Isotopic mapping and its application to understanding craton architecture and localization of mineral systems

2023-11-27

MERC Short Course, Saskatchewan Geological Open House

Kristine G. Nymoen[1] (Ph.D. Candidate)

David Mole[2], Phil Thurston[1], Douglas Tinkham[1], Richard A. Stern[3]

[1]Mineral Exploration Research Centre, Harquail School of Earth Sciences, Laurentian University, Sudbury, Canada

[2]Geoscience Australia, Canberra, Australia

[3]Canadian Centre for Isotopic Microanalysis, University of Alberta, Edmonton, Canada

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Outline:

- **Metal Earth: intro of the craton scale project**
- Background
- Results from isotopic mapping in the SE Superior Craton
  - Part 1: crustal architecture and geodynamic setting
  - Part 2: crustal architecture and mineral systems
- Summary

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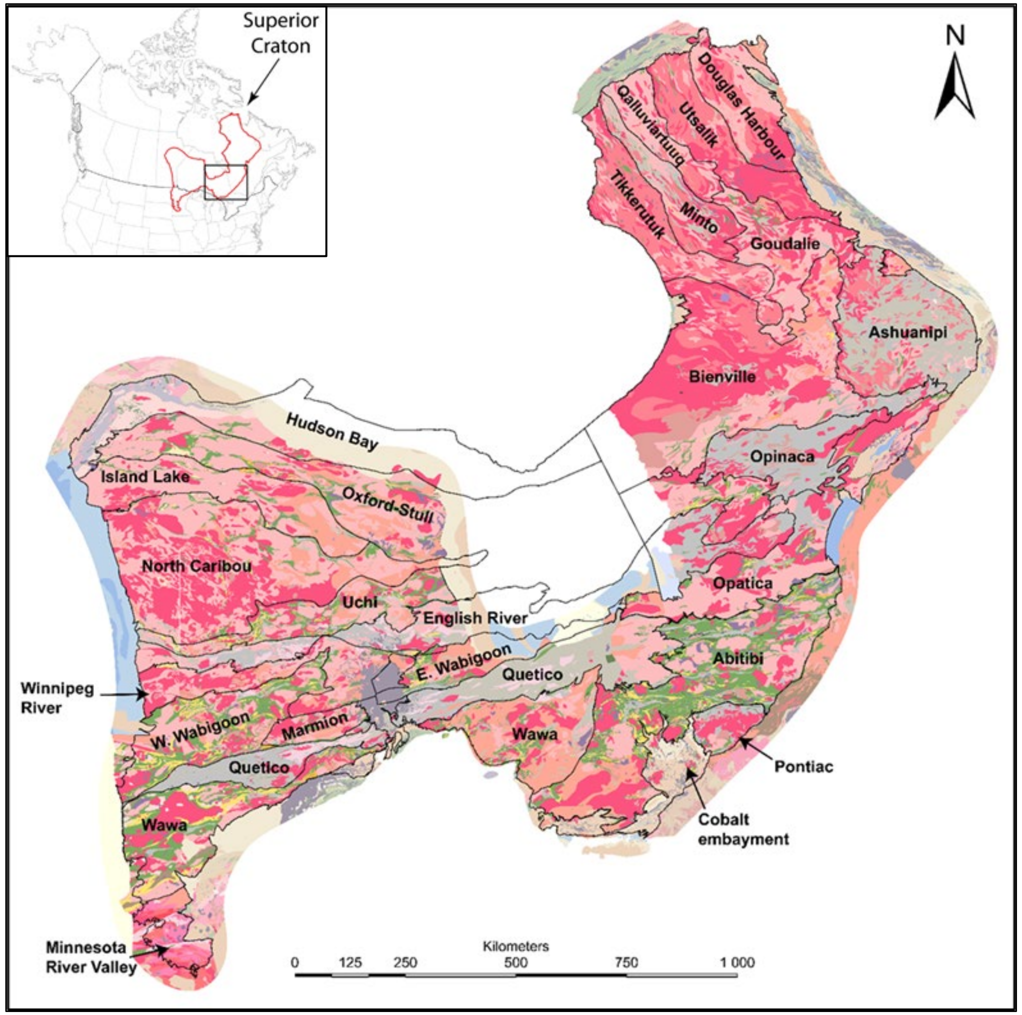
Craton scale project

- Aims to perform multi-isotopic mapping of the Superior Craton
  - Collection of large U-Pb-Hf-O-TE dataset on both new and archived zircons to:
  - Constrain time-space evolution of the craton
  - Build an advanced knowledge of crustal architecture across the craton
  - Relate the crustal architecture to localisation of mineral systems



Modified after Montsion et al. (2018)

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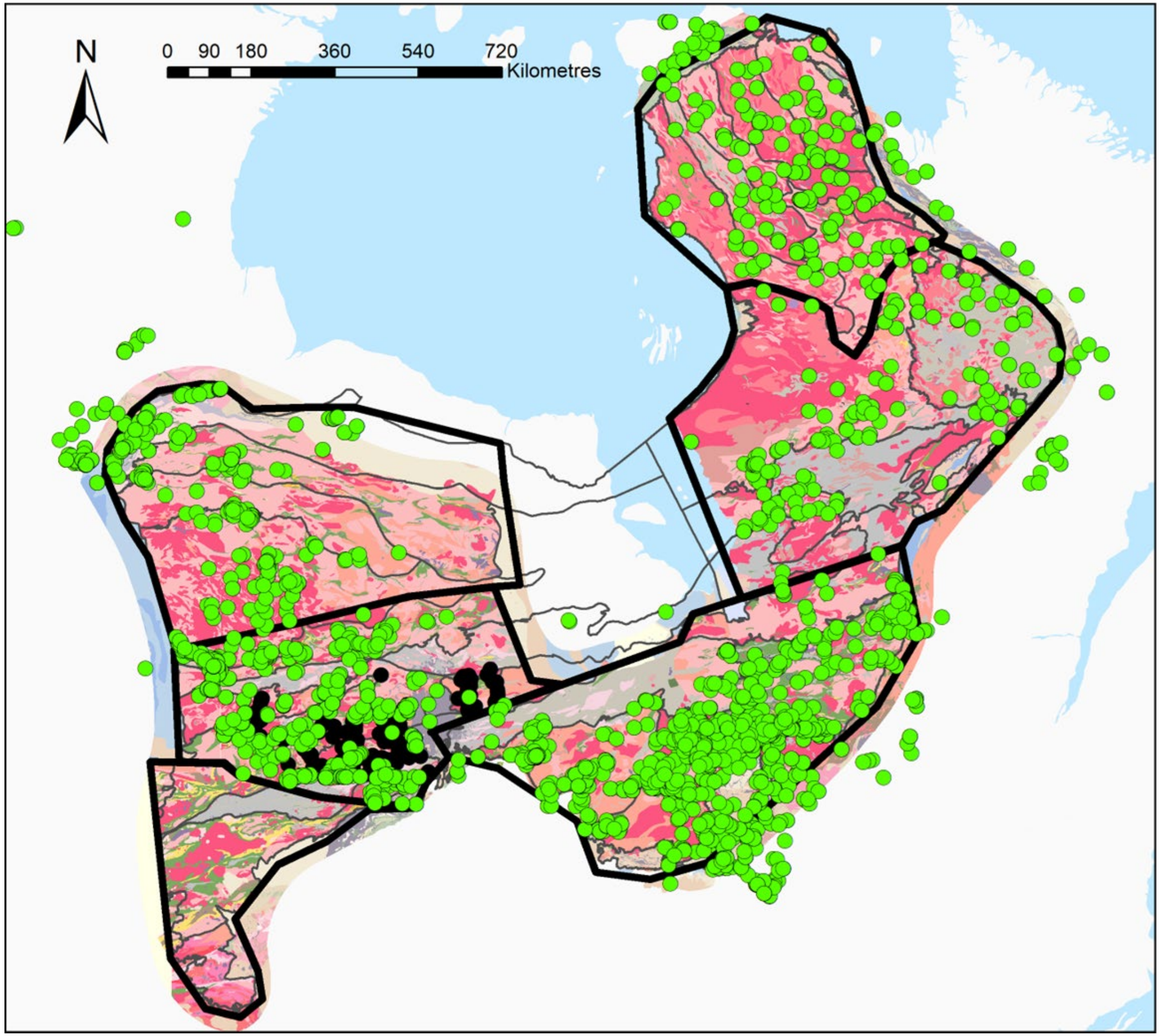
Methodology

- Sample acquisition:
  - Craton divided into quadrants
  - Sub-samples collected from existing zircon material
  - Field work in under-sampled areas
- Data Collection:
  - U-Pb-Hf-TE isotopic data collected in-situ from zircons at Laurentian University and Curtin University
  - Imaging and O-isotope data collected at University of Alberta w/ Richard Stern
- Processing and map data:
  - Reduce the data and produce contour maps and time-slices



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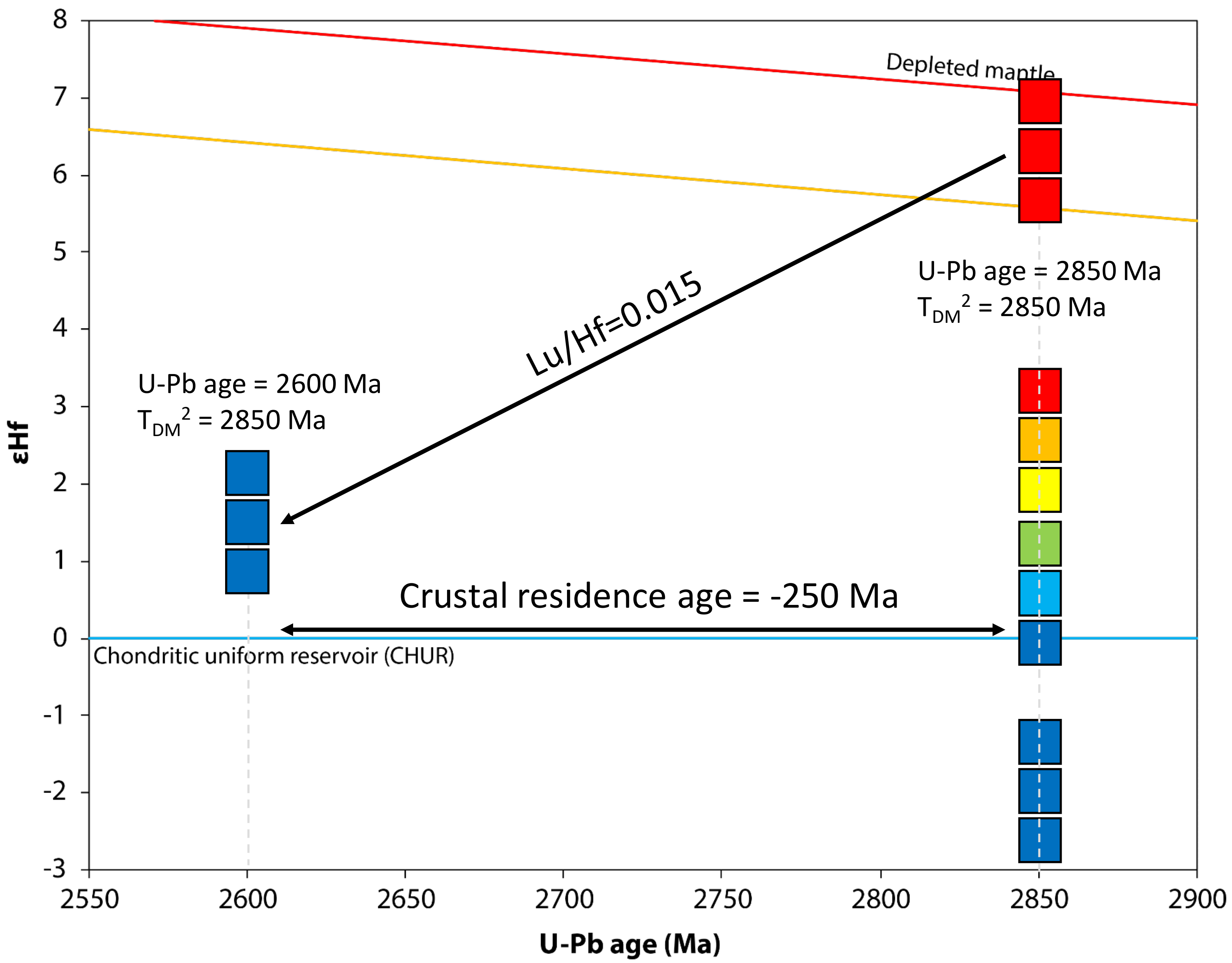
Background

- Sm-Nd/Lu-Hf system:
  - Radiogenic isotope system
  - Sm-Nd system is on whole-rock powders
  - Lu-Hf is on zircons
  - Young, mantle-derived crust typically has εHf>0
  - Old crust typically has εHf<0
  - Two-stage model age (T_{DM}^2) is the age a particular source separated from the mantle
  - Crustal residence age is the time since the crust was extracted from the mantle/residence time of the source:
    - U-Pb age - T_{DM}^2



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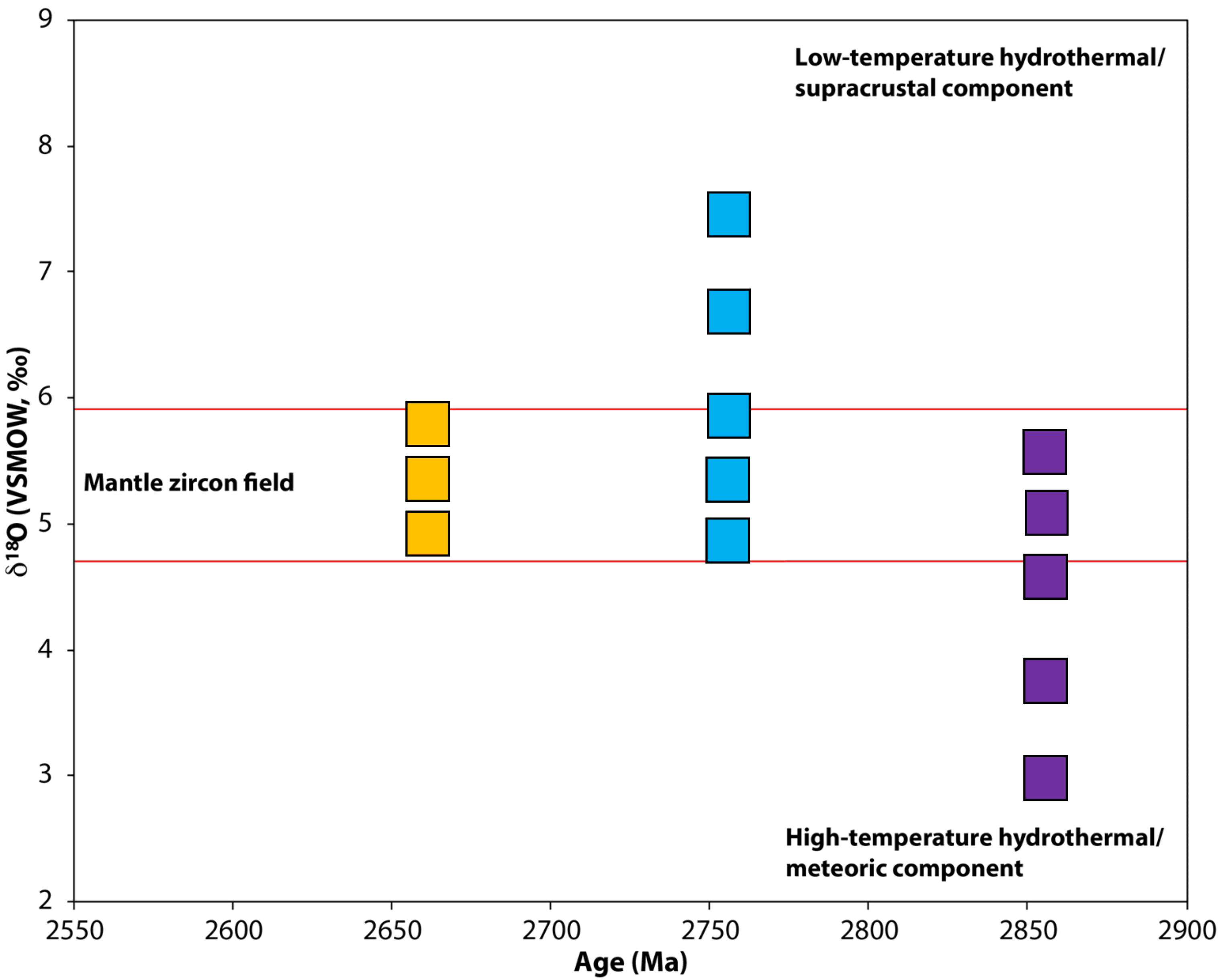
Background

- The O-isotope system:
  - $^{18}O/^{16}O$ stable isotope system
  - Collected on zircon
  - Mantle values 5.9-4.7‰
  - "Heavier" values suggest a supracrustal component, i.e. seafloor sediments
  - "Lighter" values suggest a high-temperature hydrothermal component
  - Temperature-related information
  - Source information



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The potential of isotopic mapping in mineral exploration:

- Mineral provinces and their ore deposits are heterogeneously distributed within the Earth's crust, in both space and time
- In mineral exploration, the aim is to find these ore deposits amongst the poorly-endowed crust
- To be able to do that, it requires exploration techniques that progressively select areas and down-scale, from planetary-scale, through continent-, terrane- and belt-scales
- Lithospheric and crustal architecture has been shown to have a first-order control on localisation of major ore systems
- Related to this, isotopic systems (Nd, Hf, Sr and O) have been vital in uncovering the evolution of the continental crust through time- but rarely applied spatially
- Isotopic mapping applies the power of isotopic systems spatially, to provide a new method of imaging crustal architecture, and sort the mineral-endowed areas from the poorly mineral-endowed areas at the continent- to belt-scale

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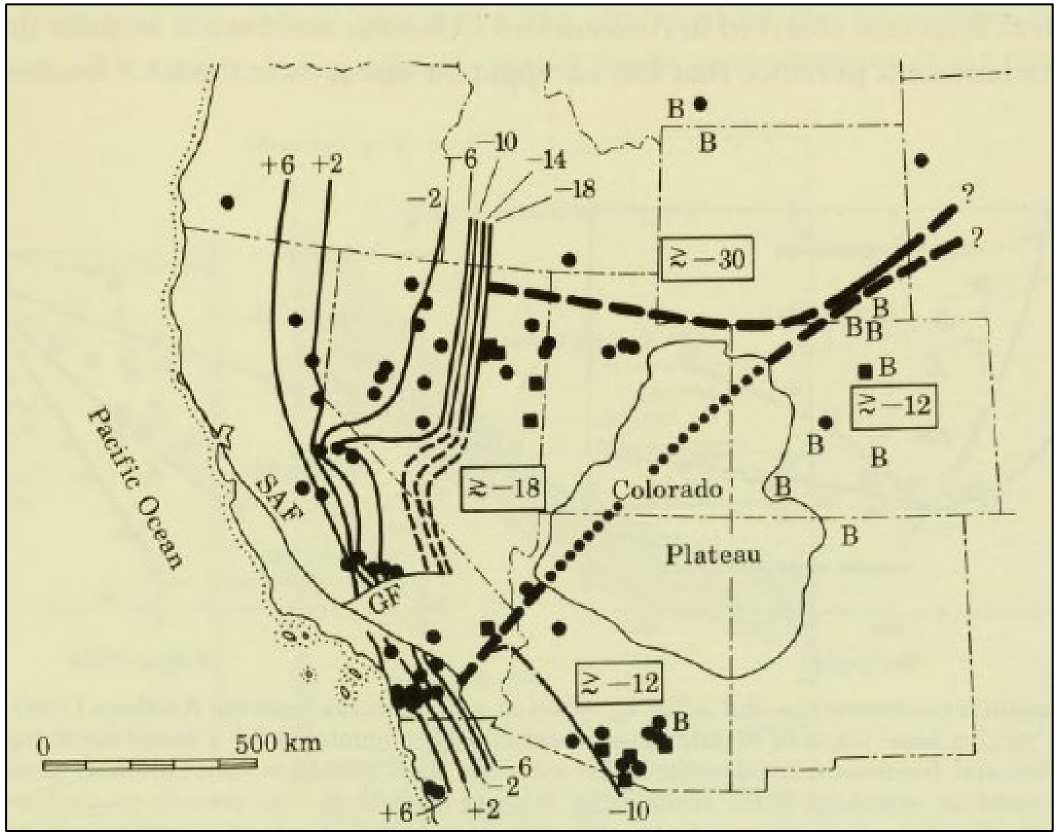
The history of isotopic mapping:

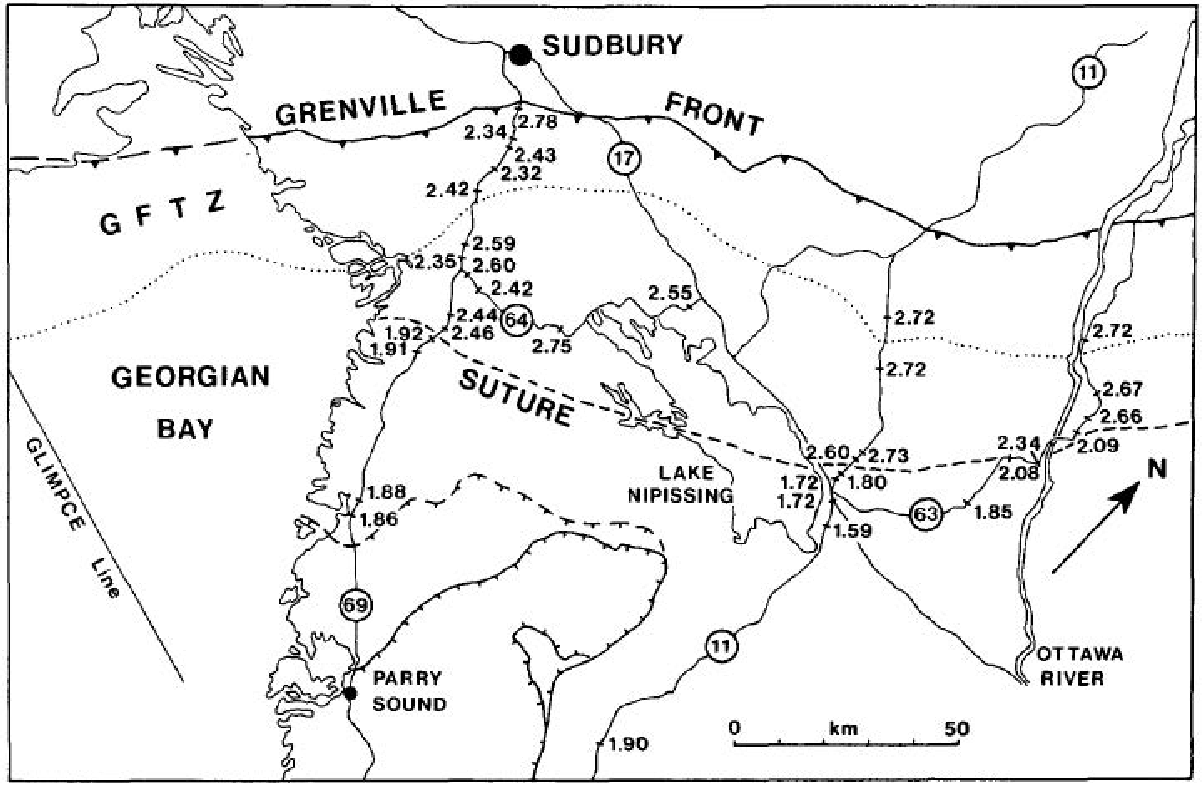
- The first maps
  - DePaulo and Farmer sampled granitoids in the northern California and northwestern Nevada in 1984
  - Sm-Nd isotopes used to draw crustal boundaries



DePaulo and Farmer (1984)

The history of isotopic mapping:

- The first maps
  - DePaulo and Farmer sampled granitoids in the northern California and northwestern Nevada in 1984
  - Sm-Nd isotopes used to draw crustal boundaries
  - Dickin and McNutt did a similar study in 1989
  - Sm-Nd isotopes from plutons were used to identify a suture zone



Dickin and McNutt (1989)

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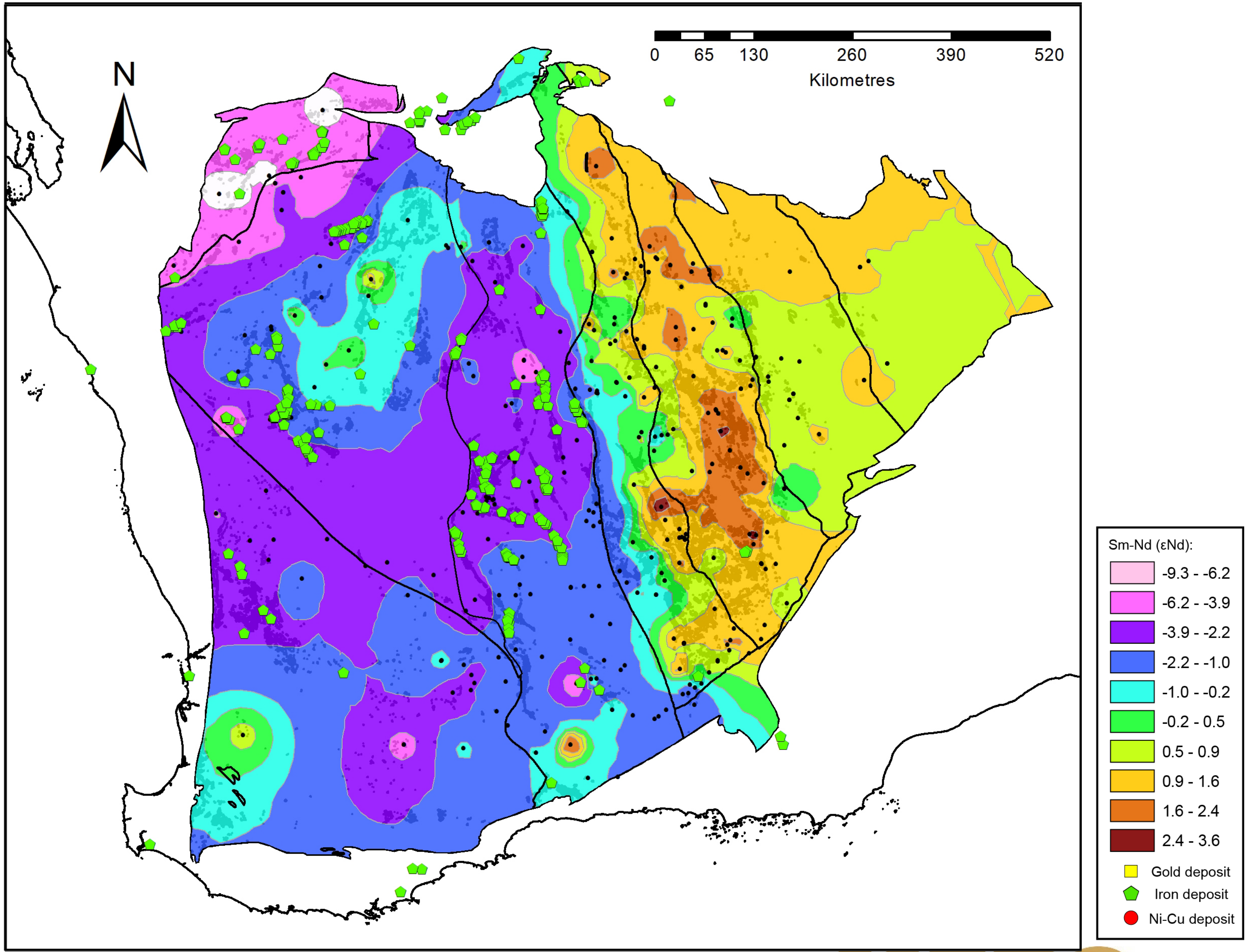
Sm-Nd mapping: Yilgarn, Australia

- Isotopic mapping:
  - Yilgarn granites show similar age ranges and geochemistry across the craton
  - How can we effectively understand spatial variations in crustal evolution?
- Radiogenic isotopes:
  - The spatial application of the Sm-Nd unveiled the cryptic architecture of the Yilgarn Craton
  - Apparent controls on multiple mineral systems
- Result:
  - Crustal architecture has a first-order control on the location of major mineral systems
  - ...and we have a way to image it

Mole *et al.* (2013) *Geol. Soc. London Spec. Pub.*



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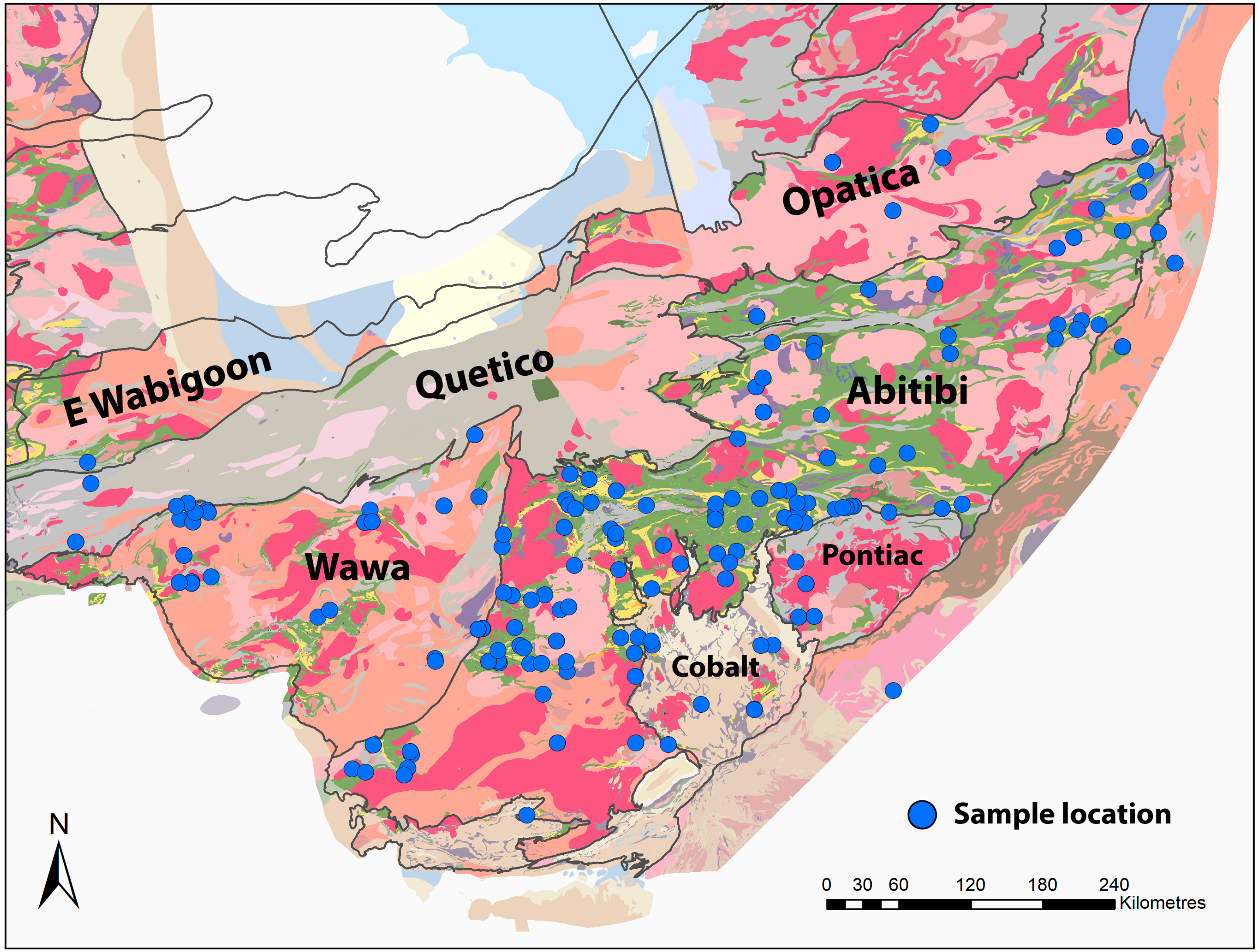
Metal Earth craton scale project:
Part 1:
Isotopic mapping of the southeastern Superior Craton, crustal architecture and geodynamic setting

Superior Craton



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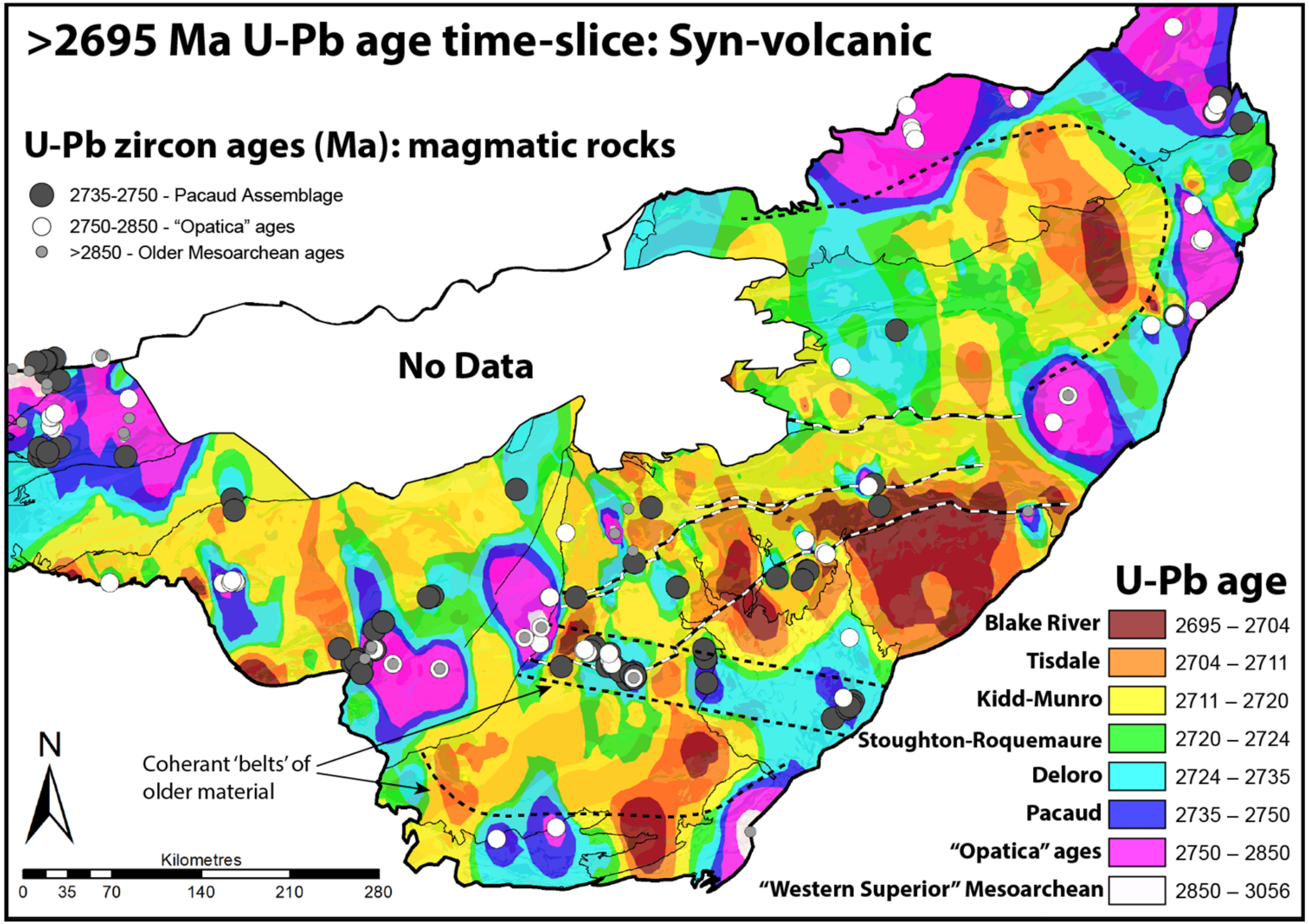
U-Pb ages: Spatial data

- Distribution of U-Pb ages:
  - NE and W edge show >2750 Ma ages
  - Central Abitibi dominated by younger ages
  - >2750 Ma xenocrysts have been found within the Abitibi



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SE Superior dataset: Hf isotopes

Three major Hf reservoirs:

1. SW Superior = 3200 Ma
2. Opatica = 3100 Ma
3. Abitibi-Wawa = ca. 2900 Ma

- Ca. 5 εHf unit range

Is contamination viable?

- DM magmas with 5-20% of Opatica crust can explain Abitibi compositions
- Ca. 5-10% for SW Superior crust
- Mesoarchean component to the Abitibi?

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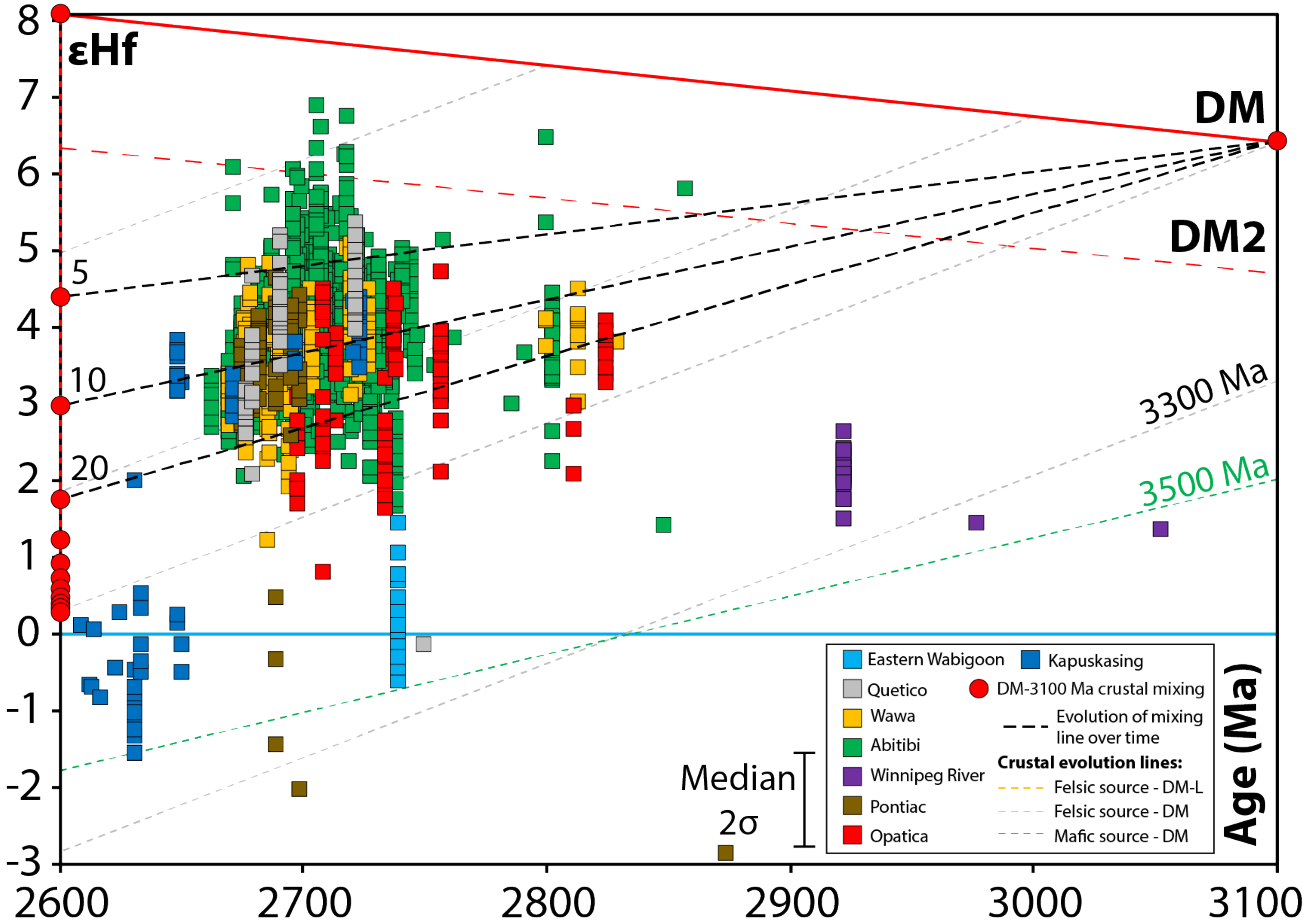

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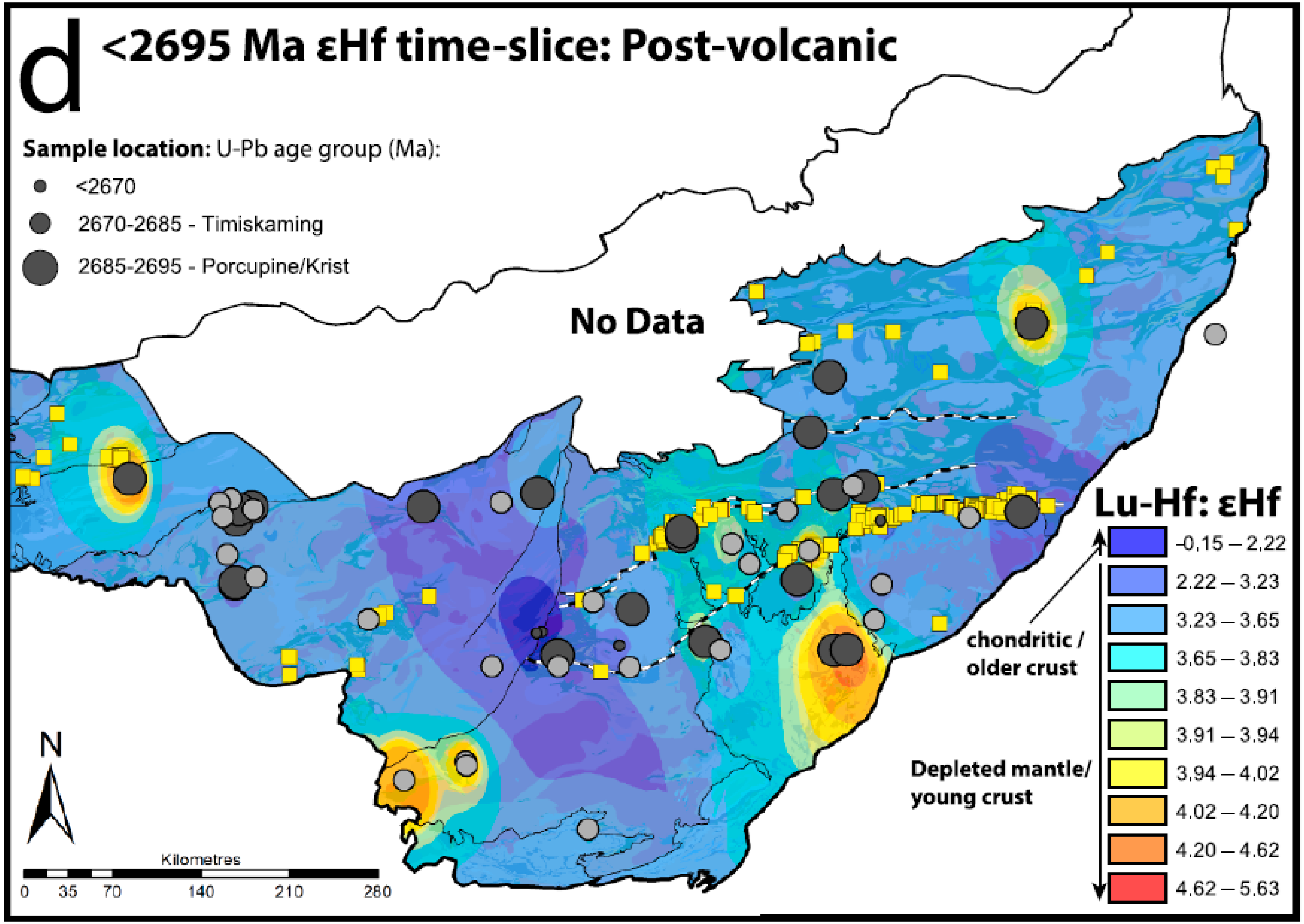
Spatial data: Hf isotopes

Lu-Hf isotopic mapping:

- Central region of more juvenile, younger crust
- Surrounded by slightly older crust
- $\delta^{18}O$ data are more "light" in the most juvenile regions

Time-slices:

- Syn-volcanic
  - Juvenile central Abitibi
- Post-volcanic
  - Overall, more evolved signatures



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SE Superior dataset: O-isotopes

- **Four major components:**
  1. 2800-2825 Ma: Mantle $\delta^{18}O$
  2. Ca. 2750-2695 Ma: Small heavy component, light component increases over time
  3. 2695-2660 Ma: Heavy component increases
  4. <2650 Ma: Heavy component only
- **Major transition at 2695 Ma:**
  - Increase in $\delta^{18}O$ correlates with other data
  - Increase in sedimentary component
  - Decrease in mantle component

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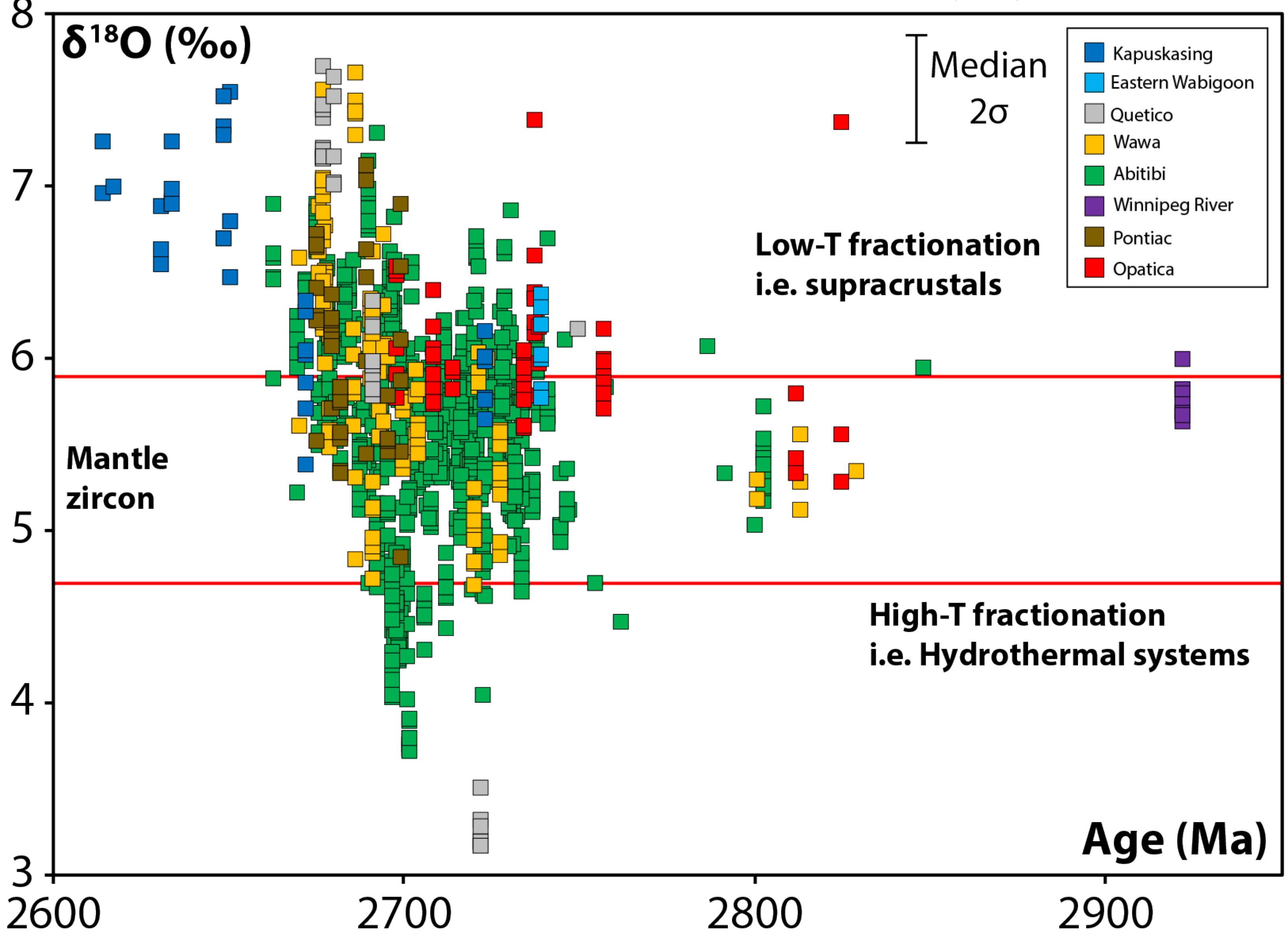
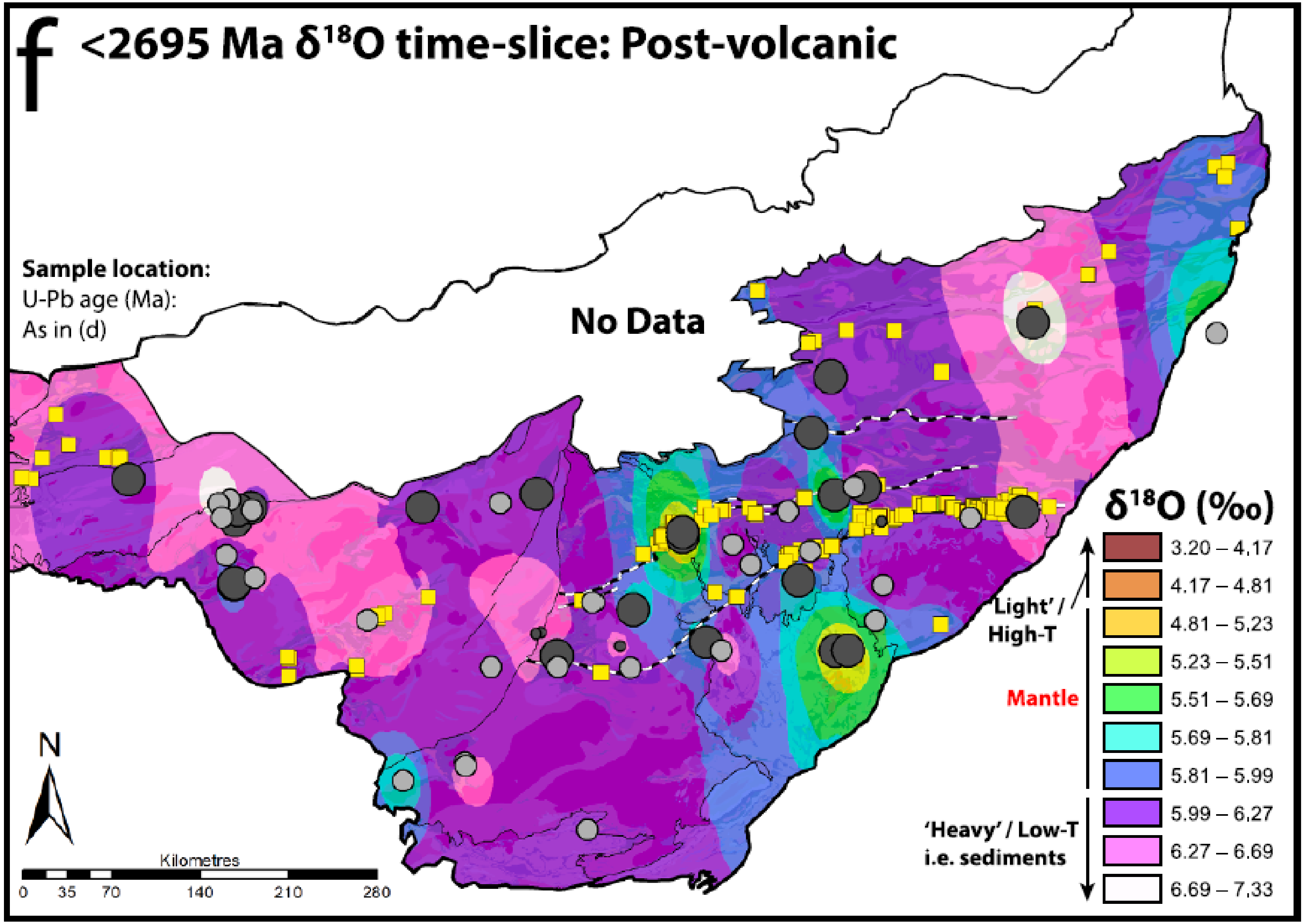


Spatial data: O-isotopes

- O-isotopic mapping:
  - Central area of light to mantle-like $\delta^{18}O$
  - Regions to east and west have relatively heavy $\delta^{18}O$
  - Central area = greater high-temperature hydrothermal interactions?
  - $\delta^{18}O$ may map out areas with high heat-flow
- Time slices:
- Syn-volcanic
  - "Light" mantle signatures in central Abitibi, "heavy signatures toward edges
- Post-volcanic
  - Overall, "heavy" signatures



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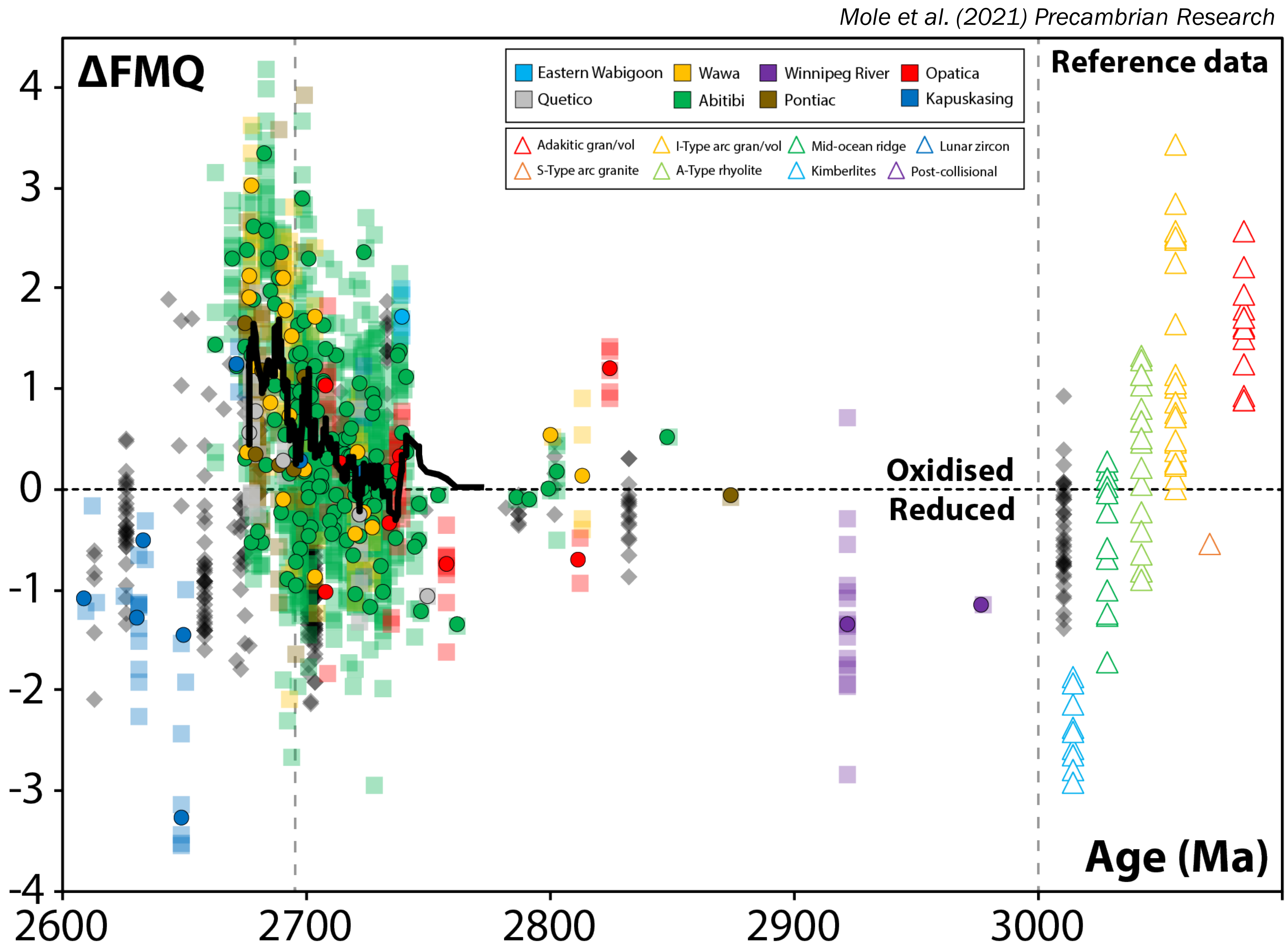
SE Superior dataset: Zircon trace elements

- Oxygen fugacity by ΔFMQ:
  - Major increase at ca. 2695 Ma to more oxidised magmas
  - This correlates with data from εHf and $\delta^{18}O$
  - Together, these observations suggest a major tectono-thermal transition at ca. 2695 Ma



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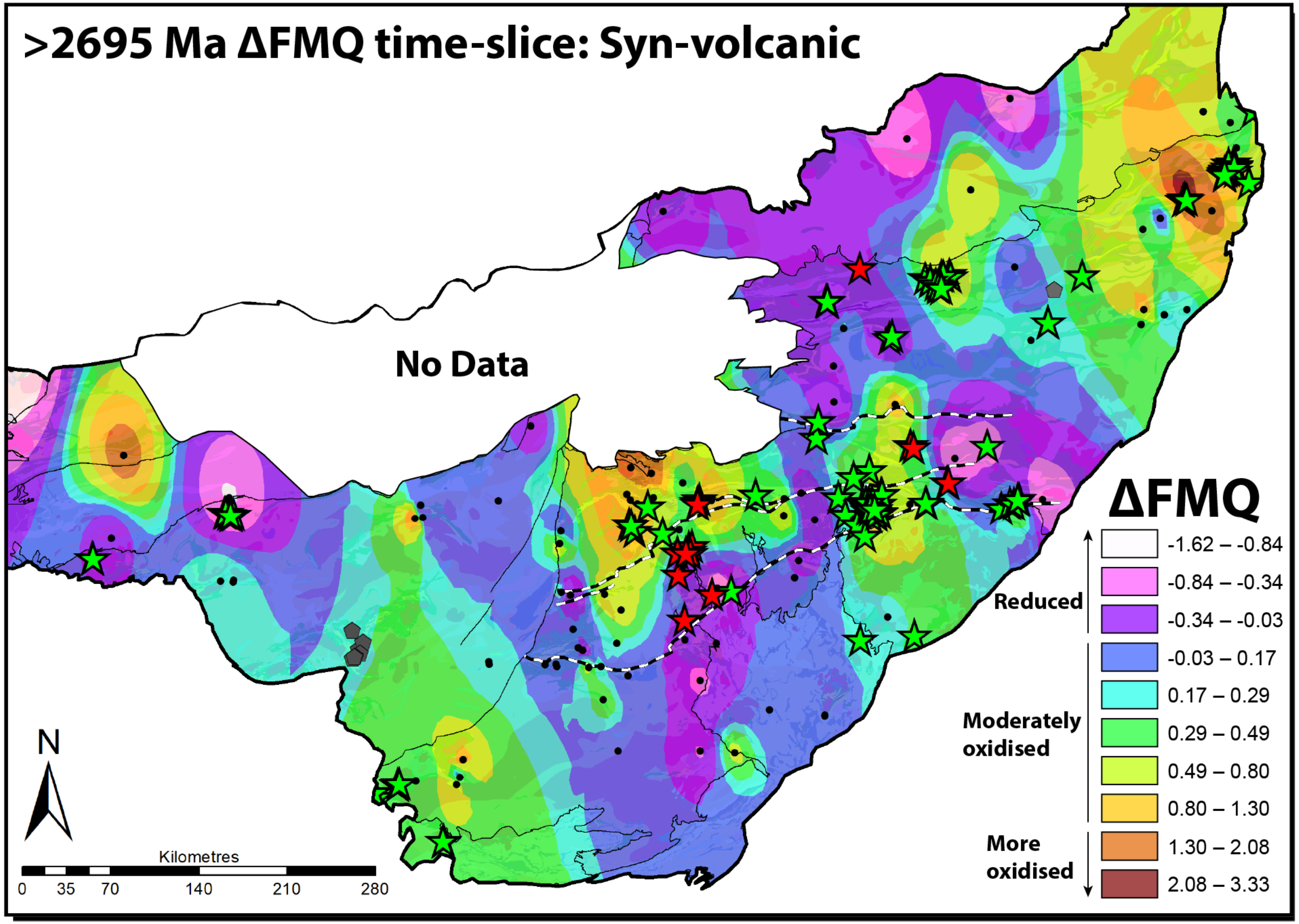
Spatial data: ΔFMQ

- ΔFMQ distribution:
  - Pattern broadly similar to that observed in εHf and $\delta^{18}O$
  - Reduced central region, more oxidised flanks
  - However, there is a noticeable higher and potentially important complexity



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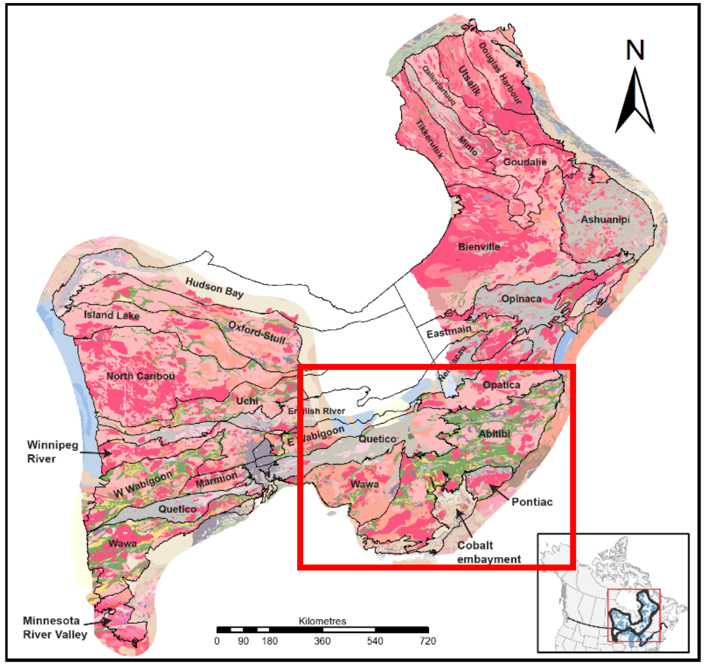
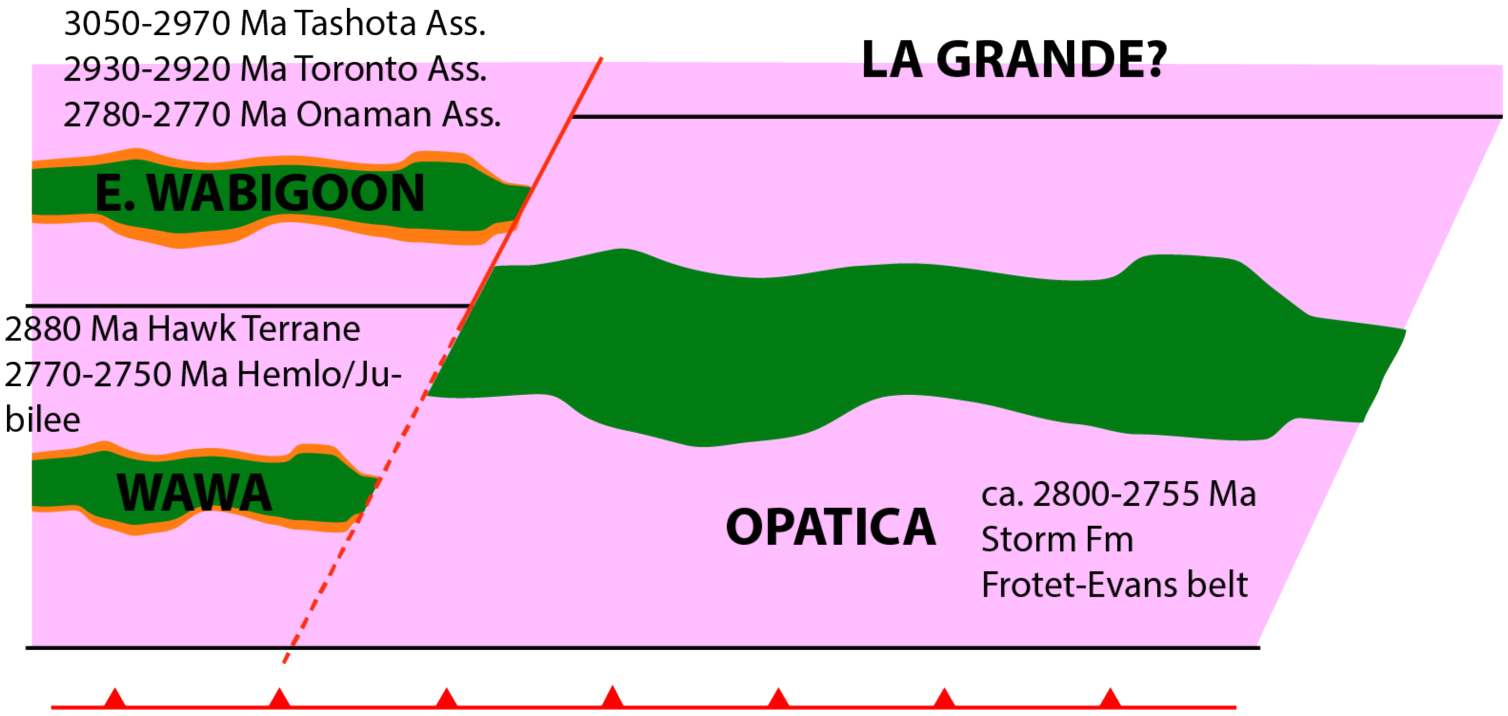
Geodynamic model: Pre-2750 Ma



A young Mesoarchean continent edge?



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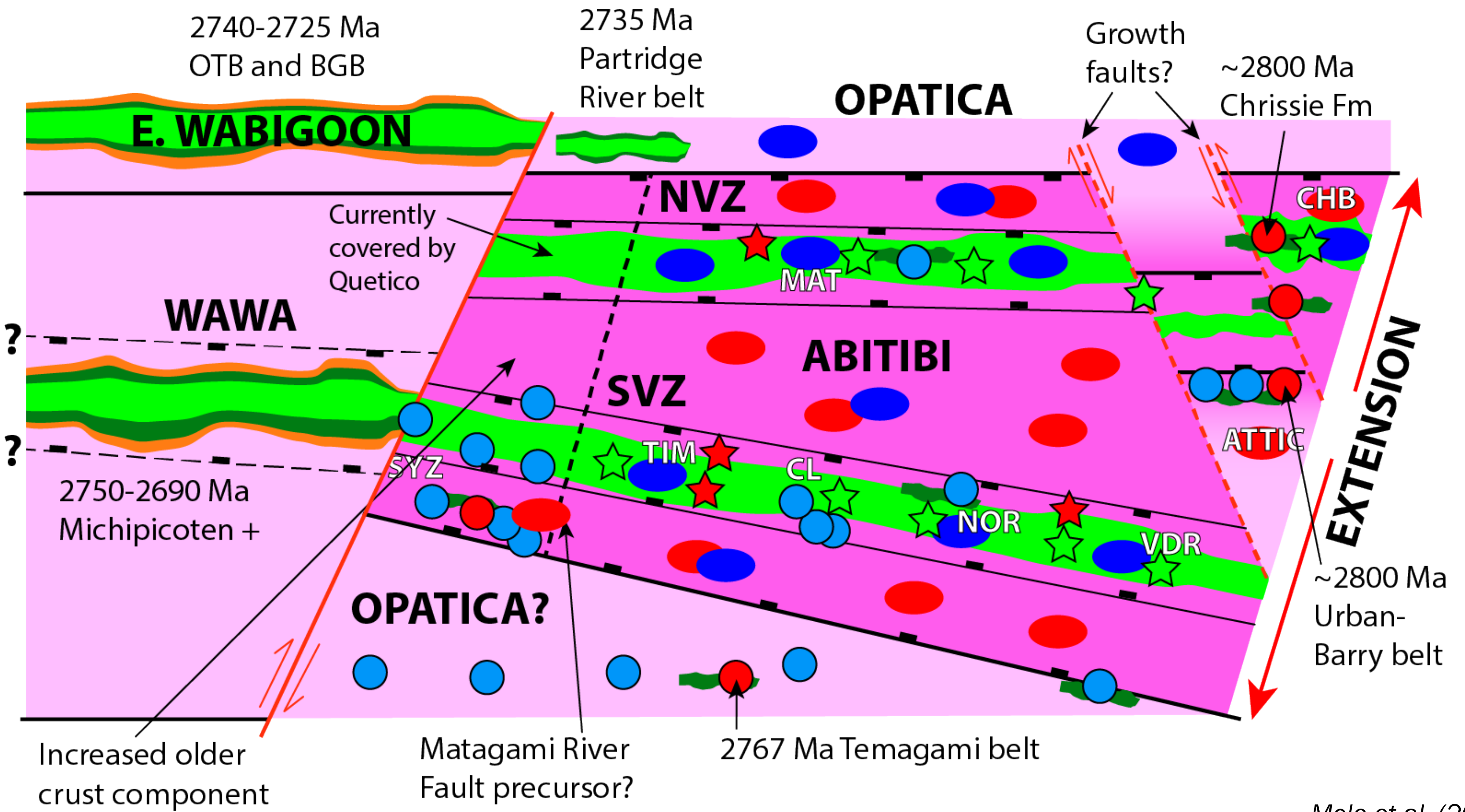
Geodynamic model: ca. 2750-2695 Ma



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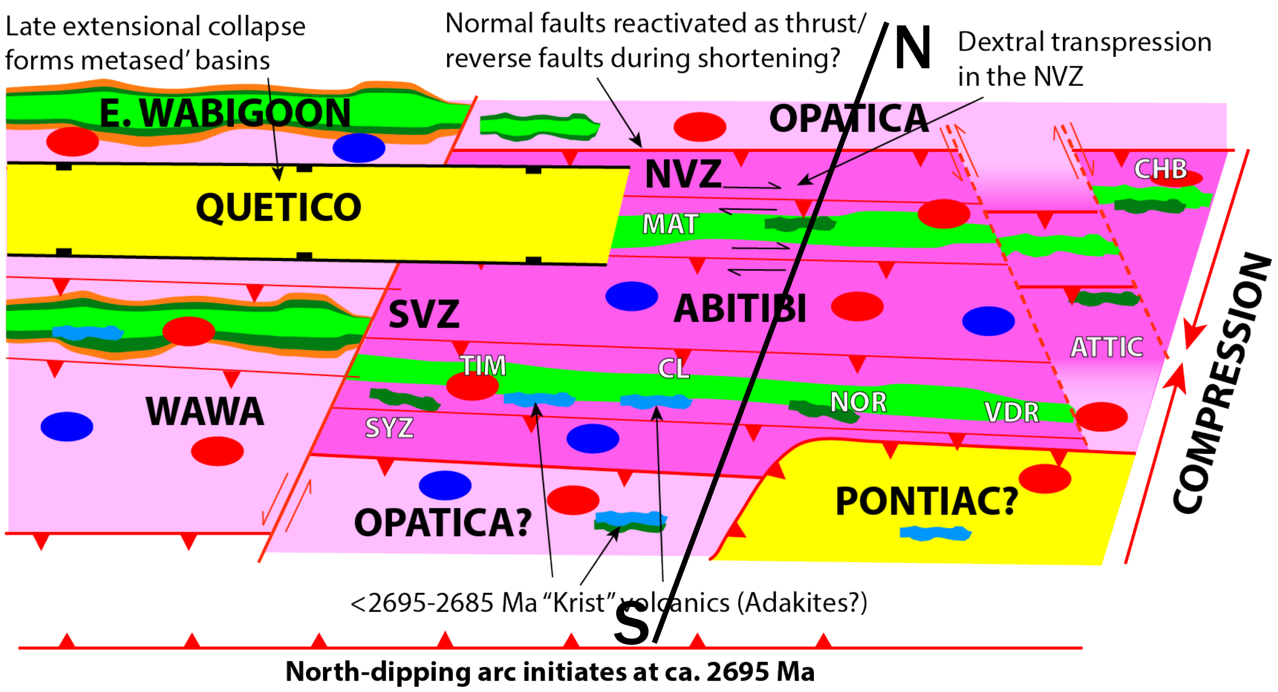
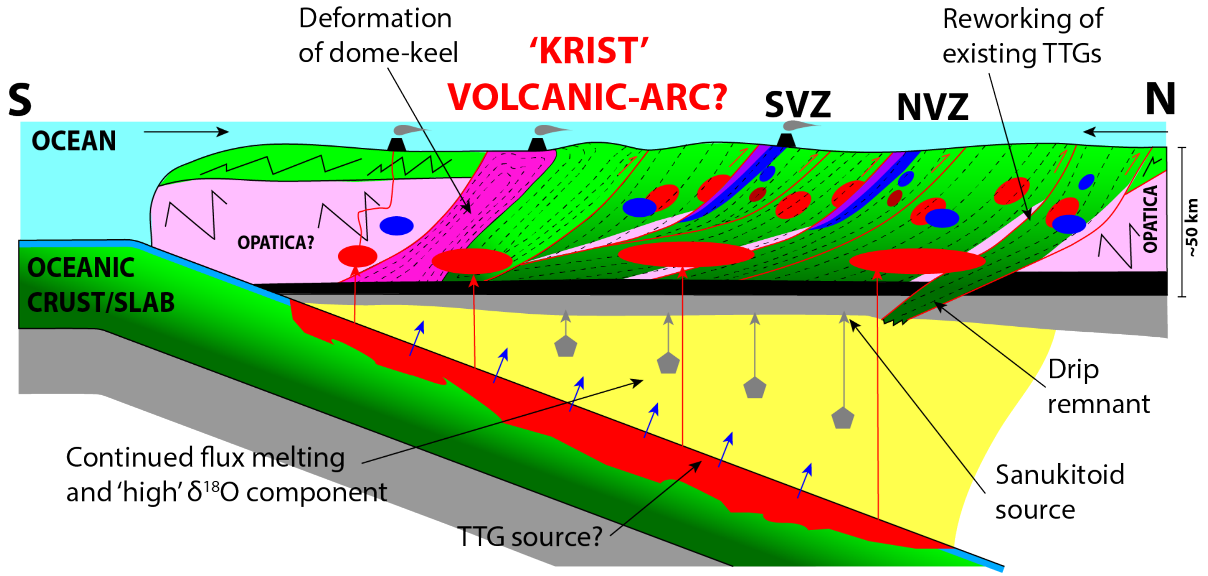
Geodynamic model: <2695 Ma





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Summary

- The changing nature of the Hf-isotope, ΔFMQ and $\delta^{18}O$ data record the changing geodynamic setting in the south-east Superior Craton
- The spatial extent of these variables records the crustal architecture
- **The south-east Superior can be characterised in four main stages:**
  1. A young (Mesoarchean) continent edge at >2750 Ma;
  2. Hyper-extension at 2750-2695 Ma in a prolonged rifting event that formed the Abitibi;
  3. Initiation of subduction at ca. 2695 Ma; and
  4. Continental collision (with MRVT) at ca. 2685-2680 Ma
- If correct, these new data suggest that Neoarchean continental growth occurred via at least two distinct mechanisms

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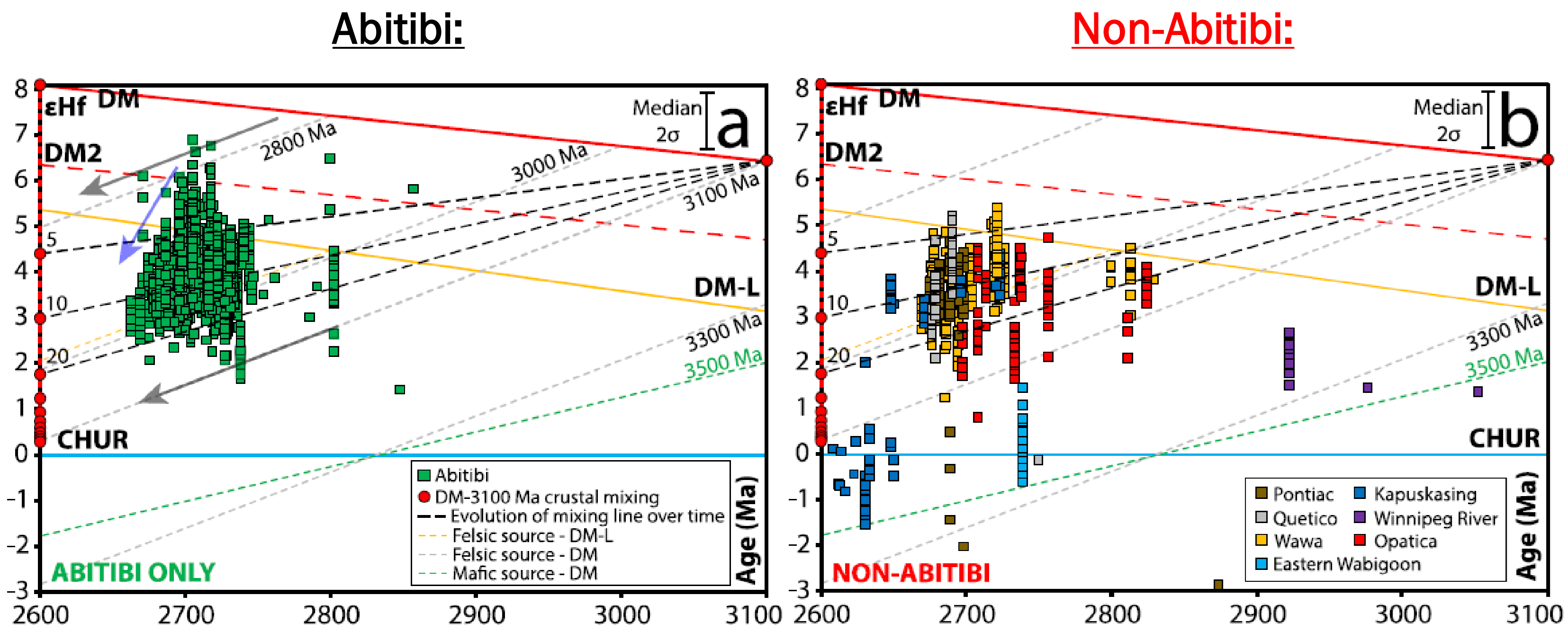
Metal Earth craton scale project:

Part 2:

Isotopic mapping of the southeastern Superior Craton, crustal architecture and mineral systems

Lu-Hf isotopes: εHf

- **Abitibi:**
  - Magmatic event starts at 2750 Ma
  - Juvenile signatures
  - Reaches εHf>+7 at ca. 2695 before it starts to decrease
- **Non-Abitibi:**
  - Two sources?
  - Both juvenile and evolved signatures
  - Overall, rocks are more unradiogenic



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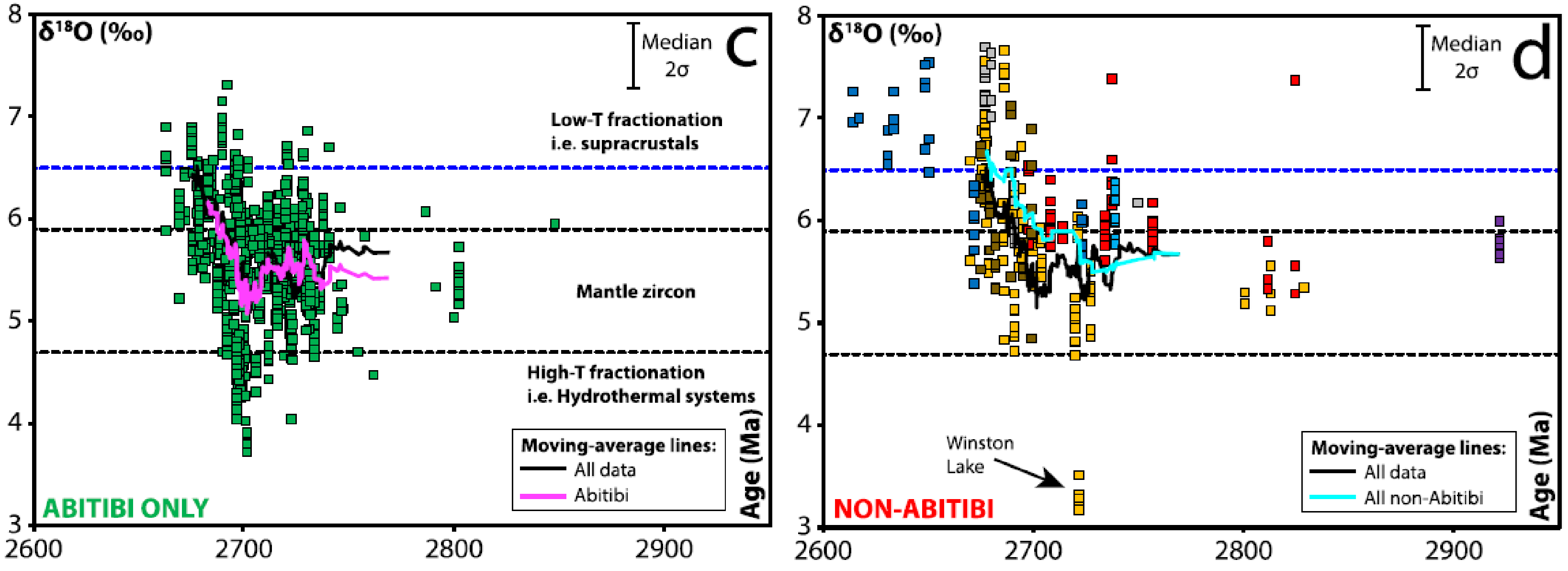
O-isotopes: $\delta^{18}O$

- Abitibi:
  - 2850-2750 Ma: mantle-zircon signatures
  - 2750-2695 Ma: small «heavy» component, increasing «light» component
  - <2695 Ma: heavy component increases, same time as we see transition in Hf-isotopes
- Non-Abitibi:
  - 2800-2750 Ma: mantle signatures
  - 2750-2700 Ma: increasingly “heavy” component
  - <2700 Ma: mostly “heavy” values, range is larger than for the Abitibi

Abitibi:

Non-Abitibi:



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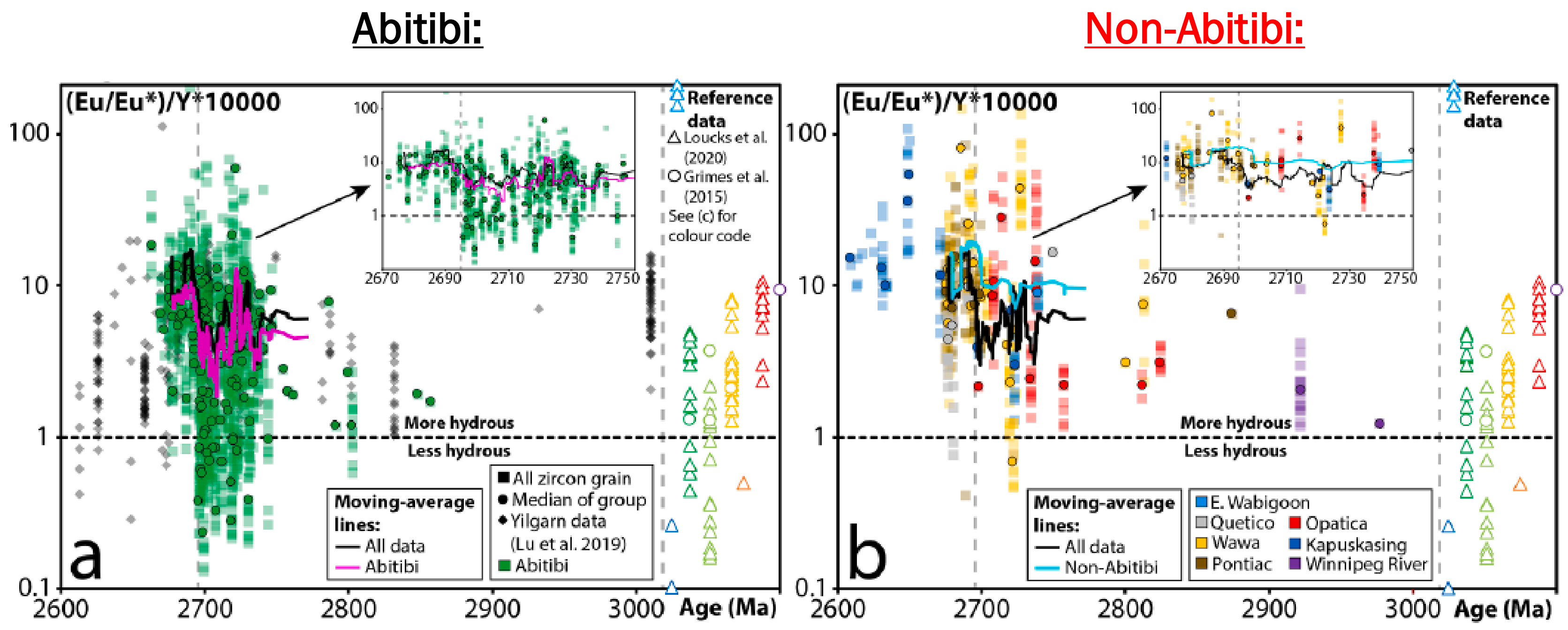
Zircon TE: Eu/Eu*/Y*10000

Hydration

- **Abitibi:**
  - 2750-2695 range 20-0.2 = hydrous magmas
  - >2695 Ma less hydrous component ceases
- **Non-Abitibi:**
  - 2750-2695 Ma similar to Abitibi
  - After 2670 Ma all >10 = wet or deep sources
  - KSZ values are high and source likely deep and dry = suggests a depth component



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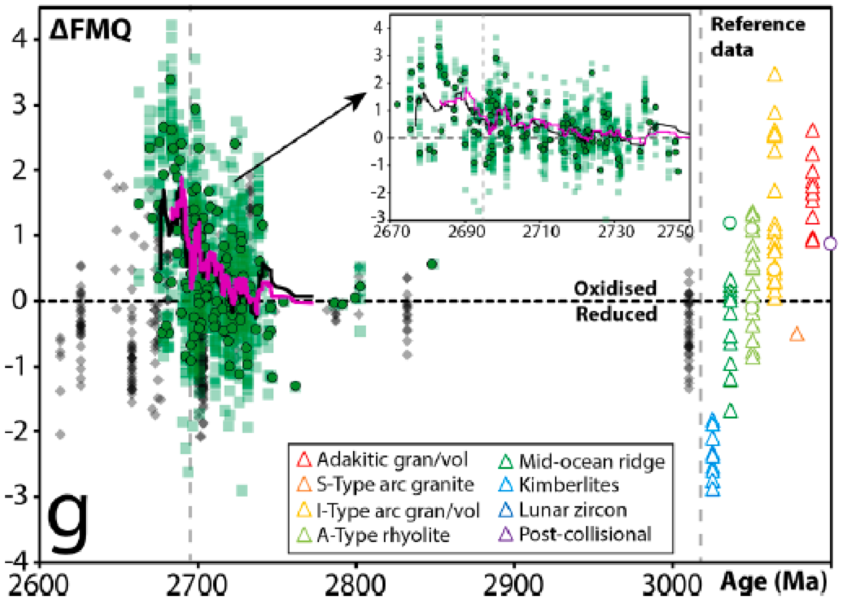
Zircon TE
ΔFMQ

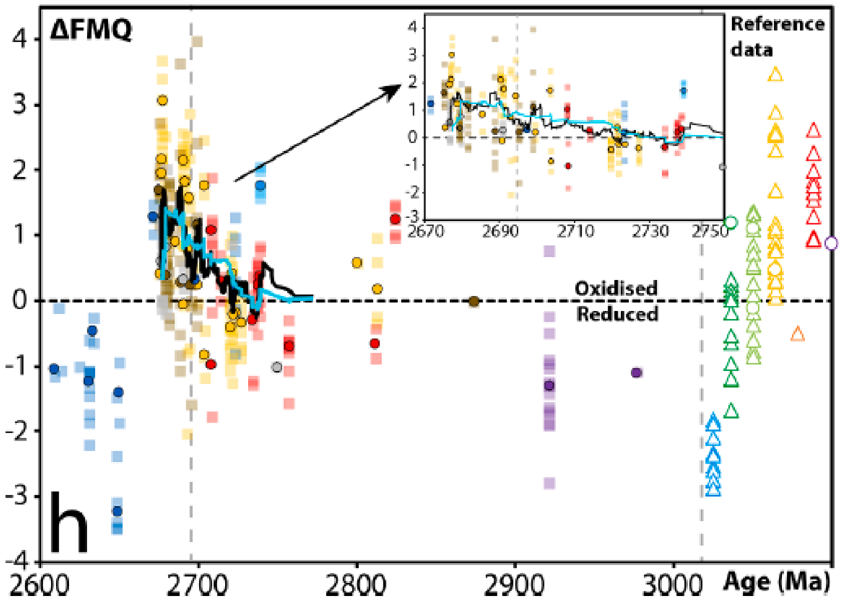
Oxygen fugacity

- Abitibi:
  - Major increase at ca. 2695 Ma to more oxidised magmas
  - This correlates with data from εHf and $\delta^{18}O$
- Non-Abitibi:
  - Similar pattern, but not as wide of a range as Abitibi data

Abitibi:



Non-Abitibi:



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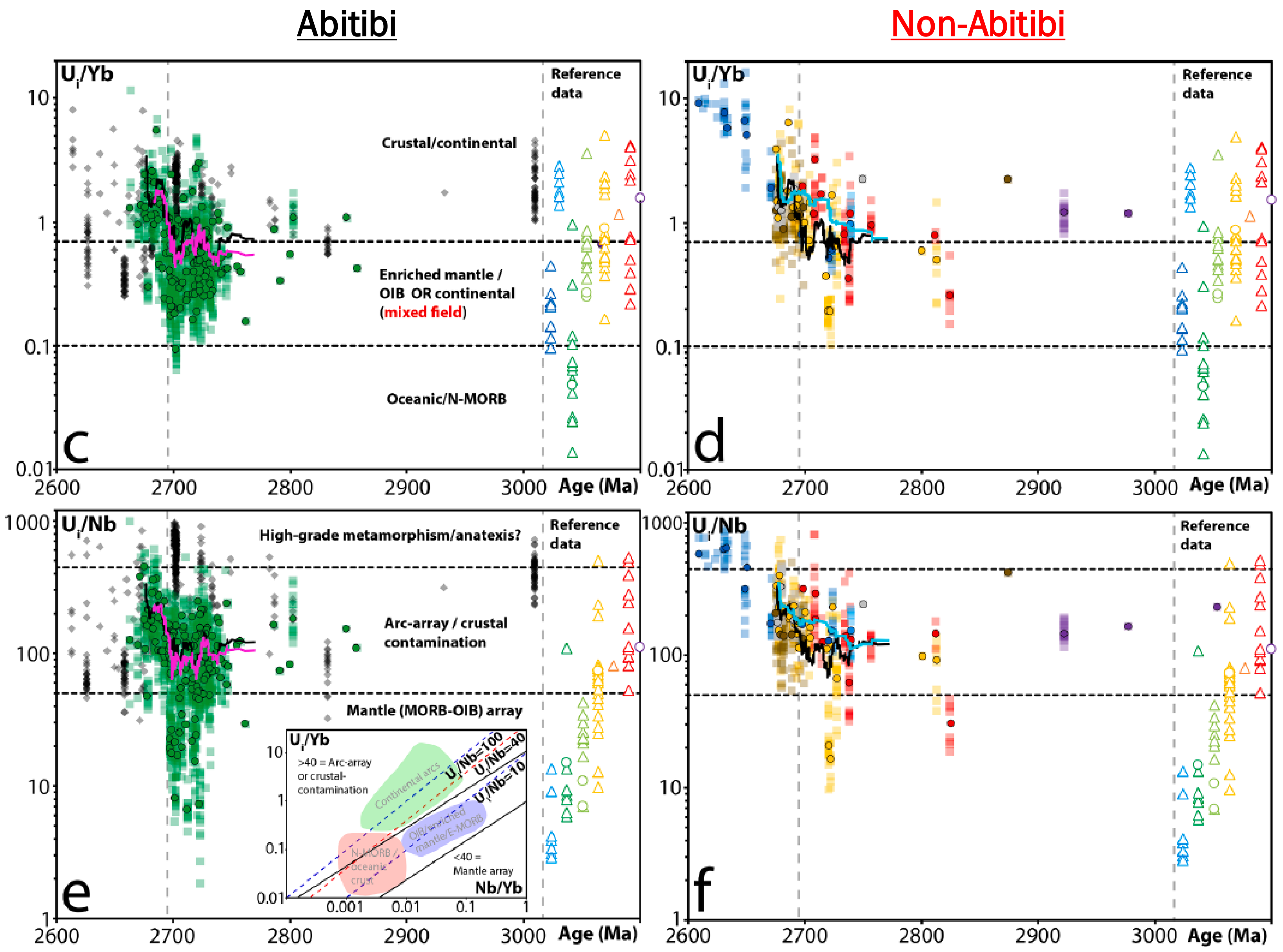
Zircon TE
U_i/Yb and U_i/Nb

Tectonic setting

- Abitibi:
  - >2750 Ma the trace elements show signatures of a continental source
  - 2750-2695 Ma the signatures are more mixed
  - <2695 Ma there is a larger crustal component
- Non-Abitibi:
  - Similar trends, but not many samples in the mixed and mantle-array field
  - Exception for samples from the Kapuskasing which show the highest ratios and plot in the high-grade metamorphism/anatexis field



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Mineral systems:

Isotope- and geochemistry summary map

- Abitibi:
  - Very juvenile εHf and low $\delta^{18}O$, high ΔFMQ
  - Juvenile magmas and mantle-like crust
- Non-Abitibi:
  - Less juvenile εHf and higher $\delta^{18}O$
  - Less juvenile magmas and more evolved crust

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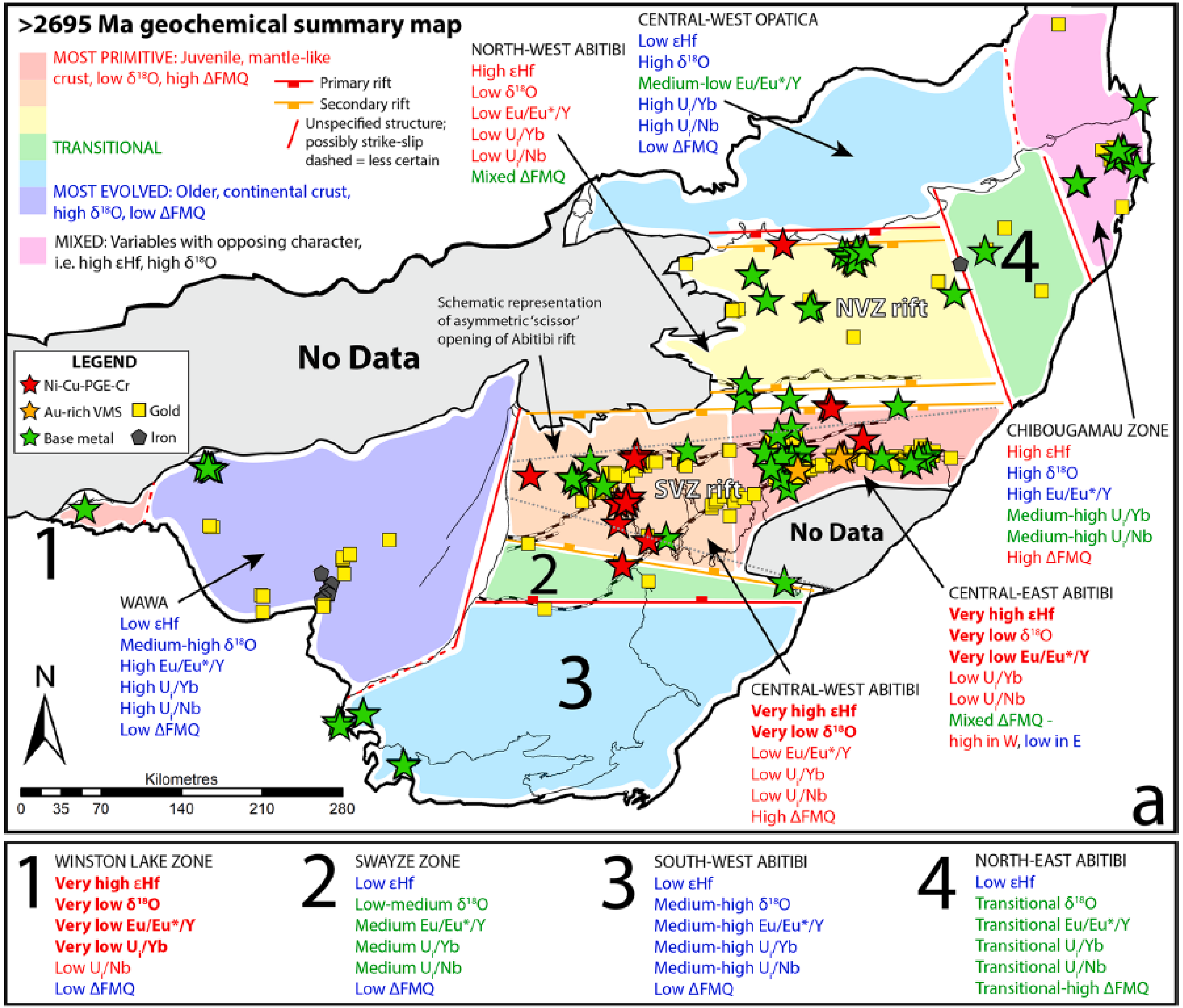

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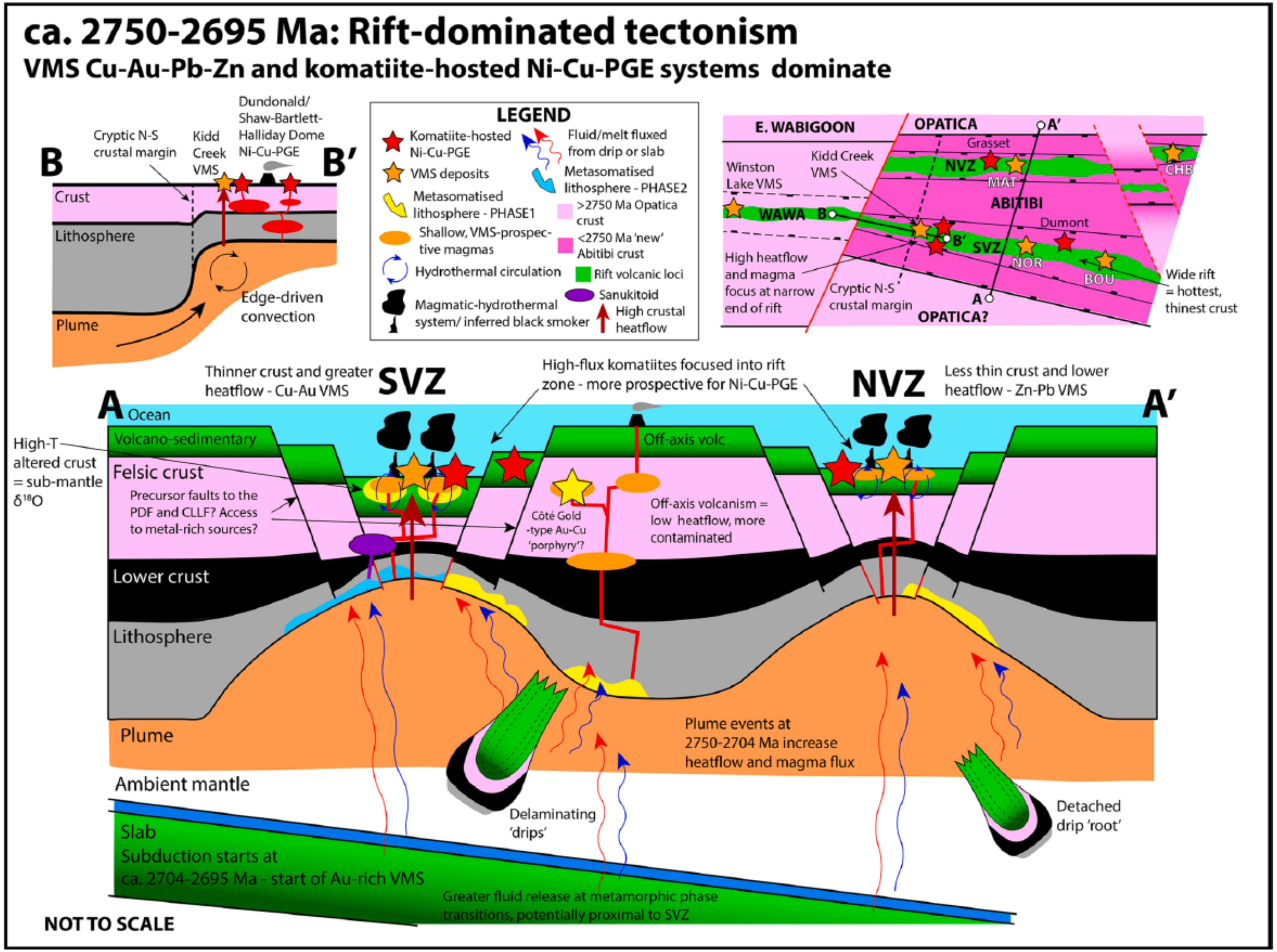
Mineral system: VMS

2750-2695 Ma

- Three volcanic assemblages:
  1. Mixed εHf and $\delta^{18}O$, lower heat flow= **Zn-Pb VMS**
  2. εHf is high, $\delta^{18}O$ relatively low,high heat flow zone= **Cu-Au VMS**
  3. Very high εHf and low $\delta^{18}O$, high heatflow= **Au-rich VMS**



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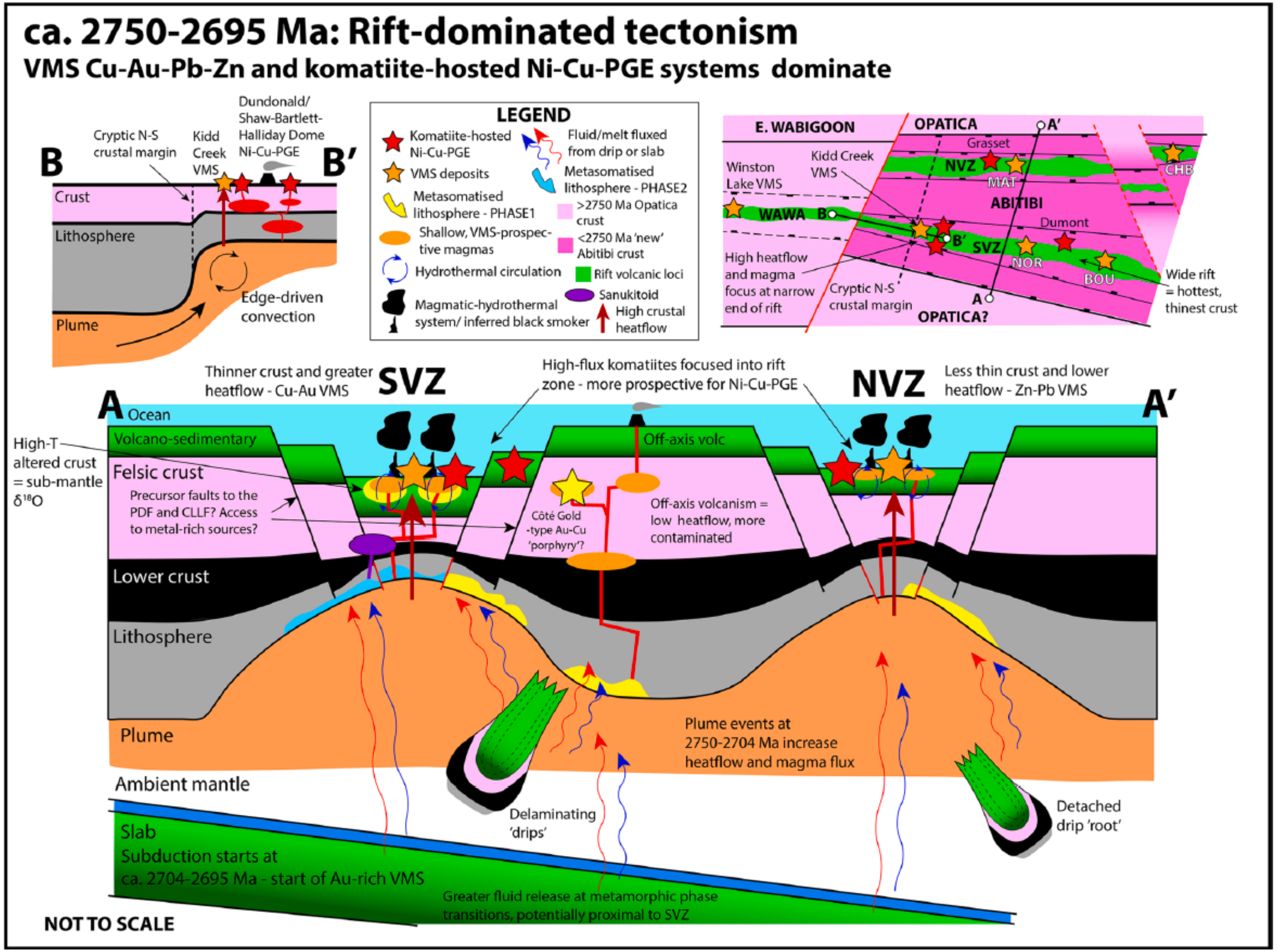
Mineral system: Ni-Cu-PGE

2750-2695 Ma

- Abitibi is relatively poorly-endowed in Ni-Cu-PGE
  - Komatiite associated
  - Number of deposits increase with time
  - Localization tied to crustal architecture
  - Very high εHf



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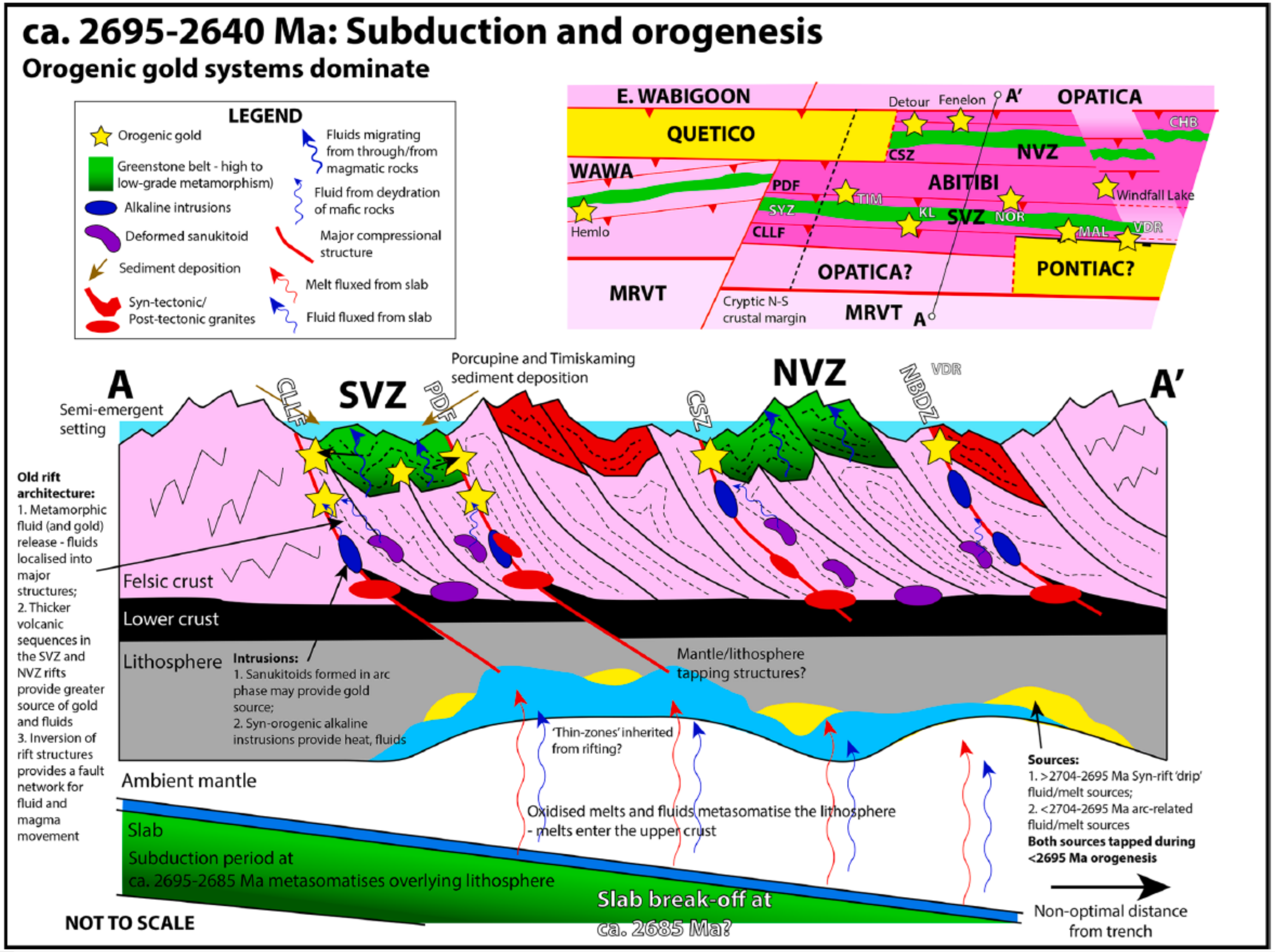
Mineral system: Gold (non-VMS)

<2695 Ma

- Follow regionally extensive east-trending fault zones
  - Gold systems
    - Elevated $\delta^{18}O$, high $Eu/Eu^{*}/Y^{*}10000$ and ΔFMQ= hydrous and oxidised magmas



Mole et al. (2022) Ore Geology Review

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Summary

>2750-2695 Ma

- A rift-dominated tectonic setting
- VMS and Ni-Cu-PGE systems are showing variable Hf- and O-isotopes, but εHf signatures are relatively high and $\delta^{18}O$ are low
- Syn-volcanic mineral systems, VMS and Ni-Cu-PGE deposits are localised within a complex and evolving rift architecture

<2695 Ma

- Major shift observed in multiple geochemical and isotopic parameters
- Orogenesis and subduction-dominated tectonic setting
- Gold systems may be driven by the more hydrous, oxidised source zones present at this time
- However, localisation appears strongly influenced by syn-volcanic architecture

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Thank you.
Questions?

Contact: knymoen@laurentian.ca

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