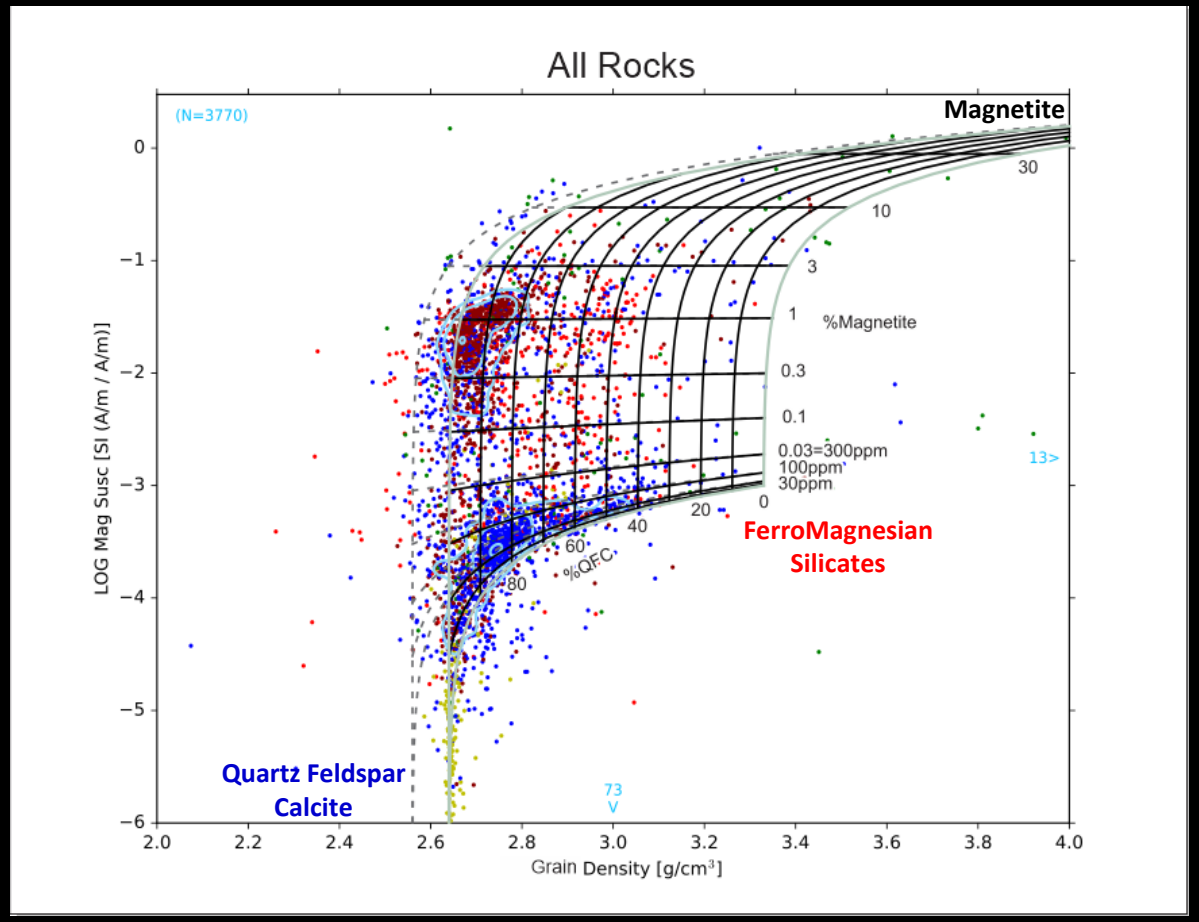
Petrophysics applied to magmatic sulfide deposits: The physical properties - mineralogy link



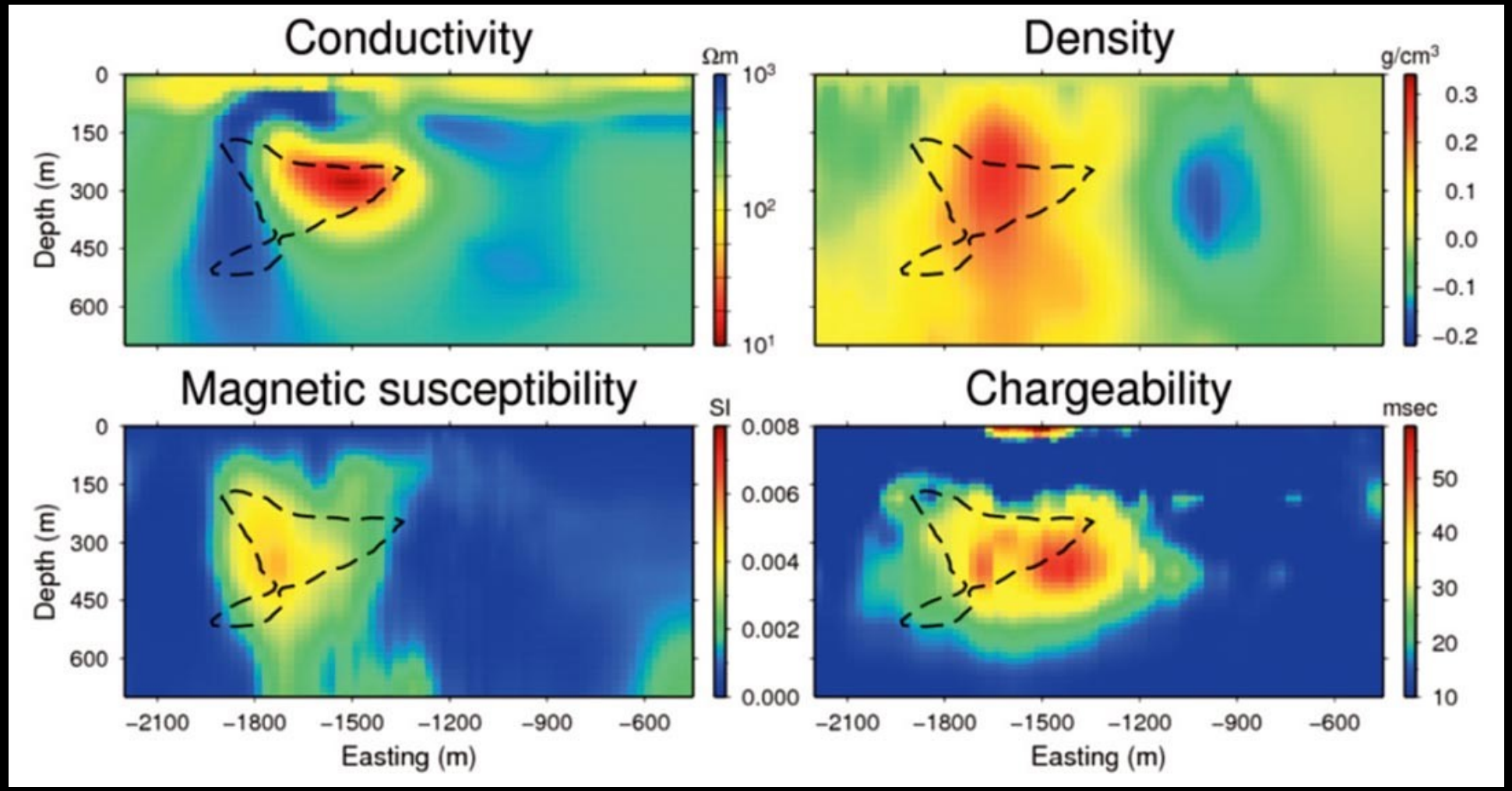
Randy Enkin

Geological Survey of Canada: Paleomagnetism and Petrophysics Laboratory

randy.enkin@canada.ca

Natural Resources Canada | Ressources naturelles Canada

① → Physical Property Contrasts → Geophysical Anomalies

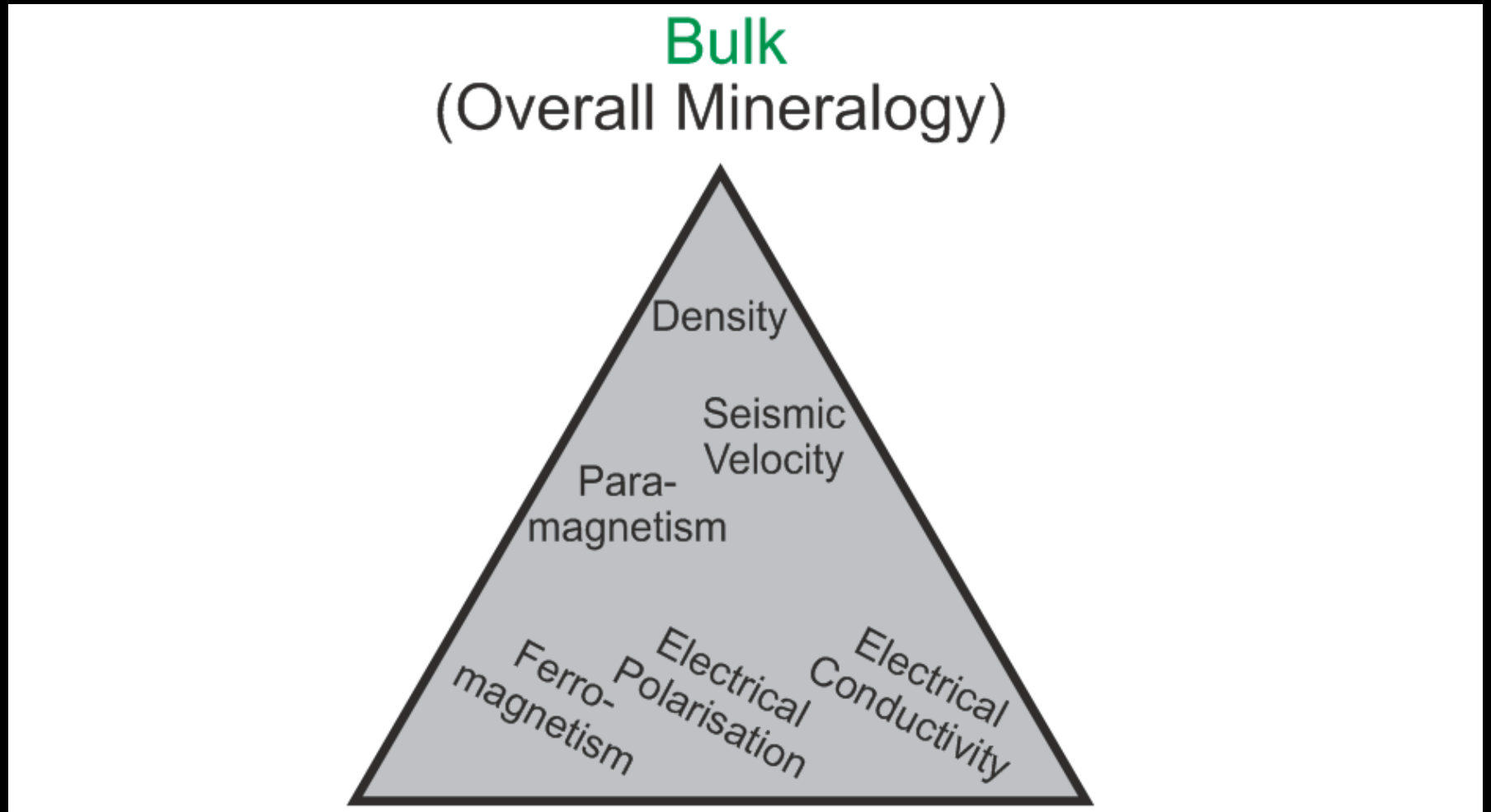


Dashed line represents deposit boundary

Doug Oldenburg

The physical properties – lithology/mineralogy link

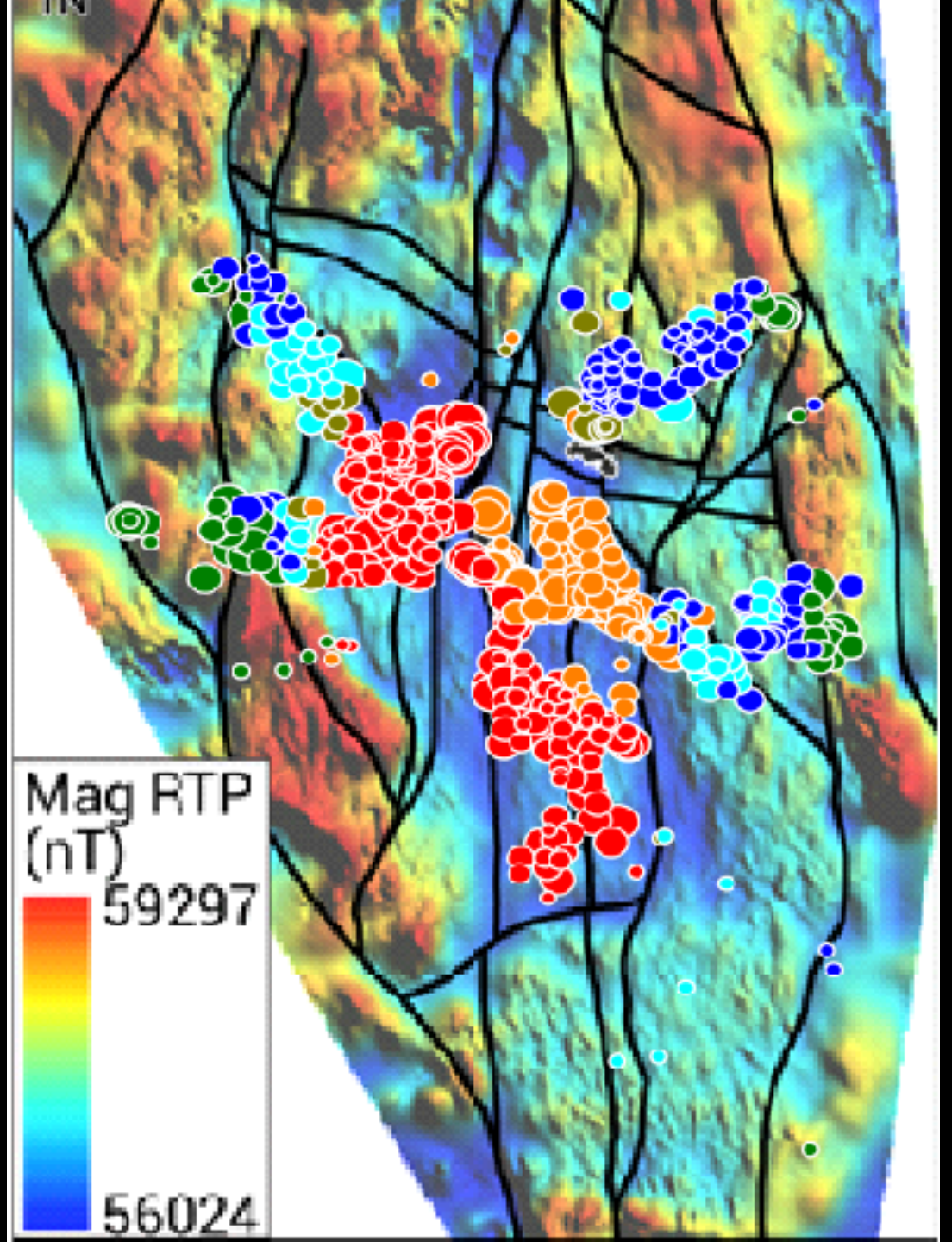
2



Mike Dentith

3

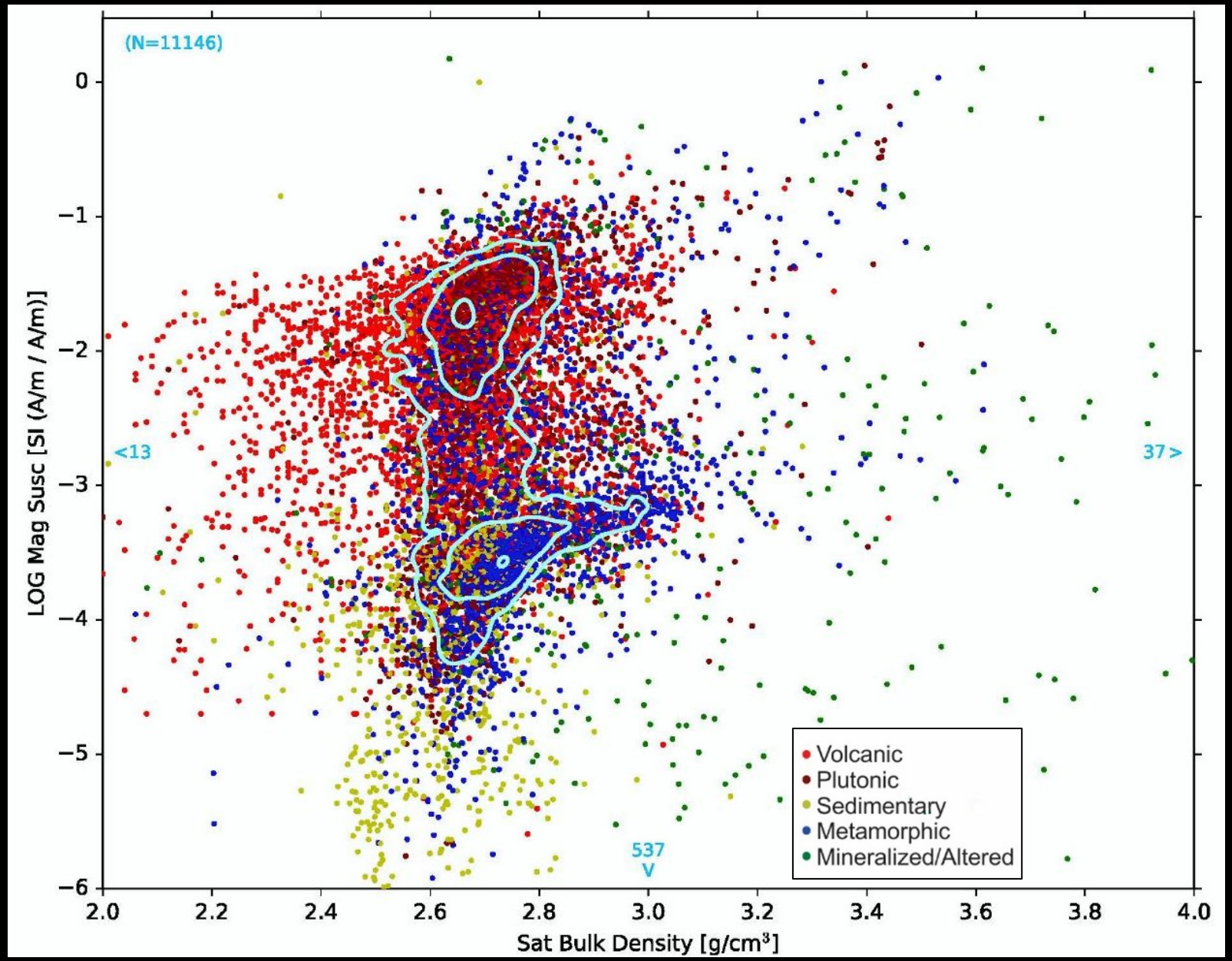
Physical properties measurements help make the link between geophysical and geological interpretation



Magnetic Survey over the Guichon Batholith, Highland Valley Copper

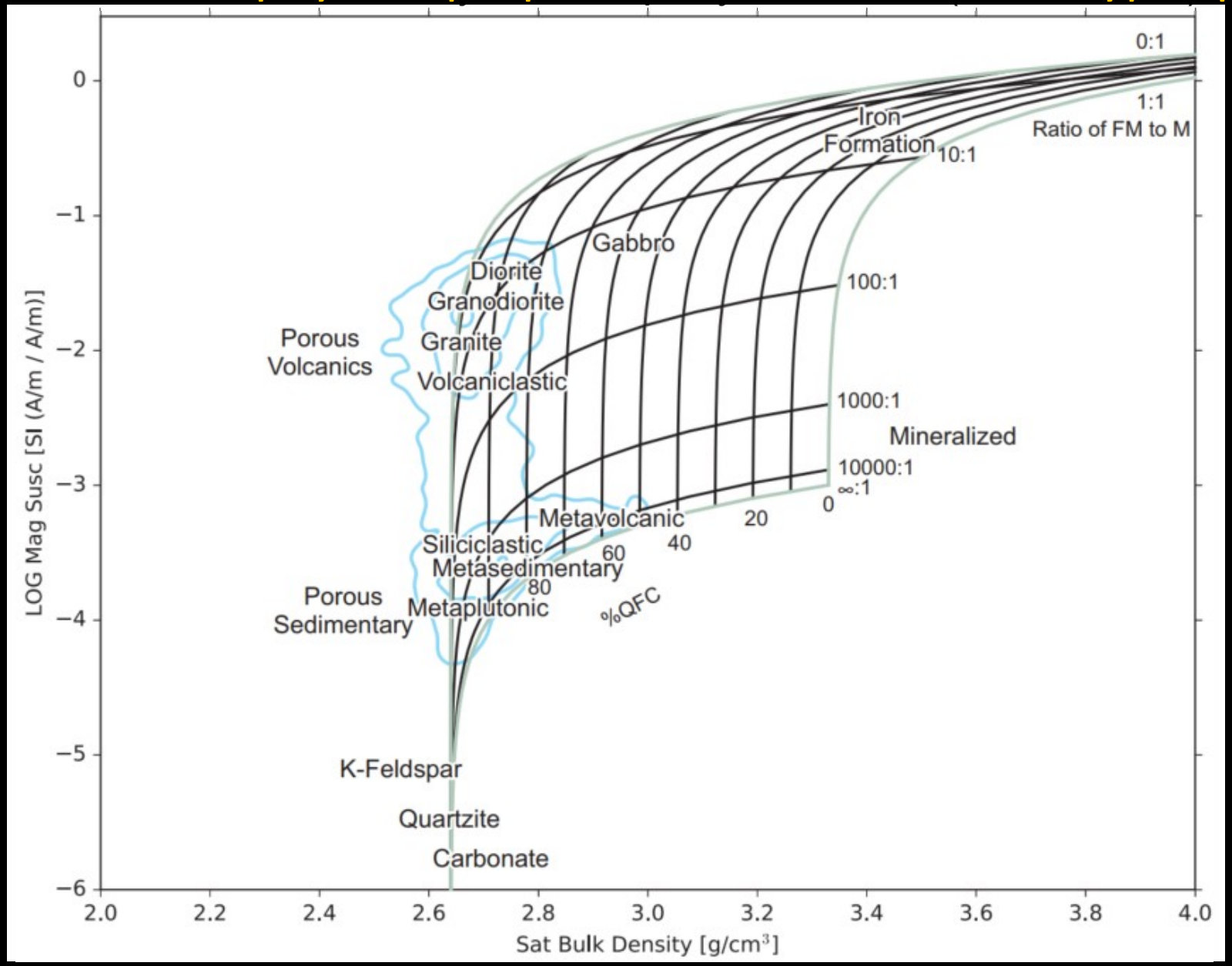
Samples from the Footprints Project, Guillaume Lesage & Kevin Byrne

Phase	Alteration
Bethsaida	None
Skeena	Trace
Bethlehem	Weak
Chataway	Moderate
Guichon	Strong
Border	



Canadian Rock Physical Property Database, GSC Open File 8460, Enkin 2018

Forward Problem: What physical properties do different rock-types present?

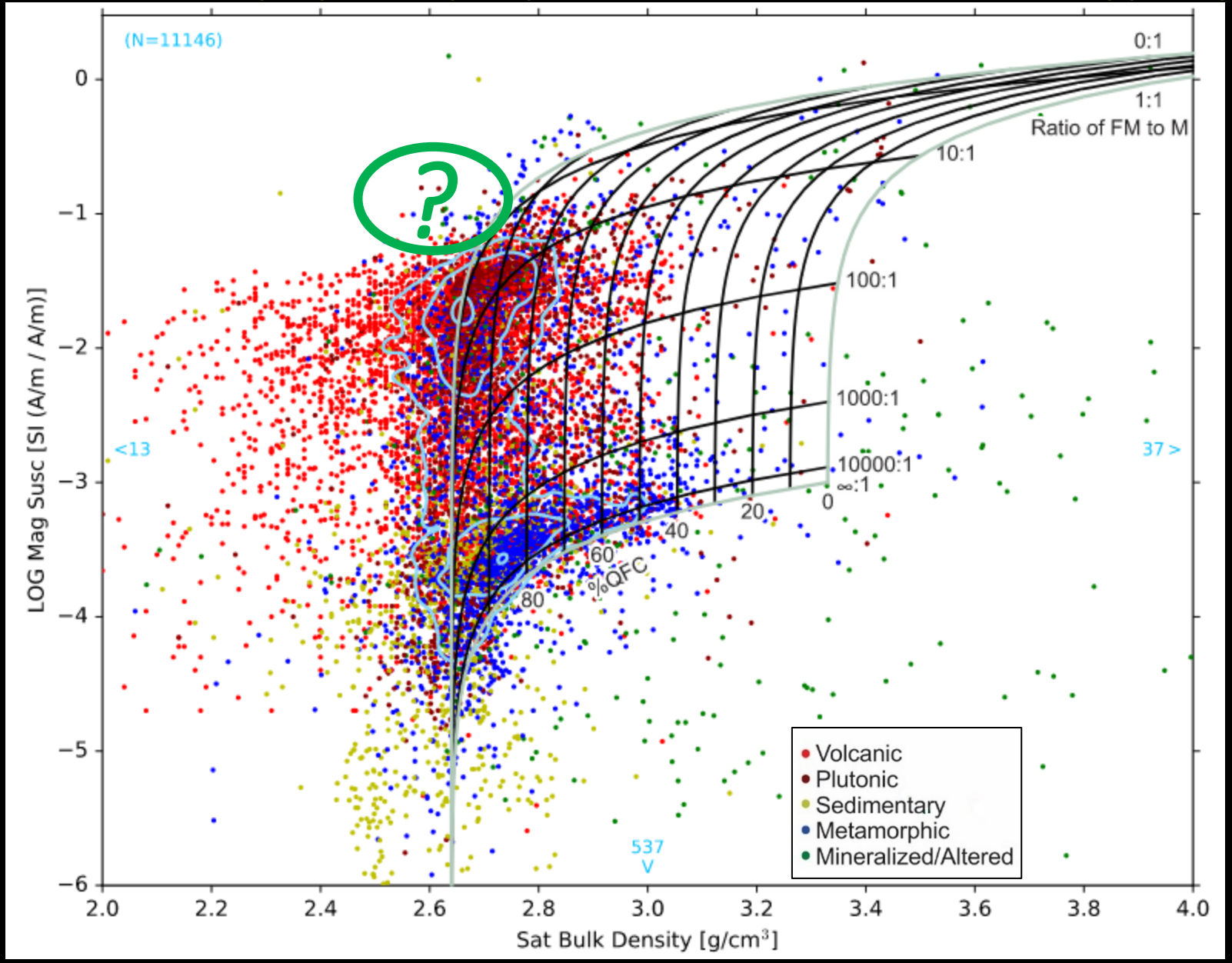


Enkin, Hamilton, and Morris, 2020

Inverse Problem: How to interpret rock-types from physical properties?

Forward Problem: What physical properties do different rock-types present?

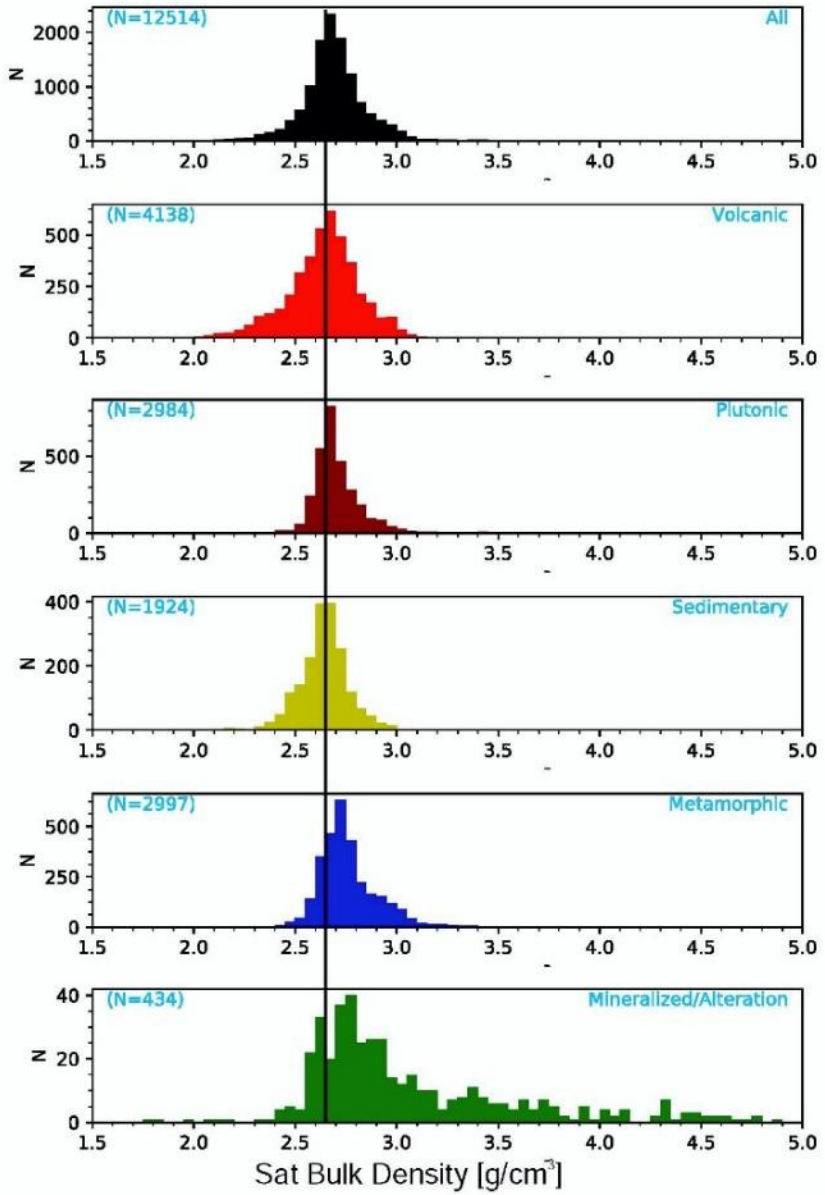
Know the properties of "ordinary" rocks to aid recognition of important exotic rocks



Enkin, Hamilton, and Morris, 2020

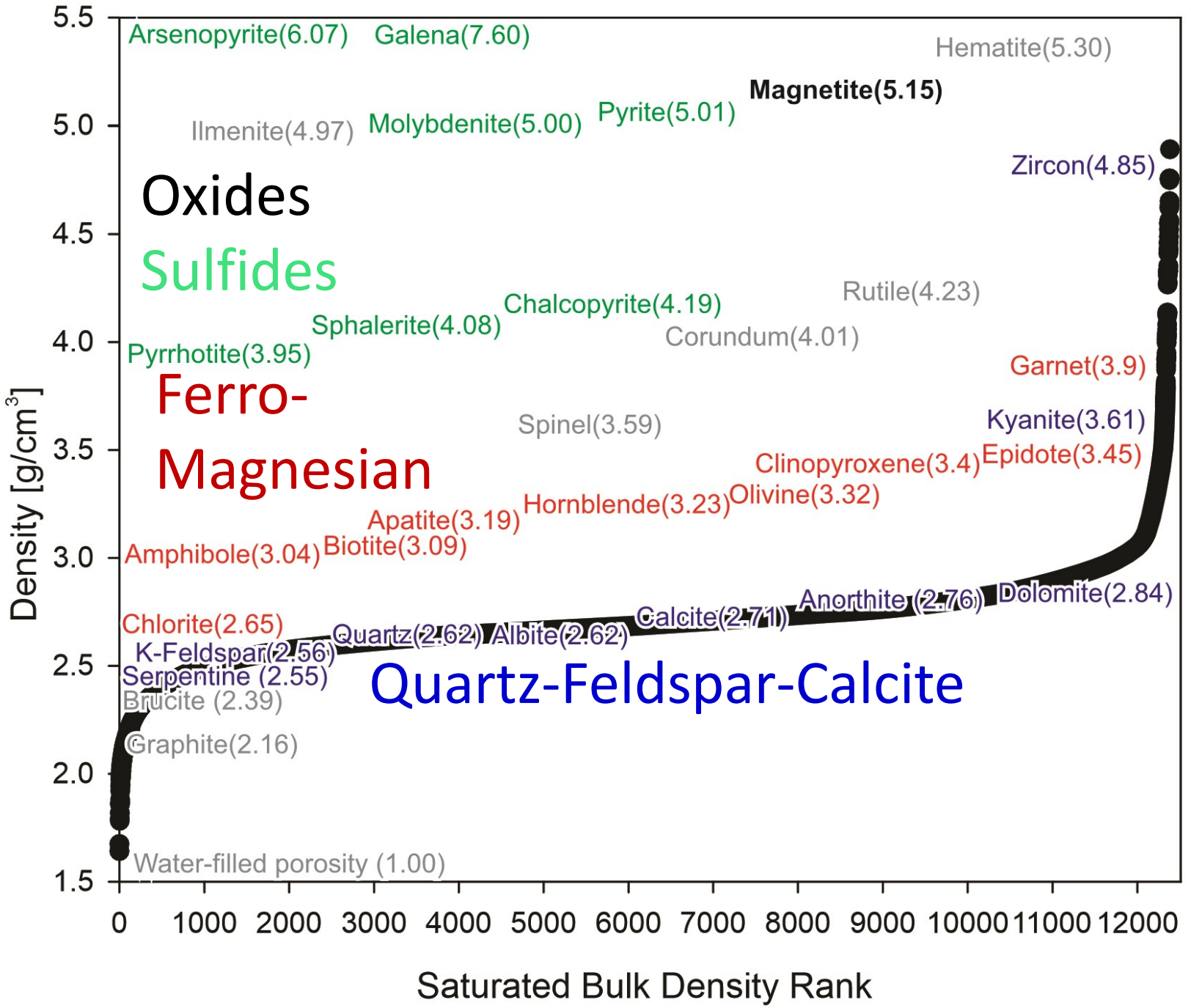
Inverse Problem: How to interpret rock-types from physical properties?

Figure 4



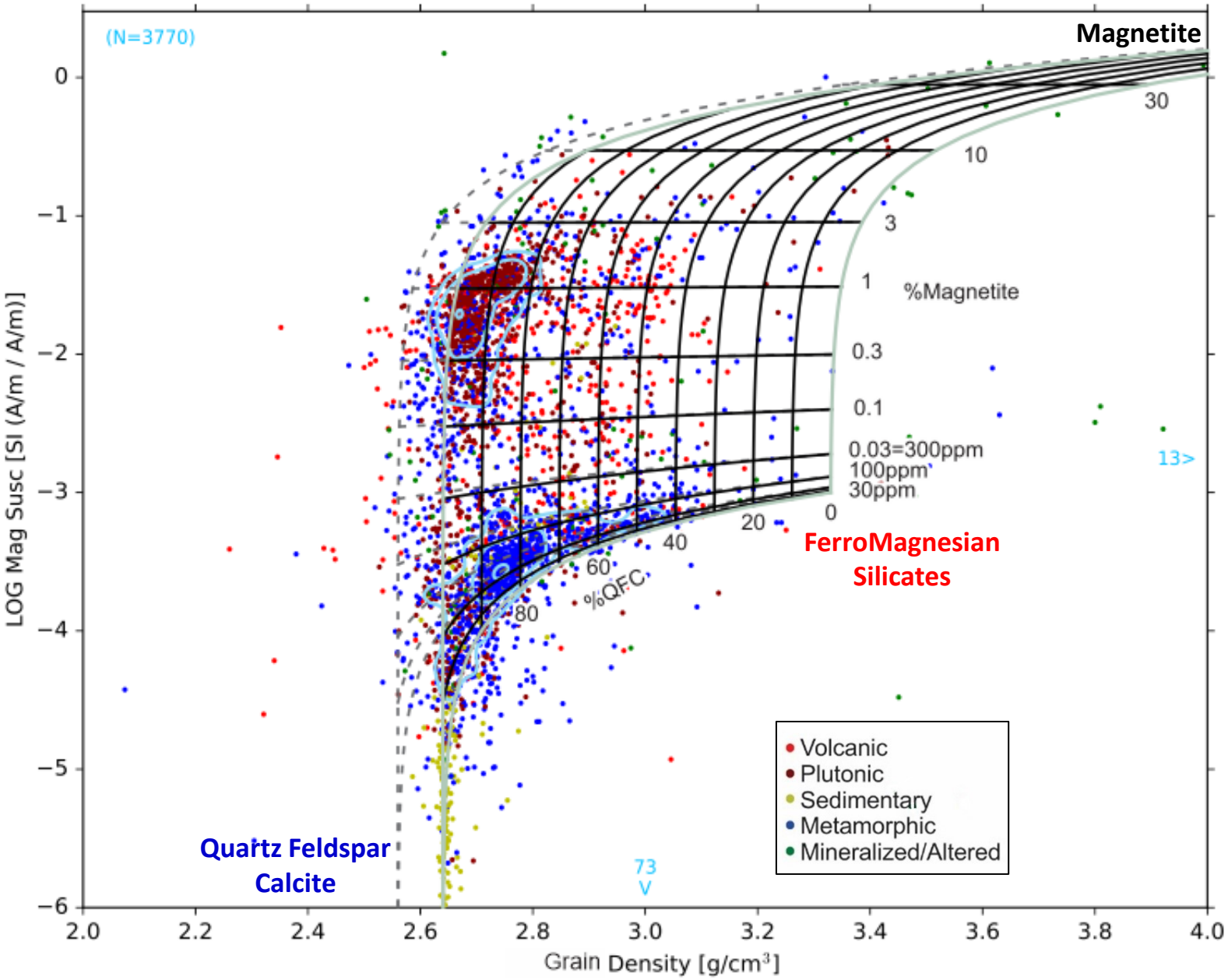
Density

Enkin, 2018


Arsenopyrite(6.07)
Galena(7.60)
Hematite(5.30)
Magnetite(5.15)
Ilmenite(4.97)
Molybdenite(5.00)
Pyrite(5.01)
Zircon(4.85)
Oxides
Sulfides
Rutile(4.23)
Chalcopyrite(4.19)
Sphalerite(4.08)
Corundum(4.01)
Pyrrhotite(3.95)
Garnet(3.9)
Ferro-
Magnesian
Spinel(3.59)
Kyanite(3.61)
Epidote(3.45)
Clinopyroxene(3.4)
Olivine(3.32)
Hornblende(3.23)
Apatite(3.19)
Amphibole(3.04)
Biotite(3.09)
Anorthite (2.76)
Dolomite(2.84)
Chlorite(2.65)
Calcite(2.71)
Quartz(2.62)
Albite(2.62)
K-Feldspar(2.56)
Serpentine (2.55)
Quartz-Feldspar-Calcite
Brucite (2.39)
Graphite(2.16)
Water-filled porosity (1.00)
Density [g/cm3]
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
Saturated Bulk Density Rank

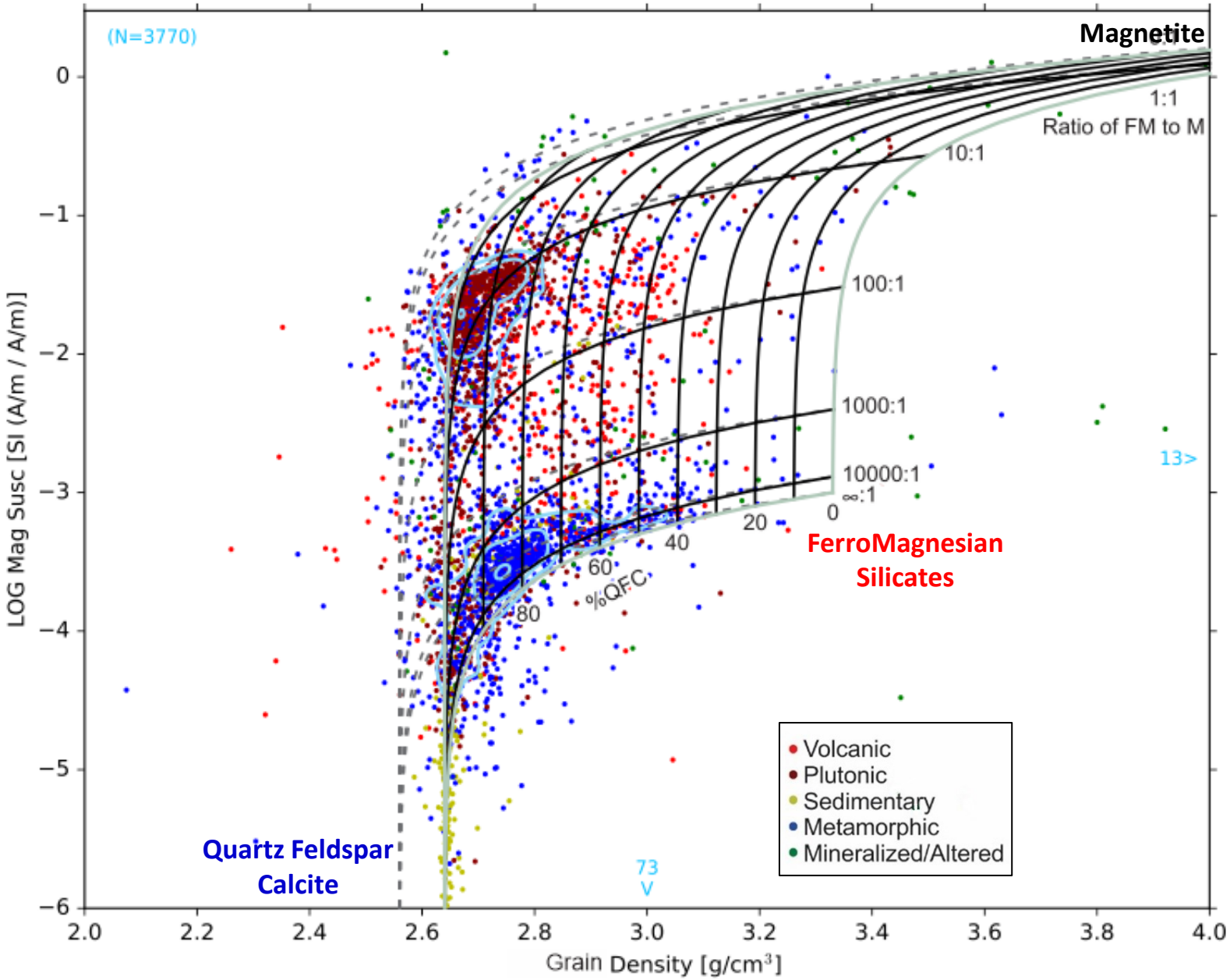
Enkin, 2018

Three Principal Components

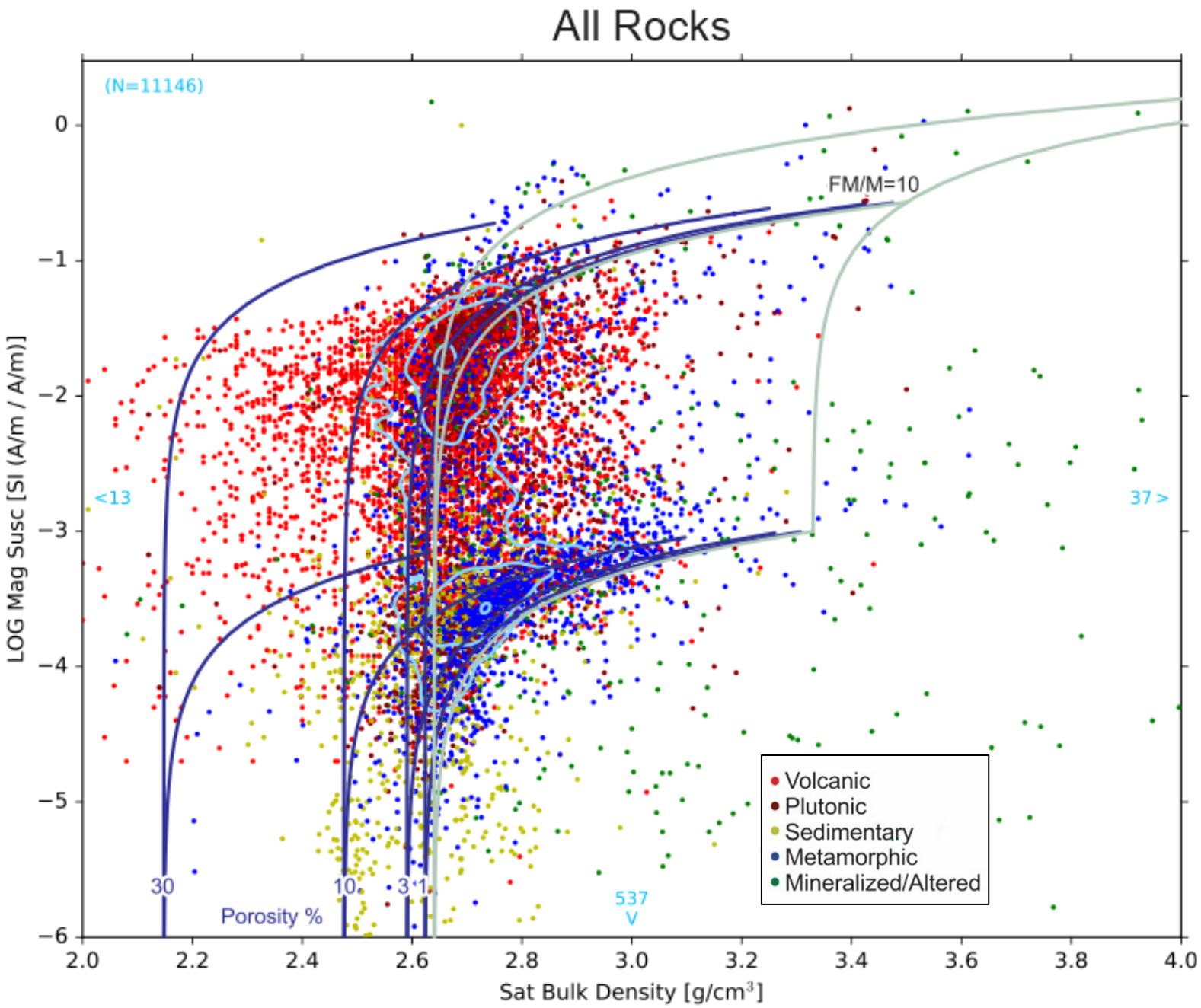


Enkin, Hamilton, and Morris, 2020

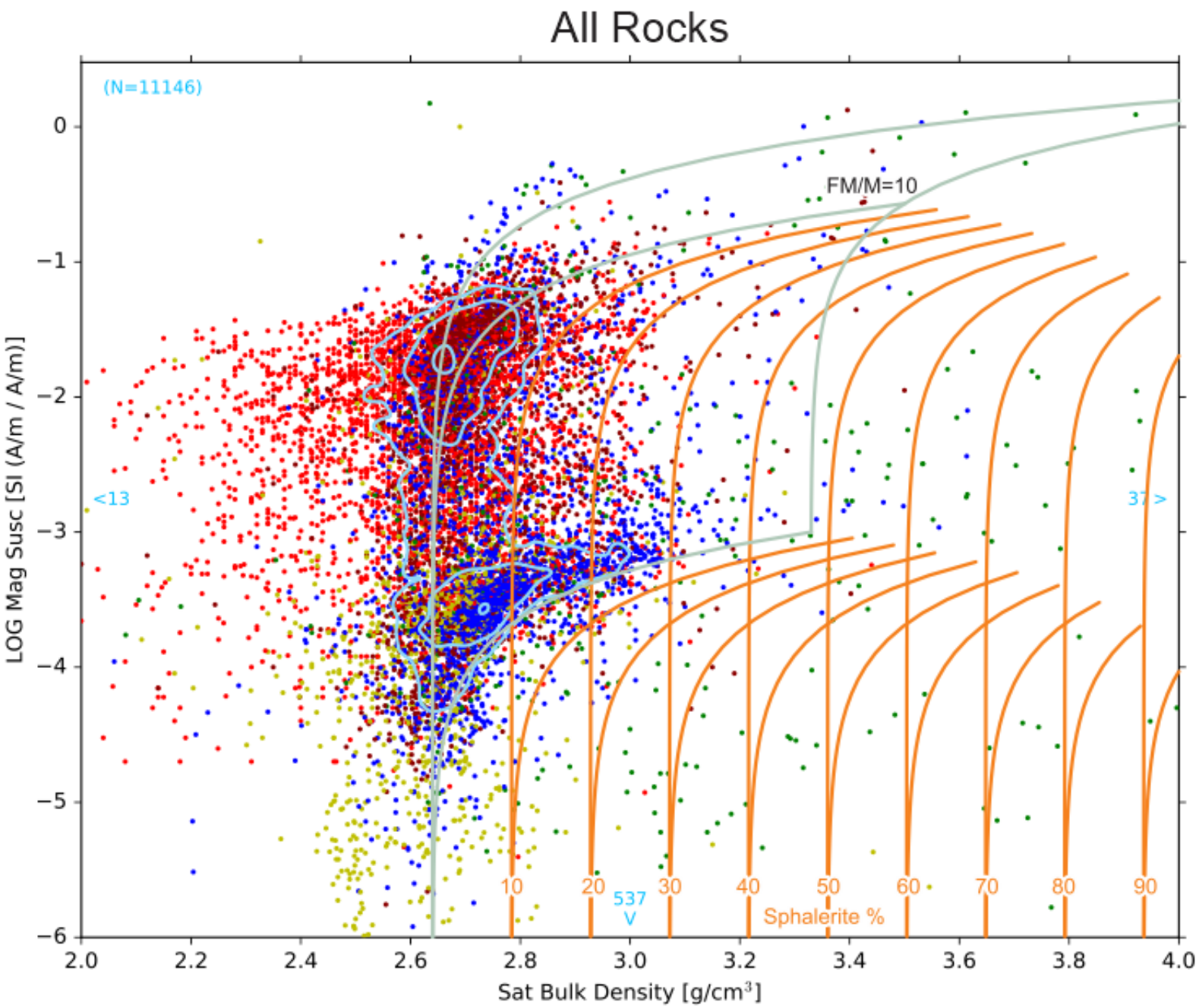
Three Principal Components



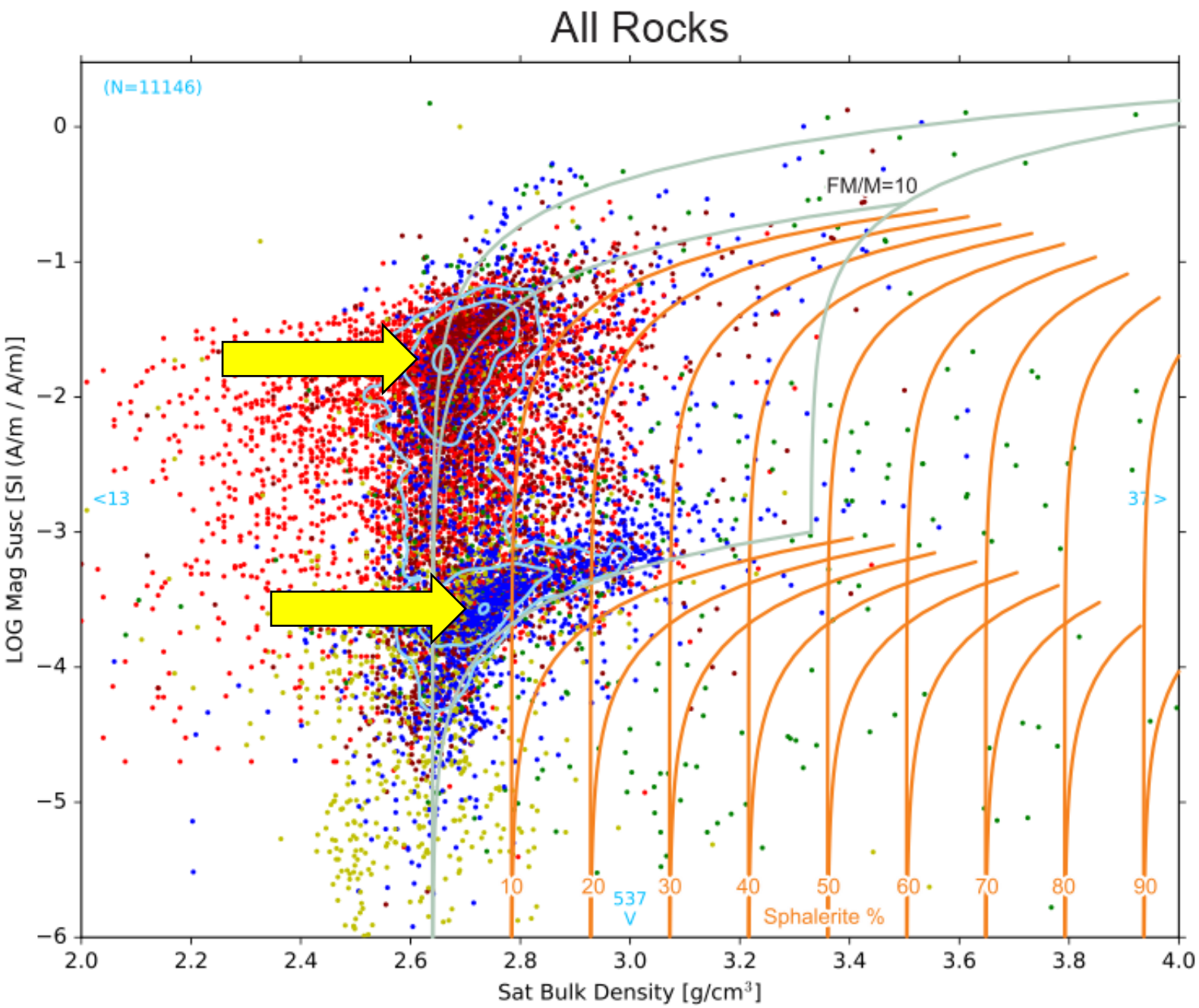
Enkin, Hamilton, and Morris, 2020



Enkin, Hamilton, and Morris, 2020



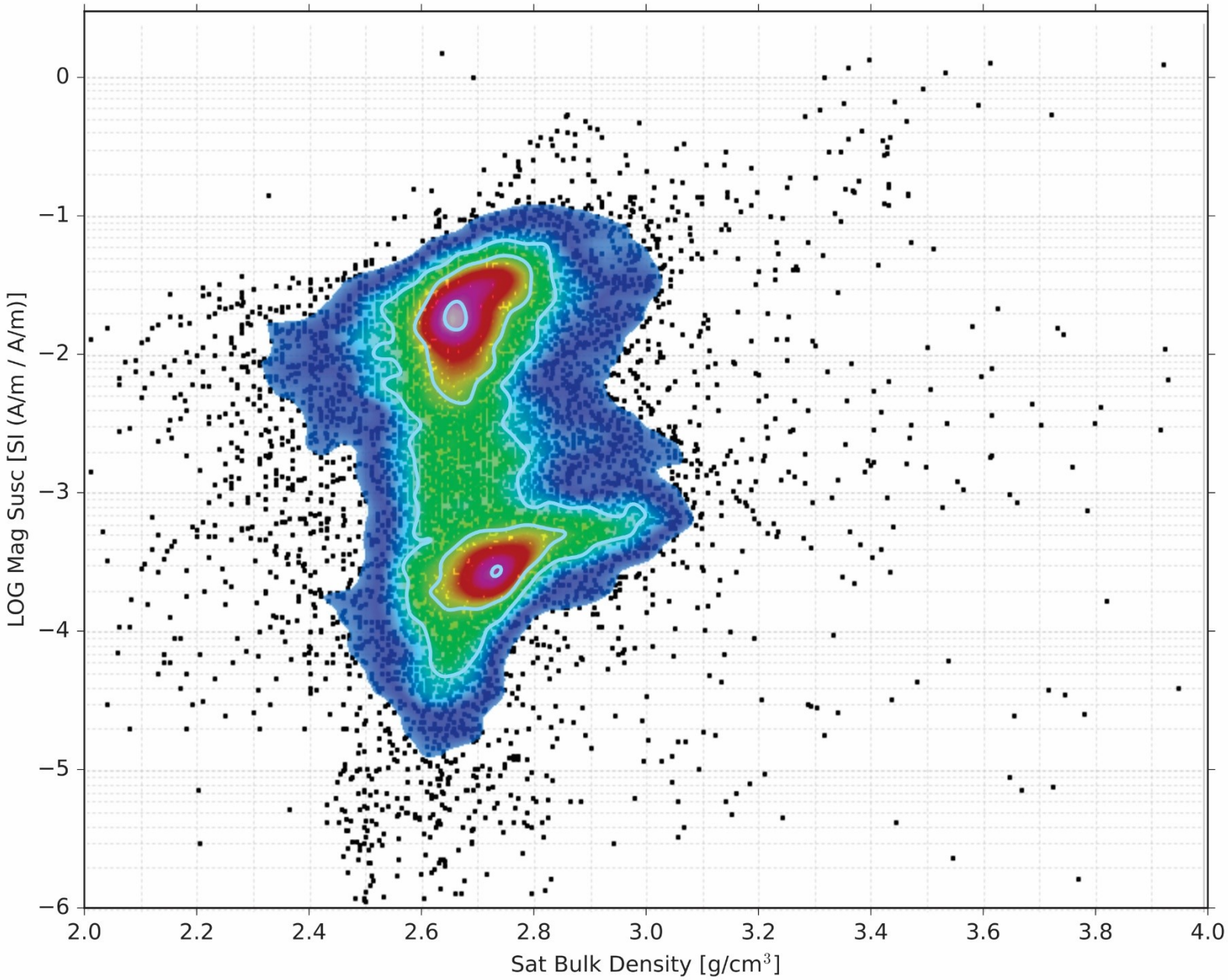
Enkin, Hamilton, and Morris, 2020



Enkin, Hamilton, and Morris, 2020

Figure A : Enkin, 2018 - Geological Survey of Canada Rock Physical Property Database

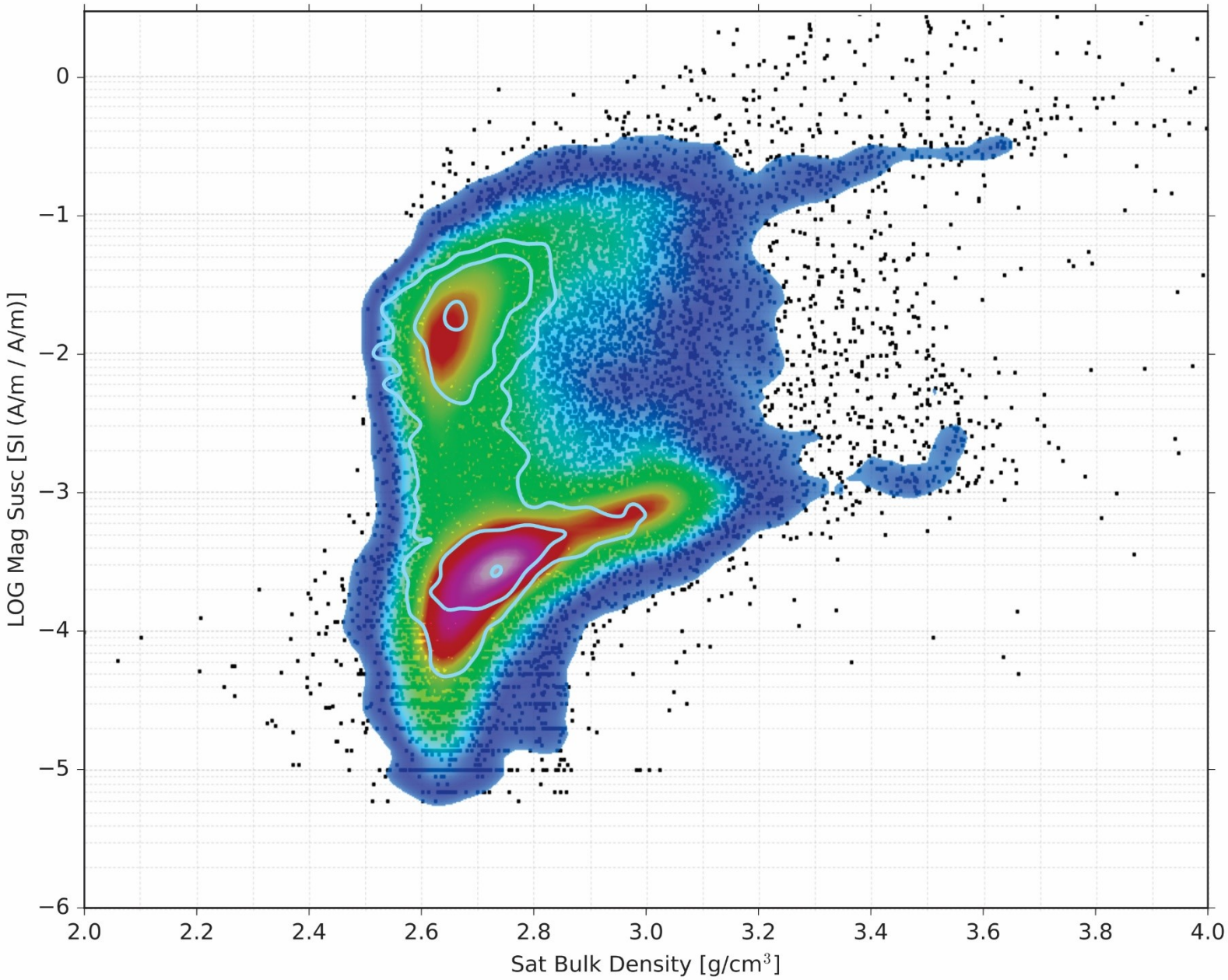
Canada



Enkin, 2018

Figure A : Oldeive Olesen et al., 2017 - Norway Petrofysisk database PETBASE 3.0

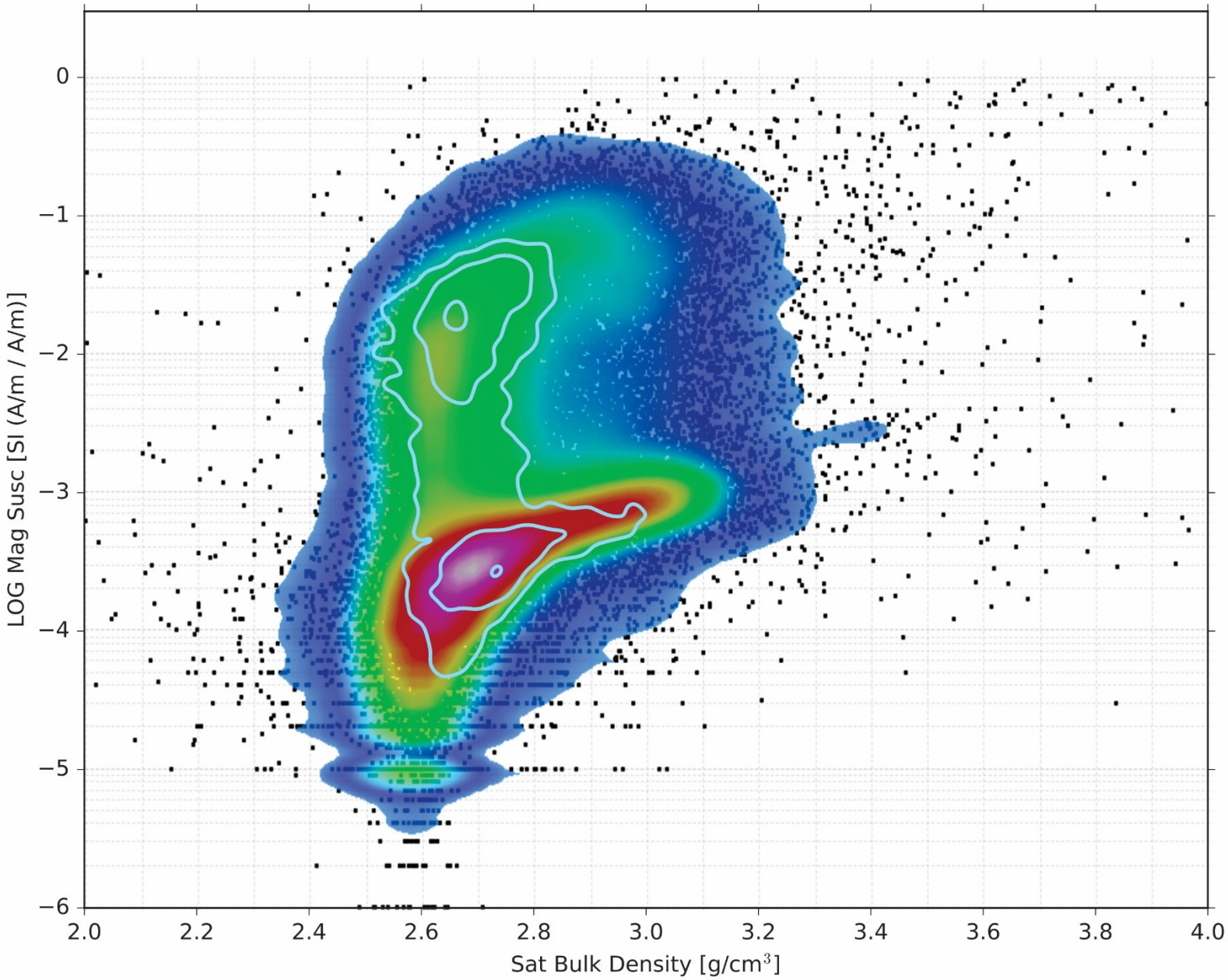
Norway



Enkin, 2018

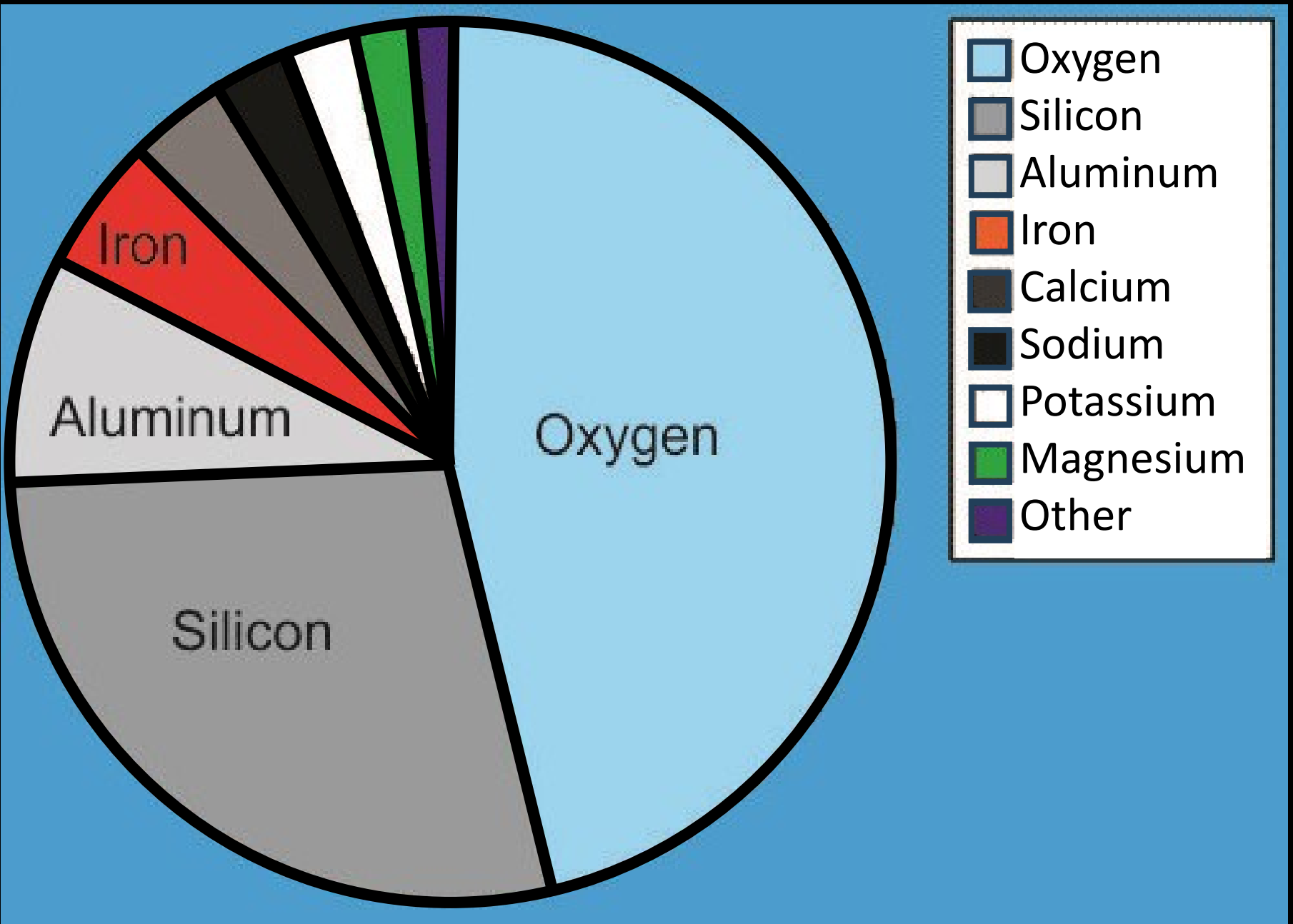
Figure A : Geological Survey of Finland, 2012 - Valtakunnallinen Petrofysiikka

Finland



Enkin, 2018

Crustal rocks are half oxygen, and 1 - 15% iron

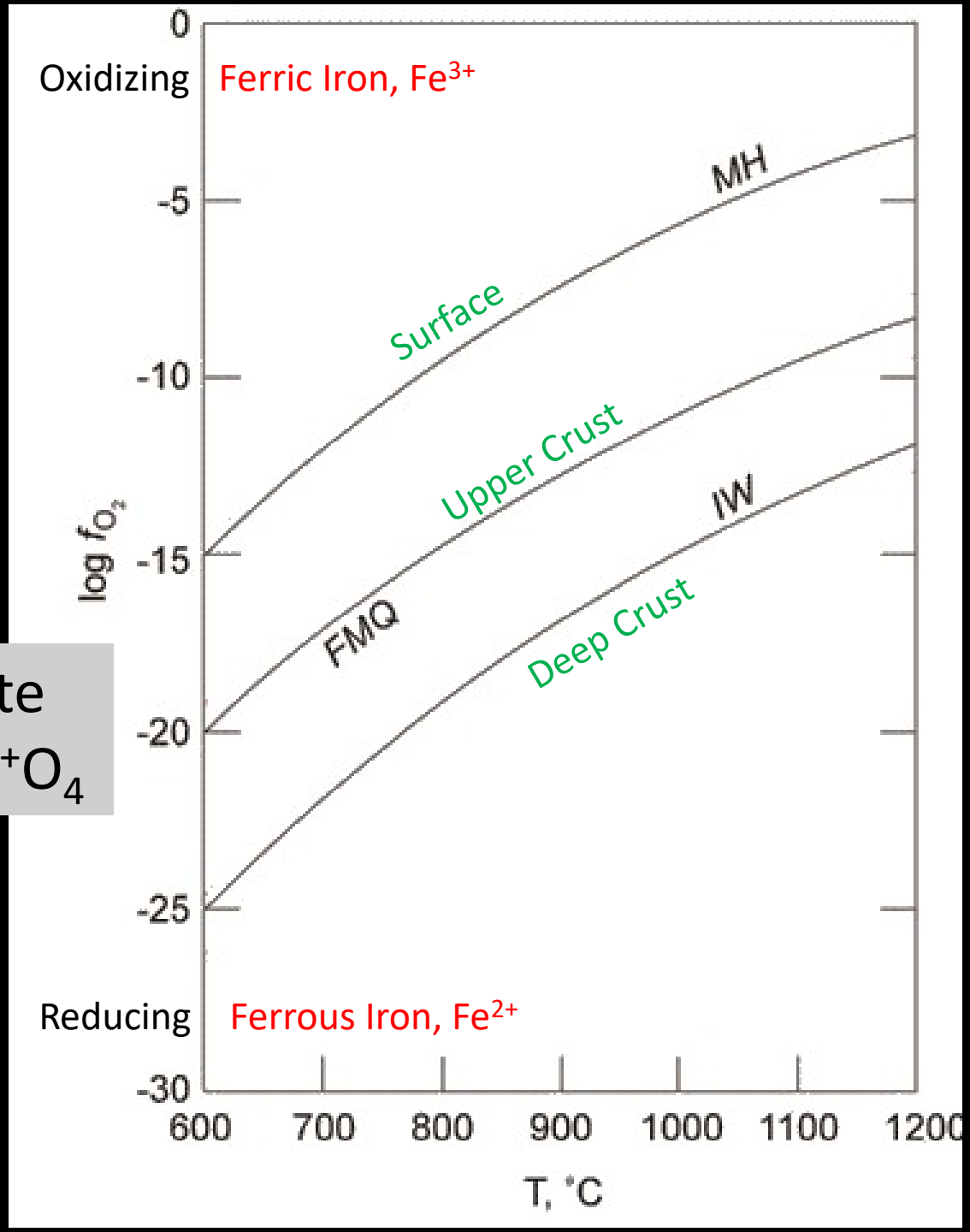


We are standing on a framework of SiO_4^{4-} tetrahedra, held together by cations

Oxygen Fugacity Buffers

Fayalite – Quartz – Magnetite

$Fe_2^{2+}SiO_4$ – SiO_2 – $Fe^{2+}Fe_2^{3+}O_4$

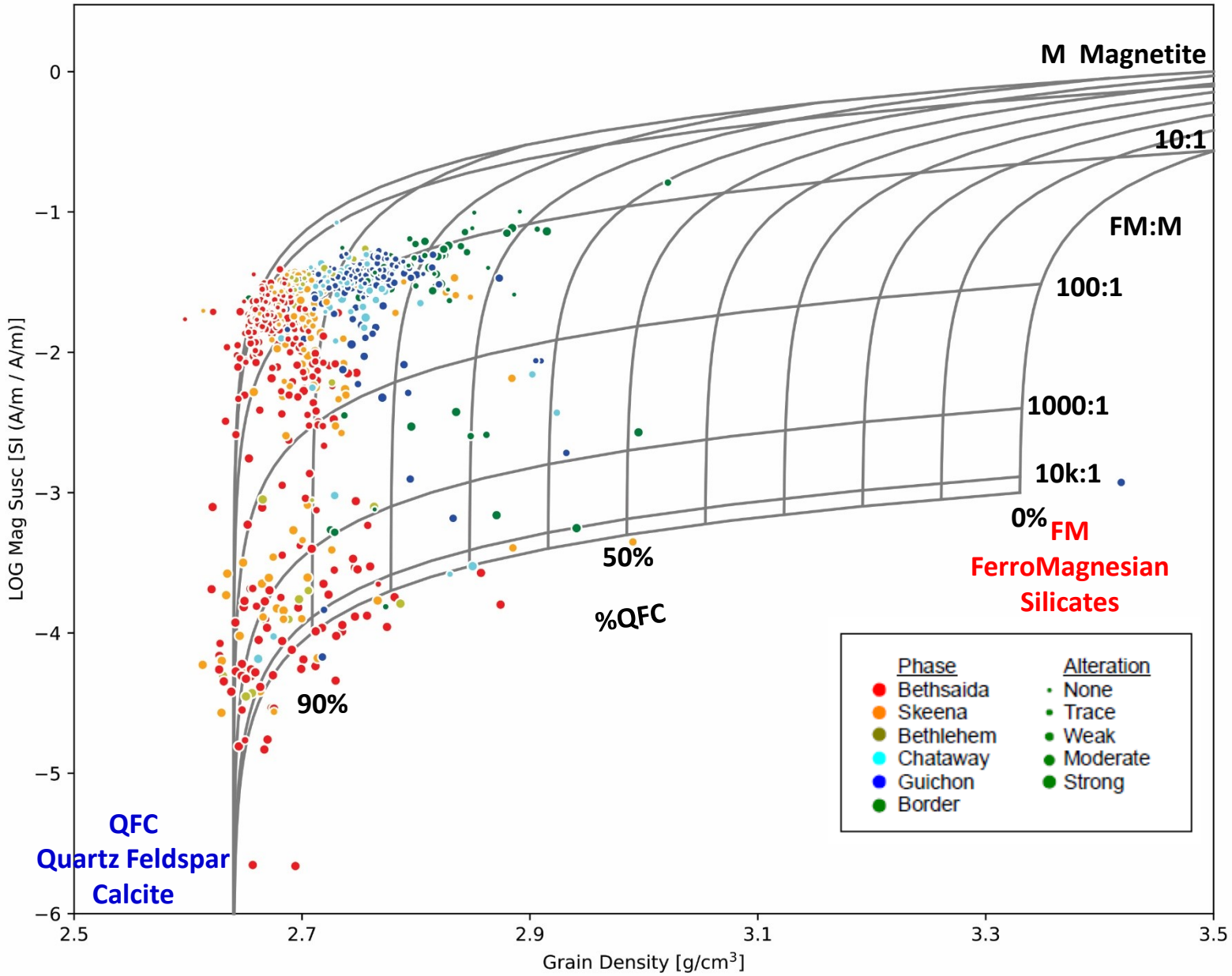


Hematite / Magnetite

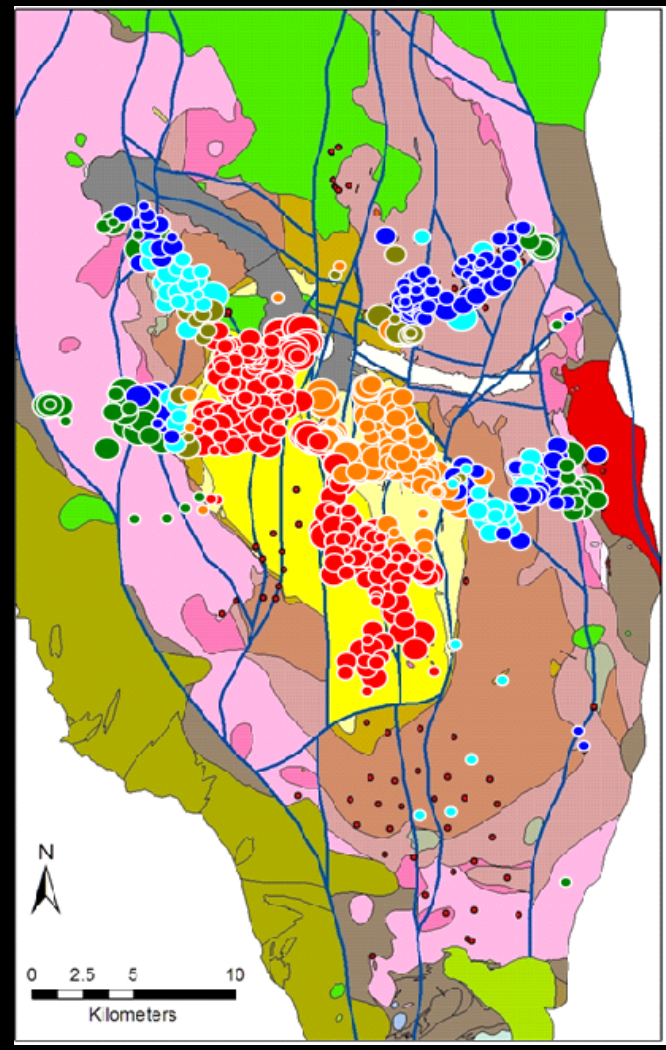
Quartz+Magnetite / Fayalite

Wustite / Ferrous Iron

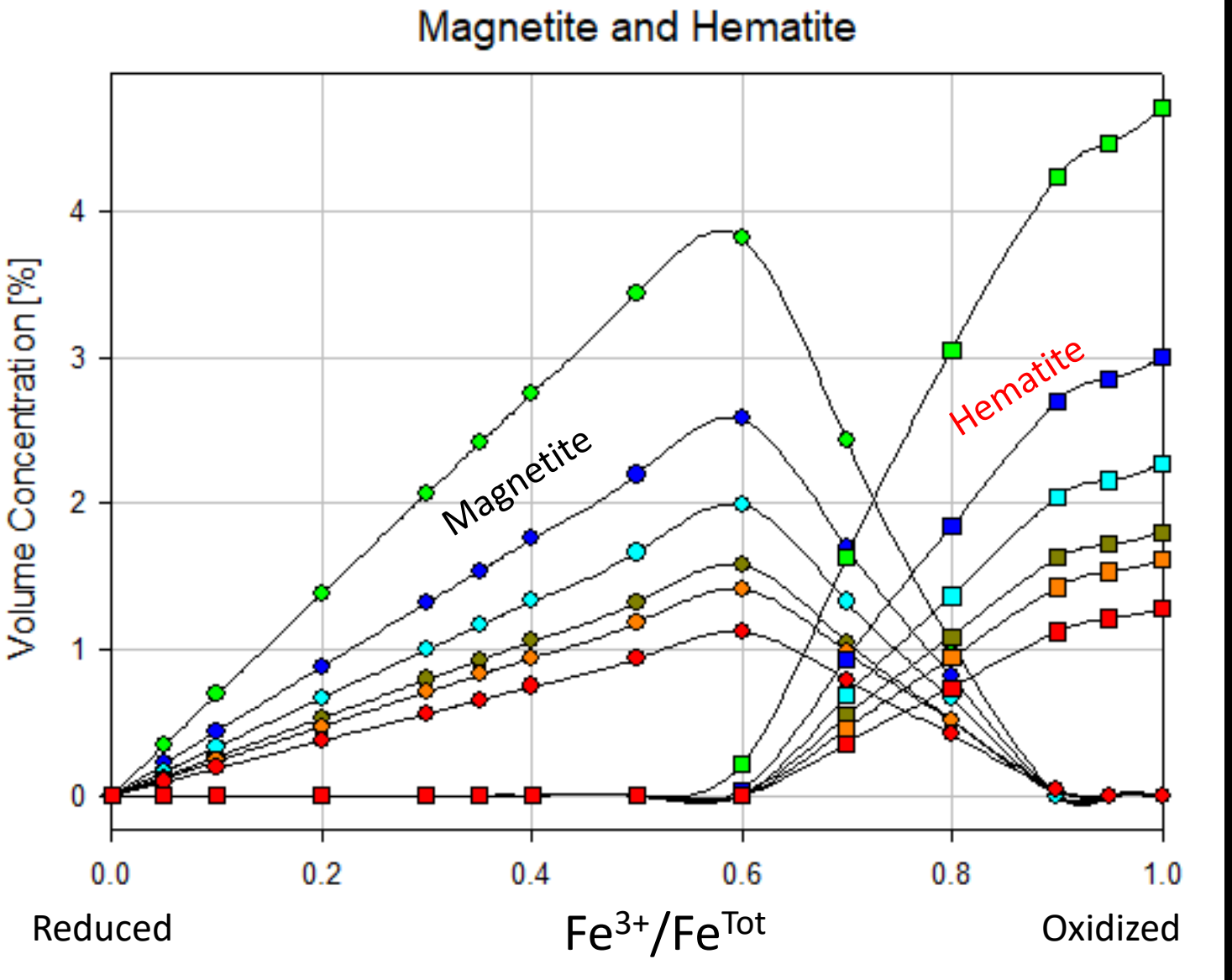
Highland Valley Copper porphyry deposit, near Kamloops, BC



NSERC-CMIC
Footprints Project



Iron Oxidation State controls Magnetite and Hematite Concentration



CIPW Norm (Cross, Iddings, Pirsson, and Washington, 1902), **estimates igneous mineralogy from geochemistry.**

Fe^{3+} incorporated into magnetite up to 60% Fe^{3+}/Fe_{Tot}, then into hematite

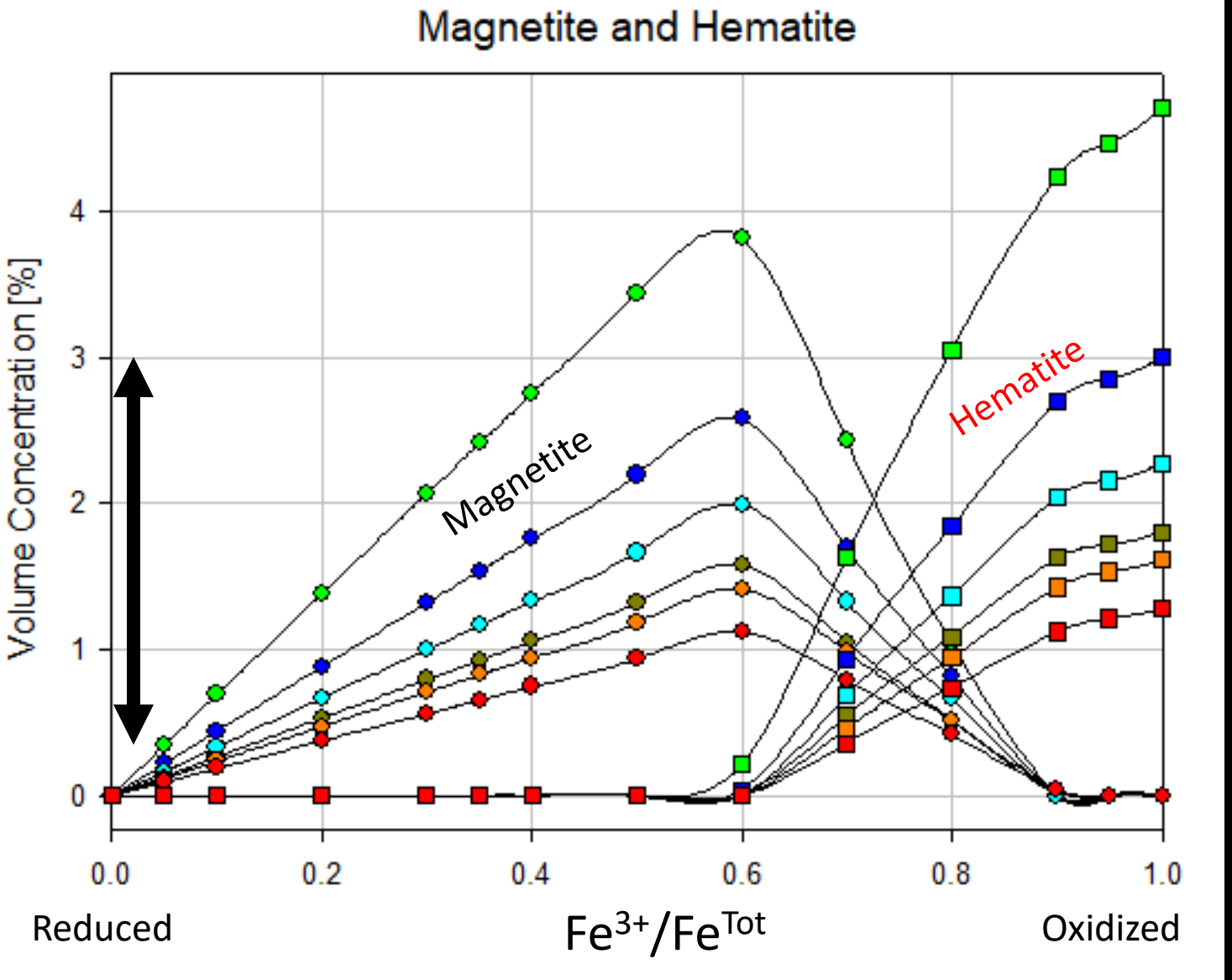
Guichon Batholith

Phase

- Bethsaida
- Skeena
- Bethlehem
- Chataway
- Guichon
- Border

Felsic ↑ Mafic

Iron Oxidation State controls Magnetite and Hematite Concentration



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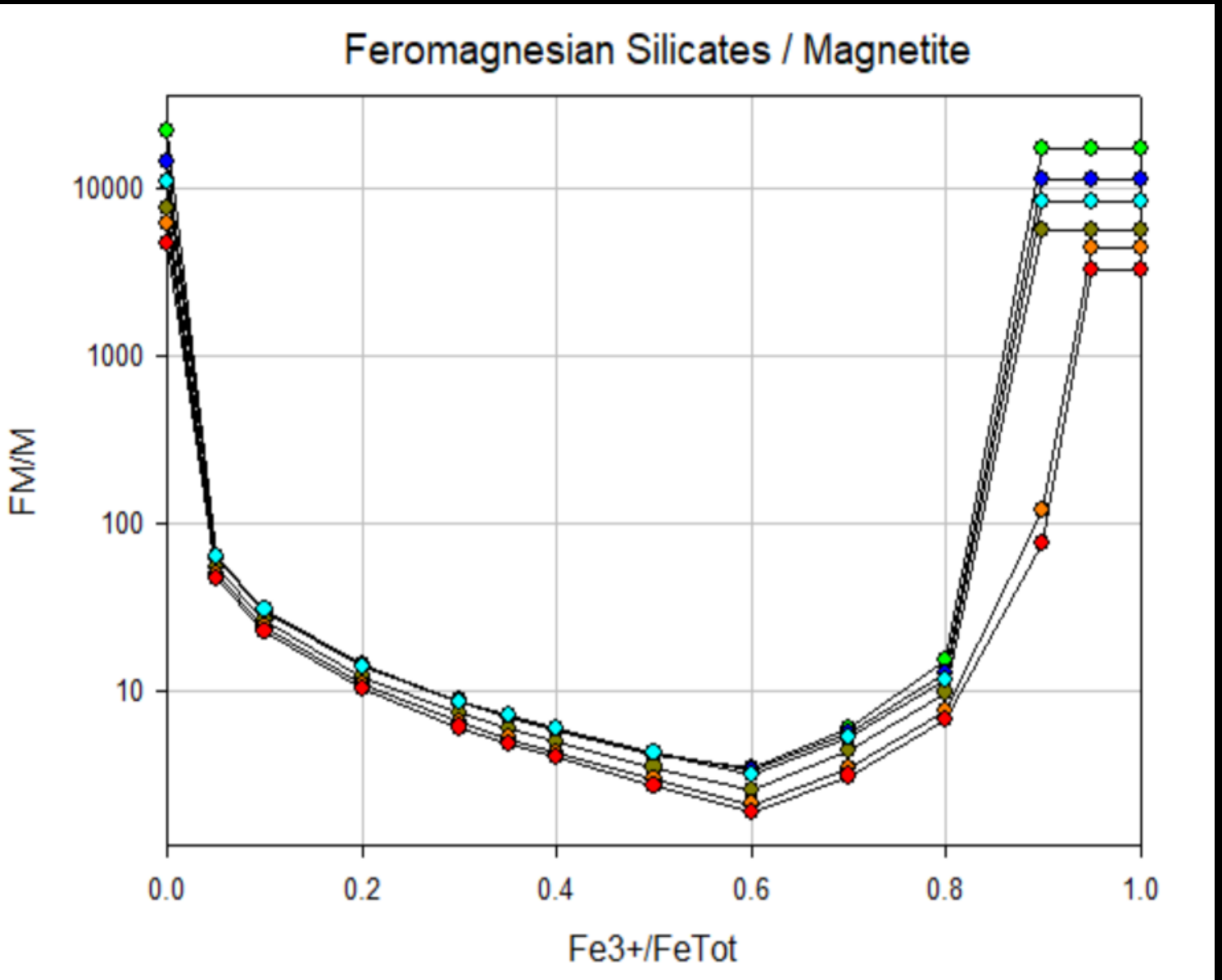

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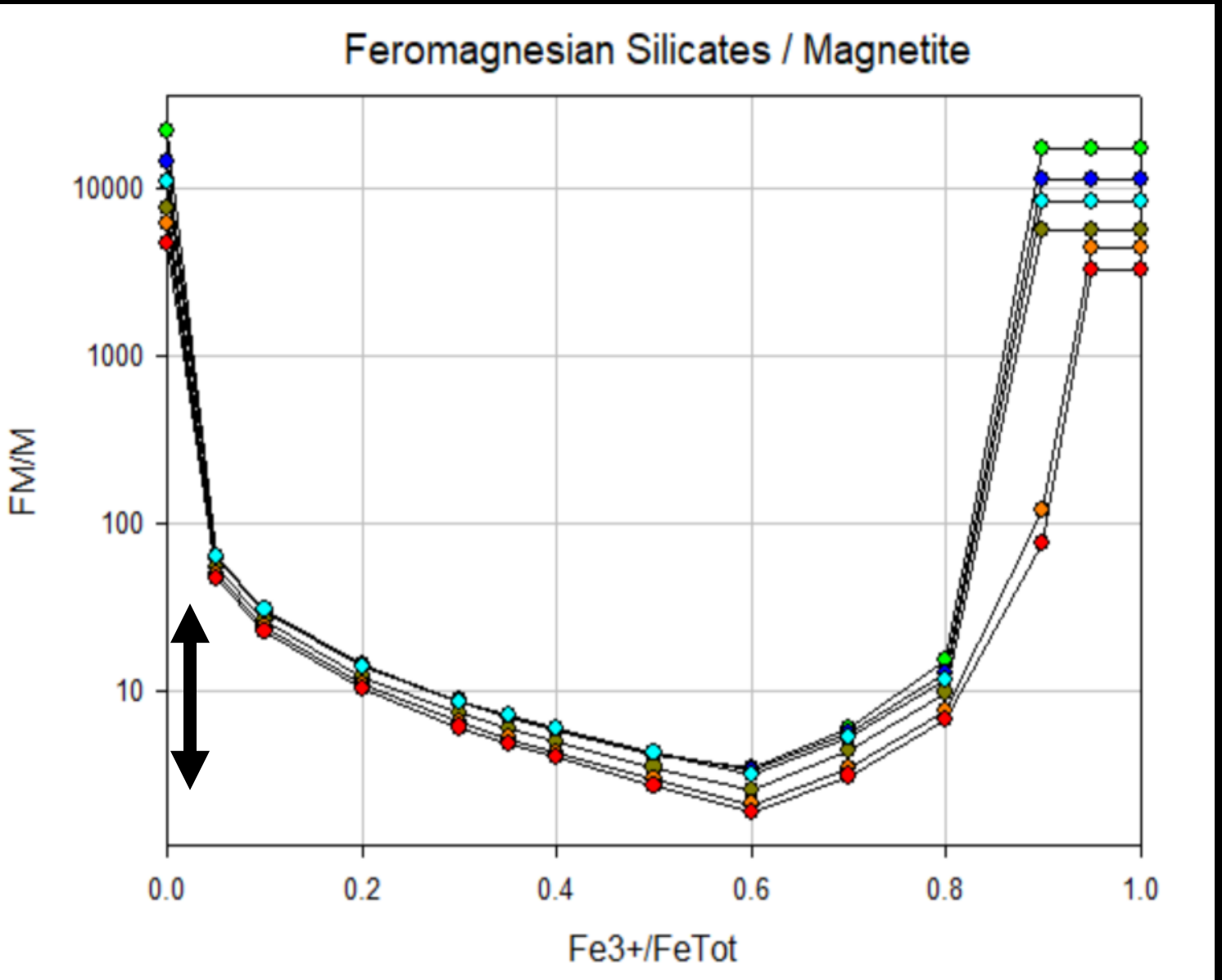

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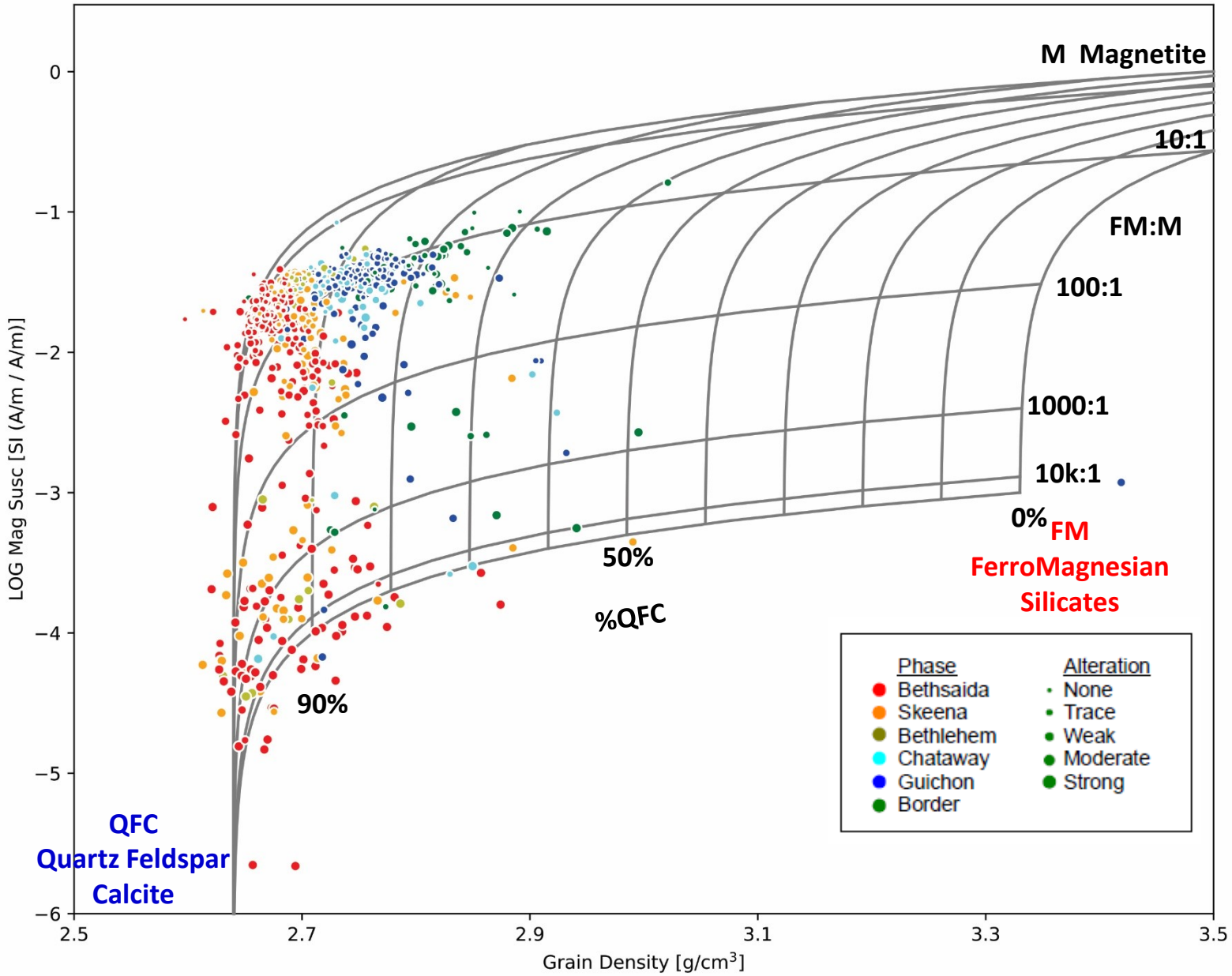
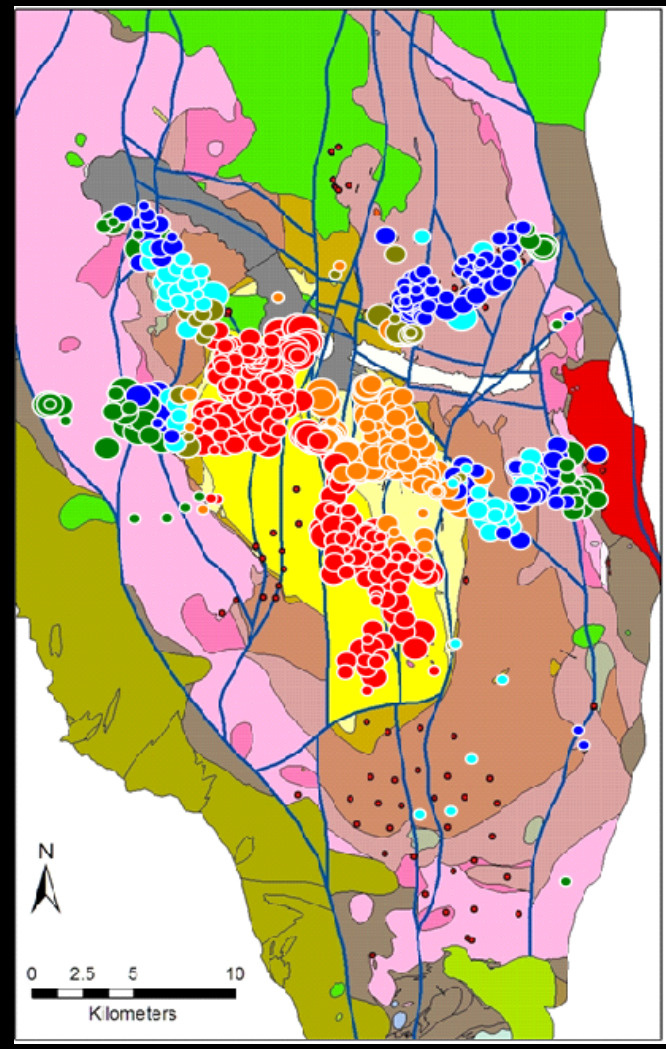
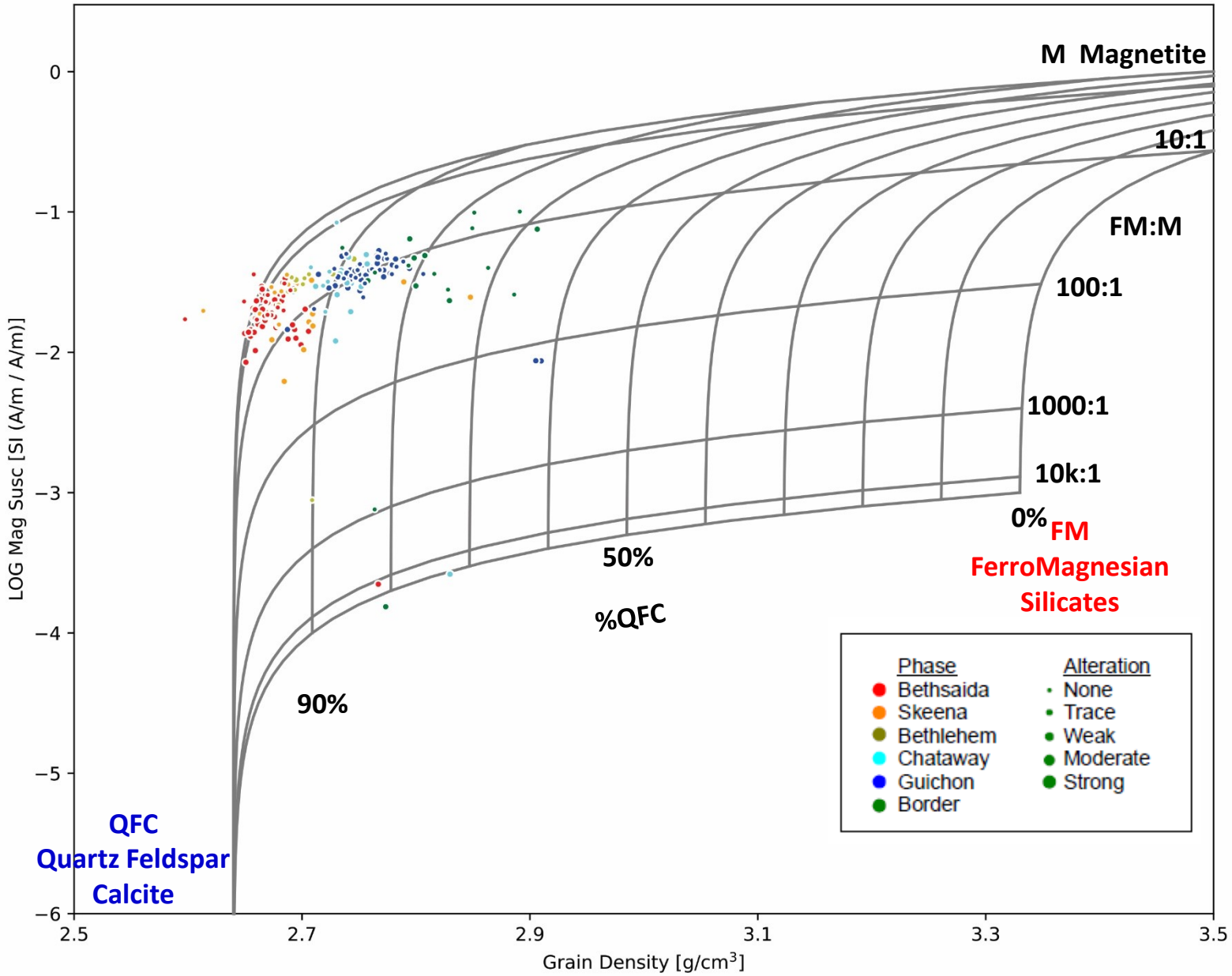
Felsic ↑ Mafic

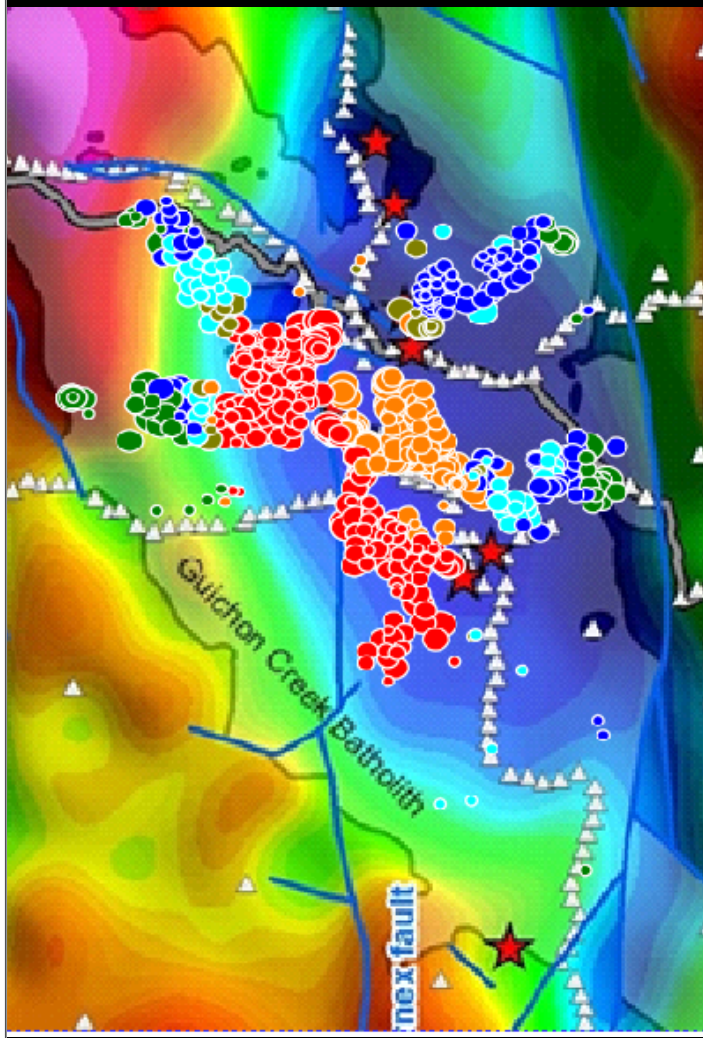
Highland Valley Copper porphyry deposit, near Kamloops, BC





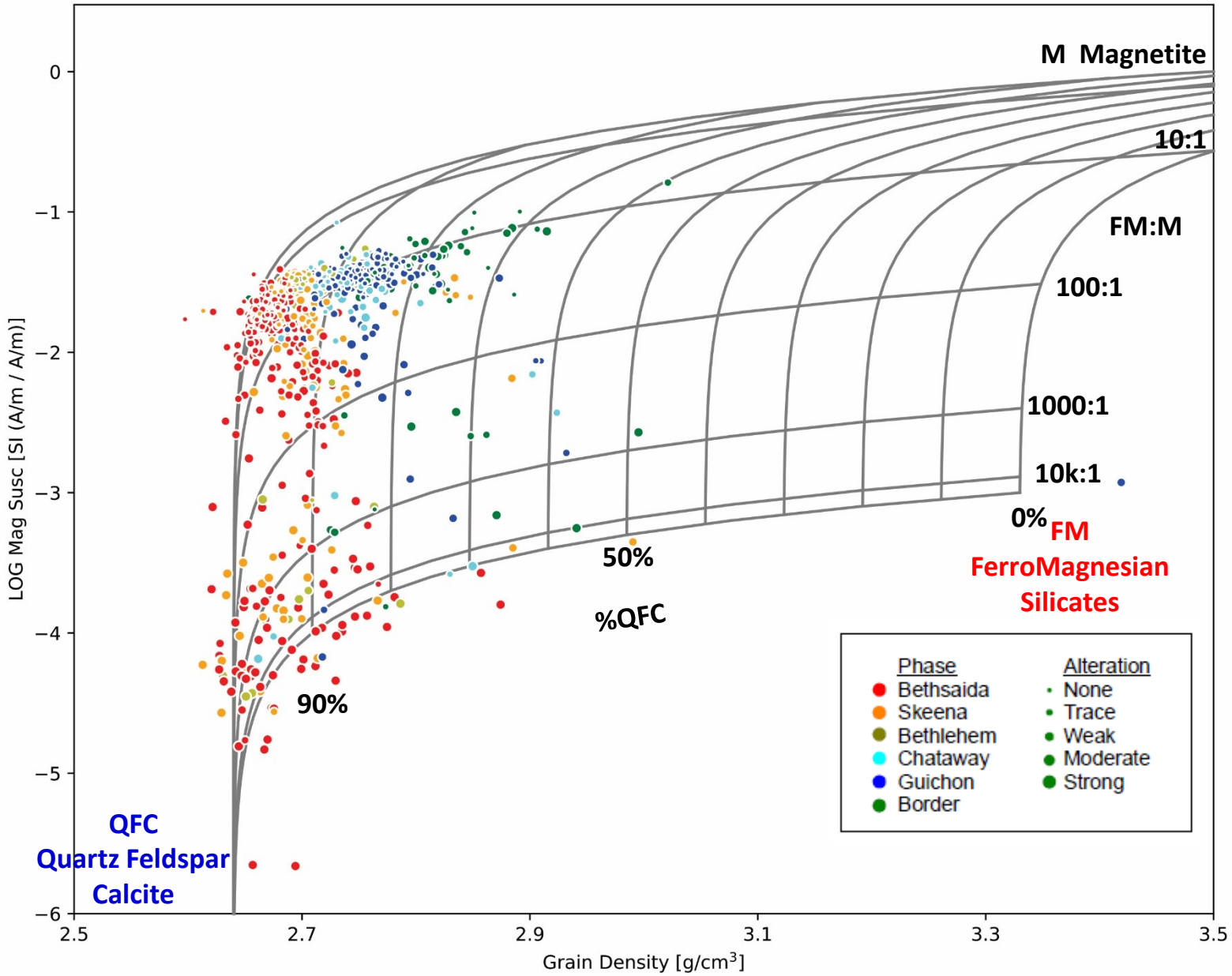
Highland Valley Copper porphyry deposit, near Kamloops, BC

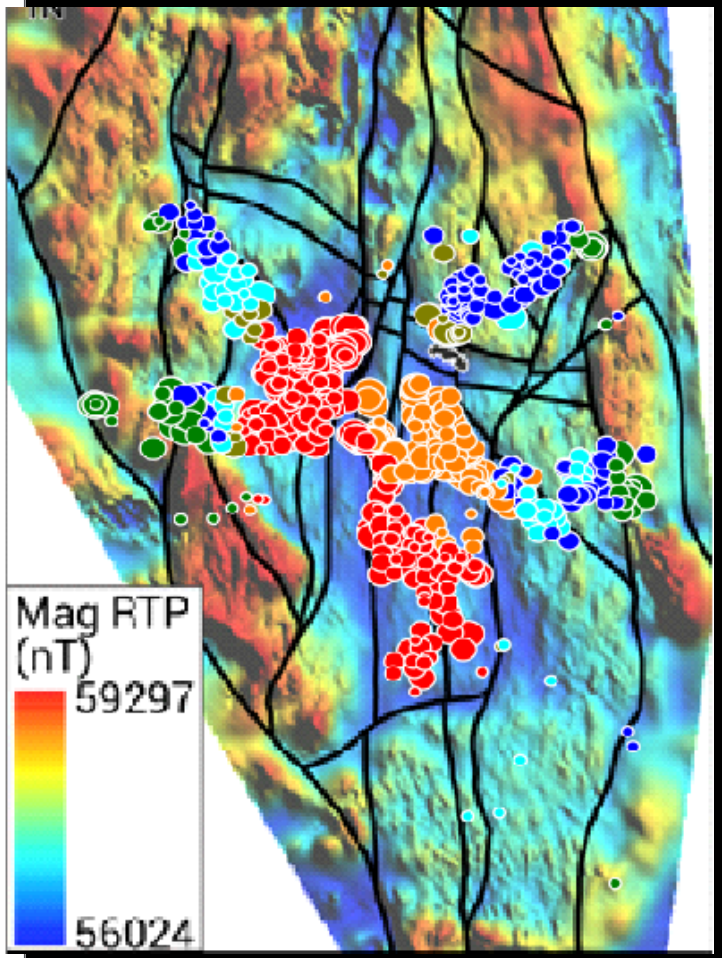




Gravity Survey

Highland Valley Copper porphyry deposit, near Kamloops, BC





Magnetic Survey

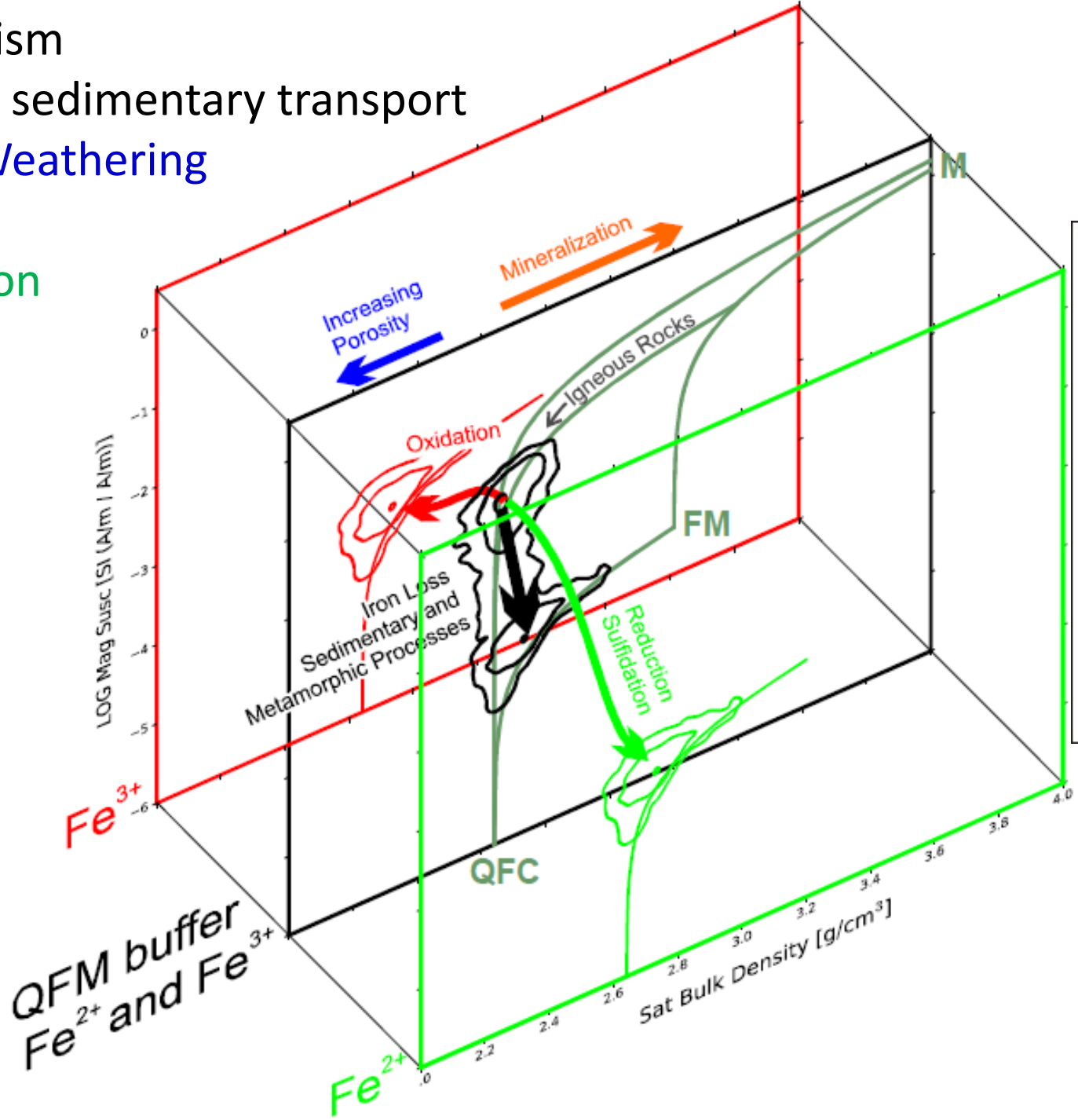
Metamorphism

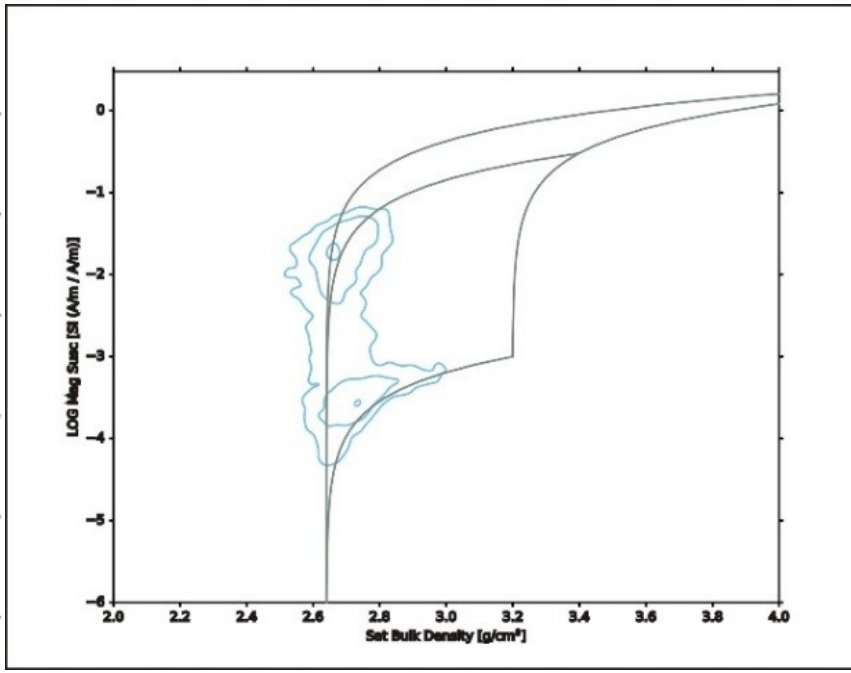
Weathering, sedimentary transport

Hydration/Weathering

Oxidation

Mineralization





Enkin, Hamilton, and Morris, 2020

Geochemistry, Geophysics, Geosystems®

RESEARCH ARTICLE
10.1029/2021GC009989

Key Points:

- The density and magnetic susceptibility of ultramafic rocks change predictably during serpentinization (hydration) and carbonation
- Density is most effective at predicting the extent of alteration, whereas magnetic susceptibility may be subject to significant variability
- Physical properties can predict the mineralogy, alteration extent, and potential of ultramafic rocks for carbon sequestration

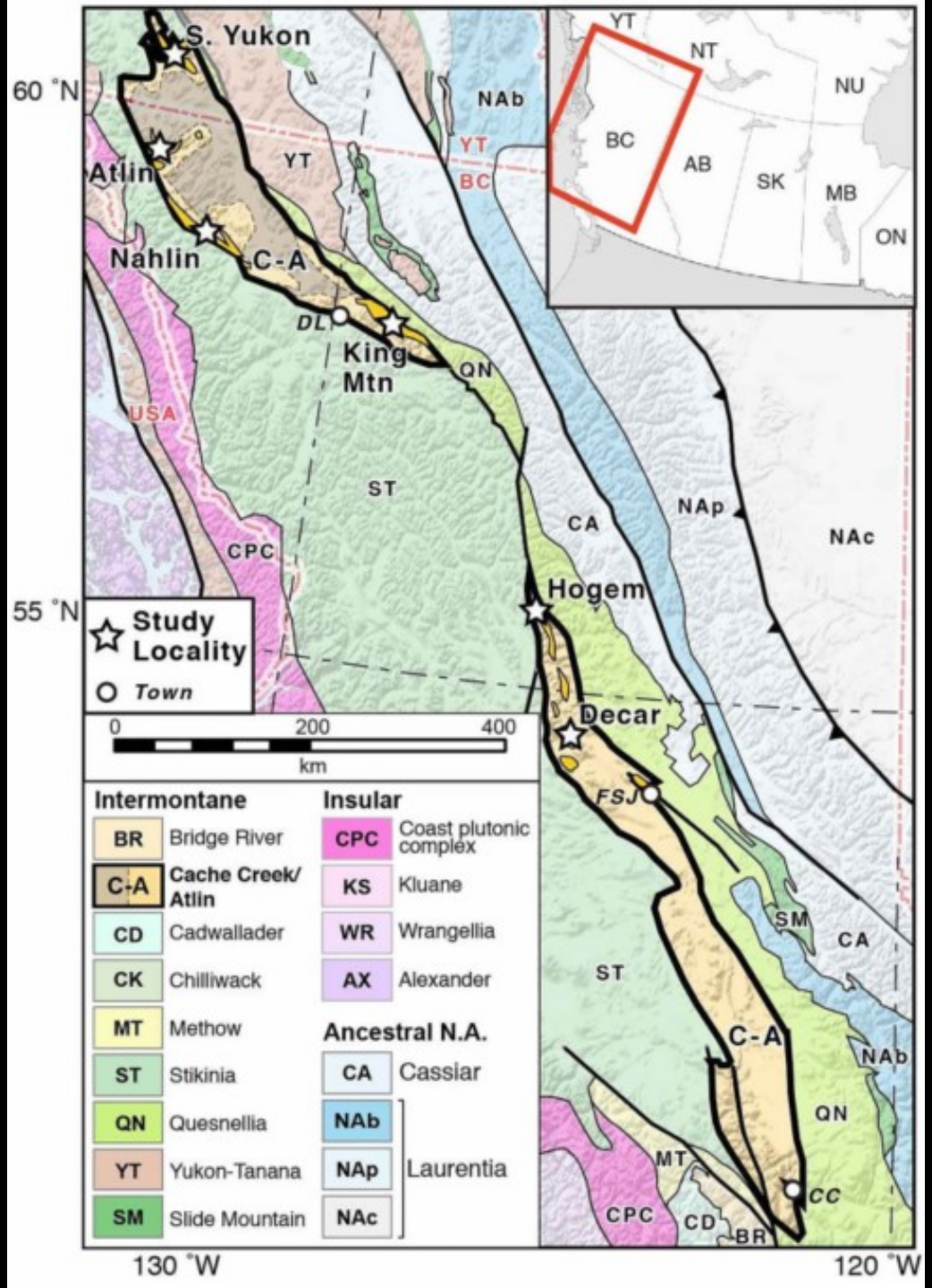
Deducing Mineralogy of Serpentinized and Carbonated Ultramafic Rocks Using Physical Properties With Implications for Carbon Sequestration and Subduction Zone Dynamics

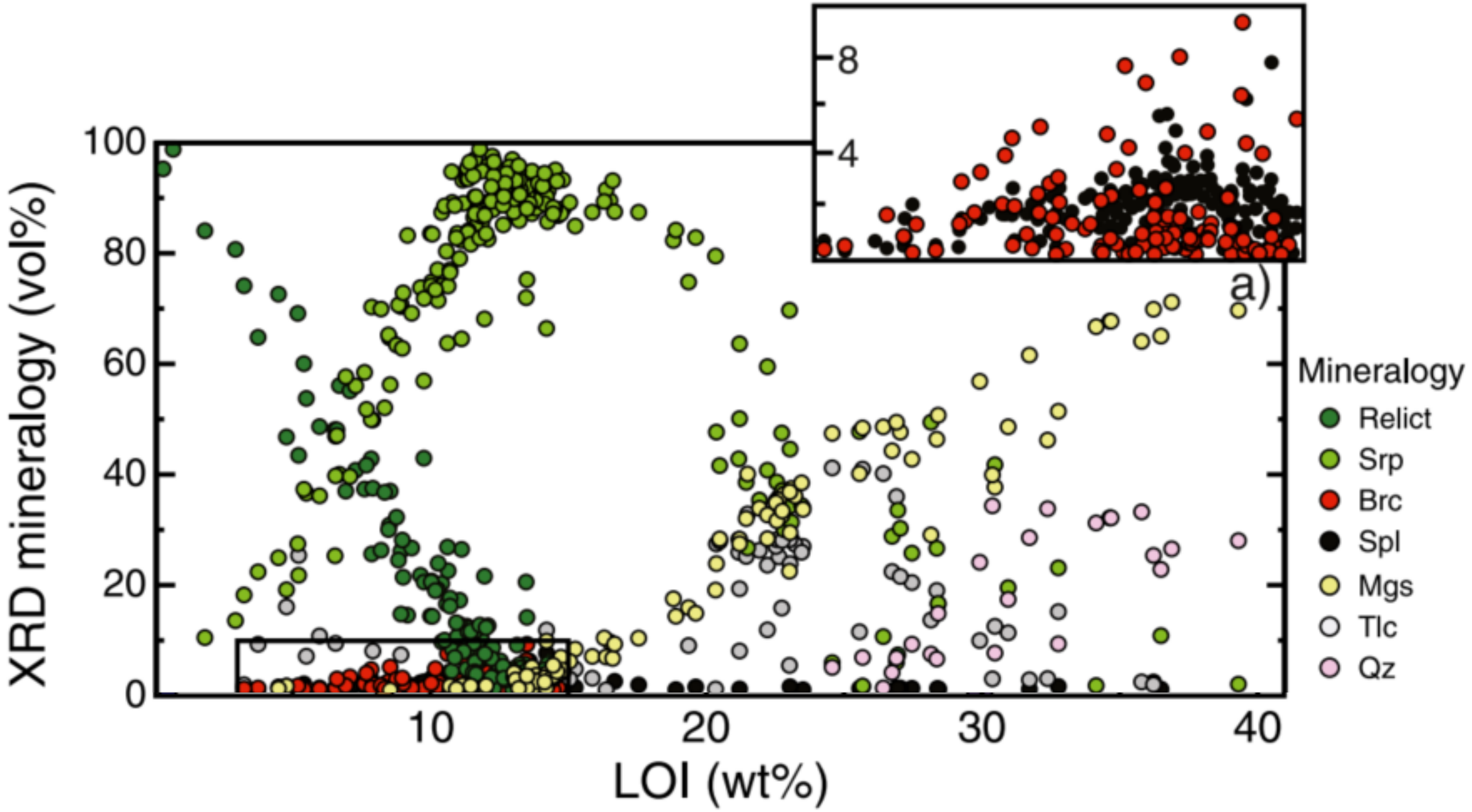
J. A. Cutts[1], K. Steinthorsdottir[1], C. Turvey[1], G. M. Dipple[1], R. J. Enkin[2], and S. M. Peacock[1]

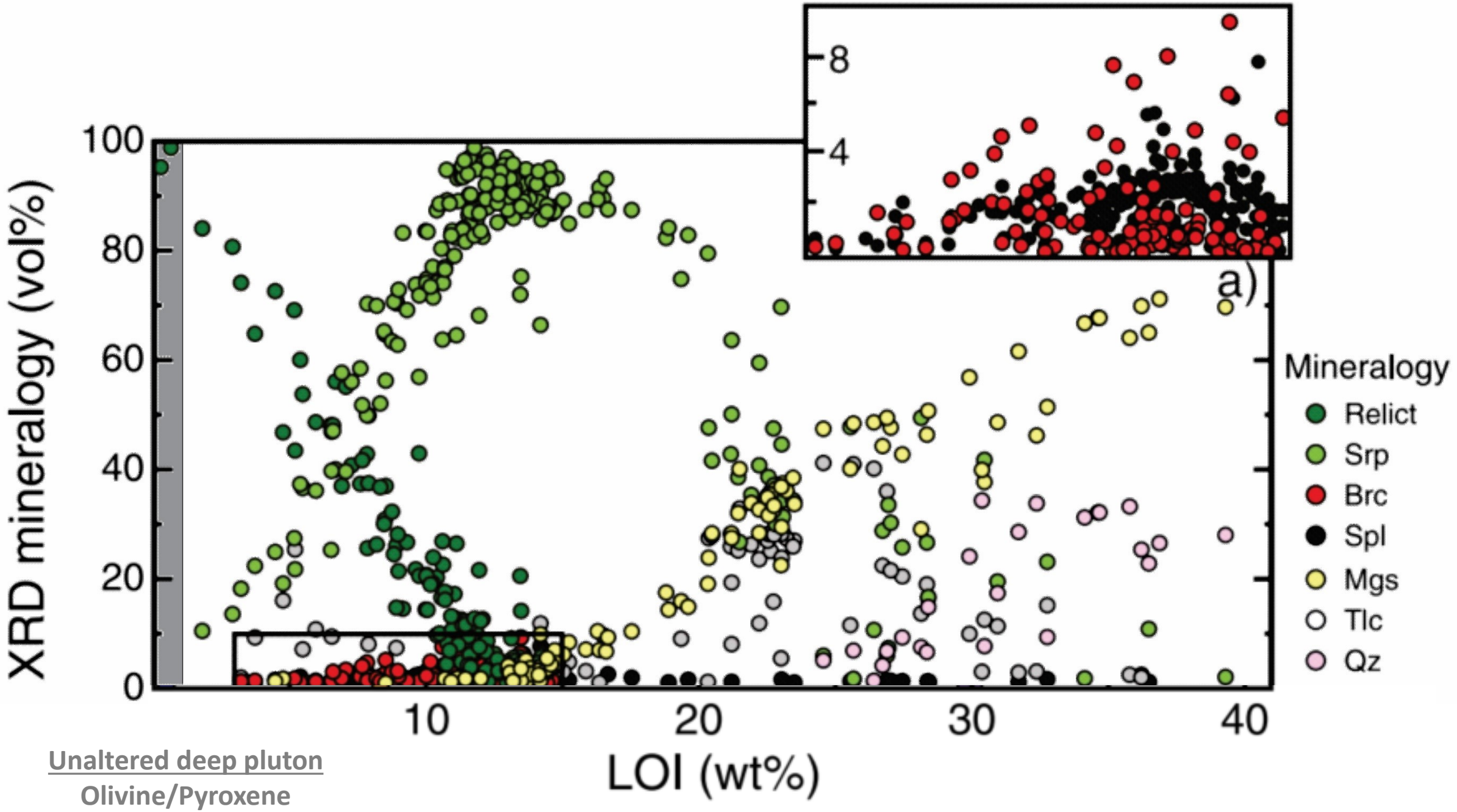
[1]Department of Earth, Ocean and Atmospheric Sciences, CarbMin Lab, The University of British Columbia, Vancouver, BC, Canada, [2]Geological Survey of Canada-Pacific, Sidney, BC, Canada

Abstract Serpentinization of ultramafic rocks is fundamental to modern plate tectonics and for volatile (re-)cycling into the mantle and magmatic arcs. Serpentinites are also highly reactive with CO_2

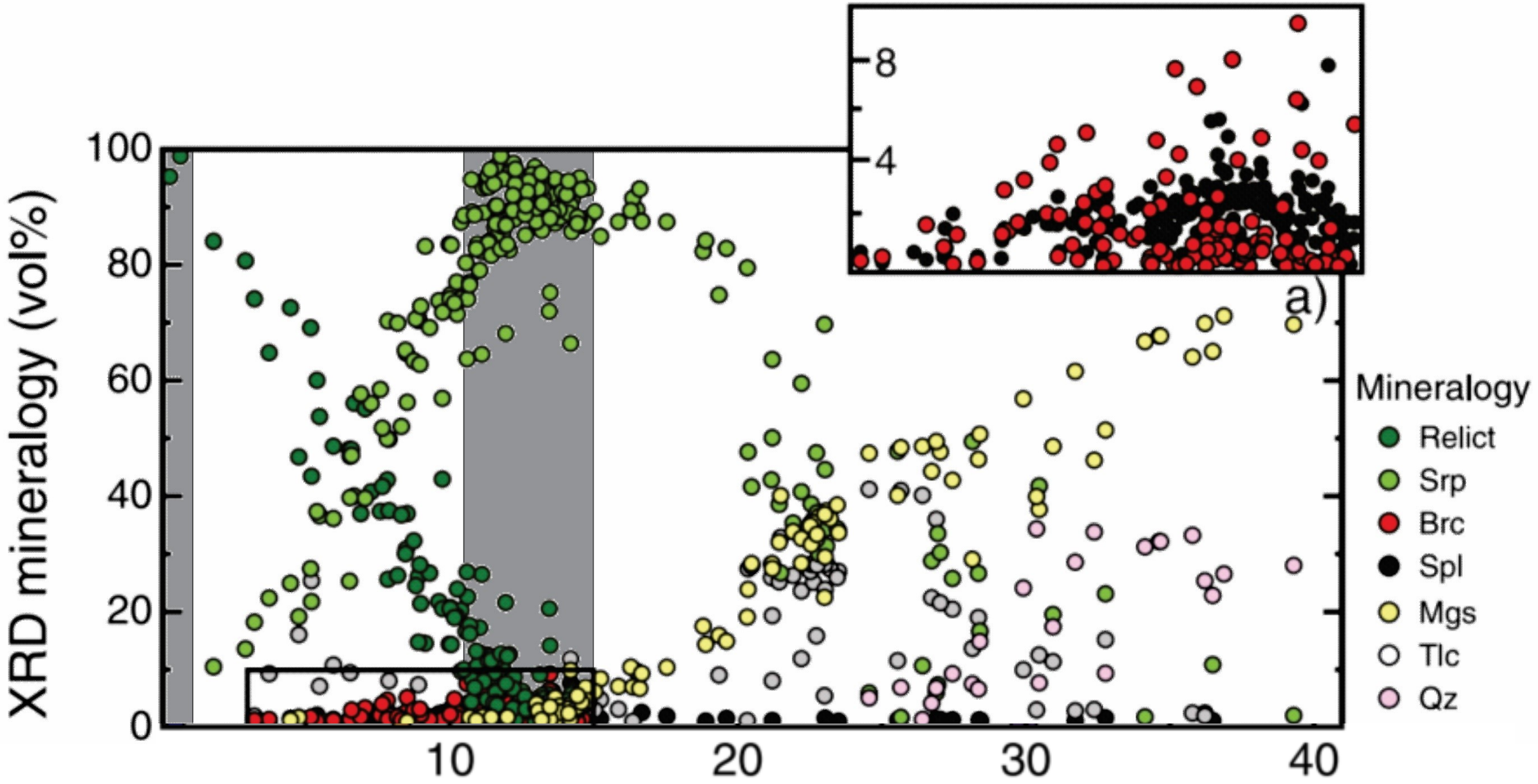
Ultramafic bodies sampled along the marine Cache Creek terrane, British Columbia and Yukon




XRD mineralogy (vol%)
LOI (wt%)
0
20
40
60
80
100
10
20
30
40
4
8
a)
Mineralogy
Relict
Srp
Brc
Spl
Mgs
Tlc
Qz

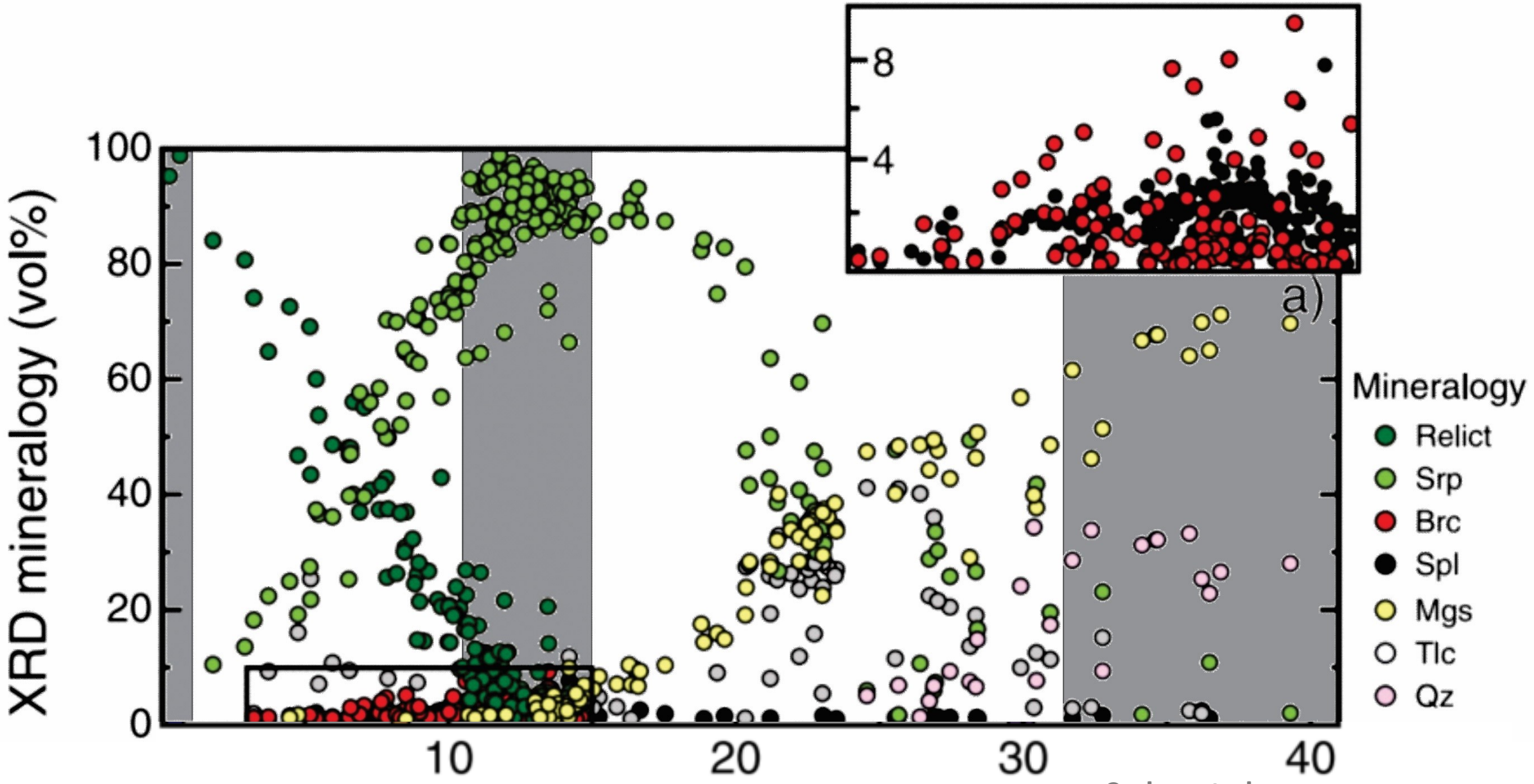


Unaltered deep pluton
Olivine/Pyroxene
No Magnetite



Unaltered deep pluton
Olivine/Pyroxene
No Magnetite

Hydrated
Serpentine/Brucite
Magnetite



Unaltered deep pluton
Olivine/Pyroxene
No Magnetite

Hydrated
Serpentine/Brucite
Magnetite

Carbonated
Magnesite
Sparce Magnetite

Hydration

$$\text{R1: olivine} \pm \text{orthopyroxene} + H_2O \rightarrow \text{serpentine} \pm \text{brucite} \pm \text{magnetite}$$

Carbonation

$$\text{R2: olivine} + \text{brucite} + CO_2 + H_2O \rightarrow \text{serpentine} + \text{magnesite} + H_2O$$

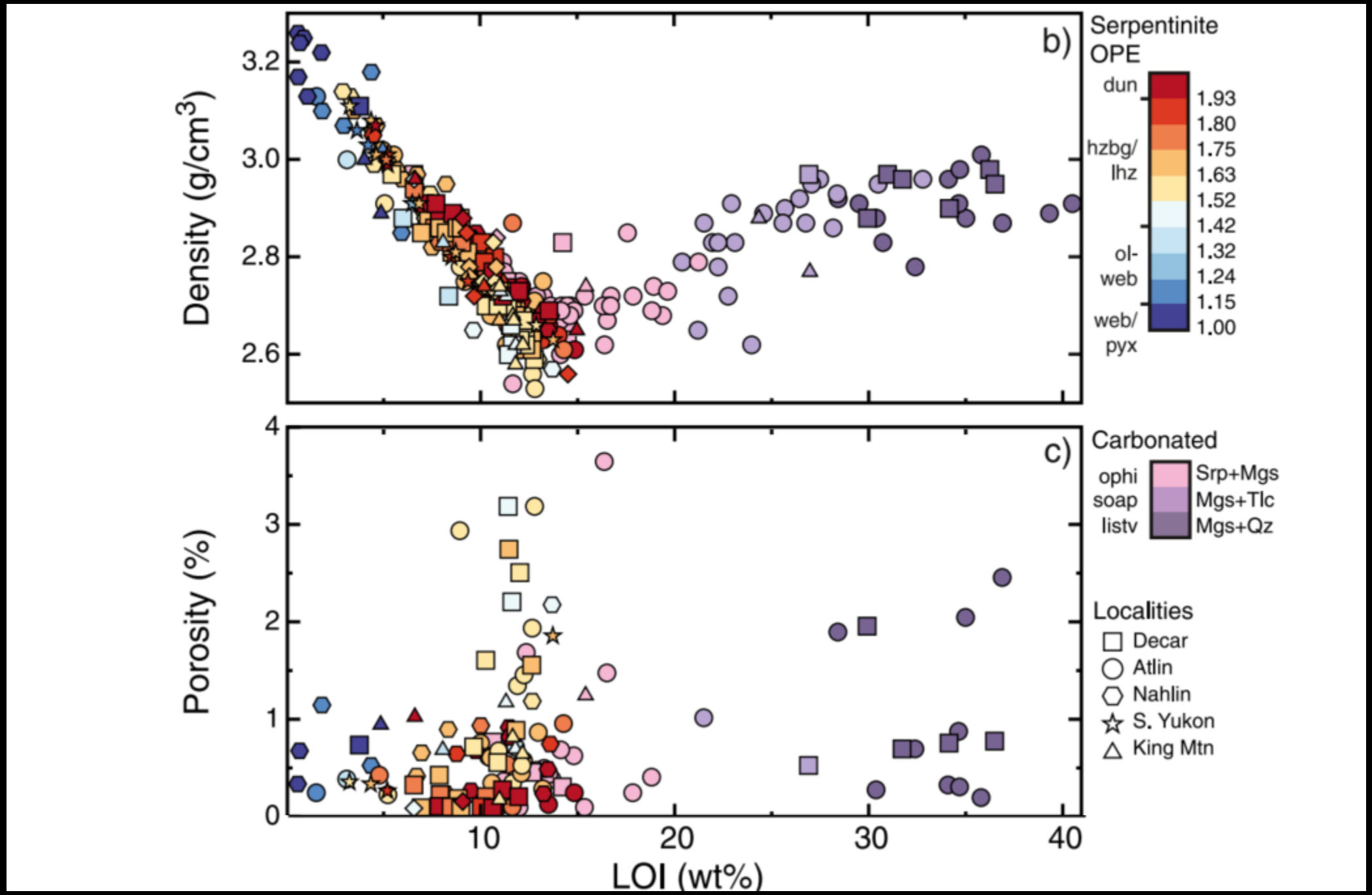
$$\text{R3: serpentine} + CO_2 \rightarrow \text{magnesite} + \text{talc} + H_2O$$

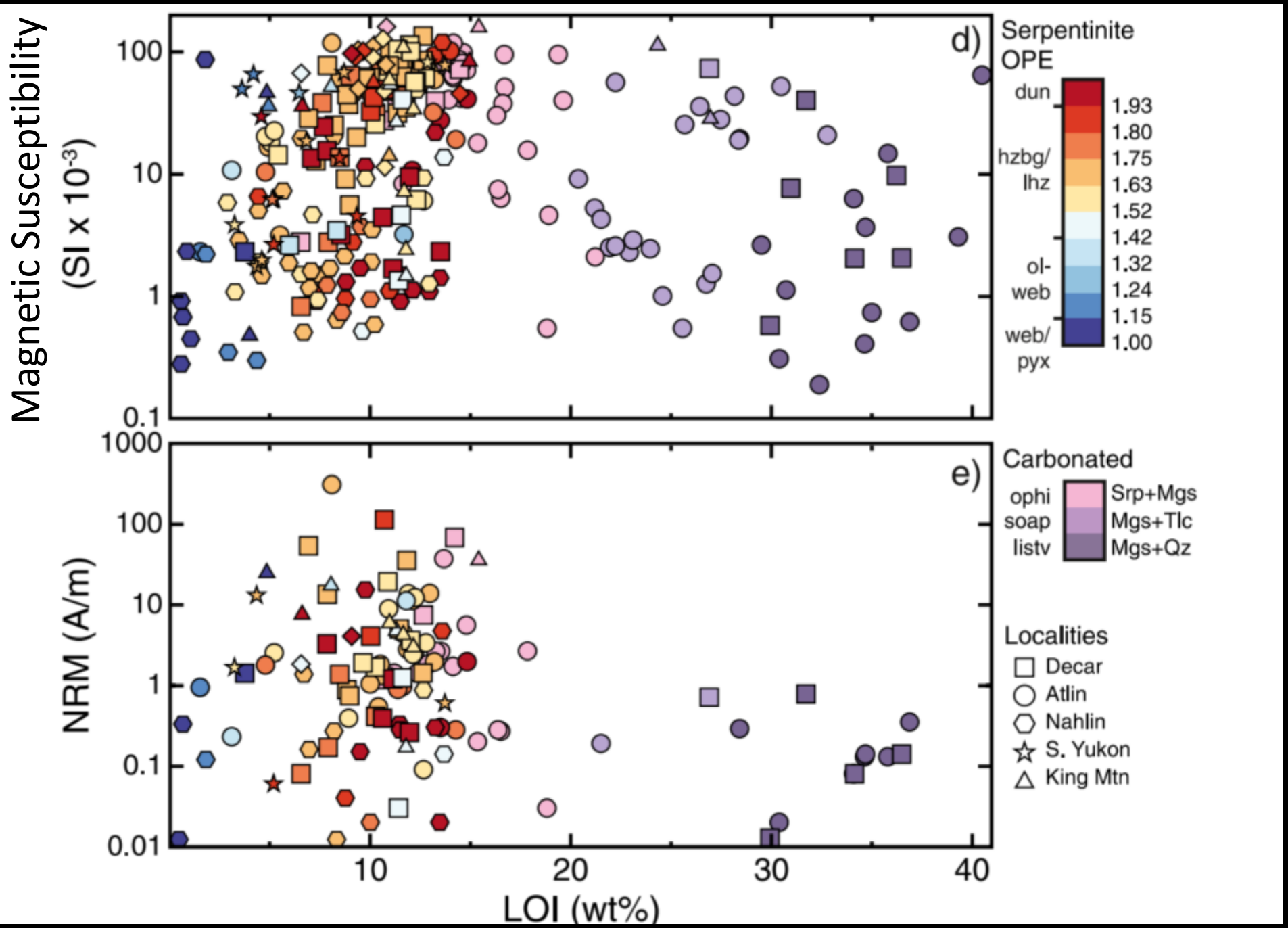
$$\text{R4: talc} + CO_2 \rightarrow \text{magnesite} + \text{quartz} + H_2O$$

Lherzolite, fully Serpentinized with dendritic Magnetite

2.5x4.5 cm

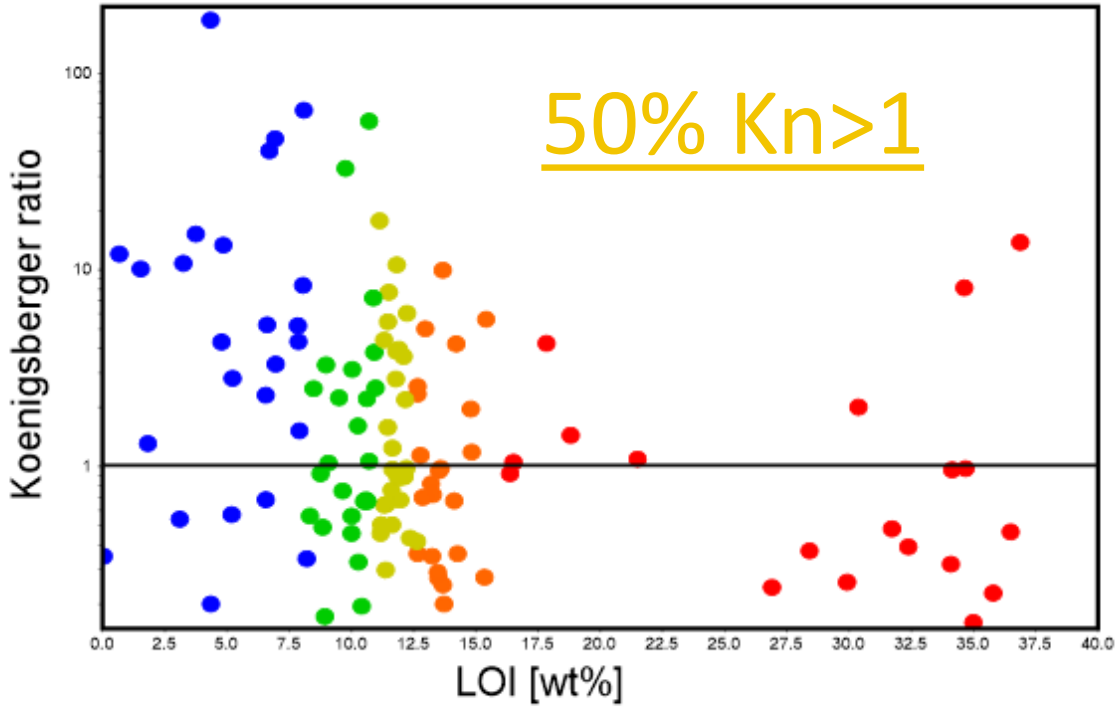
Dejan Mildragovic, Decar (BC)

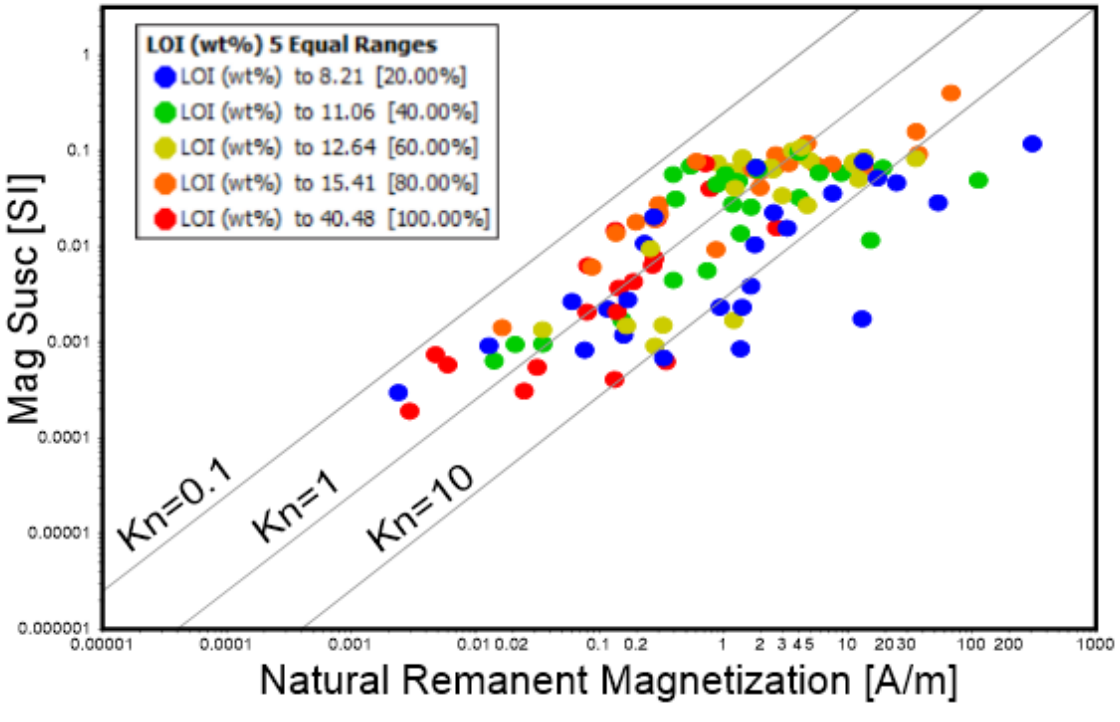

b)
Density (g/cm3)
3.2
3.0
2.8
2.6
Serpentinite
OPE
dun
hzbg/
lhz
ol-
web
web/
pyx
1.93
1.80
1.75
1.63
1.52
1.42
1.32
1.24
1.15
1.00
c)
Porosity (%)
4
3
2
1
0
10
20
30
40
LOI (wt%)
Carbonated
ophi
soap
listv
Srp+Mgs
Mgs+Tlc
Mgs+Qz
Localities
Decar
Atlin
Nahlin
S. Yukon
King Mtn

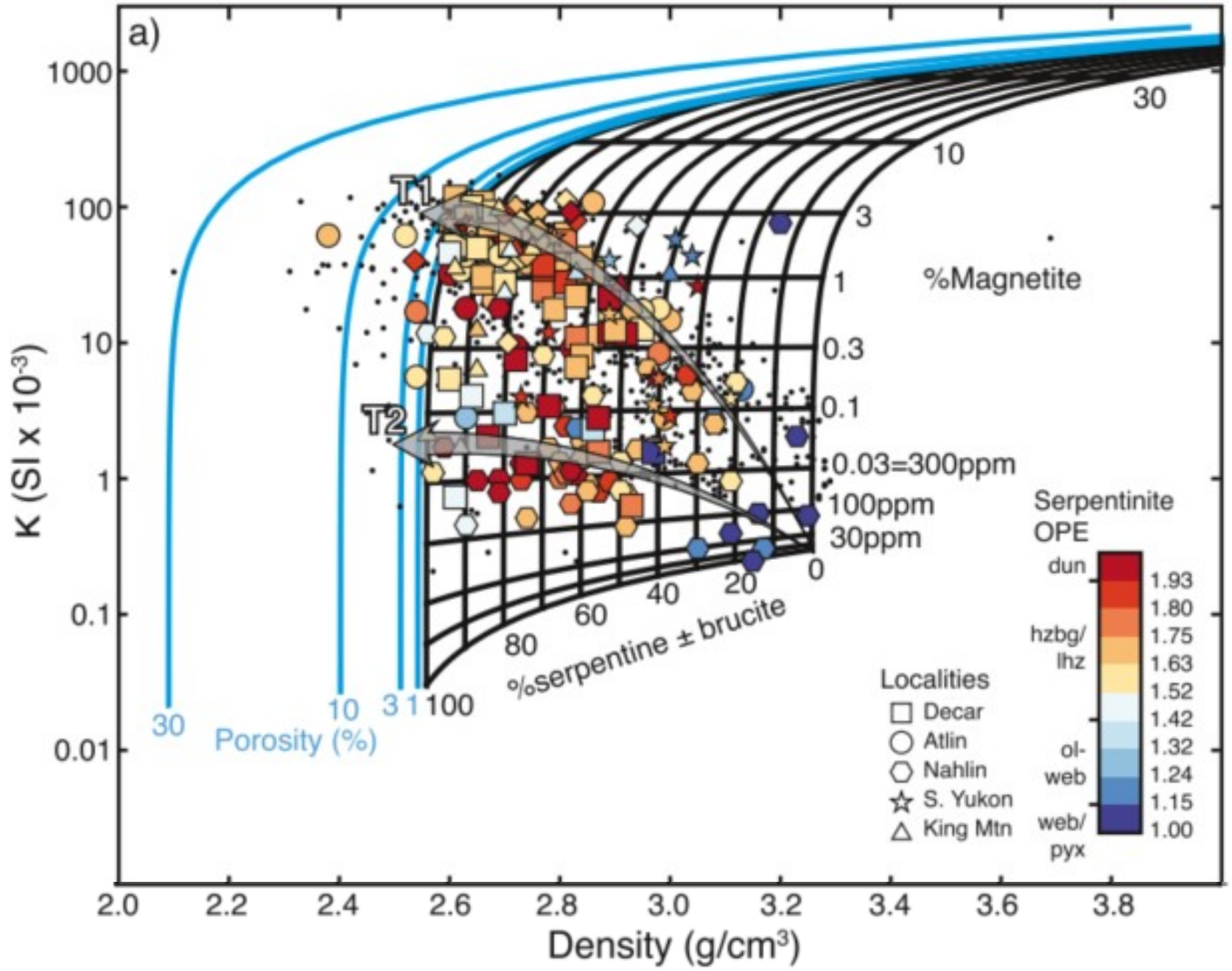

Magnetic Susceptibility
(SI x 10-3)
100
10
1
0.1
d)
Serpentinite
OPE
dun
hzbg/
lhz
ol-
web
web/
pyx
1.93
1.80
1.75
1.63
1.52
1.42
1.32
1.24
1.15
1.00
1000
100
10
1
0.1
0.01
NRM (A/m)
e)
Carbonated
ophi
soap
listv
Srp+Mgs
Mgs+Tlc
Mgs+Qz
Localities
Decar
Atlin
Nahlin
S. Yukon
King Mtn
10
20
30
40
LOI (wt%)

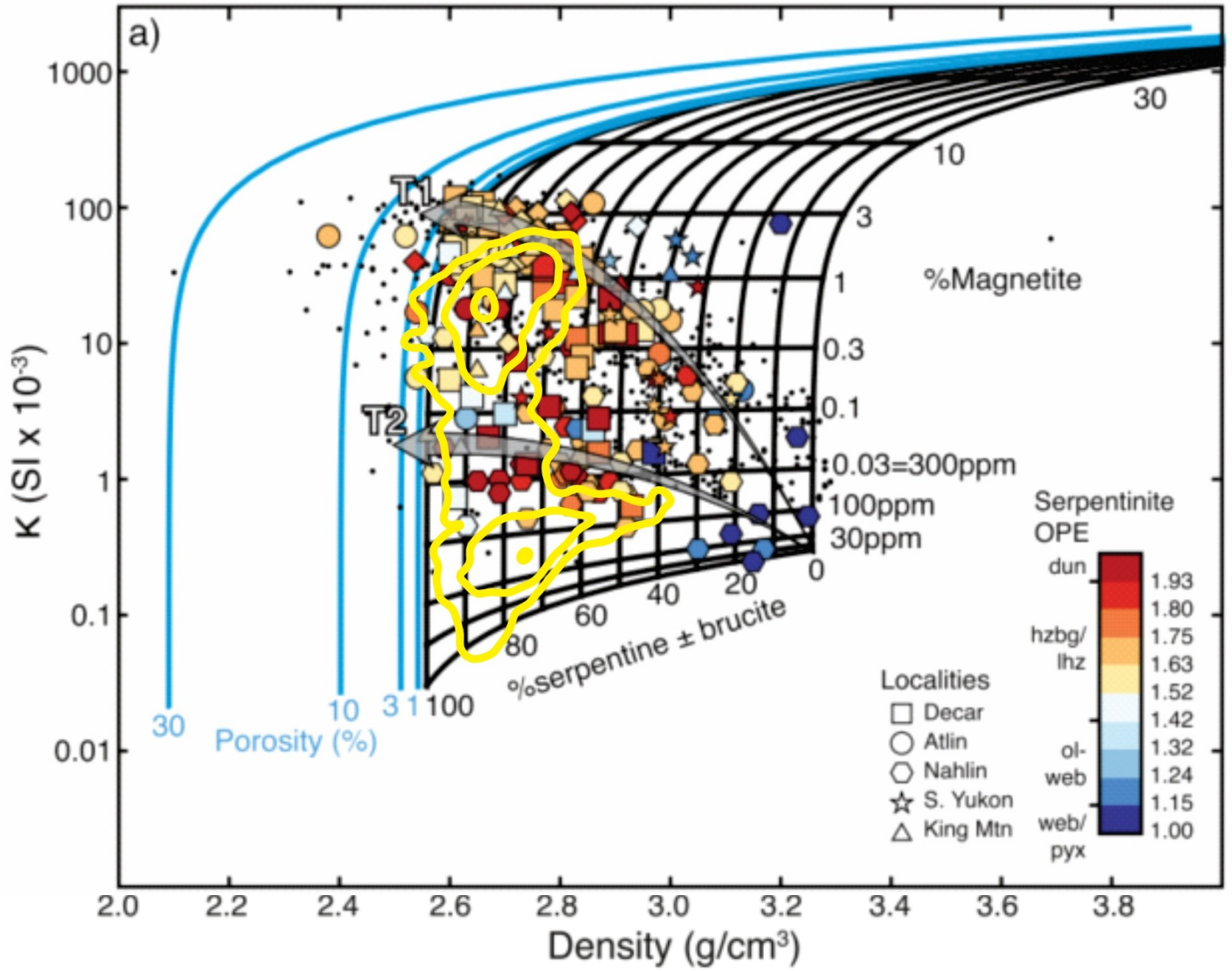
Koenigsberger Ratio

$$Kn = \frac{\text{Permanent Magnetization}}{\text{Induced Magnetization}}$$






a)
1000
100
10
1
0.1
0.01
K (SI x 10-3)
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
Density (g/cm3)
T1
T2
30
10
3
1
0.3
0.1
%Magnetite
0.03=300ppm
100ppm
30ppm
0
20
40
60
80
%serpentine ± brucite
30
10
3
1
100
Porosity (%)
Localities
Decar
Atlin
Nahlin
S. Yukon
King Mtn
Serpentinite
OPE
dun
hzbg/
lhz
ol-
web
web/
pyx
1.93
1.80
1.75
1.63
1.52
1.42
1.32
1.24
1.15
1.00


a)
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100
10
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0.1
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K (SI x 10-3)
2.0
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2.6
2.8
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10
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%Magnetite
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100ppm
30ppm
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20
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60
80
%serpentine ± brucite
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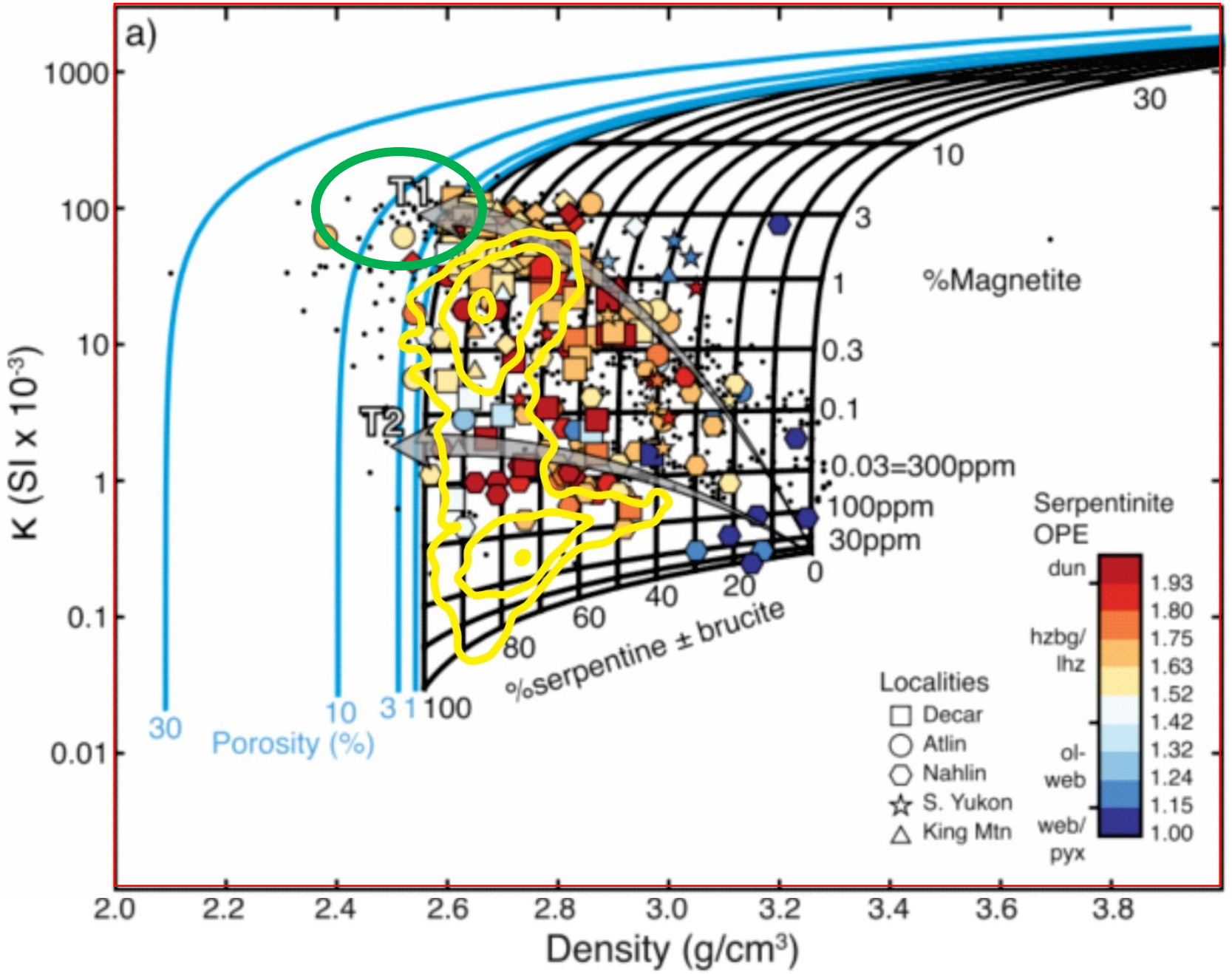
a)
1000
100
10
1
0.1
0.01
K (SI x 10⁻³)
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
Density (g/cm³)
T1
T2
30
10
3
1
0.3
0.1
%Magnetite
0.03=300ppm
100ppm
30ppm
0
20
40
60
80
%serpentine ± brucite
30
10
3
1
100
Porosity (%)
Localities
Decar
Atlin
Nahlin
S. Yukon
King Mtn
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dun
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lhz
ol-
web
web/
pyx
1.93
1.80
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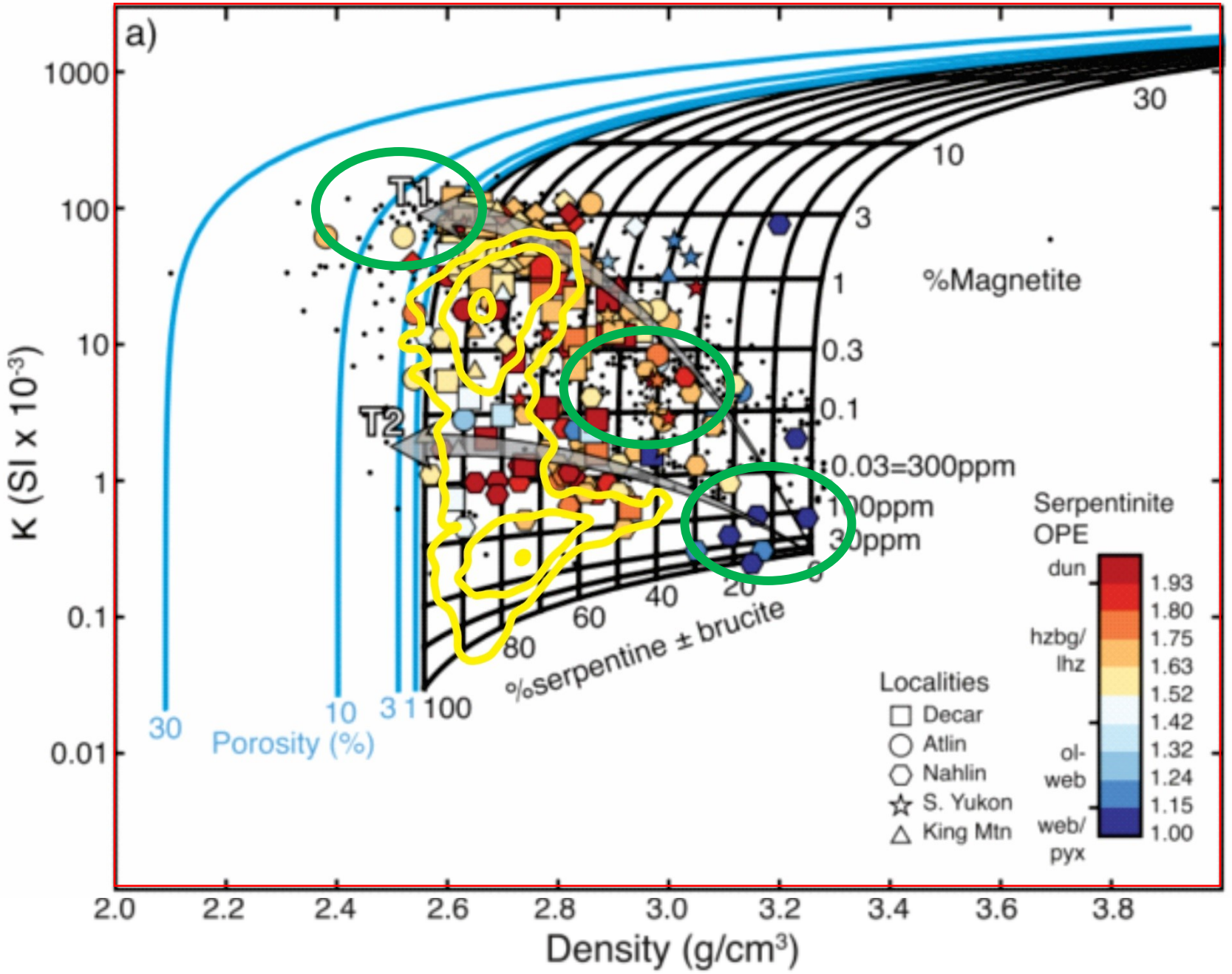
1.52
1.42
1.32
1.24
1.15
1.00


a)
K (SI x 10⁻³)
Density (g/cm³)
%Magnetite
30
10
3
1
0.3
0.1
0.03=300ppm
100ppm
30ppm
T1
T2
%serpentine ± brucite
Porosity (%)
Localities
Decar
Atlin
Nahlin
S. Yukon
King Mtn
Serpentinite
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dun
hzbg/
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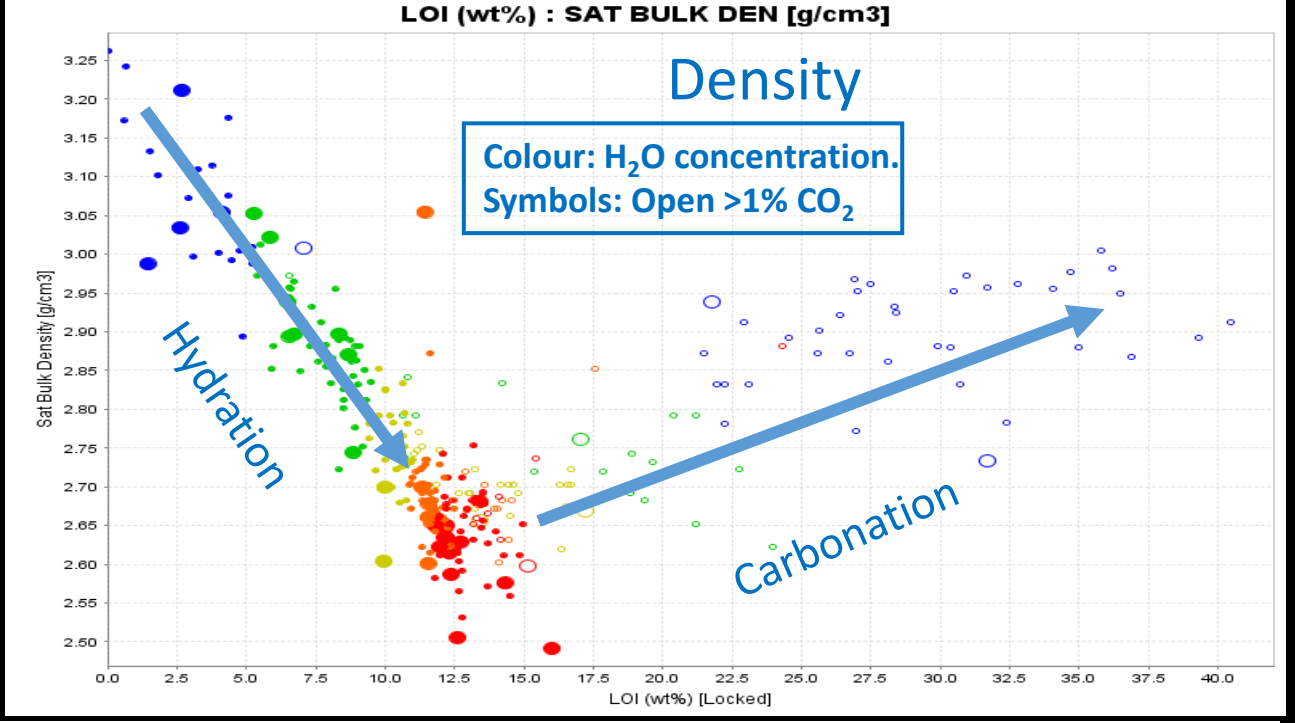
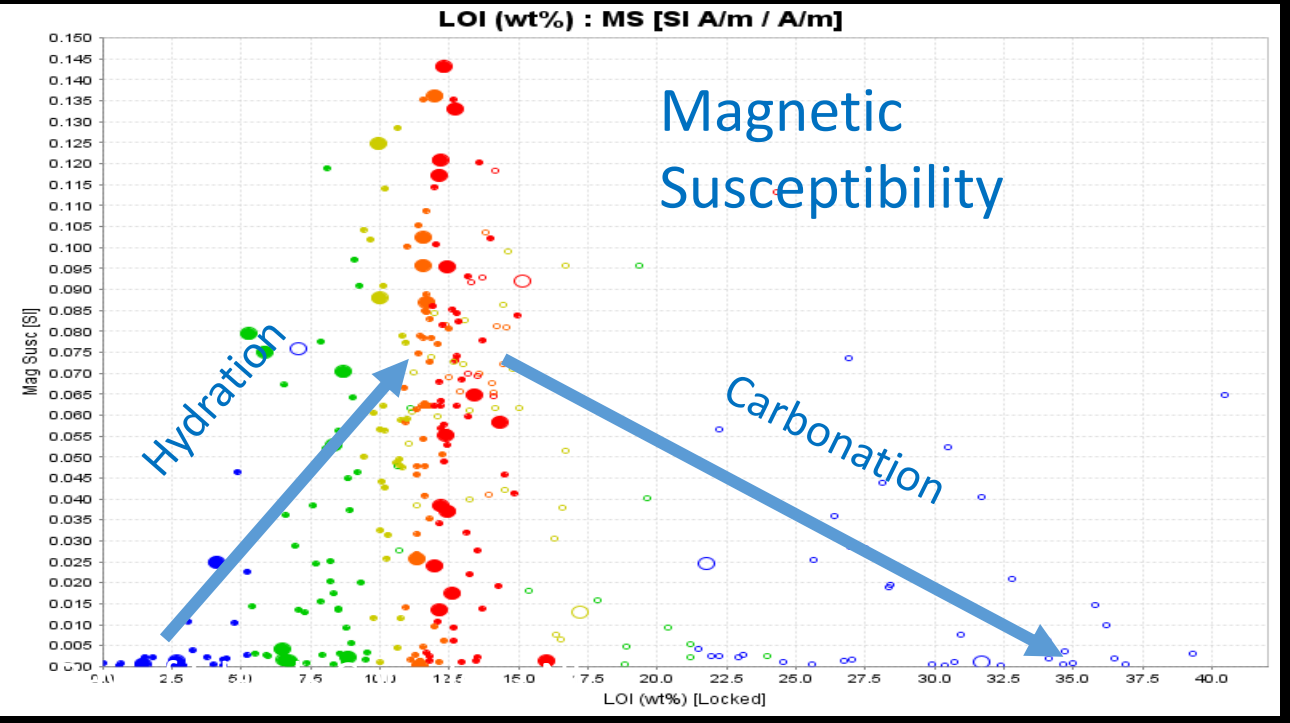
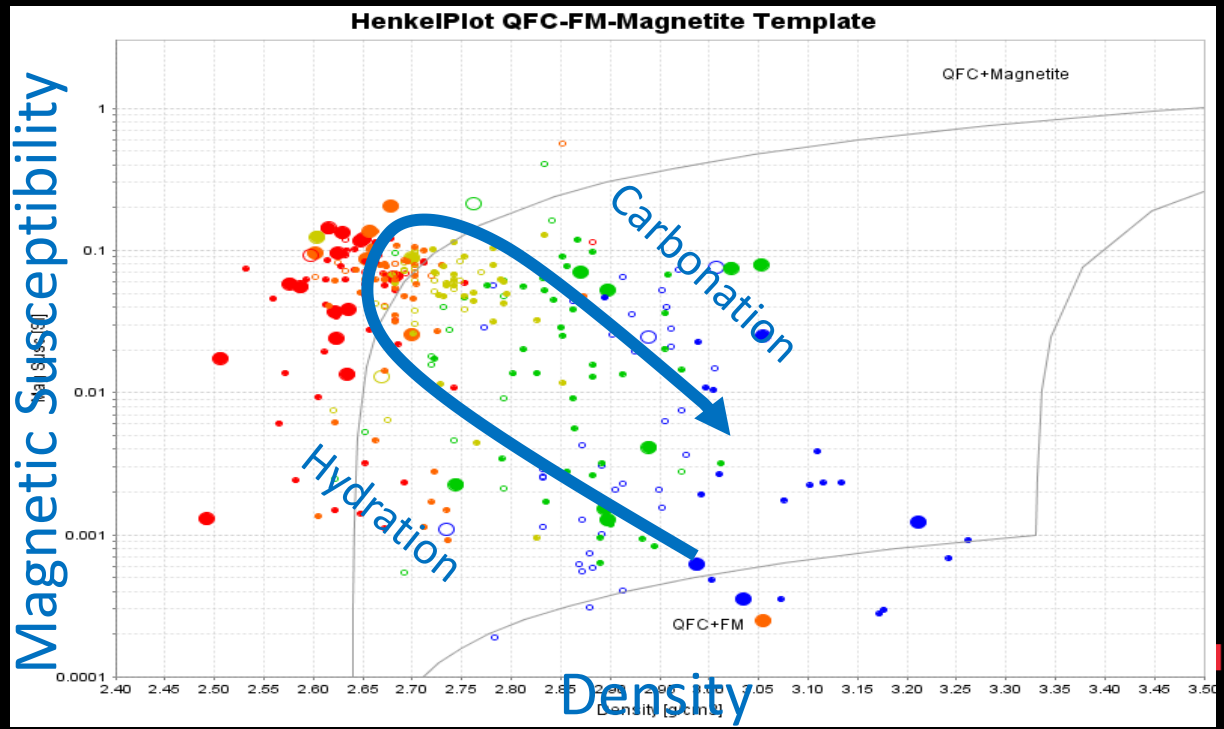
1.93
1.80
1.75
1.63
1.52
1.42
1.32
1.24
1.15
1.00

Ultramafic Petrophysics

- Serpentinization/hydration reduces density and creates magnetite
- Carbonation increases density and destroys magnetite

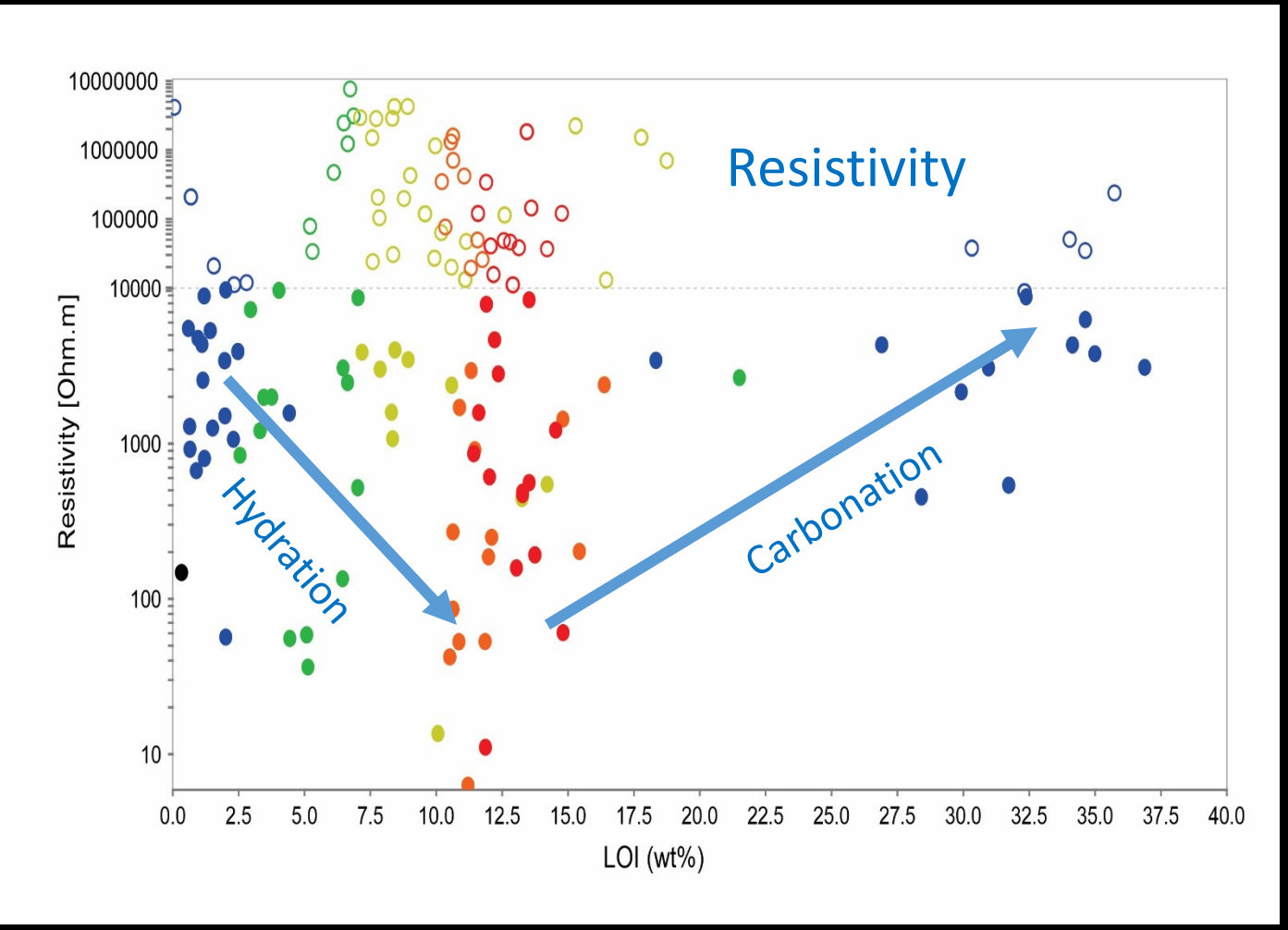


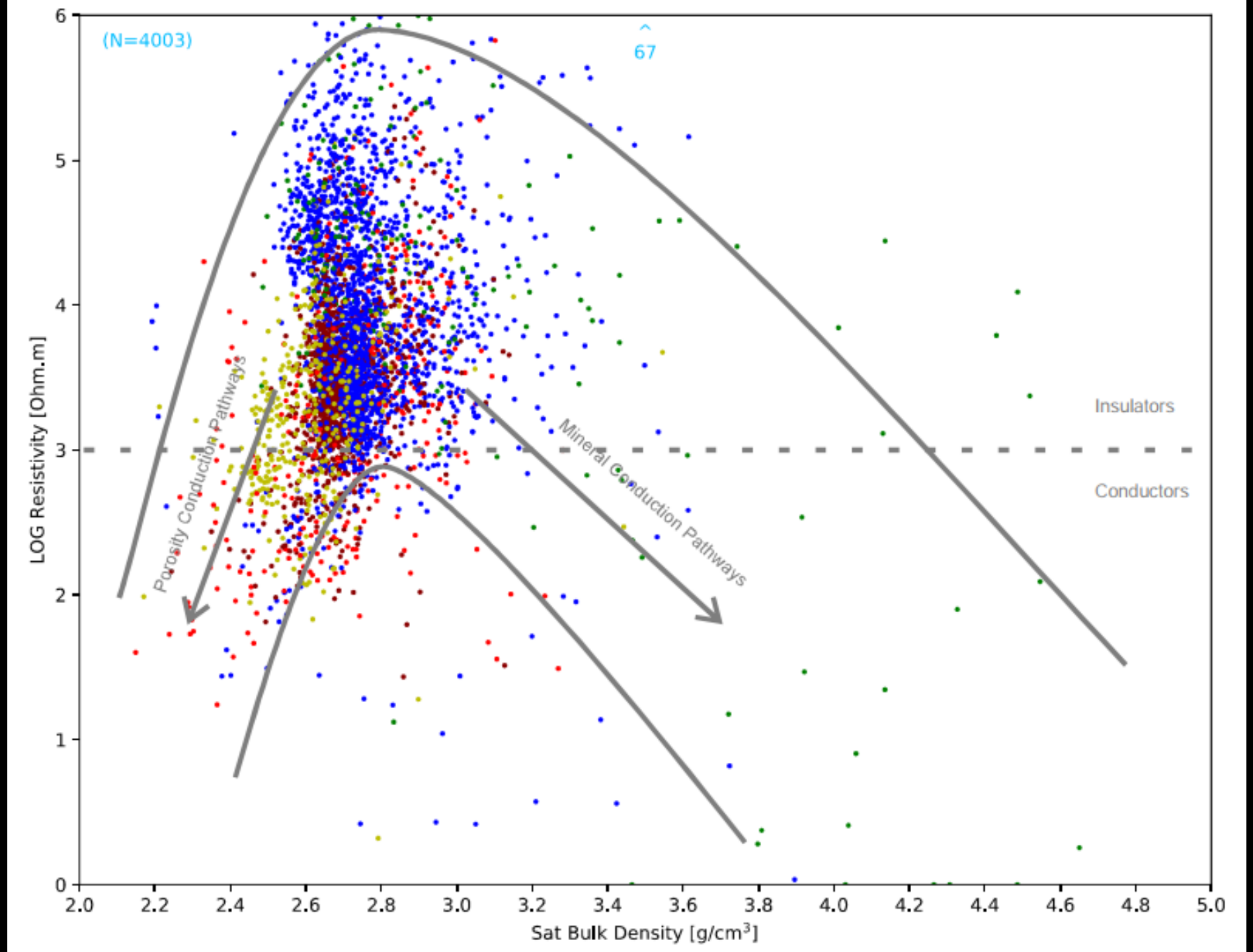




Ultramafic Petrophysics

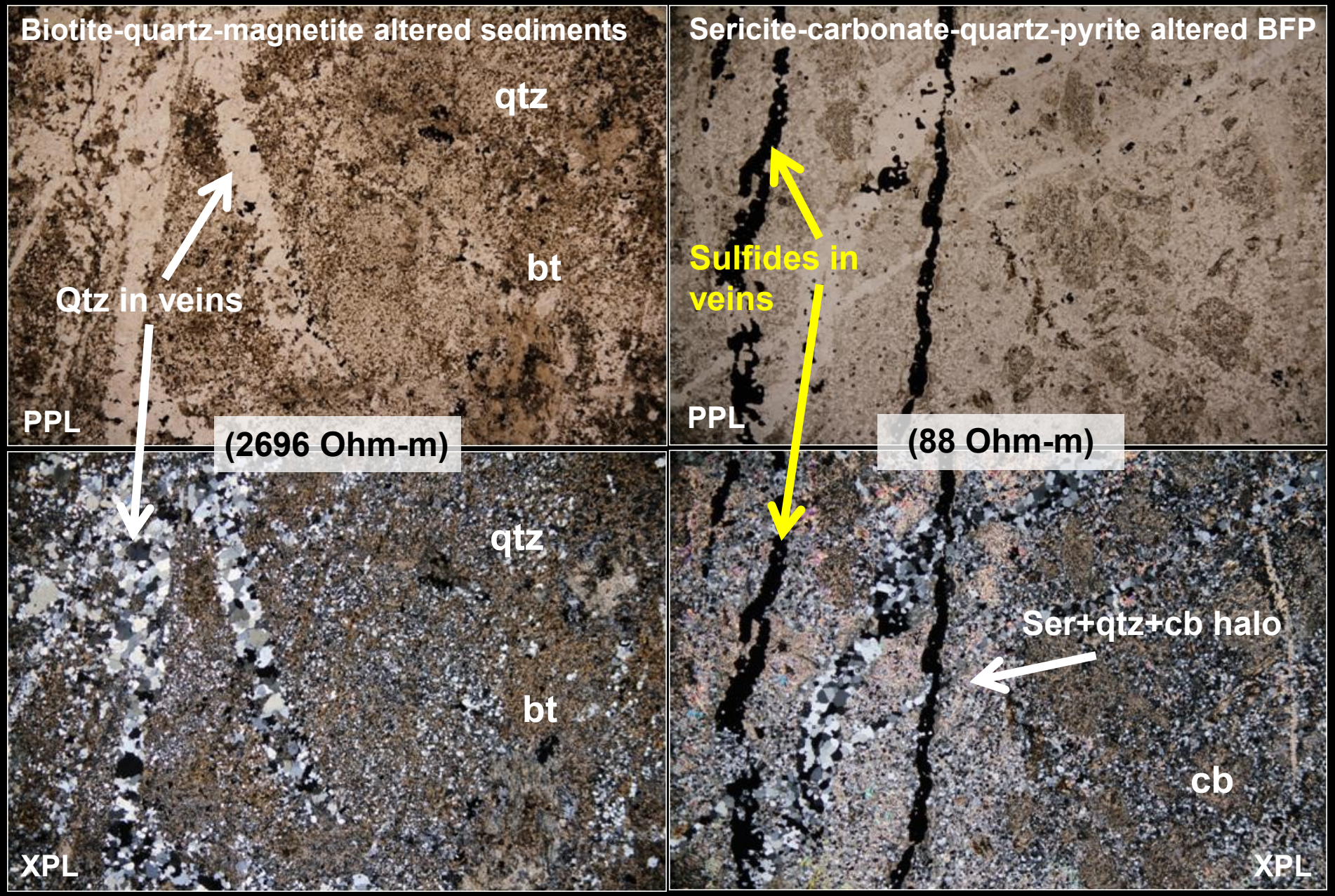
- Serpentinization/hydration reduces density and creates magnetite and creates porosity
- Carbonation increases density and destroys magnetite and removes porosity




(N=4003)
67
LOG Resistivity [Ohm.m]
Sat Bulk Density [g/cm3]
Porosity Conduction Pathways
Mineral Conduction Pathways
Insulators
Conductors
0
1
2
3
4
5
6
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
4.0
4.2
4.4
4.6
4.8
5.0

Enkin, 2018

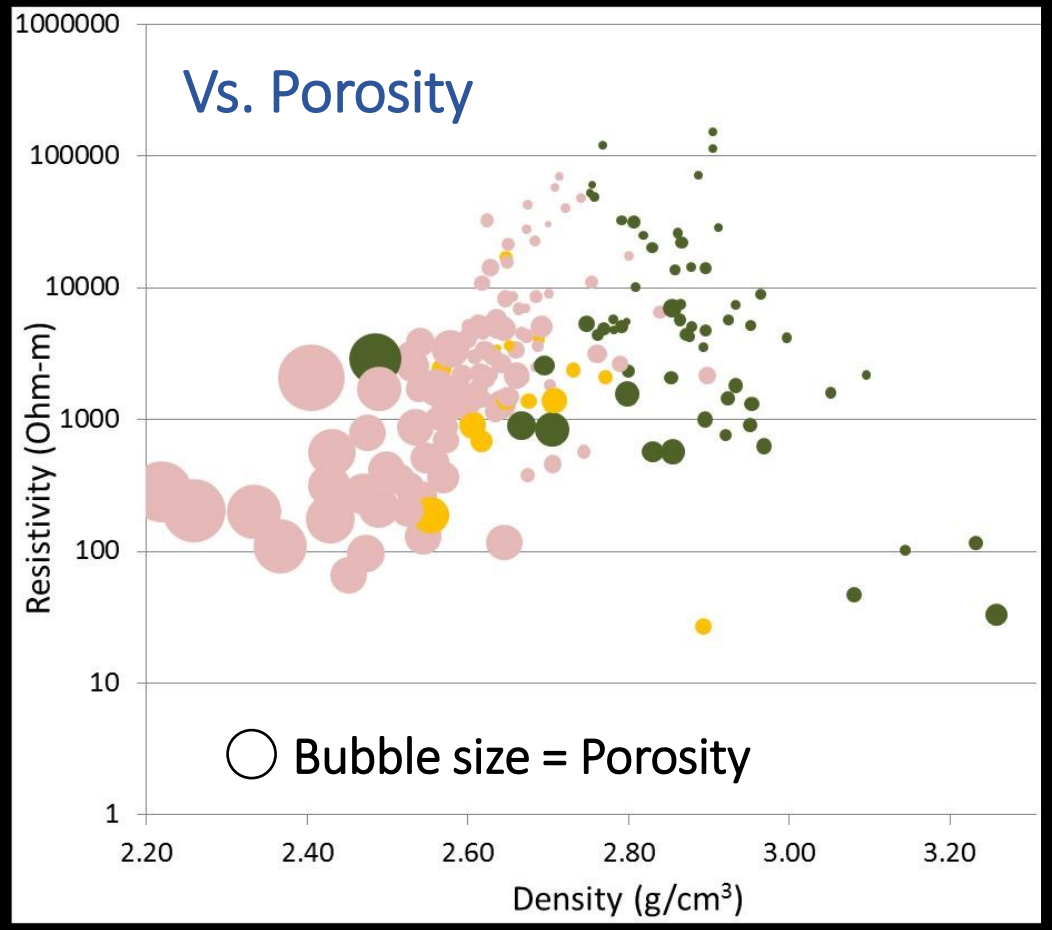
Photomicrographs – resistive and conductive samples from Bell Porphyry Deposit

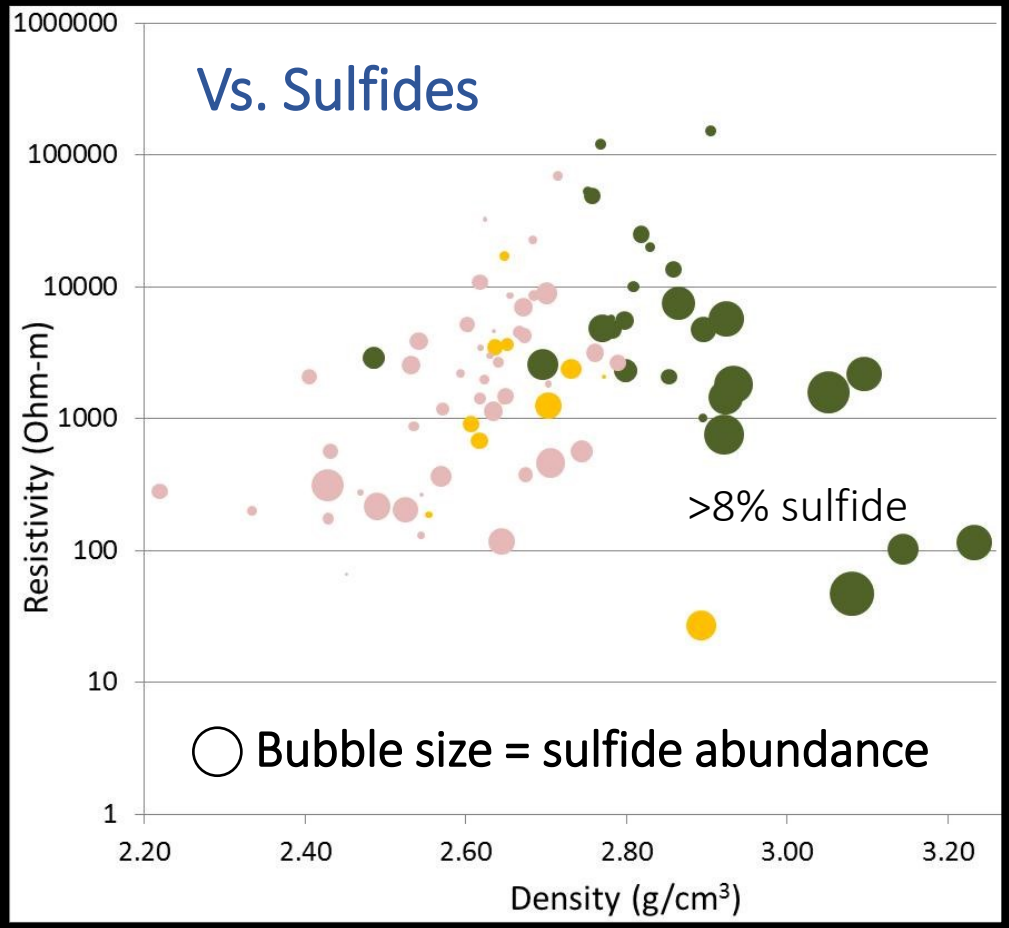


Mitchinson, Enkin, and Hart, 2013

Resistivity *vs* Density

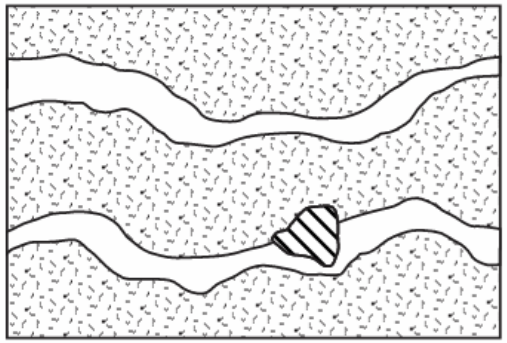
Intrusives
Volcanics
Sediments



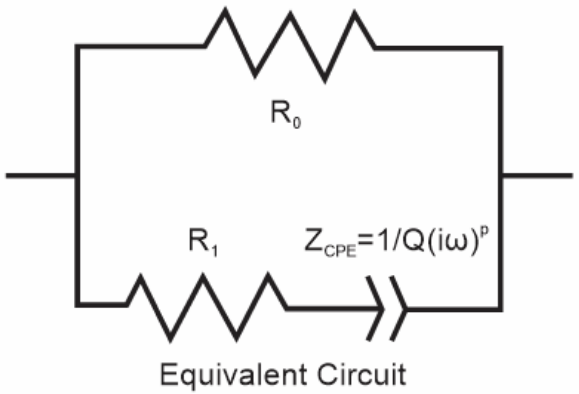


Mitchinson, Enkin, and Hart, 2013

Electric Impedance: Resistivity and Chargeability

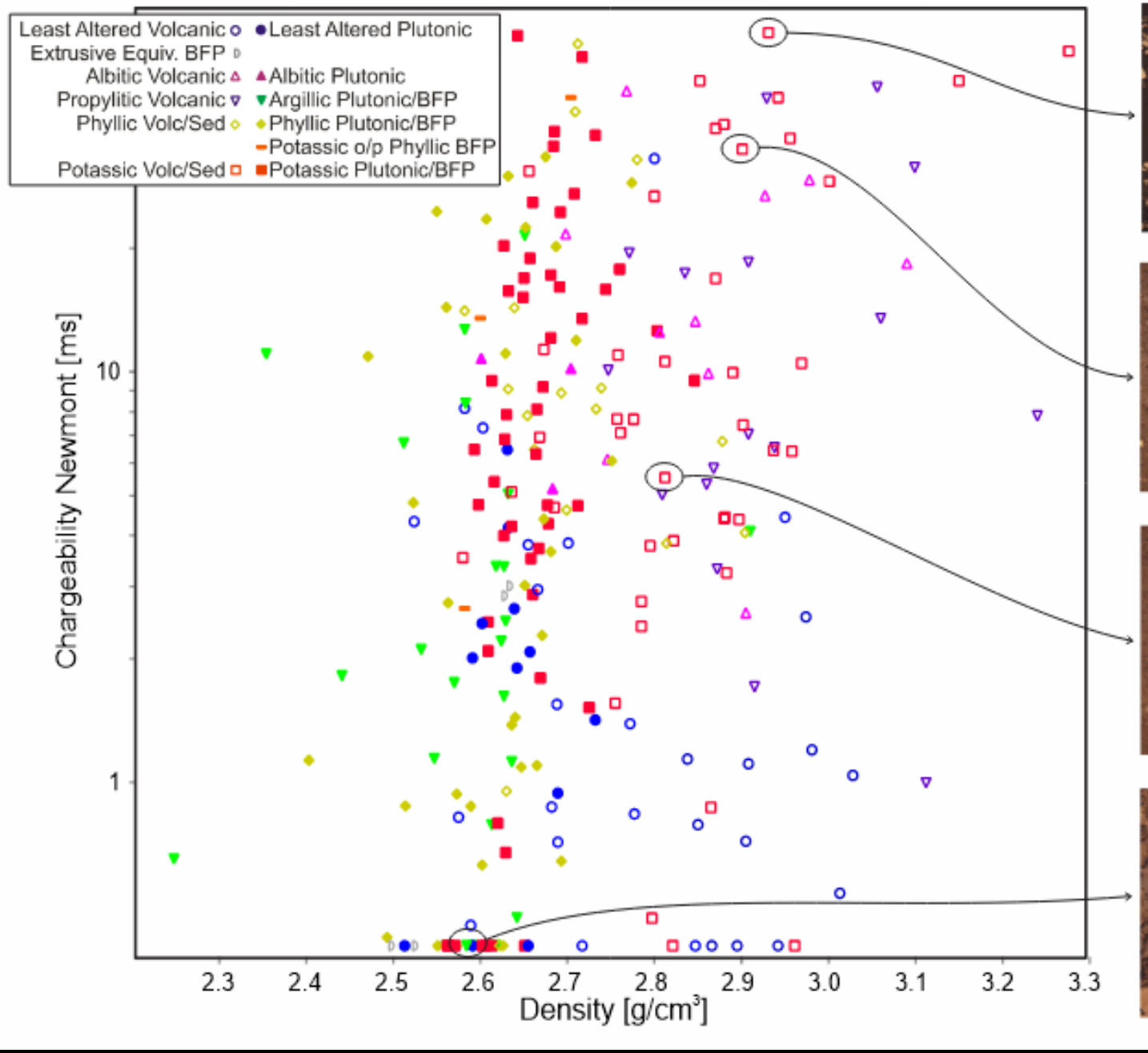


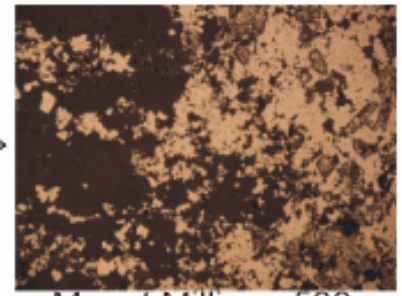
Mineralized Rock



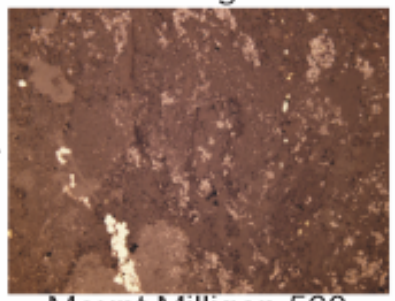
Equivalent Circuit

Pelton, 1977

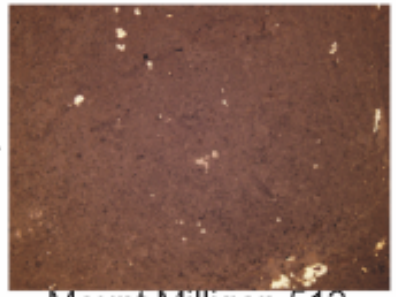




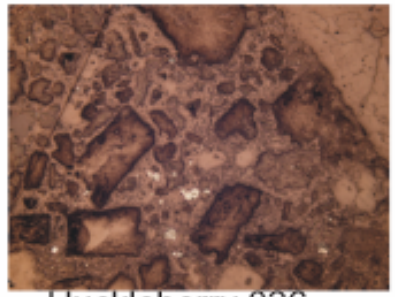
Mount Milligan 533



Mount Milligan 560



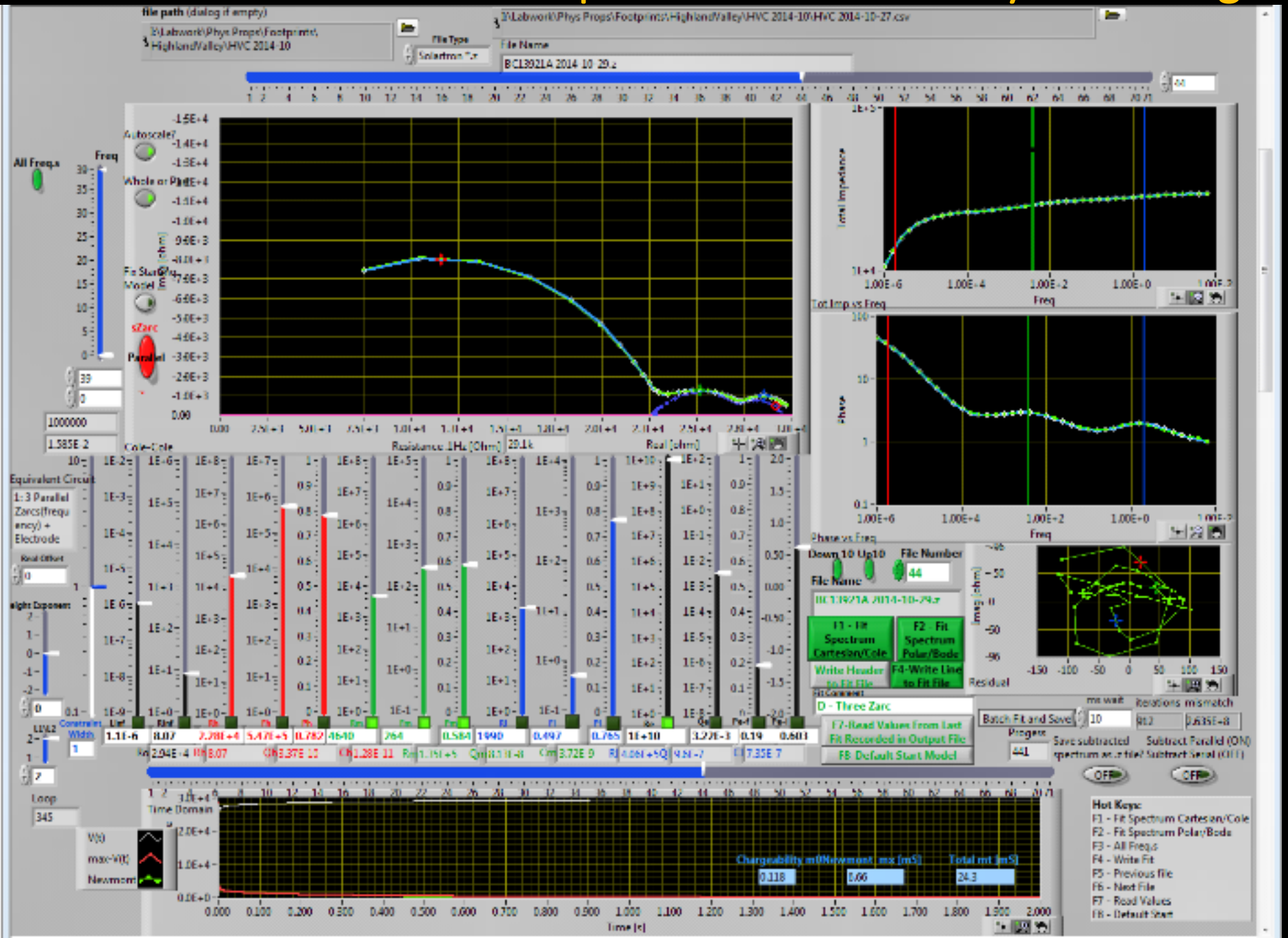
Mount Milligan 512



Huckleberry 026

Mitchinson, Enkin, and Hart, 2013

Electric Impedance: Resistivity and Chargeability



Altered porphyritic granite from Highland Valley Copper deposit, British Columbia.

“Triple-Zarc” spectral impedance curve due to sericite (~1kHz) and bornite (~1 Hz) chargeability.

1. Geophysical anomalies are caused by physical property contrasts.

2. Rock physical properties reflect lithology and mineralogy, and can be understood in terms of composition and geological history.

3. Physical properties measurements help make the link between geophysical and geological interpretation.

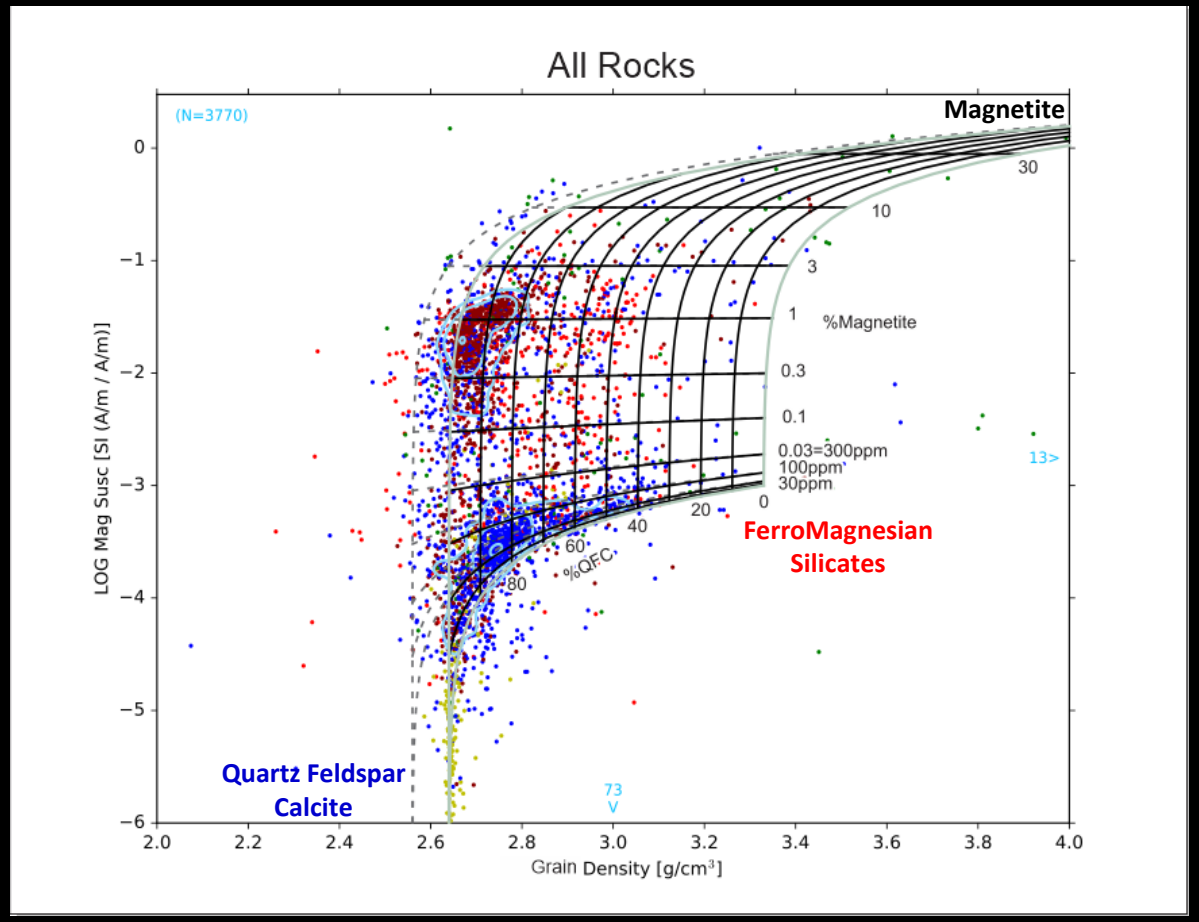
1. Geophysical anomalies are caused by physical property contrasts.

2. Rock physical properties reflect lithology and mineralogy, and can be understood in terms of composition and geological history.

3. Physical properties measurements help make the link between geophysical and geological interpretation.

4. Ultramafic systems are particularly exotic!

Petrophysics applied to magmatic sulfide deposits: The physical properties - mineralogy link



Randy Enkin

Geological Survey of Canada: Paleomagnetism and Petrophysics Laboratory

randy.enkin@canada.ca

Natural Resources Canada | Ressources naturelles Canada