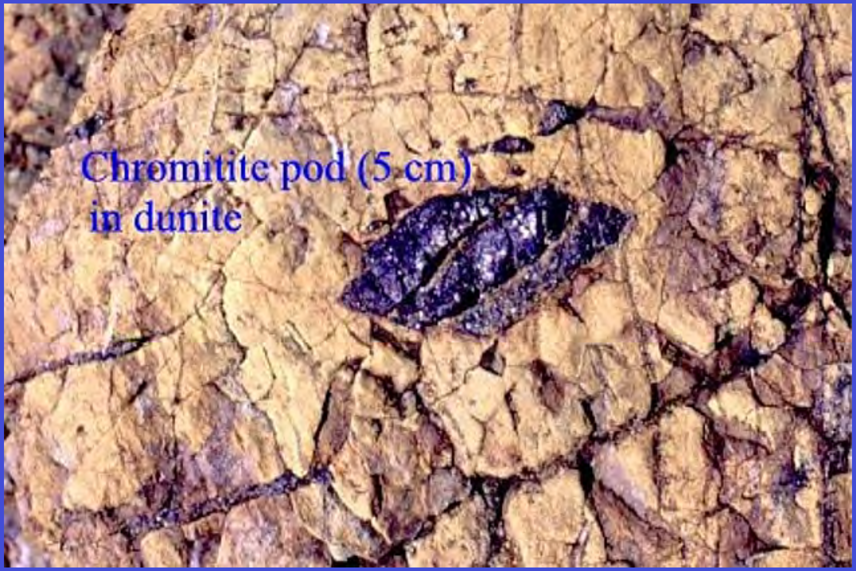
http://www.interactiveoceans.washington.edu/files/pillow.1470.anchor.web_med.jpg

http://www.esc.cam.ac.uk/images/research/research-group/terrestrial-geochemistry/sheeteddykes.jpg

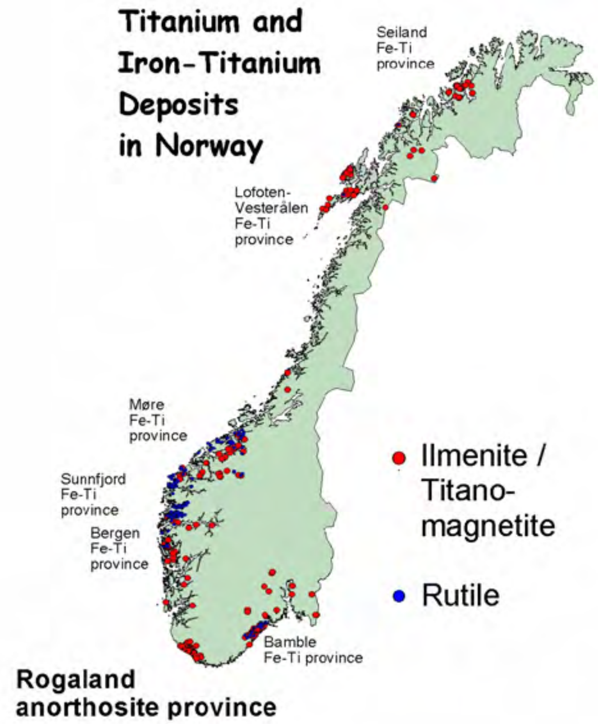
https://instruct.uwo.ca/earth-sci/200a-001/ophiolite/anorthperid.jpg



https://instruct.uwo.ca/earth-sci/200a-001/ophiolite/chromindunt.jpg

http://emvc.geol.ucsb.edu/2_infopgs/IP1GTect/fSFSpreadingSeries.html

Illmenite/Anorthosite deposit
Tellnes, Norway
(World's largest Titanium mine)



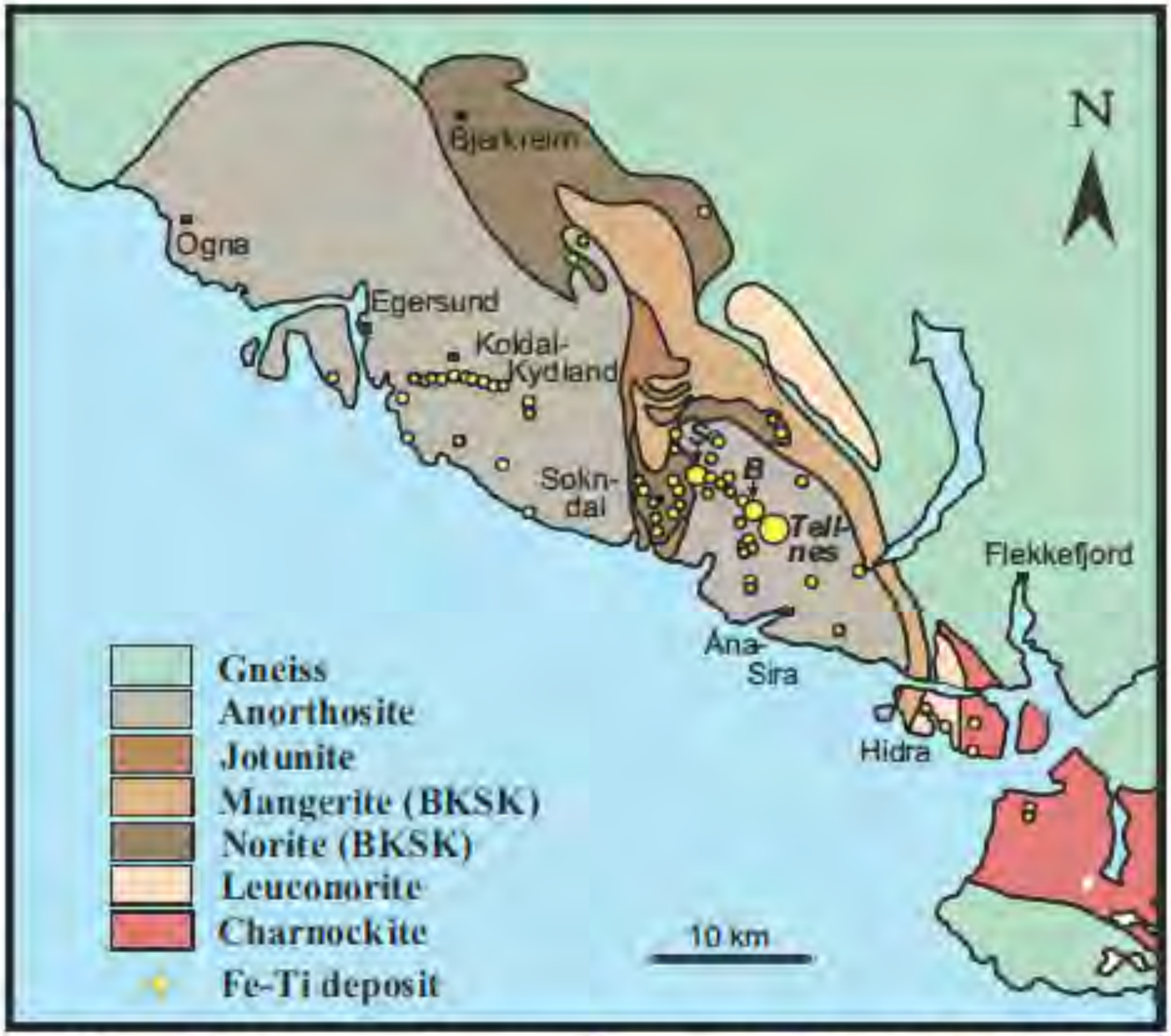


Fig. 2. Simplified geological map and ilmenite ore bodies in the Rogaland anorthosite province. S = Storgangen ilmenite deposit, B = Blåfjell ilmenite deposit. BKSK = rock units belonging to the Bjerkreim-Sokndal intrusion.

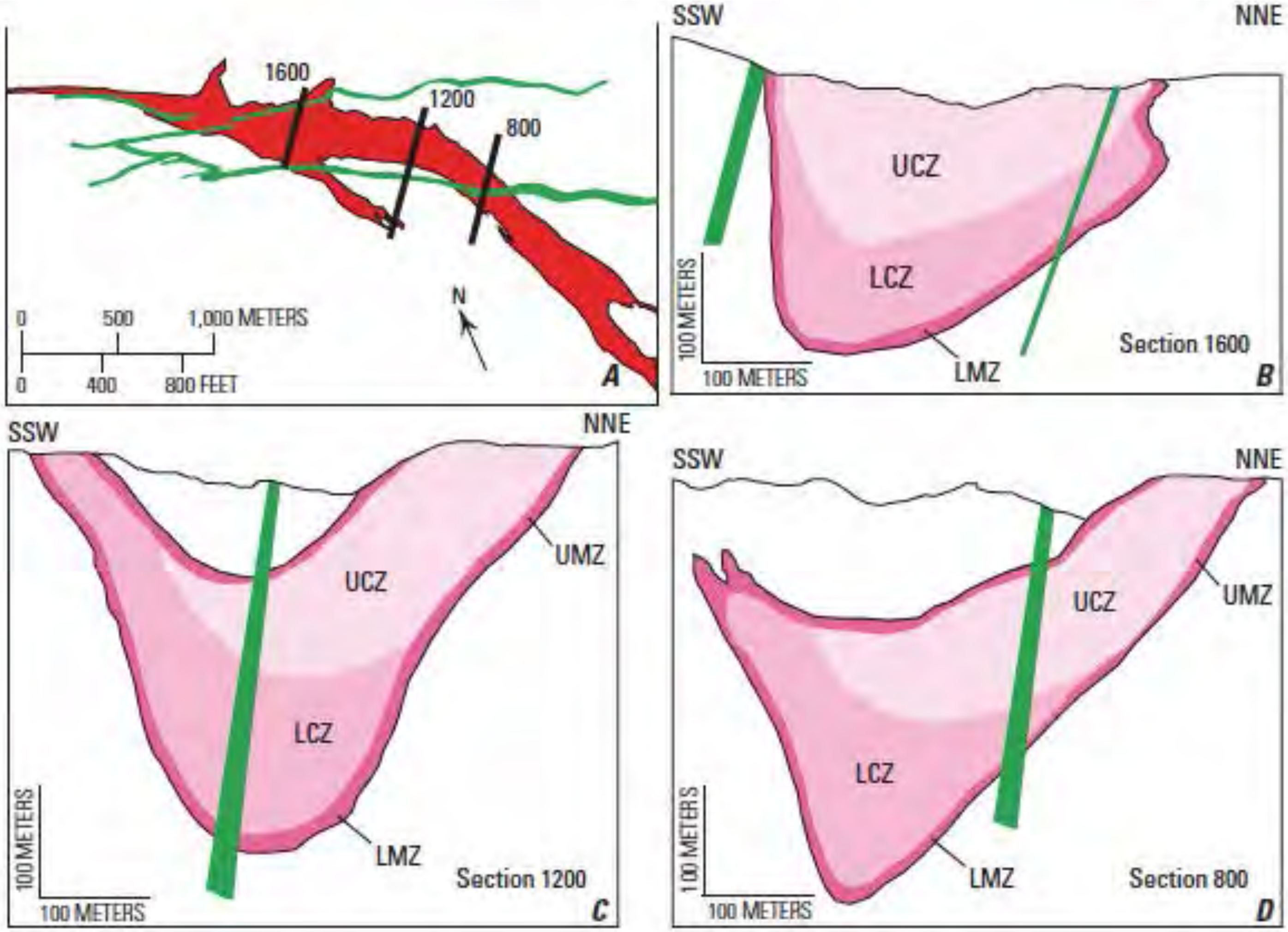


Figure 12. *A.* Location of three selected cross sections on the geological map of the Tellnes orebody, Norway (in red; cut by basalt dikes, in green; see fig. 7 for details); *B.* cross section 1600; *C.* cross section 1200; and *D.* cross section 800; cross sections are showing spatial distribution of the four different orebody zones, based on silicate and oxide mineralogy and concentration (modified from Charlier and others, 2006). UCZ = Upper central zone, with low plagioclase contents and high Fe-Mg-silicate and ilmenite contents; UMZ = Upper marginal zone with high plagioclase and Fe-Mg-silicate contents and low ilmenite contents; LCZ = Lower central zone with low Fe-Mg-silicate contents, plagioclase contents intermediate between the UCZ and UMZ, and the highest ilmenite contents; and LMZ = Lower marginal zone with decreasing ilmenite and increasing silicate contents.

What goes on within the magma chamber?

Multiple Magma Pulses (very simplified version):

Higher density pulse: new magma flows along chamber floor.

(eg Merensky & JM layered mafic intrusions)

Lower density pulse: new magma rises to chamber "ceiling".

(Eg Bushveld Cromite & Platinum Group Elements)

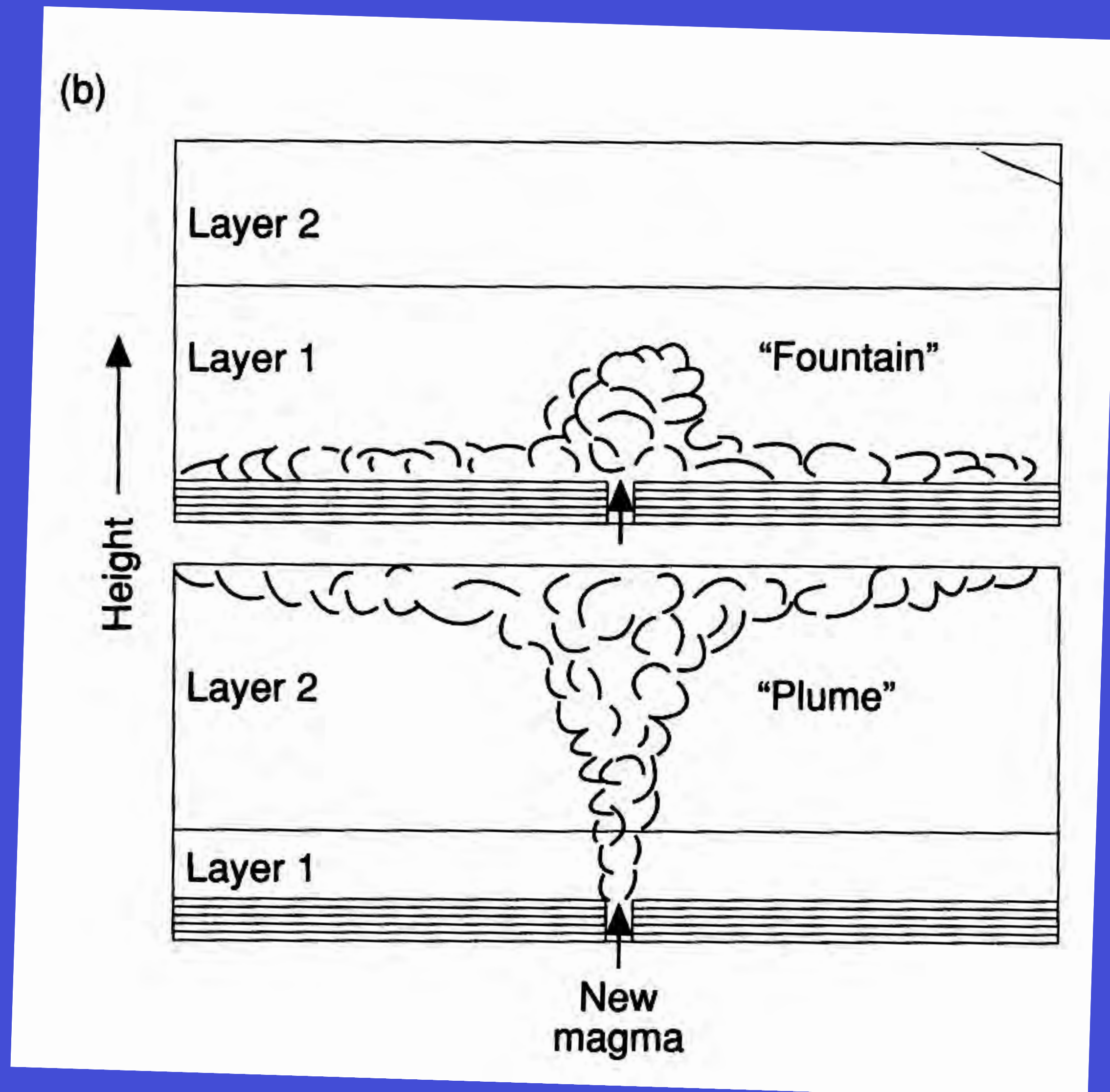


Figure 1.16 Robb (2005) Introduction to Ore Forming Processes

Mixed Archean magmas, Minnesota


Mixed Archean magmas, Minnesota


Mixed Archean magmas, Minnesota


Mixed Archean magmas, Minnesota


Mixed Archean magmas, Minnesota

Figure 2. Western Limb of the Bushveld Complex

Dwars River, Bushveldt Comples. Layers of Chromite and Anorthosite

Anorthosite (Calcium Plagioclase-white)
and Chromite layers (black)
Bushveld complex, South Africa

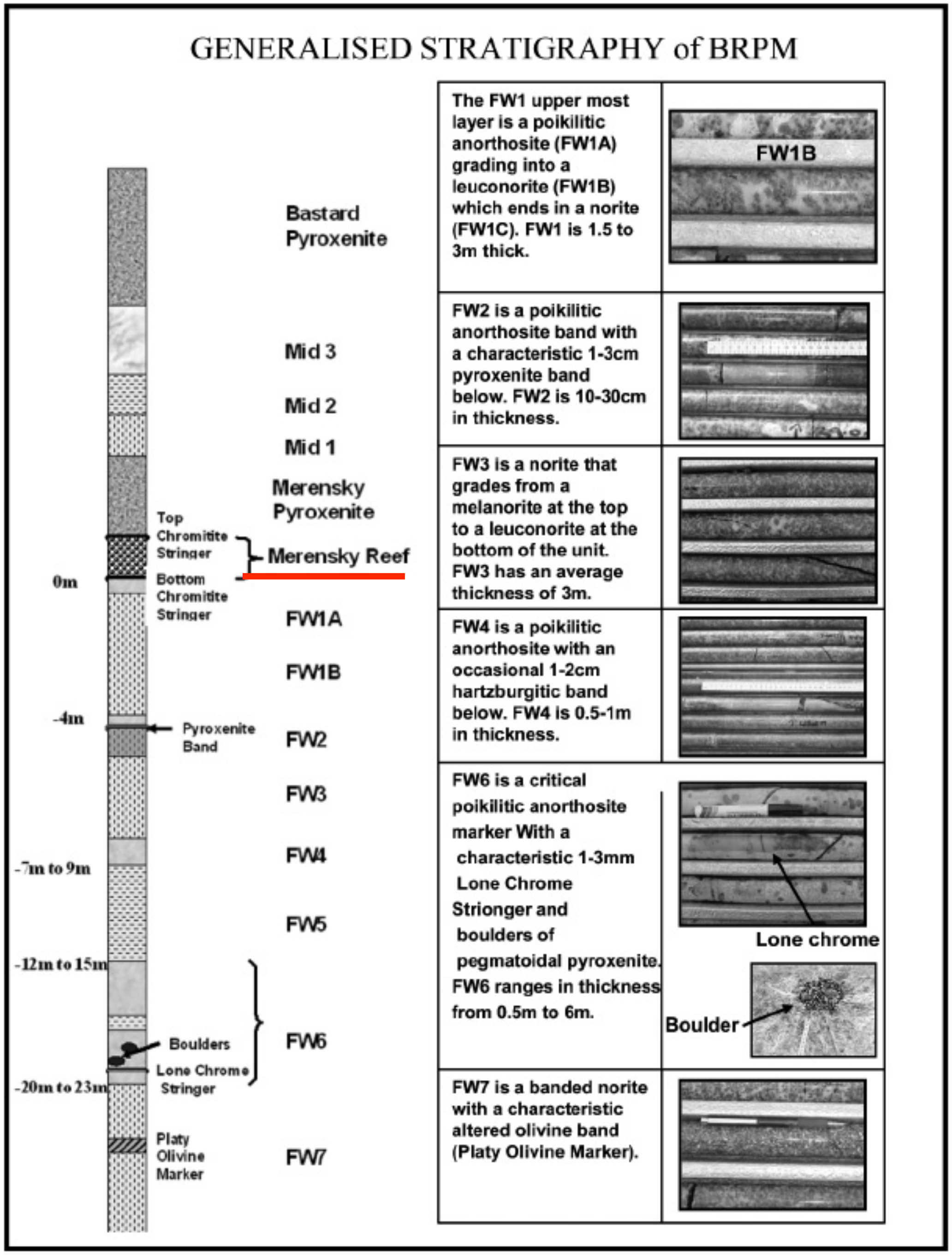
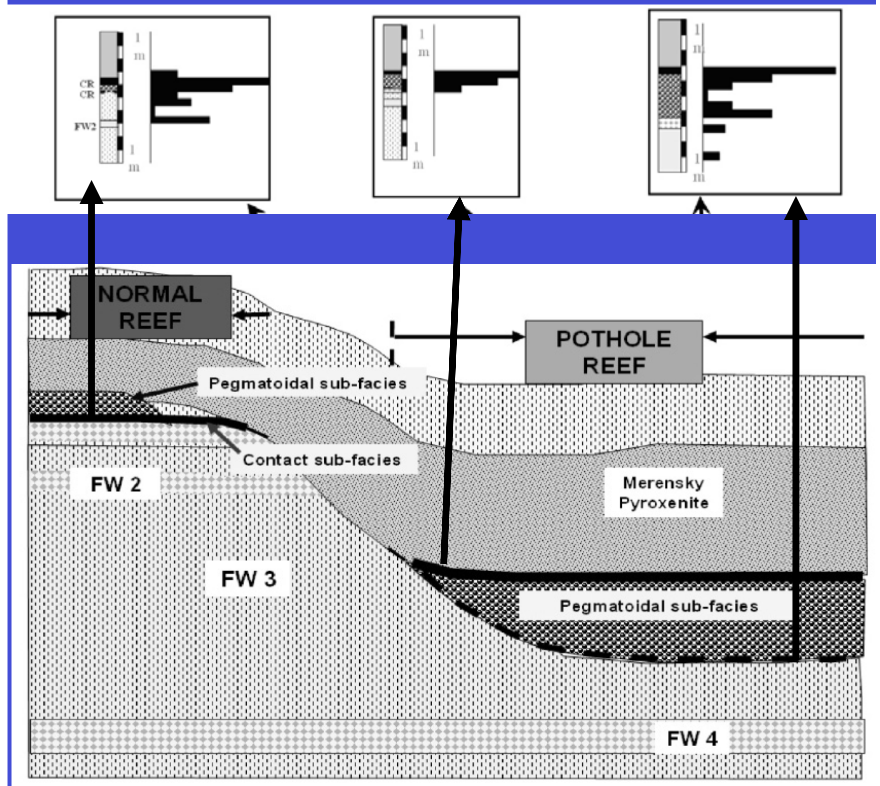


Figure 3. Generalized stratigraphy of BRPM



"Reef" facies and PGE grade (Moodley 2008)

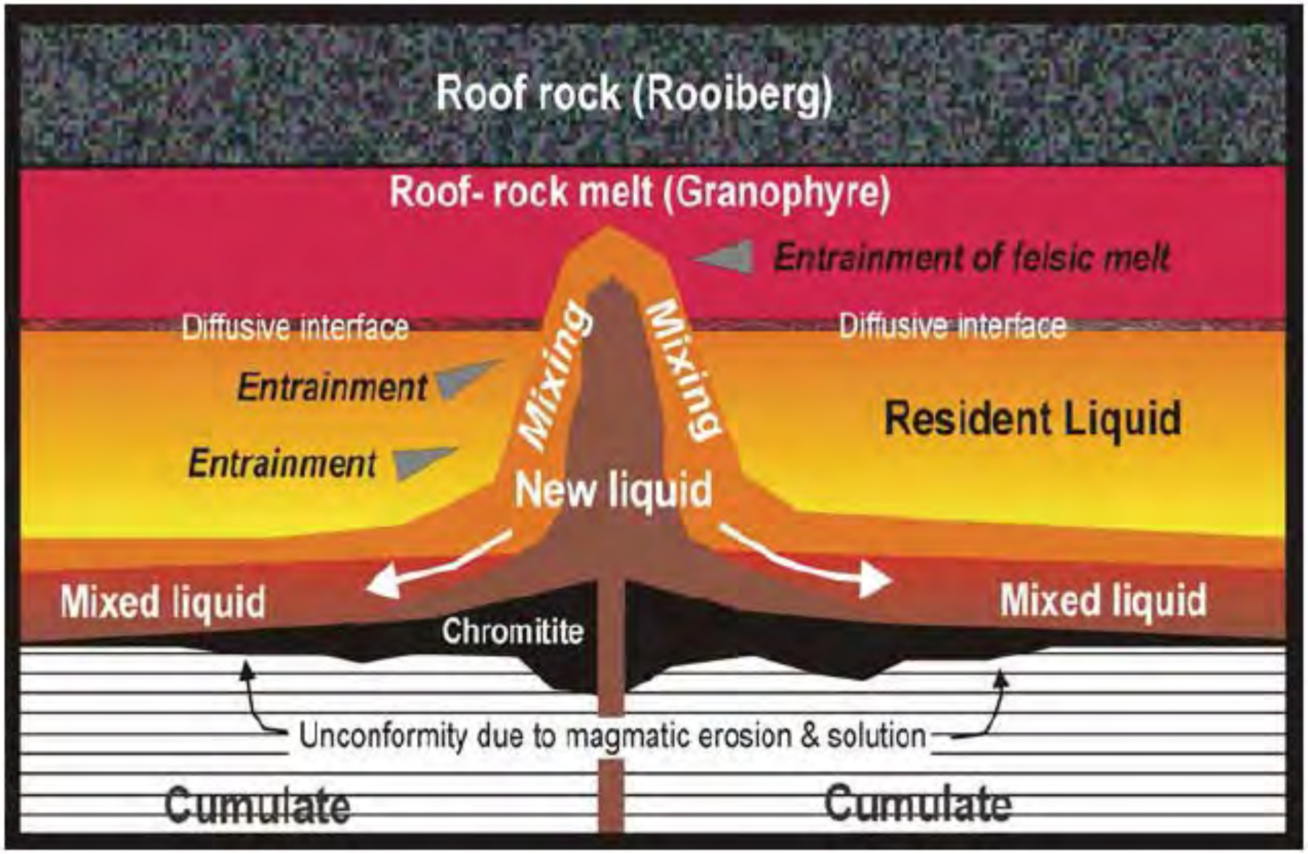


Figure 25 Schematic diagram of chromitite formation resulting from a fountain of magma into the chamber that partially melts roof rocks causing contamination and mixing (Kinnaird et al 2002)

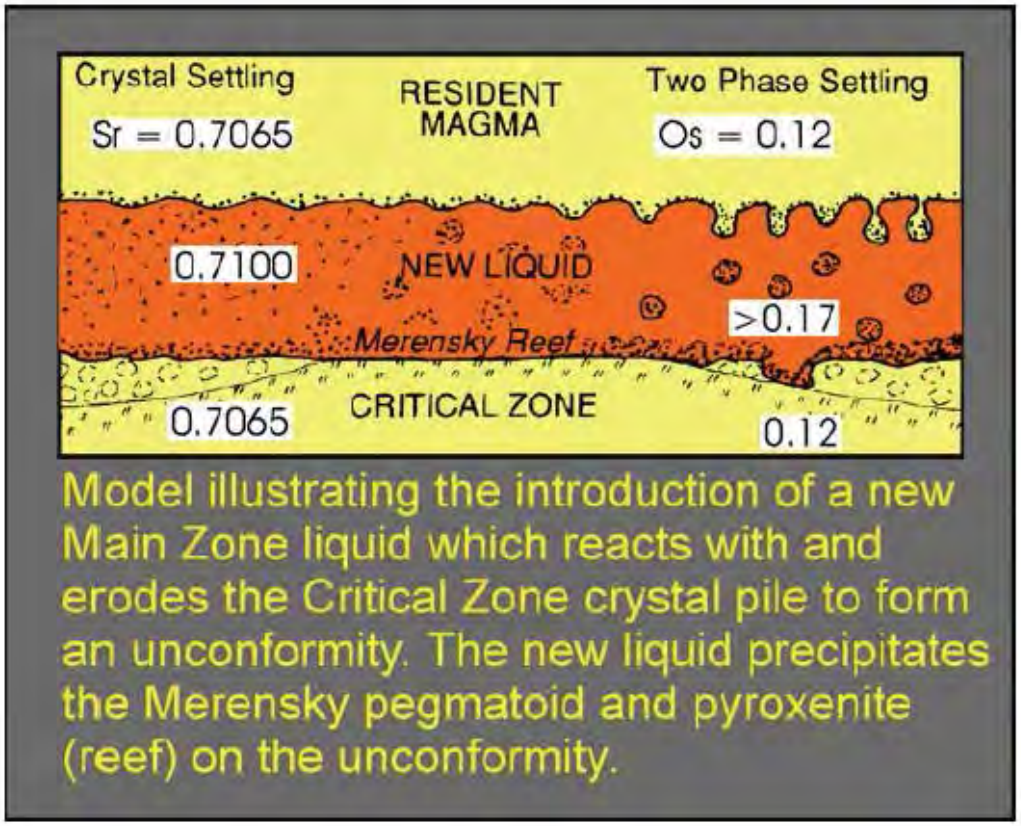


Figure 26 Schematic diagram showing the formation of the Merensky Reef by an influx of hot dense magma which reacted with the floor rocks (Kruger, 1992)

Magmatic Processes

- Within the magma chamber
- During magmatic ascent
- During volcanic venting
- The role of water
  - Magmatic water
  - Ground water

What else goes on within the magma chamber?

http://cdn.c.photoshelter.com/img-get/I0000gr6kdicfnEU/s/860/860/Fphoto-66968903C-6CC.jpg

Mixing Oil and Water

Water is a polar molecule,

Oil is not.

"Likes mix with Likes"

Polar molecules mix with other polar molecules: water and ethanol.

Non-polar molecules mix with other non-polar molecules: copper and zinc.

http://cdn.c.photoshelter.com/img-get/I0000gr6kdicfnEU/s/860/860/Fphoto-66968903C-6CC.jpg

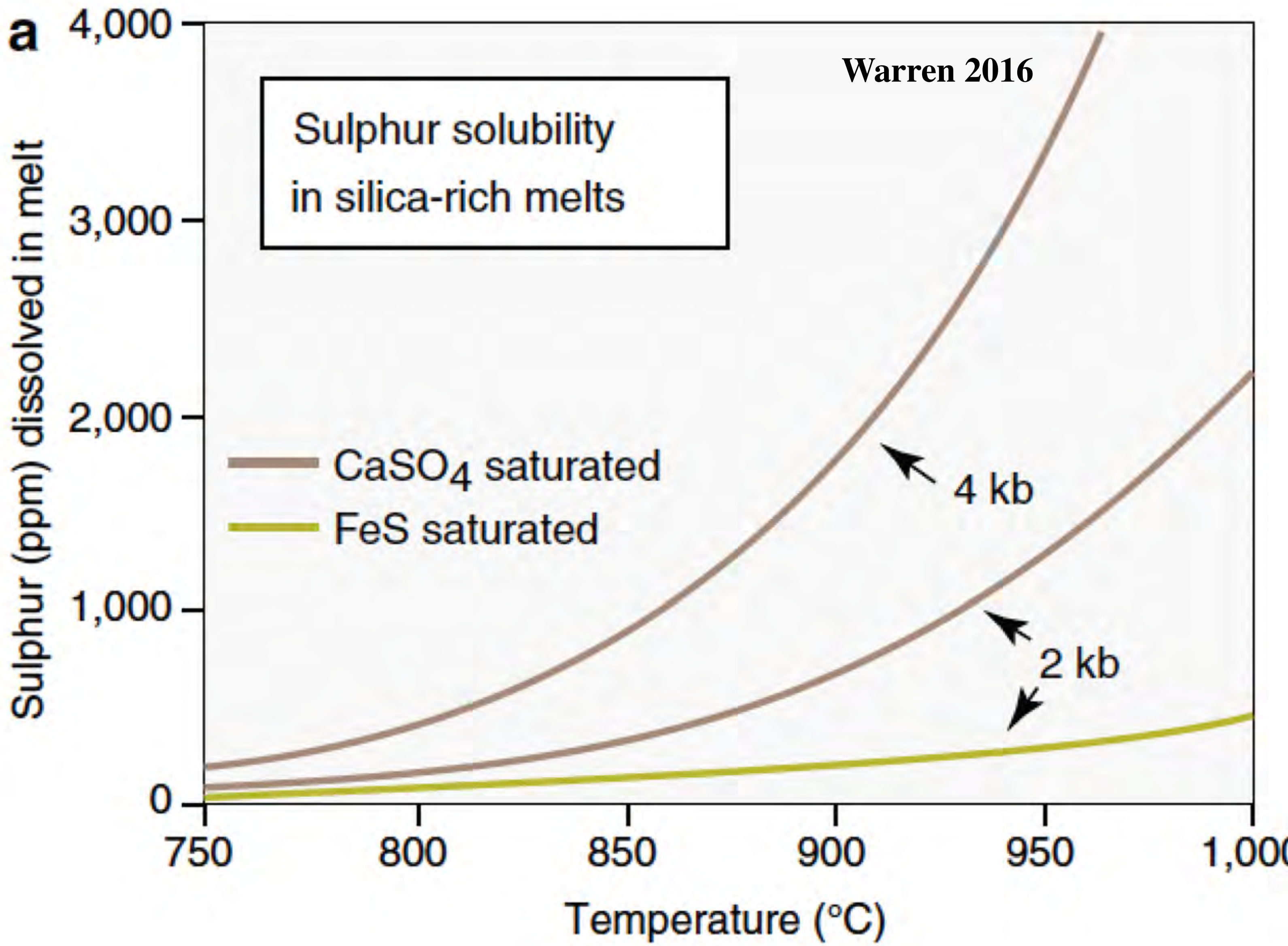
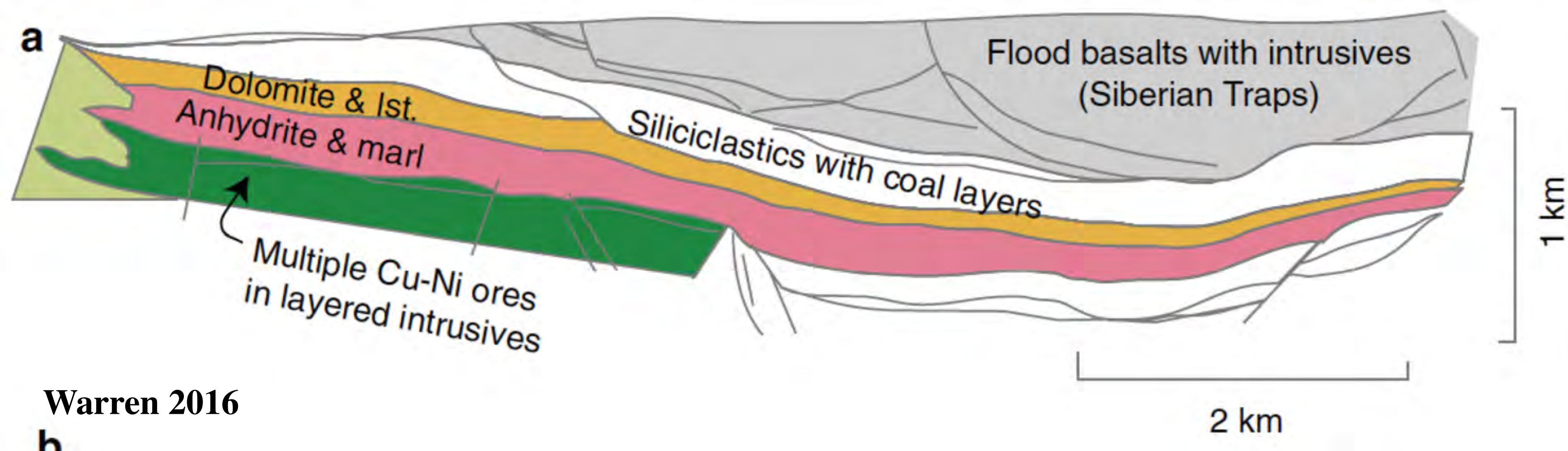


Fig. 16.1 Sulphur carrying capacity. (**a**) Experimental determinations of sulfur solubility versus temperature for hydrous silica-rich melts at different pressures and oxygen fugacities. (**b**) Sulphide sol-

What is the source of Sulfur in the magma?



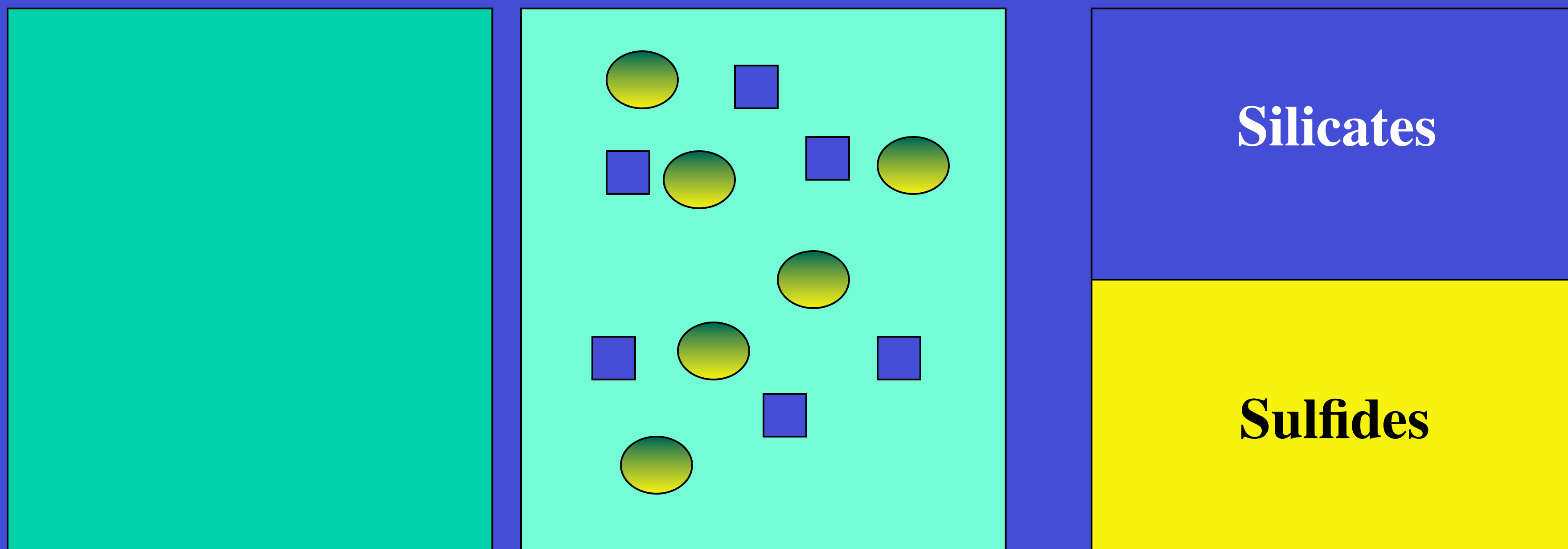
Warren 2016

Anhydrite ($CaSO_4$ a salt deposited in closed basins

1. Magma Chamber

Formation of Si & S droplets

Gravity Segregation Of immiscible phases



With sufficient sulfur in a melt, possibly absorbed from country rock adjoining the magma chamber, large volumes of sulfur and silicate liquid melts will develop late in the magma's solidification. These liquids are immiscible, so the denser sulfur liquid sinks to the bottom of the magma chamber.

Examples: copper and nickel sulphides at Sudbury, Canada

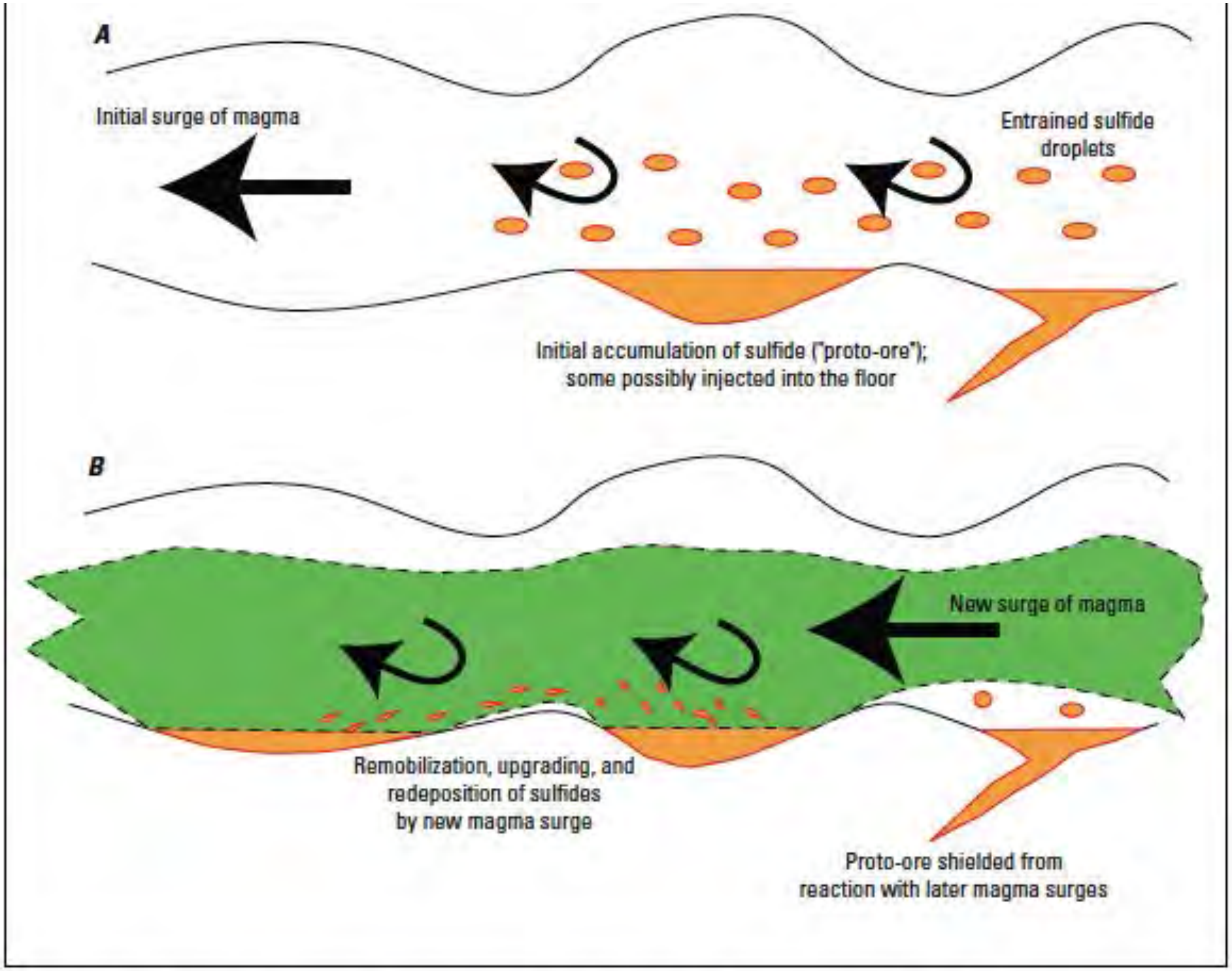


Figure 3–2. Schematic diagram illustrating the continued flow of magma through an idealized magma conduit. *A*, An initial surge of sulfur-saturated magma carries entrained sulfide droplets, which may be deposited along the footwall in widened parts of the conduit to form "proto-ore." In places, sulfide melt may be injected into the footwall. *B*, Continued surges of undepleted magma may stir up previously deposited sulfide melt, upgrading the sulfide in Ni, Cu, and PGE content and reprecipitating it downstream in the conduit. Proto-ores injected into the footwall may remain shielded from later magma surges and from upgrading in metal content. Figure modified from Maier and others (2001).

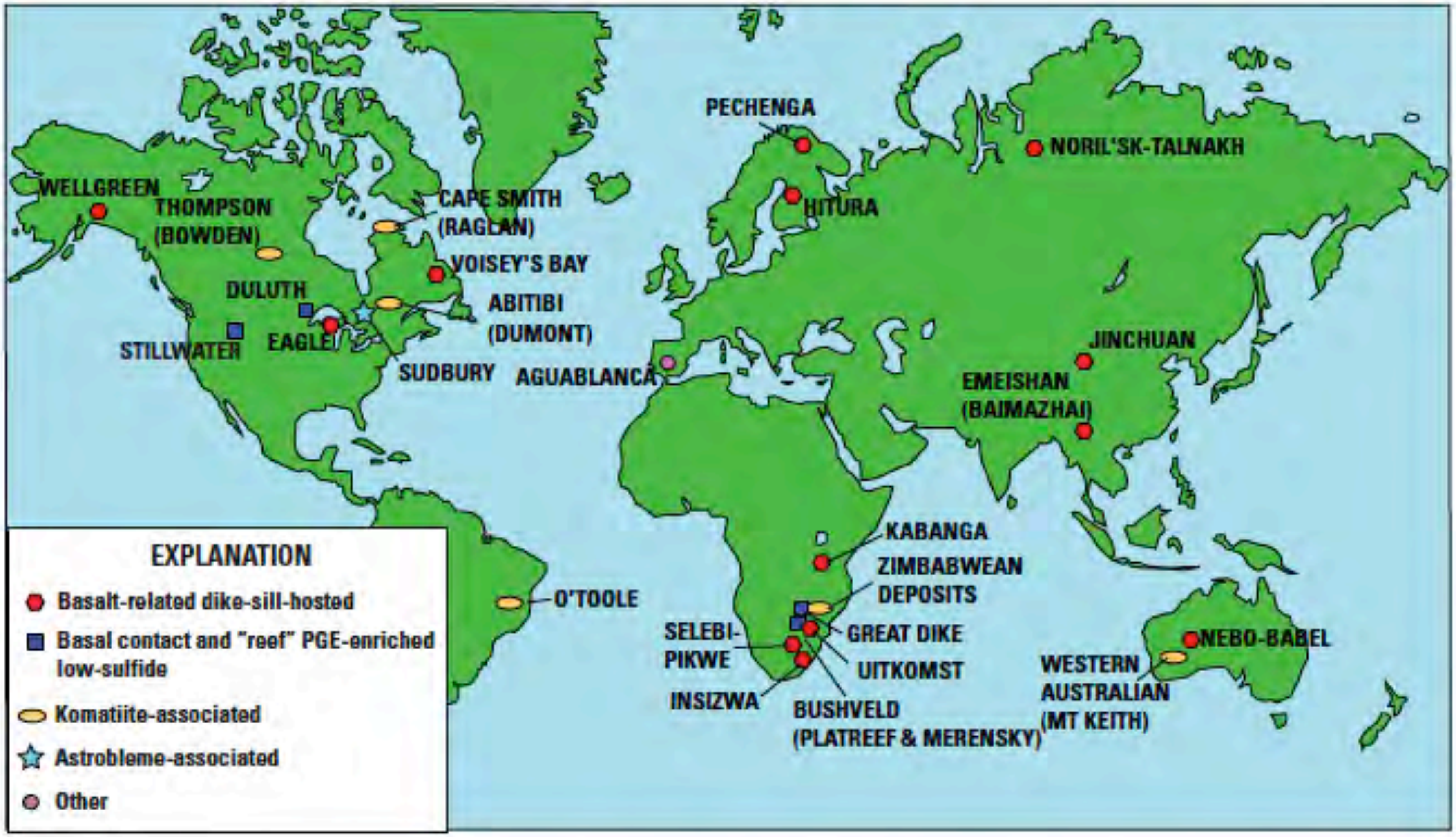
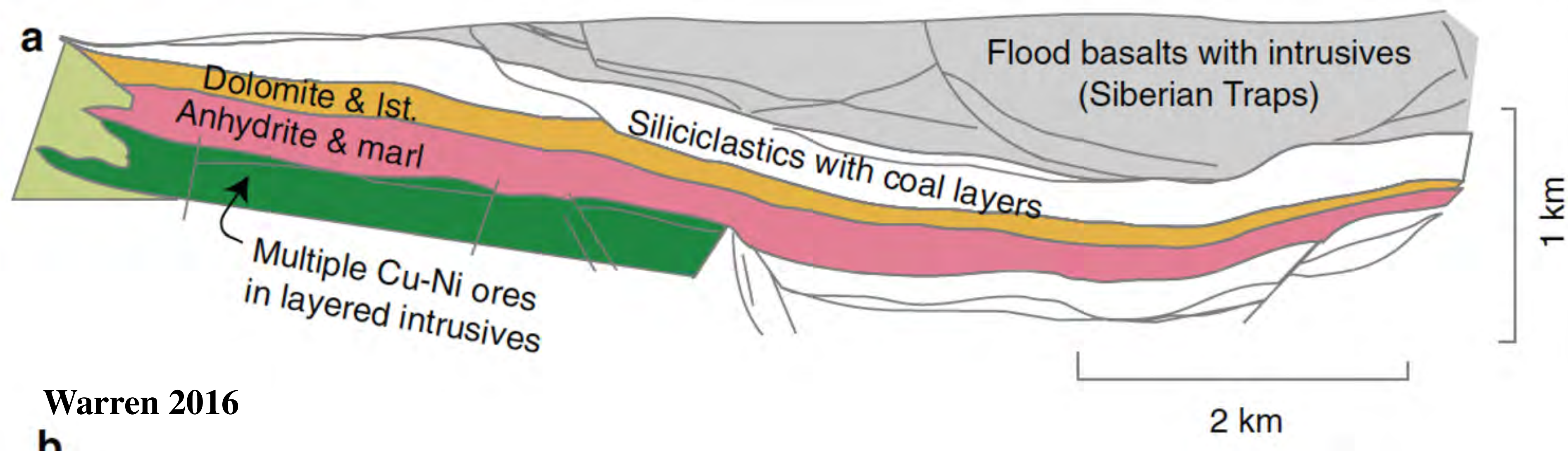


Figure 1–1. Locations of some of the world's major nickel and platinum-group element (PGE) mining camps and types of deposits.

Noril’sk Mine, Siberia, Russia

http://rostec.ru/en/news/1301

What is the source of Sulfur in the magma?



Warren 2016

Anhydrite ($CaSO_4$ a salt deposited in closed basins

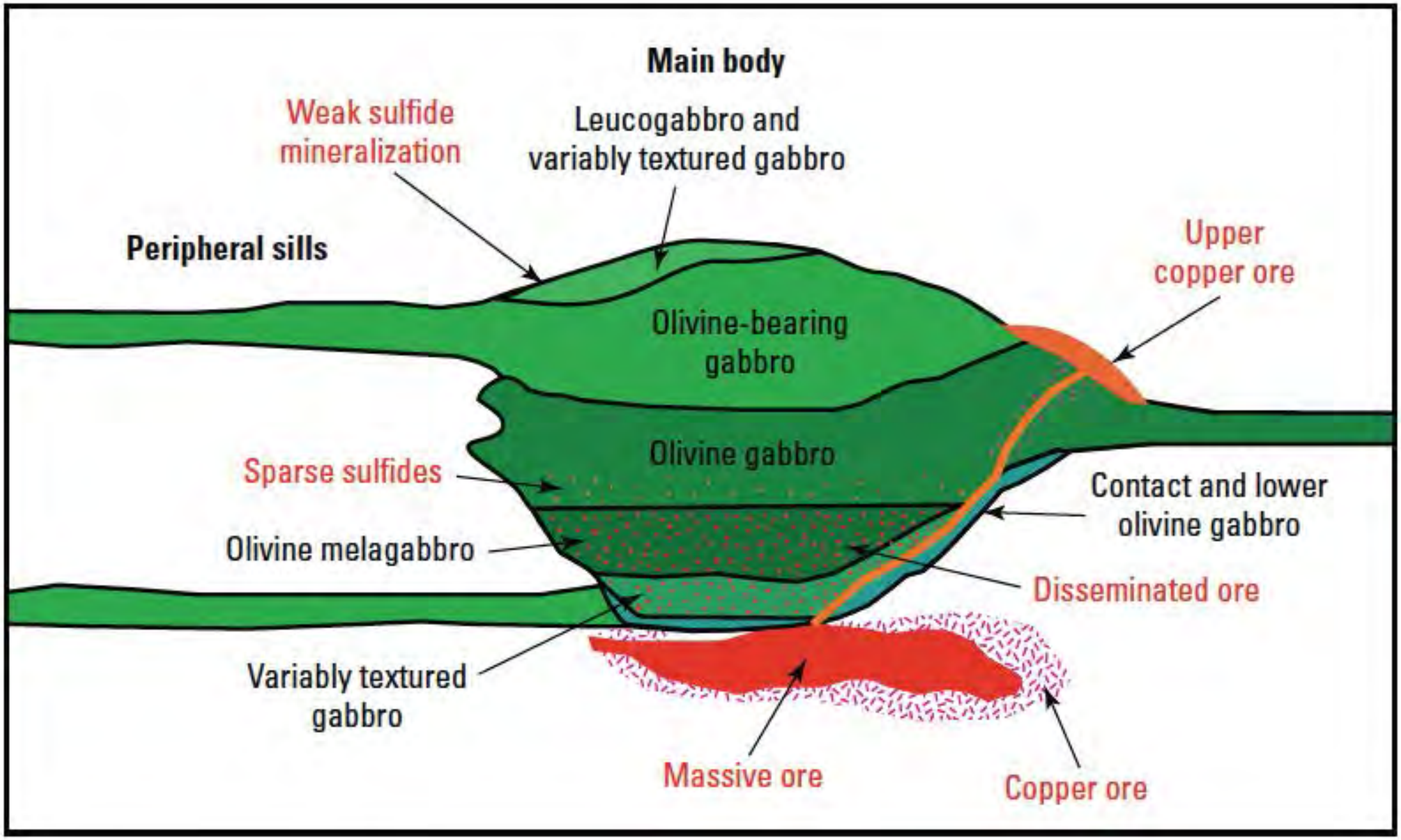


Figure 5–1. Schematic cross section of a typical Noril'sk (Russia) ore-bearing intrusion showing internal structure, lithologies, and major ore types. Figure modified after Naldrett

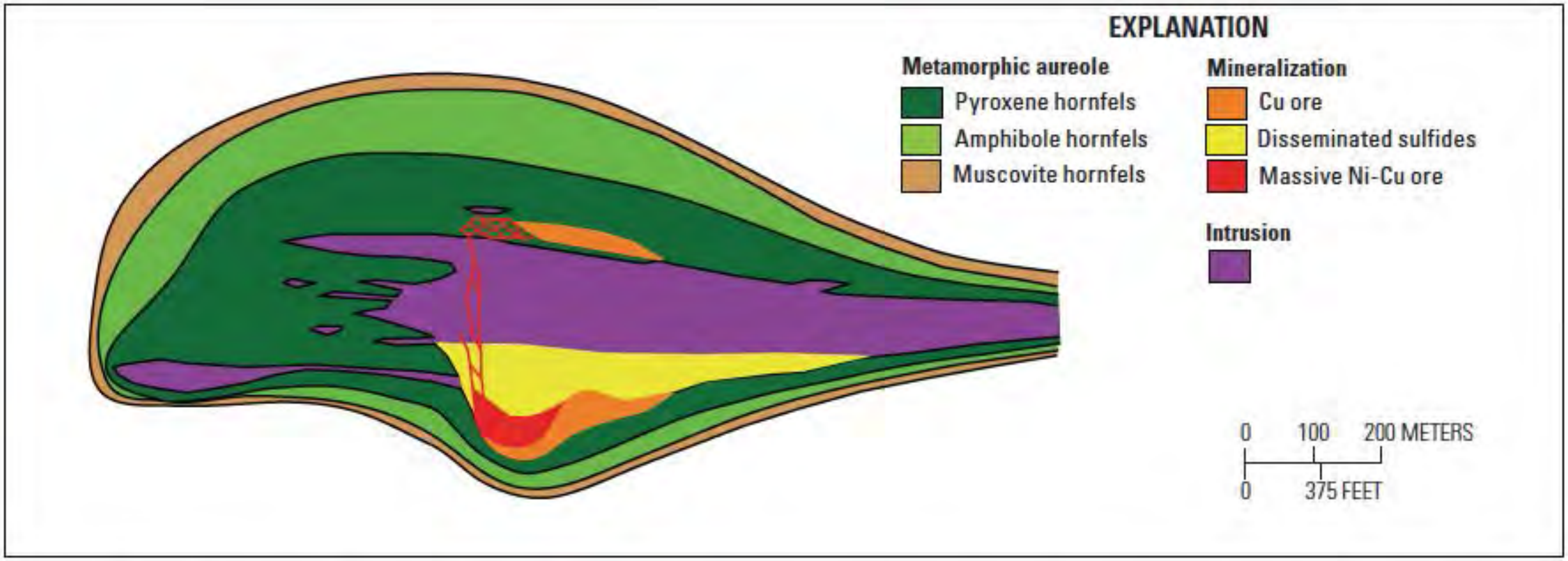


Figure 5–4. Schematic diagram showing the extent of contact metamorphism and metasomatism surrounding typical ore-bearing Noril'sk-type (Russia) intrusions. Figure modified from Naldrett and Li (2009).

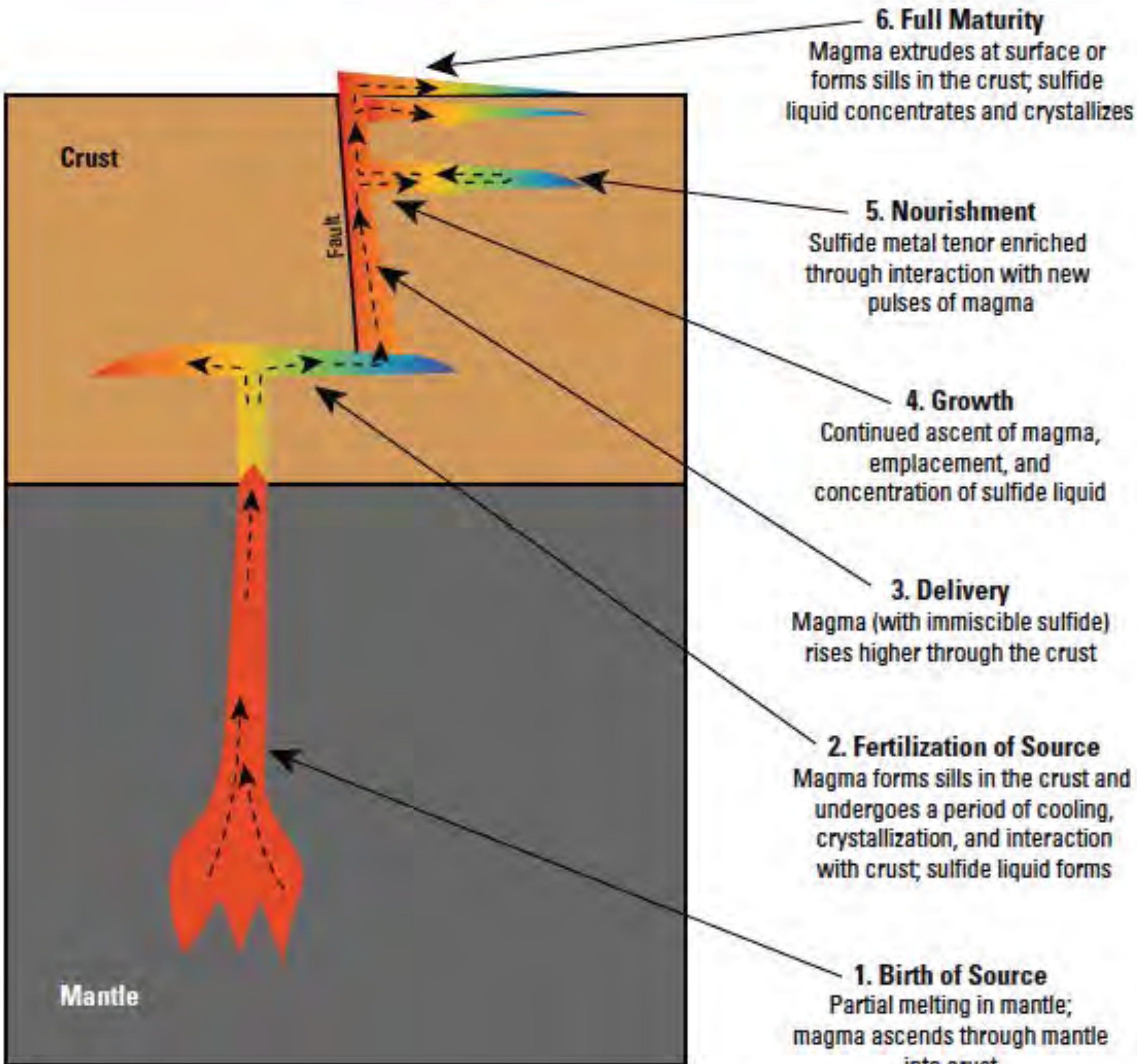
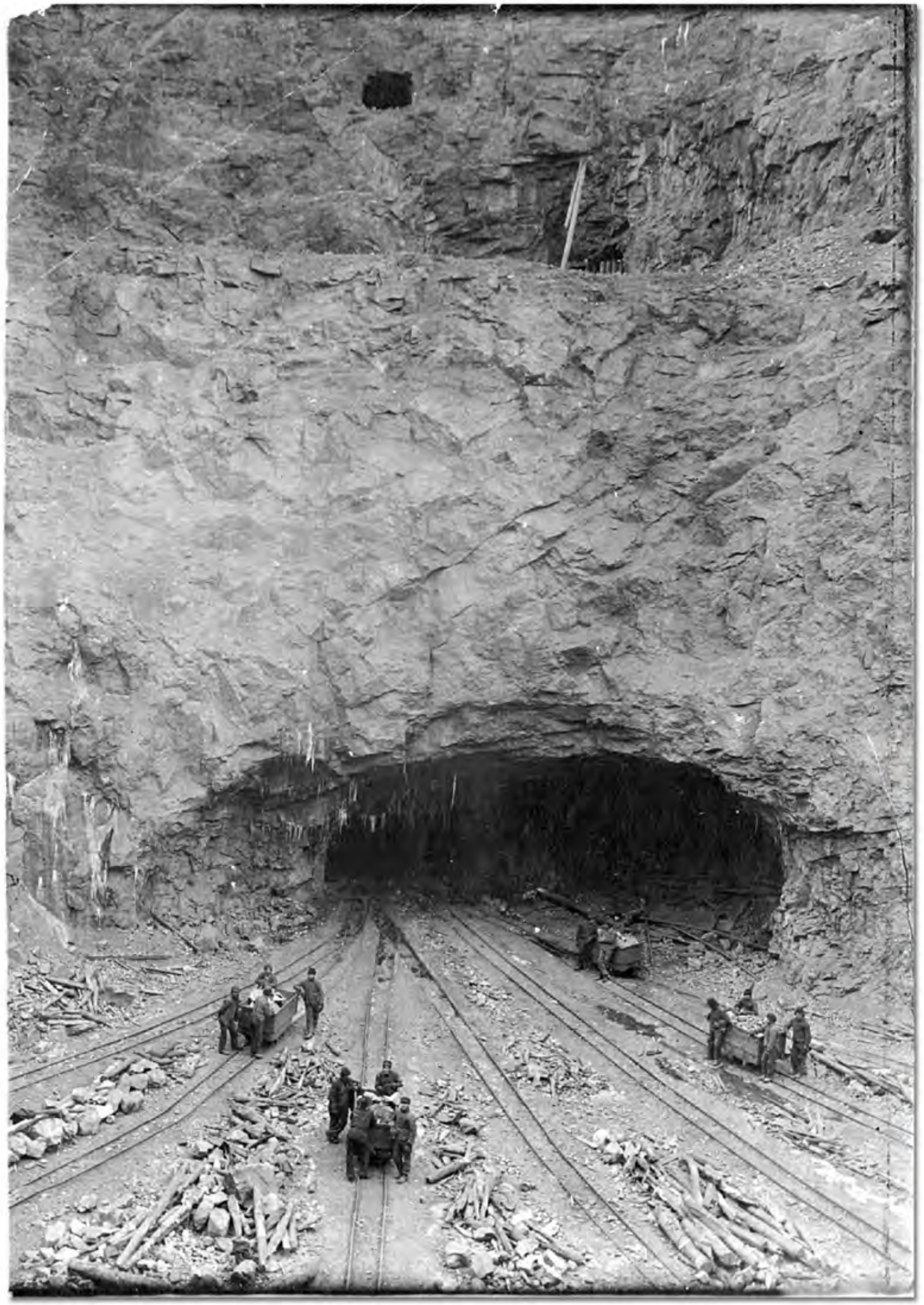
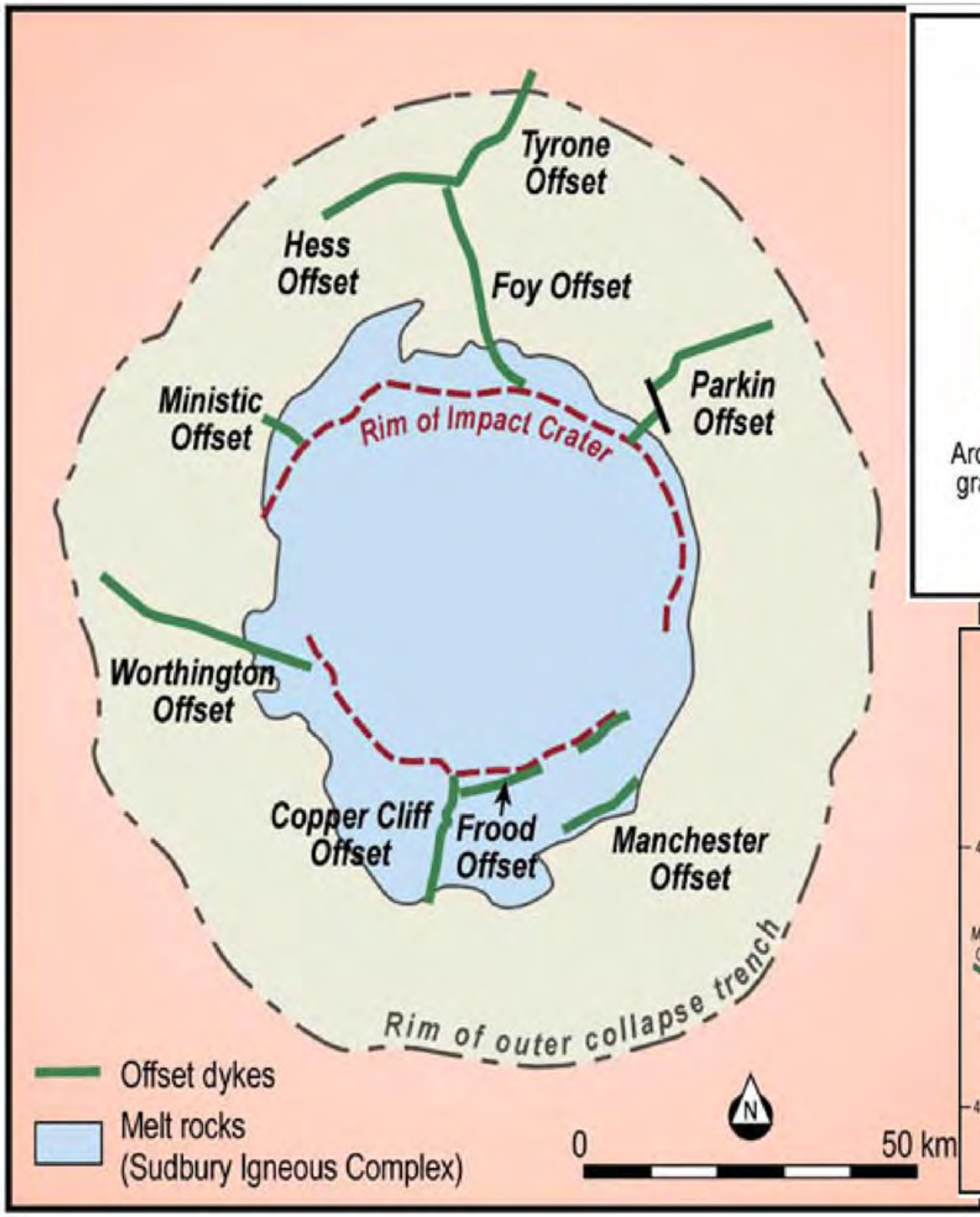


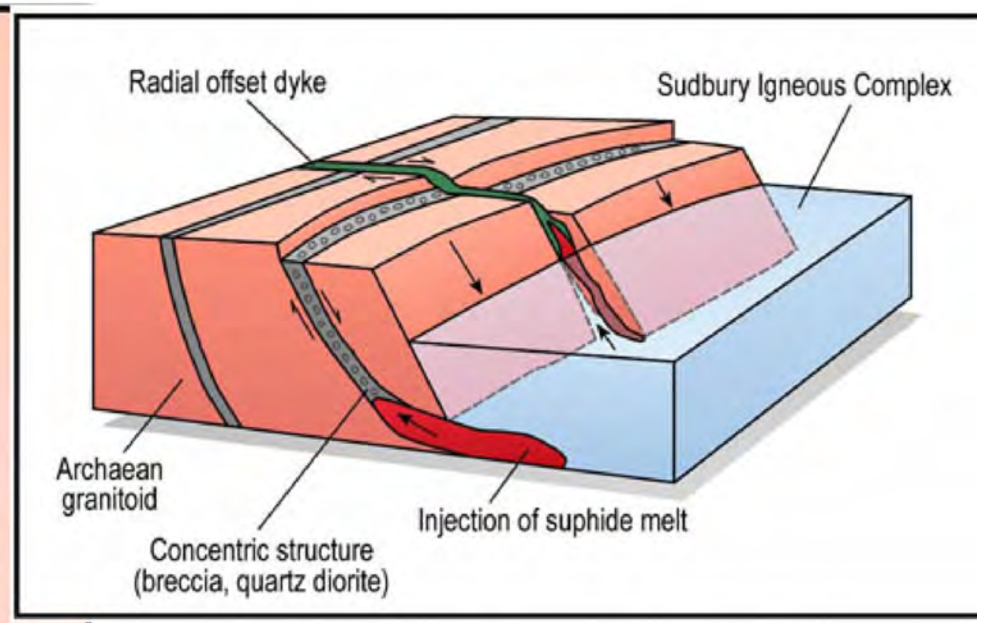
Figure 12–1. Stages in the formation of magmatic sulfide-rich Ni-Cu±PGE deposits (modified from Naldrett, 2010).

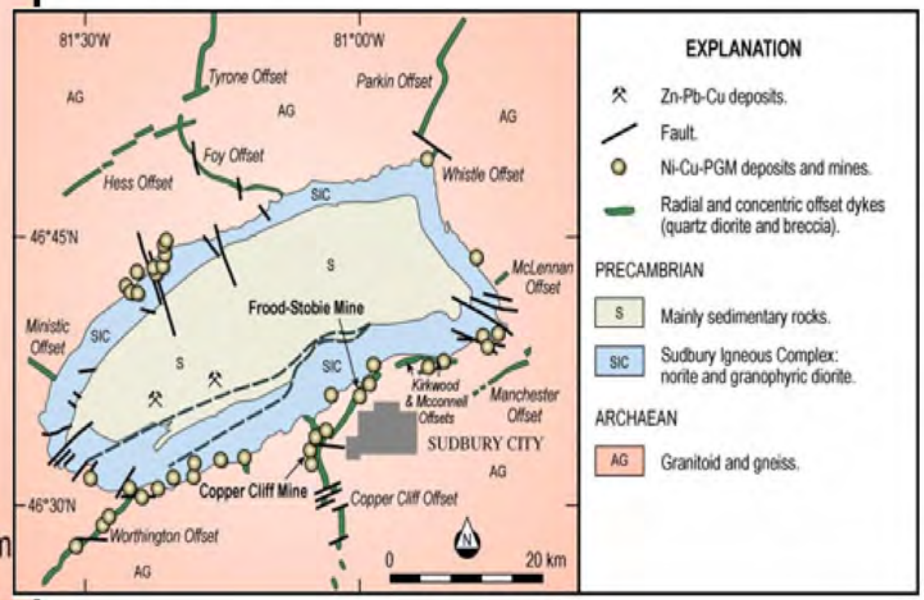


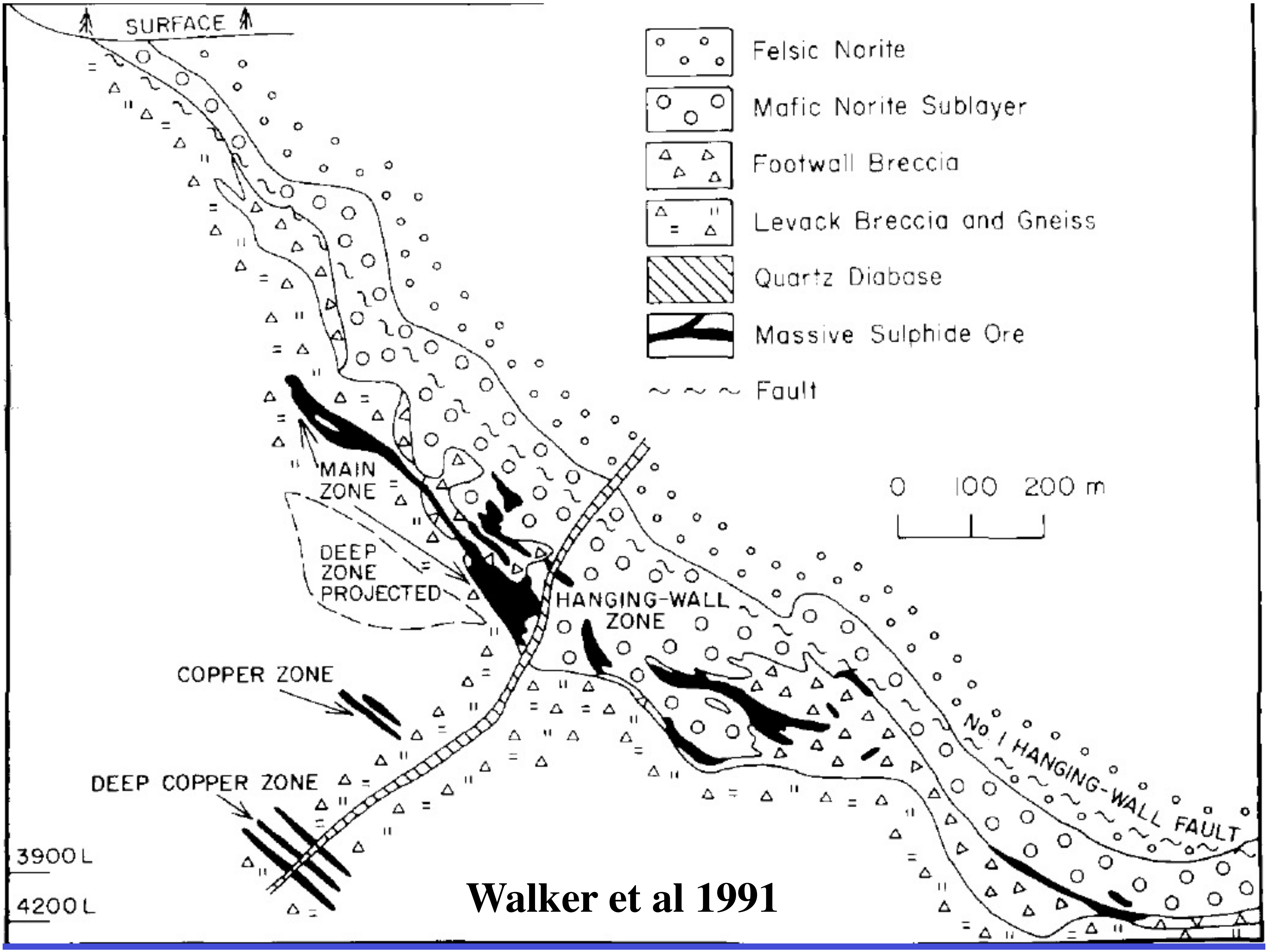
Creighton Mine
1905
Sudbury Complex
Ontario, Canada

Sudbury Nickel Mine, 2003


Tyrone Offset
Hess Offset
Foy Offset
Ministic Offset
Rim of Impact Crater
Parkin Offset
Worthington Offset
Copper Cliff Offset
Frood Offset
Manchester Offset
Rim of outer collapse trench
Offset dykes
Melt rocks (Sudbury Igneous Complex)
N
0
50 km


Radial offset dyke
Sudbury Igneous Complex
Archaean granitoid
Concentric structure (breccia, quartz diorite)
Injection of suphide melt


81°30'W
81°00'W
Tyrone Offset
Parkin Offset
AG
Foy Offset
Hess Offset
Whistle Offset
SIC
46°45'N
S
McLennan Offset
Frood-Stobie Mine
Ministic Offset
Kirkwood & Mcconnell Offsets
Manchester Offset
SUDBURY CITY
Copper Cliff Mine
Copper Cliff Offset
46°30'N
Worthington Offset
0
20 km
EXPLANATION
Zn-Pb-Cu deposits.
Fault.
Ni-Cu-PGM deposits and mines.
Radial and concentric offset dykes (quartz diorite and breccia).
PRECAMBRIAN
Mainly sedimentary rocks.
Sudbury Igneous Complex: norite and granophyric diorite.
ARCHAEAN
Granitoid and gneiss.



Walker et al 1991

Garson Mine Maps, Sudbury, Ontario

86 J. Mukwakwami et al. / Precambrian Research 196–197 (2012) 81–105

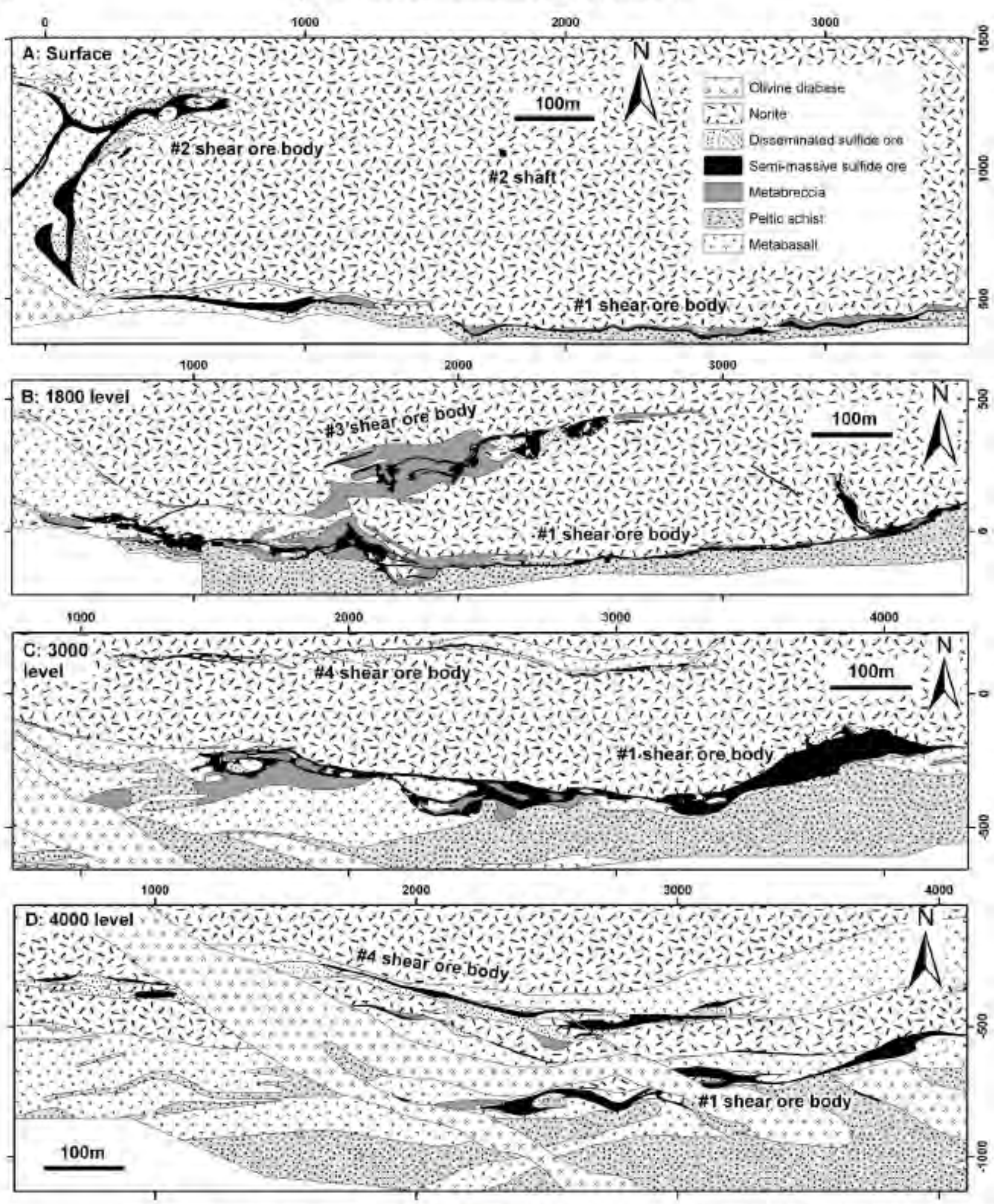


Fig. 3. Maps of the Garson mine (modified after Aniol and Brown, 1979). (a) Surface, (b) 1800 level, (c) 3000 level, (d) 4000 level.

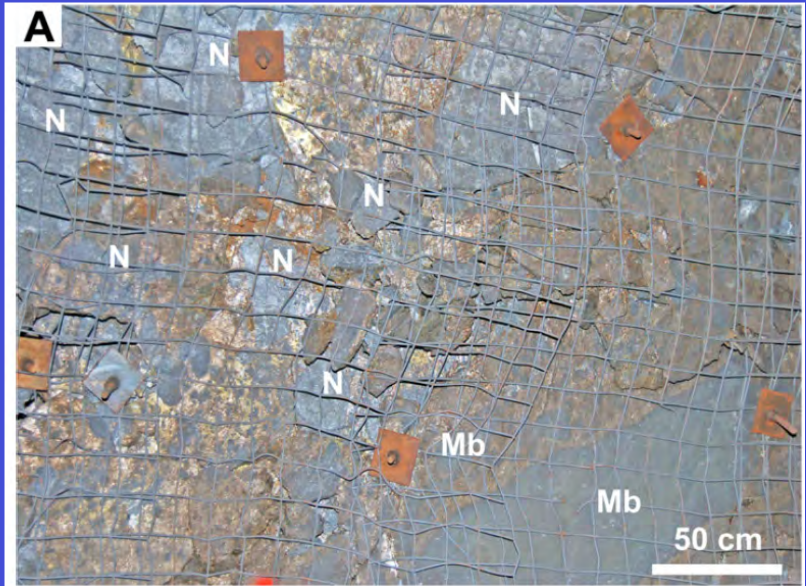
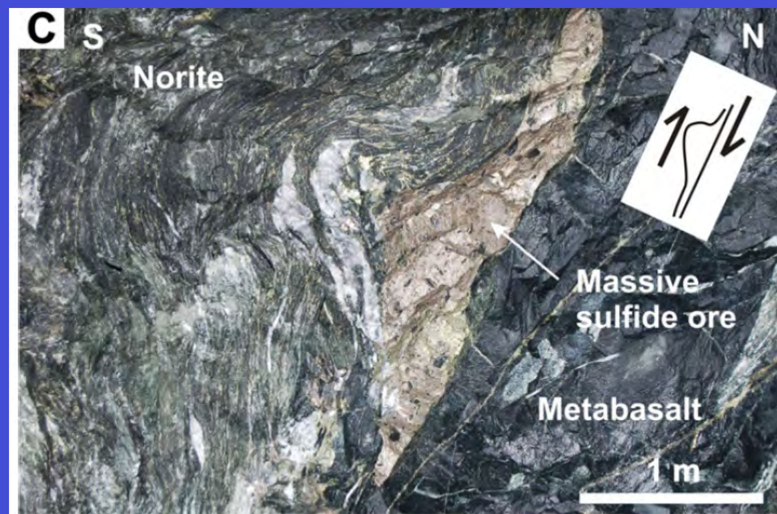
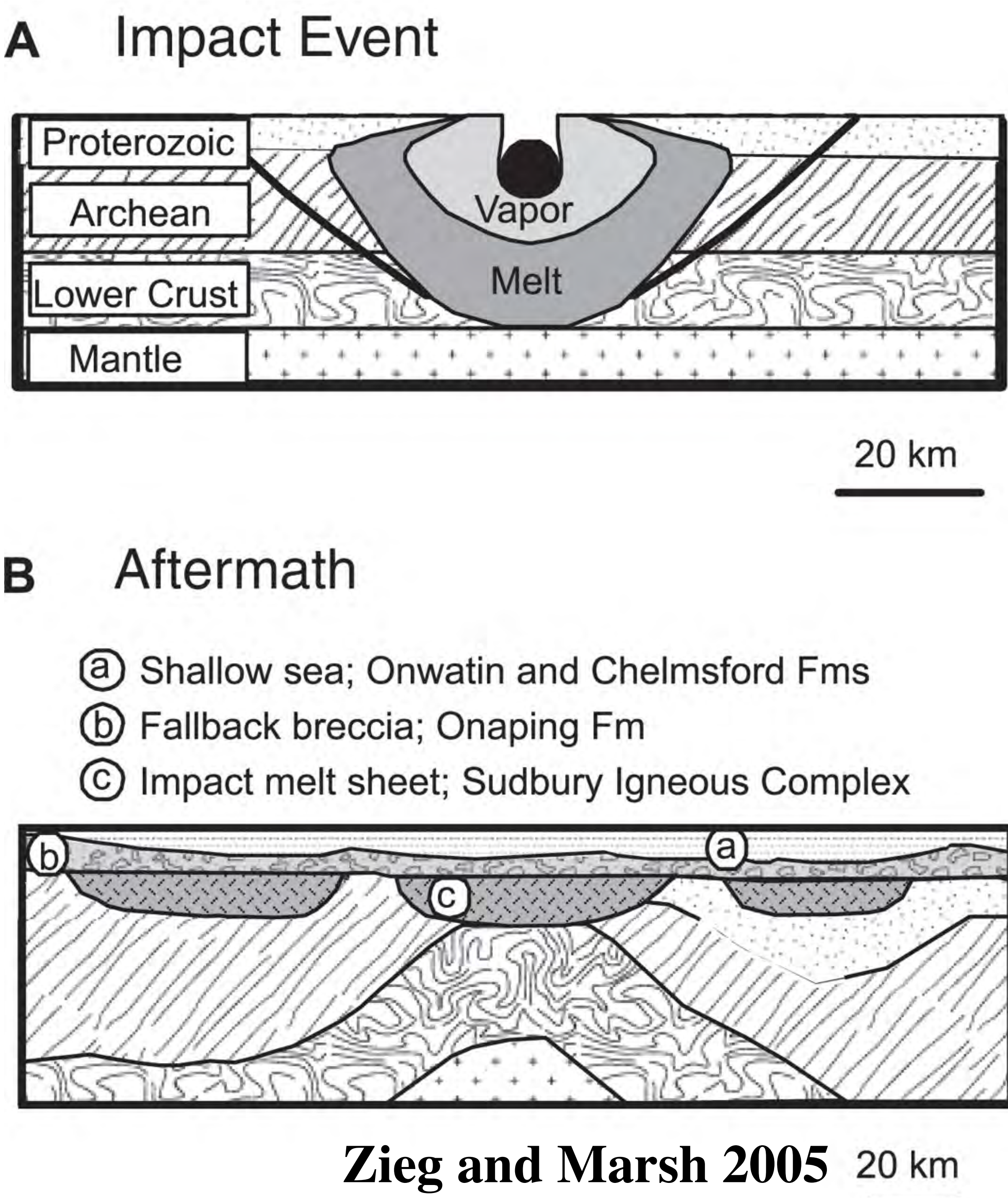


Fig. 9. (a) Underground photograph showing abundant norite inclusions in pyrrhotite-



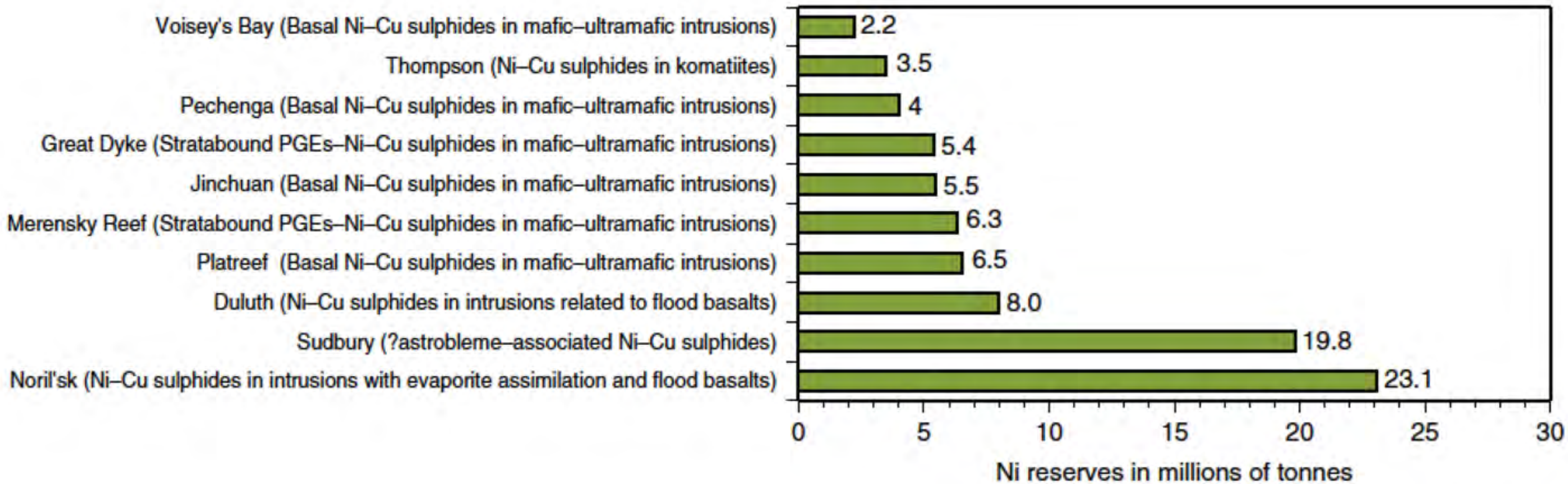
Mukwakwami et al 2012



Zieg and Marsh 2005

But where does the Sulfur come from?

A real mystery.


Voisey's Bay (Basal Ni–Cu sulphides in mafic–ultramafic intrusions)
Thompson (Ni–Cu sulphides in komatiites)
Pechenga (Basal Ni–Cu sulphides in mafic–ultramafic intrusions)
Great Dyke (Stratabound PGEs–Ni–Cu sulphides in mafic–ultramafic intrusions)
Jinchuan (Basal Ni–Cu sulphides in mafic–ultramafic intrusions)
Merensky Reef (Stratabound PGEs–Ni–Cu sulphides in mafic–ultramafic intrusions)
Platreef (Basal Ni–Cu sulphides in mafic–ultramafic intrusions)
Duluth (Ni–Cu sulphides in intrusions related to flood basalts)
Sudbury (?astrobleme–associated Ni–Cu sulphides)
Noril'sk (Ni–Cu sulphides in intrusions with evaporite assimilation and flood basalts)
2.2
3.5
4
5.4
5.5
6.3
6.5
8.0
19.8
23.1
0
5
10
15
20
25
30
Ni reserves in millions of tonnes

Warren 2016

Some Base Metal Ore Models

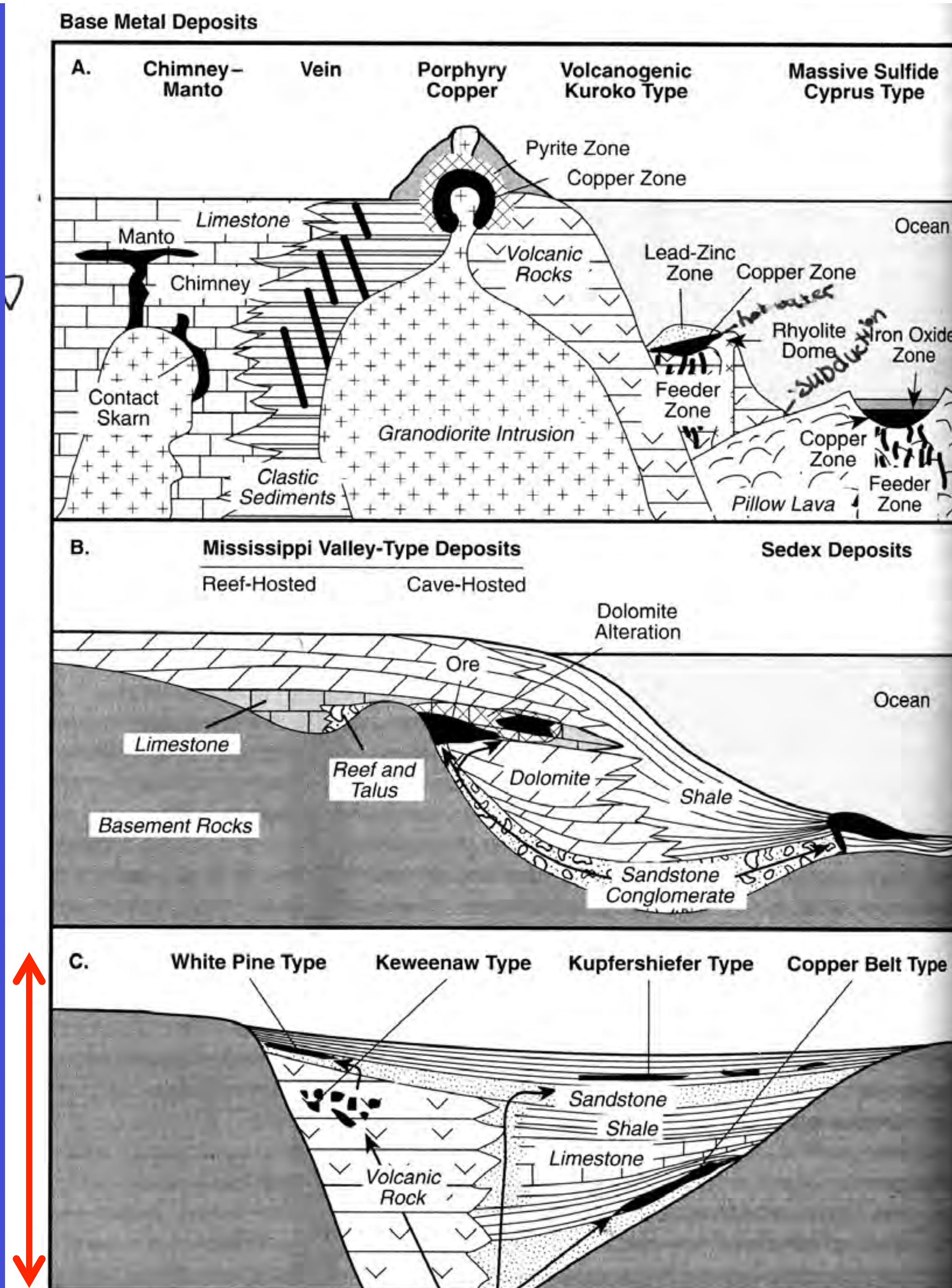
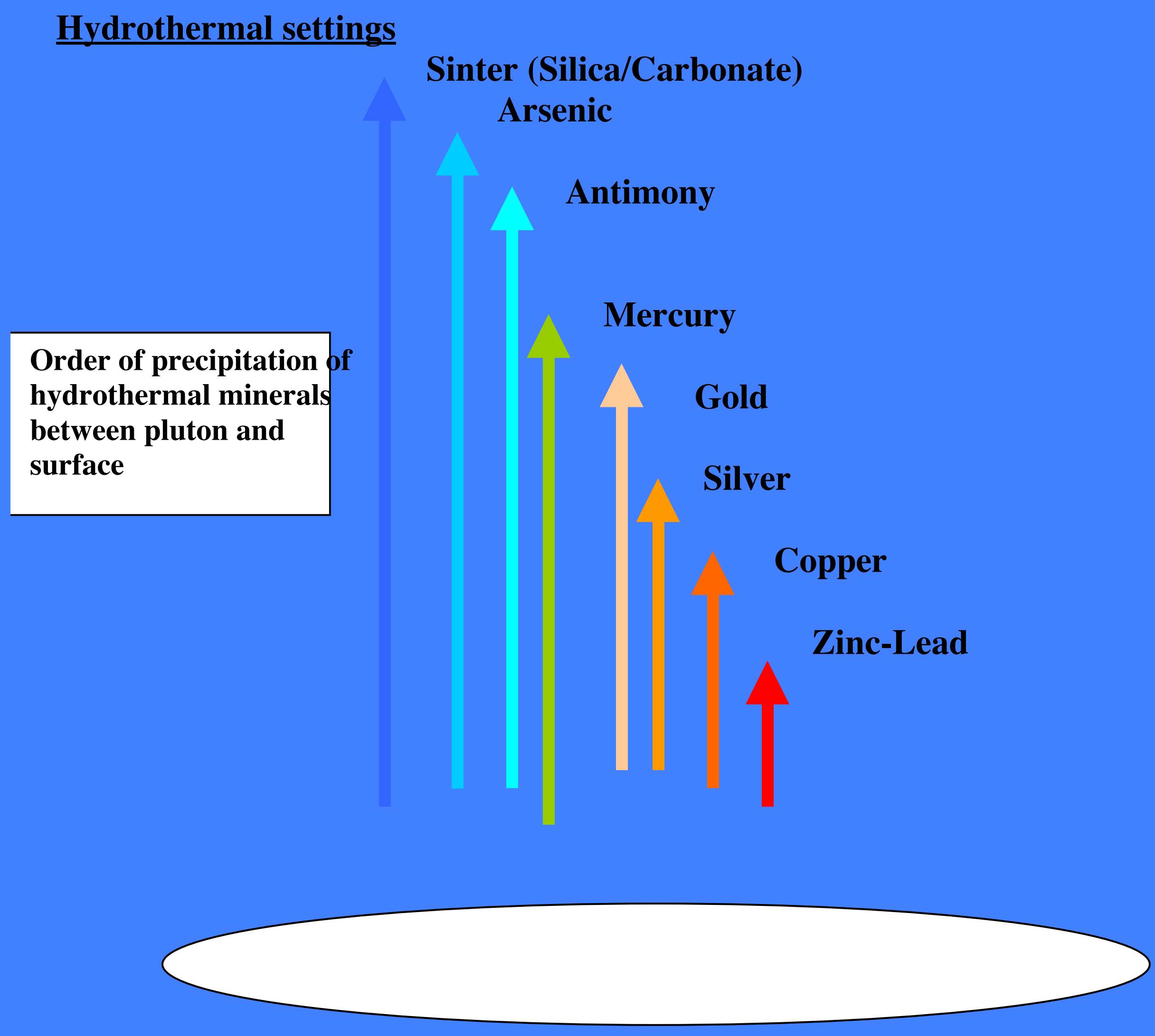
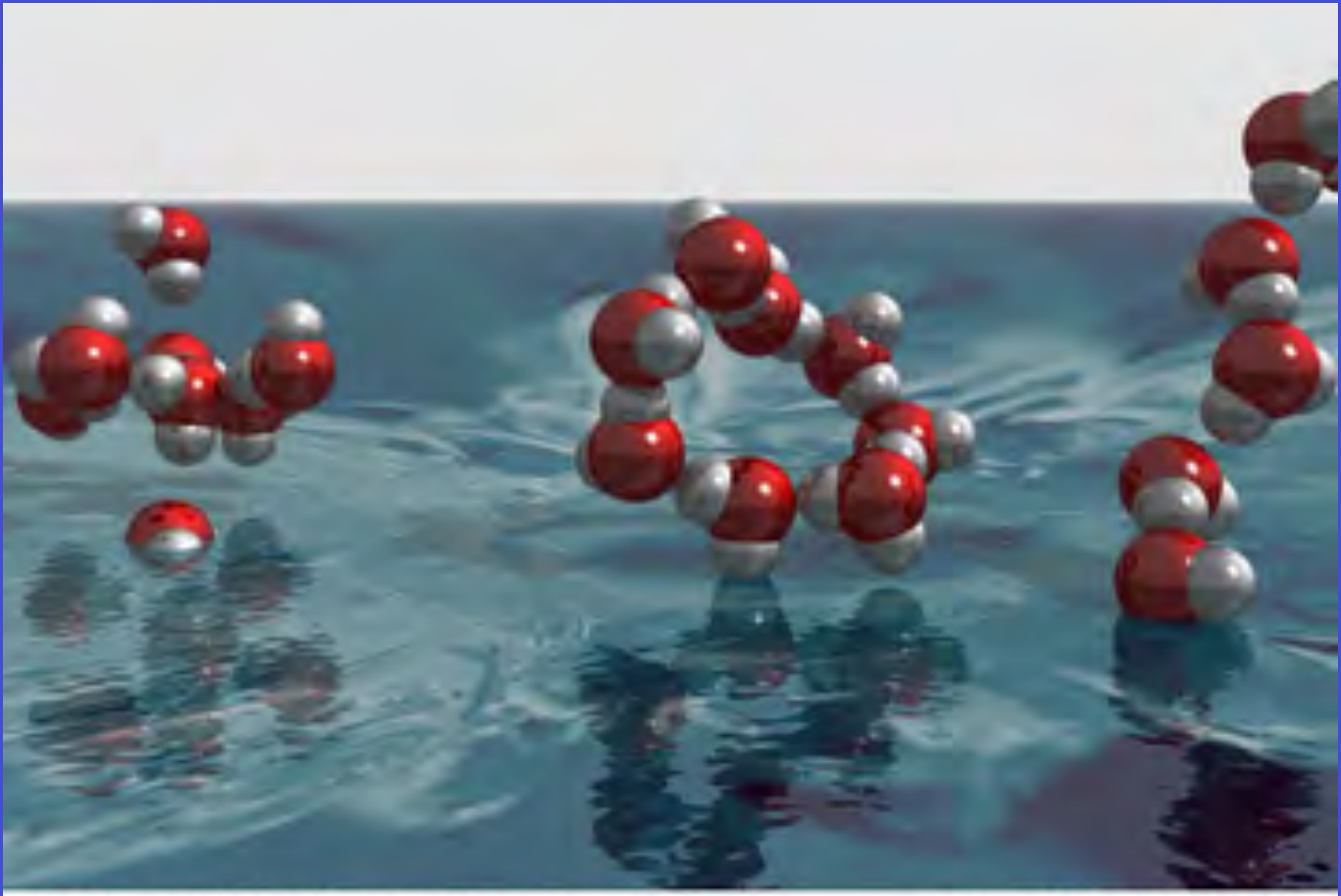


Figure 9-11 Kessler (1994) Mineral Resources, Economics, And the Environment

<u>3. Hydrothermal settings-</u> as magmas crystallize, the water present in the liquid magma is driven off into fractures or permeable beds within the host rock. Minerals species that are water-soluble will thus be carried away from the parent magma body. As the water encounters lower temperatures and pressures, it may boil. Sulfide ores will precipitate in the order shown in this diagram, beginning with zinc or lead if present, and ending with a sinter of silica and or carbonate. The host rock may thus become host to hydrothermal deposits. Hydrothermal waters may also be derived from the circulation of ground water in deep basins. If the resulting brines ascend to shallow depths, the same order of precipitation of dissolved sulfides may occur.



Water: polar, high dialectric constant, high heat capacity, high surface tension, maximum density above 32°F



The Structure of the First Coordination Shell in Liquid Water

Illustration by Hirohito Ogasawara

Figure 1. Global distribution of Mississippi Valley-Type lead-zinc deposits and districts.

USGS Scientific Investigations Report 2010-5070-A

USGS Scientific Investigations Report 2010-5070-A

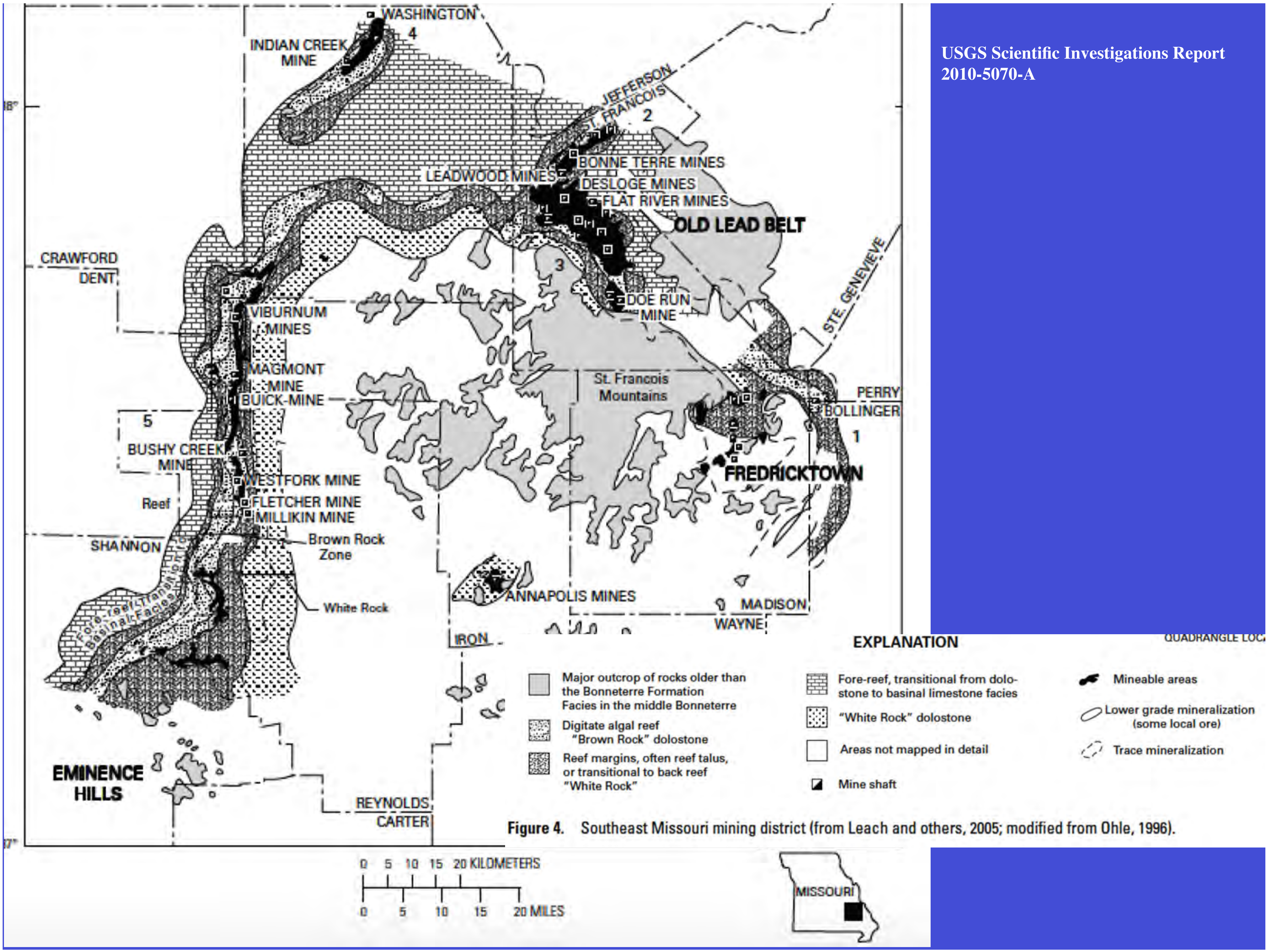


Figure 4. Southeast Missouri mining district (from Leach and others, 2005; modified from Ohle, 1996).

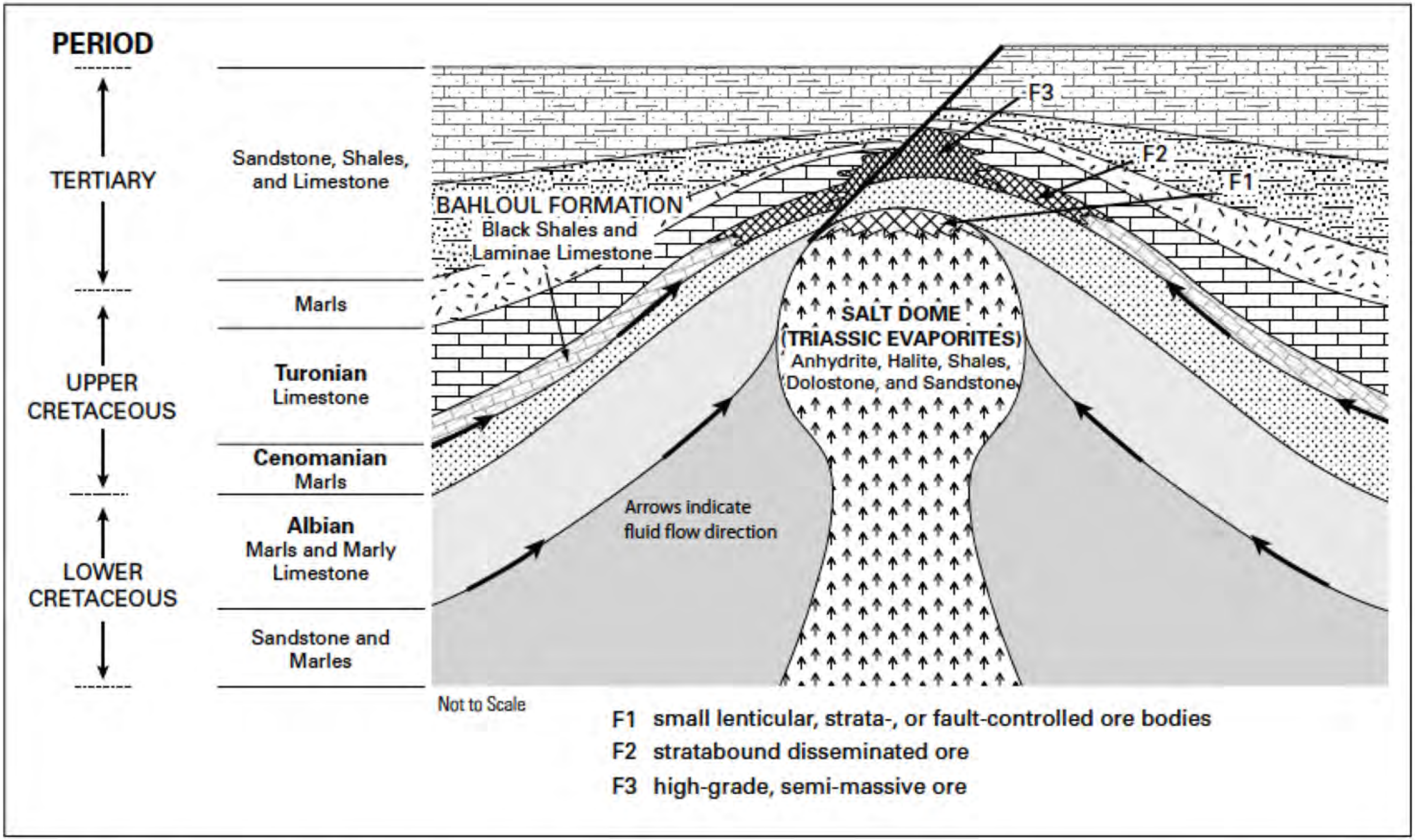


Figure 7. Mississippi Valley-Type (MVT) deposit in Tunisia displaying the relation between MVT mineralization and a salt dome environment (modified from Leach and others, 2005).

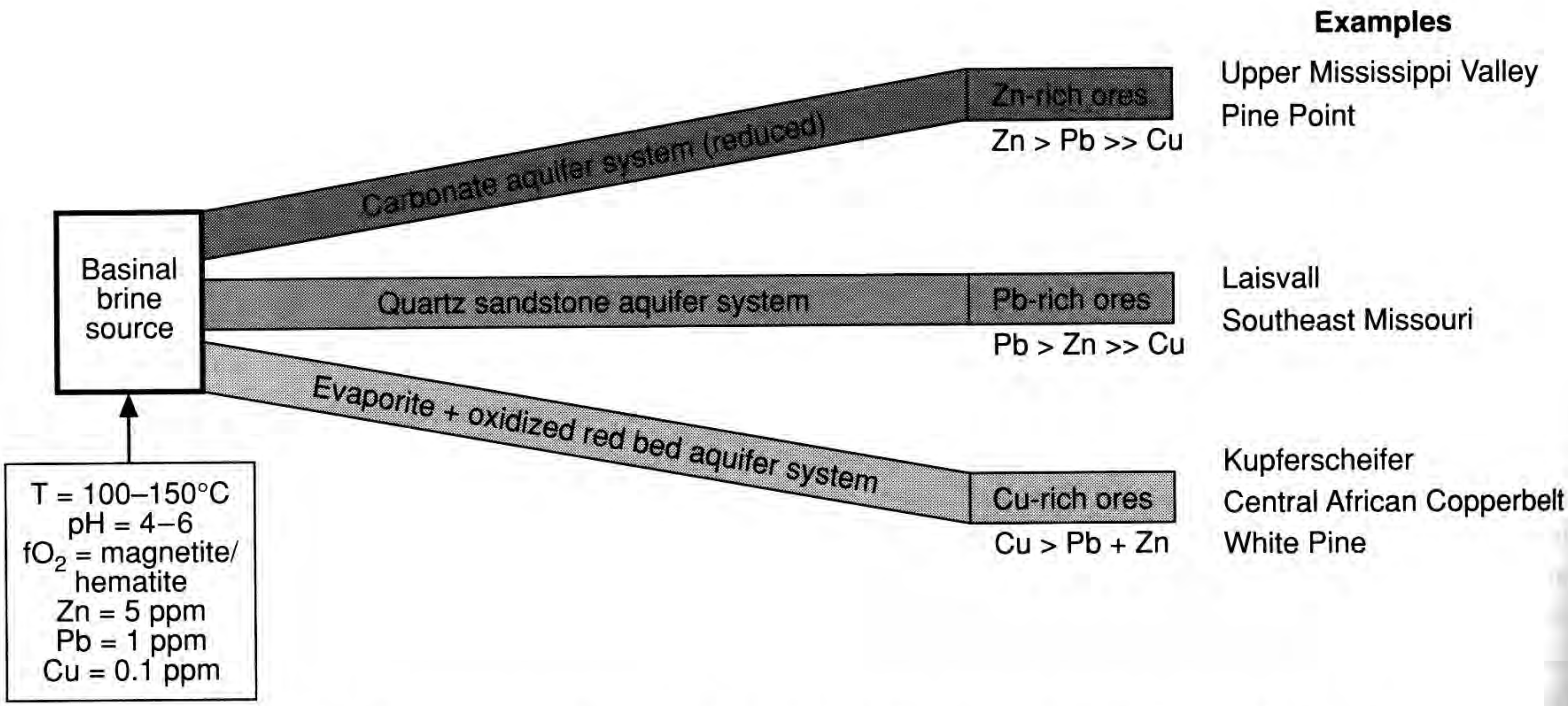


Figure 3.29 Diagrammatic representation showing the relationship between a single basinal brine and the conditions under which it might form SSC, as well as carbonate- and sandstone-hosted, MVT deposits (after Sverjensky, 1989; Metcalfe *et al.*, 1994).

Robb (2005) Introduction To Ore Forming Processes

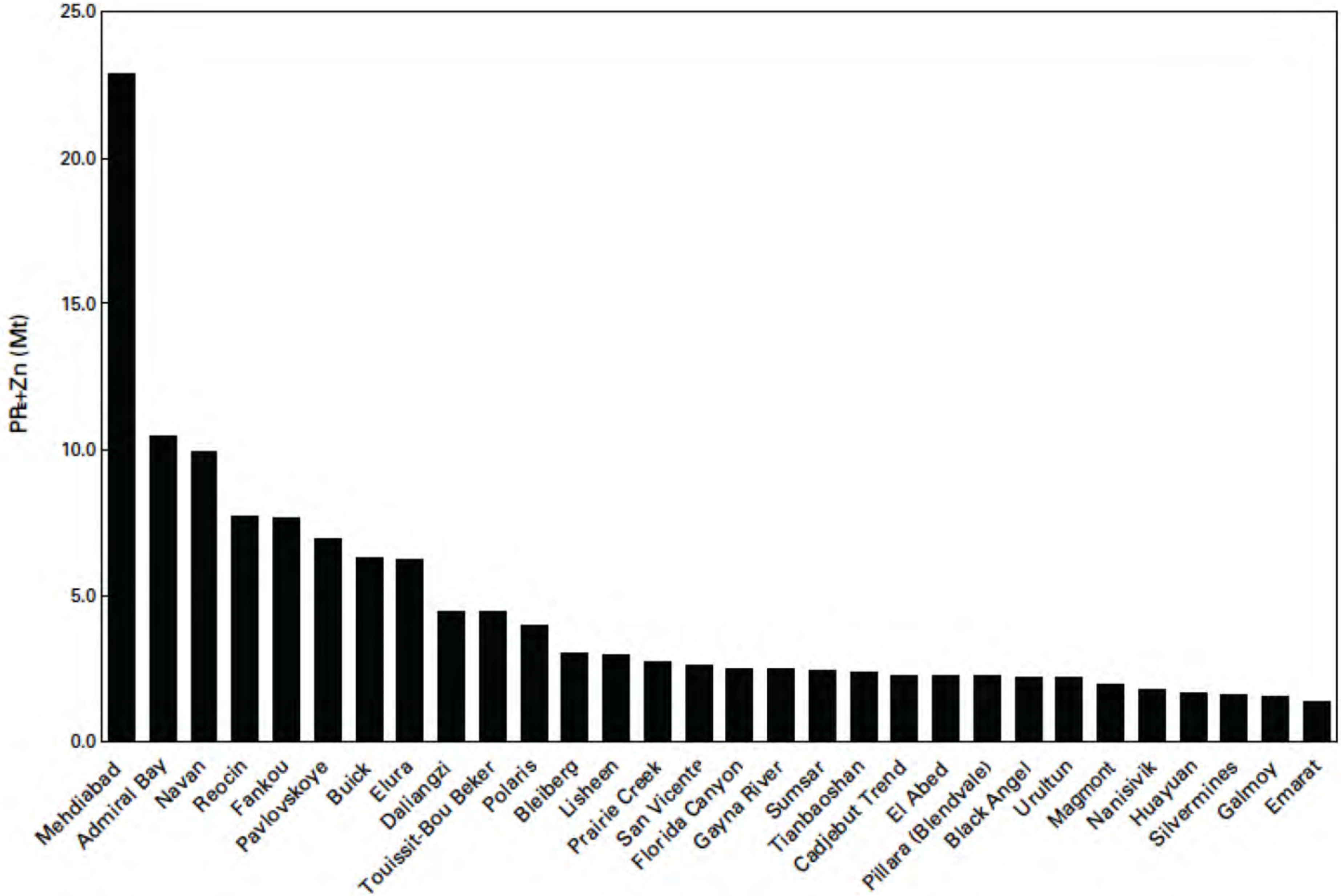


Figure A4. The largest 30 Mississippi Valley-Type deposits based on total lead and zinc content (Mt) (data from Taylor and others,

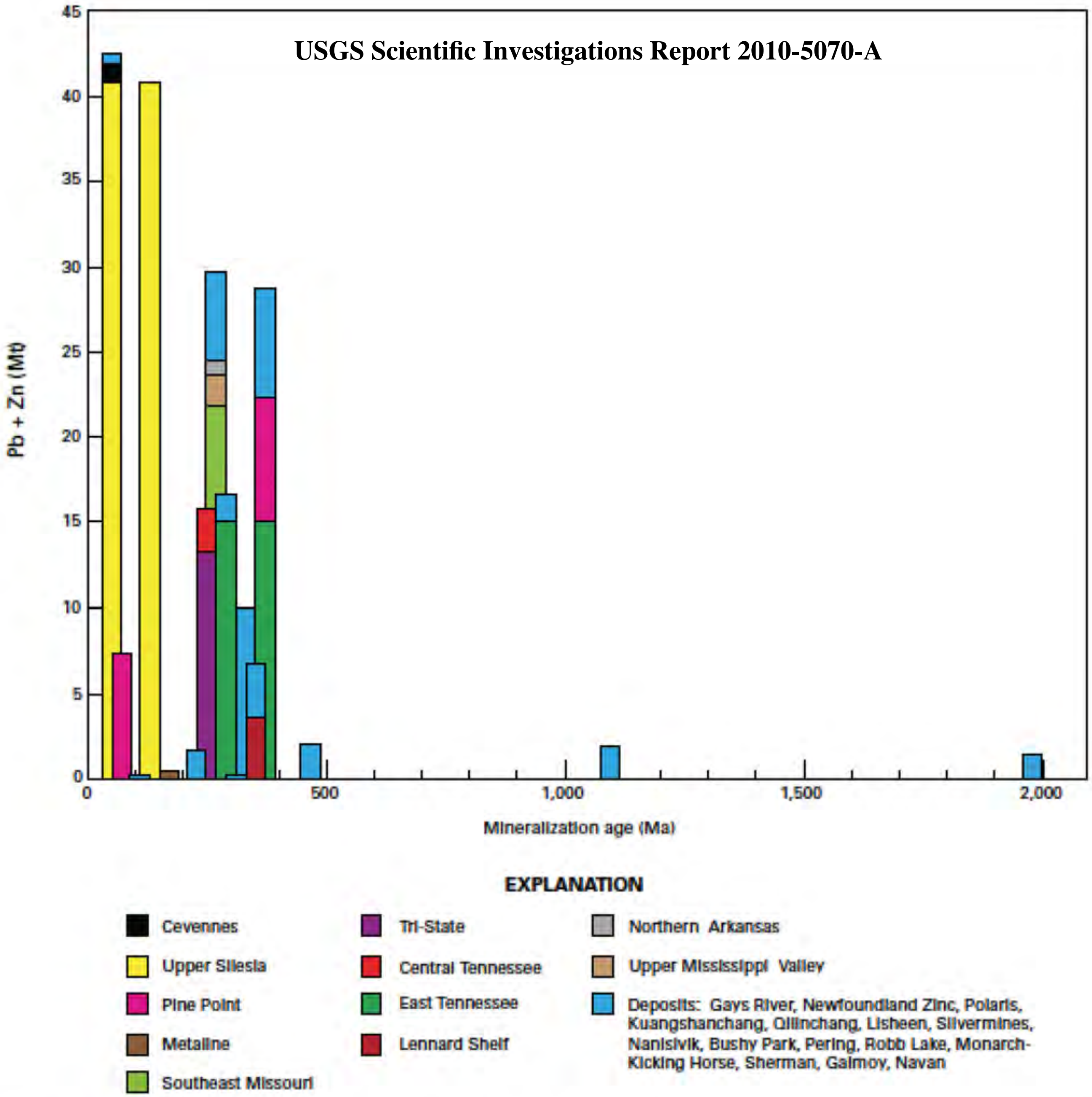


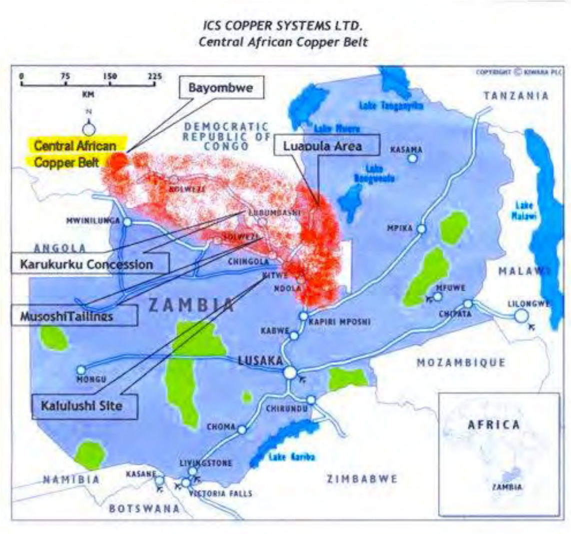
Figure A1. Secular distribution of Mississippi Valley-Type deposits and districts with paleomagnetic and/or radiometric ages of mineralization (data from Taylor and others, 2009).

Upper Mississippi Valley Zinc Mine, Dubuque, Iowa

http://www.igsb.uiowa.edu/Browse/leadzinc/leadznc1.gif

Underground lead-zinc mine, Viburnum, Missouri

http://blogs.agu.org/magmacumlaude/files/2011/03/ESCD3865L-028.jpg



Copper Mine, Zambia, Central Africa Copper Belt

http://www.womp-int.com/story/2008vol2/story024.htm

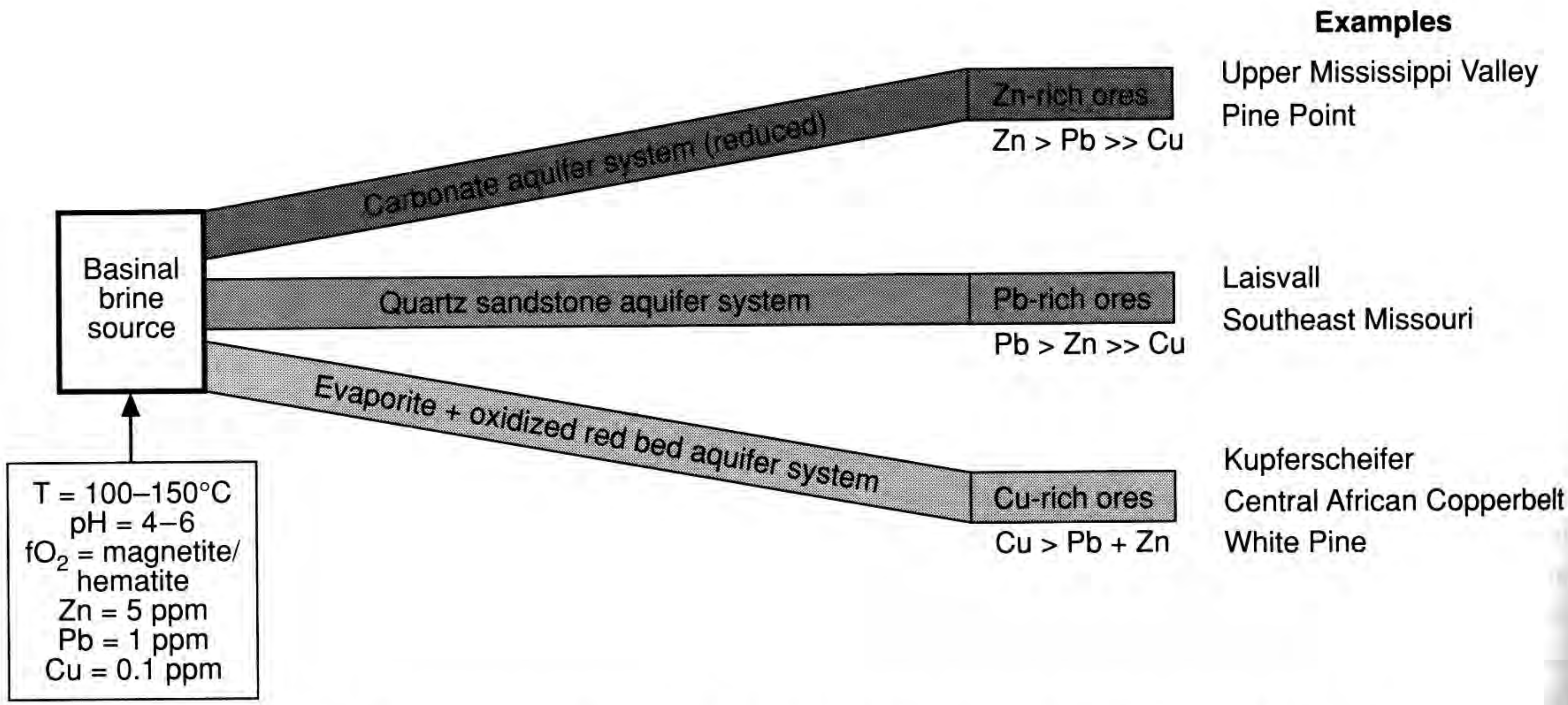
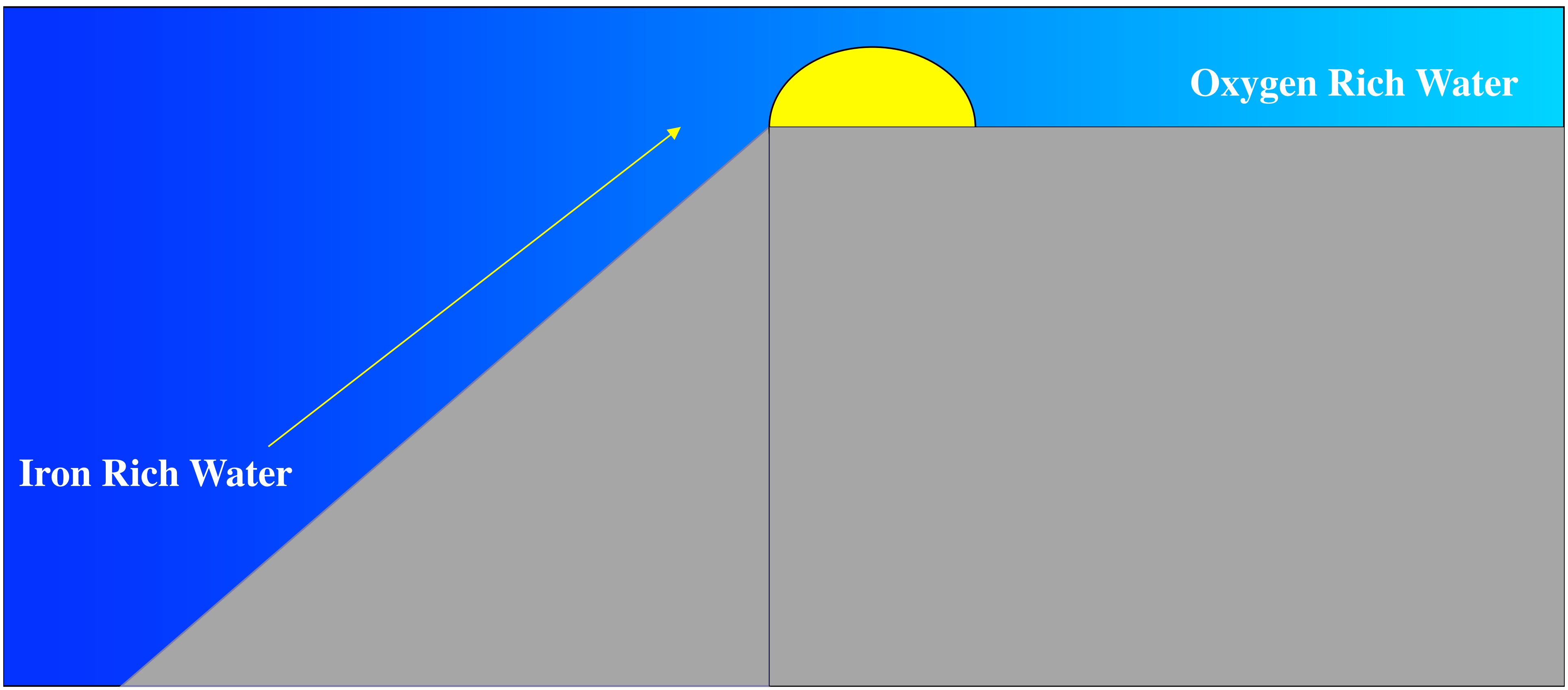


Figure 3.29 Diagrammatic representation showing the relationship between a single basinal brine and the conditions under which it might form SSC, as well as carbonate- and sandstone-hosted, MVT deposits (after Sverjensky, 1989; Metcalfe *et al.*, 1994).

Sedimentary settings-

Sedimentary Precipitates precipitation of ores in appropriate sedimentary environments, possibly aided by biota.

Banded Iron Formations (BIF)-preCambrian in age. Inferred to be deposited before abundant oxygen was present in the atmosphere.



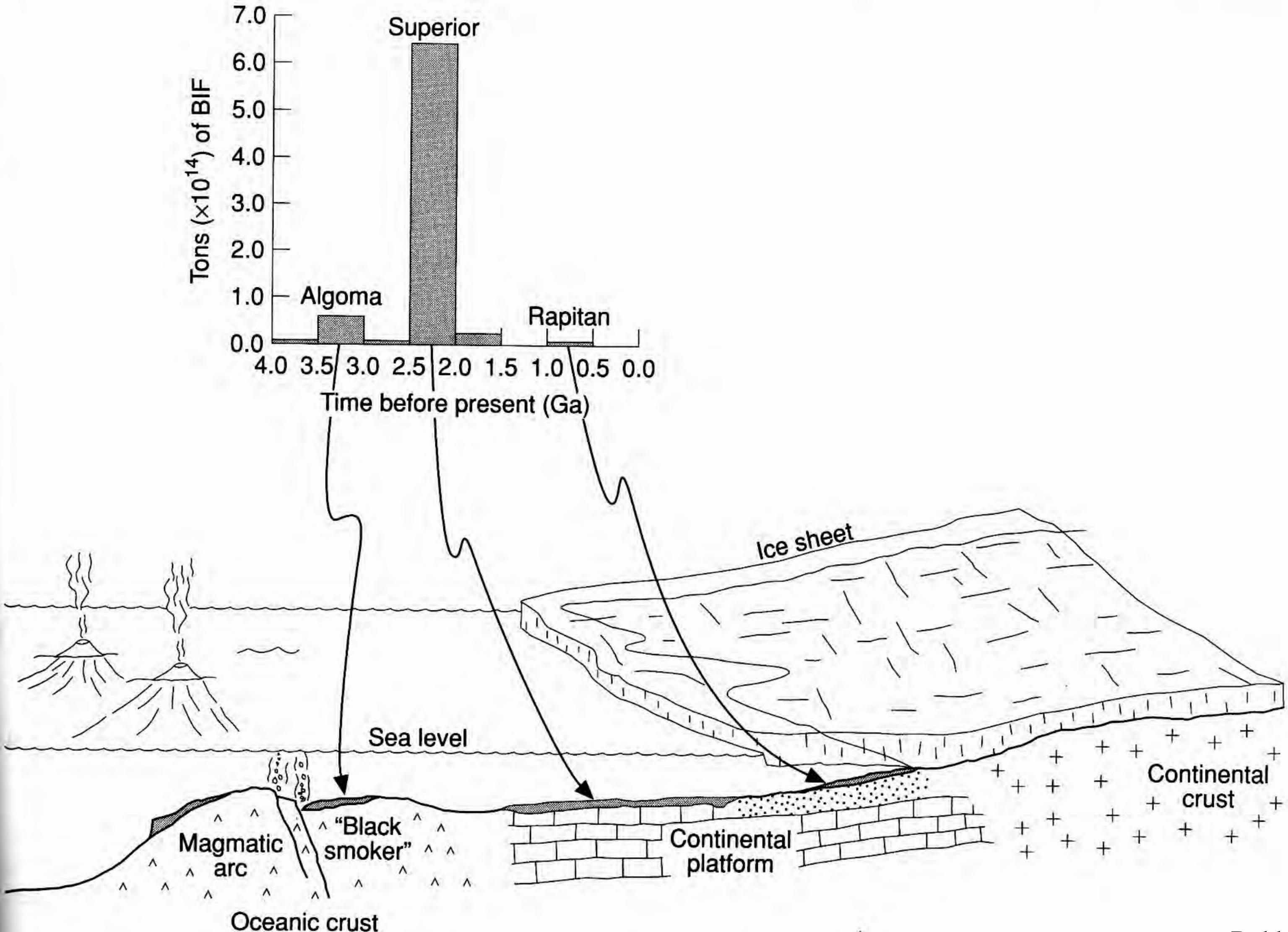


Figure 5.16 Tectonic and environmental model showing the depositional settings for Algoma, Superior, and Rapitan type BIFs (after Clemmey, 1985; Maynard, 1991). The inset histogram illustrates the approximate tonnages of BIF resource for each of the three major types as a function of time (after Holland, 1984).

Robb (2005) Introduction To Ore Forming Processes

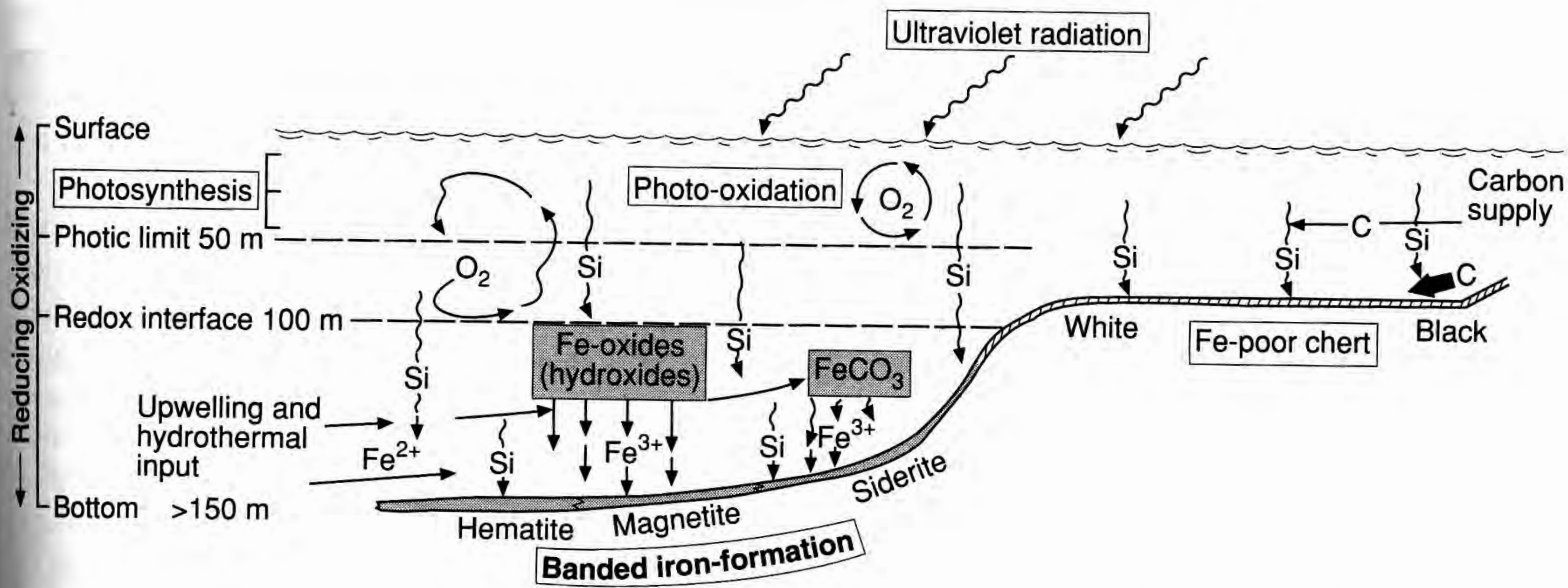
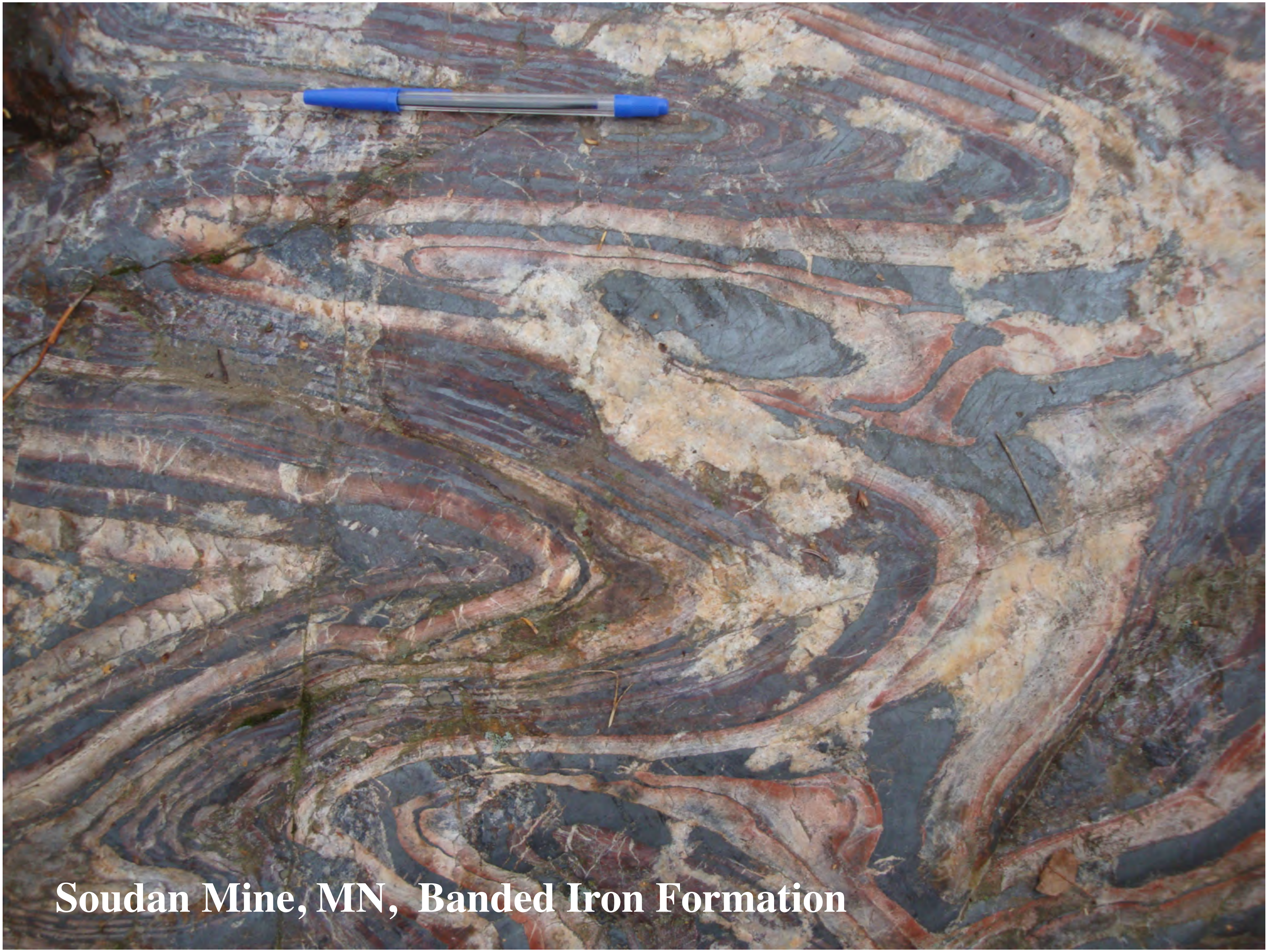


Figure 5.18 Model invoking upwelling and oxidation of ferrous iron from an oceanic source to explain the depositional environment for BIFs. Oxidation of ferrous iron and precipitation of ferric iron compounds occurs at a diffuse redox interface formed by the production of oxygen in the upper water levels, either by photosynthesizing organisms or by ultraviolet radiation induced photo-oxidation, or both. The lateral zonation of BIF facies (i.e. siderite–magnetite–hematite) shown here differs from the simple scheme envisaged by James (1954). Diagram modified after Klein and Beukes (1993).

Robb (2005) Introduction To Ore Forming Processes

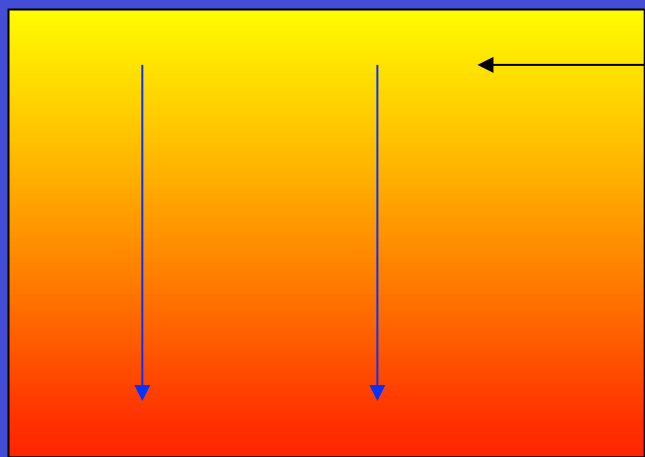

Soudan Mine, MN
Banded Iron Formation


Soudan Mine, MN, Banded Iron Formation


SOUDAN MINE
SERVICE ENTRANCE

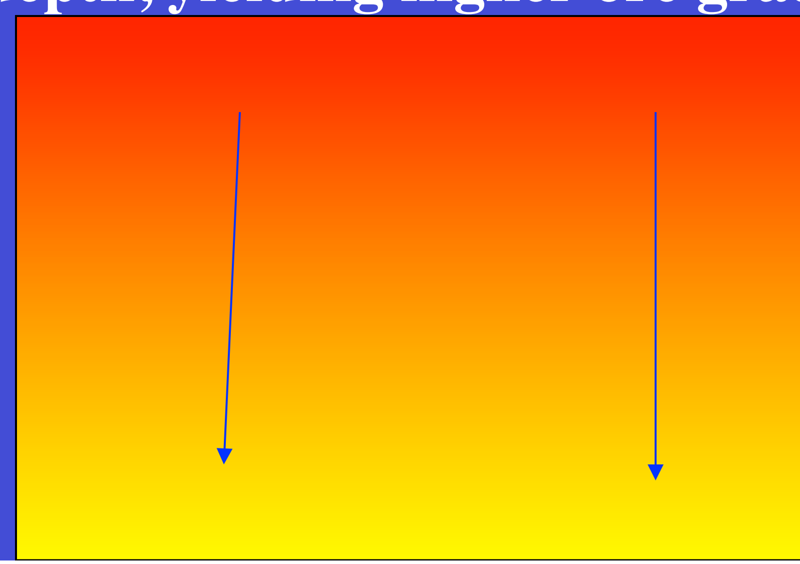
Surface Deposits

Residual process: leaching of non-ore material, leaving concentrated Insoluble elements in the remaining material



Residual Ore

Supergene process: leaching of elements from shallow deposit and precipitation of these at depth, yielding higher ore grades



Supergene Ore

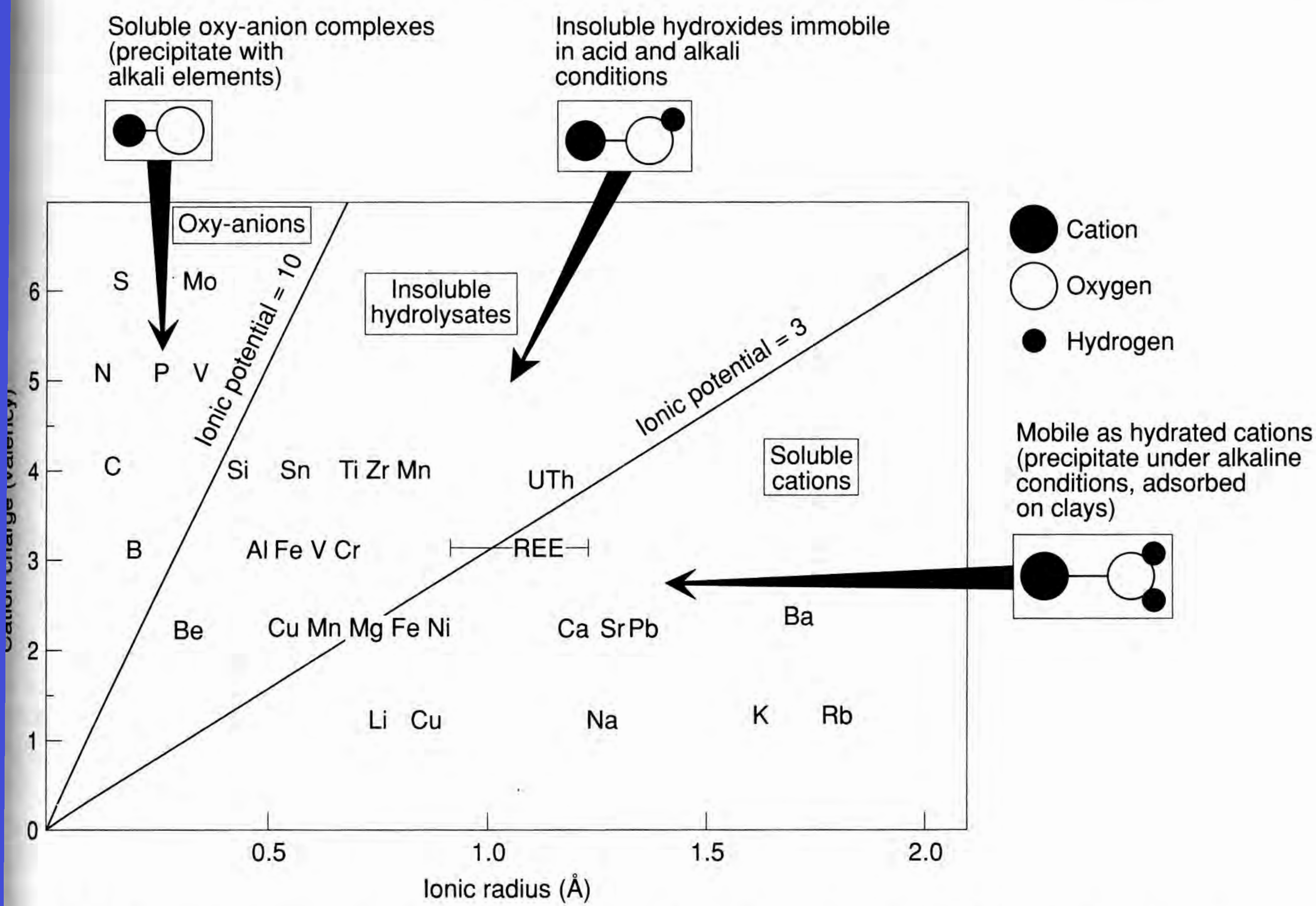
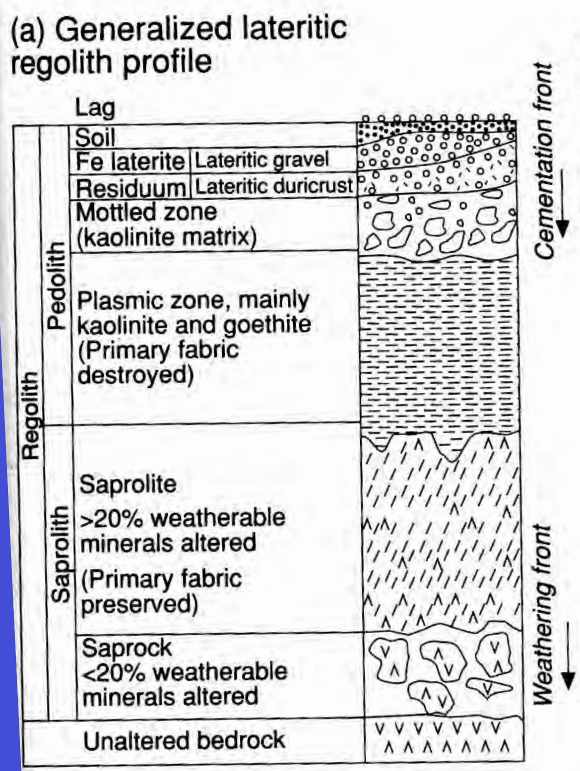


Figure 4.1 Simplified scheme on the basis of ionic potential (ionic charge/ionic radius) showing the relative mobility of selected ions in aqueous solutions in the surficial environment (modified after Leeder, 1999).



(b) Element mobility in typical lateritic profiles

Host minerals	Leached	Partly retained (in secondary minerals)
Released in the mottled and ferruginous zones		
Aluminosilicates (muscovite, kaolinite) iron oxides; gold	K, Rb, Cs Trace elements; Au	Si, Al (kaolinite)
Released in upper saprolite		
Aluminosilicates (muscovite)	Cs, K, Rb	Si, Al (kaolinite)
Ferromagnesians (chlorite, talc, amphibole)	Mg, Li	Fe, Ni, Co, Cr, Ga, Mn, Ti, V (Fe and Mn oxides)
Smectite clays	Ca, Mg, Na	Si, Al (kaolinite)
Released in the lower saprolite		
Aluminosilicates	Ca, Cs, K, Na, Rb	Si, Al (kaolinite); Ba (barite)
Ferromagnesians (pyroxene, olivine amphiboles, chlorite, biotite)	Ca, Mg	Fe, Ni, Co, Cr, Ga, Mn, Ti, V (Fe and Mn oxides)
Released at weathering front		
Sulfides	As, Au, Cd, Co, Cu, Mo, Ni, Zn, S	As, Cu, Ni, Pb, Sb, Zn, (Fe oxides; sulfates, arsenates, carbonates, alunite-jarosite)
Carbonates	Ca, Mg, Fe, Mn, Sr	

Figure 4.3 (a) A generalized lateritic regolith profile showing the different horizons and the terminology used in their description. (b) Generalized pattern of element mobility in lateritic regoliths (after Butt *et al.*, 2000).

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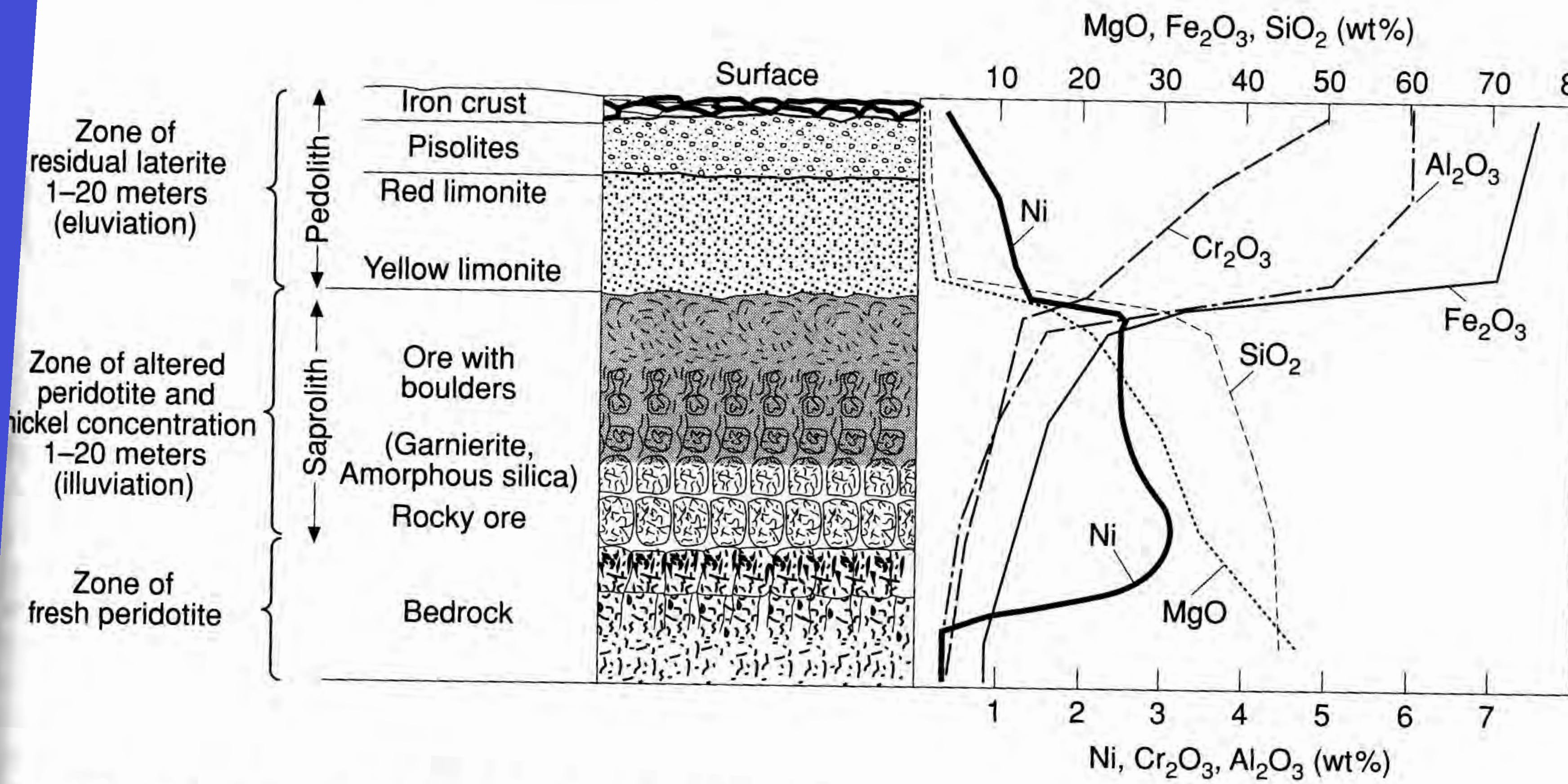

Figure 4.5 Descriptive profile and Ni ore distribution in a lateritic regolith typical of the New Caledonian deposits. The chemical profile clearly distinguishes the ferruginous/aluminous residual zone where Si, Mg, and Ni are leached, from the saprolith where illuviation has resulted in concentration of Ni (after Troly *et al.*, 1979; Guilbert and Park, 1986).

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Bauxite mine, Jamaica

http://jamaica-gleaner.com/gleaner/20111209/business/images/Bauxite-307768.jpg

Hanna Nickel Mine, Riddle, Oregon