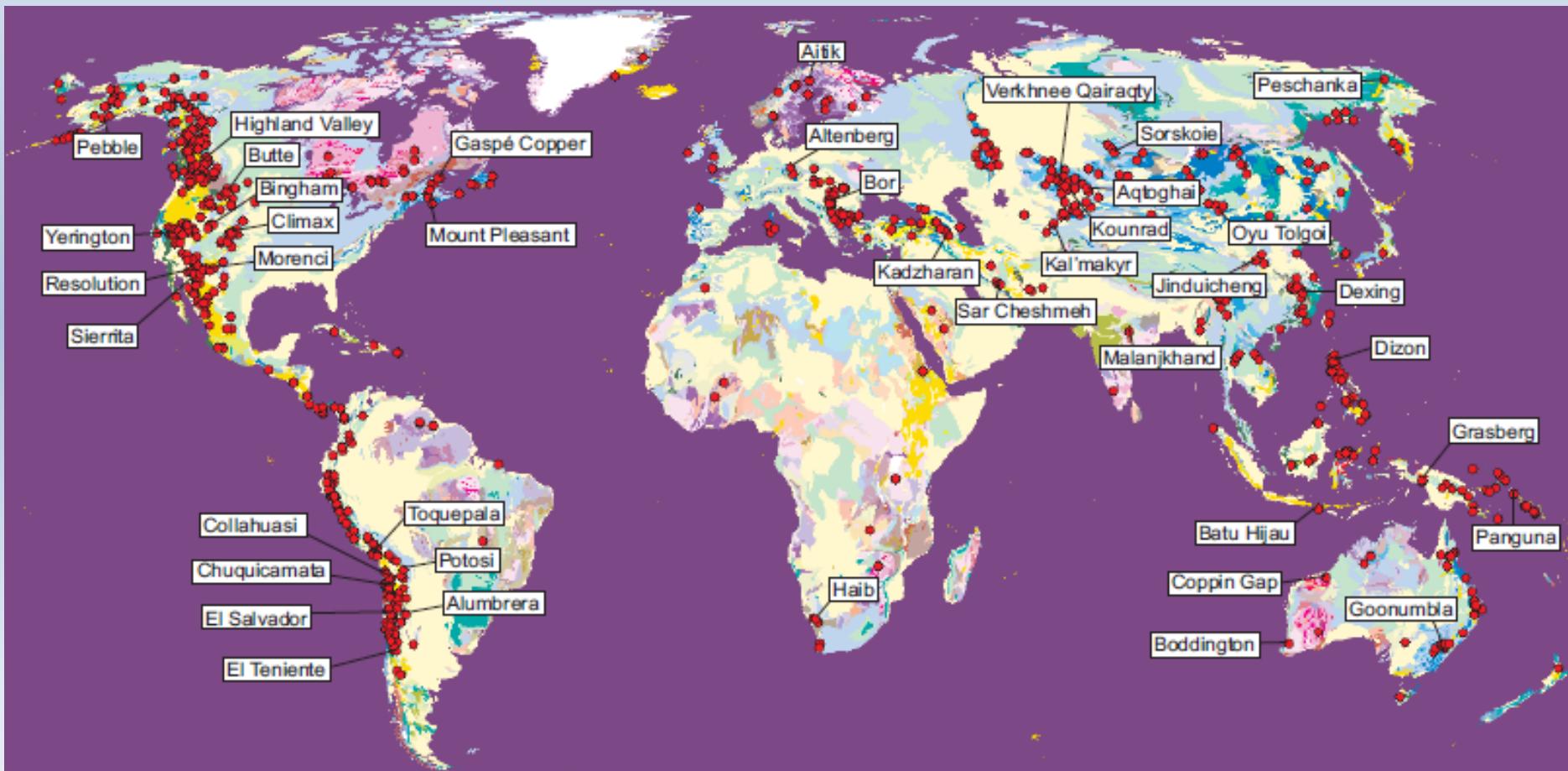
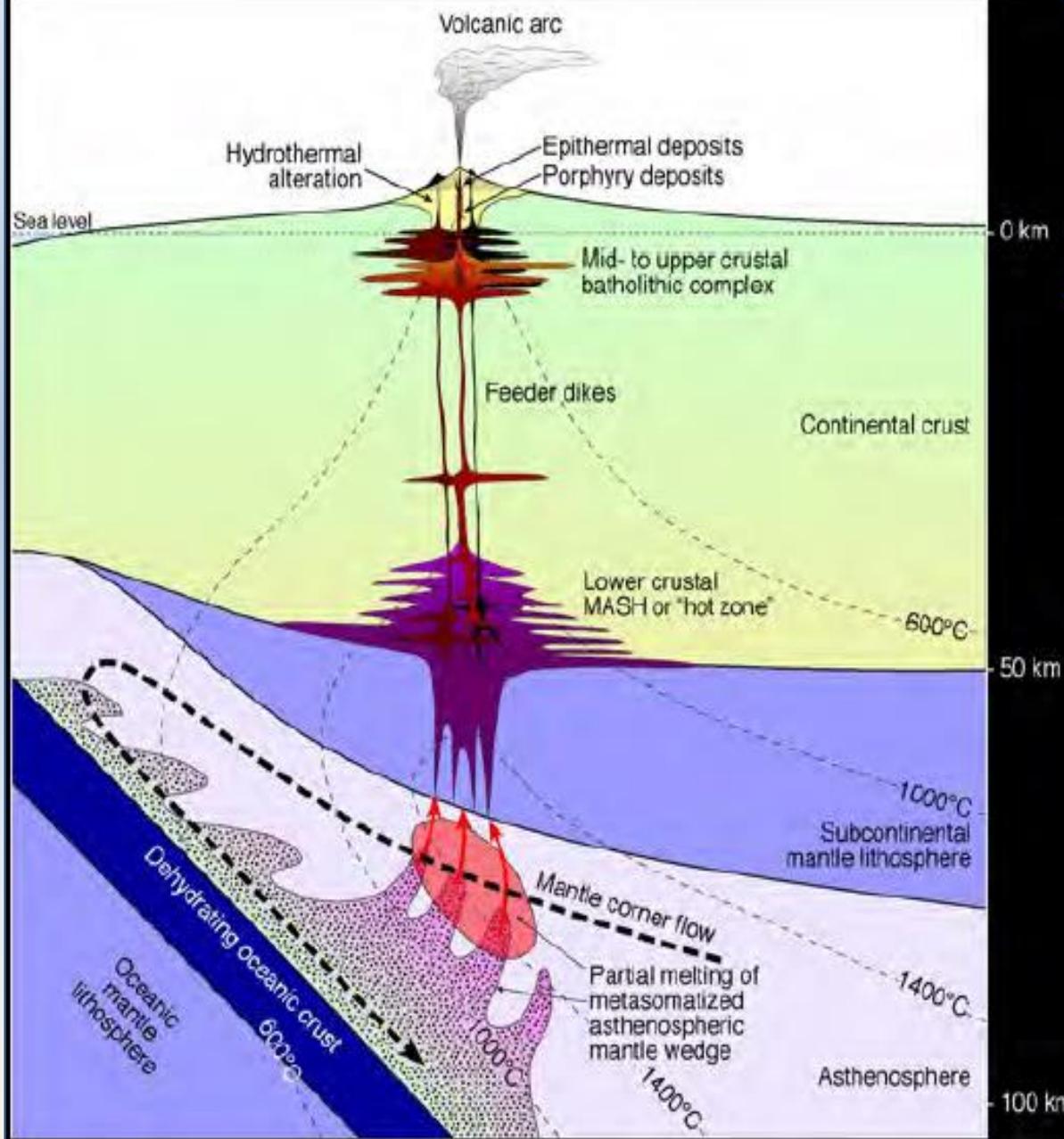


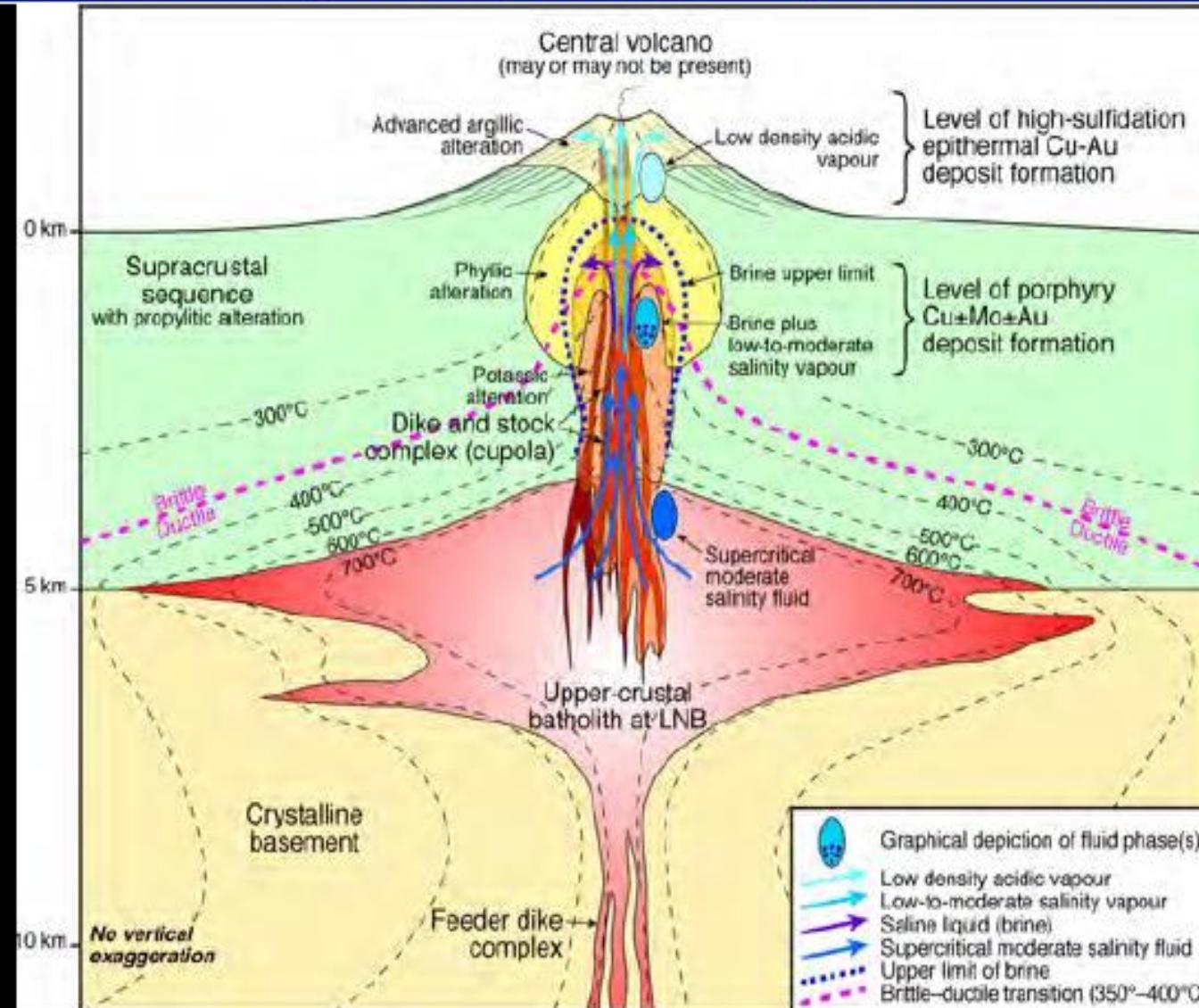
FIGURE 1. Global distribution of porphyry deposits (from Kirkham and Dunne, 2000). World geology is from Chorlton (2004). See Appendix 2 (World) for deposit details.

Subduction-related ore forming systems



Richards (2011: Ore Geol. Reviews, v. 40, p. 1–26)

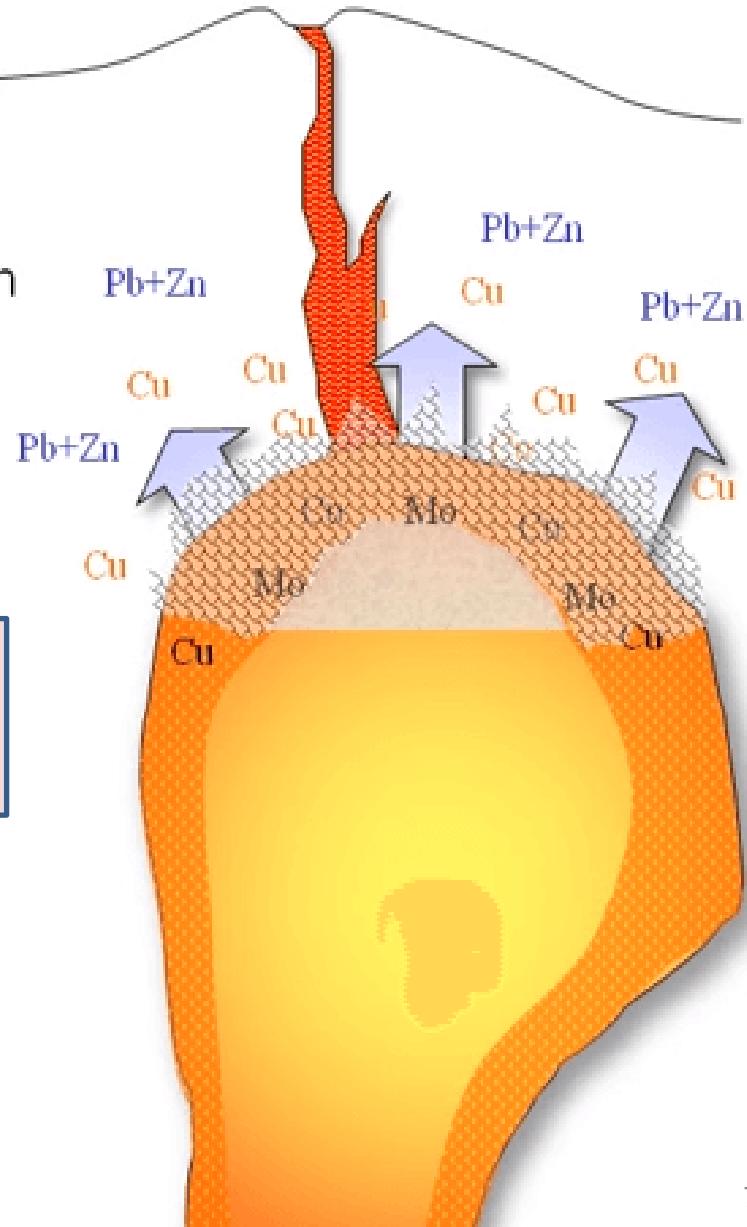
Porphyry deposits are small parts of large hydrothermal systems, themselves linked to vertically and laterally extensive magmatic systems – they are hard to miss!



Richards,
J.P., 2011:
Ore
Geology
Reviews, v.
40, p. 1–26.

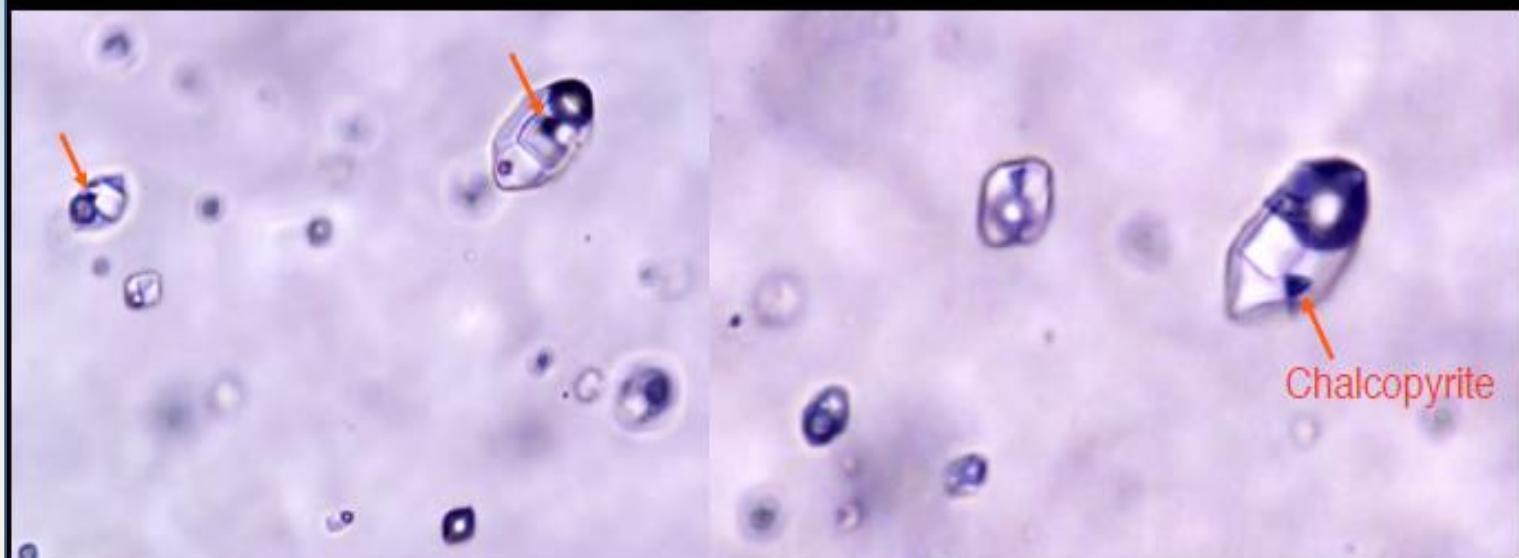
Porphyries - Formation

- Crystallizing magma releases water and gas at high pressure
 - Pressure further increased by increase in volume (feldspar crystals take up more space than when molten)
 - High pressure steam (water, CO₂, H₂S, salt, rupture the 'rind' of the intrusion
- Metals (copper, moly, gold) transported initially in steam as chlorine complexes – CuCl⁰
- Steam (600°C) gradually condenses to salty metal-rich brines which make their way outwards and upwards.
 - Metals deposited as fluids cool (350°- 250°C). Mo and Cu first, then Zn and Pb.



Magmatic-hydrothermal fluids:

- Initial fluid temperatures range up to the solidus of granitic magma ($\leq 725^{\circ}\text{C}$) and salinities up to 60 equiv. wt. % NaCl, plus high concentrations of S (initially dissolved as SO_2).
- High concentrations of Cu (250–5000 ppm Cu in fluid inclusions), as well as other metals (Fe, Mo, Pb, Zn, Ag, Au).
- Base metals (Fe, Cu, Pb, Zn) are dissolved as chloride complexes, such as CuCl° , CuCl_2^- , CuCl_3^{2-} , etc.



Ore deposition

Key processes that control deposition of sulfides from magmatic-hydrothermal fluids between 400°–300°C:

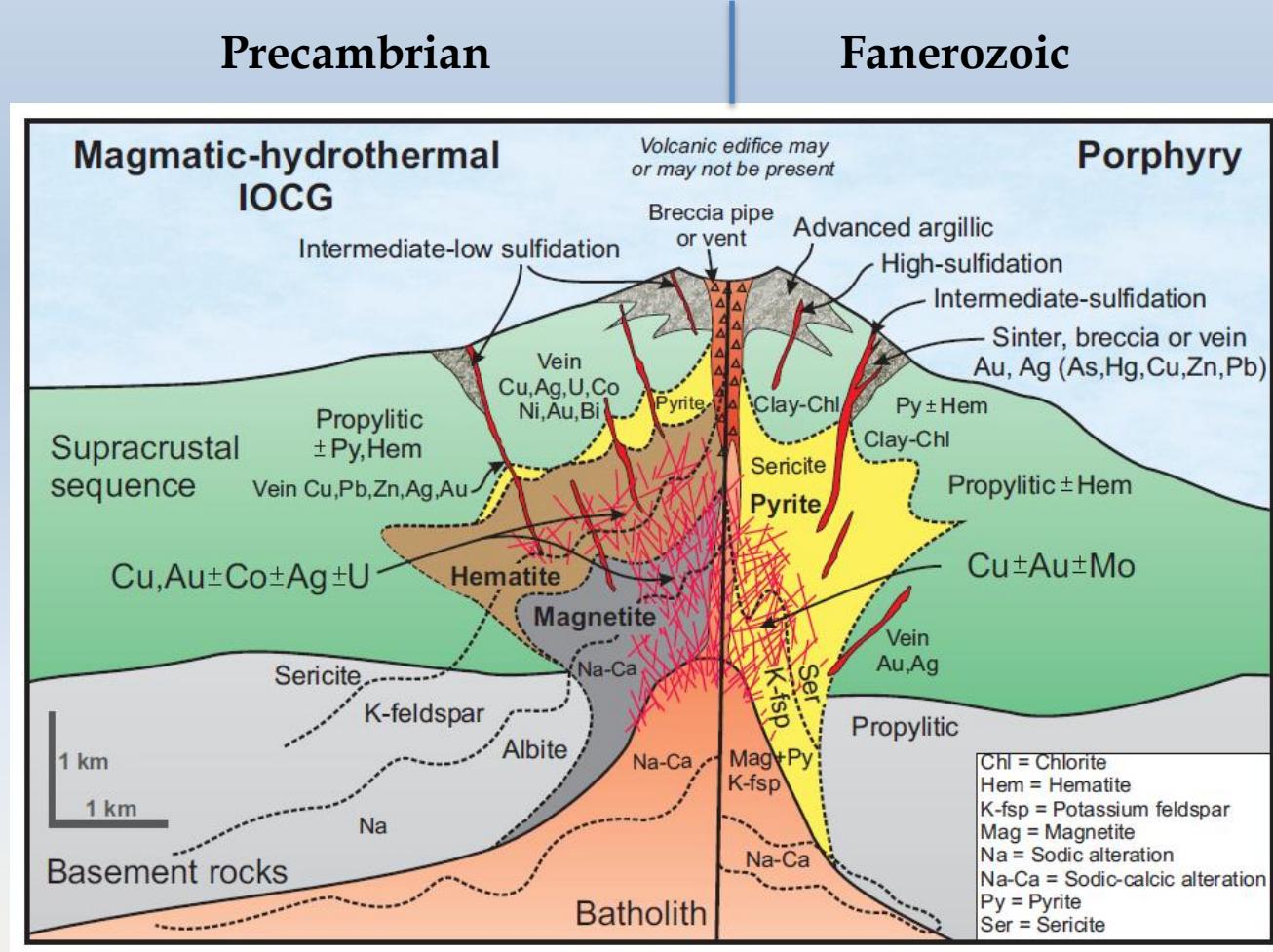
1. High initial base metal solubility in hot, saline fluids.
2. Cooling from 600° to 300°C greatly reduces solubility, with greatest changes occurring between ~425–320°C (Landtwing et al., 2005; Klemm et al., 2007).
3. SO₂ disproportionates to H₂S and SO₄²⁻ below ~400°C (Holland, 1965).

Holland, H.D., 1965, Some applications of thermochemical data to problems of ore deposits II. Mineral assemblages and the composition of ore forming fluids: Economic Geology, v. 60, p. 1101–1166.

Klemm, L.M., Pettke, T., Heinrich, C.A., and Campos, E., 2007, Hydrothermal evolution of the El Teniente deposit, Chile: Porphyry Cu-Mo ore deposit from low-salinity magmatic fluids: Economic Geology, v. 102, p. 1021–1045.

Landtwing, M.R., Pettke, T., Halter, W.E., Heinrich, C.A., Redmond, P.B., Einaudi, M.T., and Kunze, K., 2005, Copper deposition during quartz dissolution by cooling magmatic-hydrothermal fluids: The Bingham porphyry: Earth and Planetary Science Letters, v. 235, p. 229–243.

Magmatic-hydrothermal systems



Meteoric Water



Foto: Rosane Nascimento

Águas meteóricas são aquelas que tiveram contato e se equilibraram com a atmosfera (chuva, neve, névoa, orvalho, geada, etc.), as quais fornecem escoamento superficial de rios e riachos.

Águas Meteóricas

- ❖ Se movimentam da superfície em direção à níveis mais profundos, atraídas por calor (corpo ígneo), são aquecidas e transformam-se em soluções hidrotermais, participando da formação de depósitos minerais.
- ❖ Tem também papel importante nos processos supergênicos.

- ancient → can be heated as downward flow synchronous to upward flow and tectonic-magmatic activity
- recent → e.g., the past 20 million years, rainwater etc., downward flow into “cold” crust

Meteoric Water

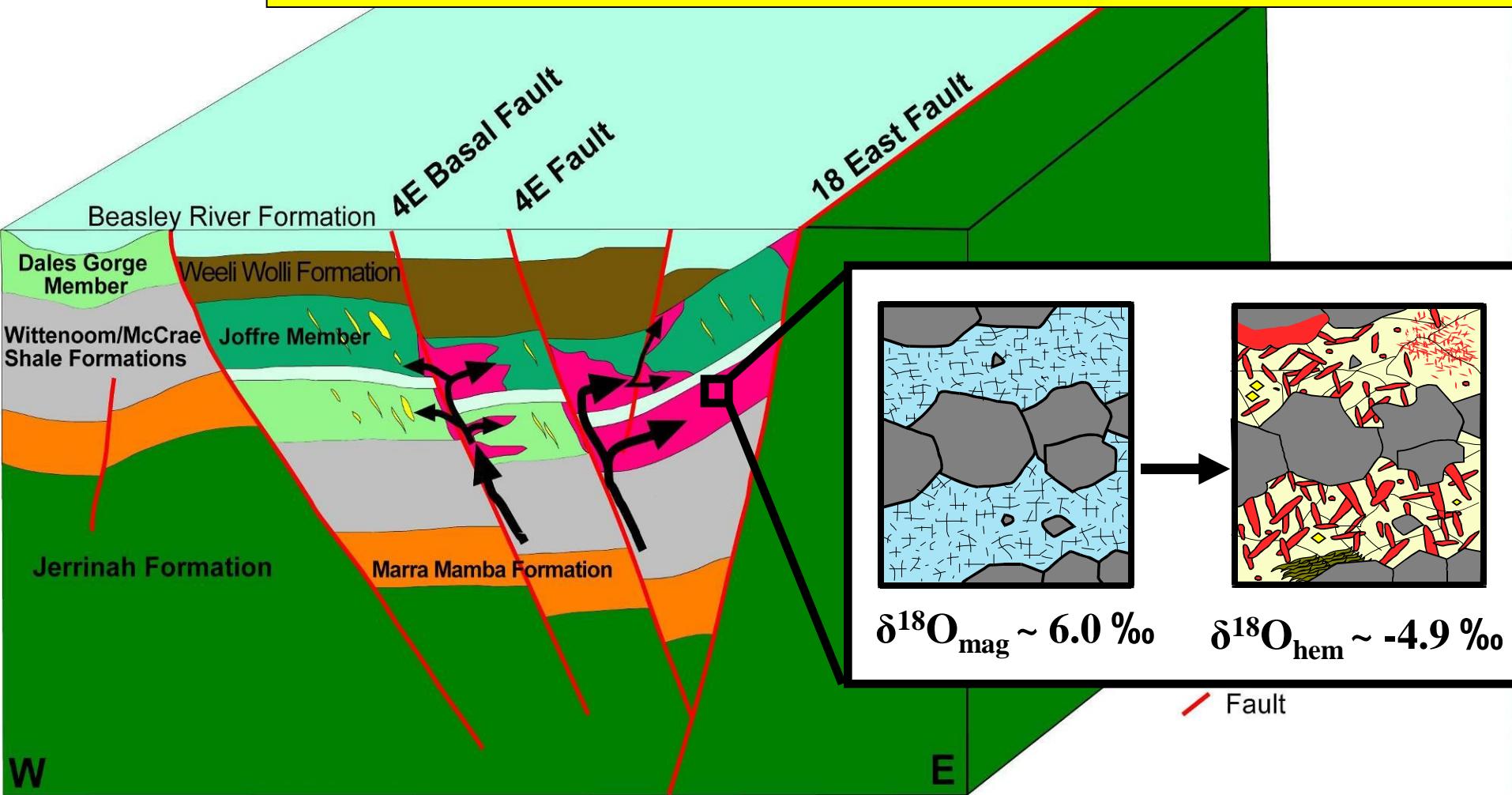
Average residence times for water in near-surface reservoirs

<u>Reservoir</u>	<u>Average Residence Times</u>
Oceans	3,500 years
Deep Groundwater	1,000 to 10,000 years
Shallow Groundwater	100 to 200 years
Lakes	50 to 100 years
Glaciers	20 to 100 years
Biosphere	≈6 months
Seasonal Snow Cover	2 to 6 months
Rivers	2 to 6 months
Soil Moisture	1 to 2 months
Atmosphere	10 days

Ex. Iron ores → Mount Whaleback - WA



Paraburadoo: A - Hypogene basinal fluids



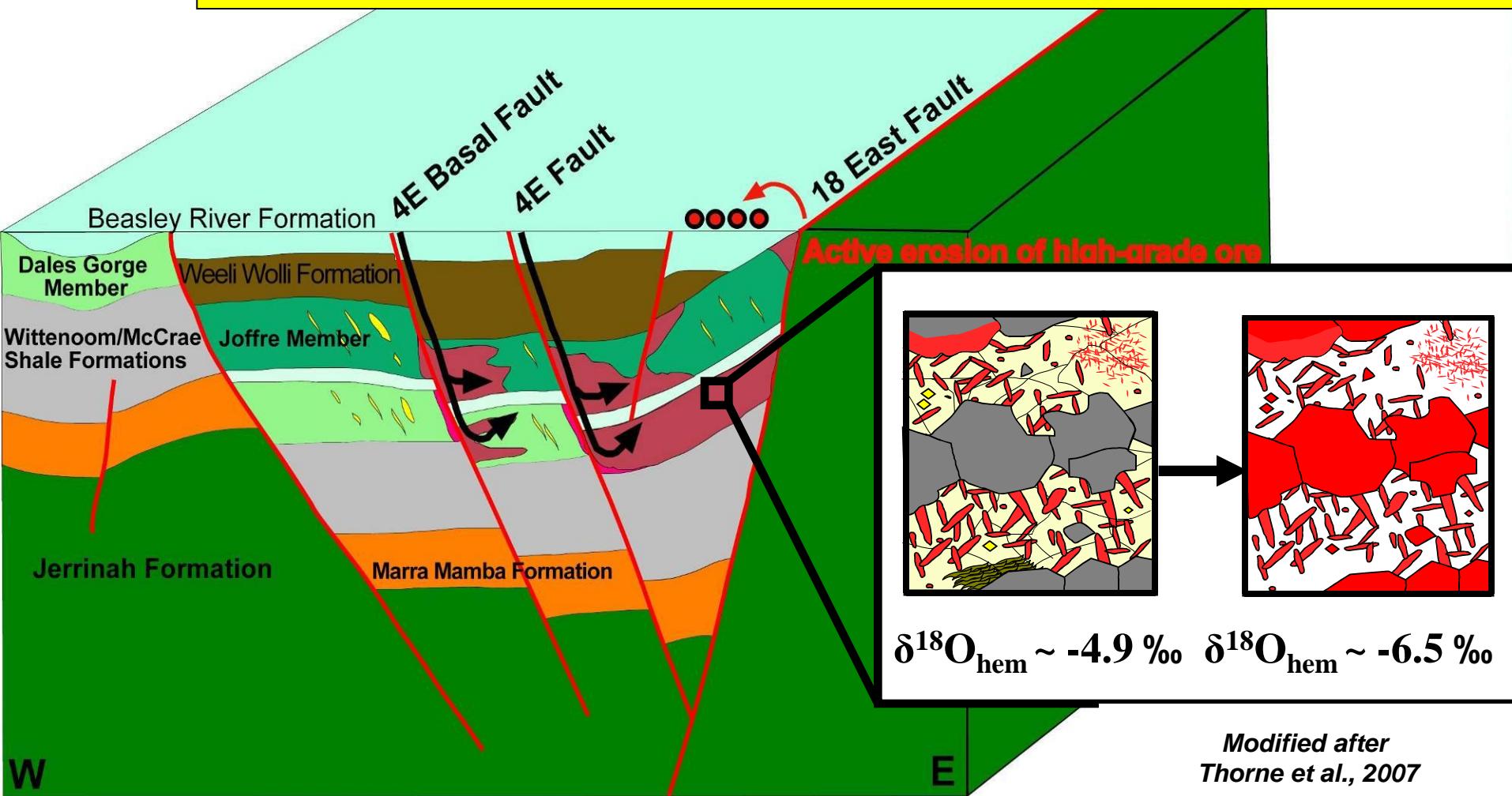
Fluid
 $\delta^{18}\text{O}_{\text{fluid}}: \sim -1.0$
High fluid flux
Basinal brine 160-180°C

Process
Desilification
Carbonatisation
MpH formation

Modified after Thorne et al., 2007

■ Proximal Alteration
■ Distal Alteration

Paraburadoo: B: Deep Meteoric fluids



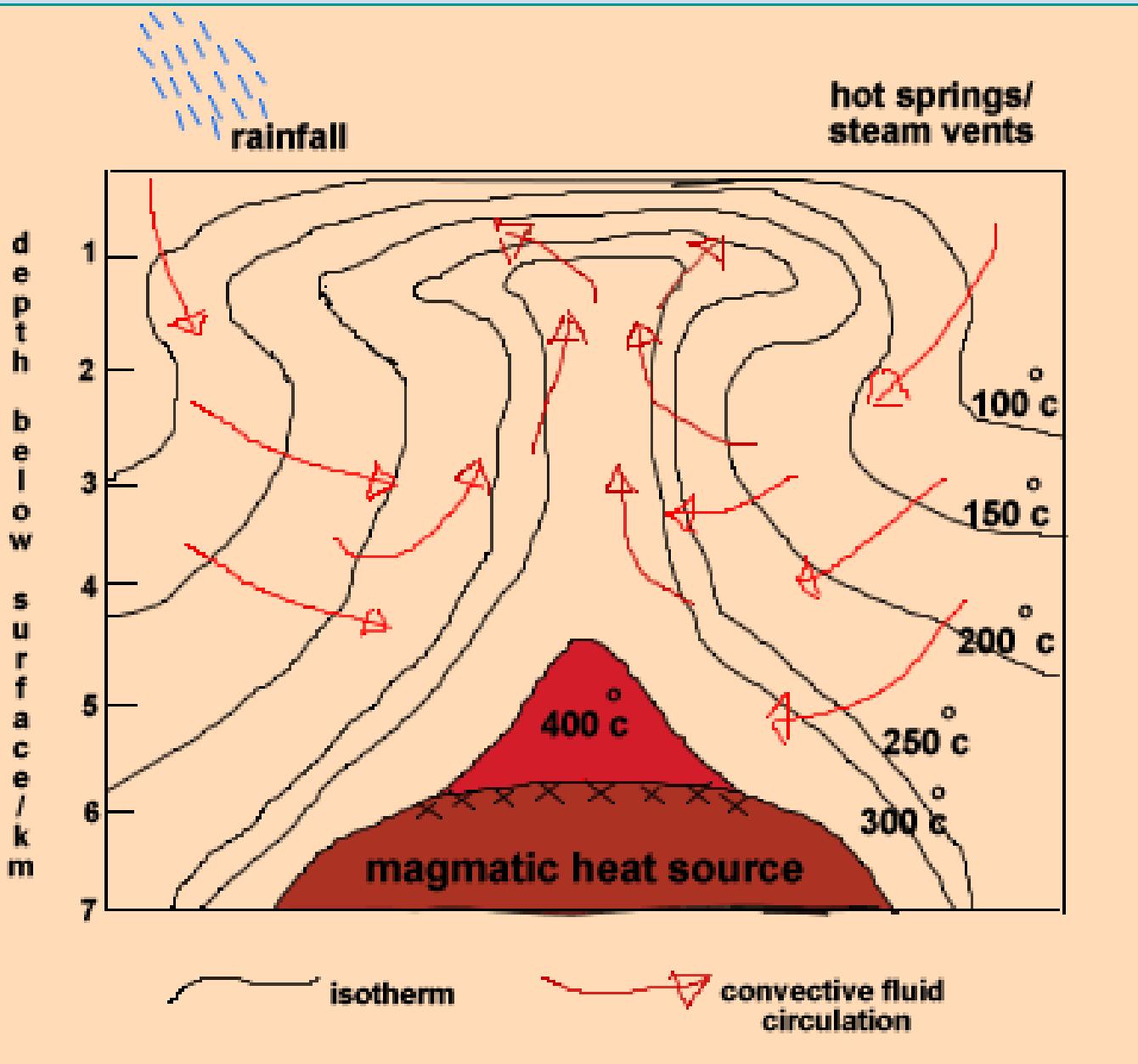
Fluid	Process
$\delta^{18}\text{O}_{\text{fluid}}: \sim -4.0$	Carbonate removal
Low fluid flux	
Meteoric Fluid: $\sim 100^\circ\text{C}$	

- Hematite Pebbles
- High-grade ore
- Proximal Alteration
- Distal Alteration

Gossan Zn



HOT SPRINGS



Hydrothermal fluid circulation feeding a hot spring system in volcanic regions where magma chambers occur at shallow depth. Convected fluids control the distribution of isotherms (temperature contours)

<http://www.dur.ac.uk/juliette.pavey/geology/>



Seawater

- Seawater as an ore-forming fluid are best described in the contexts of evaporates, phosphorites, submarine exhalites
- Some deposits related to seawaters are:
 - VMS
 - BIF
 - Sedimentary iron deposits
 - Phosphate deposits
 - Evaporites
 - Manganese modules

Hydrothermal ore deposits I: magmatic and orogenic environments

Hydrothermal deposits formed around magmatic centres

- ❖ Porphyry deposits
- ❖ Greisens and related ore deposits
- ❖ Skarn and carbonate-replacement deposits
- ❖ Polymetallic veins and vein fields associated with magmatic centres
- ❖ High-sulfidation epithermal Au-Ag deposits
- ❖ Low-sulfidation epithermal deposits
- ❖ **Volcanic-hosted massive sulfide (VHMS) deposits**



VHMS
volcanic-hosted massive sulphide
Sulfetos maciços vulcanogênicos

The “black smoker” hydrothermal vent encountered during the ROV exploration. Photo © Ocean Exploration Trust ⁸⁹

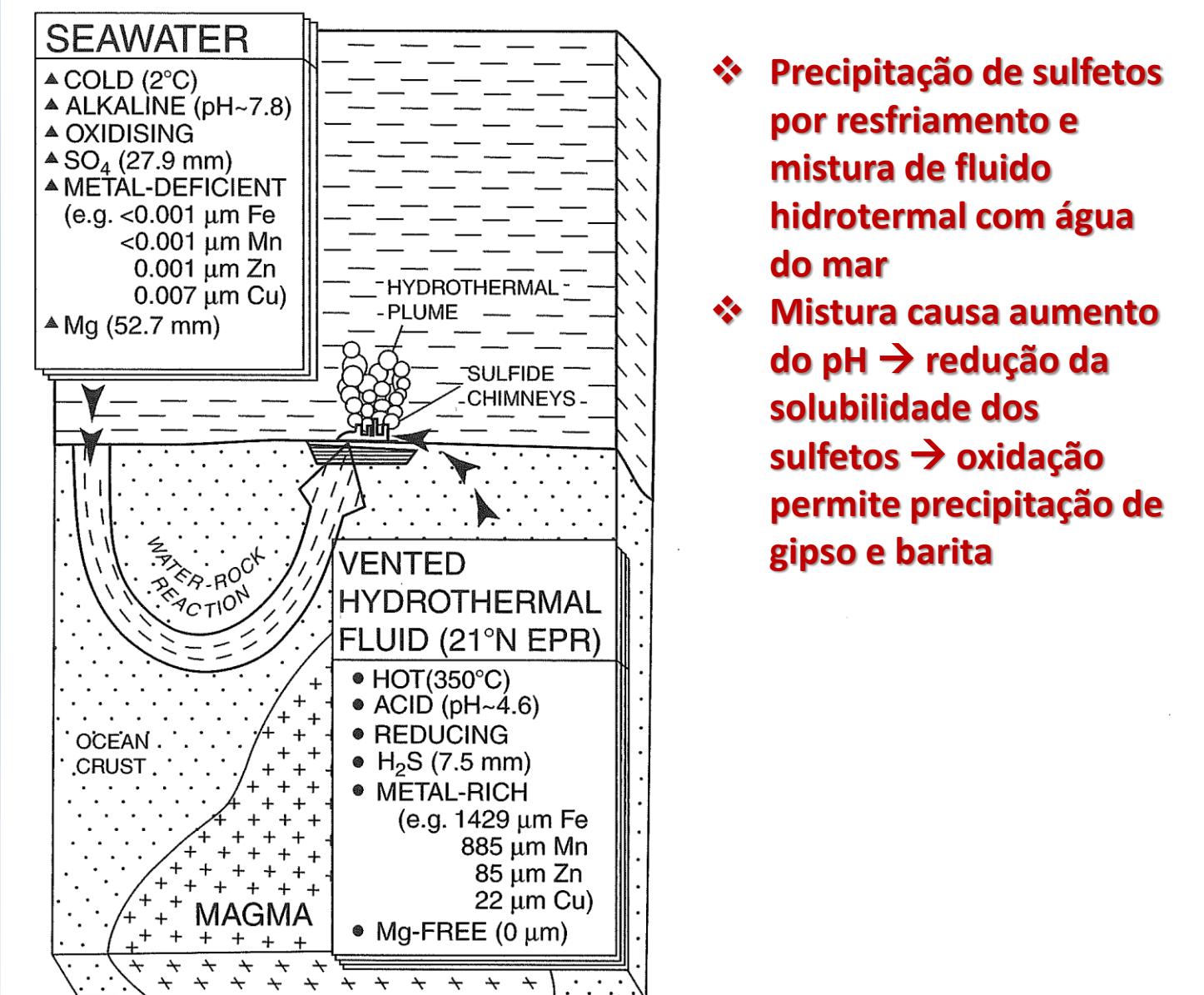


Figure 3.47 Chemical evolution of circulating seawater in a sea-floor hydrothermal system through reaction with basalt at temperatures of up to 350 °C, based on analysis of fluids vented at one of the vents of the 21° N East Pacific Rise hydrothermal field (after Scott, 1997).

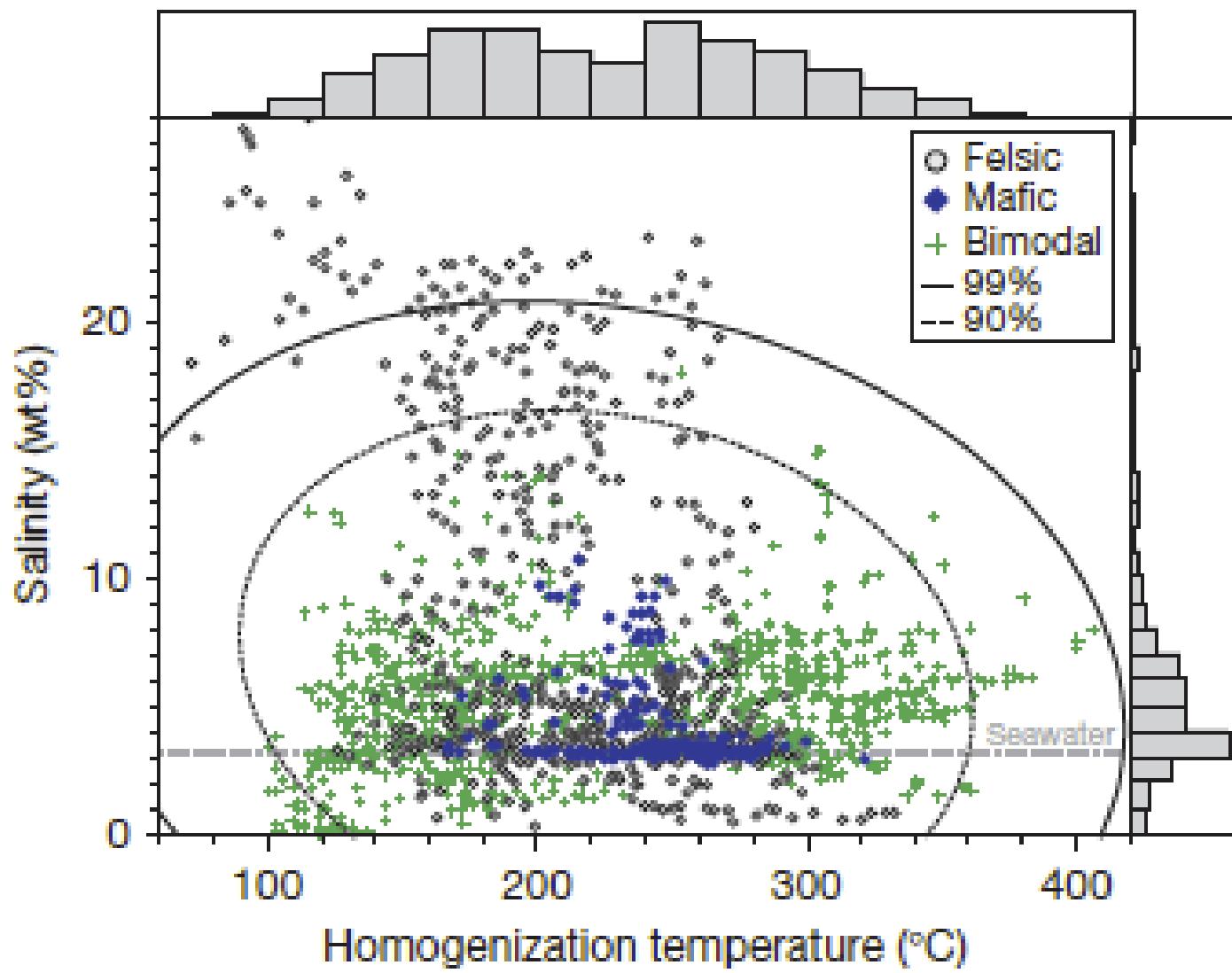


Figure 2 Summary of published homogenization temperature–salinity pairs from volcanogenic massive sulfide (VMS) ore deposits. (Bodnar, 2014)

FLUIDOS EM SISTEMAS HIDROTERMAIS OCEÂNICOS ATIVOS

Componentes (em ppm)	H ₂ O do mar	Fluido hidrotermal
Na ⁺	10.500	50.400
K ⁺	380	17.500
Ca ²⁺	400	28.000
Mg ²⁺	1280	10
Fe ²⁺	0,01	2.290
Mn ²⁺	0,002	1.400
Cu ²⁺	0,003	8
Pb ²⁺	0,00003	102
Zn ²⁺	0,01	500
Ag ⁺	0,01	1
SO ₄ ²⁻	2.650	5
S ²⁻ (como H ₂ S)	-	16
Cl ⁻	19.000	155.000
Br ⁻	65	120
pH	8,2	6,0

seafloor massive sulphide (SMS)

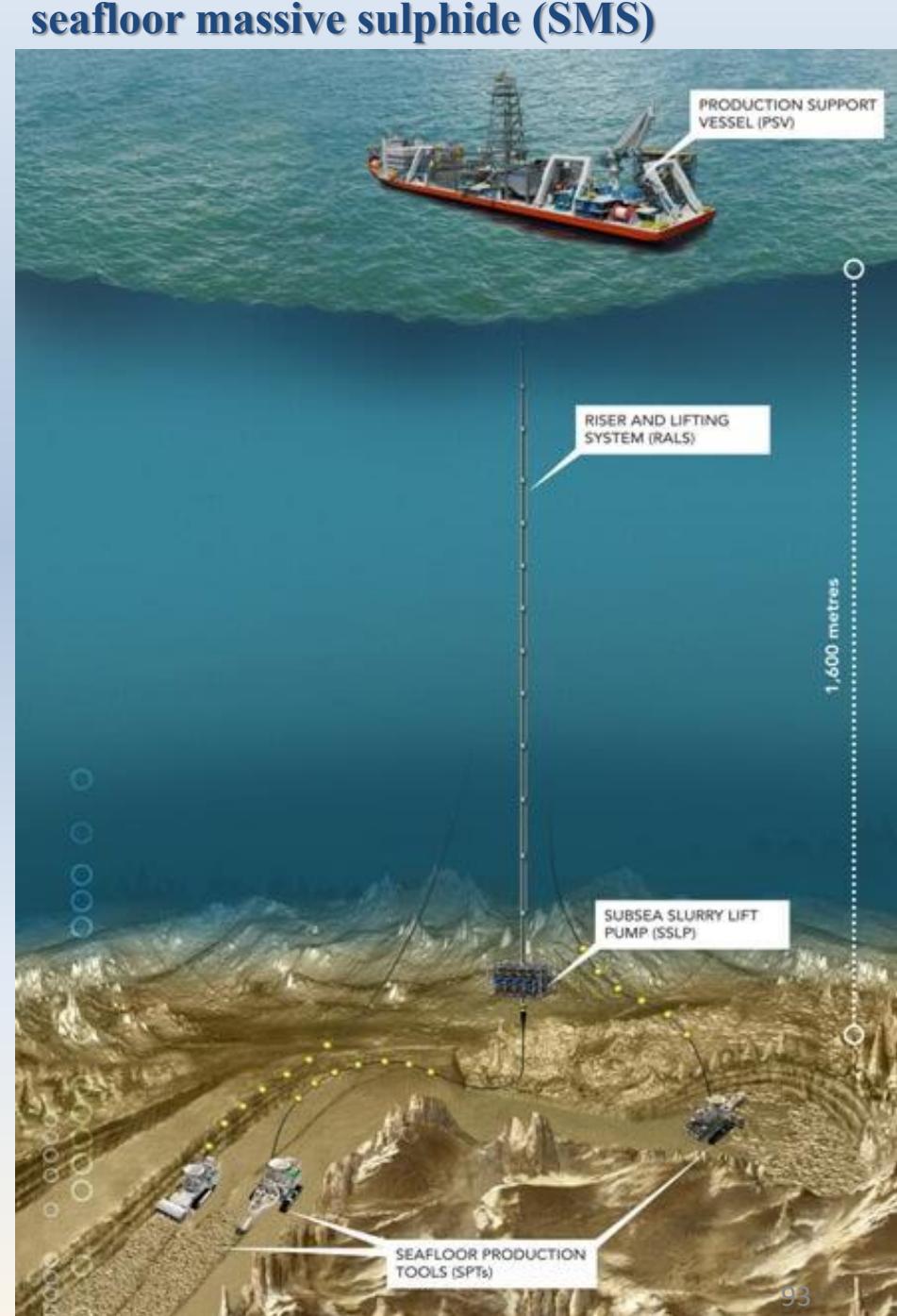
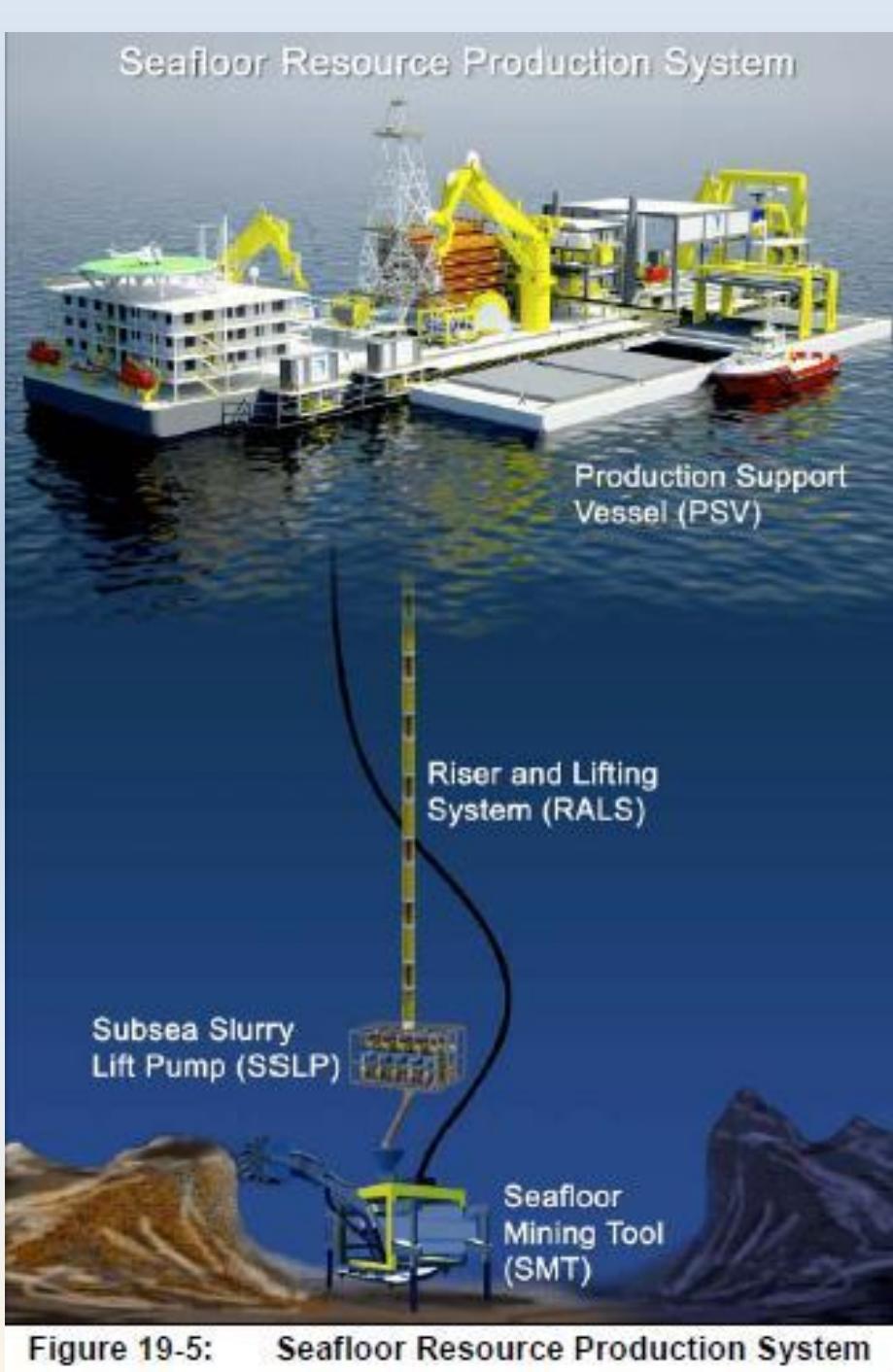
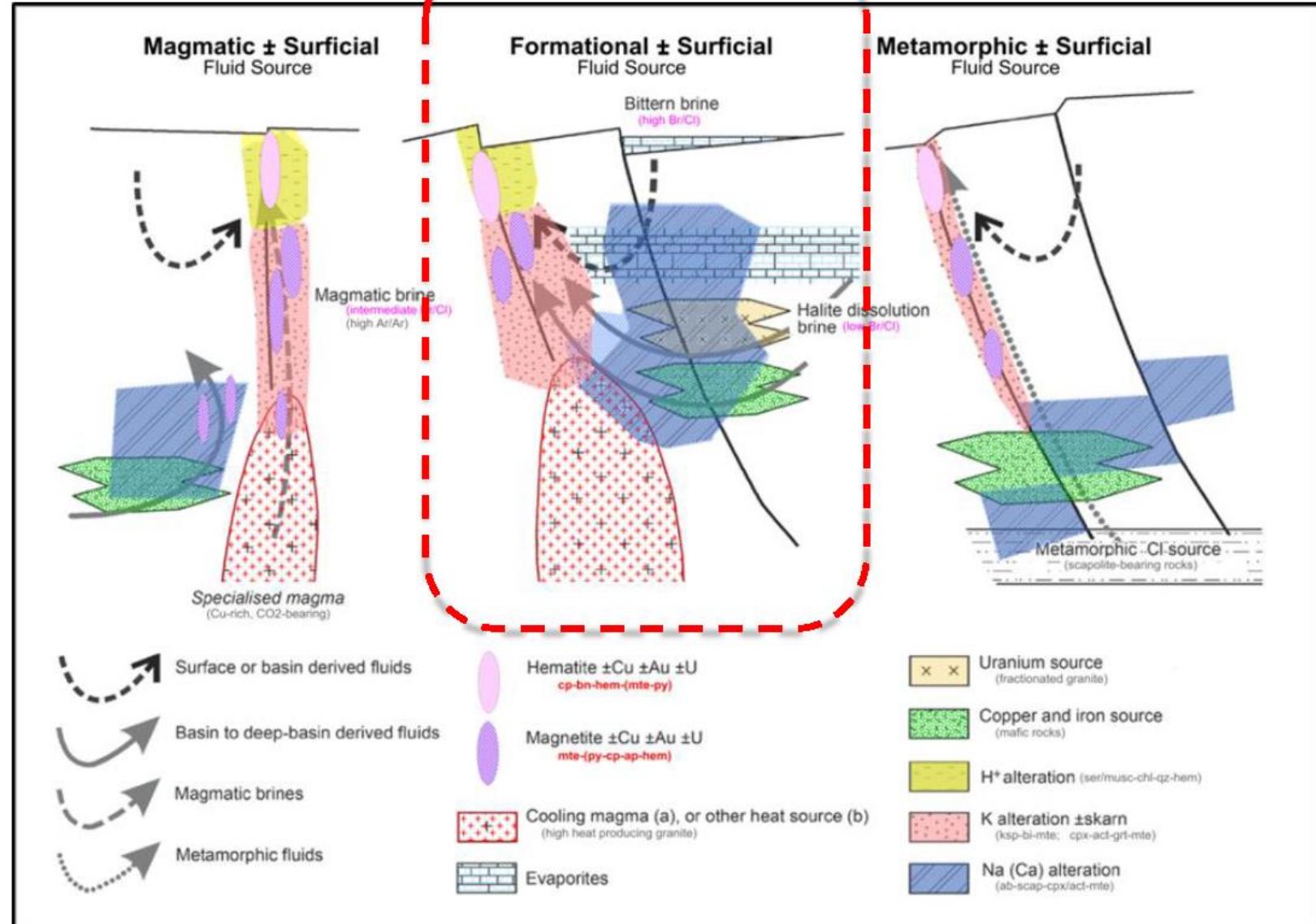


Figure 19-5: Seafloor Resource Production System

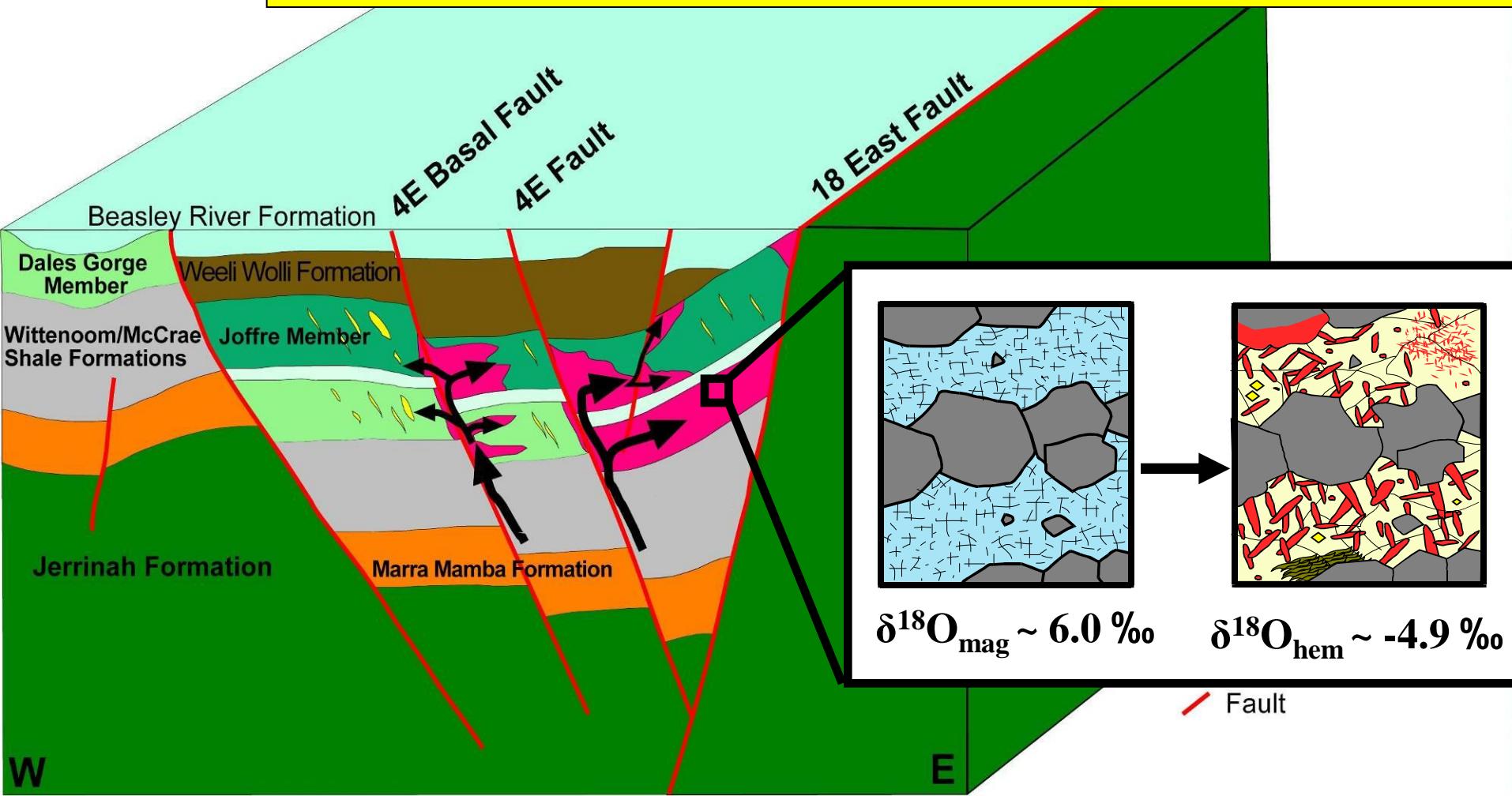
Connate waters

- ❖ water trapped in sediments at the time they were deposited is known as connate water
- ❖ connate waters are fossil waters
- ❖ observed in oil field exploration
- ❖ rich in sodium and chloride, also considerable amounts of calcium, magnesium, and bicarbonate, and many contain strontium, barium and nitrogen compounds
- ❖ can also contain light hydrocarbons
- ❖ stable isotope ratios near SMOW
- ❖ Mississippi Valley type deposits



Schematic end-member models of IOCG formation highlighting the diverse range of fluid system permutations. Figure originally produced by Barton & Johnson (2004) and subsequently modified by Williams et al. (2005) and Williams et al. (2010) incorporating source rock concepts of Hayes et al. (1995), Williams (1994) and Hitzman & Valenta (2005).

Paraburadoo: A - Hypogene basinal fluids



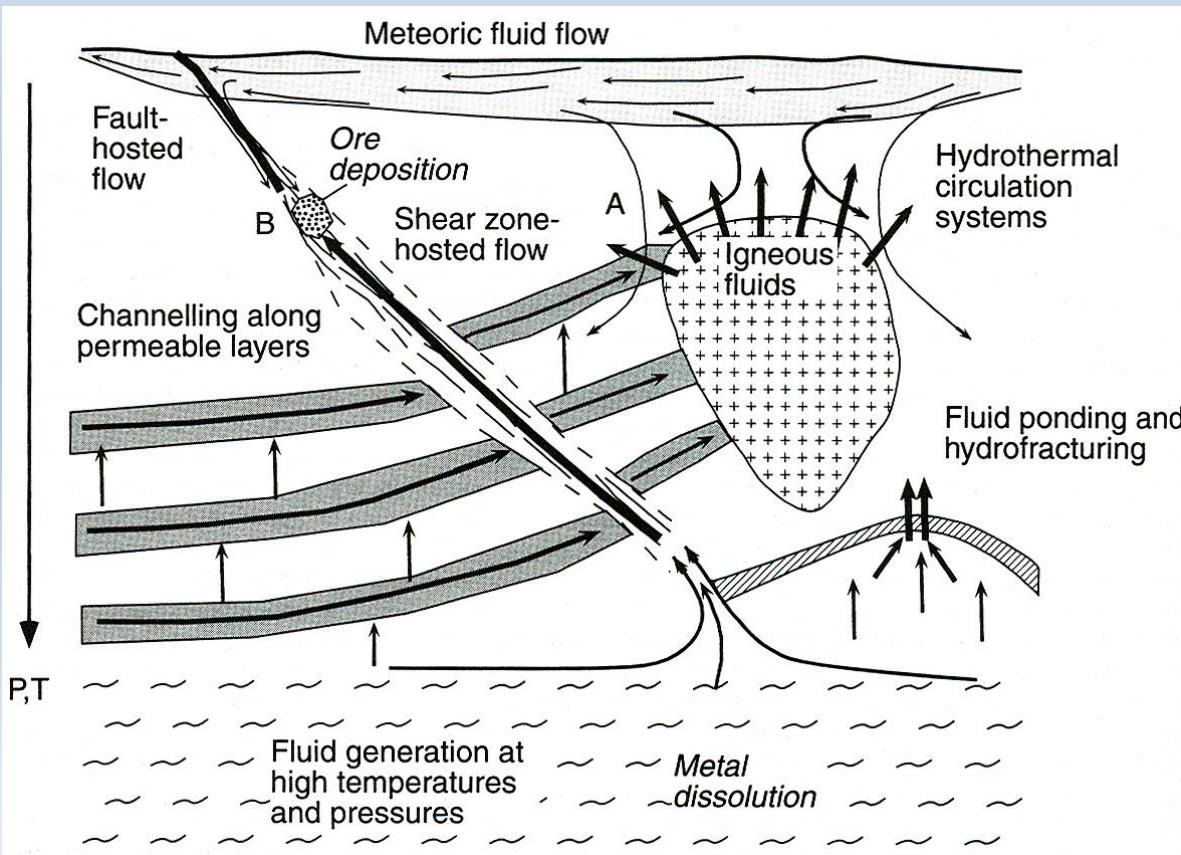
Fluid
 $\delta^{18}\text{O}_{\text{fluid}}: \sim -1.0$
High fluid flux
Basinal brine 160-180°C

Process
Desilification
Carbonatisation
MpH formation

Modified after Thorne et al., 2007

█ Proximal Alteration
█ Distal Alteration

Metamorphic Fluids



Cartwright & Oliver, Reviews in Econ. Geol., v. 11 (2000)

→ Carbonaceous
pelites

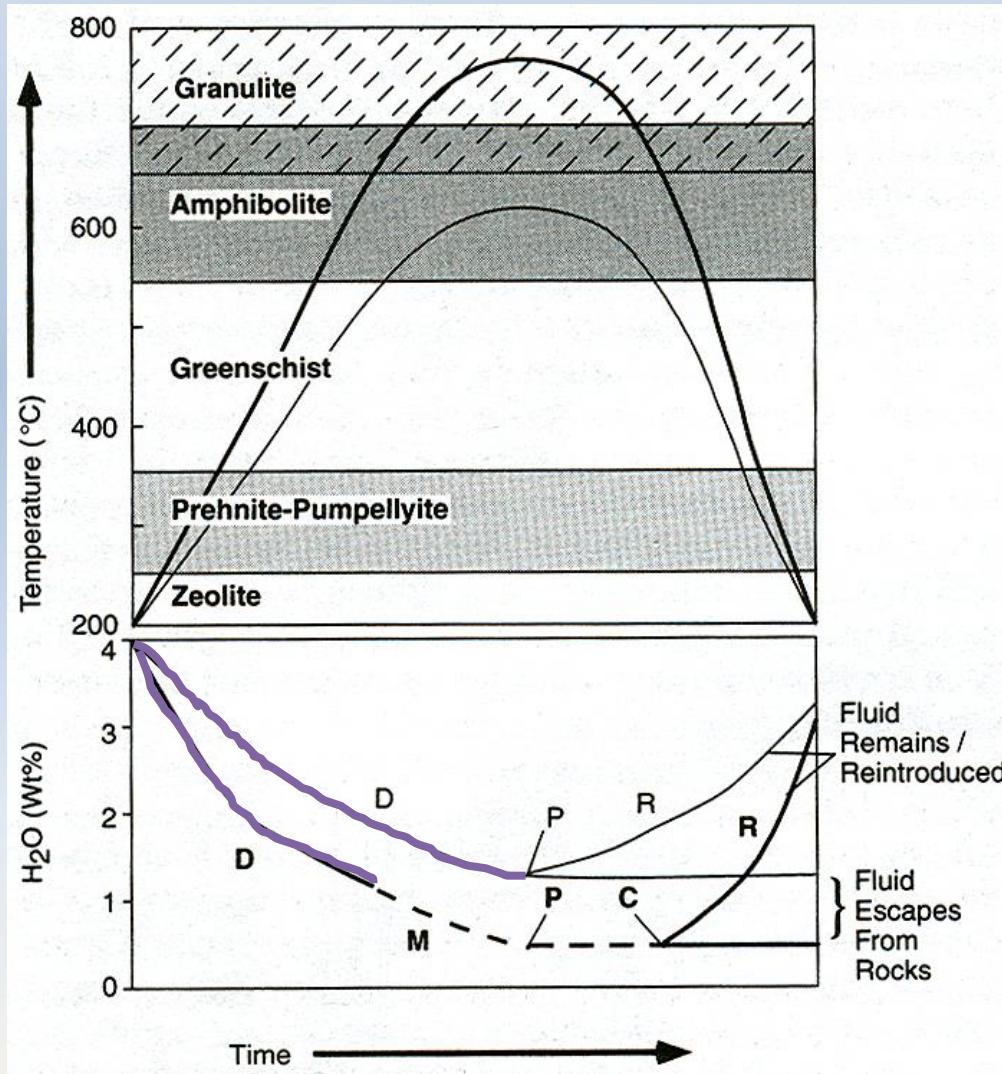
During metamorphism fluids are generated by dehydration and decarbonation reactions.

Initially, fluids migrate along grain boundaries and along layering until they intersect shear zones or faults where fluid flow becomes more focused.

Fluids may also be trapped under impermeable layers where they build pressure until fracturing occurs - this process may be repeated many times during the metamorphic history.

Fluids that eventually end up in shear zones may have swept through large volumes of rock, scavenging and delivering metals to shear zones where they may be deposited in economic concentrations.

Metamorphic Fluids



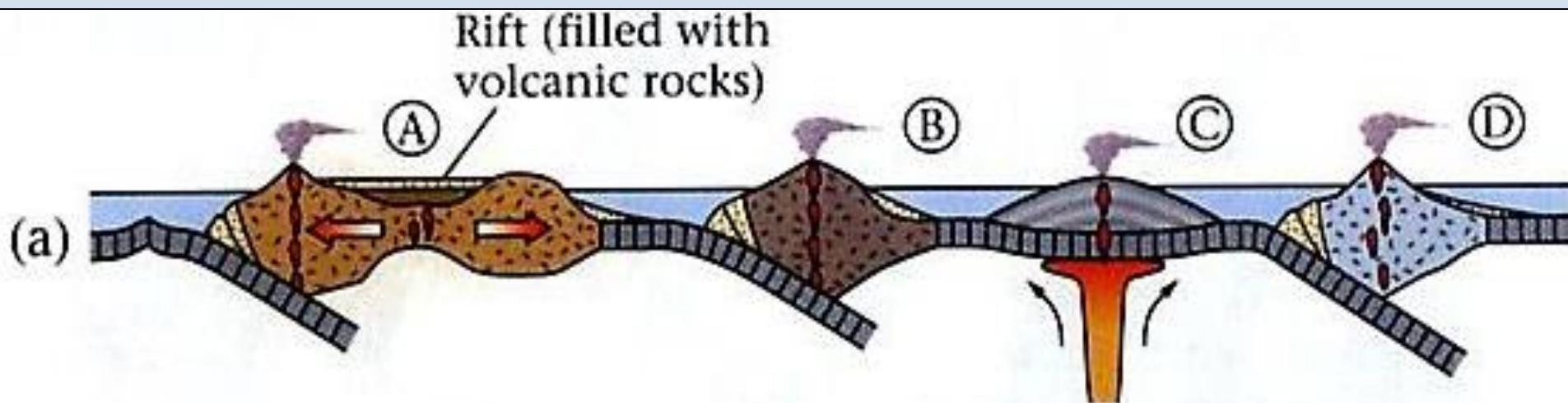
Cartwright & Oliver, Reviews in Econ. Geol., v. 11 (2000)

Schematic temperature versus time path for metamorphic rocks (above) and variation of water contents (below).

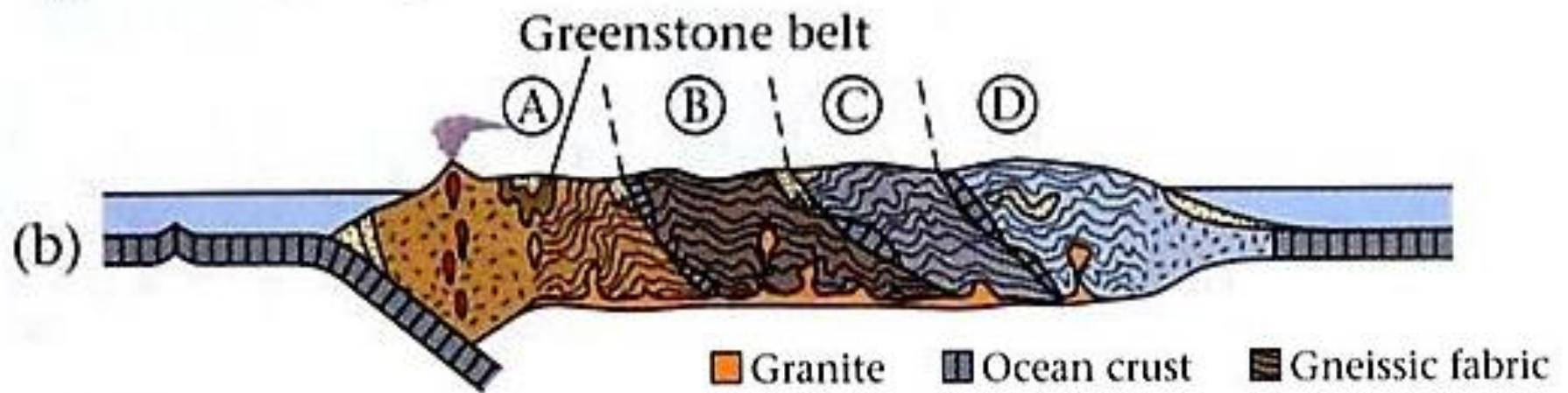
During heating, rocks lose water due to dehydration (D). Dehydration will continue in rocks that do not intersect melting reactions (hatched region) until the peak of metamorphism (P).

In rocks that melt (M), the melts represent a sink for fluids until crystallization (C) occurs and the fluids are exsolved.

During retrogression, rehydration (R) is possible if fluids remain within or are introduced into the terrane.



Hot spot igneous rock (future greenstone)	Arc rock (future granite/ gneiss)	Magma	Sediment (future graywacke)	Rift igneous rock (future greenstone)
--	--	-------	-----------------------------------	--



Granite	Ocean crust	Gneissic fabric
---------	-------------	-----------------

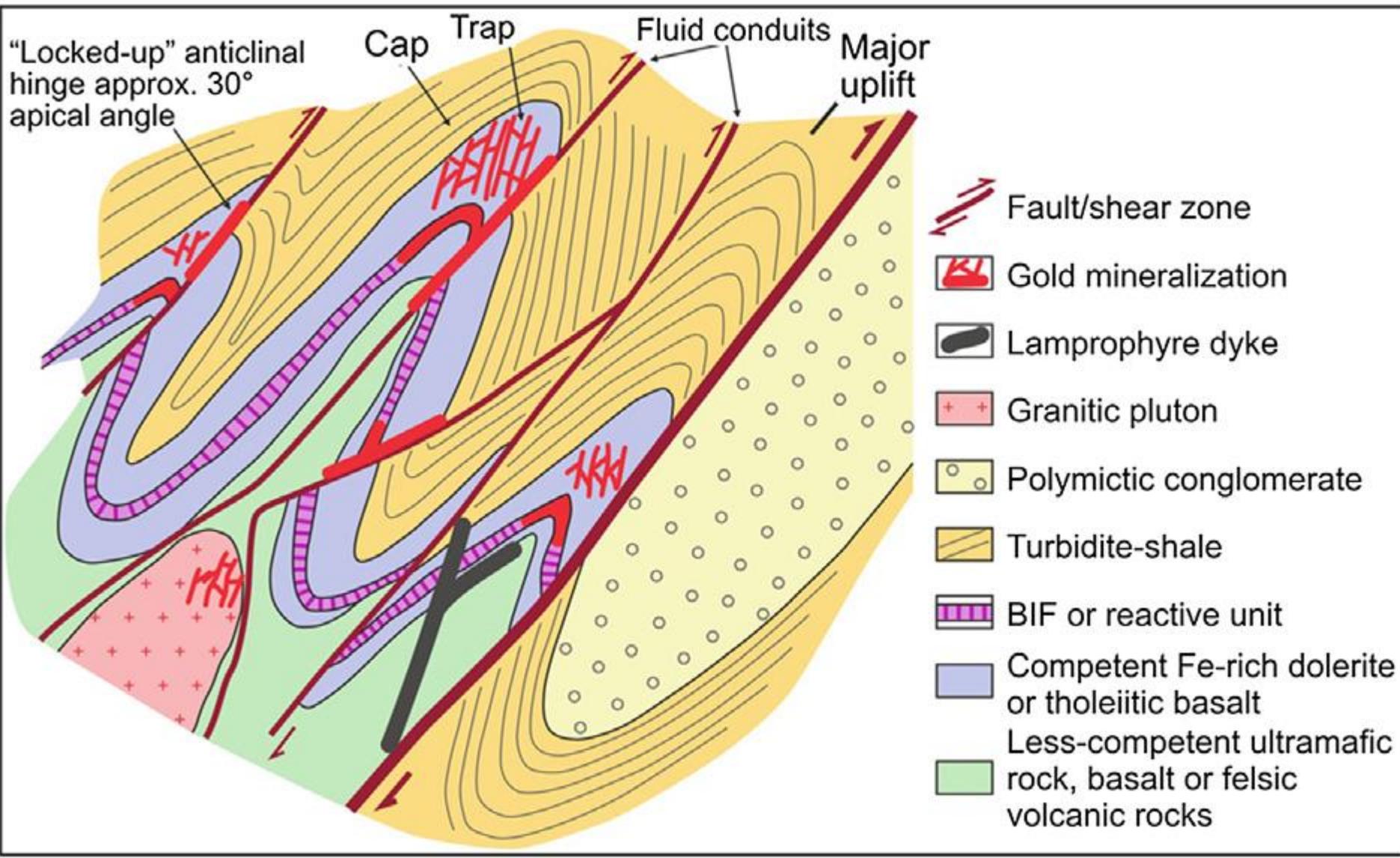
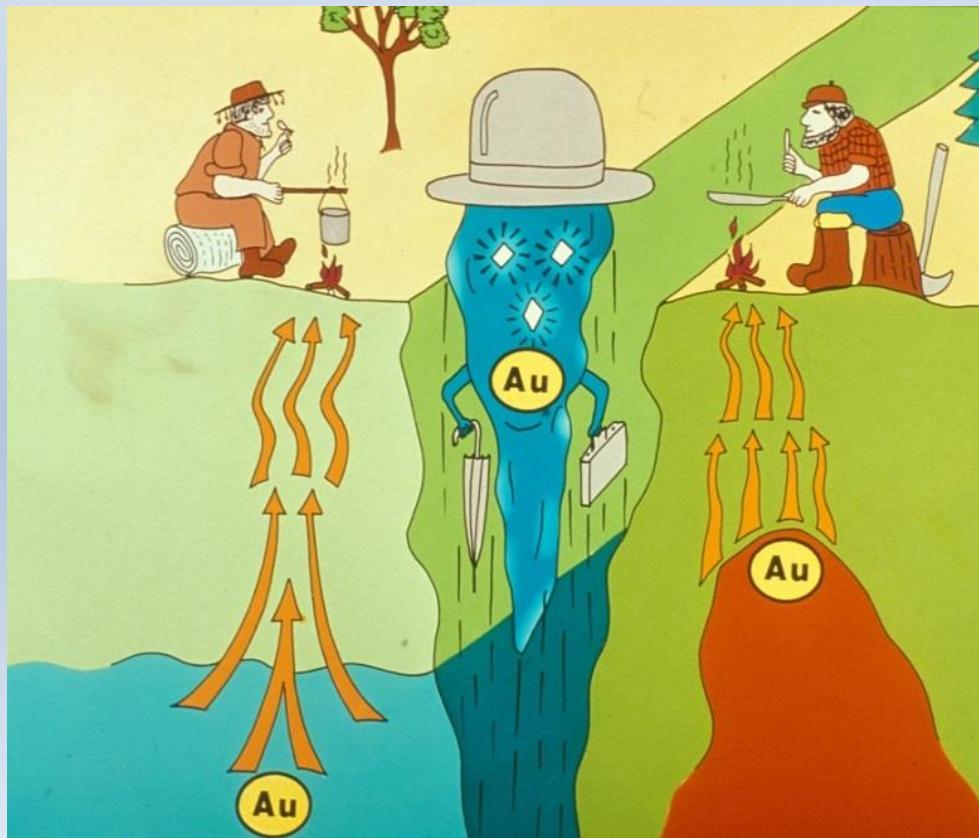
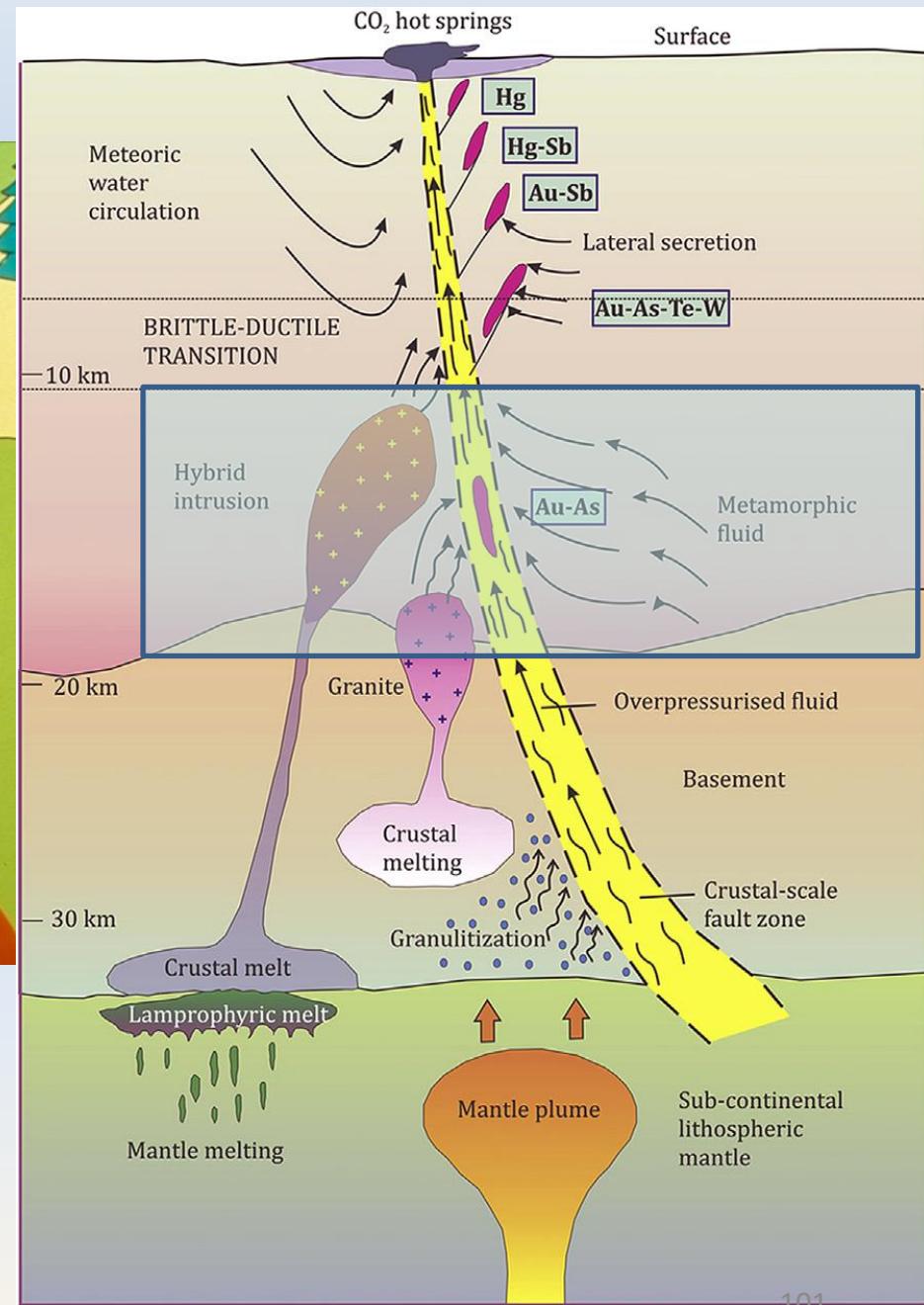


Figure 5. Schematic representation of the conjunction of parameters responsible for the formation of Archean orogenic gold deposits. Similar principles apply to younger deposits but host rocks are different and control potentially more subtle. As the sketch is a cross section, only the vertical components of transpressional faults are shown; there is clearly a strike-slip component. Oblique fault sets that represent accommodation structures are not shown for the same reason, but are an important additional parameter.



H_2O , CO_2 , S, Au, As



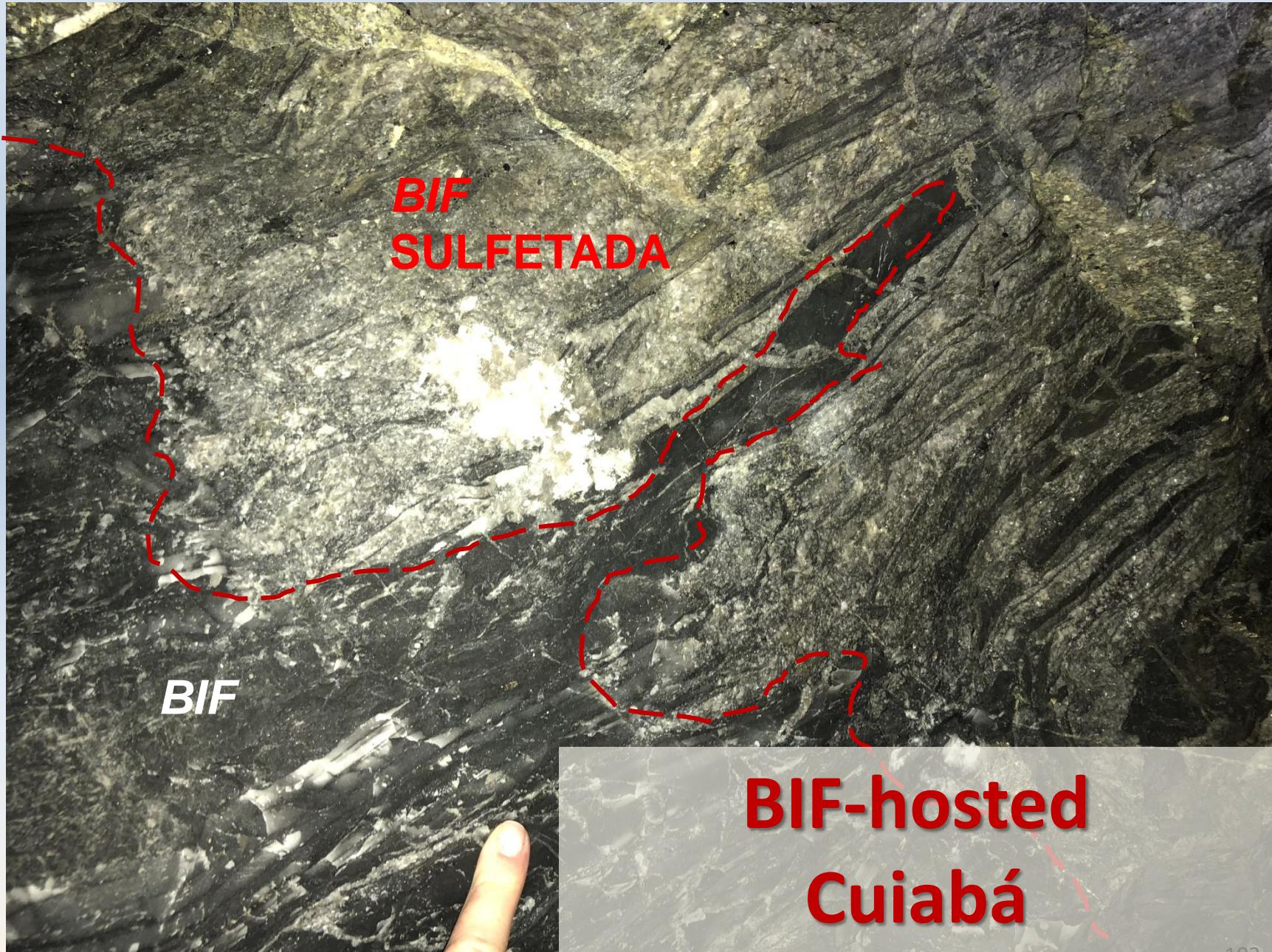




Foto: Profa. Lydia Lobato

- Depósitos de ouro orogênico → tamponamento/fixação dos principais componentes do fluido hidrotermal (metamórfico), em especial H₂O, CO₂ e enxôfre;
- Interação rocha hospedeira x fluido → extrema importância para precipitar ouro;
- **FFB** → particularmente eficientes devido à sulfetação de minerais ricos em ferro; ouro é complexado com enxôfre no fluido mineralizador;
- GBRV → FFB ricas em siderita e magnetita mais favoráveis à sulfetação, em especial (i) siderita enriquecido em matéria carbonosa (depósito Cuiabá); (ii) FFB rica em magnetita intercalada com níveis pelíticos (depósito São Bento);
- (i) $2C + 2H_2O = CO_2 + CH_4$; (ii) *metapelitos* + H₂O = *clorita* + SiO₂;
- Magnetita e siderita → ankerita → sulfetos que podem conter ouro;
- Filitos carbonosos

300°C, 1 Kbar, total sulfur = 0.05 mol, Total chloride = 0.1 mol

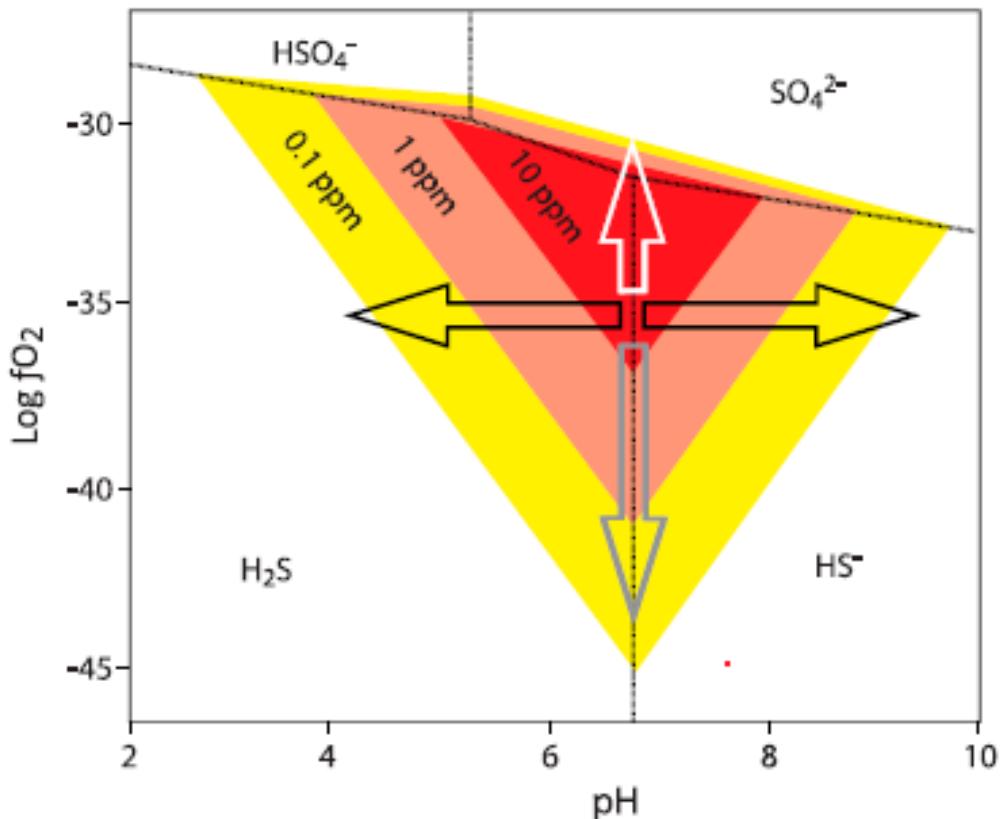
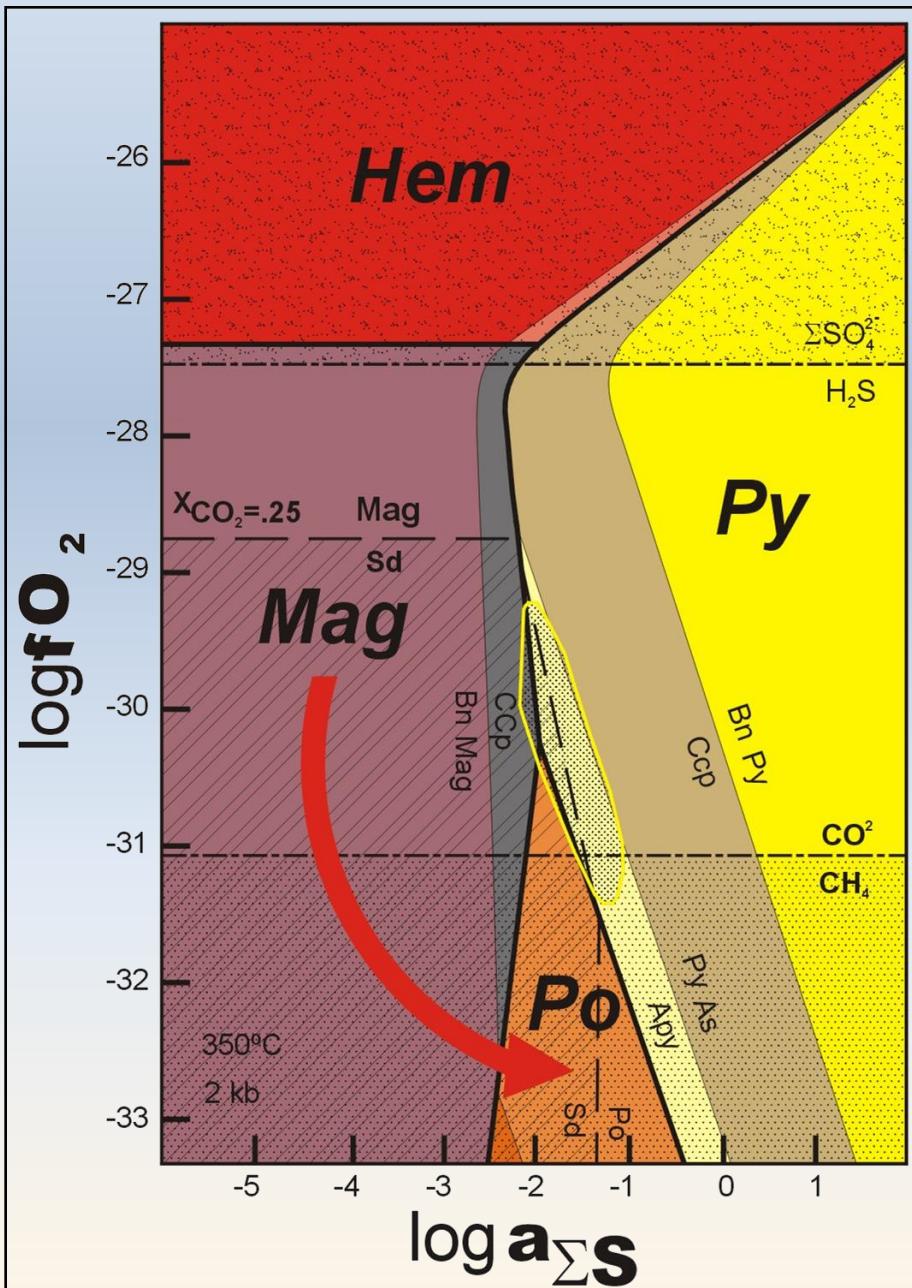


Figure 3. Schematic $\log f_{\text{O}_2}$ – pH diagram for gold solubility.
Note: This diagram shows contours (0.1, 1.0 and 10.0 ppm) for the solubility of gold–bisulfide complexes, modified from Hodkiewicz et al. (2009) and Phillips and Powell (2011). From the maximal solubility field, an increase of the oxygen fugacity (white arrow) as well as a decrease (grey arrow) will induce rapid gold precipitation, although the decrease in solubility is less abrupt. For the pH, any changes from approximately neutral values (black arrows) induce gold precipitation.

Gold solubility

Timing de formação de sulfetos



$350^{\circ}\text{C}, 2\text{ kb}$ and $\text{SO}_4 = 10^3 a_{\text{so}_4}$

Lamego gold deposit, QF

Py

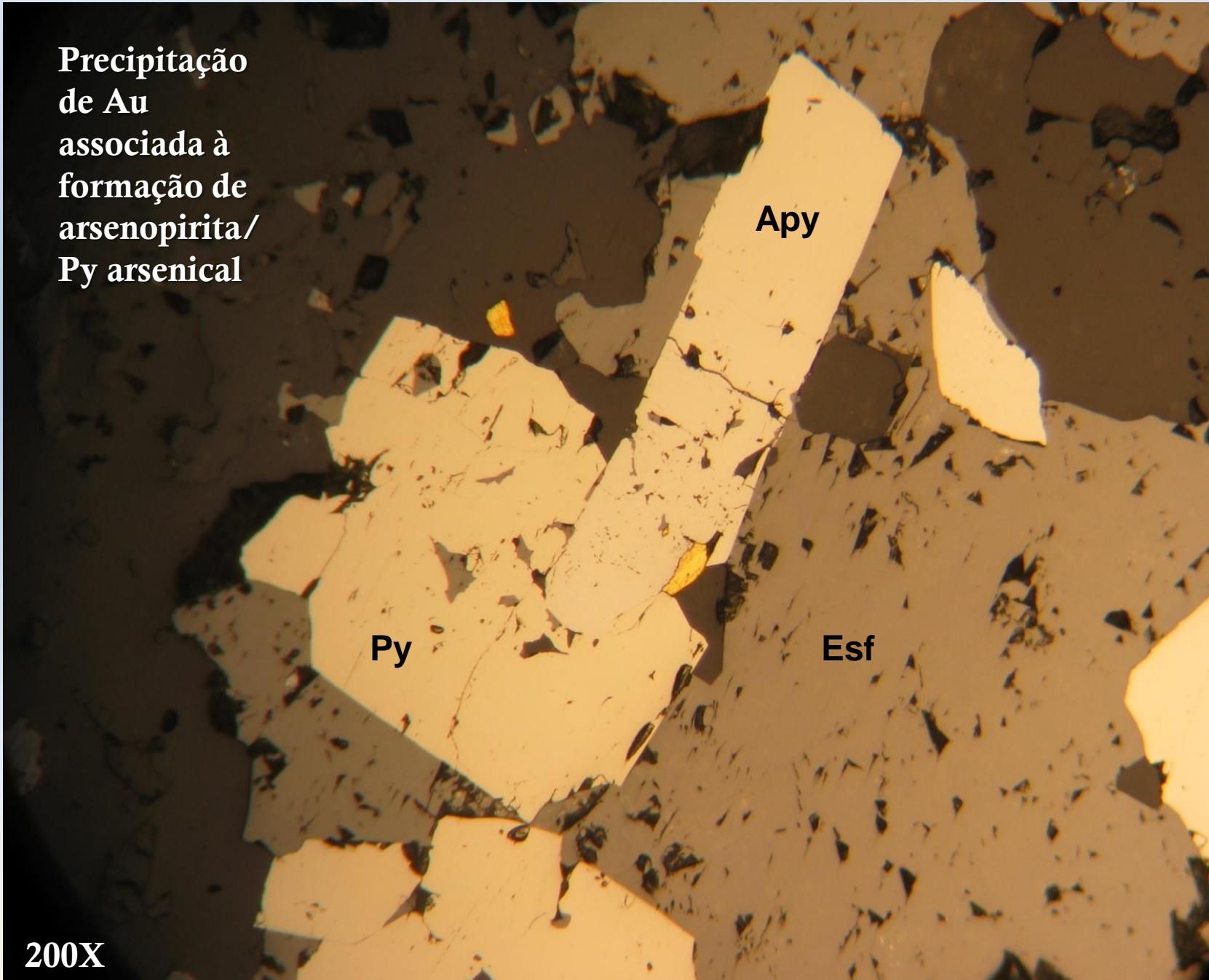
Apy

Arsenopirita forma a custa de piritas



200X

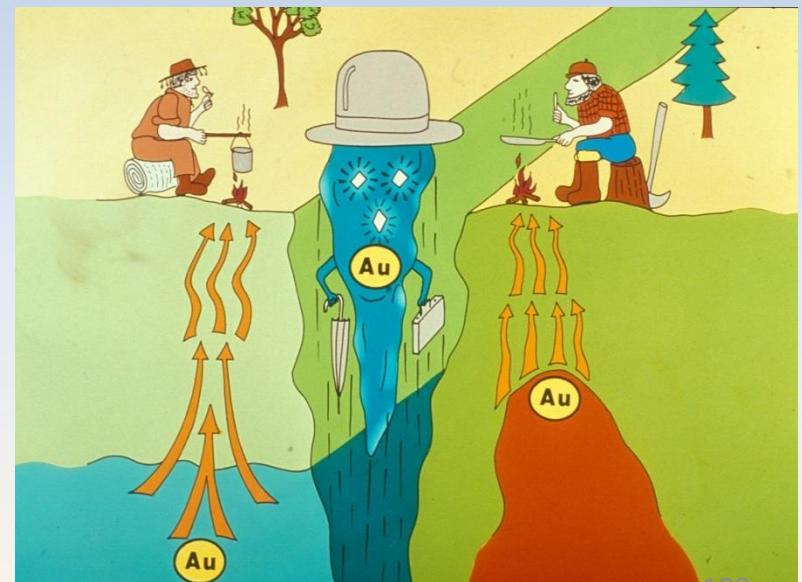
Precipitação
de Au
associada à
formação de
arsenopirita/
Py arsenical



200X

Possible sources of Au

- Pyrite nodules
- Pelitic rocks containing carbon and S → carbonaceous pelite
- Pyrite → pyrrhotite conversion (500-550°C) releasing S and Au
- Basalts and ultramafic rocks
- Possible magmatic source, from calk-alcaline affinity



TAKE HOME MESSAGE



FLUIDOS HIDROTERMAIS

- ❖ Soluções hidrotermais podem ser provenientes de fontes distintas (**magmáticos, águas meteóricas, água do mar, conatas, metamórficos**);
- ❖ Evoluem química e isotopicamente na crosta terrestre → reações com as rochas encaixantes, separação de fases, mistura de fluidos , entre outros;
- ❖ Para formar um depósito mineral
 - (1) circular por grandes volumes de rochas a uma razão fluido/rocha adequada;
 - (2) fluir para ambientes confinados;
- ❖ mecanismos de precipitação de metais - mudanças de T, P; reações com encaixantes

FLUIDOS HIDROTERMAIS

- ❖ Tipo de depósito mineral → depende da composição da solução, onde e como a precipitação ocorre.
- ❖ Transportam metais: em complexos como de Cl e S
→ Precipitação tem que ser canalizada
→ Fluxo disperso não causa concentração.

OBRIGADA!

rosalinecris@yahoo.com.br

Dicas & referências

Palestras - Geological

Society of Australia

<https://www.youtube.com/watch?v=iHDPgeUqYU>

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Link SEG

https://pubs.geoscienceworld.org/books/search-results?sort=Date+-+Newest+First&f_PublisherName=Society+of+Economic+Geologists&f_SiteID=7&page=1&f_ContentType=Book



Referências

- Araujo, J. C, S. Lobato, L. M. 2019, Depositional model for banded iron formation host to gold in the Archean Rio das Velhas greenstone belt, Brazil, based on geochemistry and LA-ICPMS magnetite analyses. *Journal of South American Earth Sciences* 94 (2019) 102205
- Bodnar, R., Azbej, T., Becker, S. P., Severs. M. J., 2006, Earth: the water planet.
- Bodnar, R., Azbej, T., Becker, S. P., Cannatelli, C., Fall, A., Severs. M. J., 2013, Whole Earth geohydrologic cycle, from the clouds to the core: The distribution of water in the dynamic Earth system Robert J.
- Cawood, P.A., and Hawkesworth, C.J., 2015, Temporal relations between mineral deposits and global tectonic cycles, in Jenkins, G.R.T., Lusty, P.A.J., McDonald, I., Smith, M.P., Boyce, A.J., and Wilkinson, J.J., eds., *Ore Deposits in an Evolving Earth: v. 393*, Geological Society, London, Special Publication 393, p. 9–21, doi: 10.1144/SP393.1.
- Cartwright I., Oliver N.H.S., 2000, Metamorphic fluids and their relationship to the formation of metamorphosed and metamorphogenic ore deposits. In: *Metamorphosed and Metamorphogenic Ore Deposits* (eds Marshall B, Vokes F). *Reviews in Economic Geology*, 11, 81–96.
- Figueiredo e Silva ,R. C., Hagemann, S. G., Lobato, L. M., Rosiere, C. A., Banks, D. A., Davidson, G. J., Vennemann, T., Herdt, J., 2013, Hydrothermal Fluid Processes and Evolution of the Giant Serra Norte Jaspilite-Hosted Iron Ore Deposits, Carajás Mineral Province, Brazil. *Economic Geology and the Bulletin of the Society of Economic Geologists*. , v.108, p.739 – 779.
- Gaboury D (2019) Parameters for the formation of orogenic gold deposits. *Appl Earth Sci* 128:124–133
- Groves et al (2015)
- Groves, D., Santosh, M., 2016, The giant Jiaodong gold province: The key to a unified model for orogenic gold deposits? [Geoscience Frontiers](#), Volume 7, Issue 3, May 2016, Pages 409-417.
- Hagemann, S. G., Lisitsin, V. A., & Huston, D. L. (2016). Mineral system analysis: Quo vadis. *Ore Geology Reviews*, 76, 504-522. <https://doi.org/10.1016/j.oregeorev.2015.12.012>
- Kesler, S.E., 2005, Ore-forming fluids: Elements, v. 1, p. 13–18, doi: 10.2113/gselements.1.1.13.
- Kresse C., LOBATO, L M., Hagemann, S. G., **Figueiredo e Silva, R. C., 2018**, Sulfur isotope and metal variations in sulfides in the BIF-hosted orogenic Cuiabá gold deposit, Brazil: Implications for the hydrothermal fluid evolution. *ORE GEOLOGY REVIEWS*. , v.98, p.1 – 27.

- Lima, L. C., 2012, GEOLOGIA DO DEPÓSITO LODE AU-AS-SB LARANJEIRAS, GRUPO NOVA LIMA, QUADRILÁTERO FERRÍFERO, MINAS GERAIS, BRASIL. Dissertação de Mestrado, UFMG.
- Lobato, L.M., Ribeiro-rodrigues, L.C., Vieira, F.W.R.V., 2001a. Brazil's premier gold province. Part II: geology and genesis of gold deposits in the Archean Rio das Velhas greenstone belt. *Quadrilatero Ferrifero. Miner. Depos.* 36, 249–277.
<https://doi.org/10.1007/s001260100180>
- Moreto, C. P. N., Monteiro, L. V. S. , Xavier, R. P., Creaser, R. A., DuFrane, S. A., Tassinari, C. C. G., Sato, K., Kemp, A. I. S., Amaral, W. S., 2015, Neoarchean and Paleoproterozoic Iron Oxide-Copper-Gold Events at the Sossego Deposit, Carajás Province, Brazil: Re-Os and U-Pb Geochronological Evidence, *Economic Geology*, v. 110, pp. 809–835.
- Ohtani, E., 2005, Water in the mantle. *Elements*, (1): 25–30. <https://doi.org/10.2113/gselements.1.1.25>
- Pirajno, F., 2009, Hydrothermal Processes and Mineral Systems.
- Richards, J.P., 2011, Magmatic to hydrothermal metal fluxes in convergent and collided margins: *Ore Geology Reviews*, v. 40, p. 1–26, doi:10.1016/j.oregeorev.2011.05.006
- Richards J.P., Mumin A.H. 2013. Magmatic-hydrothermal processes within an evolving earth: Iron oxide-copper-gold and porphyry Cu±Mo±Au deposits. *Geology*, 41(7):767-770.
- Ridley, J., 2013, Ore Deposit Geology. Cambridge: Cambridge University Press. doi:10.1017/CBO9781139135528
- Seedorff, E.; Dilles, J.H.; Proffett, J.M., Jr.; Einaudi, M.T.; Zurcher, L.; Stavast, W.J.A.; Johnson, D.A.; Barton, M.D. Porphyry deposits: Characteristics and origin of hypogene features. *Econ. Geol.* 2005, 100, 251–298. Sharma, R., and Srivastava, P. K., 2014, Hydrothermal Fluids of Magmatic Origin.
- Thorne et al., 2004 Thorne, W.S., Hagemann, S.G., and Barley, M., 2004, Petrographic and geochemical evidence for the hydrothermal evolution of the North deposit, Mt. Tom Price, Western Australia: *Mineralium Deposita*, v. 39, p. 766–783.
- Thorne, W.S., Hagemann, S.G., and Banks, D., 2007b, Hypogene fluids responsible for the transformation of BIF to high-grade iron ore (>65 wt. % Fe); insights from the 4E deposit, Paraburadoo, Western Australia: Switzerland, University of Bern, European Current Research on Fluid Inclusions (ECROFI-XIX), 17–20 July, 2007, Abstract Volume, p. 96.
- Vitorino, A. , 2017, MINERALIZAÇÃO AURÍFERA ASSOCIADA AOS VEIOS QUARTZO-CARBONÁTICOS HOSPEDADOS NA UNIDADE MÁFICA BASAL DA JAZIDA CUIABÁ, GREENSTONE BELT RIO DAS VELHAS, QUADRILÁTERO FERRÍFERO, MG. Dissertação de Mestrado, UFMG.
- Webb, A. D., Dickens, G. R., Oliver, N. H. S., 2004, Carbonate alteration of the Upper Mount McRae Shale beneath the martite-microplaty hematite ore deposit at Mount Whaleback, Western Australia. *Mineralium Deposita* (2004) 39: 632–645.
- Wyborn, L. A. I., Heinrich, C.A., and Jaques, A.L. (1994). "Australian Proterozoic Mineral Systems: Essential Ingredients and Mappable Criteria." *Australasian Institute of Mining and Metallurgy Publication Series 5/94:* 109-115.
- Zucchetti, M., 2007, Rochas maficas do Supergrupo Grão Pará e sua relação com a mineralização de ferro dos depósitos N4e N5, Carajás, (PA): Unpublished Ph.D. thesis, Belo Horizonte, Brazil, Universidade Federal de Minas Gerais, 125 p.