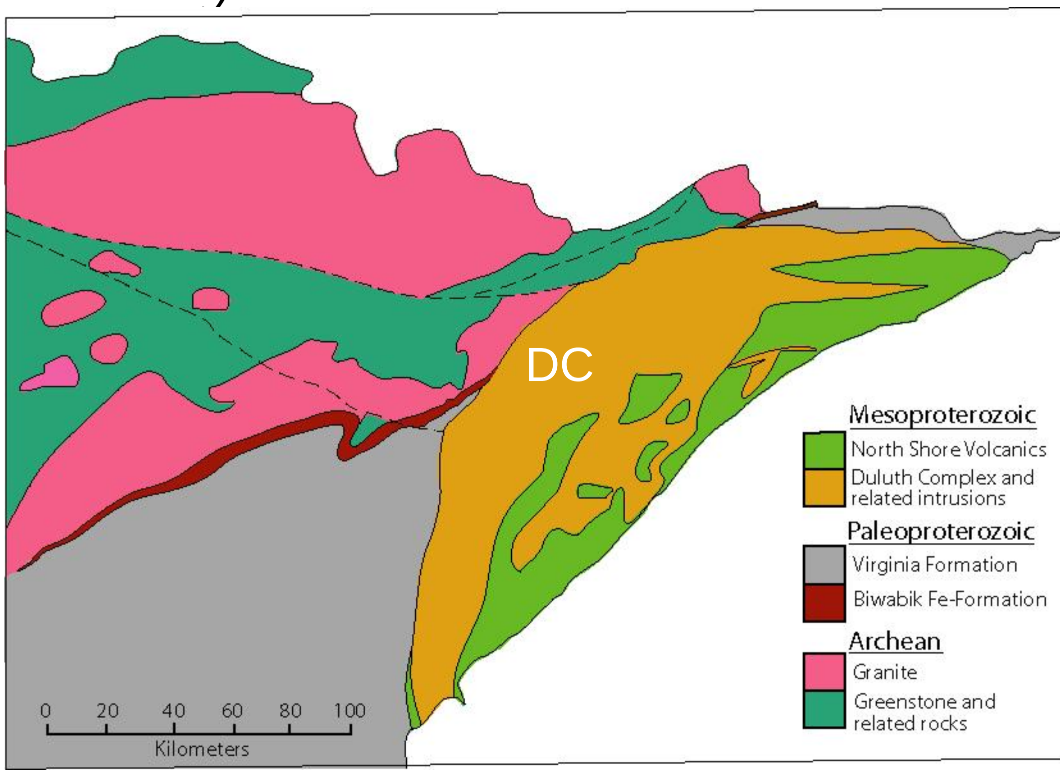
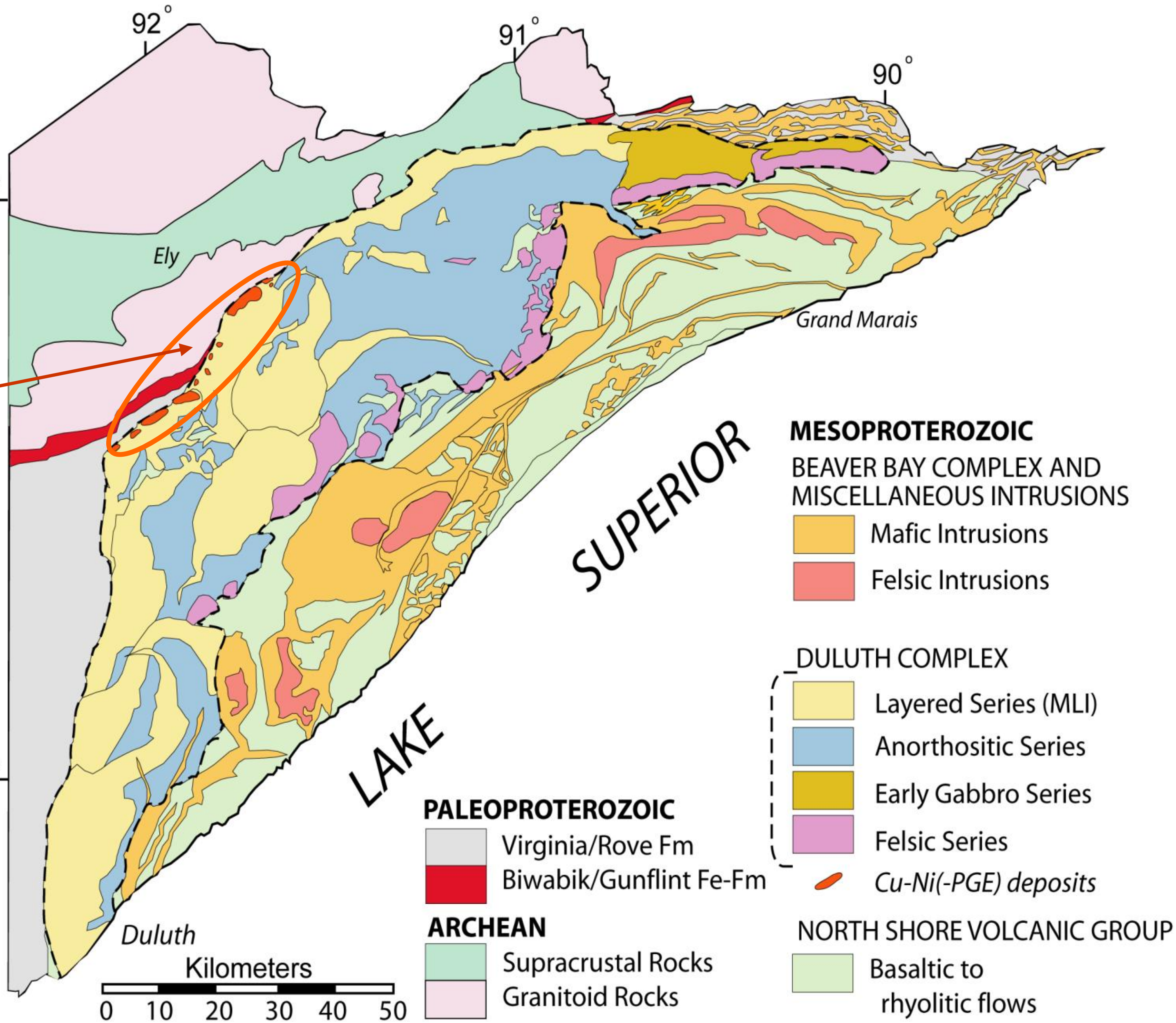
Geology and Mineral Deposits of the Duluth Complex, Minnesota
and why it will be mined someday



Jim Miller
Department of Geological Sciences
University of Minnesota Duluth

A Looming Stewardship Question for Minnesotans:

When should we develop this immense copper-nickel-precious metal mineral resource?

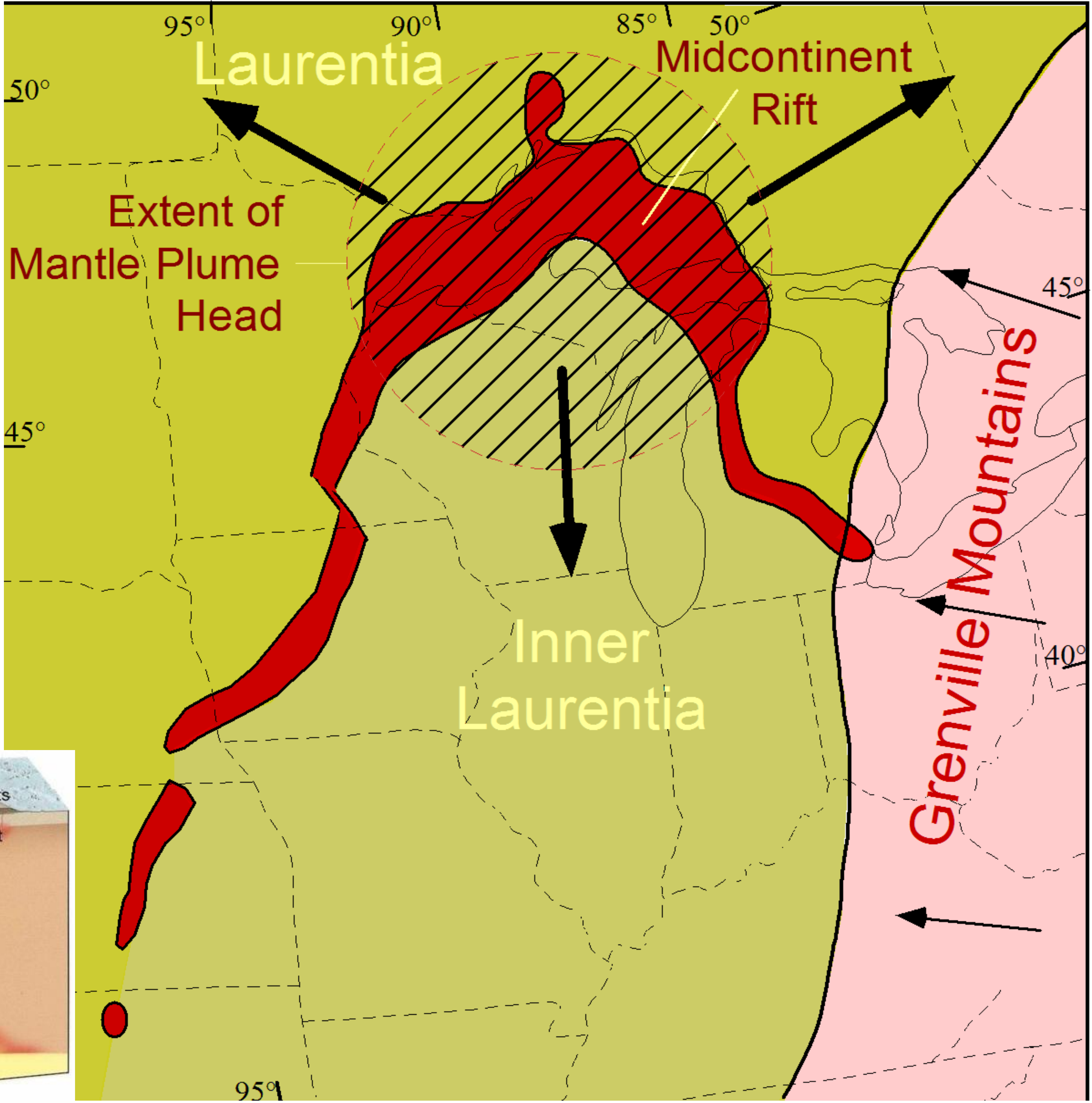


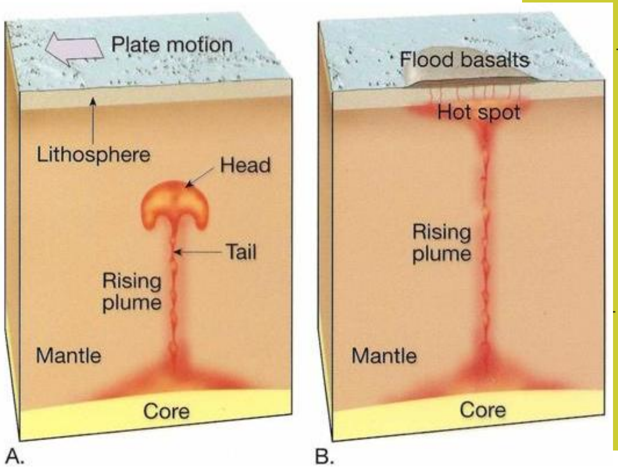
Talk Outline

- Geology of the Duluth Complex
- Mineral Deposits of the Duluth Complex
- History of Exploration
- Why the Duluth Complex ore deposits will be mined …someday

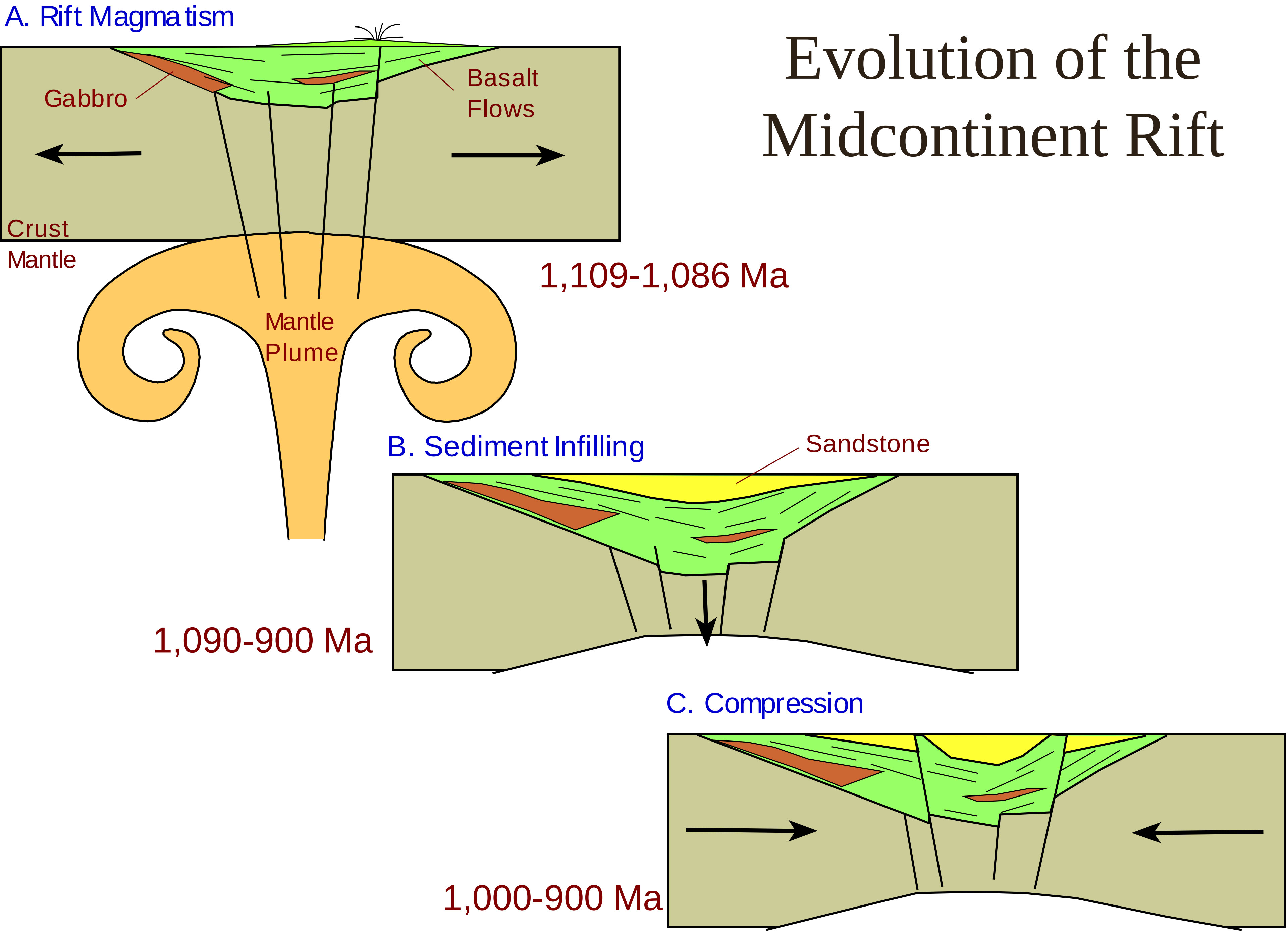
THE MIDCONTINENT RIFT

An attempt at continental separation 1.1 billion years ago

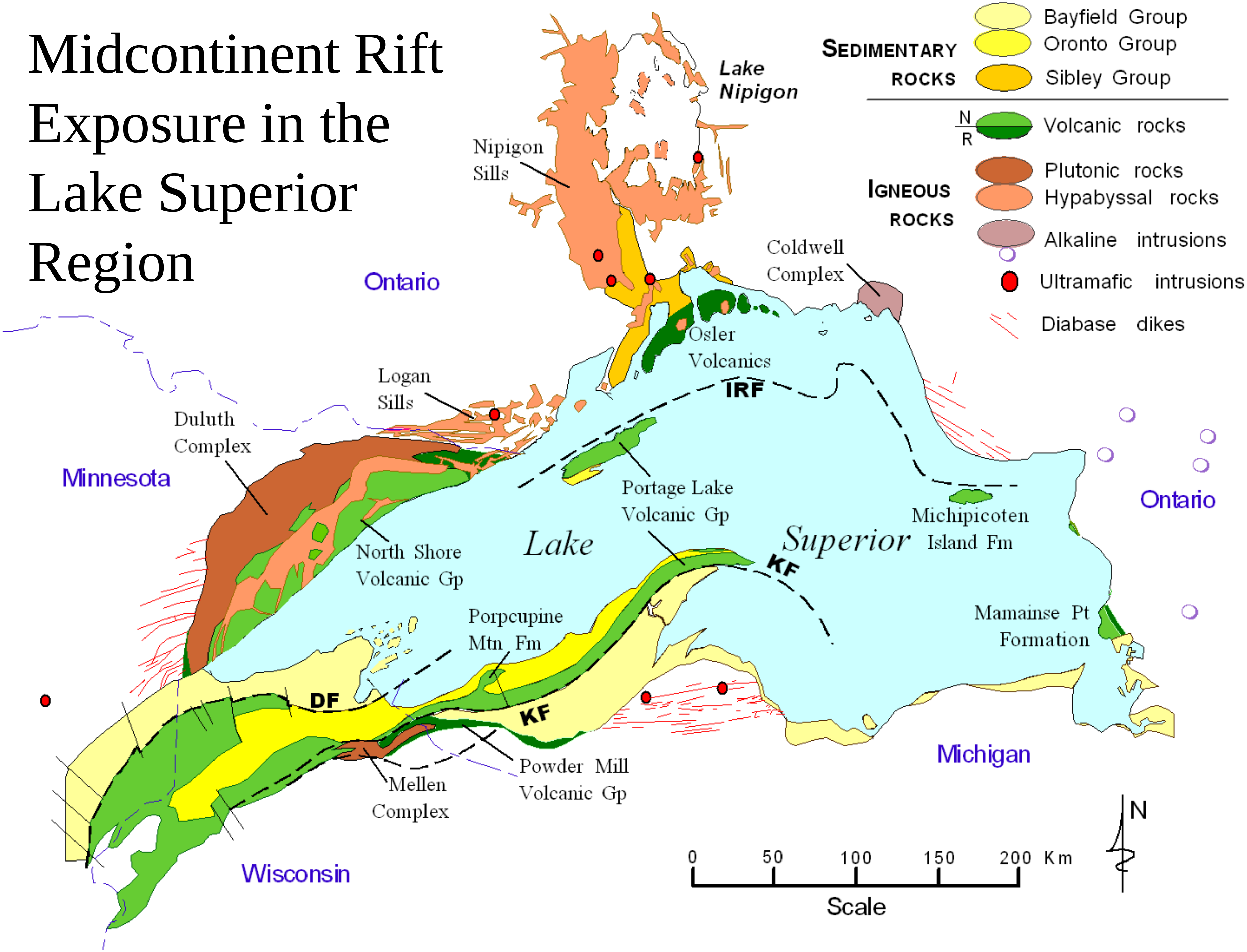




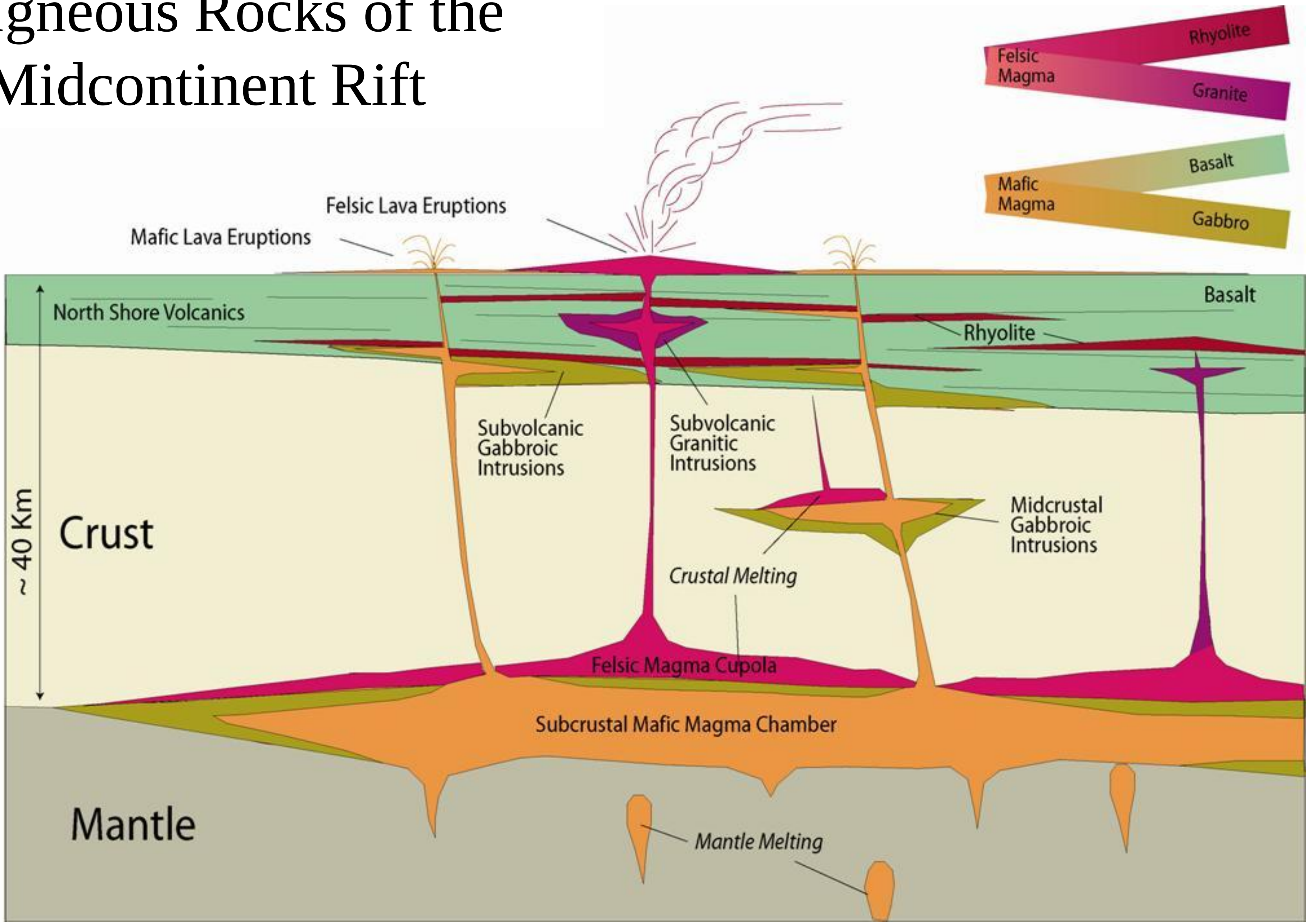
Evolution of the Midcontinent Rift

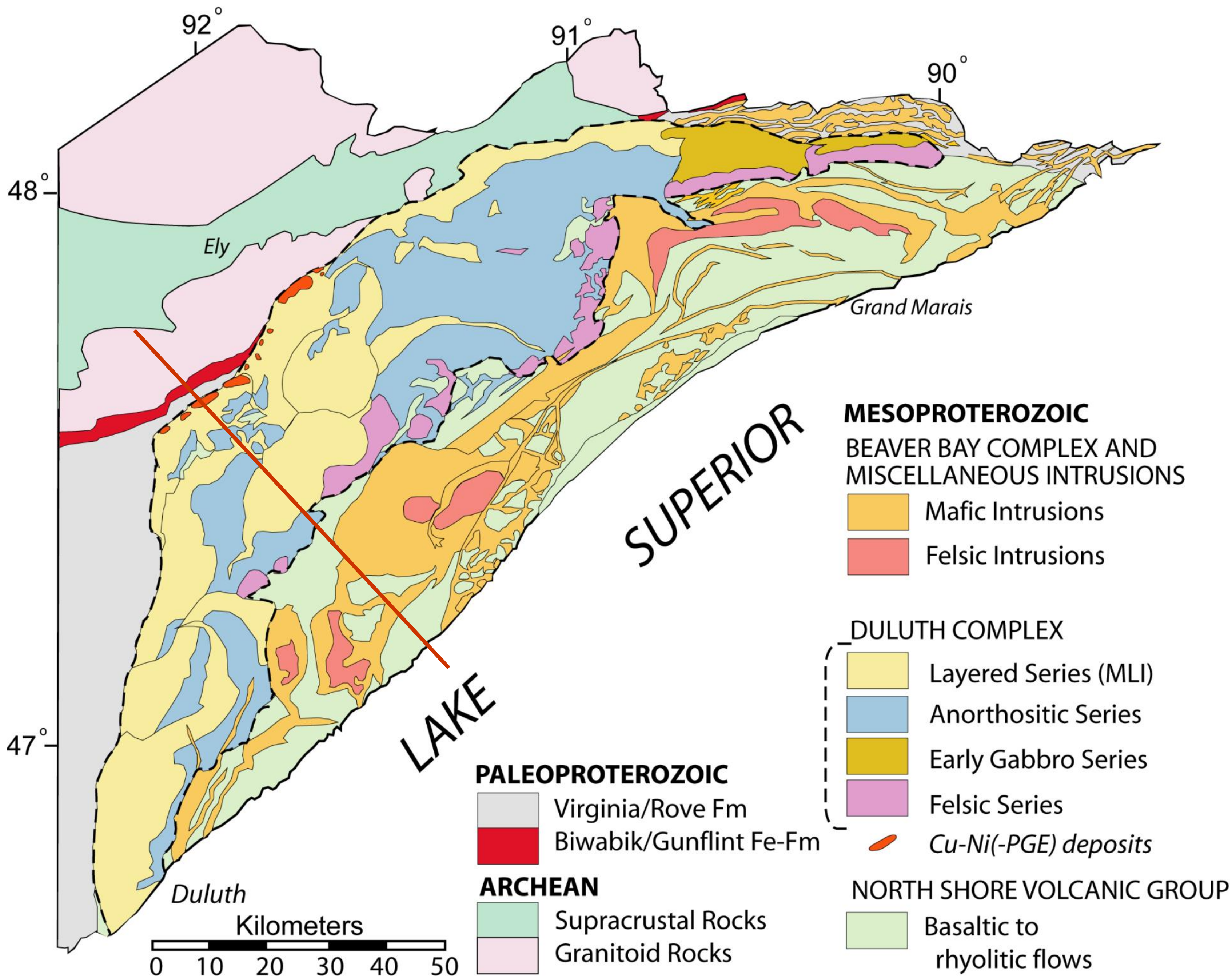


Midcontinent Rift Exposure in the Lake Superior Region

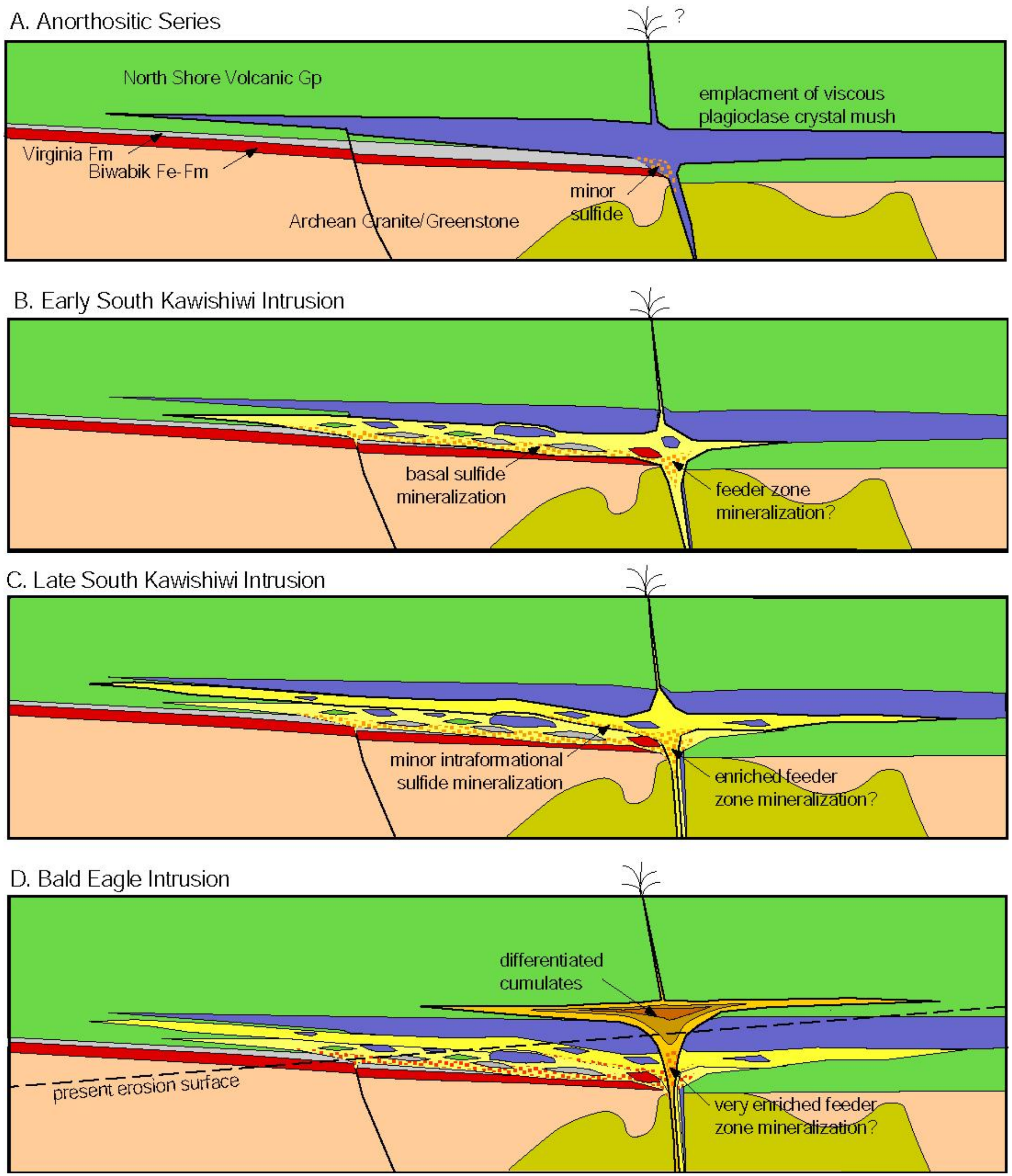


Igneous Rocks of the Midcontinent Rift

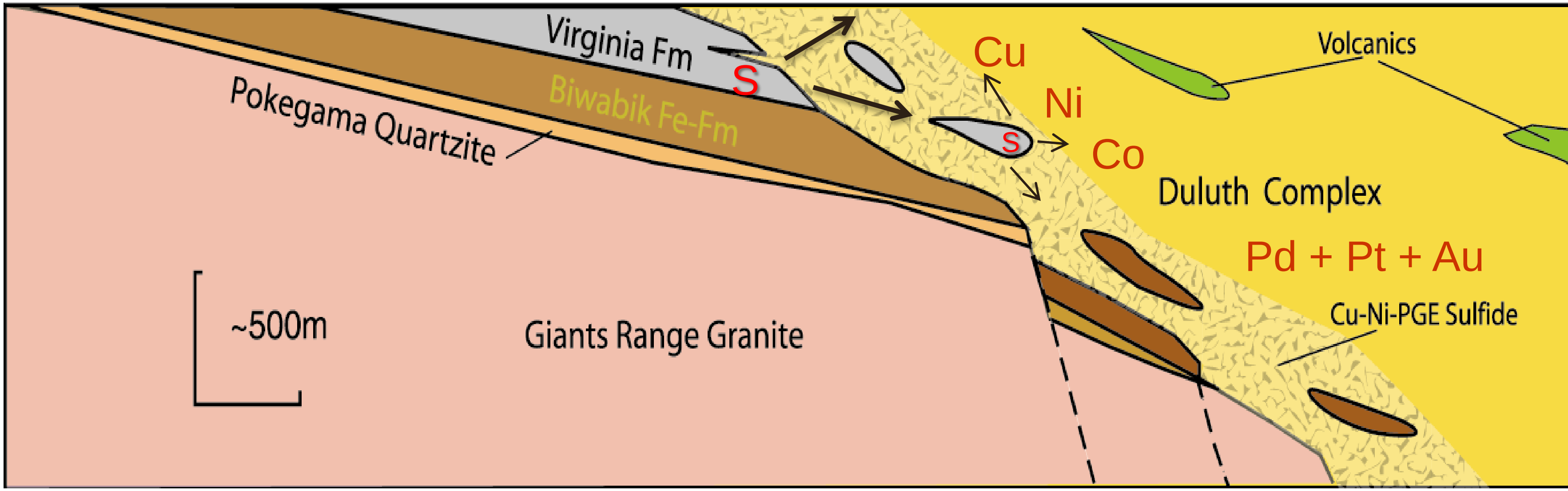


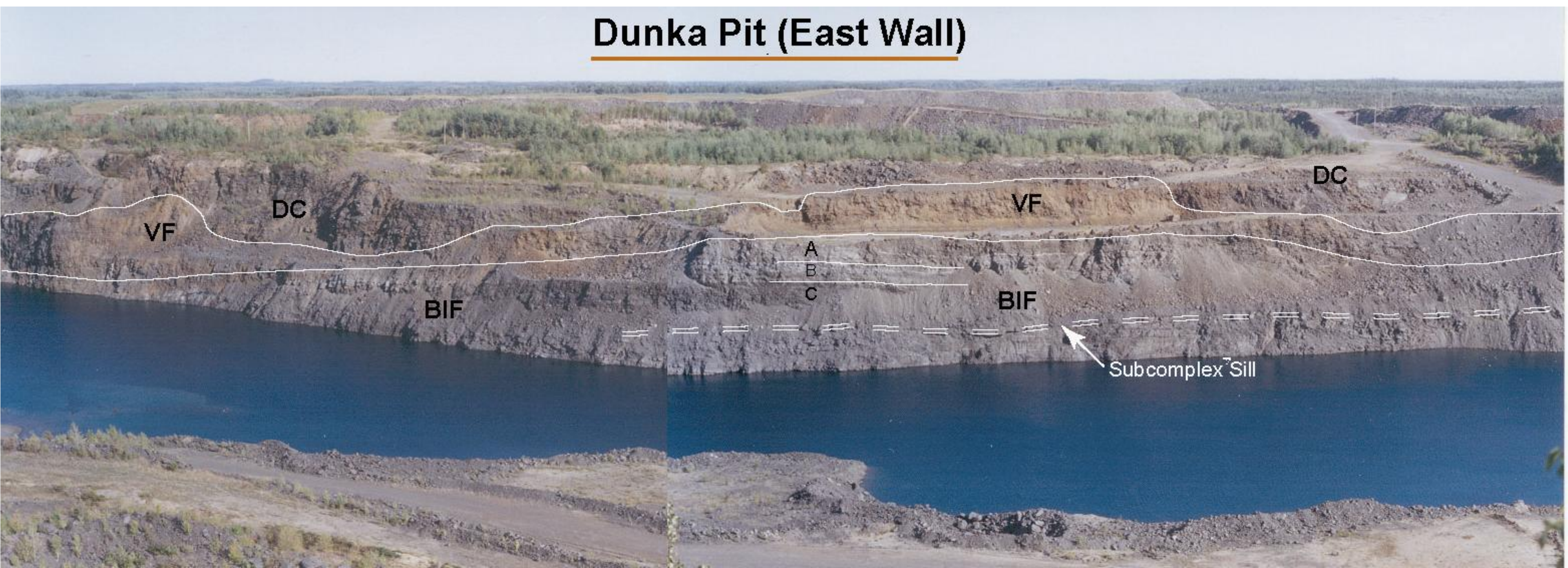

92°
91°
90°
48°
47°
Ely
Grand Marais
Duluth
SUPERIOR
LAKE
Kilometers
0 10 20 30 40 50
MESOPROTEROZOIC
BEAVER BAY COMPLEX AND MISCELLANEOUS INTRUSIONS
Mafic Intrusions
Felsic Intrusions
DULUTH COMPLEX
Layered Series (MLI)
Anorthositic Series
Early Gabbro Series
Felsic Series
Cu-Ni(-PGE) deposits
NORTH SHORE VOLCANIC GROUP
Basaltic to rhyolitic flows
PALEOPROTEROZOIC
Virginia/Rove Fm
Biwabik/Gunflint Fe-Fm
ARCHEAN
Supracrustal Rocks
Granitoid Rocks

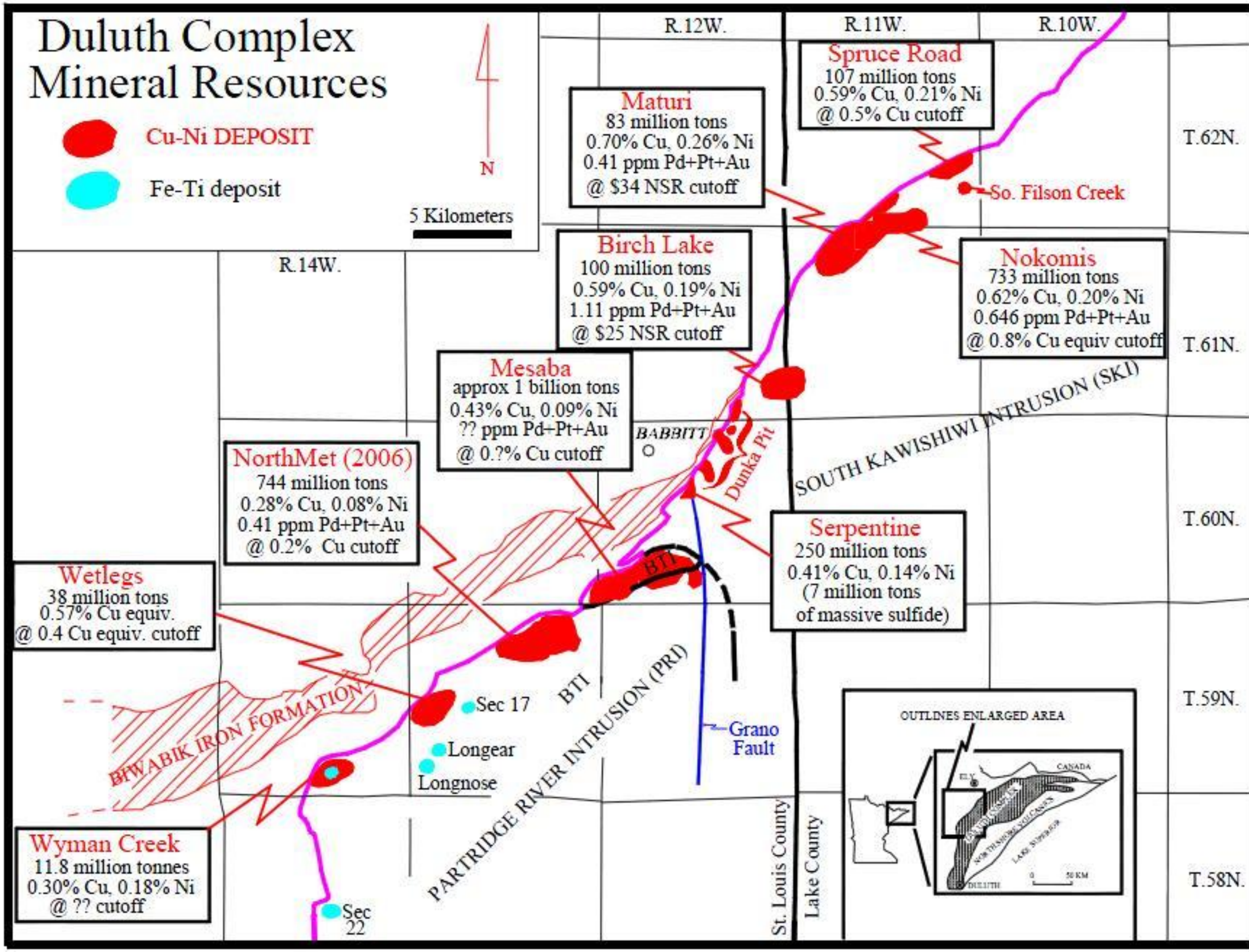
Sequential Emplacement of Duluth Complex Intrusions



Creation of the Cu-Ni-PGE Sulfide Deposits of the Duluth Complex







From Severson and Hauck, 2003

History of Cu-Ni-PGE Exploration in the Duluth Complex

1948 – Cu-sulfide mineralization discovered by F.W. Childers

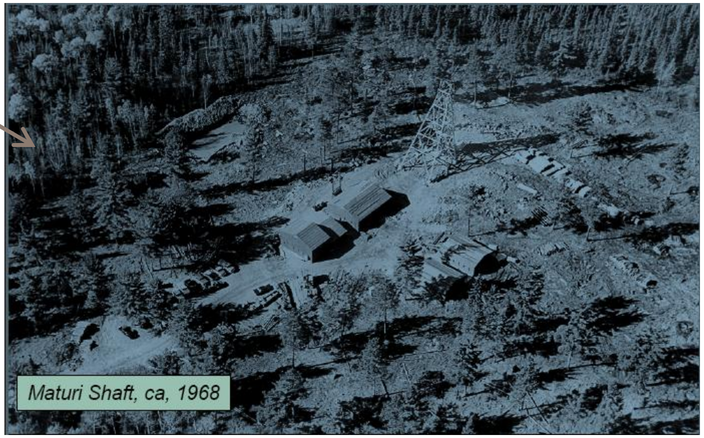
1951 – Childers and Whiteside drill first exploration drill hole at Spruce Road

1954 – INCO begins drilling program at Maturi deposit

1958 – Bear Creek (Kennecott) begins drilling program at Babbitt deposit

1966 – Minnesota opens state lands for minerals lease sale

1967 – INCO sinks shaft at Maturi deposit



Maturi Shaft, ca, 1968

1969 – Total of 198,000' of drill core acquired

1974-78 –State conducts Cu-Ni Regional Study

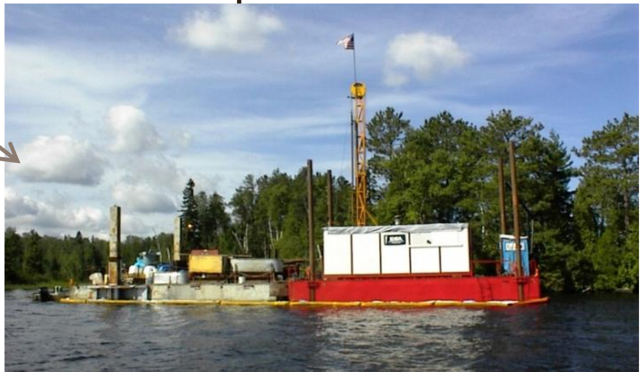
1974-82 – State suspends lease sale

1976 – AMAX sinks shaft at Babbitt deposit

1981 – AMAX abandons Babbitt deposit

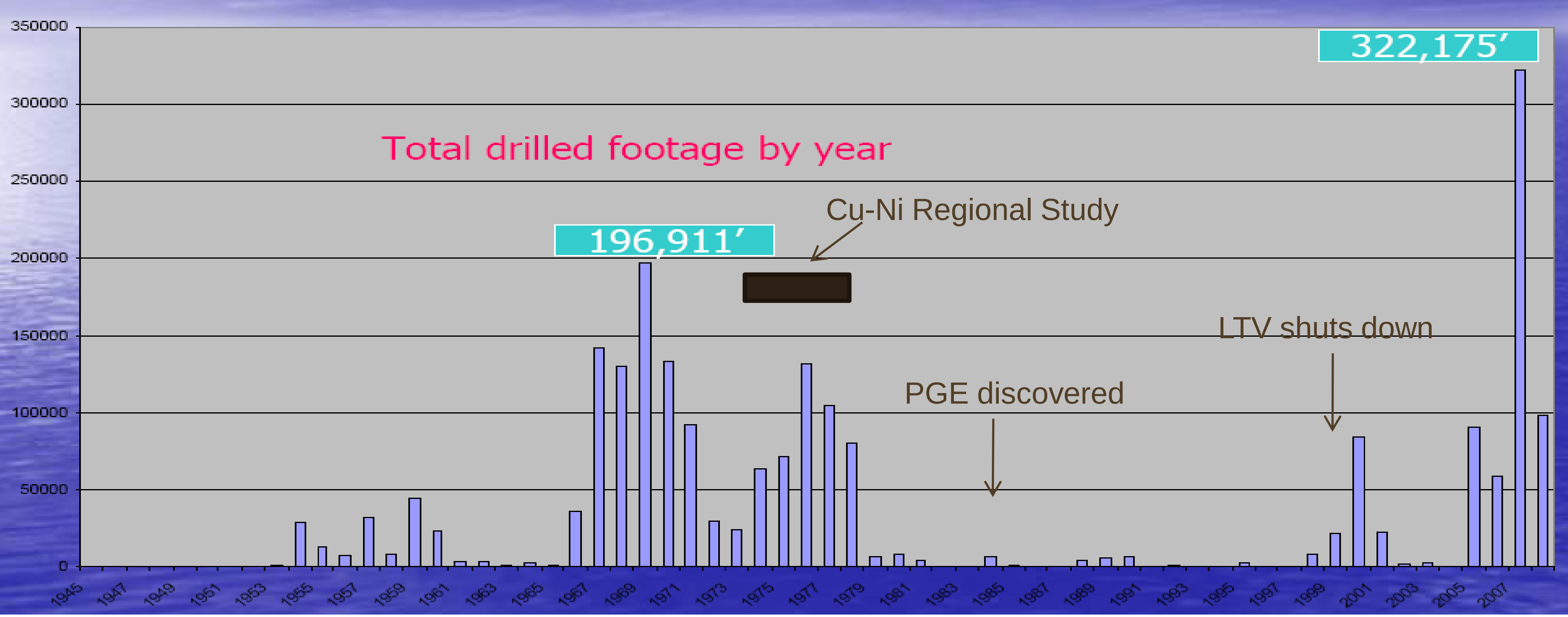
1985 – High PGE values discovered at Birch Lake deposit

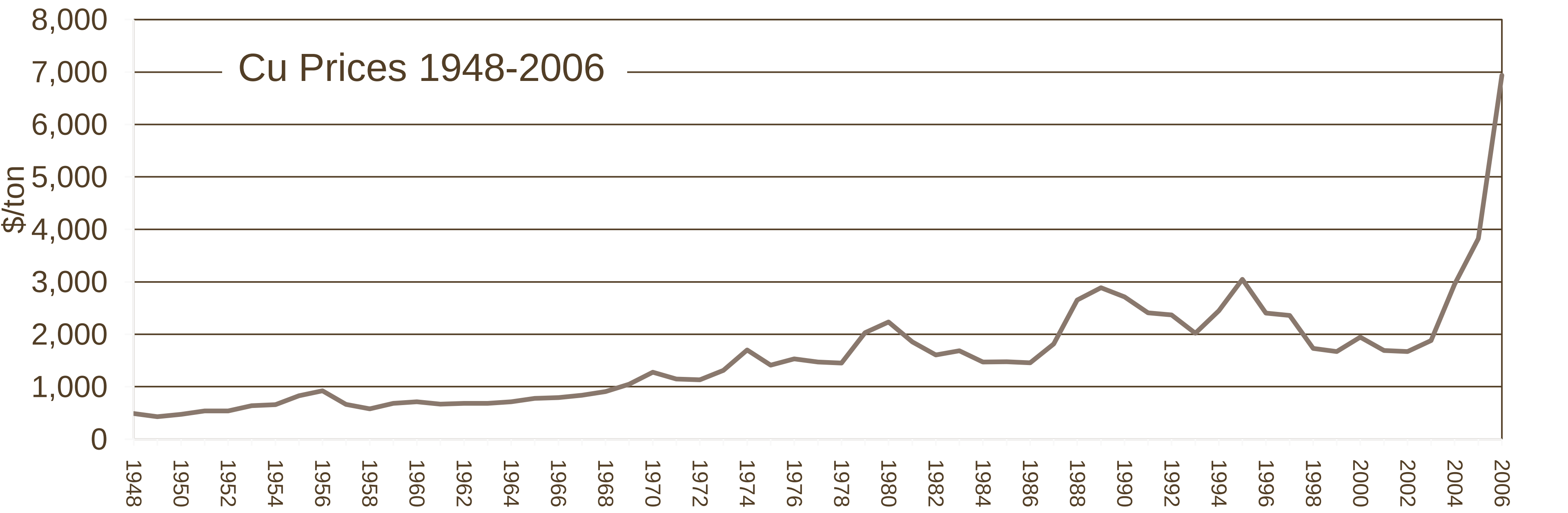
1988 – Lehmann and Assoc. begin drilling of the Birch Lake deposit

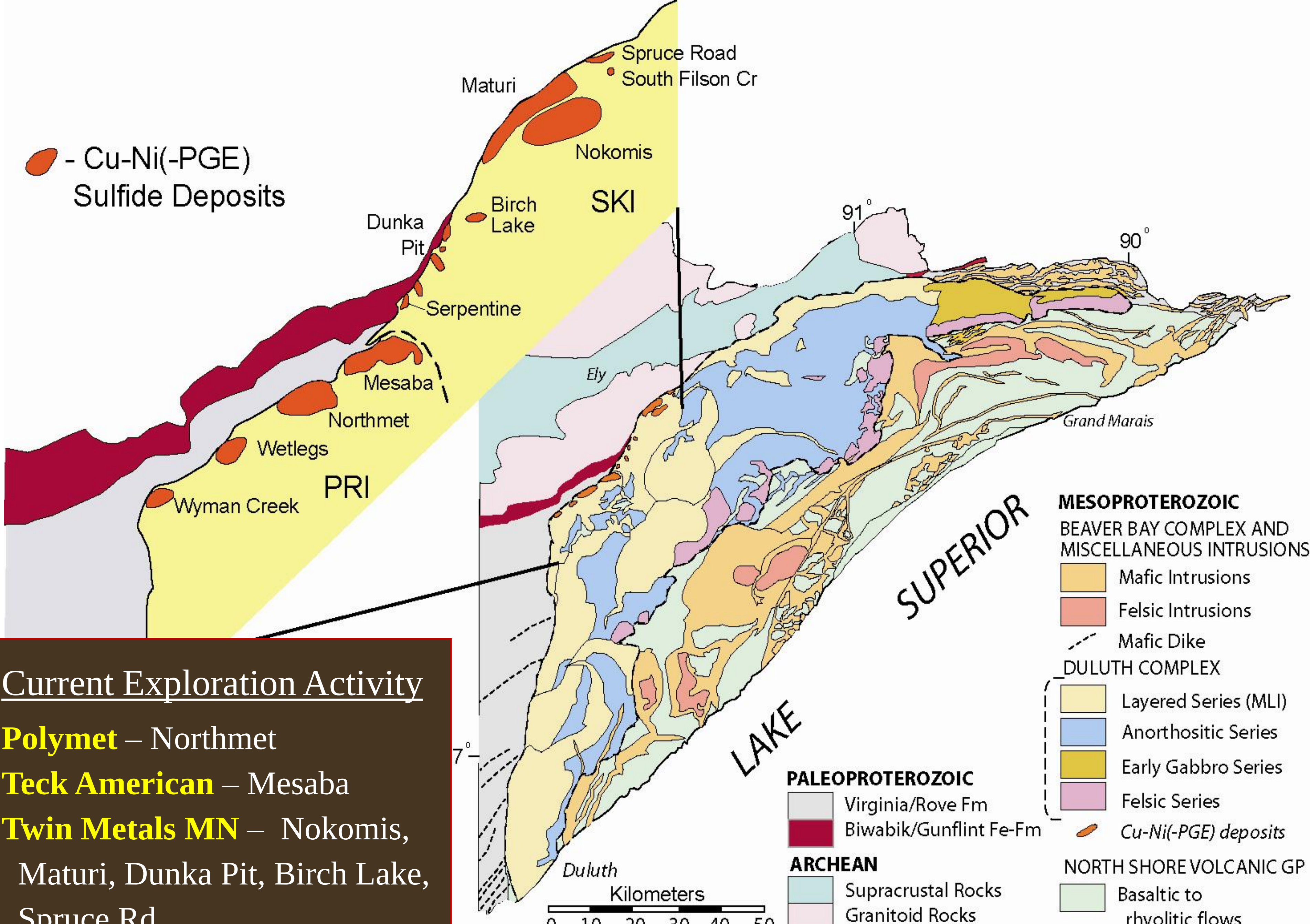


1997-2000 – Polymet, Teck Cominco,
Franconia, Wallbridge (Duluth Metals)
begin active exploration drilling

2007 – Total of 322,000' of drill core acquired


Total drilled footage by year
196,911’
322,175’
Cu-Ni Regional Study
PGE discovered
LTV shuts down


Cu Prices 1948-2006
$/ton



Current Exploration Activity

Polymet – Northmet

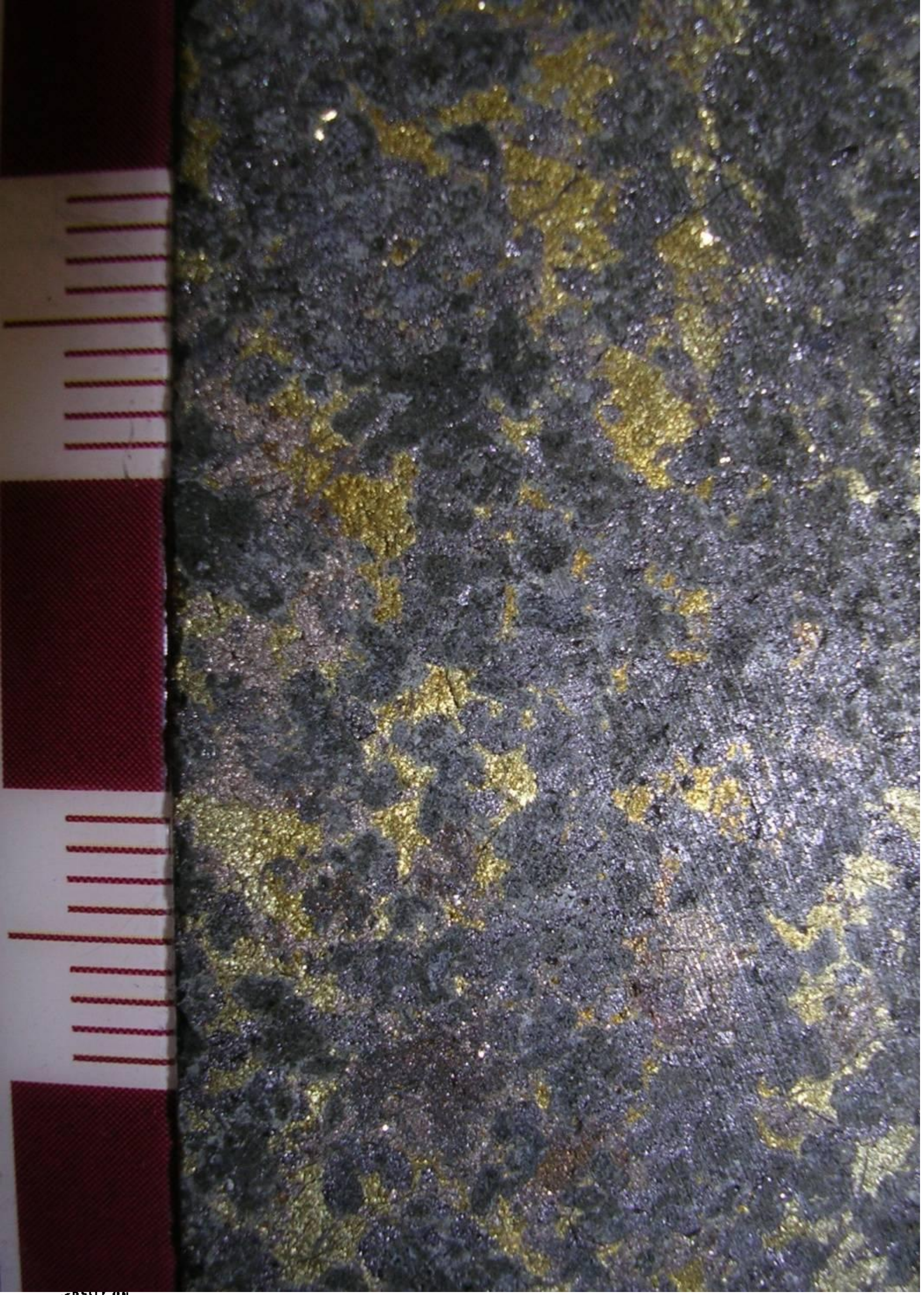
Teck American – Mesaba

Twin Metals MN – Nokomis, Maturi, Dunka Pit, Birch Lake, Spruce Rd

Encampment– South Filson Cr.

Why Will the Duluth Complex Ore Deposits be Mined Someday?

- New technological advances in processing sulfide minerals
- The US is the principal consumer of Copper, Nickel, Cobalt and Precious Metals, but relies on the rest of the world to supply these resources
- Cu, Ni, and PGE are critical metals in a modern, green world
- The deposit occur adjacent to an area of taconite mining with an estimated 50 year life span
- These deposits constitute the largest undeveloped Cu-Ni resource on Earth



Mineralogy of Magmatic Cu-Ni Sulfide Deposits

Sulfide Minerals

Pyrrohotite – FeS_{1-x}
Chalcopyrite - $CuFeS_2$
Pentlandite - $(Fe,Ni)_9S_8$
Bornite - Cu_5FeS_4
Chalcocite - Cu_2S
Cobaltite – CoAsS
Pt Group Minerals – Pt, Pd, Au, Bi, Te, As, ...

Silicate/Oxide Minerals

Olivine - $(Mg,Fe)_2SiO_4$
Plagioclase – $(Ca,Na)(Al,Si)_4O_8$
Augite – $Ca(Mg,Fe)Si_2O_6$
Titano-magnetite – $(Fe,Ti)_3O_4$

An Inconvenient Reality

Most of the world's metals comes from sulfide minerals

Chalcopyrite
$CuFeS_2$

Chalcocite
Cu_2S

Bornite
Cu_5FeS_4

Pentlandite
$(Fe,Ni)_9S_8$

Cinnabar
HgS

Sphalerite
ZnS

Molybdenite
MoS_2

Galena
PbS

Cobaltite
CoAsS

Copper Country of Upper Michigan:

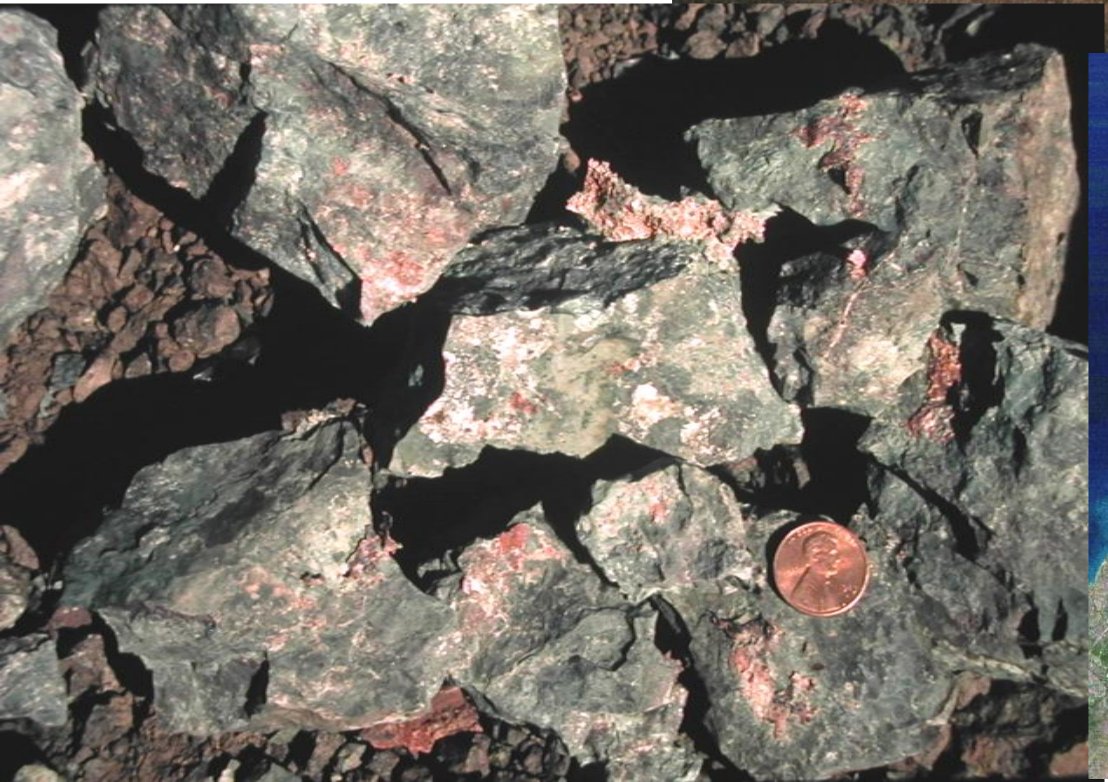
Native Cu

Native Miners

pre-1000 yrs

European Miners

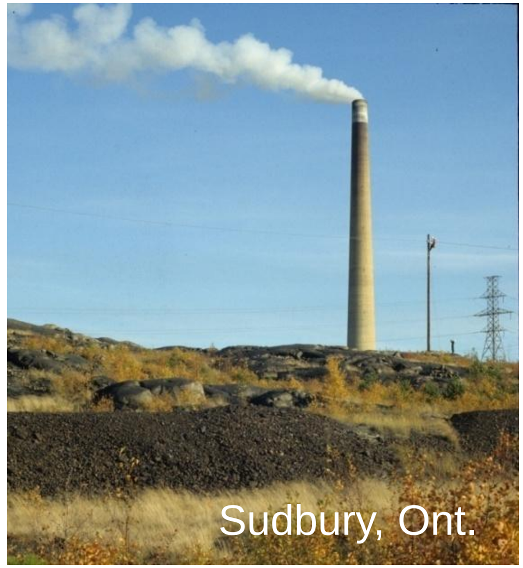
1844-1972



Separating Metal from Sulfur

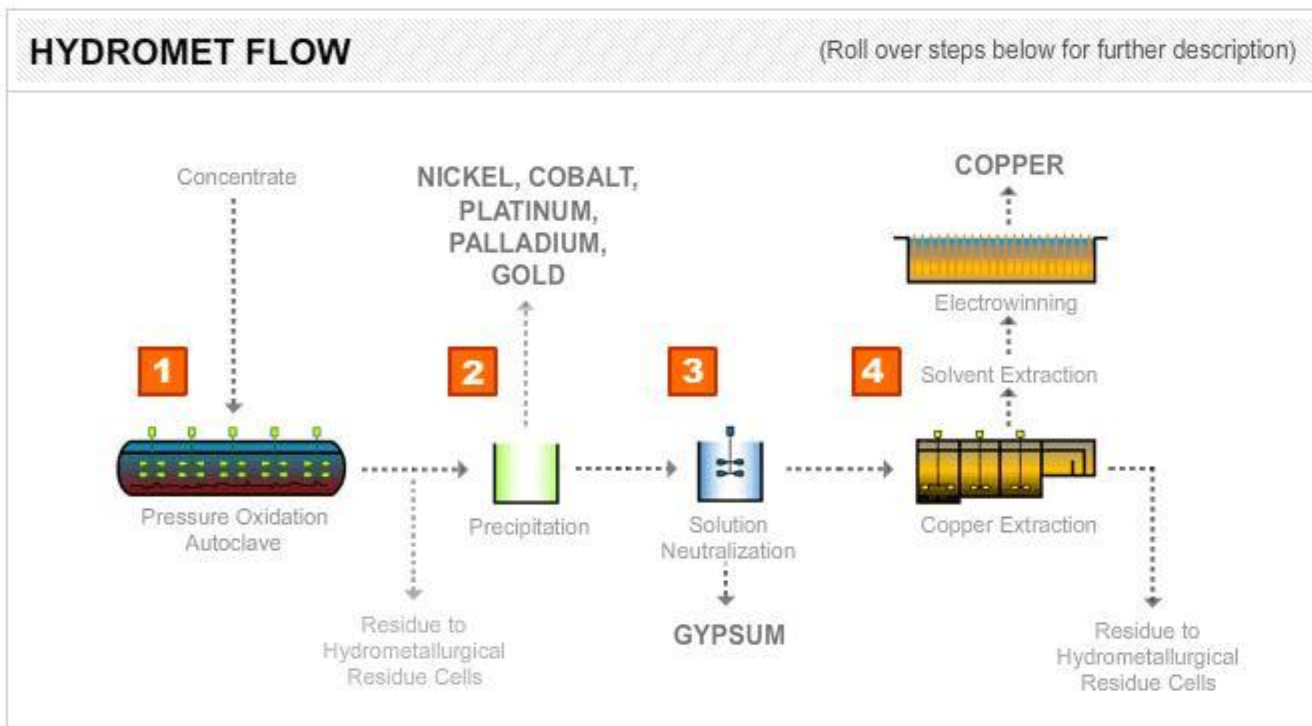
THEN

Roasting/Smelting



NOW

Hydrometallurgy



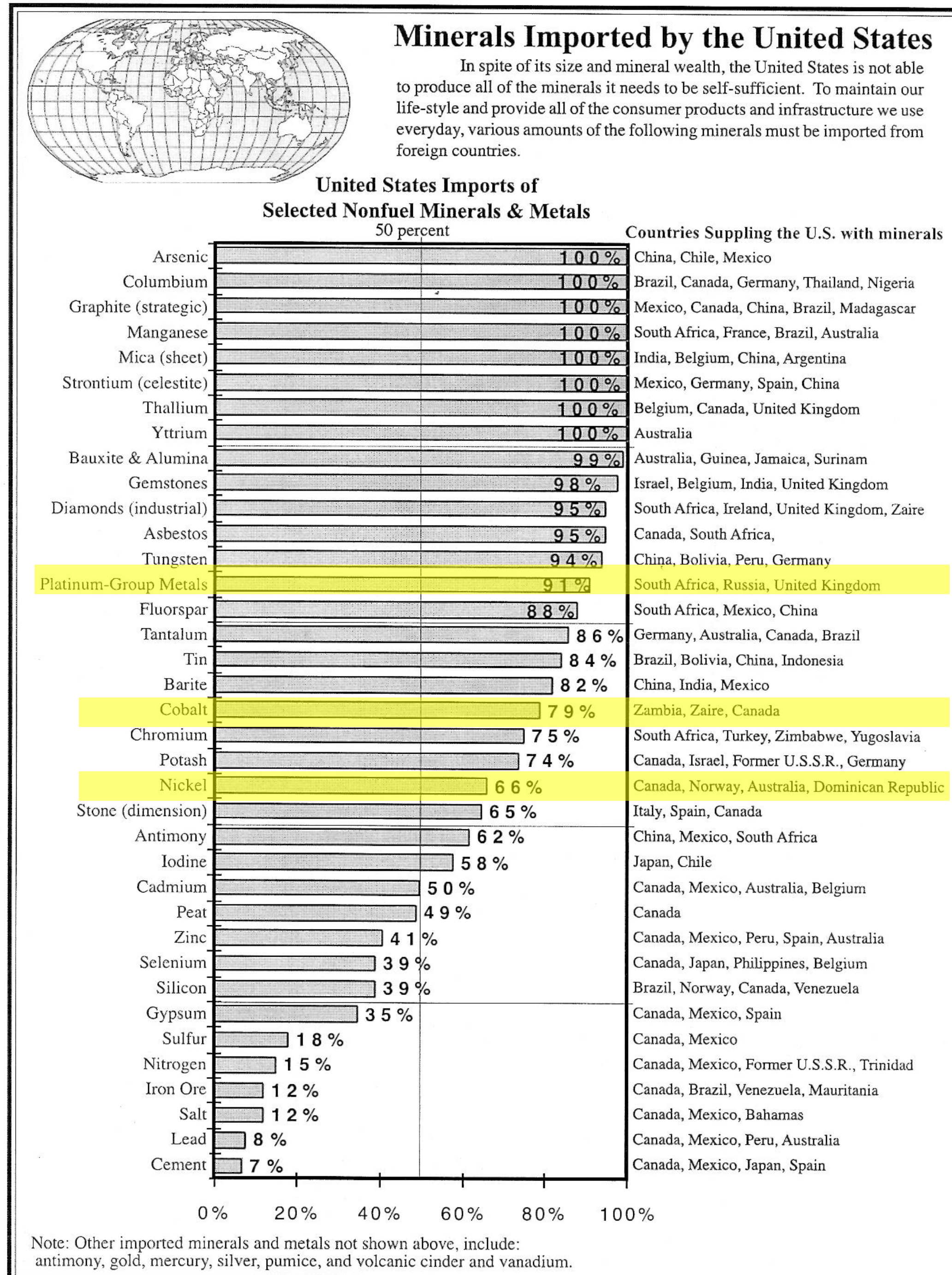
The Challenge
Preventing Acid Mine Drainage

$$2FeS_2(s) + 7O_2(g) + 2H_2O(l) \rightarrow$$
$$2Fe^{2+}(aq) + 4SO_4^{2-}(aq) + 4H^+(aq)$$

United States – The #1 consumer of mineral resources, that produces little for itself

Metal	% Mined by US vs. Total Mining	% Imported for US consumption
Copper *(Chile (30%), US, Indonesia, Peru)*	7.7%	40%
Nickel *(Russia, Australia, Canada, Indonesia)*	0%	54%
Cobalt *(Congo (30%), Zambia, Australia, Canada)*	0%	78%
Palladium *(Russia (44%), South Africa (38%))*	6.6%	78%

Statistics from US Geological Survey
Mineral Commodity Summaries, Jan. 2006



Mineral Information Institute Golden, Colorado www.mii.org

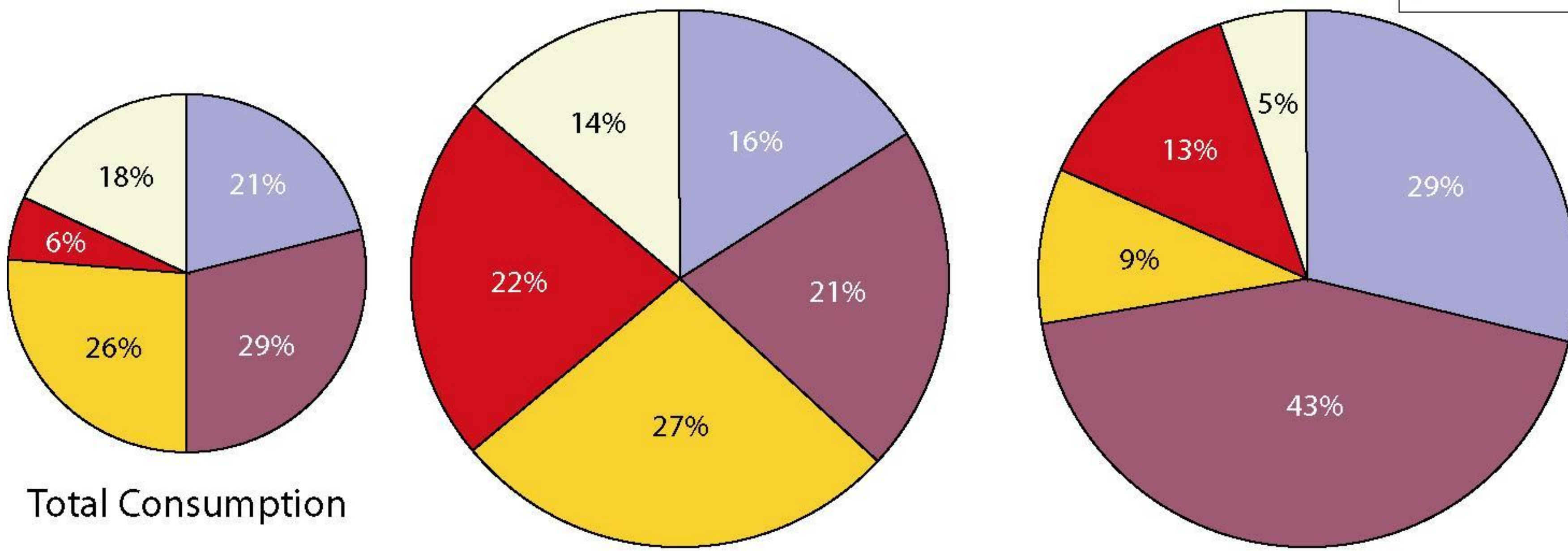
World Copper Consumption

1990

10.9 Million Metric Tons

2006

16.9 Million Metric Tons



Total Consumption

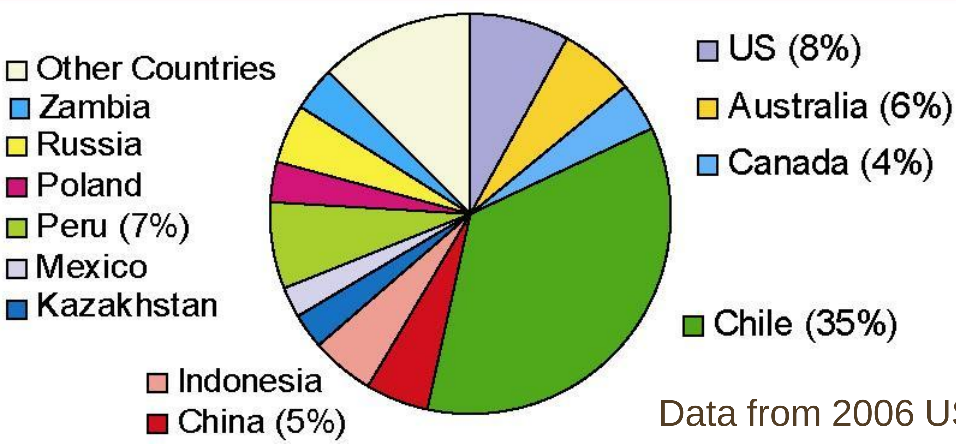
Total Consumption

Per Capita

2006

World Cu

Production



% of Cu supplied by recycling in 2006

31%

Data from 2006 USGS Mineral Commodity Summary

COPPER
An Important Metal in a Green Economy

A Single 3MW Wind Turbine Needs:

- ☑ 335 tons of steel
- ☑ 4.7 tons of copper
- ☑ 1,200 tons of concrete (cement and aggregates)
- ☑ 3 tons of aluminum
- ☑ 2 tons of rare earth elements
- ☑ Aluminum
- ☑ Zinc
- ☑ Molybdenum

NW Mining Association, 2009

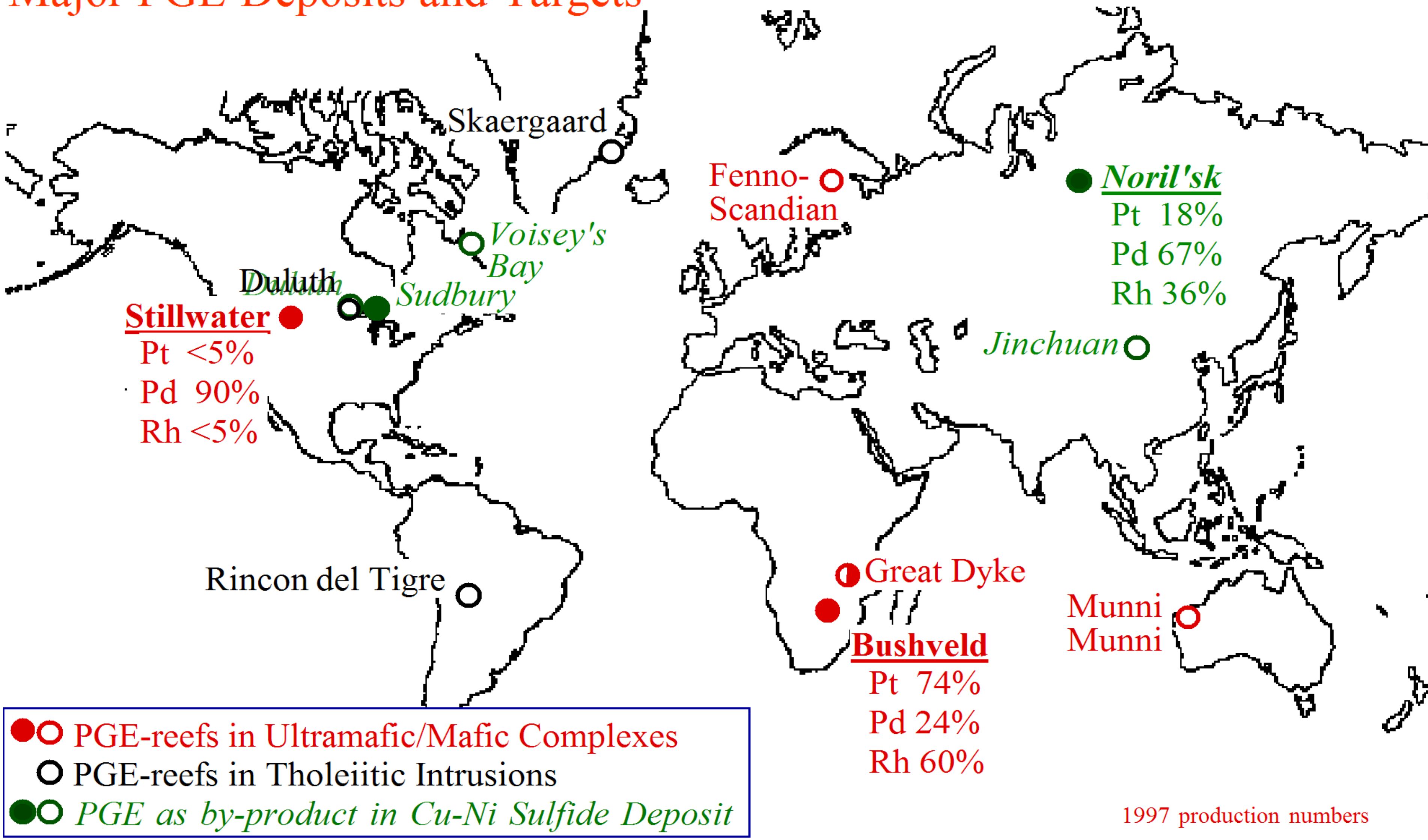
Cu in a Standard Car with Combustion Engine
43-55 lbs

Cu in a Prius
80 lbs

PGE – Platinum Group Elements

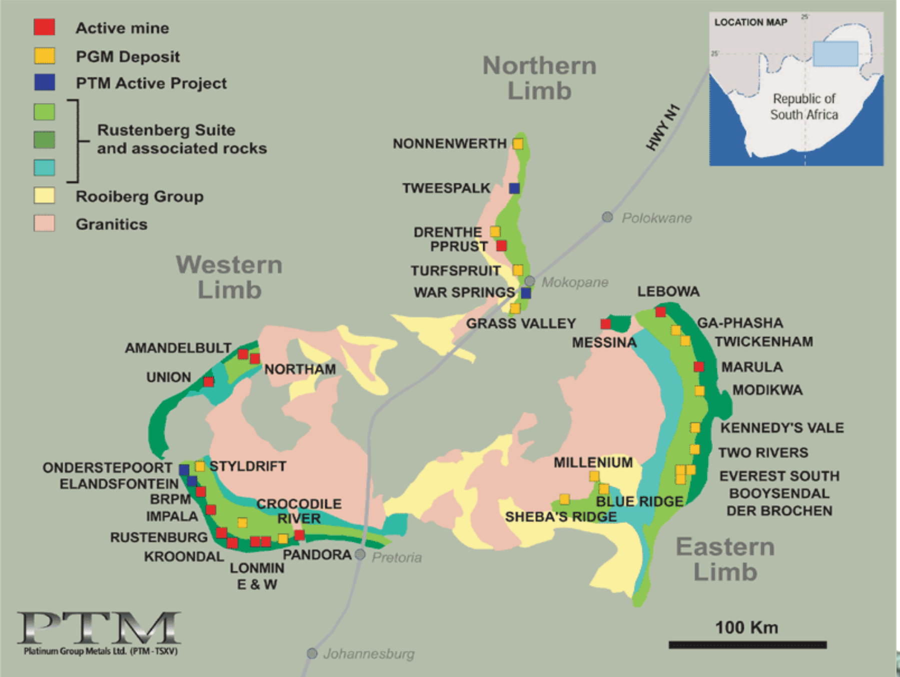
Pt – Platinum, ***Pd*** – Palladium, ***Os*** – Osmium, ***Ru*** – Ruthenium, ***Rh*** – Rhodium, ***Ir*** - Iridium

Major PGE Deposits and Targets



Bushveld Complex South Africa

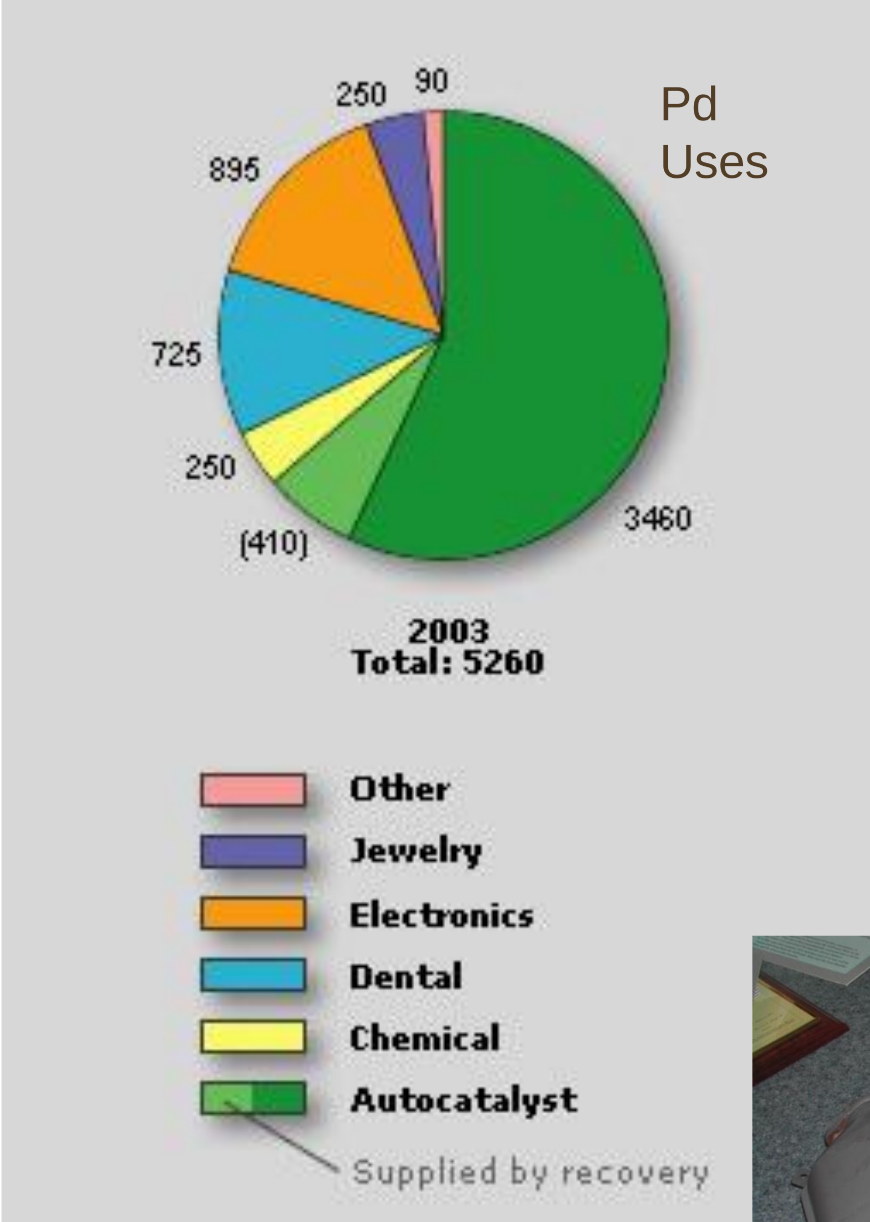
Supplying the 70% of the World's Platinum

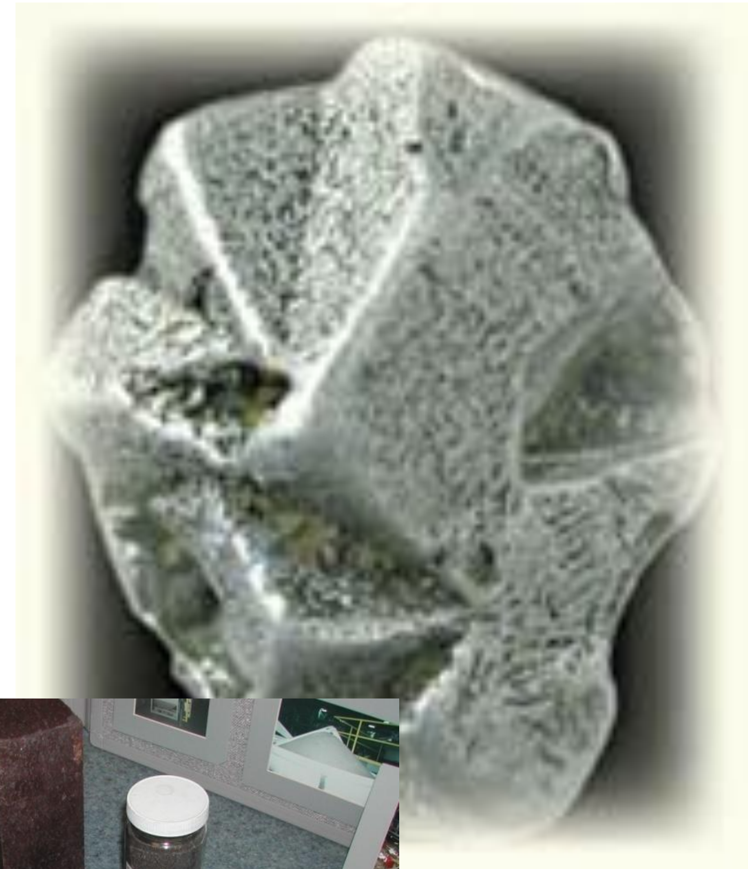


Merensky Reef, Amplats Mine, Rustenburg, SA

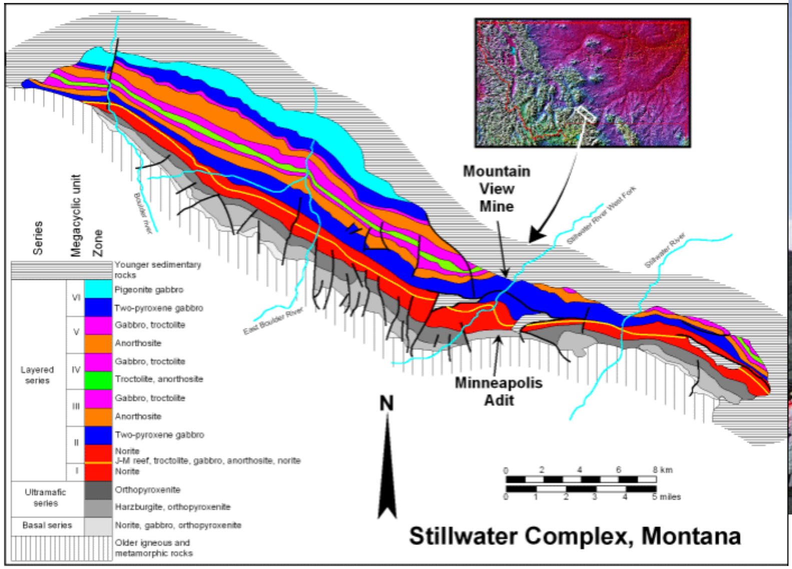
Merensky Reef, Eastern Bushveld Complex

Palladium:
“The Environmental Metal”





The Stillwater Mine (Montana)
Only Precious Metals Mine in the U.S.
(owned by Noril’sk Nickel)

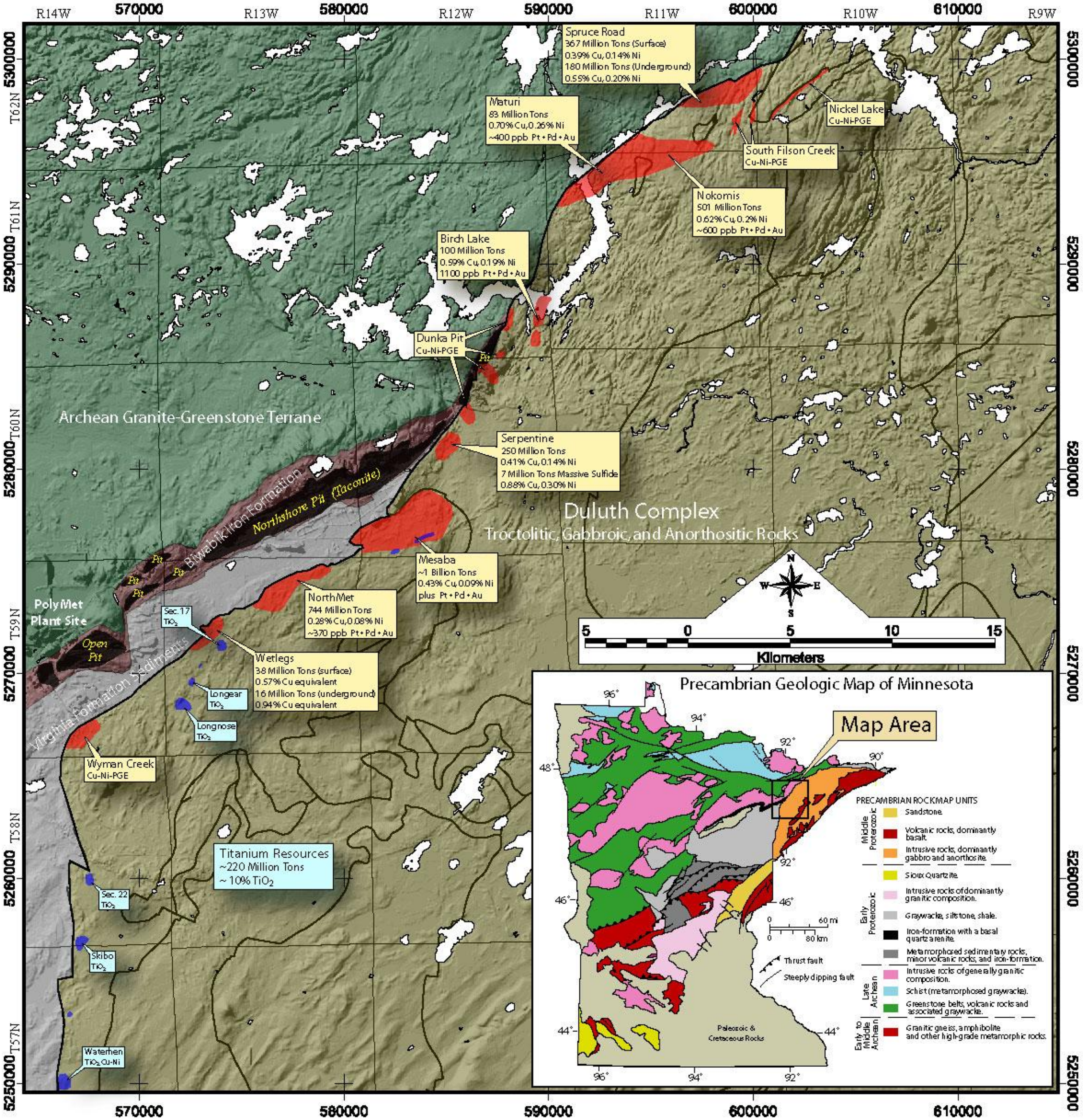


Noril'sk, Russia
Cu-Ni-PGE Deposits

Supplies 60% of the World's Palladium

Sulfide Smelter in Monchegorsk, Russia

In 1998, responsible for 50% of SO_2 in the northern hemisphere

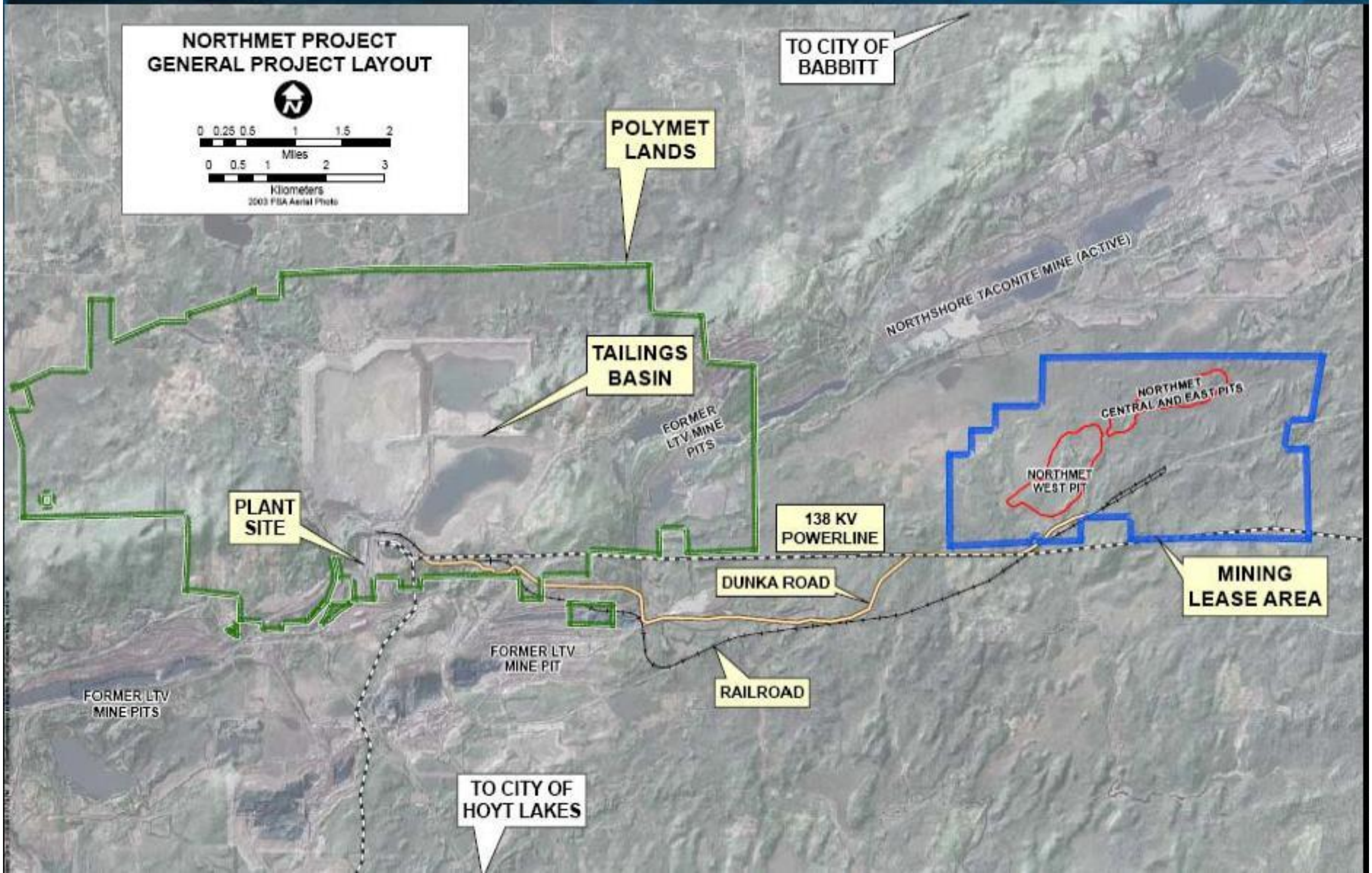


Adjacent to the Taconite Mines of the Eastern Mesabi Range

Provides a ready-made infrastructure and labor force

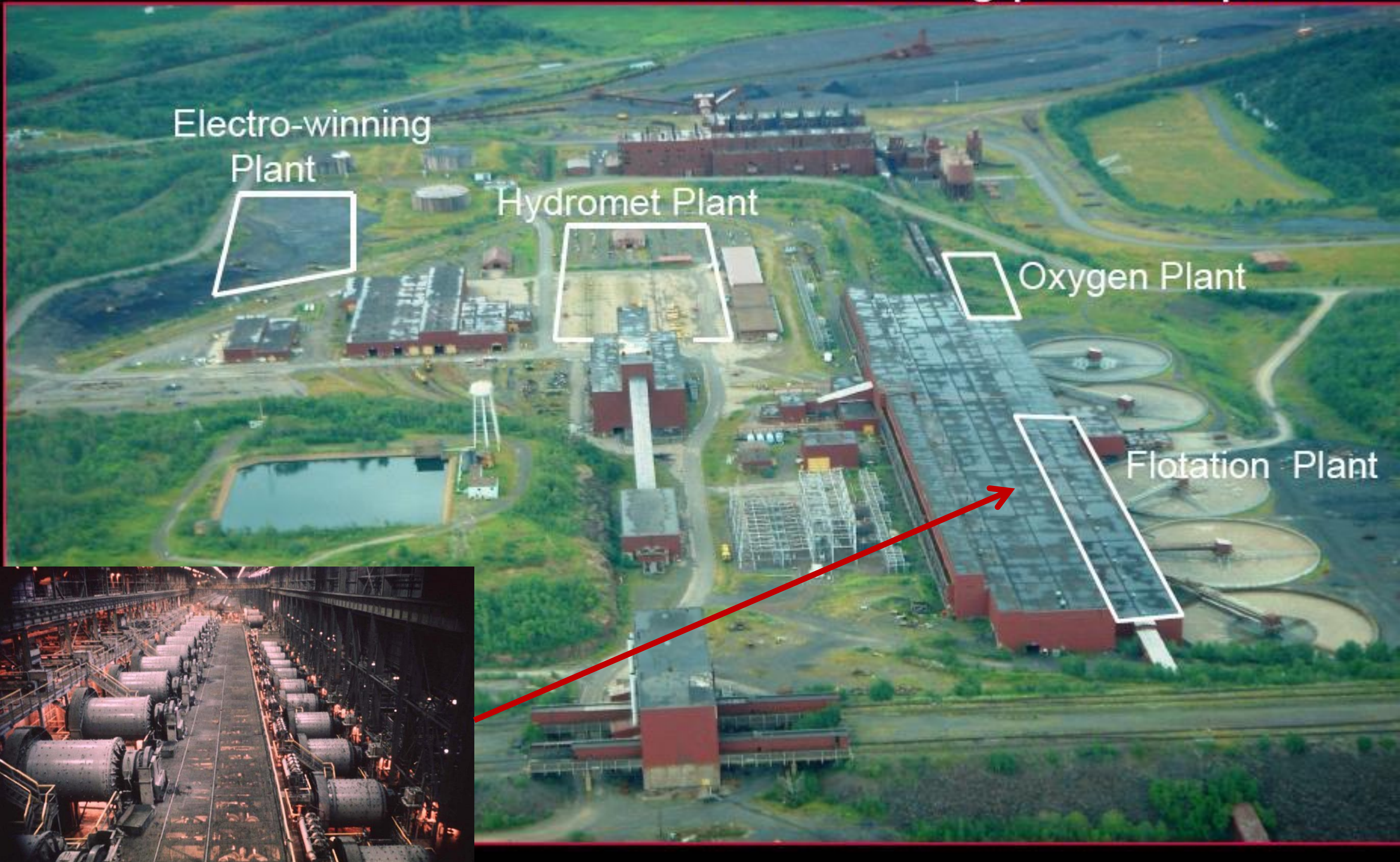
POLYMET MINING

PolyMet Project Site



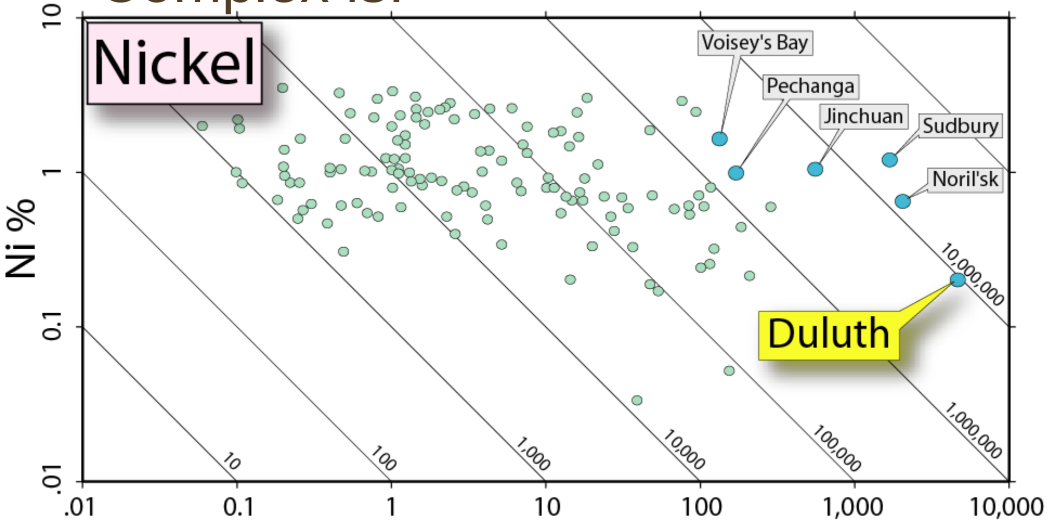
POLYMET
MINING

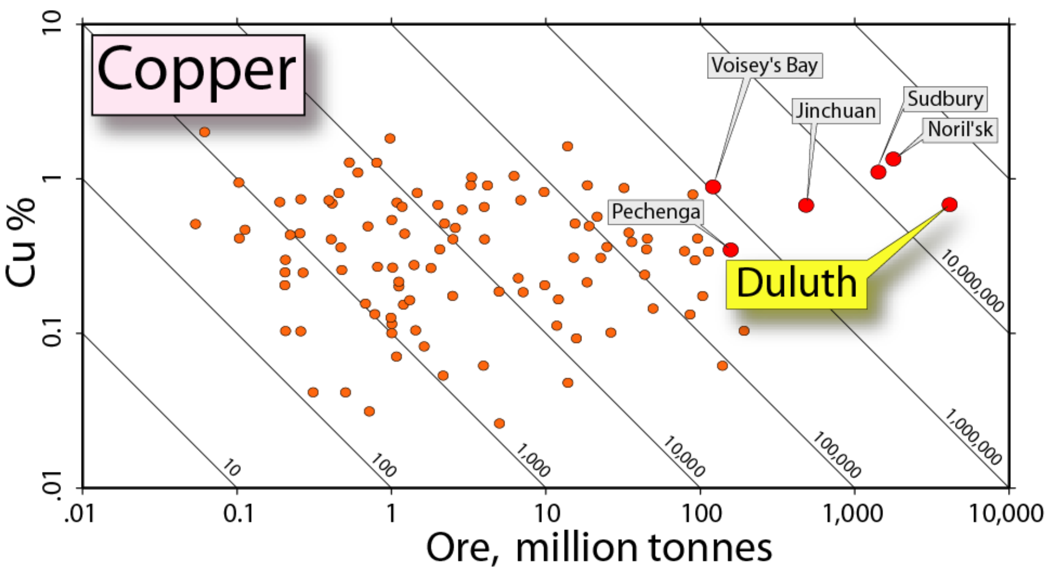
New Plant Facilities
~ within existing plant footprint



World Class Ores of the Duluth Complex

Compared to other **Magmatic Sulfide Deposits**, the Duluth Complex is:





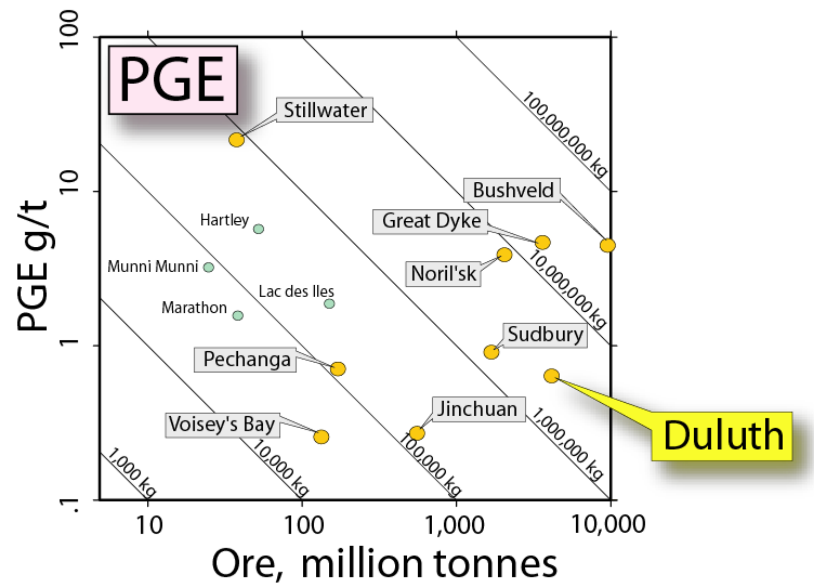
#1 or 2 in contained Copper

#2 in contained PGE

#3 in contained Nickel

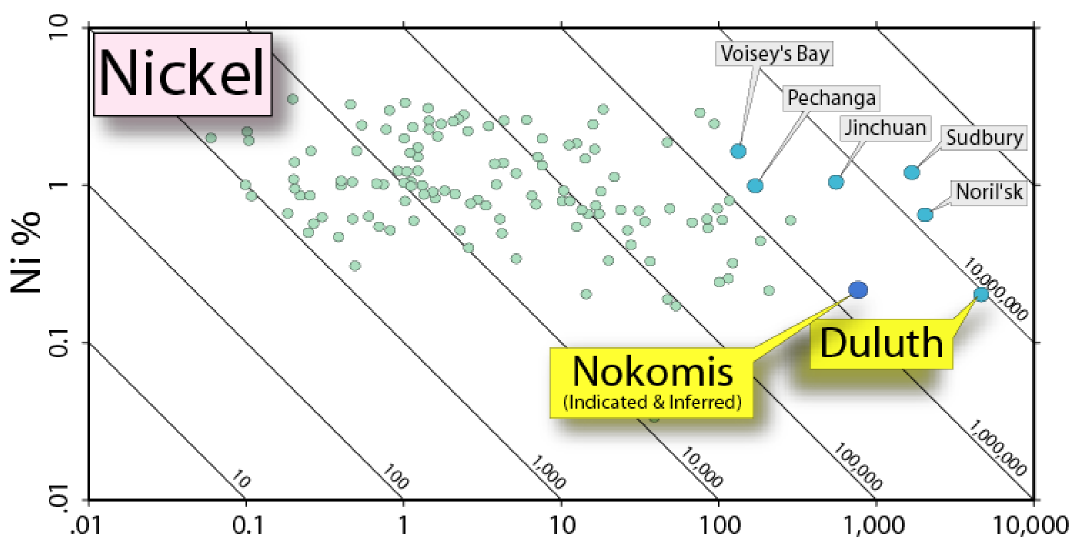
Only the Bushveld, Great Dyke *(PGE deposits)* and Noril'sk contain more PGE

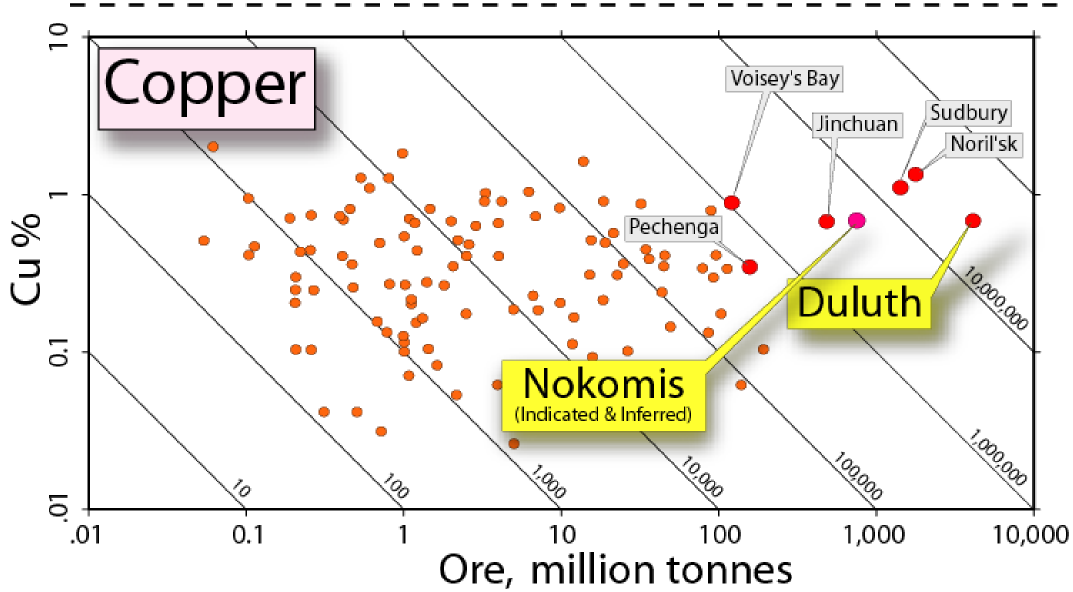
Data from Eckstrand & Hulbert, 2007

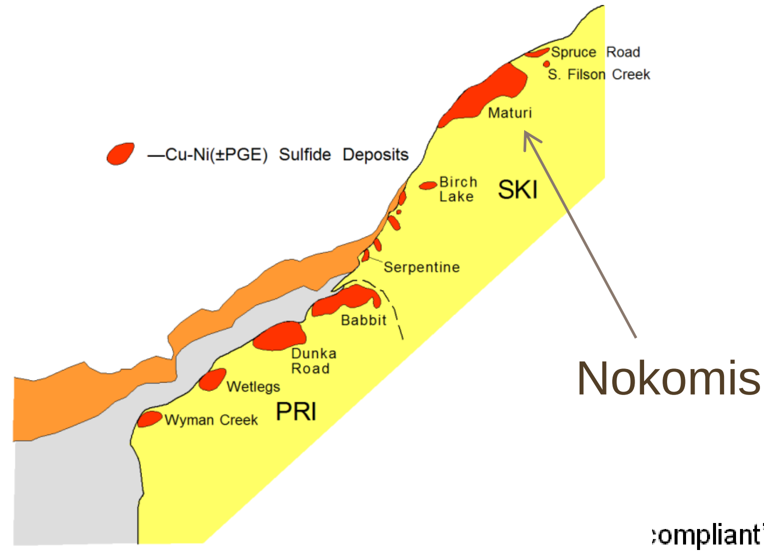


From Peterson, 2010

World Scale of the Nokomis Deposit







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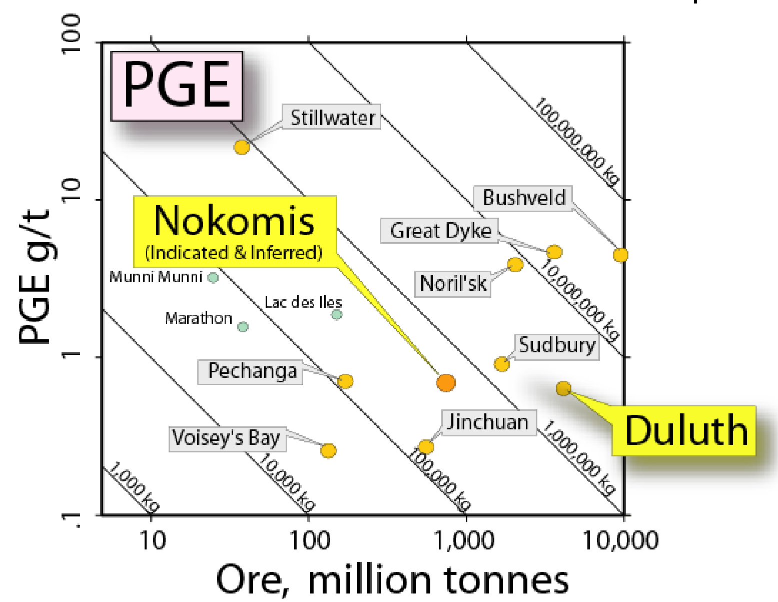
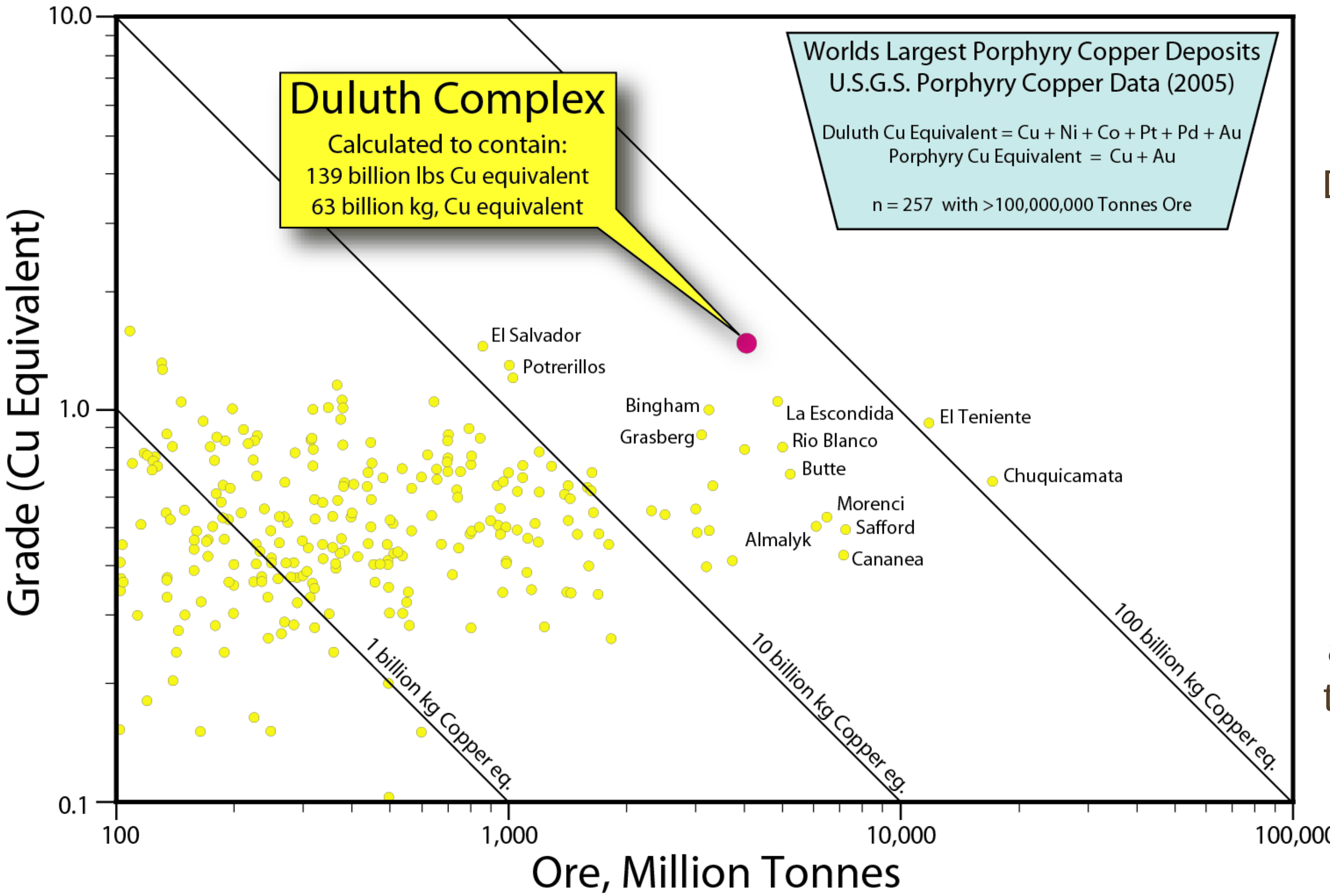


The Largest UNDEVELOPED Cu-Ni Deposit on Earth

Duluth deposits are perceived as low grade. Let's compare them to the other great type of disseminated ore deposit; Porphyry Copper's.

These data include secondary enrichment zones in the porphyry's.



Compared to porphyry copper deposits, the Duluth Complex ores are HIGHER GRADE with MORE METAL than nearly all porphyry systems.

The largest ore deposits in the USA are on this diagram, and the Duluth Complex ores are much larger then all of them.

From Peterson, 2010