An Overview of Volcanogenic Massive Sulfide (VMS) Deposits.

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Introduction

- VMS deposits - overview, general descriptive model, commodities.
- Classification
- VMS deposits - the genetic model - exploration consequences of the genetic model.
  - Subvolcanic intrusions.
  - Synvolcanic dyke swarms.
  - Alteration mapping.
  - Exhalative rocks.
- Summary

Acknowledgments

- Jim Franklin, Alan Galley, Harold Gibson, Wayne Goodfellow, Mark Hannington, Richard Herrington, Dan Layton-Matthews, Jan Peter, Nicole Tardif.

- Industry colleagues who have contributed to ideas and have supported the research herein: Kim Bailey, Terry Brace, Dave Copeland, Gilles Dessureau, Jason Dunning, Ron Fenlon, Dave Kelley, Larry Pilgrim, Jay Rickard, Barry Sparkes, Trish Toole, Lawrence Winter.

- Past funding from various companies, geological surveys (YGS, GSC, OGS, MGS, SGS), and NSERC.

- Recent research funding and logistical support: Altius Minerals, Aur Resources/Teck-Cominco Ltd., Paragon Minerals, NL Geological Survey, OZ Minerals, Rambler Metals and Mining, and NSERC.

Modern VMS Deposits

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

VMS Deposits

- ***Volcanogenic massive sulfide (VMS)***, **volcanic-hosted massive sulfide (VHMS), volcanic- and sediment-hosted massive sulfide (VSHMS), volcanic-associated massive sulfide (VAMS), etc.**

- **Lenses and sheets of massive sulfide that form from *seafloor hydrothermal systems* where metal-rich fluids (black smoke) precipitate on *(exhalative)* or near the seafloor *(subseafloor replacement)*.**

- **Predominantly sources of Zn, Cu, Pb, Ag, and Au.**

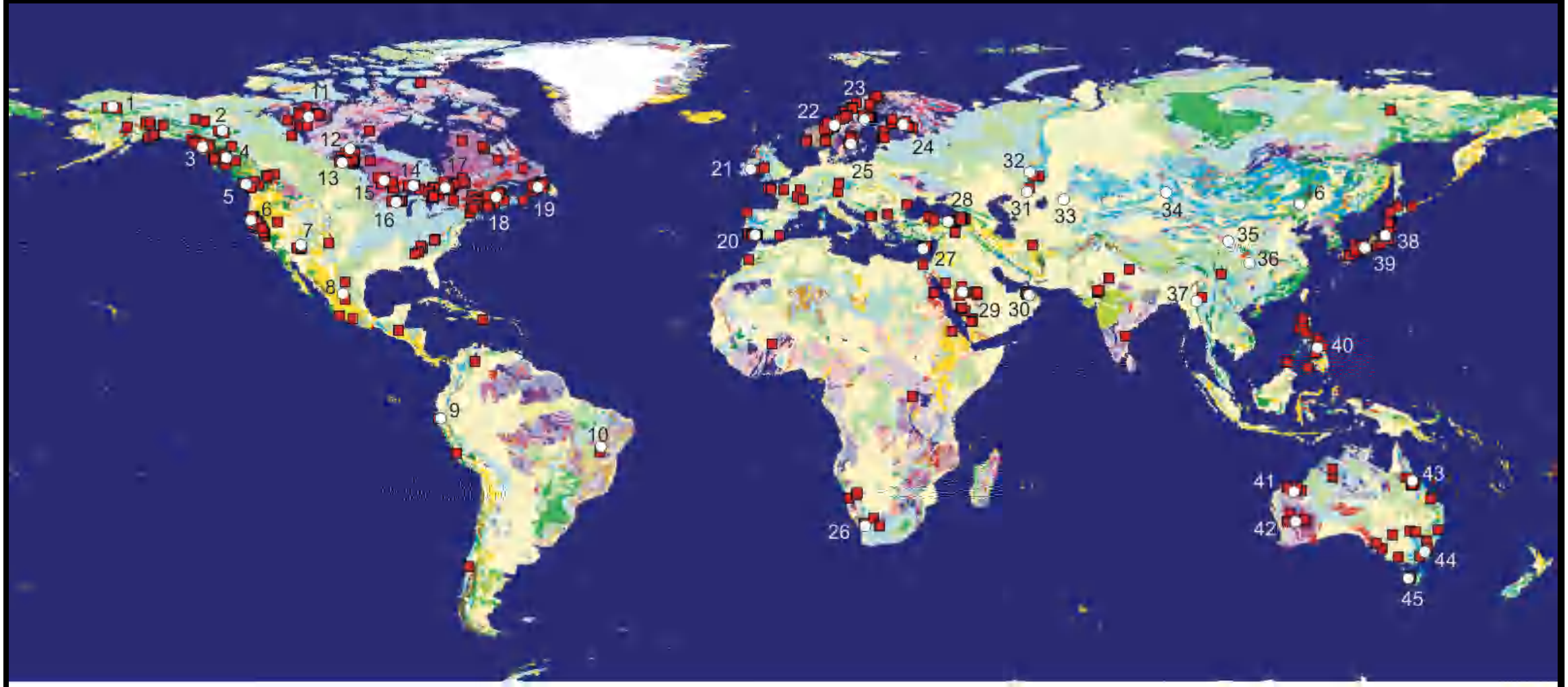
- **Also important sources for: Co, Sn, Se, Mn, Cd, In, Bi, Te, Ga, and Ge.**

- **Some have As, Sb, and Hg (e.g., Eskay Creek, Bousquet-LaRonde, Rambler).**

- **Significant contributor to Canadian economy:**

    - **27% of Canada's Cu, 49% Zn, 20% Pb, 40% Ag, 3% Au production.**

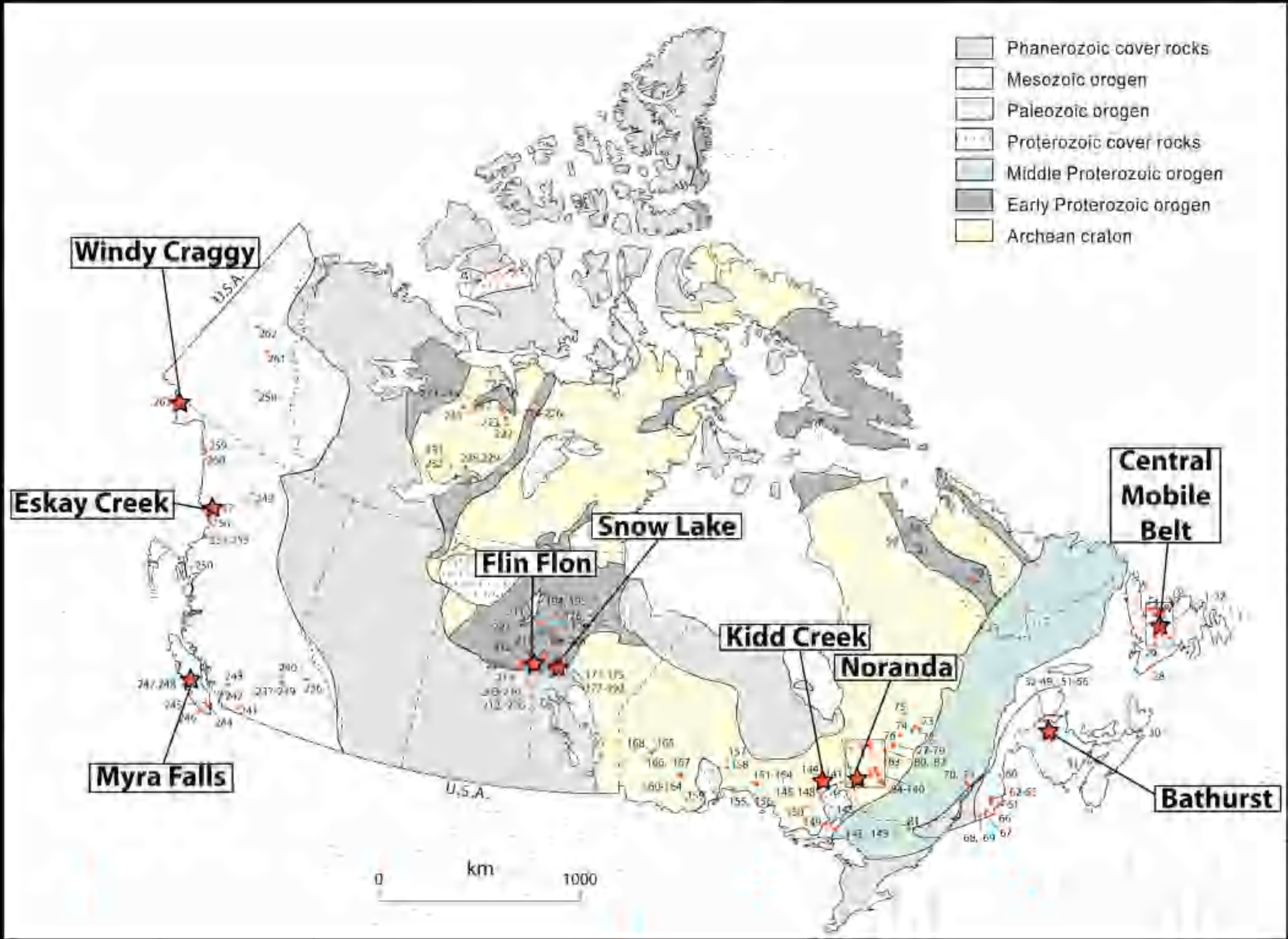
VMS Deposit Distribution



From Galley et al. (2007)

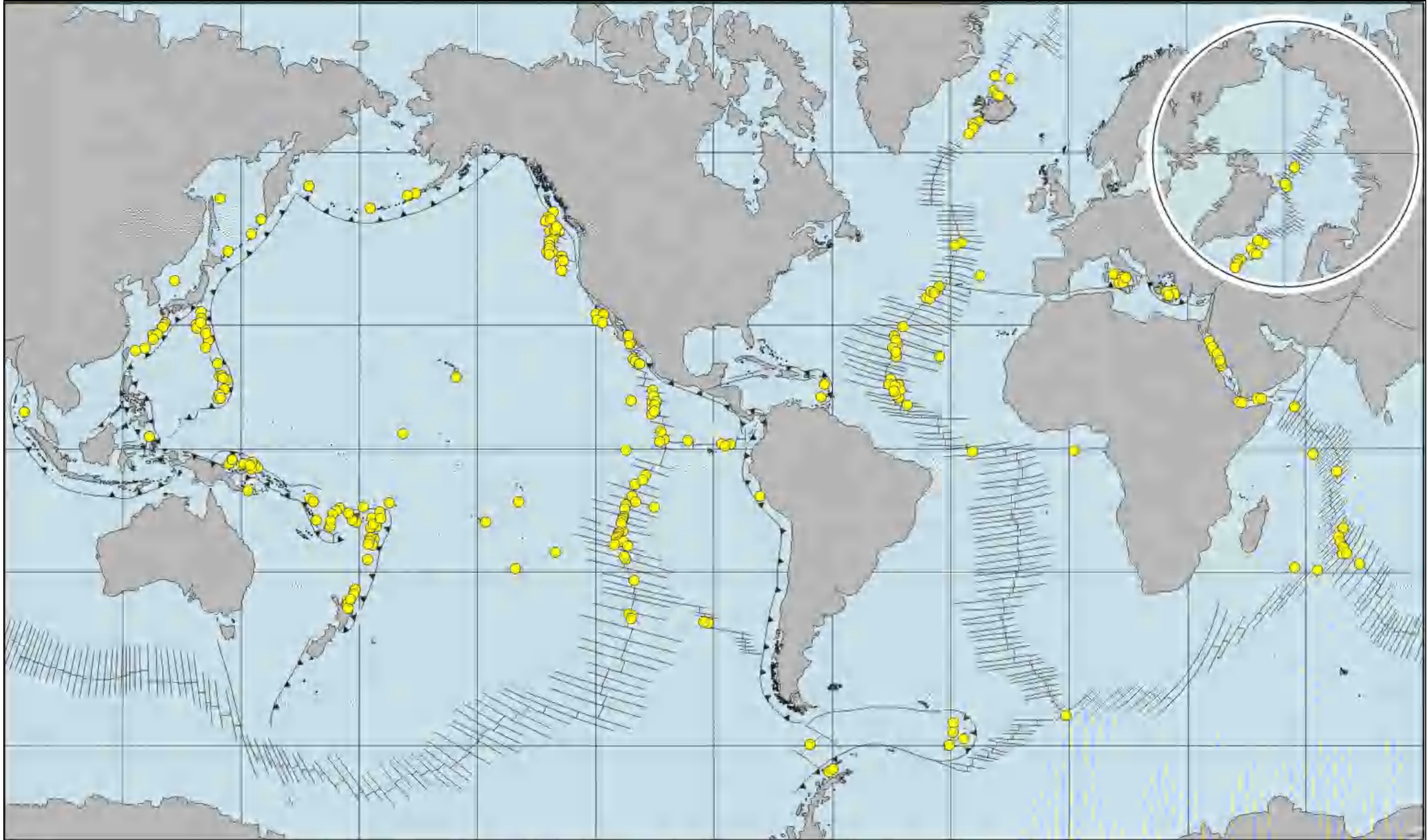
- 850 deposits >200,000 t.
- Range from 3.4 Ga to present.
- Actively forming VMS and hybrid VMS systems.
- World metal production: 22% Zn, 6% Cu, 9.7% Pb, 8.7% Ag, 2.2% Au.

Some Key Canadian VMS Districts



From Galley et al. (2007)

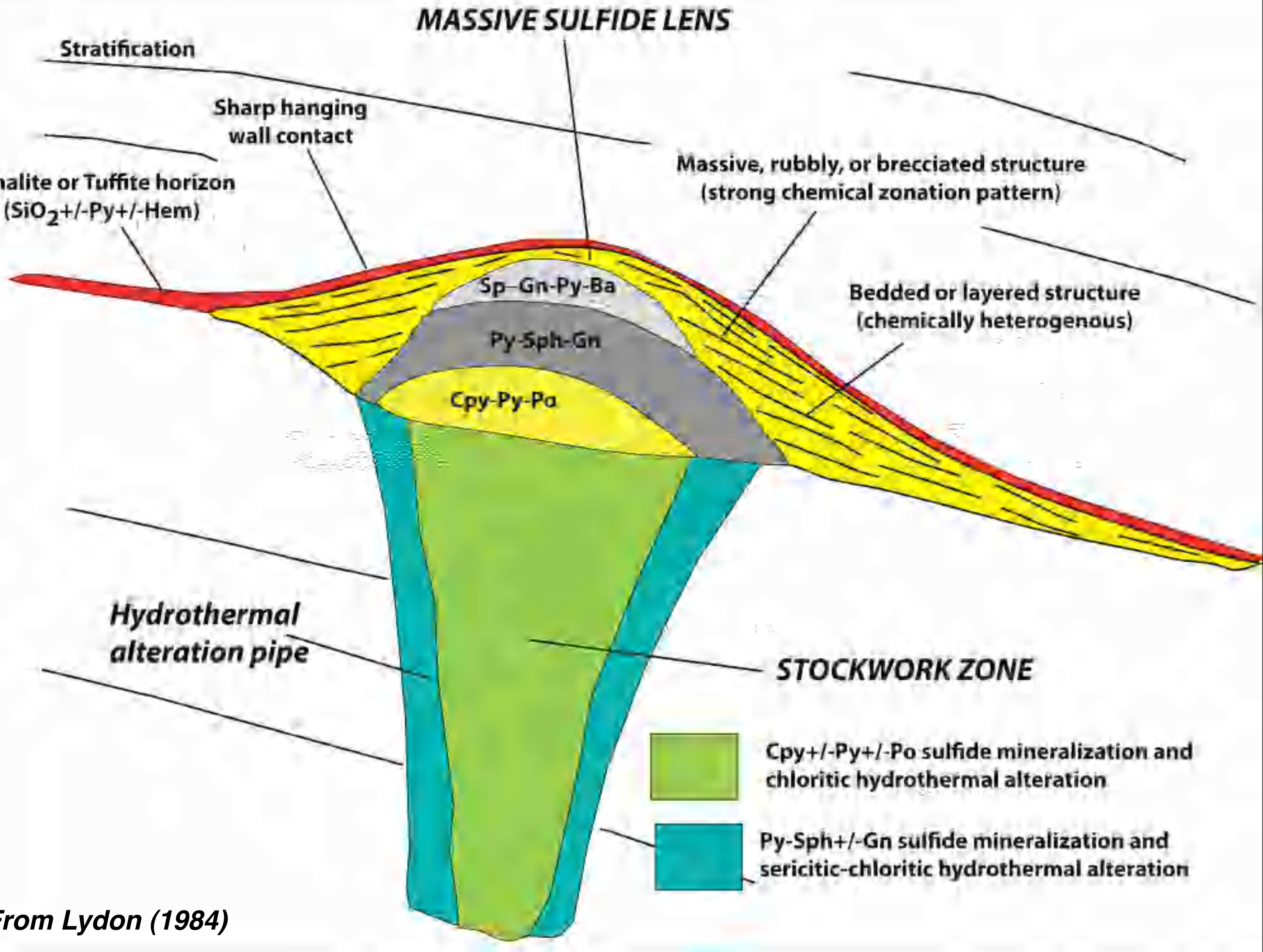
Seafloor Hydrothermal Vents and Related Mineral Deposits



Hannington et al., 2005, 100th Anniv. Vol. Economic Geology
(Slide from M. Hannington and Harold Gibson)

“World First Seafloor Massive Sulphide Resource”
Nautilus Mineral Inc. (Press Release Dec. 20, 2007)

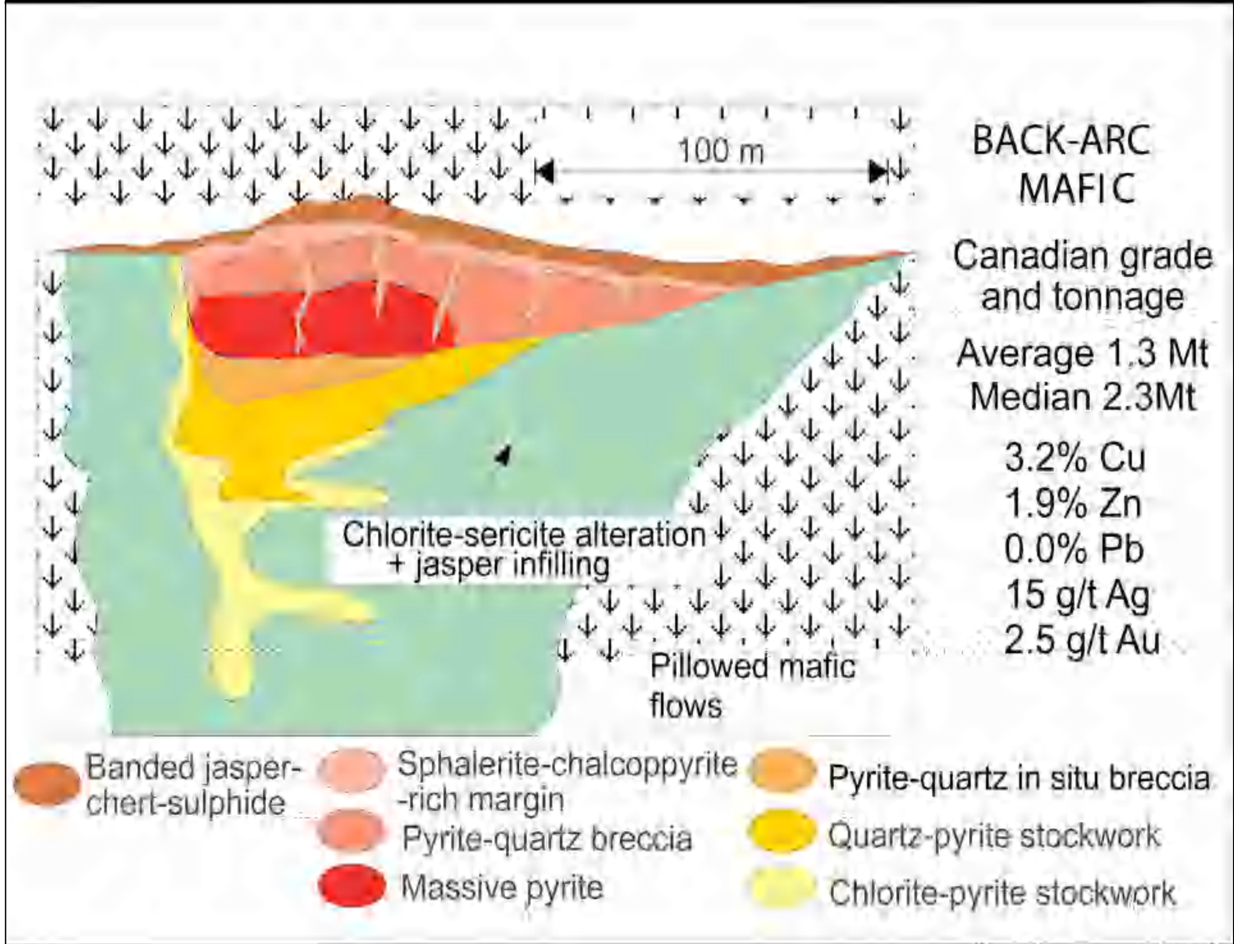
http://www.nautilusminerals.com



From Lydon (1984)

VMS Deposit Classification

- Numerous classifications for VMS
  - Metals - Zn-Cu, Cu-Zn, Zn-Pb-Cu, Au-rich
  - Type locale - Cyprus, Kuroko, Besshi
- Six-fold classification of VMS most useful as based on rock type and associations (Barrie and Hannington, 1999; Franklin et al., 2005; Galley et al., 2007):
  - Mafic (Cyprus-type).
  - Bimodal Mafic (Noranda-type).
  - Mafic Siliciclastic (Besshi-type) (aka Pelitic Mafic)
  - Bimodal Felsic (Kuroko-type).
  - Felsic Siliciclastic (Bathurst-type).
  - Hybrid Bimodal Felsic/Siliciclastic (Eskay Creek-type).

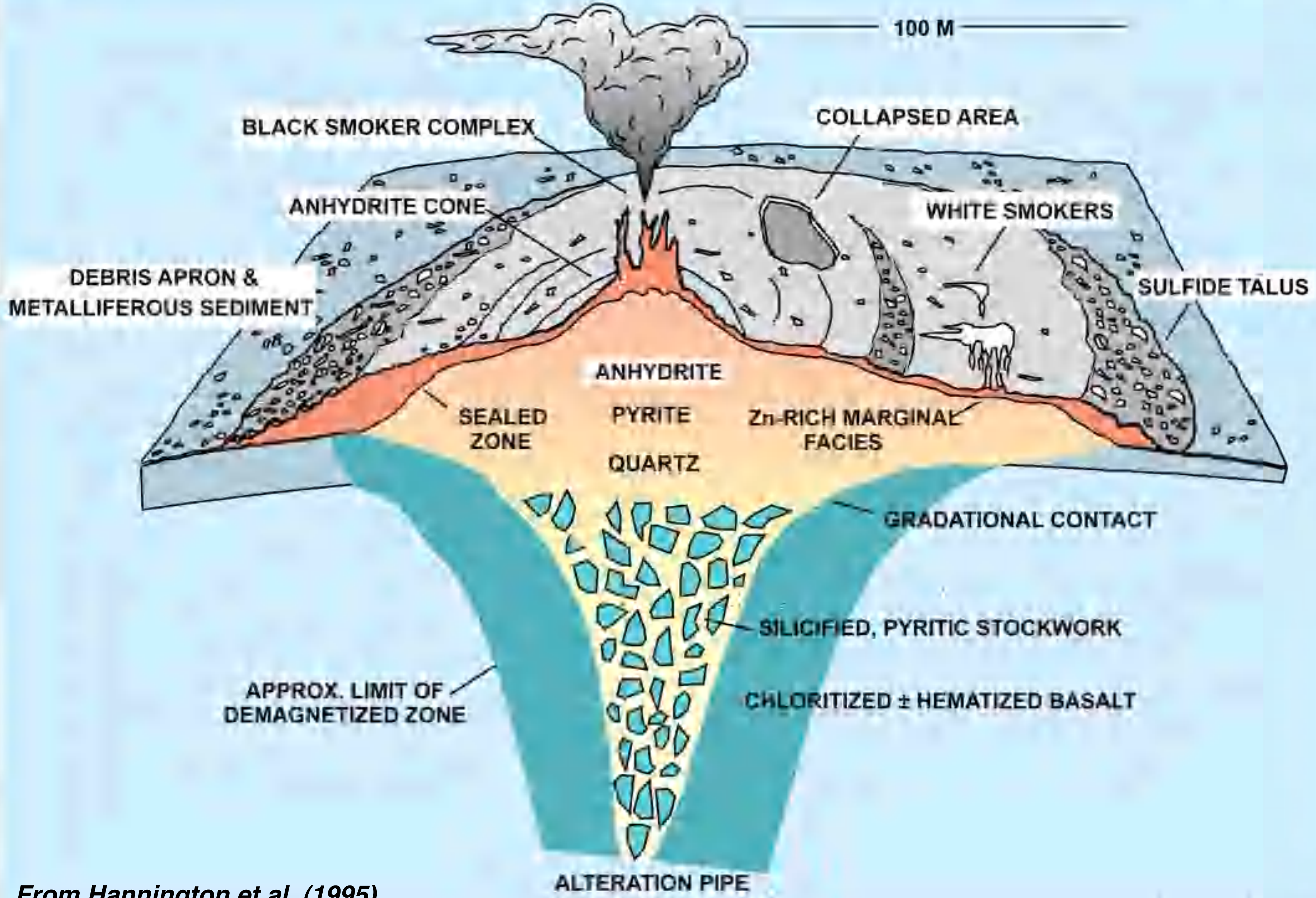


From Galley et al. (2007)

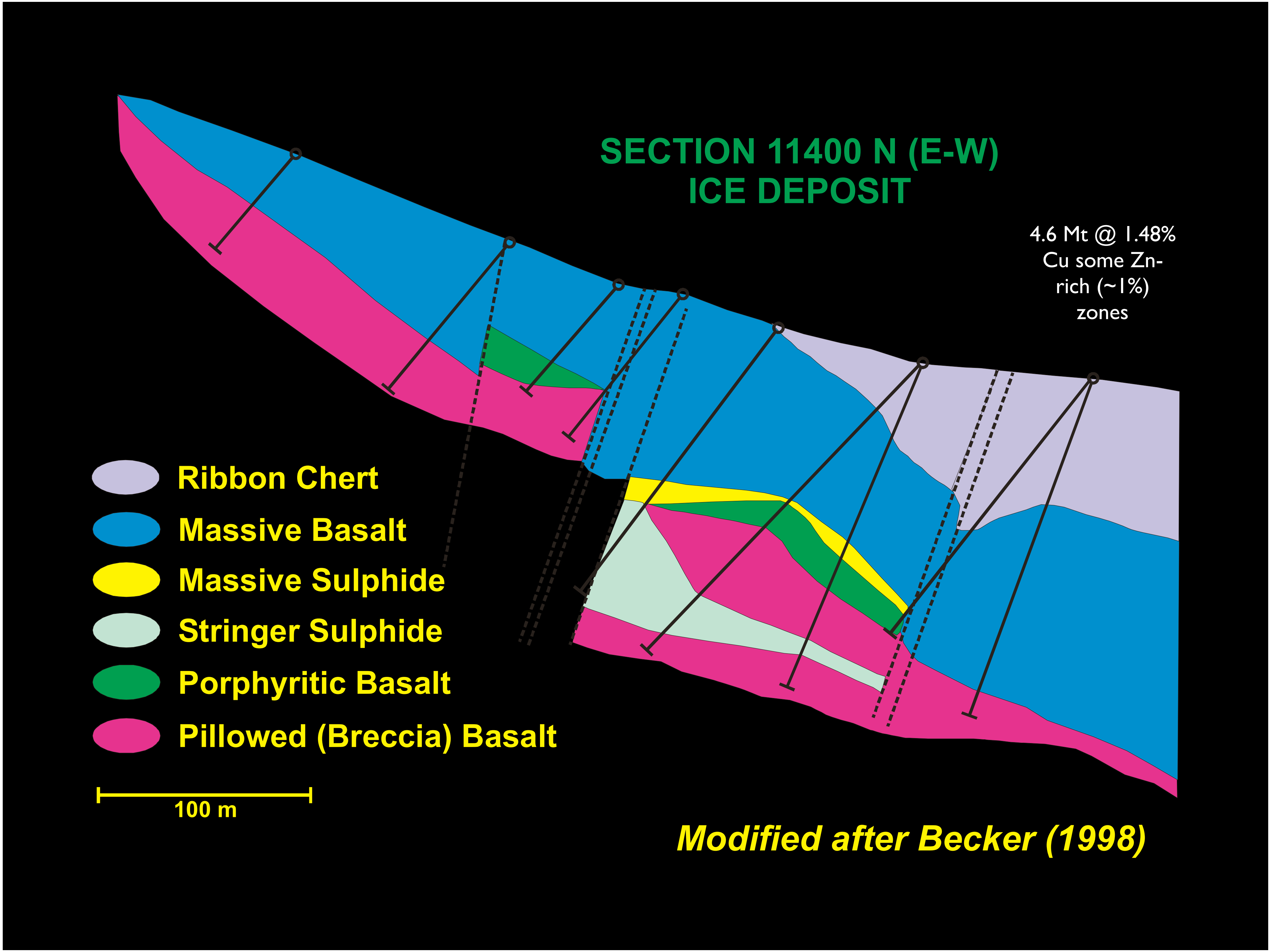
Mafic (Mafic-Backarc)

- Ophiolite-hosted.
- Forearc or back-arc.
- Basalts and sheeted dyke hosted.
- Cu-(Zn-Au) rich.
- Global Examples:
  - Cyprus
  - Oman
  - NL Ophiolites

Cordilleran Examples:
  - Chu Chua
  - Ice



From Hannington et al. (1995)


SECTION 11400 N (E-W)
ICE DEPOSIT
4.6 Mt @ 1.48% Cu some Zn-rich (~1%) zones
Ribbon Chert
Massive Basalt
Massive Sulphide
Stringer Sulphide
Porphyritic Basalt
Pillowed (Breccia) Basalt
100 m
Modified after Becker (1998)

Ice Deposit

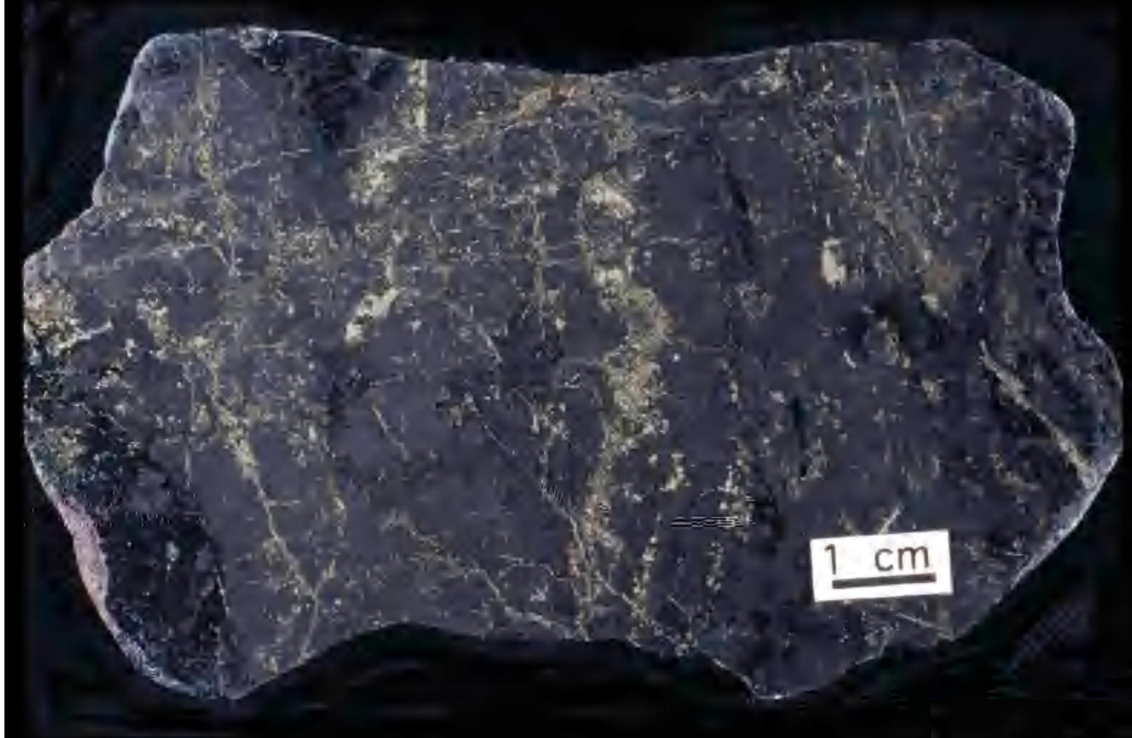
FW to sulfides– plag-phyrric basalt

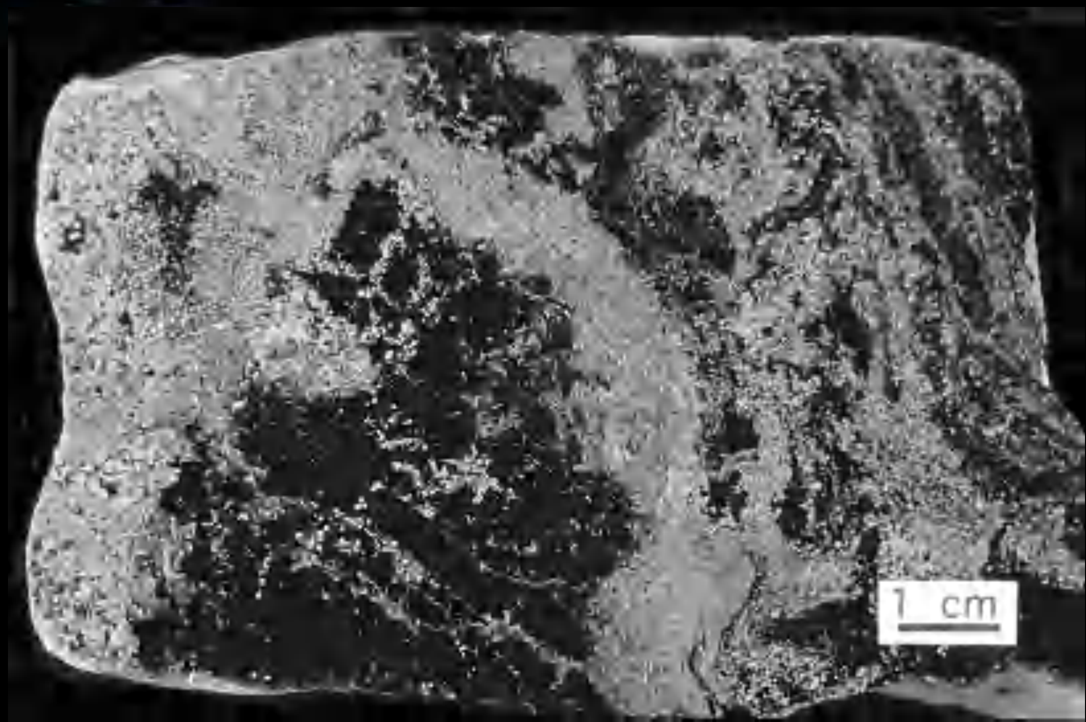
Epi-Hem altered interpillow hyaloclastite

Py-sulfides cut by Bo+Cpy

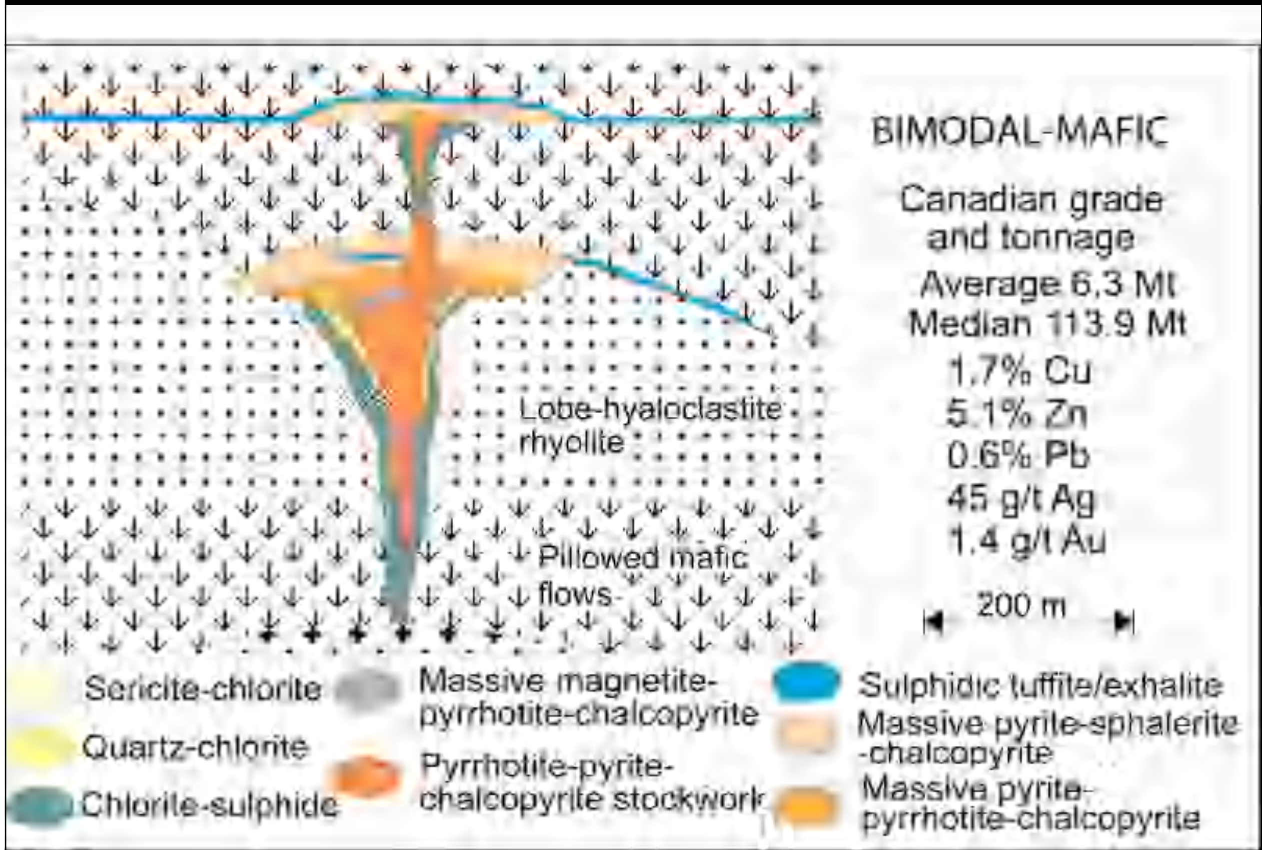
Chl-Py altered basalt breccias

Tilt Cove VMS Deposit, NL





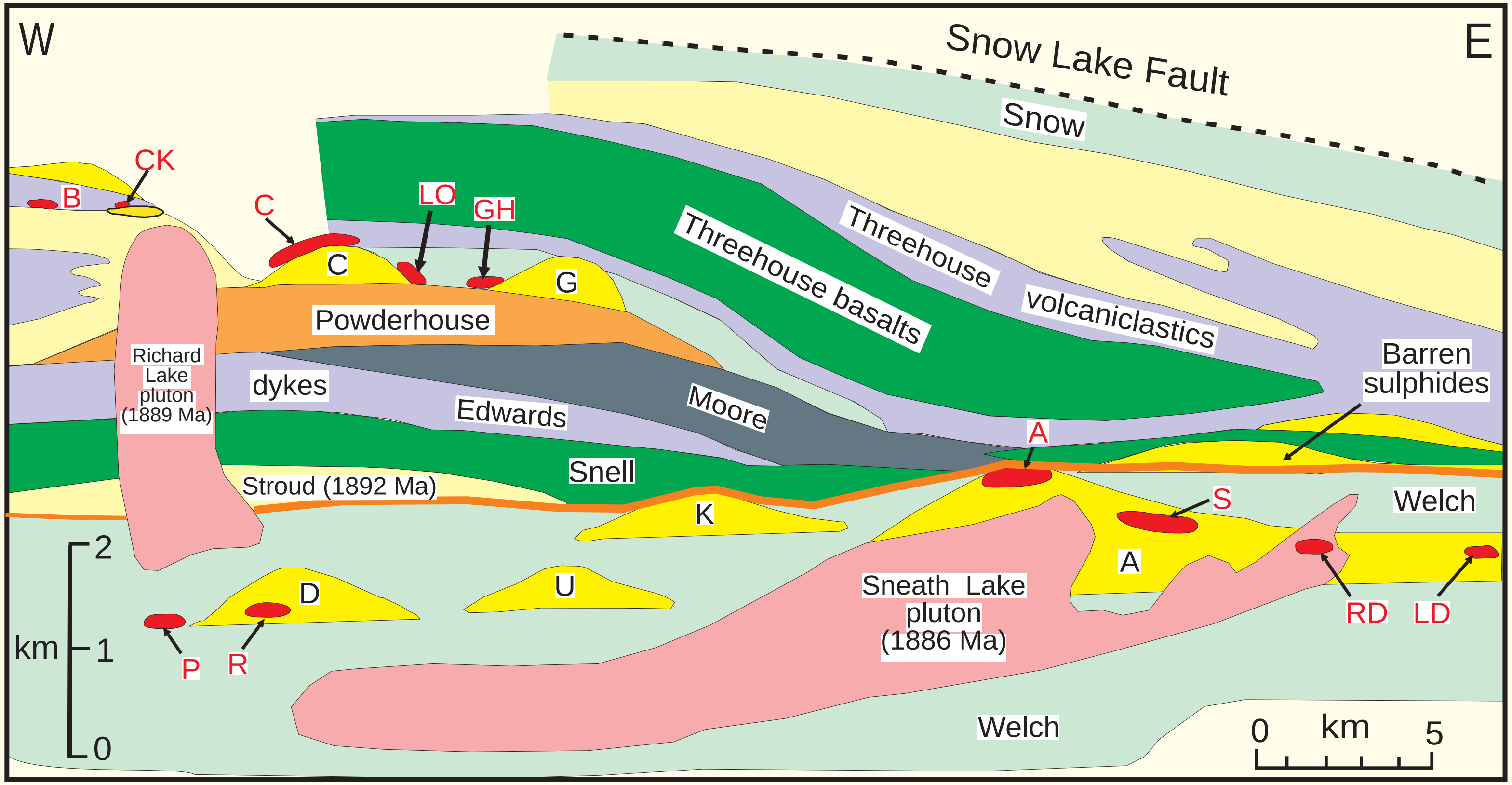
From Sangster et al. (2007).



From Galley et al. (2007)

Bimodal Mafic

- Mafic-dominated settings.
- Deposits often hosted by felsic rocks.
- Cu-Zn-(Au)-rich.
- Global Examples:
  - Noranda
  - Flin Flon
  - Rambler-Ming
- Cordilleran Examples:
  - Hidden Creek
  - Brittania



- Synvolcanic tonalite
- Felsic breccias/volcaniclastics
- Rhyolite:
  - **A** Anderson
  - **C** Chisel
  - **D** Daly
  - **G** Ghost
  - **K** Konzie
  - **U** Unnamed
- Dacite
- Mafic volcaniclastics
- Fe-basalt
- Porphyritic basalt
- Aphyric basalt
- Sulphidic layer
- Sulphide deposits:

A Anderson Lake Cu-Zn
C Chisel Lake Zn-Cu
GH Ghost Lake Zn-Cu
LD Linda Zn-Cu
LO Lost Lake Zn-Cu
P Pot Lake Zn-Cu
R Raindrop Cu-Zn
RD Rod Cu-Zn
S Stall Lake Cu-Zn
CK North Cook
B Bomber

From Bailes and Galley (1999)

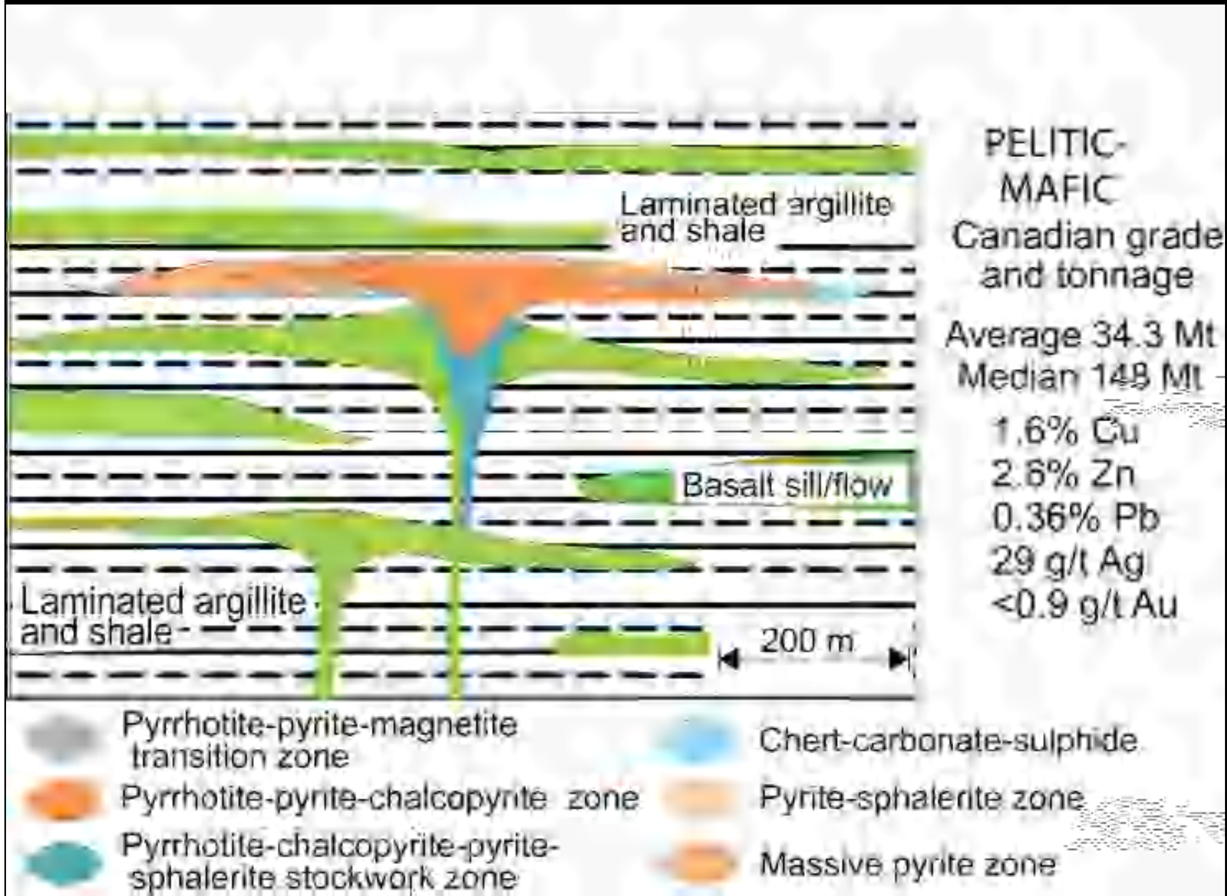
Welch Lake fm - boninites/LOTI, Snow Lake

Welch Lake fm - boninites/LOTI with qtz alt’n

Rhyolite flow lobes, Snow Lake

Sph-rich ore, Chisel North, Snow Lake

Sph-rich ore, Chisel North, Snow Lake

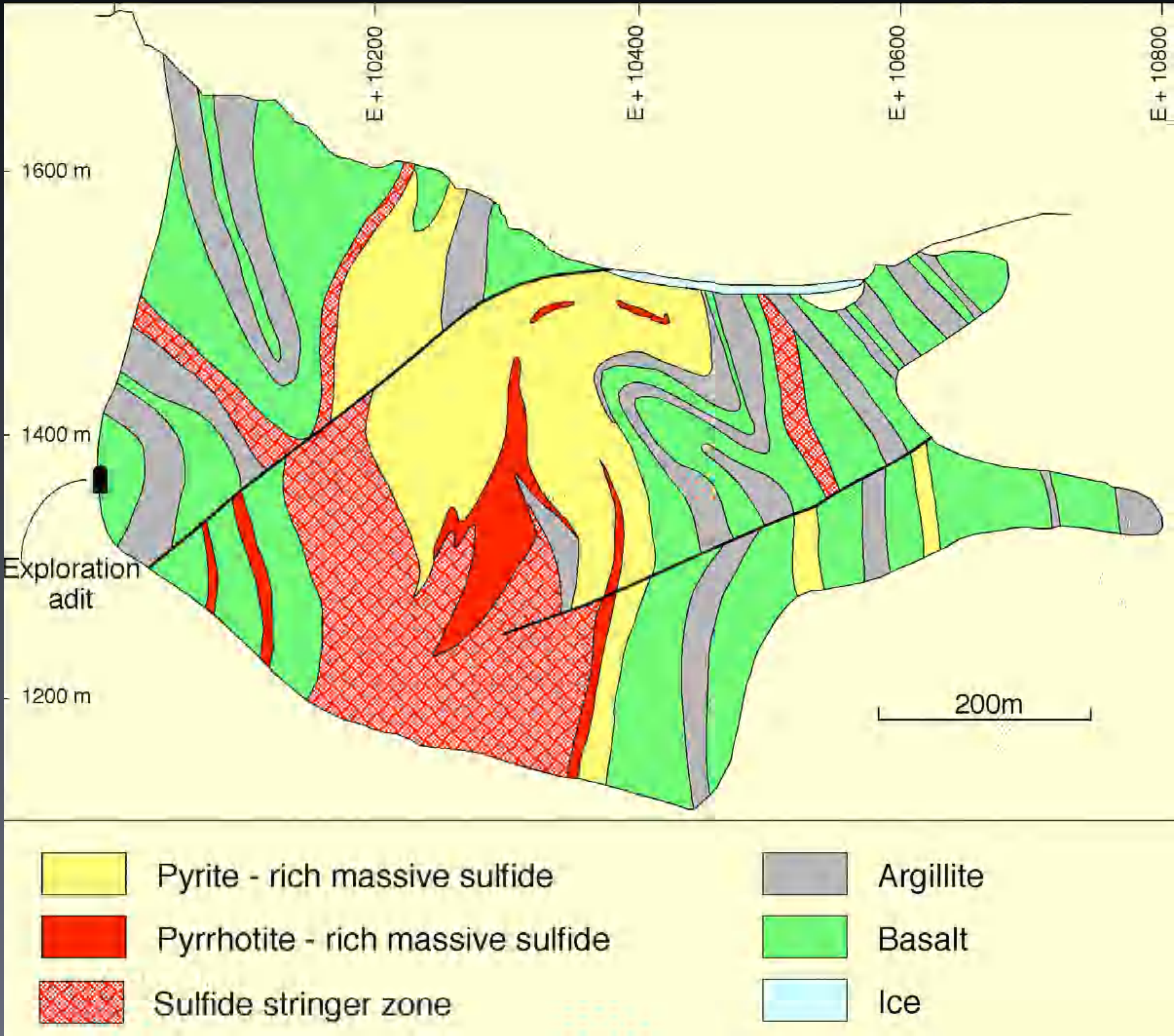


From Galley et al. (2007)

Mafic Siliciclastic

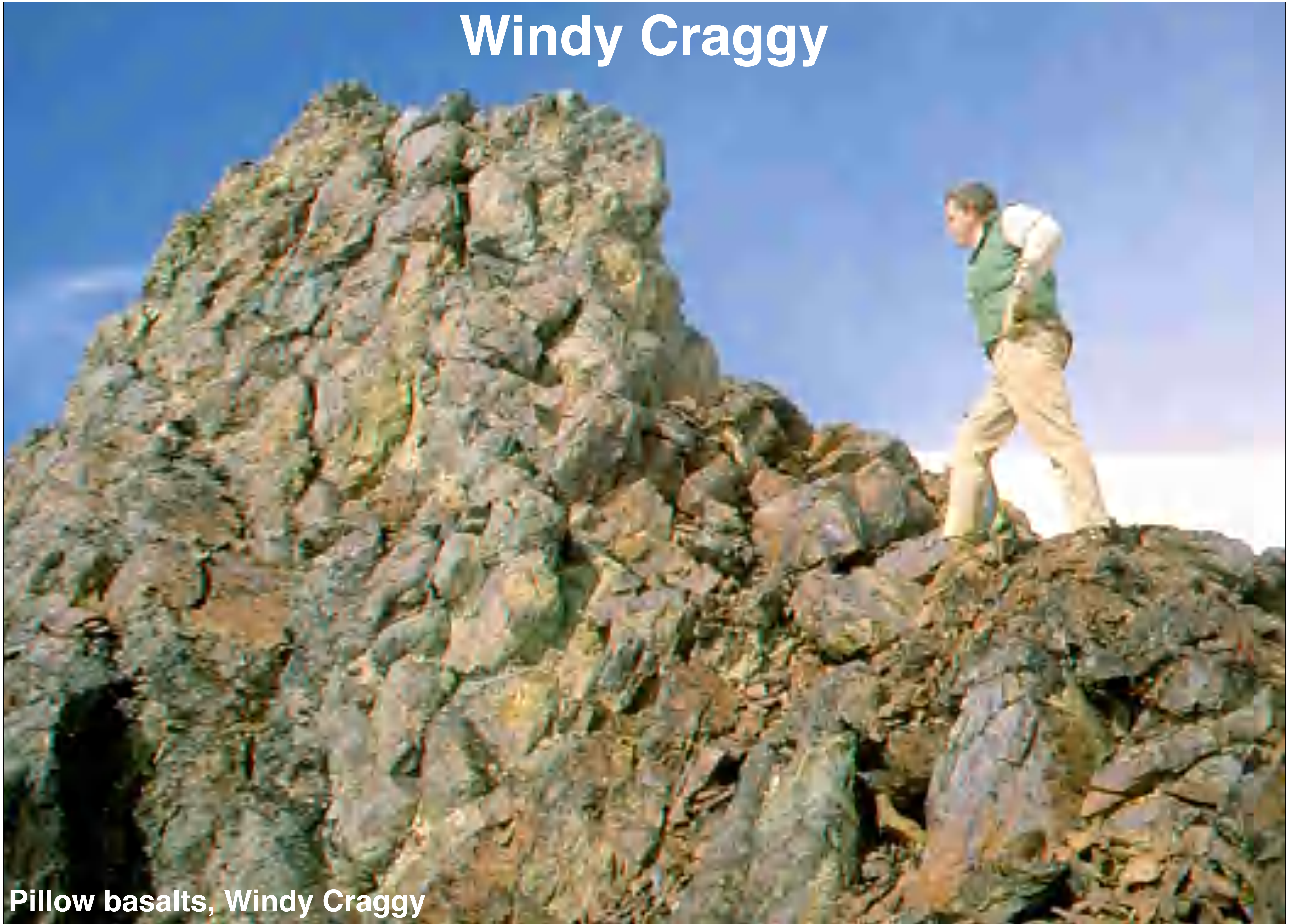
- Mafic rocks and sediments.
- Mafic/ultramafic intrusions.
- Cu-(Zn,Co,Au)-rich
- **Global Examples:**
  - Besshi, Windy Craggy
- **Cordilleran Examples:**
  - Windy Craggy
  - Greens Creek?
  - Goldstream
  - Fyre Lake

Windy Craggy



From Peter and Scott (1999)

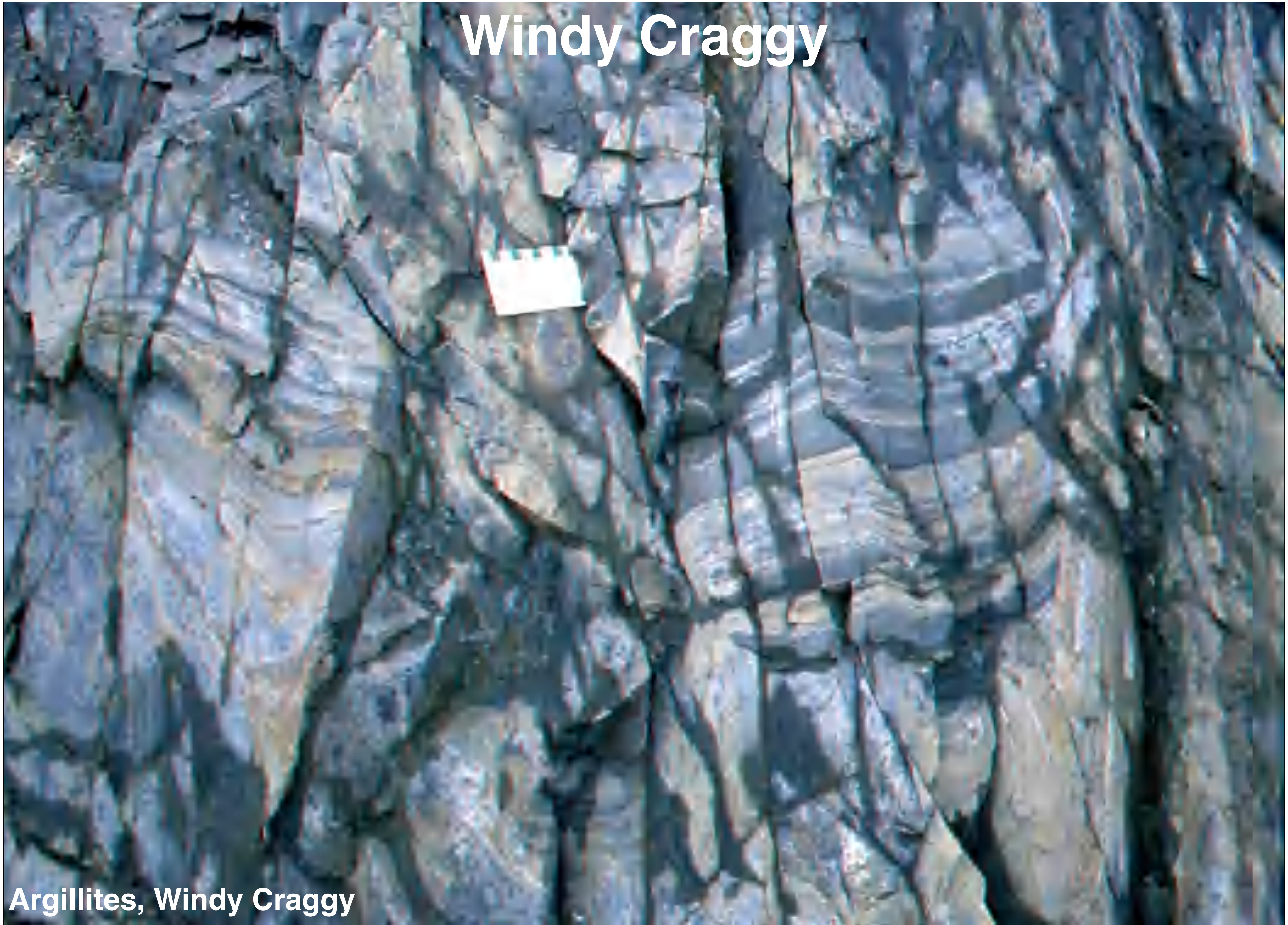
Windy Craggy



Pillow basalts, Windy Craggy

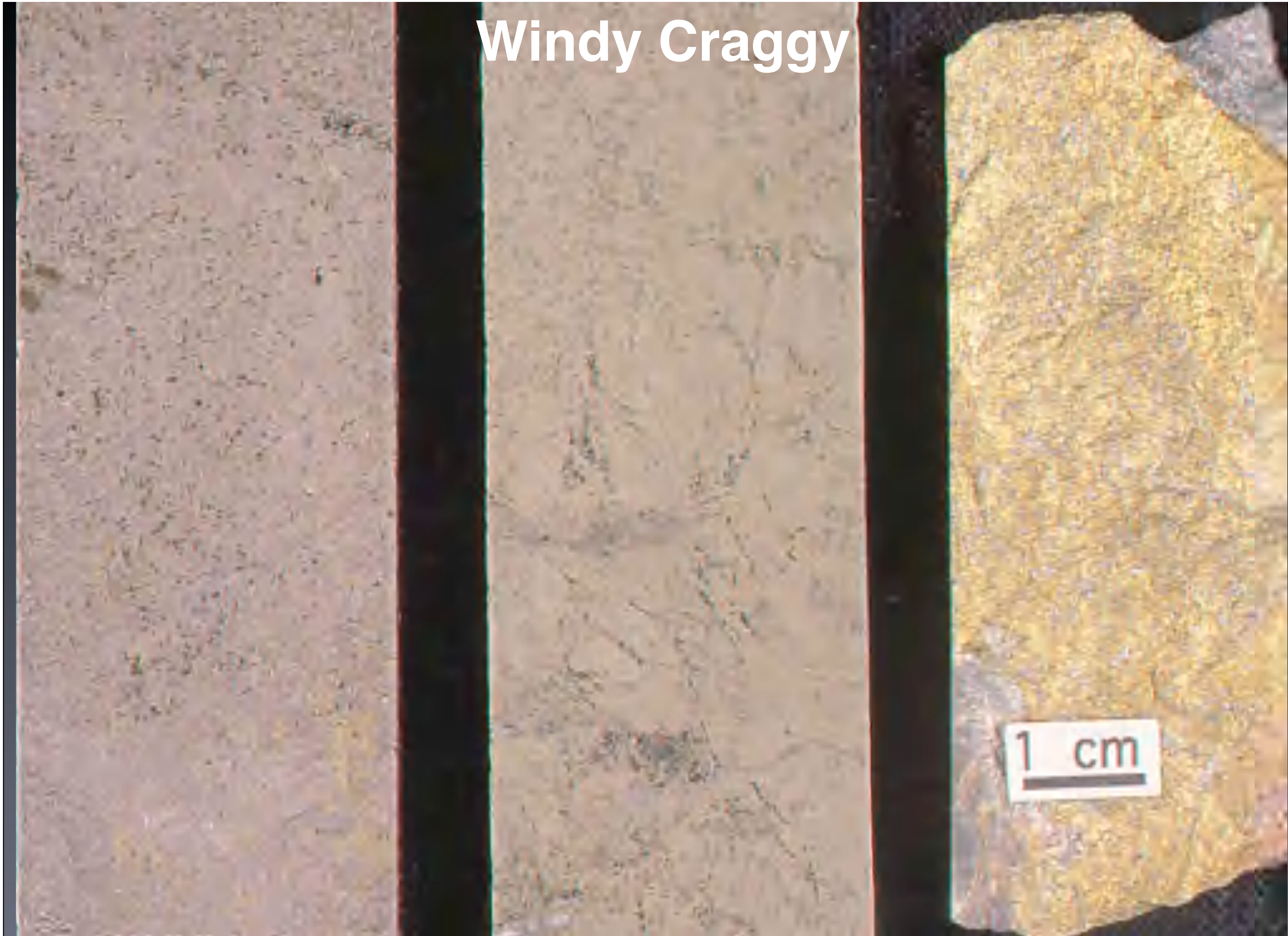
From Peter and Scott (1999)

Windy Craggy



From Peter and Scott (1999)

Windy Craggy

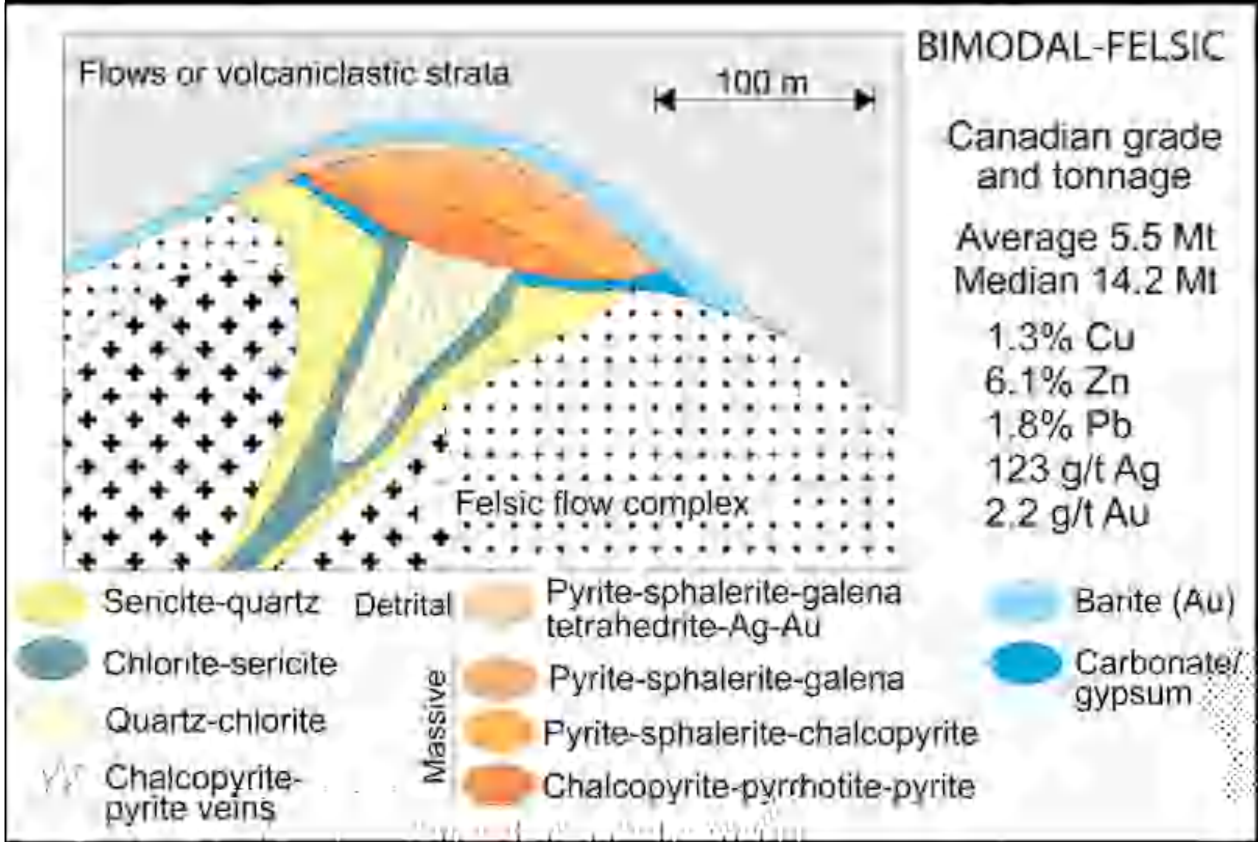


From Peter and Scott (1999)

Windy Craggy

Stringer zone, Windy Craggy

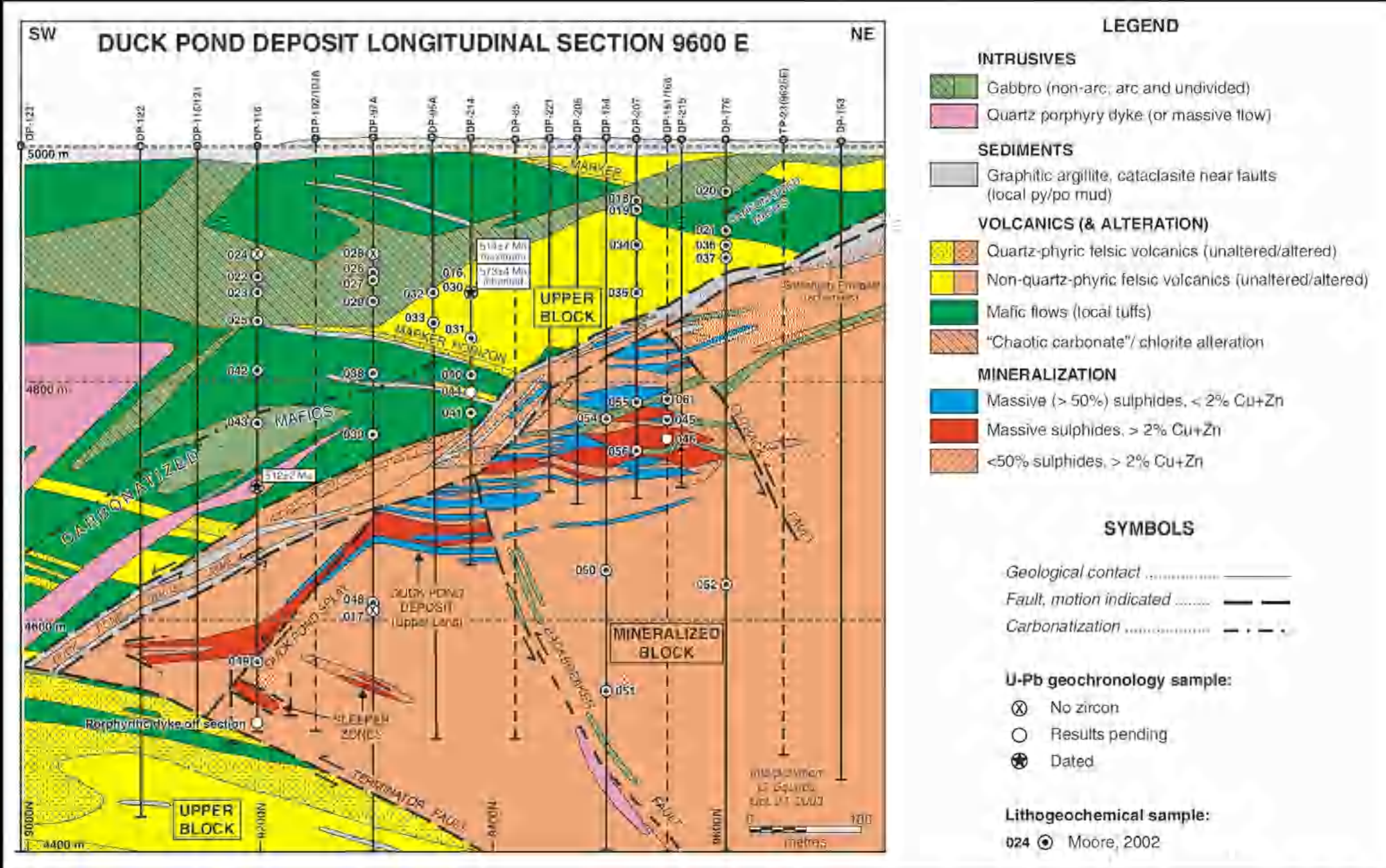
From Peter and Scott (1999)



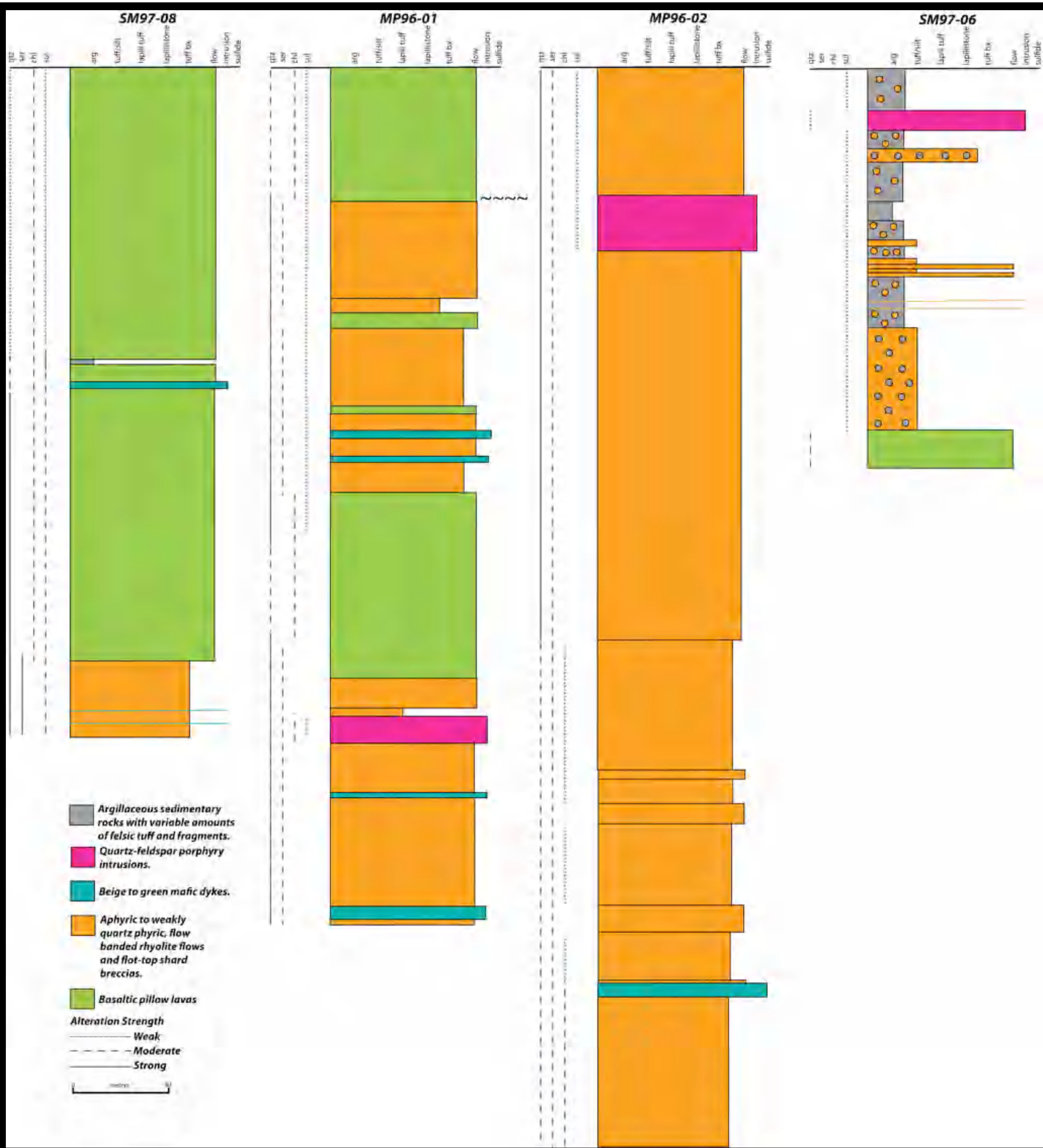
From Galley et al. (2007)

Bimodal Felsic

- Felsic-dominated settings.
- Flow dominated environments.
- Bimodal.
- Zn-Pb-Cu-rich.
- **Global Examples:**
  - Kuroko, Hellyer, Buchans
- **Cordilleran Examples:**
  - Myra Falls Camp
  - Kudz Ze Kayah
  - Tulsequah
  - Kutcho?



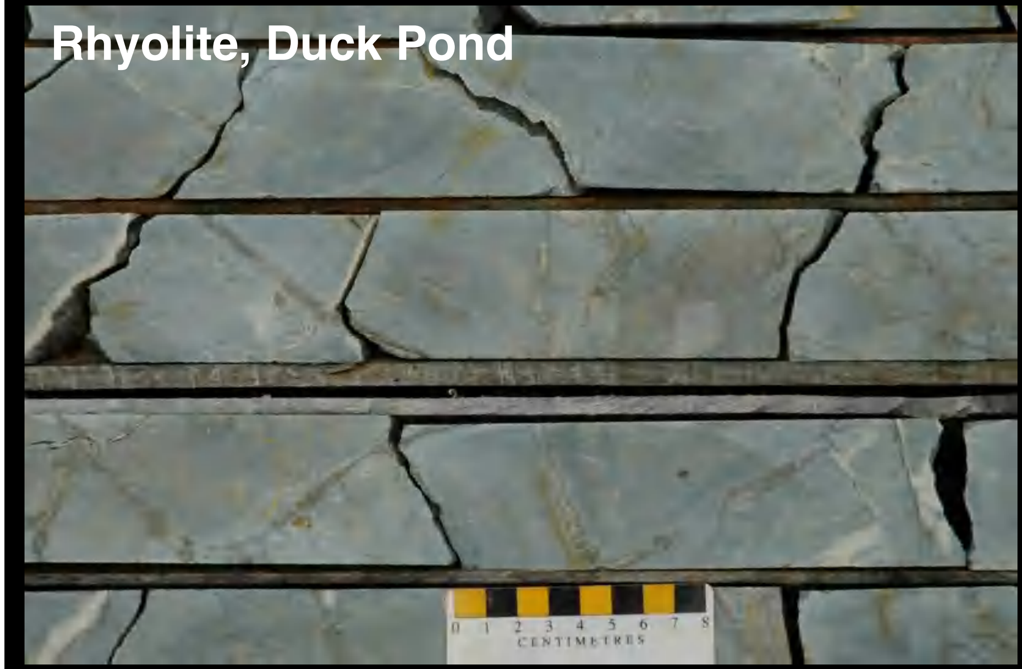
From Squires and Moore (2004)



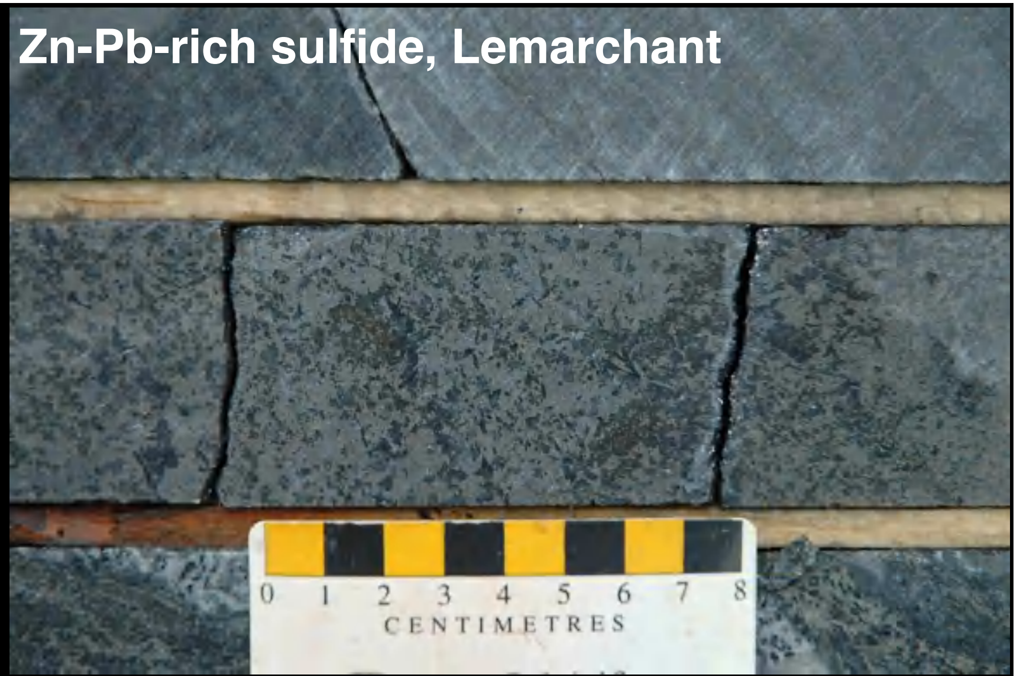
SM97-08
MP96-01
MP96-02
SM97-06
qtz
ser
chl
sul
arg
tuff/silt
lapilli tuff
lapillistone
tuff bx
flow
intrusion
sulfide
Argillaceous sedimentary rocks with variable amounts of felsic tuff and fragments.
Quartz-feldspar porphyry intrusions.
Beige to green mafic dykes.
Aphyric to weakly quartz phyric, flow banded rhyolite flows and flot-top shard breccias.
Basaltic pillow lavas
Alteration Strength
Weak
Moderate
Strong

Flow banded rhyolite, Duck Pond

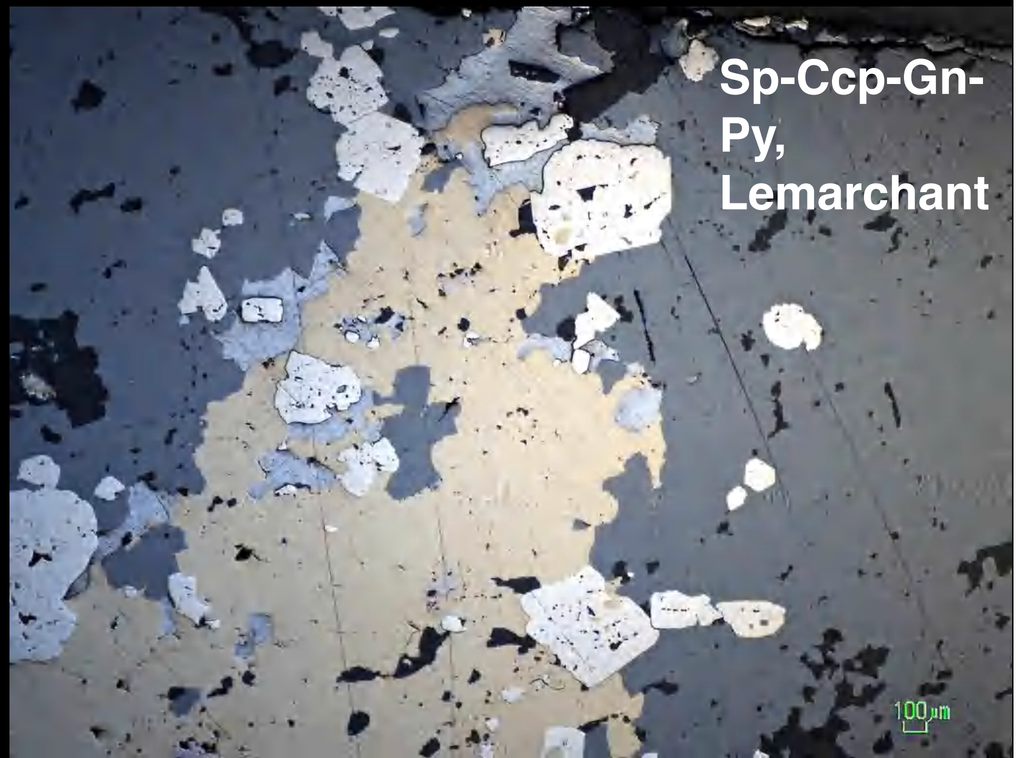
Pillow basalt, Lemarchant

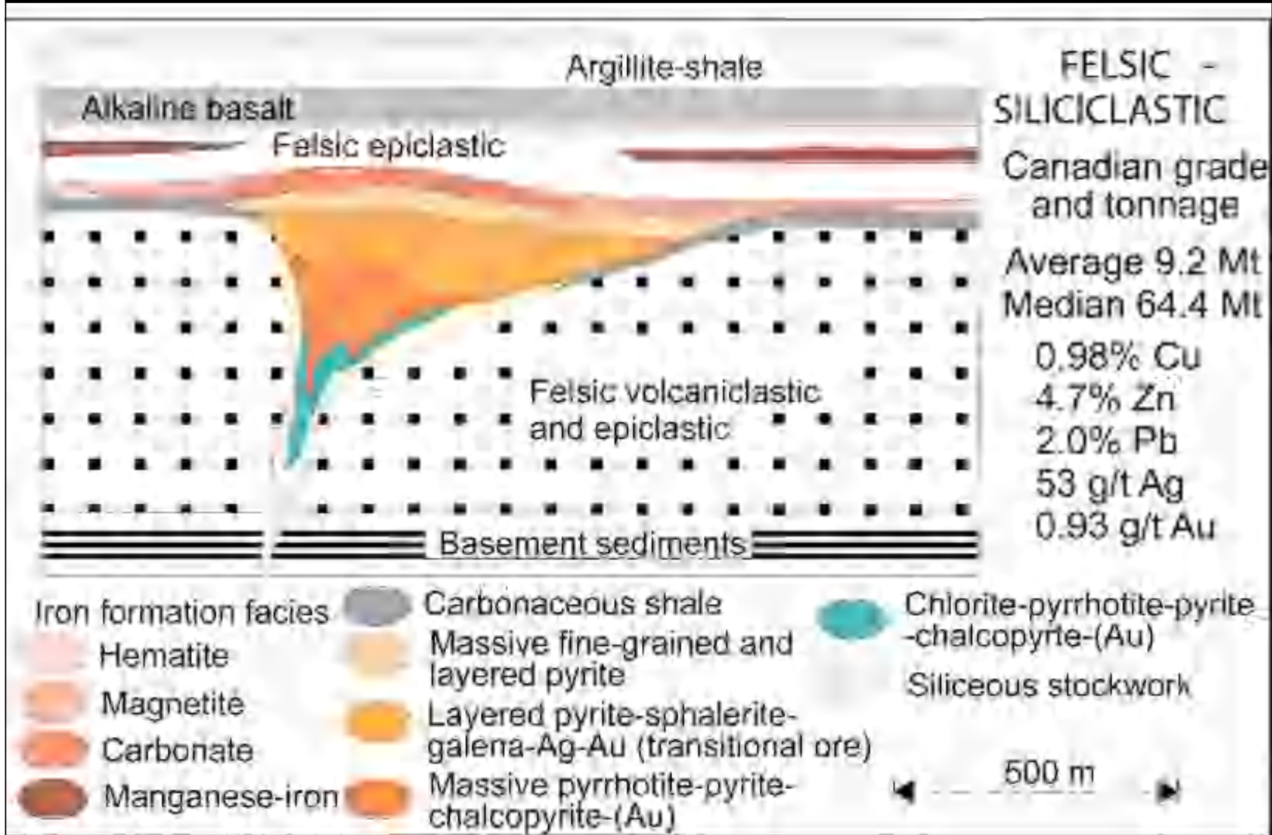

Rhyolite, Duck Pond

Basalt, Duck Pond



Cu-Zn-rich sulfide, Duck Pond



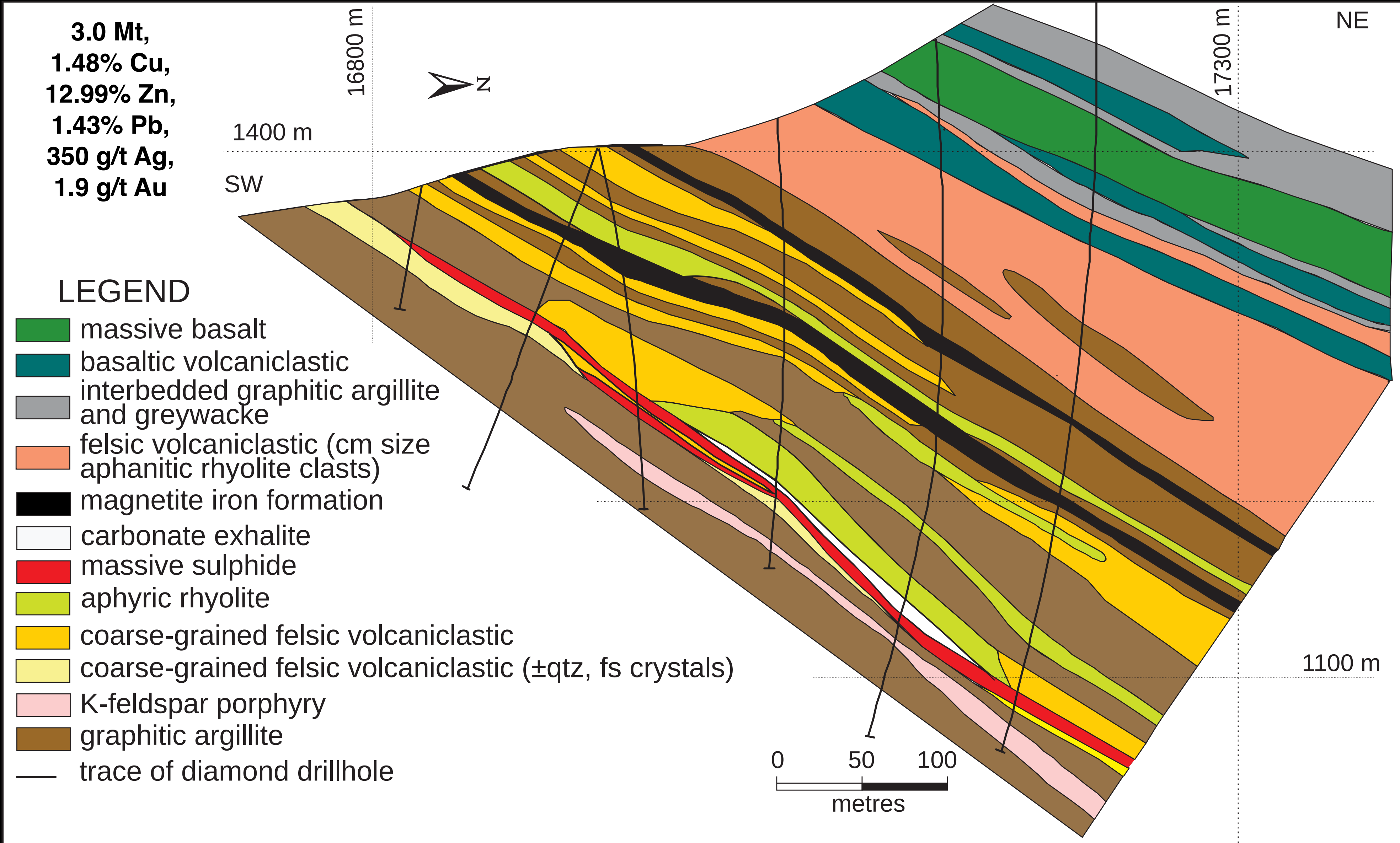


From Galley et al. (2007)

Felsic Siliciclastic

- Sediment-rich.
- Felsic volcaniclastic rocks.
- Abundant felsic and mafic sills.
- Graphitic shales +/- iron formations/ exhalites.
- Tabular deposits.
- Zn-Pb-(Ag,Au)-rich.
- Global Examples:
  - Bathurst, IPB.
- Cordilleran Examples:
  - Wolverine
  - Marg
  - Ambler
  - Delta?

Wolverine Deposit



From Bradshaw et al. (in press) and Peter et al. (2007)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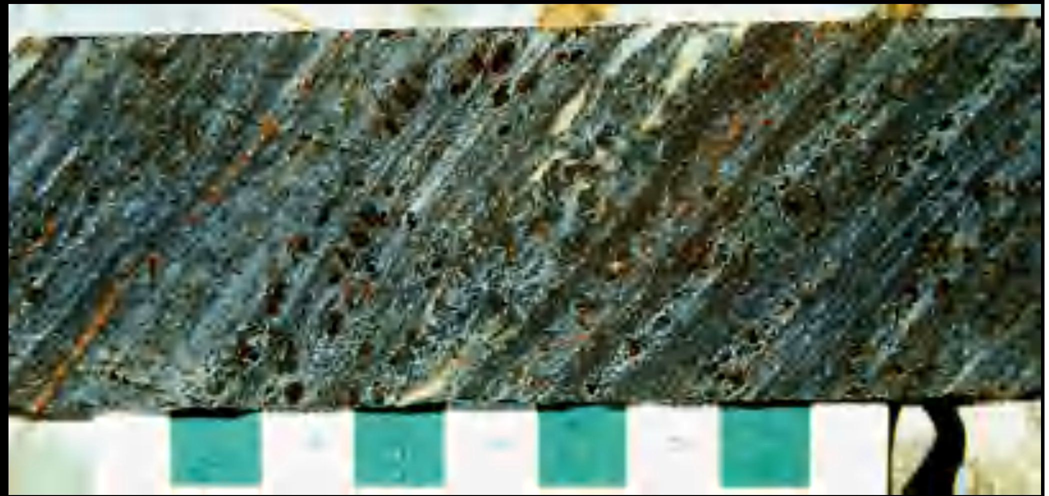
CENTIMETRES

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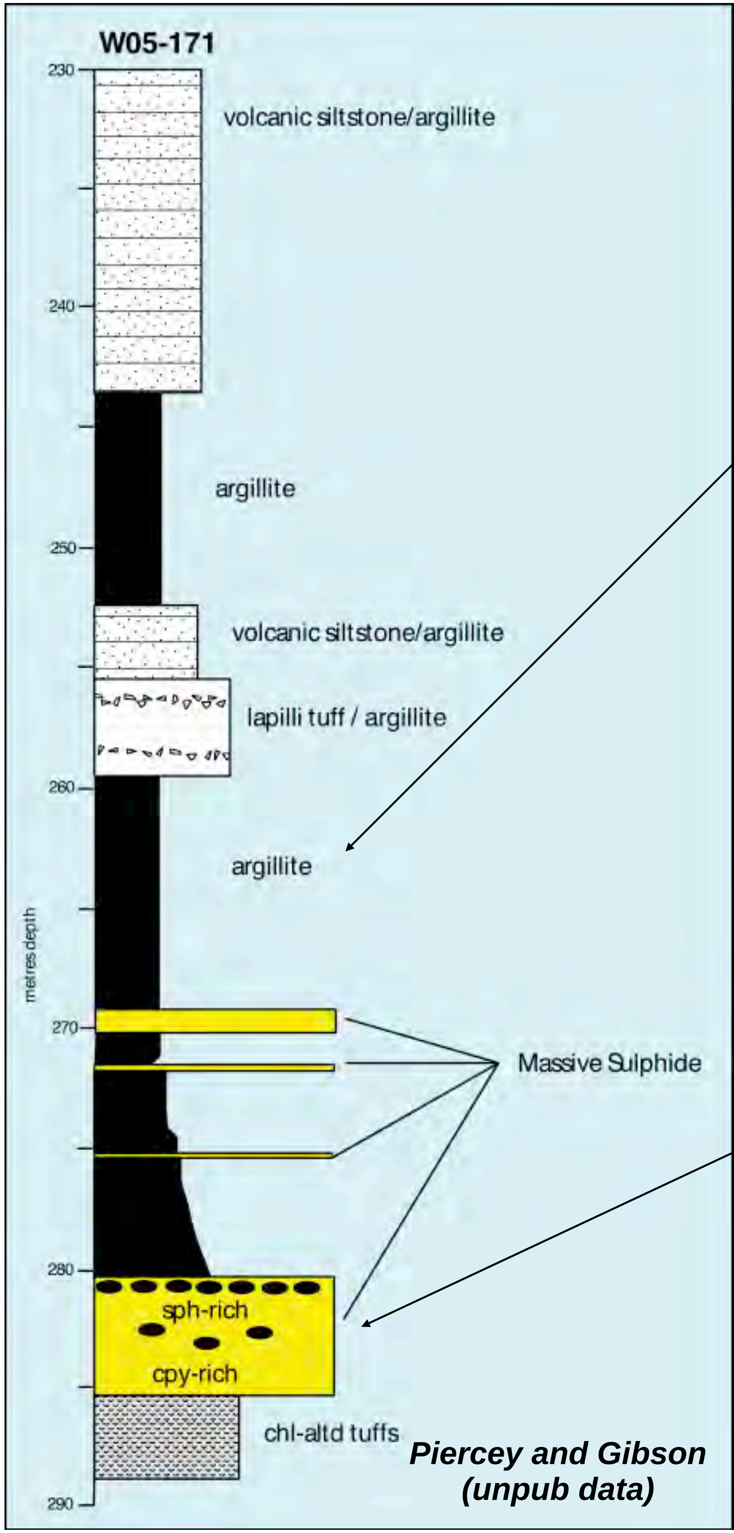
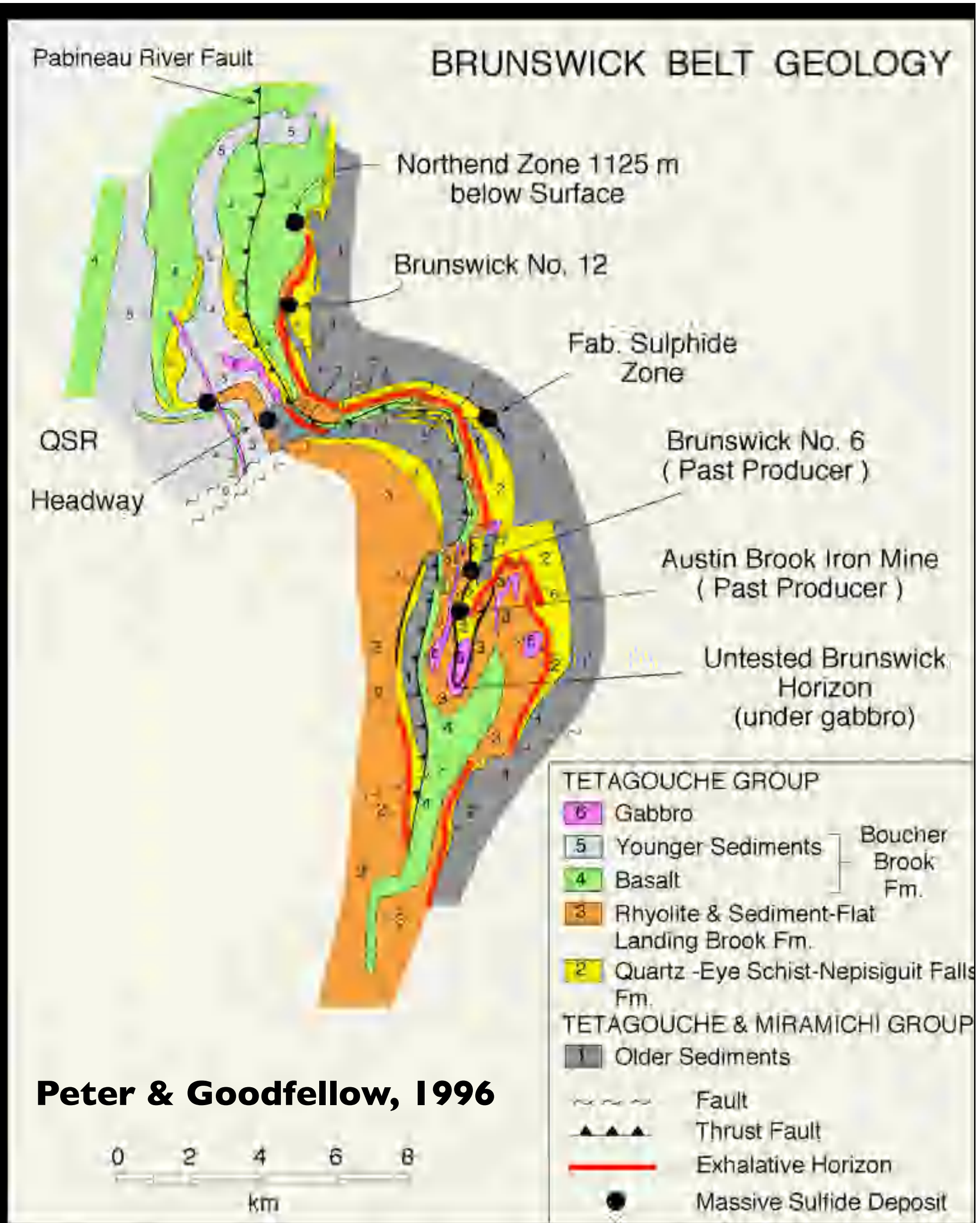
CENTIMETRES
Geological Survey Branch


W05-171
230
240
250
260
270
280
290
metres depth
volcanic siltstone/argillite
argillite
volcanic siltstone/argillite
lapilli tuff / argillite
argillite
Massive Sulphide
sph-rich
cpy-rich
chl-altd tuffs
Piercey and Gibson
(unpub data)

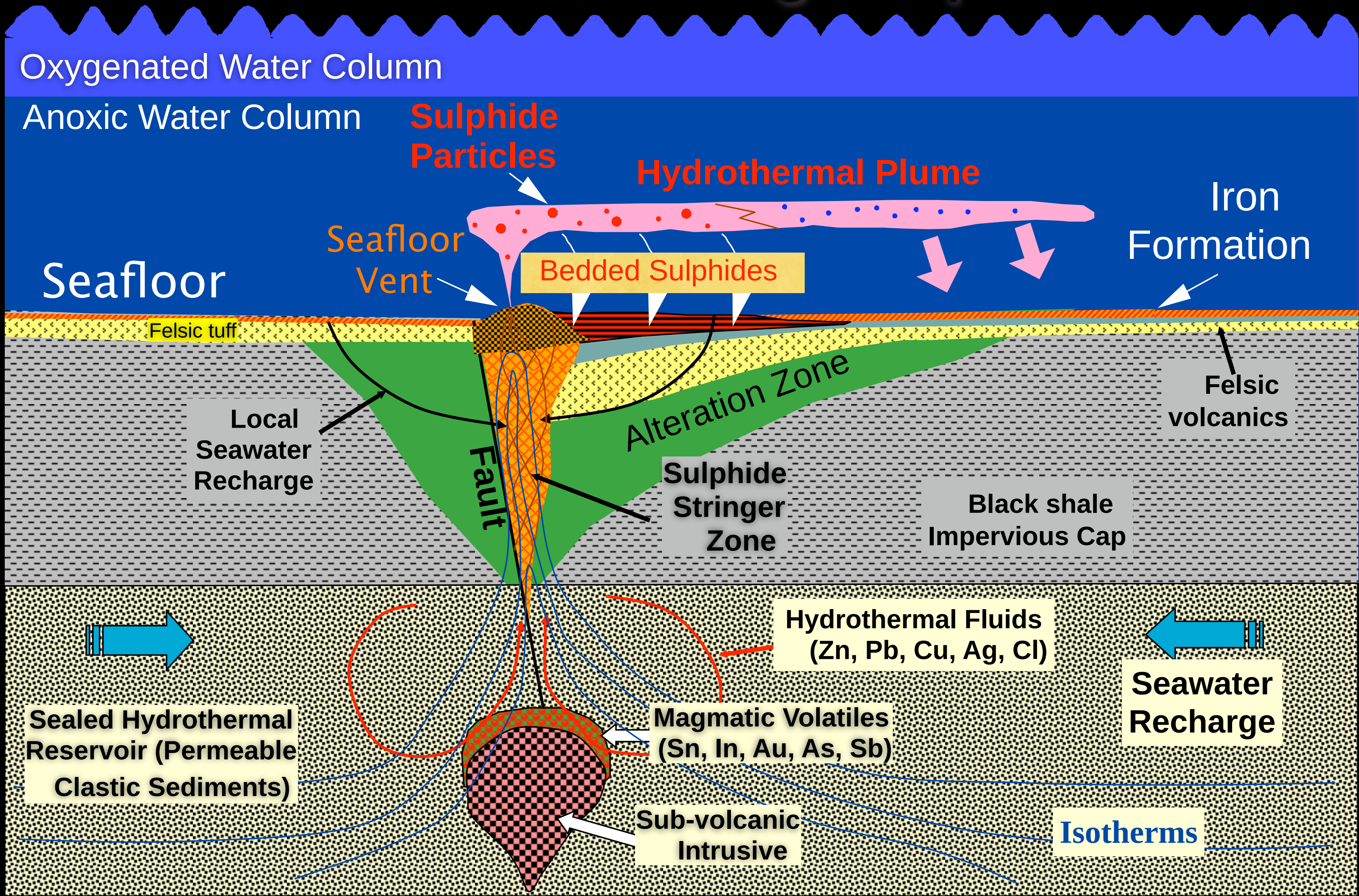

Hanging wall shales, Wolverine deposit, YT


Subseafloor replacement of shales by
Zn-rich massive sulfides, Wolverine deposit, YT


Fe-Formation
Austin Brook,
Brunswick Belt


BRUNSWICK BELT GEOLOGY
Pabineau River Fault
Northend Zone 1125 m below Surface
Brunswick No. 12
Fab. Sulphide Zone
QSR
Headway
Brunswick No. 6 (Past Producer)
Austin Brook Iron Mine (Past Producer)
Untested Brunswick Horizon (under gabbro)
TETAGOUCHE GROUP
6 Gabbro
5 Younger Sediments
4 Basalt
Boucher Brook Fm.
3 Rhyolite & Sediment-Flat Landing Brook Fm.
2 Quartz -Eye Schist-Nepisiguit Falls Fm.
TETAGOUCHE & MIRAMICHI GROUP
1 Older Sediments
Fault
Thrust Fault
Exhalative Horizon
Massive Sulfide Deposit
0 2 4 6 8
km
Peter & Goodfellow, 1996

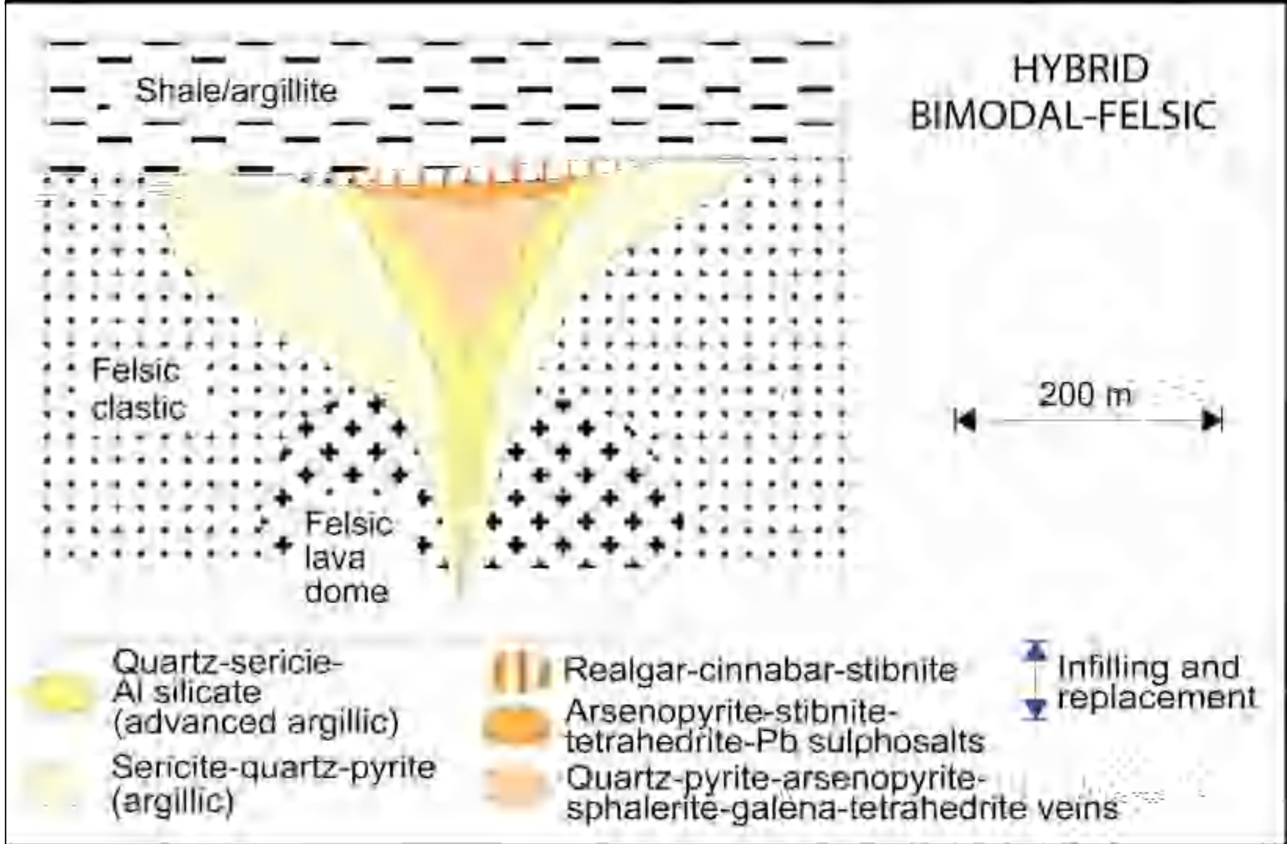
Sulphide Depositional Model
Bathurst Mining Camp



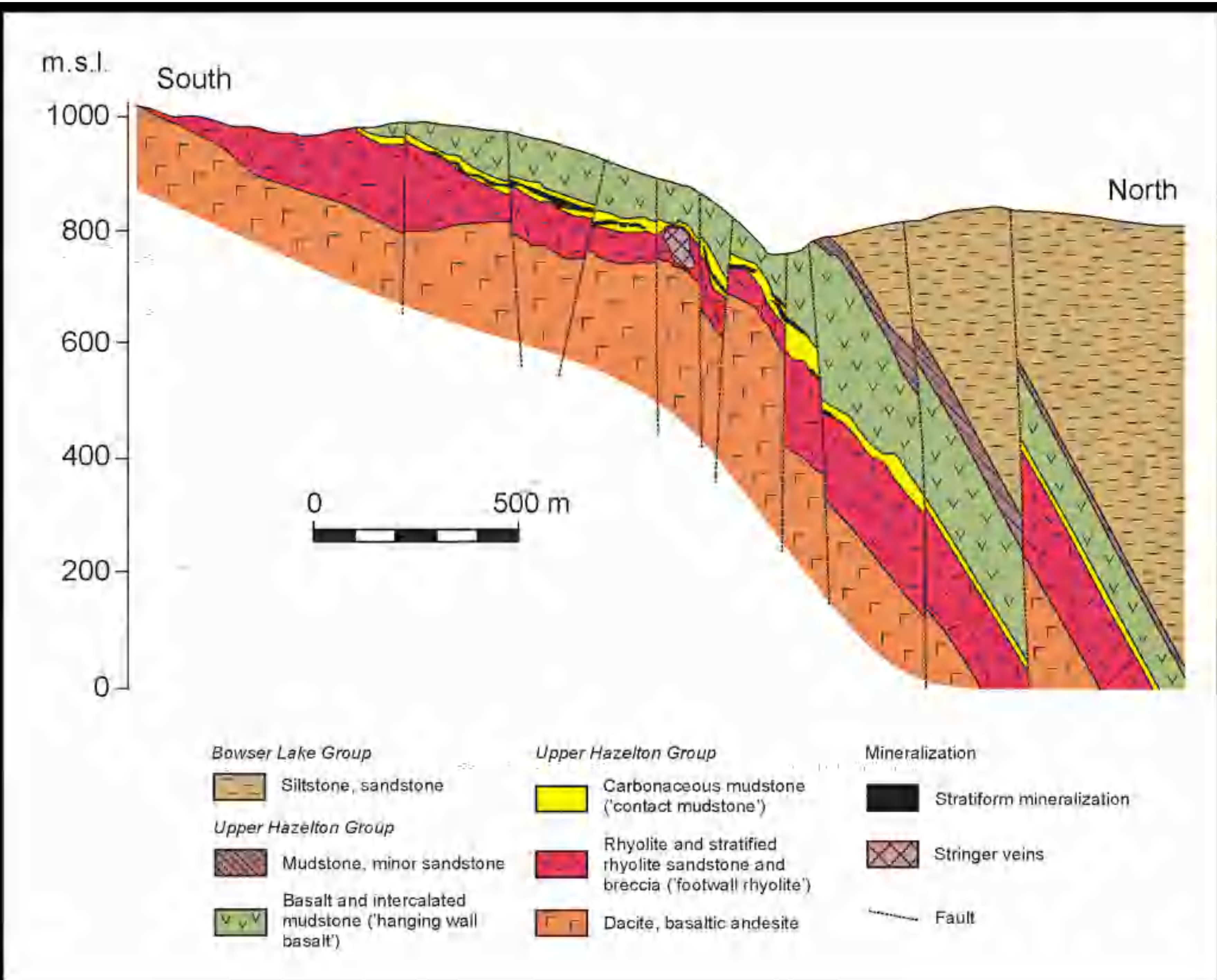
From Goodfellow and McCutcheon (2003).

Hybrid Bimodal Felsic

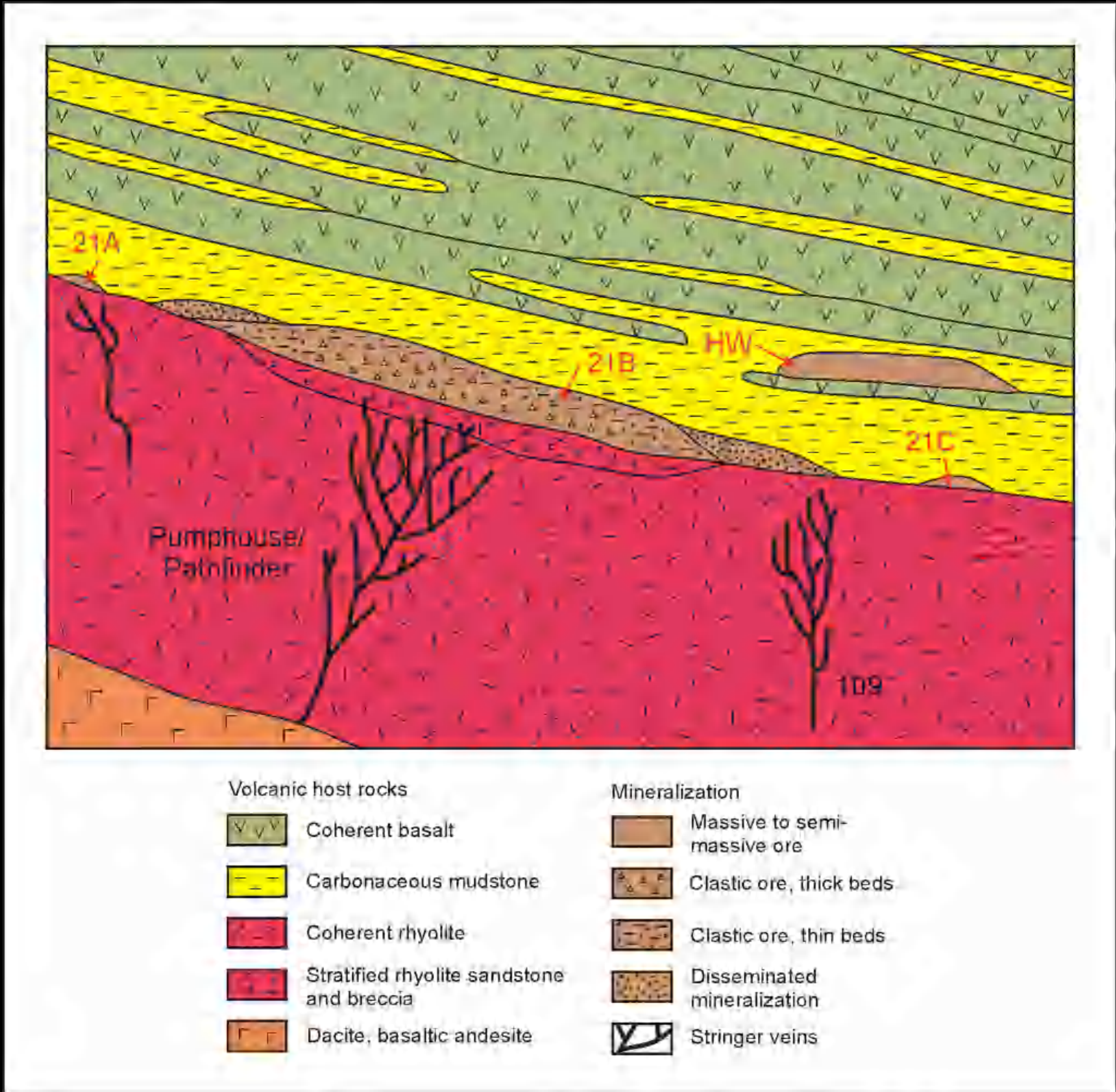
- Felsic and mafic rocks with sediments.
- Characteristics of epithermal and VMS.
- Aluminous alteration (pyrophyllite, etc.).
- Hg-Bi-Sb-As-Au-Ag-S-rich (epithermal).
- Zn-Pb-rich (VMS).
- **Global Examples:**
  - Eskay Creek, LaRonde, Rambler, Mt. Lyell.
- **Cordilleran Examples:**
  - Eskay Creek



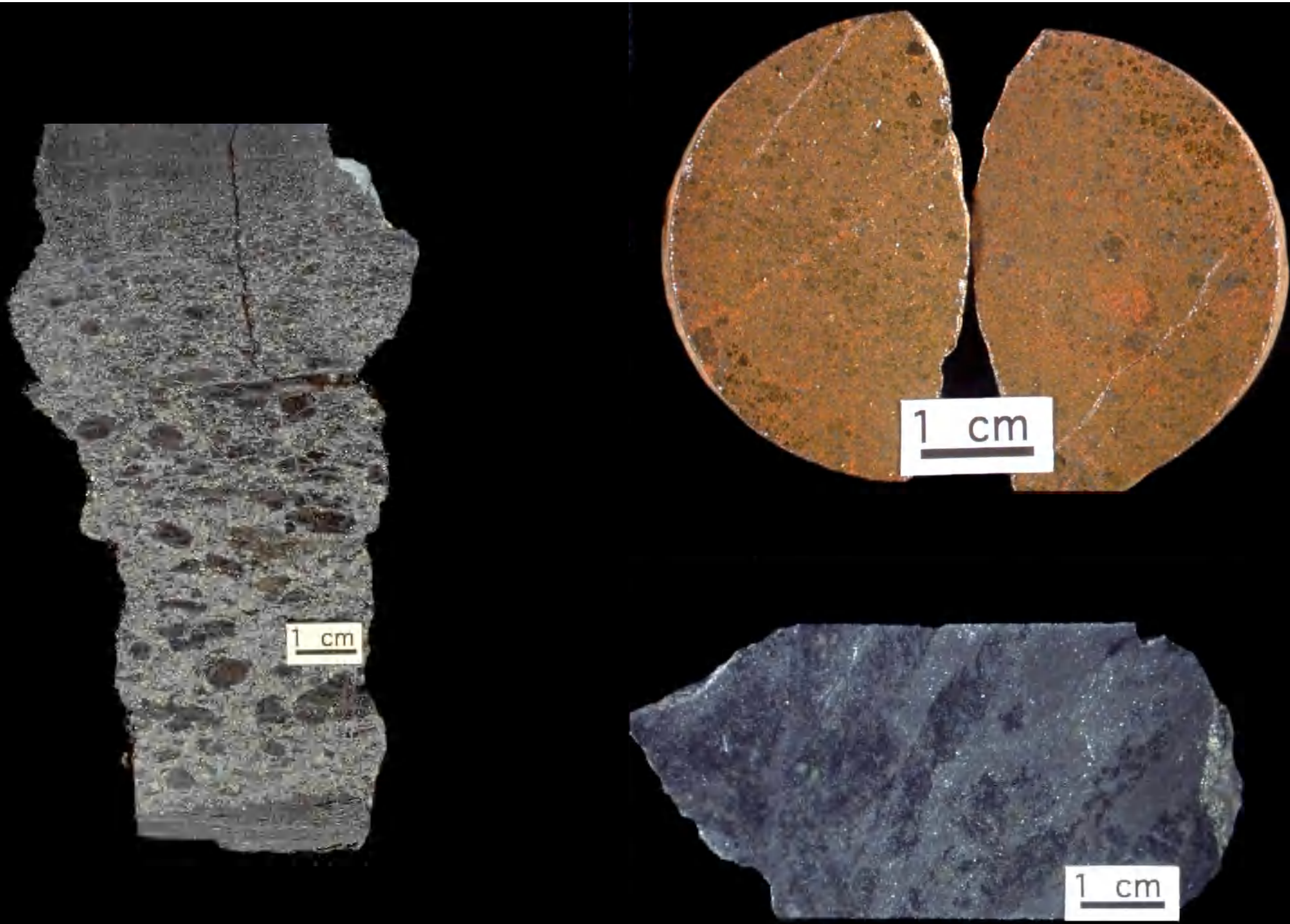
From Galley et al. (2007)



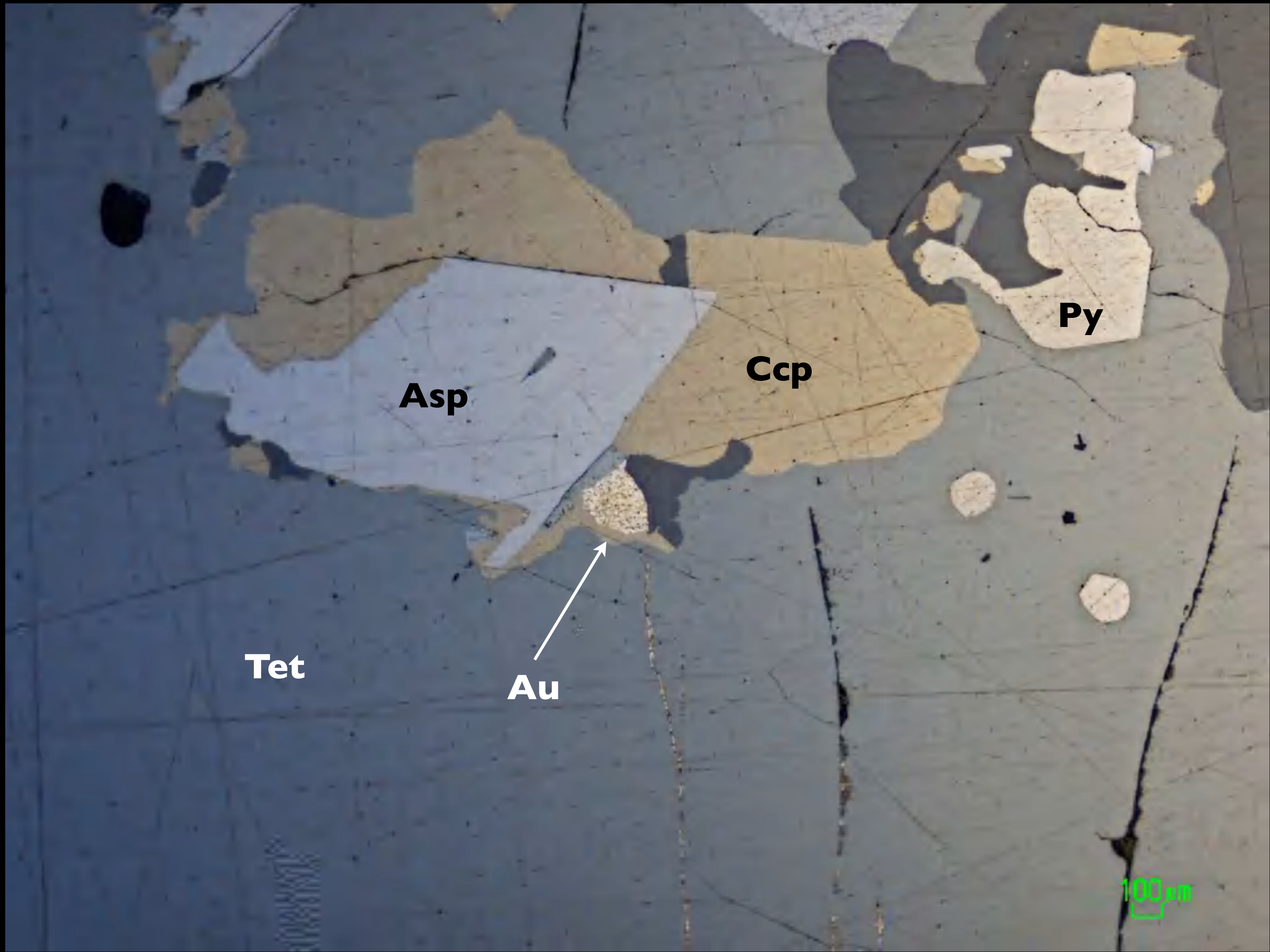
From Roth et al. (1999) and Monecke and Jonasson (2007)



From Roth et al. (1999) and Monecke and Jonasson (2007)

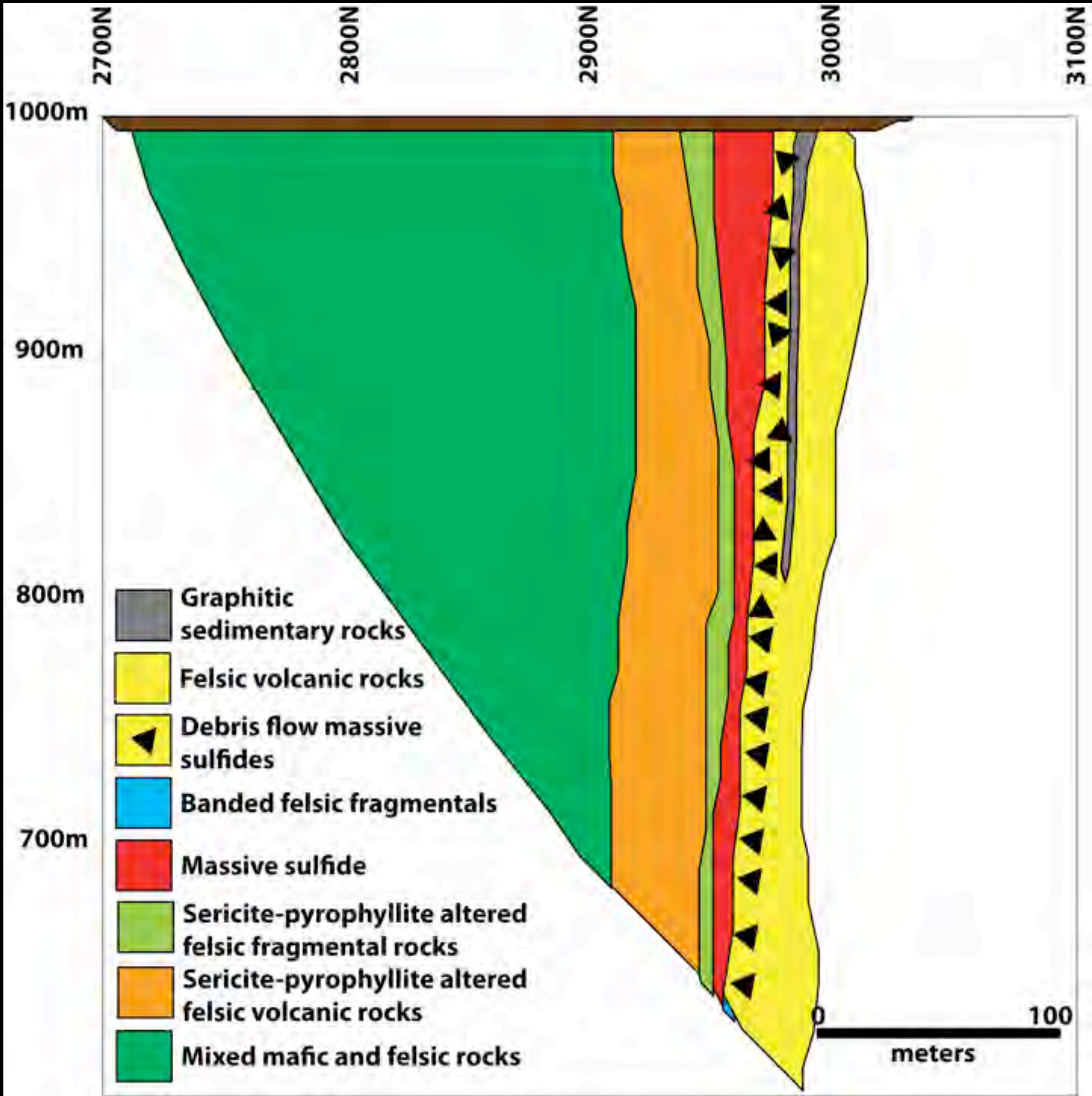


From Monecke and Jonasson (2007)

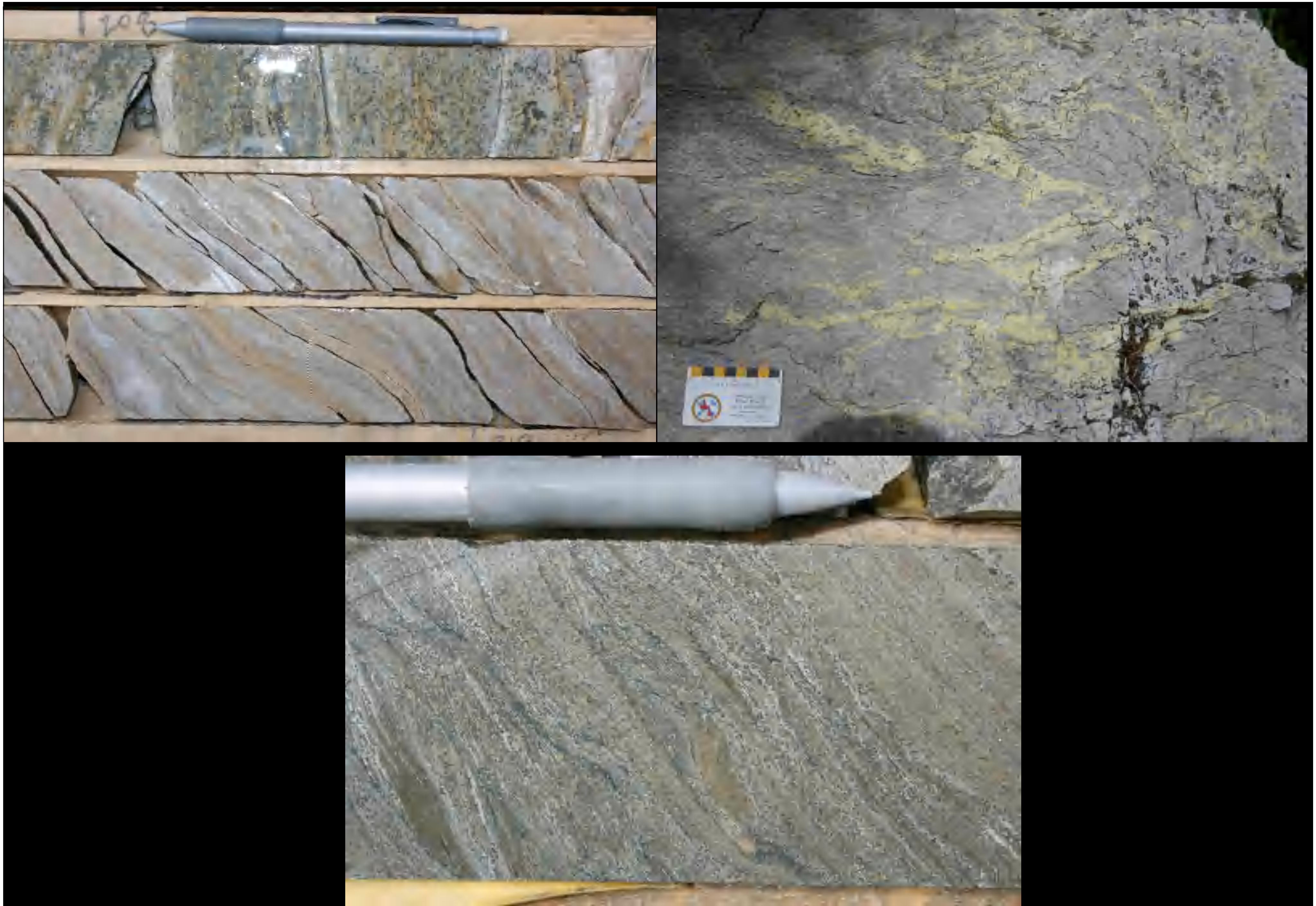

Py
Ccp
Asp
Tet
Au
100µm


Py
Sp
Ccp
Stan
Asp
100µm

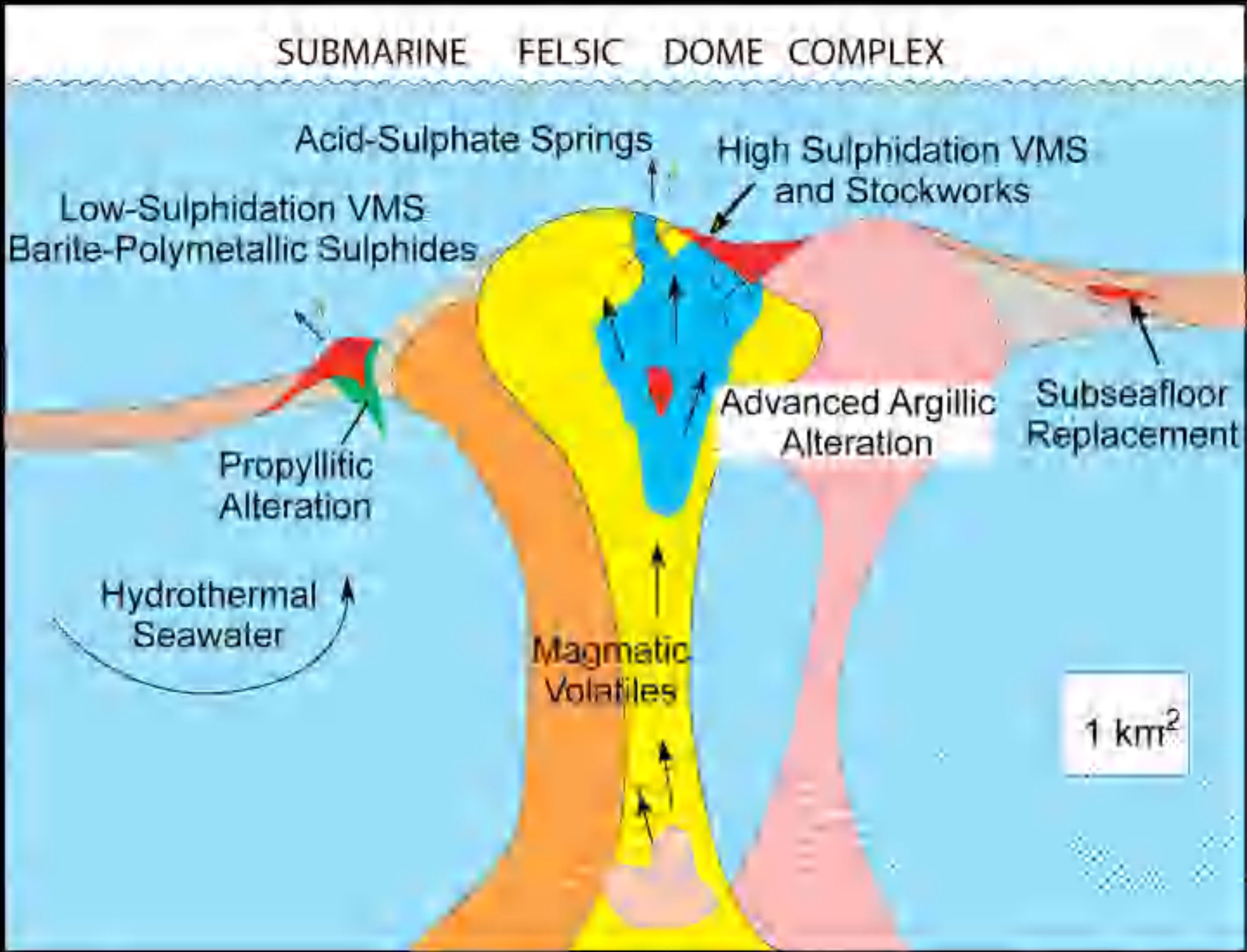
Daniel's Pond



Modified from Noranda (1998)



Photos from John Hinchey (2007)

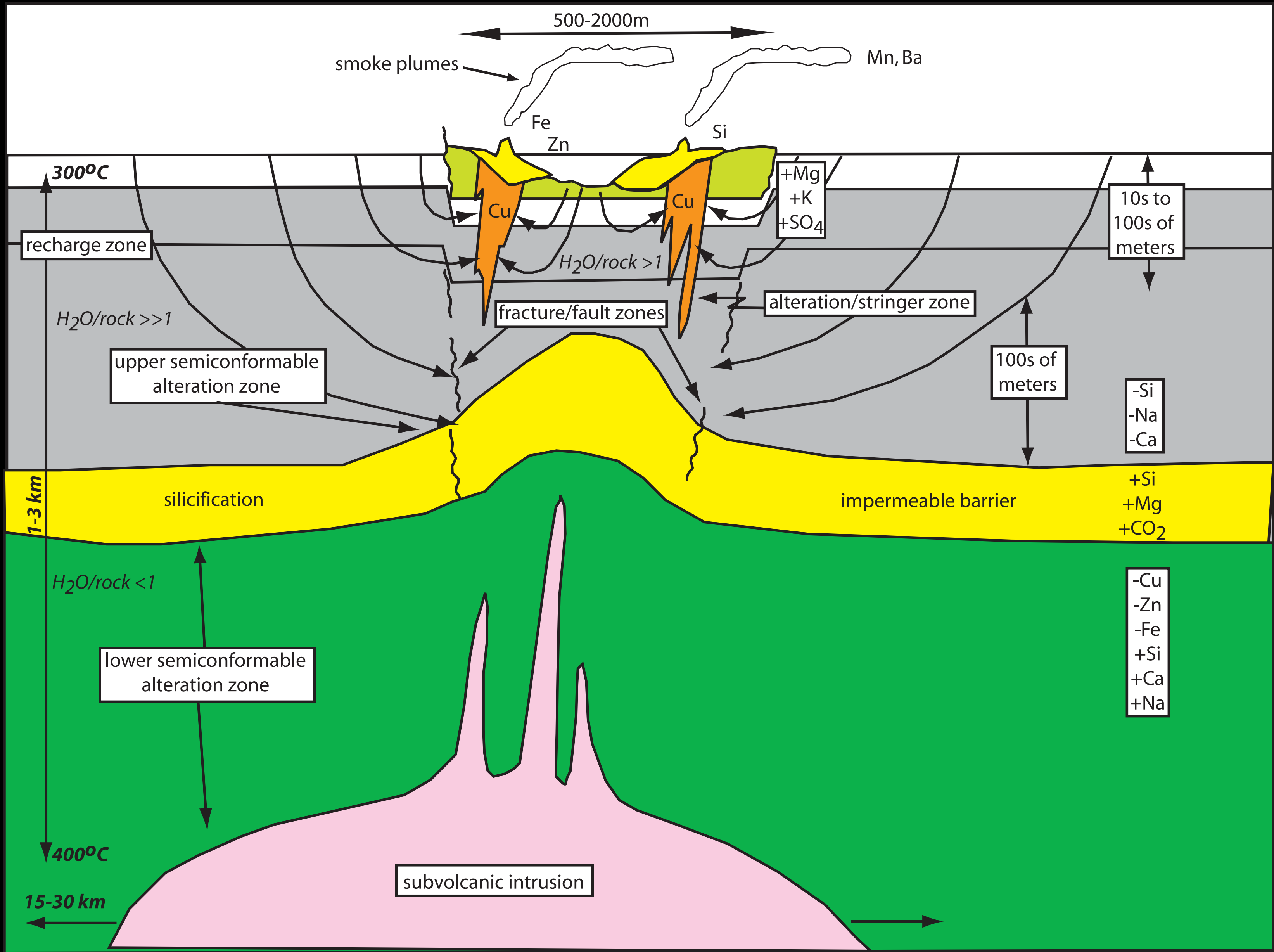


From Sillitoe et al. (1996) and Dubé et al. (2007)

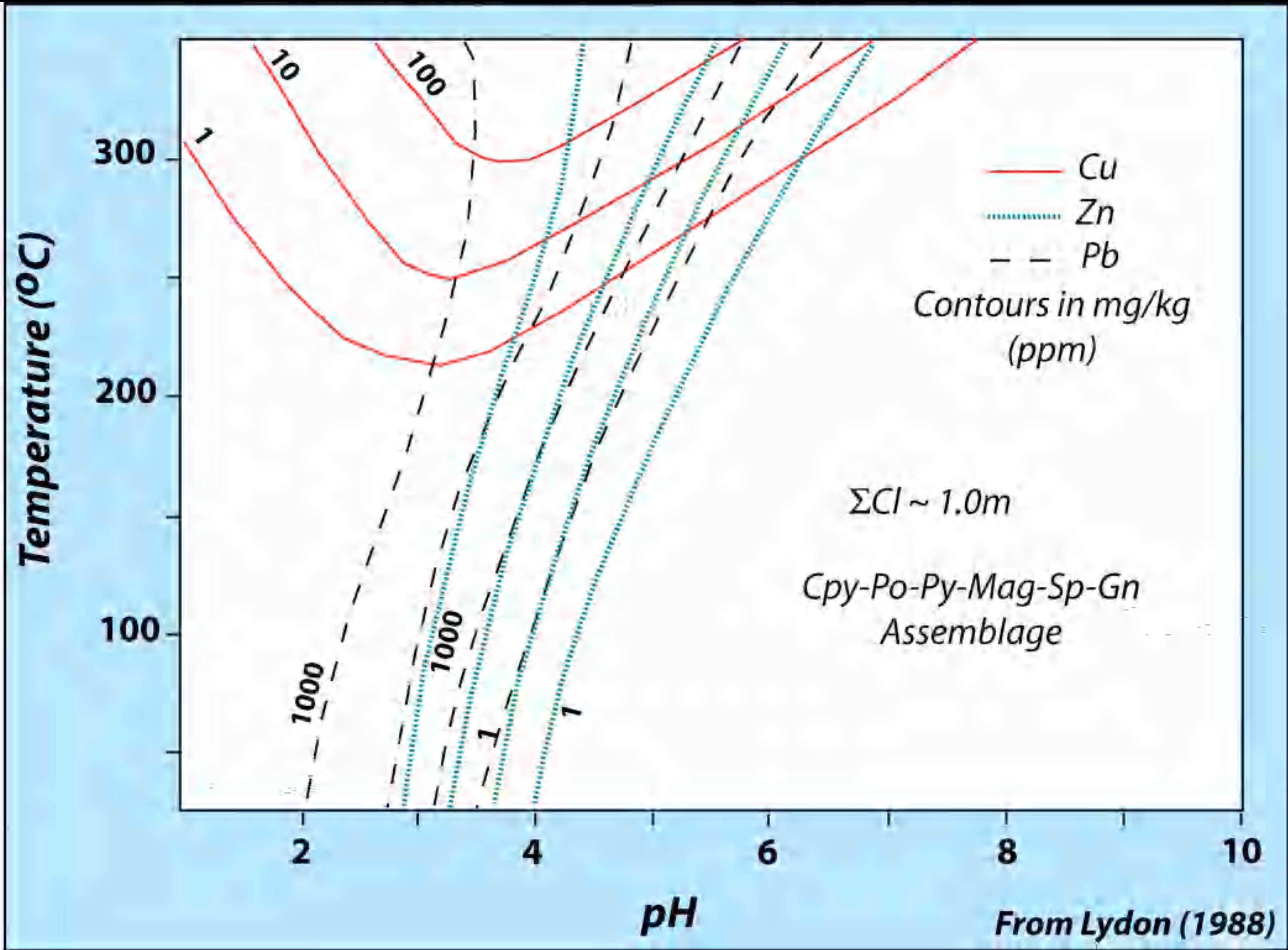
VMS Deposits: Descriptive Data

- Submarine hydrothermal systems.
- Mound to lense to tabular shaped.
- Important sources for base (Cu, Pb, Zn) and precious (Au, Ag)metals.
- Classified into six groups:
  - Mafic
  - Mafic Siliciclastic
  - Bimodal Mafic
  - Bimodal Felsic
  - Felsic Siliciclastic
  - Hybrid Bimodal Felsic.
- Siliciclastic-rich - highest tonnage.
- Bimodal systems - highest grade (polymetallic).

The VMS Model

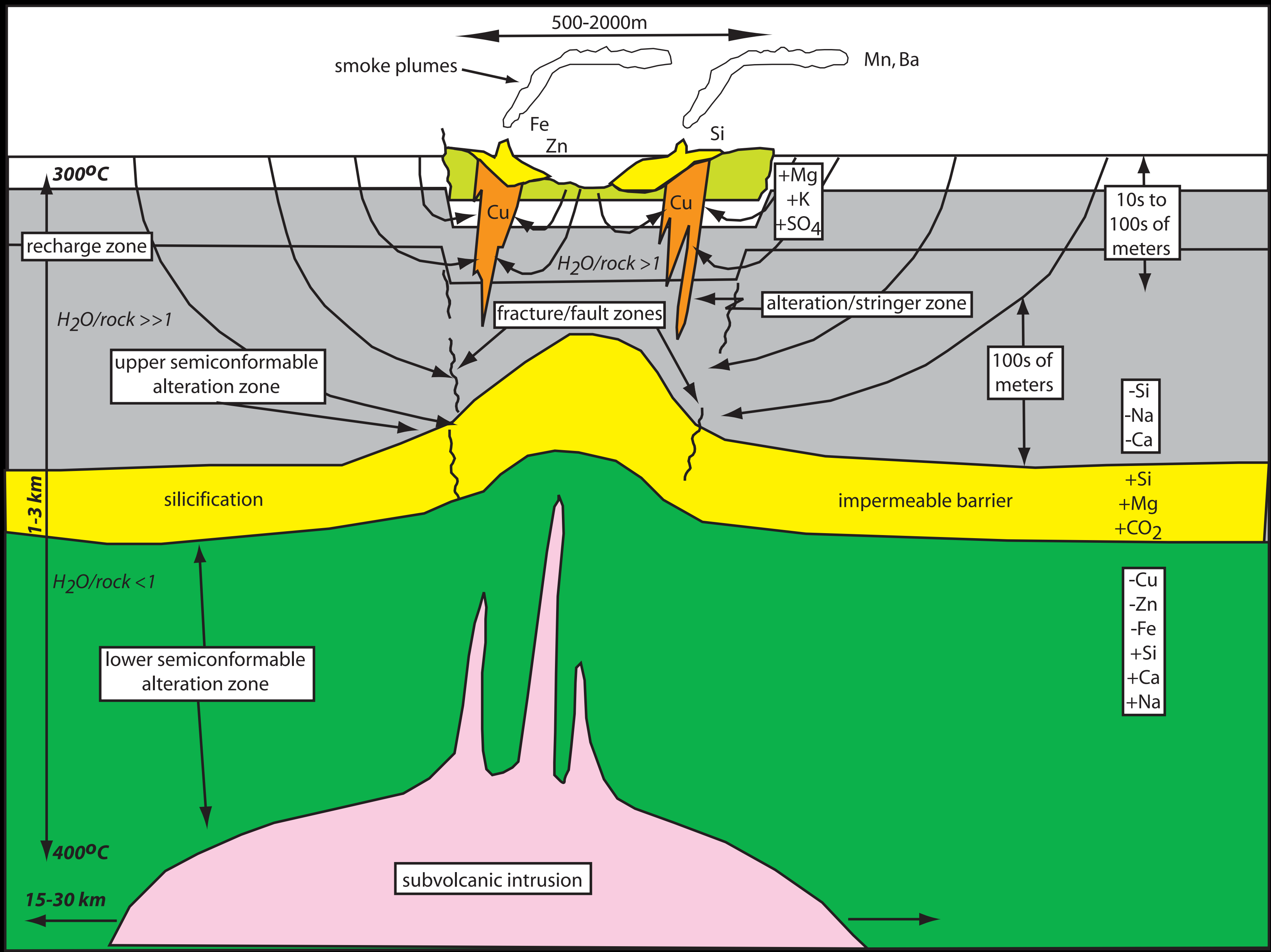


From Galley (1993), Franklin (1996) and Franklin et al. (2005)



Semi-conformable and reaction zone decreases pH and increases temperature - both critical for increasing solubility of ore metals!

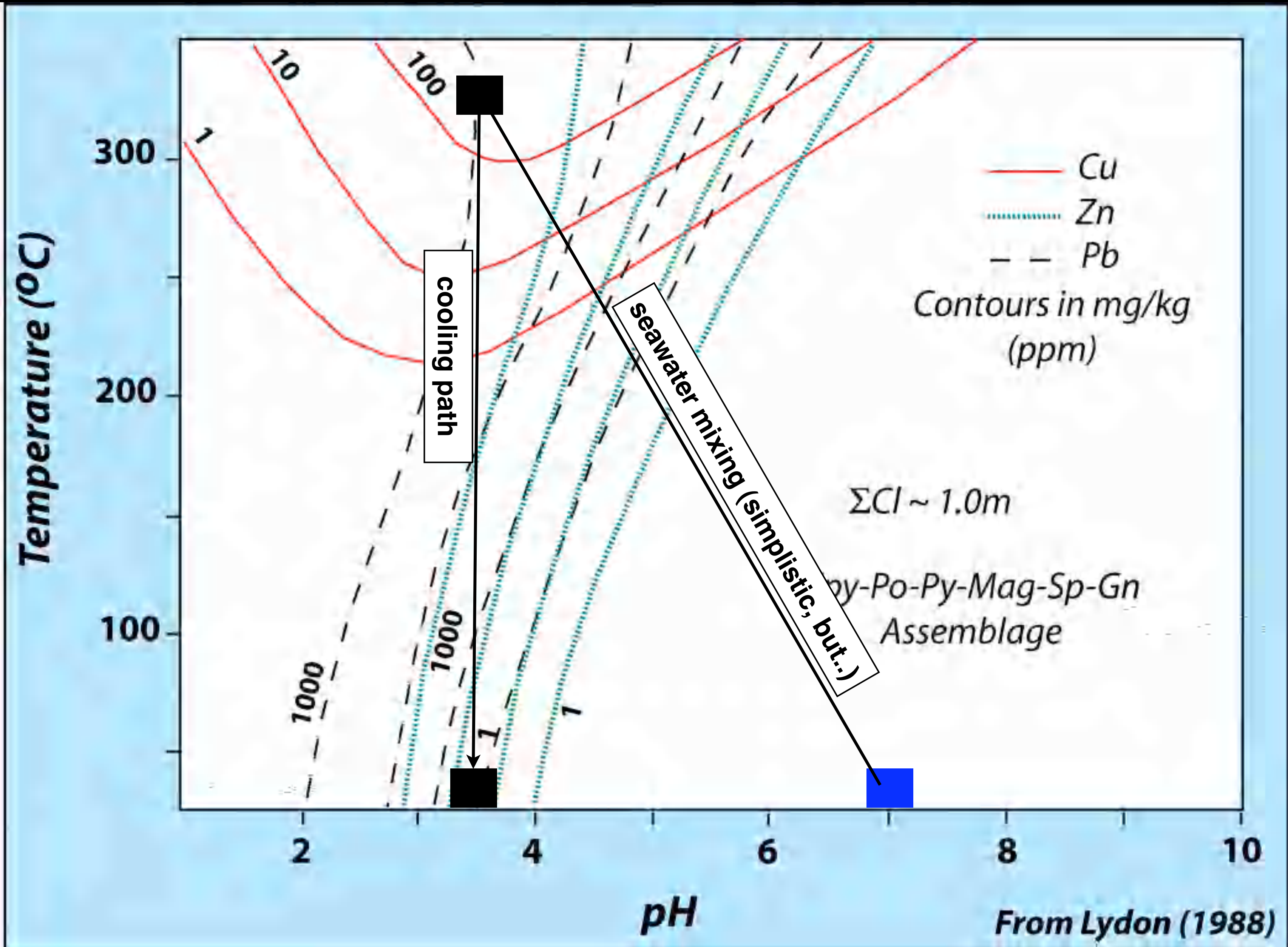
The VMS Model



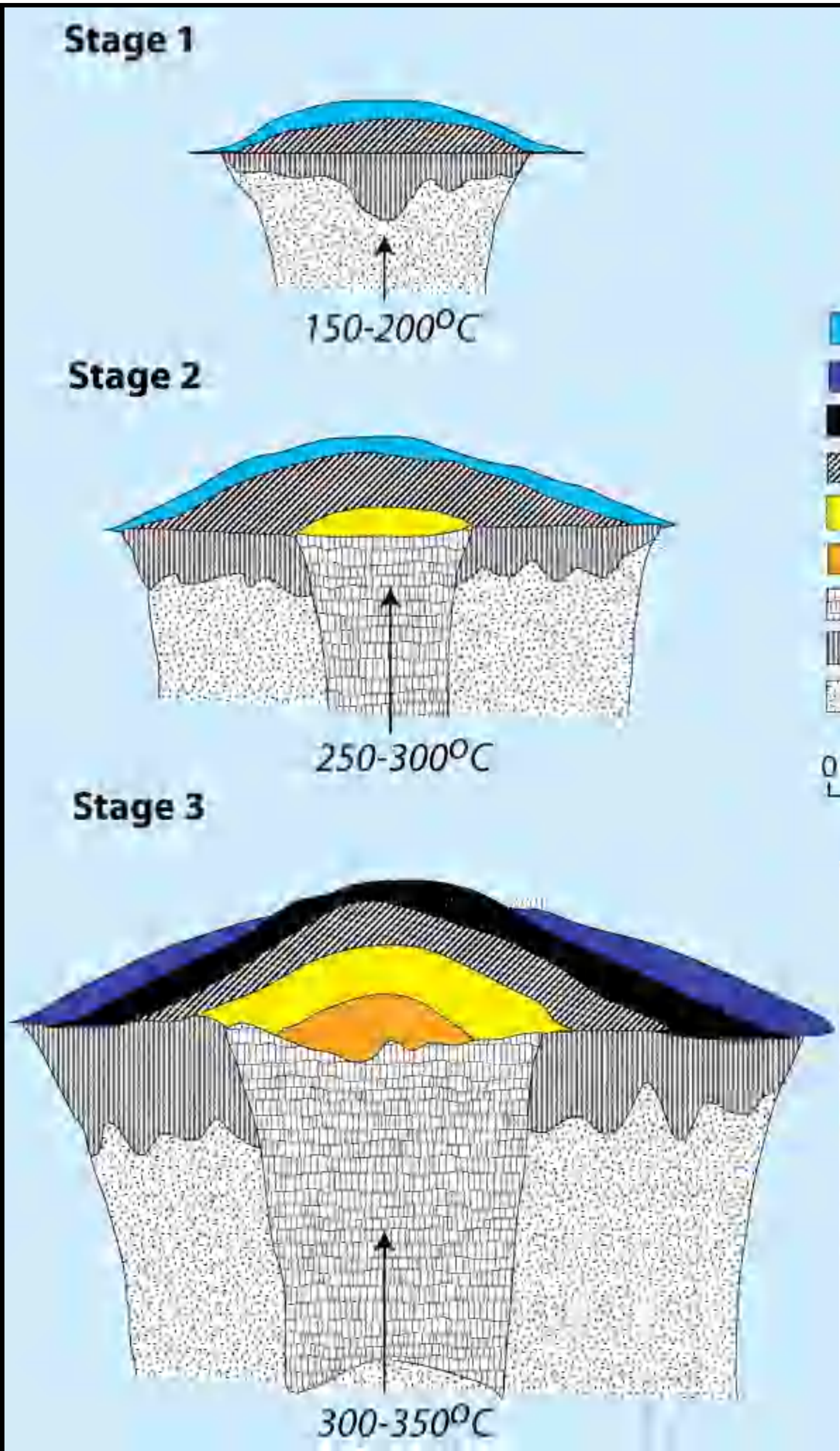
From Franklin (1996) and Franklin et al. (2005)

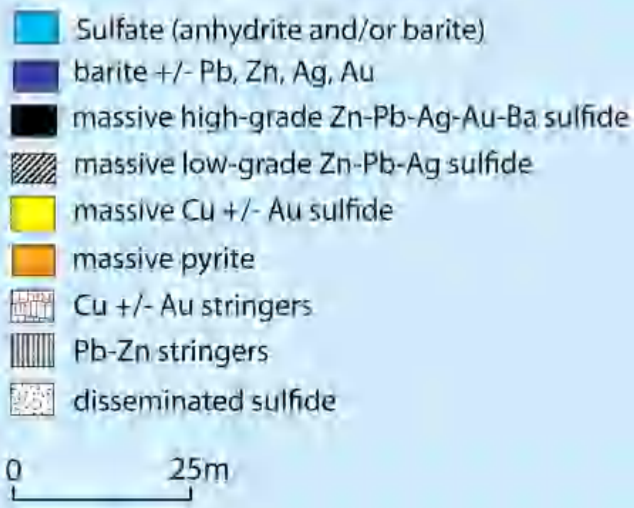
Precipitation and Formation of Sulfide Mounds and Deposits

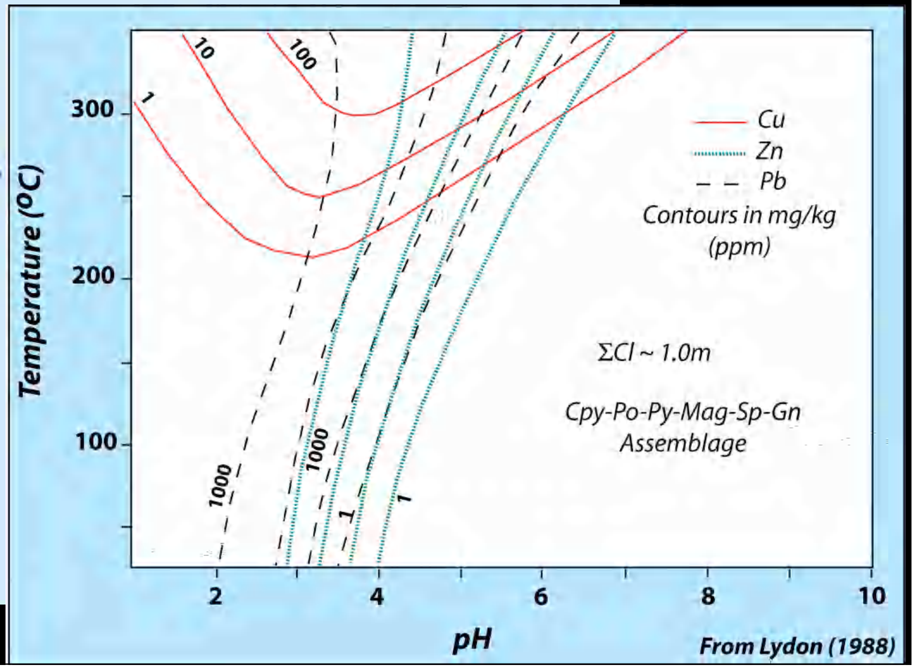
- **Hot, low pH, H_2S- and Cl-bearing, metal-rich fluids in the recharge zone.**
- **Buoyant and desire to come up synvolcanic faults.**
- **React with wall-rocks to alter wall rocks via replacement, exchange, and destruction reactions.**
- **Fluids cool en-route to surface via *conductive cooling*.**
- **Fluids cool due to *mixing with seawater*.**
- **Fluids cool due to *interaction with wall rock*.**
- ***Evolving process - not a single fluid, but many with varying temperature and composition!***
- ***ZONE REFINING PROCESSES - early low temperature then progressive heating and then subsequent cooling. Precipitation, dissolution, reprecipitation, etc.***



Cooling and mixing with seawater are the main mechanisms of sulfide precipitation from hydrothermal fluids.







From Large (1992), based on concepts from Eldridge et al. (1983), Pisutha-Arnond and Ohmoto (1983) - see also Ohmoto (1996).

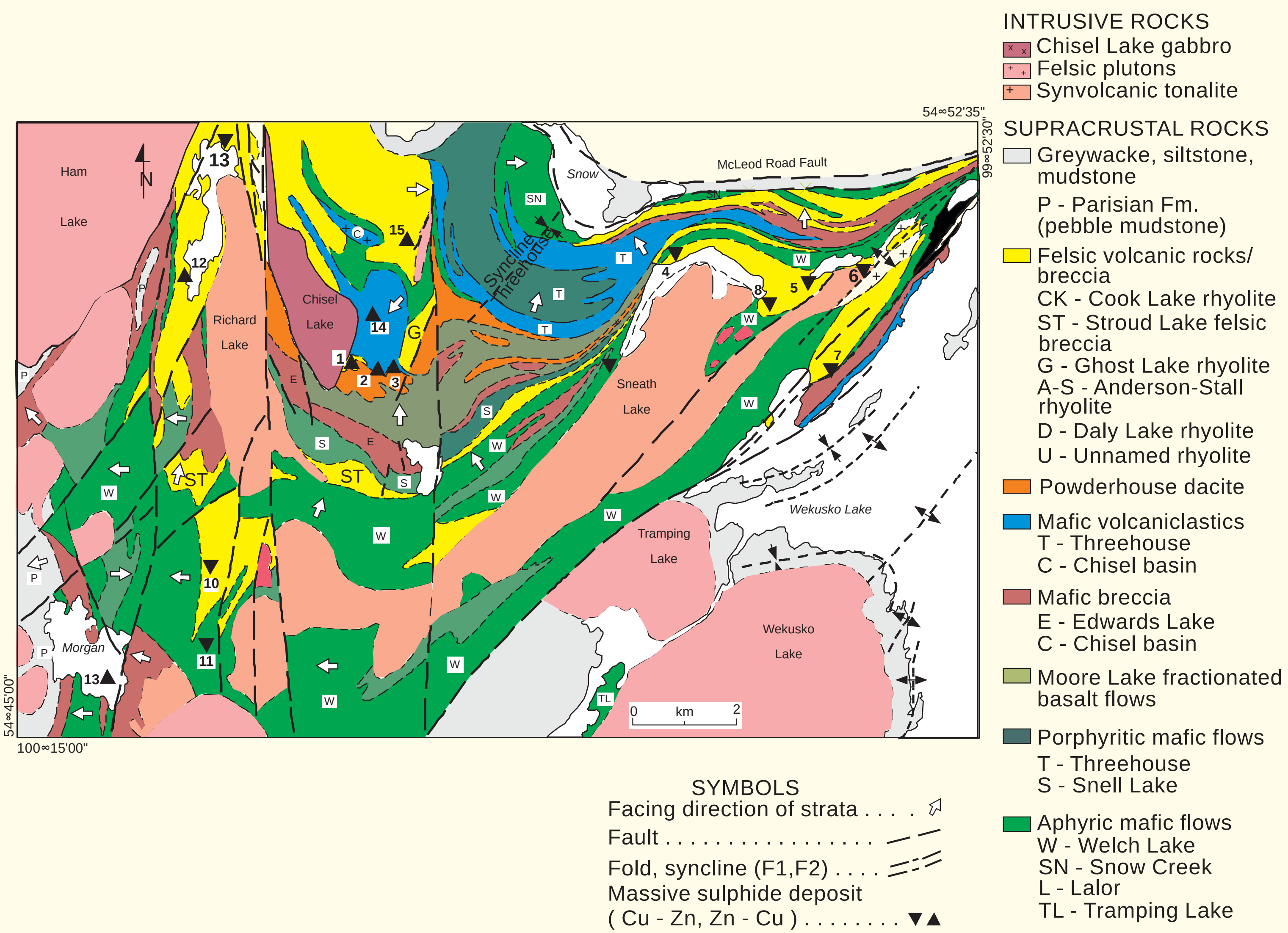
Consequences of the Genetic (and Empirical) Model: Key Exploration Criteria

- Deposits form in *rift environments* with *elevated heat flow*.
- Should have geological and petrological indicators of rifting and heat flow (e.g., subvolcanic intrusions, synvolcanic dyke swarms, vent-proximal volcanic and sedimentary facies, certain petrological suites of rocks).
- The hydrothermal system should have lateral and vertical zonation in both alteration assemblages and metals - there are predictable chemical consequences of these alteration types.
- Metalliferous sediments (exhalites, iron formations, tuffites) - vary mineralogically and chemically with proximity to deposits.

Other Geological Evidence of Rifting and Elevated Heat Flow: *Subvolcanic Intrusions*

- ***Polyphase intrusions with extended lifespan*** **(i.e., over millions of years) - evidence for elevated geotherm for extended period of time - late phases can post-date VMS formation.**
- **Often tonalitic to trondjhemitic in basalt-dominated settings (e.g., Flin Flon, Abitibi), can be mafic (e.g., Matagami), in felsic-dominated terrranes can be calc-alkalic to within-plate (e.g., Bathurst, Finlayson Lake).**
- **Kilometers to 100s of km in scale.**
- **Contact aureoles are absent or weak - synvolcanic.**
- **Often exhibit strong hydrothermal alteration.**
- **Spatially associated with synvolcanic dyke swarms.**
- **Evidence for high-level emplacement (e.g. miarolitic cavities).**
- **Chemically equivalent to erupted rocks and dyke swarms.**

Subvolcanic Intrusions



From Bailes and Galley (1999)

Miarolitic cavities, Flavrian Intrusion, Noranda, PQ, Canada

Epidote-quartz alteration, Flavrian Intrusion, PQ, Canada

Xenoliths and epidote-quartz alteration, Flavrian Intrusion, PQ, Canada

Xenolith-rich tonalite, Cliff Lake Pluton, Flin Flon, MB.

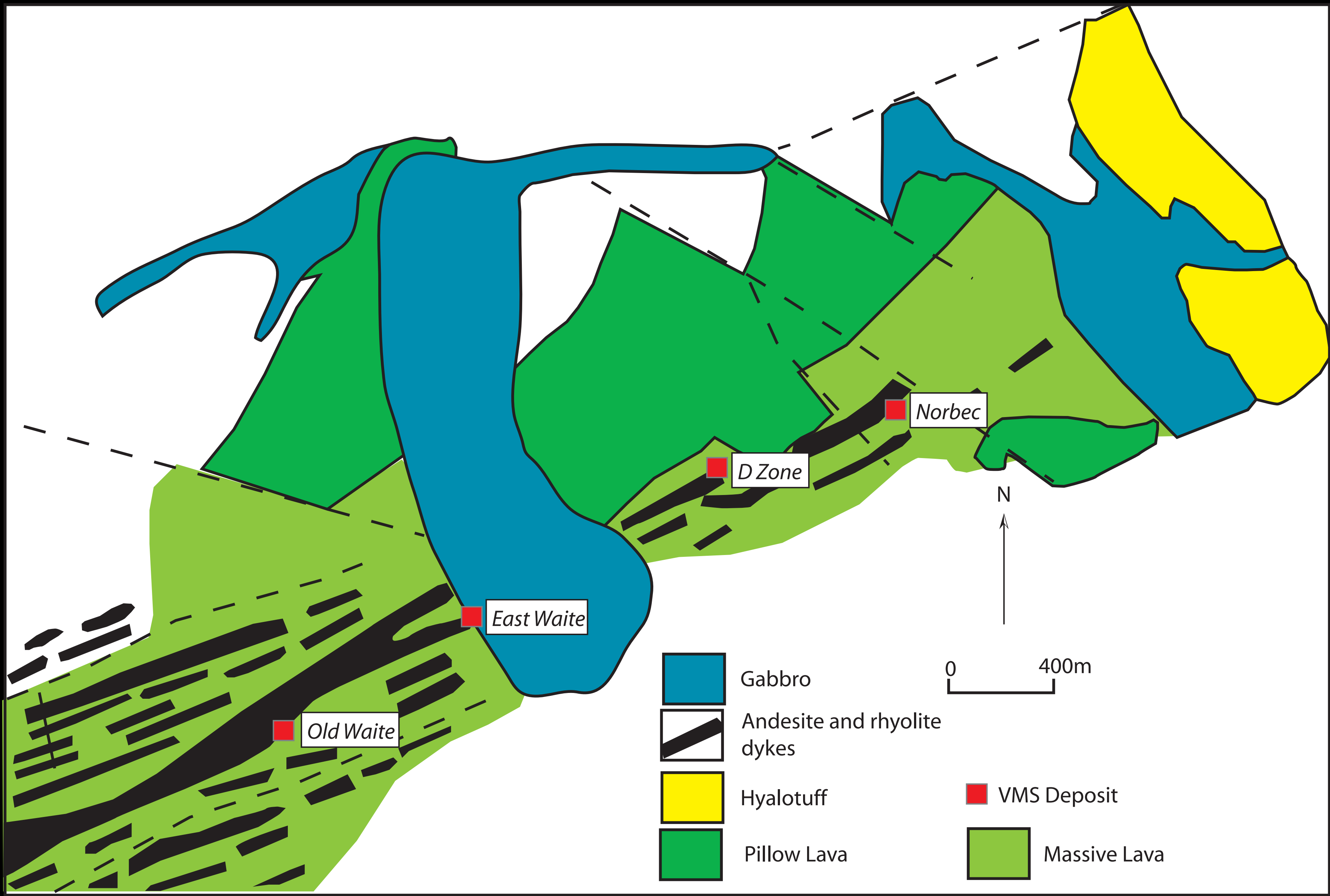
Xenolith-rich tonalite and polyphase plutonism, Cliff Lake Pluton, Flin Flon, MB.

Quartz patches, Cliff Lake Pluton, Flin Flon, MB.

Epidote patches, Cliff Lake Pluton, Flin Flon, MB.

Other Geological Evidence of Rifting and Elevated Heat Flow: *Synvolcanic Dyke Swarms*

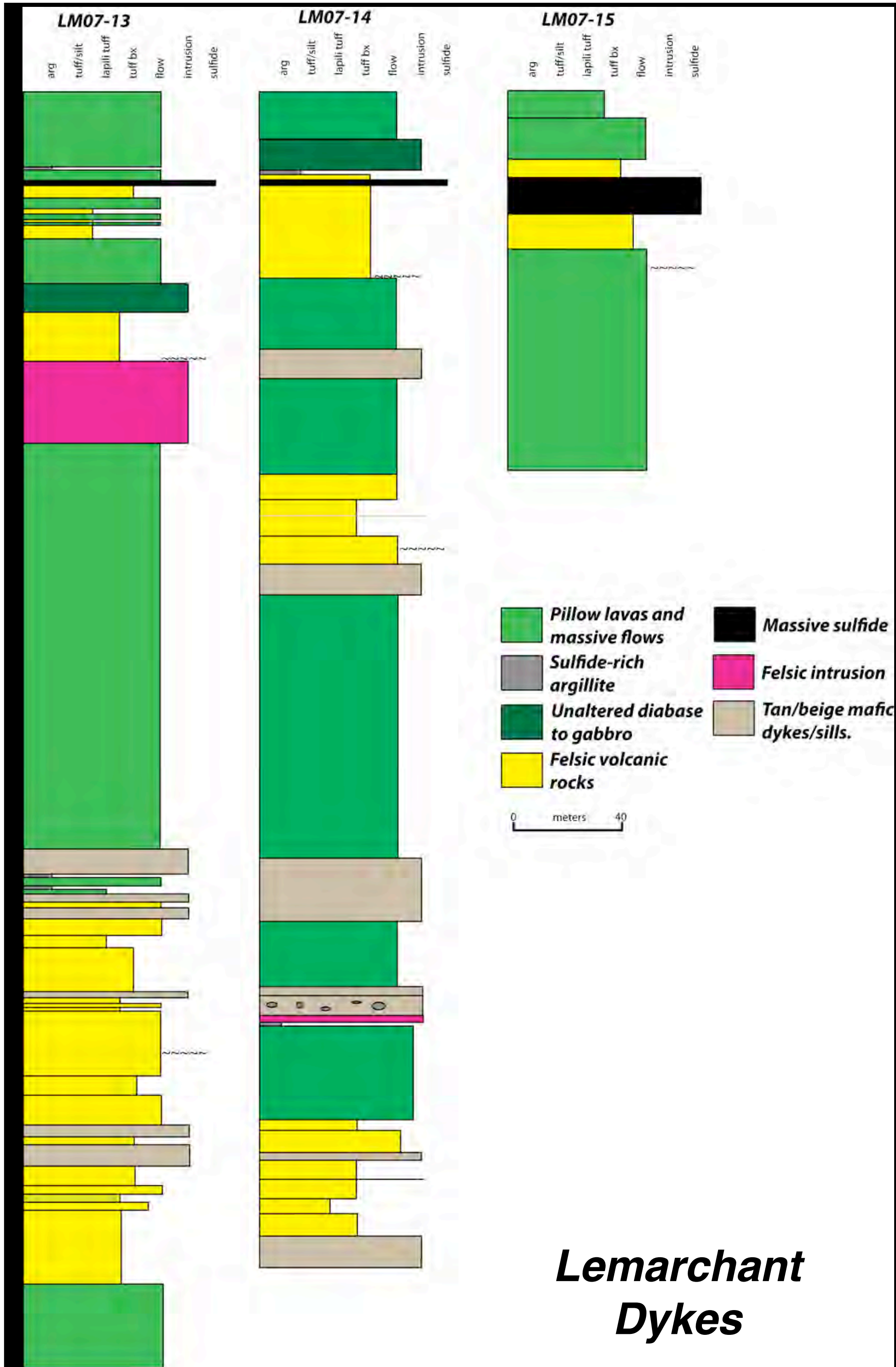
- *Synvolcanic dyke swarms* = paleovent corridors (fluid conduits).
- Typically show irregular margins into volcaniclastic and sedimentary strata = unconsolidated sediment = synvolcanic/synsedimentary.
- Often show peperitic textures with surrounding sediment = unconsolidated sediment = synvolcanic/synsedimentary.
- Sometimes show chilled margins, but often without them. Sometimes margins are altered.
- Typically show alteration similar to surrounding host rocks.
- Can post-date ore, but exhibit alteration akin to late stages of VMS hydrothermal system (e.g., post-ore mafic dykes at Duck Pond).
- Typically form swarms that map upflow zones and mirror alteration patterns.



From Gibson (1990) and Gibson et al. (1999)

Synolcanic dyke, Blake River Group, Noranda Camp, PQ, Canada

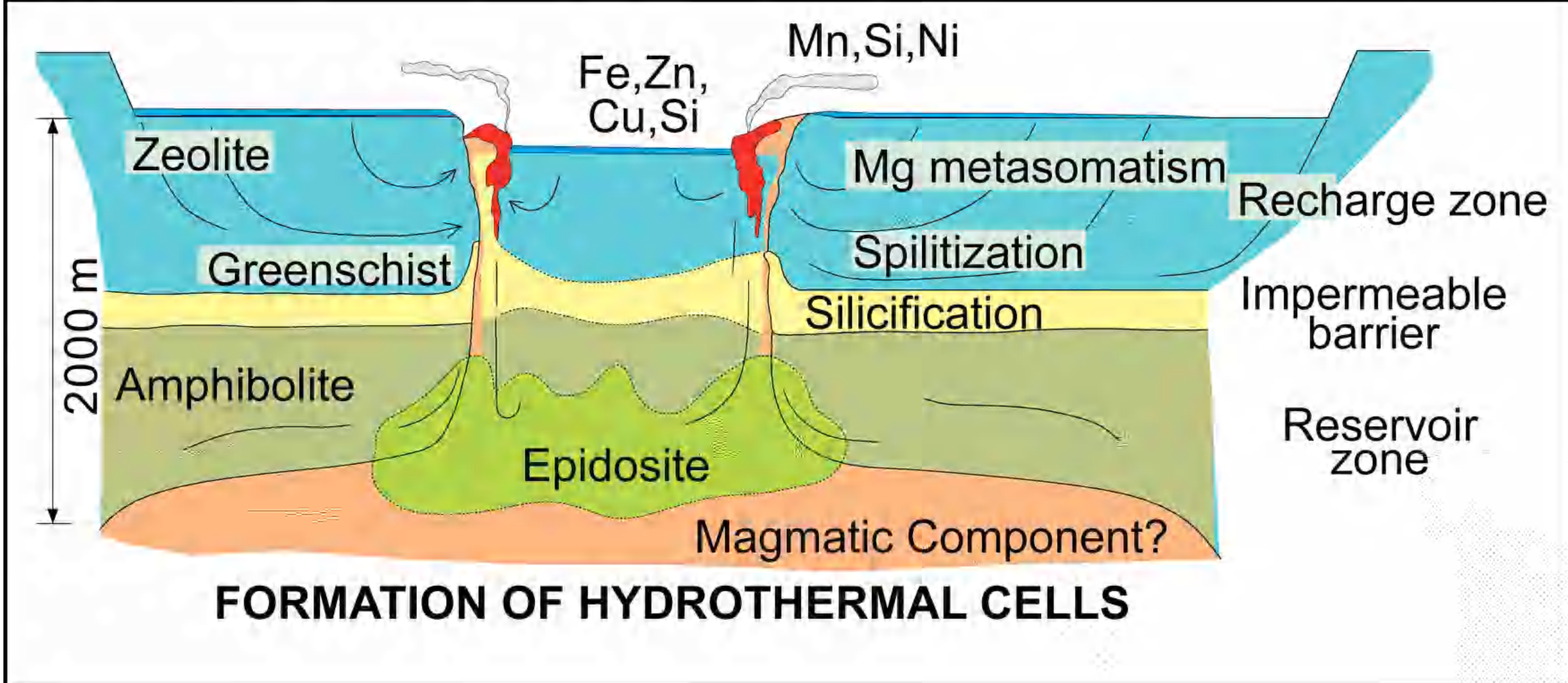
Synvolcanic dyke, Snow Lake, MN, Canada



Lemarchant Dykes

Hydrothermal Alteration

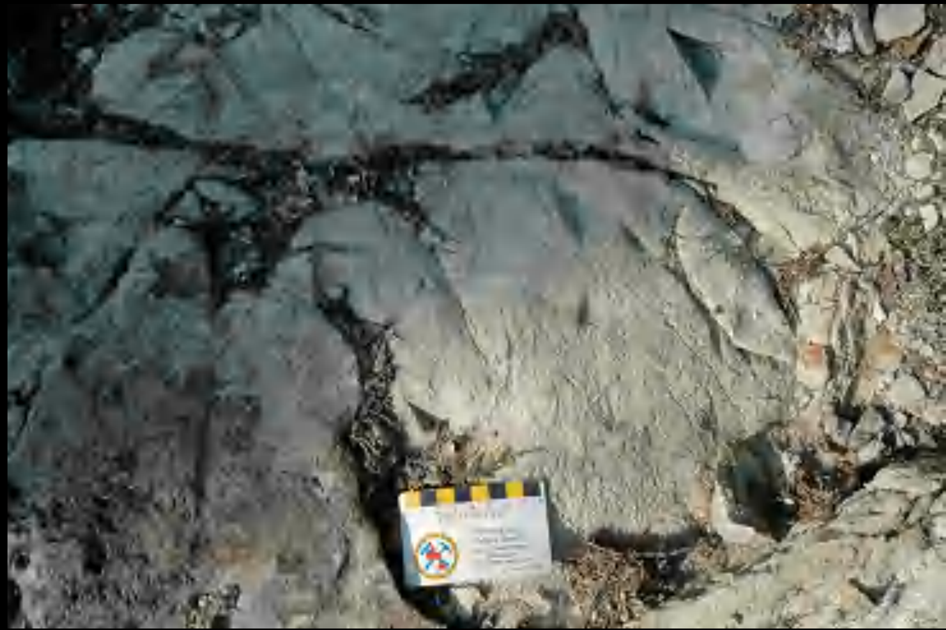
- VMS hydrothermal systems have a well defined zonation wtih both lateral and vertical zonation in mineralogy and chemistry.
- *Semi-conformable alteration*: lateral fluid flow - metal leaching - patchy.
    - In mafic-dominated substrates = epidote-quartz and silicificiation.
    - In felsic-dominated substrates = sericite-quartz and silicification.
    - Semi-conformable to stratigraphy (i.e., not discordant)
- *Pipe-like or proximal alteration*: vertically and laterally zoned.
    - Chlorite-(quartz) - proximal.
    - Chlorite-sericite - medial.
    - Sericite-quartz - medial to distal.
    - Quartz - distal.



- *Semi-conformable alteration (recharge)* - **involves Mg-metasomatism, pH decreases of seawater, leaching of metals and H_2S, heating of hydrothermal fluids.**

Semi-Conformable Alteration

Epidote-quartz patches in basalt, Noranda, PQ



Bleached (qtz-altered) pillow lavas, Lake Douglas, NL

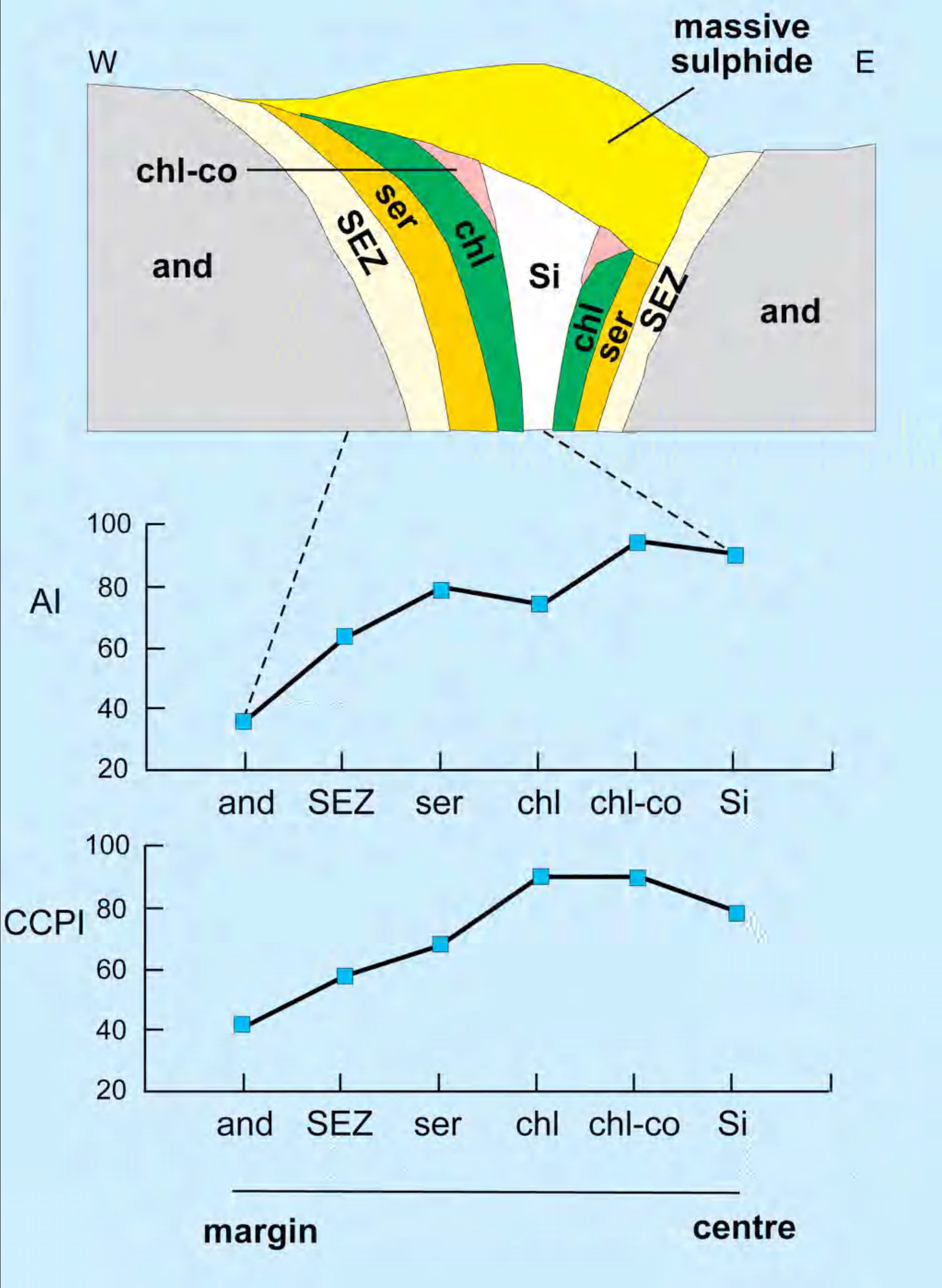
Qtz patches in basalt, Upper Block, Duck Pond, NL

Epi- Qtz patches in basaltic volcaniclastic, Upper Block, Duck Pond, NL

Pipe-Like or Proximal Alteration

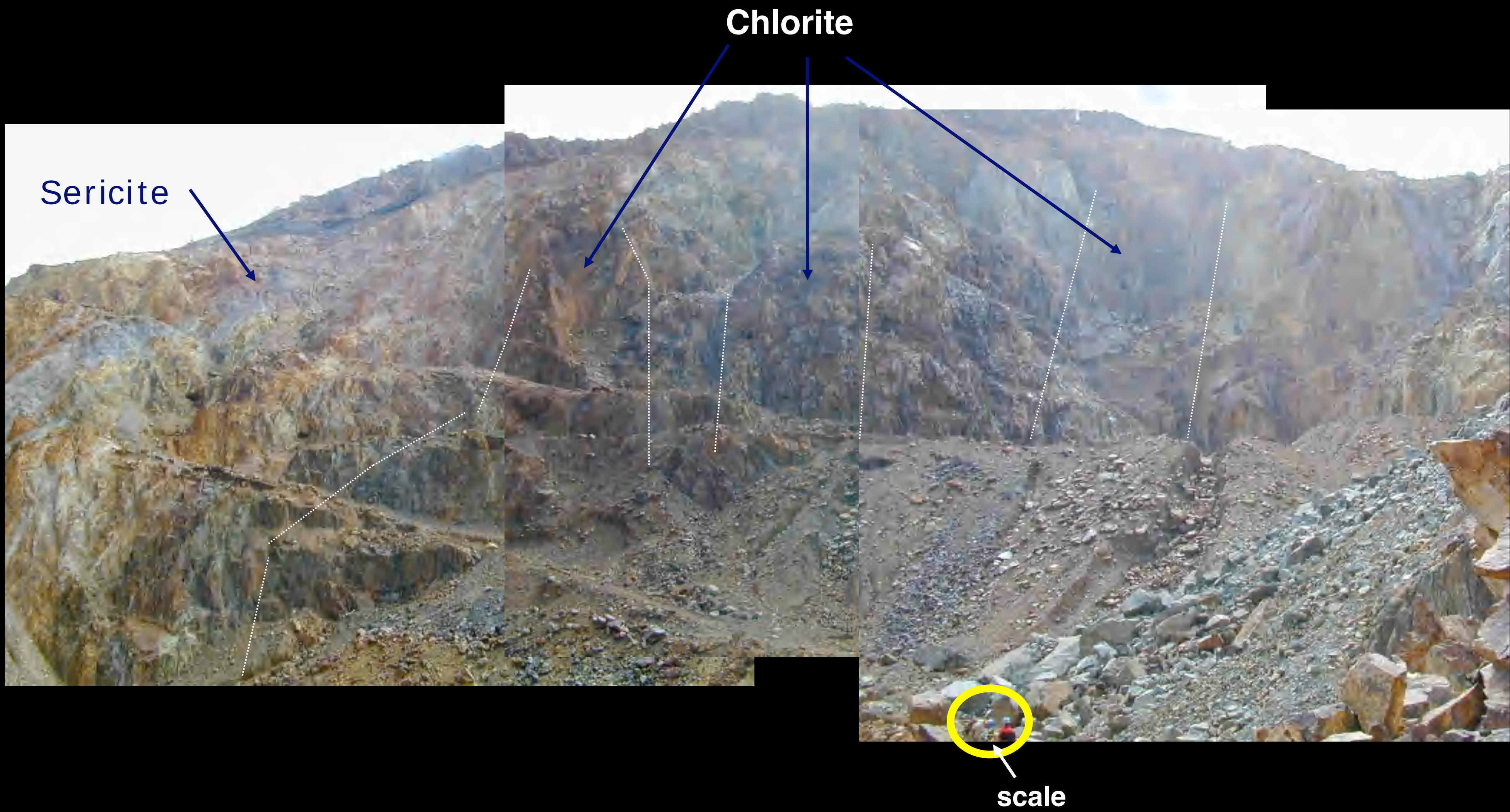
- Pipes have a discordant morphology relative to stratigraphy.
- Pipes are zoned in mineralogy and chemistry.
- Represent upflow zones.
- We have addition of elements via ore fluids and seawater (e.g., Fe, Mg, K, S, Si, metals).
- We have removal of elements due to fluid-rock interaction (e.g., Na, Ca)
- The physical characteristics of the sub-ore zone determine the alteration distribution and composition (e.g., permeable versus impermeable strata).

Alteration Pipe: Flow Dominated Environment



From Gemmell and Fulton (2001)

Jerome, Arizona



View of Open Pit looking to south, southeast to left, southwest to right

Slide courtesy of Nicole Tardif


Chloritic Altn with cpy
24% FeO, 19% MgO,
0.08% Na_2O, 0.08% K_2O
Sericite Altn
0.59% FeO, 0.95% MgO,
0.18% Na_2O, 3.71% K_2O
Slide courtesy of
Nicole Tardif

Alteration Pipe: Wolverine - Clastic Dominated Environment

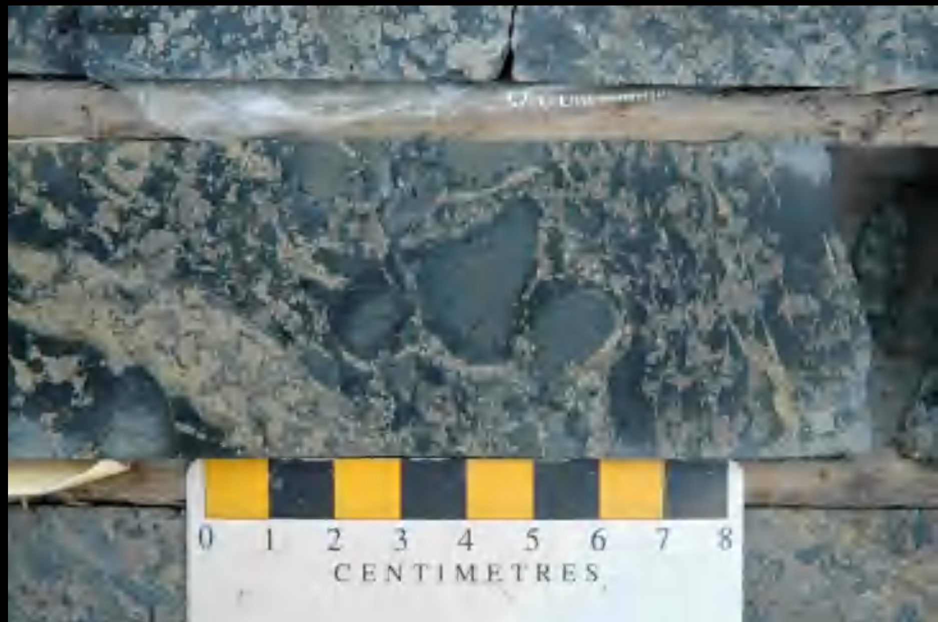
Chl-altd FW tuffs with chl clots± Si alt'n (proximal)

FW – chl-alt'd tuffs with cpy-rich sulphide (proximal)

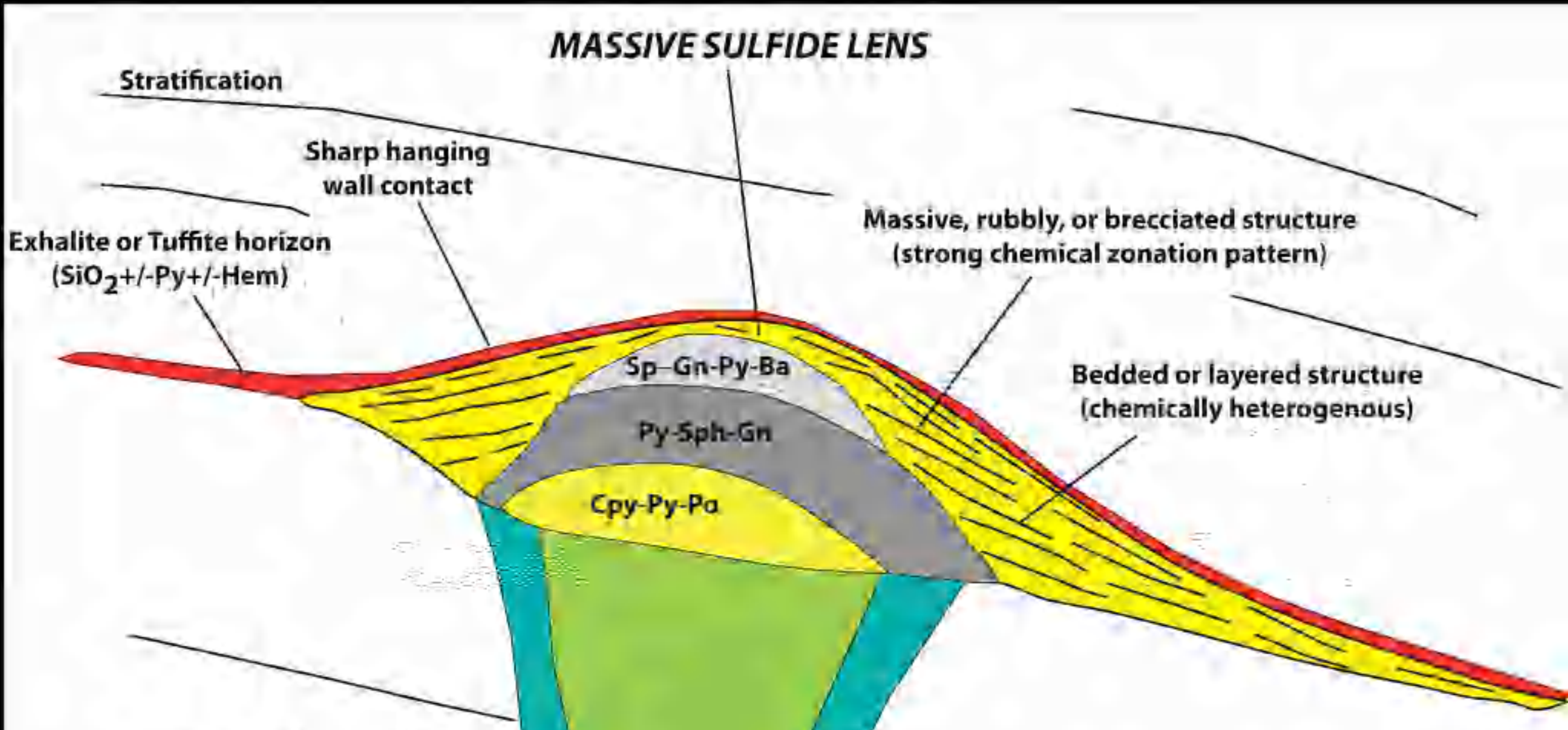
FW – qtz-po-py altered tuffs (proximal)

FW – ser-alt'd felsic tuffs (distal)

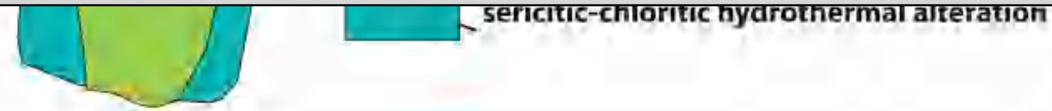
Alteration Pipe: Boundary (North Zone) - Clastic Dominated Environment



Exhalites - Iron Formations, Tuffites, Metalliferous Muds



- **Laterally extensive - up to 10s of km away from deposits.**
- **Can be low or high temperature venting into water column.**
- **Chemistry and mineralogy can be used to decipher proximity to vents and whether high or low temperature.**



From Lydon (1984)

Exhalative Rocks

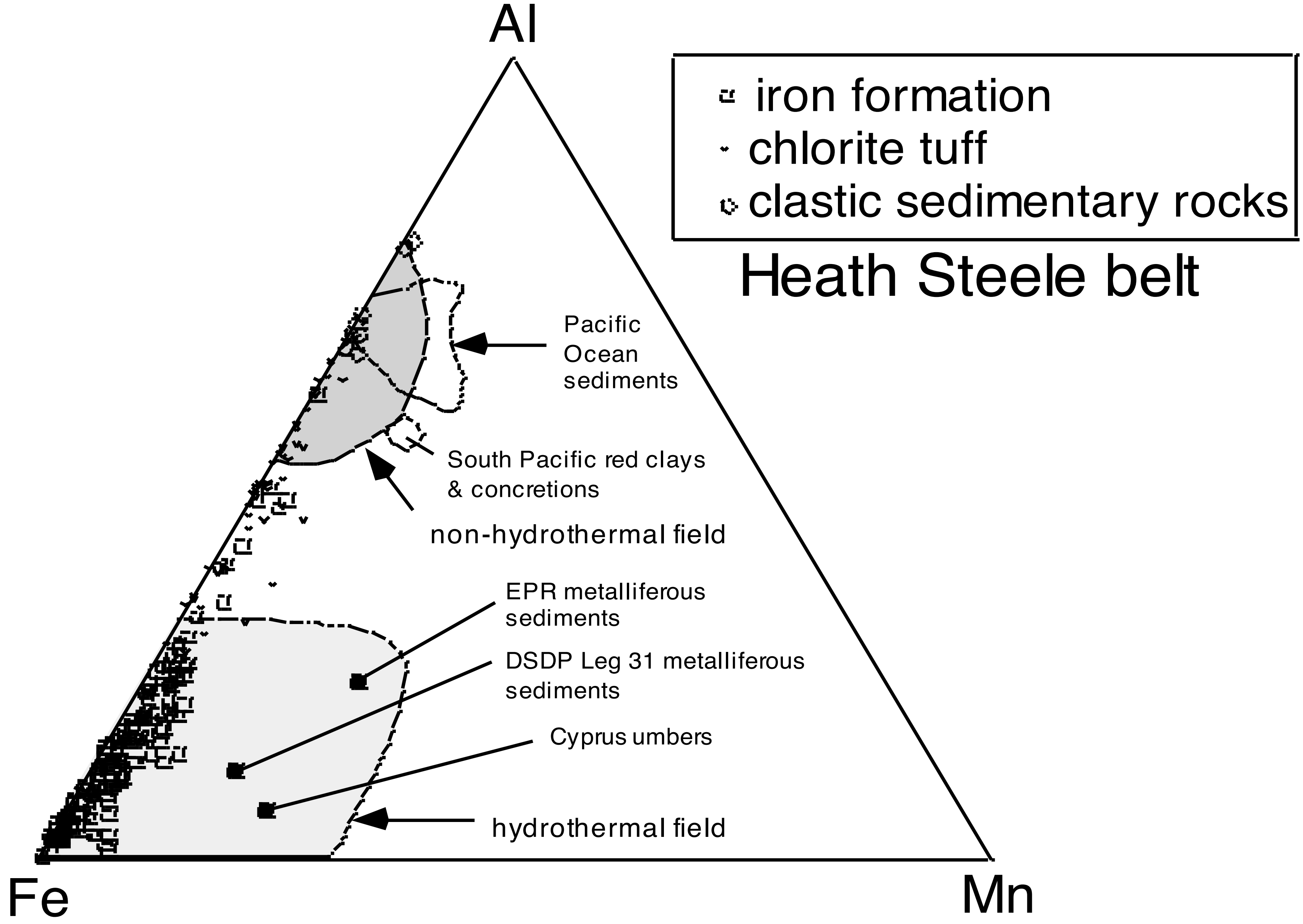
Magnetite Fe-formation, Wolverine

Py-rich mudstone,
Lemarchant Prospect

Fe-Formation Austin Brook,
Brunswick Belt

Po-rich mudstones, Duck Pond

Py-rich mudstone/black chert
Old Camp Prospect



From Peter et al. (2004)

Parting Points

- ***VMS has been and will be a significant deposit target in Canada and globally into the future.***
- **There are vast tracts of Canada (greenfields) with great potential yet are severely under-explored (e.g., Slave Province (High Lake, Izok, Hackett River), northern Cordillera (Palmer)).**
- **Even developed camps have seen the discovery of new deposits in recent years (e.g., NL Appalachians (Boomerang), Flin Flon-Snow Lake (Lalor), Matagami (Perseverance)) - much potential exists even in brownfields areas.**
- **We must use *integrated approaches* to search for these deposits - geology (mapping, facies and alteration reconstructions), geochemistry (both lithogeochemistry and surficial), and geophysics (e.g., airborne, inversions, etc.).**
- **Resurrecting vintage data is critical (e.g., old maps, drill logs, lithogeochemical datasets, geophysics).**
- **Old drill core archives are a wealth of information.**

Summary

- VMS can be classified into six broad groups based on geology and stratigraphy: mafic, bimodal mafic, mafic siliciclastic, bimodal felsic, felsic siliciclastic, and hybrid bimodal felsic.
- VMS deposits form via seawater recharge, metal stripping in recharge zone, cooling and mixing of hydrothermal fluids with seawater leading to precipitation. Zone refining in an important process. The role of magmatic volatiles and basin anoxia are likely important but remain not fully understood.
- The model has geological consequences that can be used in exploration: subvolcanic intrusive complexes, synvolcanic dyke swarms, and exhalative rocks.
- Exploration continues and will be important for VMS deposit types in the future.

Thank you!