Origin of sedimentary hosted high-grade iron ore deposits

Old models, new ideas and implications for exploration in the Labrador Trough

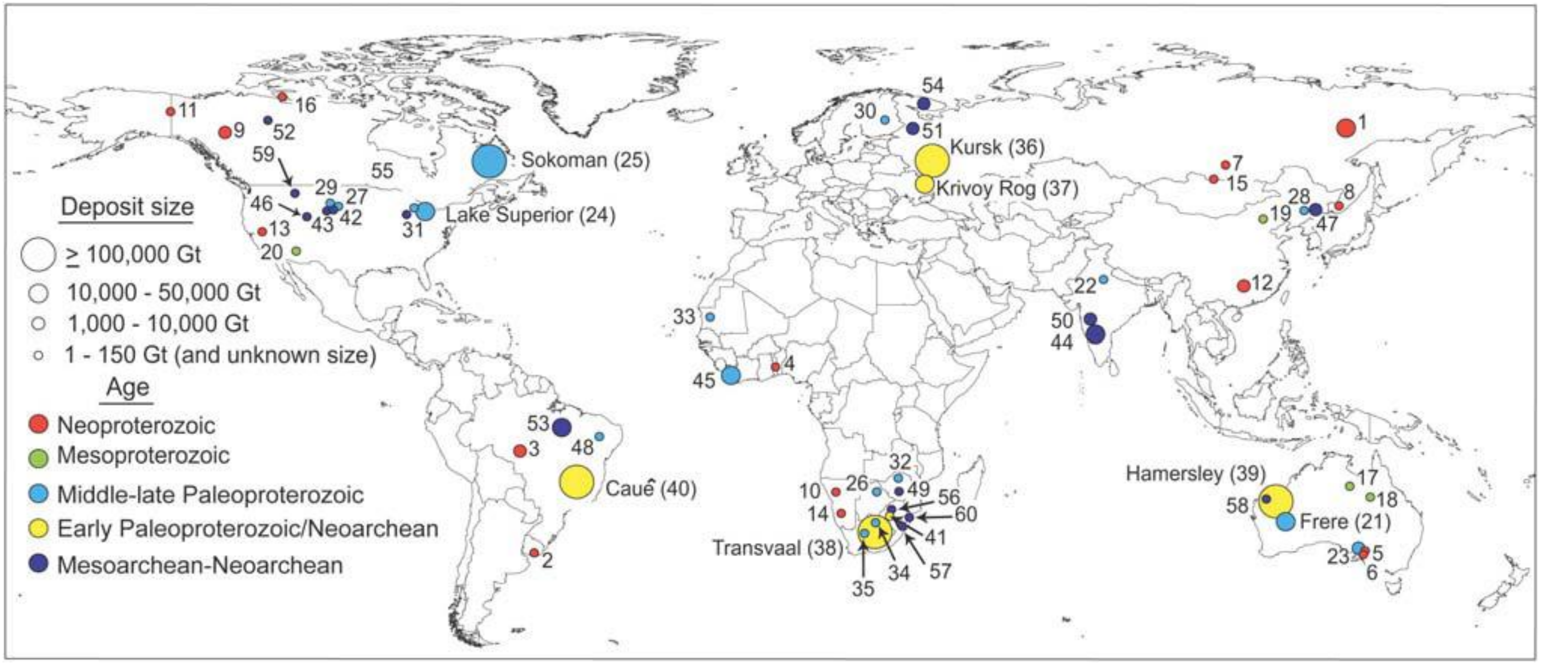
James Conliffe

Geological Survey of Newfoundland and Labrador

GEOLOGICAL SURVEY
NEWFOUNDLAND AND LABRADOR
Celebrating 150 years

Newfoundland Labrador
Natural Resources

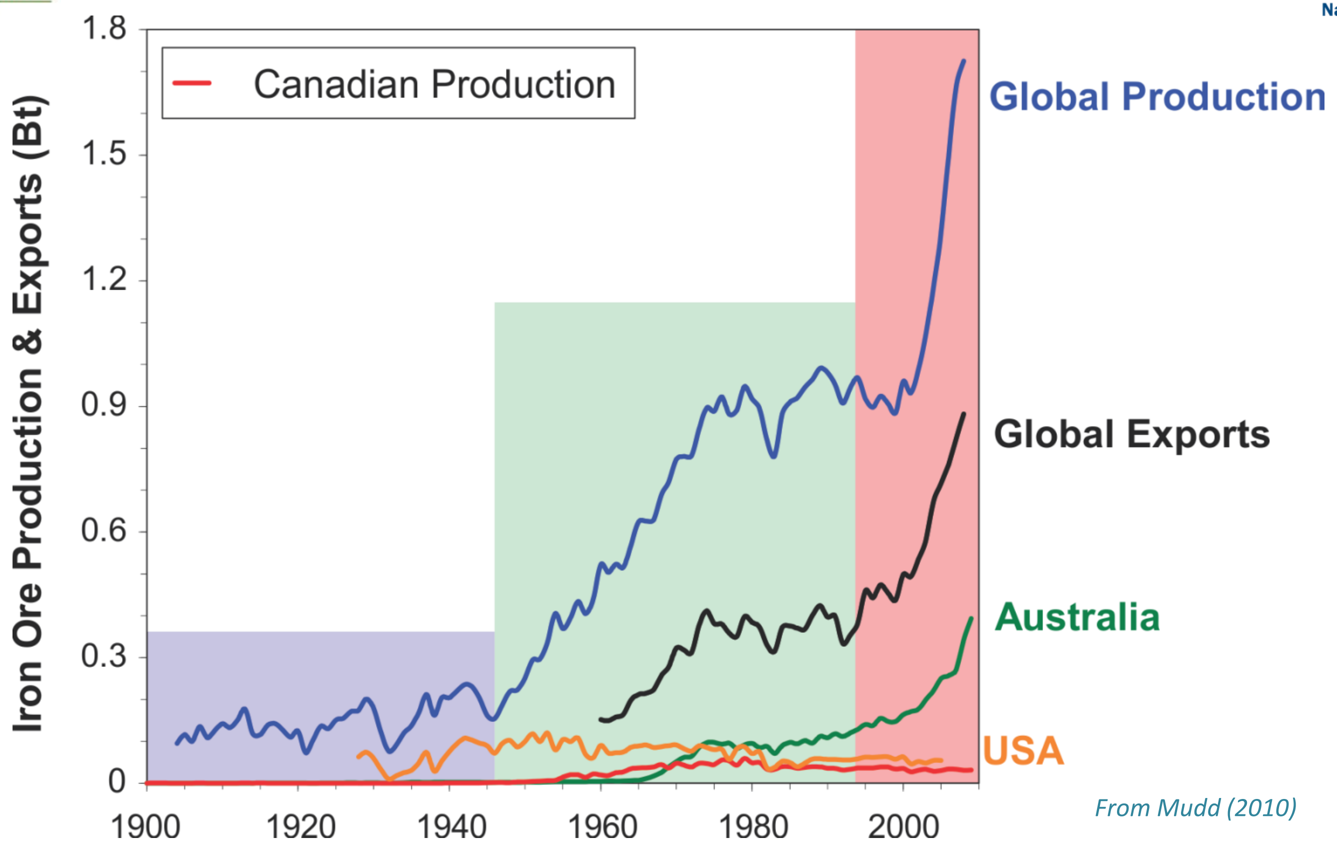
Sedimentary hosted high-grade iron ore deposits



From Bekker et al., 2010

- Sedimentary hosted iron ore deposits account for ~ 90% of current iron production worldwide
- Most production comes from high-grade (> 55% Fe) iron ore deposits hosted in Precambrian iron formations

Ideas driven by demand



From Mudd (2010)

- 1890s to 1940: Development of early genetic models
- 1940s to 1990s: Global Expansion
- 1990s to 2010s: Development and refinement of new models

Genesis of high-grade iron ore deposits

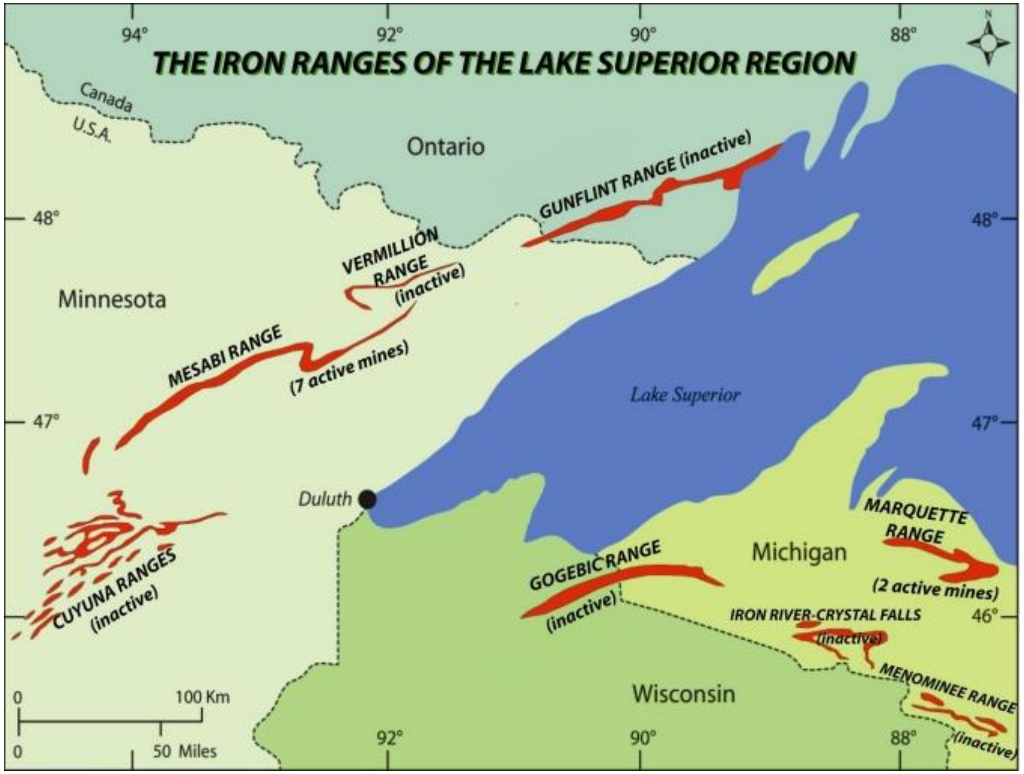
- Numerous genetic models proposed since the late 19th century
  - Supergene
  - Hydrothermal (Hypogene)
  - Syngenetic
  - Supergene-metamorphic
  - Supergene modified hypogene

Genesis of high-grade iron ore deposits

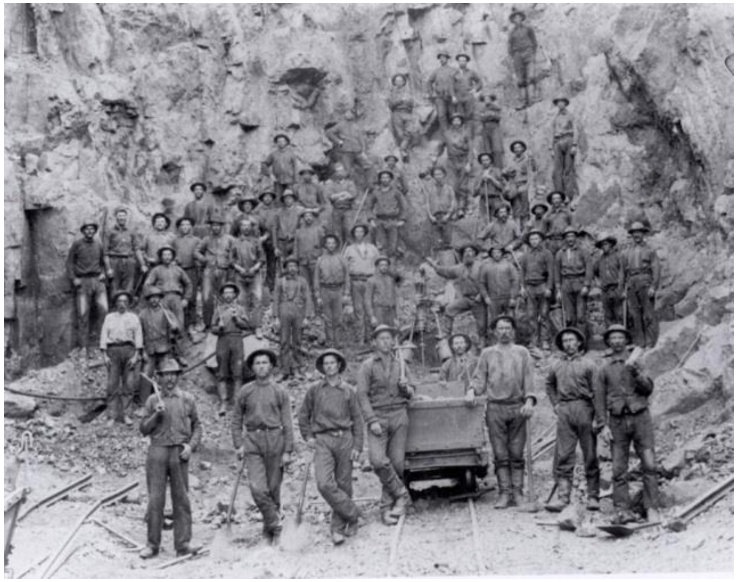
- ***Supergene (iron ore) deposit:*** Mineral deposit or enrichment formed near to or at the surface, commonly by descending groundwater (*supergene fluids*)
- ***Hypogene (iron ore) deposit:*** Mineral deposit formed below the surface, usually associated with mostly ascending, "warm" water rich fluids (*hypogene/hydrothermal fluids*)
- ***Hydrothermal fluids:*** Water-rich fluids at higher temperature than ambient rock temperature
  - Magmatic-hydrothermal, meteoric, metamorphic, basinal brines……..

1890s to 1940s

Development of early genetic models



- Geological mapping throughout the late 1800's and early 1900's identified iron formations throughout the Lake Superior region
- A number of competing models proposed for the enrichment of primary iron formations (~30% Fe) to form high-grade ore bodies



- From the 1840s to the 1960s more than 3 billion tonnes of iron ore were mined from sedimentary-hosted high grade iron ore deposits in Michigan, Minnesota and Ontario
- This abundant source of iron ore coupled with new steelmaking processes helped fuel rapid industrial expansion in North America and Europe

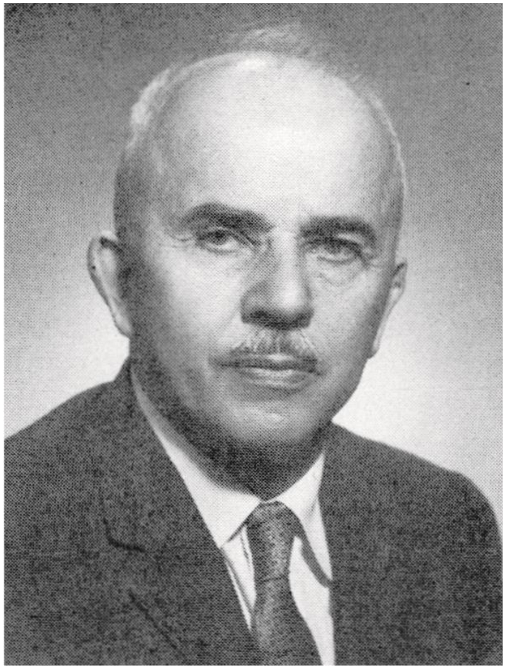
Supergene lateritic enrichment
(Leith, 1903; van Hise and Leith, 1911)

- Early geological investigations showed that high-grade iron ore deposits in the Lake Superior region formed due to the oxidation and leaching of the primary iron formation (Leith, 1903; van Hise and Leith, 1911) due to circulation of large volumes of fluids
- These authors argued that enrichment was associated with downward percolation of groundwater after exposure of the iron formation
  - Complete dissolution of chert bands leaving a residue of high-grade (>60 wt% Fe) iron ore

Charles Leith
USGS

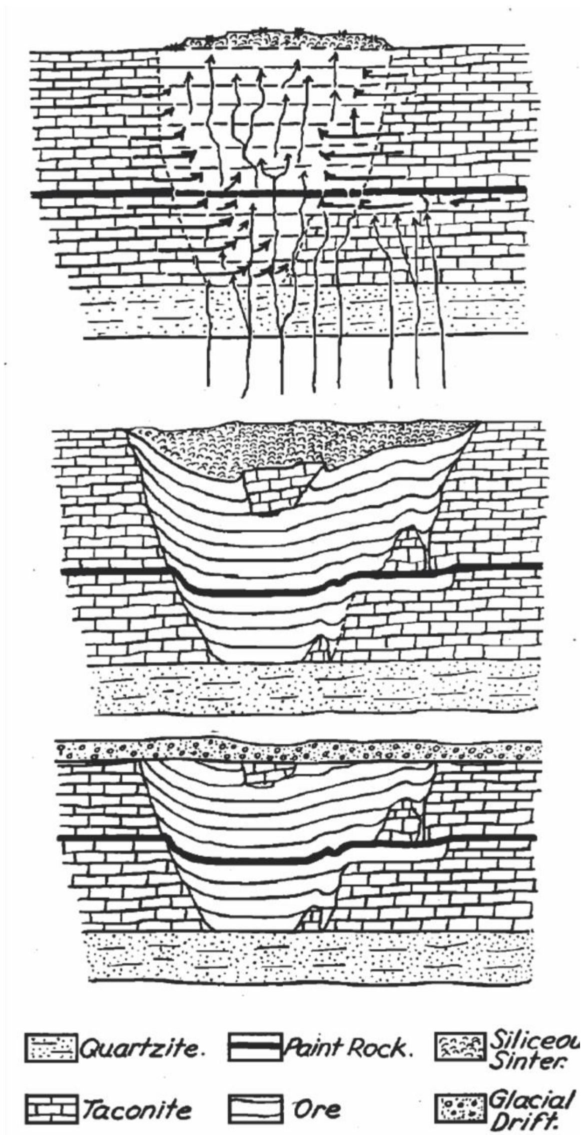
Hypogene enrichment
(Gruner, 1930, 1932, 1937)

- Supergene model challenged based on a number of factors
  - Inability of groundwater to remove large volumes of silica
  - Difficulties in circulating large volumes of oxygenated groundwater through the iron formation
- Gruner (1930, 1932, 1937) argued that the geological features of the ore bodies were better explained by ascending hydrothermal fluids



John Gruner
University of Minnesota

Hypogene enrichment
(Gruner, 1930, 1932, 1937)



From Gruner, 1937

- Gruner (1930): Iron enrichment and leaching associated with ascending magmatic fluids
  - Lack of intrusions associated with ore bodies
- Gruner (1937): orebodies formed from meteoric waters heated by "igneous emanations”
  - Unable to identify an adequate source of fluids

Supergene lateritic enrichment model accepted by most authors as most likely genetic model

1940s to 1980s

A global perspective

The post war years

Mount Whaleback Mine, Western Australia

- Exhaustion of high-grade ore bodies in the US and increased demand for steel after WW2 drove worldwide exploration and development of new mines
  - Western Australia: Massive ore bodies discovered in the 1950s, exports began in the 1960s
  - Sishen Mine (South Africa): Mining operations began in 1953
  - Ore deposits in Carajás region (Brazil) discovered in 1960s
  - High-grade iron ore deposits in the Labrador Trough entered production in 1954

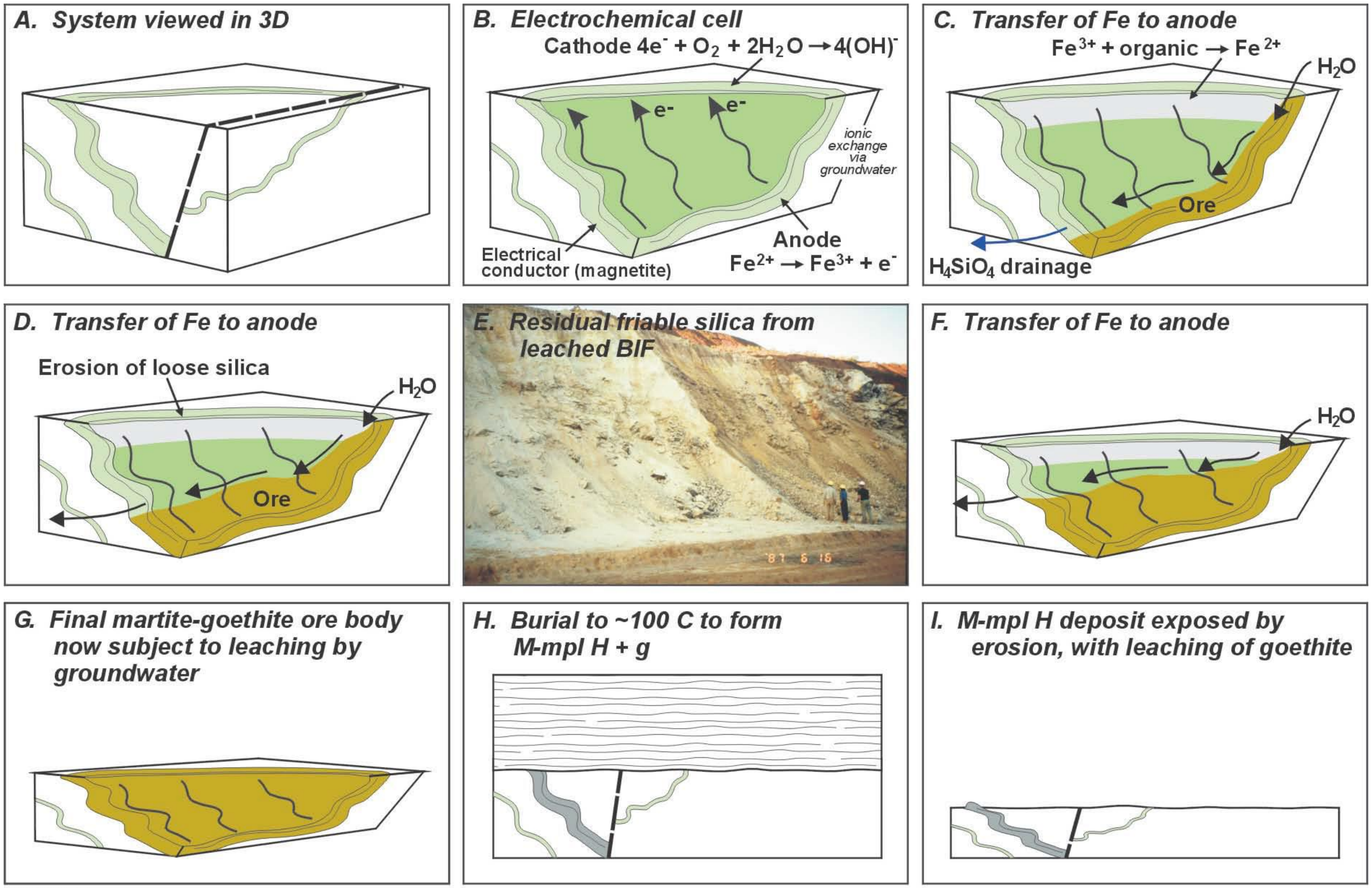
The post war years

- Early exploration models assumed the supergene lateritic enrichment model of Leith (1903) applied to all high-grade iron ore deposits
  - *Discovery outcrop of high-grade hematite/goethite and drill!*
- Geological observations contradicting these models were largely ignored
- Once mining began it became clear that this caused problems in predicting metallurgical properties, lump fines rations, Fe Grades and phosphorous content
- In the late 1970s major mining companies, government and academia in Western Australia sponsored a major research project into the origin of these deposits, under the direction of Dr Richard Morris

Supergene mimetic enrichment
(Morris, 1980, 1985)

- Deposit classified based on mineralogy
  - Martite goethite ore: Most common in Western Australia
  - Martite- microplaty hematite ores (± residual goethite): Common worldwide, including Labrador Trough
- Model of deep-seated supergene mimetic enrichment proposed (Morris, 1980)
  - Unlike previous models involve mimetic replacement of gangue minerals by goethite, forming martite-goethite ores
  - Late stage metamorphism and dehydration of goethite forms martite-microplaty hematite ores

Supergene mimetic enrichment
(Morris, 1980, 1985)



RCMf003-02

1990s to 2010s

Development and refinement of new models

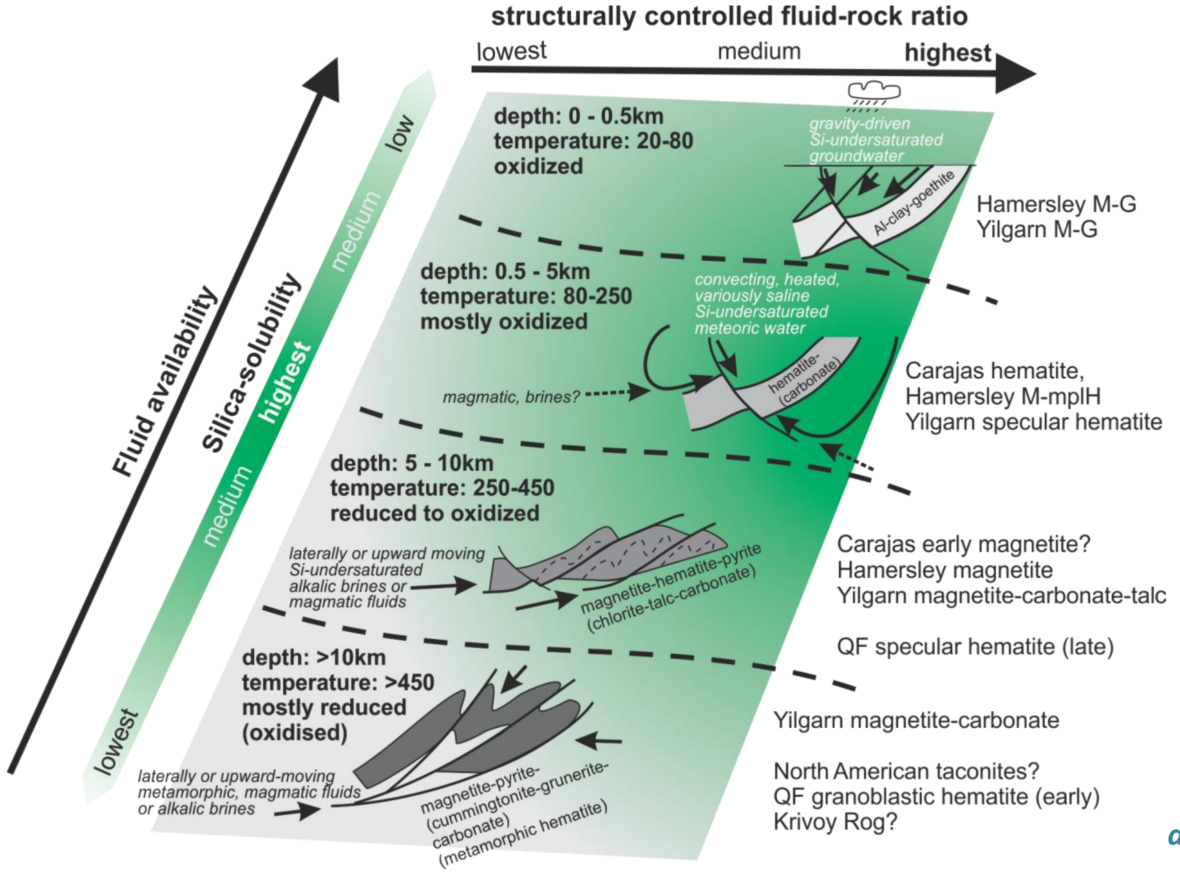
Shanghai Skyline

- Massive increase in demand for iron ore, driven by Chinese economy
- Resurgence of interest in the origin of sedimentary hosted high-grade iron ore deposits

Hypogene enrichment

- Return of the Hypogene/Hydrothermal Model
  - **General Papers:** Beukes et al. 2003; Gutzmer et al., 2006, 2008; Dalstra and Rosiere, 2008; Lobato et al., 2008
  - **Australia:** Li et al., 1993; Barley et al., 1999; Taylor et al., 2001; Thorne et al., 2003; Angerer and Hagemann, 2010
  - **South Africa:** Netshiozwi, 2002; Lobato et al, 2008
  - **Brazil:** Spier et al., 2003; Dalstra and Guedes, 2004; Rosiere and Rios, 2004; Figueiredo et al., 2008, 2013; Hensler et al., 2014
  - **India:** Beukes et al., 2008; Roy and Venkatesh, 2008
  - **West Africa:** Cope et al., 2008
  - **North America:** Morey, 1999

Hypogene enrichment

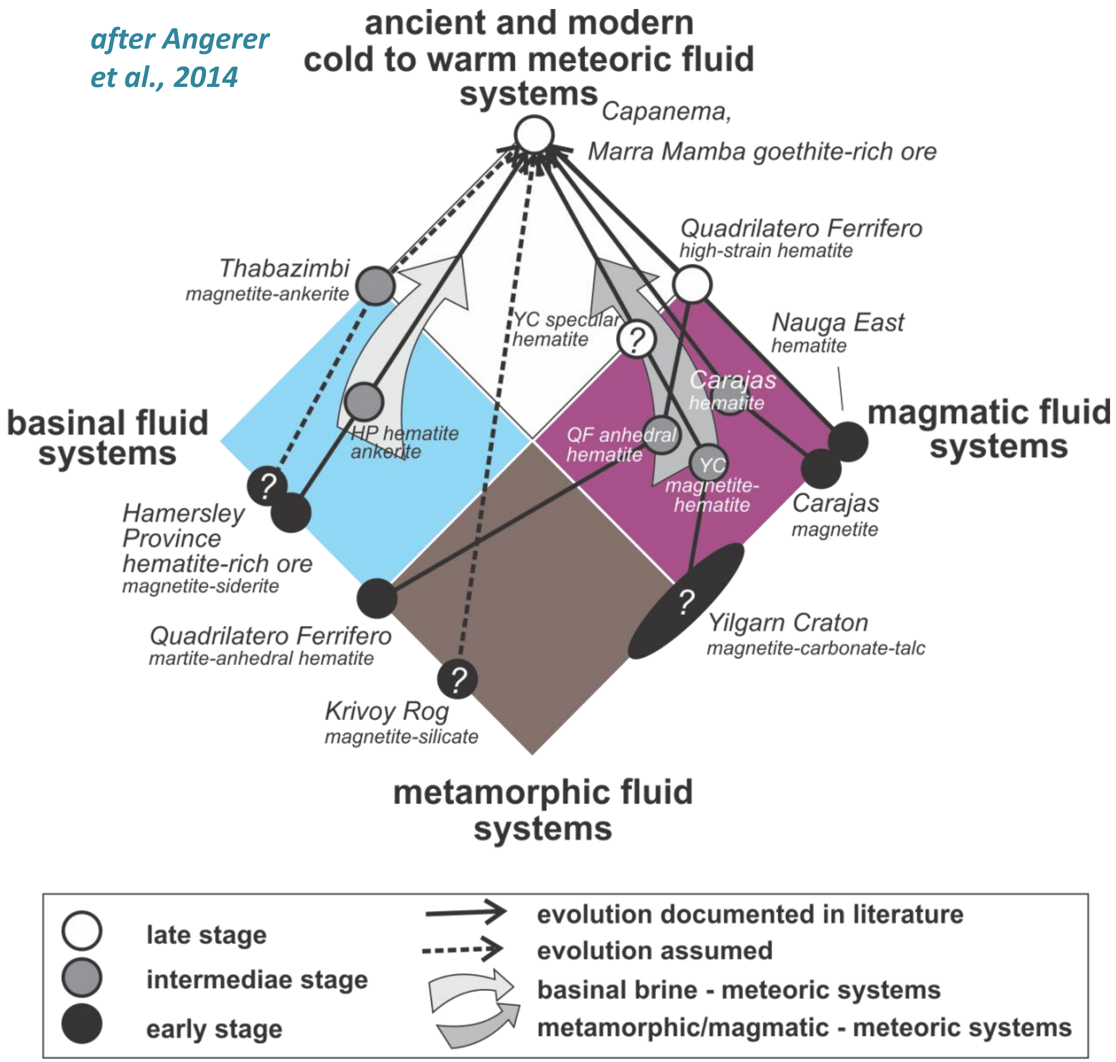


after Angerer et al., 2014

- Leaching of silica and carbonates, oxidizing fluids, mobility of iron
- High volume of fluid flow
- Strong structural control
- Magmatic, deep basinal or meteoric fluids
- Wide range in alteration styles and tectonic settings

Current State of Understanding

after Angerer et al., 2014



Recognition that high grade iron ore deposits can form due to a variety of processes

Often multiple overprinted enrichment events

"consensus on formation processes……..has not been reached and a strong and healthy debate still rages"

GEOLOGICAL SURVEY
NEWFOUNDLAND AND LABRADOR
Celebrating 150 years

High-grade iron ore deposits in the Labrador Trough

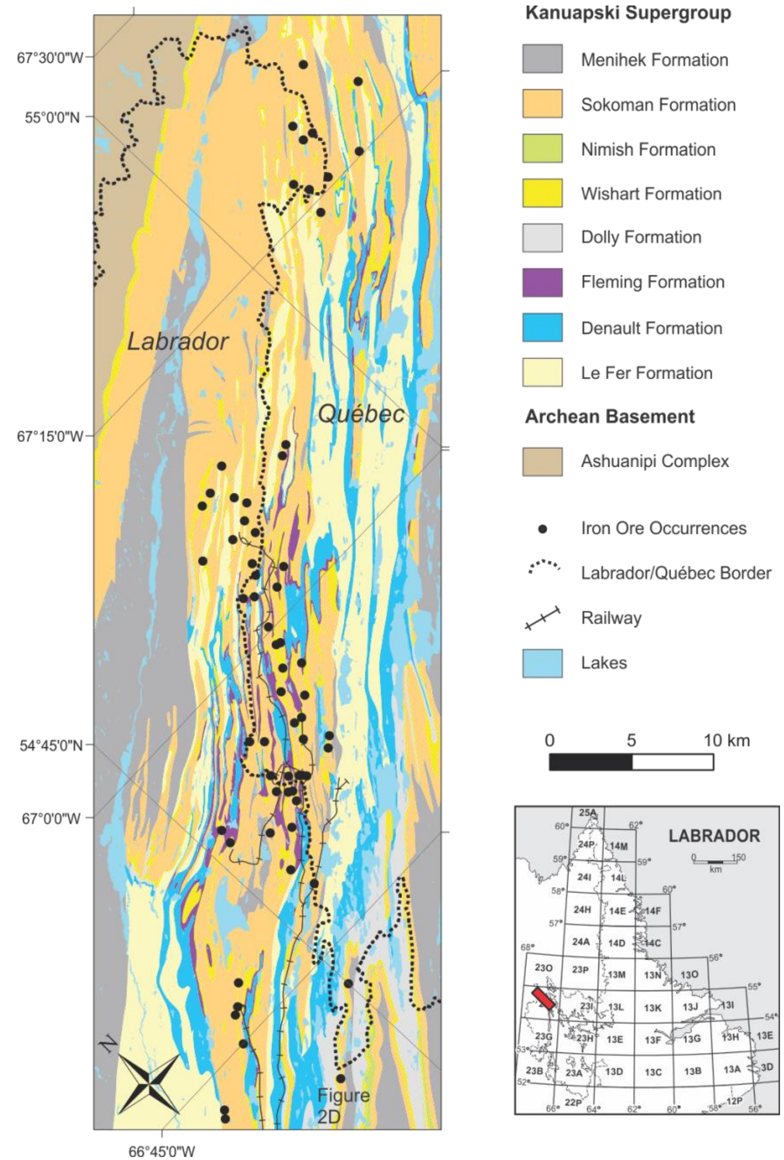
Newfoundland Labrador
Natural Resources

GEOLOGICAL SURVEY
NEWFOUNDLAND AND LABRADOR
Celebrating 150 years

Newfoundland Labrador
Natural Resources

- More than 80 high-grade iron ore occurrences in linear belt along Labrador-Québec border
- Intermittently mined since 1954

James Mine, 2012



Blue Ores

Hematite ± goethite, martite

Dominantly soft and friable, minor hard ore

Yellow Ores

High goethite content

Replacement of Fe-silicates and Fe-carbonates

Red Ores

Red hematite ± goethite, clay minerals

Replacement of Ruth Formation shales

Rubble Ores

Angular fragments of hematite in goethite matrix

Detrital ore deposit

Diagram of Typical DSO Cross-section

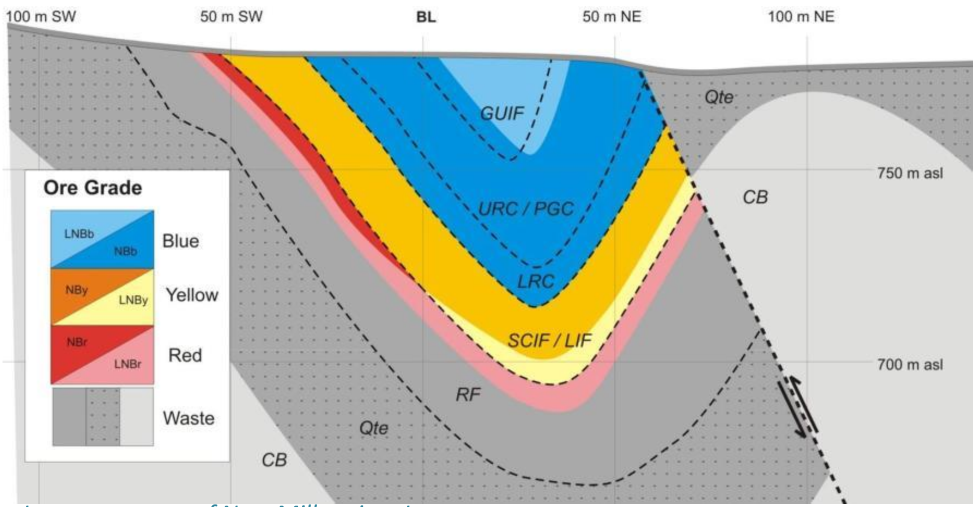
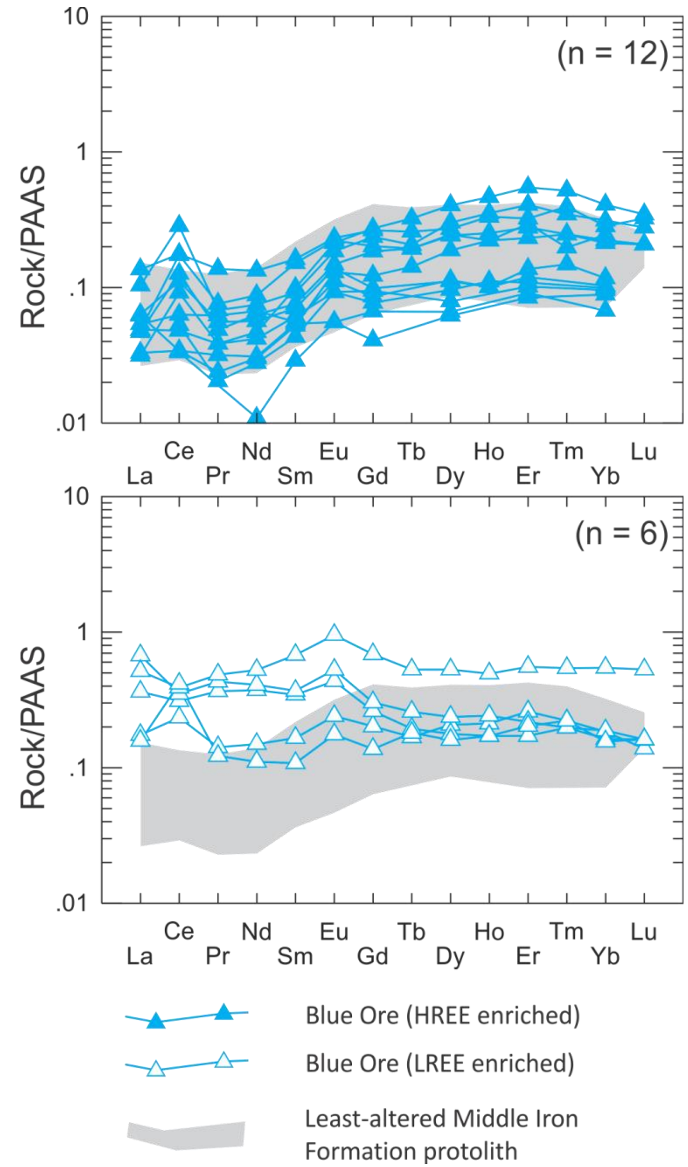


Image courtesy of New Millennium Iron

- Strong stratigraphic and structural control
  - Blue Ores from Middle Iron Formation
  - Yellow Ores from Lower Iron Formation (silicate-carbonate iron formation: SCIF)
  - Red Ores from Ruth Formation shales
  - Deposit located in syncline and homoclines, commonly cut by high-angle reverse faults

- Early studies concluded that deposits formed due to the supergene lateritic processes
  - Downward percolation of groundwater and subsequent leaching of silica, forming enriched residual iron ore deposits (Stubbins et al., 1961; Gross, 1968)
- Considerable variation in metallurgy, Fe-grade, structural setting and relative proportion of ore types between individual ore bodies
- Geochemical analysis consistent with multiple, overprinting enrichment phases



Supergene Lateritic Enrichment

- Goethite-rich “duricrust ” above some deposits
- Secondary goethite and Mn-Oxides in vugs and pores
- Some ore bodies decrease in grade and degree of leaching with depth
- Most enrichment syn- to post-deformation, ore bodies commonly in fault contact with unaltered iron formation
- Significant Fe enrichment and depletion of Al in red ores
- REE profiles in some blue ores
- Presence of hard lenses and layers, w. microplaty hematite

Supergene Mimetic Enrichment

- Abundant martite-goethite ore (especially in yellow ores)
- Goethite pseudomorphing Fe-silicates and Fe-Carbonates
- Leached, Fe-depleted, silica-rich cap over some ore bodies (e.g. Knob Lake)
- Goethite generally paragenetically late, cannot explain all supergene features
- Hematite-rich ores require metamorphism (80 to 100°C) after enrichment; no evidence of post enrichment burial and lower ores (yellow ores) still goethite rich

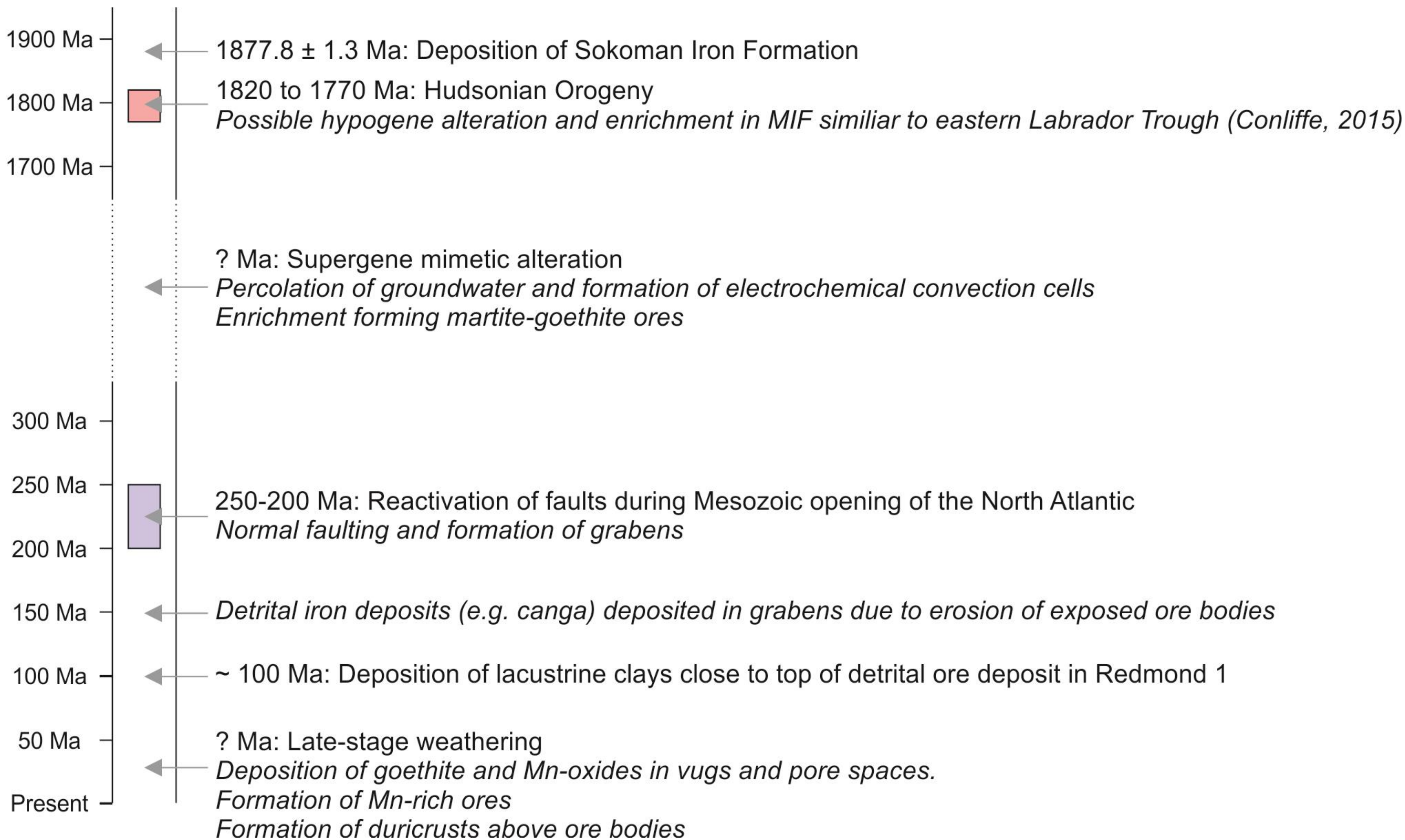
Hypogene Enrichment

- Explains lenses and layers of hard, microplaty hematite
- Hypogene enrichment documented from Eastern Labrador Trough in similar structural settings
- REE data, remobilization of some “immobile” elements
- Oxidized altered iron formation recorded between some ore bodies (w. iron remobilization)
- No carbonate protore
- Cannot explain goethite-rich ores of friable ore (requires supergene modification)
- Evidence obscured by later supergene alteration

Enrichment likely a multistage process with superimposed hypogene and supergene enrichment

GEOLOGICAL SURVEY
NEWFOUNDLAND AND LABRADOR
Celebrating 150 years

Newfoundland Labrador
Natural Resources



Farley and McKeon (2015)

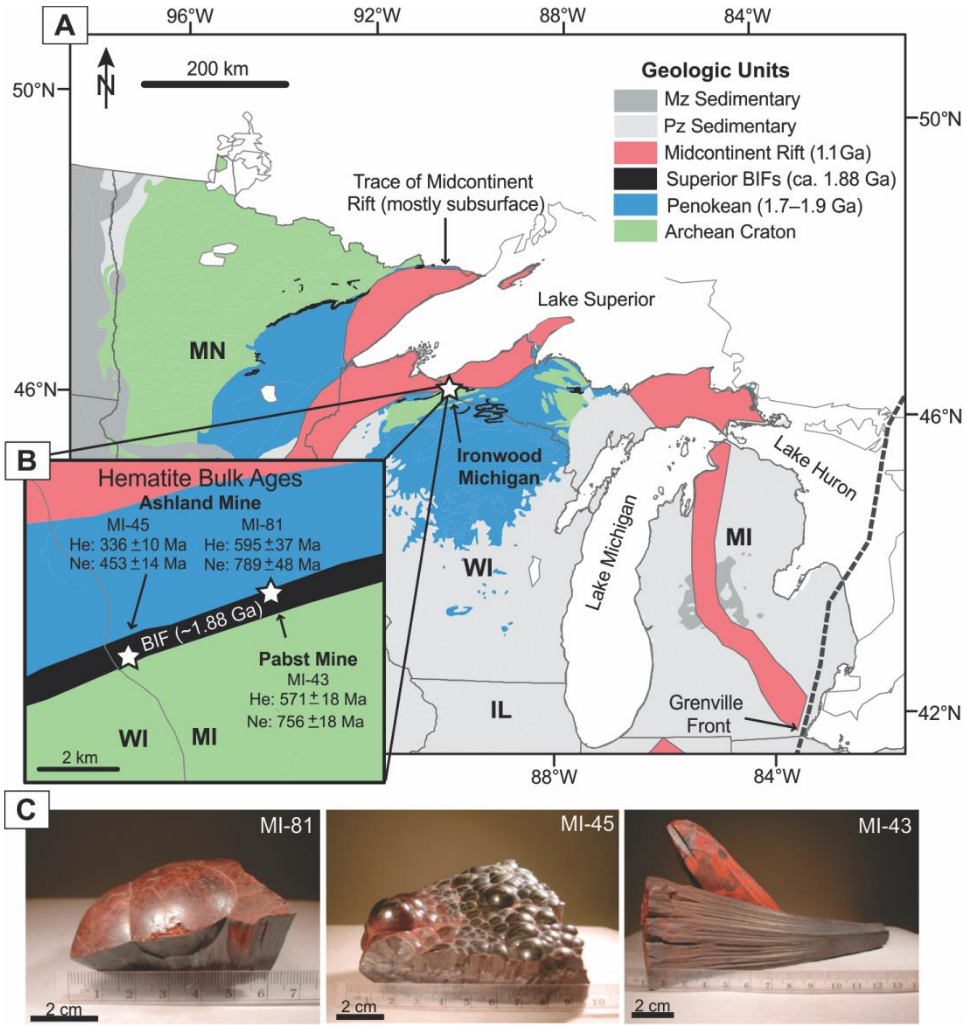


Figure 1. A: Generalized bedrock geology map showing sampling location (white star). BIF—banded iron formation; Mz—Mesozoic; Pz—Paleozoic. B: Mine sites and ages. C: Hand sam - ple photographs of the dated hematite samples.

From Farley and McKeon (2015)

- (U-Th)/^{21}Ne and ^{4}He/^{3}He ages of hematite samples
- Late stage (lateritic??)

772 ± 41 Ma

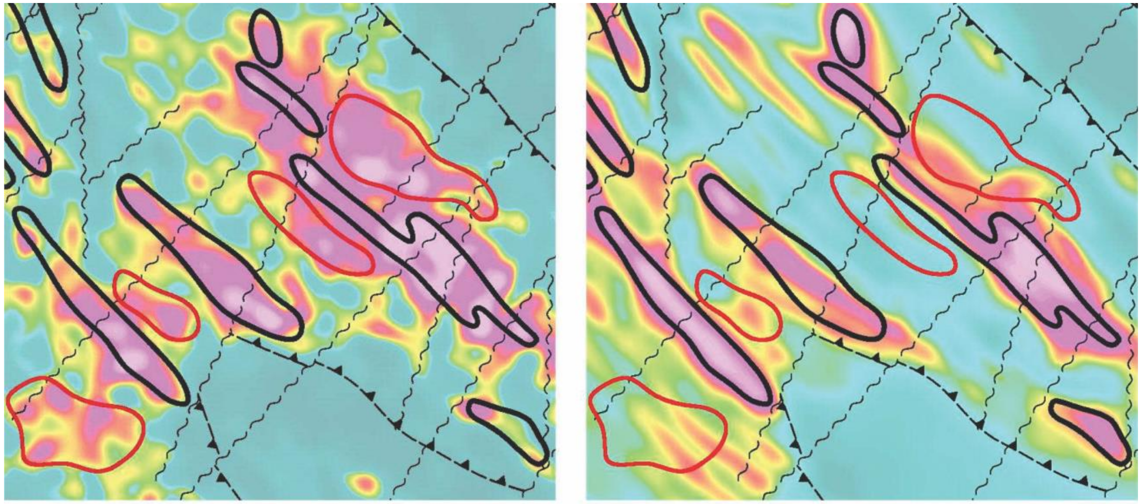
(@ 150 ± 70°C)

453 ± 14 Ma

(@ ~ 60°C)

- Dehydration of goethite??
- Episodic or continuous process??

- Geological and geochemical studies have shown that high-grade iron ore deposits in the Labrador Trough have a wide range of characteristics, consistent with a complex and multistage enrichment of both hypogene and supergene processes.
- Future work required to relative importance of hypogene or supergene processes
  - Geochronology of goethite and hematite (± monzonite, apatite etc.)
  - In-situ geochemistry of hematite, goethite



GDD grid showing several selected DSO (RED) and Magnetite (BLACK) targets

Total magnetic intensity grid showing several selected DSO (RED) and Magnetite (BLACK) targets

DSO Target Areas, from Geofile LAB/1592

- Exploration should not be limited to deposits that outcrop on the surface (Supergene Lateritic)
- Potential for deposits below leached and silica-rich zones (Supergene Mimetic) or close to low-grade oxidized iron formation (Hypogene)
- Geophysics used to identify targets (high gravity, low magnetics)

Positive results of ground gravity north of Timmins area announced by Cap-Ex (December 2105): Numerous DSO targets which require drilling to test

THANKS TO

Department of Natural Resources

Alex Calon, Garrett Martin, Wayne Tuttle, Tim van Nostrand

Staff at McGill Subarctic Research Station

Steve Zajac, Jim Orth, Tata Steel Minerals Canada, New Millennium Iron Corp., Labrador Iron Mines, Mamba Minerals Limited