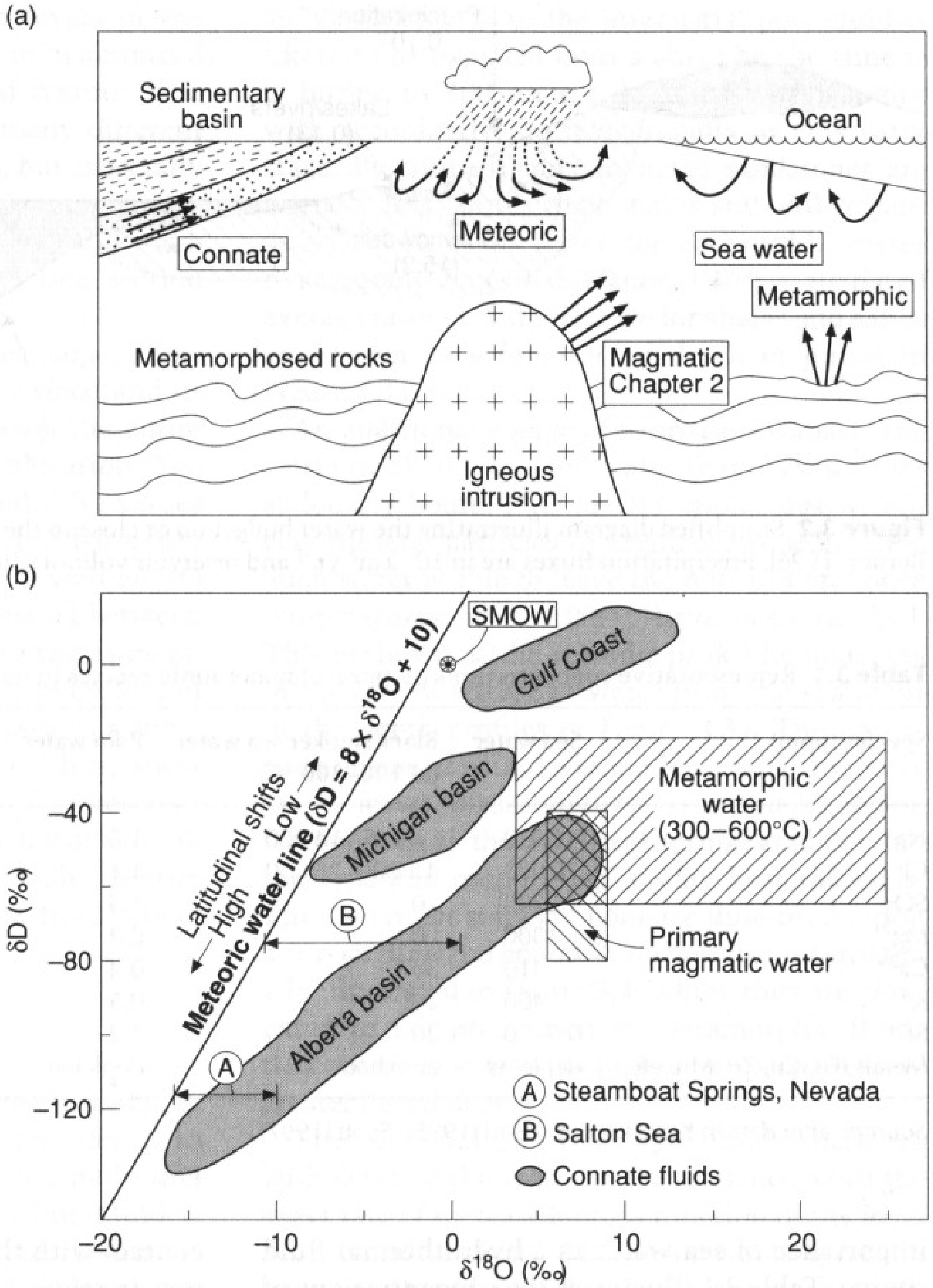
Applied and Environmental Geochemistry

OCTOBER 2025

Harilaos ("Harry") Tsikos
UNIVERSITY OF PATRAS

Sources of hydrothermal fluids

- **Magmatic**
- **Metamorphic**
- **Connate**
- **Meteoric**
- **Sea-water**



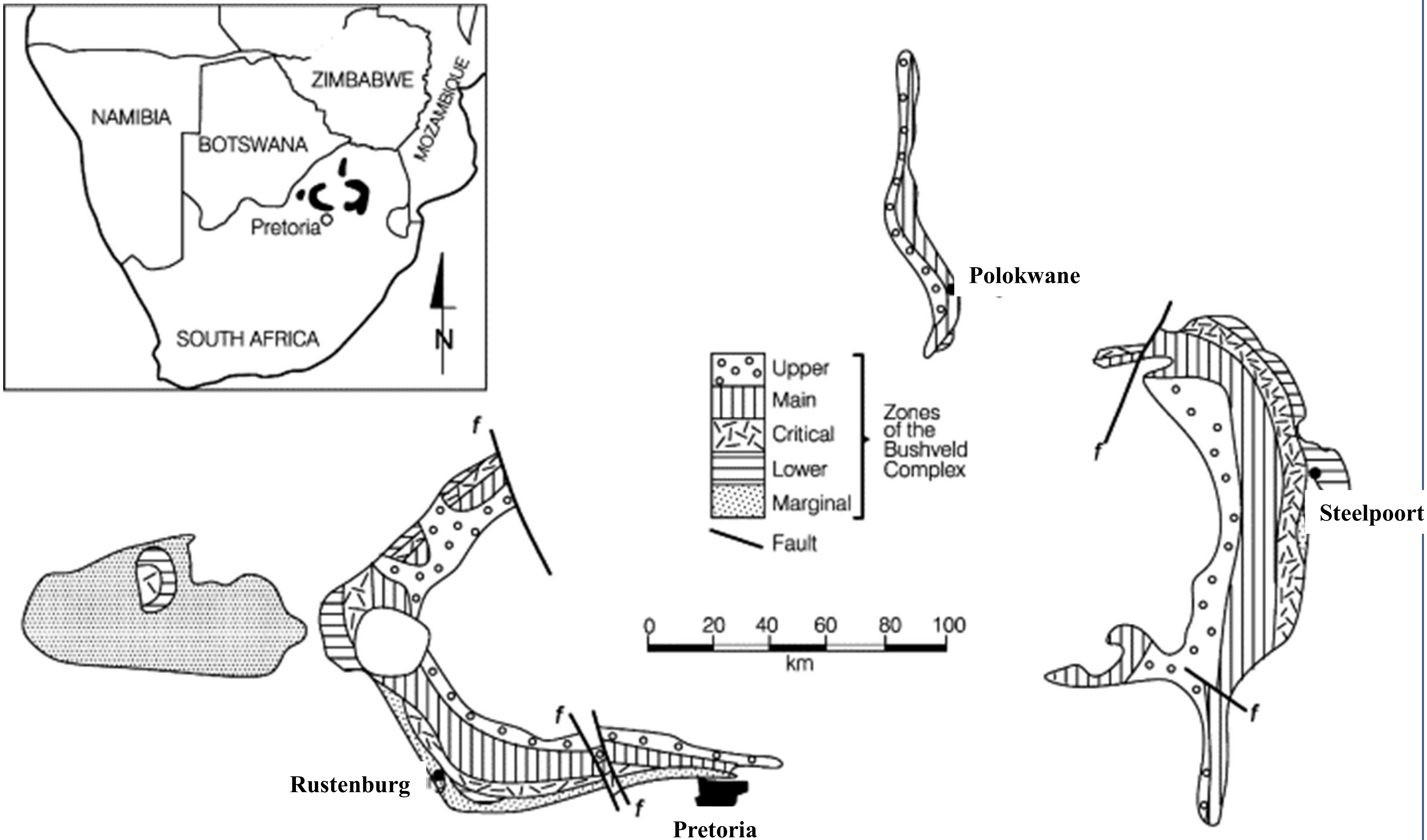
The Bushveld Igneous Complex

- ***The Bushveld Igneous Complex (BIC)*** is the world's largest layered mafic intrusion, covering an area of some 67000 km^2 and attaining a total thickness of igneous rock in excess of 9000m in places.

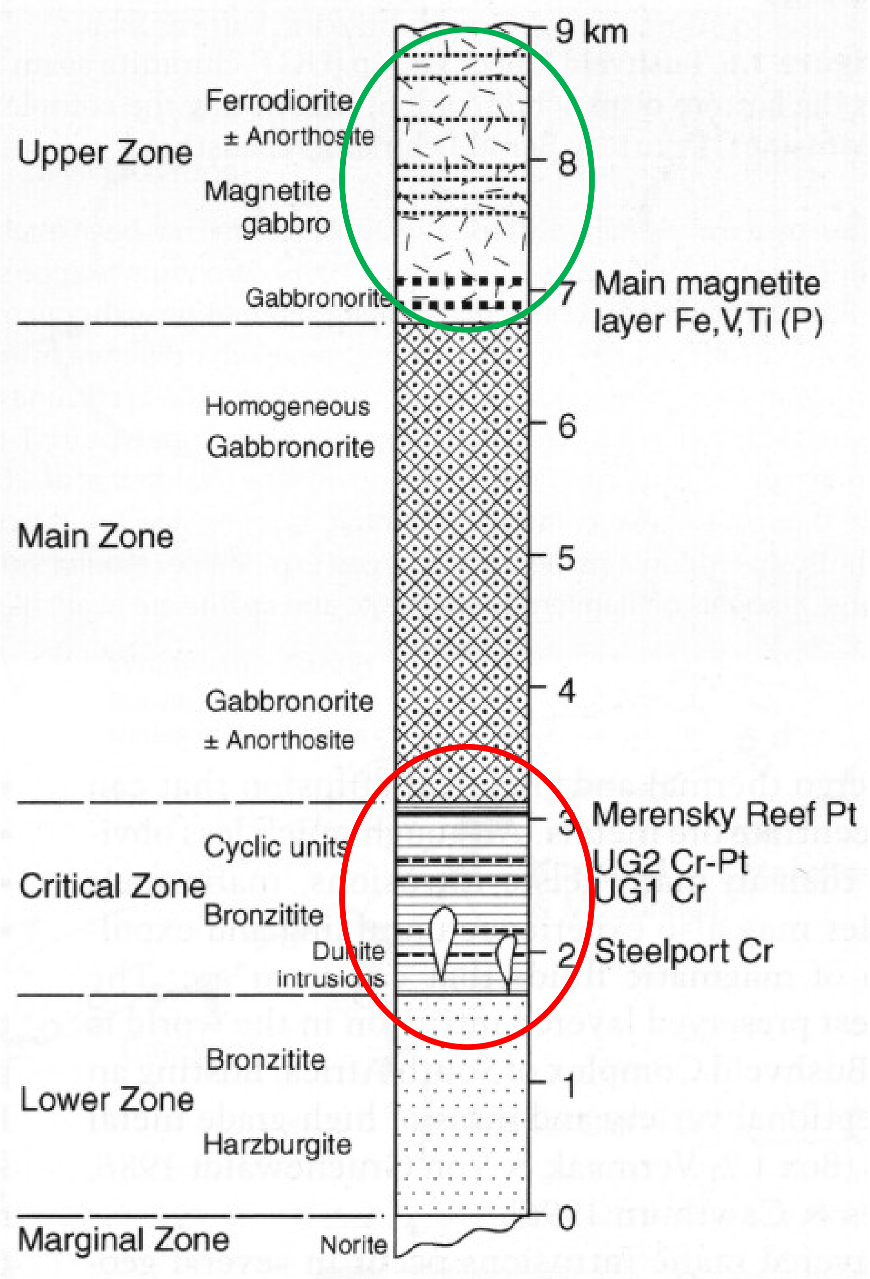
- Similar intrusions (but much smaller) include the Stillwater Complex (USA), the Skaergaard Complex (Greenland) and the Great Dyke (Zimbabwe).

- The BIC contains more than <u>three quarters</u> of the world's chromite reserves, aside from its proven resources in PGMs as well as Fe-Ti-V.

Magmatic processes: the Bushveld Igneous Complex



Chromitites in the Bushveld Igneous Complex



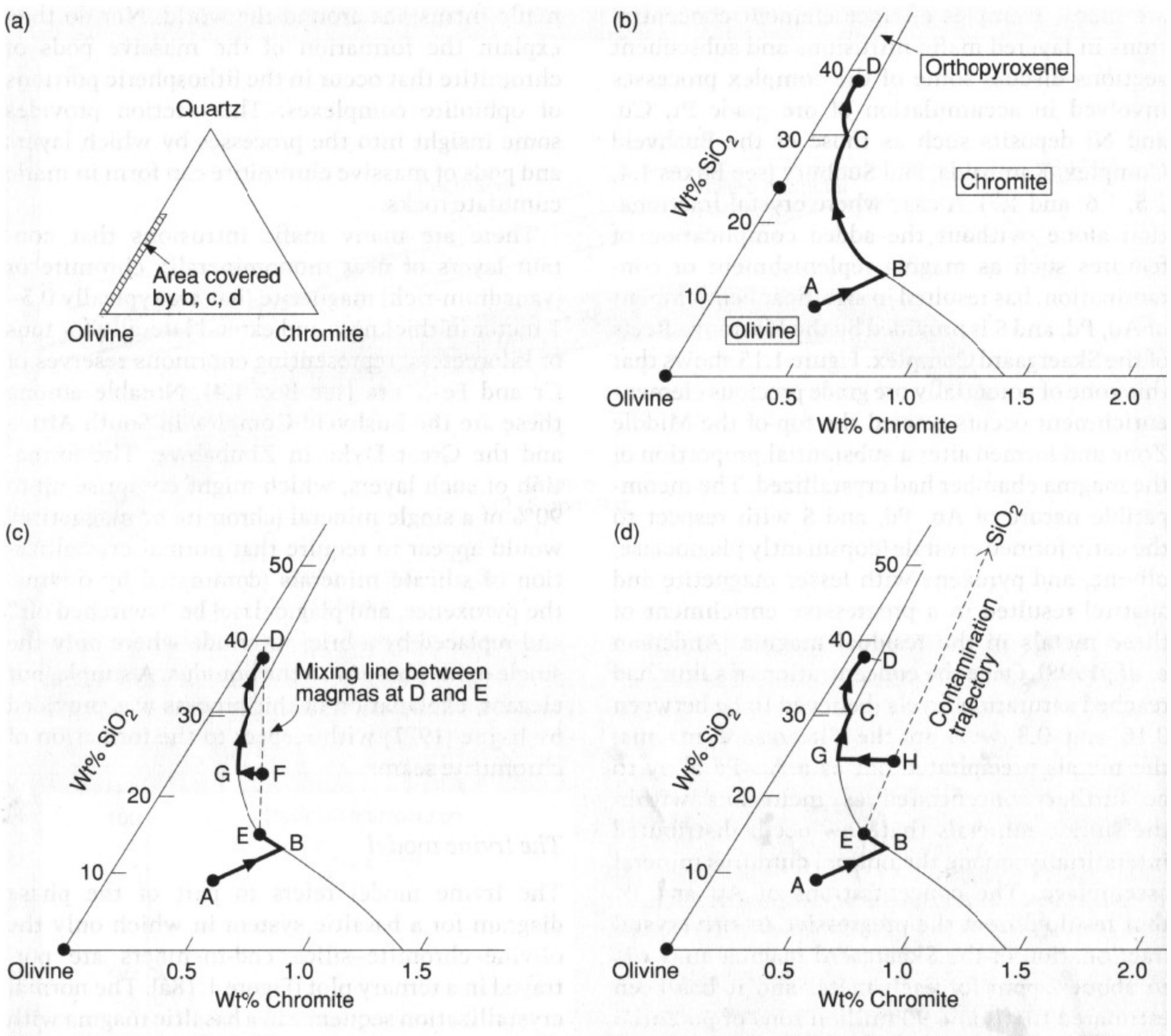


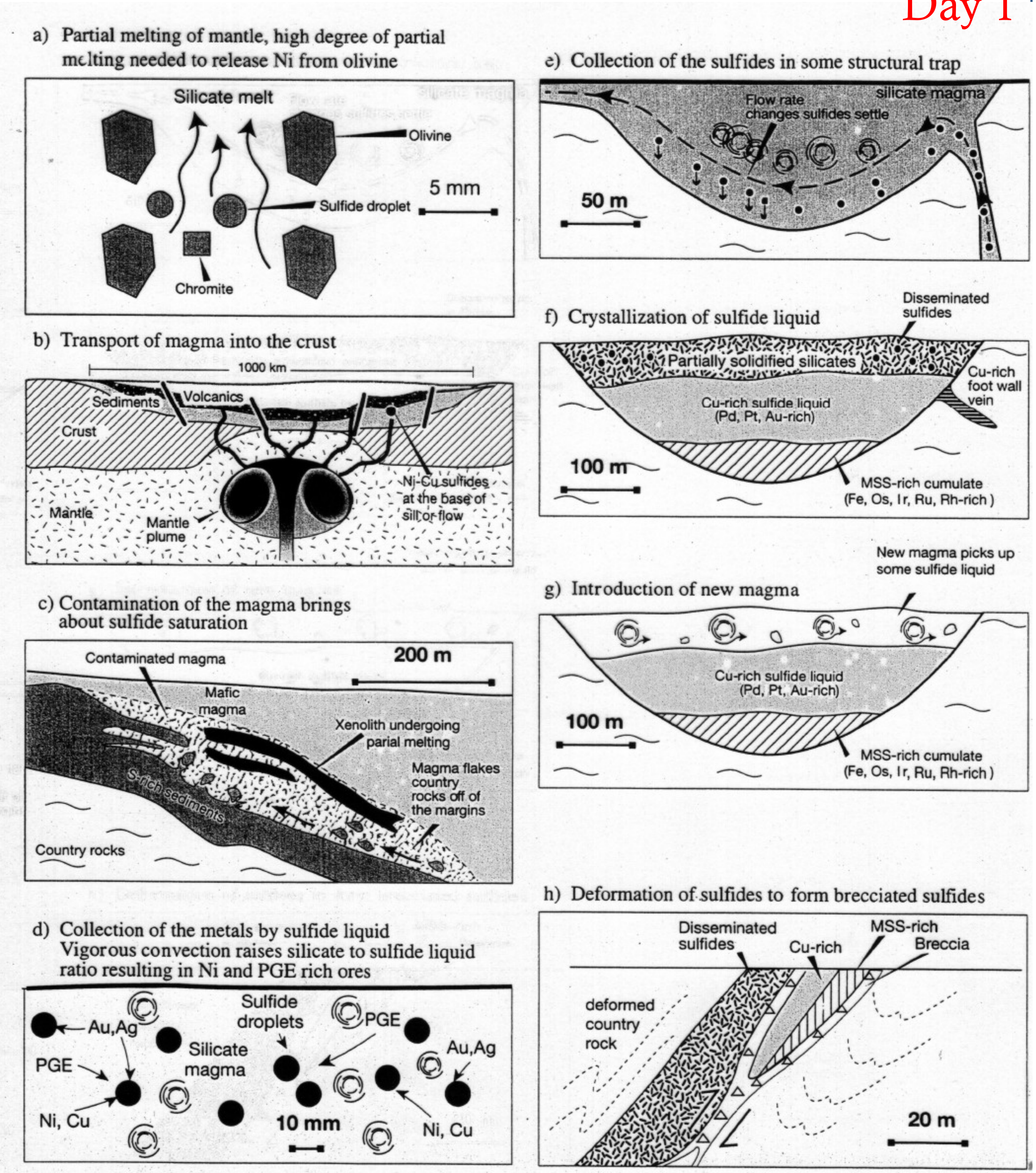
Figure 1.18 A portion of the ternary system quartz–olivine–chromite (a) showing the nature of crystallization in a mafic magma (b). Scenarios in which magma mixing (c) and magma contamination (d) occur as mechanisms for promoting the transient crystallization of only chromite are also shown (after Irvine, 1977).

Magmatic Cu-Ni sulphide deposits

- A relatively uncommon class of ore deposits: mineralisation is simple, composed typically of pyrrhotite (FeS), pentlandite [$(Fe,Ni)_9S_8$], chalcopyrite ($CuFeS_2$) and magnetite as the principal metal hosts.

- Ore grades are variable from one deposit to another, but in general, those associated with ultramafic rocks have a **low** Cu/Ni ratio whilst those associated with mafic (gabbroic) rocks have a **high** Cu/Ni ratio.

Genetic model for Ni-Cu sulphide deposits



a) Partial melting of mantle, high degree of partial melting needed to release Ni from olivine

b) Transport of magma into the crust

c) Contamination of the magma brings about sulfide saturation

d) Collection of the metals by sulfide liquid Vigorous convection raises silicate to sulfide liquid ratio resulting in Ni and PGE rich ores

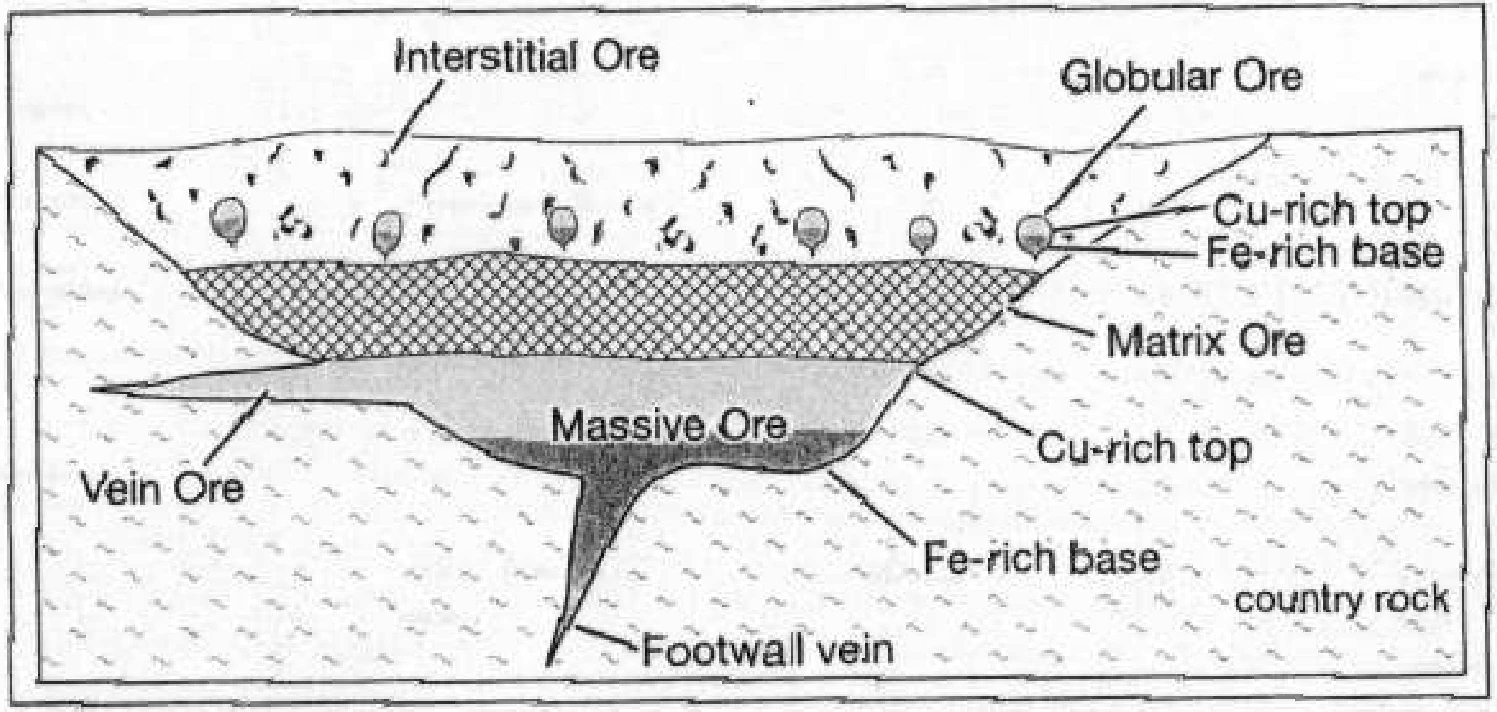
e) Collection of the sulfides in some structural trap

f) Crystallization of sulfide liquid

g) Introduction of new magma

h) Deformation of sulfides to form brecciated sulfides

Anatomy of magmatic Ni-Cu sulphide deposits



Idealized sketch of the relationship between massive, matrix, disseminated, and vein sulfides (modified after Barnes et al., 1997b).

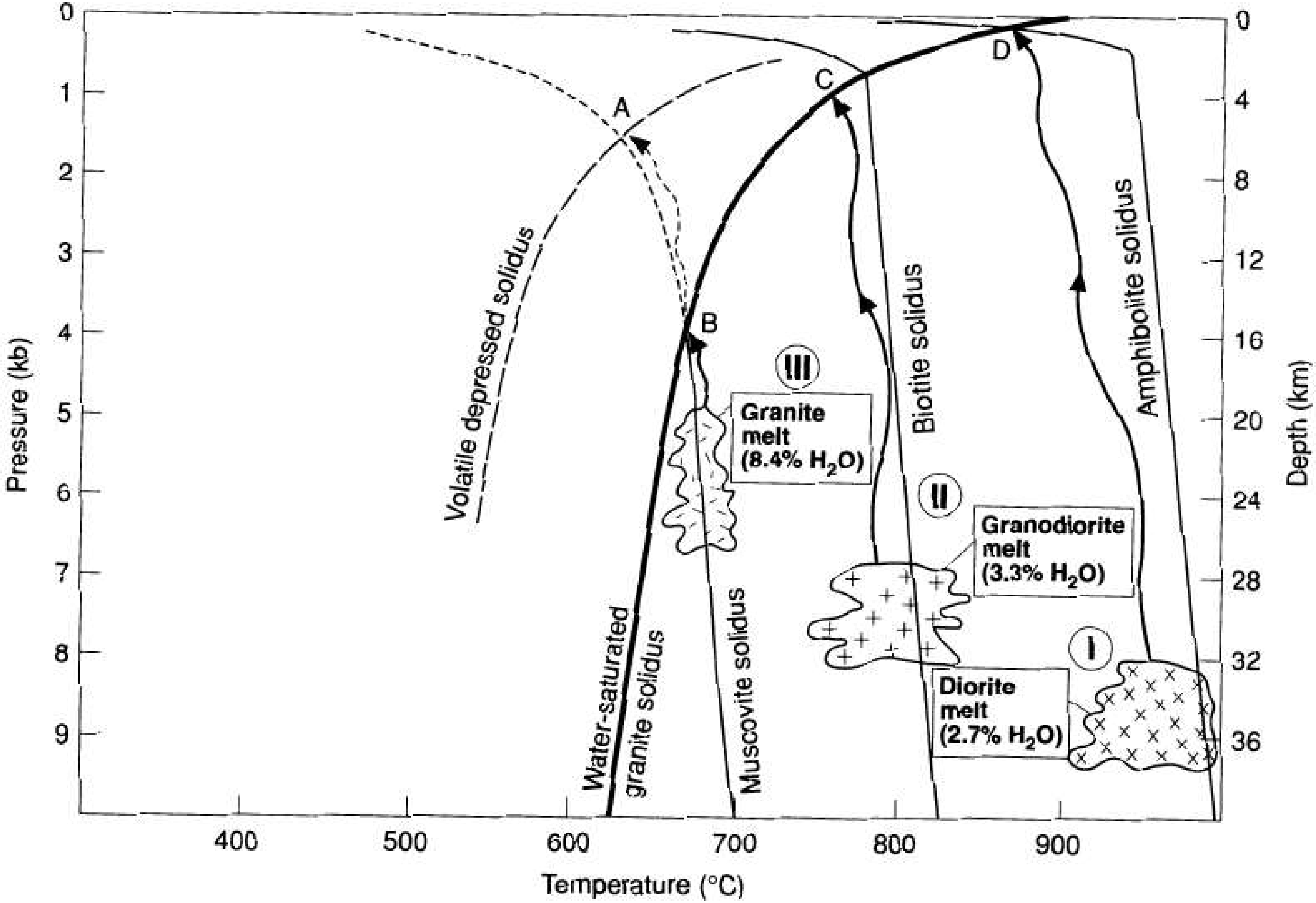
Ore-forming processes in granites: the role of H_2O

- Most of the water present in granitic magmas is derived from dehydration of minerals in the crust that were themselves melted to form the magma, without the need for the presence of free water in the rock.

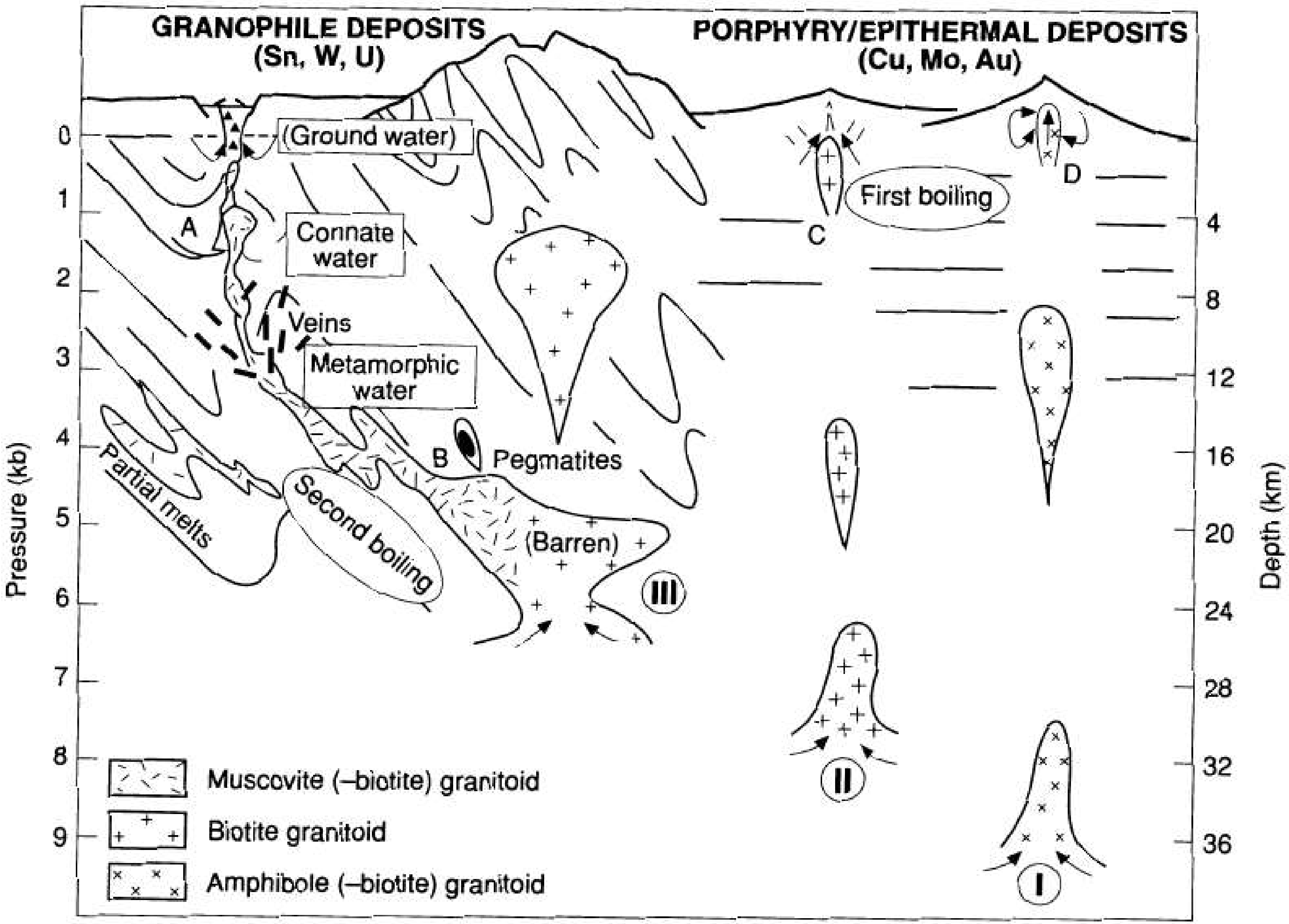
- Melting of a muscovite+biotite-bearing rock (typically meta-sediments) is likely to yield peraluminous, *S-type* granite compositions. These relatively "wet" granites are common hosts to deposits of **Sn**, **W** and **U**.

- By contrast, melting of predominantly biote/hornblende-rich protoliths (represented by meta-igneous rocks) will yield metaluminous, *I-type* granitic compositions. The **porphyry Cu-Mo(+Au)** suite of ore deposits are associated globally with the latter, which are typically relatively "dry" compared to the S-type granites.

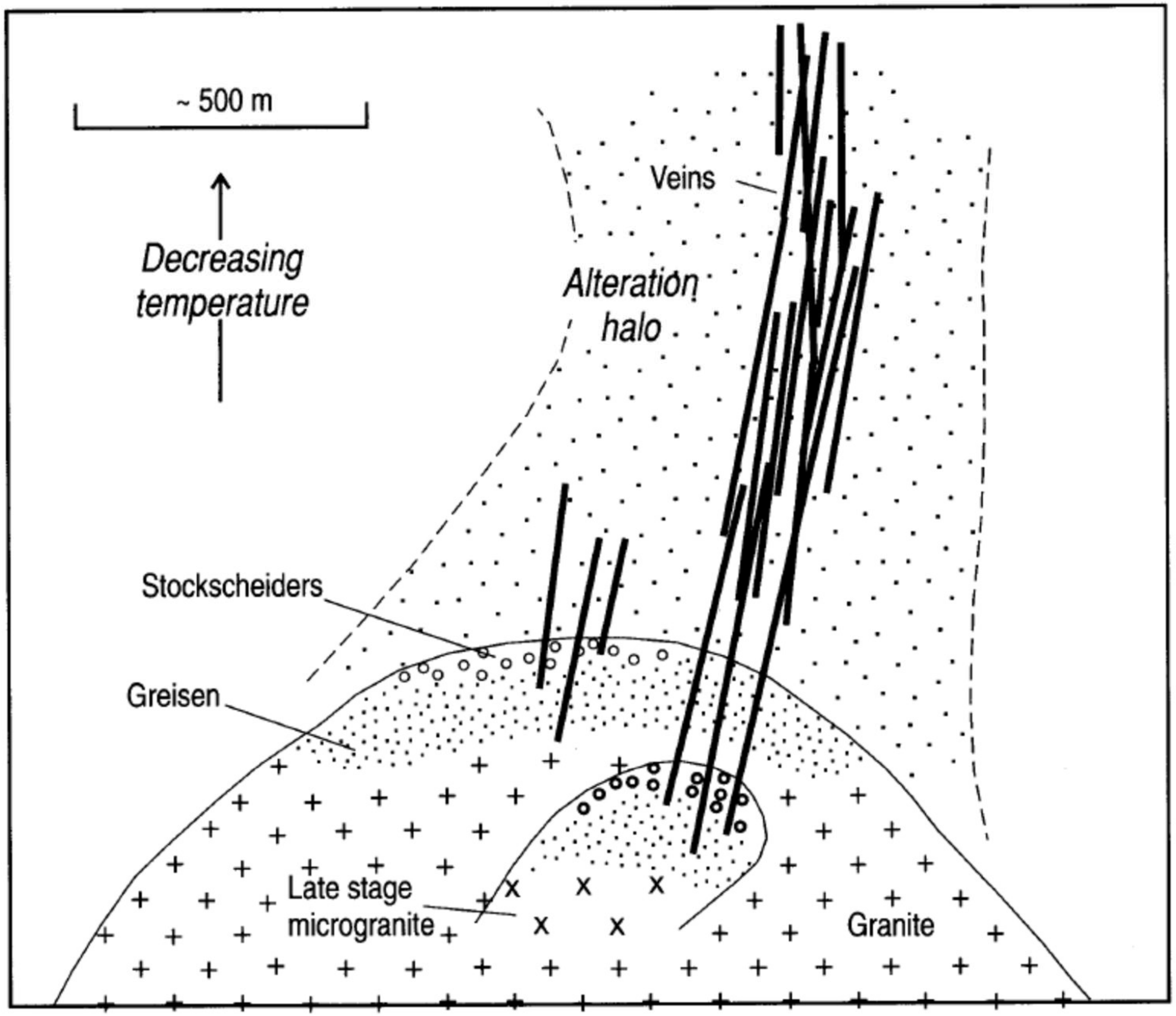
Granite-related ore-genesis: the role of water



Granites and mineralisation

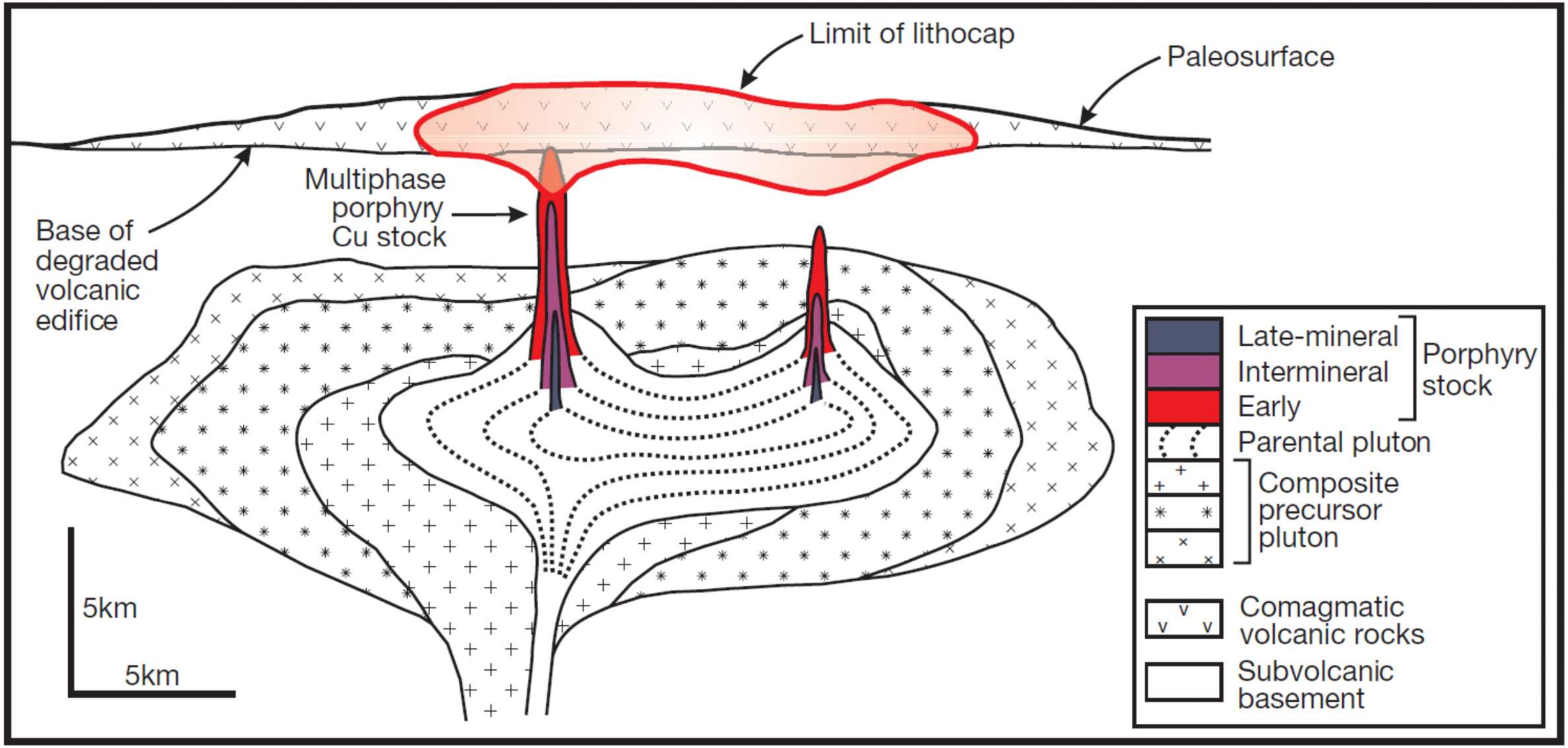


Hydrothermal mineralisation in S-type granites

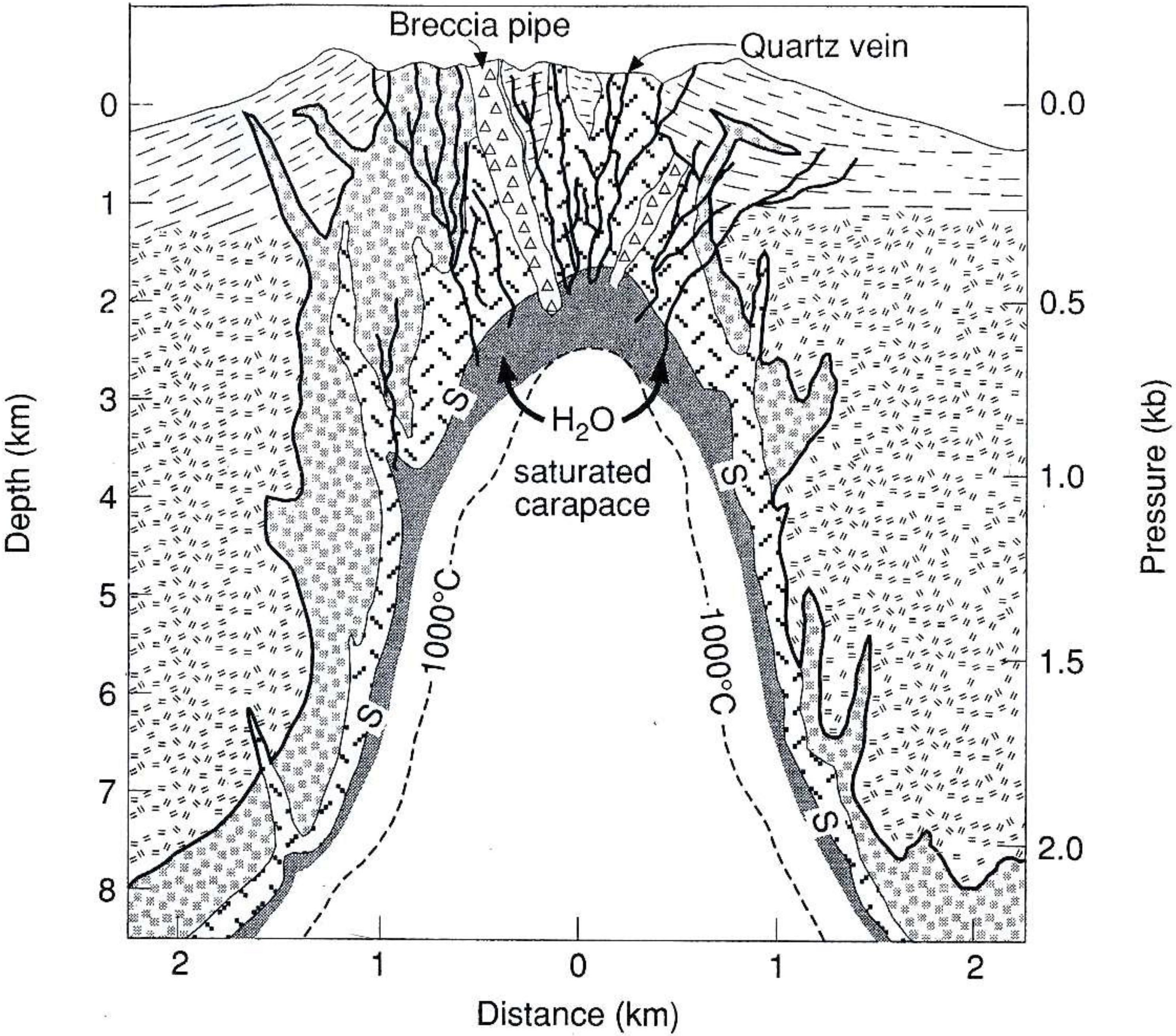


Schematic vertical section across a typical hydrothermally mineralized granite cupola, showing salient features of shallow granite-related Sn-, W-, and Mo-mineralized systems.

I-type granites and the porphyry ore-forming system



Fluid circulation around a porphyry system




AEG 25
Day 1

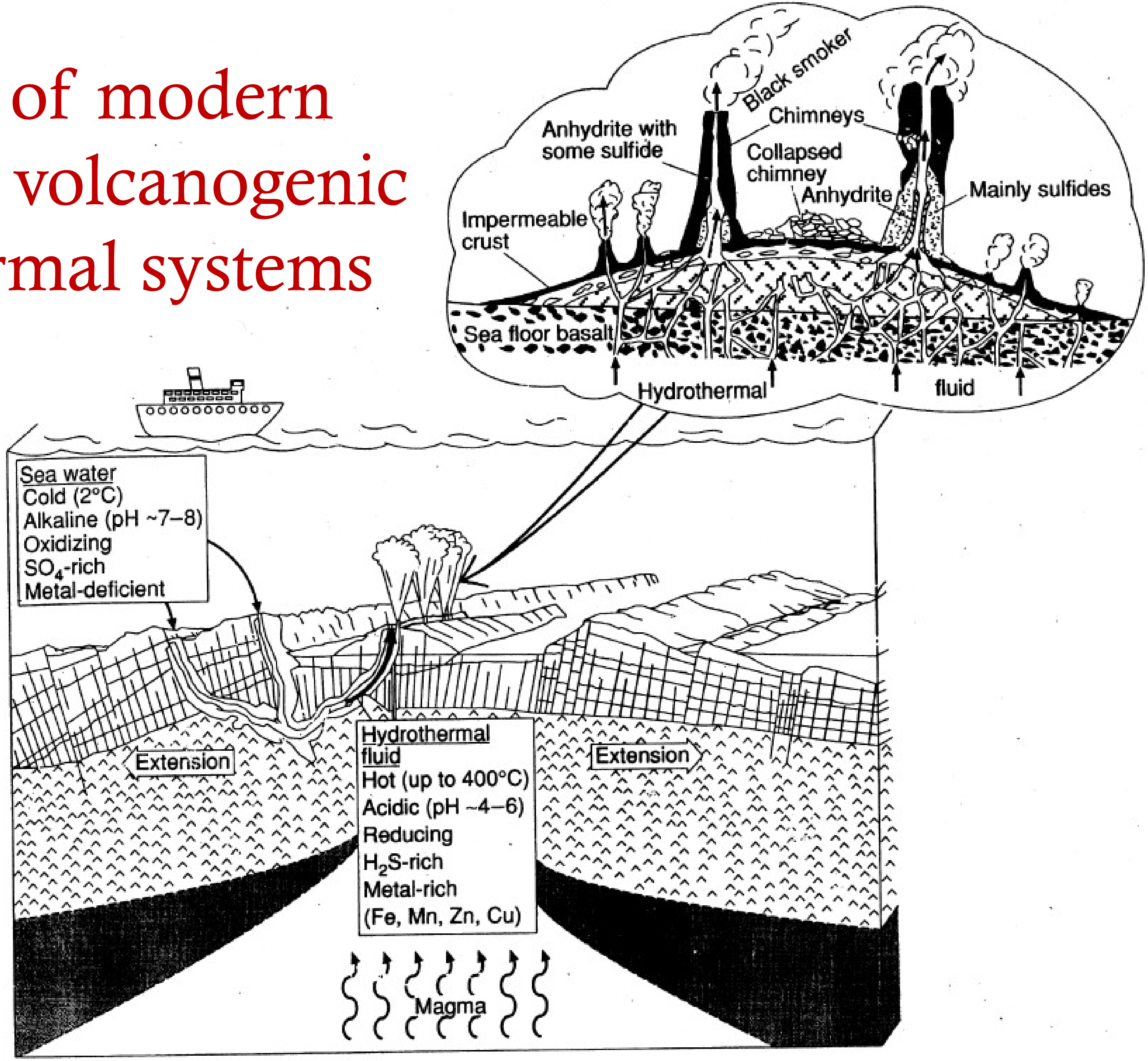

AEG 25

Day 1

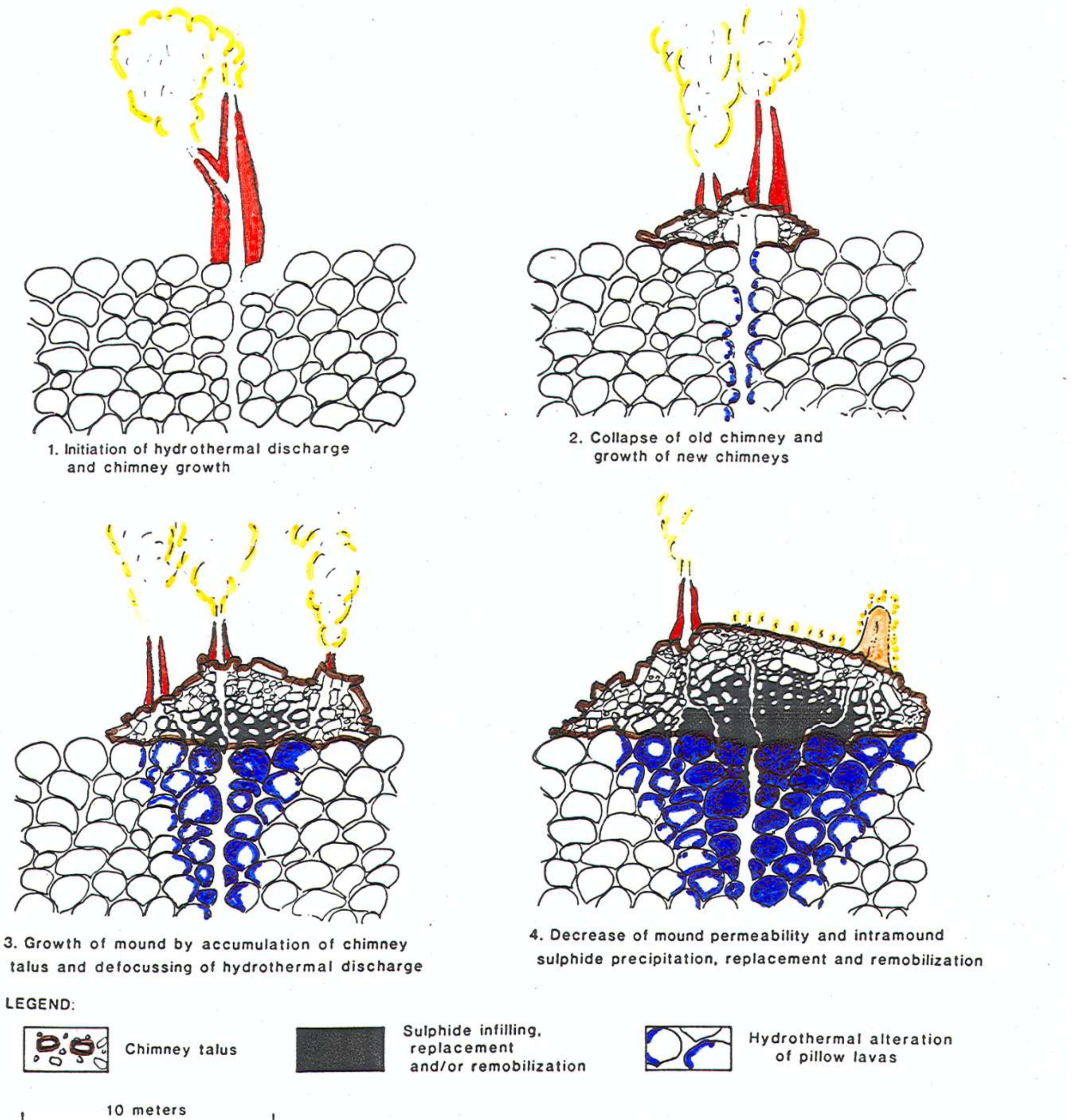
Hydrothermal ore formation in the marine realm

- Volcanogenic massive sulphide deposits, or ***VMS***, epitomise processes of ore-deposit formation in the marine environment, as a result of seawater circulation through volcanically active spreading centres;
- VMS deposits are typically poly-metallic, containing accumulations of sulphides of Cu, Zn and Pb.
- Sedimentary-exhalative deposits, or ***SEDEX***, contain more than half of the world's known resources of Pb and Zn and are generally represented by bigger and richer (albeit fewer) deposits than the VMS class;
- SEDEX deposits are typically formed within intracratonic to plate-margin rift basins and are hosted by marine clastic or chemical sediments that exhibit little or no direct association with volcanic rocks.

Genesis of modern submarine volcanogenic hydrothermal systems



Evolution of a black smoker vent *en route* to a mound-like VMS orebody



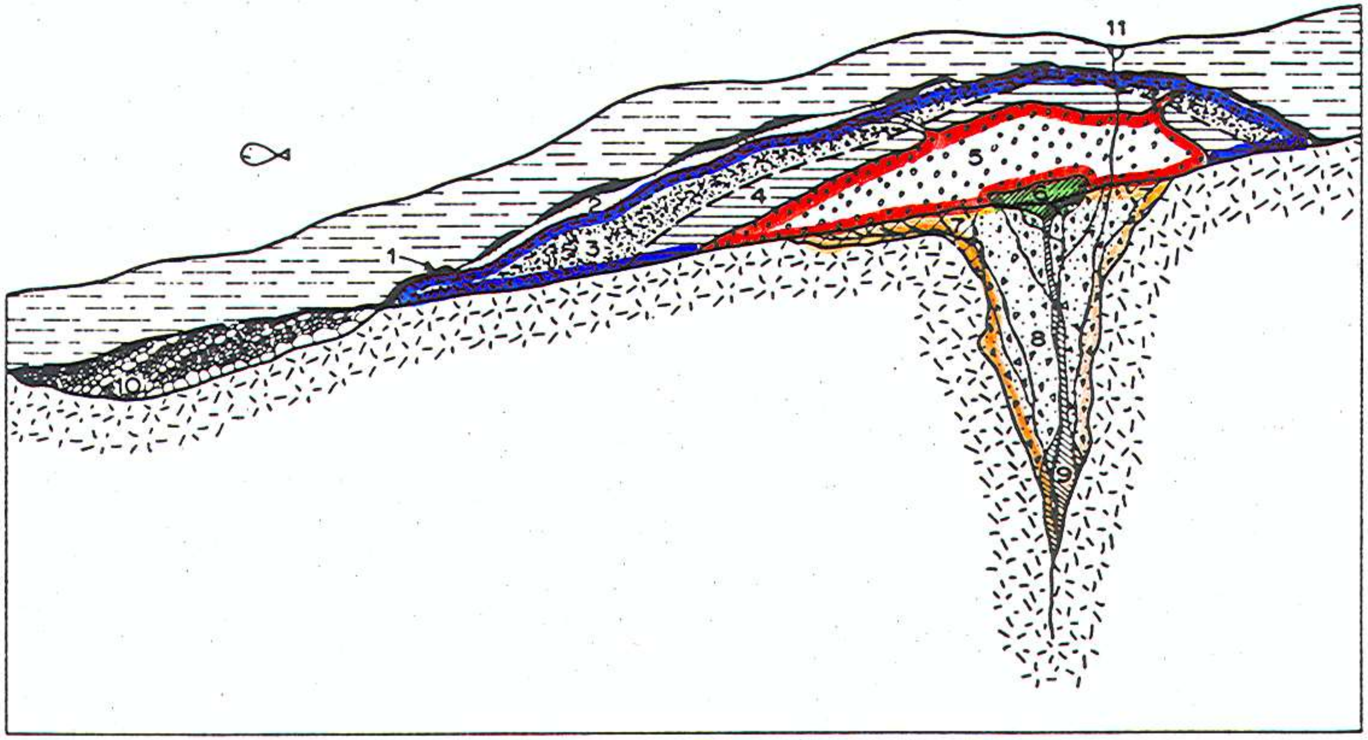
1. Initiation of hydrothermal discharge and chimney growth

2. Collapse of old chimney and growth of new chimneys

3. Growth of mound by accumulation of chimney talus and defocussing of hydrothermal discharge

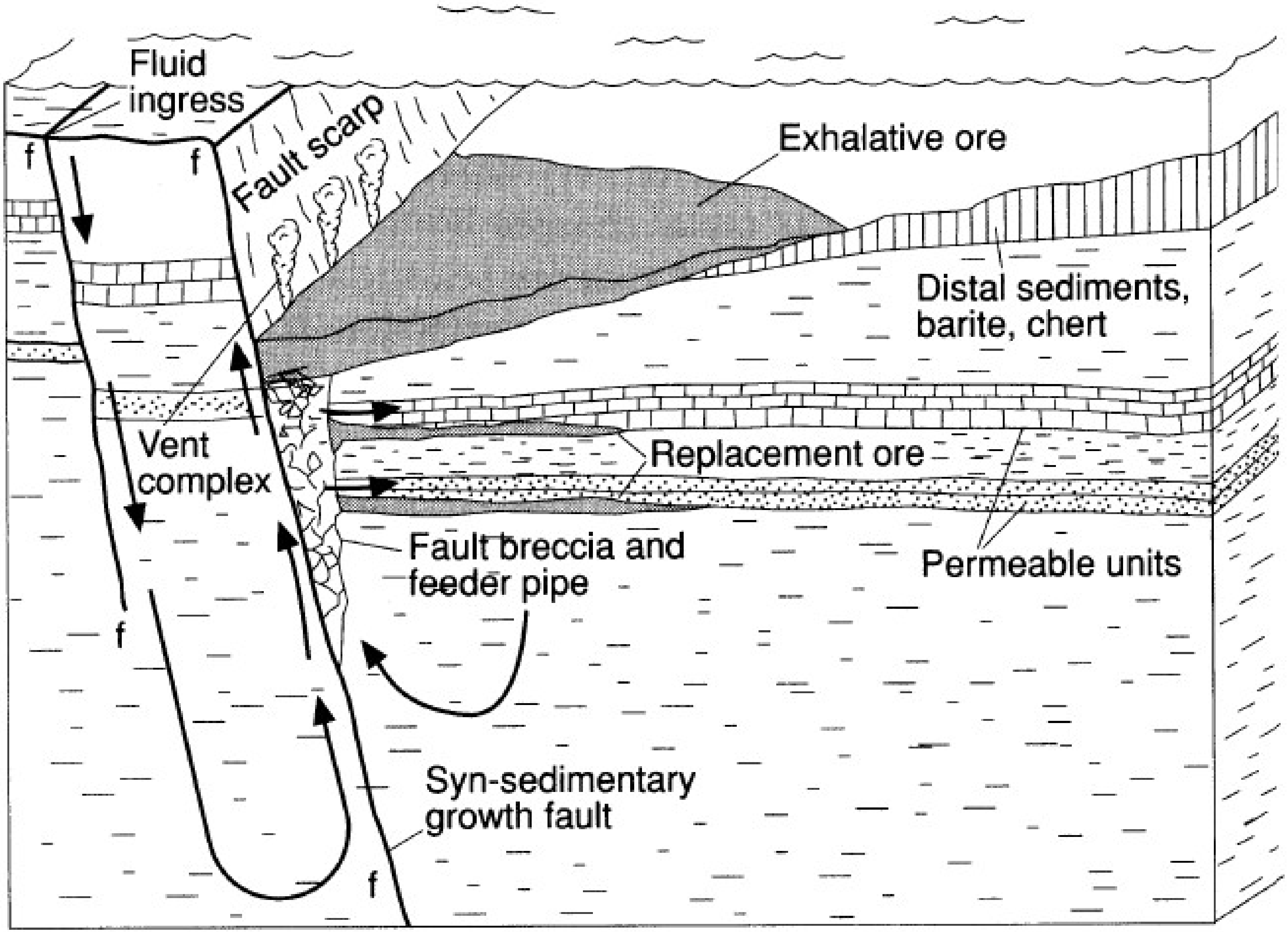
4. Decrease of mound permeability and intramound sulphide precipitation, replacement and remobilization

Architecture of a classic Kuroko-type VMS deposit

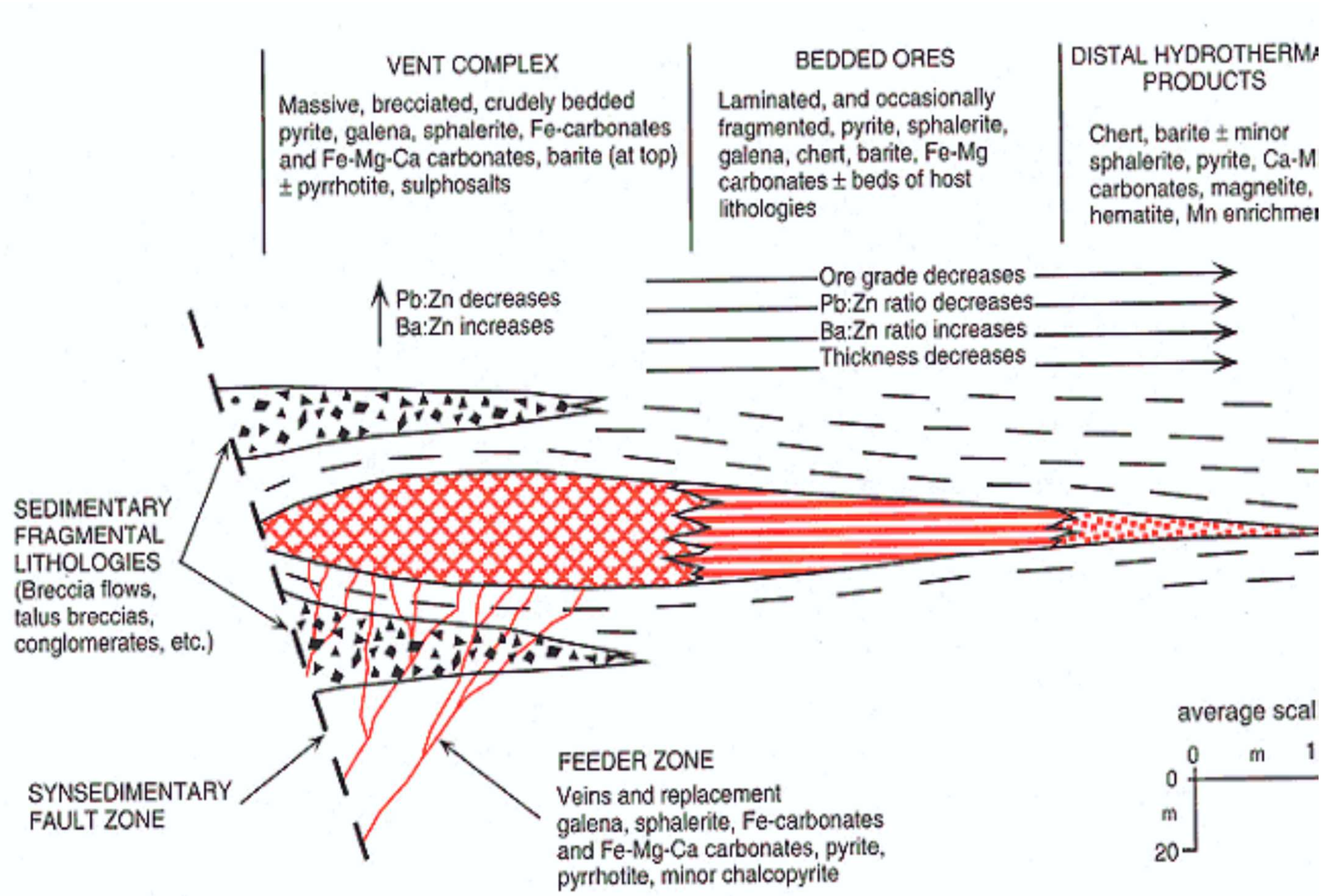


An idealized representation of a relatively undisturbed Kuroko deposit. 1 = tetsusekiei or chert-hematite layer, 2 = barite ore, 3 🟦 massive black ore (sphalerite + pyrite + galena + barite) where the fine dotted line separates the overlying fine-grained ore from the coarser grained ore below, 4 🟦 massive semiblack ore (sphalerite + pyrite + chalcopyrite), 5 🟥 massive yellow ore (chalcopyrite + pyrite), 6 🟩 massive pyrite ore (pyrite + quartz), 7 = siliceous black ore (sphalerite + pyrite + galena + quartz) 8 = siliceous yellow ore (chalcopyrite + pyrite + quartz), 9 = siliceous pyrite ore (pyrite + quartz), 10 = transported, fragmental massive ore (mostly black), 11 = late-stage sulfide veins which can be either black or yellow ore. Though gypsum ore is often present underneath and peripheral to massive ores, we did not examine any in this study and have chosen to delete it for the sake of simplicity.

Sedimentary-exhalative (SEDEX) Pb-Zn deposits



Anatomy of a SEDEX ore-body



Mississippi-Valley type (MVT) Pb-Zn deposits

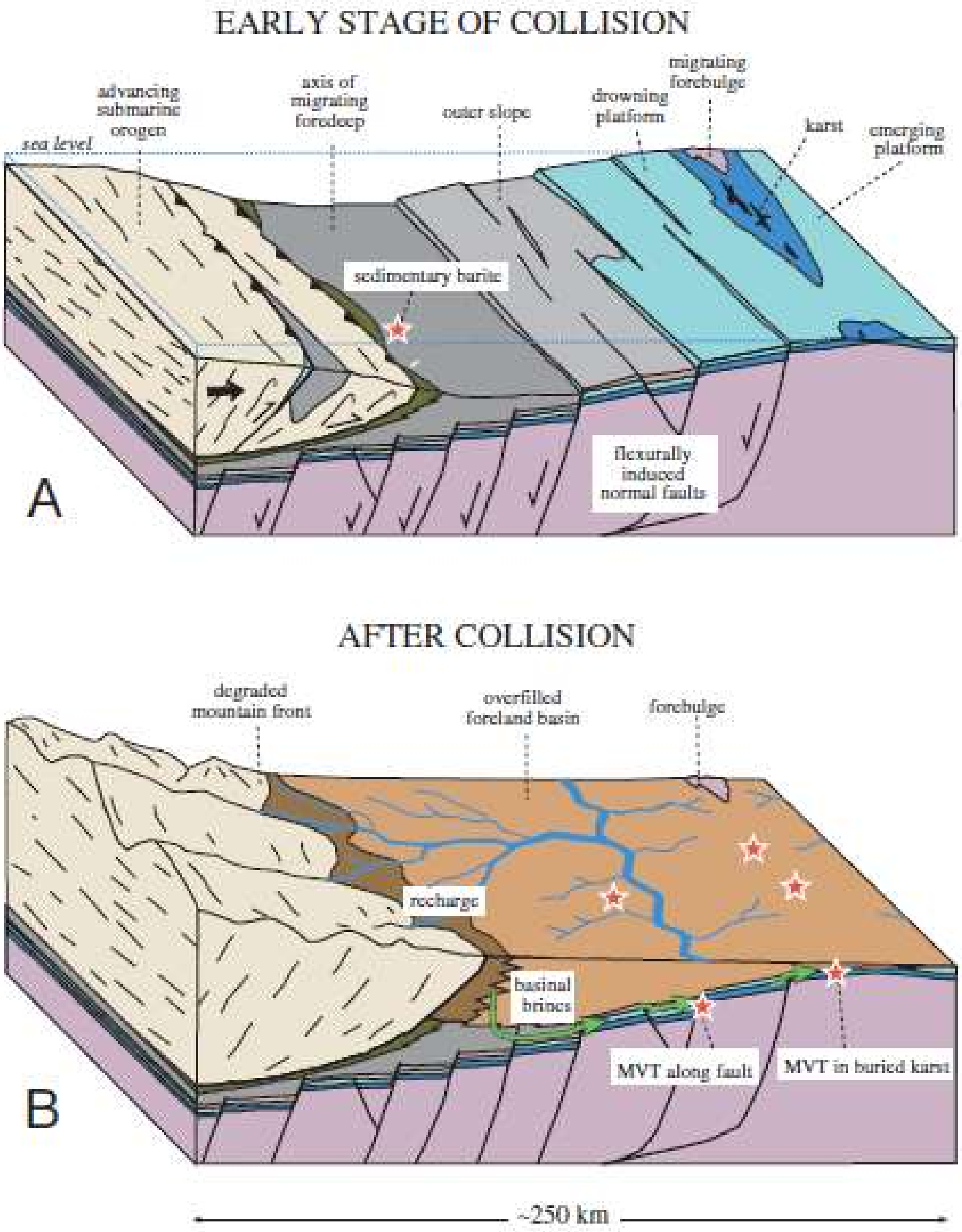
- MVT-type deposits owe their origin to fluid circulation and metal transport and deposition within sedimentary basins.

- They are distinctly epigenetic deposits, and the contained metals can be deposited on the order of tens of millions of years after host-rock deposition.

- MVT deposits form from relatively low-T fluids (<150^{o}C) and are mainly carbonate- (most commonly dolostone-) hosted.

- From a mineralogical point of view, MVTs are simple: they are dominated by sulphides of Zn (sphalerite) and Pb (galena), along with some fluorite and barite.

Geotectonic setting of MVT deposit formation

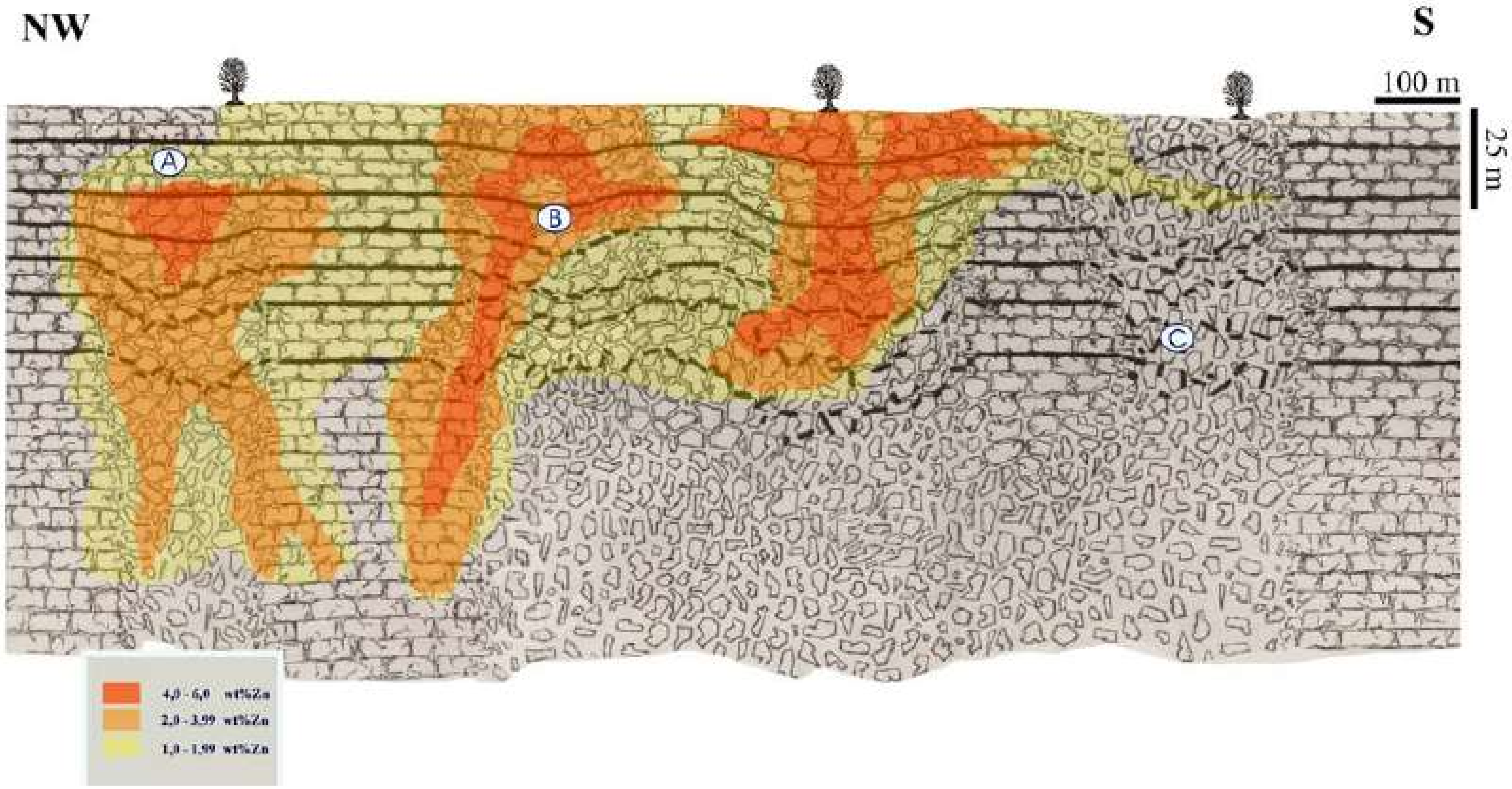


Anatomy of an MVT deposit

- Although MVTs are frequently bedded and focused along conformable dolostone/limestone contacts, their most common occurrence is in the form of discordant, dissolution-related *breccia* zones.

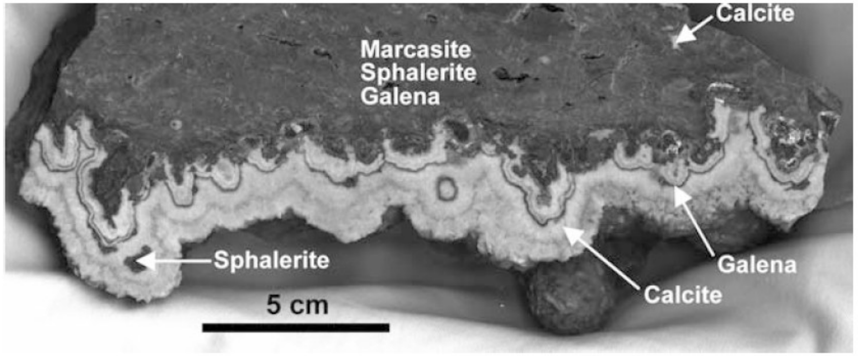
- These structures may pre-date the mineralising event due to, for example, pre-existing karst features; alternatively, the breccia bodies can form during metal deposition, i.e., by carbonate dissolution caused by the mineralised fluids themselves, provided that the fluids were acidic enough or became such by the precipitation of sulphides:

$$H_2S + Zn^{2+} \leftrightarrow ZnS + 2H^+$$



Idealized NW to S directed cross section through the Pering deposit. Note the obvious slumping of thin carbonaceous shale marker beds into the subvertical breccia bodies. Note also the close relation between style of brecciation and grade. Highest grades are restricted to the margins and roof zones of breccia bodies, where chemical breccia and mosaic breccia styles prevail. (*A*) denotes typical occurrence of crackle breccia, (*B*) of mosaic and chemical wear breccia and (*C*) of pyritic rock matrix breccia


a
4 cm


Calcite
Marcasite
Sphalerite
Galena
Sphalerite
5 cm
Calcite
Galena


c
4 cm

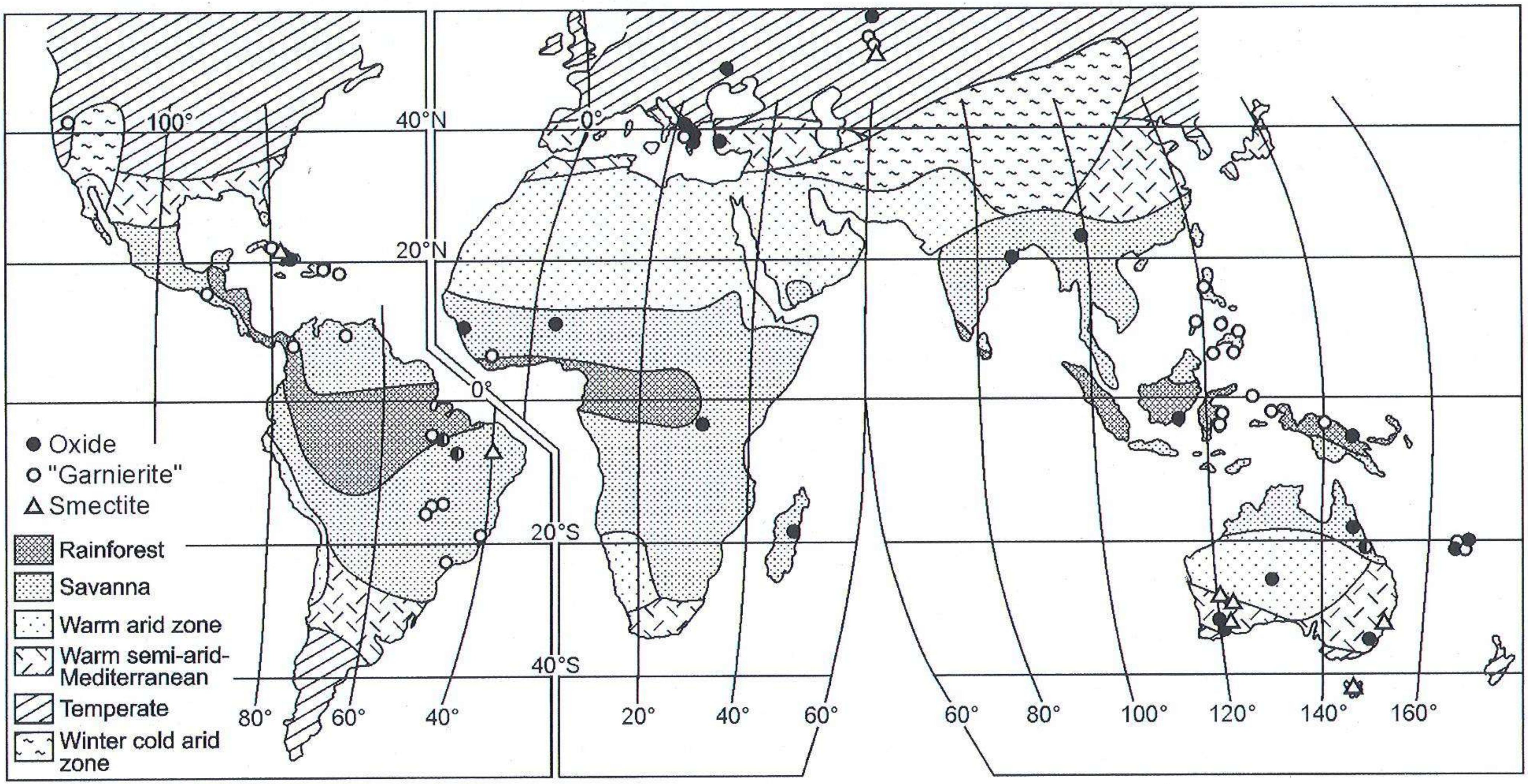
Lateritic deposits

Metallogenesis in the supergene environment involves three main processes:

- Dissolution of rock material and transport/removal of soluble ions by aqueous solutions;
- Production of new minerals, particularly clays, (hydr-)oxides and carbonates;
- Accumulation of residual insoluble material.

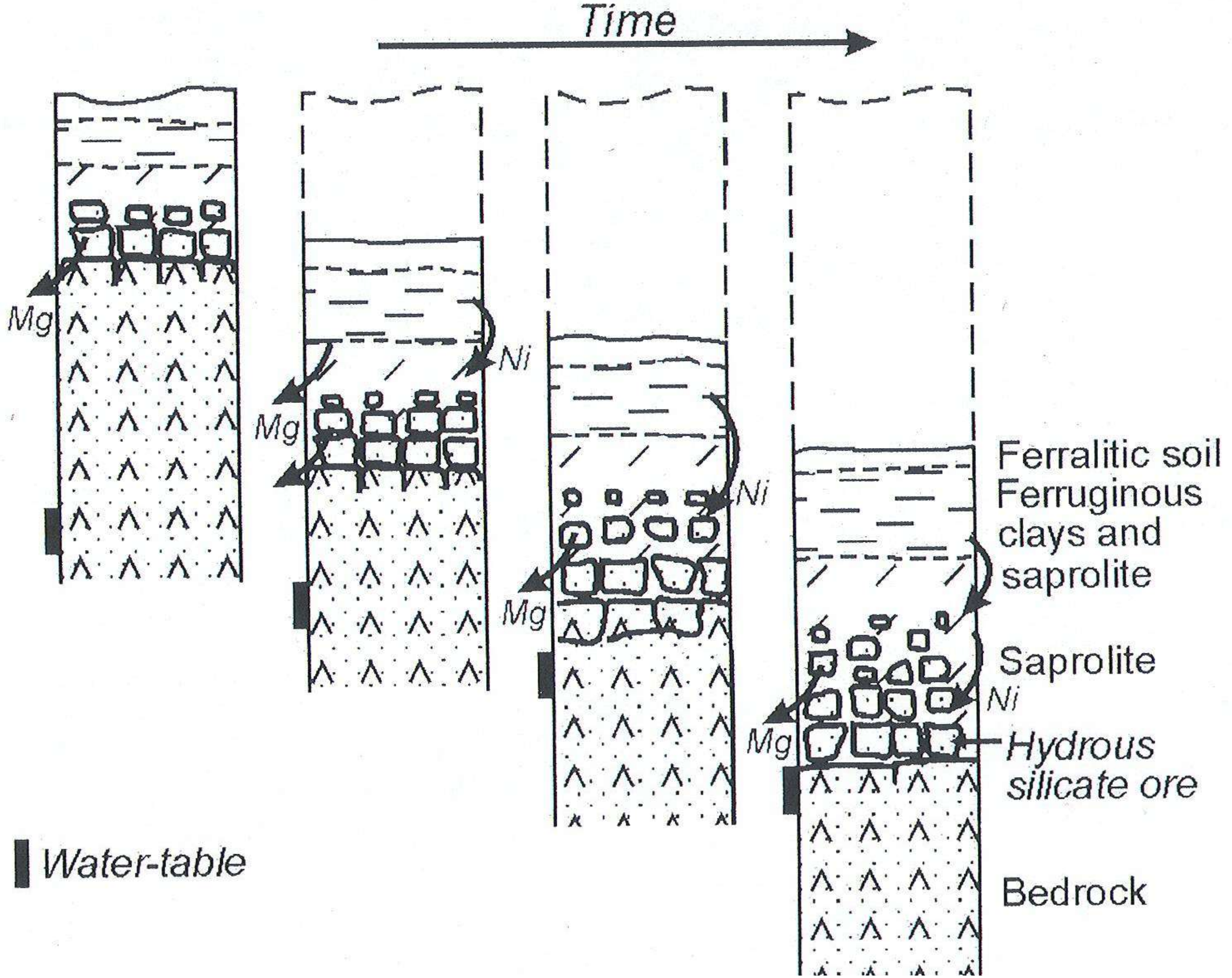
Each of the above processes has its own relevance with respect to ore formation in the (near-)surface environment.

Geographical distribution of lateritic deposits

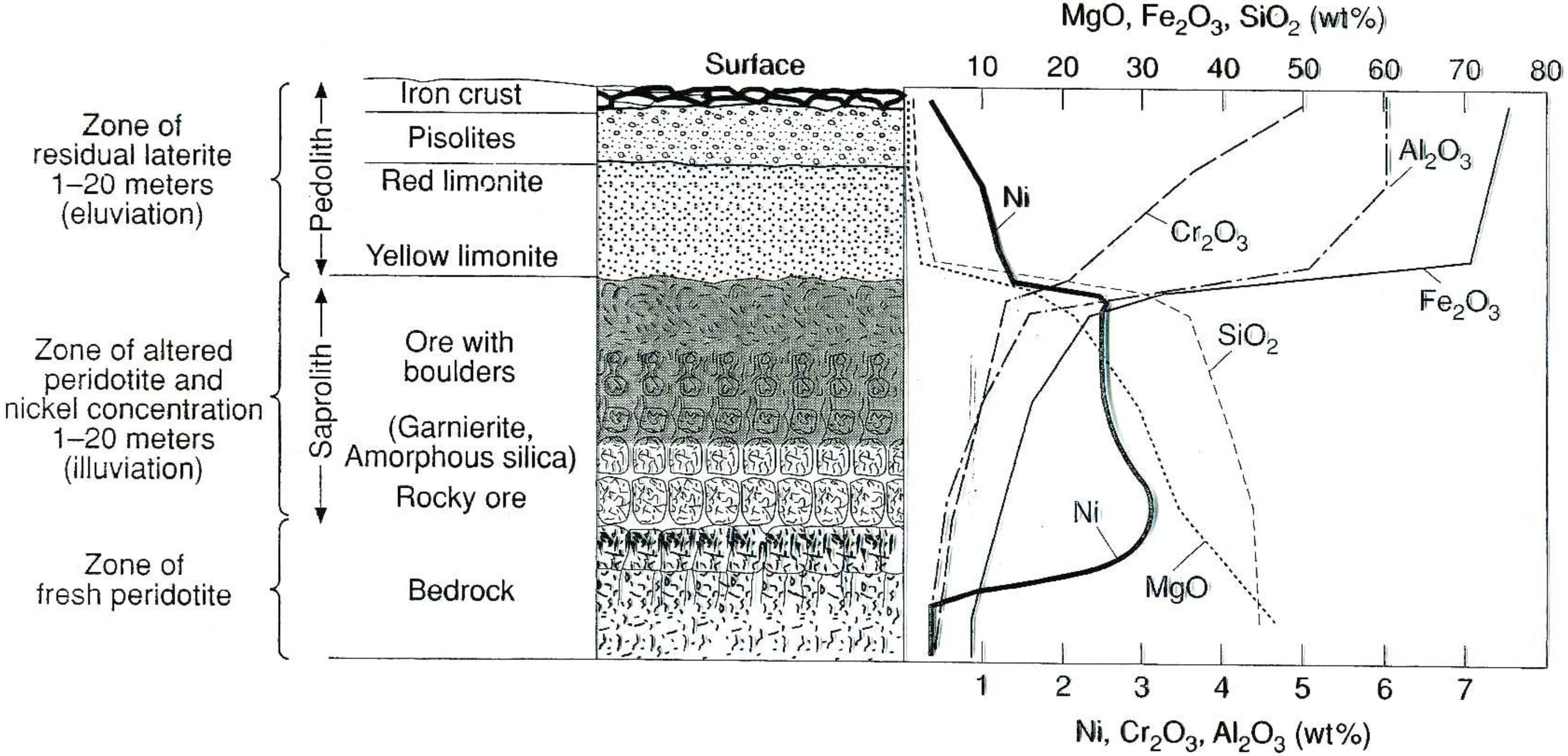


Global distribution of Ni laterite deposits, classified according to principal deposit type, on a morphoclimatic map (modified after Budel, 1982).

Lateritization and nickel ore-formation



Anatomy of a Ni-laterite deposit



Descriptive profile and Ni ore distribution in a lateritic regolith typical of the New Caledonian deposits. The chemical profile clearly distinguishes the ferruginous/aluminous residual zone where Si, Mg, and Ni are leached, from the saprolith where illuviation has resulted in concentration of Ni (after Troly *et al.*, 1979; Guilbert and Park, 1986).

Key textbook

Robb, L. (2005)
Introduction to ore-forming processes

Blackwell Science Ltd.
373p.