Sulfide Deposits and Associated Geology in Michigan and Wisconsin

Klaus J. Schulz
U.S. Geological Survey

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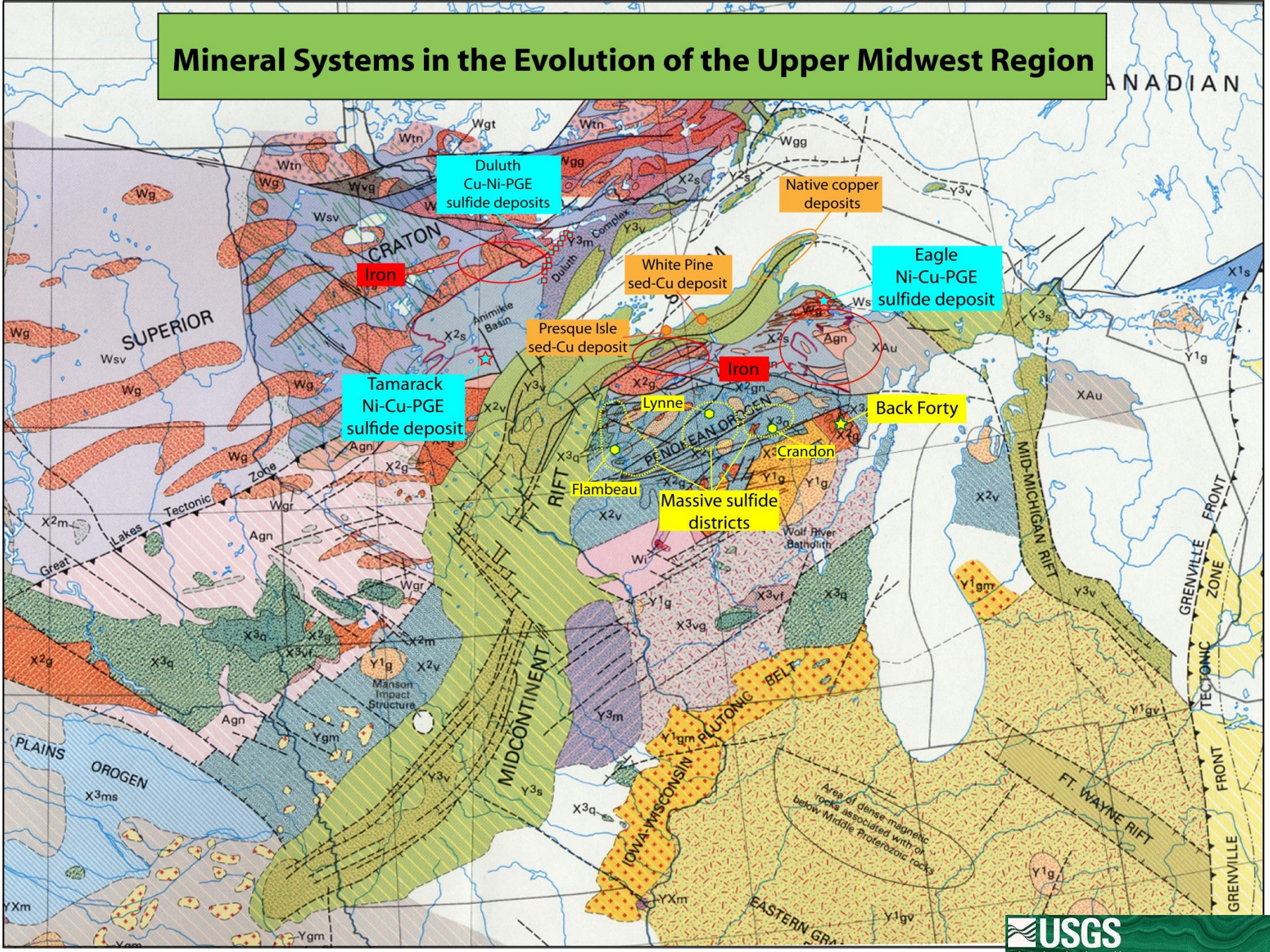
Mineral Systems in the Evolution of the Upper Midwest Region



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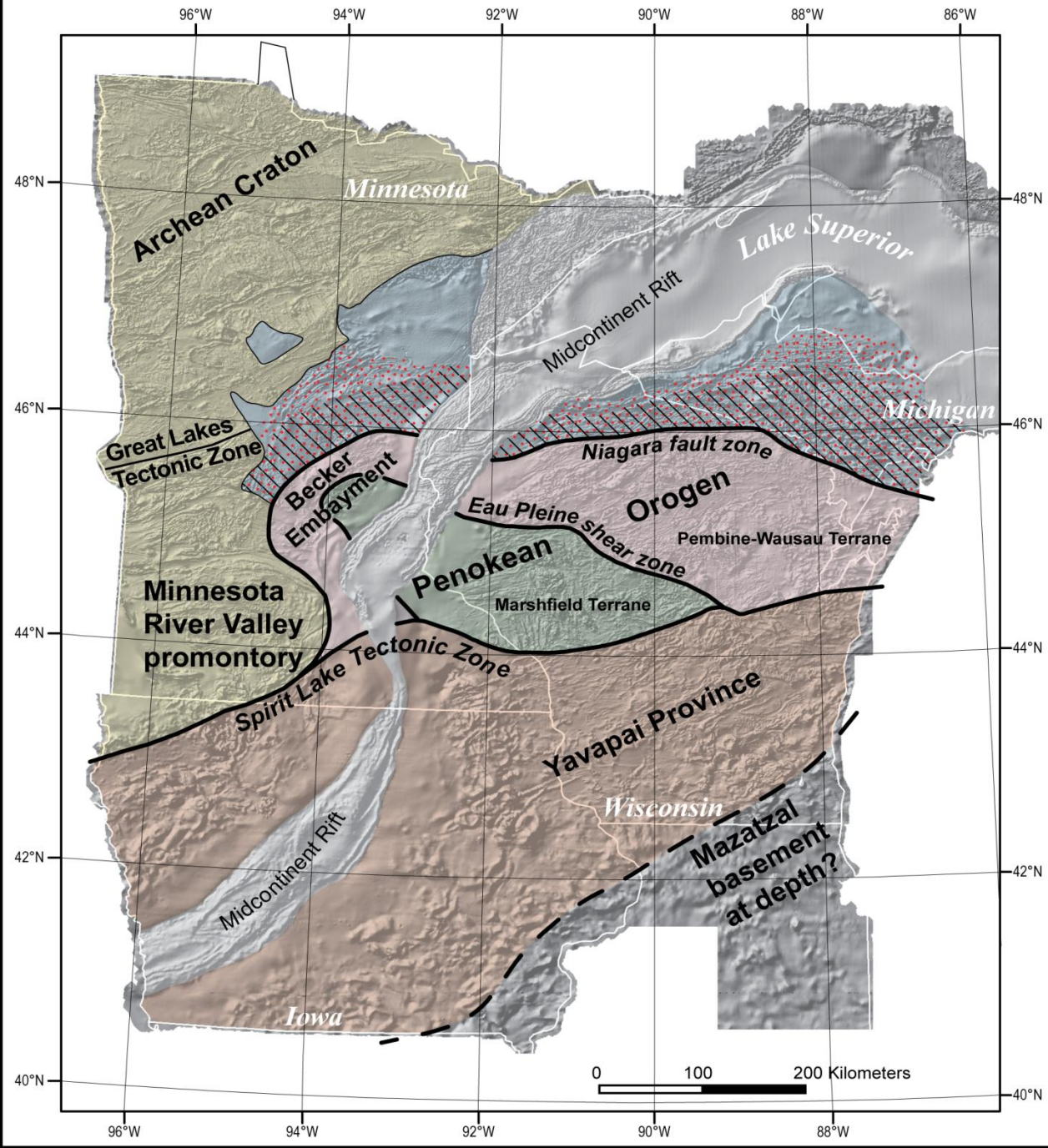
GEOLOGIC MAP OF PRECAMBRIAN BASEMENT ROCKS IN WISCONSIN, MINNESOTA AND IOWA



Description of map units

Midcontinent Rift

~1.1 Ga volcanic, intrusive, and sedimentary rocks

Yavapai Province

1.8 - 1.72 Ga rhyolite, granite, gneiss

Craton Margin Domain

Yavapai and Penokean bains - *2.3 - 1.77 Ga Paleoproterozoic sedimentary and volcanic rocks*

Gneiss dome corridor, affected by Yavapai deformation

Area of Penokean deformation

Wisconsin Magmatic Terranes

Pembine-Wausau Terrane - *Penokean volcanic rocks and coeval granitoid*

Marshfield Terrane - *Archean gneiss with infolded Penokean volcanic rocks and coeval granitoid intrusions*

Archean Craton

~3.5 - 2.6 Ga greenstone, granitoid rocks, gneiss

(from Holm and others, 2007)

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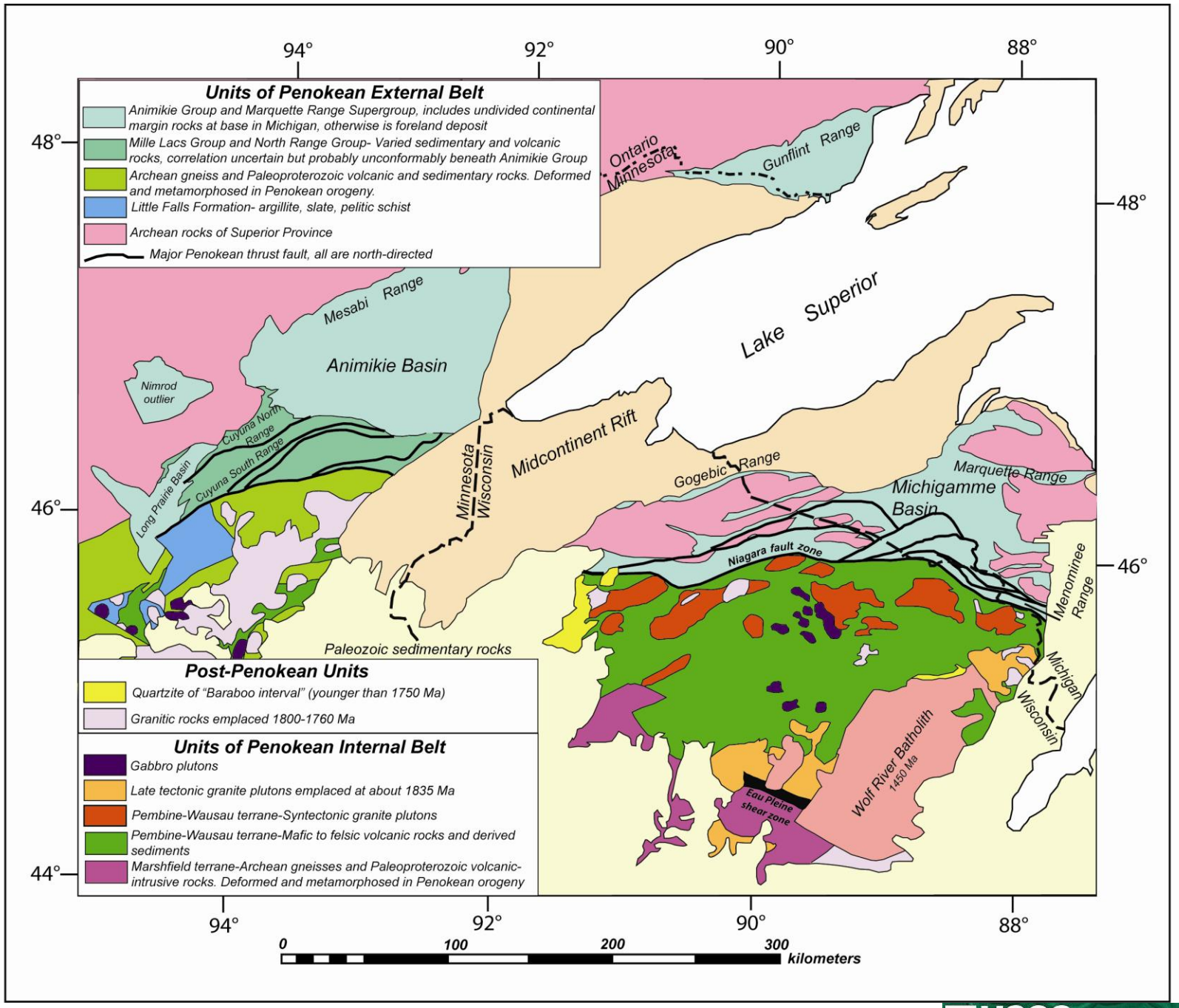

(from Schulz and Cannon, 2007)

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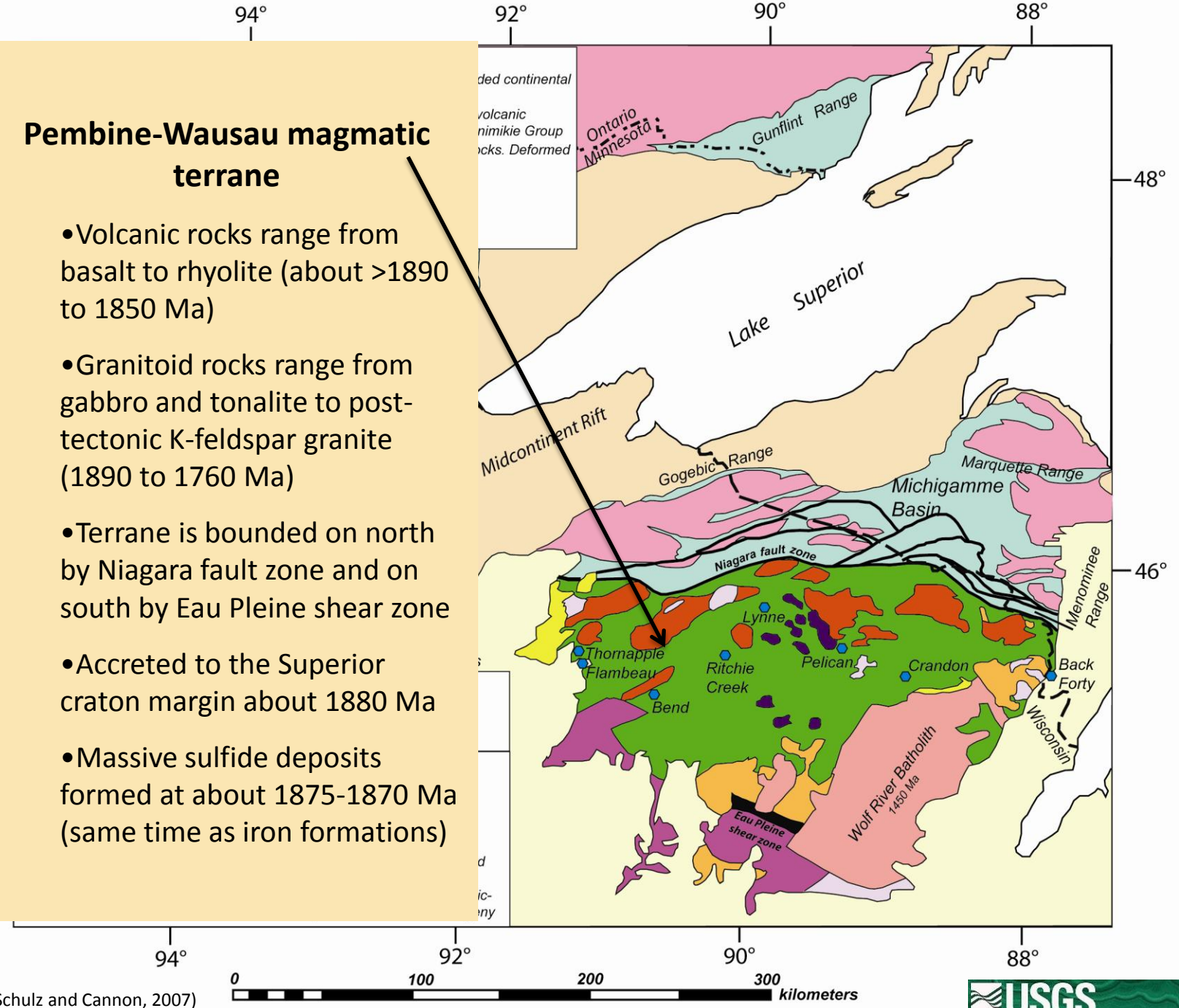
Pembine-Wausau magmatic terrane

- Volcanic rocks range from basalt to rhyolite (about >1890 to 1850 Ma)
- Granitoid rocks range from gabbro and tonalite to post-tectonic K-feldspar granite (1890 to 1760 Ma)
- Terrane is bounded on north by Niagara fault zone and on south by Eau Pleine shear zone
- Accreted to the Superior craton margin about 1880 Ma
- Massive sulfide deposits formed at about 1875-1870 Ma (same time as iron formations)



(from Schulz and Cannon, 2007)

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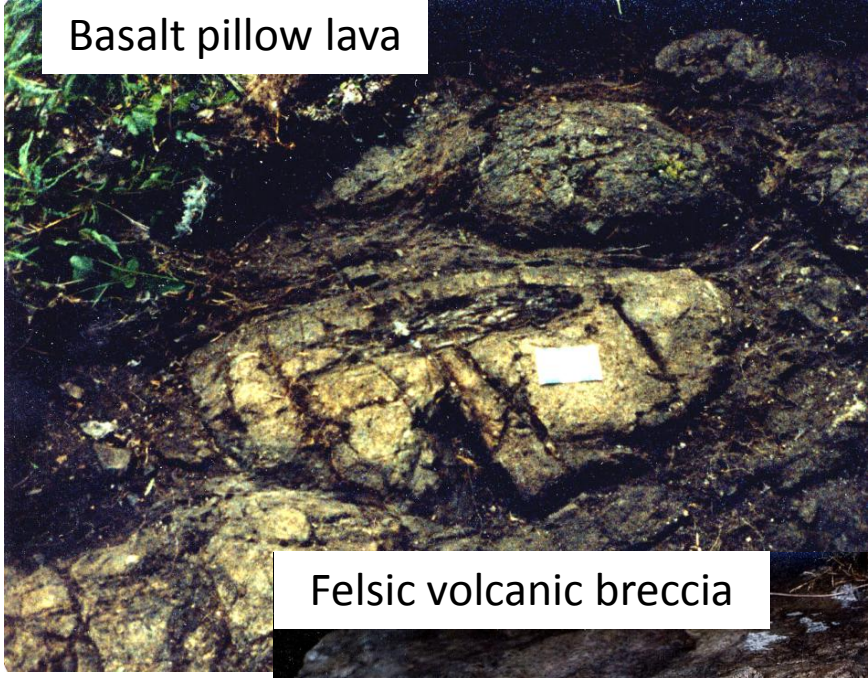
Basalt pillow lava

Basalt pillow lava

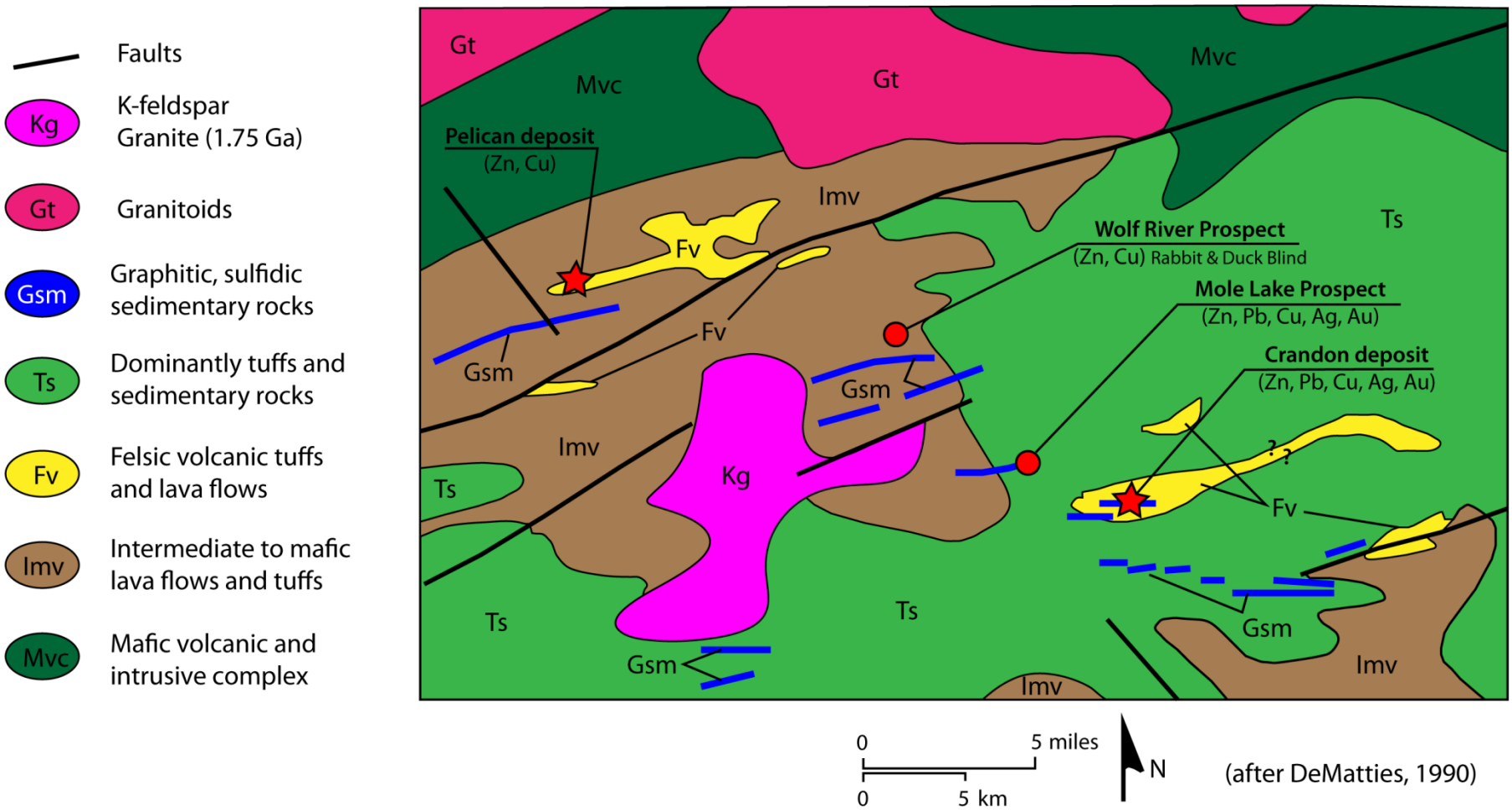


Felsic volcanic breccia

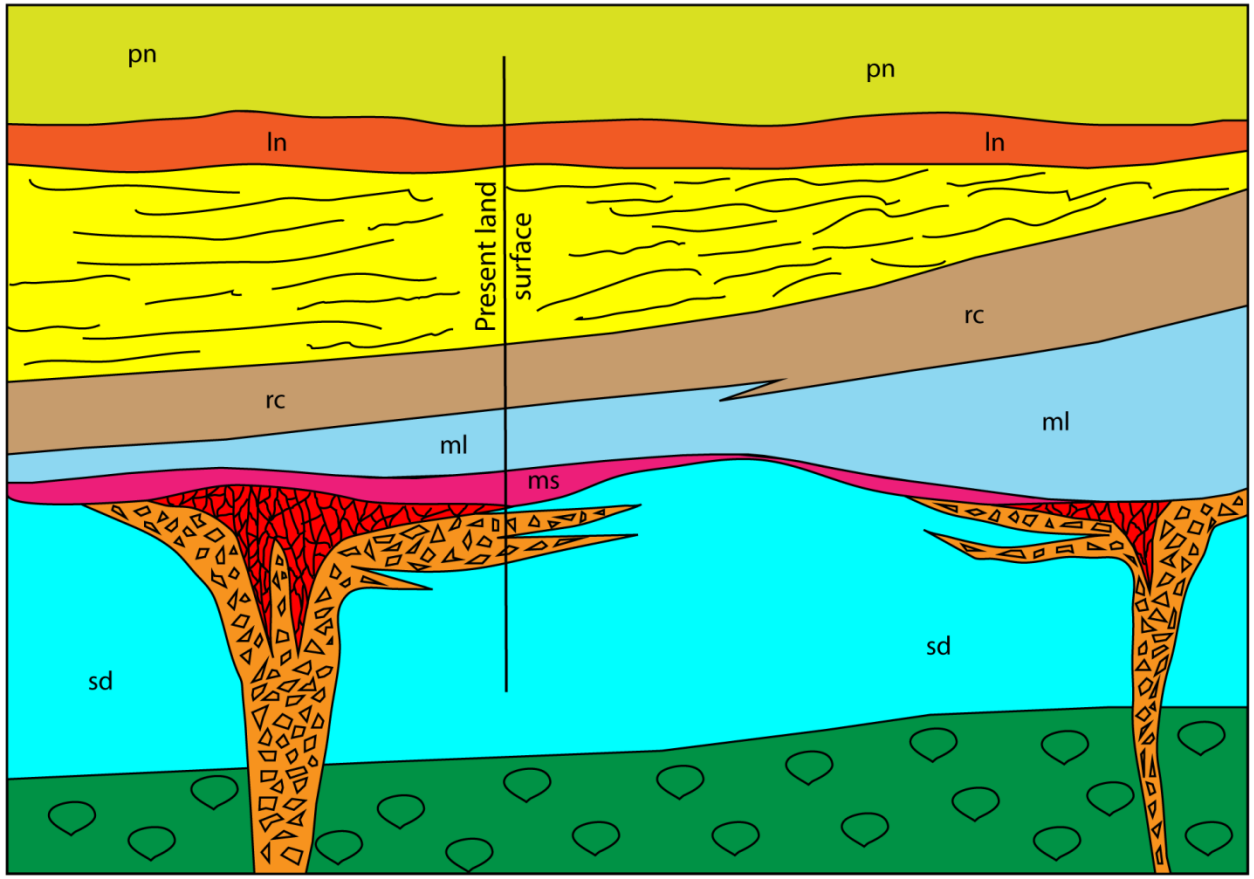
Felsic volcanic breccia

Felsic tuffs

Geology of the Pelican - Crandon area



Schematic pre-deformation stratigraphy of the Crandon massive sulfide deposit



pn — Chert, cherty tuff, tuff

ln — Rhyolite lava flows

Contorted chert and argillite

rc — Debris flows and ash flows

ml — Hangingwall felsic tuffs

ms — Massive sulfide

Stringer mineralization

Footwall volcanic breccia

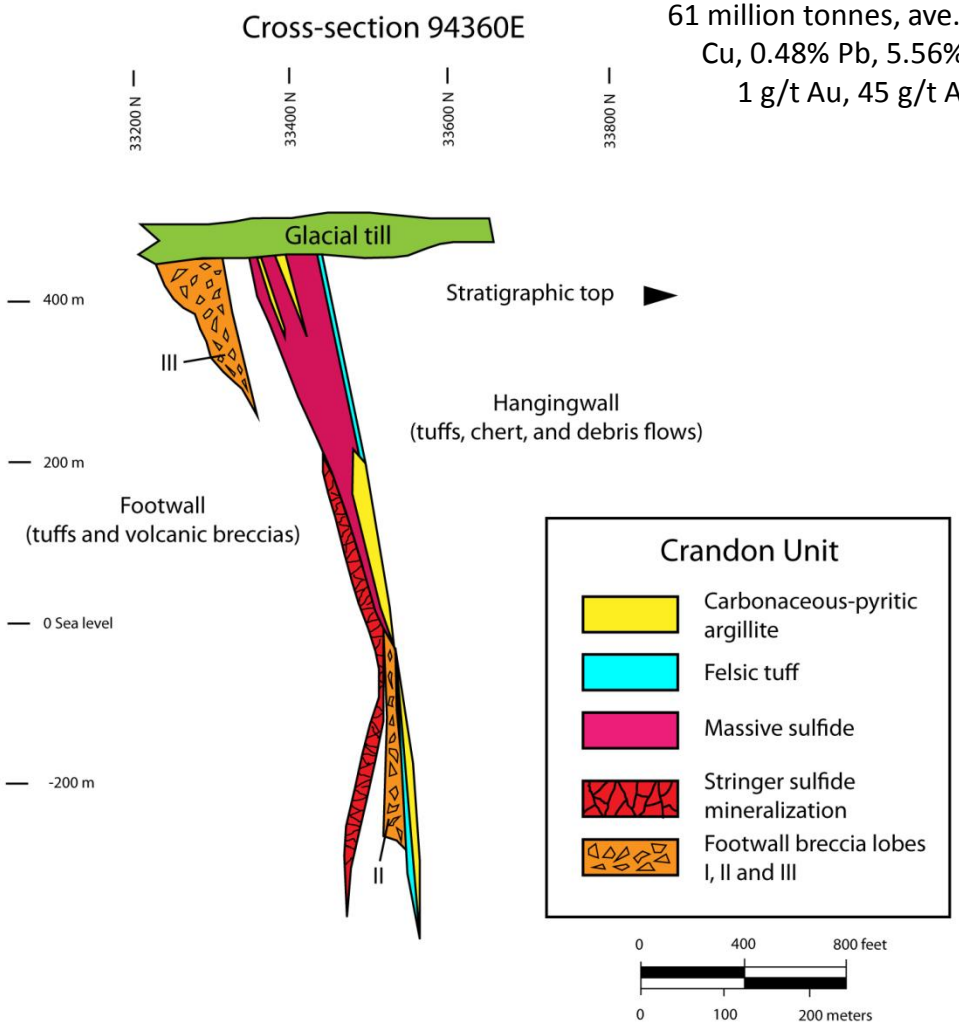
sd — Footwall felsic tuffs

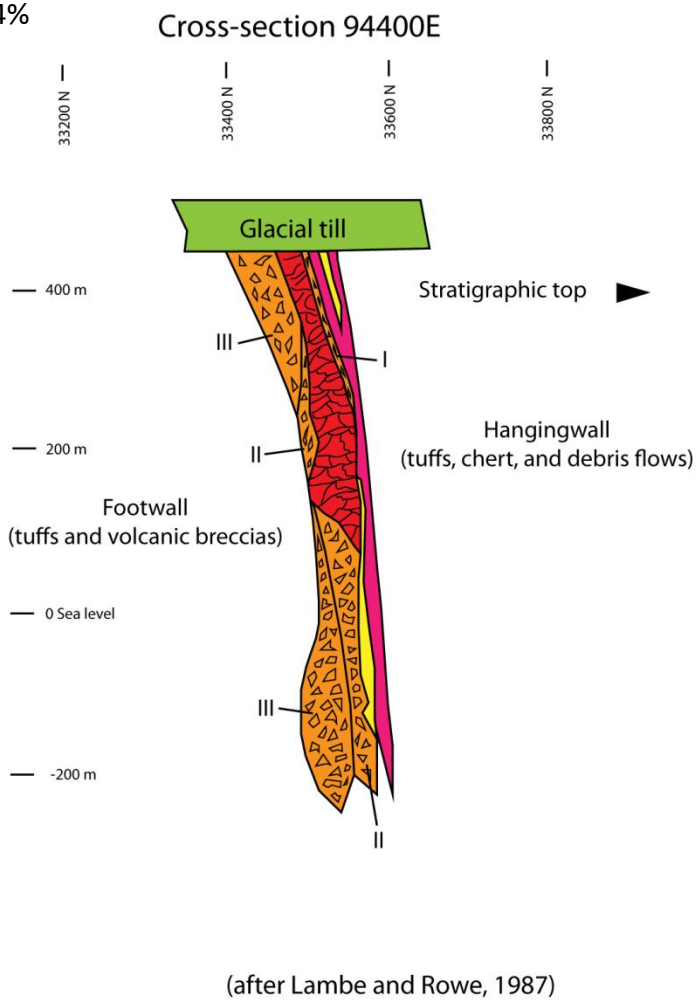
Pillowed basalt lava flows

modified after Lambe and Rowe, 1987

Crandon Massive Sulfide Deposit

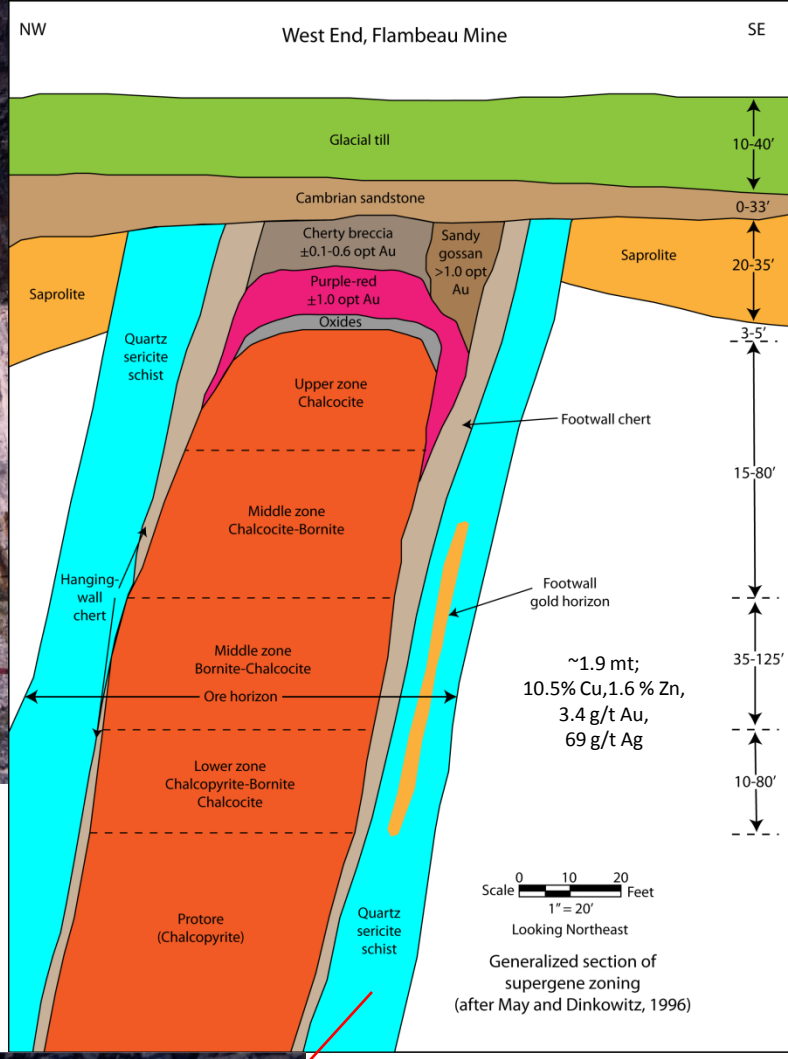
61 million tonnes, ave. 1.04% Cu, 0.48% Pb, 5.56% Zn, 1 g/t Au, 45 g/t Ag

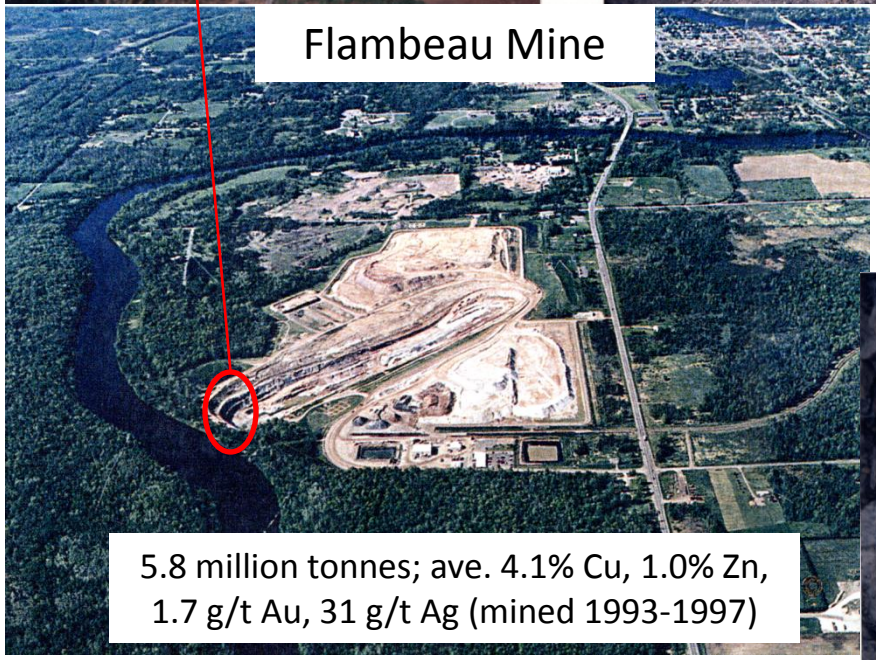




(after Lambe and Rowe, 1987)

Flambeau ore zone





Flambeau Mine

5.8 million tonnes; ave. 4.1% Cu, 1.0% Zn, 1.7 g/t Au, 31 g/t Ag (mined 1993-1997)

Bornite – Cu_5FeS_4
Chalcocite – Cu_2S
Chalcopyrite – $CuFeS_2$
Pyrite – FeS_2

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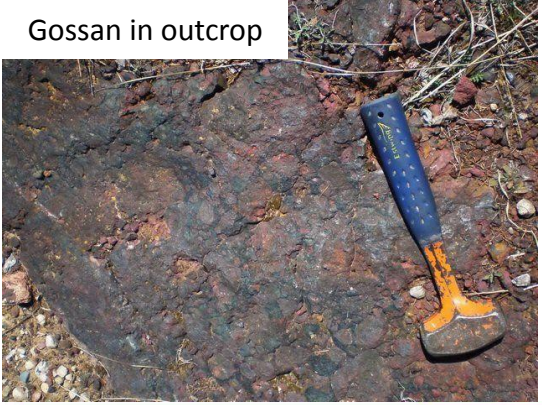
Gossan in outcrop

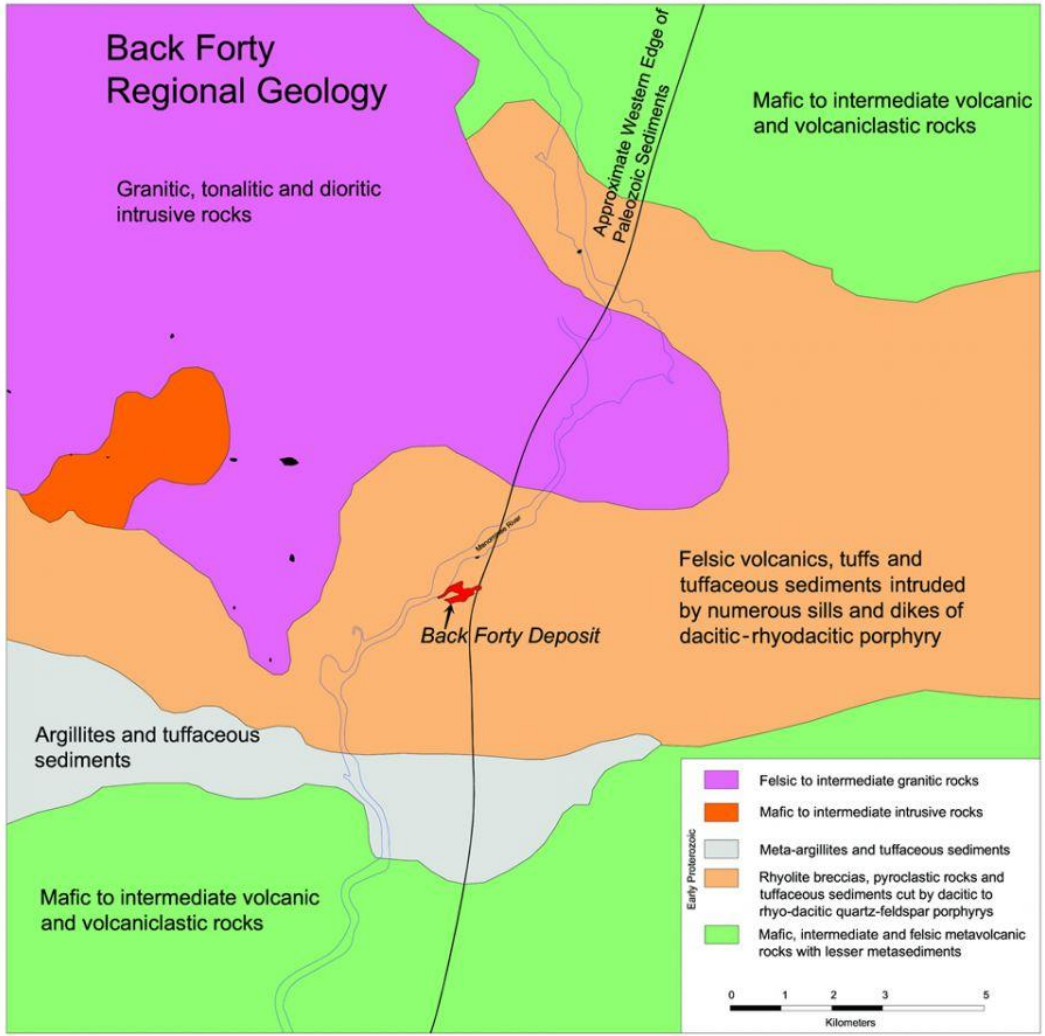


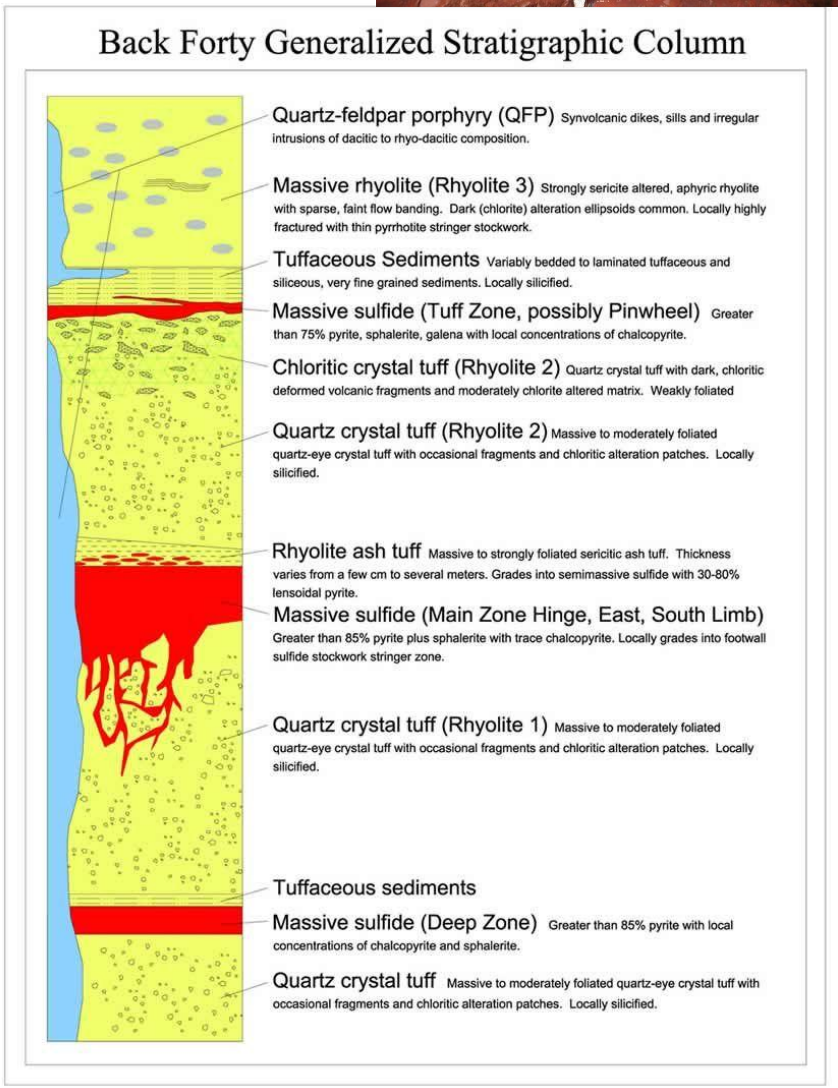
Back Forty Massive Sulfide Deposit

Deposit discovered in 2002 along the east side of the Menominee River in the Upper Peninsula of Michigan

Gossan in drill core

From Aquila Resources website



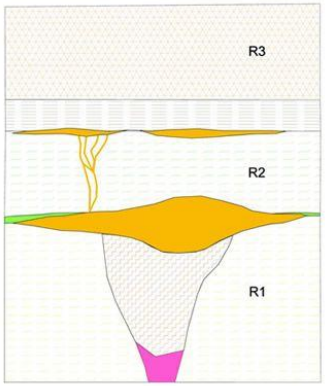


Back Forty Massive Sulfide Deposit

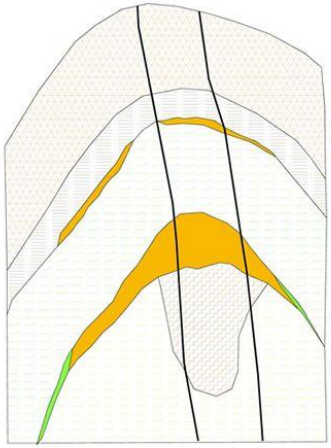
As of 2011-17.9 million tonnes (measured and indicated) with 2.44% Zn, 0.19% Cu, 1.57 g/t Au, 19.60 g/t Ag

Back Forty Genetic Model (idealized cross sections looking west)

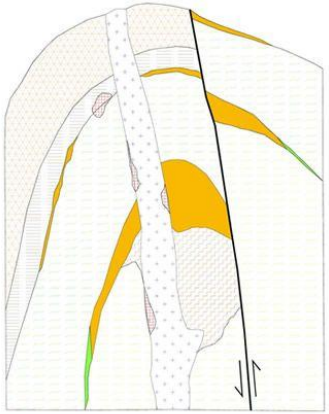
Development of typical Kuroko style/ bimodal felsic VMS pile



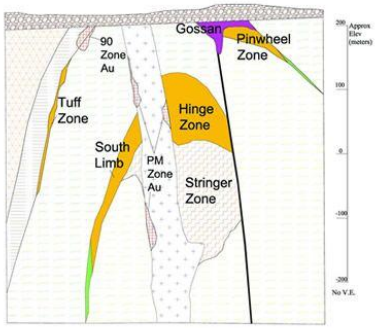
Initial folding, development of major axial planar faults and zones of weakness



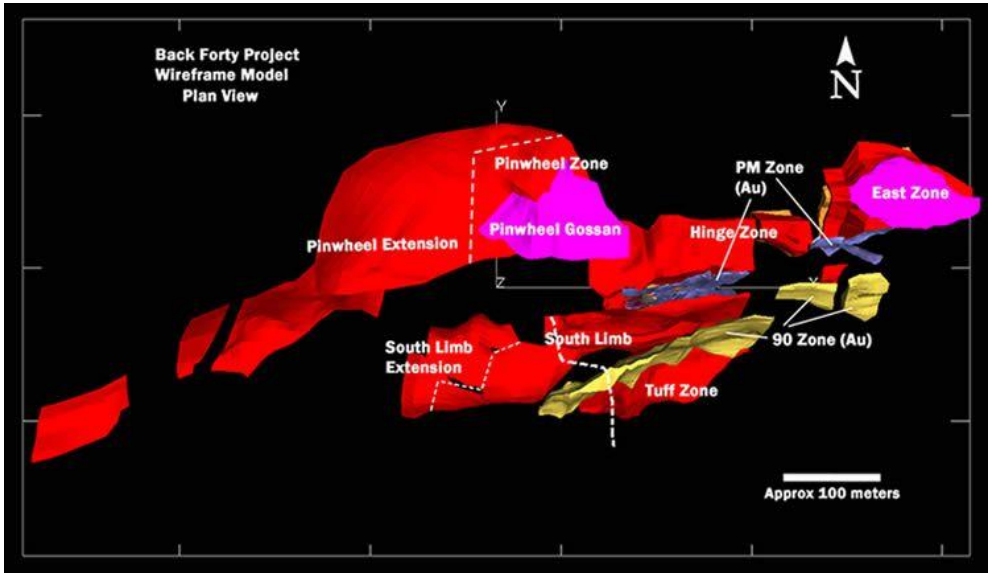
Intrusion of QFP dikes, (probable hydrothermal gold mineralizing event), subsequent faulting

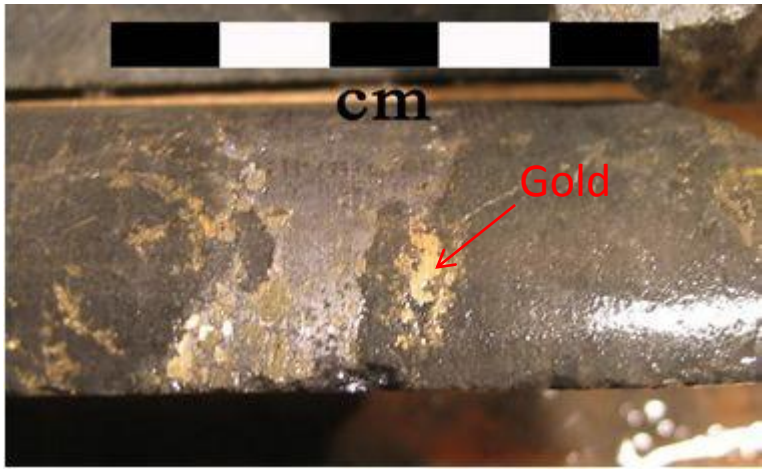


Uplift, erosion, supergene enrichment (gossans)



Overburden, glacial sands and tills
Gossan
Gold mineralization
Quartz-feldspar porphyry dike
Massive rhyolite (R3)
Tuffaceous sediments
Rhyolite crystal tuff (R2)
Rhyolite ash tuff
Massive sulfide
Sulfide stringer
Rhyolite crystal tuff (R1)





From Aquila Resources website

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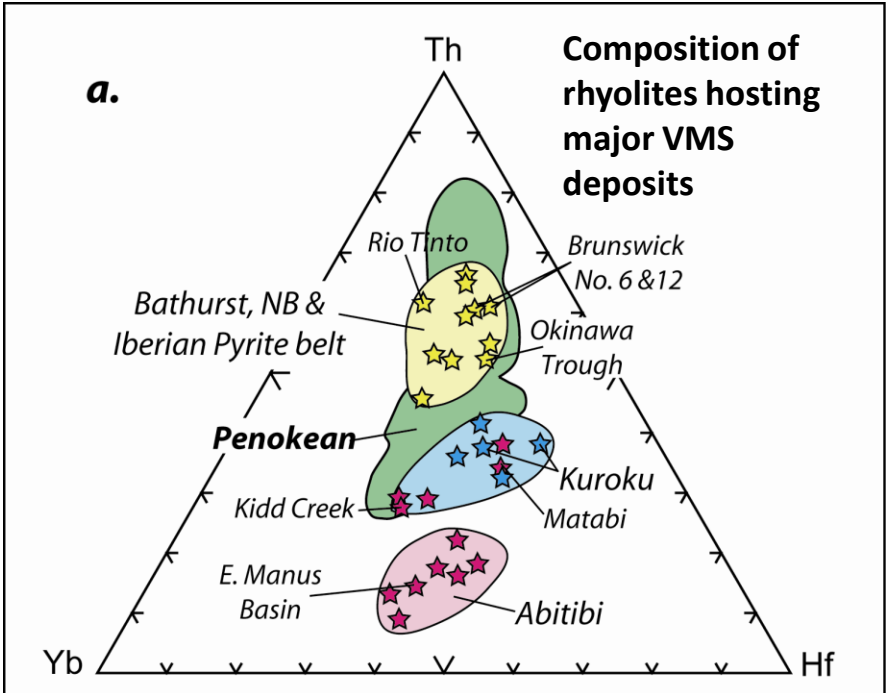
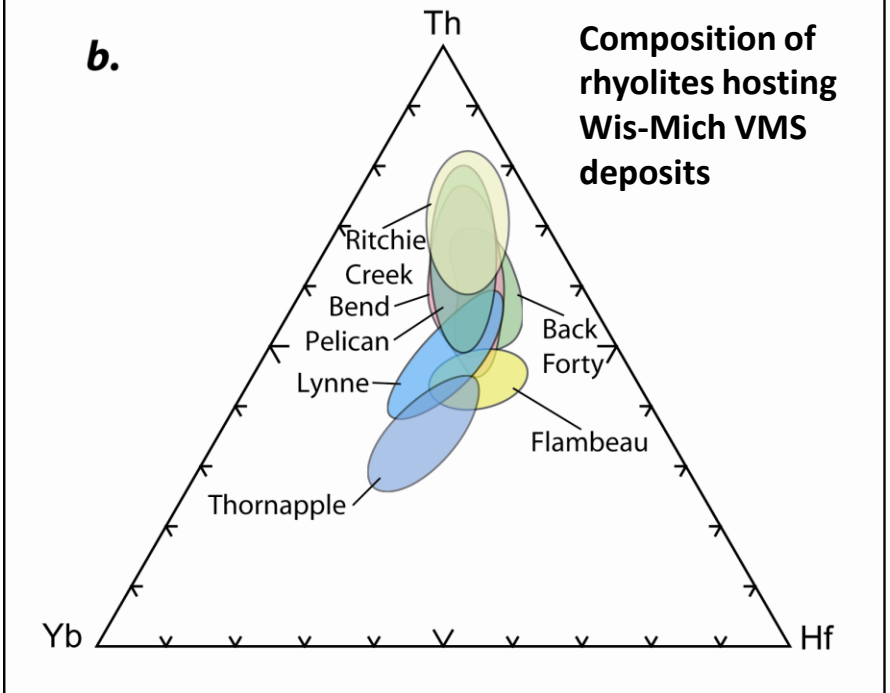
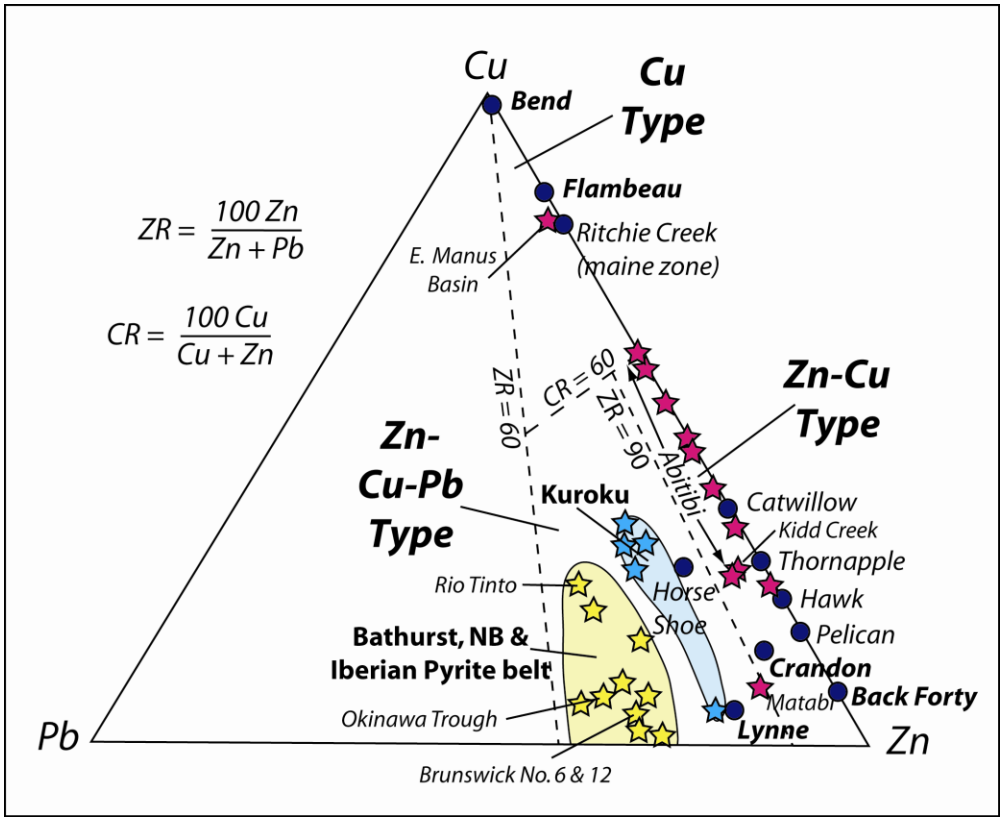


Composition of rhyolites hosting major VMS deposits



Composition of rhyolites hosting Wis-Mich VMS deposits

Cu – Zn – Pb in Massive Sulfide Deposits



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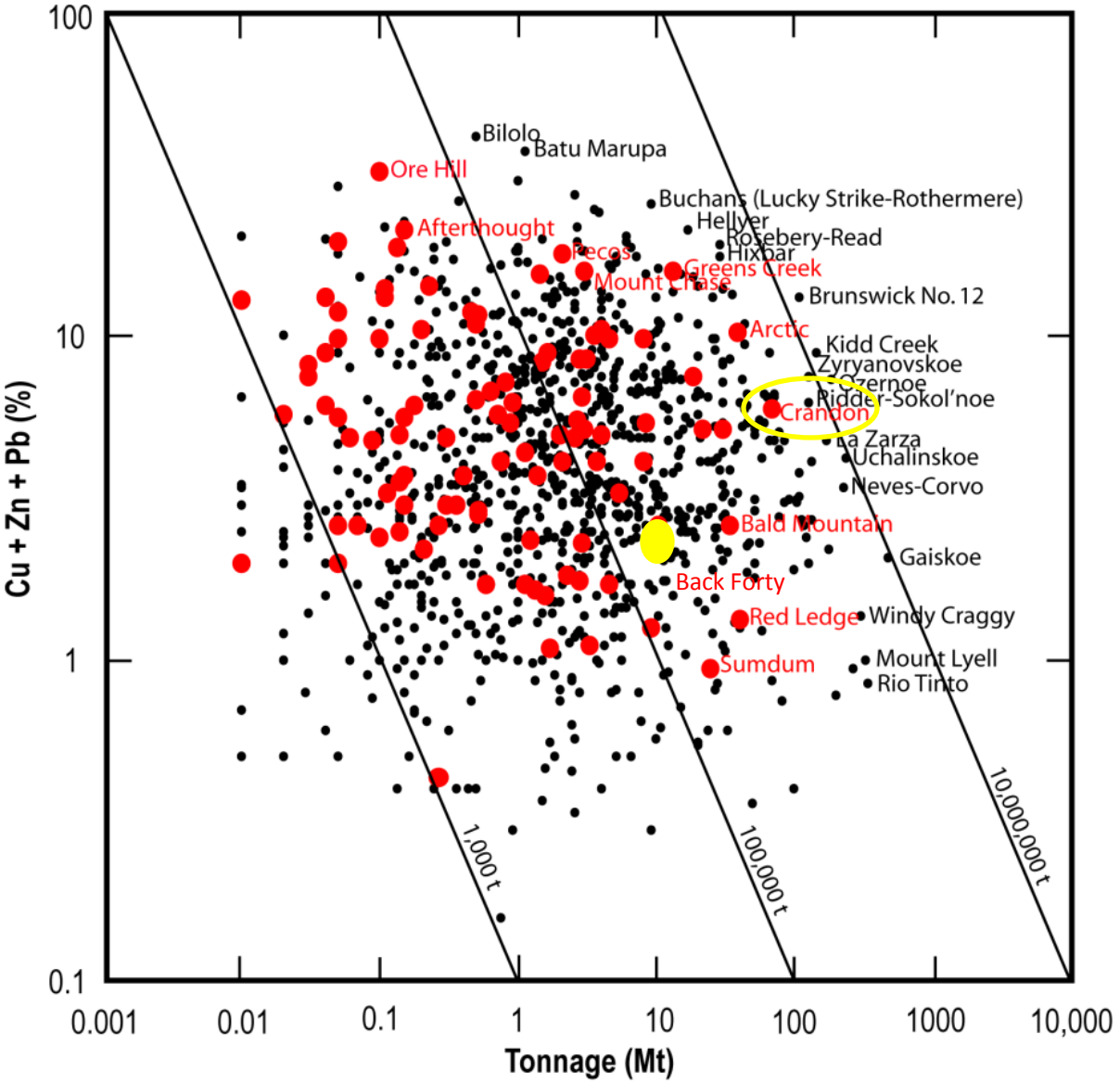
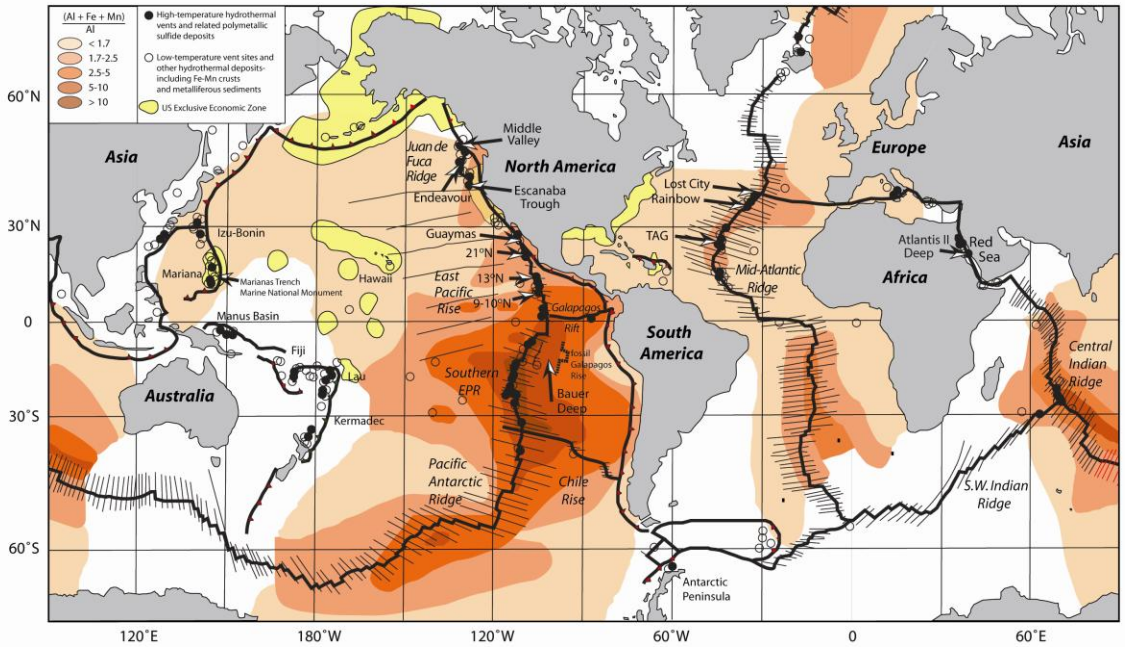


Fig. 2.1. Grade and tonnage of volcanogenic massive sulfide deposits. Data are shown for 1,021 deposits worldwide. U.S. deposits are shown as red dots. Data from Mosier and others, 2009.

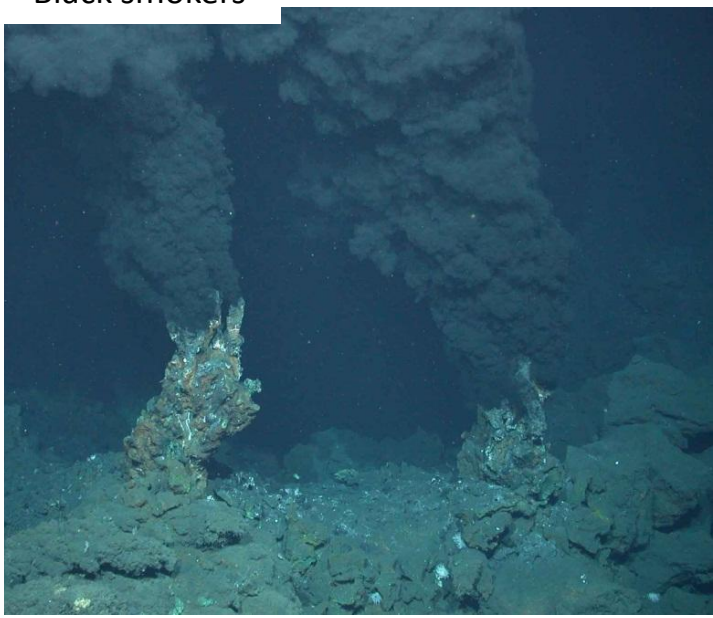
(from Shanks and others, 2010)

Distribution of Seafloor Metalliferous Sediment, Massive Sulfide Deposits, and Hydrothermal Vents

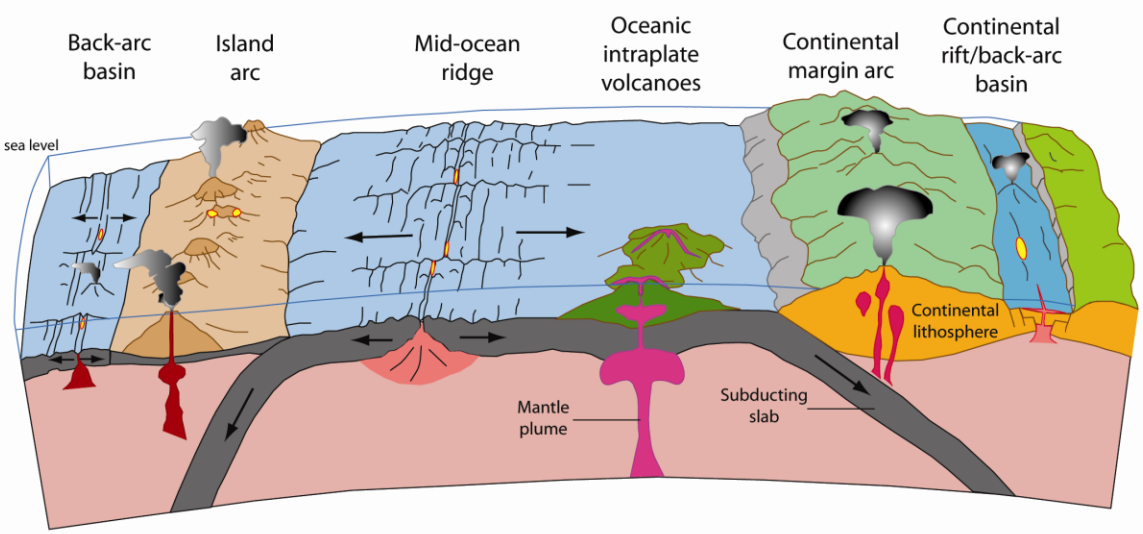
(modified after Hannington and others (2007) and Bostrom and others (1969)



Black smokers

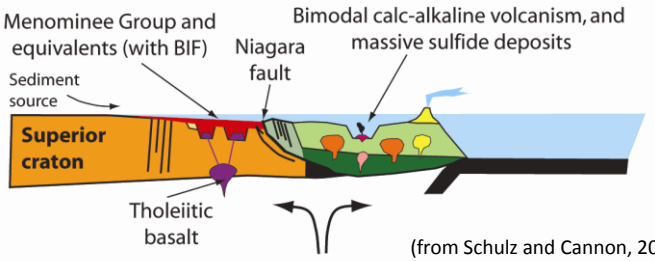


Tectonic settings of modern volcanogenic massive sulfide deposits



(from Shanks and others, 2010)

~1875 Ma: Accretion of the Pembine-Wausau Terrane, subduction flip and back-arc basin development



(from Schulz and Cannon, 2007)

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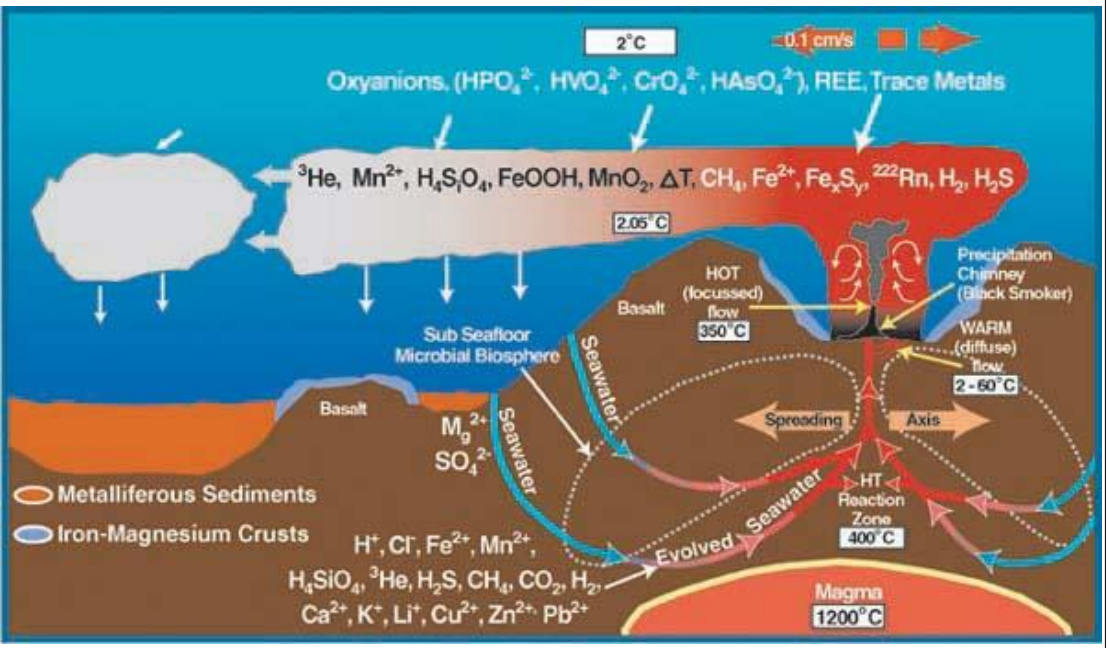
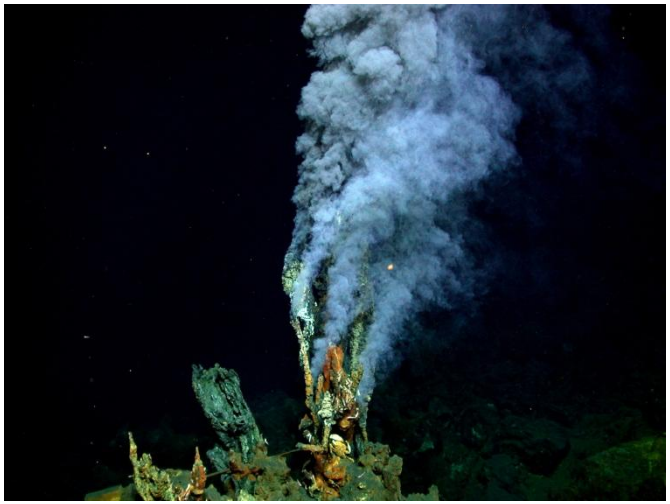
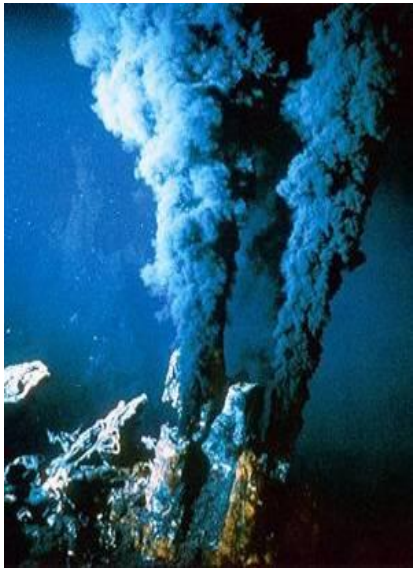
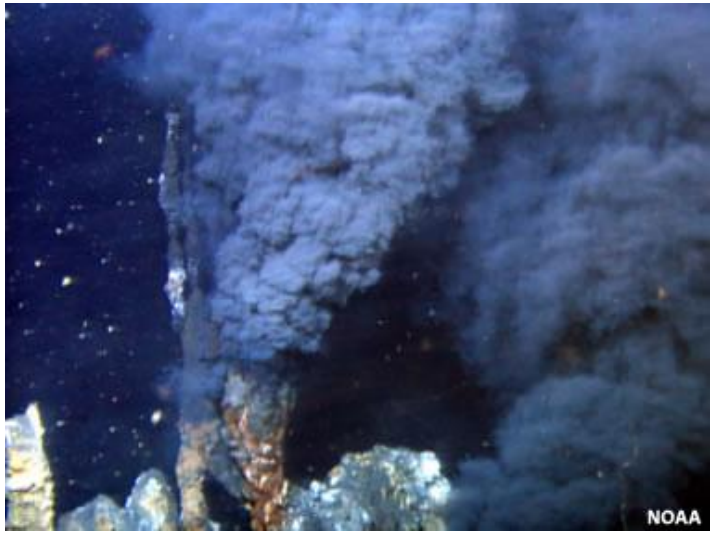


(from Shanks and others, 2010)







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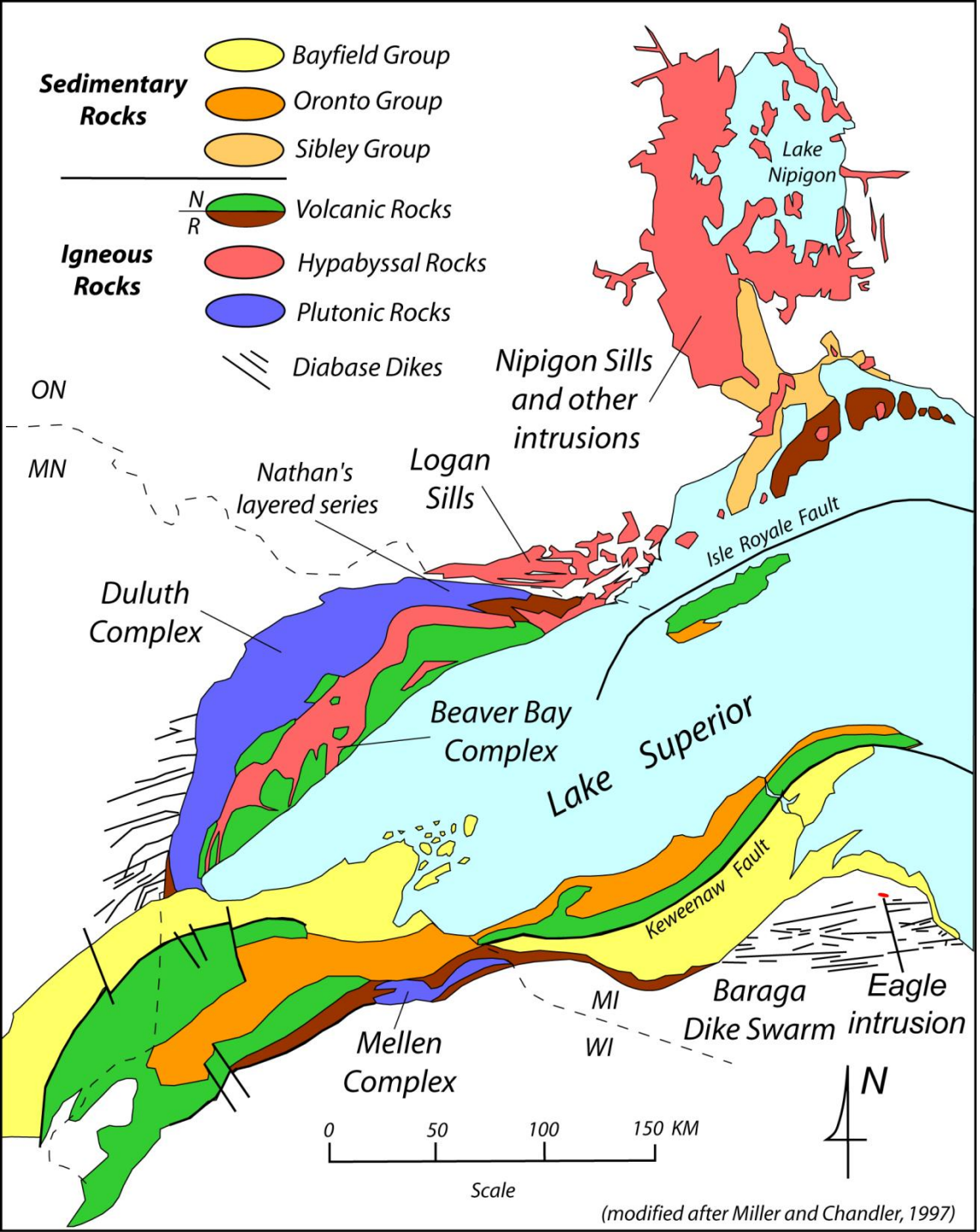
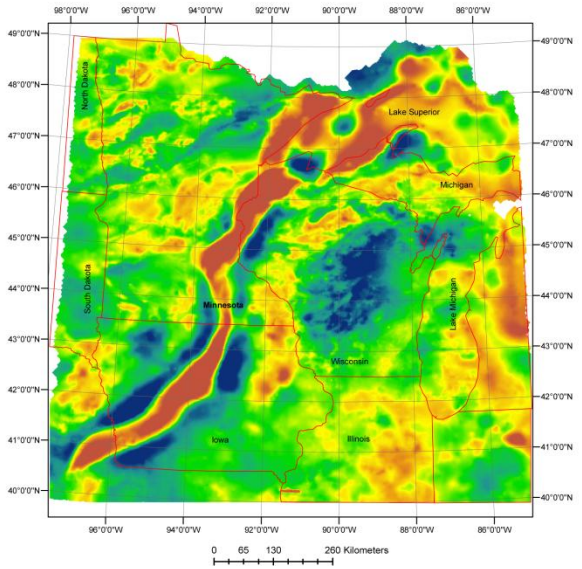
Midcontinent Rift System





Bouguer Gravity Anomaly

Milligals

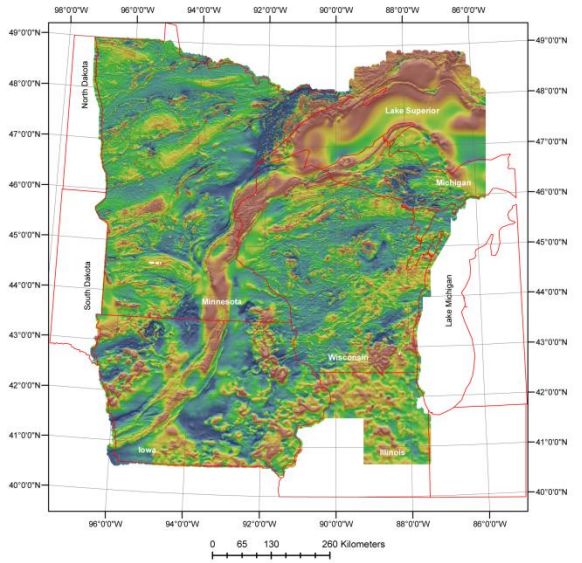
High : 67.668045

Low : -113.232445

Bouguer gravity anomaly map of the north-central United States. Data compiled by David L. Daniels and Stephen L. Snyder of the U.S. Geological Survey from various sources. Gravity station coverage over much of Minnesota and Wisconsin is 1-2 miles (1.6-3.2 km); in other areas the coverage is commonly 3-6 miles (4.8-9.6 km) or wider. For more detailed descriptions of the original data sets the reader is referred to:

U.S. Geological Survey Crustal Imaging and Characterization Team Web Site

Gravity data in Minnesota and Wisconsin were largely acquired by the Minnesota Geological Survey, the Wisconsin Geological and Natural History Survey, and Northern Illinois University.



Shaded-Relief Total Magnetic Intensity Anomaly

NanoTesla

High : 30661.777344

Low : -9982.036133

Shaded-relief map of the total magnetic intensity anomaly for the north-central United States. Data compiled by David L. Daniels and Stephen L. Snyder of the U.S. Geological Survey from various sources. Most of Minnesota was flown with a line spacing of 400 meters and an elevation (above land surface) of 150 meters, whereas much of Wisconsin was flown at line spacings of 400-800 meters and elevations between 150 to 305 meters. The remaining areas were generally flown at flight line spacings of 1600 meters or wider and at elevations of 305 meters or greater. Following gridding, all data were continued to a common elevation of 305 meters and merged. For more detailed descriptions of the original data sets the reader is referred to:

U.S. Geological Survey Crustal Imaging and Characterization Team Web Site

Aeromagnetic data in Minnesota were acquired by the Minnesota Geological Survey (MGS), with support from the Legislative Commission on Minnesota Resources. Aeromagnetic data in Wisconsin were acquired with support from the Wisconsin Geological and Natural History Survey and the U. S. Geological Survey. Hillshade illumination is from the North with an inclination of 30 degrees.

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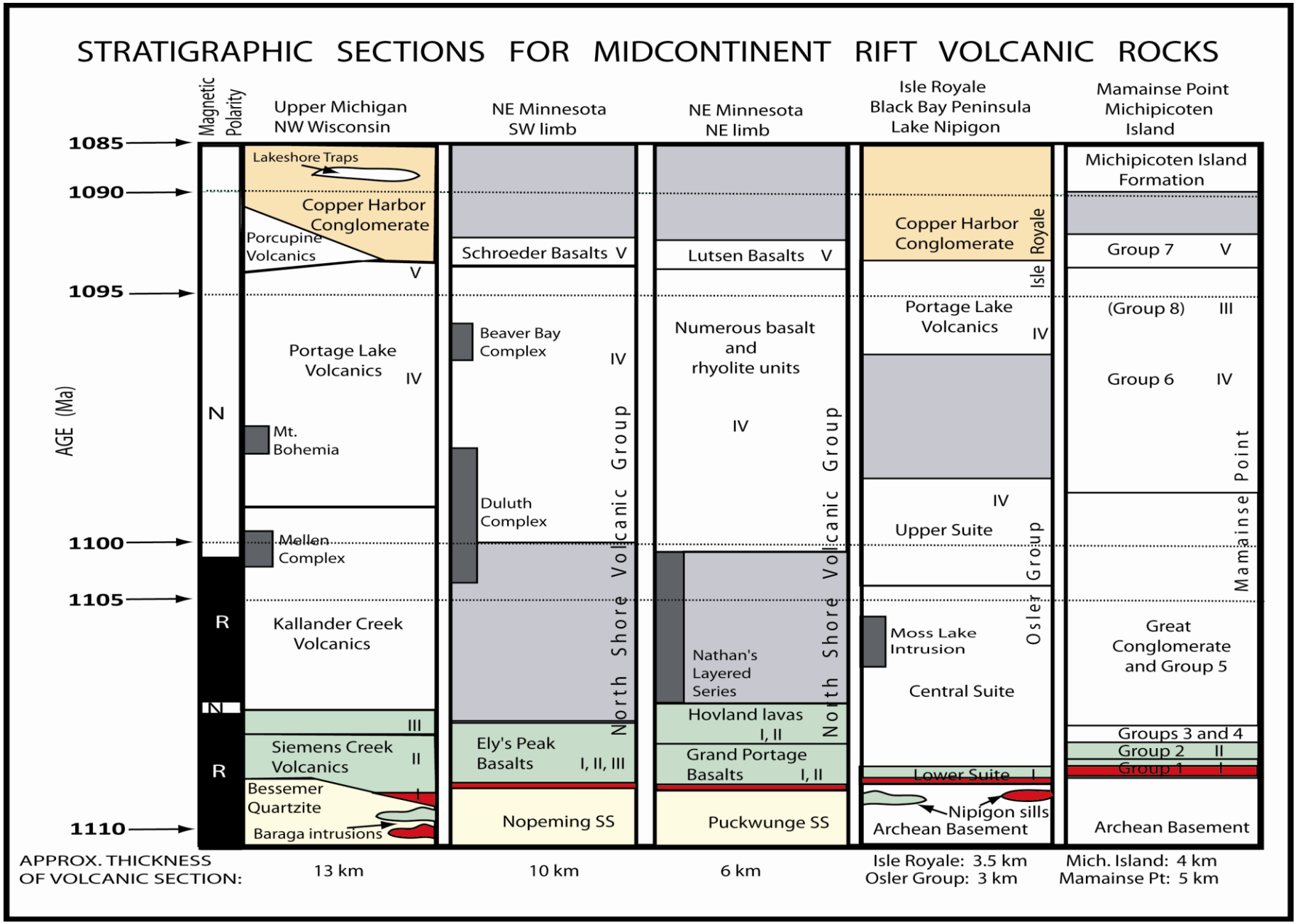

(modified after Nicholson and others, 1997)

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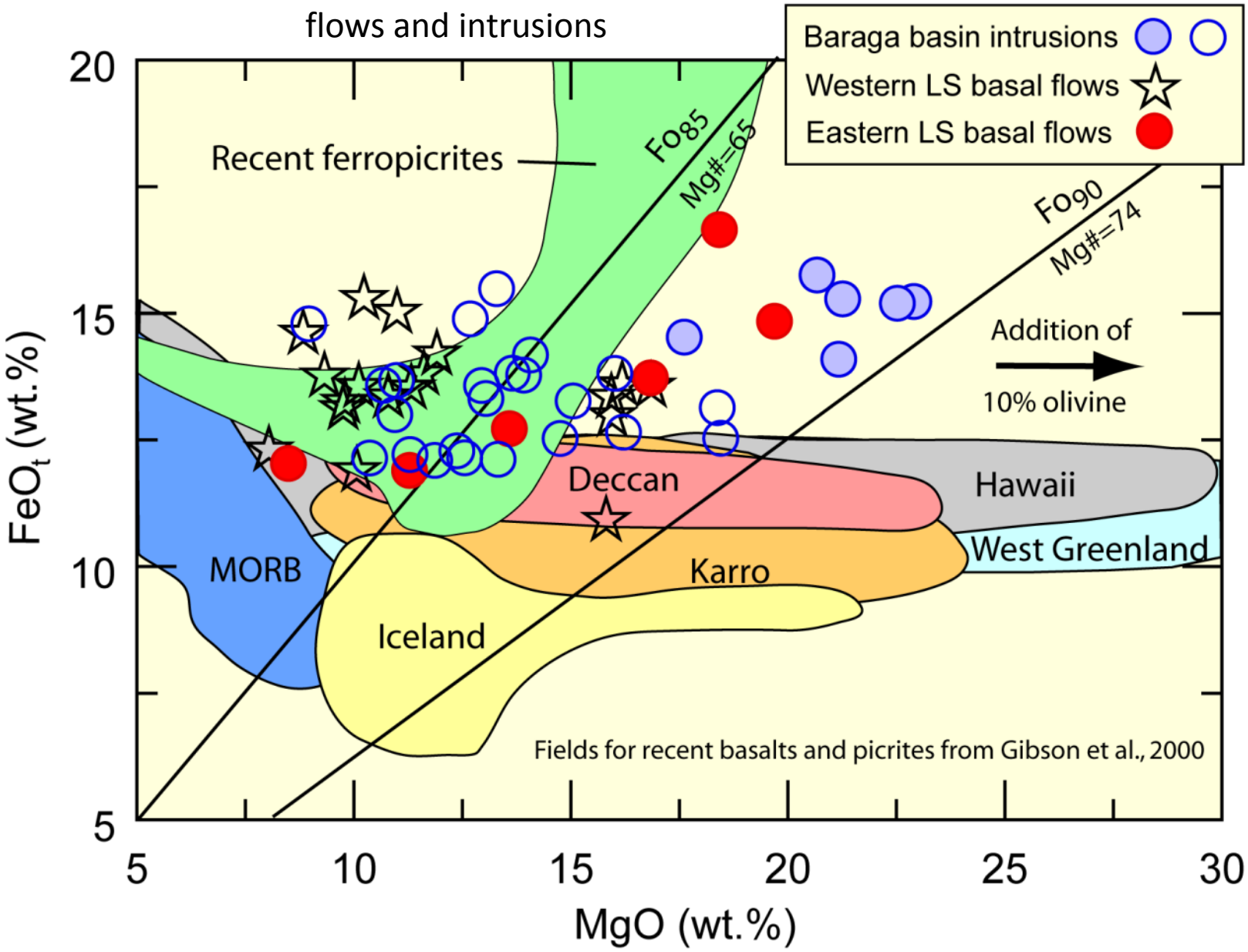
Diabase sills (Thunder Bay-Nipigon area)

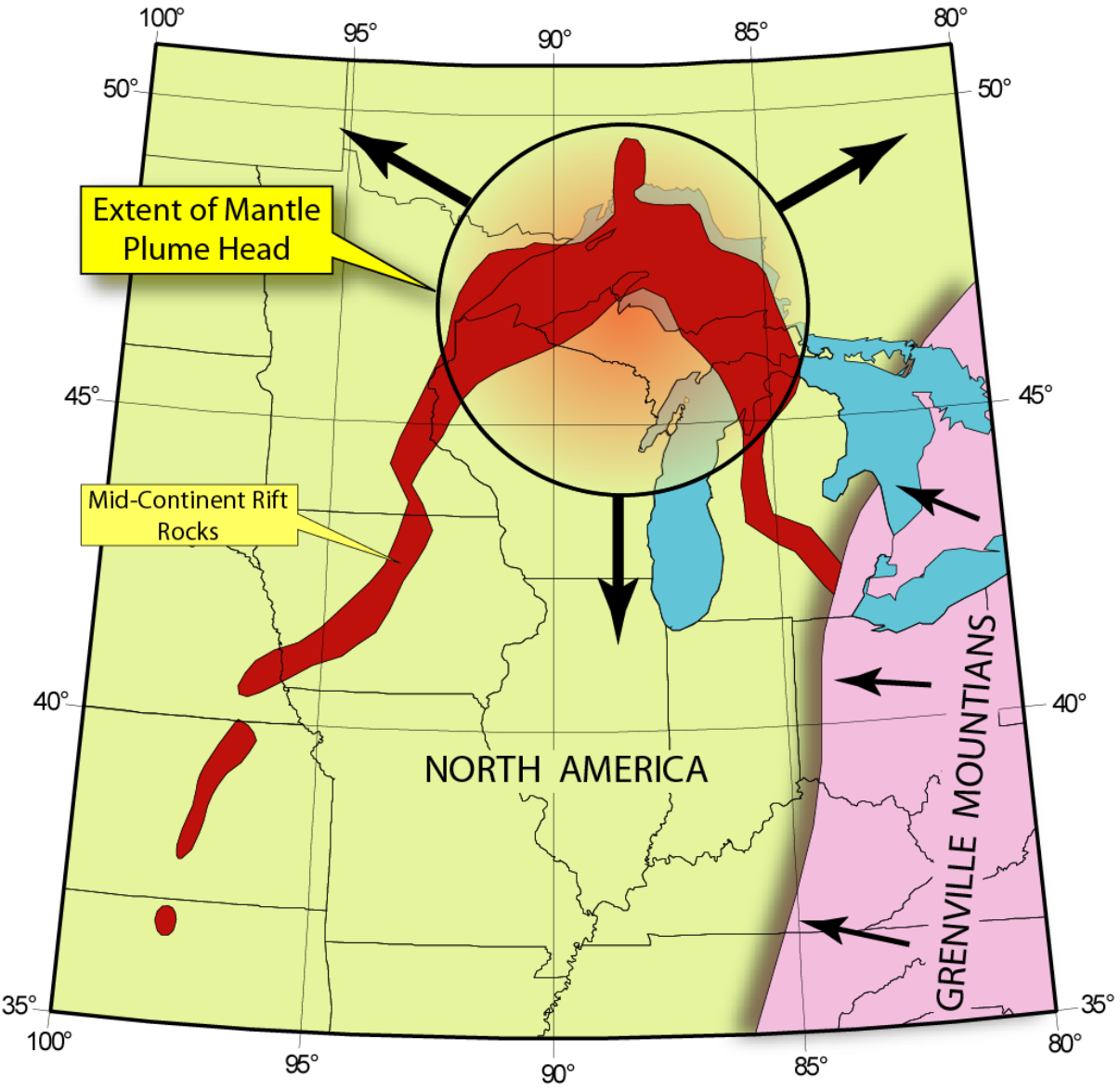
Diabase texture

Porphyritic (plagioclase) diabase

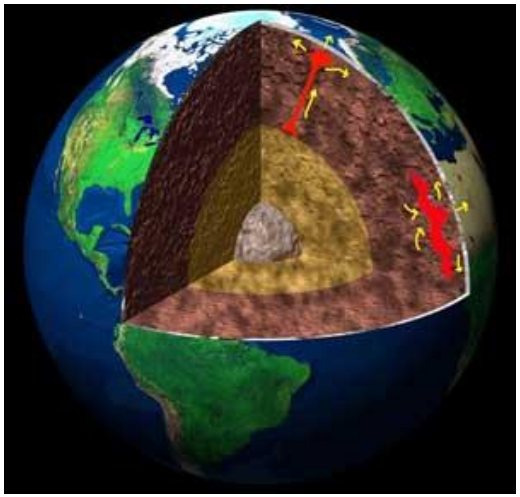
Diabase dike

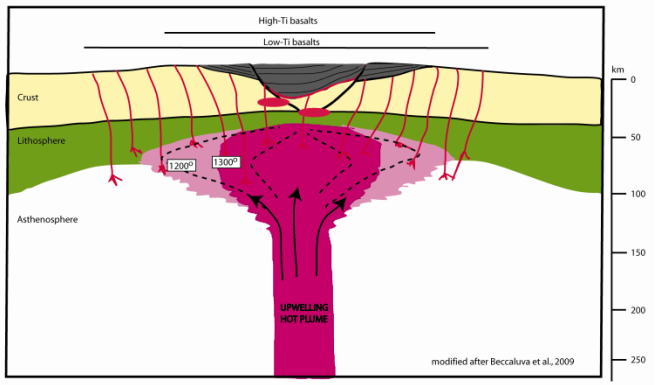
Composition of early (~1107 Ma) lava flows and intrusions





At about 1.1 billion years ago a mantle plume was centered under Lake Superior and gave rise to the Midcontinent Rift.





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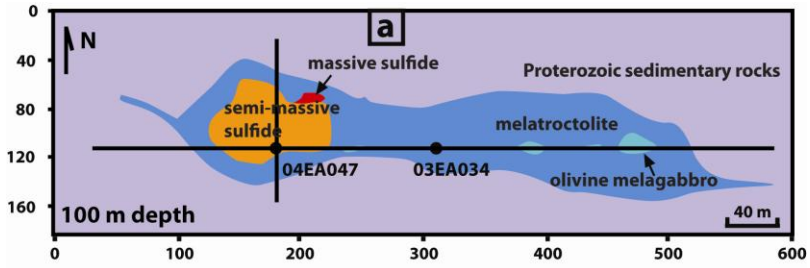
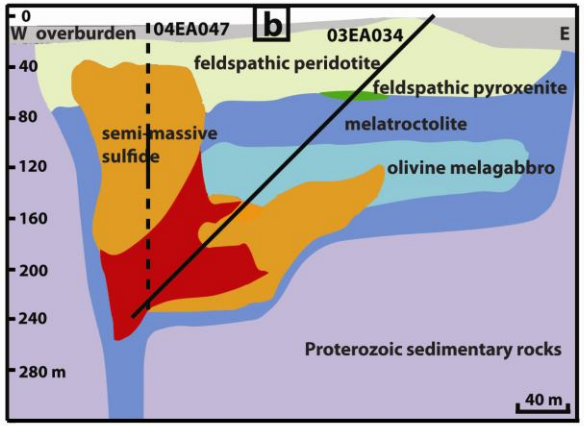
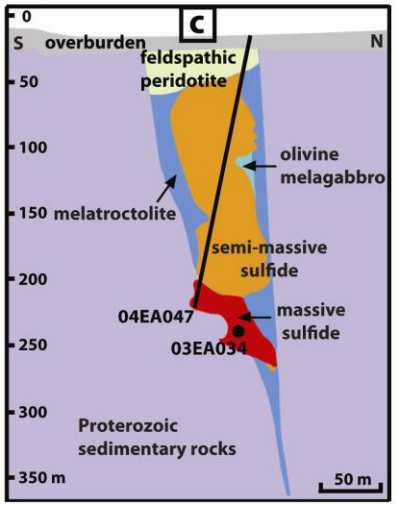
Eagle Ni-Cu-PGE sulfide deposit

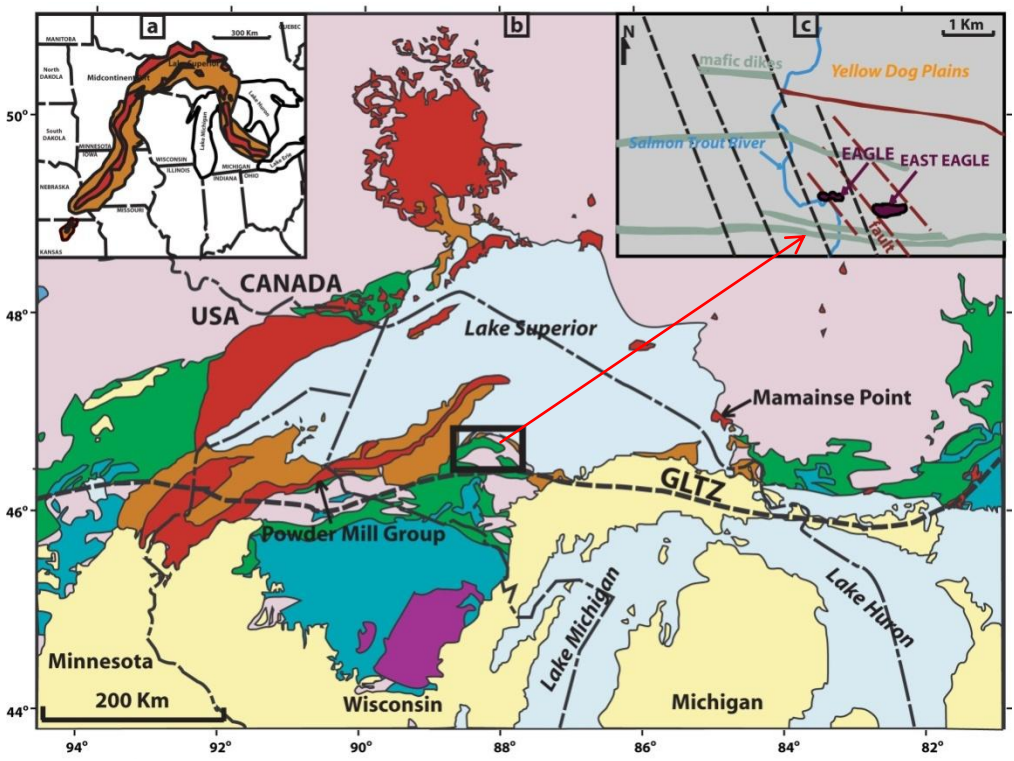
Eagle dike-like intrusion; ~480 m long, ~100-200 m wide







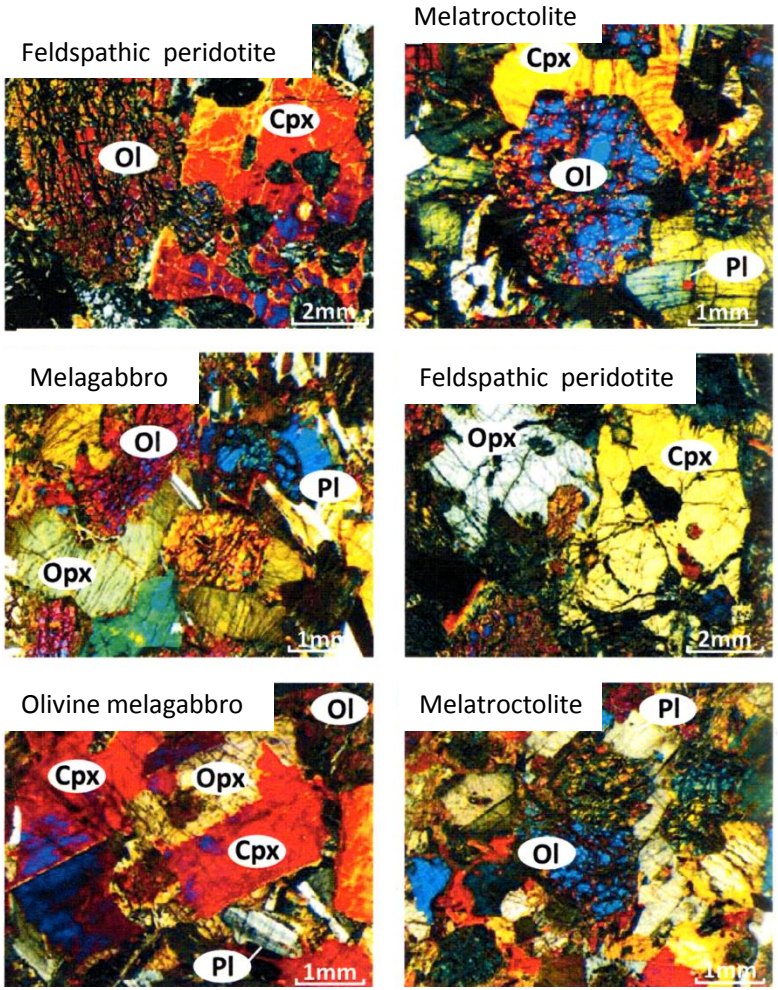
From Ding and others, 2011



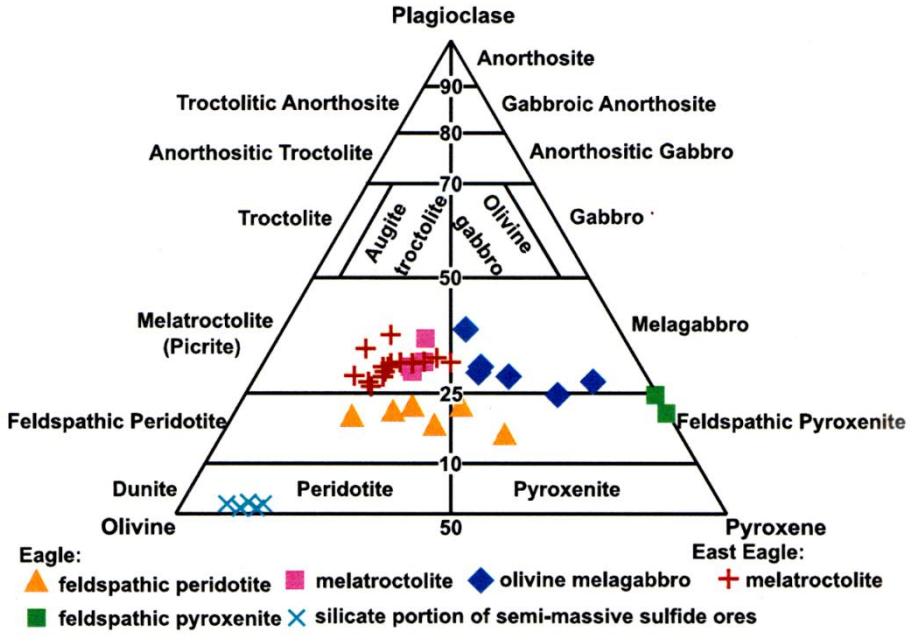
Eagle peridotite

Eagle Ni-Cu-PGE sulfide deposit

Rock textures and mineralogy



From Ding and others, 2010

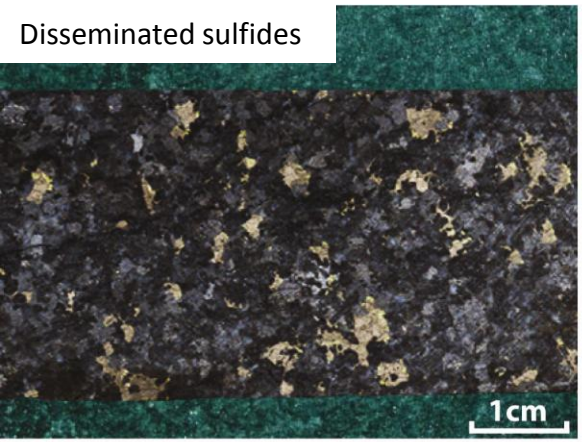


Ol = Olivine
Cpx = Clinopyroxene
Opx = Orthopyroxene
Pl = Plagioclase

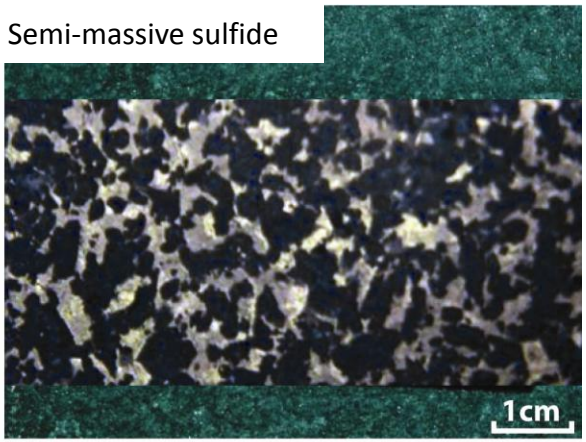
Eagle Ni-Cu-PGE sulfide deposit

4.05 million tonnes; ave. 3.57% Ni, 2.91% Cu,
0.10% Co, 0.28 g/t Au, 0.73 g/t Pt, 0.47% g/t Pd)

Disseminated sulfides

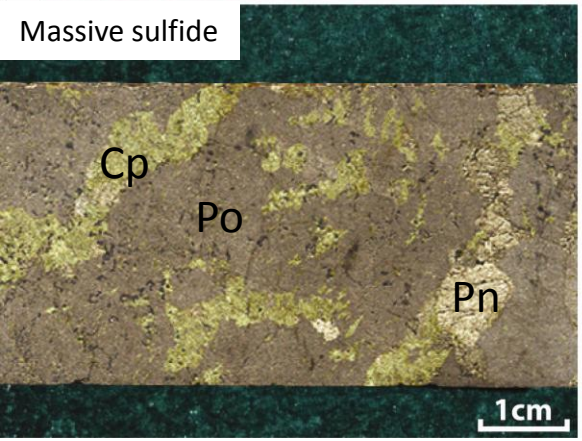


Semi-massive sulfide

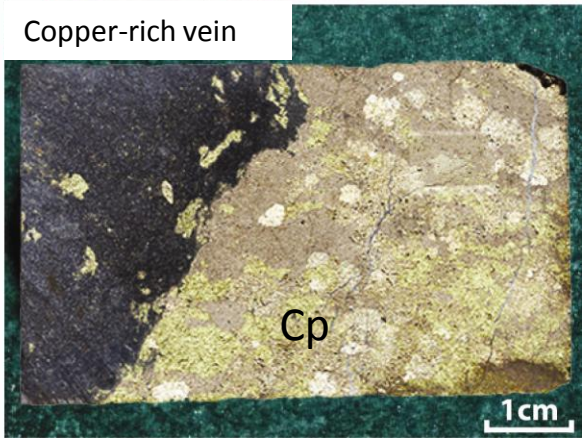


Massive sulfide

Massive sulfide



Copper-rich vein



From Ding and others, 2011

Cp = Chalcopyrite ($CuFeS_2$)
Po = Pyrrhotite ($Fe_{1-x}S$)
Pn = Pentlandite ($(Fe, Ni)_9S_8$)

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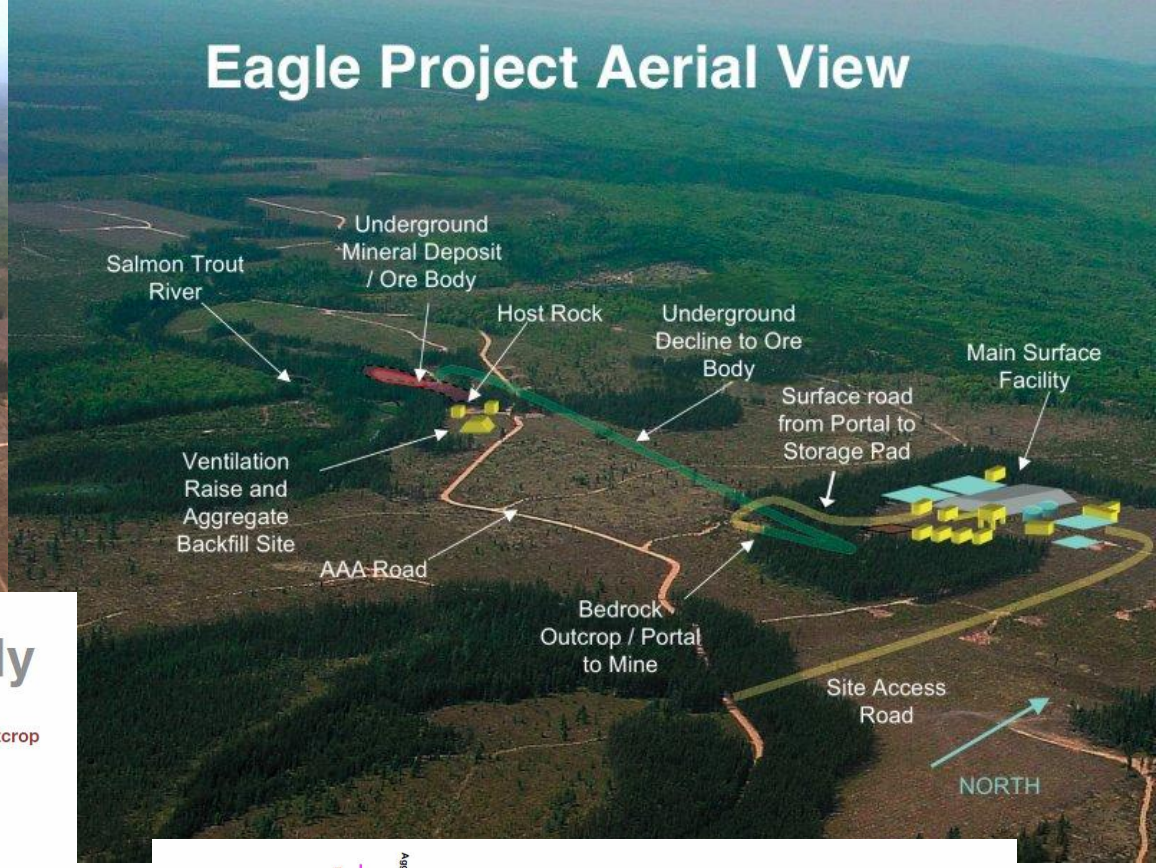
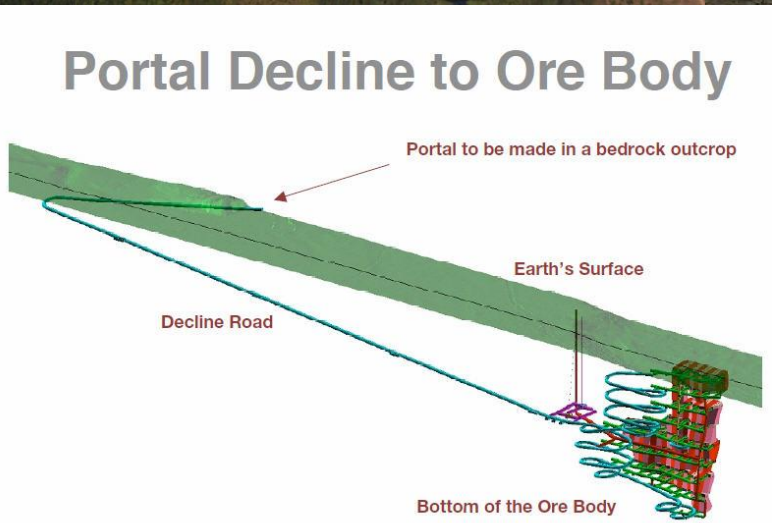
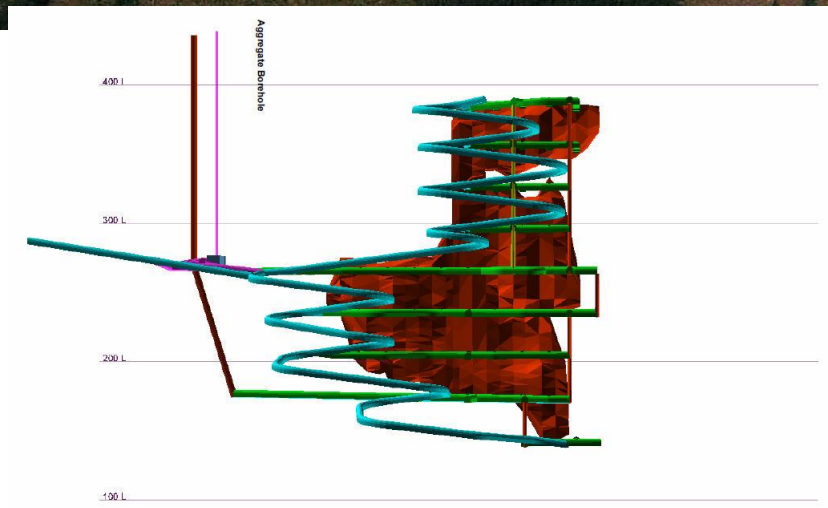
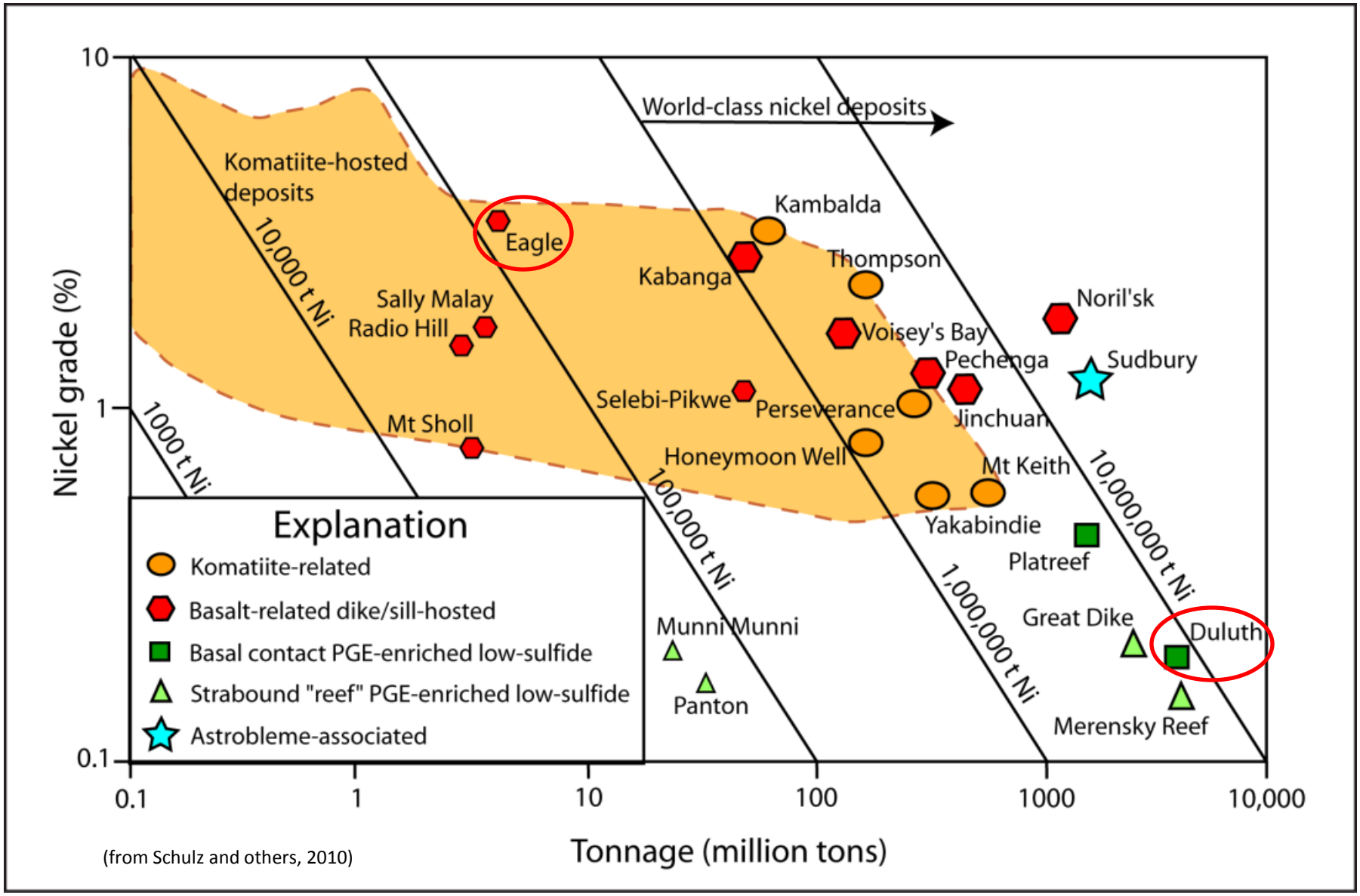






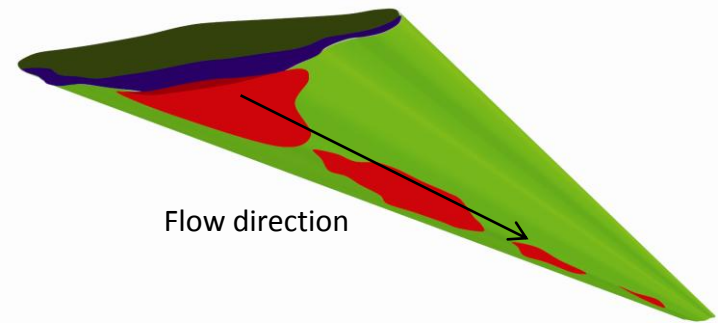
(from Kennecott Eagle Minerals website)

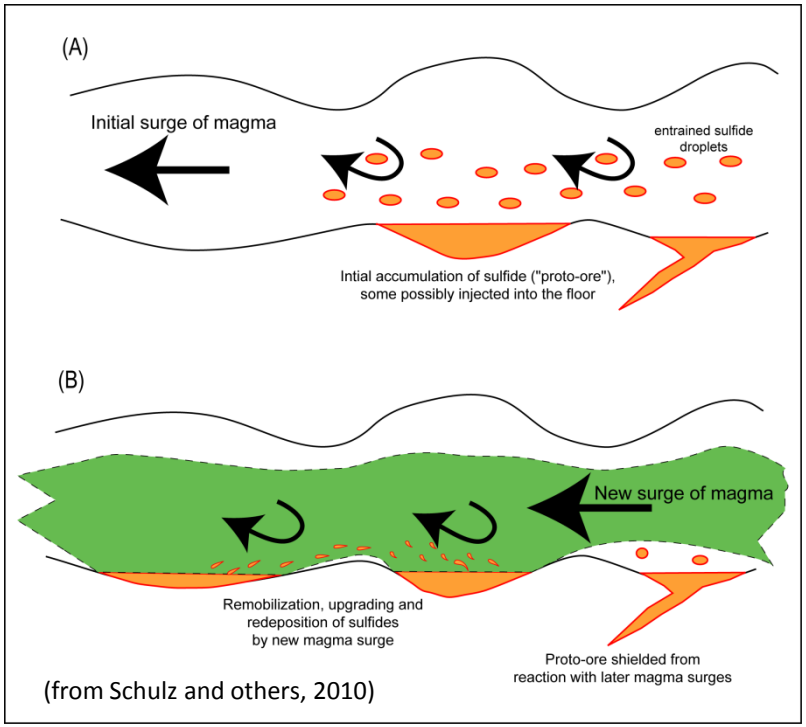


(from Schulz and others, 2010)

Conduit-type magmatic Ni-Cu-PGE sulfide deposits

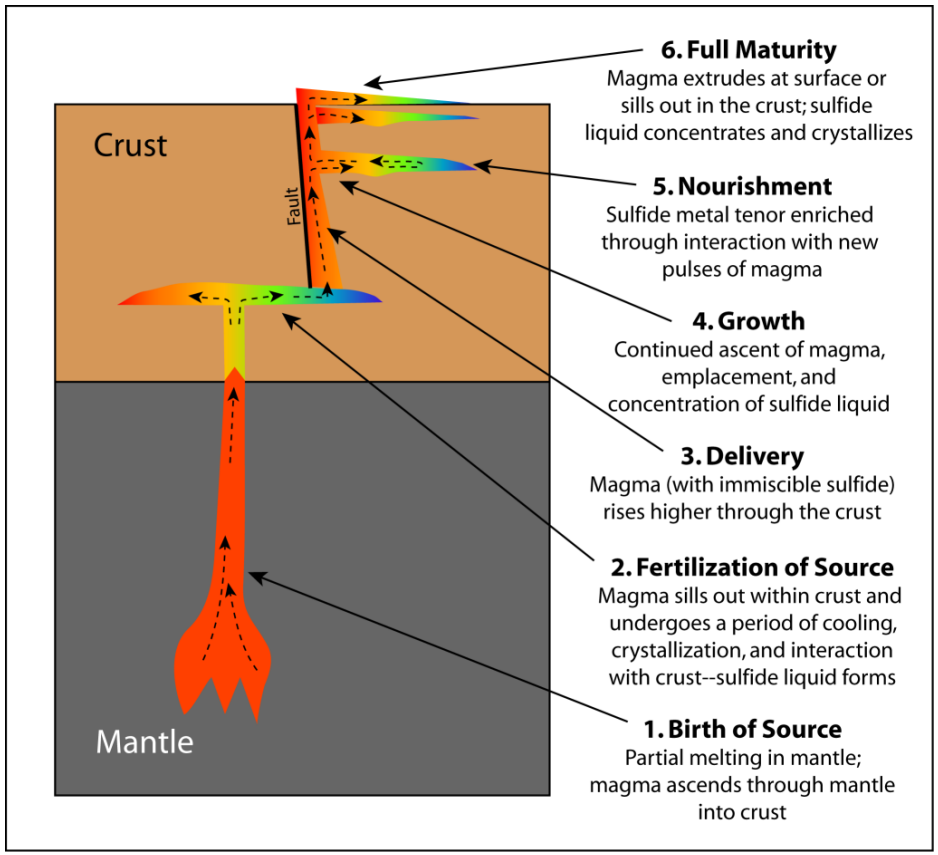
Deposit formation involves repeated injections of basaltic magma and accumulation of sulfides

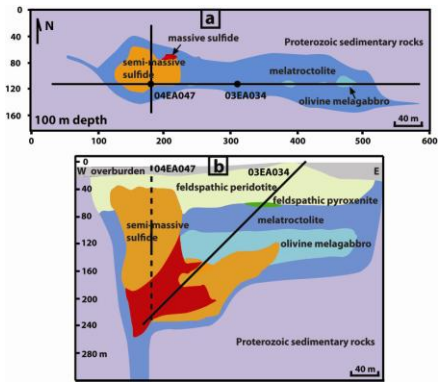




(from Schulz and others, 2010)

Life cycle of a conduit-type sulfide deposit system





Eagle deposit
(from Ding and others, 2011)

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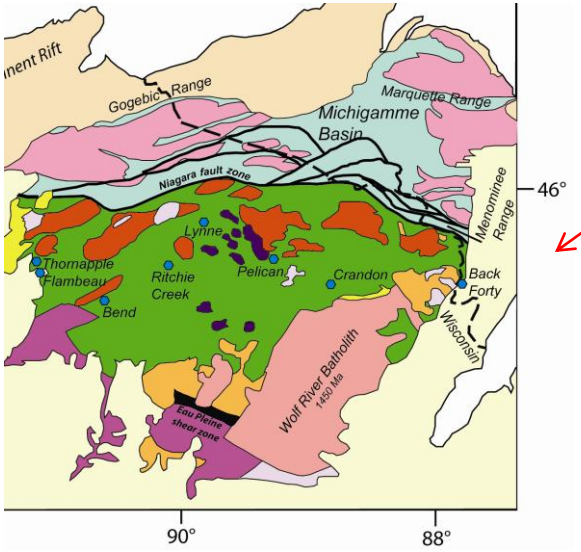
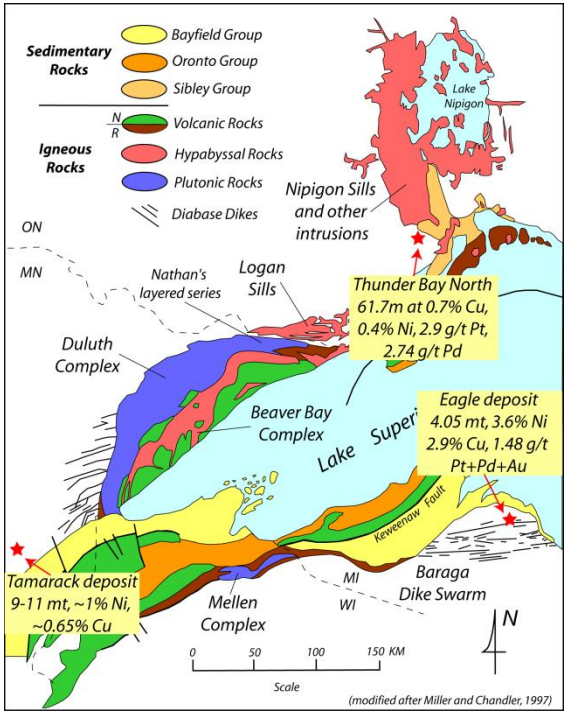
Volcanogenic Zn-Cu-Au massive sulfide deposits

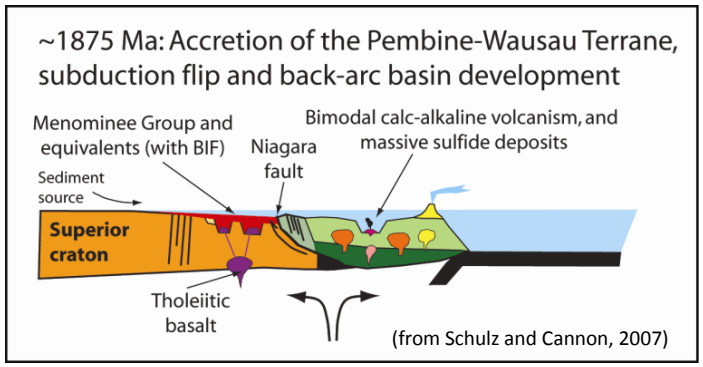


In Summary

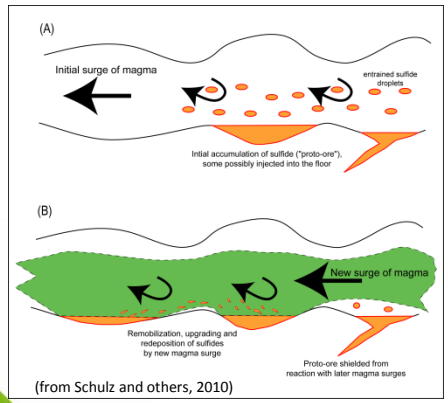
Two types of sulfide deposits

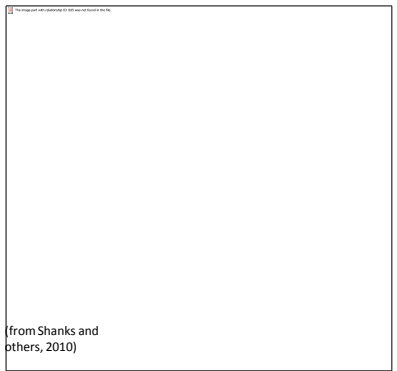
Conduit-type magmatic Ni-Cu-PGE sulfide deposits

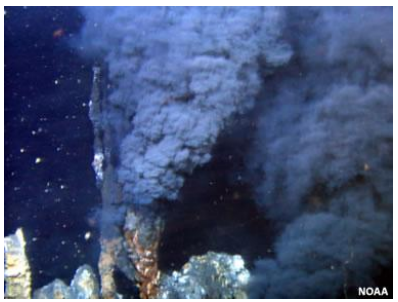


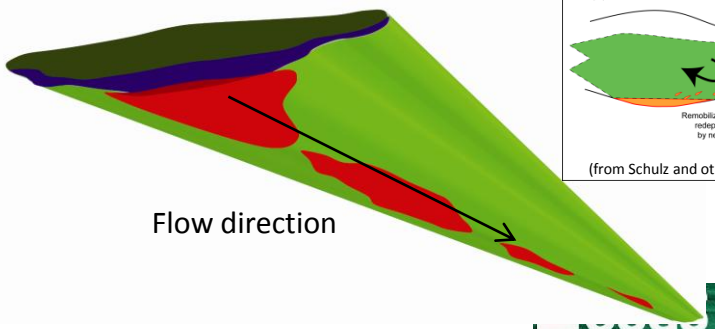


Deposit formation involves repeated injections of basaltic magma and accumulation of sulfides









Thank you