EARTH 471
Mineral Deposits

Hydrothermal Ore deposits (I): VMS

VMS

volcanogenic massive sulfide deposits

13.18 Volcanogenic Massive Sulfide Deposits

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13.18.1 Introduction

Volcanogenic massive sulfide (VMS) deposits are stratiform or stratabound accumulations of base metal sulfides that formed on or near the seafloor by precipitation from 250 to 350 °C, dominantly seawater-derived hydrothermal fluids. They are an important subclass of the more general 'massive sulfide' deposits, which also includes sedimentary-exhalative massive sulfides. VMS deposits consist of >60% sulfide minerals, mainly pyrite and/or pyrrhotite, with variable amounts of Cu, Zn, and Pb sulfides (chalcopyrite, sphalerite, and galena) as the main ore minerals. Most deposits are characterized by internal metal zoning, with Cu-rich sulfides occurring dominantly at the base and Zn- or Pb-rich sulfides at the top or outer margins, reflecting temperature-dependent solubilities of the ore minerals in cooling hydrothermal fluids discharged onto the seafloor (Figure 1). The massive ore may be underlain by a vertically extensive network of Cu-rich veins and disseminated sulfides, referred to as the 'feeder zone' or 'stringer zone,' and by intensely altered rocks (i.e., the 'alteration pipe'). Proximal deposits are those that formed immediately above or adjacent to the discharge site, whereas distal deposits may have accumulated at some distance from the vents. Host strata are predominantly volcanic rocks, although the ores themselves may have been deposited in sediments that occur within the volcanic succession. The metals and reduced sulfur are considered to be mainly derived from leaching of the underlying volcanic rocks, with a potentially important contribution of metals from contemporaneous magmas. Some portion of the reduced sulfur may also have been derived from coeval seawater. The flow of hydrothermal fluids to the seafloor is driven by convective circulation above a deep heat source, most commonly a subvolcanic magma chamber, ~2 km below the seafloor (Figure 2). The most spectacular examples of this process are the presently active submarine hydrothermal vents or 'black smokers' that occur at modern mid-ocean ridges, submarine volcanic arcs, and in back-arc basins. Because ancient VMS formed by essentially the same geological and geochemical processes occurring on the ocean floor today, many parallels have been drawn between modern and ancient deposits.

The genetic link between seafloor volcanism and hydrothermal activity in a modern context was first articulated as an outgrowth of plate tectonic theory, about 20 years before the discovery of black smokers, although the notion of metallic mineral deposits forming at submarine volcanoes existed long before then (e.g., see Stanton, 1984). The current model was introduced in the late 1950s (Knight, 1957; Oftedahl, 1958; Stanton, 1955), and by 1965 a clear picture of the likely origin of VMS deposits at seafloor hydrothermal vents was established (Gilmour, 1965; Roscoe, 1965; Stanton, 1960). When black smoker sulfide deposits were discovered at mid-ocean ridges (Francheteau et al., 1979; Hekinian et al., 1980), many of the details of ore formation in the submarine environment were already known from the study of ancient VMS deposits. However, black smoker vents provided the first opportunity to sample hydrothermal fluids responsible for VMS formation. Until that time, the major characteristics of the hydrothermal fluids were inferred mainly from the study of the ore minerals and the alteration of the volcanic host rocks.

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Volcanogenic Massive Sulphide Deposits

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Abstract

Volcanogenic massive sulphide (VMS) deposits, also known as volcanic-associated, volcanic-hosted, and volcano-sedimentary-hosted massive sulphide deposits, are major sources of Zn, Cu, Pb, Ag, and Au, and significant sources for Co, Sn, Se, Mn, Cd, In, Bi, Te, Ga, and Ge. They typically occur as lenses of polymetallic massive sulphide that form at or near the seafloor in submarine volcanic environments, and are classified according to base metal content, gold content, or host-rock lithology. There are close to 350 known VMS deposits in Canada and over 800 known worldwide. Historically, they account for 27% of Canada's Cu production, 49% of its Zn, 20% of its Pb, 40% of its Ag, and 3% of its Au. They are discovered in submarine volcanic terranes that range in age from 3.4 Ga to actively forming deposits in modern seafloor environments. The most common feature among all types of VMS deposits is that they are formed in extensional tectonic settings, including both oceanic seafloor spreading and arc environments. Most ancient VMS deposits that are still preserved in the geological record formed mainly in oceanic and continental nascent-arc, rifted-arc, and back-arc settings. Primitive bimodal mafic volcanic-dominated oceanic rifted arc and bimodal felsic-dominated siliciclastic continental back-arc terranes contain some of the world's most economically important VMS districts. Most, but not all, significant VMS mining districts are defined by deposit clusters formed within rifts or calderas. Their clustering is further attributed to a common heat source that triggers large-scale subseafloor fluid convection systems. These subvolcanic intrusions may also supply metals to the VMS hydrothermal systems through magmatic devolatilization. As a result of large-scale fluid flow, VMS mining districts are commonly characterized by extensive semi-conformable zones of hydrothermal alteration that intensifies into zones of discordant alteration in the immediate footwall and hanging wall of individual deposits. VMS camps can be further characterized by the presence of thin, but areally extensive, units of ferruginous chemical sediment formed from exhalation of fluids and distribution of hydrothermal particulates.

Résumé

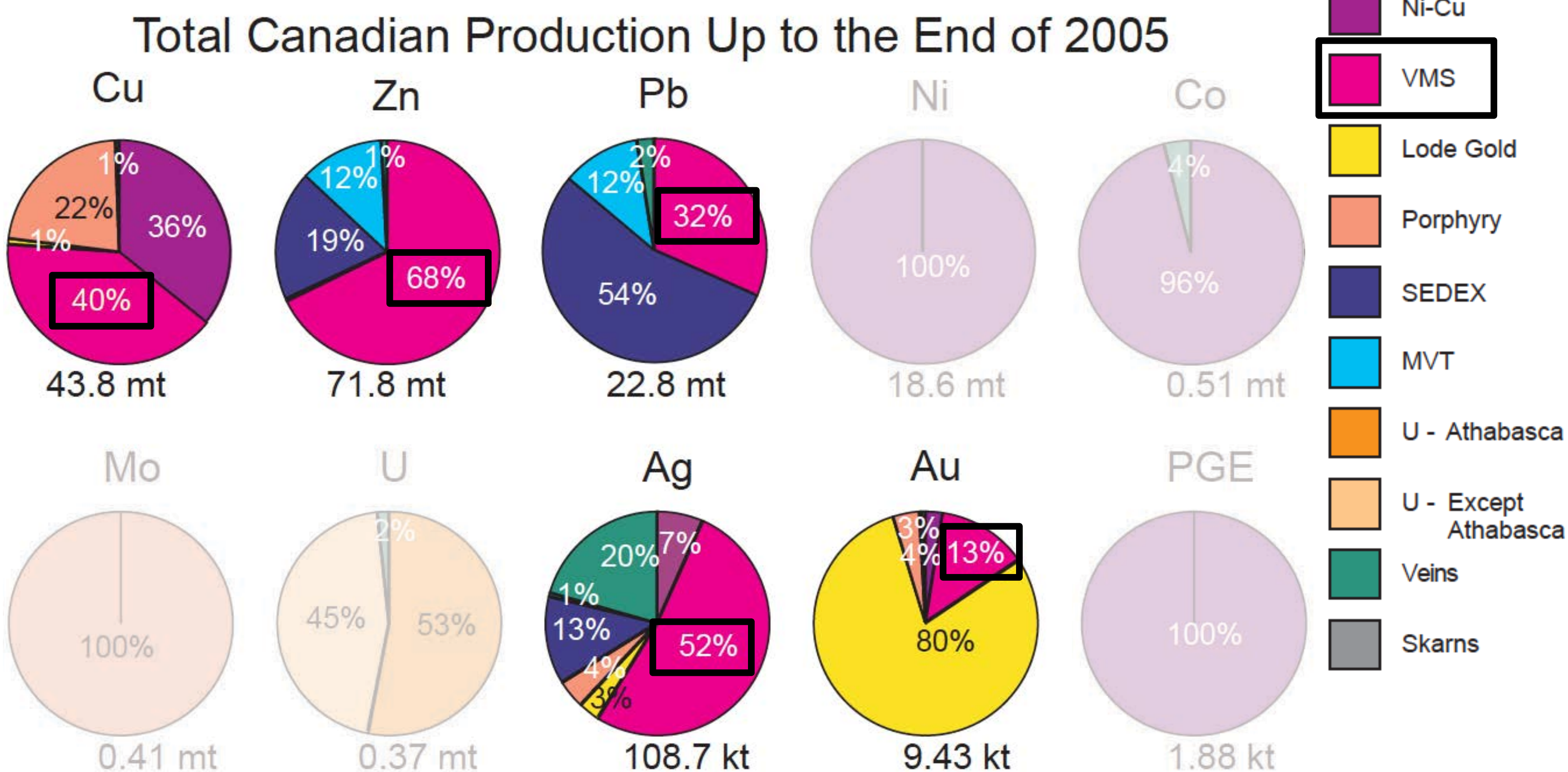
Les gîtes de sulfures massifs volcanogènes (SMV) sont connus sous diverses appellations parmi lesquelles on peut mentionner les gîtes de sulfures massifs associés à des roches volcaniques, encaissés dans des roches volcaniques ou logés dans des assemblages volcano-sédimentaires. Ils constituent des sources considérables de Zn, Cu, Pb, Ag et Au, ainsi que des sources importantes de Co, Sn, Se, Mn, Cd, In, Bi, Te, Ga et Ge. Ils consistent généralement en lentilles de sulfures massifs polymétalliques formées dans des milieux volcaniques sous-marins, au sein ou à proximité du fond océanique, et sont classés d'après leur contenu en métaux communs ou en or ou selon la lithologie des roches encaissantes. Près de 350 gîtes SMV ont été découverts au Canada et plus de 800, de par le monde. Dans l'histoire de la production minière du Canada, 27 % du cuivre, 49 % du zinc, 20 % du plomb, 40 % de l'argent et 3 % de l'or ont été extraits de gisements SMV. On trouve de tels gîtes aussi bien dans des terrains volcaniques sous-marins datant de 3,4 Ga que dans les fonds océaniques actuels où de nouveaux gîtes sont en cours de formation. La caractéristique la plus commune à tous les gîtes de SMV tient à leur formation dans des milieux tectoniques de distension, parmi lesquels on peut mentionner les fonds océaniques en expansion et les arcs. La plupart des anciens gîtes SMV conservés dans les archives géologiques se sont formés dans des milieux océaniques et continentaux d'arc naissant, d'arc de divergence et d'arrière-arc. Quelques-uns des districts à gisements SMV les plus importants dans le monde sur le plan économique se trouvent dans des terrains océaniques primitifs d'arc de divergence caractérisés par un volcanisme bimodal à dominante mafique, de même que dans des terrains continentaux d'arrière arc caractérisés par un volcanisme bimodal à dominante felsique et la présence de matériaux silicoclastiques. La plupart des principaux districts miniers à gisements SMV consistent en amas de gisements formés dans des rifts ou des caldeiras. Leur regroupement est attribuable à l'existence d'une source de chaleur commune qui donne naissance à de vastes réseaux de convection de fluides sous le plancher océanique. Les intrusions subvolcaniques qui produisent cette chaleur peuvent aussi fournir des métaux aux réseaux hydrothermaux des gîtes SMV par le biais d'un dégagement magmatique de matières volatiles. En raison de l'écoulement de fluides sur une grande étendue, les districts miniers à gisements SMV se caractérisent souvent par la présence de vastes zones semi-concordantes d'altération hydrothermale, qui gagnent en intensité pour devenir des zones d'altération discordantes, dans l'éponte inférieure et l'éponte supérieure immédiates des gisements. Ces districts se distinguent aussi par la présence d'unités minces mais étendues de sédiments chimiques ferrugineux qui résultent de l'exhalaison et de la diffusion de particules hydrothermales.

Definition

Volcanogenic massive sulphide (VMS) deposits are also known as volcanic-associated, volcanic-hosted, and volcano-sedimentary-hosted massive sulphide deposits. They typically occur as lenses of polymetallic massive sulphide that form at or near the seafloor in submarine volcanic environments. They form from metal-enriched fluids associated with seafloor hydrothermal convection. Their immediate host rocks can be either volcanic or sedimentary. VMS deposits are major sources of Zn, Cu, Pb, Ag, and Au, and significant sources for Co, Sn, Se, Mn, Cd, In, Bi, Te, Ga, and Ge. Some also contain significant amounts of As, Sb, and Hg. Historically, they account for 27% of Canada's Cu production, 49% of its Zn, 20% of its Pb, 40% of its Ag, and

Galley, A.G., Hannington, M.D., and Jonasson, I.R., 2007, Volcanogenic massive sulphide deposits, *in* Goodfellow, W.D., ed., Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods: Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5, p. 141-161.

VMS – major source of Cu, Pb, Zn, Ag (Au)



Lydon, 2007

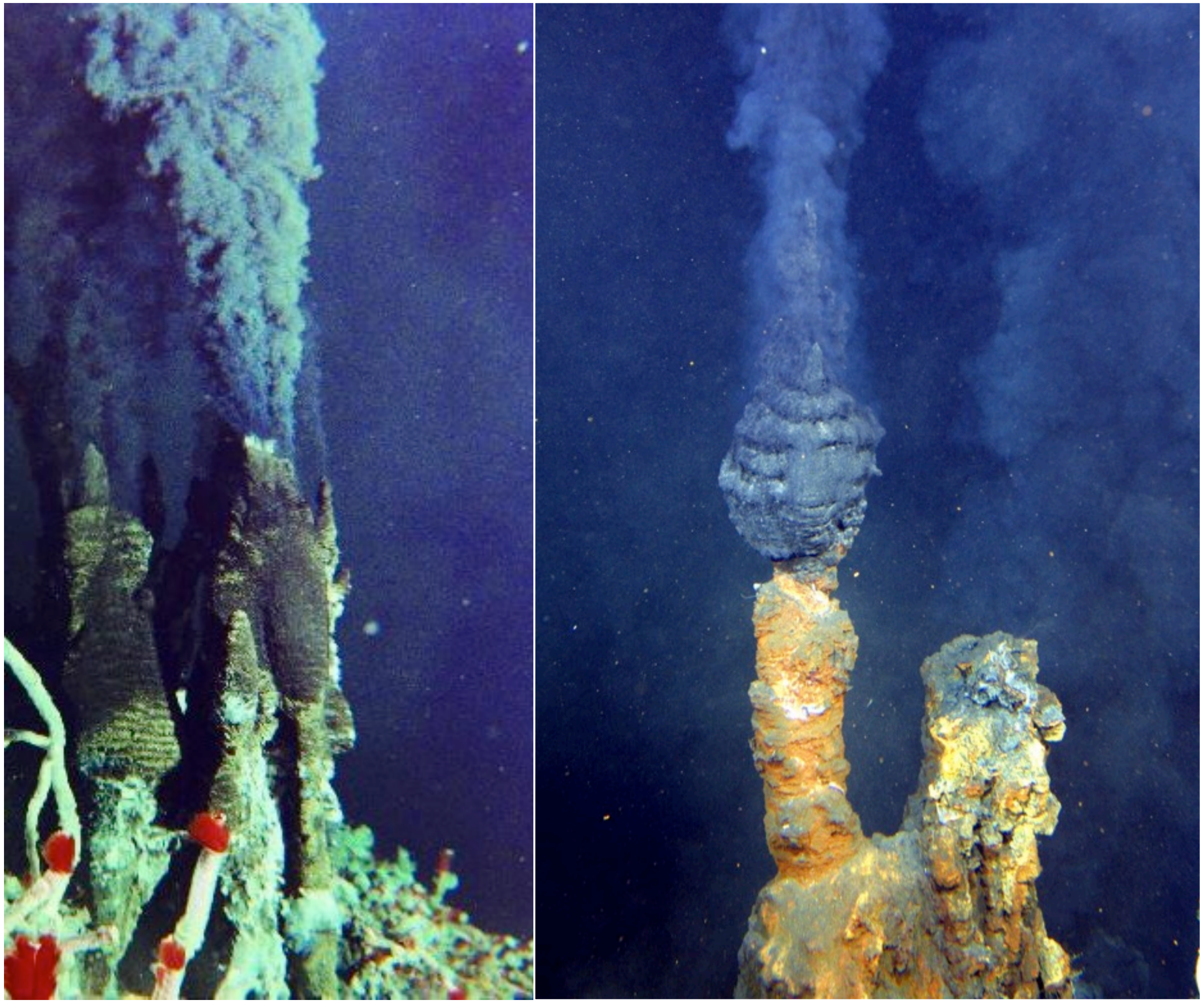
Black smokers are modern analogues for VMS

1960s: known that warm brines vented on to the sea floor

1970s: Black smokers discovered on the East Pacific Rise

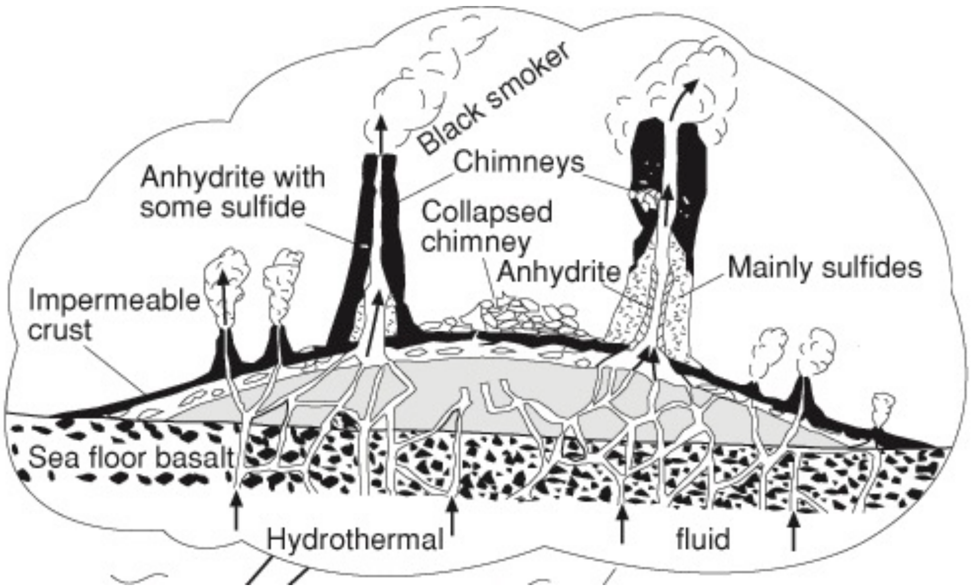
<u>*Fluids are*</u>:

- Hot (up to 400°C)
- Reducing
- Acidic (pH 2–5)
- Plenty of dissolved metals (Fe, Mn, Zn, Cu)
- H_2S rich



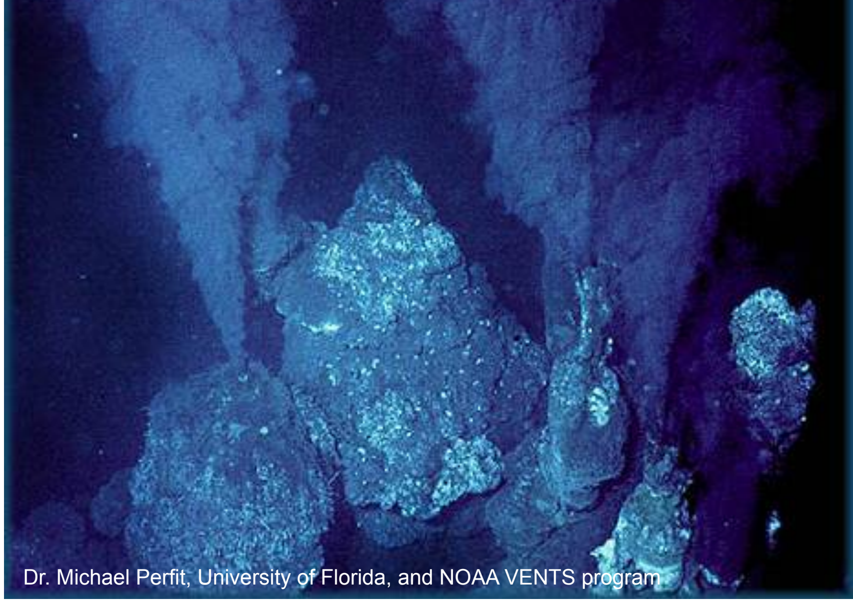
Black smokers – what do they look like?

- Chimneys made of anhydrite, barite, sulfides and silica
  - Pyrite, pyrrhotite, chalcopyrite, sphalerite
  - Cu, Zn, Fe



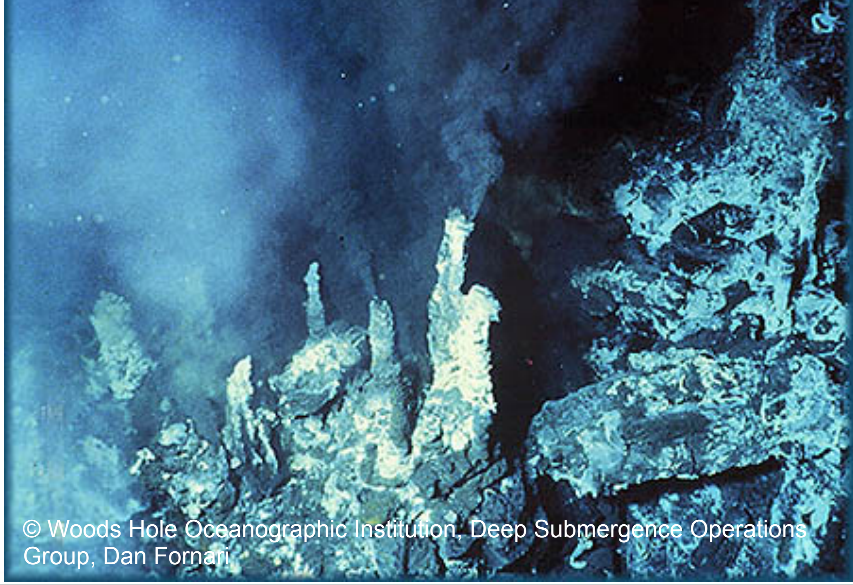
Robb (2005)

Juan de Fuca Ridge, at 44°58' N & 130°14' W



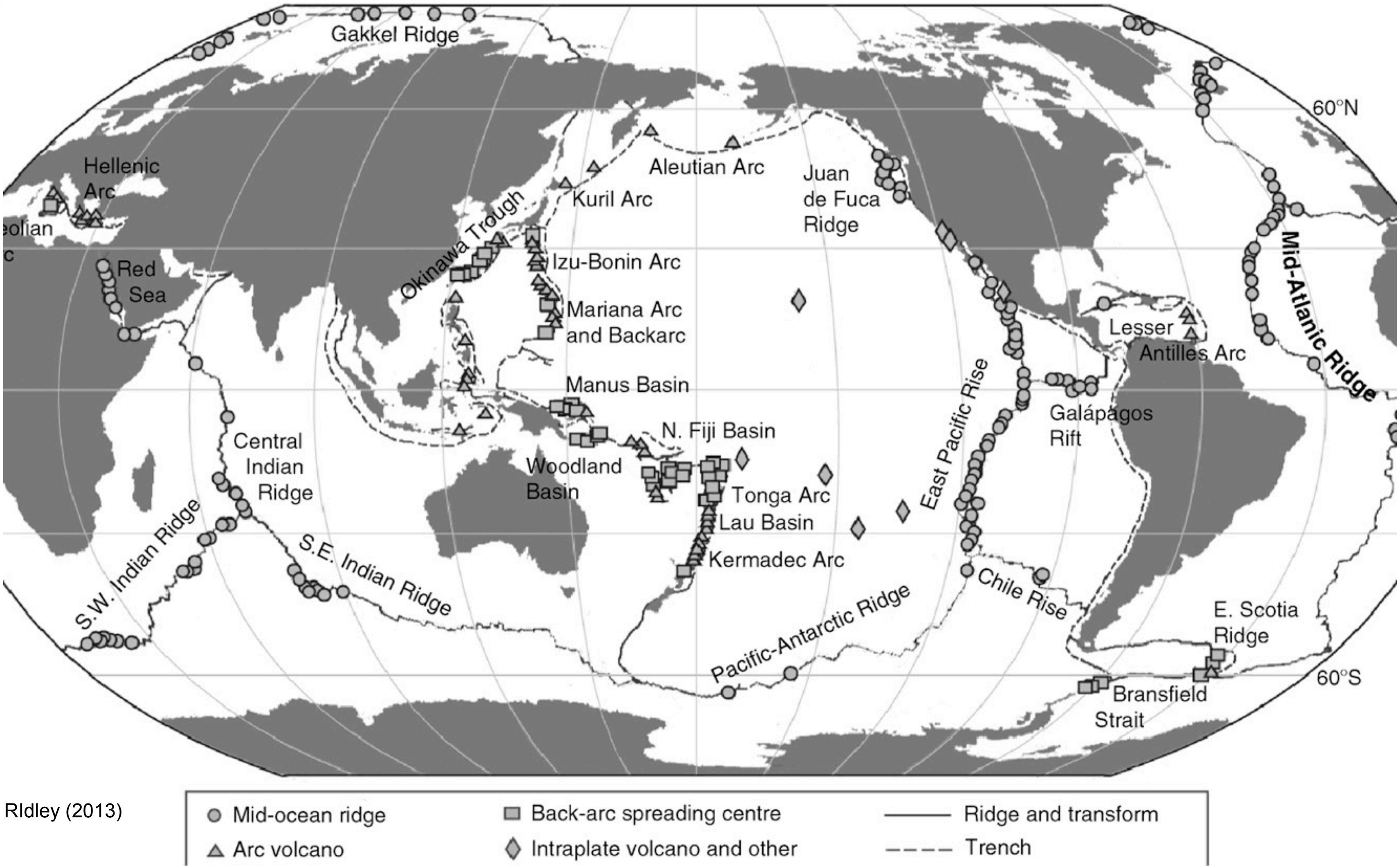
Dr. Michael Perfit, University of Florida, and NOAA VENTS program

9°50' N on the East Pacific Rise



© Woods Hole Oceanographic Institution, Deep Submergence Operations Group, Dan Fornari

Black smokers – where do they form?



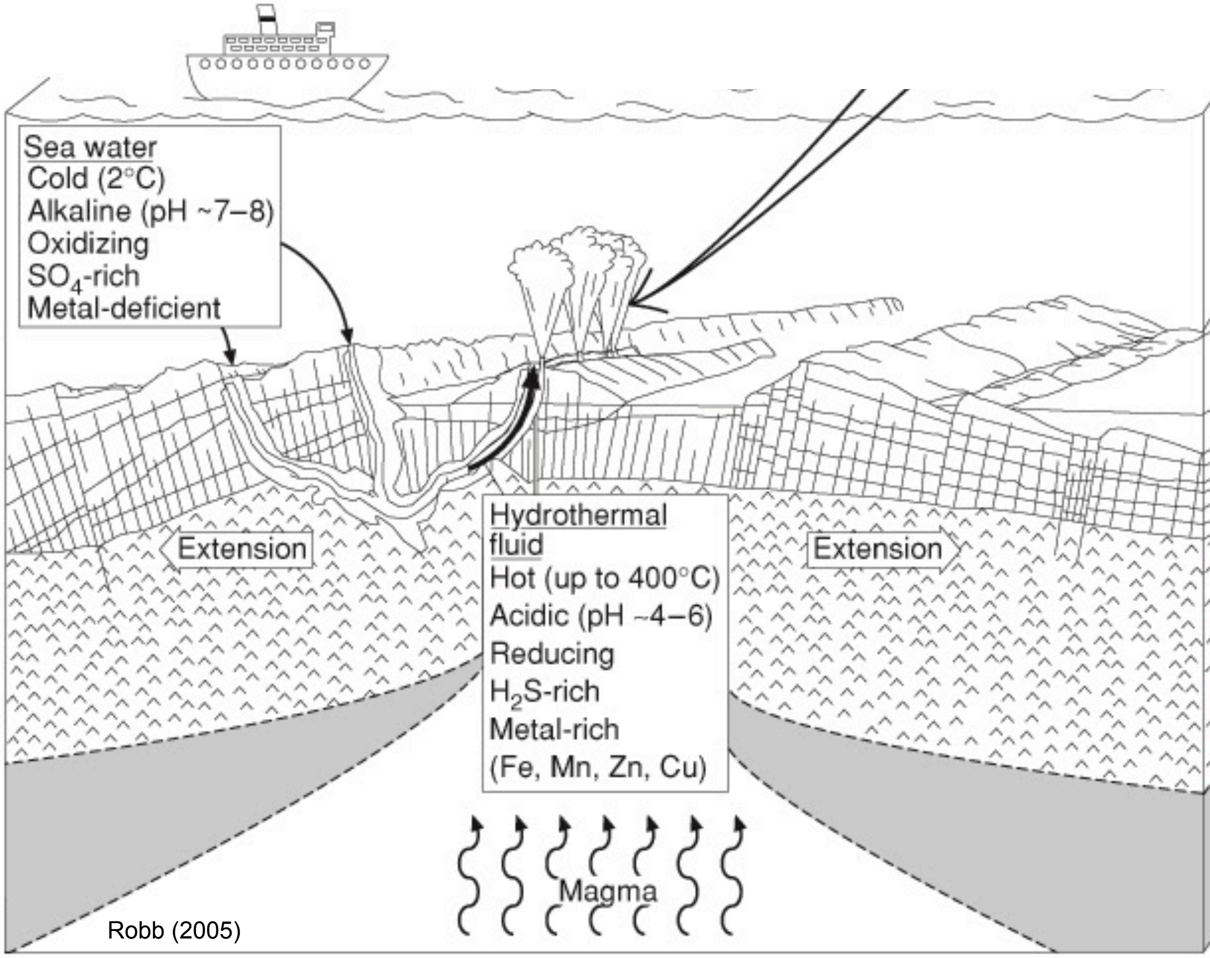
RIdley (2013)

Black smokers – where do they form?

Extensional tectonic environments (e.g. mid-ocean ridges)

At the seawater–rock/ sediment interface

Above magma chambers, which produce heat that fuel water circulation



Robb (2005)

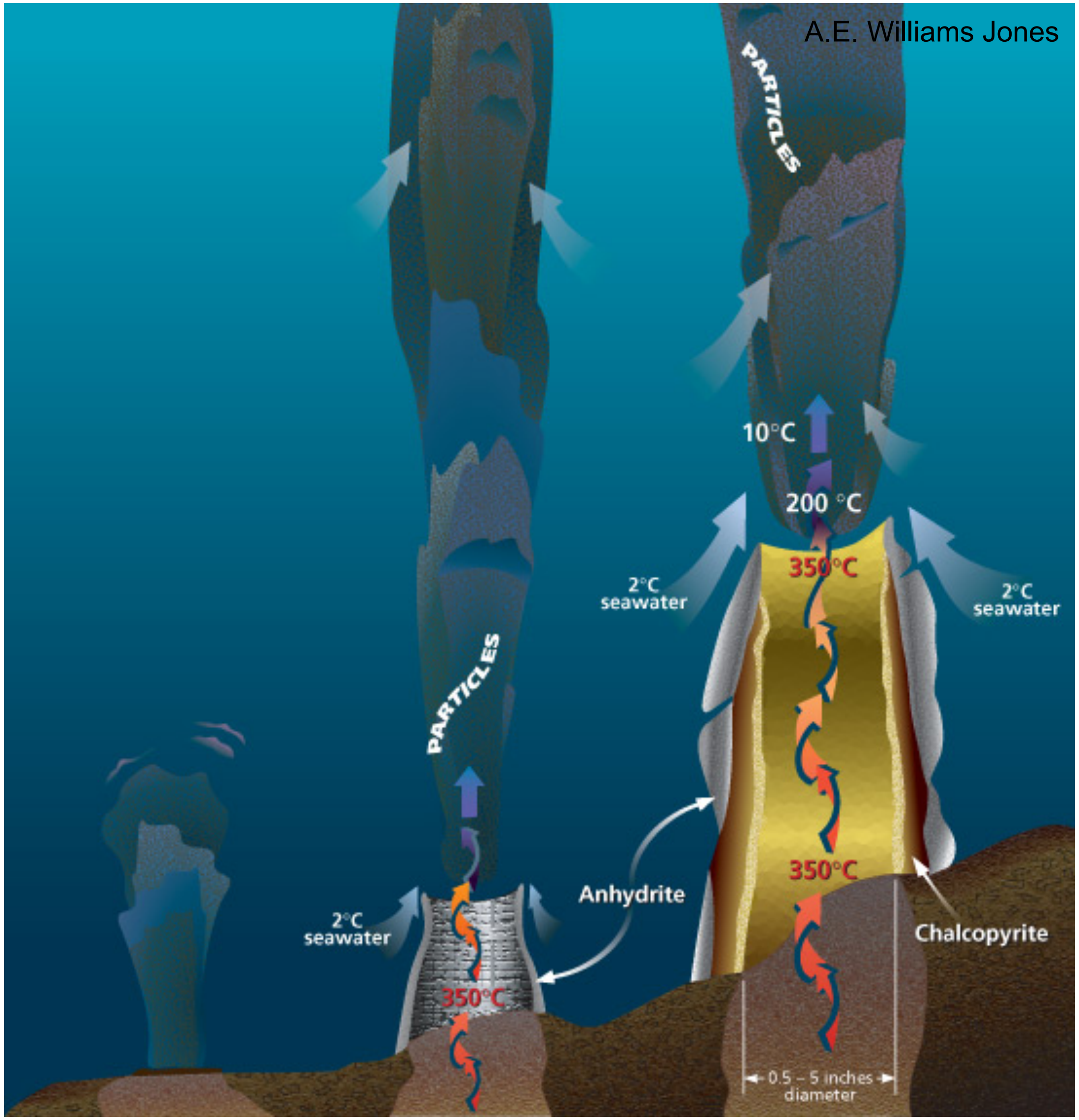
Black smokers – how do they form?

Cool dense seawater migrates down into the oceanic crust through fractures and cracks

Fluids heated to 350–450°C above magma chamber

Mineral–fluid reactions deplete fluid in Mg which ultimately results in an acidic solution

Acidic fluids leach Cu, Zn, Fe, S, Si from the host
Hot fluids become buoyant and ascend



Black smokers – how do they form?

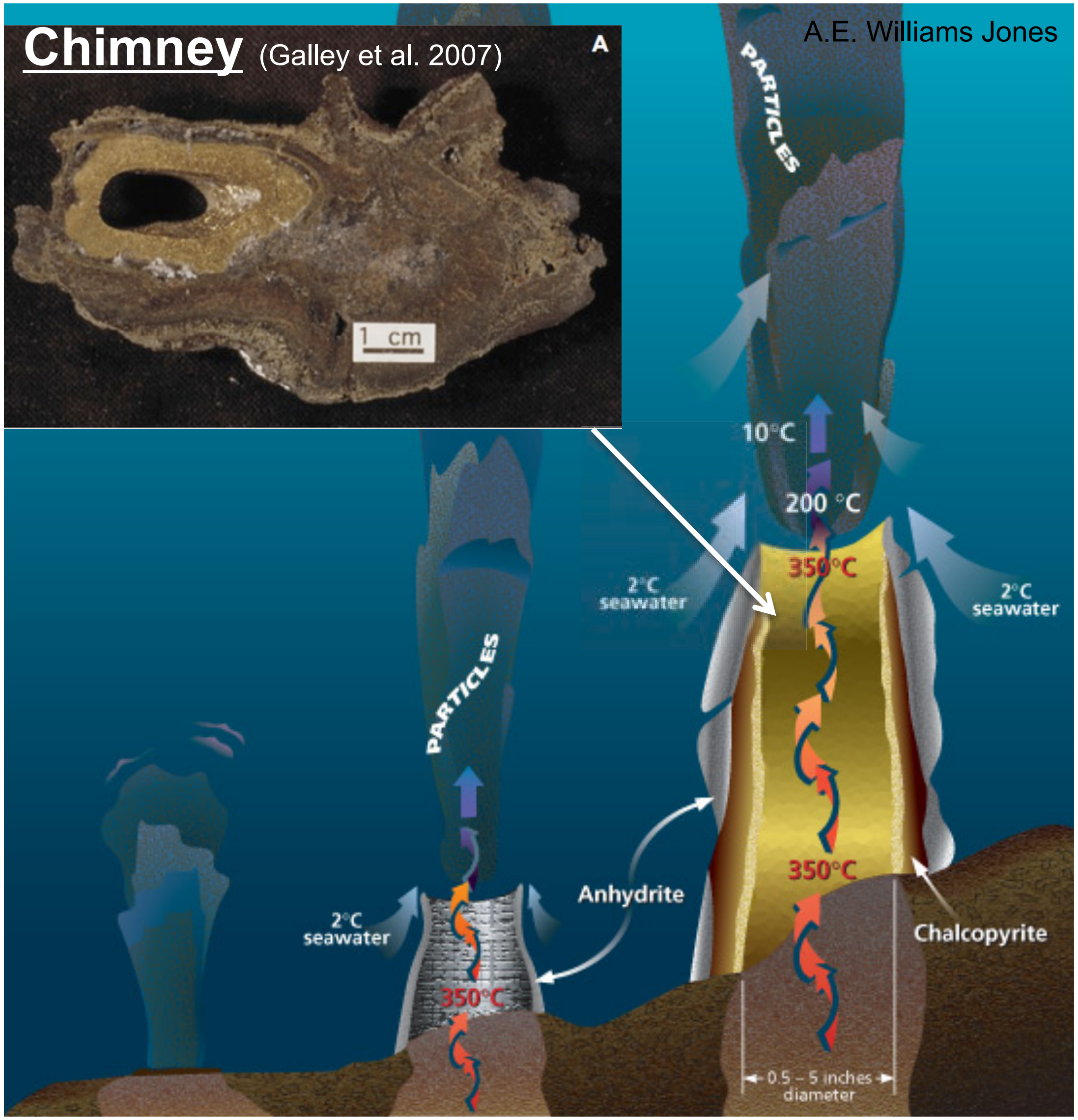
Hot buoyant fluids reach the sea floor and are rapidly cooled

Rapid cooling causes precipitation of fine-grained Fe-, Cu- and Zn-sulfides

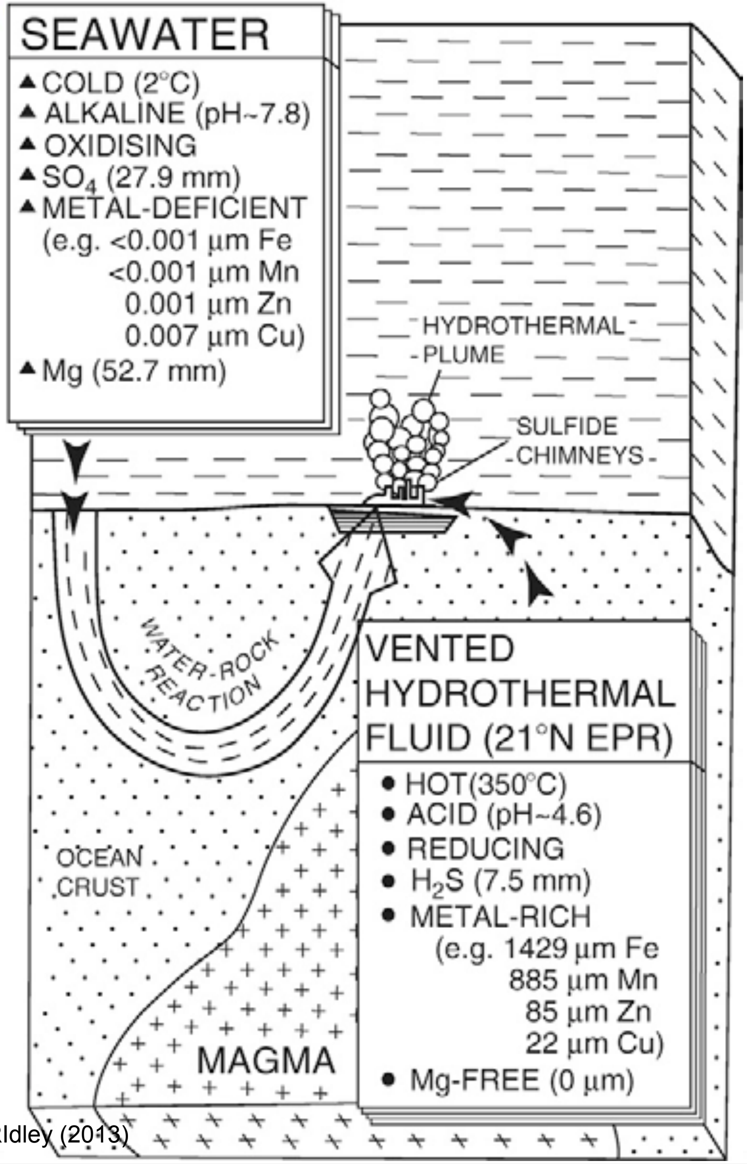
Most of the fine-grained sulfides ejected upwards by jet-like plumes (these sulfides give the black colour)

Some of the sulfides are deposited around the opening of the vent

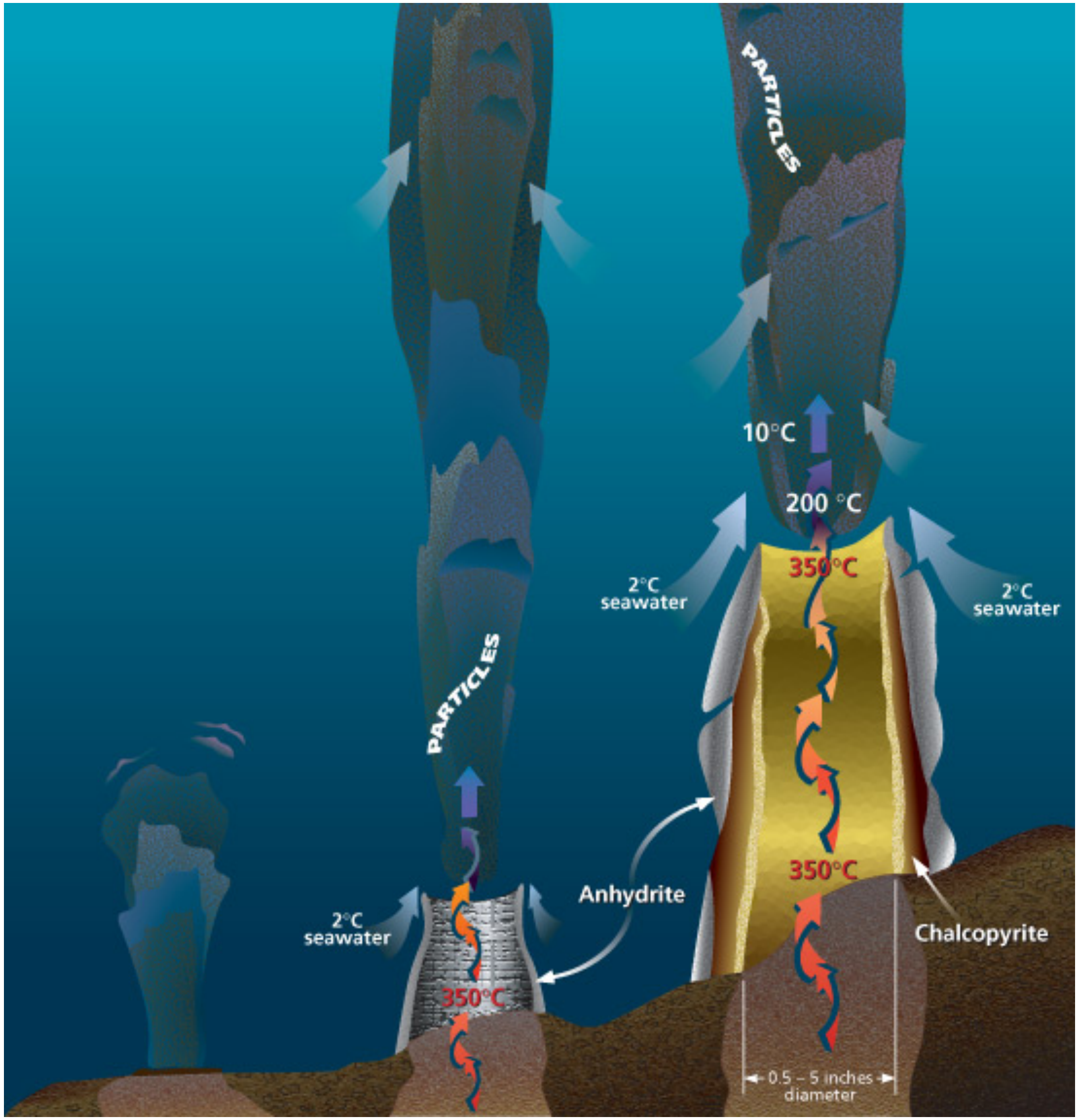
Vent grows upwards over time



Black smokers – how do they form?



RIdley (2013)



Reminder

Chloride precipitation (Me = metal) (Barnes, 1979)

$$MeCl_{2(aq)} + H_2S_{(aq)} \rightarrow MeS_{(s)} + 2\,H^+ + 2\,Cl^-$$

[Use Le Chatelier's principle]

- Increase H_2S through (1) sulfate reduction, (2) reaction with organic compounds, (3) mixing with sulfide solutions
- Increase pH by (1) reaction with carbonates or feldspars, (2) boiling off acid gases
- Reduce Cl^- content: (1) dilution by circulating meteoric waters
- **Decrease T** due to hot metal-rich fluids interacting with cool ocean waters and/or interaction with cool wall rock.

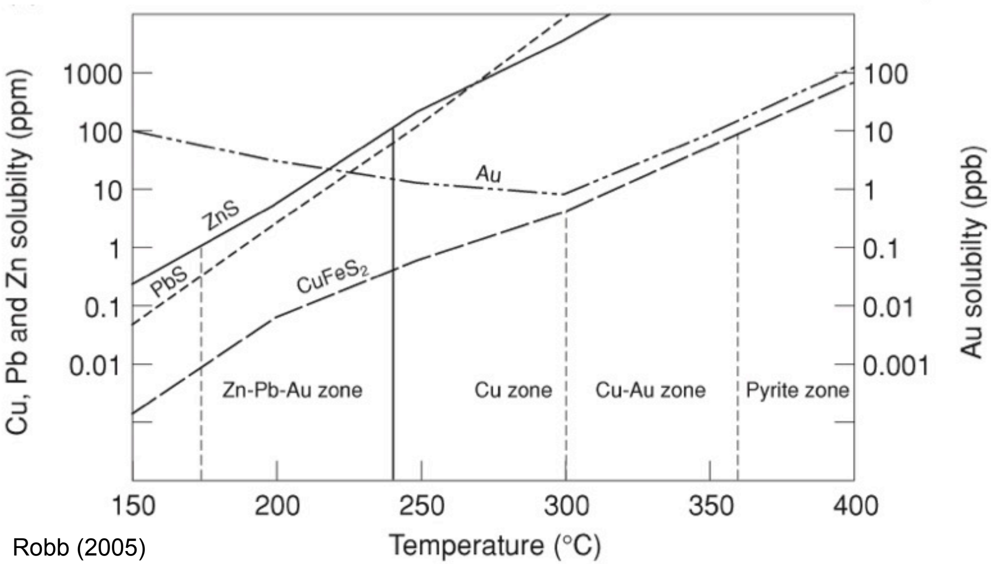
Black smokers – petrogenesis

Zoning in black smokers (and VMS deposits) is caused by the different solubilities of Cu, Fe, Zn and Au

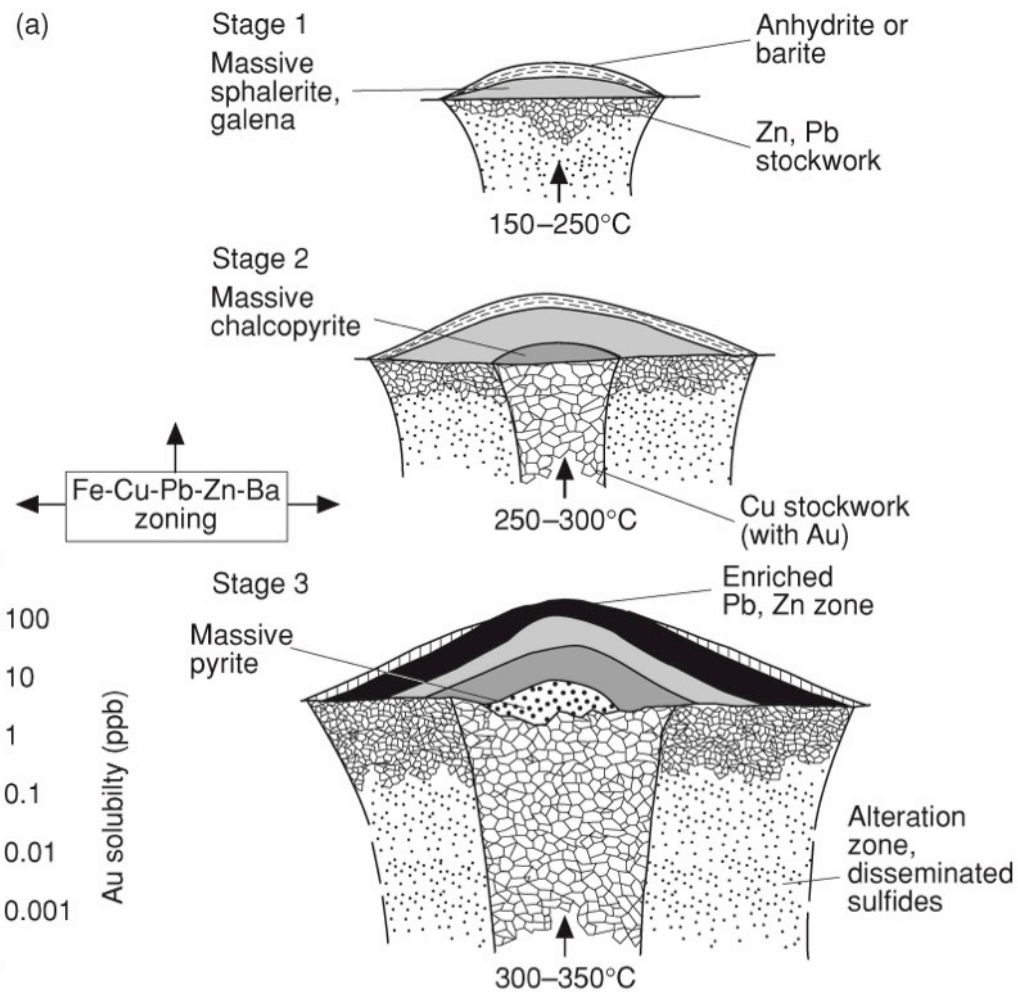
Zoning also reflects the changing composition of fluids over time

Low T ------> High T

Pb–Zn– Ba -> Cu–Pb–Zn -> Fe–Cu -> Fe



Robb (2005)



Robb (2005)

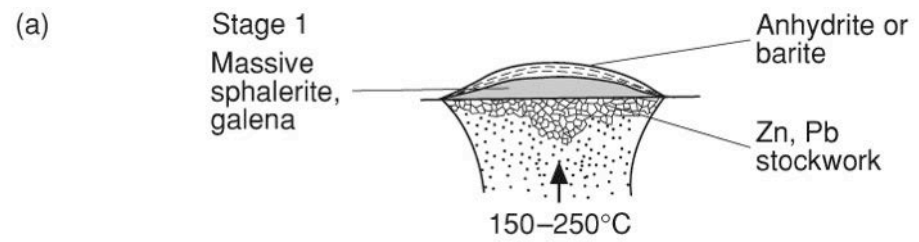
Black smokers – petrogenesis

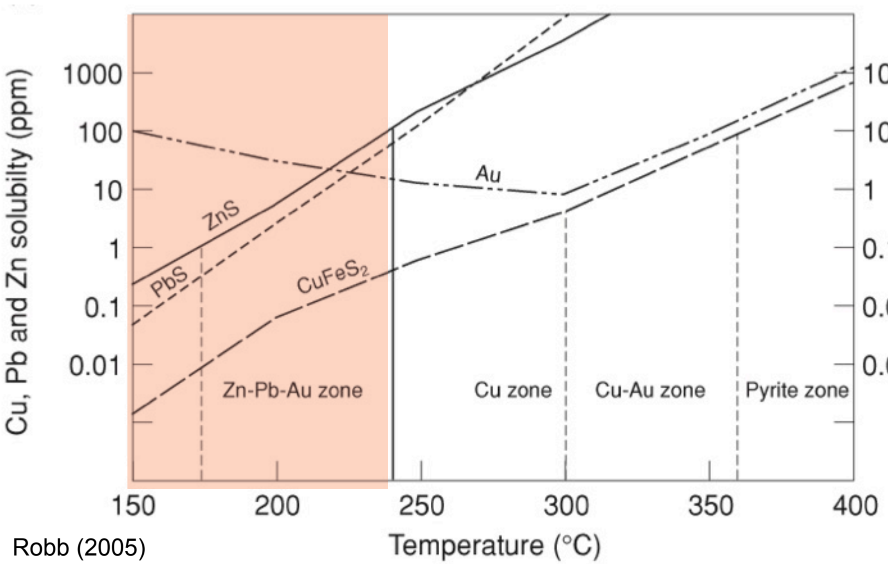
150–250°C

Sulfates (e.g. barite, anhydrite) soluble at $T < 250$°C

Sulfate precipitation produces ‘white smokers’

At $T \sim 250$°C, Zn and Pb chlorides are fairly soluble (Sph, Gal precip.)





Robb (2005)

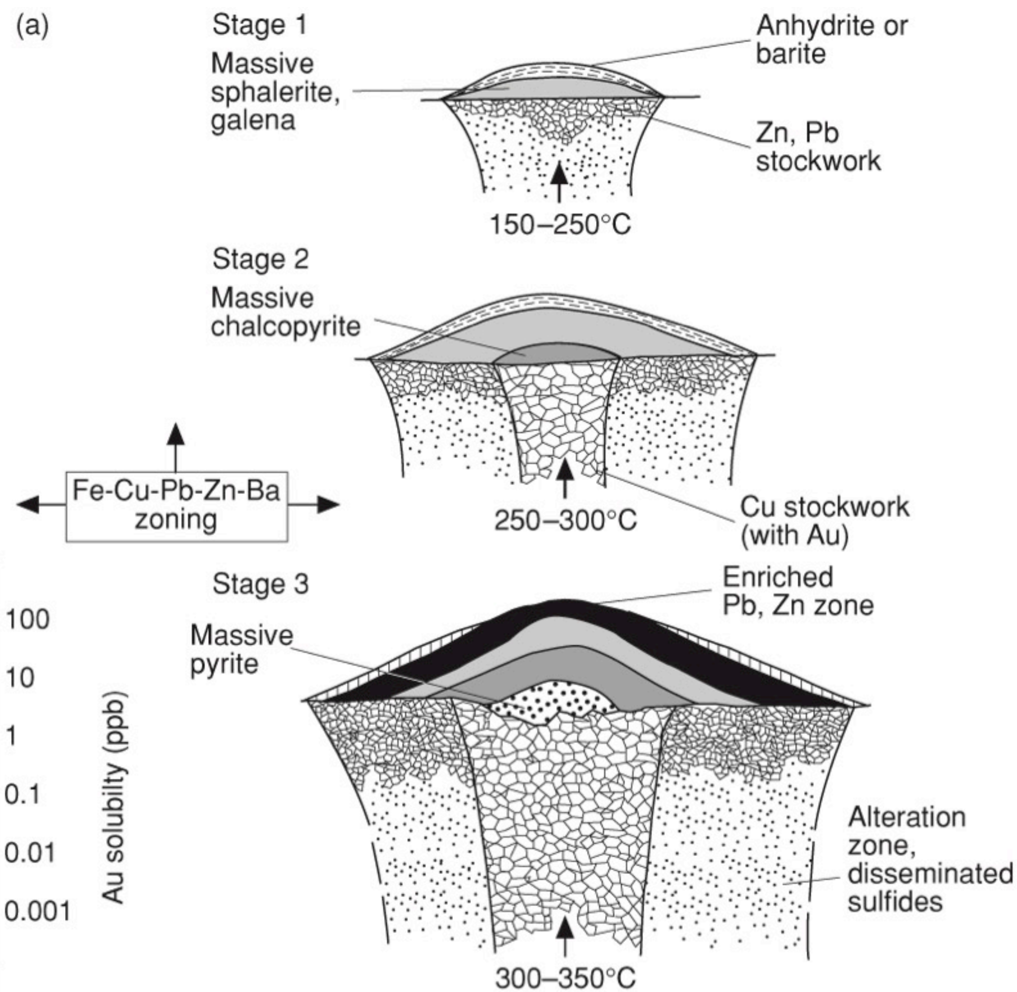
Black smokers – petrogenesis

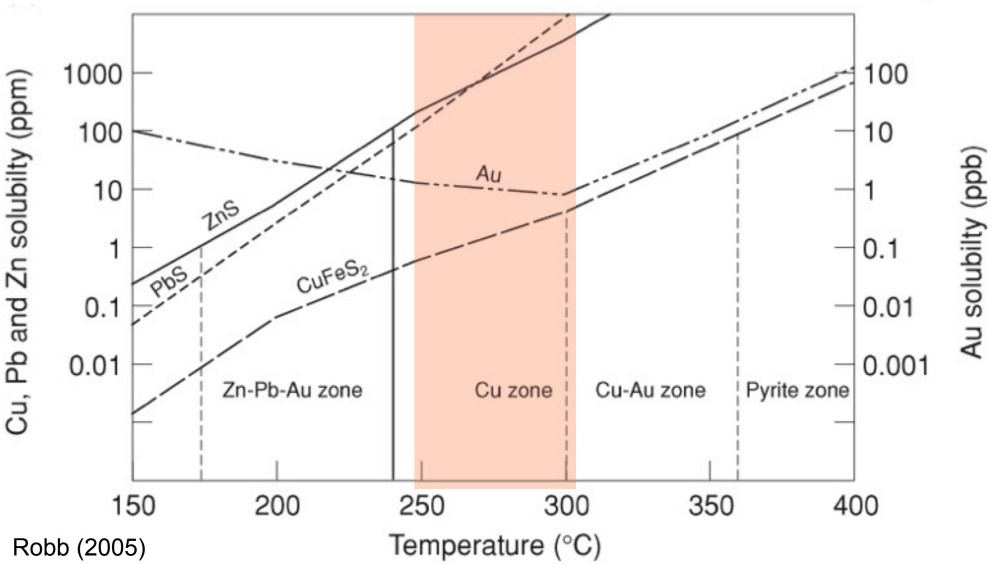
<u>250–300°C</u>

Cu soluble as chloride complex

Chalcopyrite precipitation at the base of the stockwork zone

Some Zn and Pb sulfides may be redissolved and precipitate higher





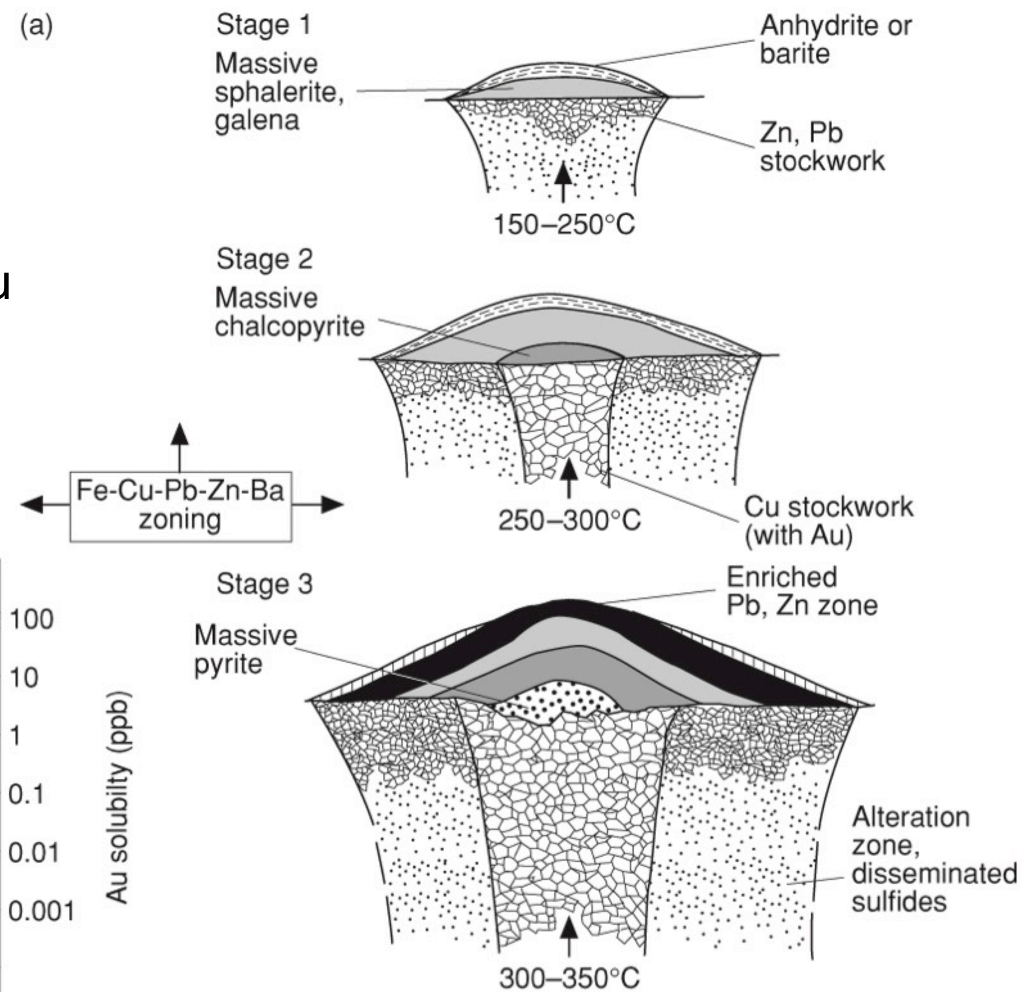
Robb (2005)

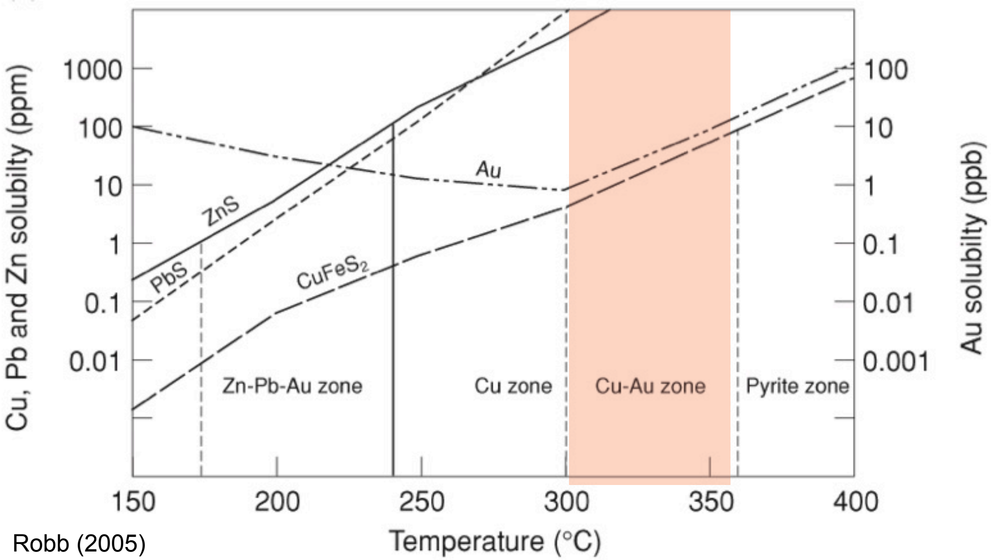
Black smokers – petrogenesis

300–350°C

Cu and Au are in solution as chloride complexes

Precipitation of chalcopyrite and Au in pyrite





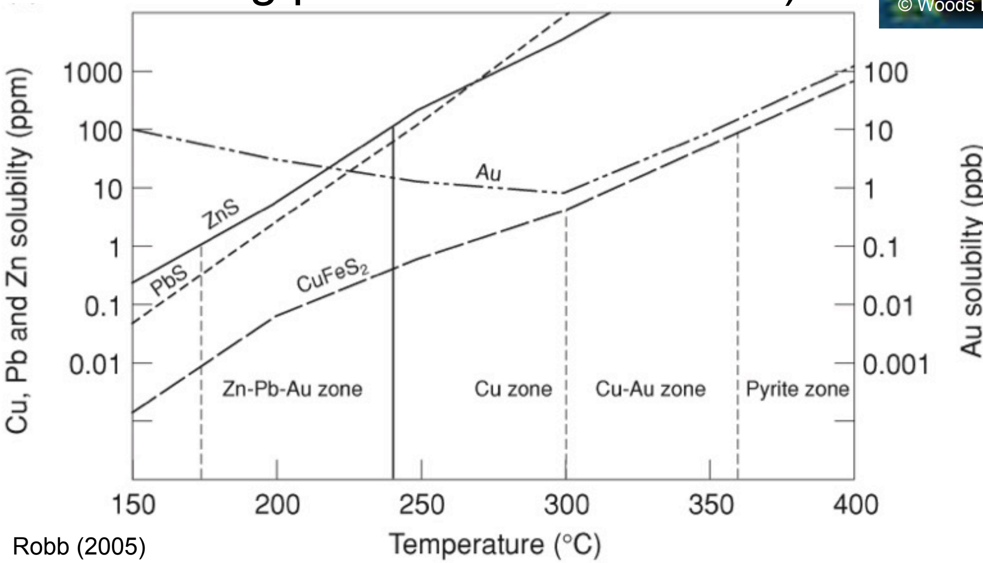
Robb (2005)

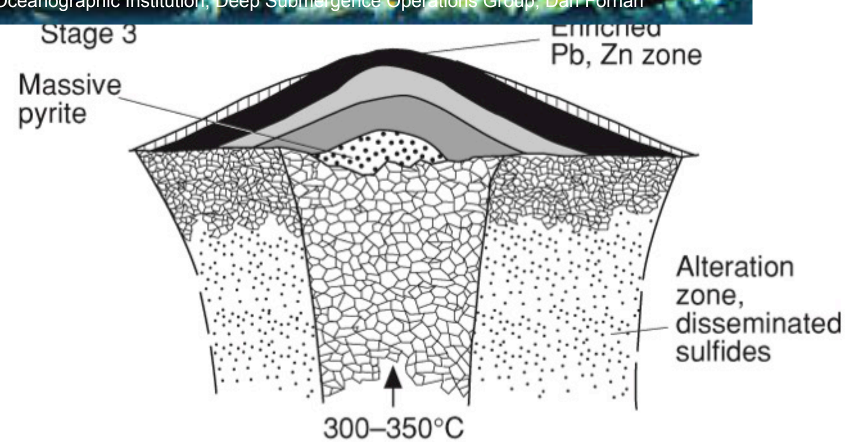
Black smokers – petrogenesis

<u>Complications</u>

Biologically mediated precipitation mechanisms may also play a role (e.g. Irish Zn–Pb–Ba deposits)

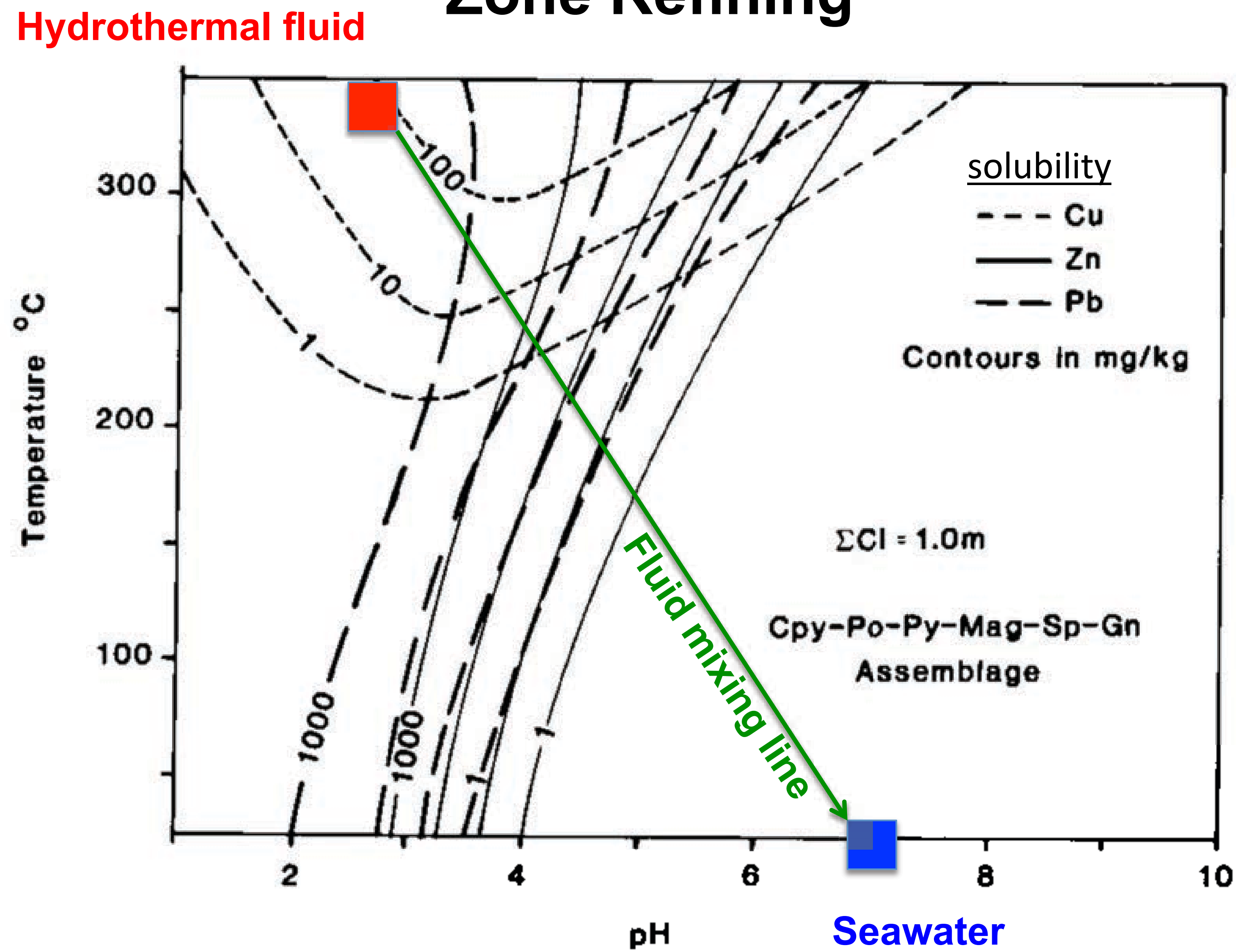
Boiling may affect the sequence of precipitation (although most are not thought to boil considering the confining pressure of the ocean)





Robb (2005)

Zone Refining



Lydon (1988)

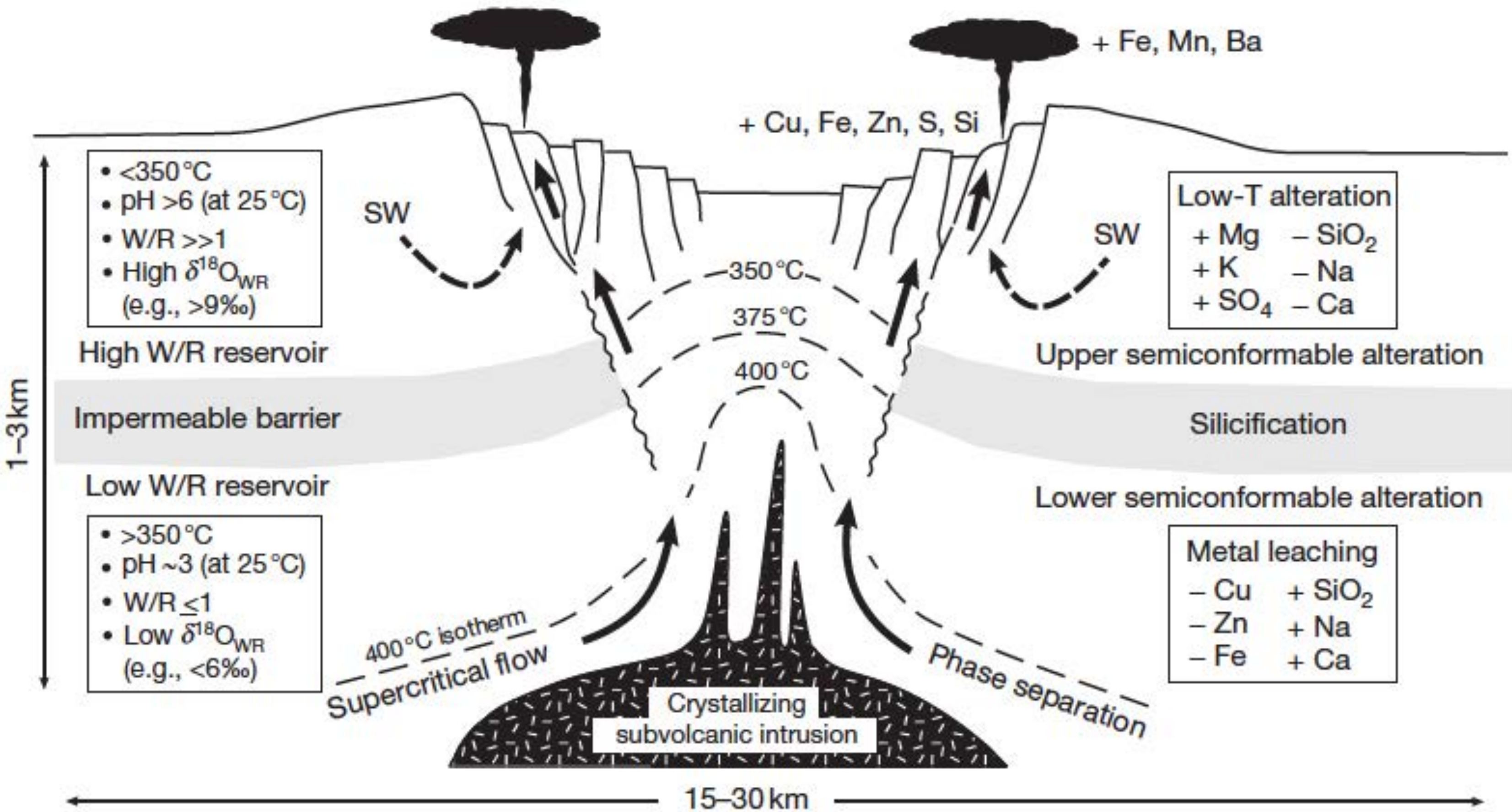


Figure 16 Summary of the main features of convective hydrothermal systems responsible for forming VMS deposits, including compositions of hydrothermal fluids in the recharge zone and high-temperature reaction zone, major mass gains and losses of elements in different parts of the hydrothermal alteration system, and the distribution of large-scale semiconformable alteration zones. Reproduced from Galley AG (1993) Semi-conformable alteration zones in volcanogenic massive sulfide districts. *Journal of Geochemical Exploration* 48: 175–200; Franklin JM, Gibson HL, Jonasson IR, and Galley AG (2005) Volcanogenic massive sulfide deposits. In: Hedenquist JW, Thompson JFH, Goldfarb RJ, and Richards JP (eds.) *100th Anniversary Volume of Economic Geology*, pp. 523–560. Littleton, CO: Society of Economic Geologists.

Hannington (2014)

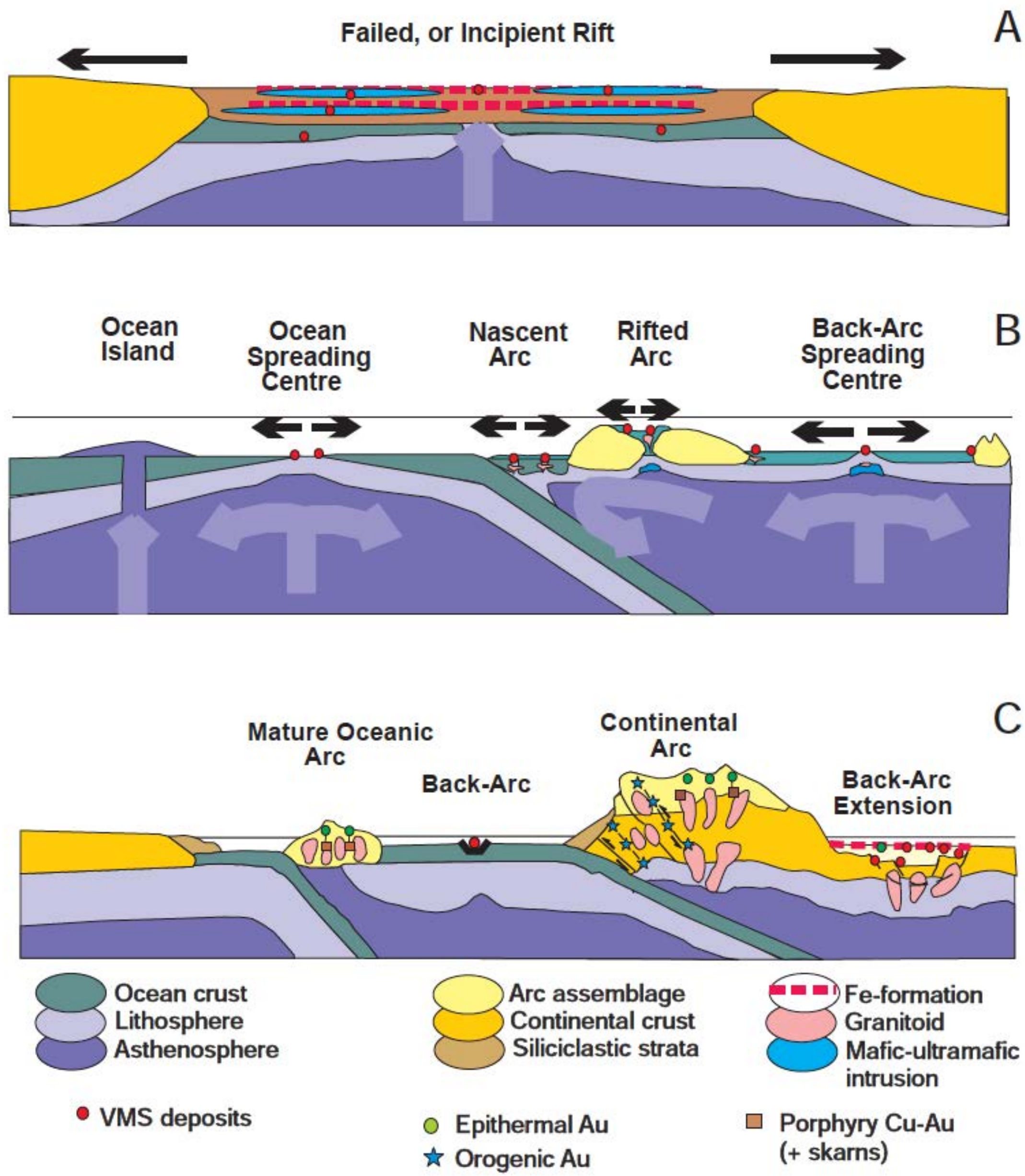
Tectonic setting of VMS deposits

Extensional tectonics!

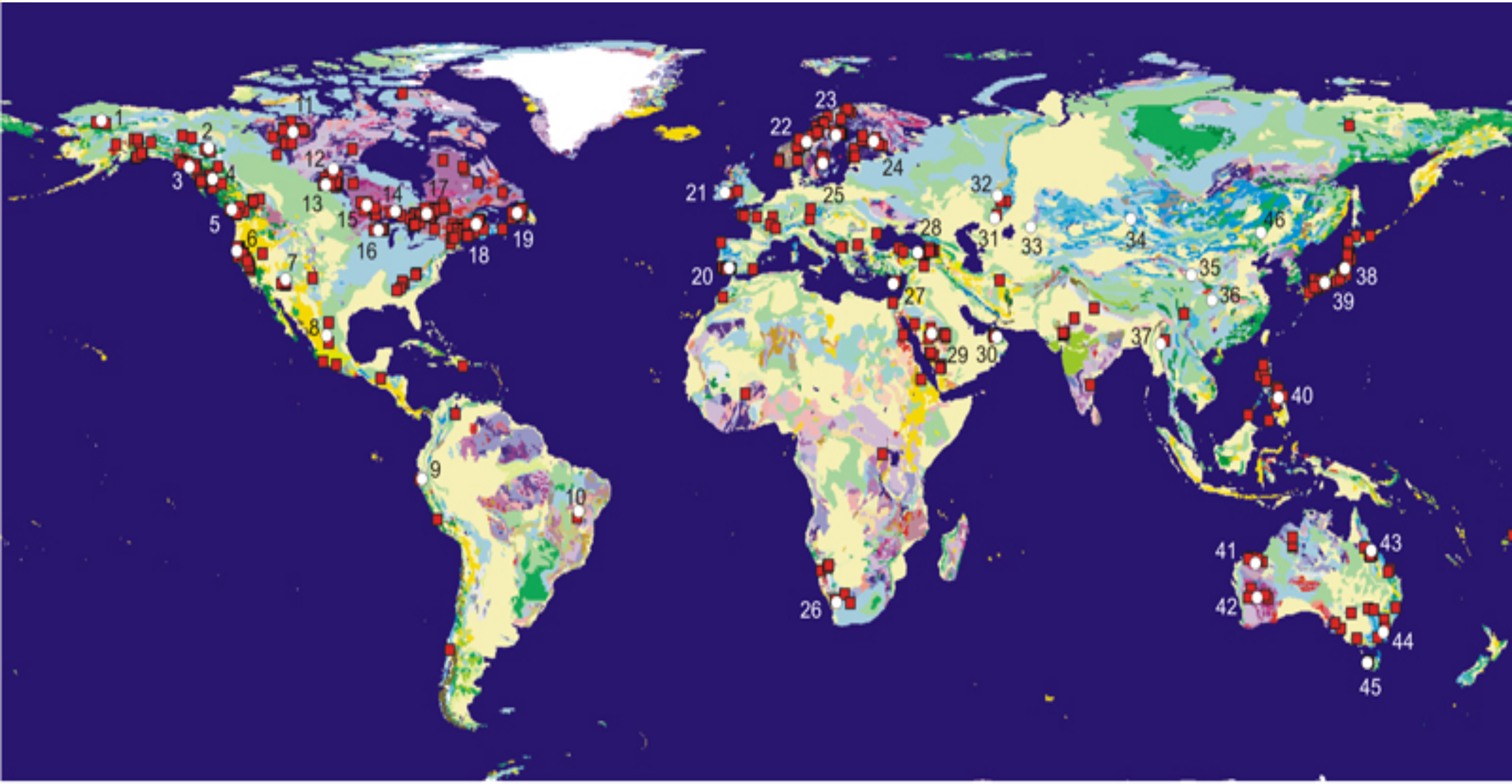
It is important to consider what settings are more likely to be preserved…

<u>Most VMS deposits formed at mid-ocean ridges have been lost to subduction!</u>

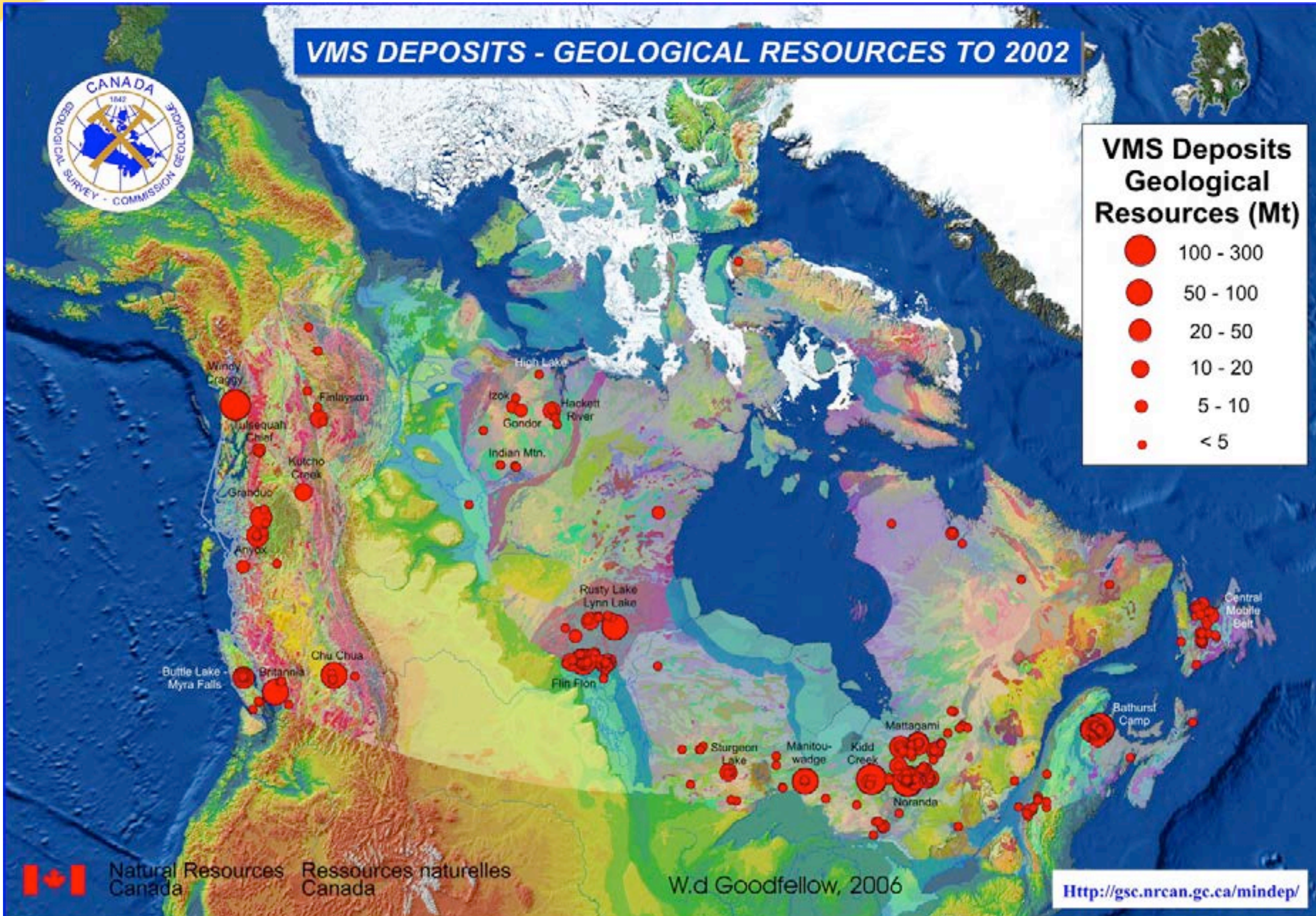
Many VMS deposits are deformed since they have to be pushed up on the continental crust



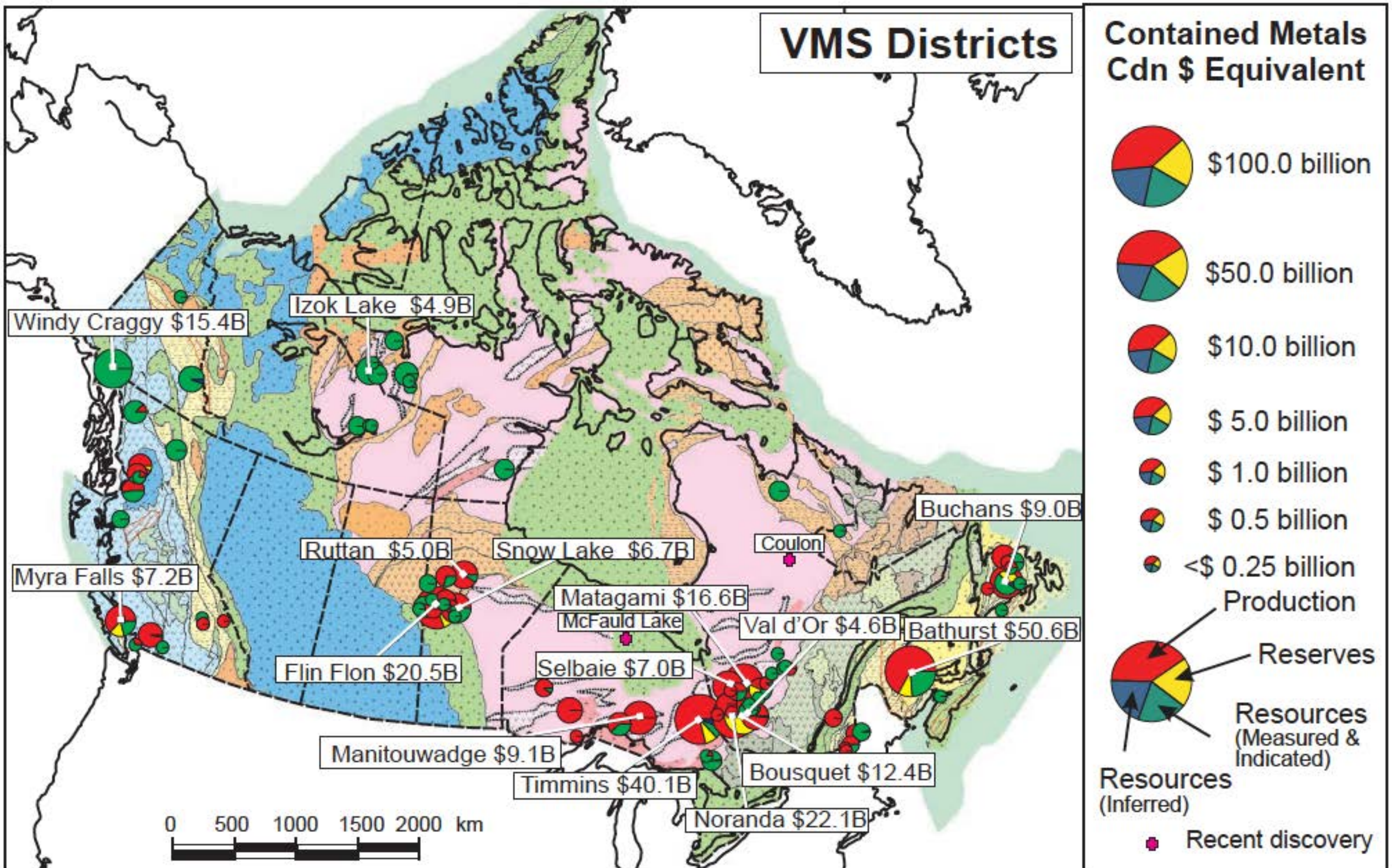
VMS deposits – where in the world?



Galley et al. (2007)


VMS DEPOSITS - GEOLOGICAL RESOURCES TO 2002
CANADA
GEOLOGICAL SURVEY - COMMISSION GEOLOGIQUE
VMS Deposits Geological Resources (Mt)
100 - 300
50 - 100
20 - 50
10 - 20
5 - 10
< 5
Windy Craggy
Tulsequah Chief
Finlayson
Kutcho Creek
Granduc
Anyox
High Lake
Izok
Hackett River
Gondor
Indian Mtn.
Rusty Lake
Lynn Lake
Flin Flon
Chu Chua
Buttle Lake - Myra Falls
Britannia
Sturgeon Lake
Manitou-wadge
Kidd Creek
Mattagami
Noranda
Bathurst Camp
Central Mobile Belt
Natural Resources Canada
Ressources naturelles Canada
W.d Goodfellow, 2006
Http://gsc.nrcan.gc.ca/mindep/

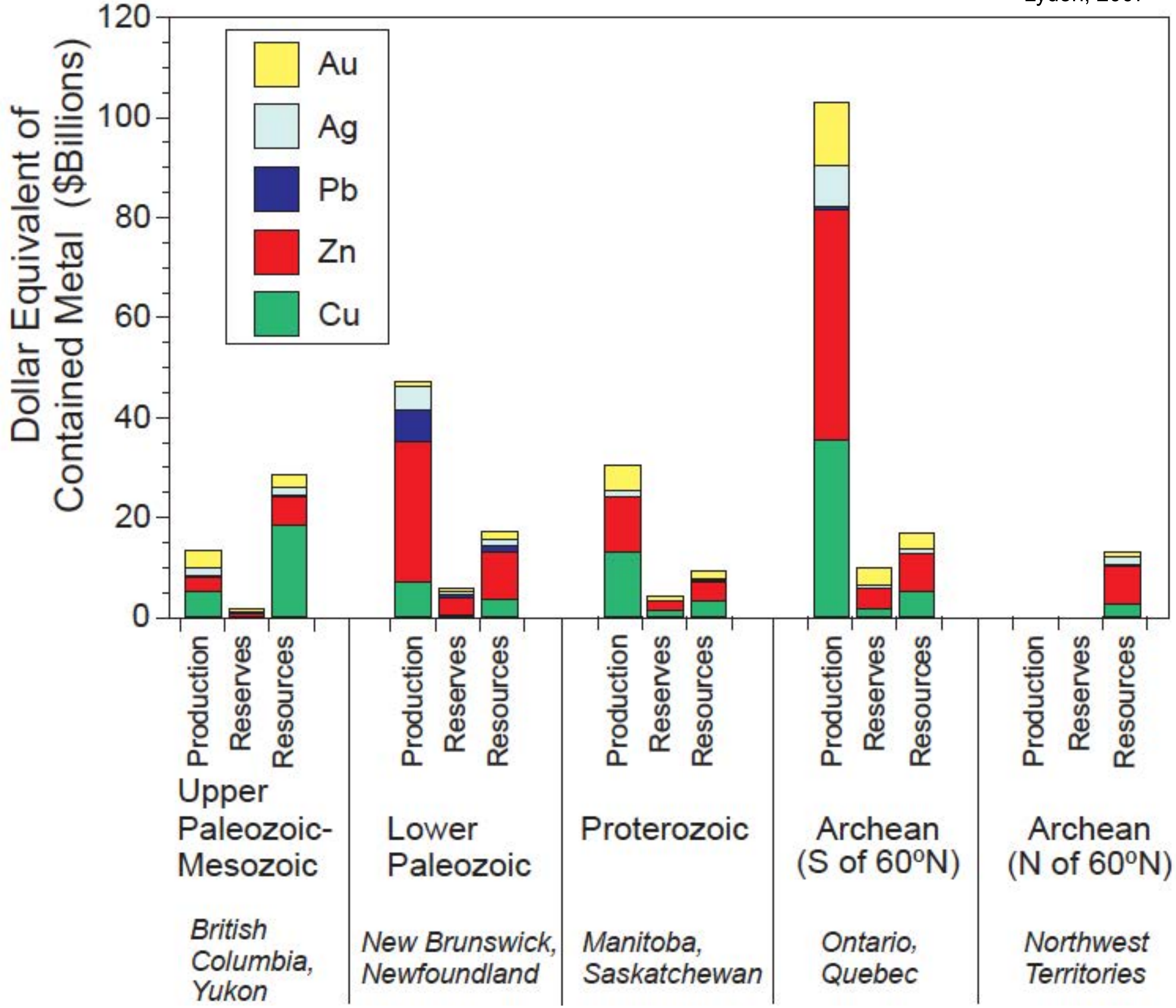
Lydon, 2007



Dollar equivalent of metal contained in ores (Cdn $ billions)

No. of Deposits: 280 **Production:** 192.32 **Reserves:** 20.05 **Resources: (Measured and Indicated)** 78.67 **Resources: (Inferred)** 3.96 **TOTAL:** 295.00

Lydon, 2007


Dollar Equivalent of Contained Metal ($Billions)
120
100
80
60
40
20
0
Au
Ag
Pb
Zn
Cu
Production
Reserves
Resources
Upper Paleozoic-Mesozoic
British Columbia, Yukon
Lower Paleozoic
New Brunswick, Newfoundland
Proterozoic
Manitoba, Saskatchewan
Archean (S of 60°N)
Ontario, Quebec
Archean (N of 60°N)
Northwest Territories

Ore Minerals

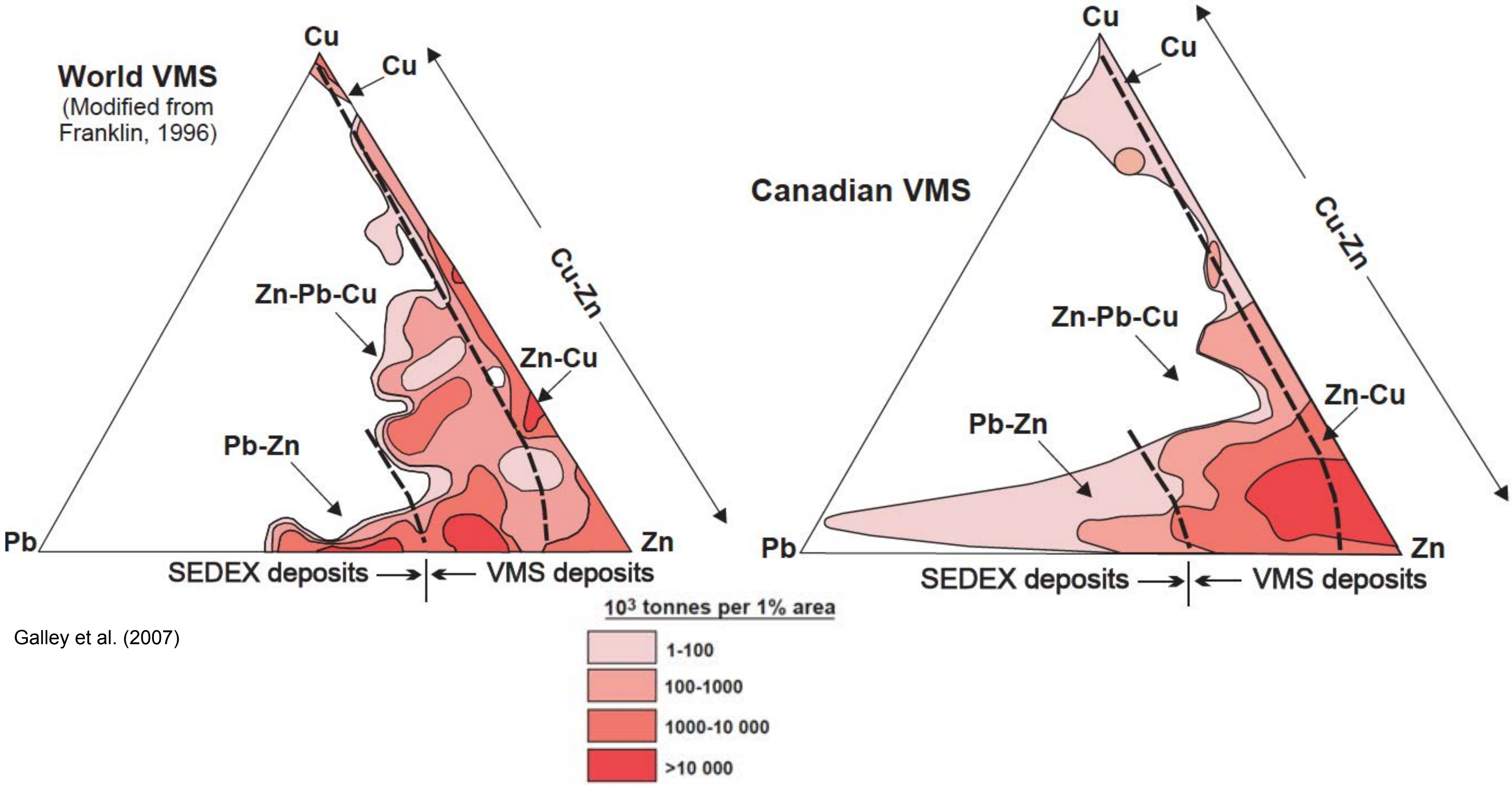
Table 2 Ore mineralogy of VMS deposits

Most abundant	*Second*	*Third*	*Fourth*	*Other trace minerals*
Pyrite (74)	Chalcopyrite (39)	Sphalerite (35)	Galena (28)	*Covellite*, *digenite*, gold, electrum, silver, argentite, cubanite, bournonite, boulangerite, cobaltite, mackinawite, stannite, cassiterite, bismuthinite, bismuth, *limonite*, *copper*, *cuprite*, idaite, molybdenite, pentlandite, tellurides, selenides, antimonides, Ag–Pb–As–Sb-sulfosalts
Chalcopyrite (9)	Sphalerite (27)	Chalcopyrite (32)	Chalcopyrite (20)	
Sphalerite (8)	Pyrrhotite (14)	Galena (12)	Pyrrhotite (7)	
Pyrrhotite (7)	Pyrite (11)	Pyrrhotite (9)	Magnetite (6)	
Magnetite (<5)	Galena (<5)	Pyrite (5)	Pyrite (5)	
Galena	Marcasite	Magnetite	Sphalerite	
Bornite	Bornite	Hematite	Hematite	
	Magnetite	Bornite	*Chalcocite*	
	Arsenopyrite	Tetrahedrite	Bornite	
	Enargite	*Chalcocite*	Arsenopyrite	
		Arsenopyrite	Tetrahedrite	
		Marcasite	Tennantite	

Numbers in brackets refer to the percentage of deposits in which the indicated mineral is the first, second, third, or fourth most abundant ore mineral. Other trace minerals are listed in approximate order of importance based on the number of deposits that contain the mineral. Based on data for 509 deposits in Mosier et al. (1983). Minerals in italics are mainly, although not exclusively, secondary in origin (i.e., supergene).

Hannington (2014)

VMS – main commodities



Galley et al. (2007)

VMS fun facts

- 850 known VMS deposits
- Found on 6/7 continents
- Zn–Cu–Pb–Au–Ag
- Also: Co, Sn, Cd, Te, Bi, Ge, Ga, Ba
- Polymetallic: many metals
  - This protects mining companies from metal price fluctuations
- Oldest is 3.4 Ga, youngest are forming now on the sea floor

VMS deposits worldwide

TABLE 1. Major world volcanogenic massive sulphide deposits and districts.

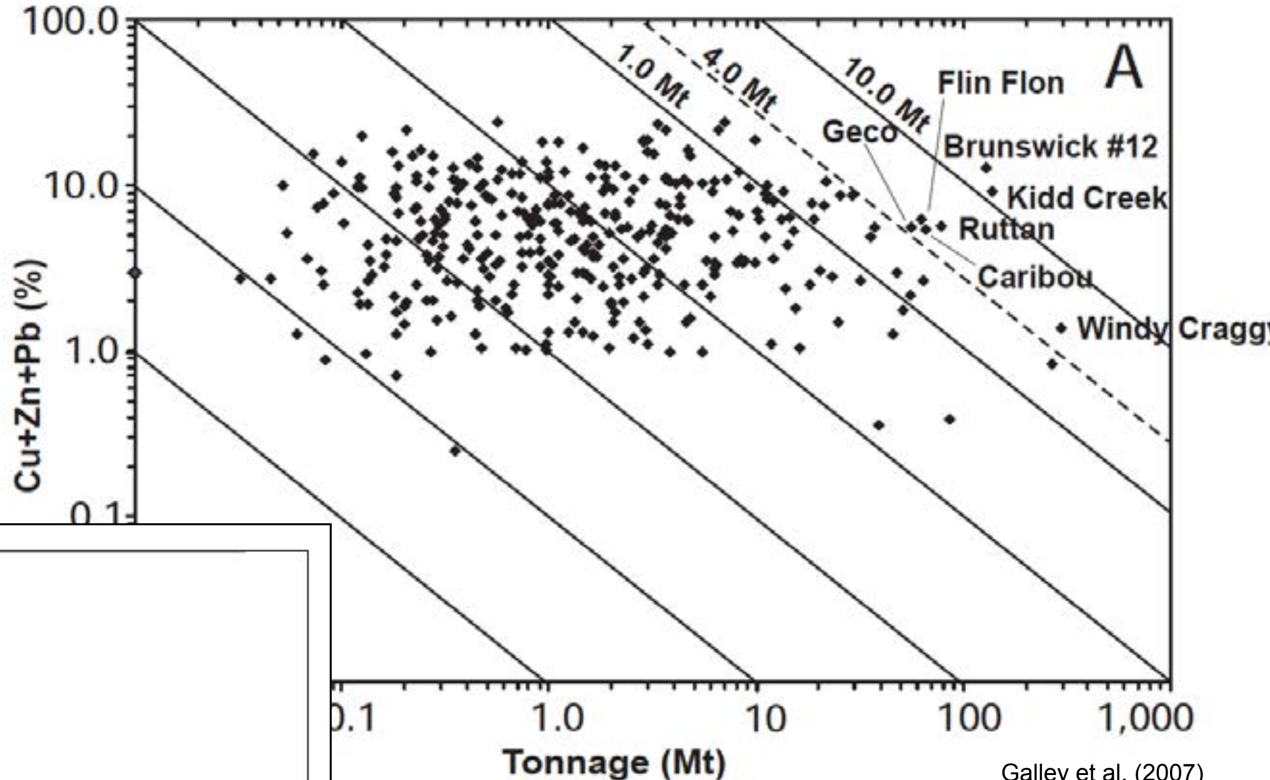
No.*	Deposit/District, Country	Tonnage (Mt)	No.*	Deposit/District, Country	Tonnage (Mt)
1	Brooks Range, Alaska	35	23	Skellefte, Sweden	70
2	Finlayson Lake, Yukon	20	24	Outokumpu-Pyhasalmi, Finland	90
3	Windy Craggy, BC & Green's Creek, Alaska	300	25	Bergslagen-Orijarvi, Sweden & Finland	110
4	Northern Cordillera, British Columbia	100	26	Preiska, South Africa	45
5	Myra Falls, British Columbia	35	27	Troodos, Cyprus	35
6	Shasta, California	35	28	Black Sea, Turkey	200
7	Jerome, Arizona	40	29	Saudi Arabia	70
8	Central Mexico	120	30	Semail, Oman	30
9	Tambo Grande, Peru	200	31	Southern Urals, Russia / Kazahkstan	400
10	Amazonian craton, Brazil	35	32	Central Urals, Russia	100
11	Slave Province, Northwest Territories, Nunavut	30	33	Rudny Altai, Kazahkstan / Russia	400
12	Ruttan, Manitoba	85	34	Altai Shan, Mongolia	40
13	Flin Flon-Snow Lake, Manitoba	150	35	North Qilian, China	100
14	Geco, Manitouwadge, Ontario	60	36	Sanjiang, China	50
15	Sturgeon Lake, Ontario	35	37	Bawdwin-Laochang, Burma /	40
16	Ladysmith-Rhinelander, Wisconsin/Michigan	80	38	Hokuroku, Japan	80
17	Abitibi, Ontario-Quebec	600	39	Besshi, Japan	230
18	Bathurst, New Brunswick	495	40	Phillipines arc	65
19	Dunnage Zone, Newfoundland	75	41-42	Pilbara, Yilgarn Western Australia	75
20	Iberian Pyrite Belt, Spain & Portugal	1575	43	Central Queensland, Australia	80
21	Avoca, Ireland	37	44	Lachlan Fold Belt, Australia	100
22	Trondhjeim, Norway	100	45	Mt. Read, Tasmania	200
			46	Sino-Korean Platform	40

* numbers refer to Figure 5; tonnage is approximate

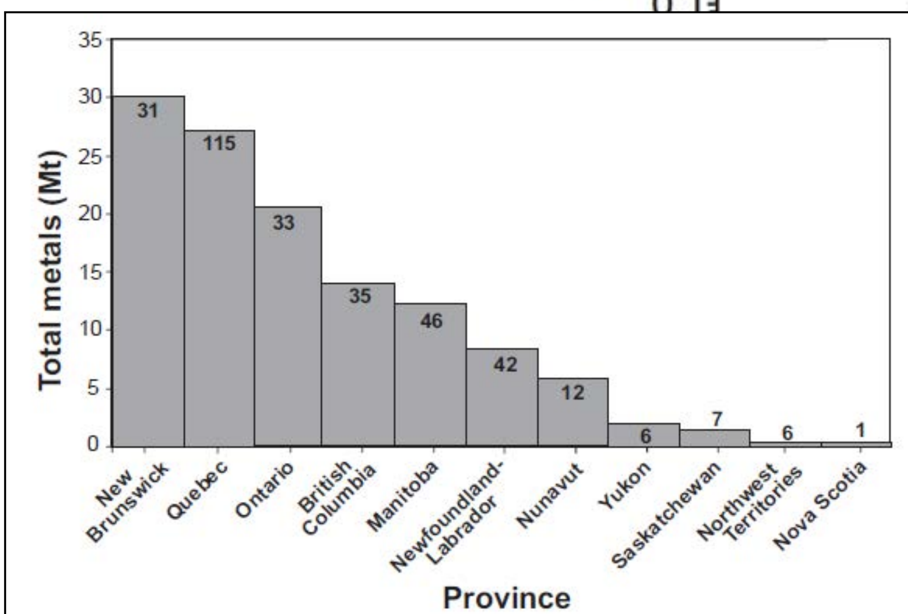
Galley et al. (2007)

Canadian VMS deposits – size and grade

Lots of small <1.0 Mt deposits



Galley et al. (2007)



Canadian VMS producers

TABLE 2. Canadian volanogenic massive sulphide deposits presently in production (2005).

Deposit	Location	(1) Mt	Cu wt.%	Zn wt.%	Pb wt.%	Ag g/t	Au g/t	Age
Brunswick No. 12	Bathurst, New Bruswick	229.8	0.46	7.66	3.01	91	0.46	Ordovician
Kidd Creek	Abitibi, Ontario	149.3 (181 mined + all resources)	2.89	6.36	0.22	92	0.05	Archean
LaRonde (incl. LaRonde II)	Abitibi, Quebec	88.1	0.32	1.71		40.9	5.07	Archean
Selbaie	Abitibi, Quebec	47.3	0.98	1.98		20	0.9	Archean
Myra Falls Gp.,Buttle Lake	Wrangellia, British Columbia	29.3	1.83	6.25	0.55	49	2.01	Devonian
Trout Lake	Trans-Hudson Orogen, Manitoba	20	1.83	5.59		17.4	1.73	Paleoproterozic
Louvicourt	Abitibi, Quebec	19.3	3.1	1.71		28.7	0.83	Archean
Triple 7	Trans-Hudson Orogen, Manitoba	14.5	3.32	5.78		37.7	2.71	Paleoproterozic
Bouchard-Hébert	Abitibi, Quebec	10.2	2.11	4.79		15	1.4	Archean
Callinan	Trans-Hudson Orogen, Manitoba	9.16	1.41	3.59		23.5	2.08	Paleoproterozic
Duck Pond*	Central Volcanic Belt,	5.2	3.24	5.97	1.1	61.5	0.88	Ordovician
Perseverence Group *	Abitibi , Quebec	5.1	1.24	15.82		29.4	0.38	Archean
Eskay Creek	Stikine, British Columbia	4	0.33	5.4	2.2	998	26.4	Jurassic
Bell Allard	Abitibi, Quebec	3.2	1.5	13.77		43.5	0.76	Archean
Chisel North	Trans-Hudson Orogen, Manitoba	2.8	0.15	9.36	0.4	22	0.4	Paleoproterozic
Konuto	Trans-Hudson Orogen,	1.28	5.27	1.44		10.6	2.09	Paleoproterozoic

* In preproduction (2006)
(1) Includes production and estimated reserves where applicable.

Galley et al. (2007)

<u>Major mining camps:</u>
Abitibi (ON and QC)
Bathurst (NB)
Cordillera (BC)
Trans-Hudson (MB)

VMS deposits – classification

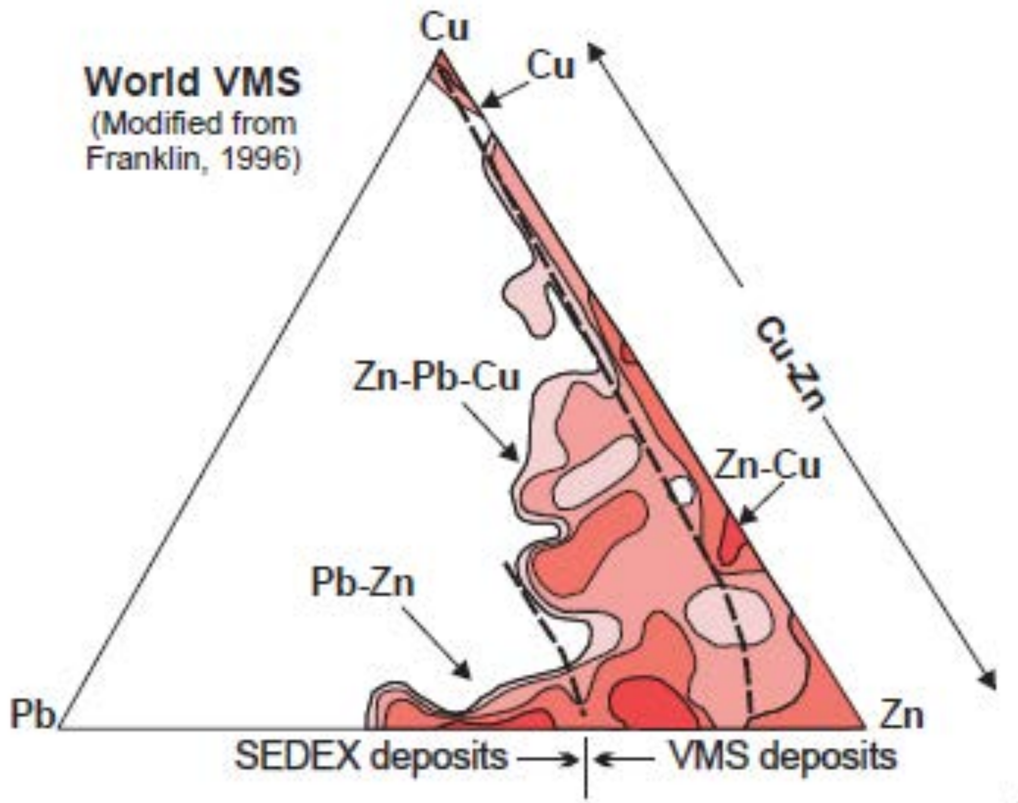
(1) Base metal content

(2) Associated with gold

(3) Host Rock

Three groups:

Cu–Zn
Zn–Cu
Zn–Pb–Cu



Galley et al. (2007)

VMS deposits – classification

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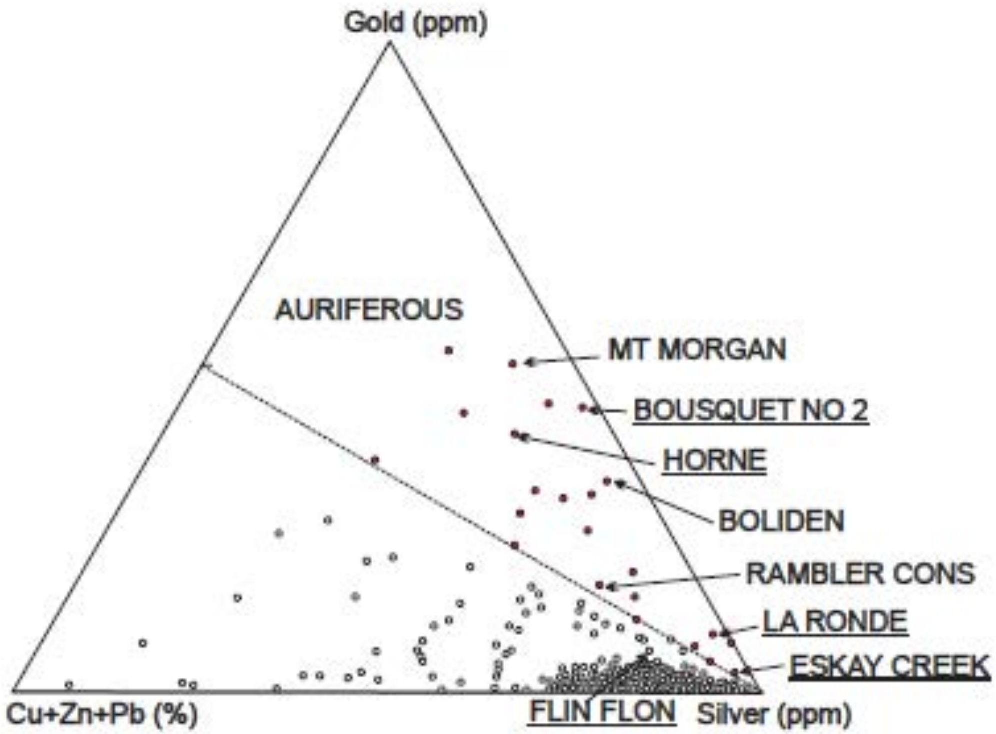


Galley et al. (2007)

Two groups:

Normal

Au(ppm) < Cu + Zn + Pb (wt%)

Auriferous

Au(ppm) > Cu + Zn + Pb (wt%)

VMS deposits – classification

(1) Base metal content

(2) Associated with gold

(3) Host Rock

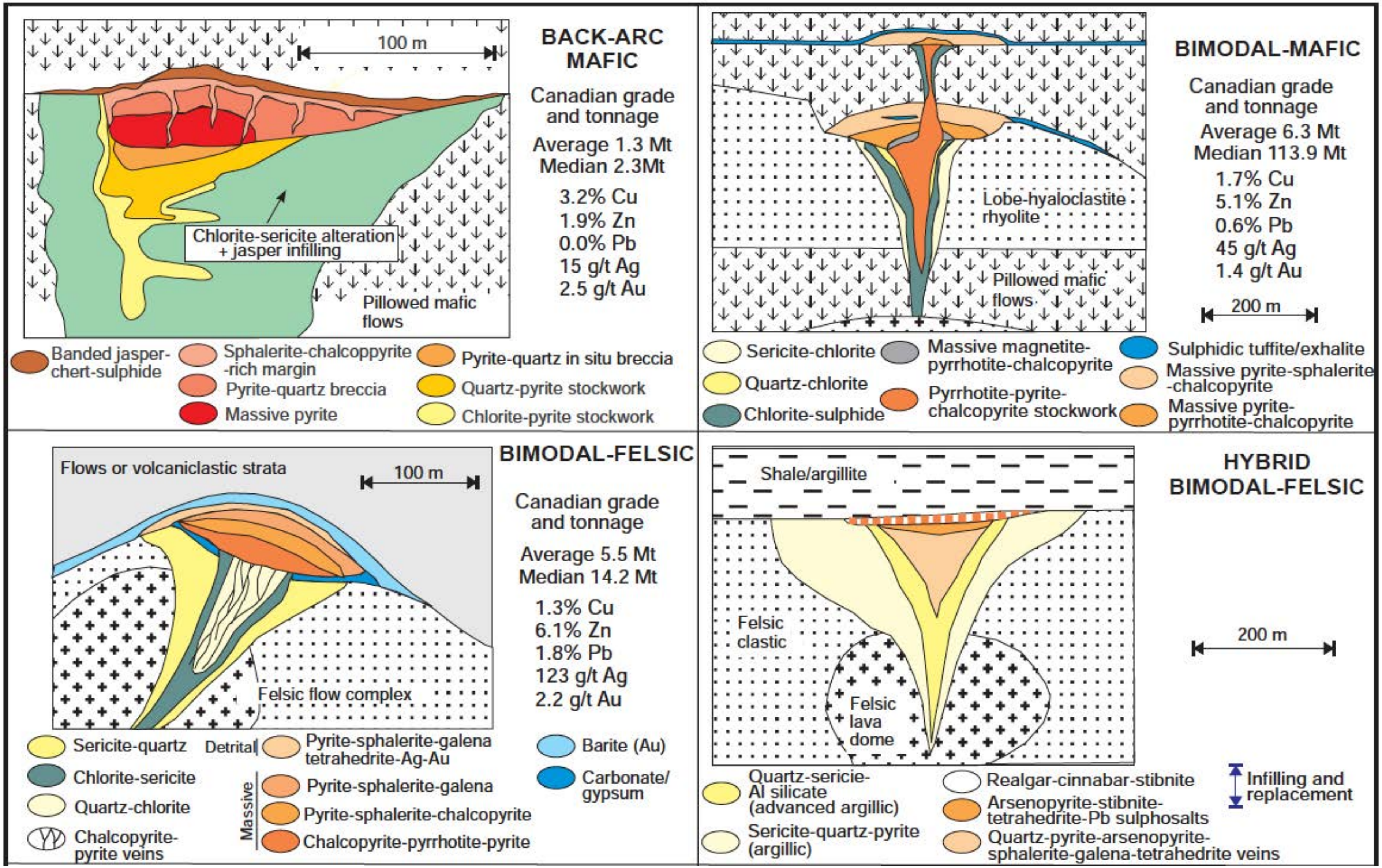
Table 1 Geometric mean concentrations of metals in VMS ores according to host-rock type

Hannington (2014)

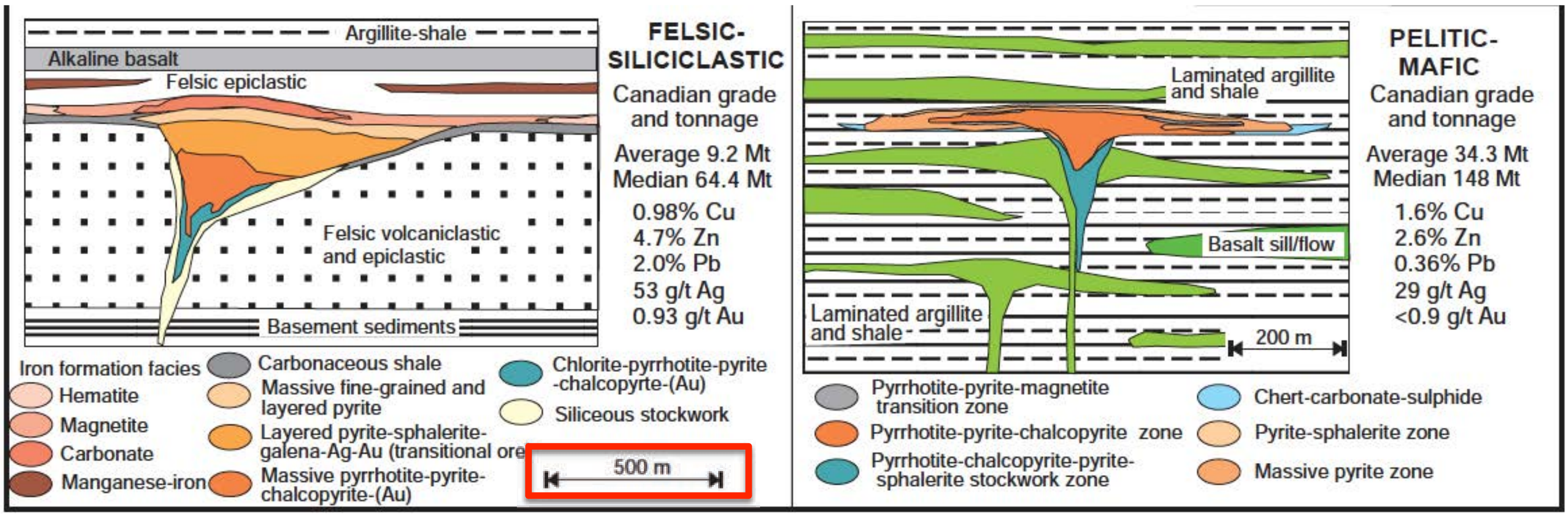
	Mafic	*Bimodal mafic*	*Mafic–pelitic*	*Bimodal felsic*	*Felsic–siliciclastic*
Cu (wt%)	1.82	1.24	1.23	1.04	0.62
Zn (wt%)	0.84	2.32	1.58	4.36	2.70
Pb (wt%)	0.02	0.30	0.68	1.14	1.09
Au (ppm)	1.40	0.81	0.75	1.06	0.59
Ag (ppm)	11	21	19	56	39
Total ore (tonnes)	2699466	3421075	4721093	3320784	7139305
Total metal (tonnes)	63035	128515	132968	198461	324748
N	76	291	90	241	106

Source: Franklin JM, Gibson HL, Jonasson IR, and Galley AG (2005) Volcanogenic massive sulfide deposits. In: Hedenquist JW, Thompson JFH, Goldfarb RJ, and Richards JP (eds.) *100th Anniversary Volume of Economical Geology*, pp. 523–560. Littleton, CO: Society of Economic Geologists.

- Cu concentrations are similar (except Felsic–siliciclastic type)
- Siliciclastic deposits are much larger on average (more permeable host rocks)



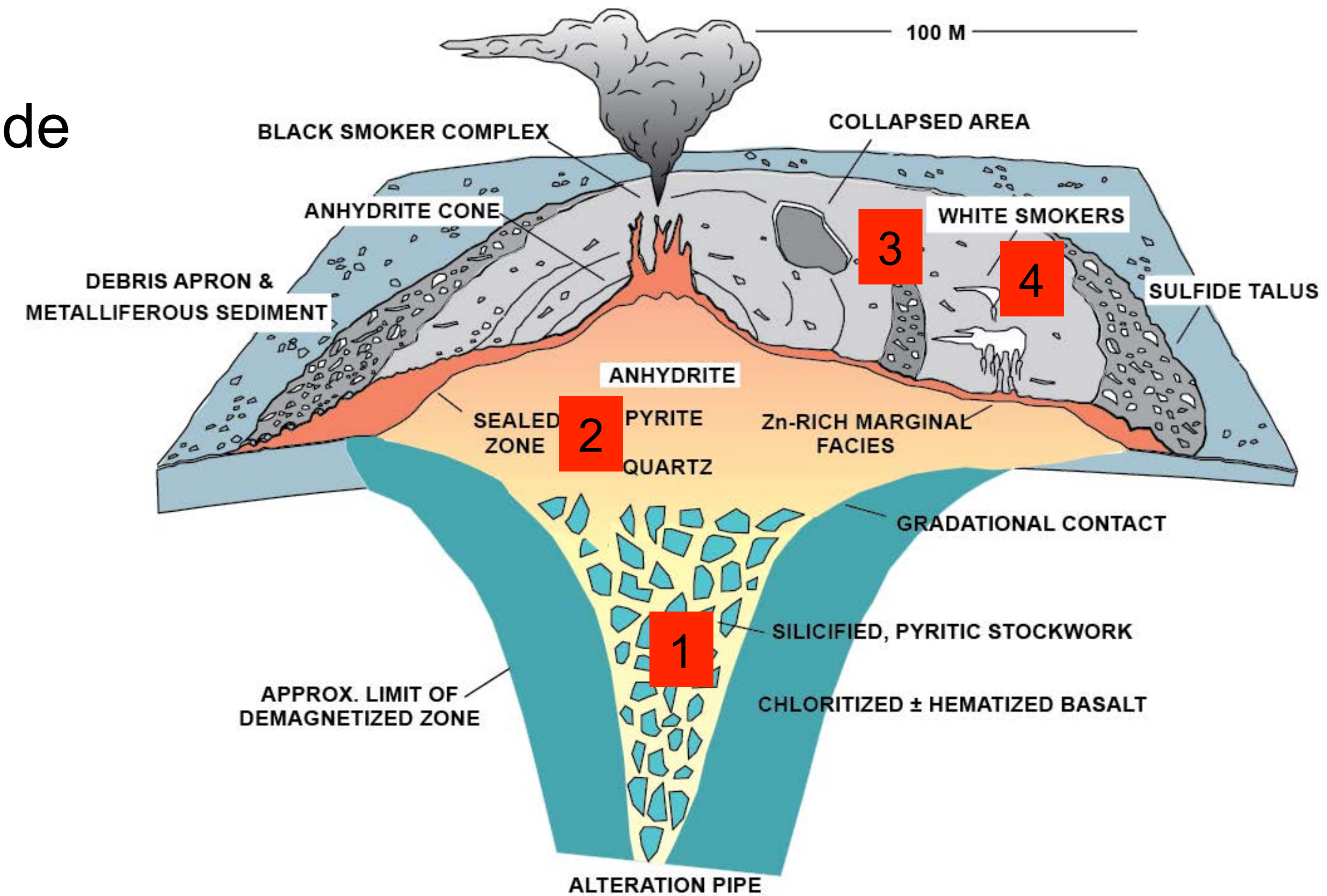
Galley et al. (2007)



Galley et al. (2007)

VMS deposits – ore textures

1) Stringer
2) Massive sulfide
3) Brecciated
4) Exhalative



VMS deposits – ore textures

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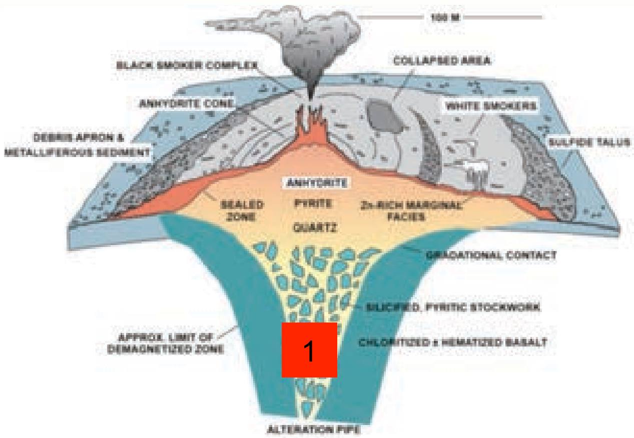

VMS deposits – ore textures

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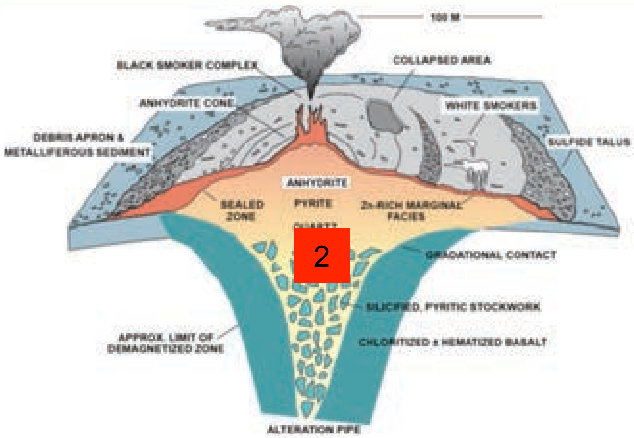

VMS deposits – ore textures

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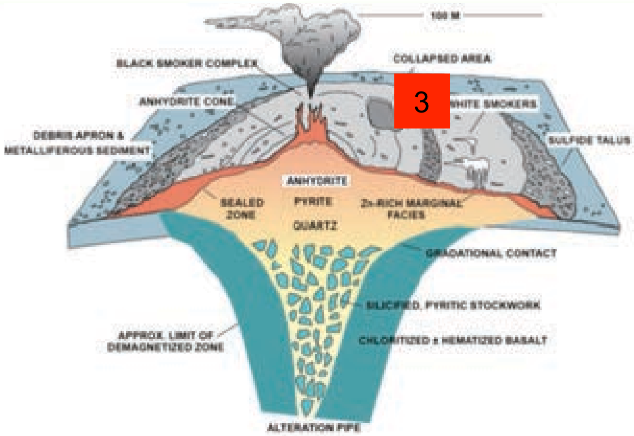

VMS deposits – ore textures

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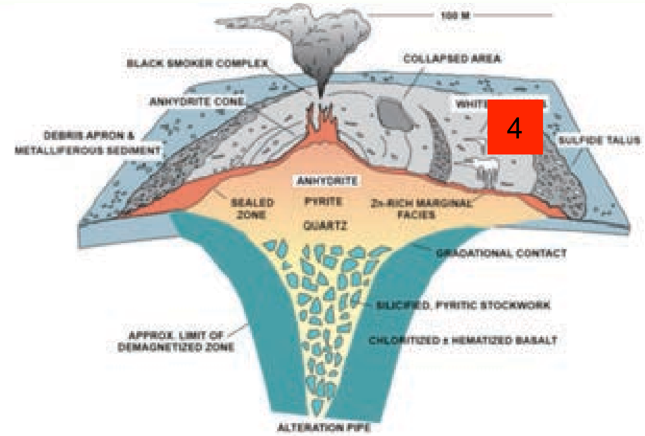
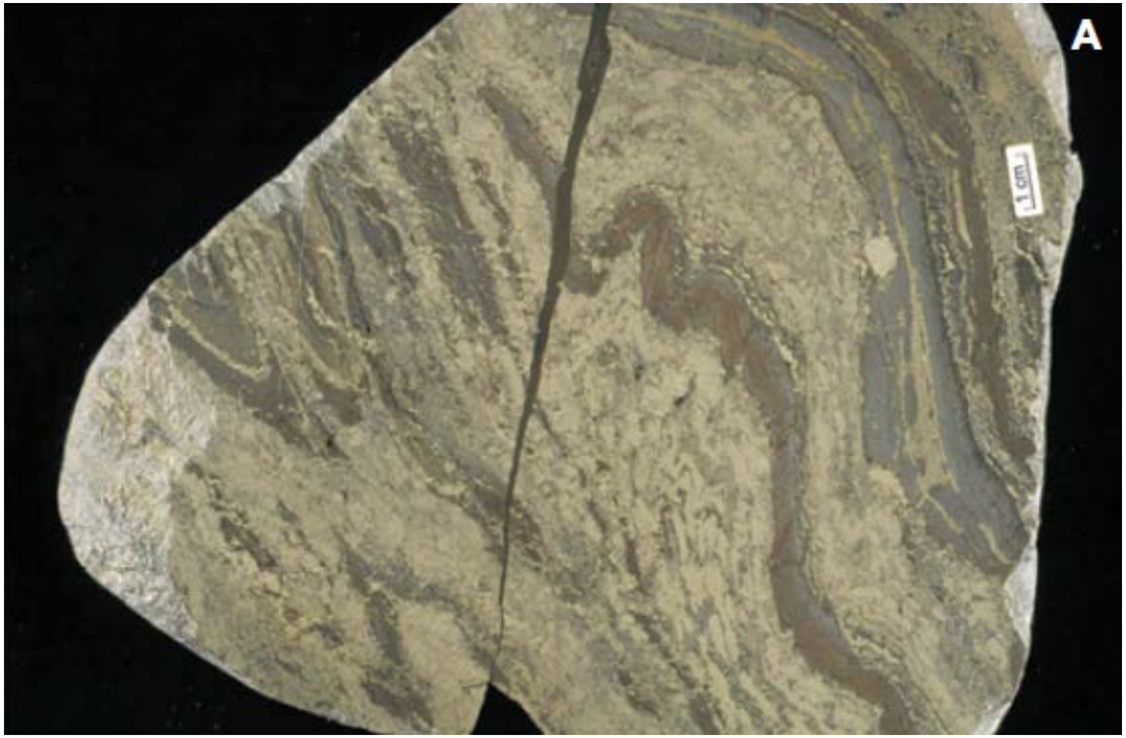
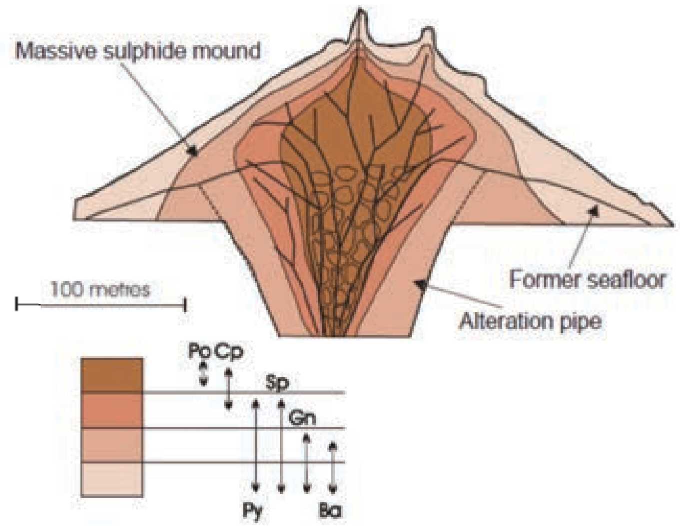
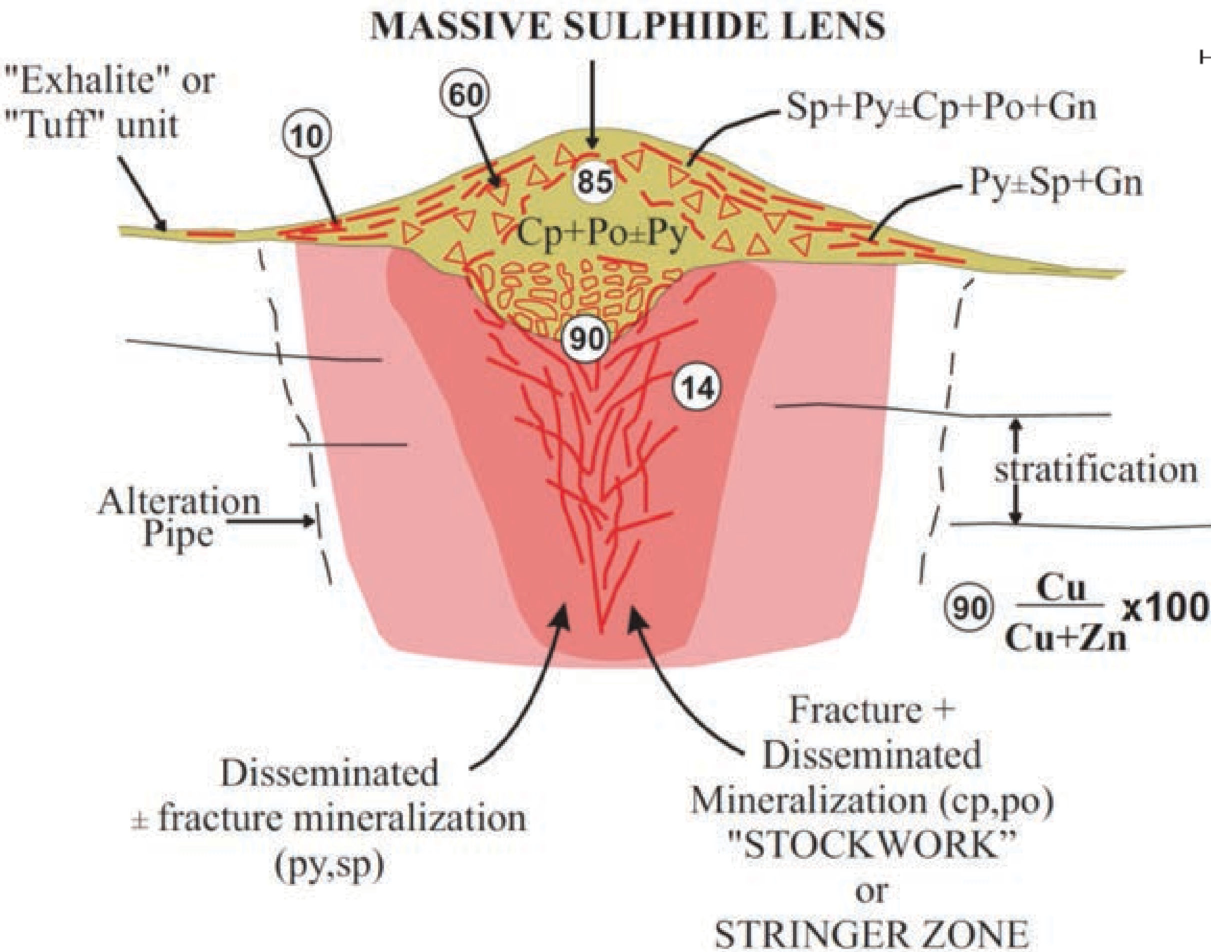




Ore Mineral Zoning

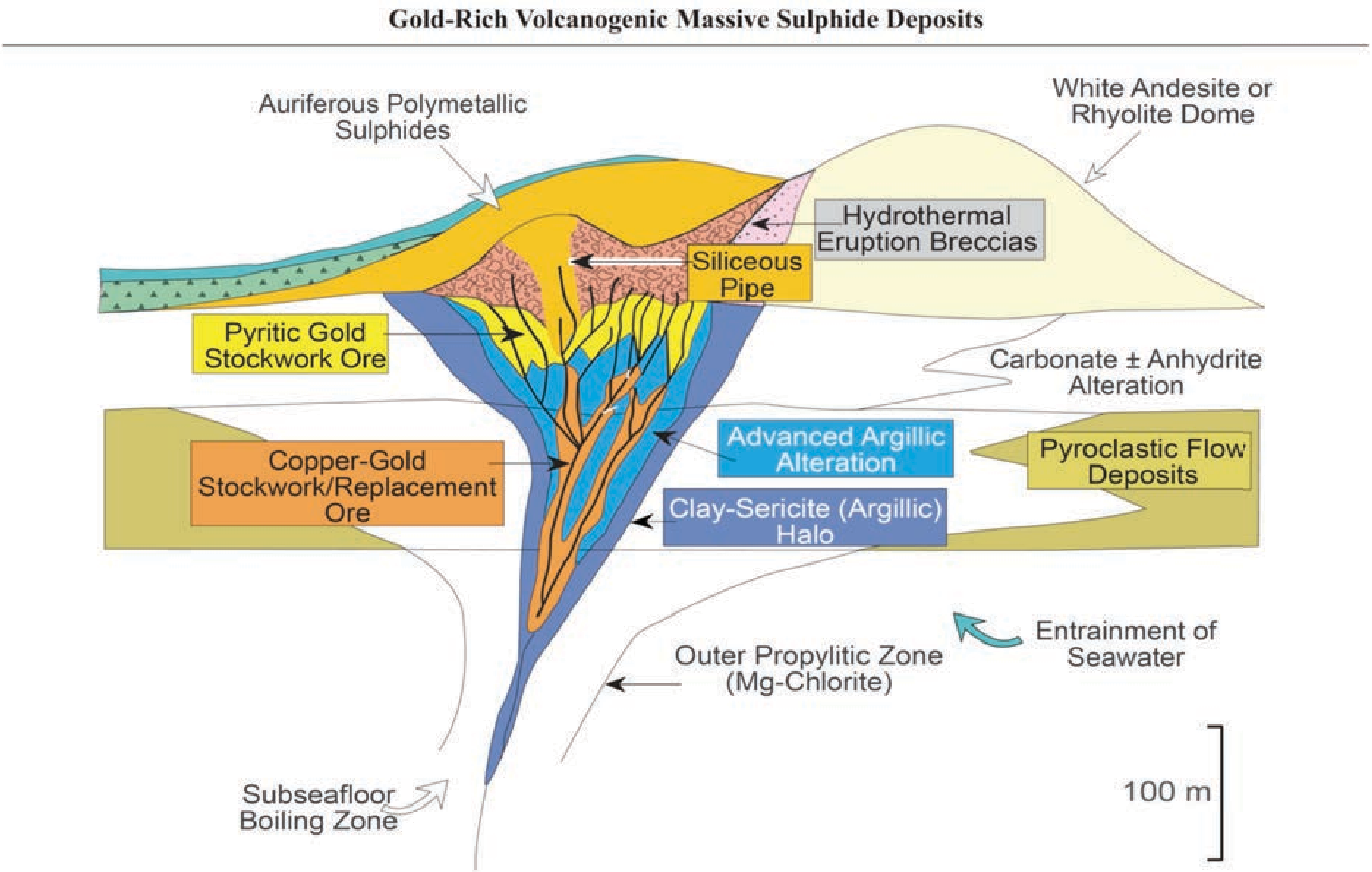




- Stringer Zone (parallel / crossing veins) **14**
- Breccia zone (brecciated host rock cemented by sulfides) **90**
- Massive sulfide lens **85**
- Brecciated sulfides (brecciated fragments of massive sulfide, anhydrite) **60**
- Exhalite zone (sedimentary sulfides) **10**

Galley et al. (2007)

Alteration zoning – an exploration tool



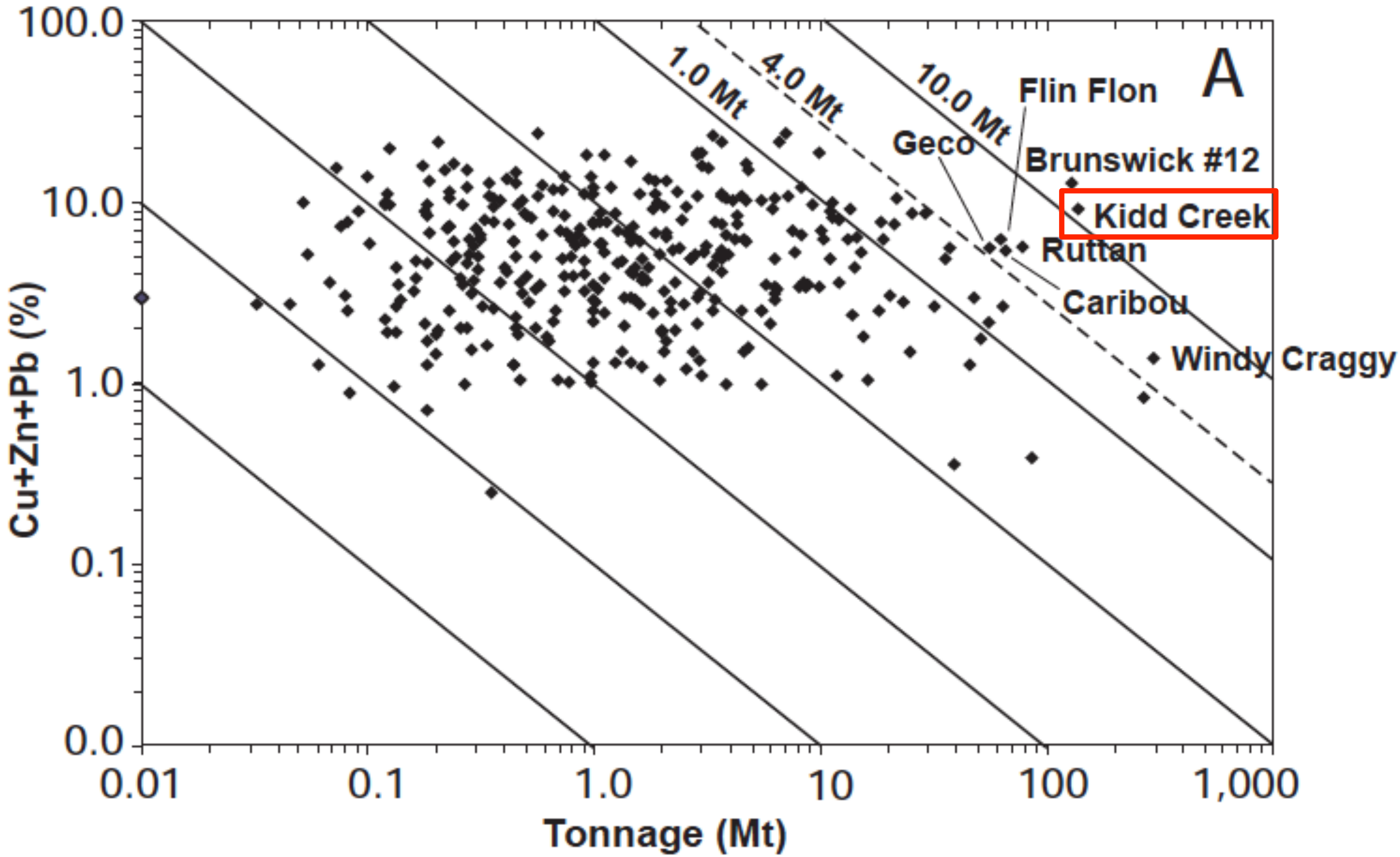
Dubé et al. (2007)

Kidd Creek (Abitibi greenstone belt)

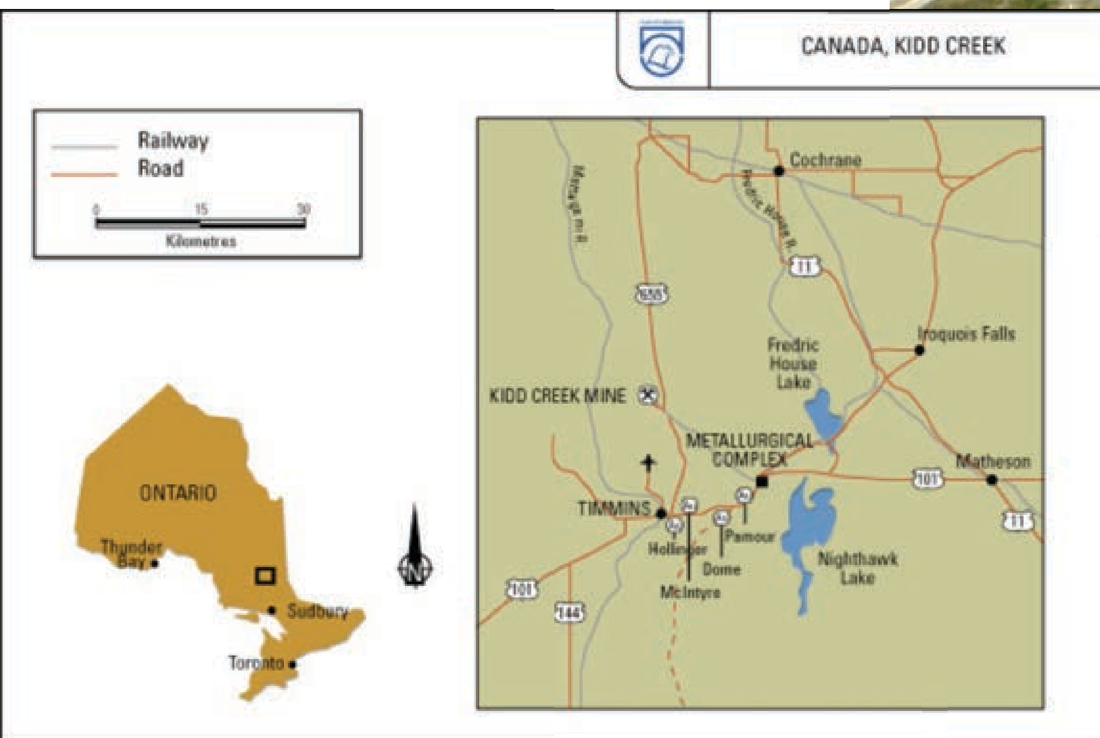
TABLE 3. Examples of large-tonnage volcanogenic massive sulphide deposits of the World (Canadian deposits in red).

NAME	COUNTRY	Orogen	Mtonnes Ore (Geol.)	CU %	PB %	ZN %	AU (g/t)	AG (g/t)	Orebody Age (est. Ma)
SUPERGIANT									
Rio Tinto (Stockwork)	Spain	Hercynian	1200.00	0.15		0.15		7.00	320
Rio Tinto (Massive)	Spain	Hercynian	335.00	0.39	0.12	0.34	0.36	22.00	320
Kholodnina	Russia	Baikal-Vitim	300.00	0.04	0.79	5.2			750
Windy Craggy (Cu,Co)	Canada	N.Cordilleran	297.40	1.38		0.25	0.22	3.83	220
Neves Corvo Group	Portugal	Hercynian	270.00	1.59	0.15	1.41		9.87	320
Gai East	Russia	Uralides (Hercynian)	269.00	1.2		0.7	1.10	7.70	395
Aljustrel Group (total)	Portugal	Hercynian	250.00	1.2	1.2	3.2	1.00	38.00	320
Brunswick #12	Canada	Appalachian	229.80	0.46	3.01	7.66	0.46	91.00	465
Gai	Russia	Uralides (Hercynian)	205.00	1.4	0.06	0.5	1.10	7.90	395
La Zarza	Spain	Hercynian	164.00	1.2	1.1	2.5	1.80	47.00	320
Ducktown	USA	Grenvillean? (Oecee)	163.34	1		0.9	0.30	3.00	1000
GIANT									
Kidd Creek	Canada	Abitibi (Kenoran)	147.88	2.31	0.22	6.18	0.01	87.00	2714
Horne - No. 5 Zone	Canada	Abitibi (Kenoran)	144.00	1		0.9	1.40		2698
Ozernoe	Russia	Baikal-Vitim	130.00	0.01	1.2	6.2			500
Ridder-Sokol	Kazakhstan	Altaides (Hercynian)	125.00	0.3	2	4	2.50	10.00	400
Zyryanov	Kazakhstan	Altaides (Hercynian)	125.00	0.4	2.7	4.5	0.13	20.00	395
Gacun	China	Yidun, Indosinian (Tethyan)	124.00	0.72	4.62	6.66	0.46	157.00	200
Masa Valverde	Spain	Hercynian	120.00	0.5	0.6	1.3	0.80	38.00	320
Sibai	Russia	Uralides (Hercynian)	115.00	1	0.04	1.56	0.60	16.00	392
Tharsis	Spain	Hercynian	110.00	0.5	0.6	2.7	0.70	22.00	320
Yubileinoe	Russia	Uralides (Hercynian)	107.00	1.9	0.1	1.2	2.50	16.00	392
Uchaly	Russia	Uralides (Hercynian)	106.00	1.1		3.8	1.10	15.50	392
Madneuli	Georgia	Caucasian (Tethyan)	102.60	1.29		1.8	0.73	4.31	70
VERY LARGE									
Mount Lyell	Australia	Tasman	98.57	1.17	0.01	0.04	0.39	7.20	495

Kidd Creek (Abitibi greenstone belt)



Kidd Creek



http://www.mining-technology.com/projects/kidd_creek

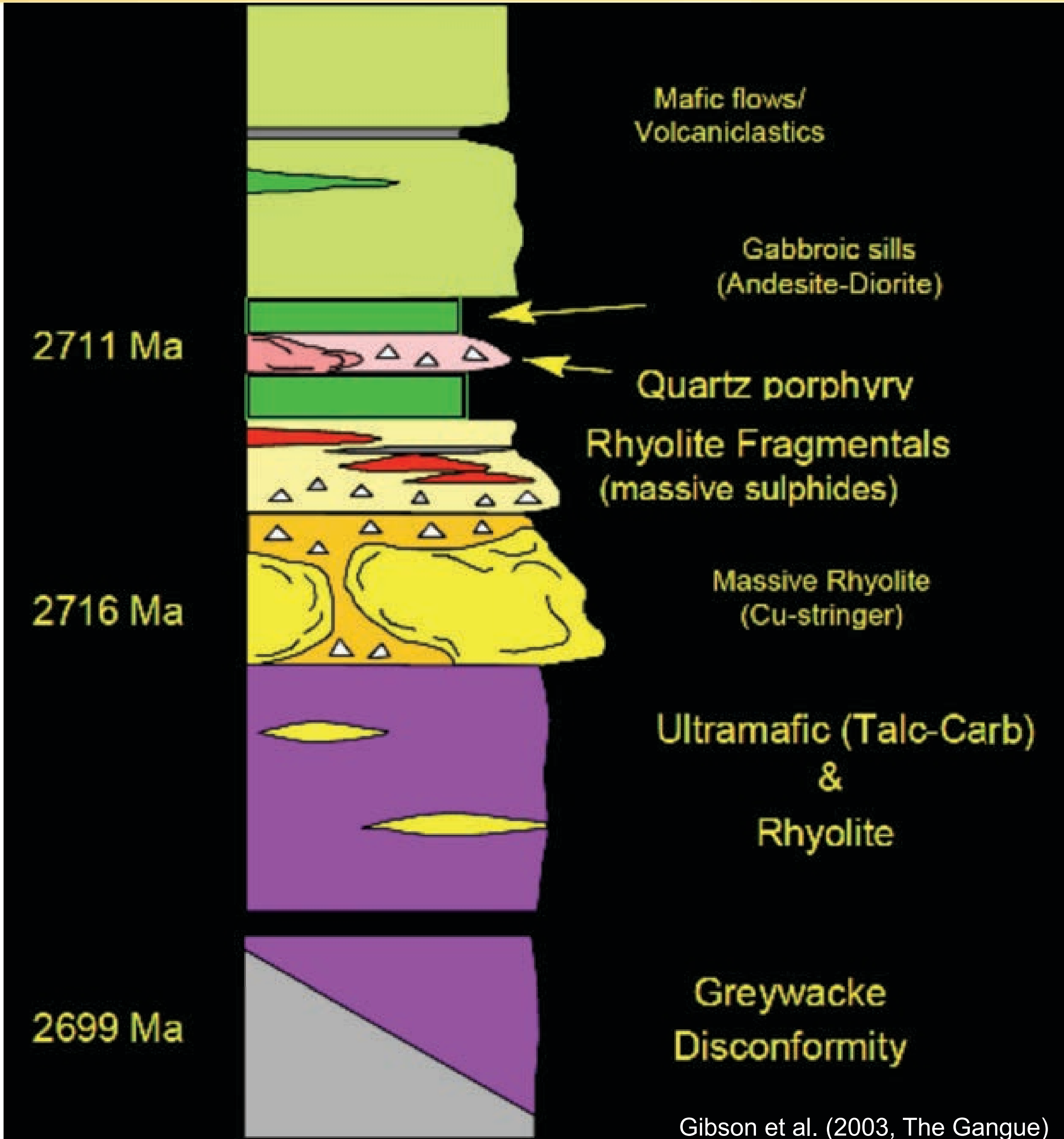
http://www.mining-technology.com/projects/kidd_creek/kidd_creek8.html

Kidd Creek

- 24 km north of Timmins (Western Abitibi)
- Giant VMS (138.7 Mt ore)
- Archean (~2.7 Ga)
- Long lived hydrothermal venting
- Deposit extends >2000m down plunge (still <u>open at depth</u>)
- Individual lenses up to 100 m thick (500m wide) – could lenses be part of a once continuous body that have been dismembered by deformation?

Kidd Creek

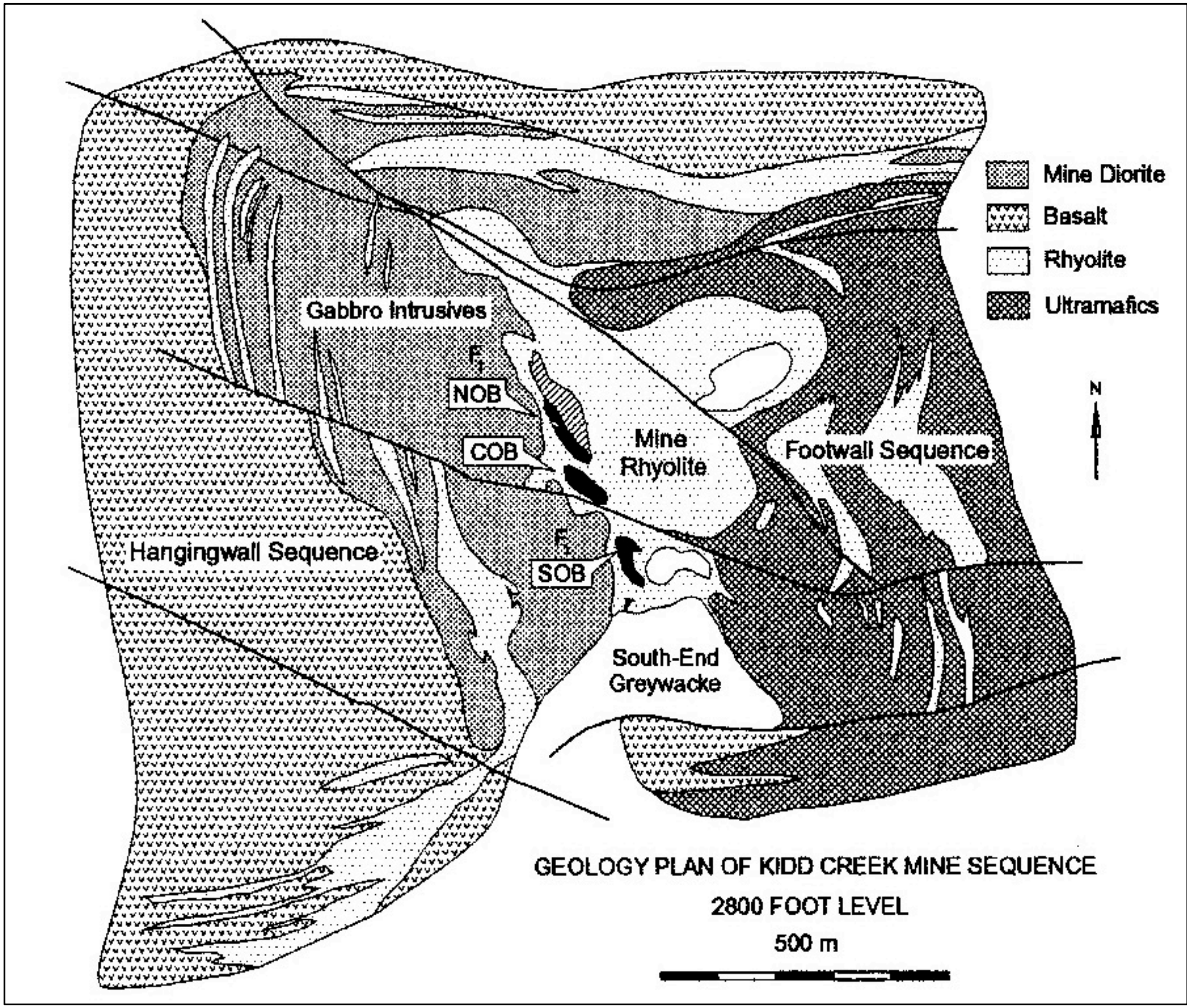
- Komatiite–basalt–rhyolite association
- Komatiite base
- Rhyolites on top
- Tectonic setting: crustal extension
- Rhyolite flows deposited into an extensional graben (this optimized preservation)
- Porous fragmental rocks also optimized sulfide deposition



Gibson et al. (2003, The Gangue)

Kidd Creek

Geologic setting of the Kidd Creek orebodies based on drilling at the 2800 foot level. The mine sequence occupies an anomalous, S-shaped fold structure, with axes of the major F_1 folds plunging steeply to the north. Because the major axes of the orebodies correspond to those of the F_1 folds, stratigraphic relationships are best observed in mine plan view. The projected locations of the North, Central, and South Orebodies (NOB, COB, and SOB) are indicated.

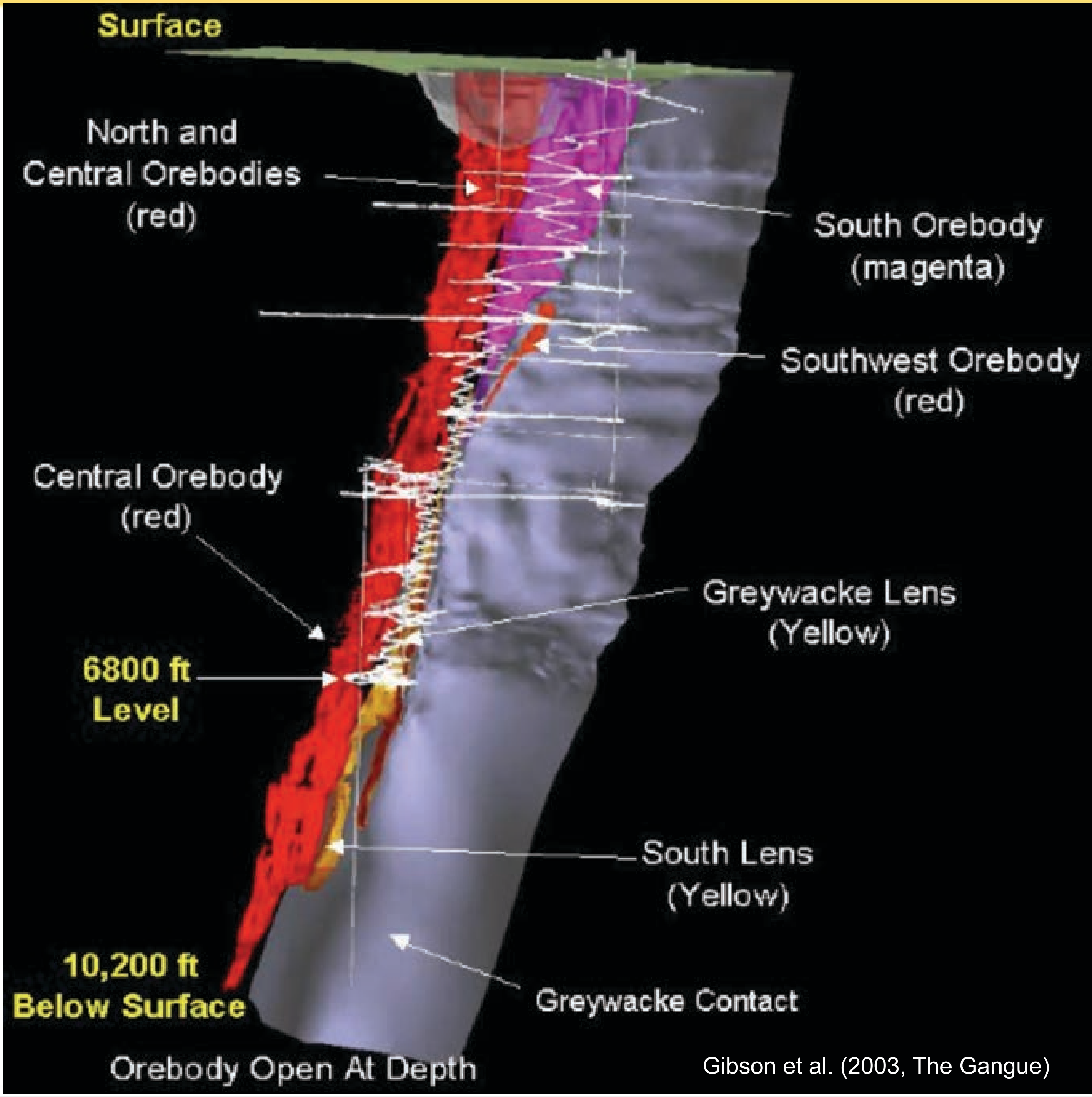


Kidd Creek

Looking east from the surface to 10,200 ft

Ore body plunges steeply to the north

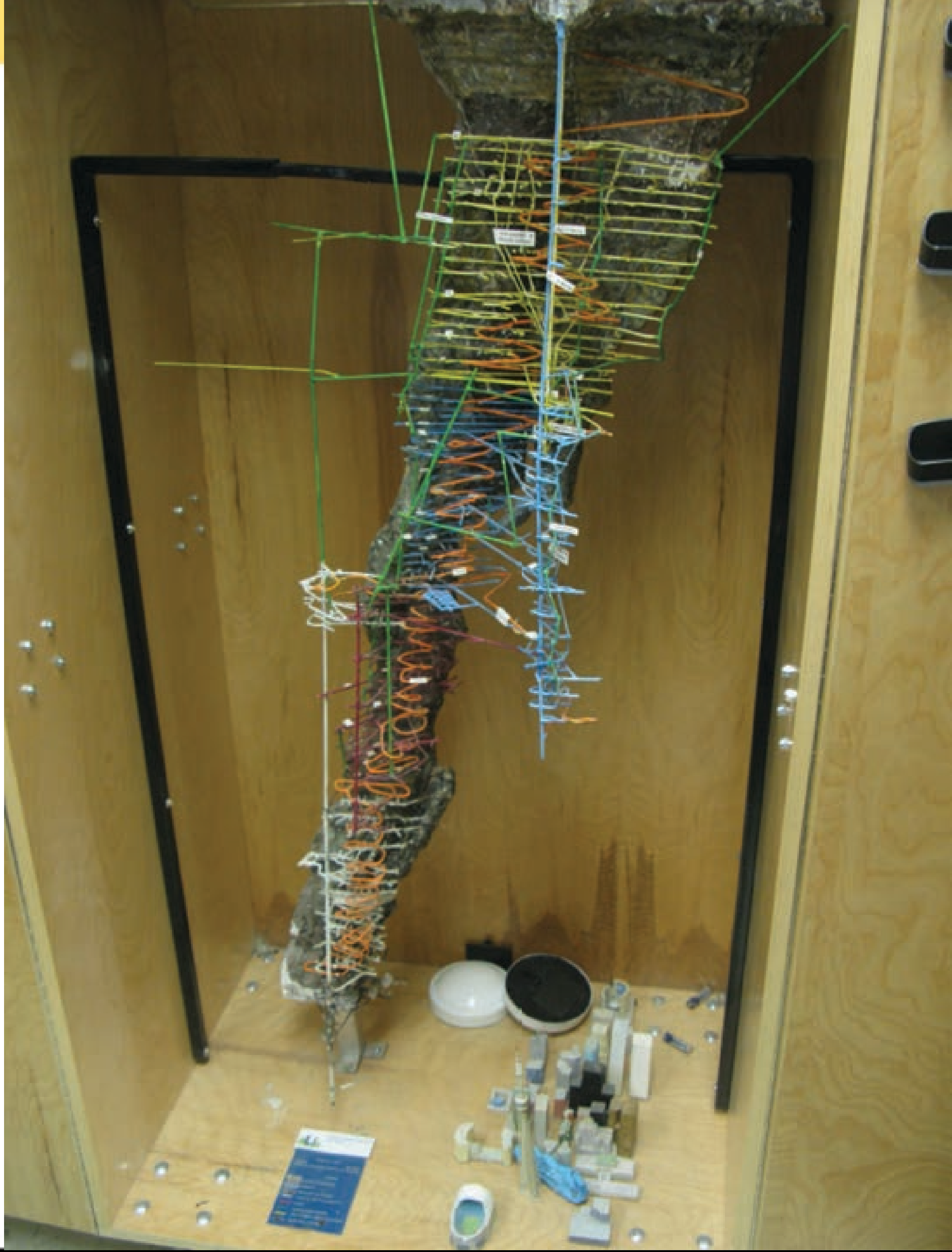
10,200 ft = 3109 m!!



Gibson et al. (2003, The Gangue)

Kidd Creek mine

(Downtown Toronto buildings for scale at bottom)



http://blogs.agu.org/martianchronicles/files/2011/07/IMG_5529.jpg

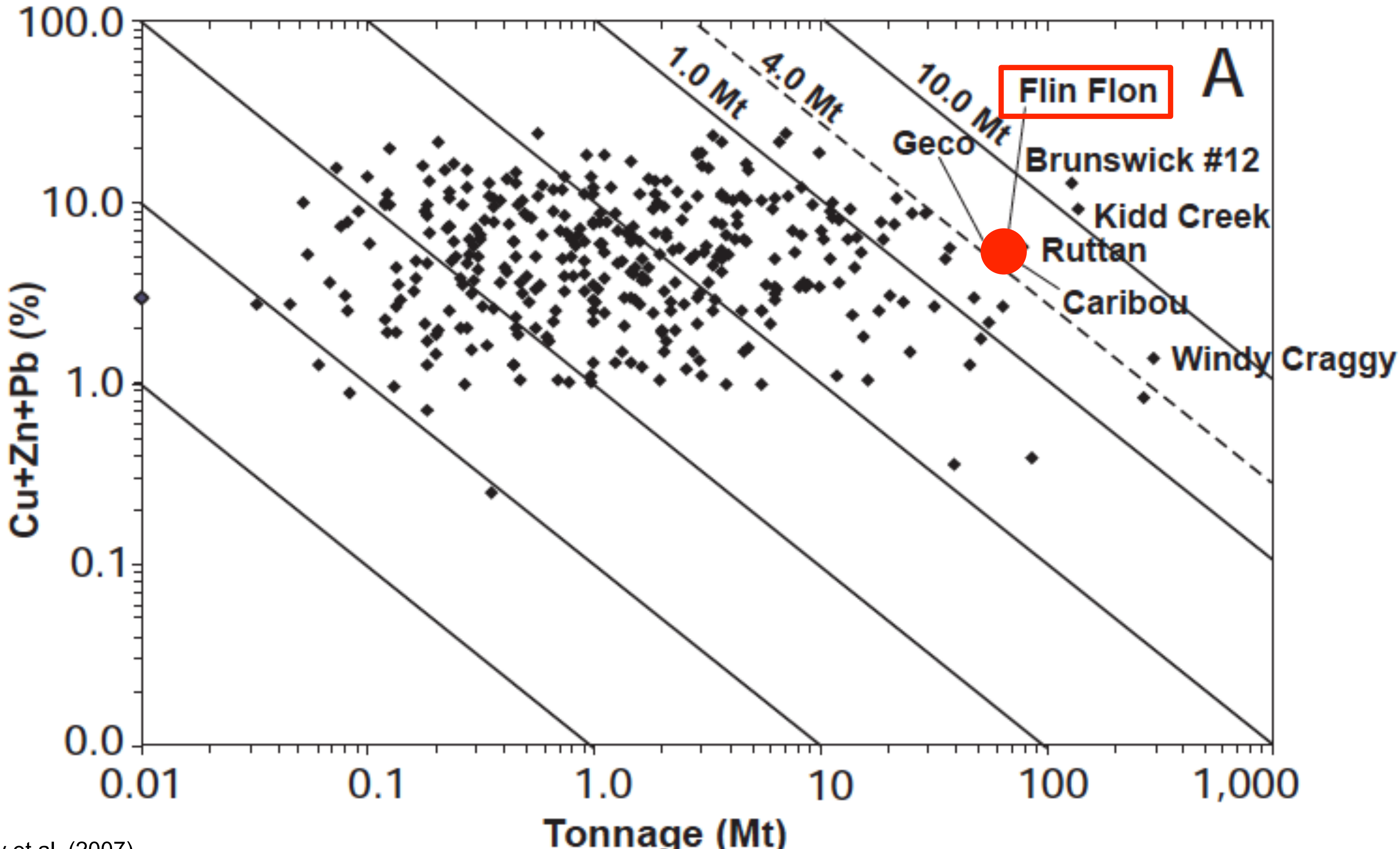
Kidd Creek

Stringer of bornite in massive chalcopyrite immediately overlying the bornite zone (field of view is 1 m).

Sulfide turbidite layer (20 cm thick) in hanging-wall argillites of NOB (1450 level).

Coarse, mixed fragmental containing black cherty rhyolite fragments, sericitized rhyolite lapillistone fragments, altered mafic clasts, and deformed sulfide clasts. The pyritic fragments are mainly sphalerite clasts that have been partly to completely replaced by pyrite. Strong stretching of the clasts is evident.

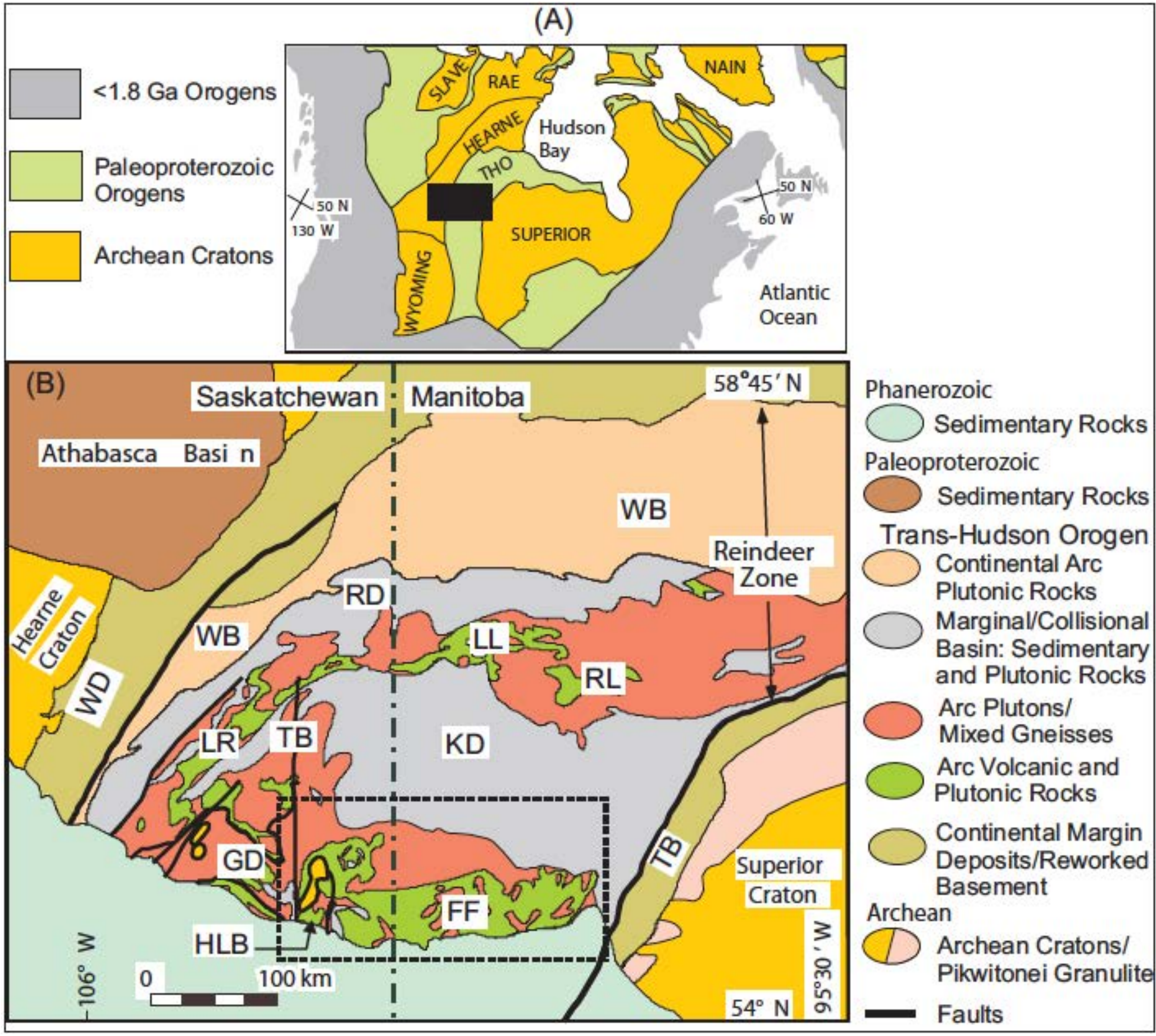
Flin Flon



Galley et al. (2007)

Flin Flon Belt

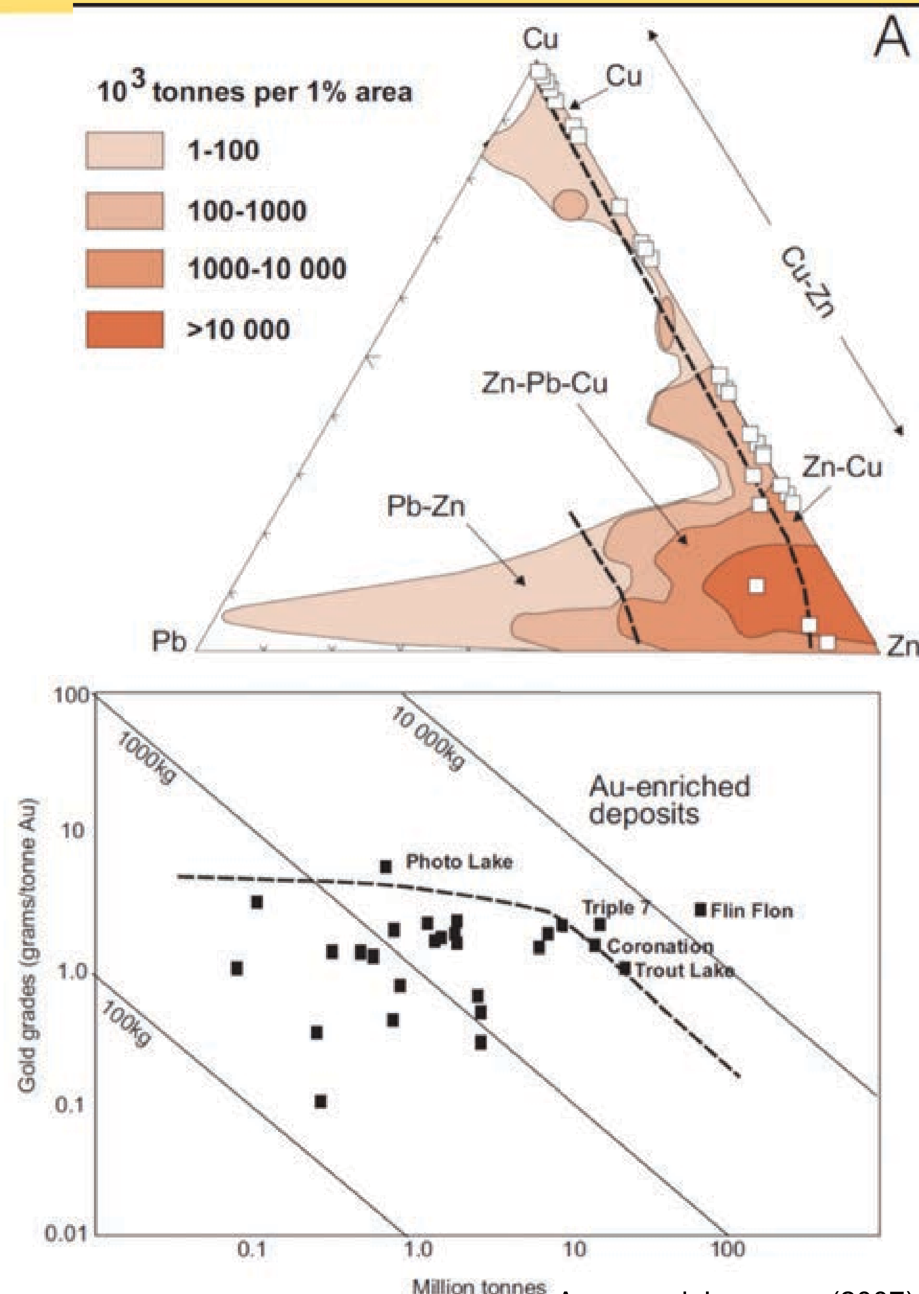
- N. Sask.
- 27 VMS deposits
- Polymetallic
- 2 big camps:
  - Flin Flon
  - Snow Lake
- Sulfide mineralization discovered in 1914
- Economic in 1930 due to improvements of Zn extraction from sphalerite



Ames and Jonasson (2007)

Flin Flon Belt

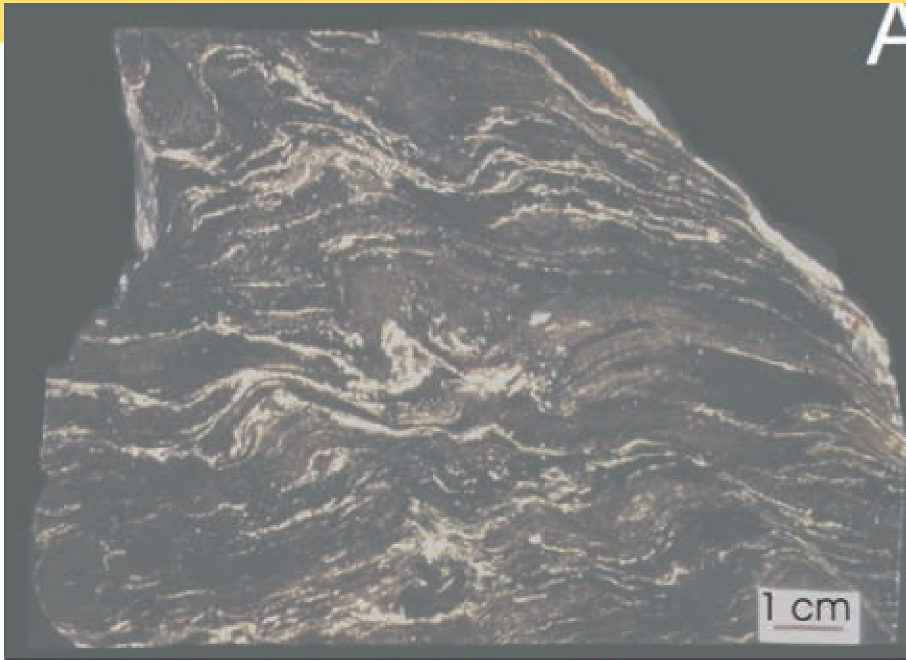
- Paleoproterozoic (~ 1.8 Ga) accreted assemblage of oceanic–continental margin terranes
- Metavolcanic and metasedimentary rocks
- Cu, Cu–Zn, Zn–Cu, and Zn–Cu–Pb VMS types
- Most VMS deposits contain 1–2 g/t Au
- 4 deposits could be classified as Au rich

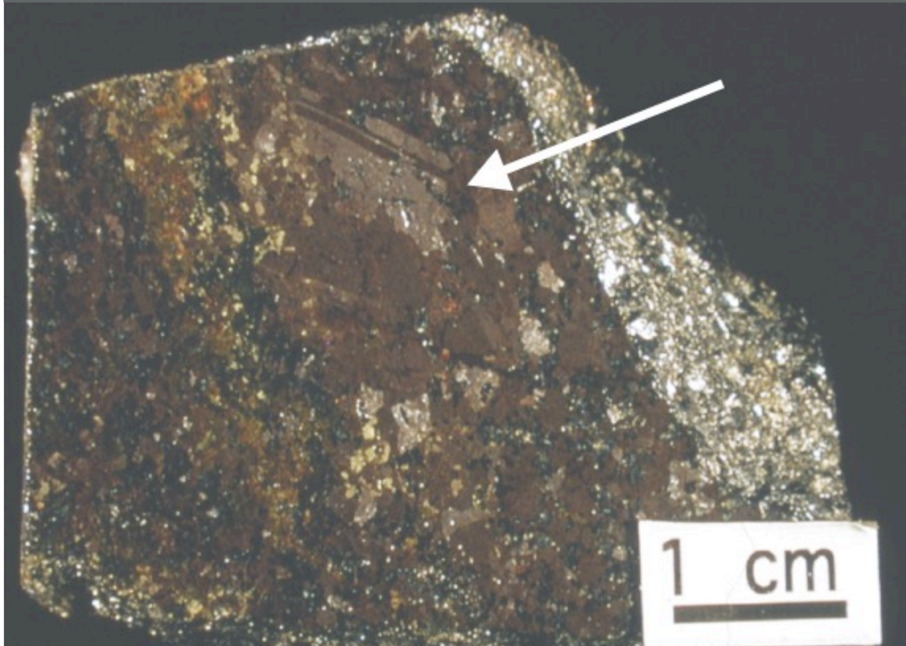


Ames and Jonasson (2007)

Flin Flon Belt – Ore

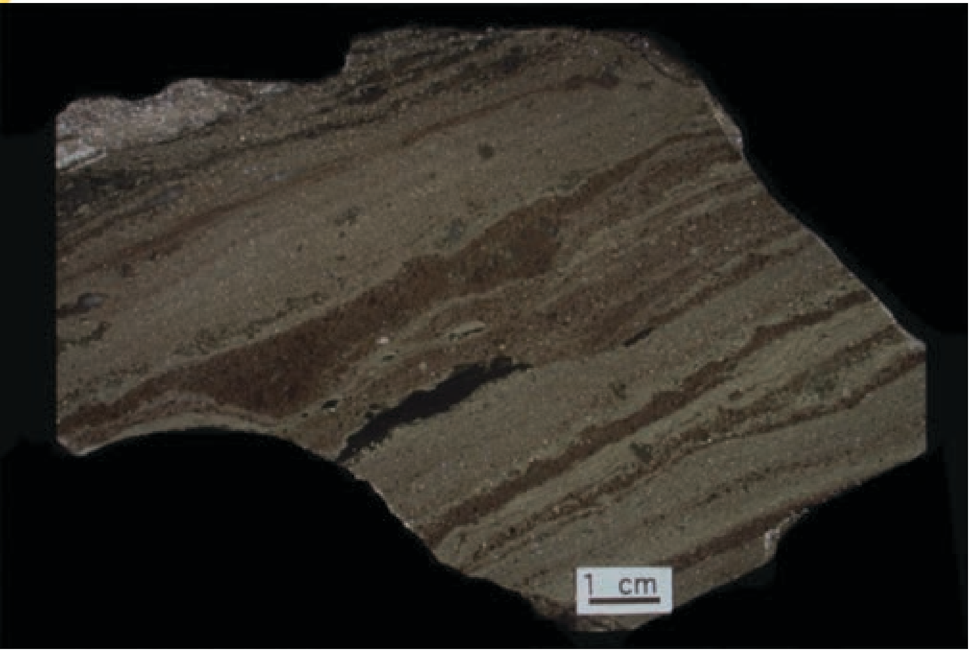
- Strongly deformed sulfide layers (original 'lens' shapes distorted and bedding not preserved)
- Coarse-grained sphalerite (arrow)
    - Metamorphic processes have remobilized sphalerite resulting in coarse grains
- Finer grained pyrite
- Metamorphism and deformation have changed the original metal zoning patterns



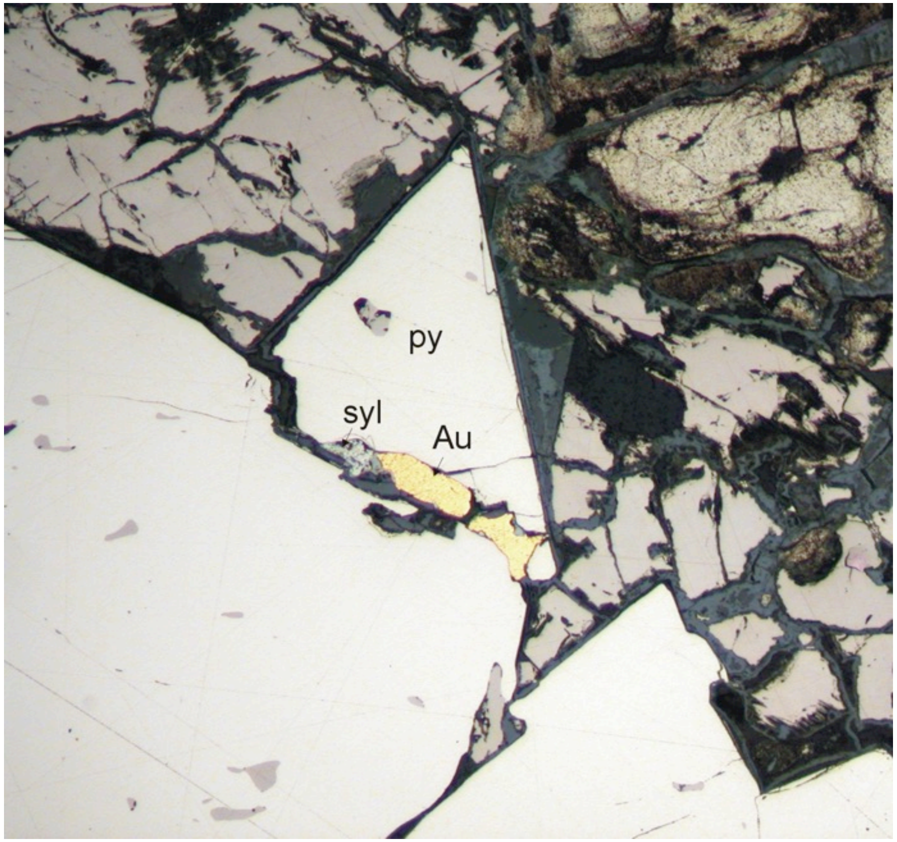


Ames and Jonasson (2007)

Flin Flon



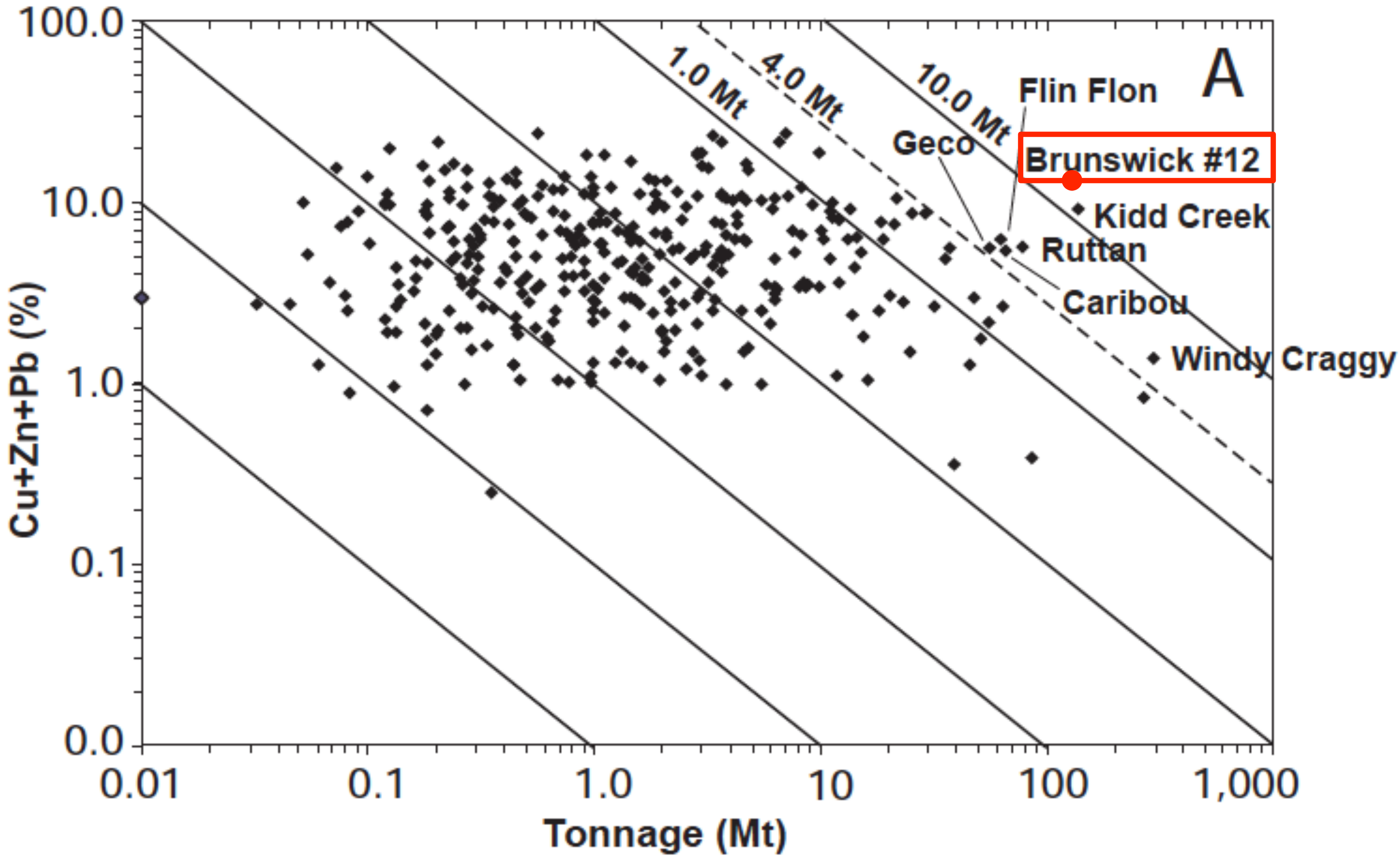
Flin Flon Cu-Zn- (Pb, Au) deposit- Massive tectonically banded ore with ~monomineralic bands of sphalerite and pyrite. Composed of sphalerite/chalcopyrite/pyrite + galena chlorite/ stilpnomelane, 650' Level, Flin Flon main mine.



Flin Flon Cu-Zn- (Pb, Au) deposit-Gold with 1-2 wt% mercury is intergrown with sylvanite (syl; $(Ag,Au)Te_2$) interstitial to coarse pyrite with pyrrhotite (po) and altered pyrite (upper right). Flin Flon main mine; 390 ft. level, long edge 0.25 mm.

Ames and Jonasson (2007)

Brunswick #12



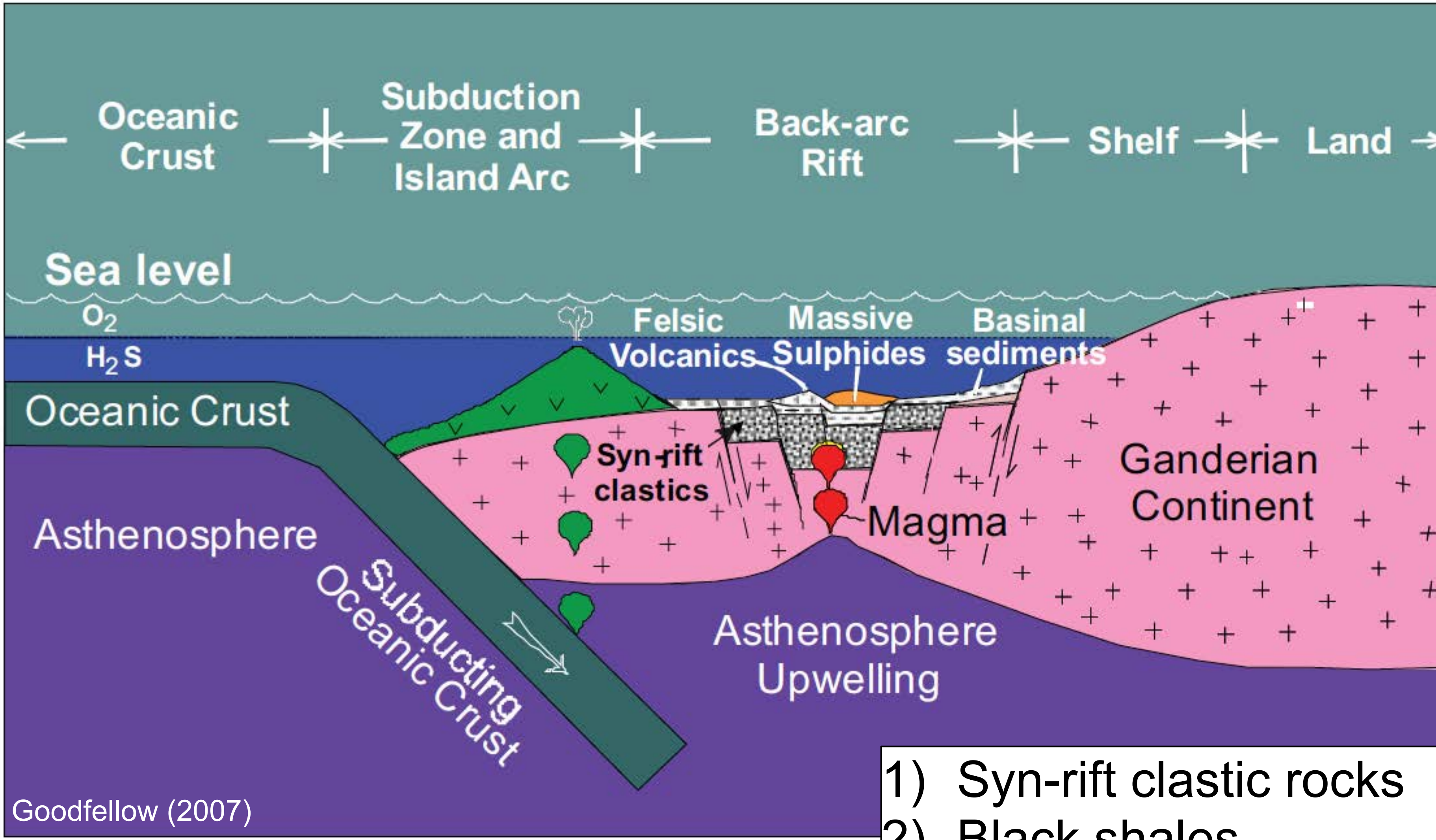
Brunswick #12

- Bathurst Camp (directly employed 2,000 people in 2001)
- Officially closed April, 2013
- **Super giant**
- Canada's largest VMS
- 229 Mt of ore 7.66% Zn, 3.01% Pb, 0.46% Cu, 91 ppm Ag, 0.46% Au
- Discovered in 1950s by geology, geophysics and geochemistry

TABLE 1. Tonnage and grades of past and present producers, Bathurst Mining Camp.

Deposit	Million tonnes (Mt)	Type	Pb (%)	Zn (%)	Cu (%)	Ag (g/t)	Au (g/t)
Primary Sulfides							
Brunswick No. 12	88.807	present	3.49	8.81	0.34	99.9	
Brunswick No. 6	12.197	past	2.15	5.43	0.40	67.0	
Captain North Ext (CNE)	0.039	past	4.42	9.97		134.7	
Heath Steele ACD Zones	2.472	past	1.73	7.38	0.73	76.7	
Heath Steele B Zone	20.723	past	1.75	4.79	0.98	65.5	
Heath Steele N-5 and Stratmat Boundary	1.137	past	2.98	8.11	0.35	44.0	
Caribou	1.343	past	3.24	6.78	0.32	97.0	
Restigouche	0.231	past	5.49	6.34		132.9	
Wedge	1.504	past	0.65	1.61	2.88	20.6	
Chester	0.003	past			1.46		
Total	128.455	(avg)	2.87	6.58	0.93	82	

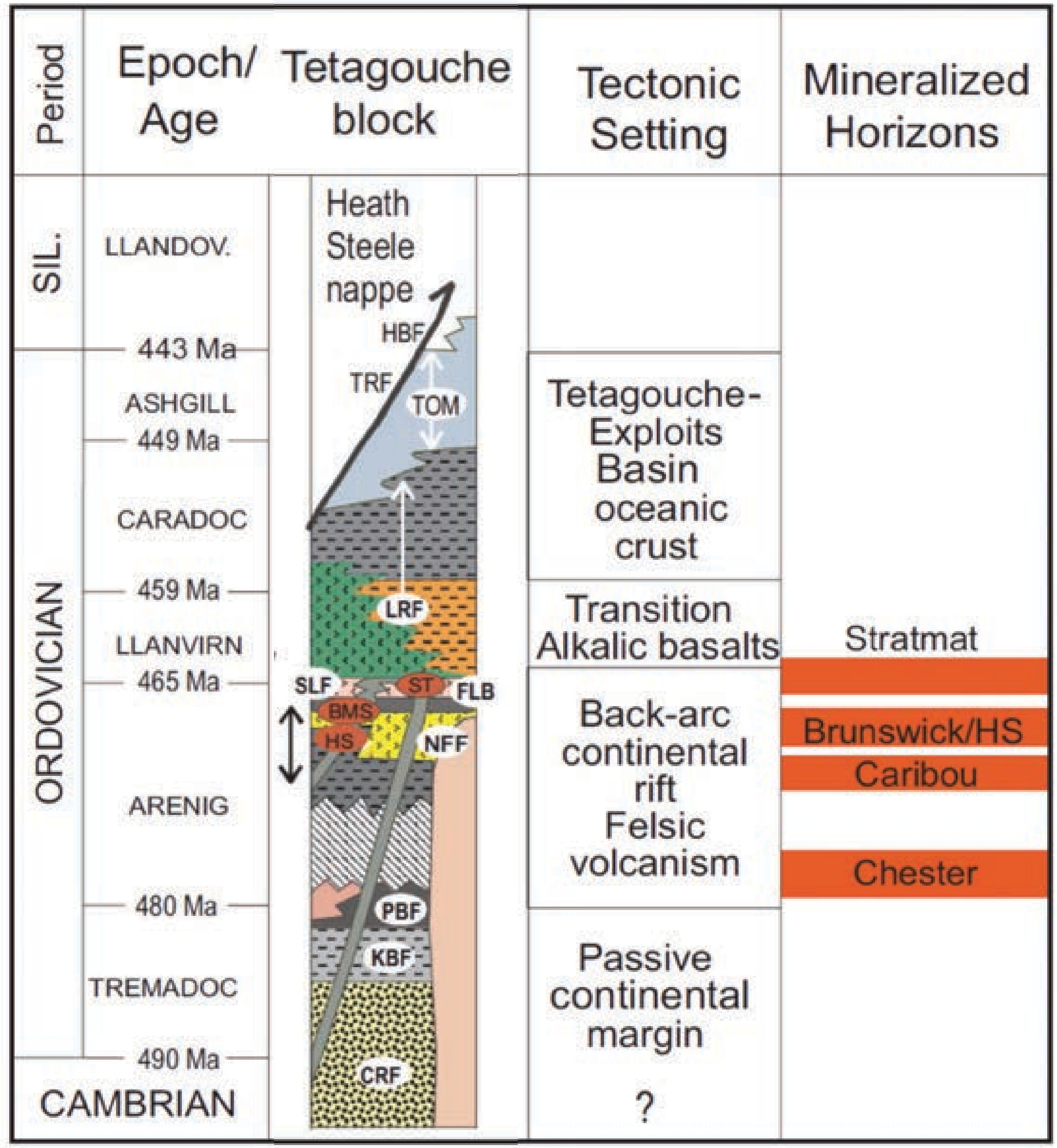
Brunswick #12 – Tectonic setting



1) Syn-rift clastic rocks
2) Black shales
3) Felsic volcanic rocks*

Brunswick #12 – Geology

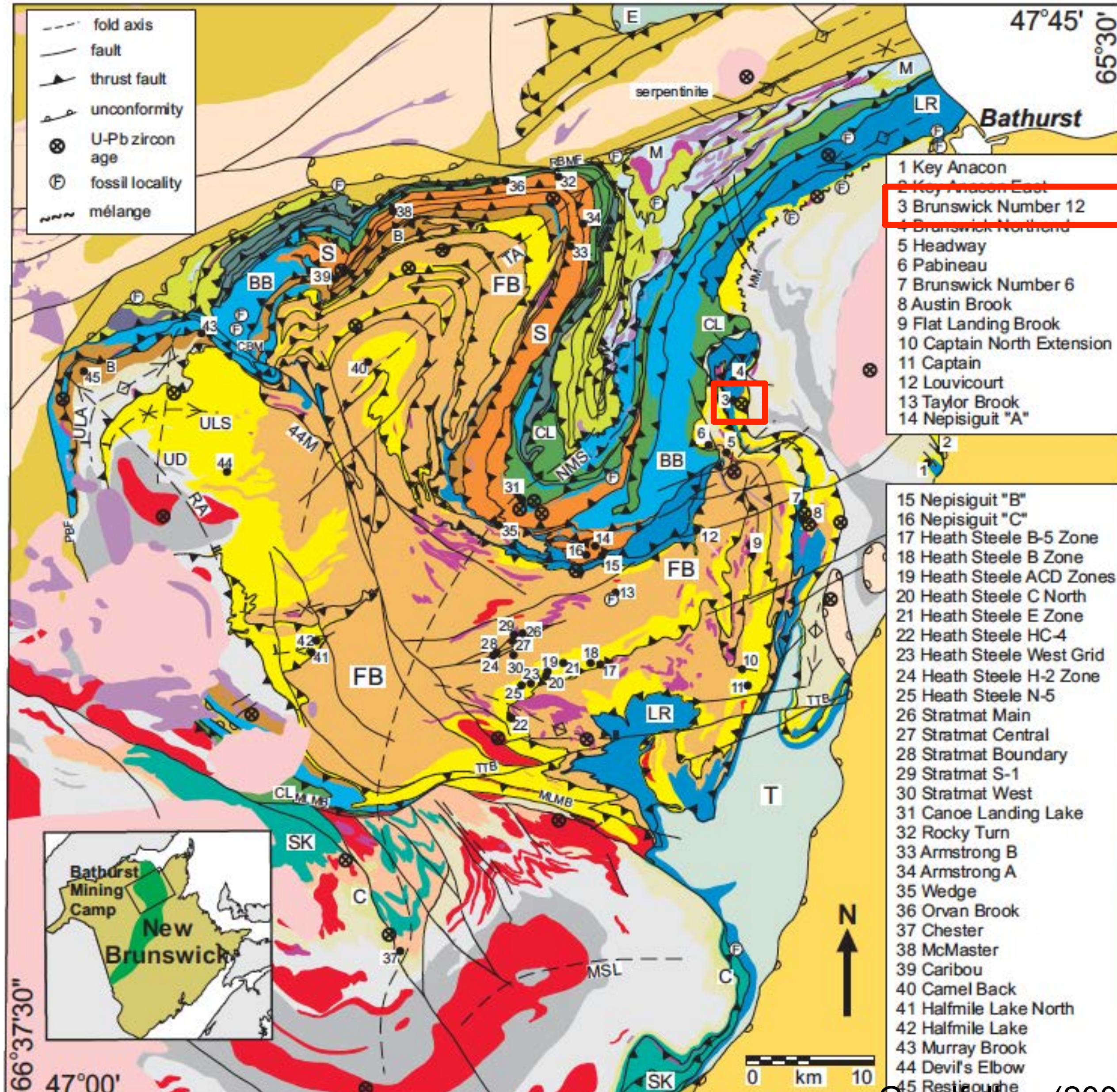
- Hosted by submarine felsic volcanic rocks
- Formed in sediment-covered back-arc continental rift
- Ordovician Tetagouche Group (hosts 30 other deposits)
- **Complex deformation history**



Goodfellow (2007)

Bathurst Camp:

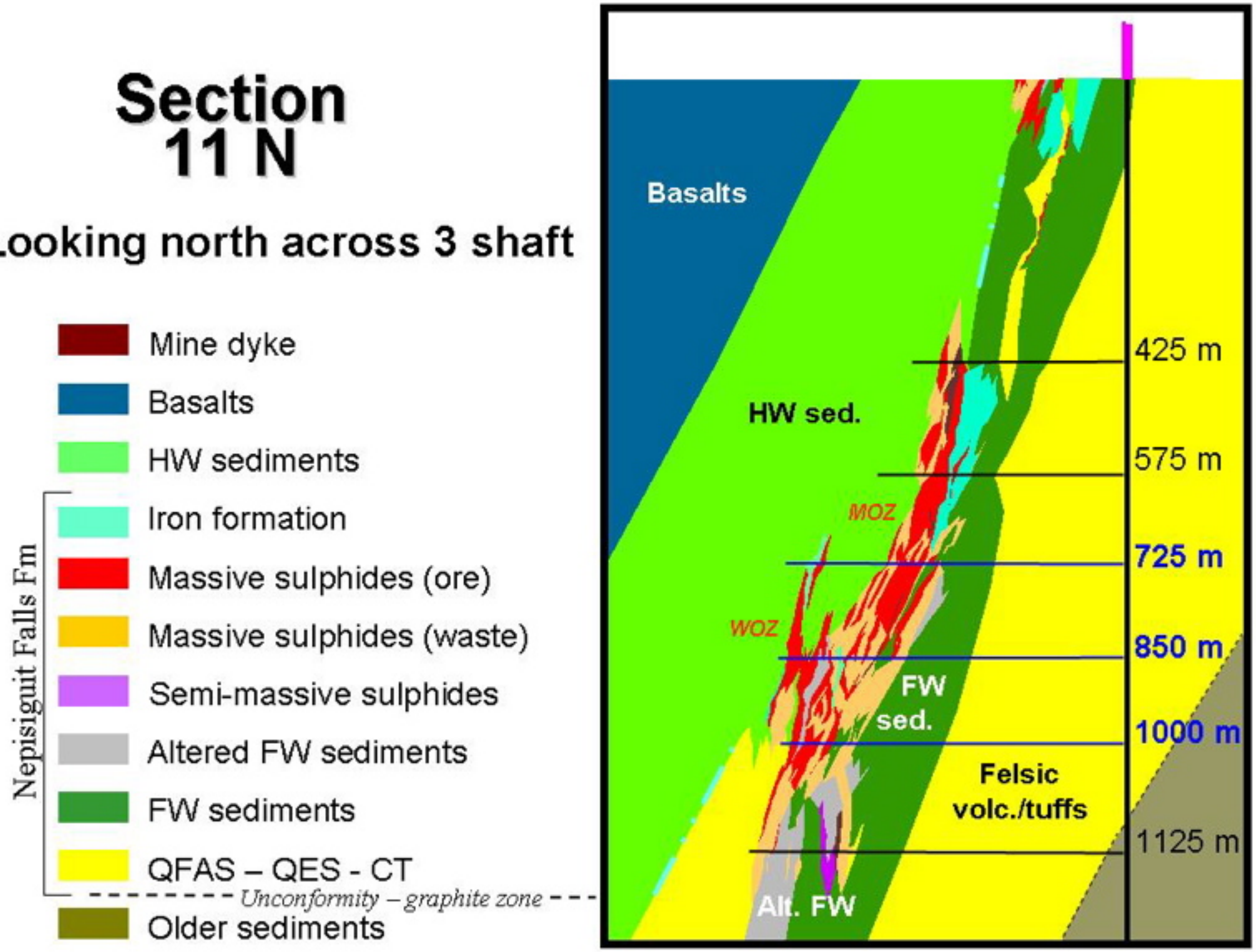
Complex deformation history



Goodfellow (2007)

Section 11 N

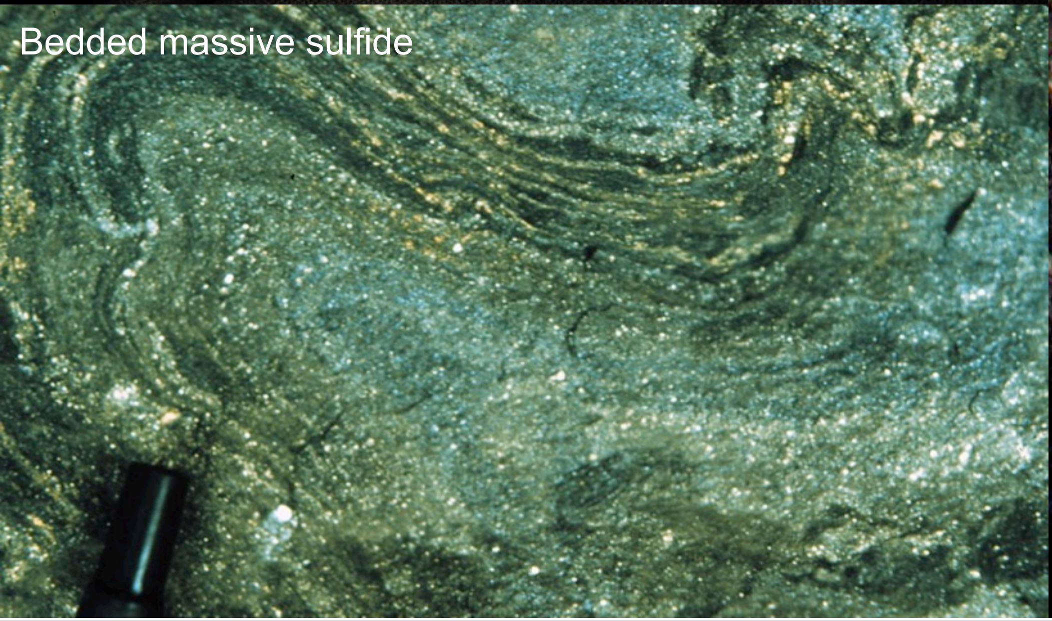
Looking north across 3 shaft



Section 11N, Number 3 shaft (see Fig. 8 for location) (from Brunswick Mining and Smelting, unpublished, 2005)

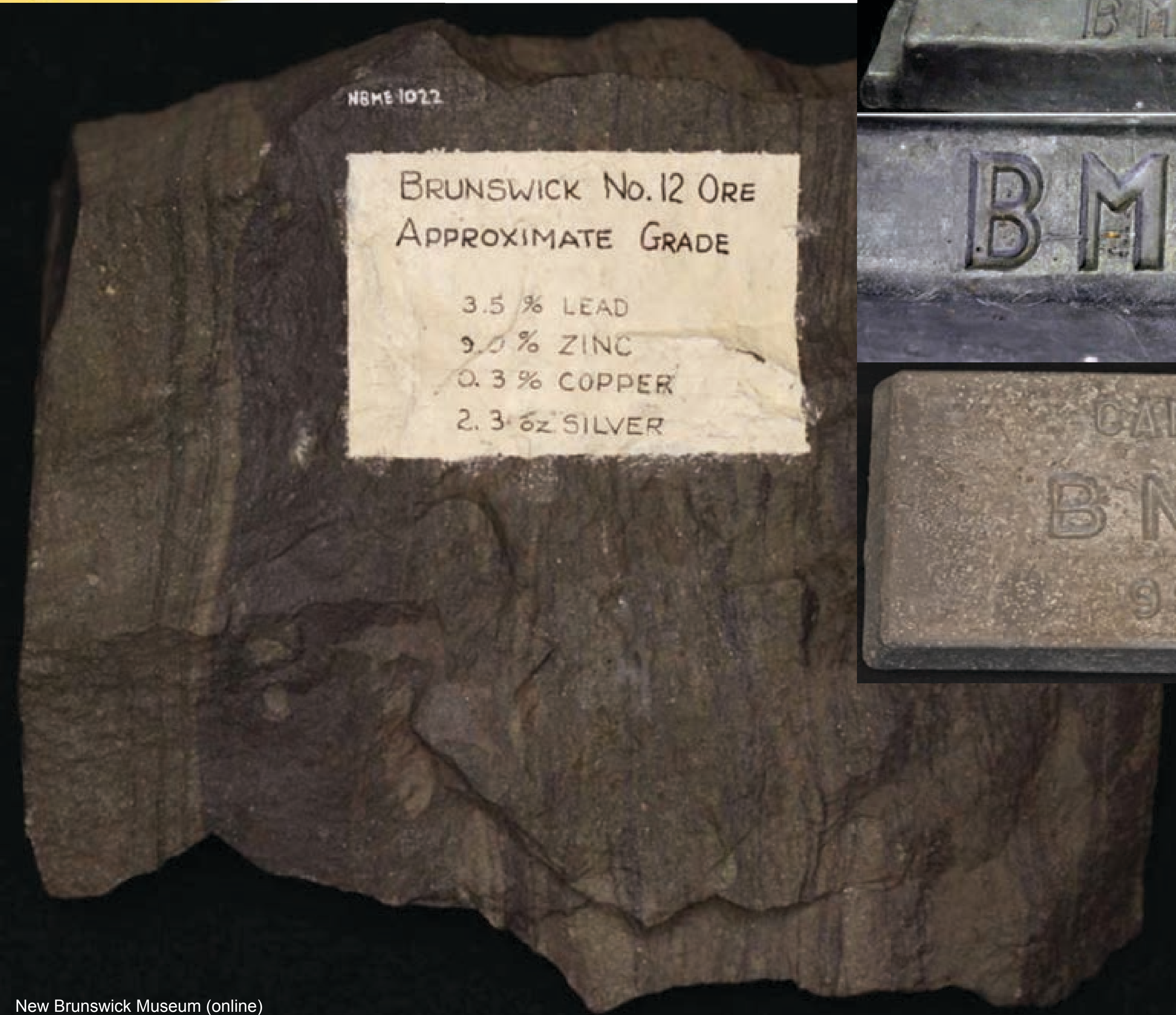

Vent complex sulfides


Pyrite–quartz stringers in silicified wall rocks


Bedded massive sulfide

Oblique air photograph of Brunswick Number 12 mine looking southeast

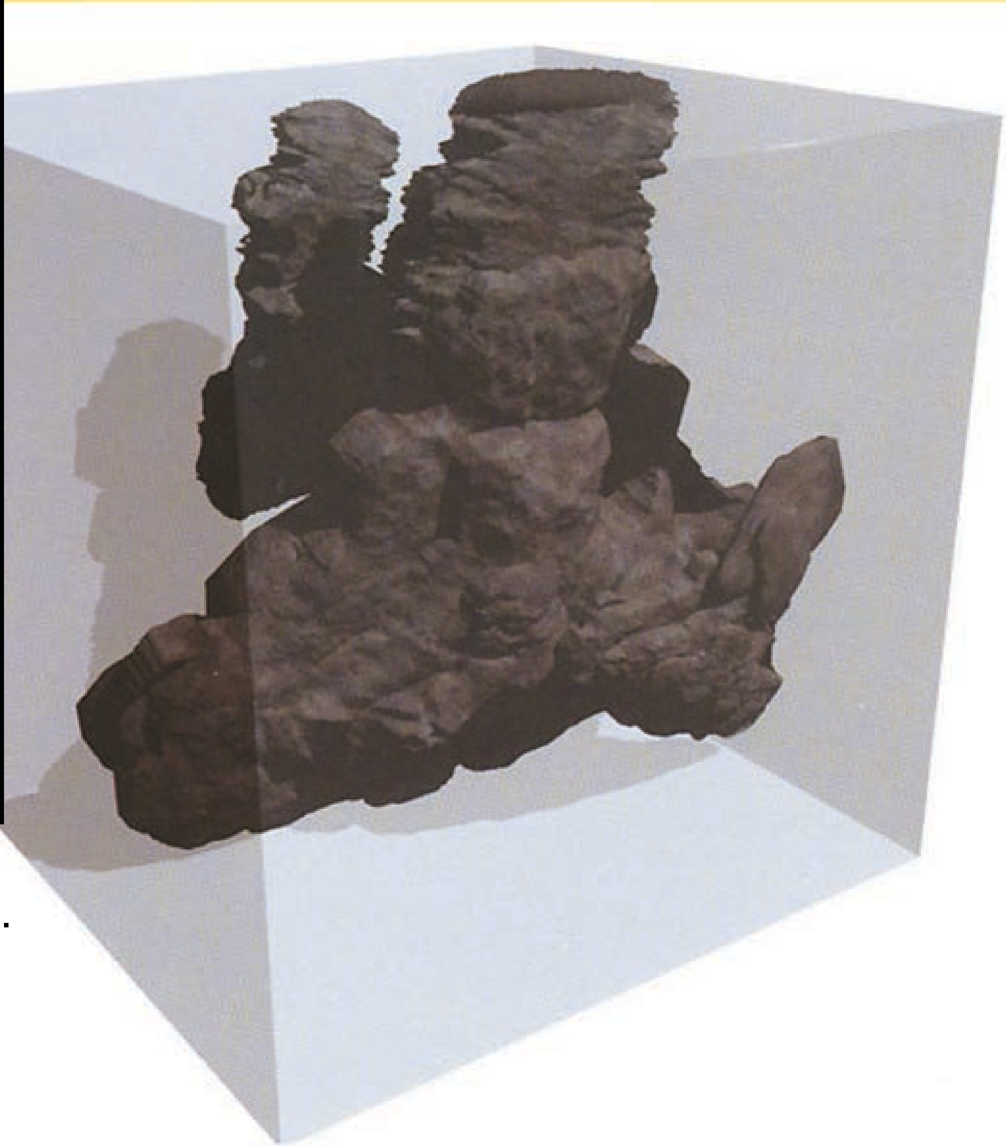
Goodfellow et al. (2007)



New Brunswick Museum (online)

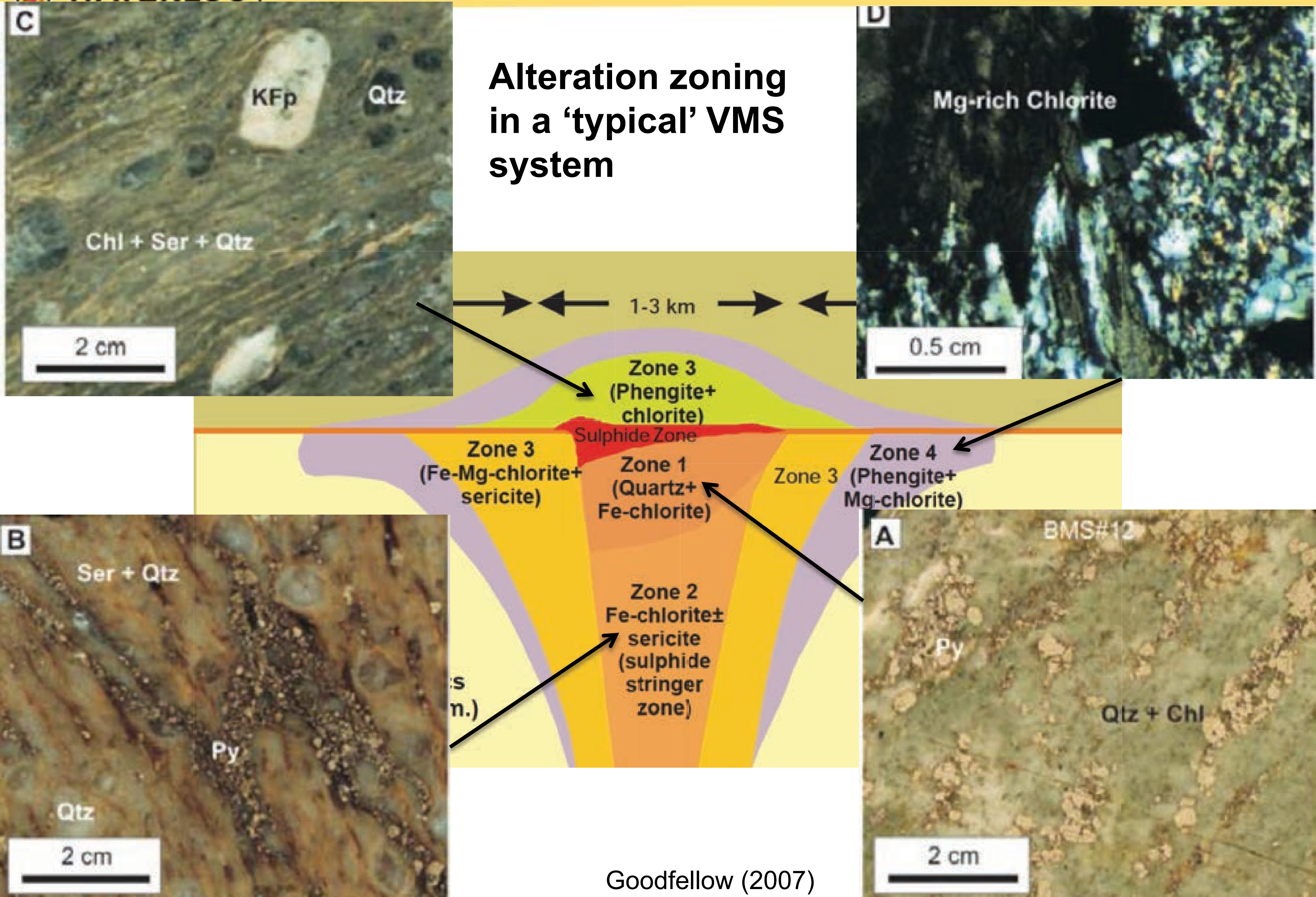
Refined Lead and Zinc bars (Brunswick mining and smelting)

Brunswick 12: drill core. Ordovician. Brunswick Mines, New Brunswick. Collector: W. Luff, 1984. New Brunswick Museum (NBME 1012). Specimen width 14.5 cm. A section of the ore zone recovered from a large drill core. Typical "ore" from Brunswick No. 12 includes layers of pyrite and galena-sphalerite with small amounts of chalcopyrite.



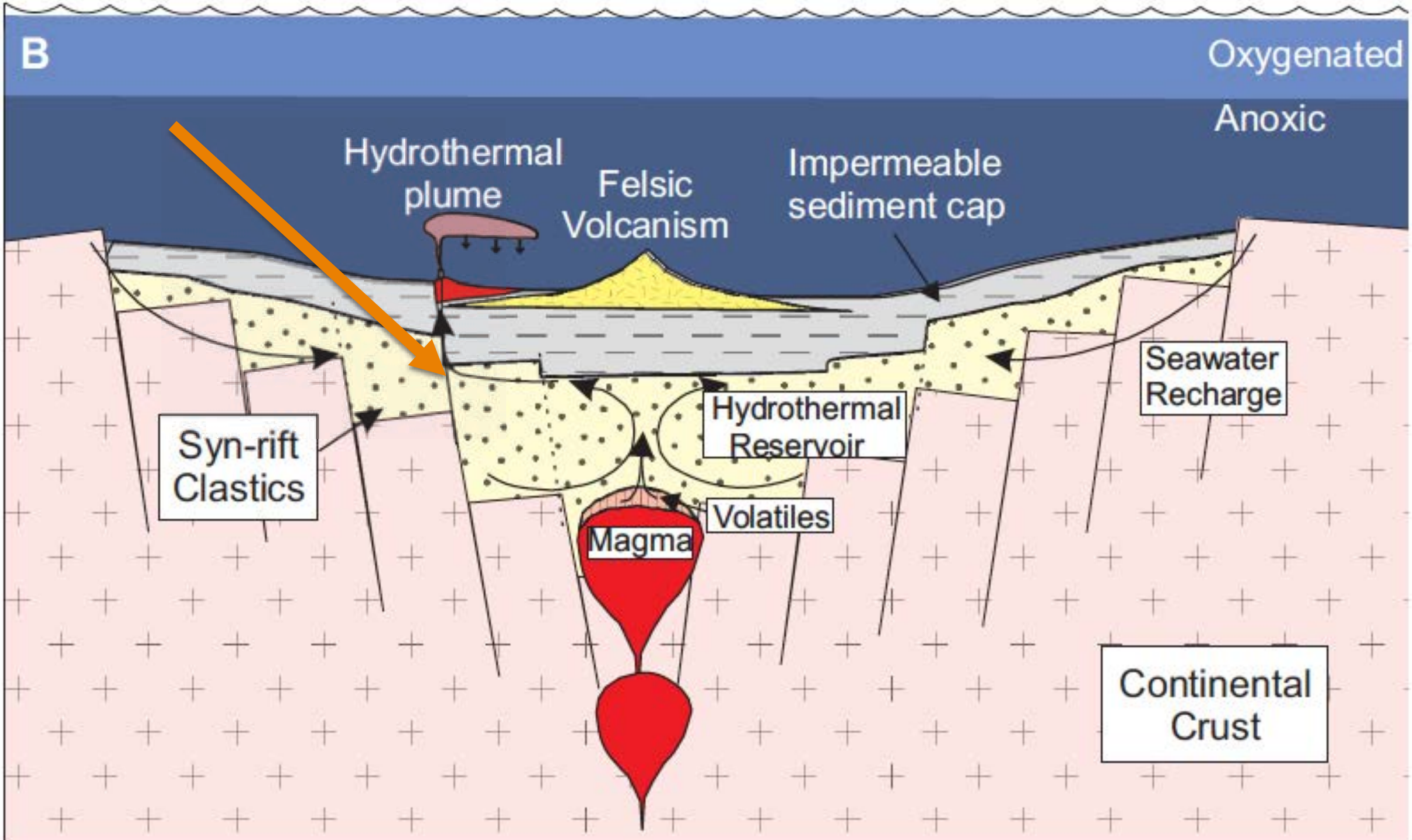
Three-dimensional image of the No.12 orebody (mining-technology.com)

Alteration zoning in a 'typical' VMS system



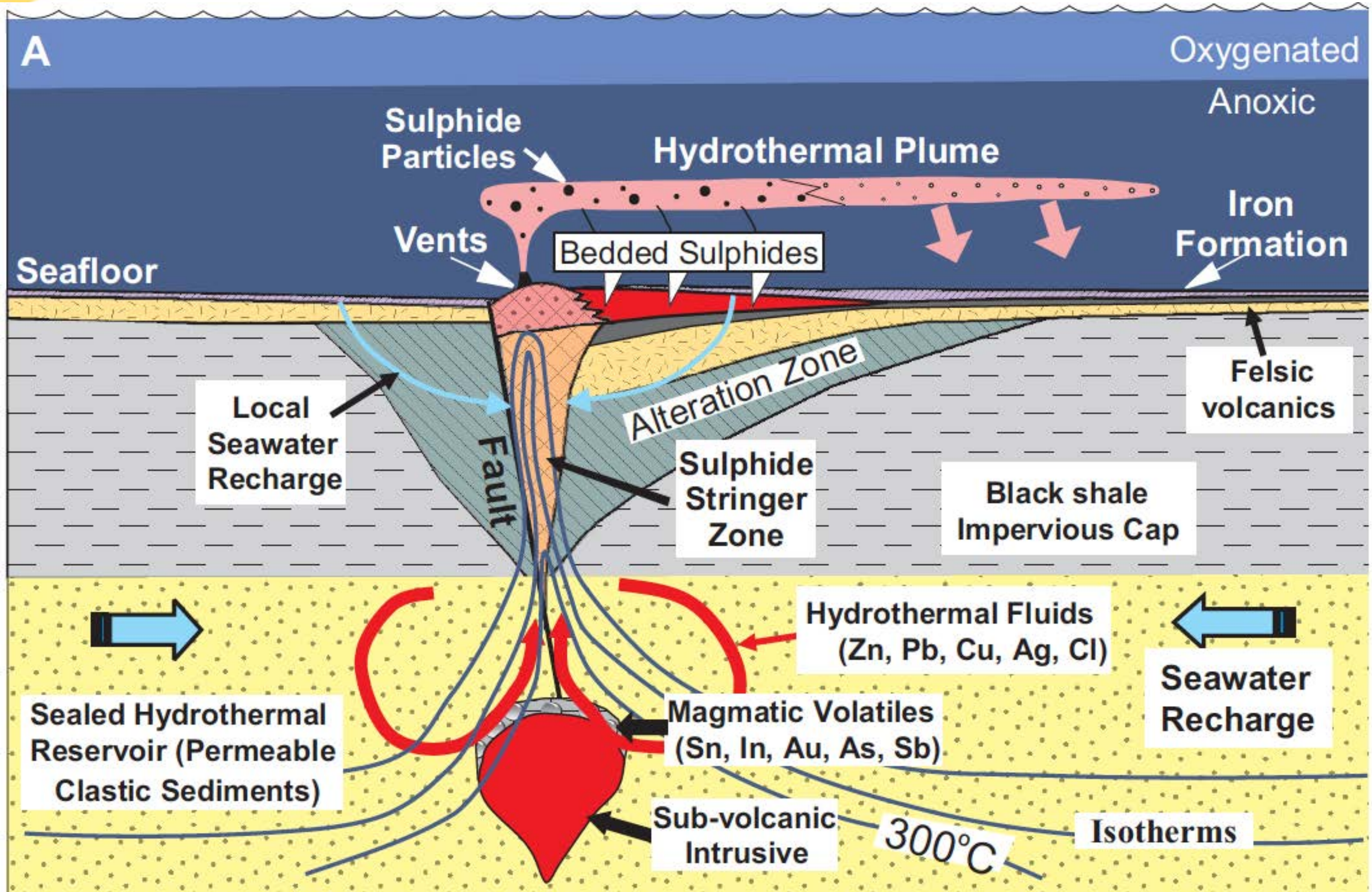
Goodfellow (2007)

Extensional faults may be important transport conduits!



Goodfellow (2007)

Alteration zone >> ore zone



Goodfellow (2007)

VMS Summary

- Modern analogue are ‘black smokers’
- Stratiform or stratabound
- Associated with subaqueous volcanic rocks
- Accumulation of base metal sulfides that formed at or near the sea floor
- Mineralization is ‘massive’, ‘stringer’ and ‘breccia’
- High-temperature alteration in surrounding rocks is common
- Minerals: sphalerite, galena, chalcopyrite, pyrite and pyrrhotite

Fluid and ligands: seawater (Cl^-)

Source of metals: underlying volcanic rocks ± magmas

Transport: hydrothermal fluid driven by convective circulation above a heat source

Trap: interaction of hot metal-rich fluids with cold seawater