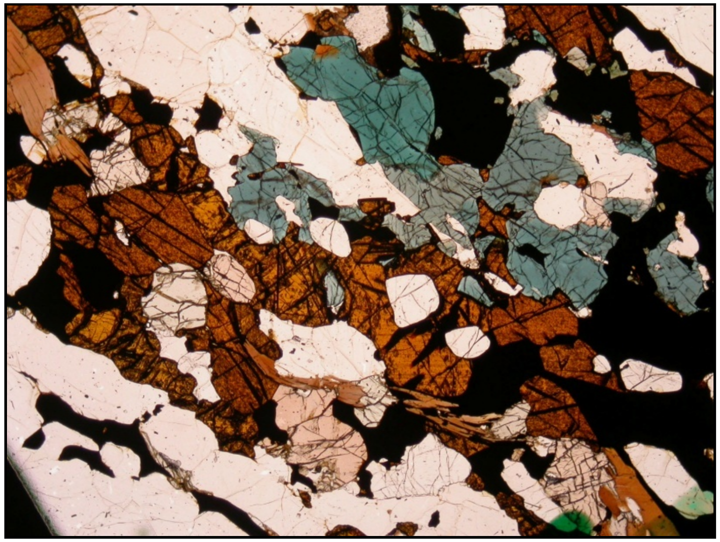
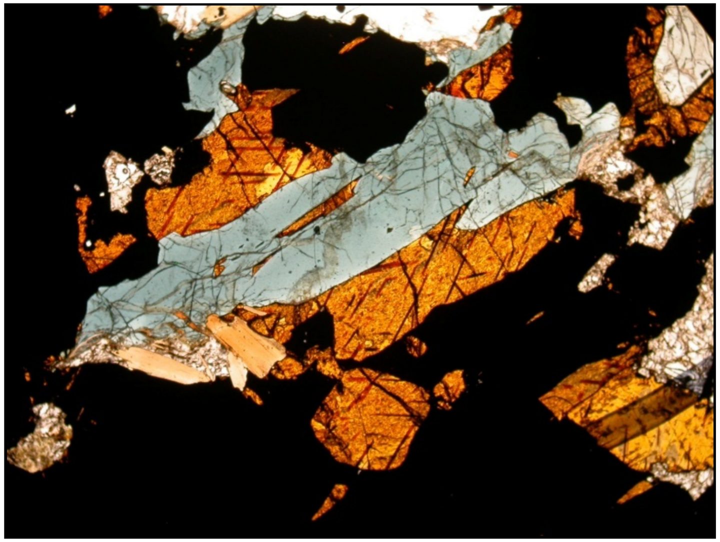
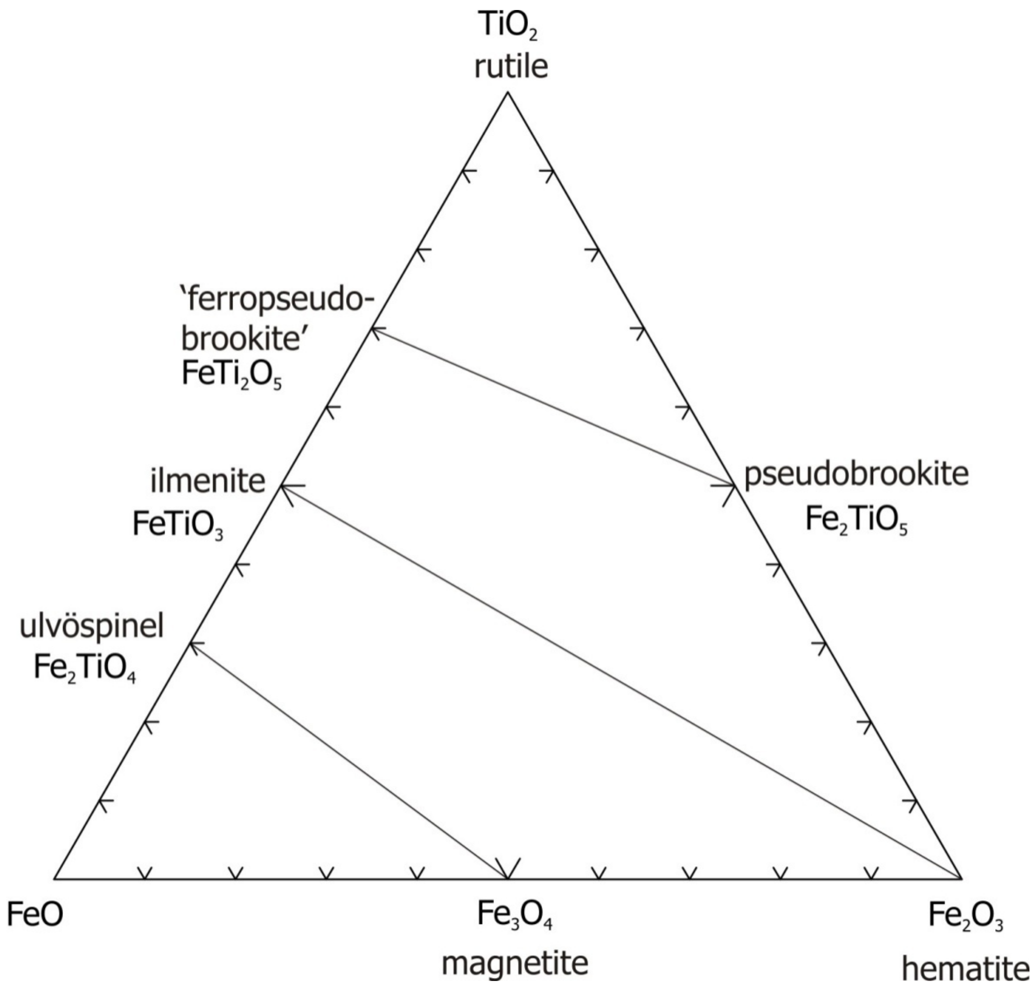
# Formation des gîtes de Fe-Ti contenant du rutile associés aux massifs anorthositiques de la Province du Grenville

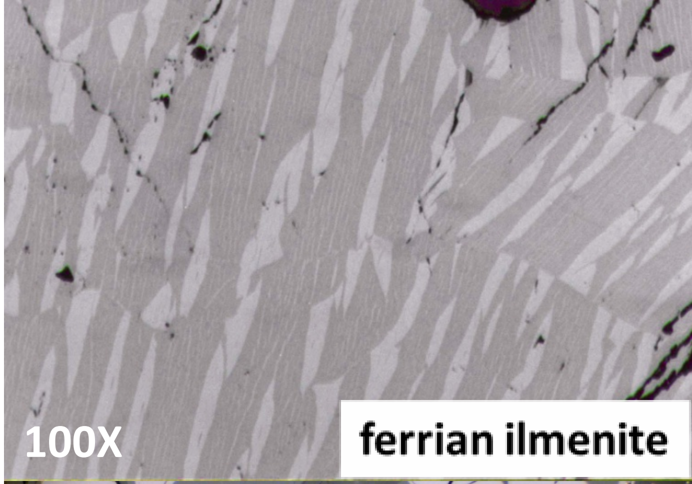


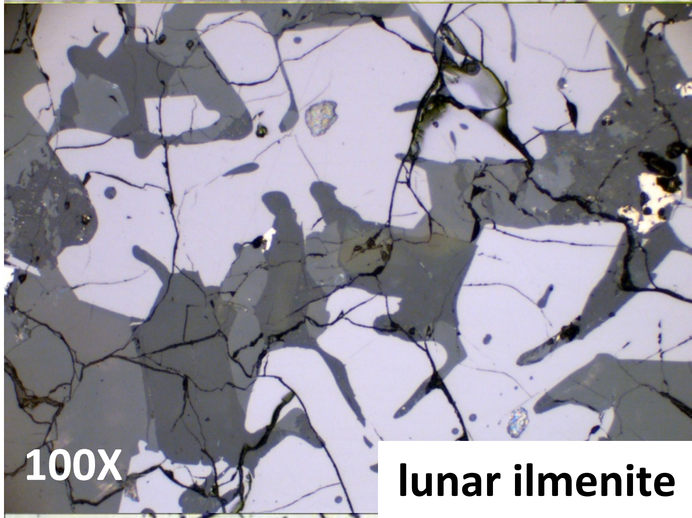


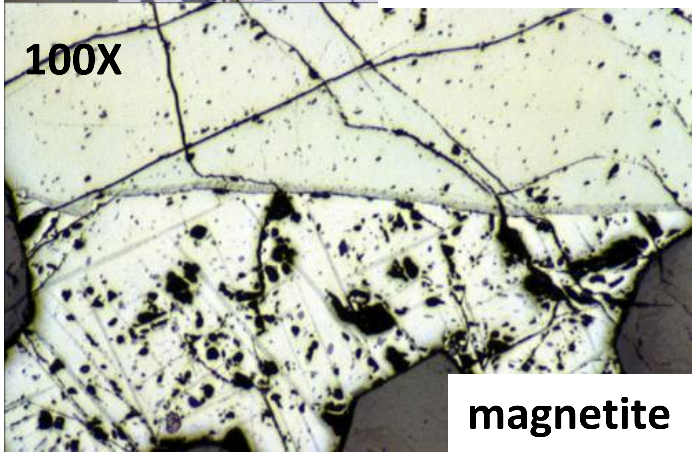
Caroline-Emmanuelle Morisset
géochimiste, Golder Associés

# Fe-Ti oxides


TiO2
rutile
'ferropseudo-
brookite'
FeTi2O5
ilmenite
FeTiO3
ulvöspinel
Fe2TiO4
pseudobrookite
Fe2TiO5
FeO
Fe3O4
magnetite
Fe2O3
hematite


100X
ferrian ilmenite


100X
lunar ilmenite


100X
magnetite

# Fe-Ti deposits: uses

**mineral**

Ilmenite ($FeTiO_3$)

Rutile ($TiO_2$)

**% of the market**

Ilmenite: **95%**

Rutile: **5%**

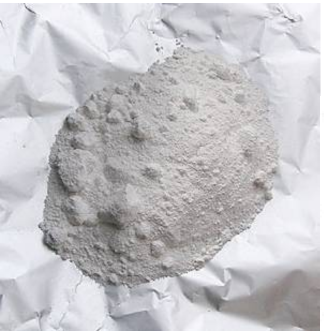
**use**

**$TiO_2$ white pigment** (opaque, non-flammable and non-toxic)

- paint (58%)
- plastics (22%)
- paper (11%)
- food (white candies)
- cosmetics (UV protection)

**Ti metal** (strong, flexible, light , resistant to shock, corrosion and heat)

- aerospace industry
- automobile industry
- medicine
- sports equipment
- jewellery

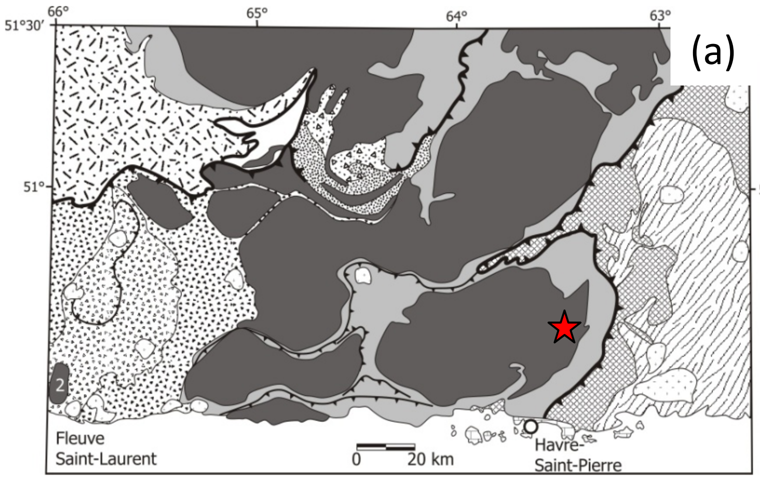


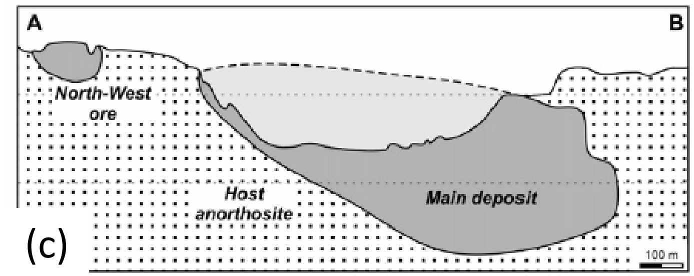
# Fe-Ti oxides deposits

- Two types of deposits:
  - 1- Placer deposits:
    - – ilmenite, altered ilmenite and rutile
  - 2- Magmatic:
    - – layered intrusions:
      - magnetite (V deposits) + ilmenite
    - – anorthosite massifs:
      - magnetite + ilmenite + apatite
      - magnetite + ilmenite
      - ilmenite
      - ilmenite + rutile

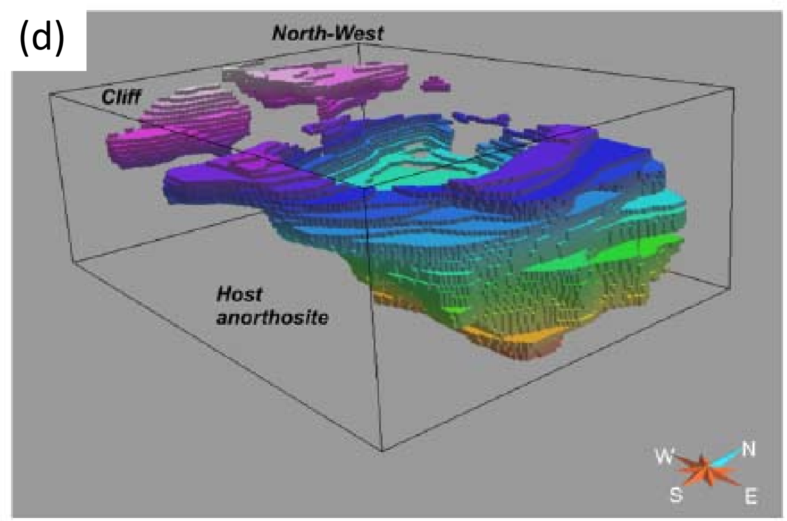

Source: www.niobioinformatics.in/images/ilmenite_placers.jpg


# Massive Fe-Ti oxides deposits: Lac Allard deposit





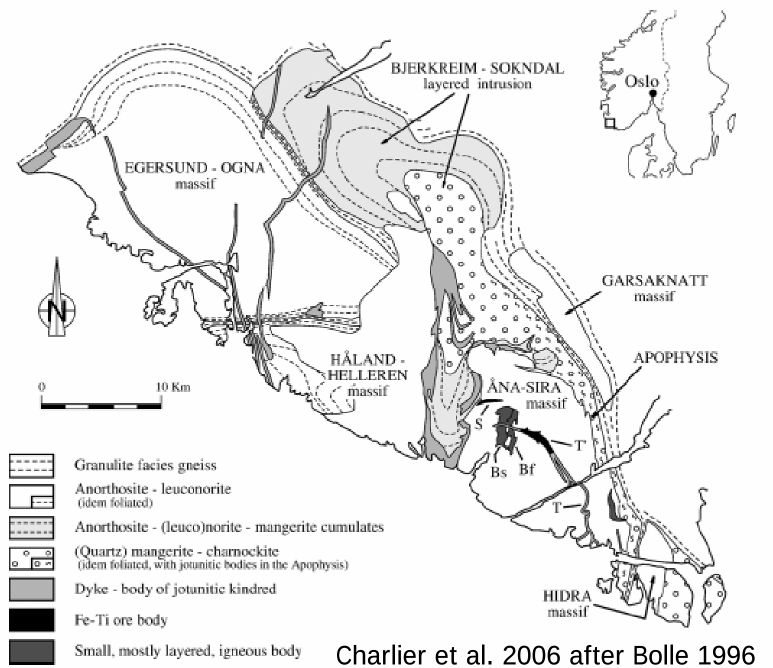



Massive ilmenite
(ferrian ilmenite)

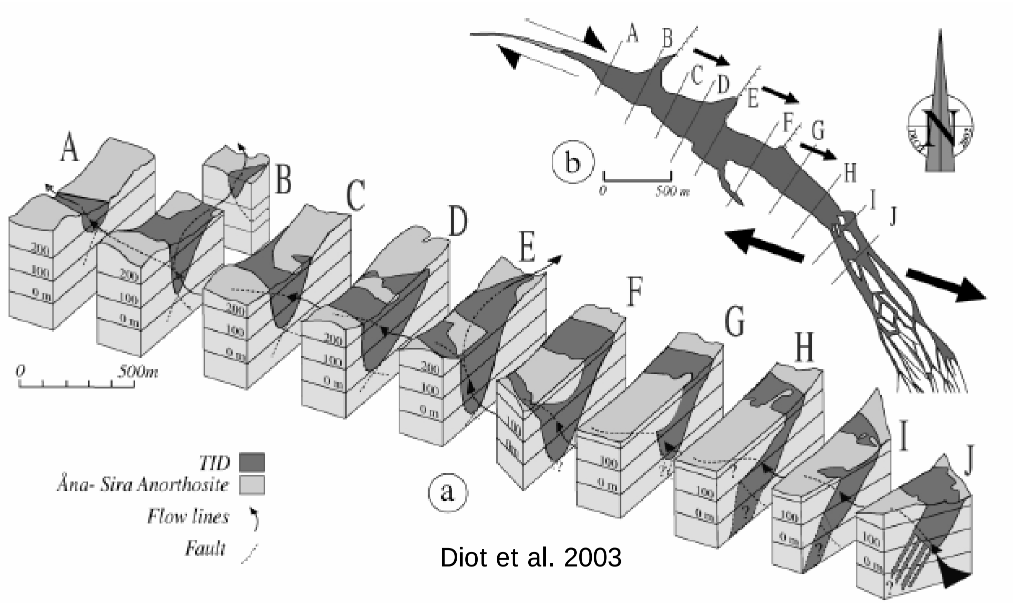
50% of the deposit samples have
>76% ilmenite (Charlier et al. 2010)

(a) Morisset et al. 2010 after Gobeil et al. 2003;
b, c, and d from Charlier et al. 2010

# Semi-massive Fe-Ti oxides deposits: Tellnes deposit




Charlier et al. 2006 after Bolle 1996

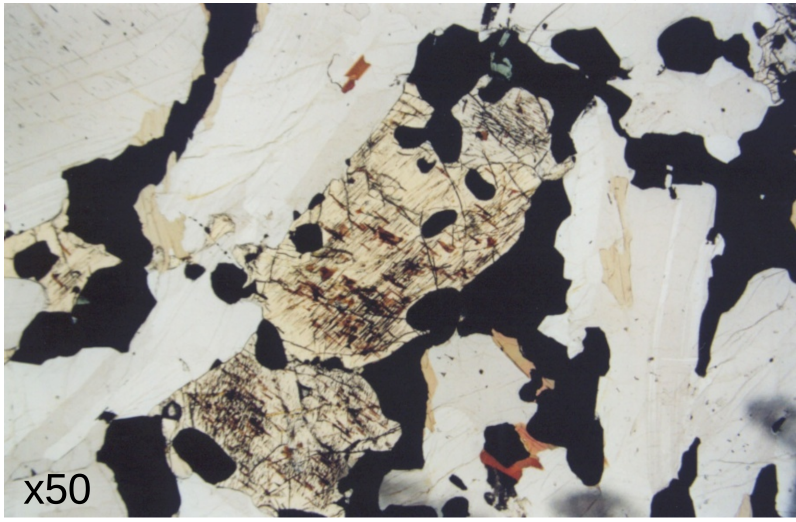



Diot et al. 2003

Semi-massive ilmenite deposit (ferrian ilmenite)

Ore has between 25 and 50% ilmenite

Concentration of ilmenite increases with depth

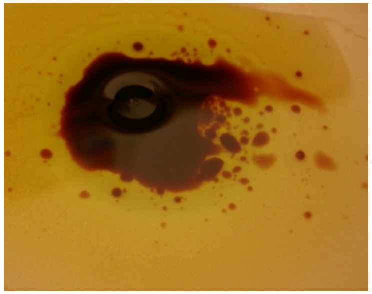


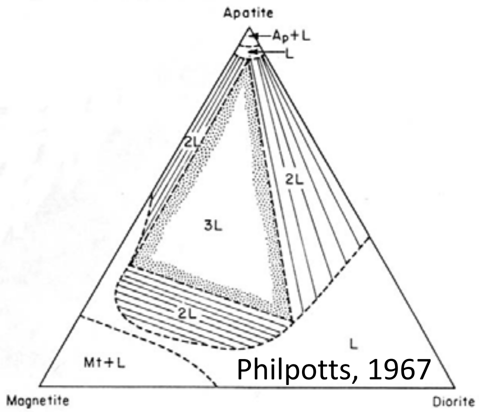
# Formation of Fe-Ti oxides deposits

- Problems: how to form rocks that contain 100% oxides and how to explain the enrichment in Fe-Ti to form semi-massive deposits?

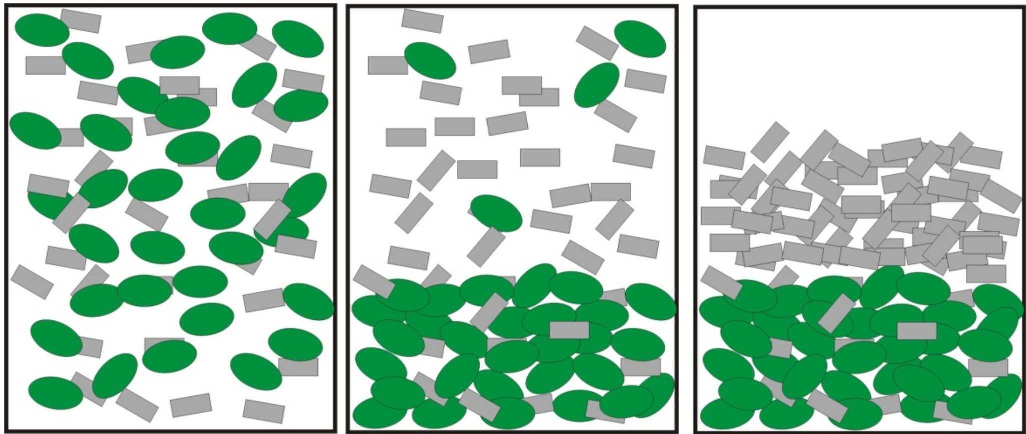
  1. Philpotts (1967) experiments: immiscible Fe-O-P (no Ti) liquid at T = 1400°C but ~25 years of experiment have never succeeded in lowering the T or having Ti in the immiscible high-Fe liquid (Lindsley 2003)

  2. Fractional crystallization that enriches the magma in Fe and Ti and accumulation of the oxides by density (ilmenite density = 4.72, plagioclase density = 2.6, magmas parental or residual to anorthosite density = 2.65 to 2.9, Scoates 2000)

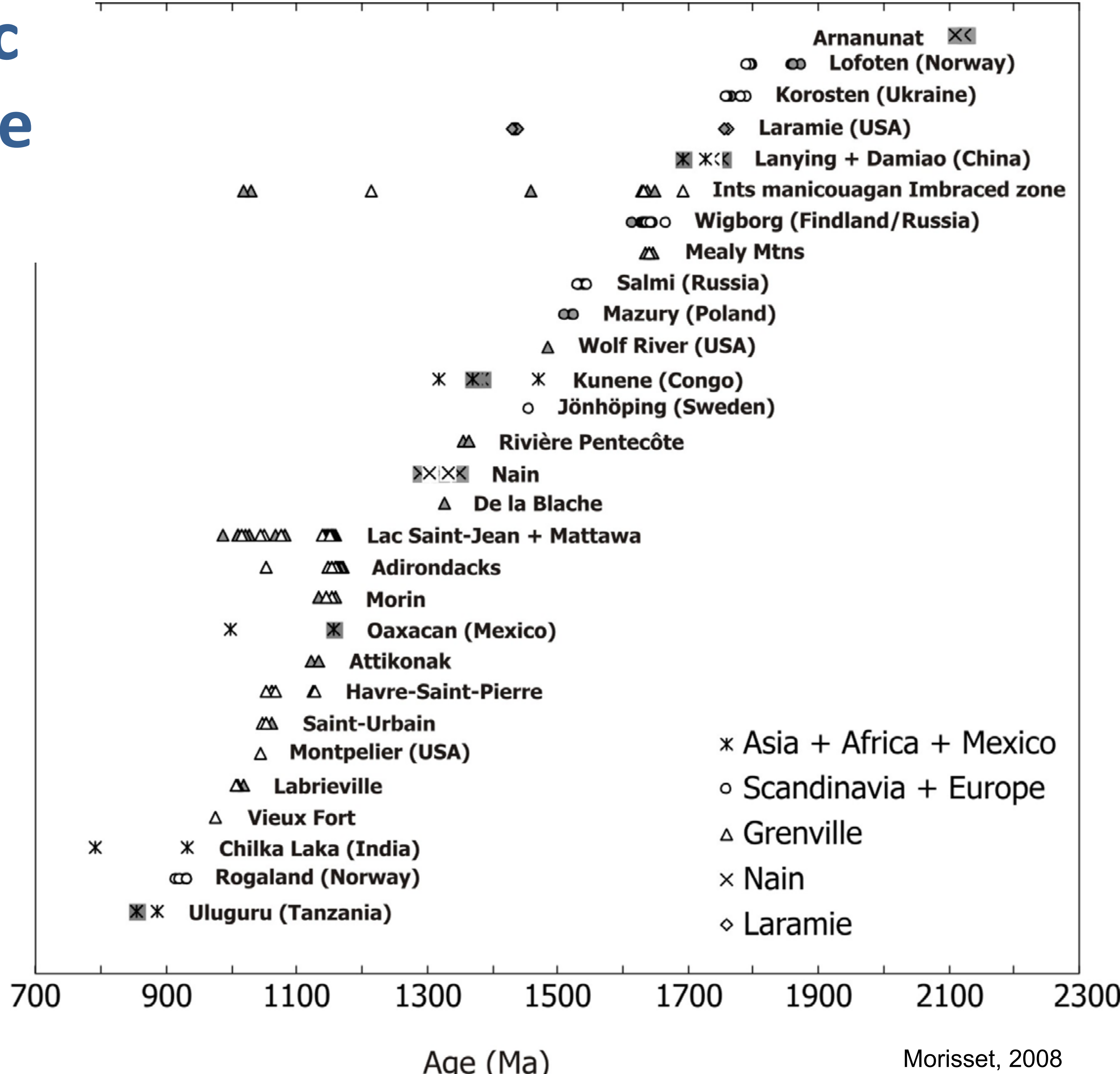




Philpotts, 1967



# Proterozoic Anorthosite Massifs

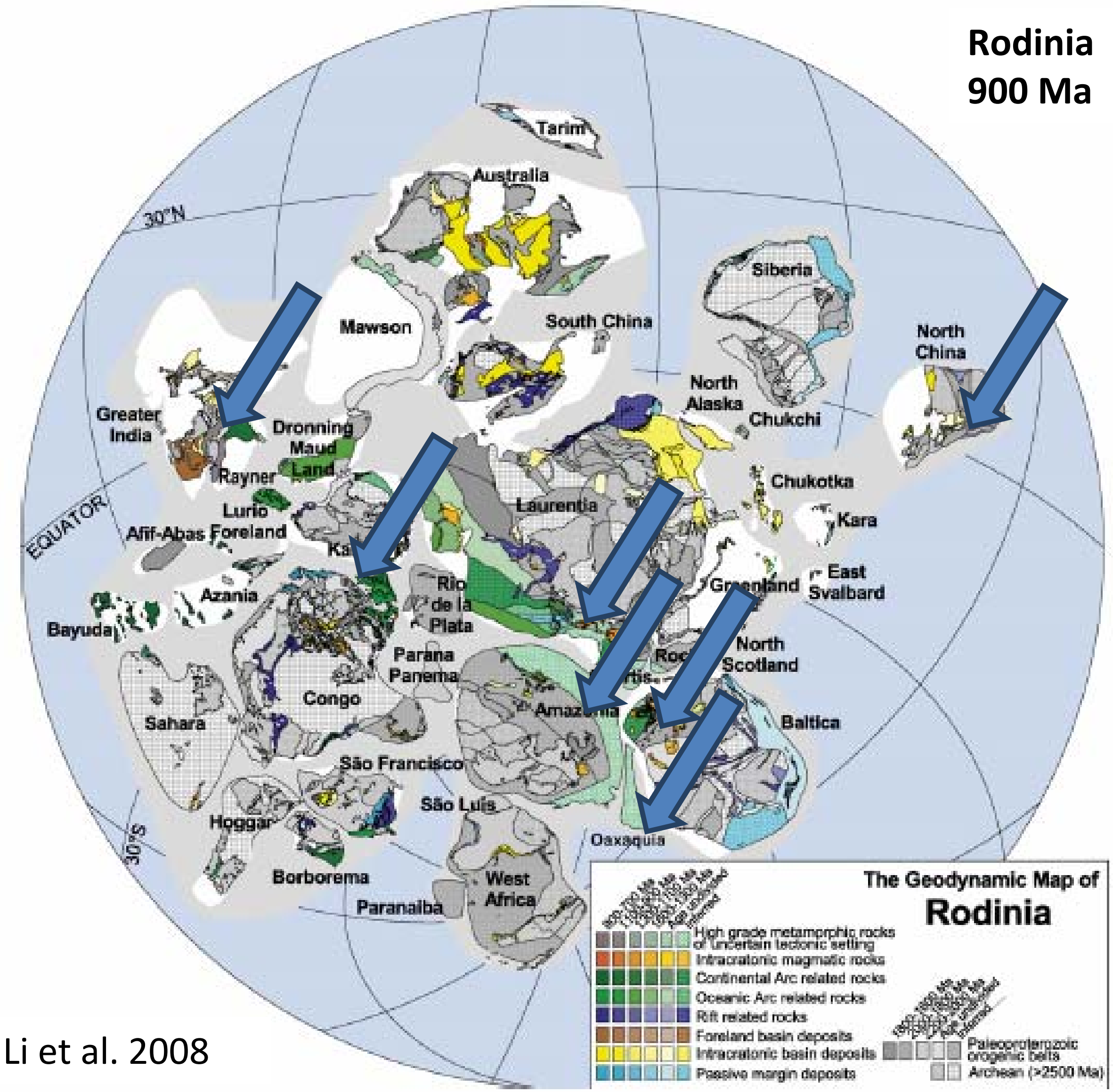



Morisset, 2008

White symbols: anorthosite

Grey symbols: associated mangerite-charnockite-granite

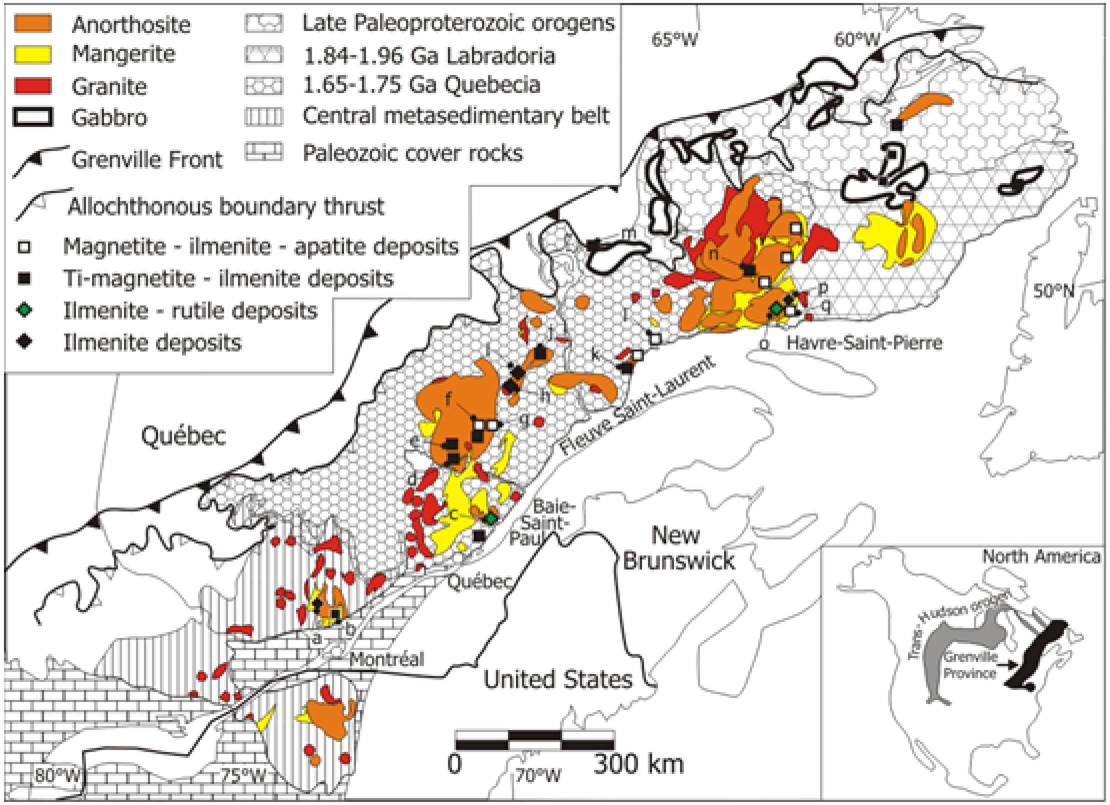
# Proterozoic anorthosite massifs




Li et al. 2008

660 Ma (Madagascar) – 2100 Ma (Nain)

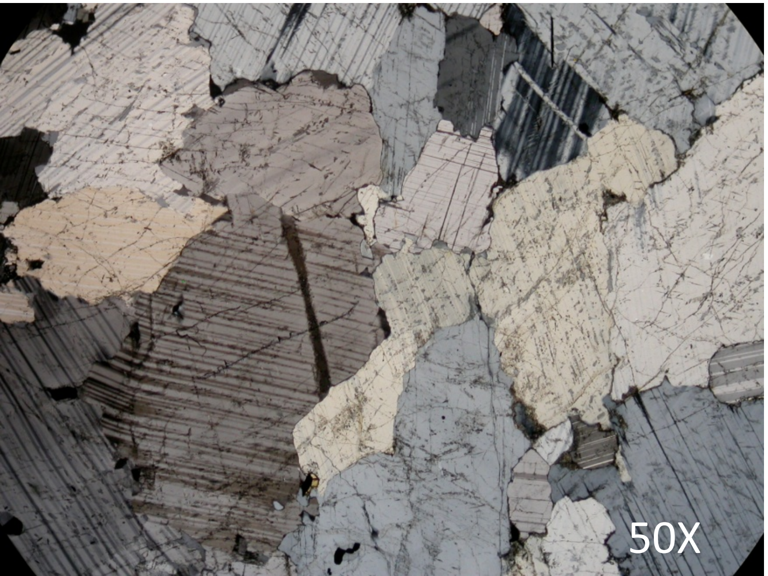
# Grenvillian Proterozoic anorthosite massifs

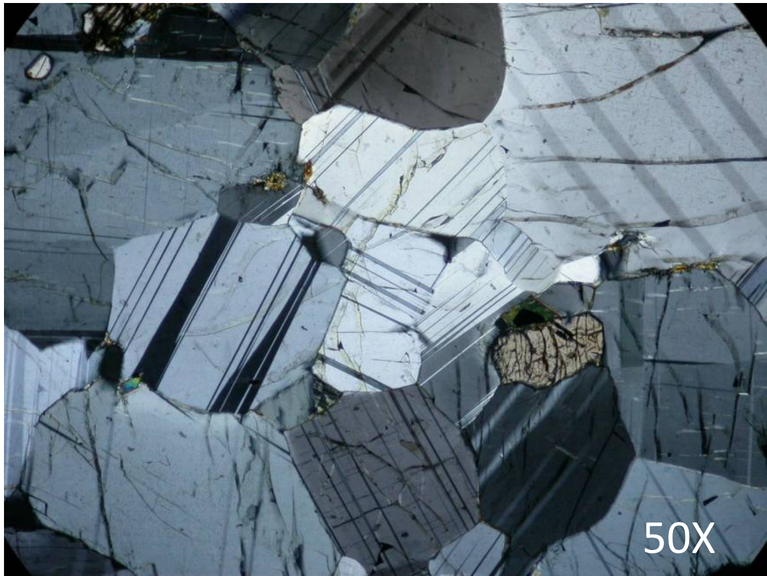



- Anorthosite massifs covers 10% of the Grenville Province surface
- Anorthosite rock : more than 90% plagioclase (An35-65)
- Proterozoic anorthosite massif:
  - anorthosite
  - leuconorite, leucogabbro
  - troctolite
  - norite, gabbronorite
  - Fe-Ti oxide (±apatite) rich rocks
  - jøtunite (ferrodiorite)

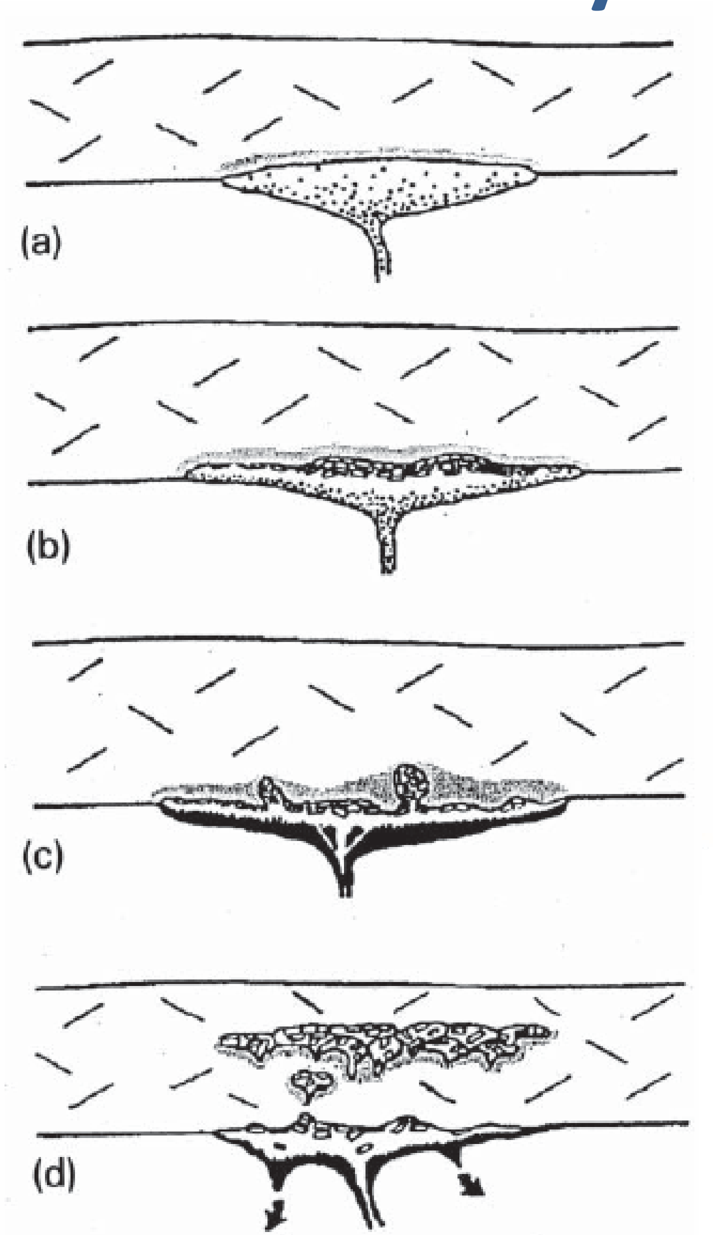

# Model for the formation of Proterozoic anorthosite massifs

- How can we crystallize rocks that contain so much plagioclase (>90%)?
  - Are there particular mechanisms involved in their formation?
  - What are the parental magma compositions?
  - Where are these magmas from?

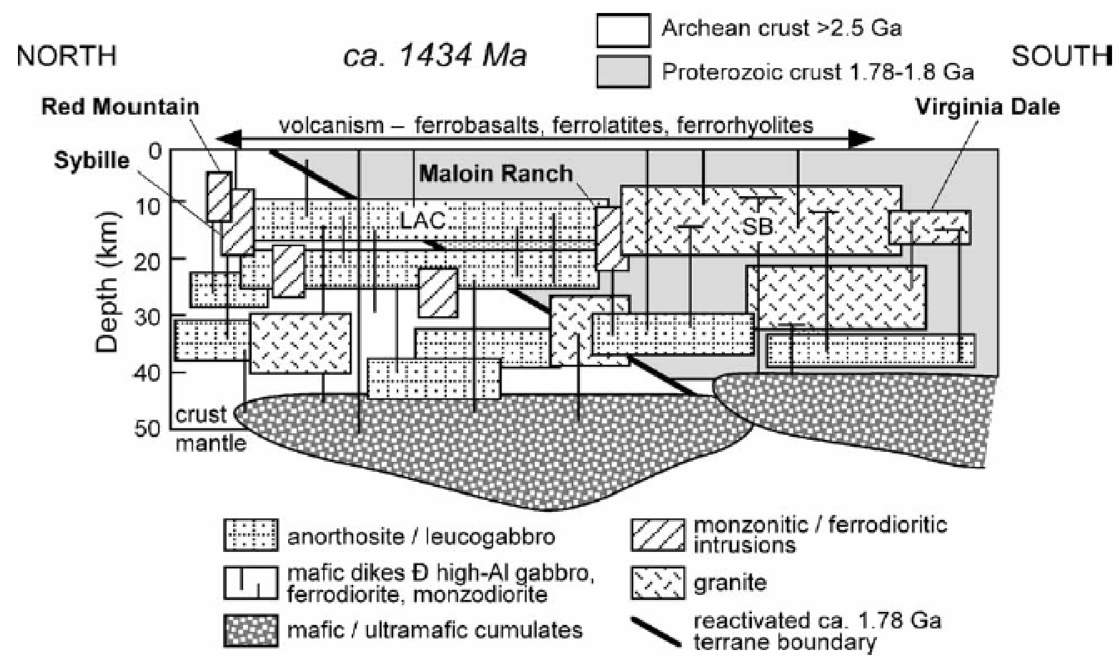


# Polybaric crystallization

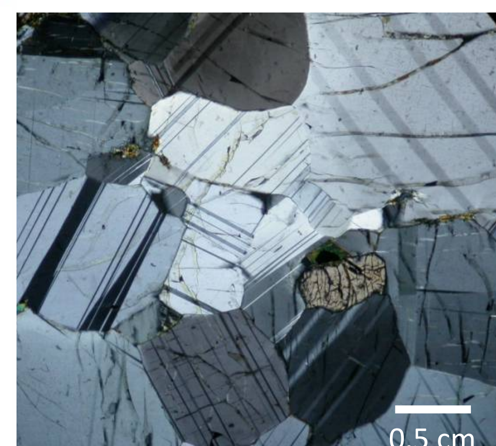



Loghi and Aswal 1985 and Ashwal 1993

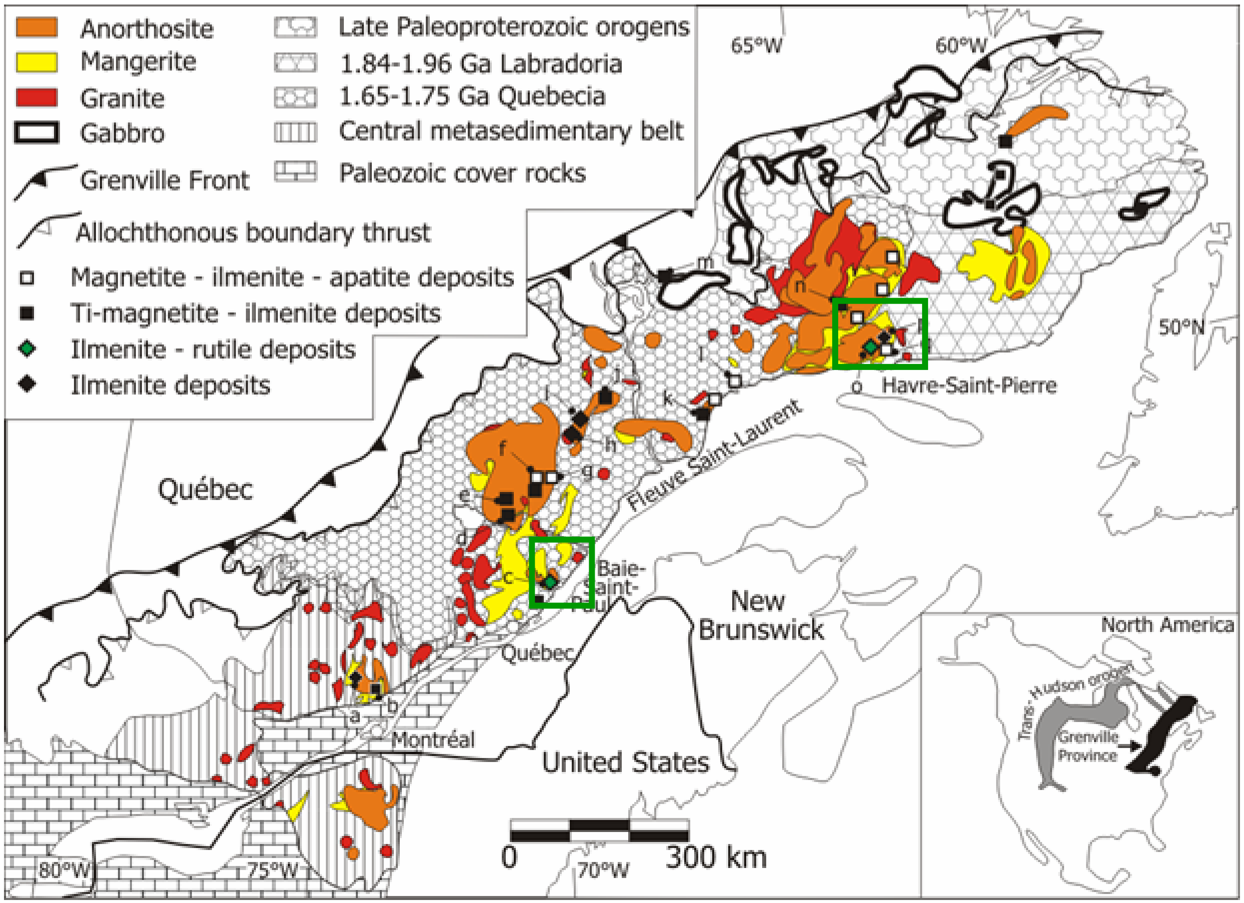


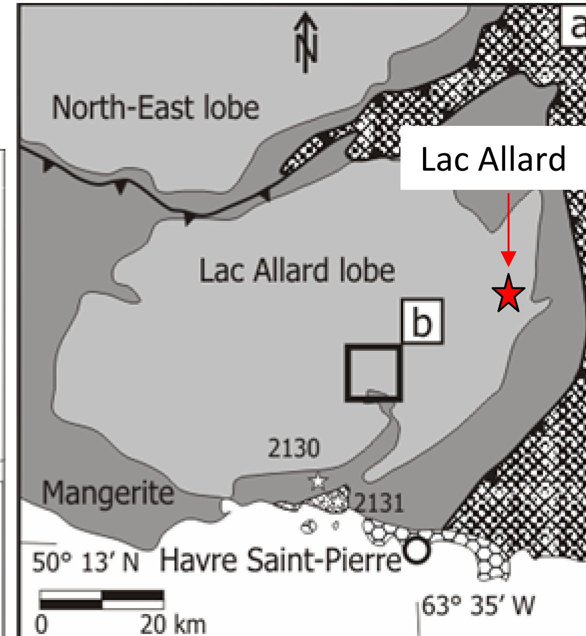

Scoates and Chamberlain 2003

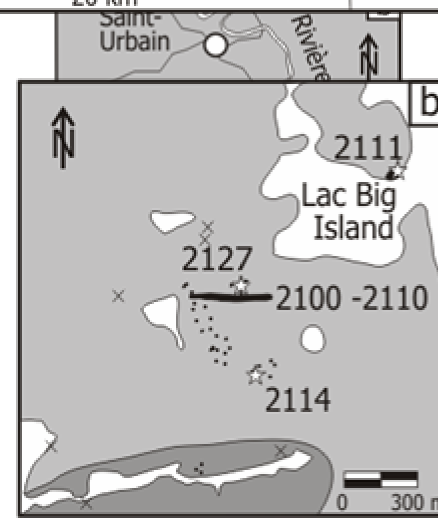
Scoates et al. 2010

# Geological setting of the study

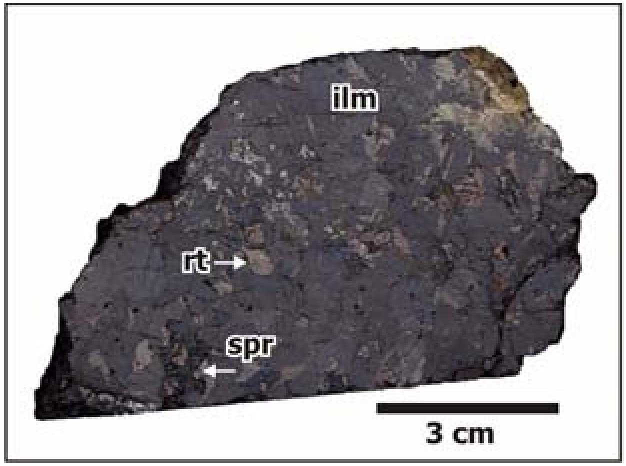


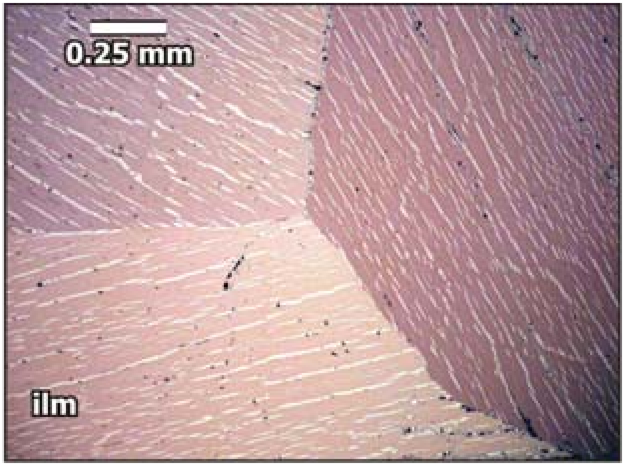



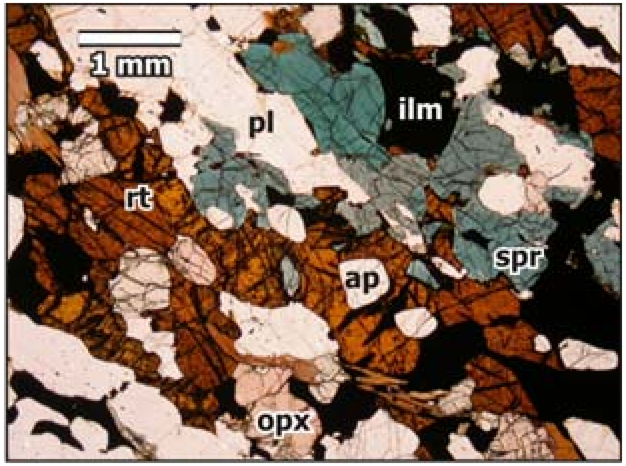



# Rutile-bearing massive ilmenite deposits






- plagioclase (An 39-48)
- orthopyroxene (XMg 70-75)
- sapphirine (Fe, Mg)$_8$(Al,Si)$_6$O$_{20}$

- ferrian ilmenite
- rutile
- hercynite

- apatite
- sulfides
- corundum

# What we did not know about the deposits?

1. Timing of the intrusions emplacement relative to Grenvillian event (U-Pb geochronology)

2. Cooling history of the intrusions (U-Pb and $^{40}Ar/^{39}Ar$ geochronology)

3. The magmatic, sub-solidus or metamorphic origin of the mineral phases in the deposits (major and trace elements and geochemical modeling)

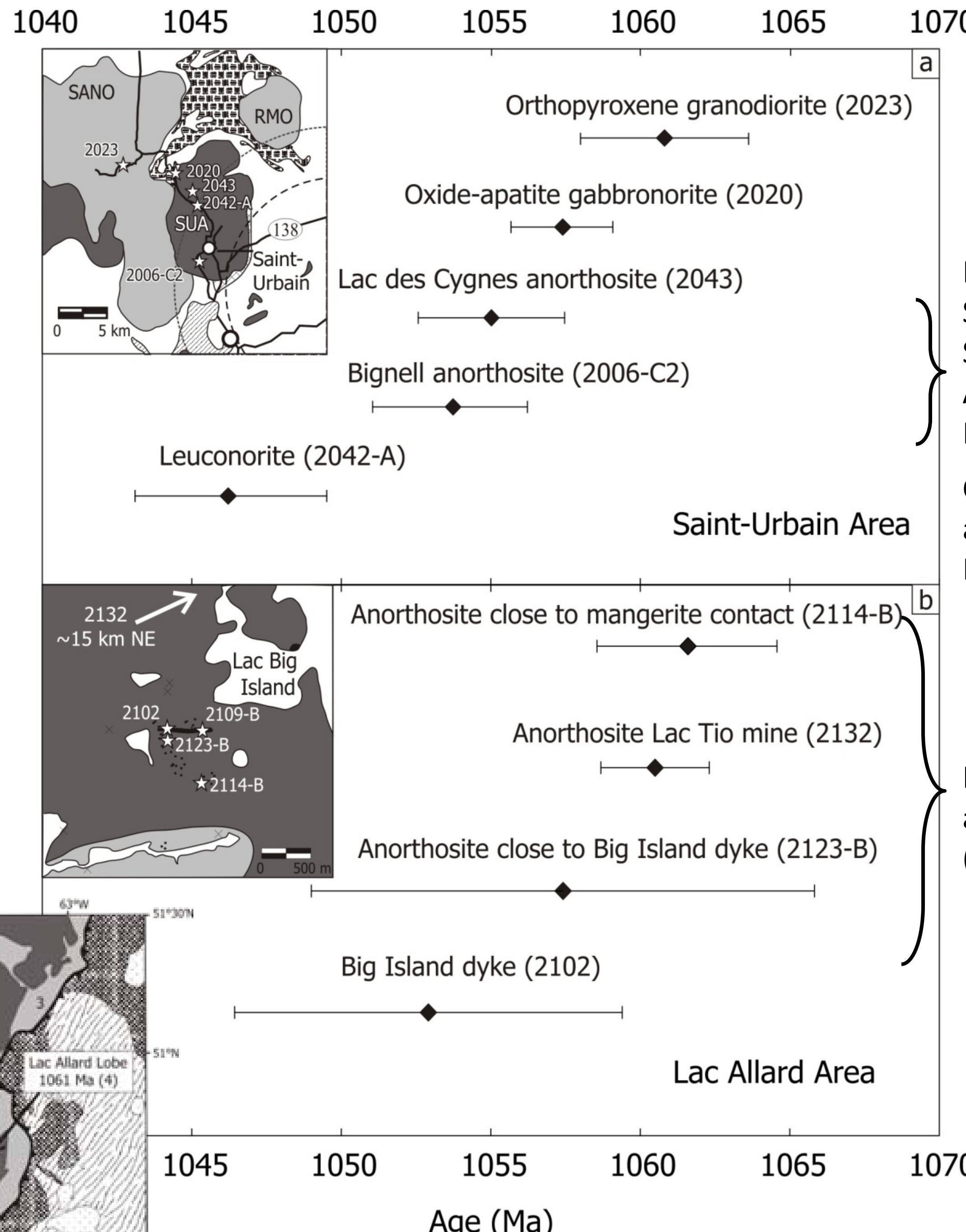
4. The conditions that lead to ilmenite + rutile saturation (geochemical modeling and published data on oxides stability)

5. Genetic link between the anorthosite and deposits (radiogenic isotopes)

6. Mantle or crustal source of the magma (radiogenic isotopes)

Understand the magmatic processes that enrich mafic magmas in Fe and Ti leading to the saturation of ilmenite and rutile and whether these processes are related to the formation of anorthosites

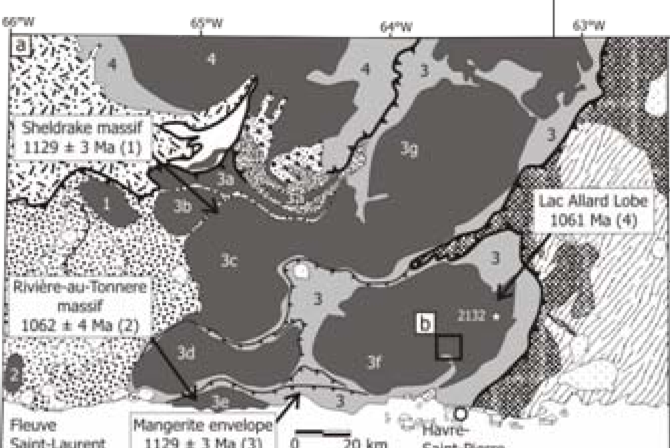
# Saint-Urbain and Lac Allard ages




Northern and Southern Saint-Urbain Anorthosite (ca 1055 Ma)

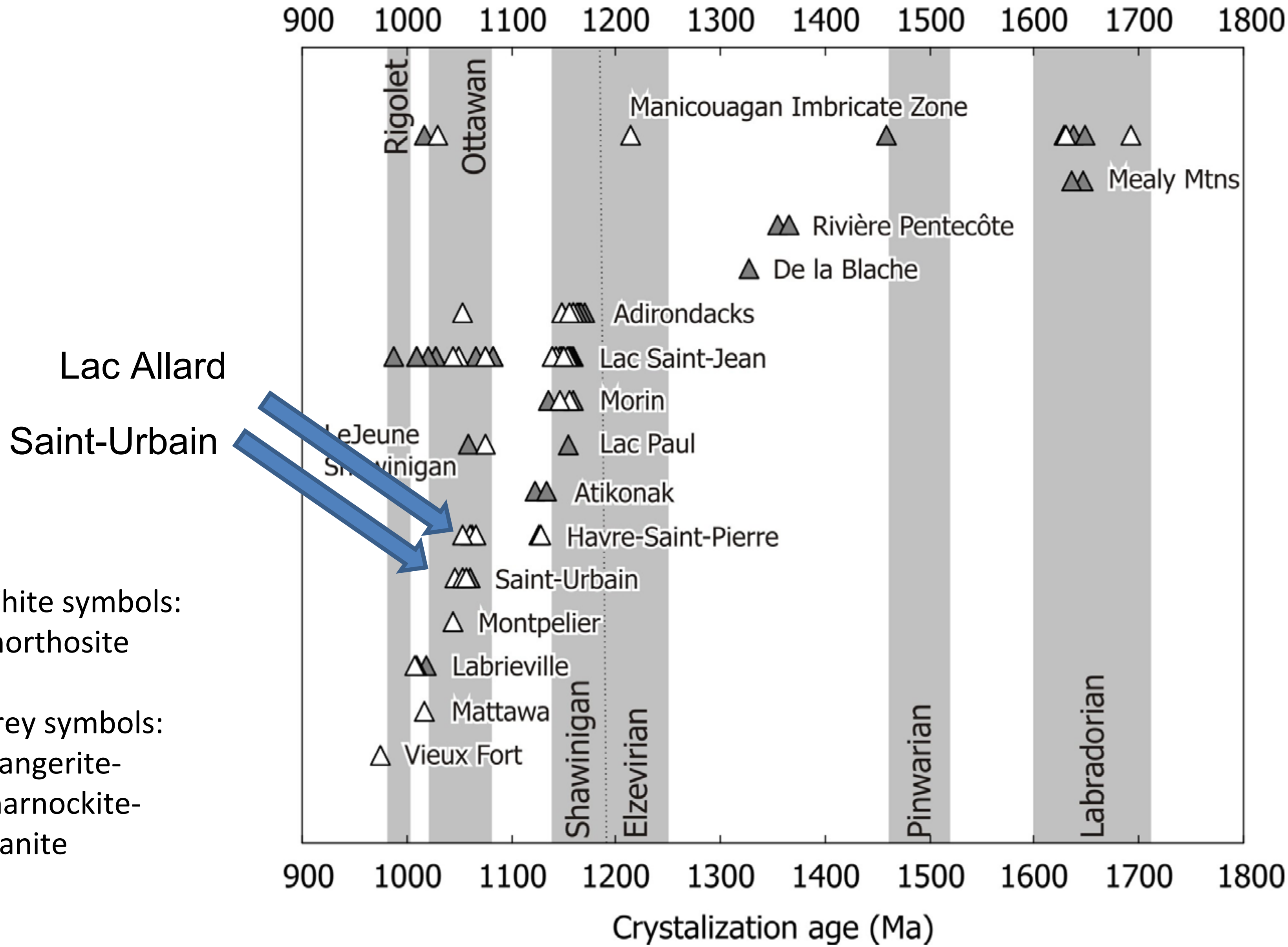
Central Saint-Urbain anorthosite (ca 1046 Ma)

Lac Allard anorthosite (ca 1057-1060 Ma)




Morisset , Scoates, Weis, Friedman 2009

# Grenvillian anorthosite massifs

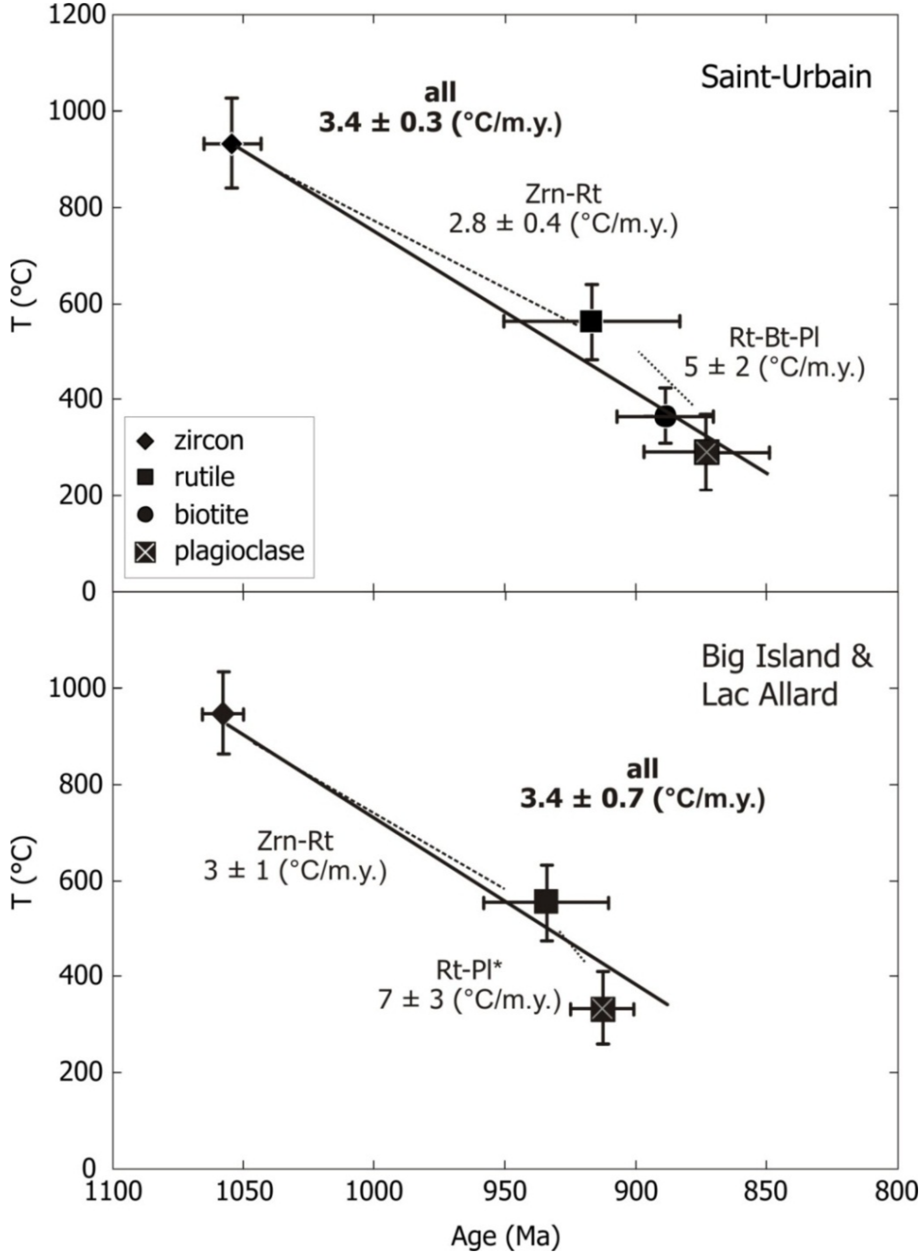


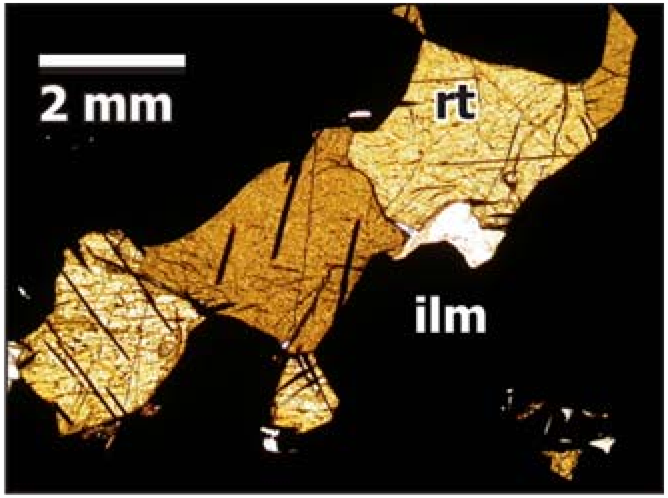

White symbols: anorthosite

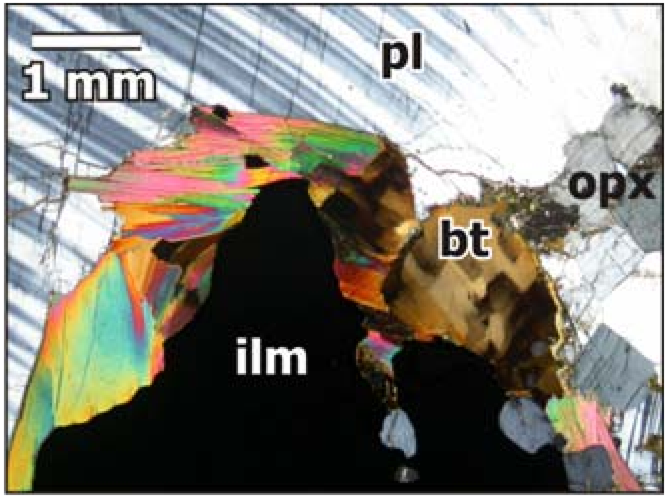
Grey symbols: mangerite-charnockite-granite

Morisset , Scoates, Weis, Friedman 2009

# Saint-Urbain and Lac Allard cooling rates

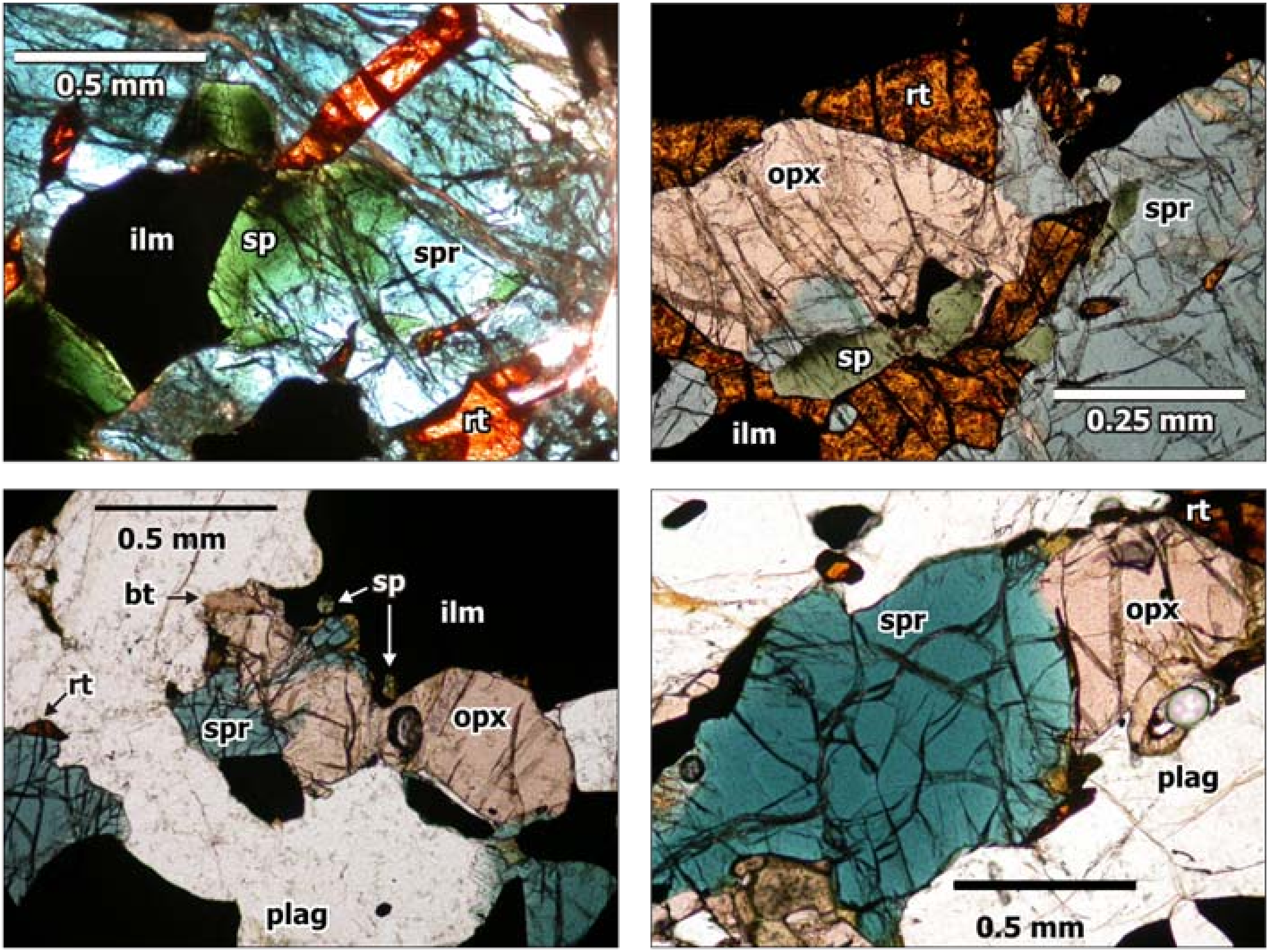



Morisset , Scoates, Weis, Friedman 2009

# Sapphirine sub-solidus reactions

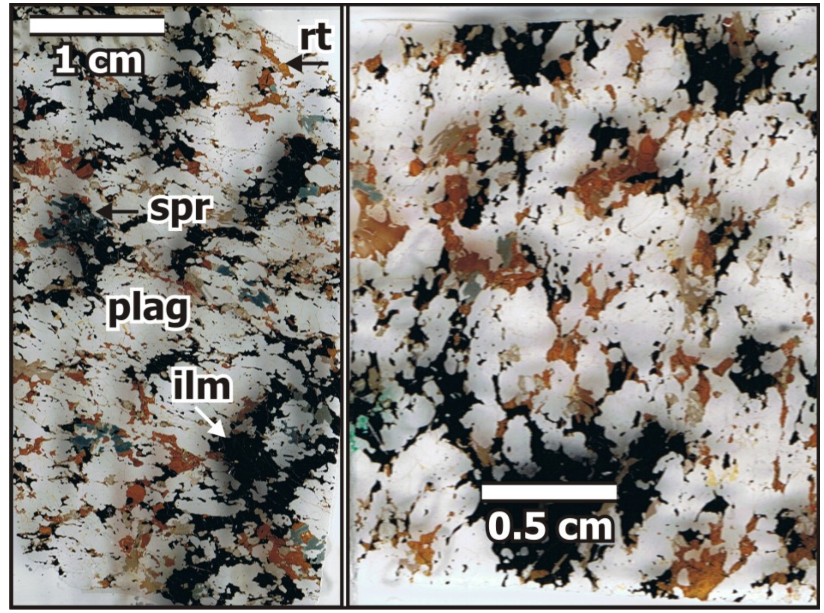


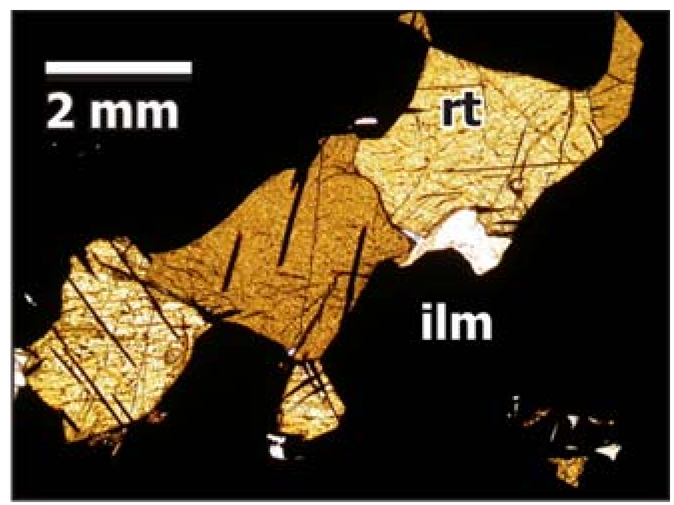

orthopyroxene + spinel + rutile ± corundum → sapphirine + ilmenite

Morisset, Scoates, Weis, Sauvé, and Stanaway 2010

# Rutile grains formation

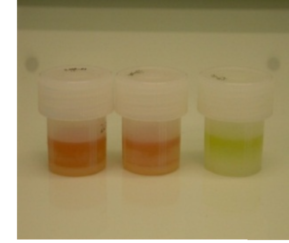
- Coarse discrete grains (1 x 1.5 mm to 3.3 x 5.5 mm)
- Formation
  - (metamorphism)
  - (breakdown of ferrospeudobrookite)
  - crystallized from the magma

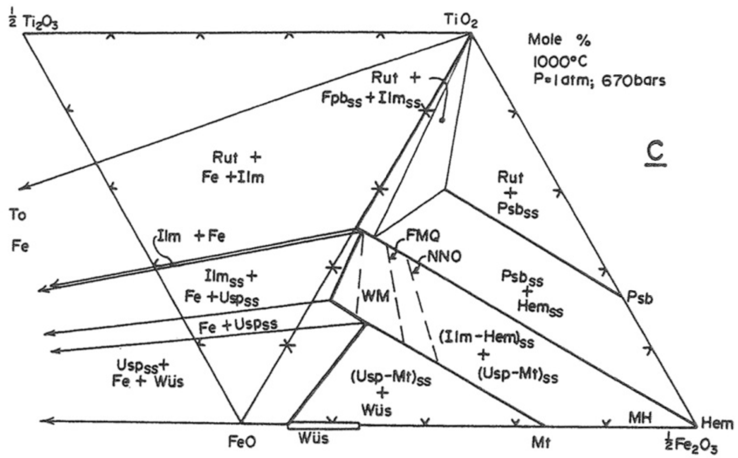


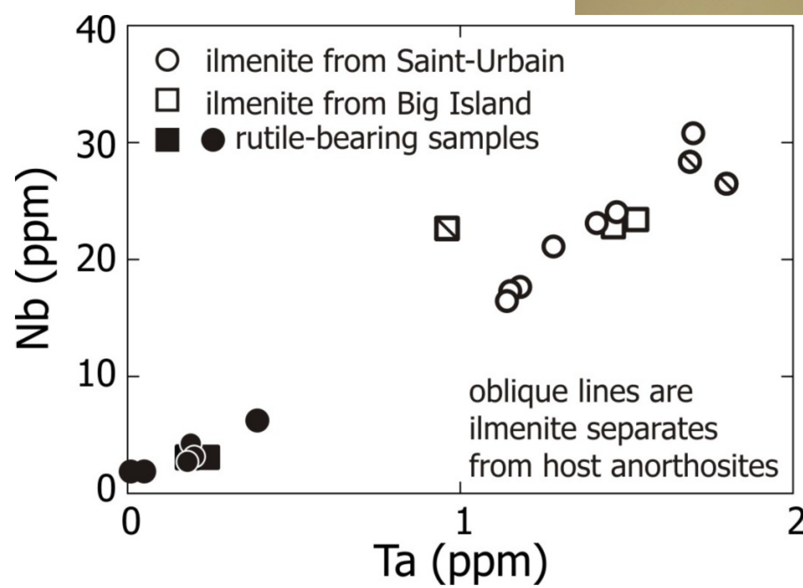
# Rutile grains formation

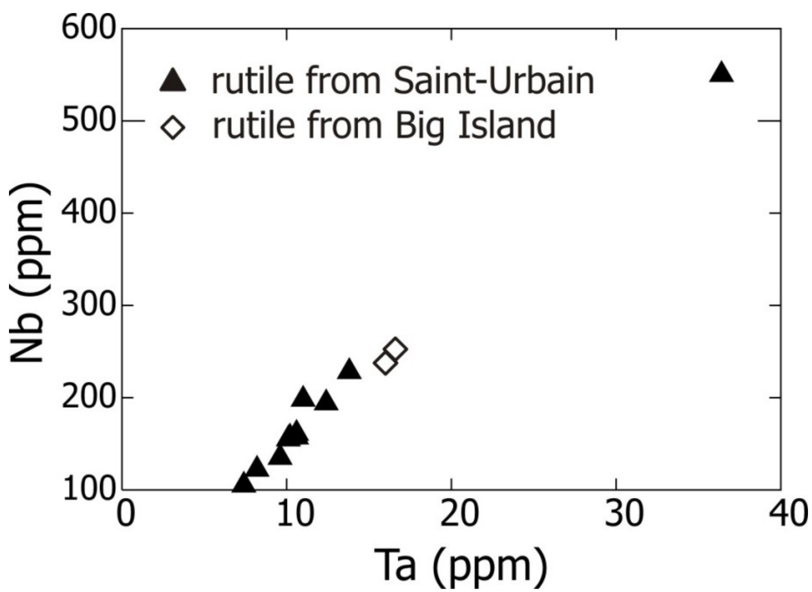
Solution HR-ICP-MS data suggest differentiation trend for Nb and Ta



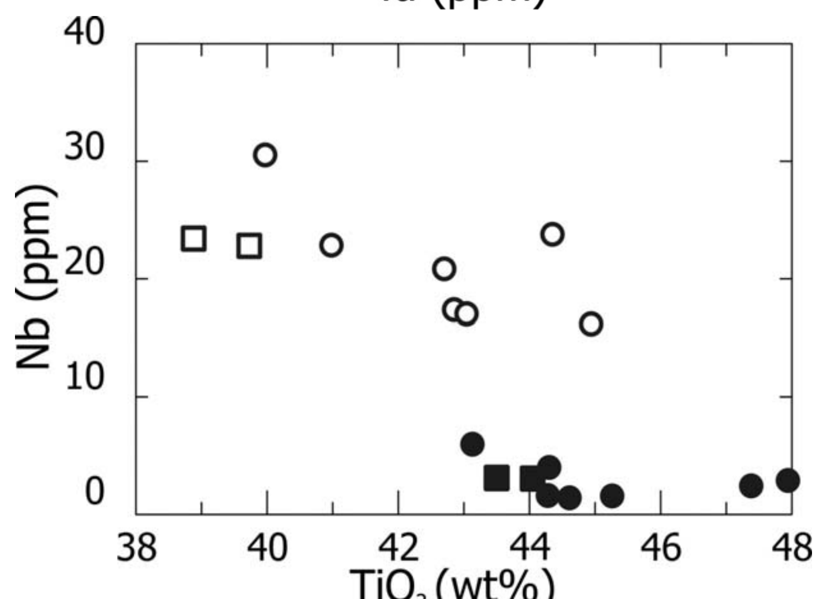



Lindsley 1976 and 1991



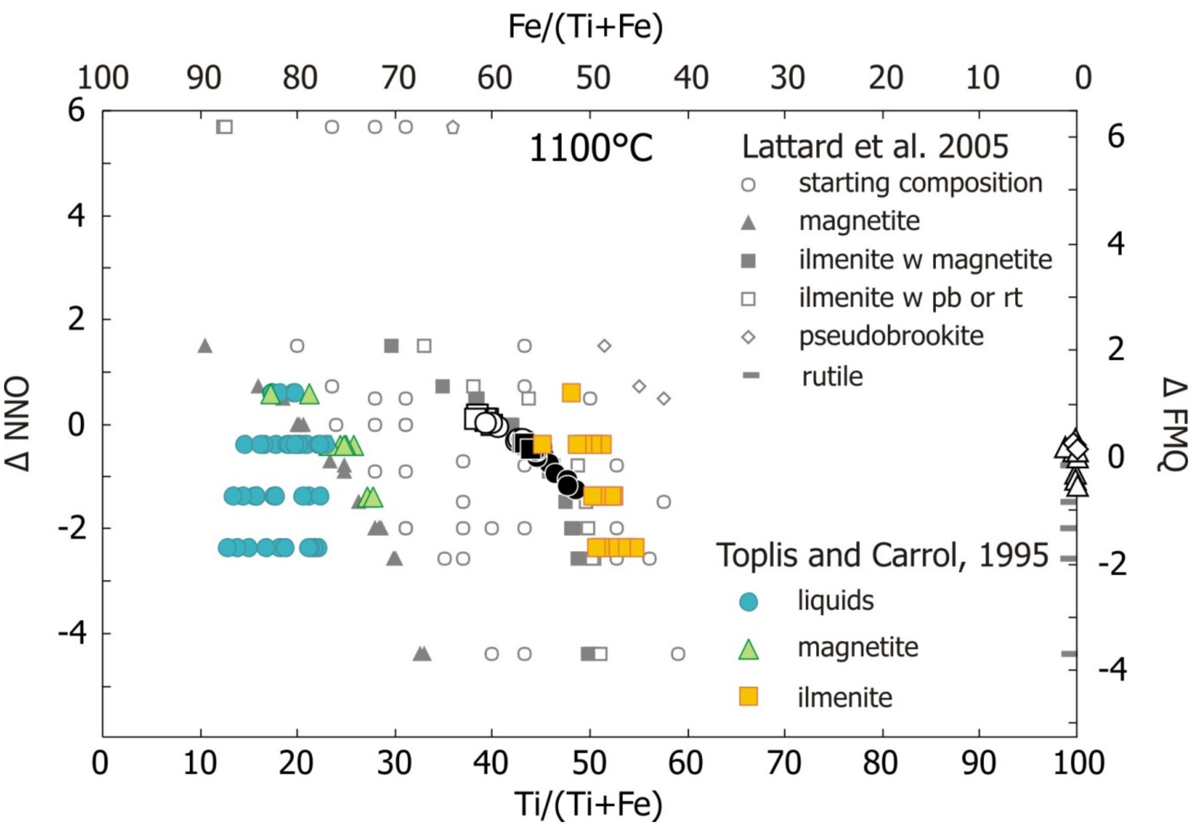

Morisset, 2008




Morisset, 2008

# Experiment on oxides stability

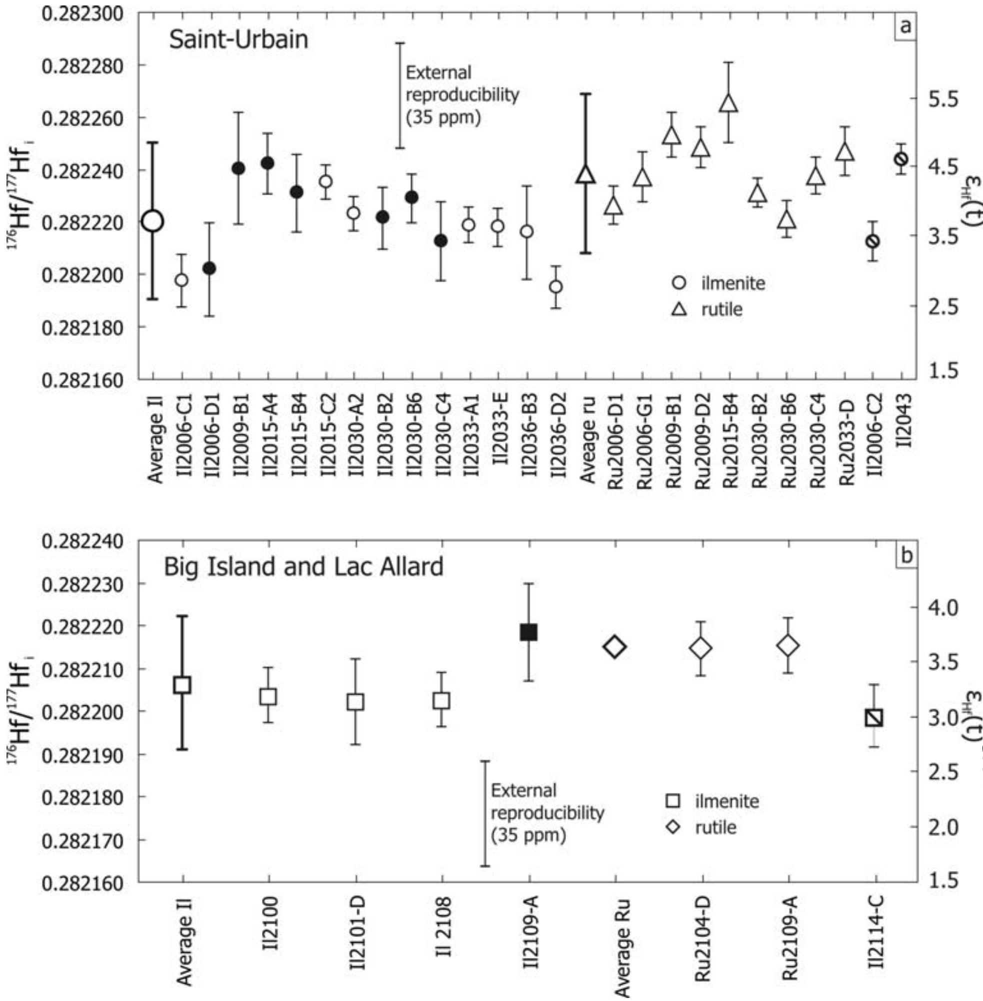
- Ilmenite compositions are within the filed of ilm + rutile assemblage (bulk compositions in Lattard experiments suggest XTi (Ti/(Ti+Fe))> 50 in the Fe-Ti-O system)
- Liquids in equilibrium with magnetite and ilmenite are more Fe-rich than predicted by Ti-Fe-O experiments
- Experimental data on compositions with XTi = 23 are dominated by magnetite
- What compositions or conditions favour the crystallization of ilmenite rich in $Fe^{3+}$ ± rutile? (need more experimental data)



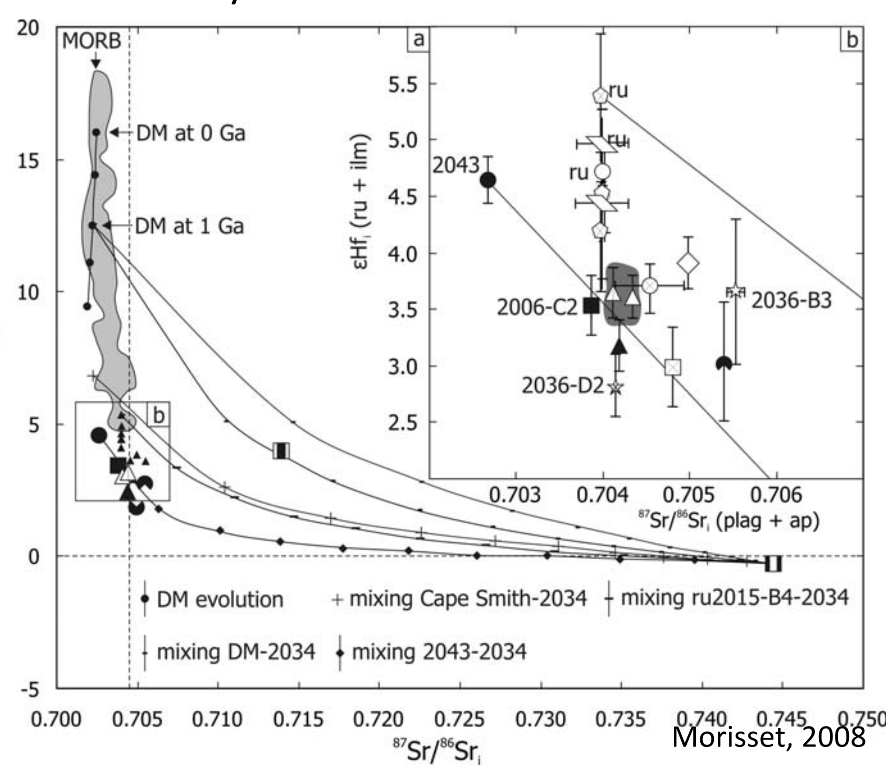

Morisset, Scoates, Weis, Sauvé, and Stanaway 2010

# Hf isotopes

- Hf, Pb, and Sr isotopic compositions support the same source for the deposits and anorthosite.
- Small amount of contamination (5%) from the country rock were calcualted using Hf and Sr data.
- Isotopic modelling suggest a DM source with about 10% contamination from the country rocks



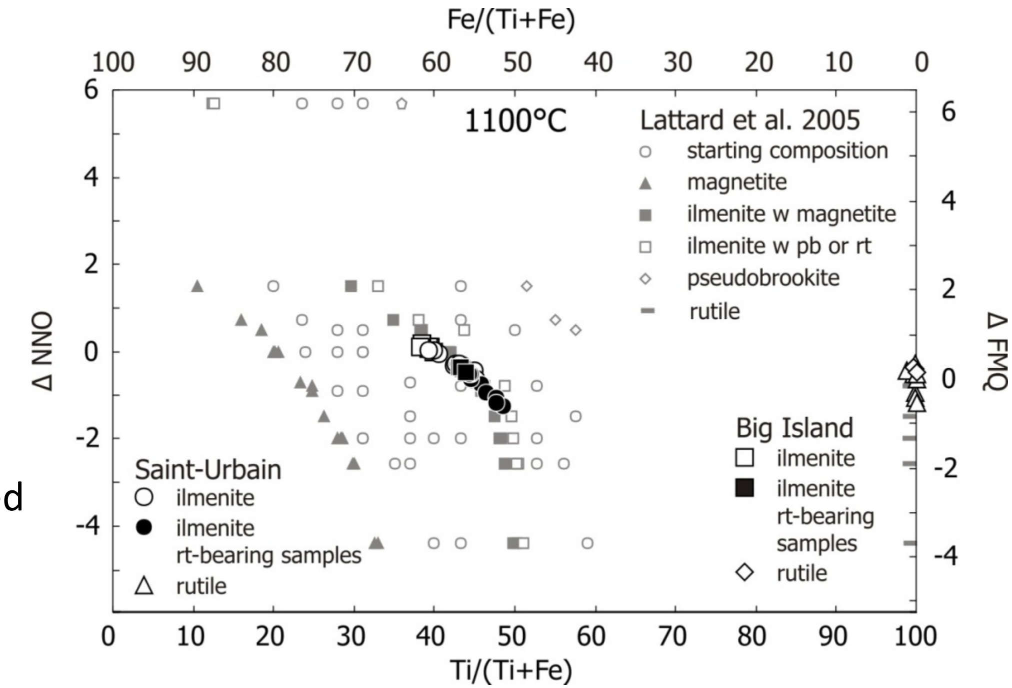

Morisset, Scoates, Weis and Rahier 2013




Morisset, 2008

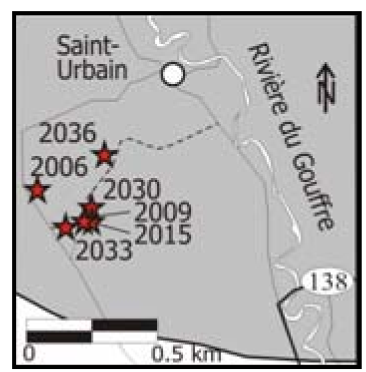
# Genesis of the rutile-bearing Fe-Ti deposits

- Fe-Ti enriched residual liquid from the crystallization of the anorthosite
- ilmenite rich in $Fe^{3+}$ $fO_2$ starts to crystallize at ΔFMQ close to +1, which increase the $Fe^{2+}/Fe^{3+}$ of the residual magma
- Perhaps high Al content of the magma (corundum) helps to stabilize ilmenite rich in $Fe^{3+}$ with hercynite instead of magnetite (need more experimental data)
- $X_{Ti}$ (>23) of the magma and the $fO_2$ is favourable to ilmenite + rutile assemblage (need more experimental data)
- Oxide minerals accumulated by density at the bottom of a magma chamber at Saint-Urbain and a dyke at Big Island (ferrian ilmenite density > 4.72, plagioclase density = 2.6, magmas parental or residual to anorthosite density = 2.65 to 2.9, Scoates 2000)

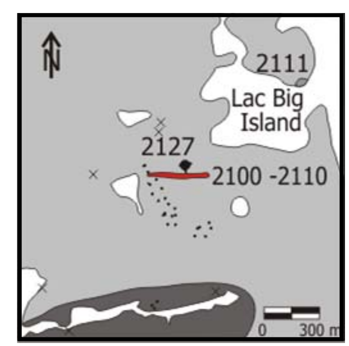



Morisset, Scoates, Weis, Sauvé, and Stanaway 2010

Saint-Urbain deposits




Big Island dyke



# Summary of the origin of rutile-bearing ilmenite deposits

1. the Saint-Urbain anorthosite (ca. 1055 Ma) and the Lac Allard anorthosite (ca. 1060 Ma) were emplaced during the Ottawan orogeny (1080-1020 Ma);
2. very slow cooling rates estimated for both intrusions (3-4°C/m.yr.);
3. sub-solidus reactions: formation of sapphirine following the general reaction: spinel + orthopyroxene + rutile ± corundum→ sapphirine + ilmenite;
4. ilmenite (relatively enriched in $Fe^{3+}$) was the primary oxide to crystallize;
5. rutile is a magmatic phase and co-precipitated with ilmenite during the final stage of crystallization;
6. the parent magmas of the deposits and their respective anorthosites share the same source;
7. magmas originated from a relatively depleted upper mantle;
8. this mantle could be the source to all Grenvillian anorthosite massifs and appears to have existed for over 600 m.y. during the Proterozoic.