Hf-Nd-Pb isotopic evidence for variable impact devolatilization and its relevance for Ni-Cu-(PGE) sulfide ore formation in the Sudbury Igneous Complex

Dustin Peters, Michael Lesher, Edward Pattison

Harquail School of Earth Sciences, Laurentian University

dpeters@laurentian.ca

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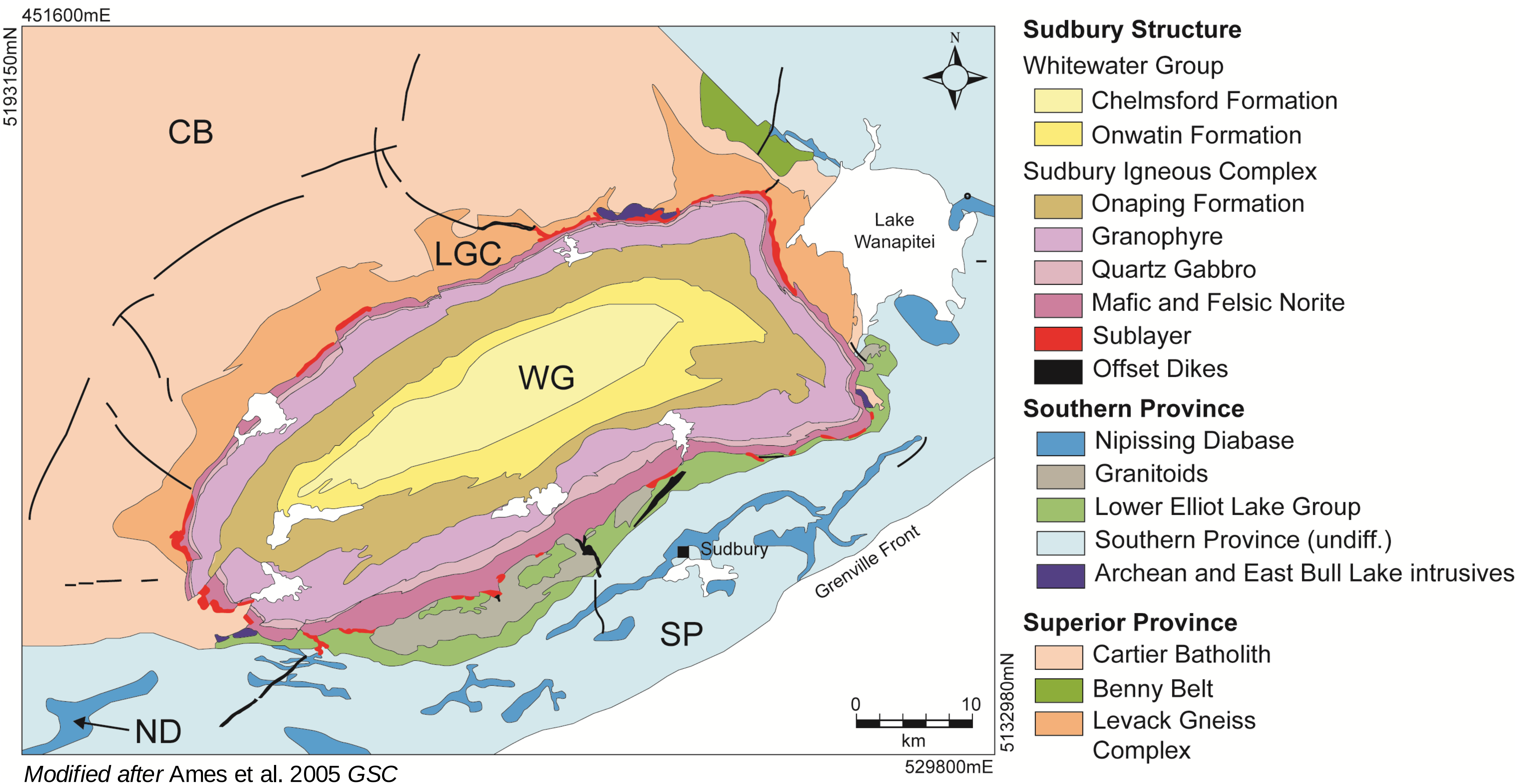
Introduction – Geological Setting



Modified after Ames et al. 2005 *GSC*

Introduction – Impact Origin

Impact evidence

Macroscopic

- Shatter cones, pseudotachylite bodies, breccias in country rocks

Microscopic

- PDFs in quartz and feldspar, and shock mosaicism in olivine

Geochemical

- Upper-middle crustal trace element signature
- Crustal Sr-Nd-Hf-Os-Pb isotope signatures

Shatter cones in Mississagi Formation

Pseudotachylite vein at Trill

Footwall Breccia along Highway 144

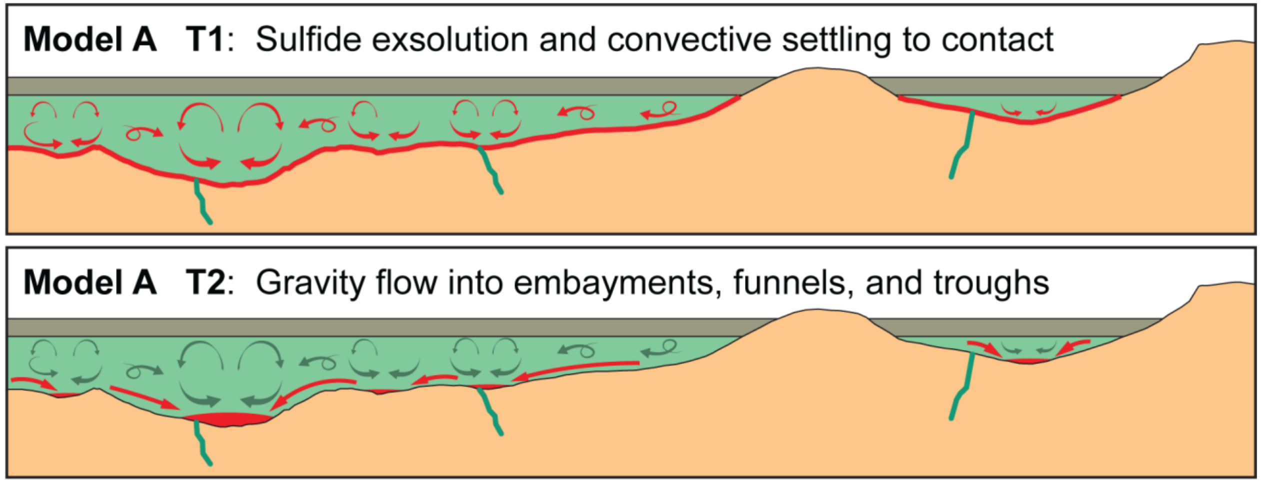
Introduction – Sulfide Ore Formation

Model A

- Complete dissolution of metals and sulfur in superheated impact melt sheet
- Exsolution of immiscible sulfides upon cooling and gravitational settling towards base
- Accumulation of sulfides in embayments/troughs by convective currents and/or gravity-driven density flows

Problems:

- **Heterogeneous** Pb>S>Os isotopic composition of **ores** vs. relatively **homogeneous** Hf>Nd>>Os>S>Pb isotopic composition of overlying **impact melt**
- Exsolution and settling of sulfides is slow
- Not all embayments are mineralized



References: e.g., Golightly 1994 *OGS*, Keays & Lightfoot 2004 *Min Pet*, Li & Ripley 2005 *Min Dep*, Zieg & Marsh 2005 *GSA*, Lightfoot 2016 *Elsevier*

References: McNamara et al. 2017 *Econ Geol*, Lesher 2019 *GAC-MAC*, Wang et al. 2022 *Econ Geol*

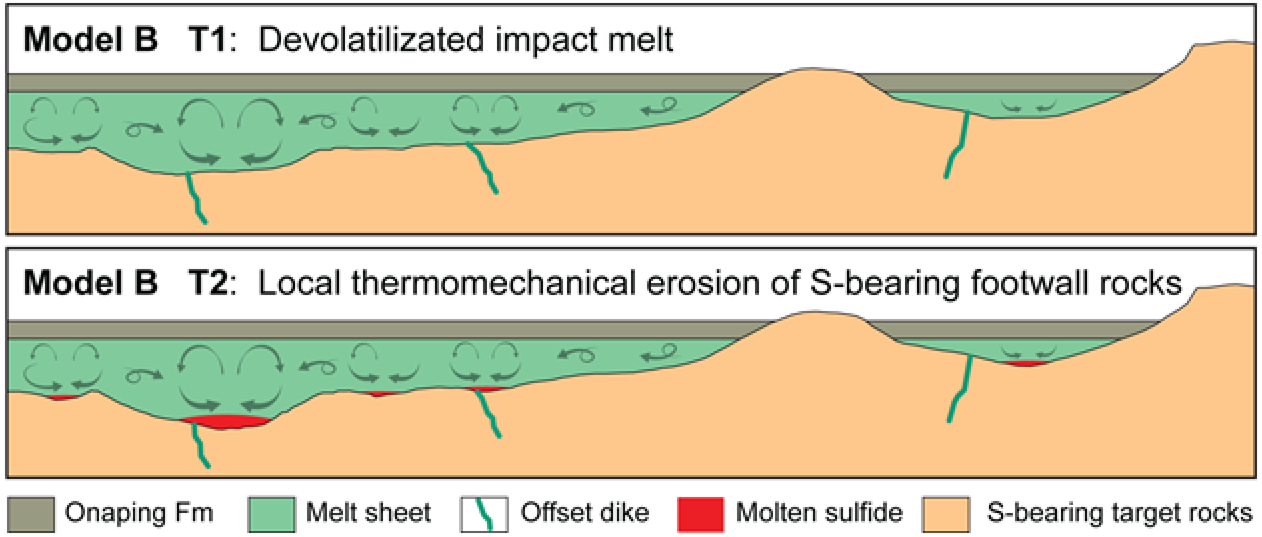
Model B

- **Pb-S**-Zn-Cd-Rb-Cs-depleted melt sheet due to variable devolatilization during impact
- Local thermomechanical erosion of S-bearing footwall rocks to form local sulfide xenomelts
- Accumulation of sulfide xenomelts in embayments/troughs by convective currents and/or gravity-driven density flows

Objective – Use Hf-Nd-Pb-S isotopes to:

- Determine **homogeneity/heterogeneity** of initial impact melt
- Test variable impact **devolatilization**
- Test validity of models for Ni-Cu-(PGE) **sulfide ore formation** associated with the SIC

References: e.g., Golightly 1994 *OGS*, Keays & Lightfoot 2004 *Min Pet*, Li & Ripley 2005 *Min Dep*, Zieg & Marsh 2005 *GSA*, Lightfoot 2016 *Elsevier*



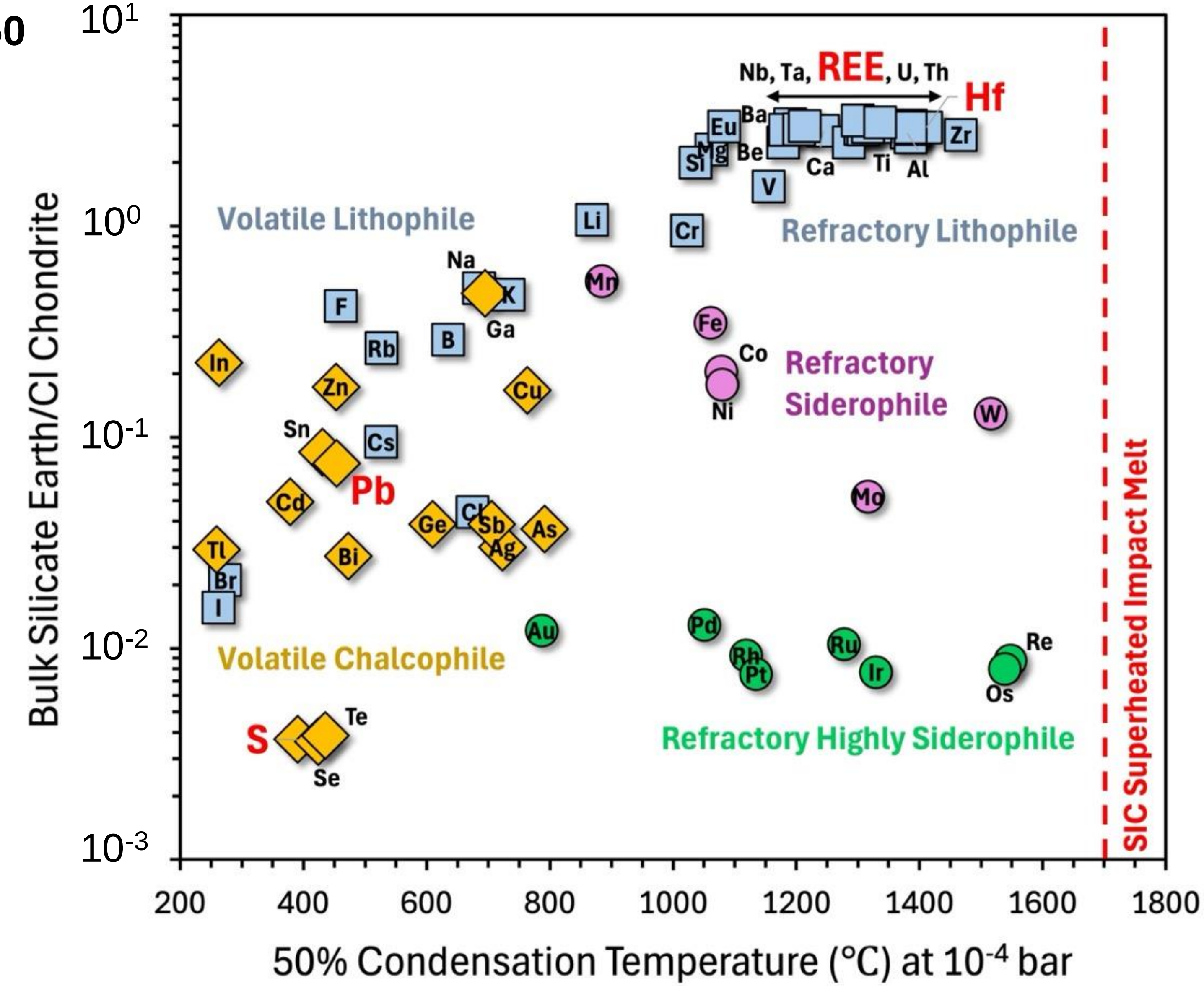
References: McNamara et al. 2017 *Econ Geol*, Lesher 2019 *GAC-MAC*, Wang et al. 2022 *Econ Geol*

Introduction – Element Volatility

Condensation Temperature T_{50}

- **T_{50}** is defined as temperature at which 50% of element would condense from solar nebula *(Lodders 2003 Astrophys J)*
- Increasing volatility and therefore syn-impact element-loss of **S>Pb>>Nd>Hf**
- S-Pb isotopes should be more susceptible to post-impact contamination than Nd-Hf
- Initially superheated (>1700℃) impact melt (e.g., Prevec&Cawthorn 2002 *J of Geophys)* suggests even most refractory elements may have experienced minor loss during impact

Modified after Wood et al. 2019 *Am Min*



Sampling and Methodology

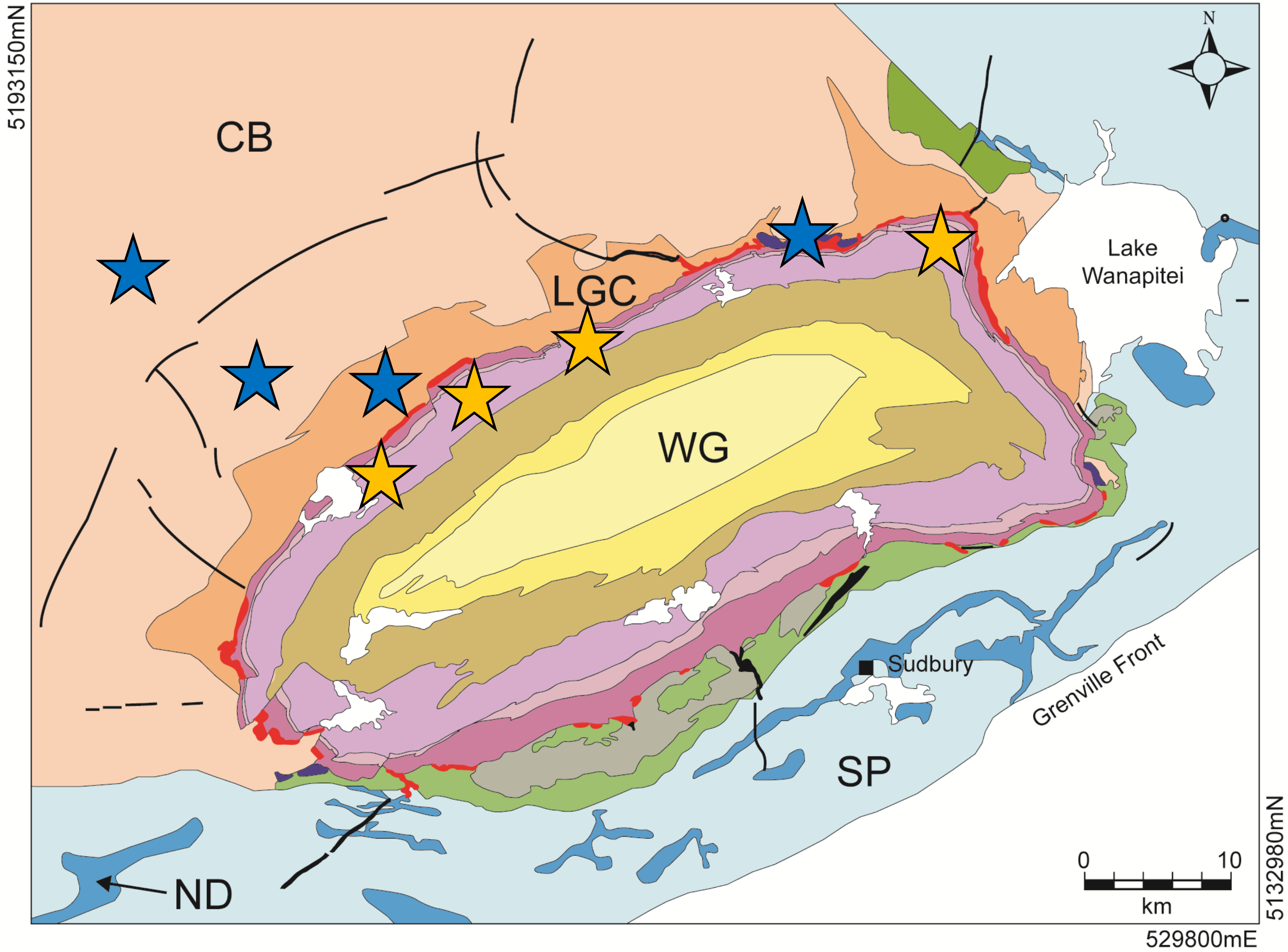
North Range Main Mass

- Good Pb isotope database, but very little Hf and Nd isotope data available
- No systematic sampling to test for both stratigraphic and lateral variations

Sampling Strategy

- Representative samples of each **Main Mass lithology** from 4 different transects + selective **footwall rocks**
  - Mafic Norite, Felsic Norite, Quartz Gabbro, Granophyre
  - Levack Gneiss Complex, Cartier Granite, Joe Lake Gabbro
- Combination of LA-ICP-MS (Hf), and whole-rock MC-ICP-MS (Hf-Nd-Pb)

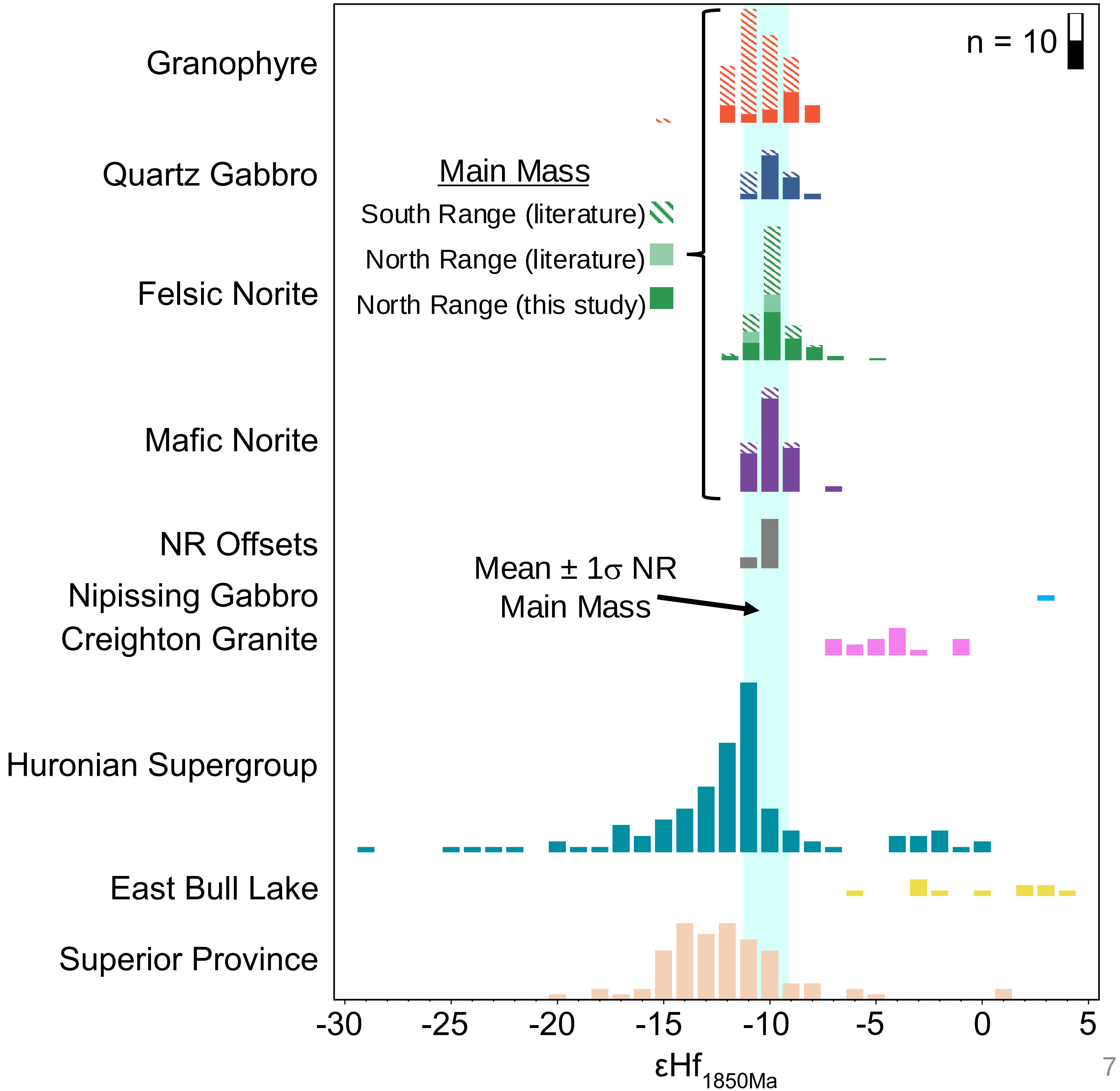
Modified after Ames et al. 2005 *GSC*



Main Mass – Hf-Nd-Pb Isotope Characteristics

Hf isotope characteristics

- **NR and SR Main Mass relatively homogeneous** (including Mafic Norite)
  - Initially well-mixed impact melt
- **NR Offset Dikes similar to overlying Main Mass**
  - Little to no Hf volatilization→ little to no contamination effect during dike emplacement

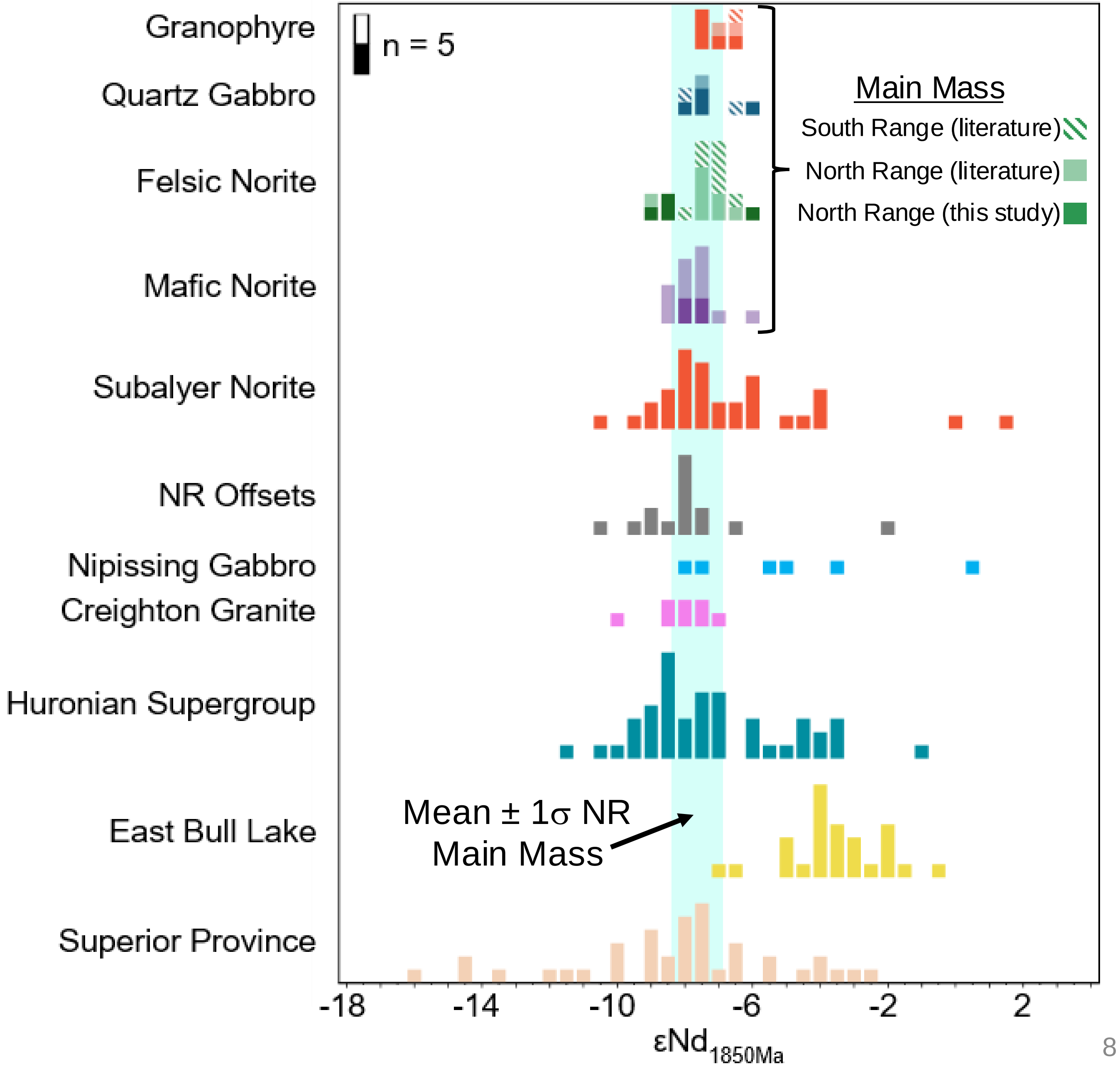


Modified after Wang et al. 2022 *Econ Geol*

Main Mass – Hf-Nd-Pb Isotope Characteristics

Nd isotope characteristics

- **NR and SR Main Mass relatively homogeneous** (including Mafic Norite)
  - Initially well-mixed impact melt
- **NR Offset Dikes slightly more variable than overlying Main Mass**
  - Minor Nd volatilization → weak contamination effect during dike emplacement

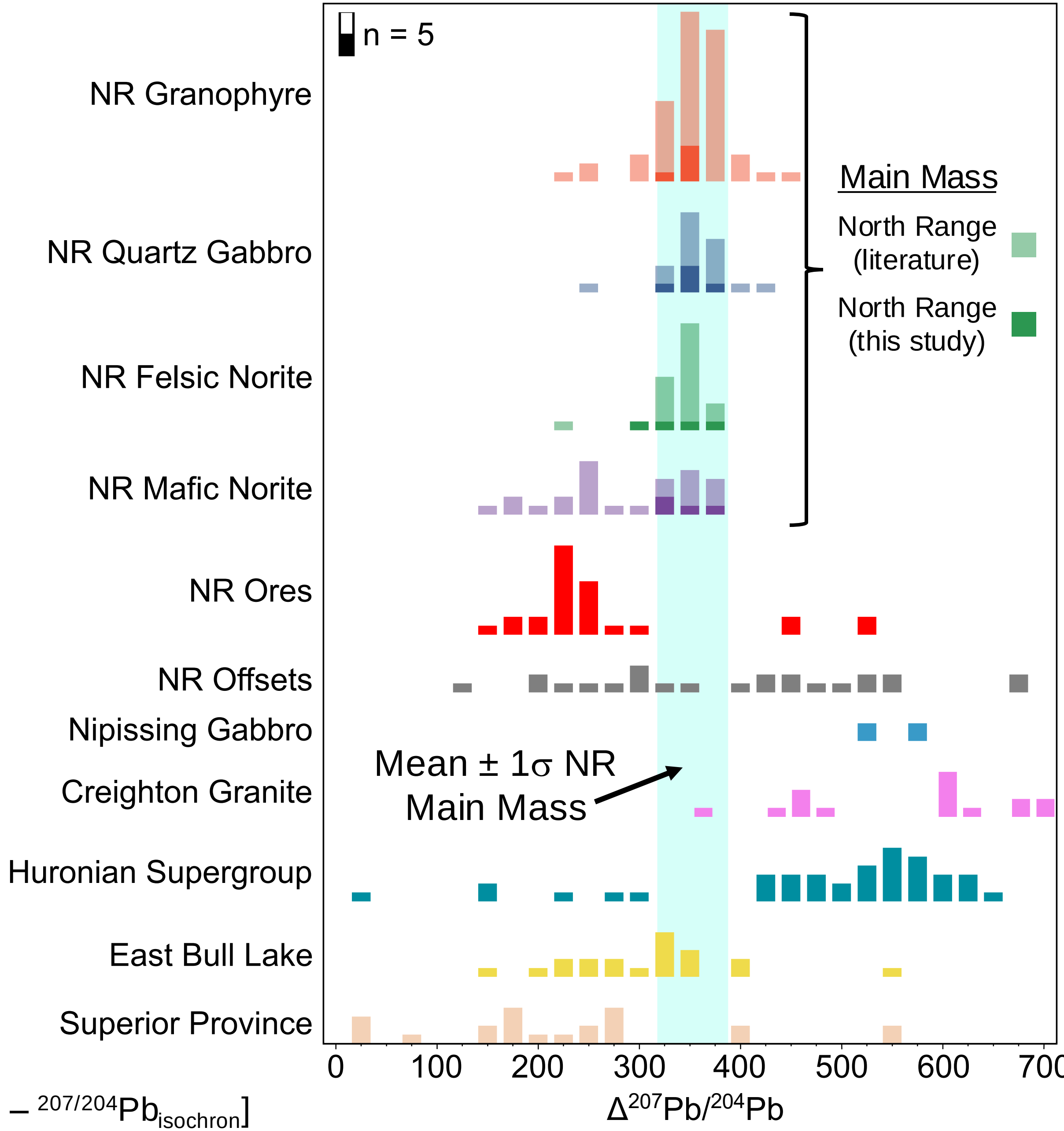


Modified after Wang et al. 2022 *Econ Geol*

Main Mass – Hf-Nd-Pb Isotope Characteristics

Pb isotope characteristics

- **NR Main Mass relatively homogeneous** (except for Mafic Norite)
  - Contamination of melt sheet at base
- **Heterogeneous NR Offset Dikes**
  - Significant Pb volatilization → strong contamination effect during dike emplacement
- **NR Ores differ from overlying Main Mass**
  - Shifted towards Superior Province
  - Dominantly local sulfide source

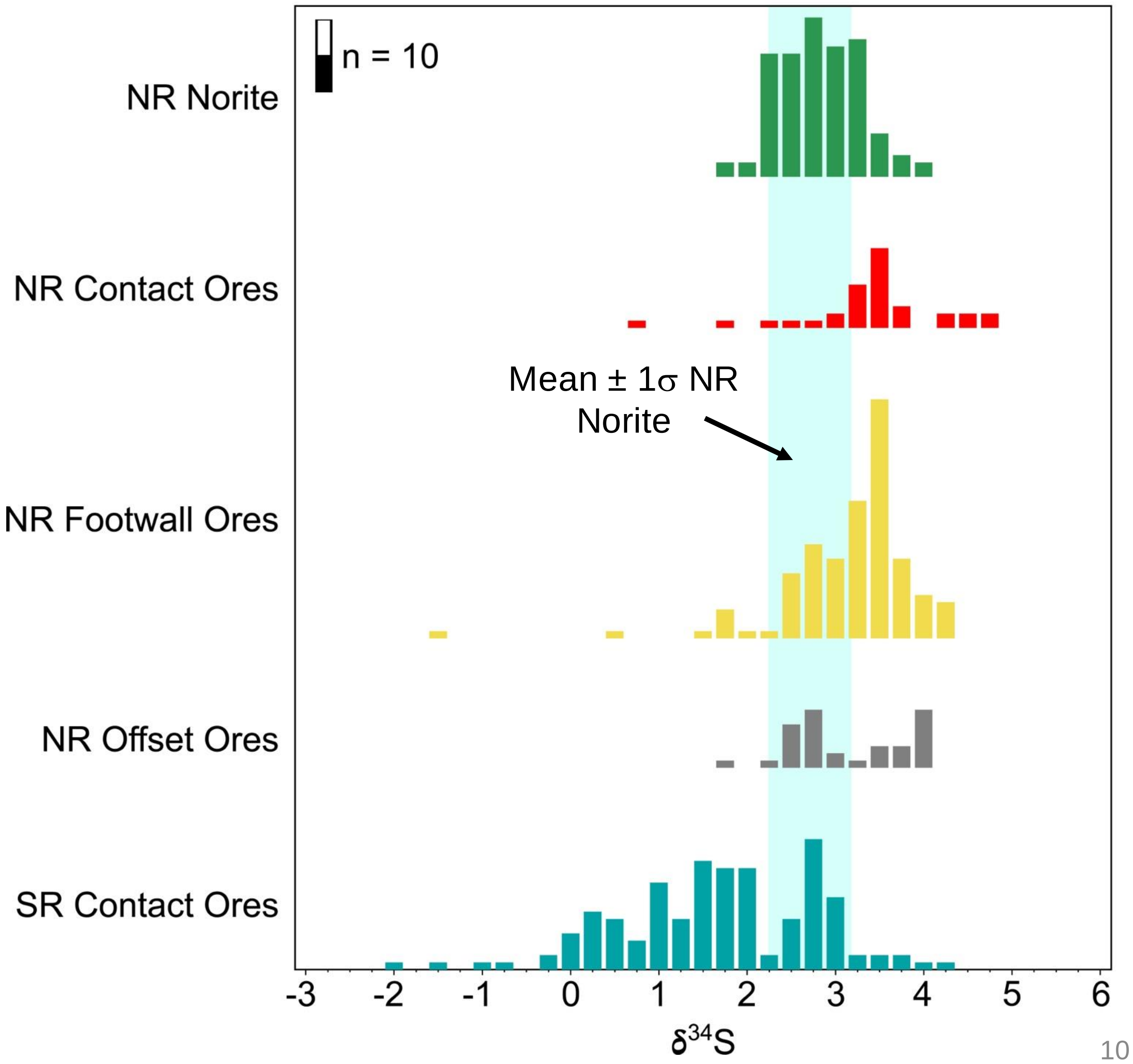


Modified after Wang et al. 2022 *Econ Geol;* $\Delta^{207/204}Pb = 1000 \times [^{207/204}Pb_{sample} - {}^{207/204}Pb_{isochron}]$

Main Mass – Hf-Nd-Pb Isotope Characteristics

S isotope characteristics

- **NR Norite relatively homogeneous**
  - Initially well-mixed impact melt
- **NR Ores are similar but more variable than overlying Norite**
  - Contamination effect (S volatilization)
  - Variable local sulfide sources
- **SR Ores differ from NR Ores**
  - Variable local sulfide sources
  - Huronian-East Bull Lake-Nipissing as likely sulfide sources

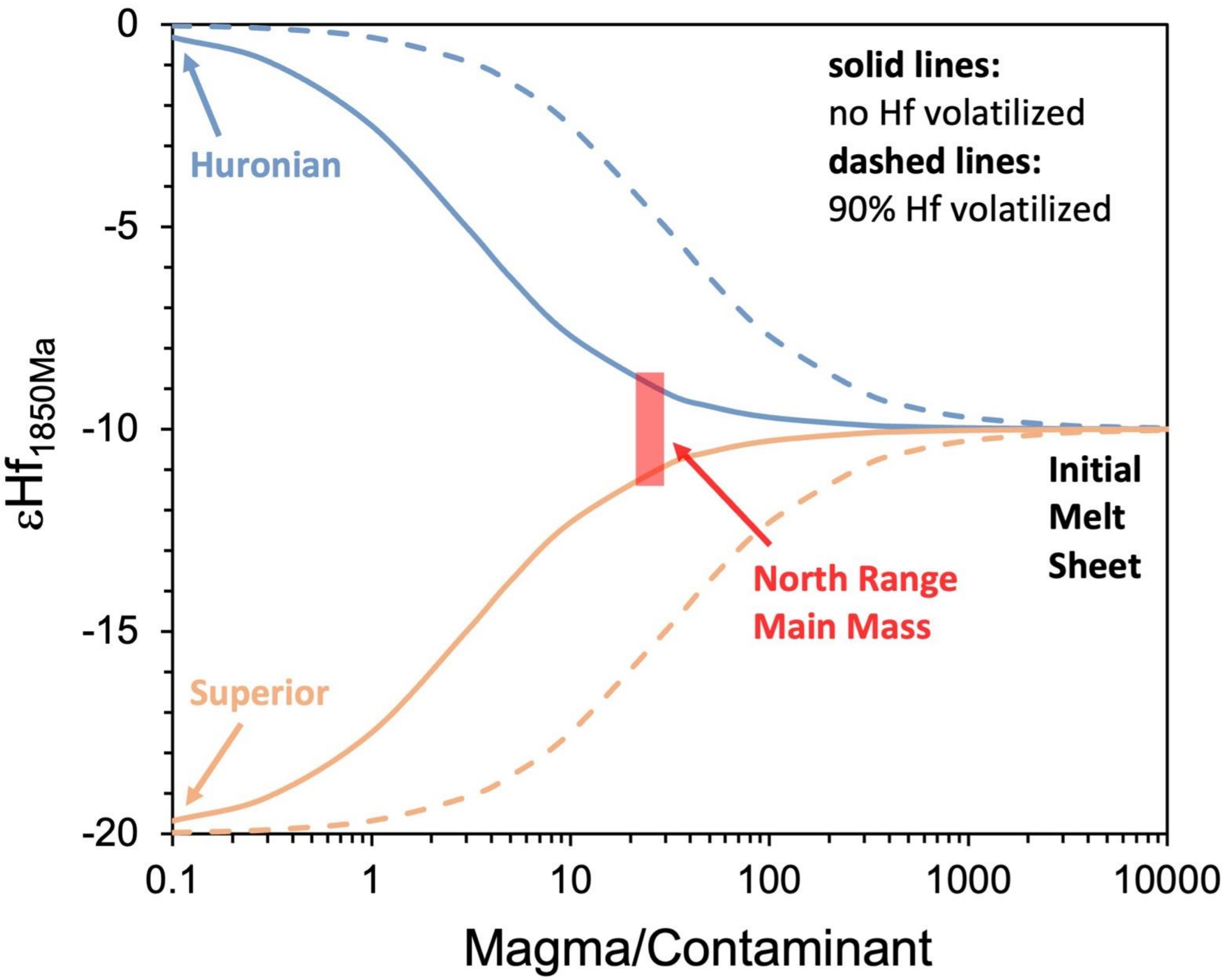


Modified after Wang et al. 2022 *Econ Geol*

Main Mass – Mass balance/contamination effects

Hf Mass Balance

- Hf in Main Mass is **relatively homogeneous** and can be explained by non-volatilized model
  - No Hf volatilization required during impact to explain observed variations

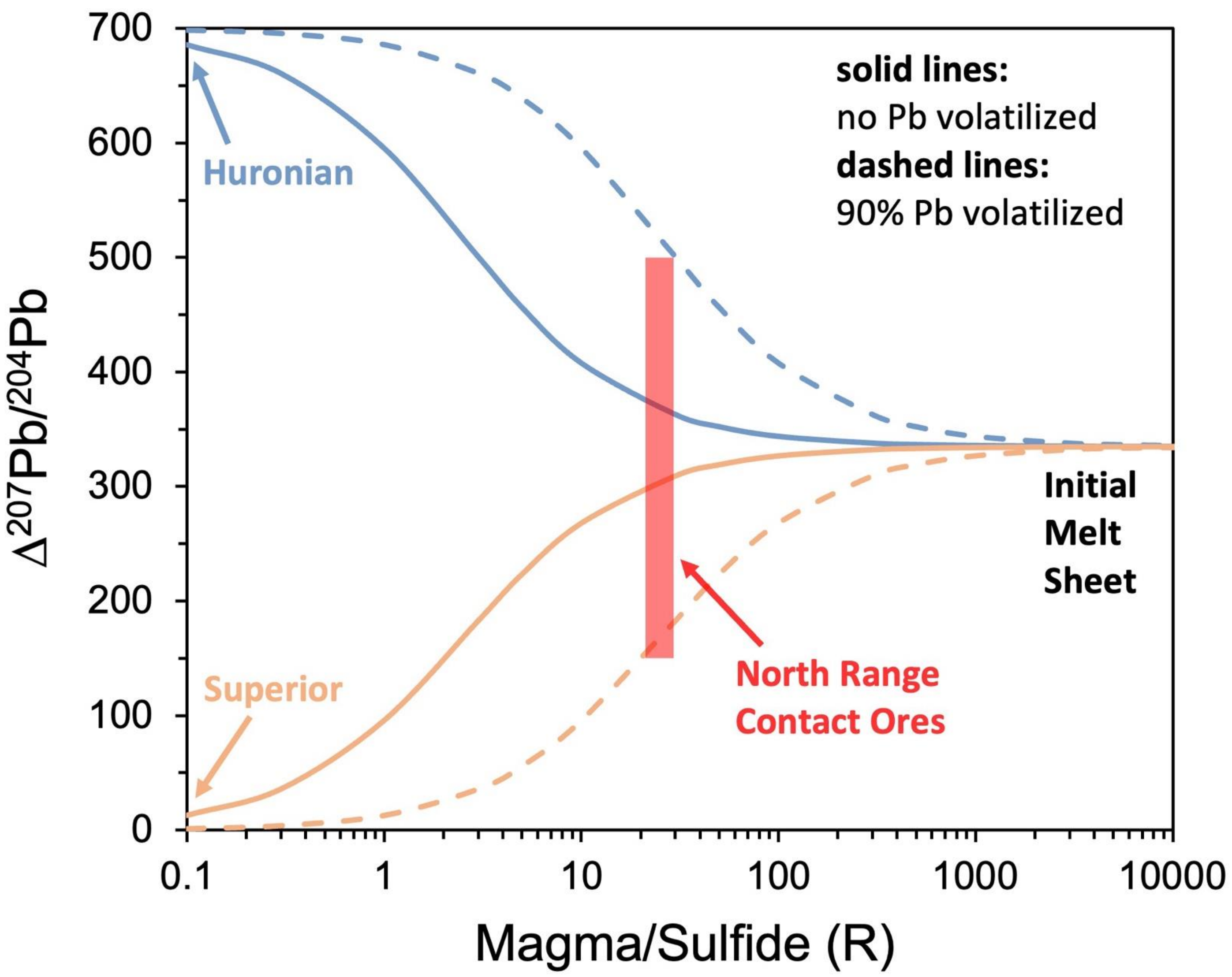


Modified after Lesher 2023 *GAC-MAC,* mixing calculations after Lesher & Burnham 2001 *Can Min*

Main Mass – Mass balance/contamination effects

Pb Mass Balance

- Pb in NR contact ores varies much more than permissible by non-volatilized model
- **90% volatilization** AND **wide range of target rocks** required to explain observed variability
- Modelling suggests **low magma:sulfide ratios**
    - Consistent with local formation of sulfides at base



Modified after Lesher 2023 *GAC-MAC,* mixing calculations after Lesher & Burnham 2001 *Can Min*

Summary

- Hf-Nd-Pb-S isotopic signatures of SIC record **variable impact devolatilization (S>Pb>>Nd>Hf)**
- Nd-Hf isotopes of Main Mass are relatively homogeneous, suggesting **initially well-mixed impact melt sheet**
- Heterogeneous Pb isotope compositions in offset dikes and contact ores due to **post-impact contamination** and dominantly **local sulfide sources**
- Homogenized impact melt and mass balance calculations support model in which **sulfides dominantly form locally at the base** rather than exsolving from the impact melt

Thank you – Questions?

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