CIDER 2019

A Petrologist's Eye View of Magmatic Systems (Determining P-T-X ± t conditions)

EPIC
experimental petrology & igneous processes center
epic.asu.edu

ASU School of Earth and Space Exploration
Arizona State University

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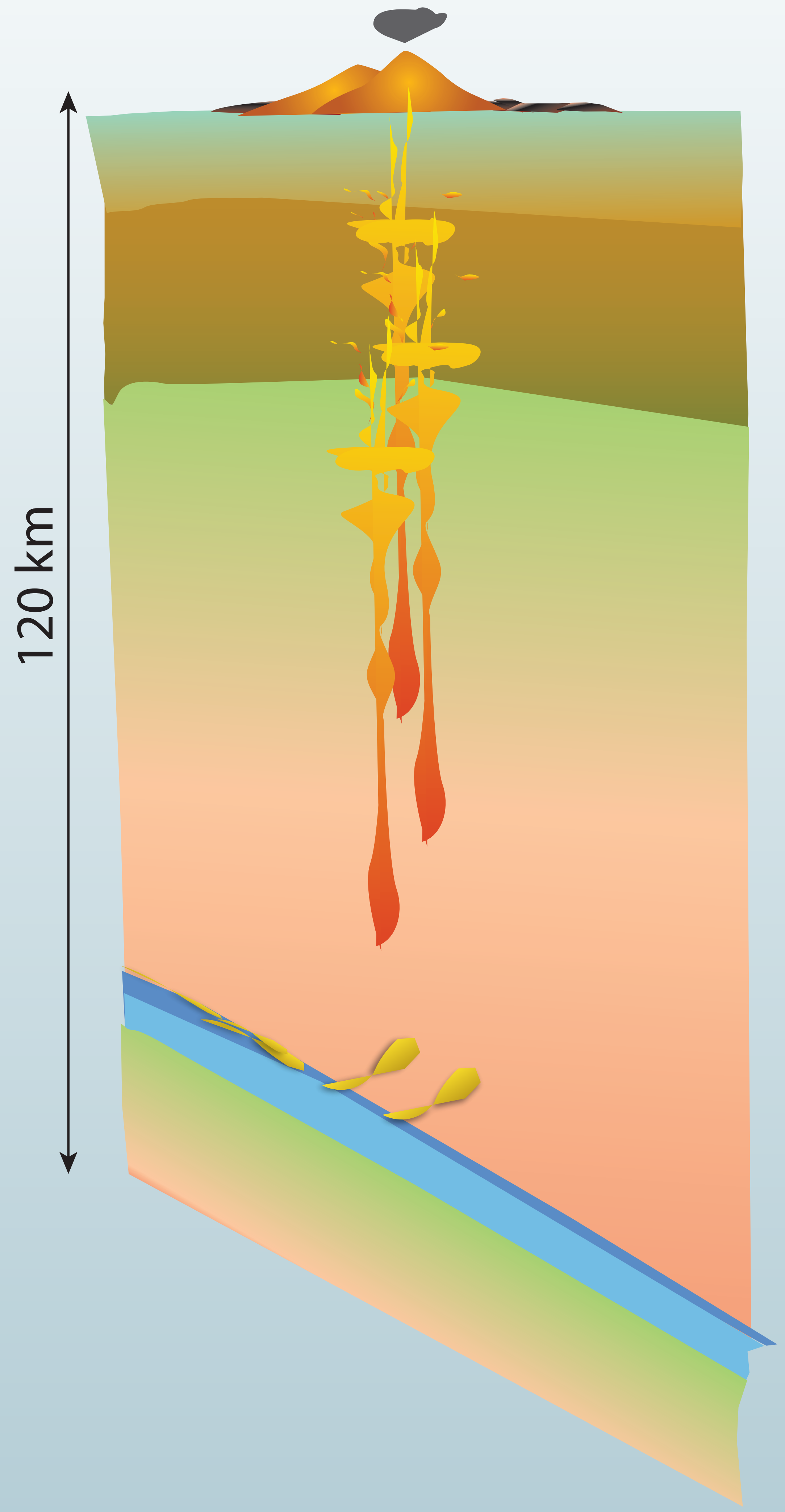
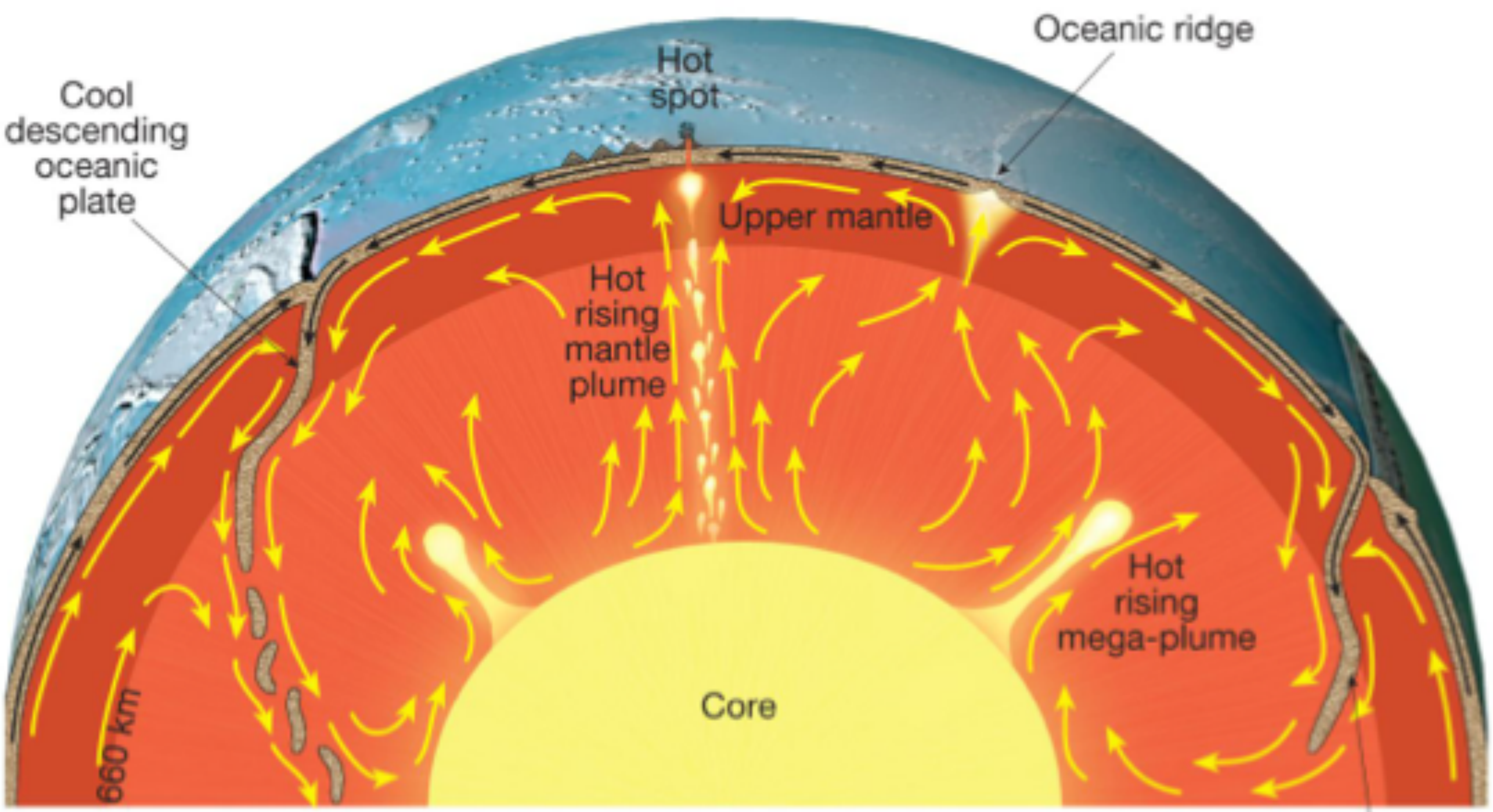
Experimental Petrology & Igneous Processes Center (EPIC)
Arizona State University

Goals For This Talk

- Transmagmatic system perspective
- Reconstructing the P-T-X±t evolution of magmas in the crust
- Recent advances & exciting future directions
  - Causes of eruption initiation?
  - Causes of intra-arc diversity?

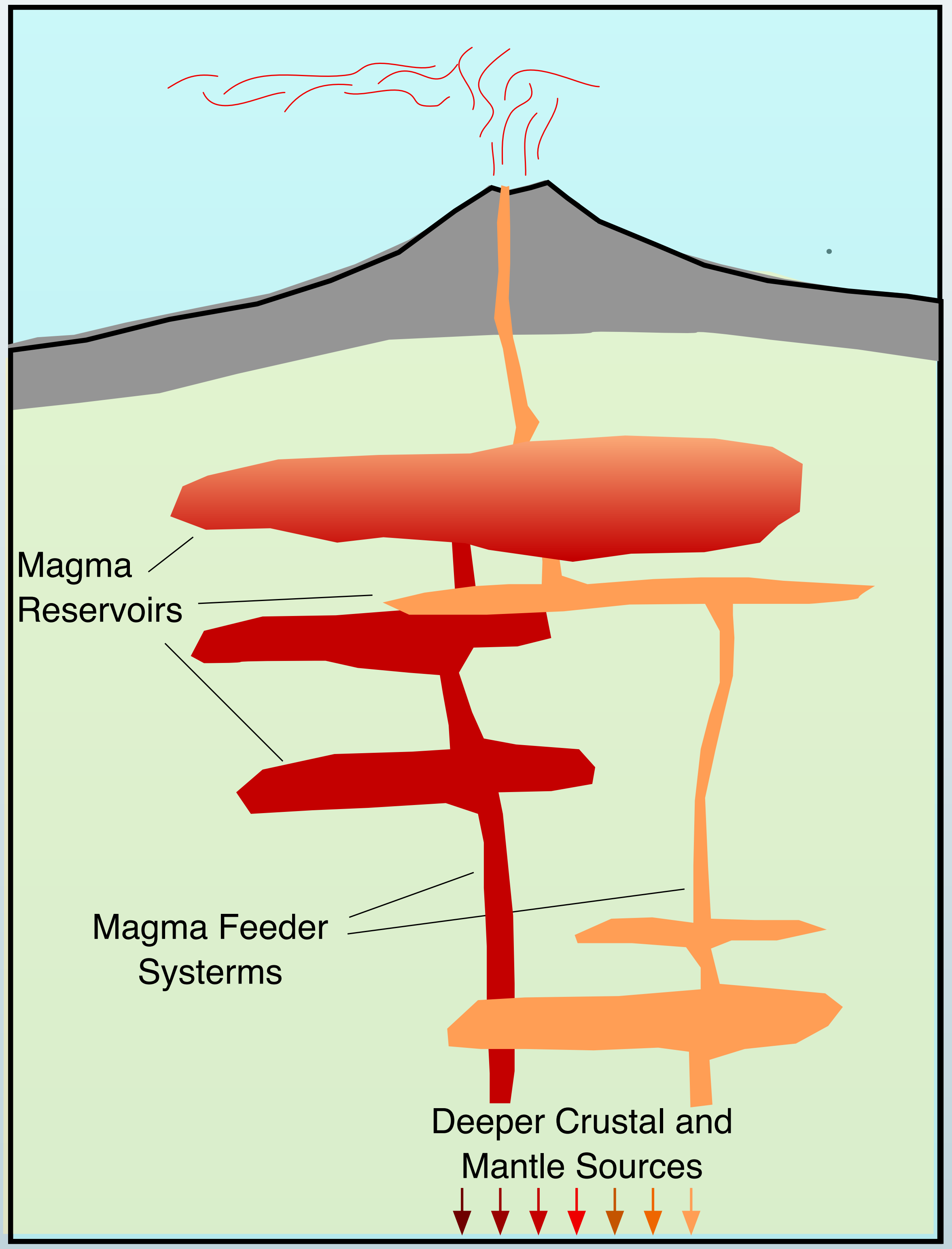


Putting Things in Context



B. Whole mantle convection

Putting Things in Context



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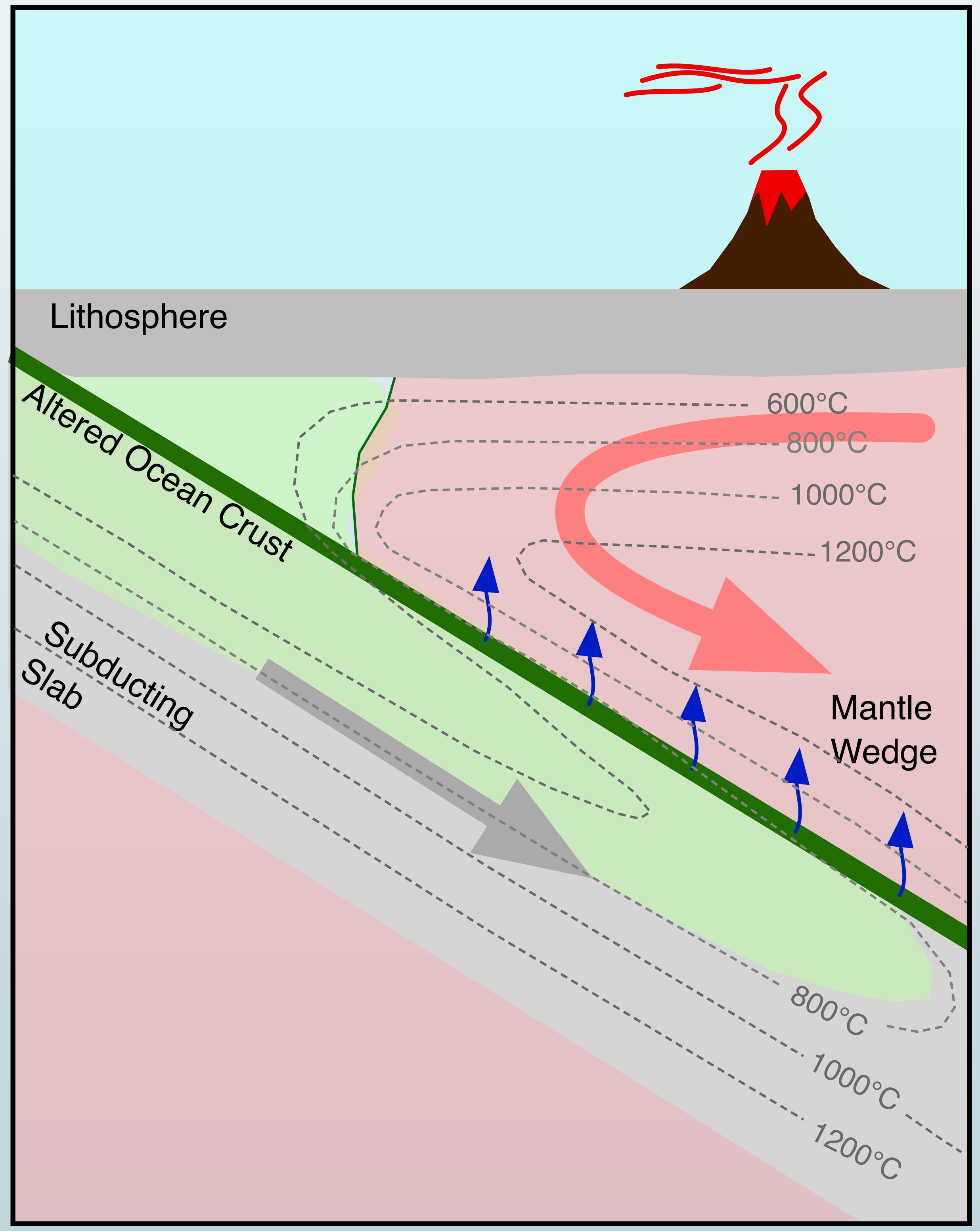
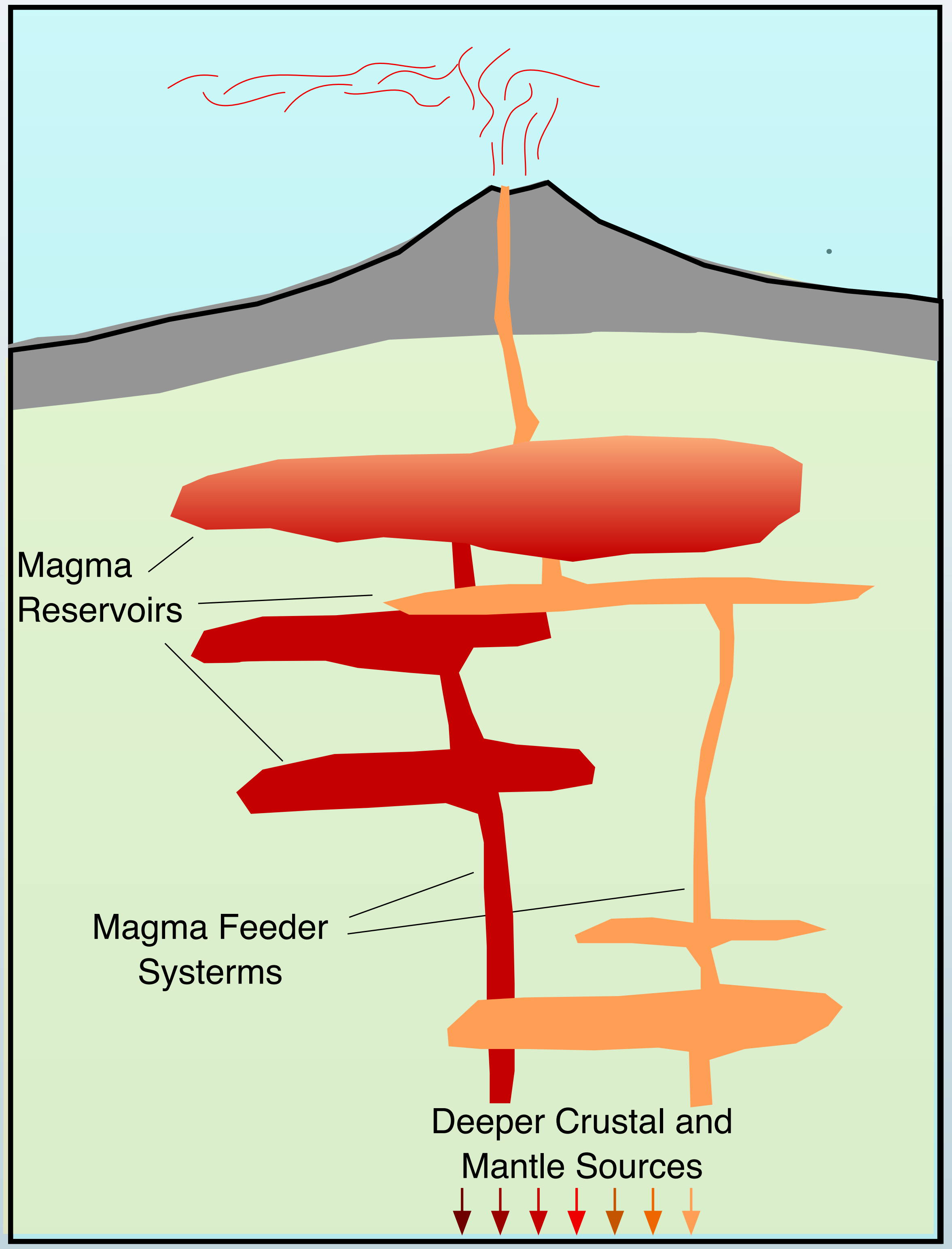
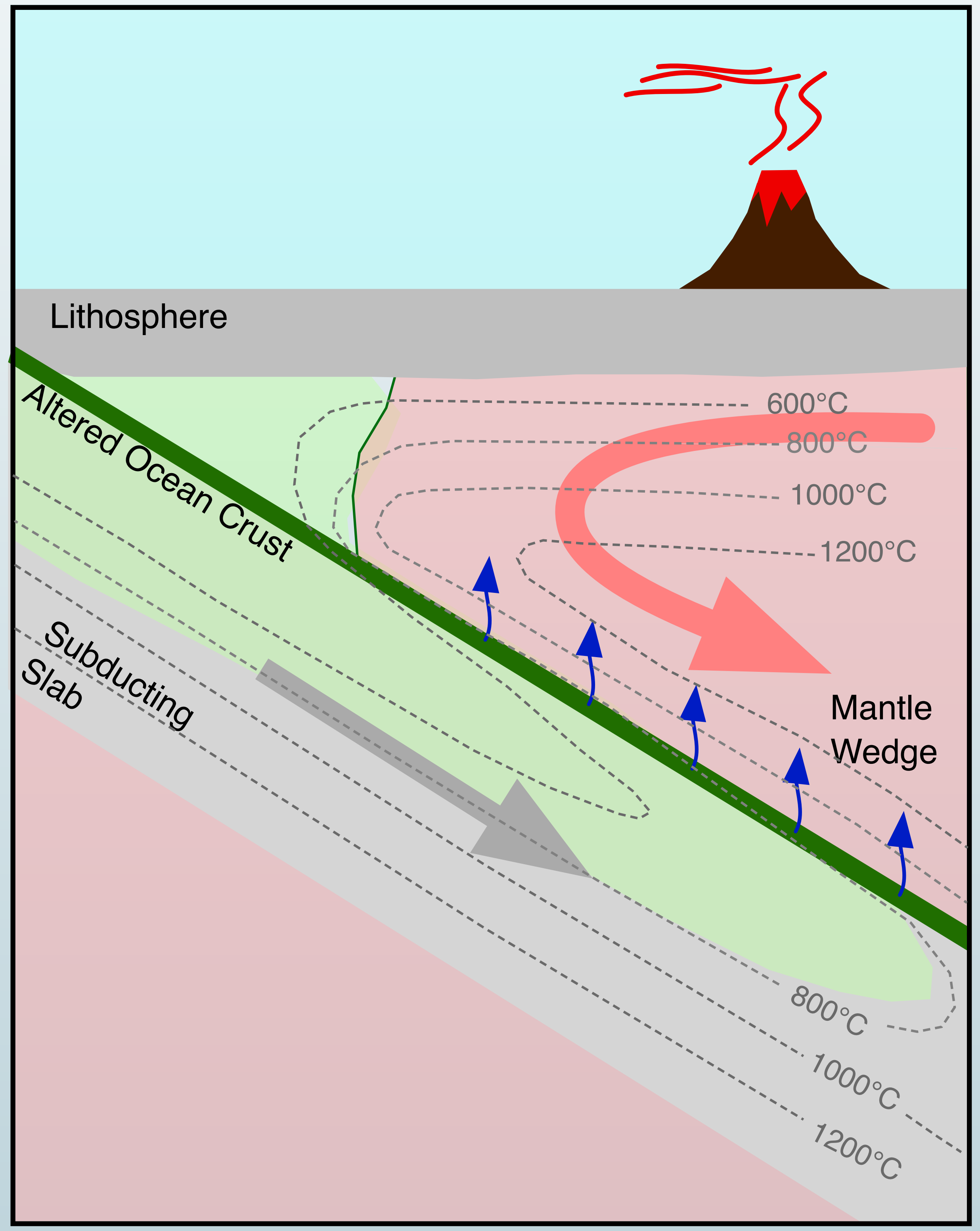




Till et al., 2019, Nat. Comm.

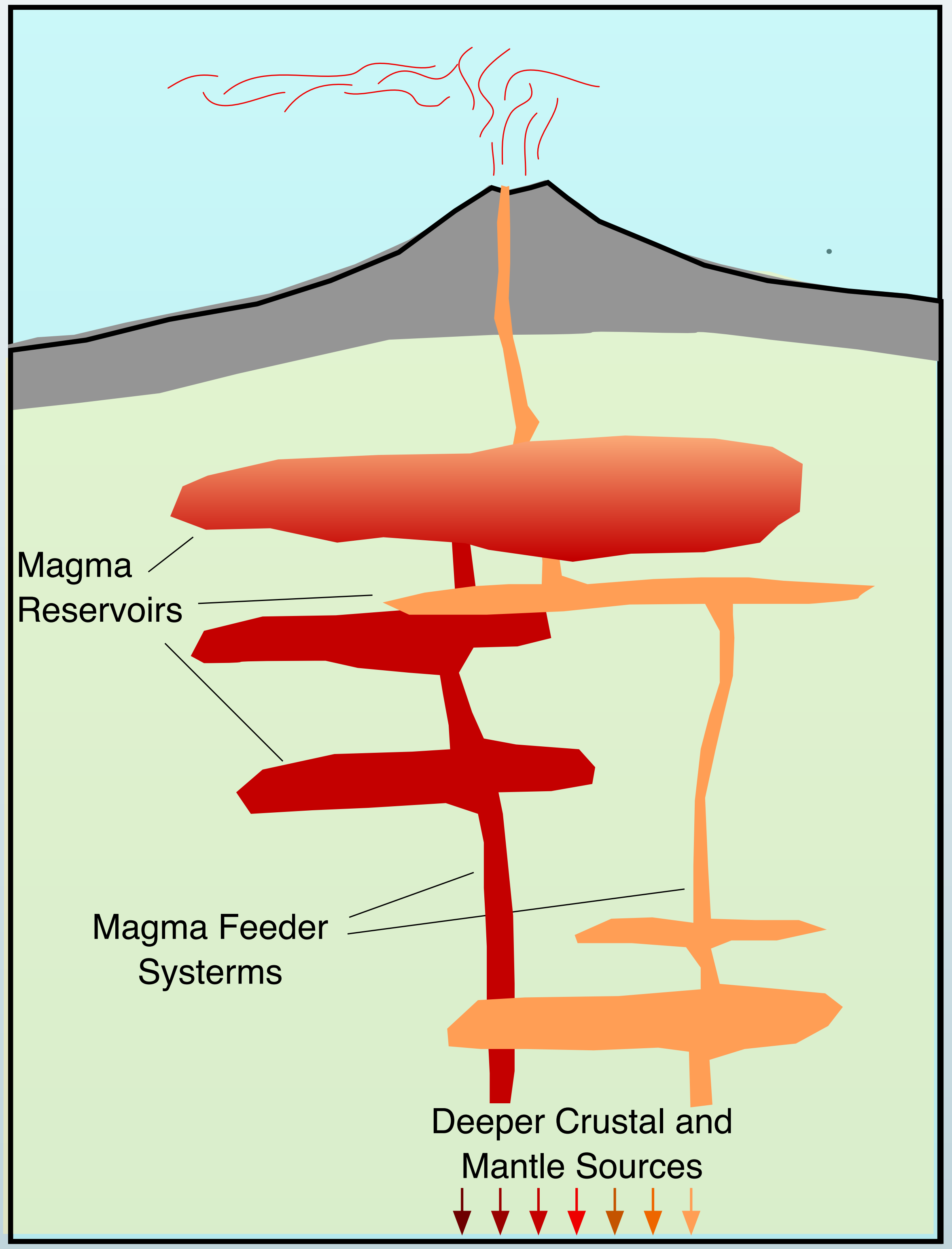
Putting Things in Context

“emoji volcano”



Till et al., 2019, Nat. Comm.

“decapitated volcano”



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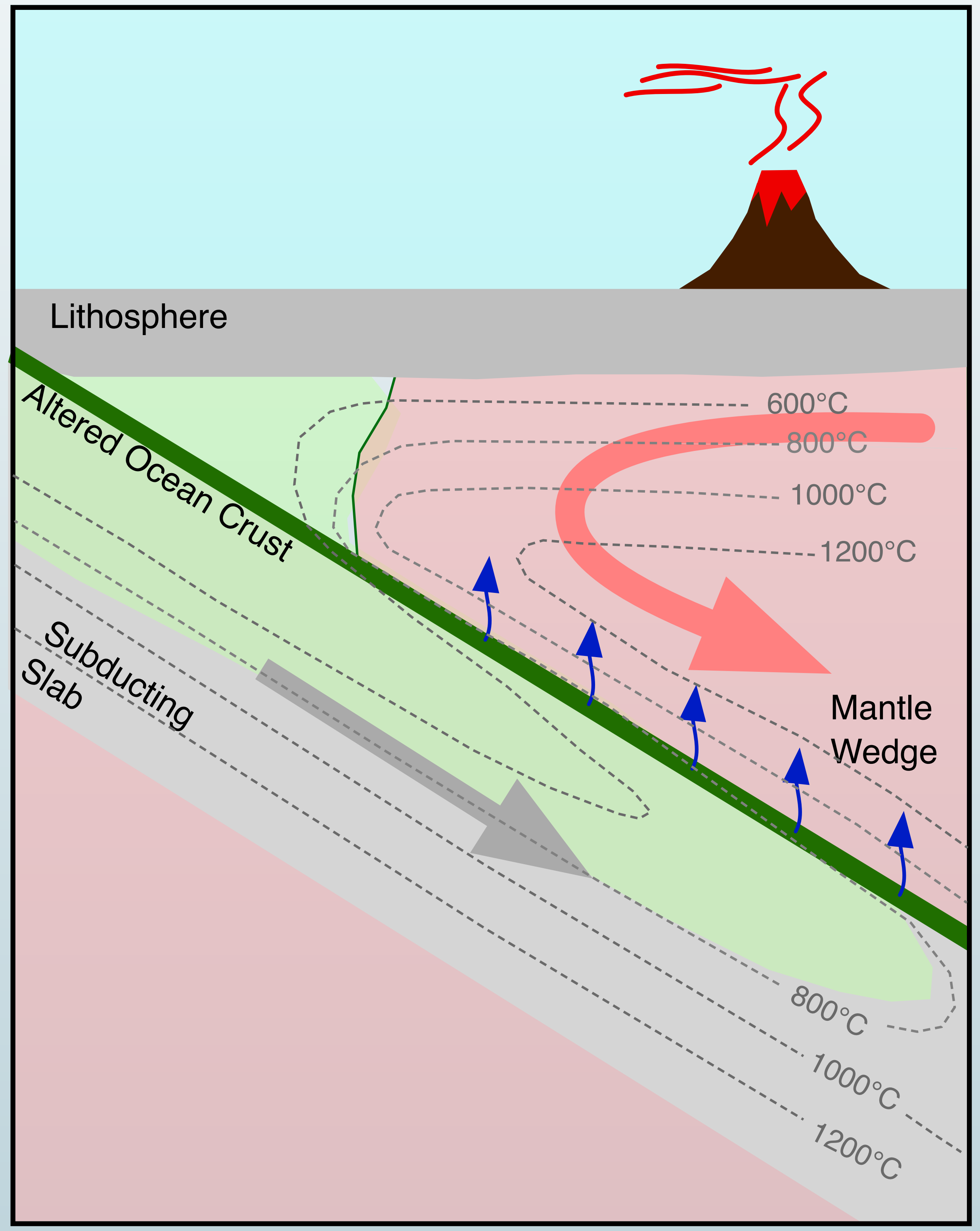

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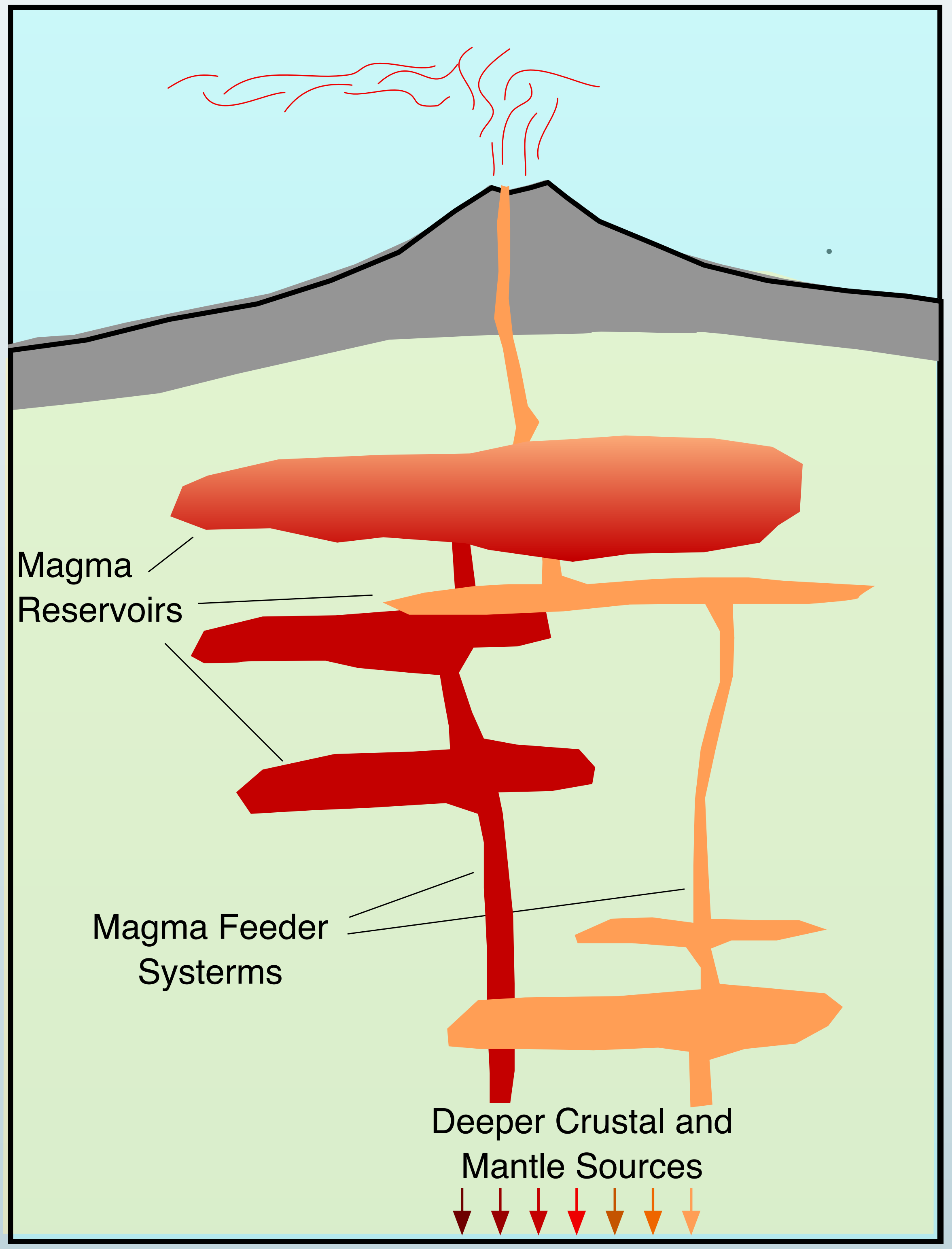

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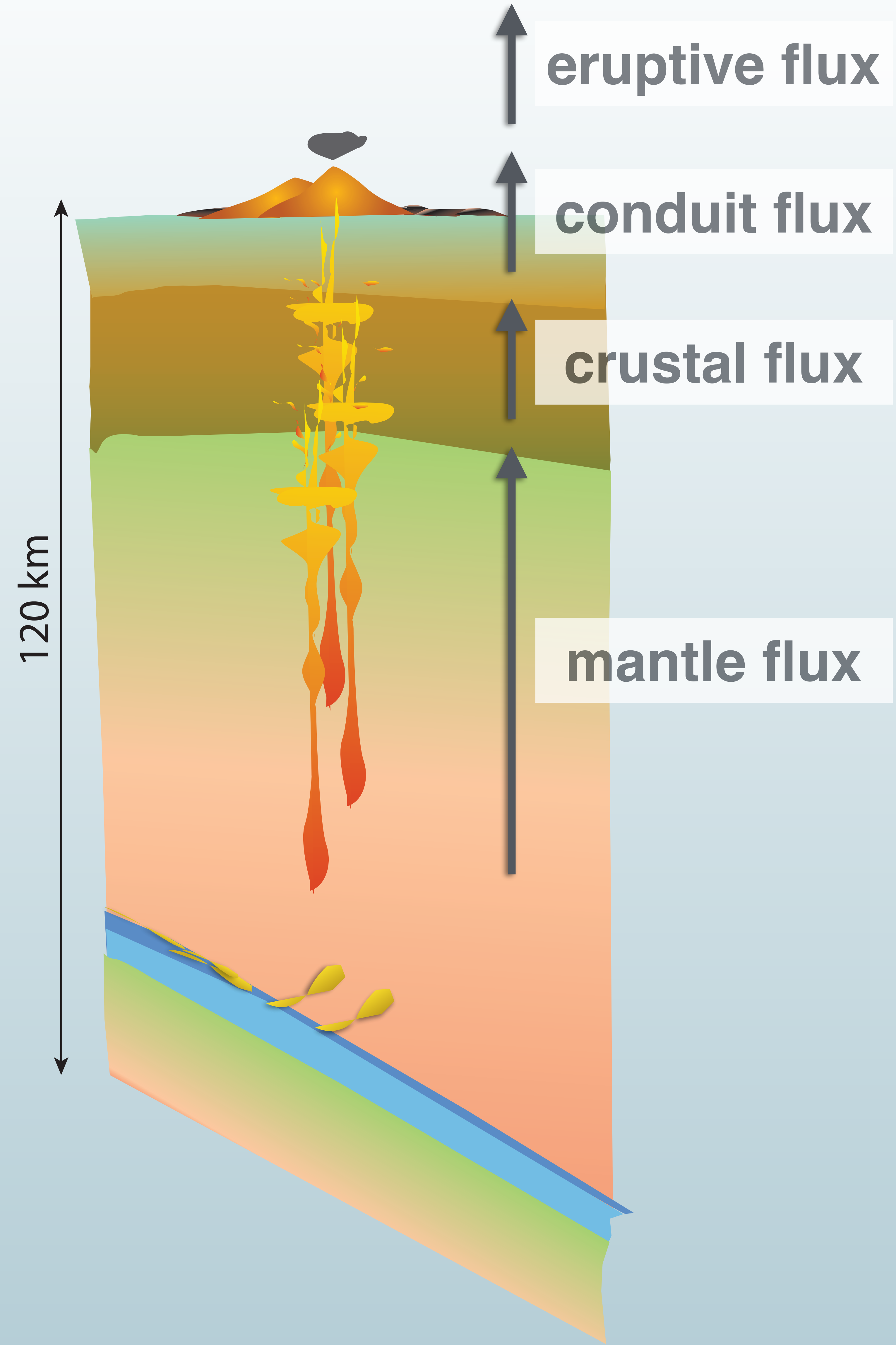


Adam Soule
Tobias Fischer
Simon Carn

Kyle Anderson
Larry Mastin (lec)
Steve Self
Joe Dufek

Bruce Hougton
Shaul Hurwitz
Einat Lev
Diana Roman

Chuck Conner
David Damby

Helge Gonnerman
Kathy Cashman

Larry Mastin (tut)
Paul Wallace*

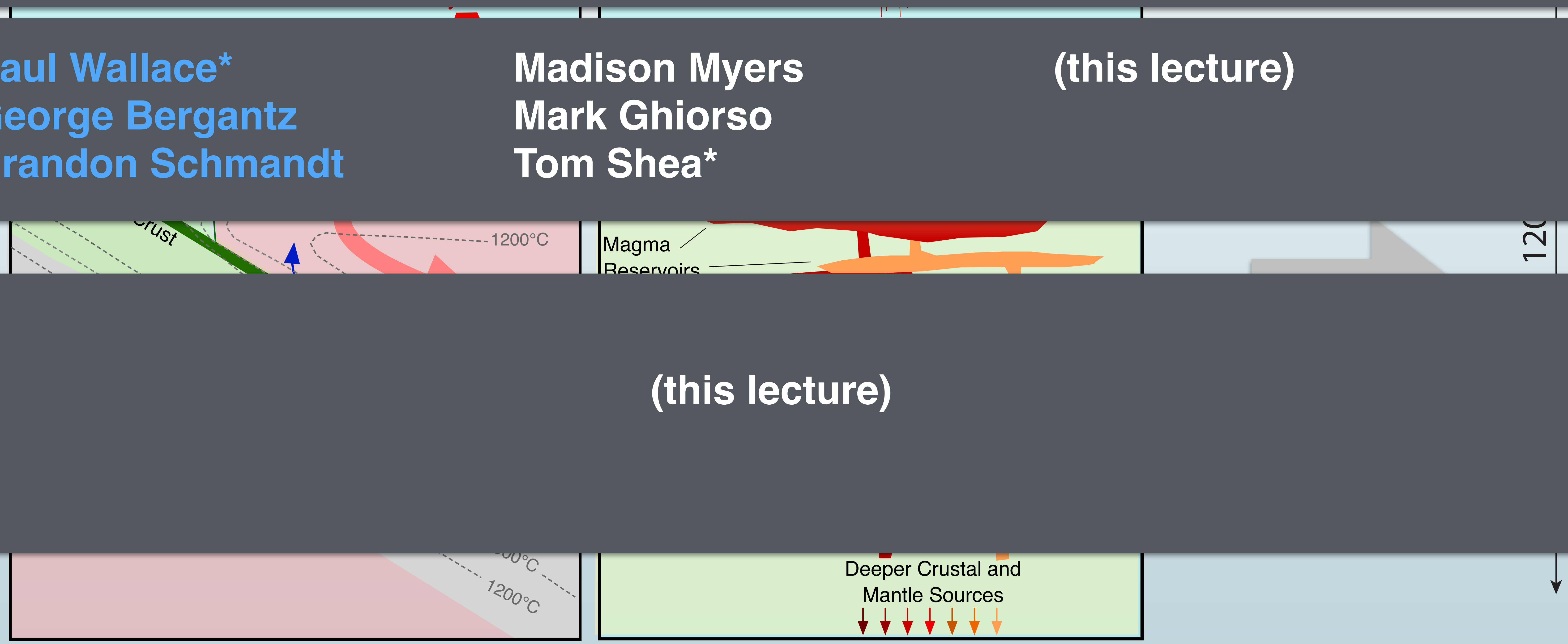
Tom Shea*

Paul Wallace*
George Bergantz
Brandon Schmandt

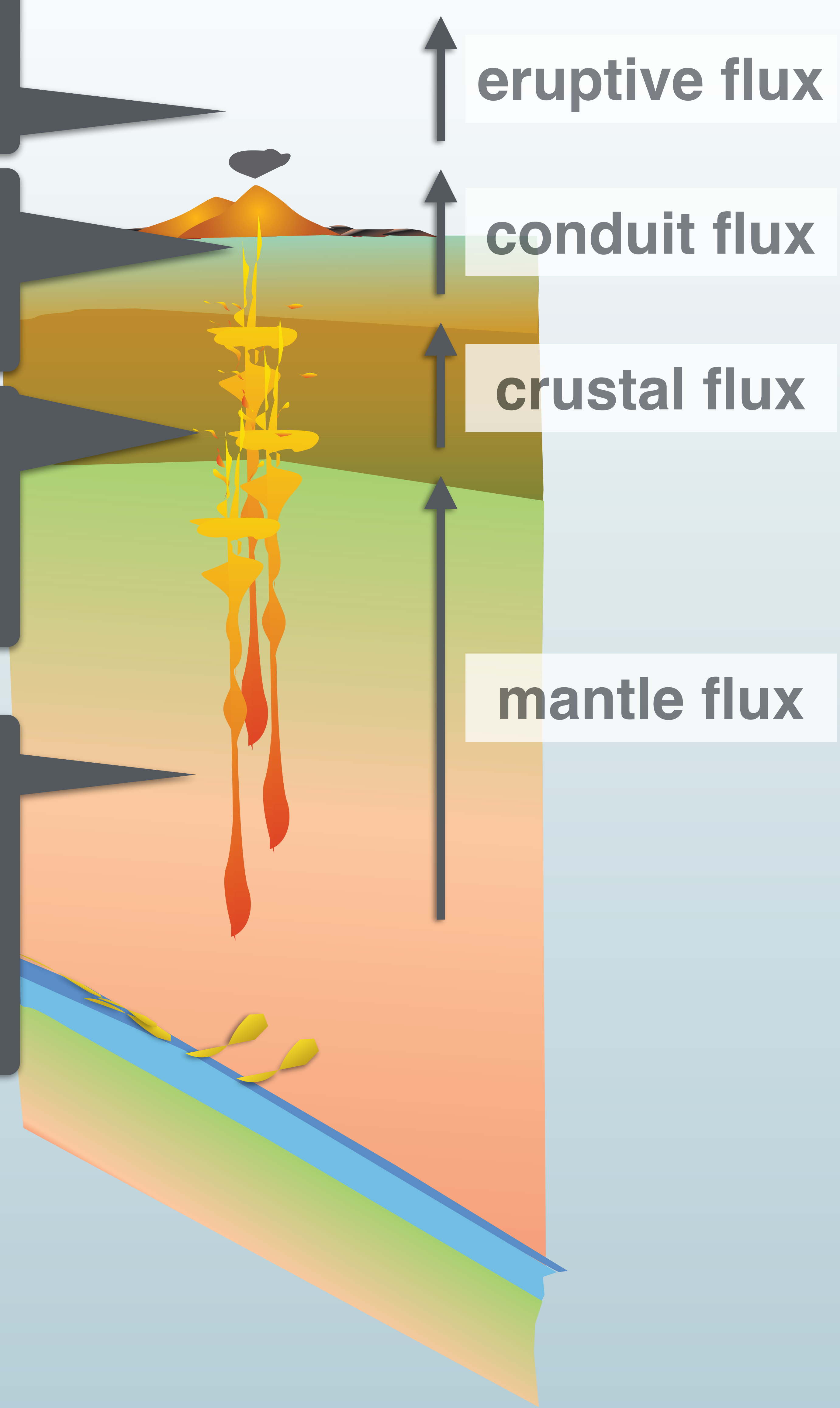
Madison Myers
Mark Ghiorso
Tom Shea*

(this lecture)

(this lecture)

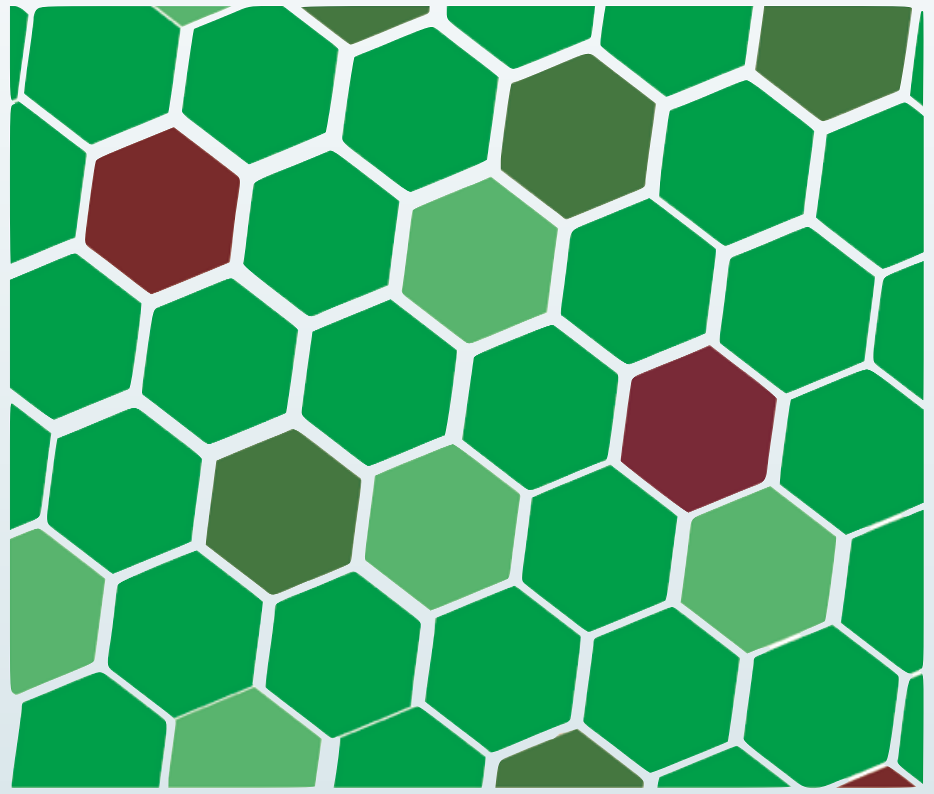


Till et al., 2019, Nat. Comm.

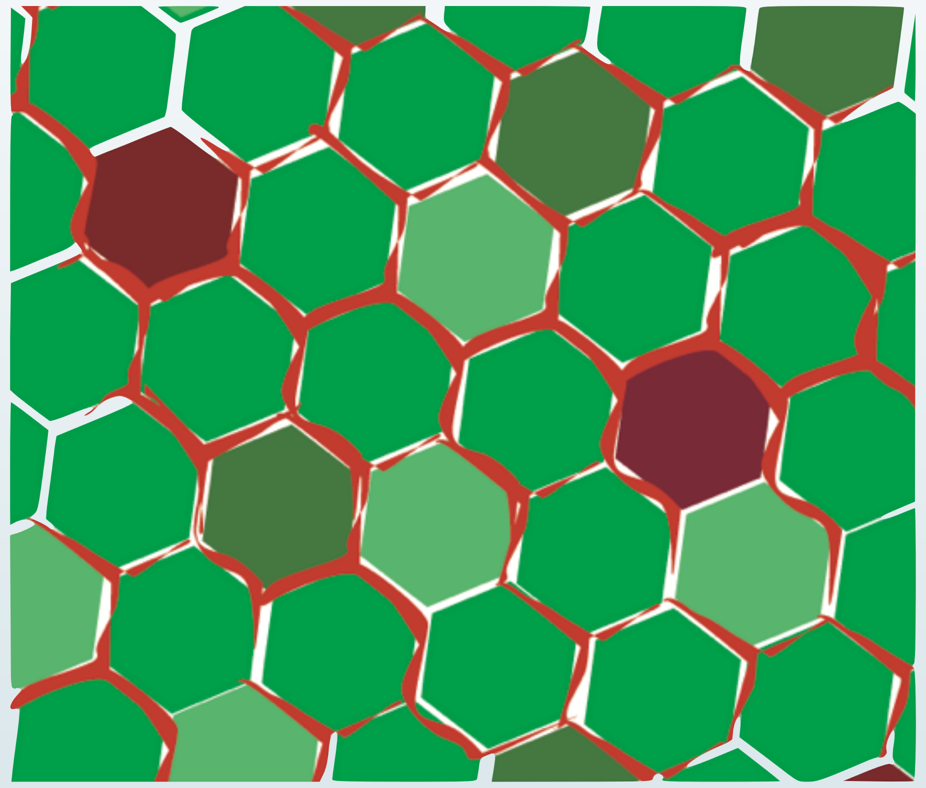


The Mantle Matters

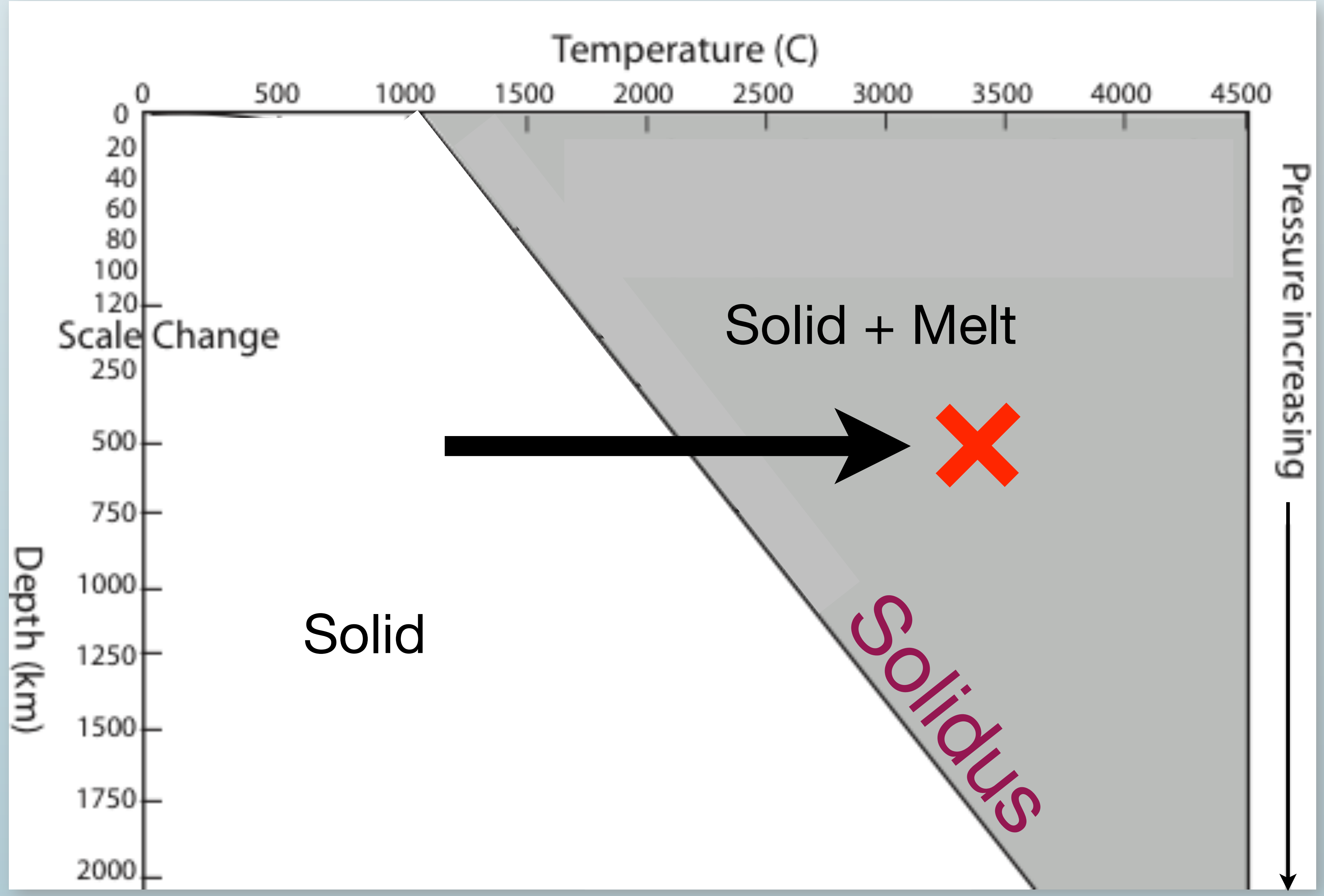
What does mantle melting really mean?



solid



solid + melt



Peridotite =

60% **olivine**

15% **clinopyroxene**

15% **orthopyroxene**

10% **plagioclase/spinel/garnet**

<9.5 kbar >9.5 kbar >18 kbar


Temperature
Pressure
Tp
Adiabat
Solidus
Dry, Decompression Melting Dominates
Temperature
Pressure
Tp
Adiabat
Dry Solidus
Flux Melting Dominates
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Oceanic Lithosphere
Wet Melting
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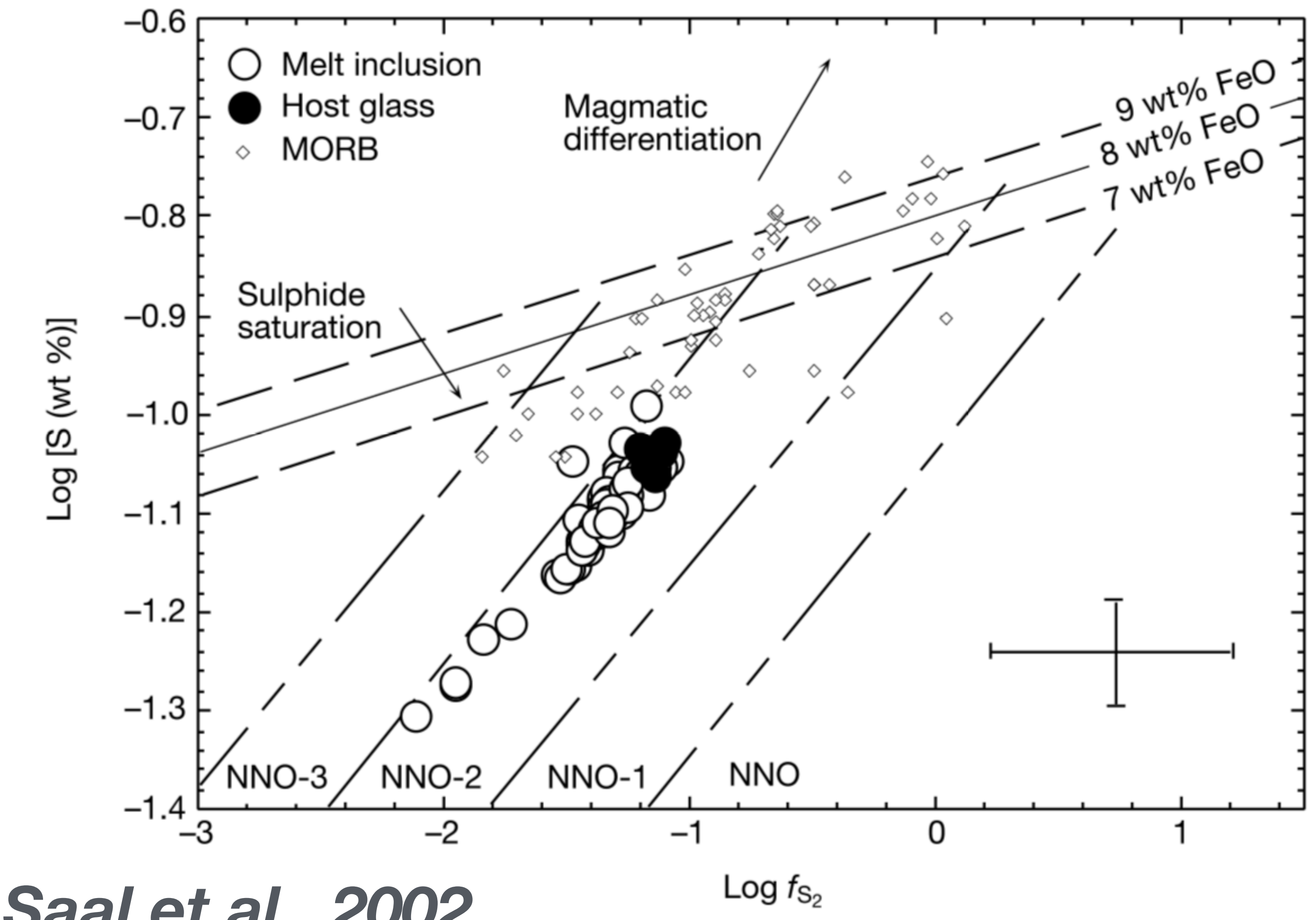
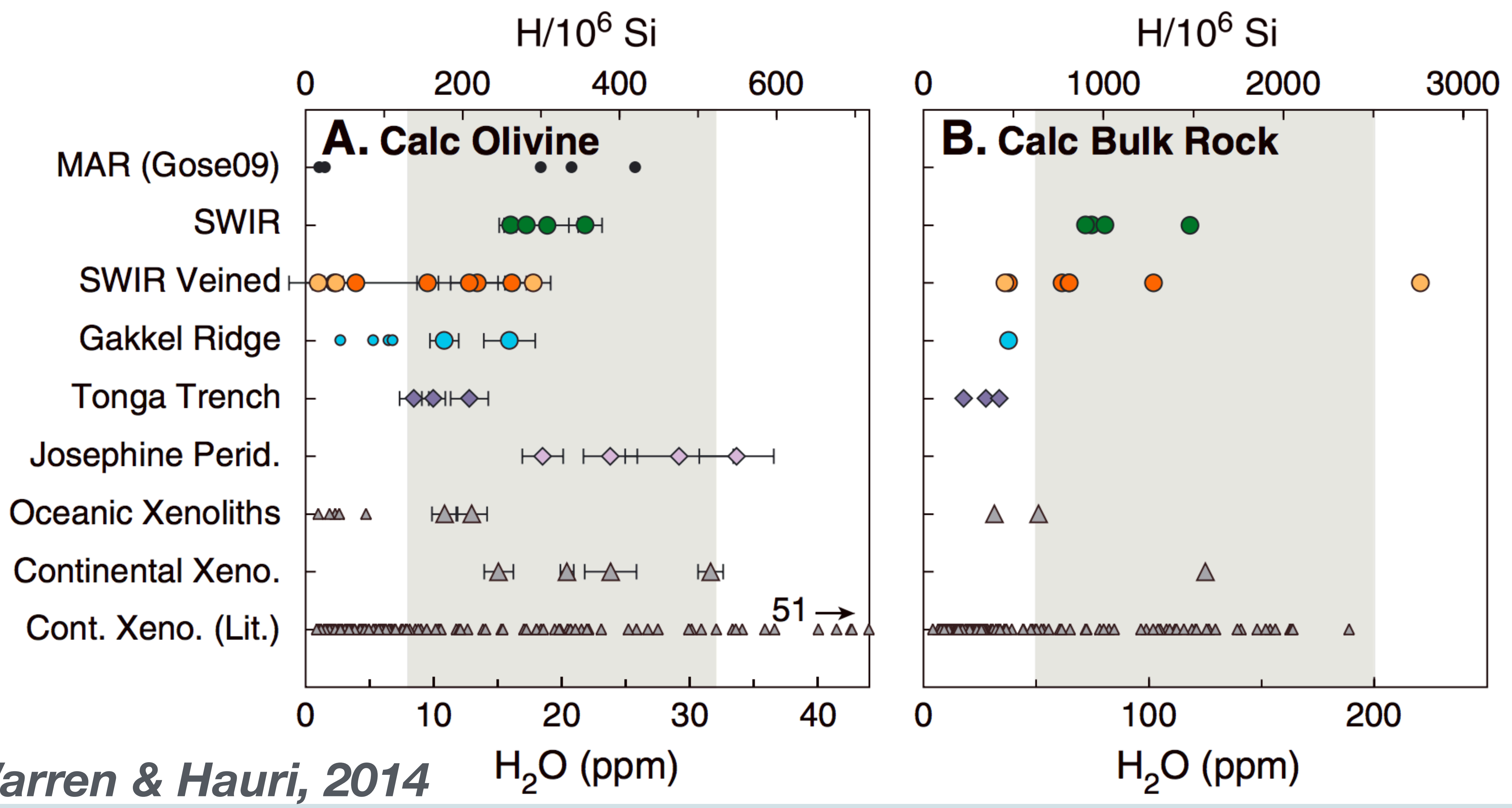
Magmatic Volatiles are Largely Mantle Derived



Saal et al., 2002



Warren & Hauri, 2014

Estimates of av. depleted upper mantle volatile contents:

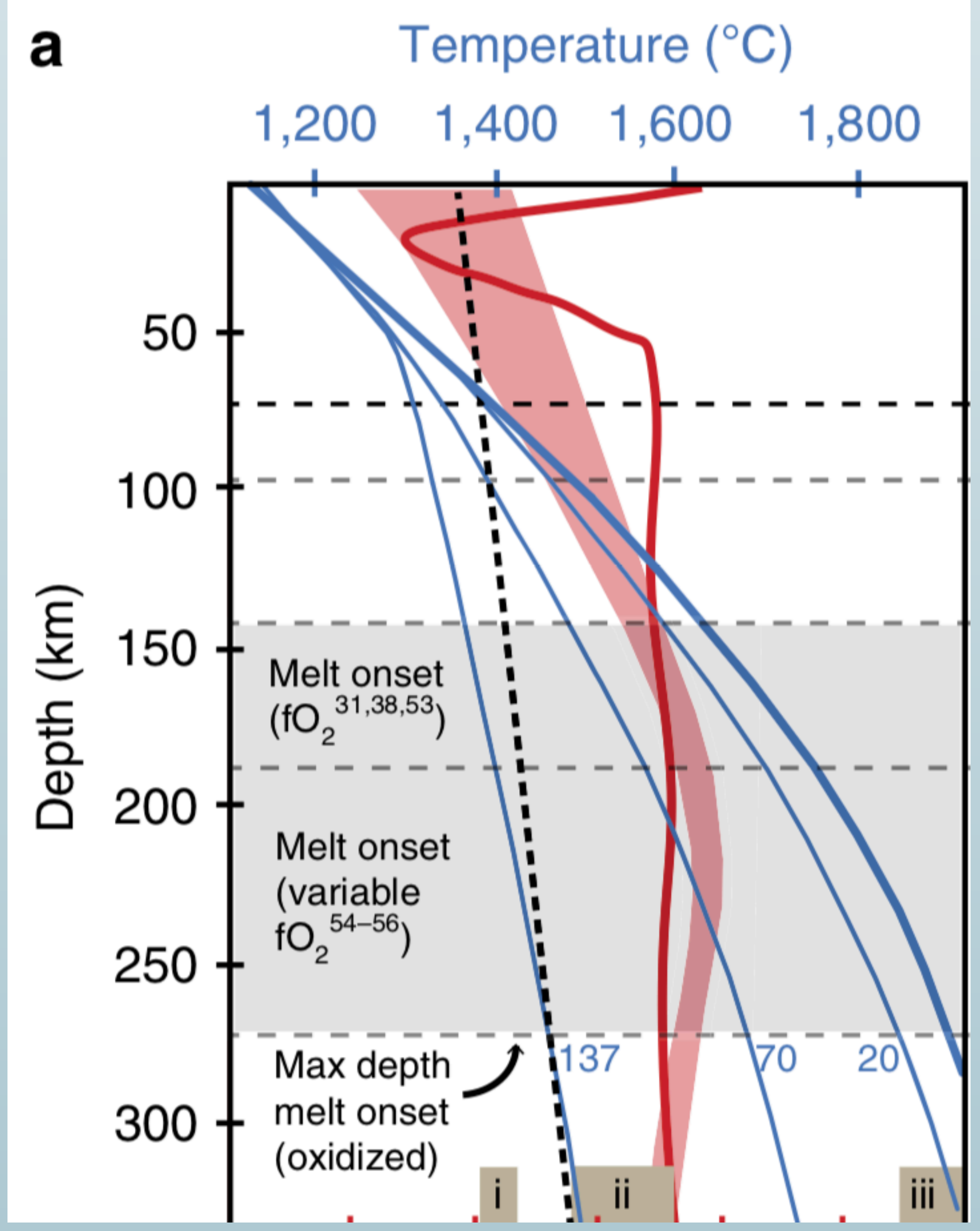
F: 250 ± 50 ppm

S: 146 ± 35 ppm

Cl: 1 ± 0.5 ppm

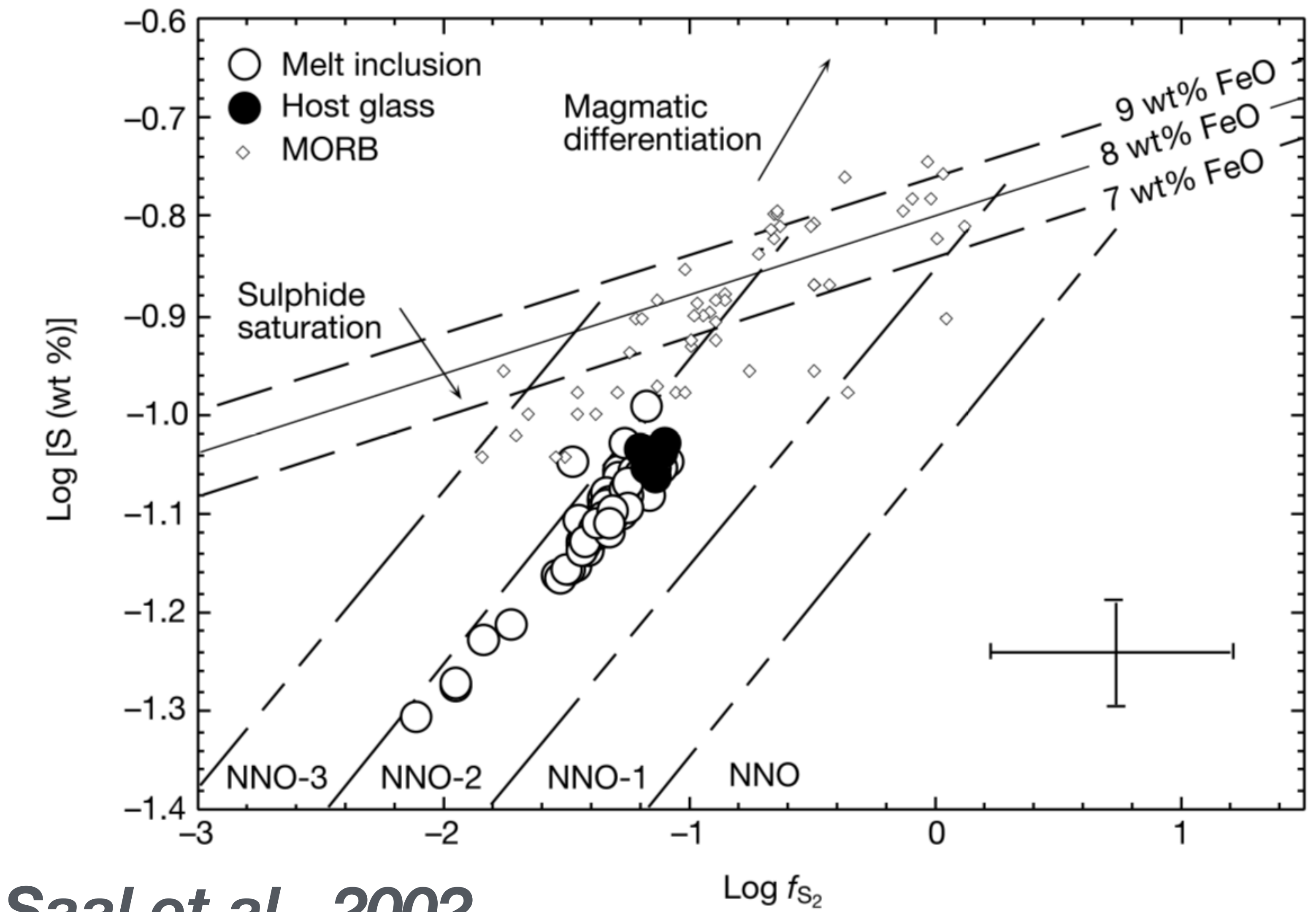
CO_2: 20 - 260 ppm

H_2O: 20-220 ppm

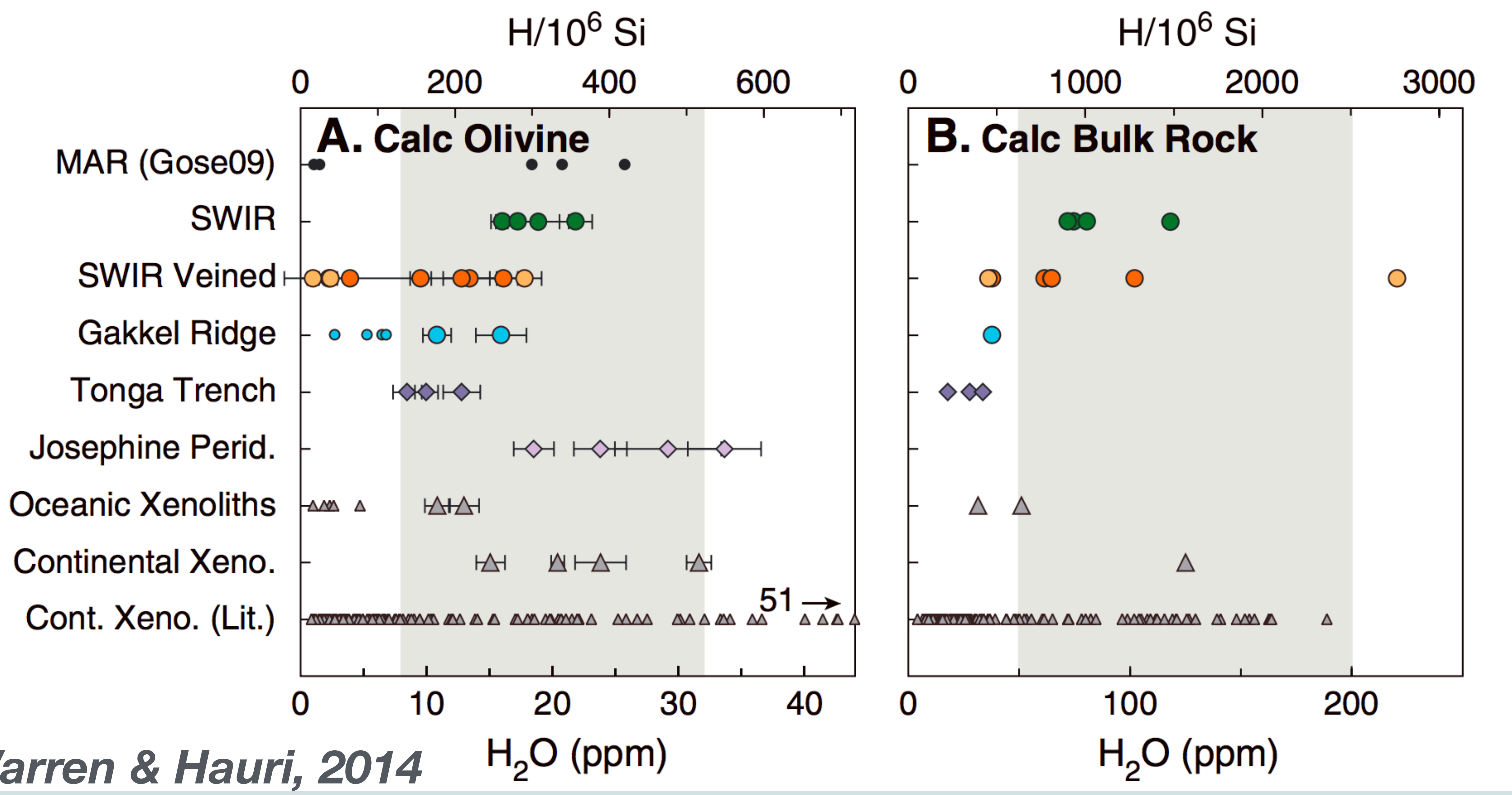


Le Voyer et al., 2017

Magmatic Volatiles are Largely Mantle Derived



Saal et al., 2002



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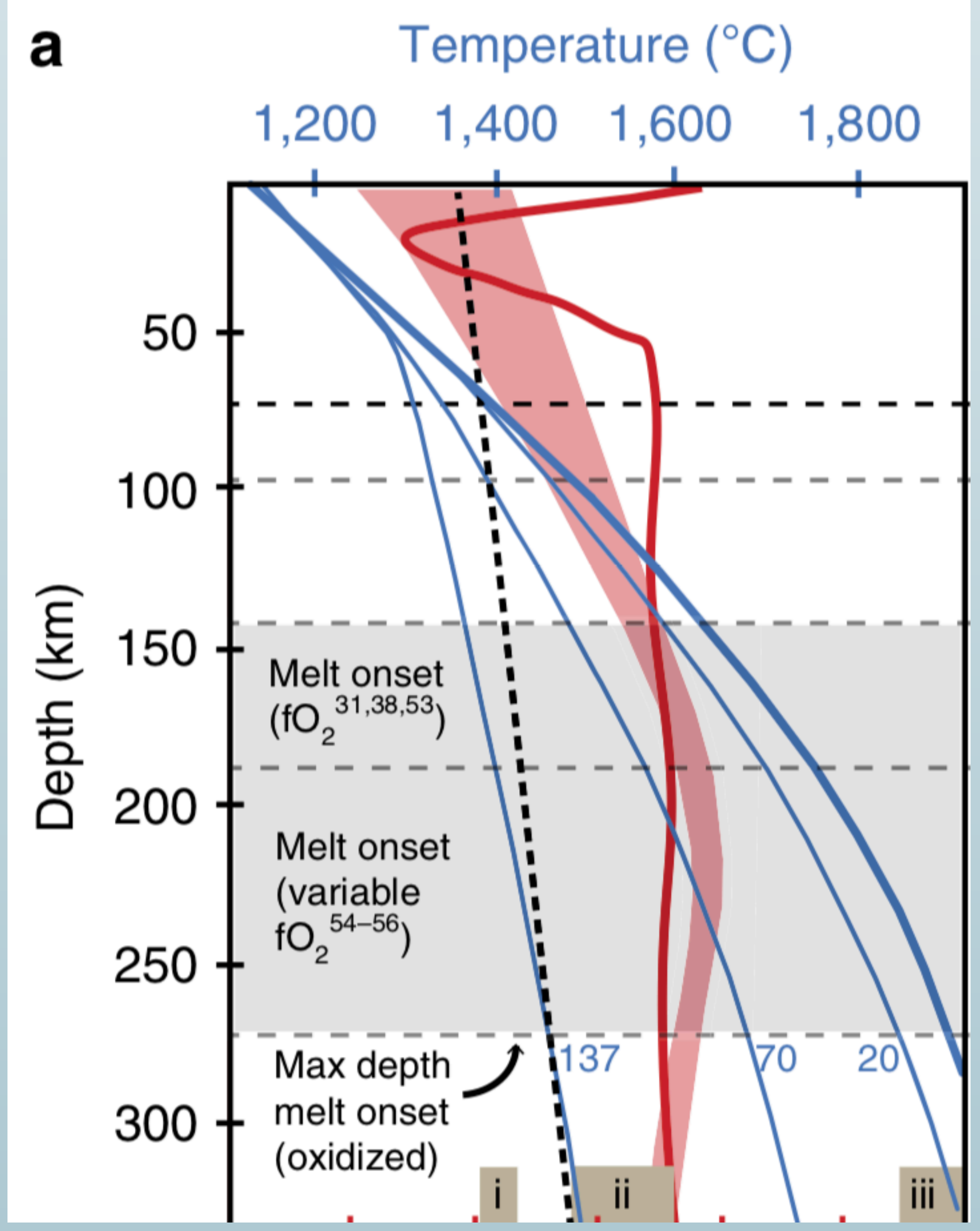
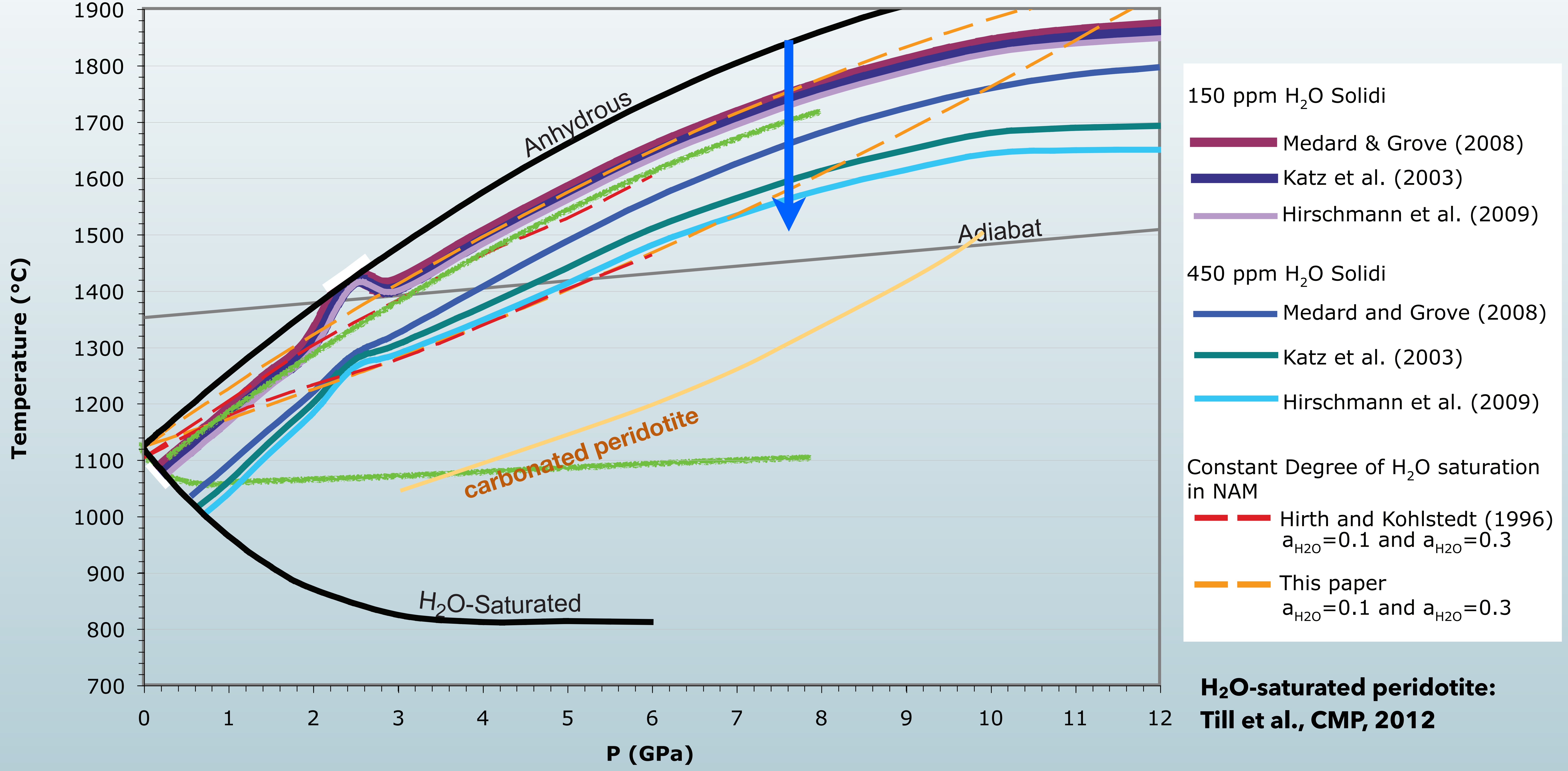
enough to create the flux out of volcanoes?



Le Voyer et al., 2017

Volatile-Effects on Mantle Solidi

volatiles (H_2O, CO_2) lower melting temperature at a given depth



H_2O-saturated peridotite: Till et al., CMP, 2012

H2O + peridotite: Katz et al, 2003

carbonated peridotite: Dasgupta & Hirschmann, 2006

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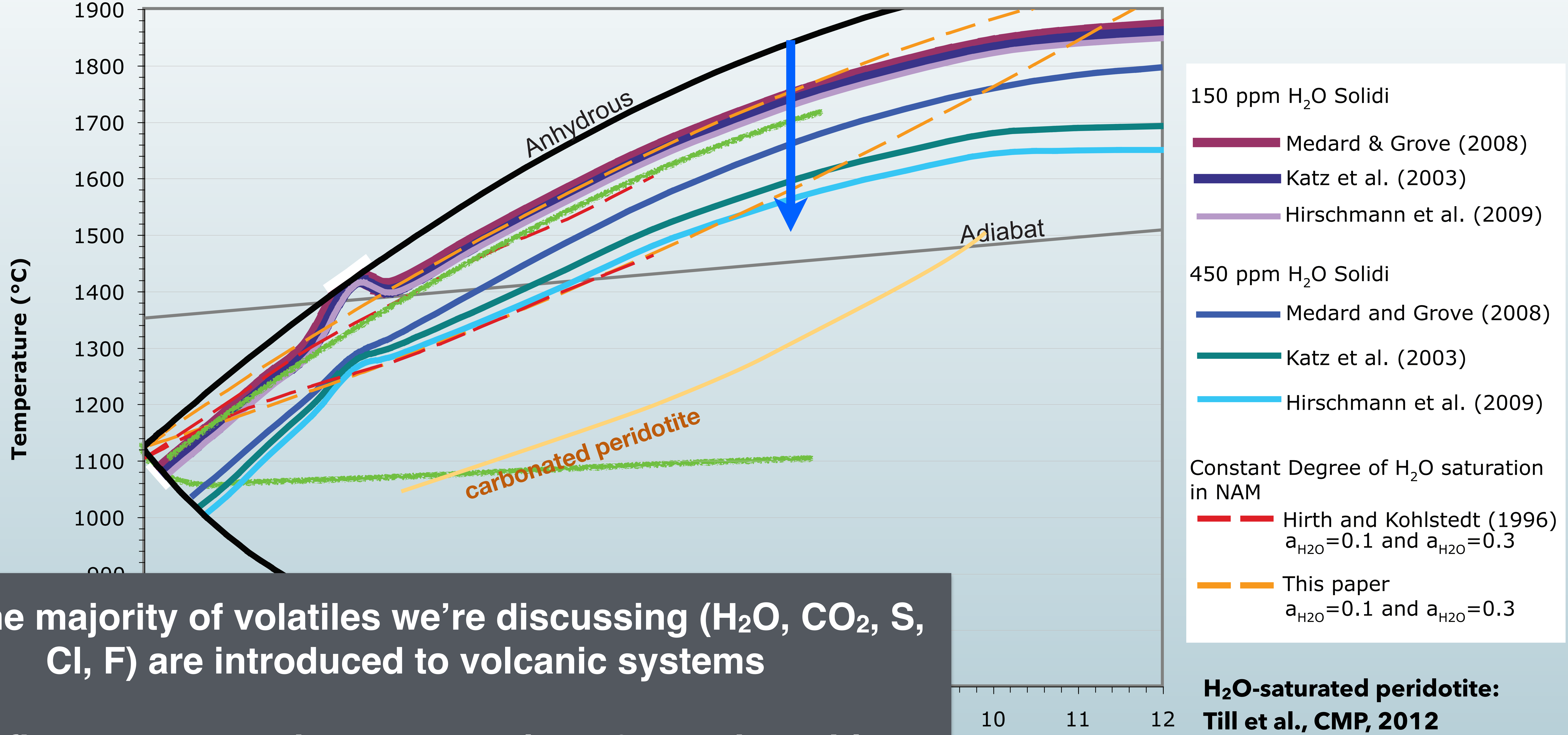


how the majority of volatiles we're discussing (H_2O, CO_2, S, Cl, F) are introduced to volcanic systems

—> reflect upper mantle concentrations & mantle melting processes

H_2O-saturated peridotite: Till et al., CMP, 2012

2O + peridotite: atz et al, 2003

carbonated peridotite: Dasgupta & Hirschmann, 2006

Magmatic Diversity Inherited From the Mantle

Illustrates relationships between
Pressure,
Temperature,
Extent of Melting (Melt %)
&
Melt Major Element Composition
generated during mantle melting

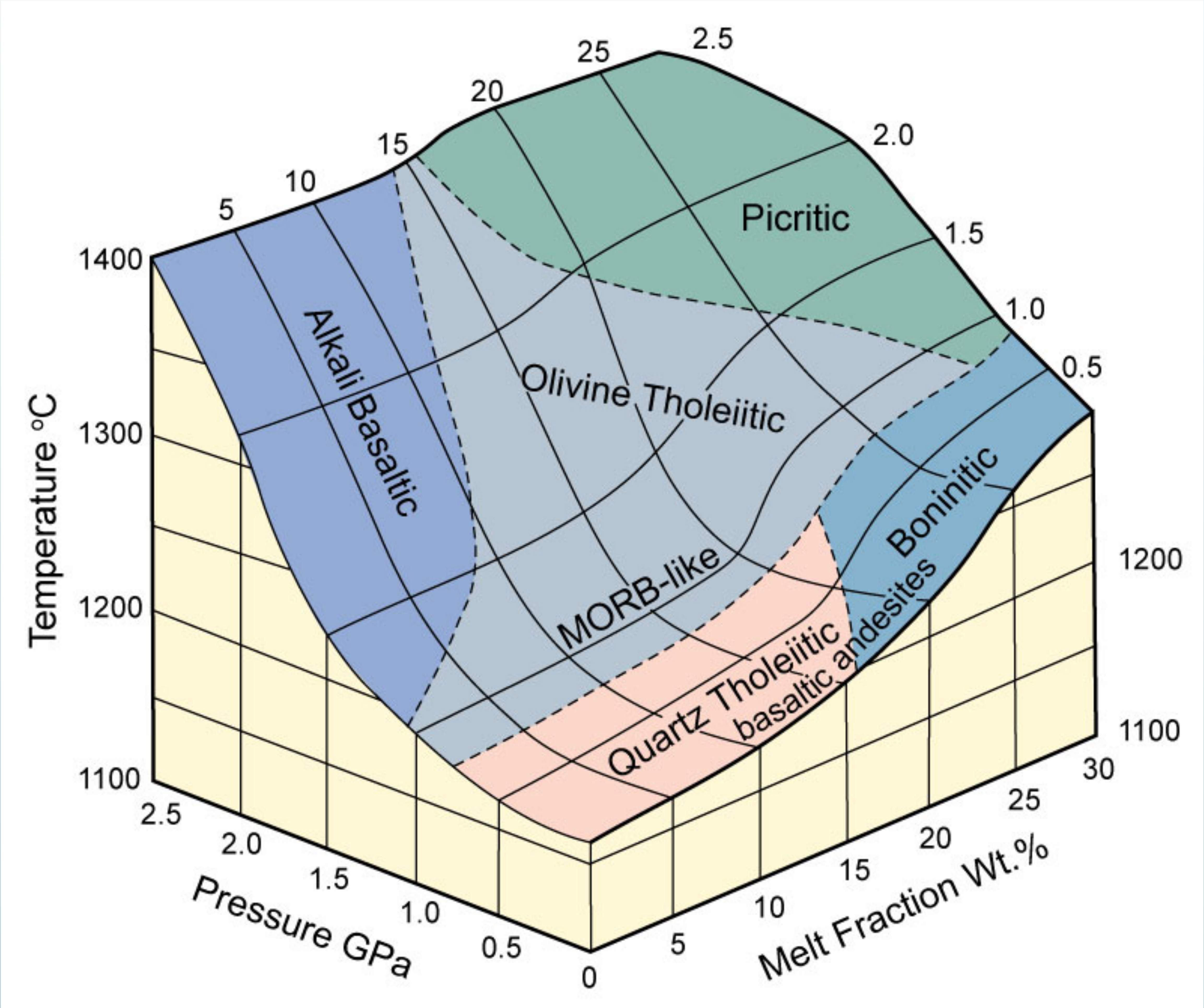
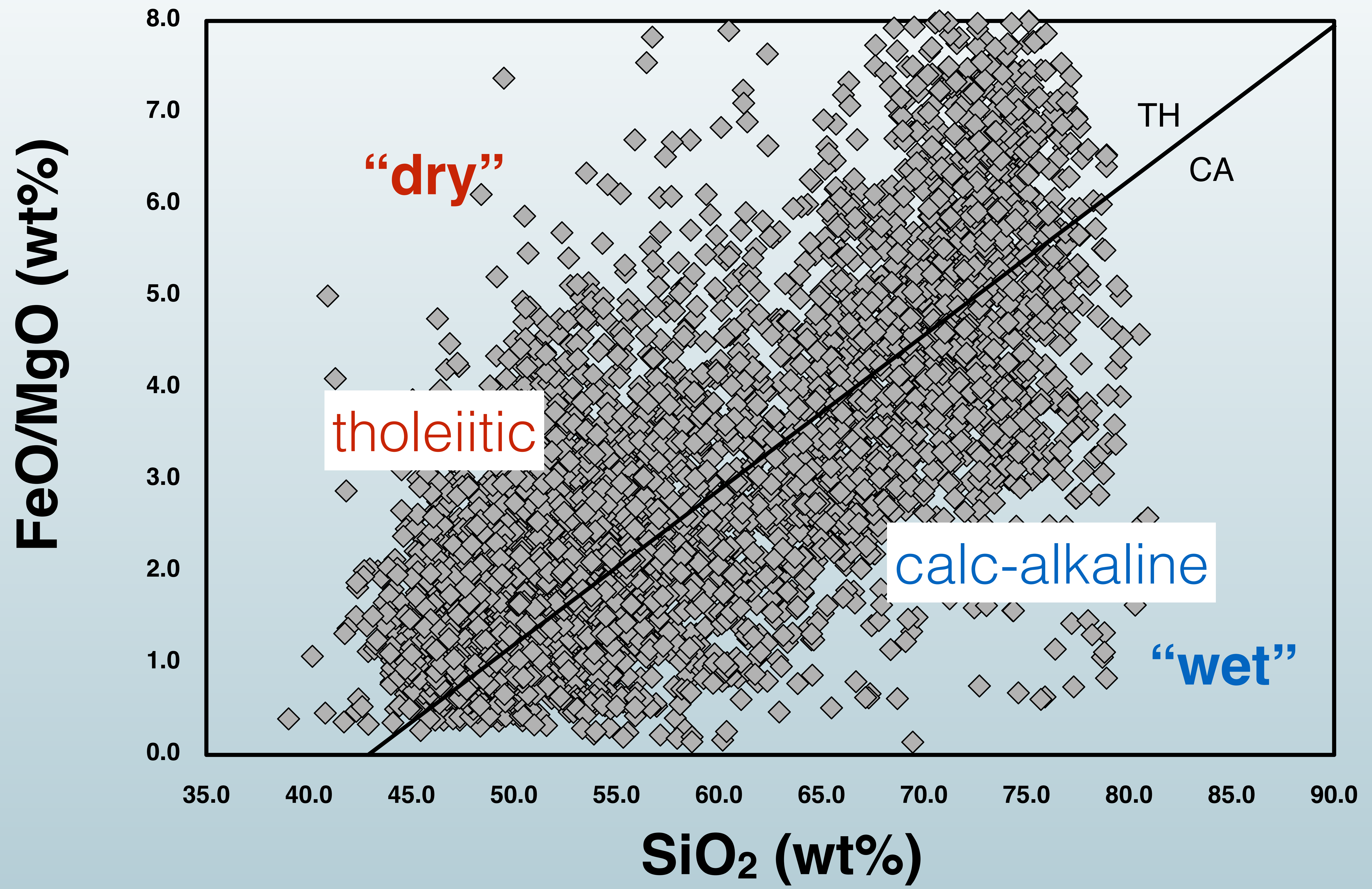
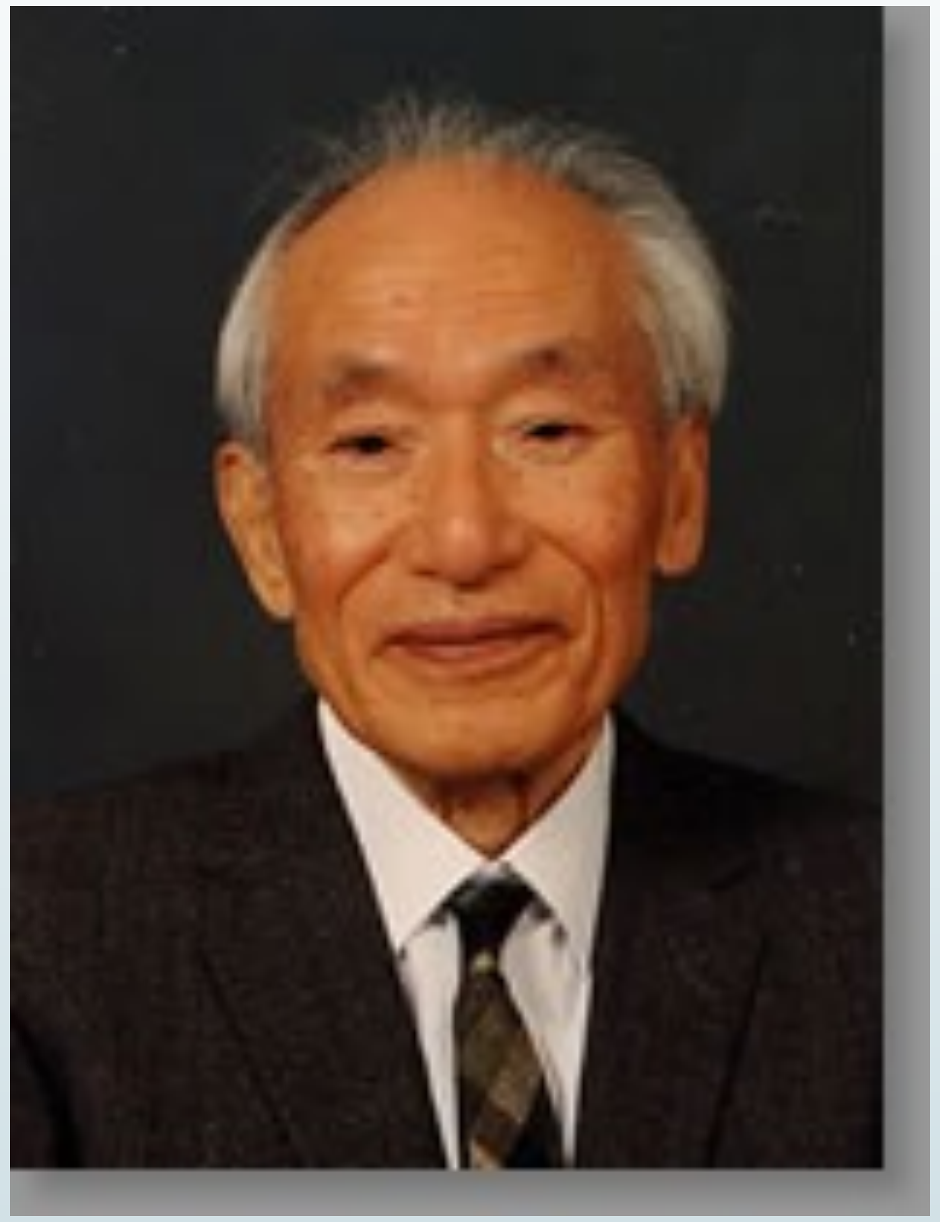


Figure after Kushiro (2001)

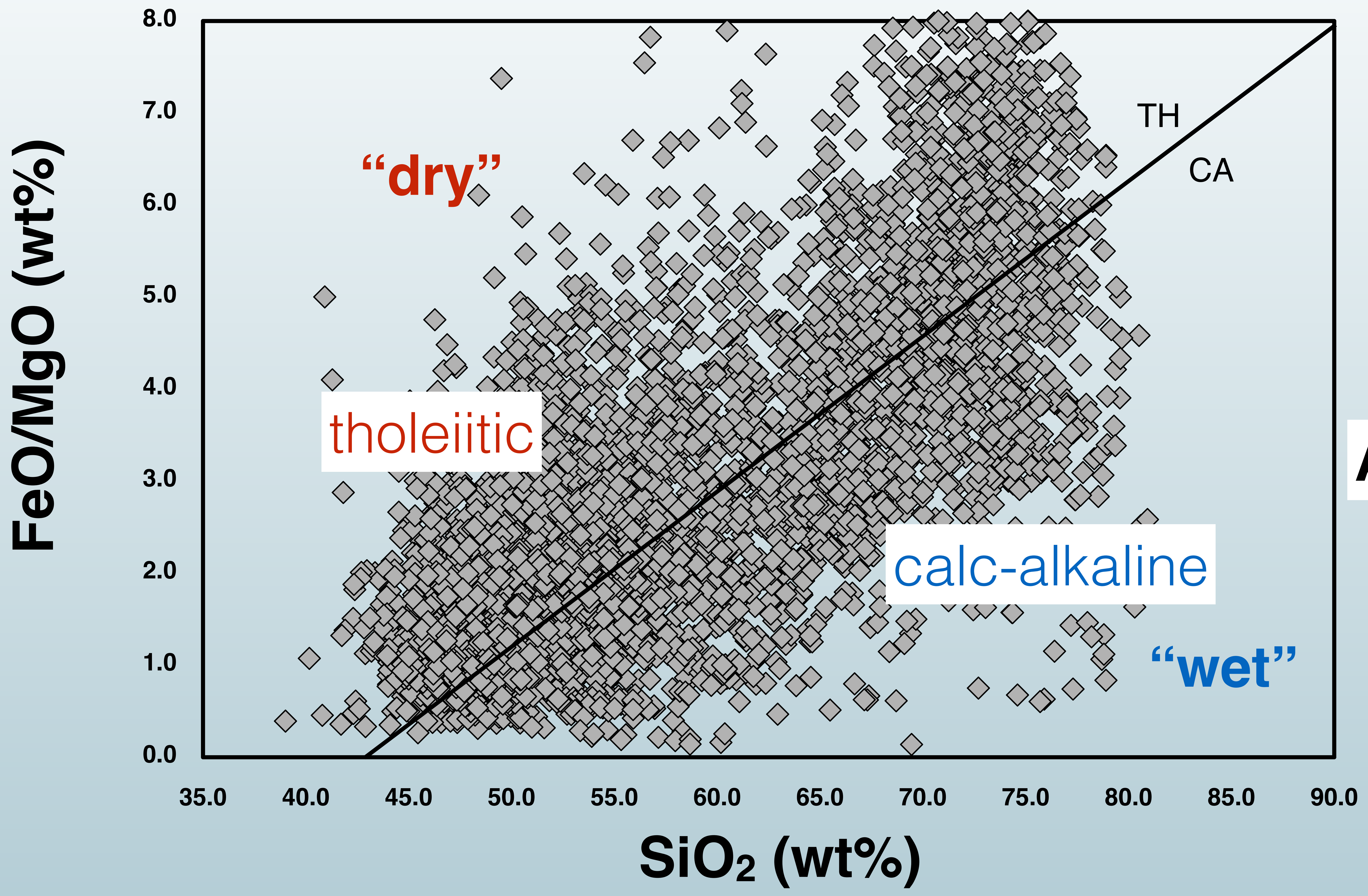
Magmatic Diversity Inherited From the Mantle

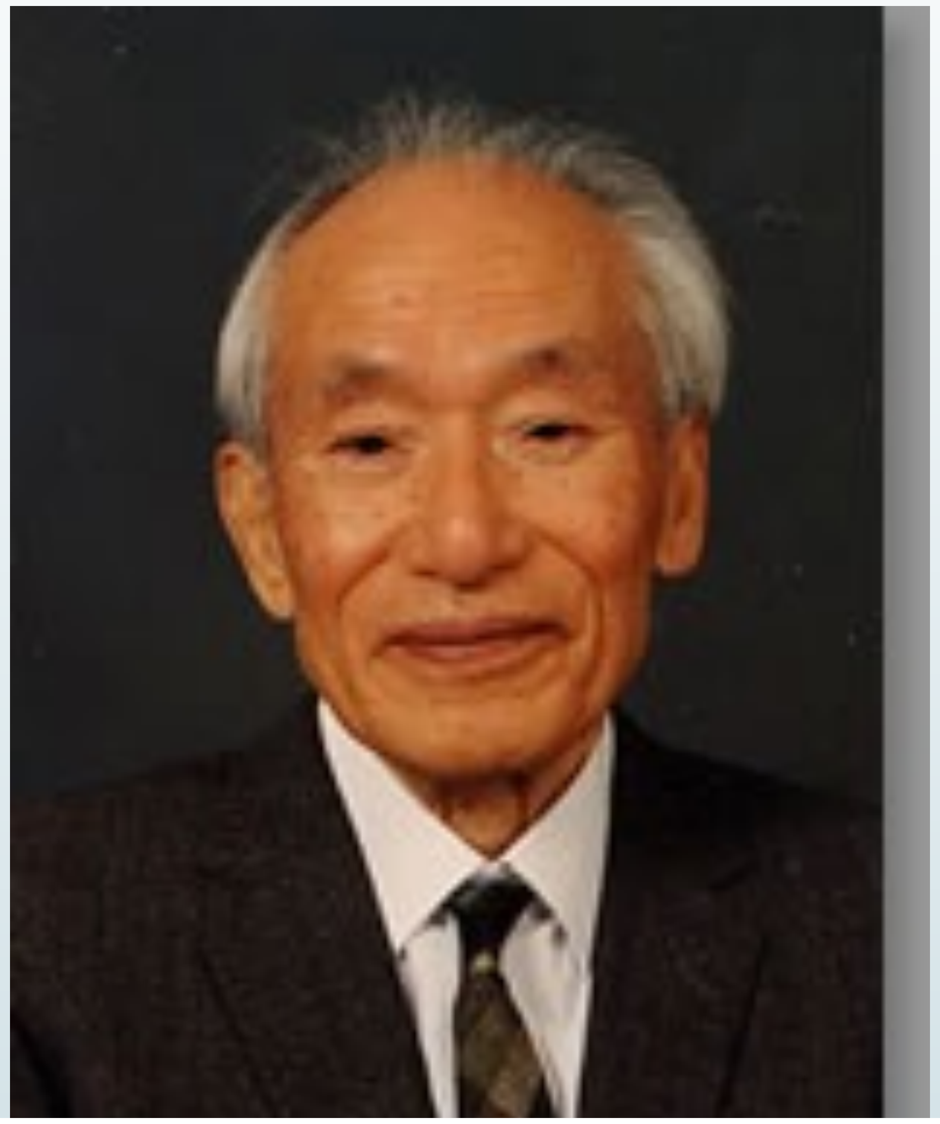




Data from GEOROC: 2014 Compilation of Arc Melt Inclusions

Magmatic Diversity Inherited From the Mantle

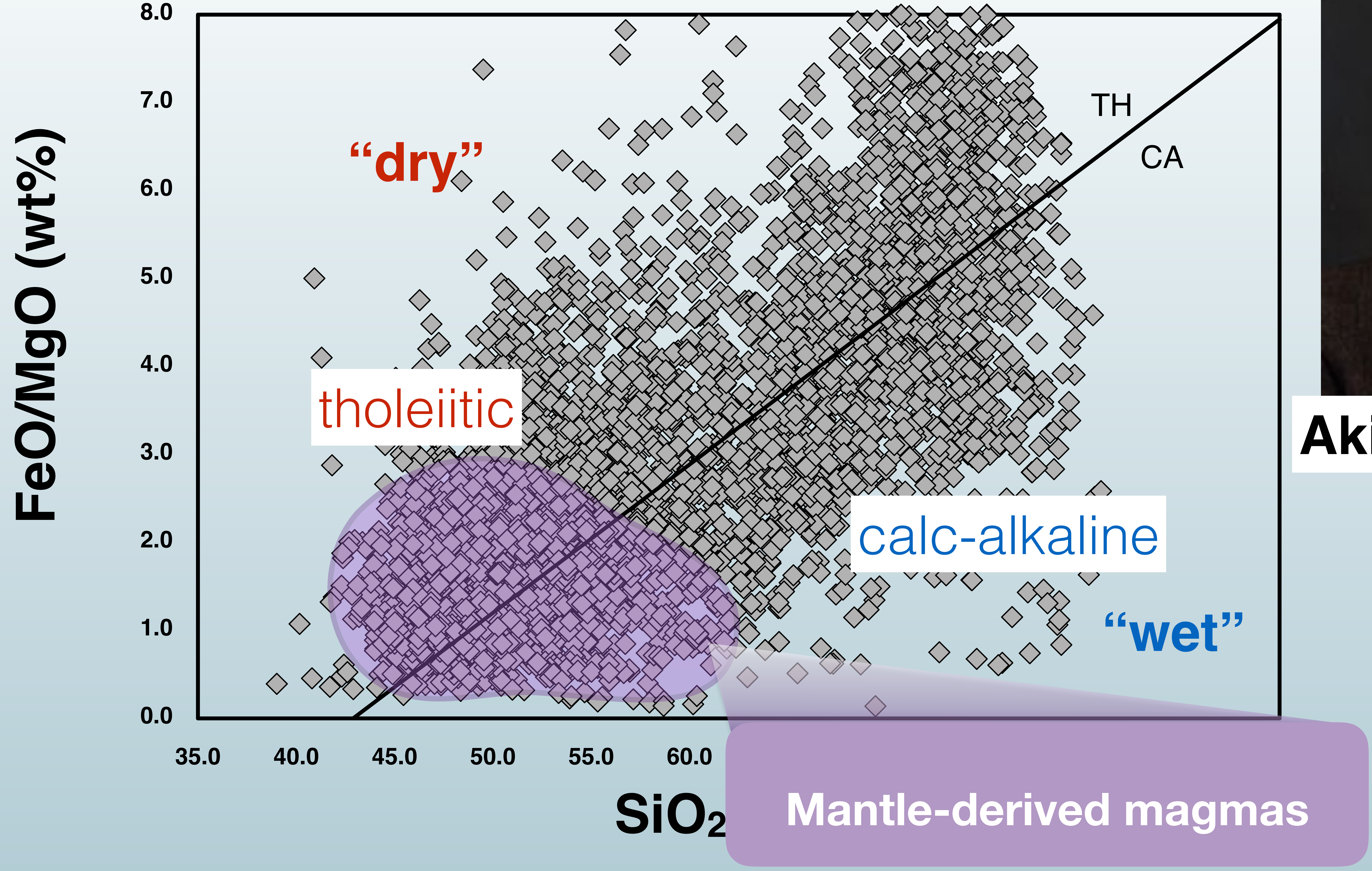


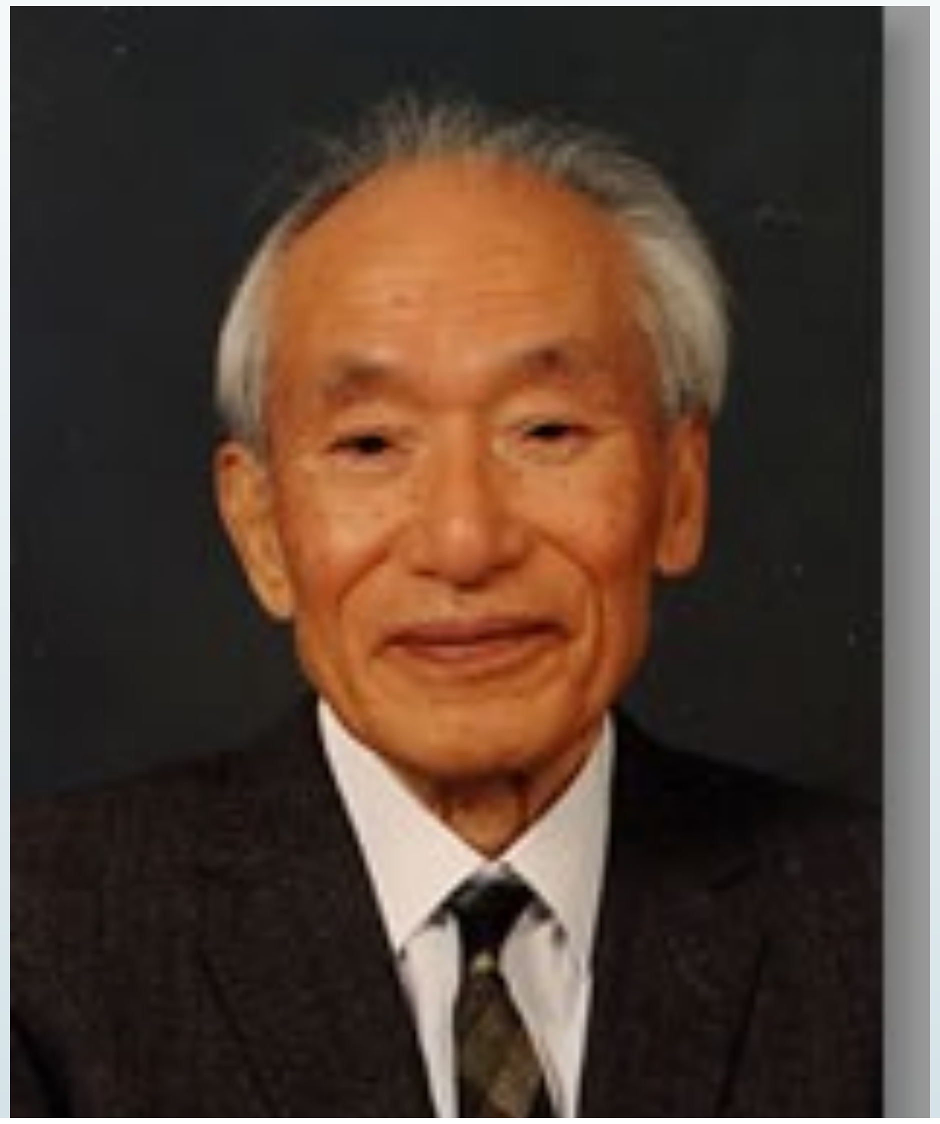


Akiho Miyashiro

Data from GEOROC: 2014 Compilation of Arc Melt Inclusions

Magmatic Diversity Inherited From the Mantle



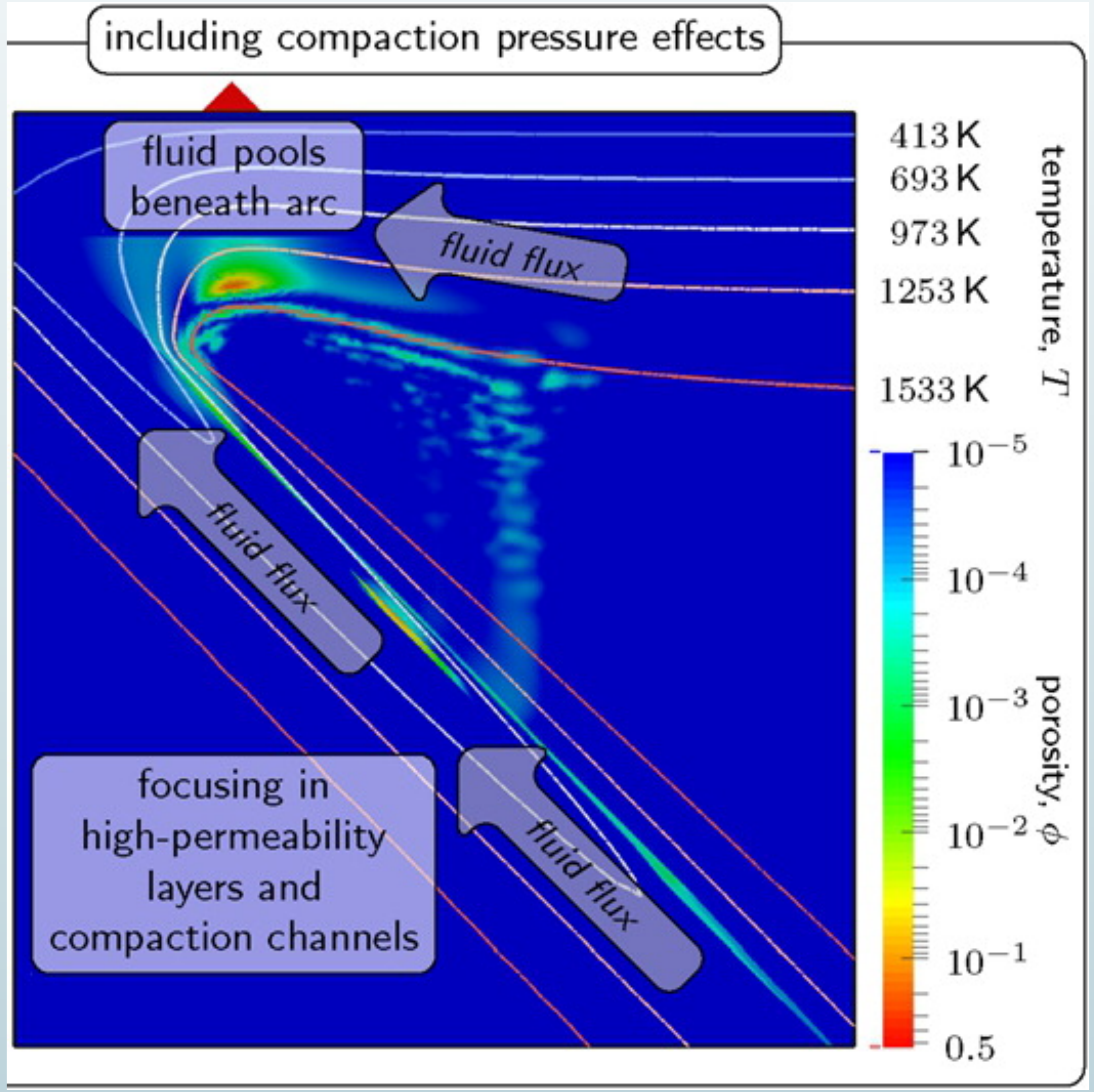


Akiho Miyashiro

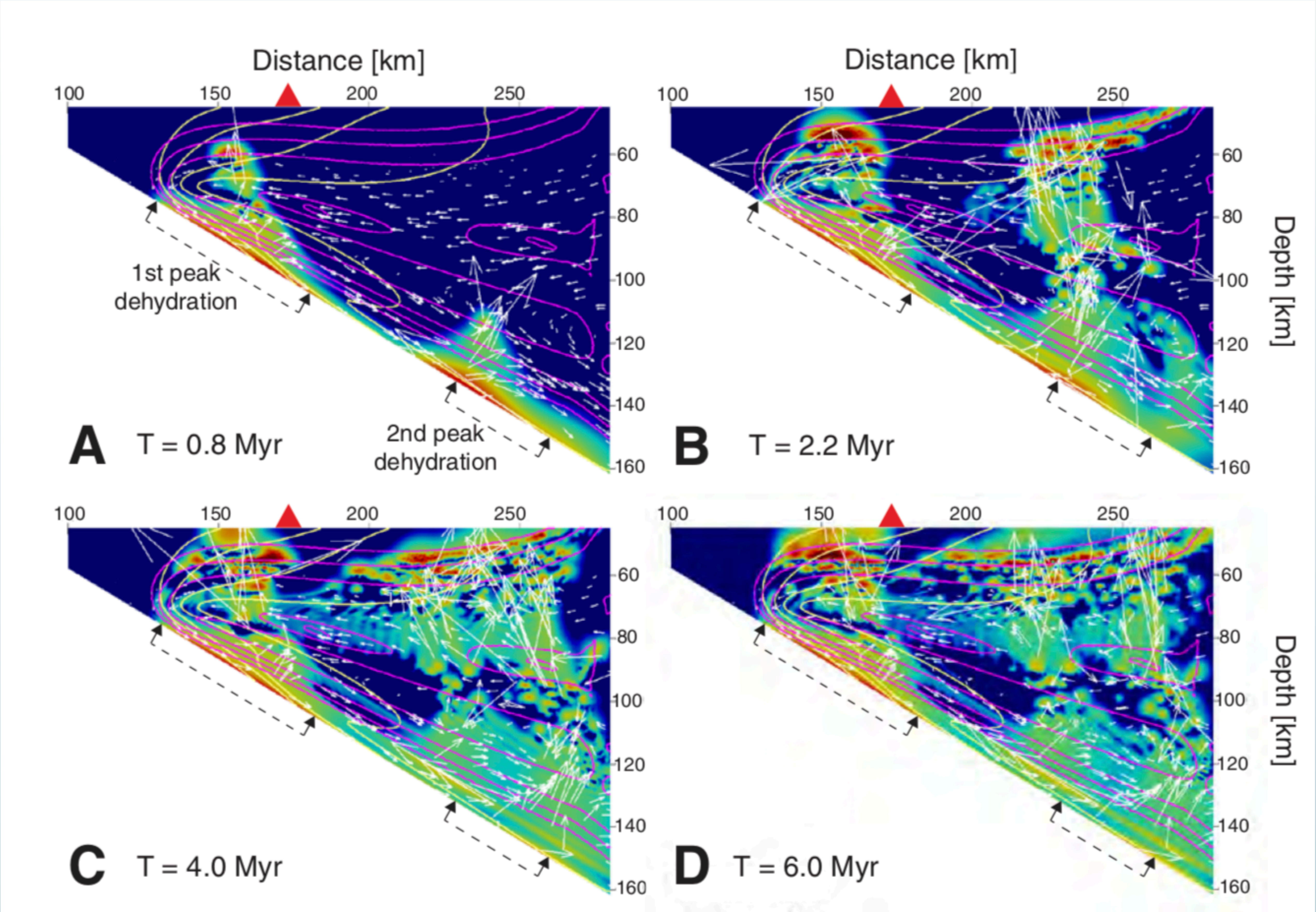
Data from GEOROC: 2014 Compilation of Arc Melt Inclusions

Mantle Flow & Delivery of Melts to the Lower Crust

newer models include fluid flux & viscosity, temperature- & strain-dependent grain size, porosity, compaction pressure etc.



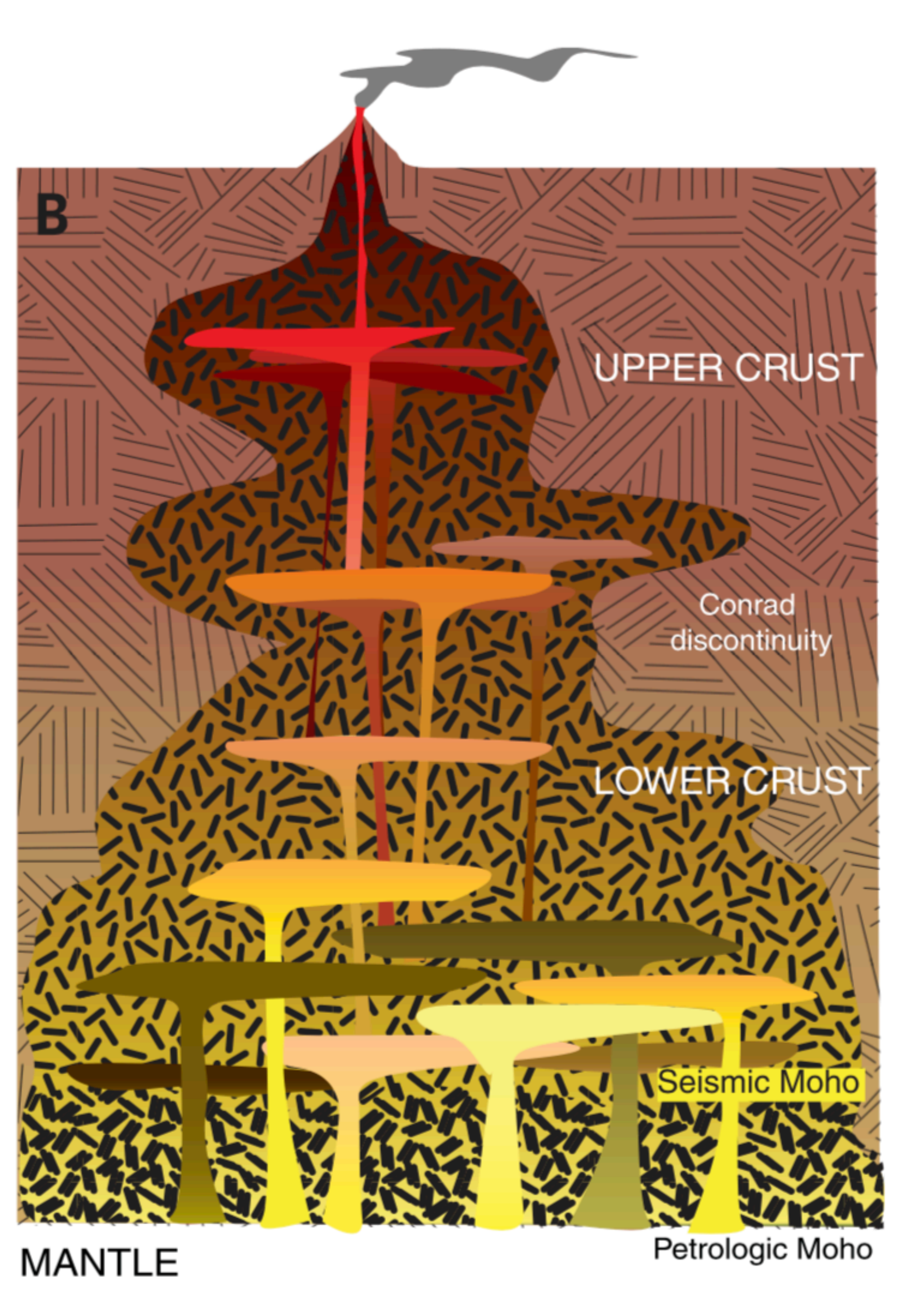
Wilson et al., 2014



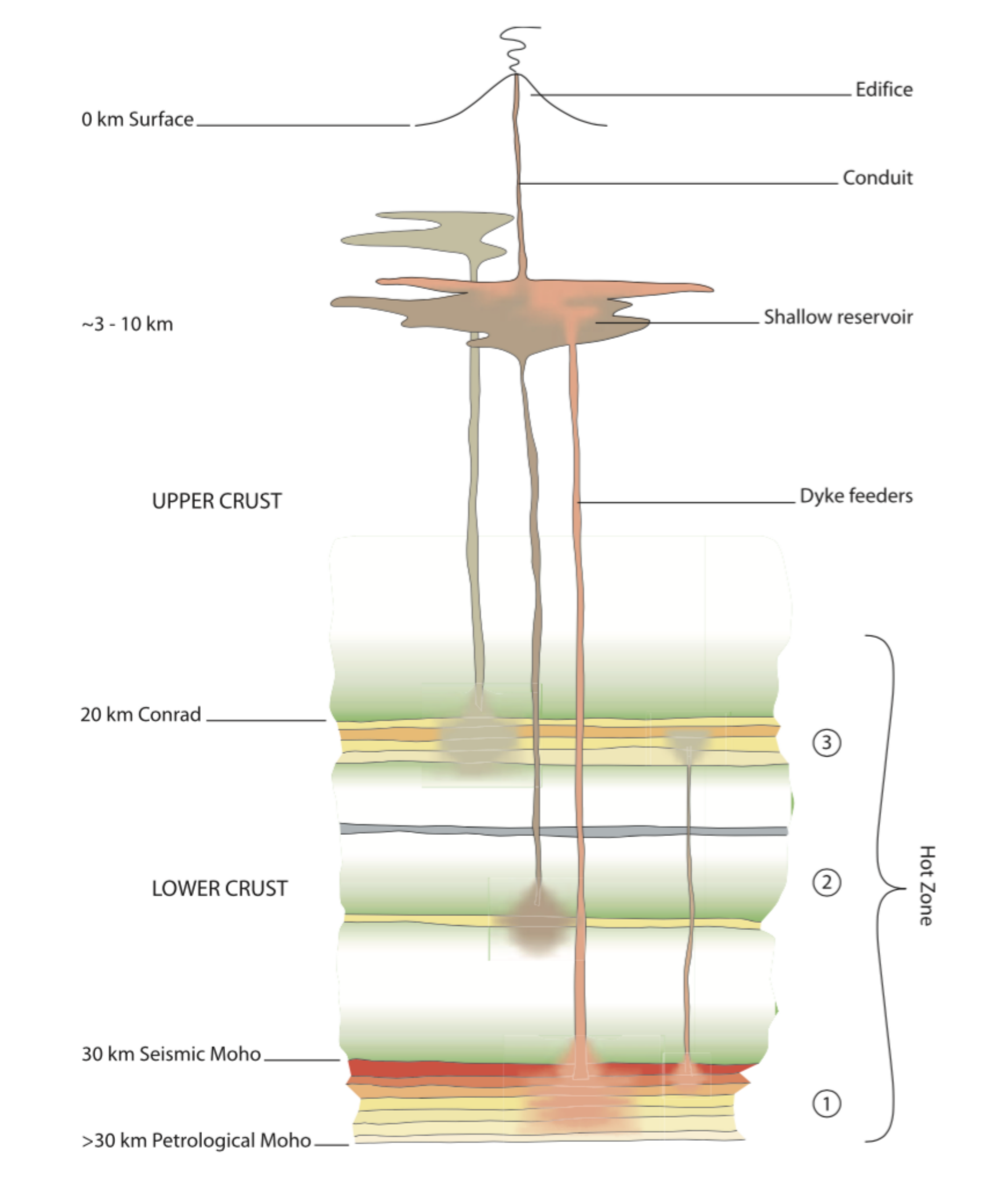
Cerpa et al., 2019

Evidence for punctuated mantle flux?

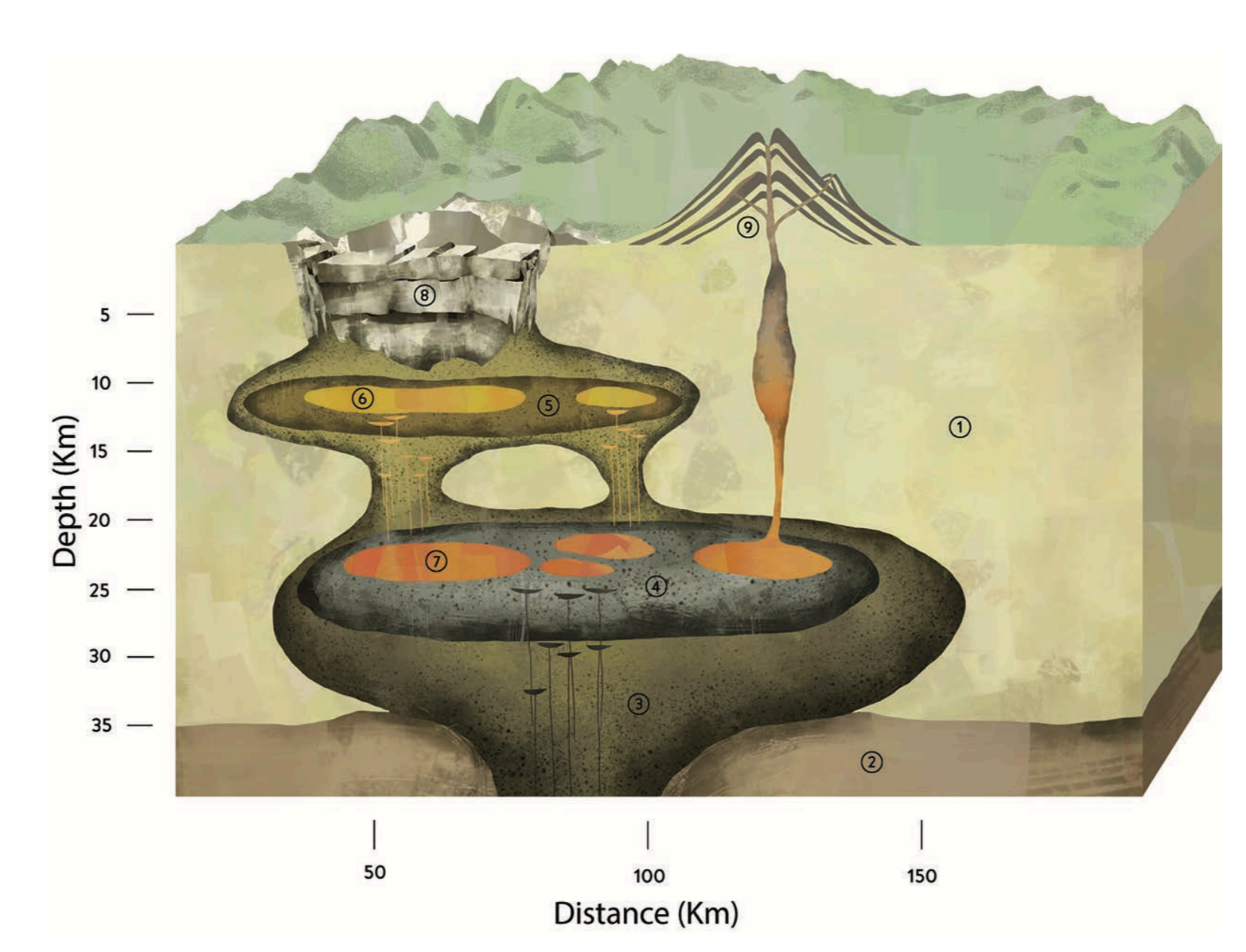
Crustal Anatomy of Magmatic Systems



Cashman et al. (2017)

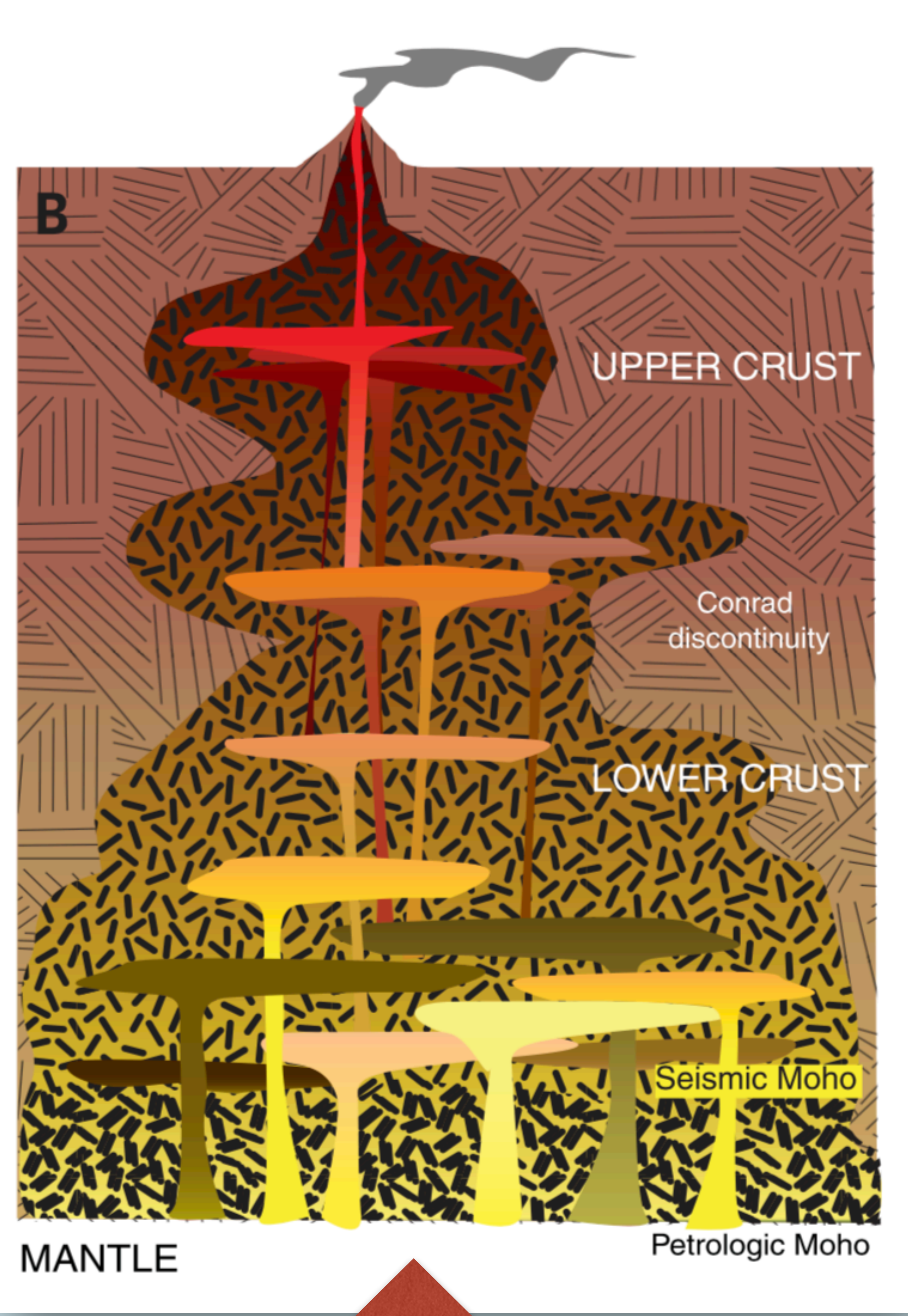


Annen et al (2006)

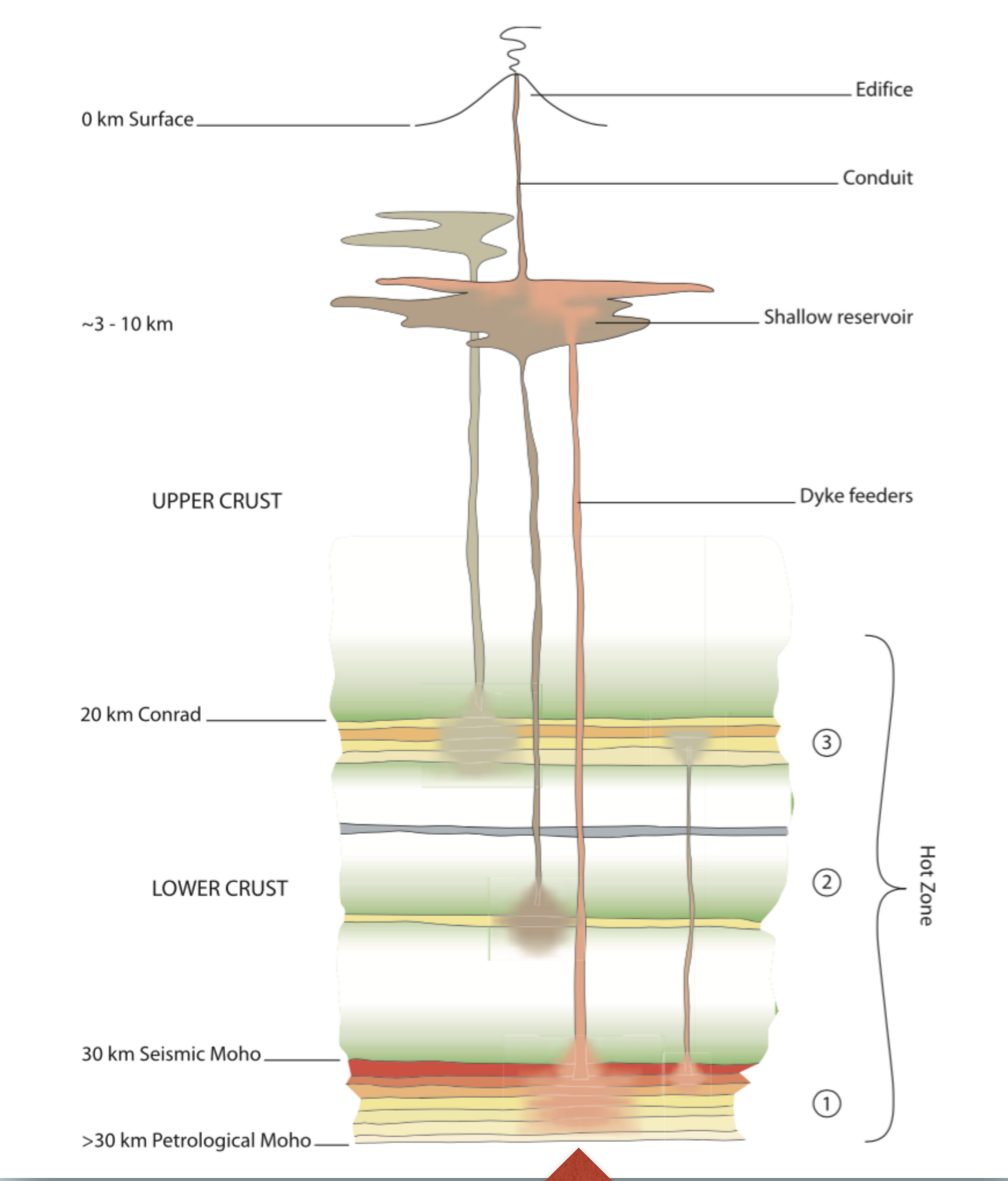


Bachmann and Huber (2016)

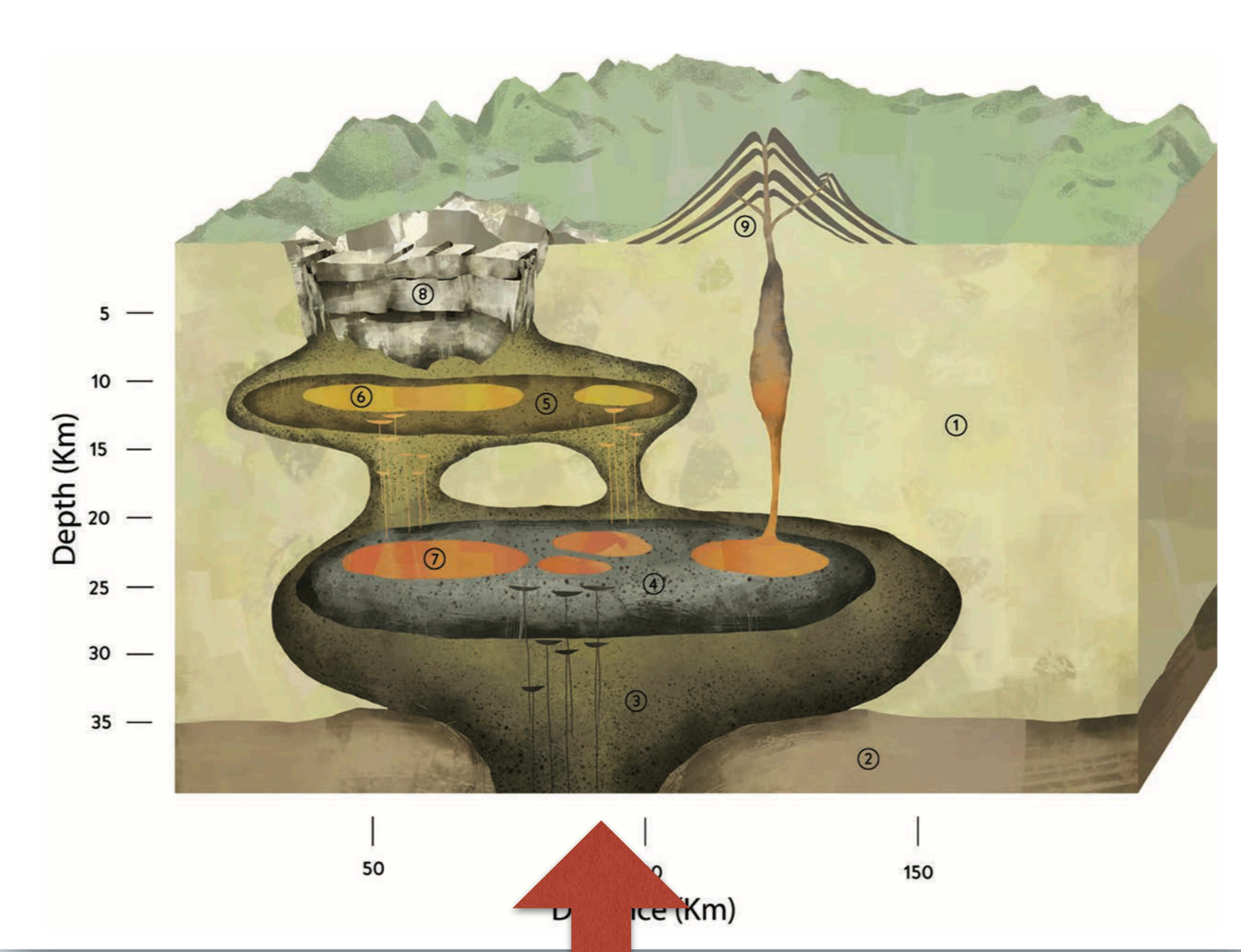
Crustal Anatomy of Magmatic Systems



Cashman et al. (2017)

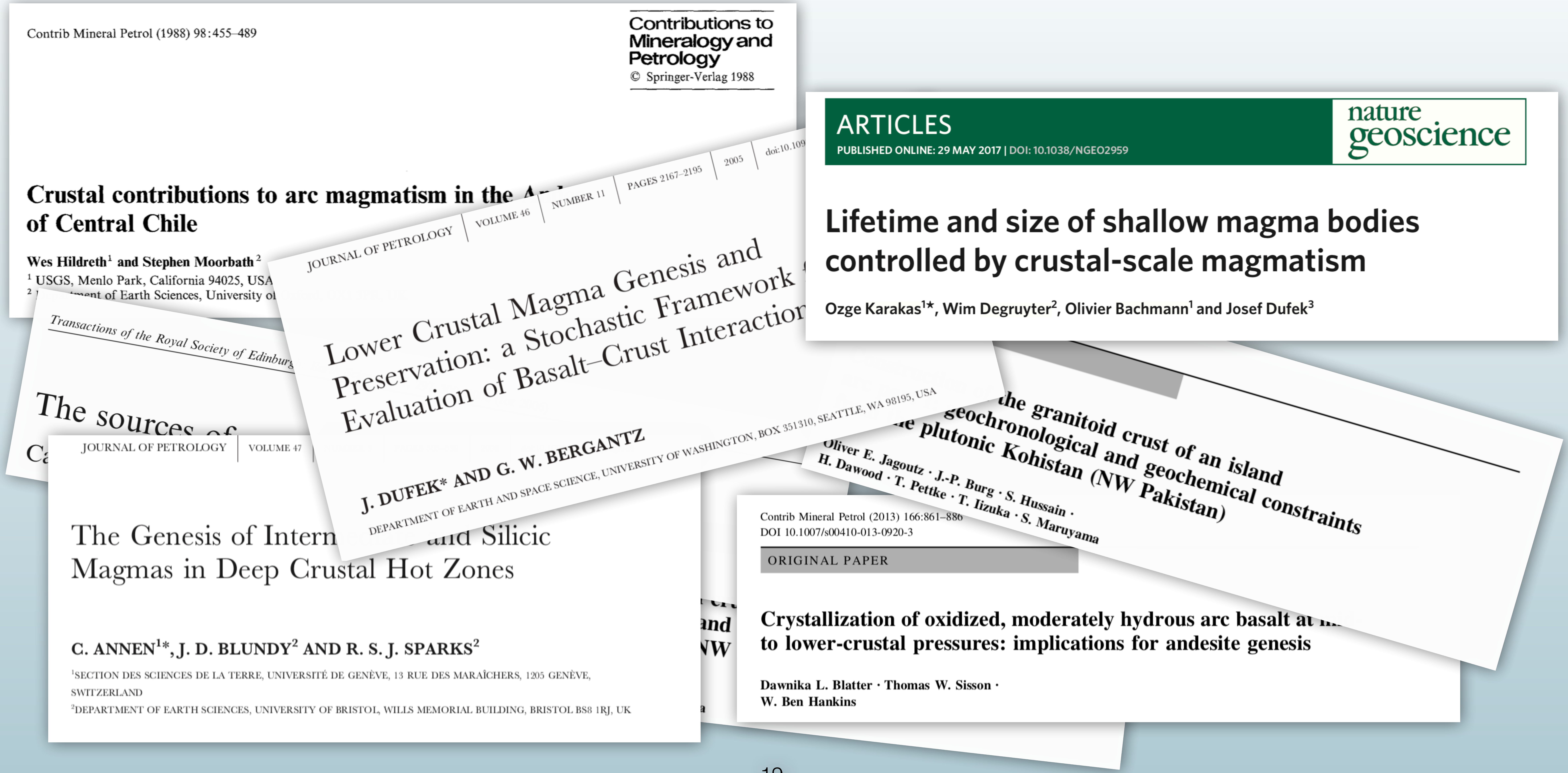


Annen et al (2006)



Bachmann and Huber (2016)

Evidence for Important Role of the Lower Crust



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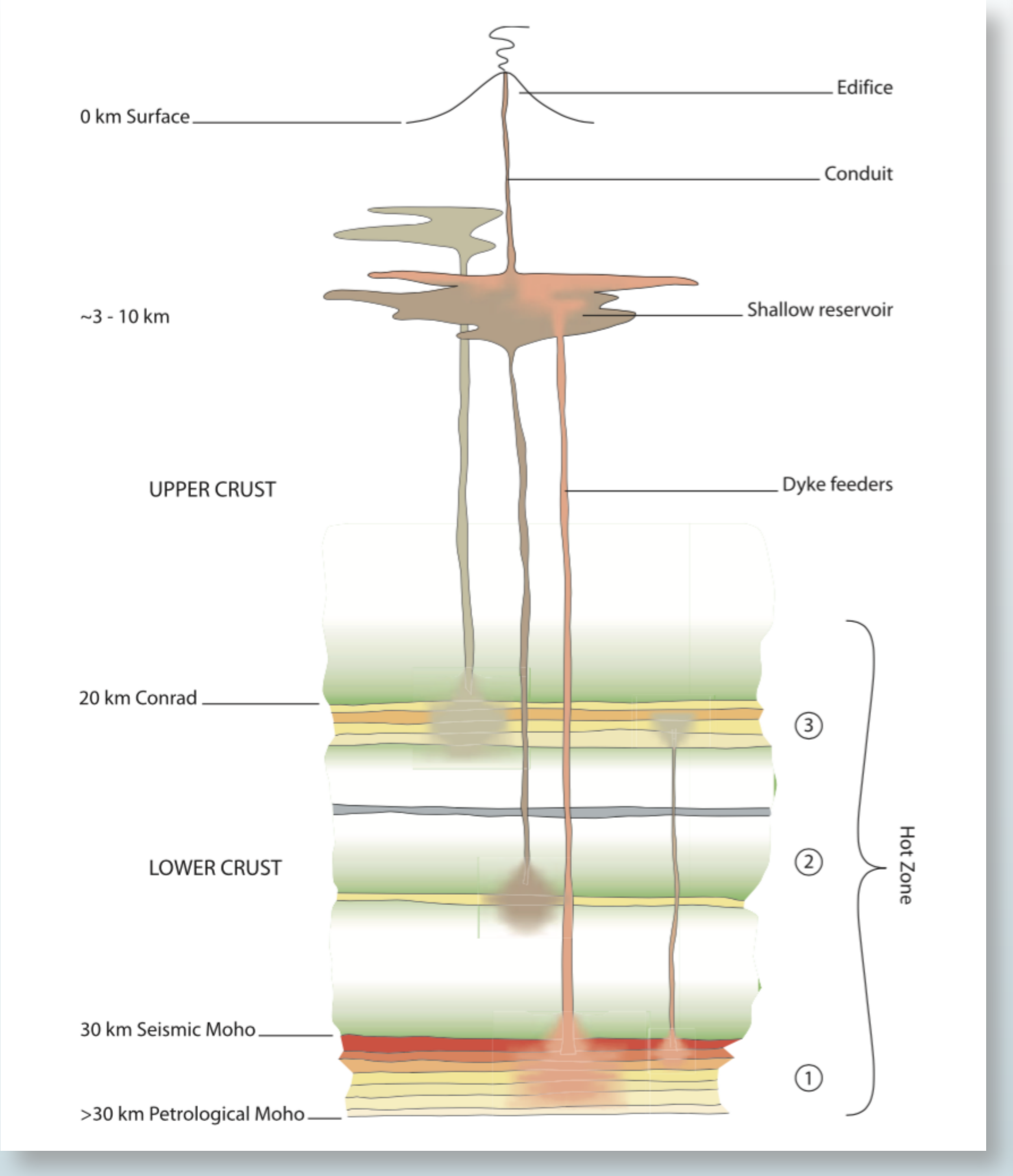
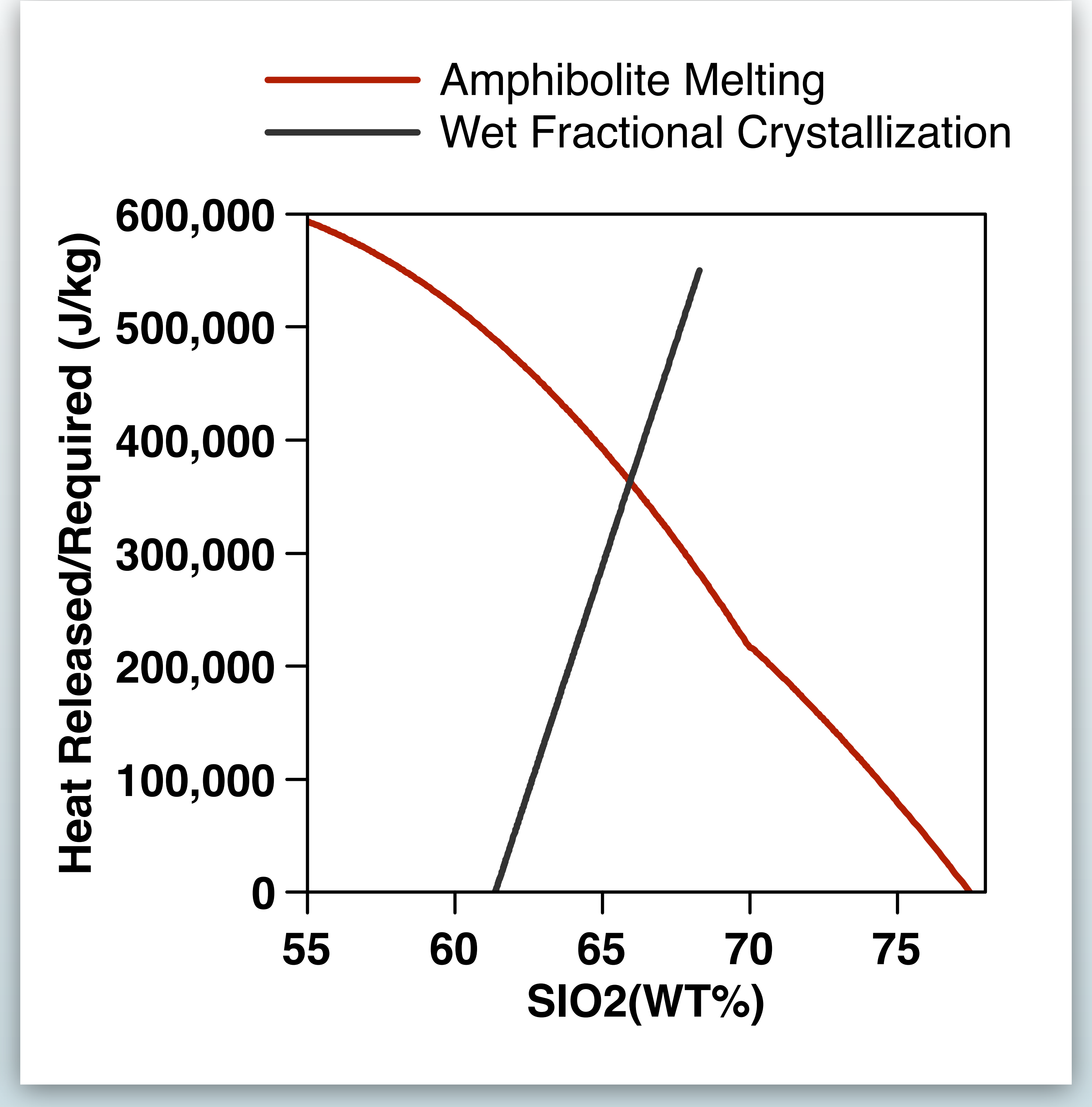
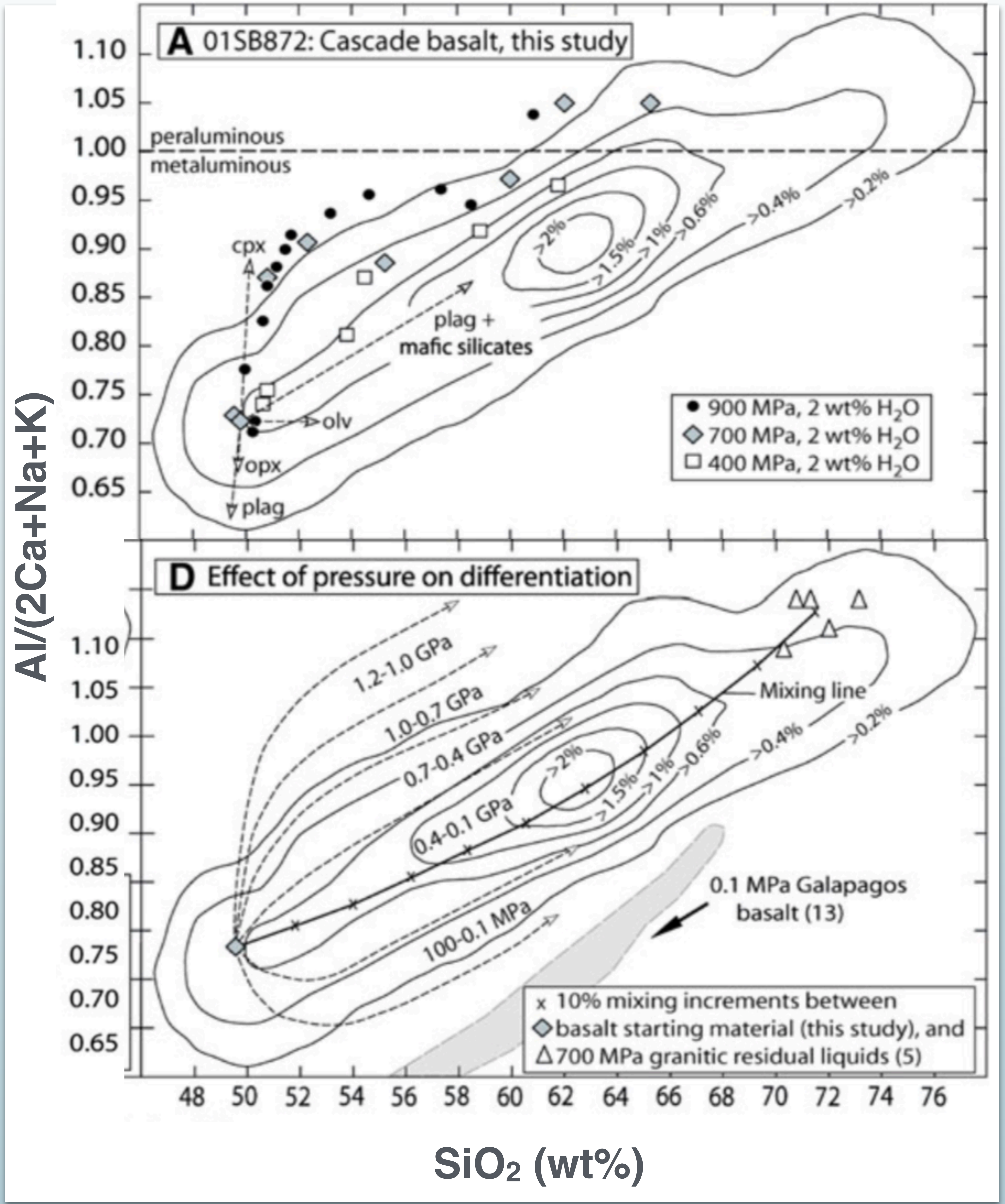


Annen et al., 2006



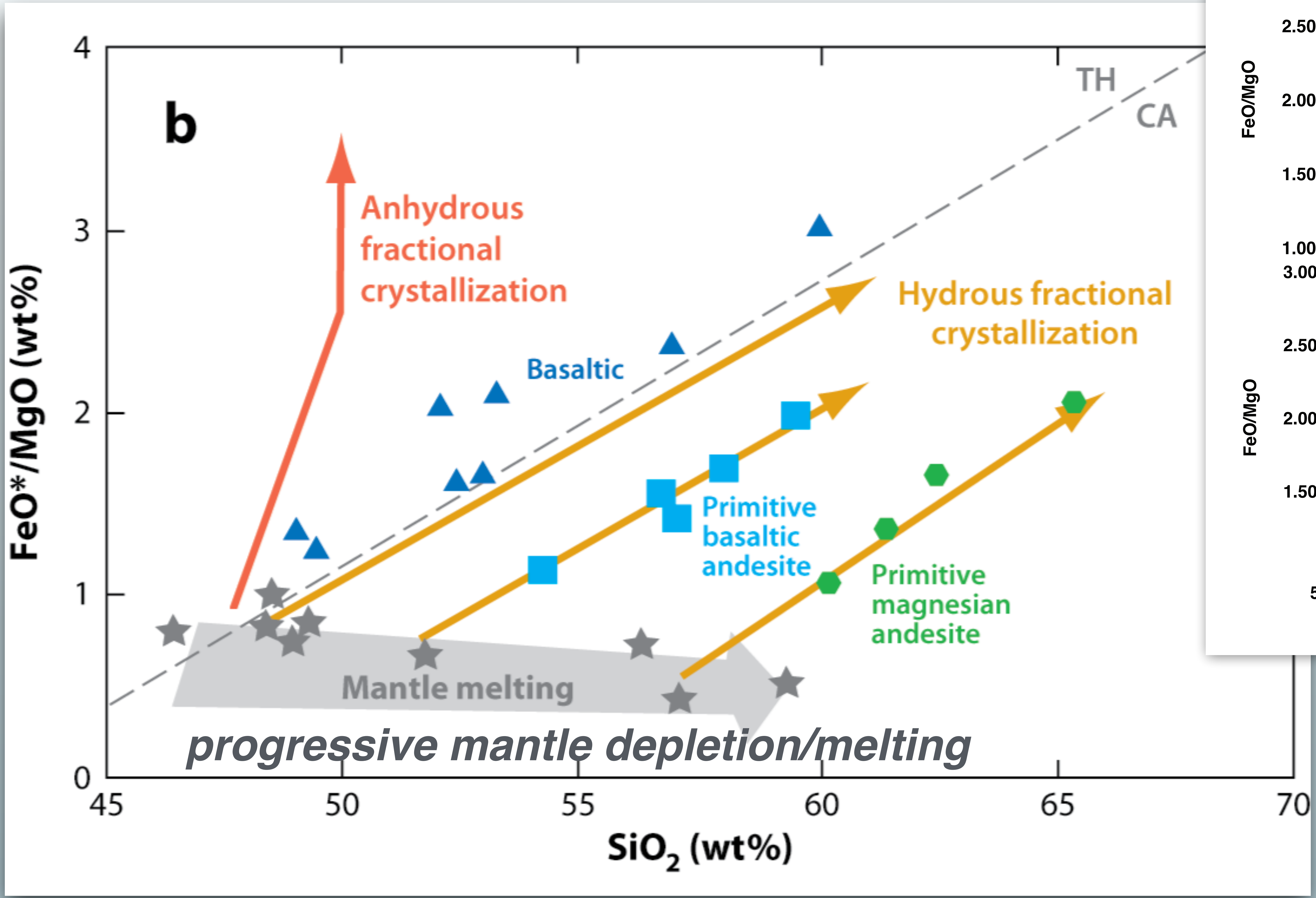
Wyllie & Wolf, 1994



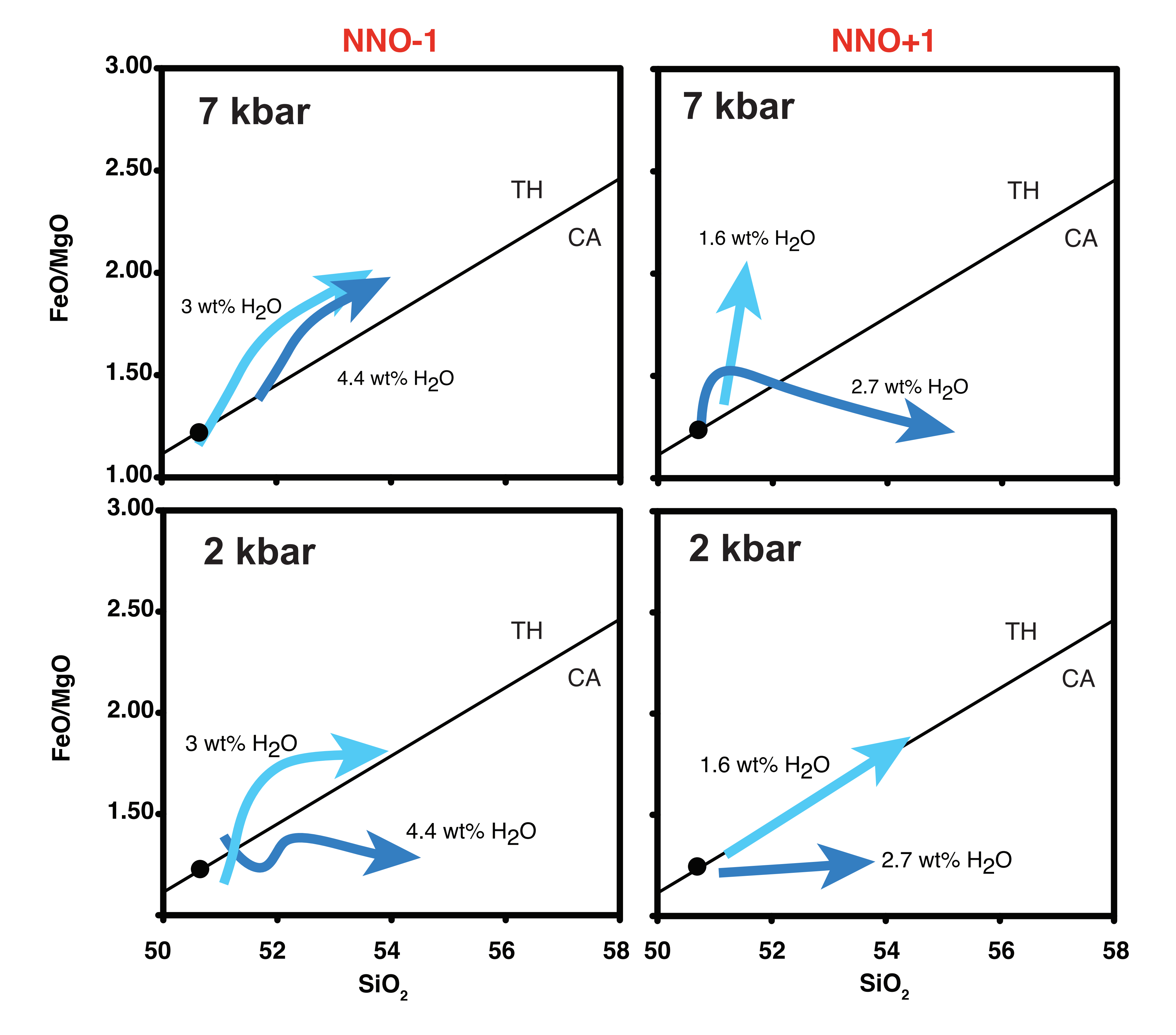
Lower crustal crystallization does not dominate the creation of intermediate arc magmas, or of the continental crust. Open system processes are critical to the production of intermediate arc magmas.

Blatter et al. (2013)

Experimentally-Constrained Crustal Crystallization Paths ("Liquid Line of Descent")

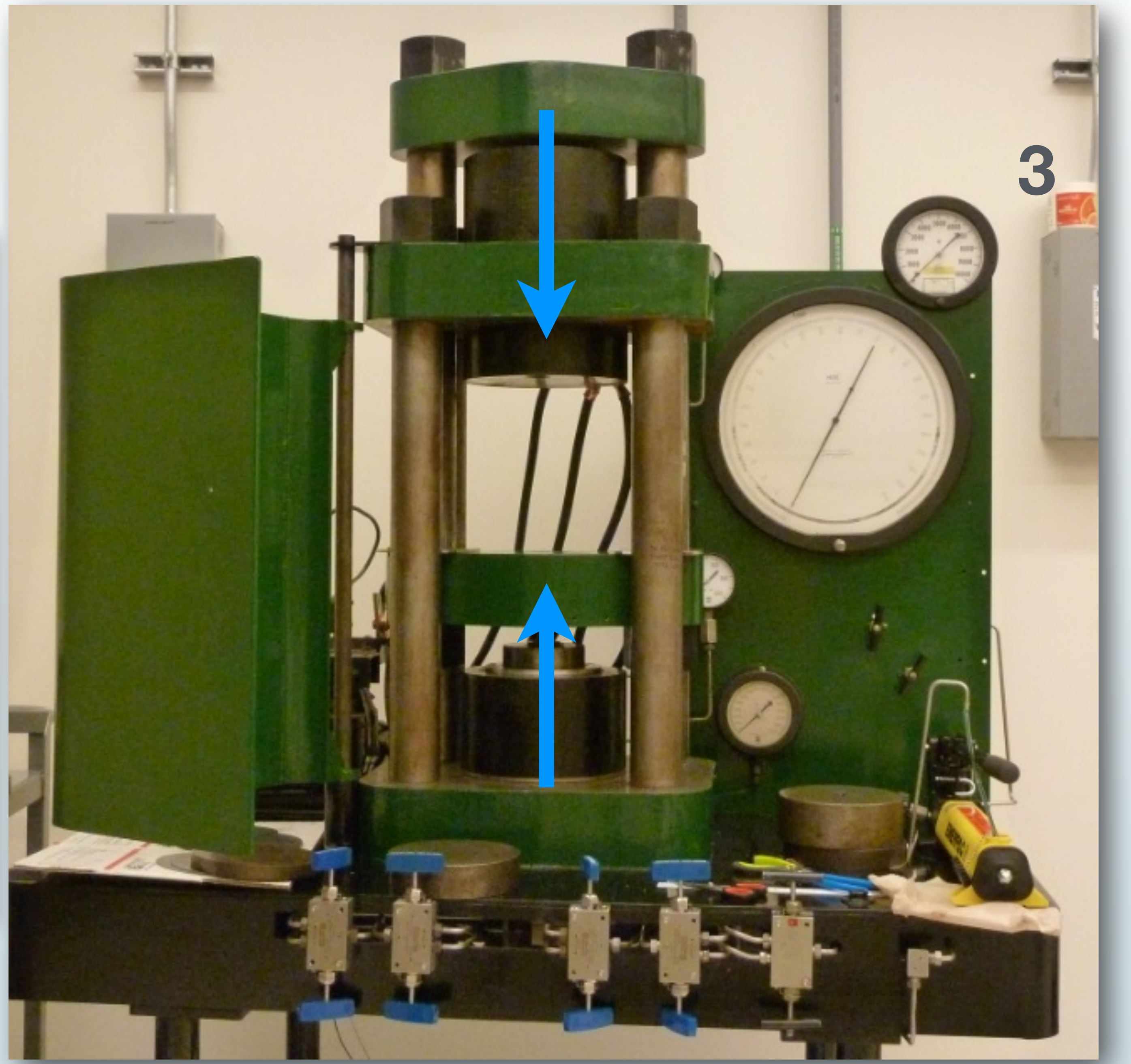


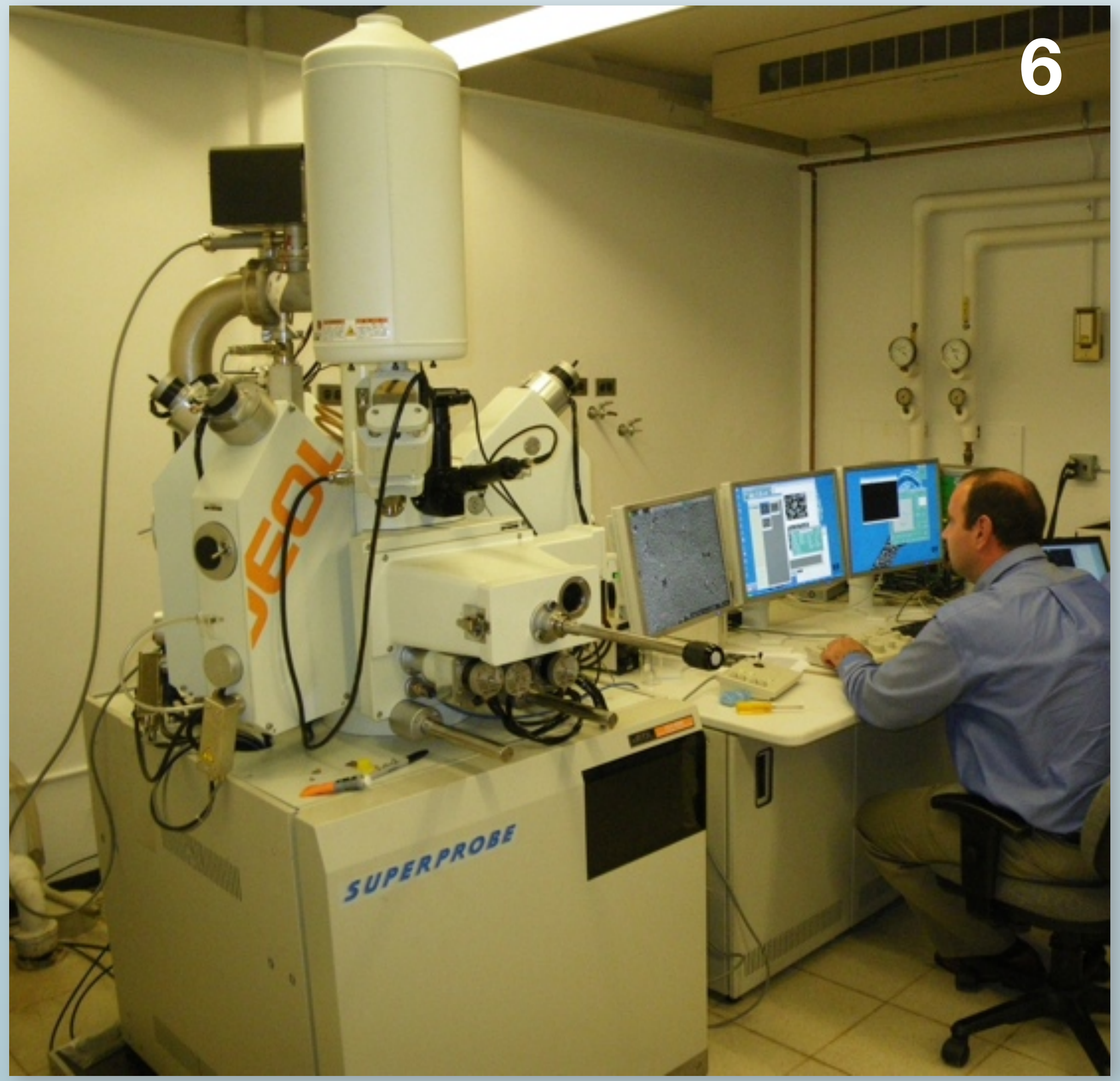
Grove et al., 2012, AREPS



Till, 2017

How We Do An Experiment?

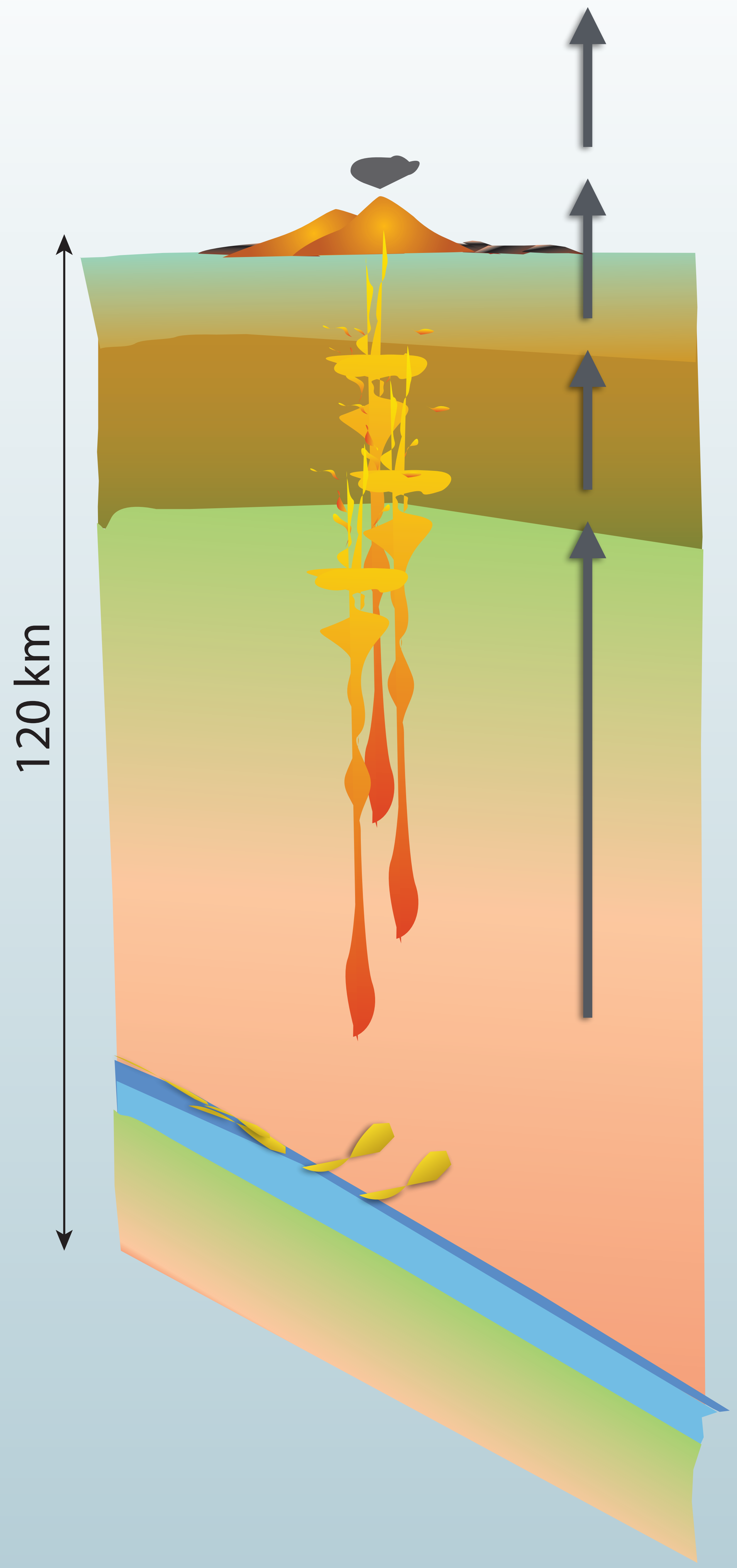




Goals For This Talk

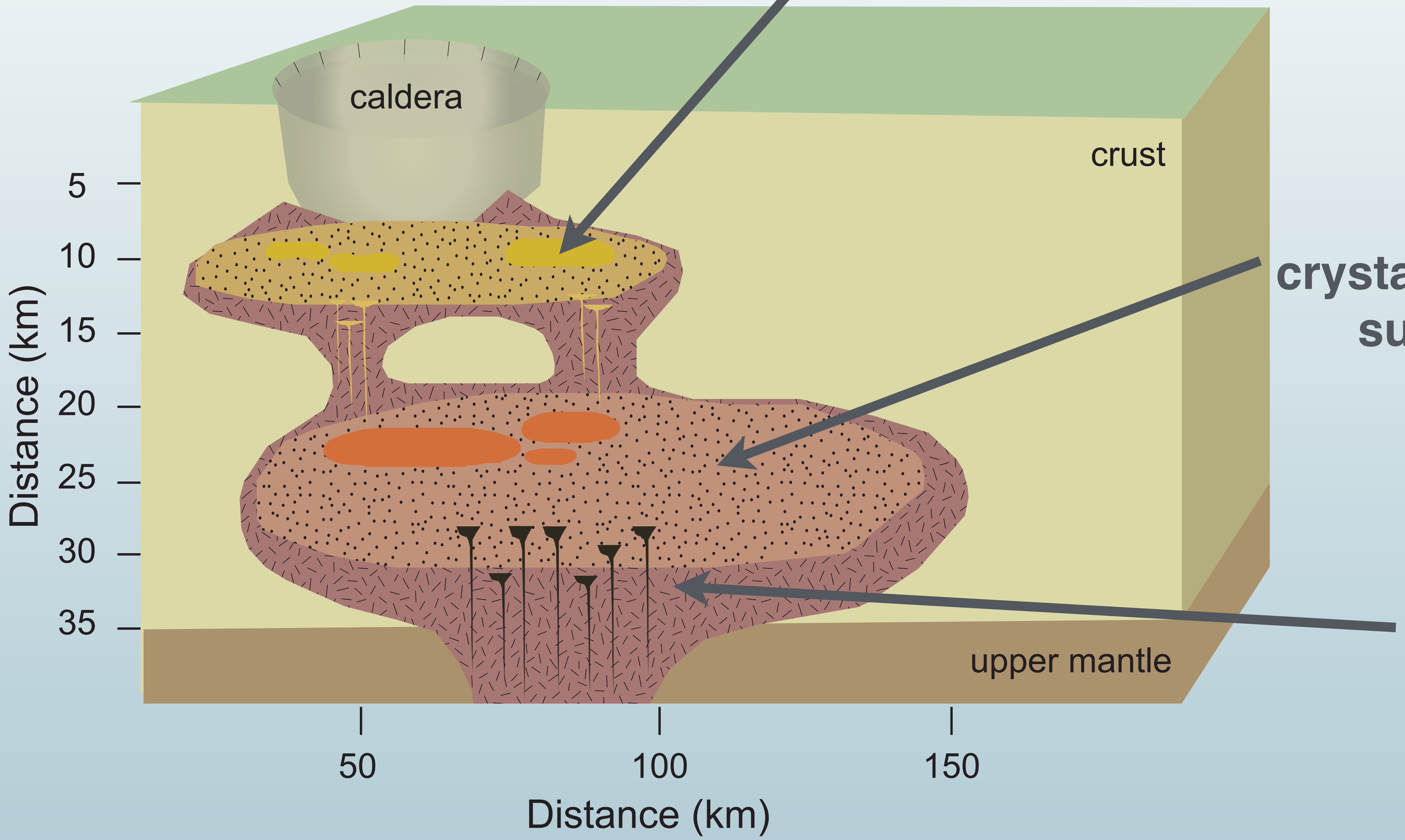
✓Transmagmatic system perspective

- Reconstructing the P-T-X±t evolution of magmas in the crust
- Recent advances & exciting future directions
  - Causes of eruption initiation?
  - Causes of intra-arc diversity?



Anatomy of Silicic Volcano

evolution to silicic melt & progressive assembly of individual magma bodies

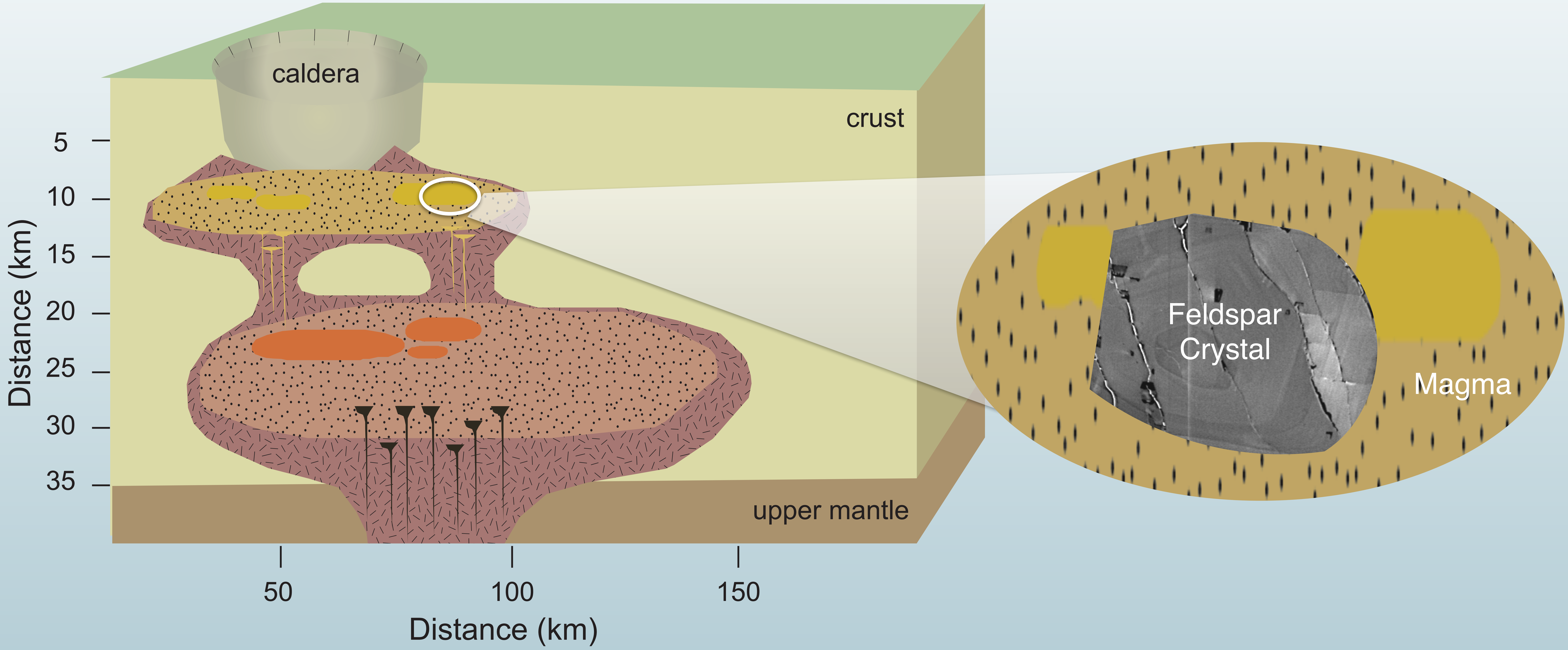


magma stalls, crystallizes & assimilates surrounding crust

mantle-derived basaltic magma

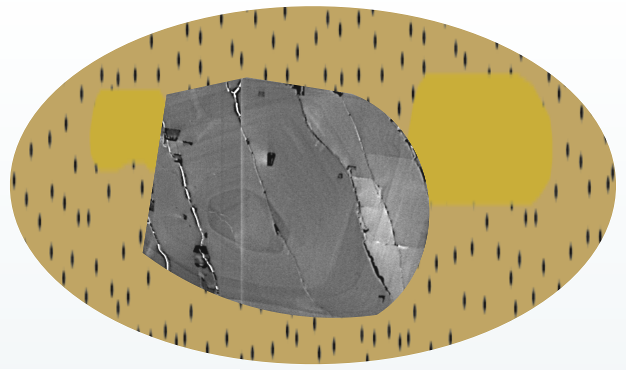
Modified from Hildreth and Wilson (2007) and Bachmann and Huber (2016)

What can we learn from a feldspar crystal?



Modified from Hildreth and Wilson (2007) and Bachmann and Huber (2016)

Under what temperature & pressure conditions did this crystal form?



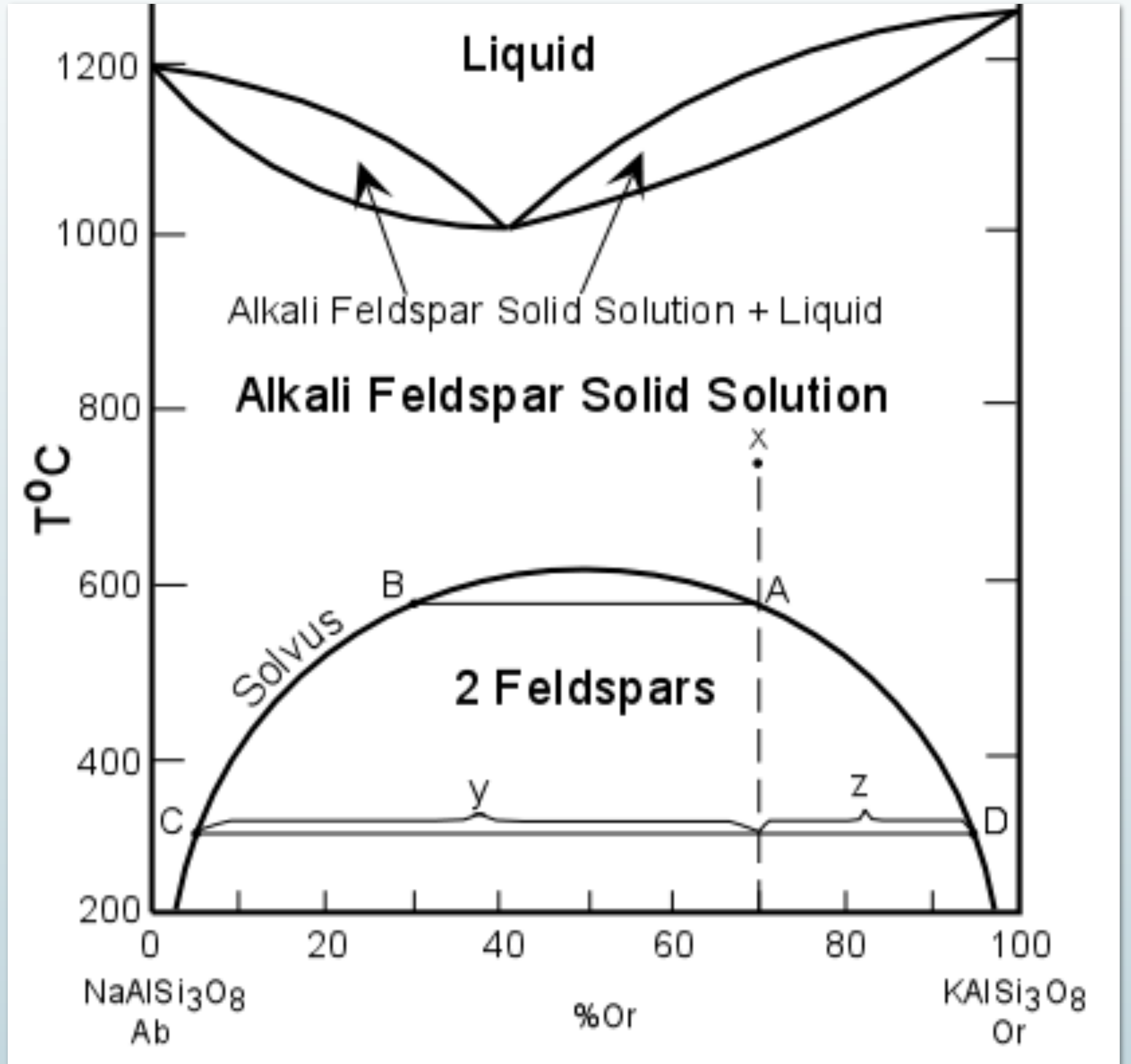
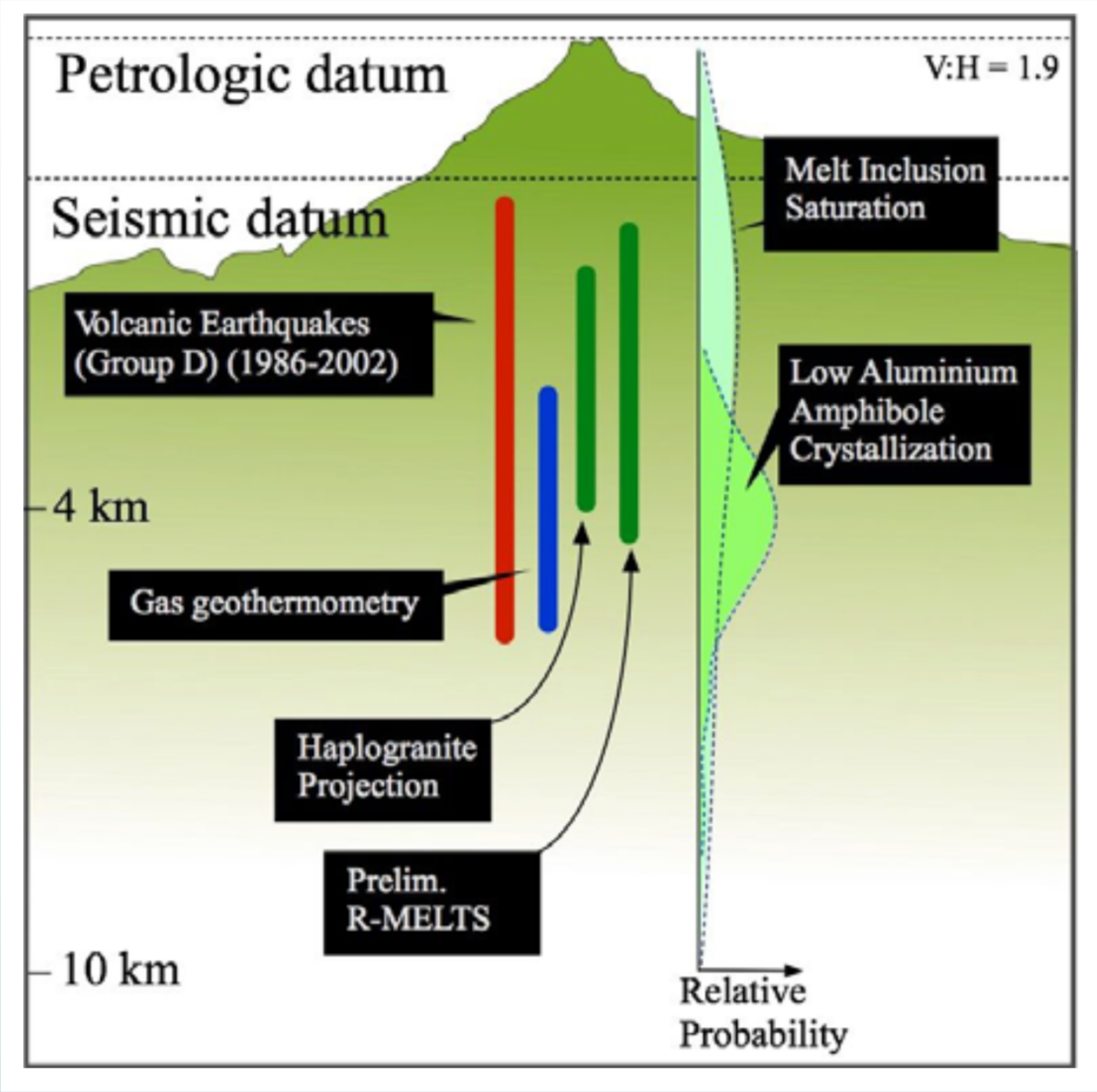


Figure 4

www.tulane.edu/~sanelson



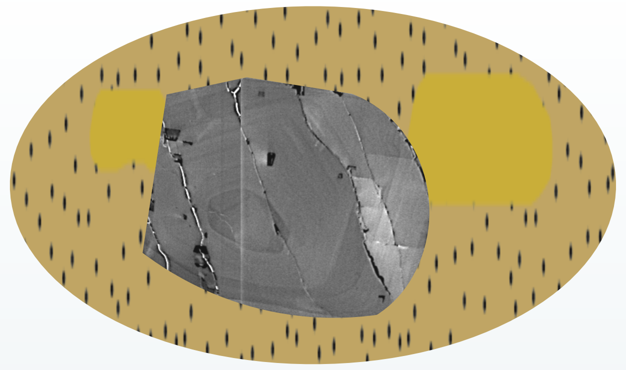
Kent & Koleszar, IAVCEI, 2017

Composition of feldspar + co-existing melt are temperature-dependent (good thermometers)

Other minerals have a compositions that are strongly pressure-dependent (good barometers)

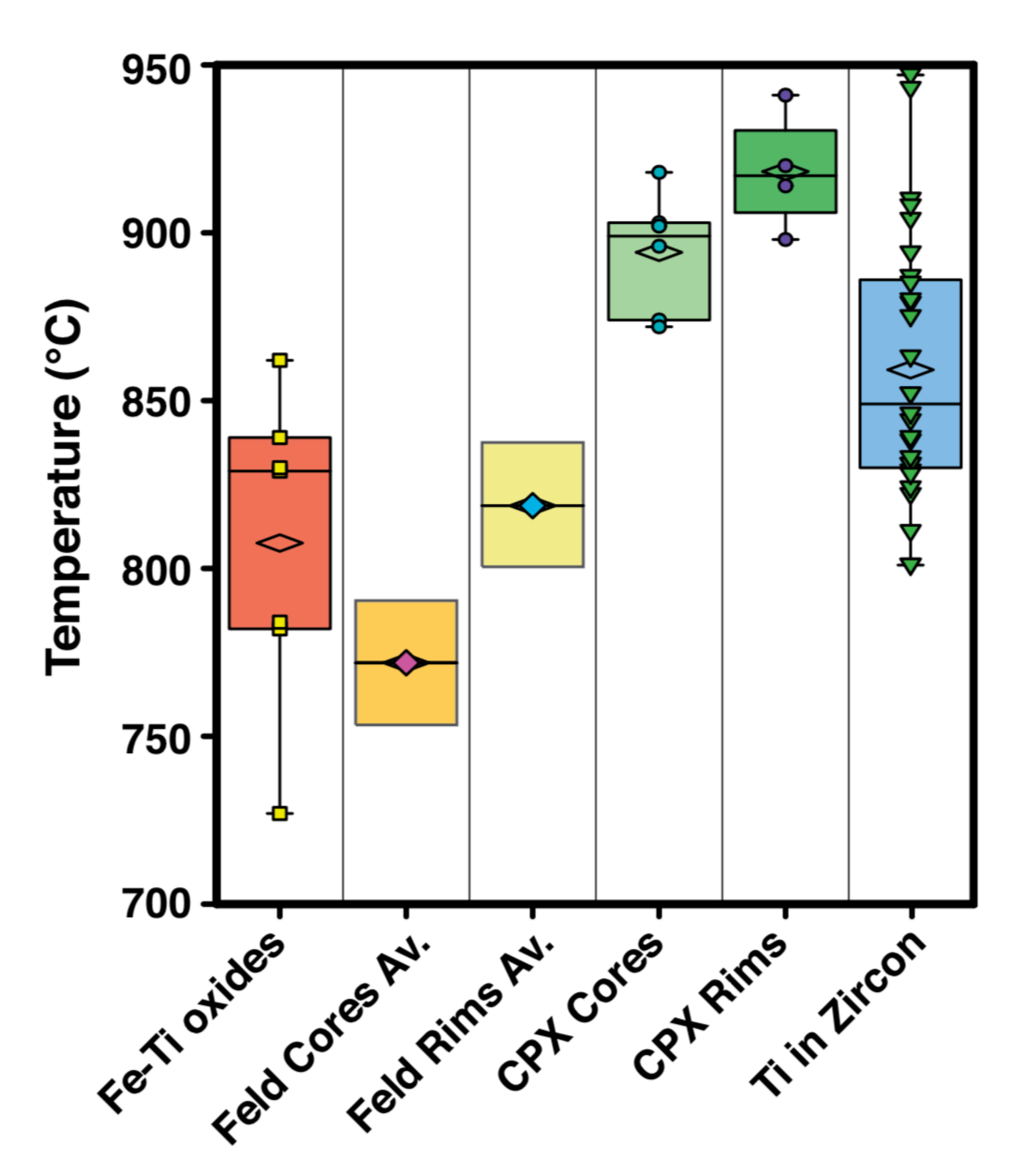
good compendium of volcanic thermometers & barometers: Putirka, RiMG, 2008

Under what temperature conditions did this crystal form?



with a single eruptive unit
(history of particular magma body)

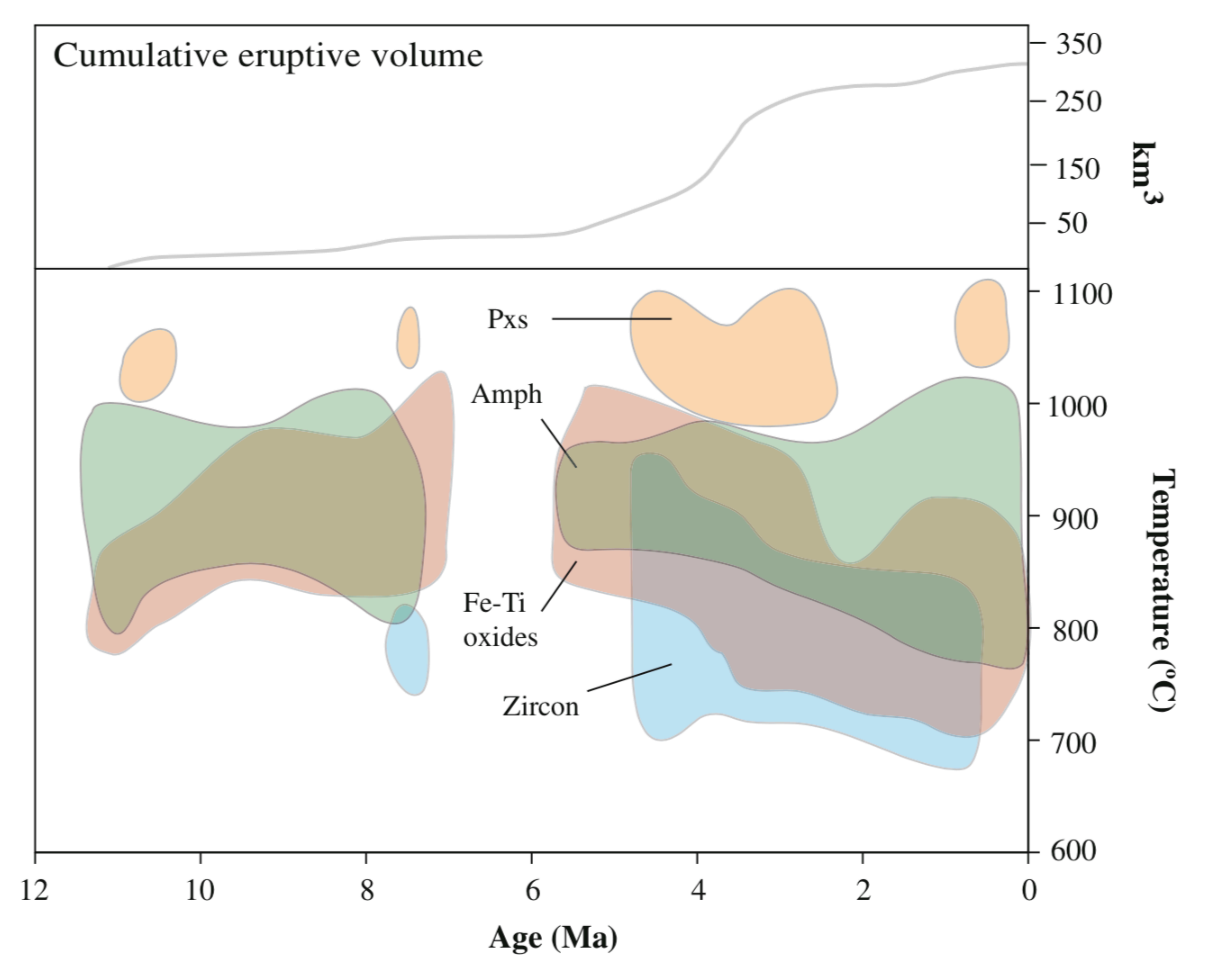
Yellowstone, Wyoming
ca. 260 ka rhyolite lava



Till et al., 2015

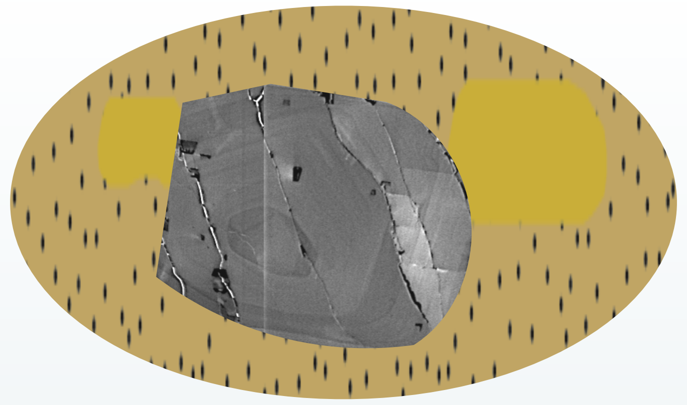
over time at same volcano
(history of a magma reservoir)

Aucanquilcha Volcanic Cluster, Chile
andesite-dacite lavas

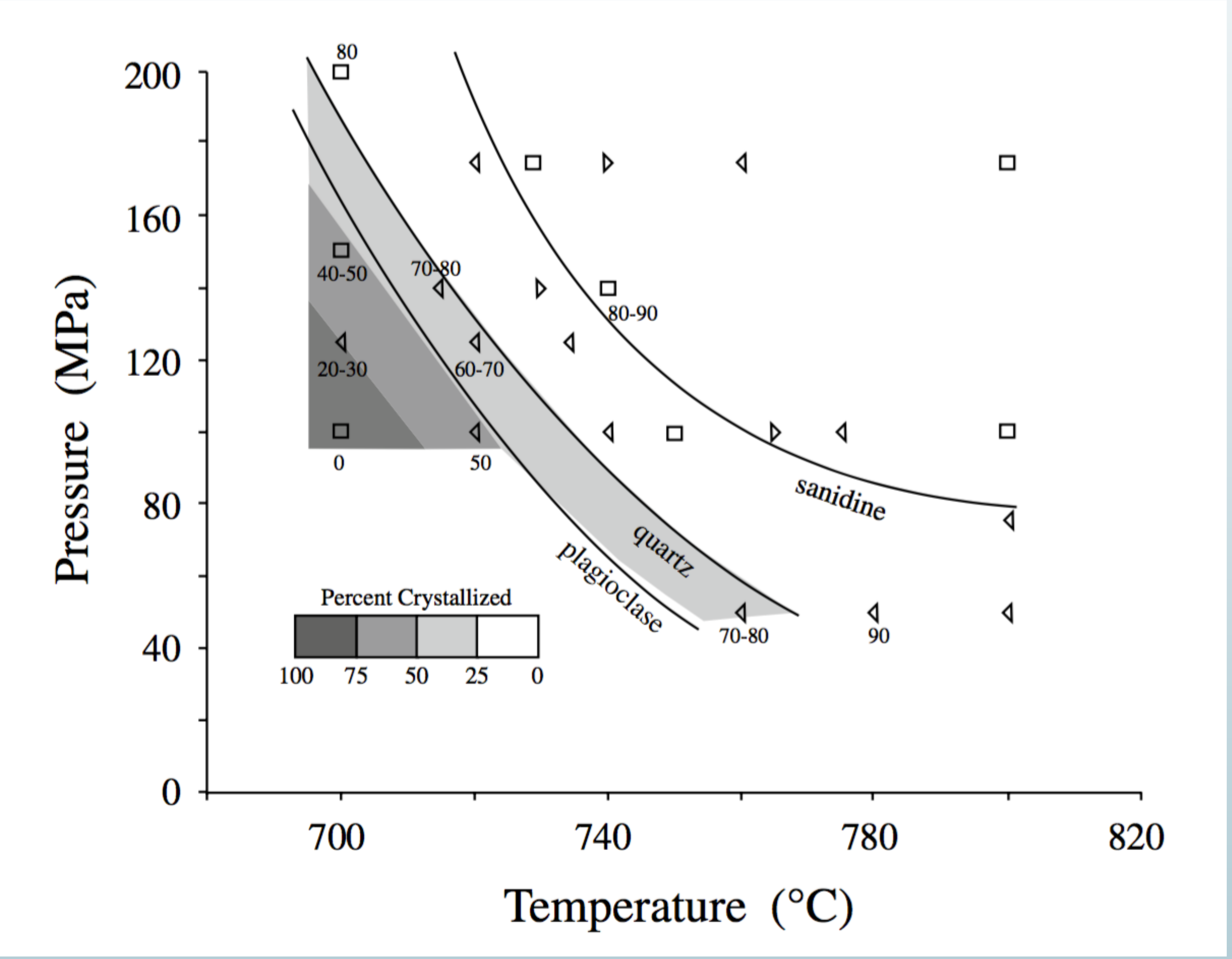


Walker et al., 2013

Under what P-T-X conditions did this crystal form?



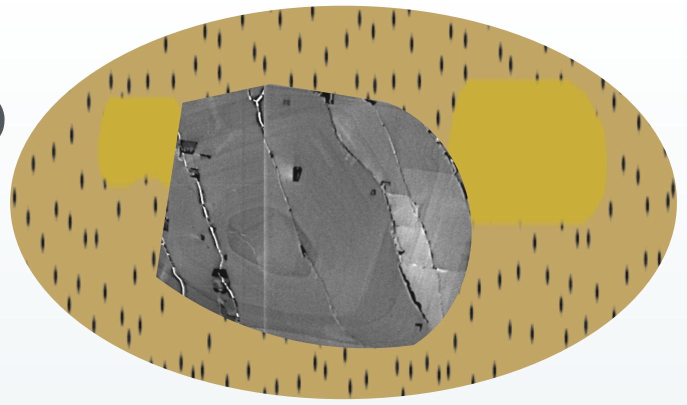
Cold Seal Experiments on Late Bishop Tuff



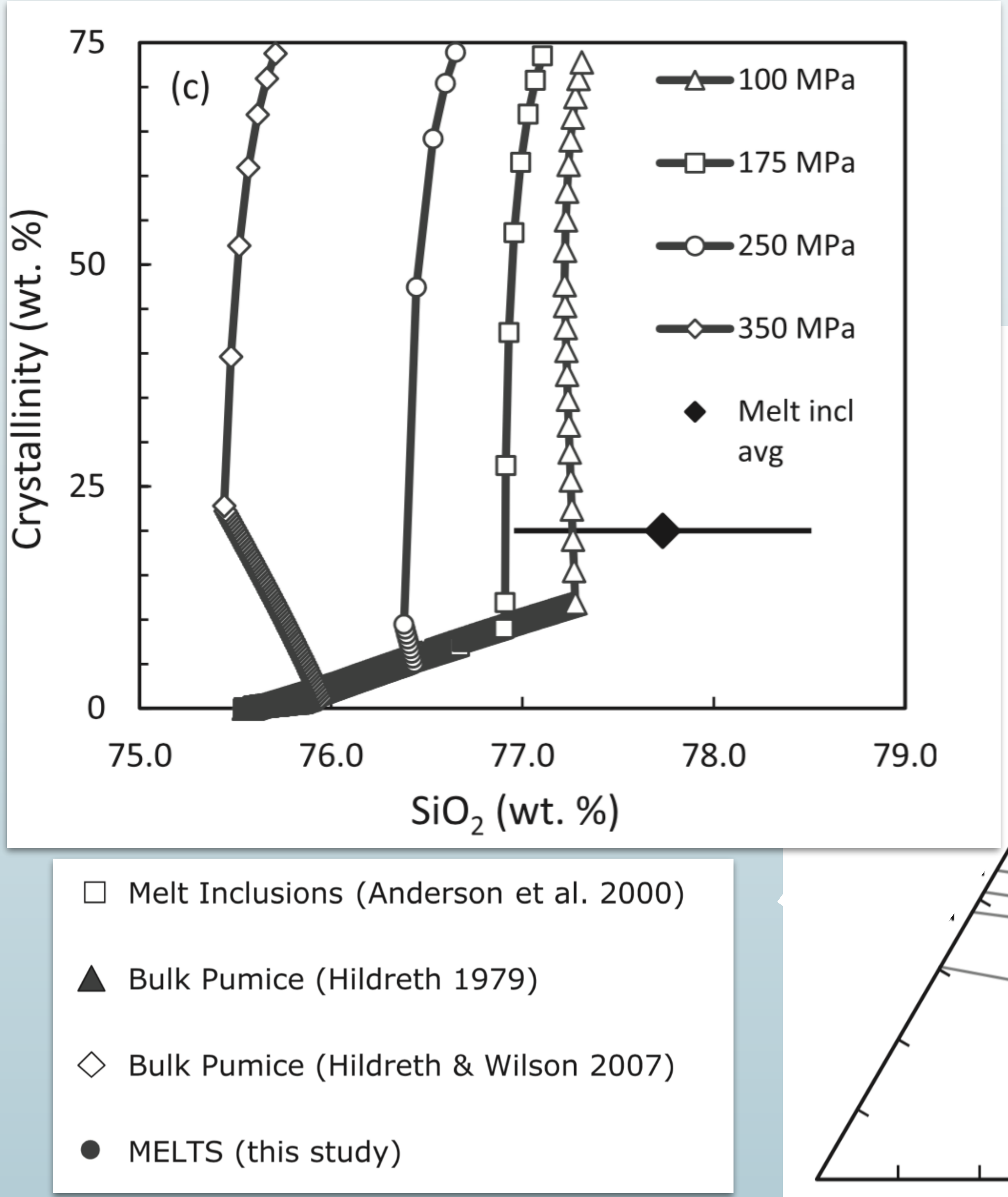
Gardner et al., 2014

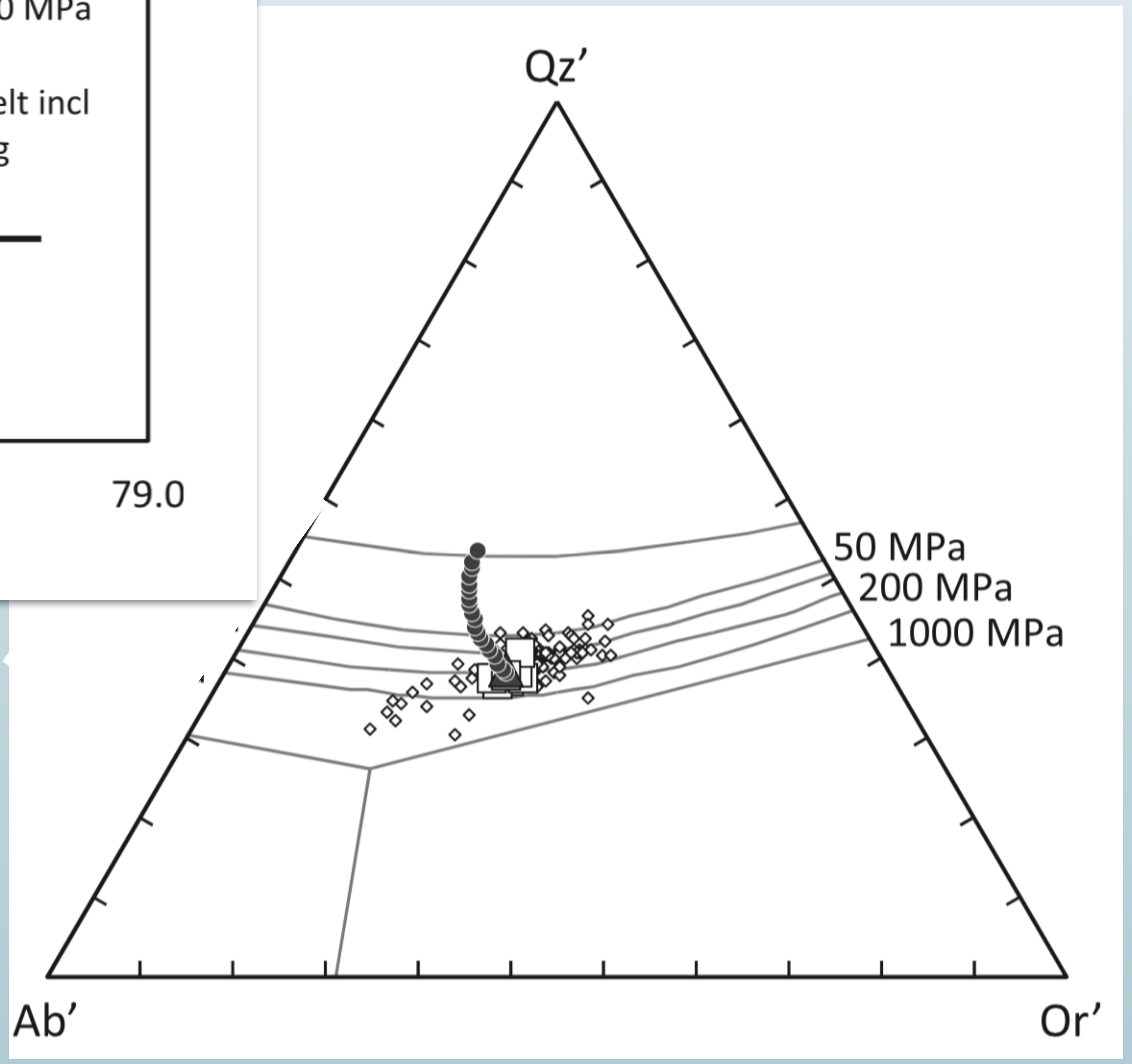
P-T conditions of feldspar formation:
720°C, 150 MPa
(for Late Bishop Tuff bulk composition)

Where in the crystallization sequence did this crystal form?



Thermodynamic Modeling of Silicic Magmas:
Rhyolite-MELTS calculations for the Late Bishop Tuff

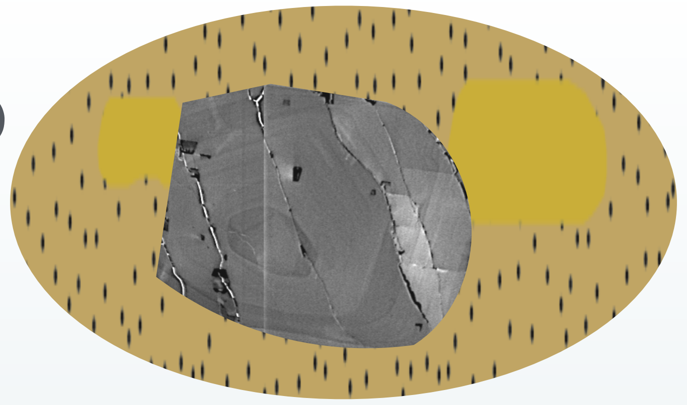




Range of P-T-X-crystallinity that match observations:
750°C, 150 MPa, 3.5 wt% H_2O, formed at ~40 wt% crystals

Gualda et al., 2012

Where in the crystallization sequence did this crystal form?



Thermodynamic Modeling of Silicic Magmas:
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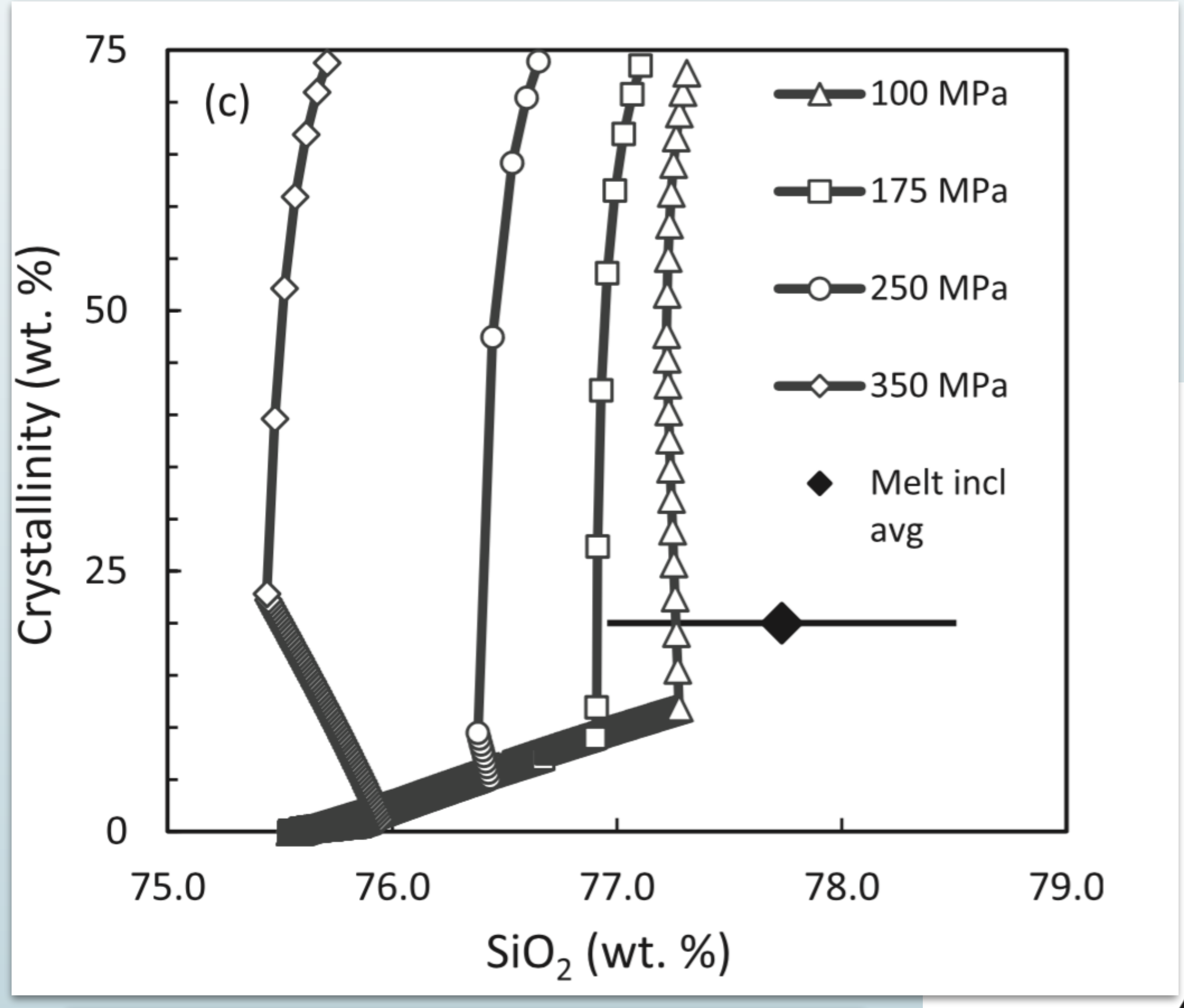
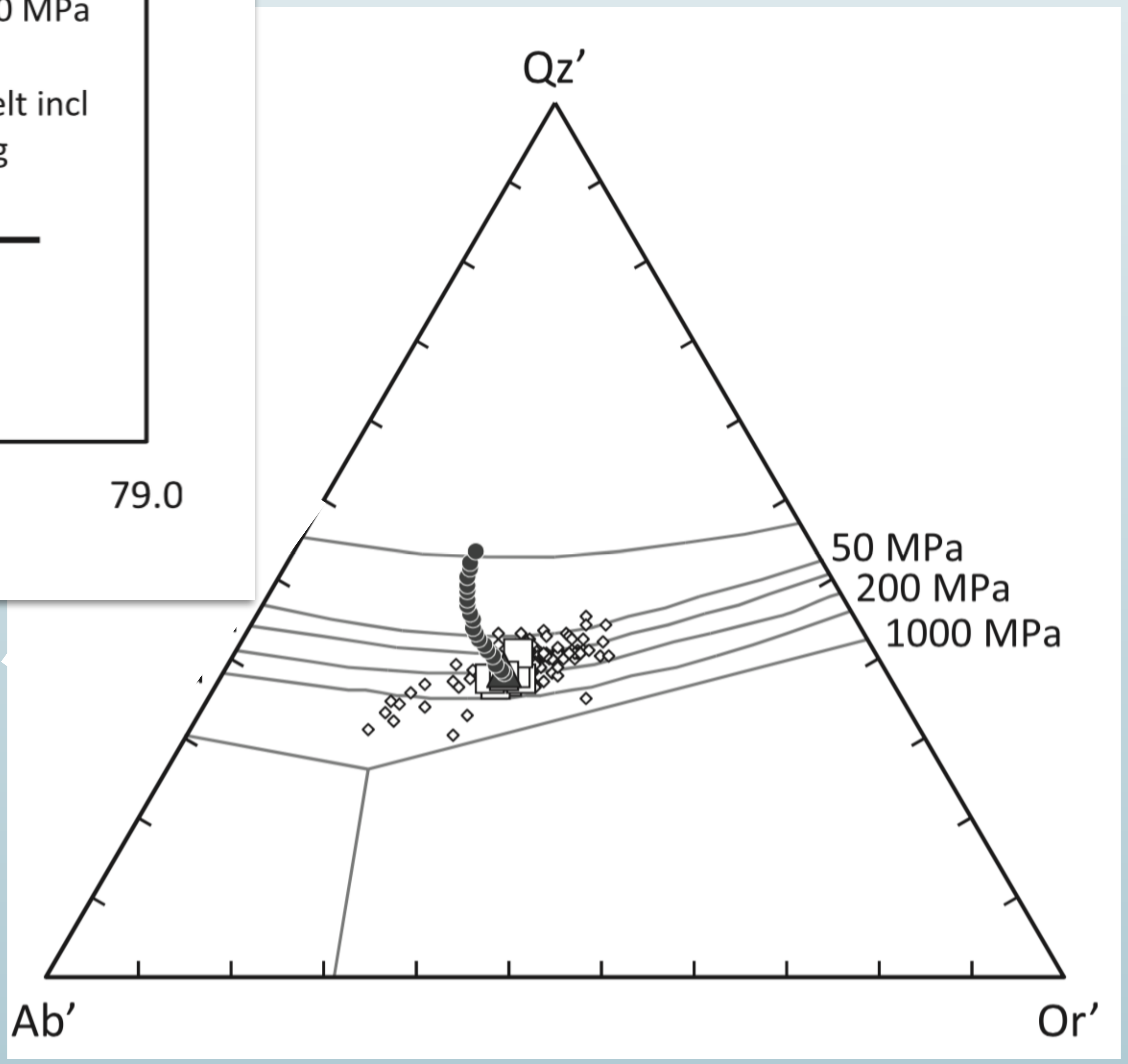


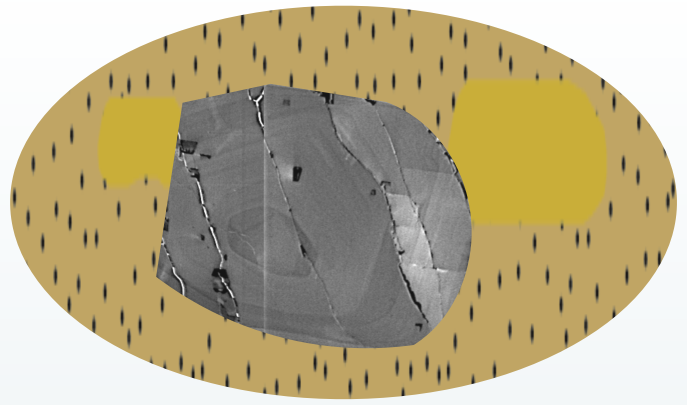


Gualda et al., 2012

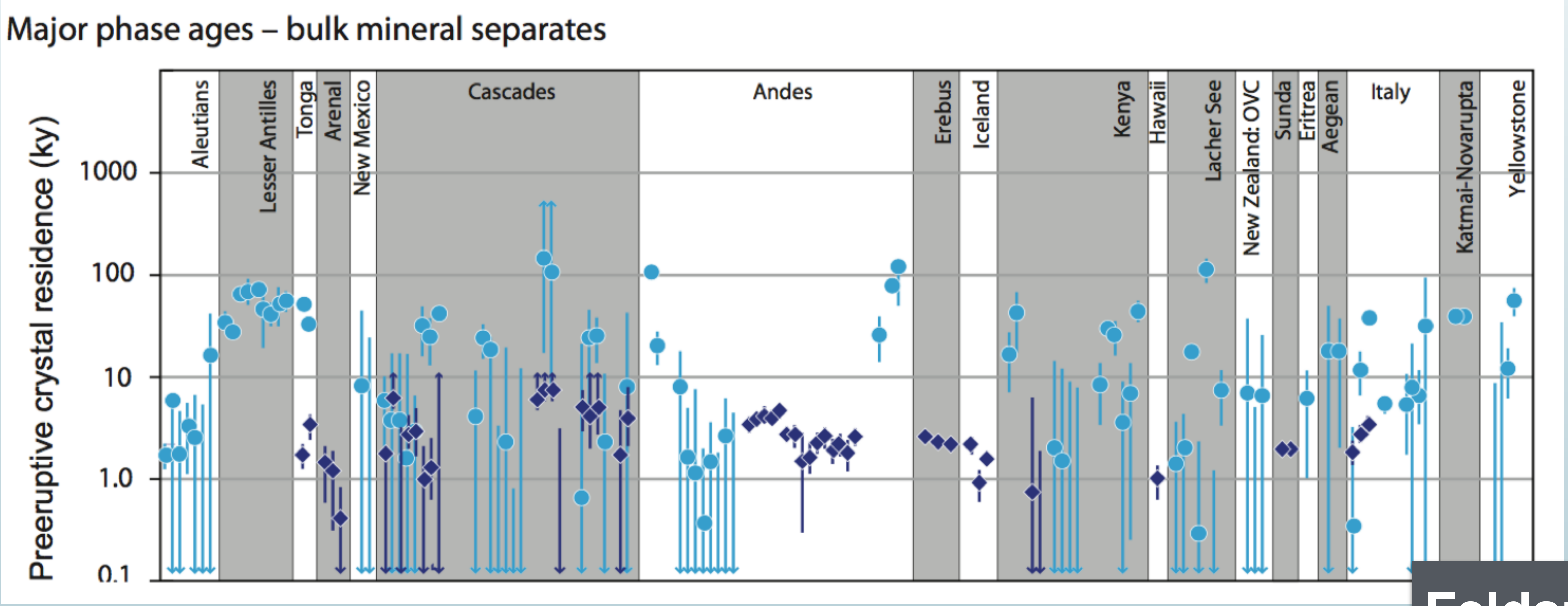
Range of P-T-X-crystallinity that match observations:
750°C, 150 MPa, 3.5 wt% H_2O, formed at ~40 wt% crystals

Mark Ghiorso (Today's Tutorial!)

How old is this crystal?



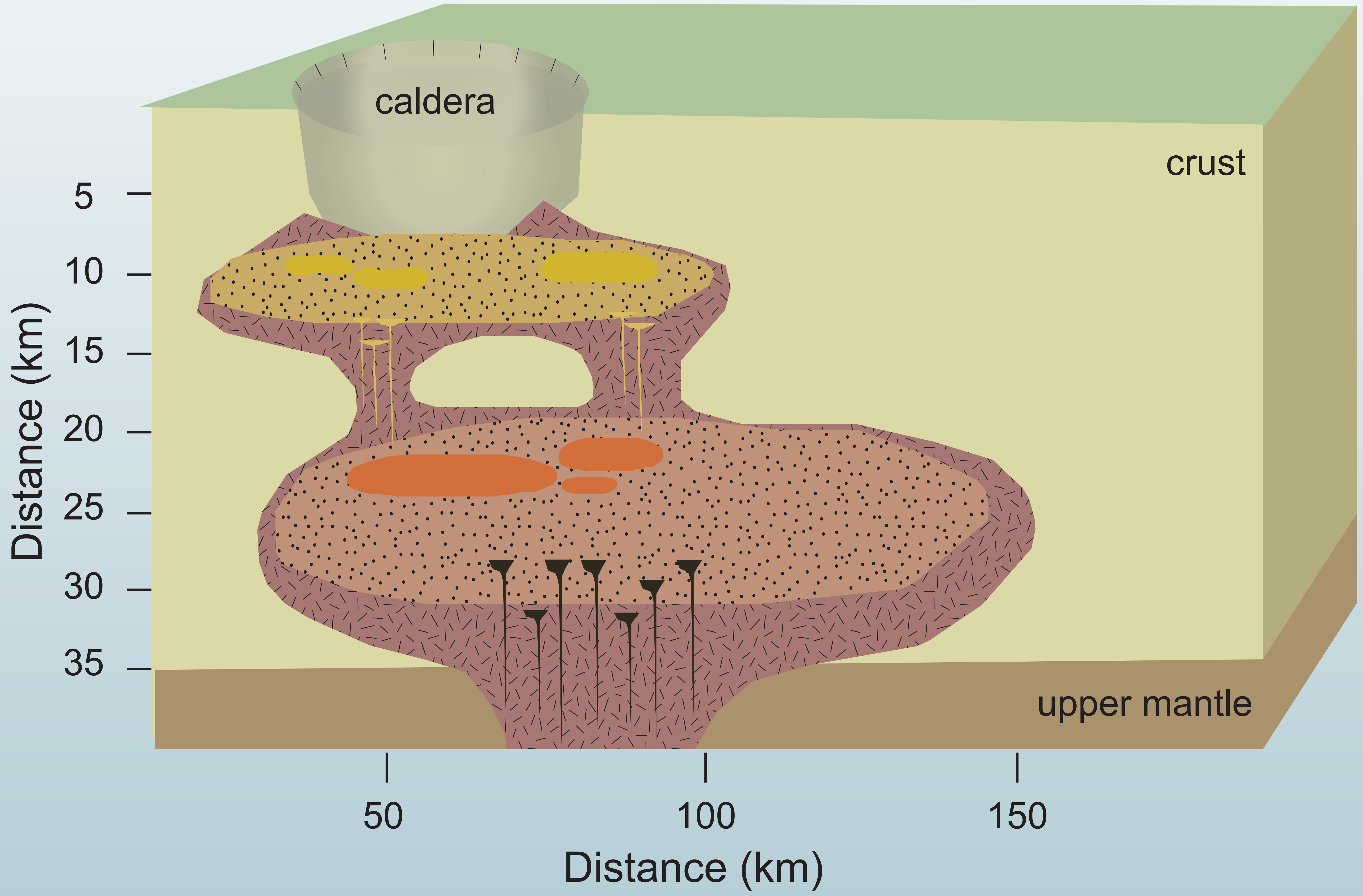
Compilation of ^{238}U–^{230}Th (light blue circles) and ^{230}Th–^{226}Ra (dark blue diamonds) ages of bulk mineral separates of major phases, expressed as pre-eruptive residence age



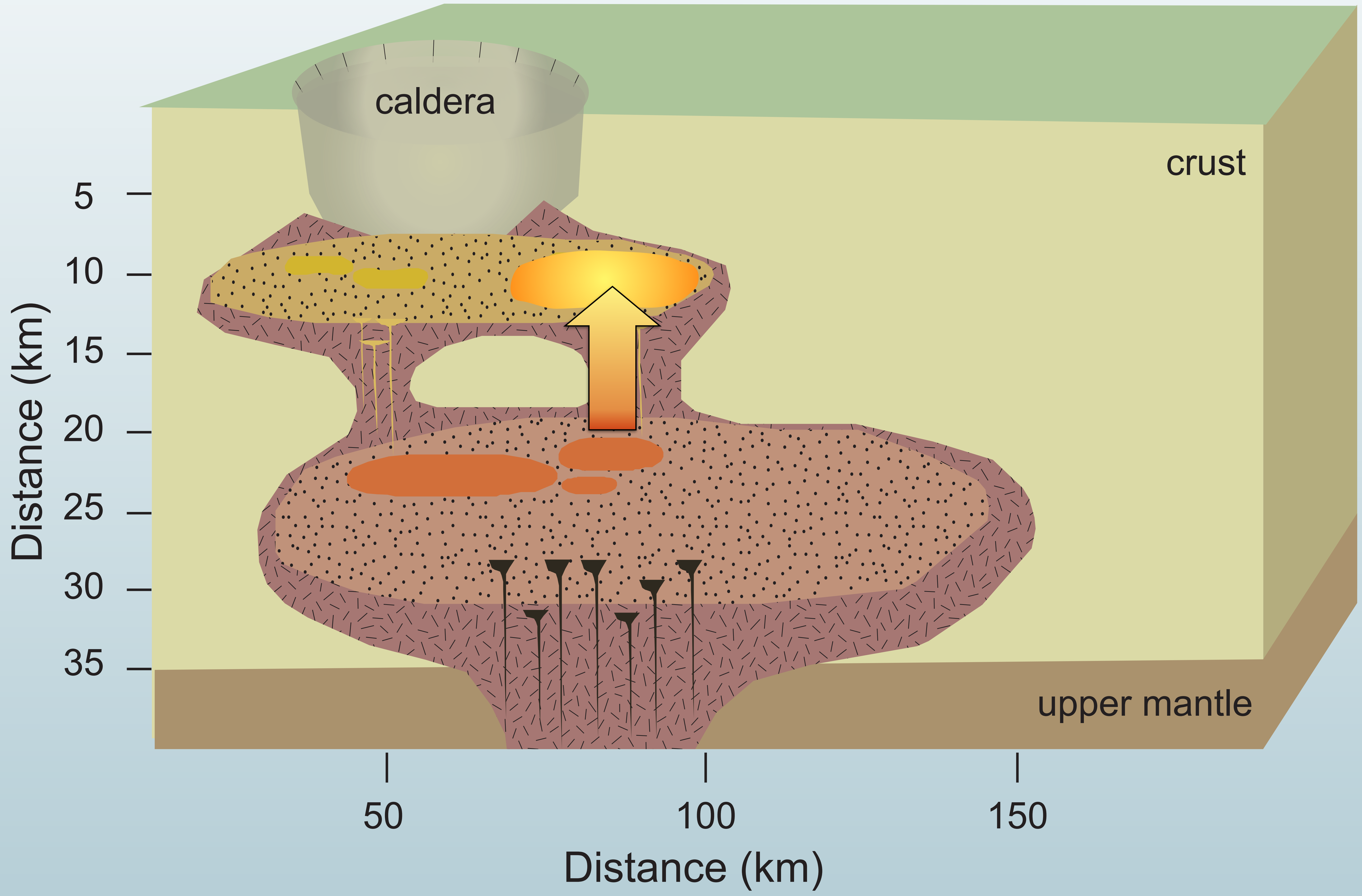
Cooper, 2017

Feldspar was in magma reservoir for ~80,000 years

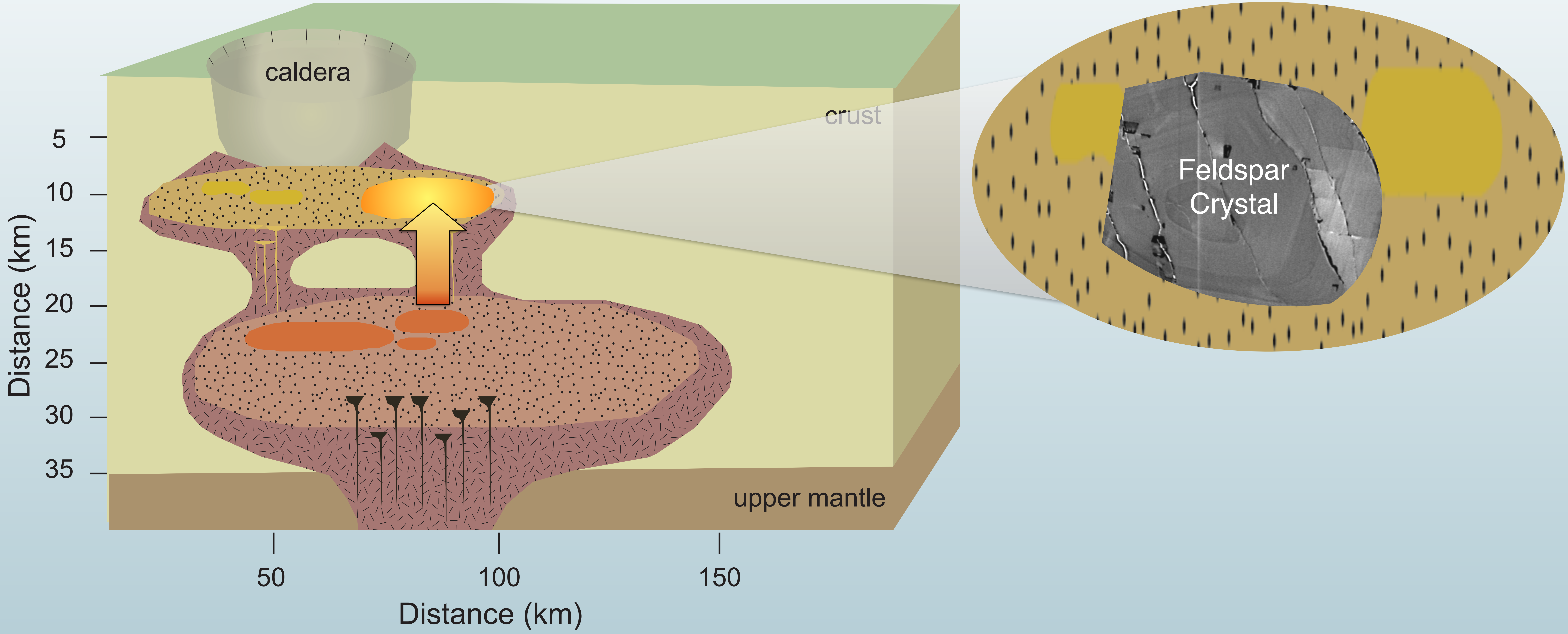
Clues from intracrystalline disequilibrium



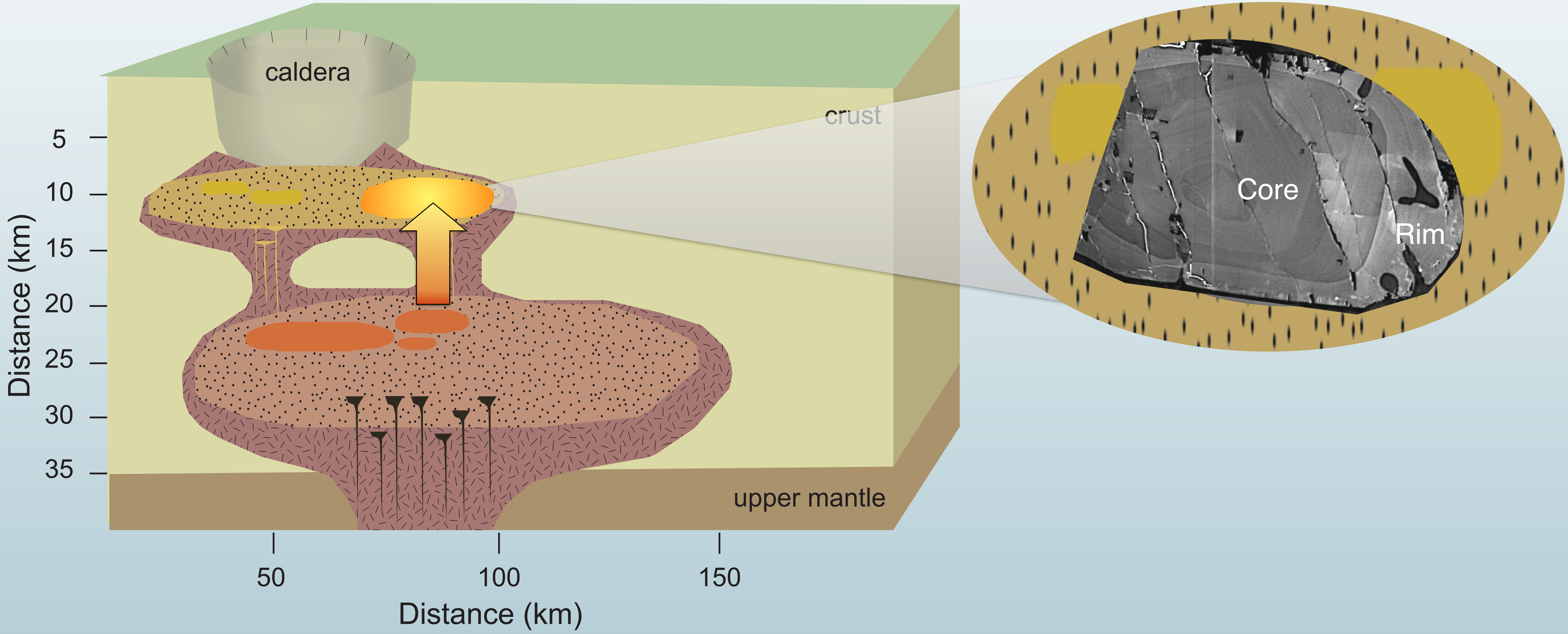
Clues from intracrystalline disequilibrium



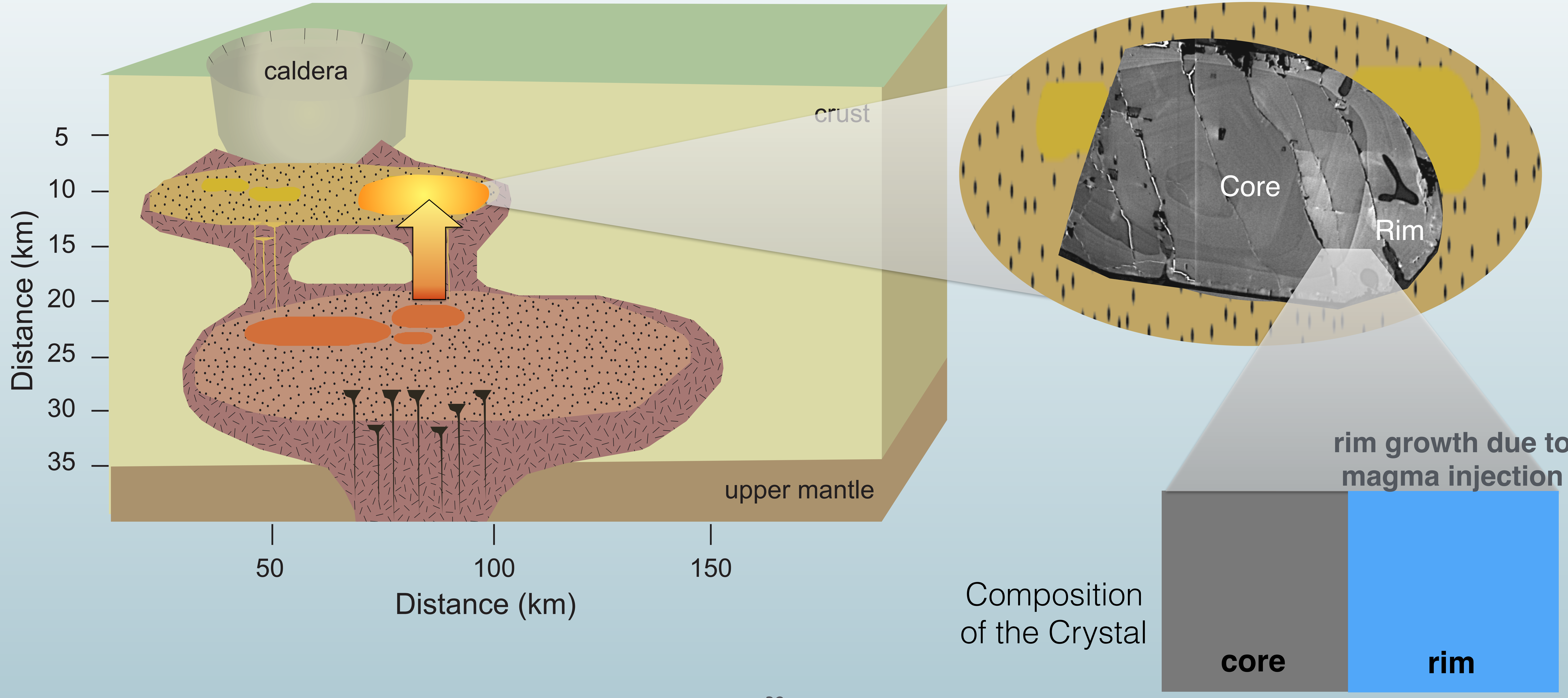
Clues from intracrystalline disequilibrium



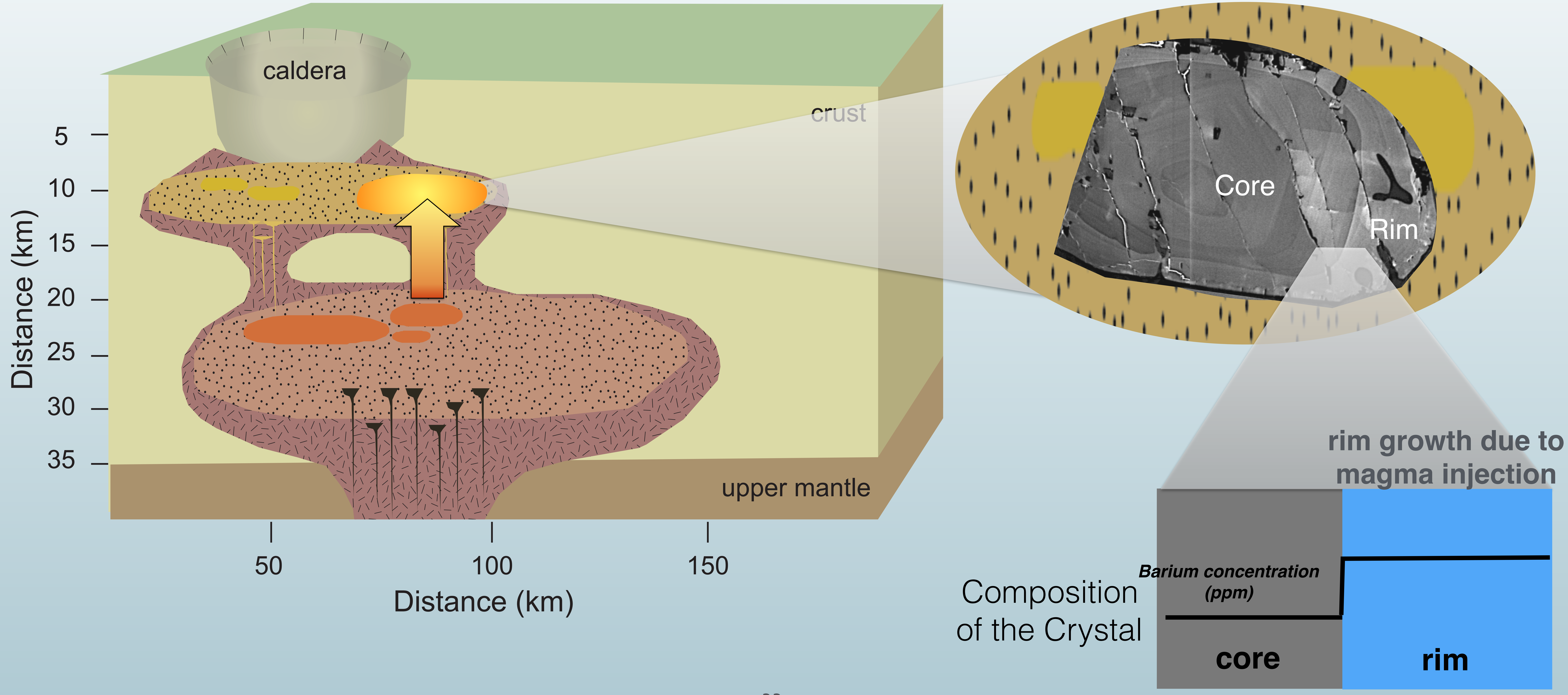
Clues from intracrystalline disequilibrium



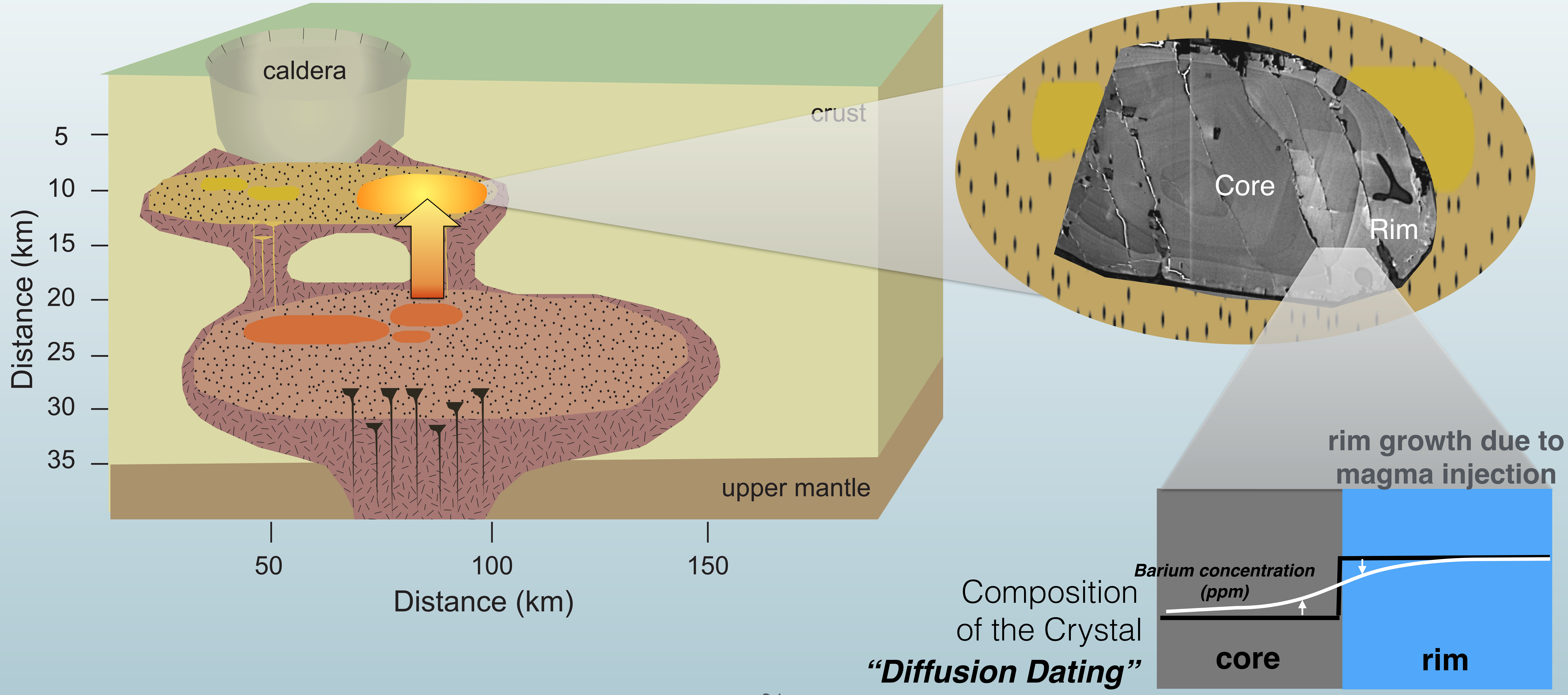
Clues from intracrystalline disequilibrium



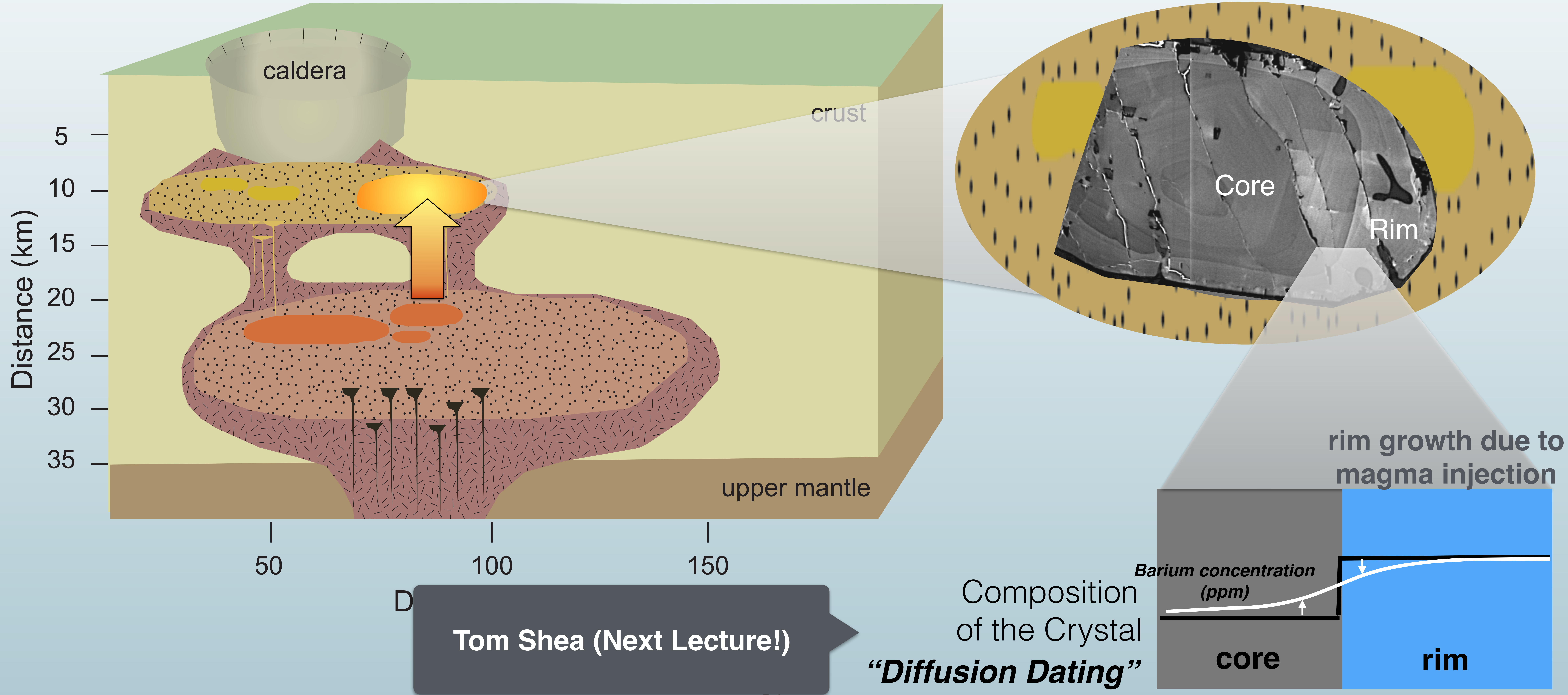
Clues from intracrystalline disequilibrium



Clues from intracrystalline disequilibrium

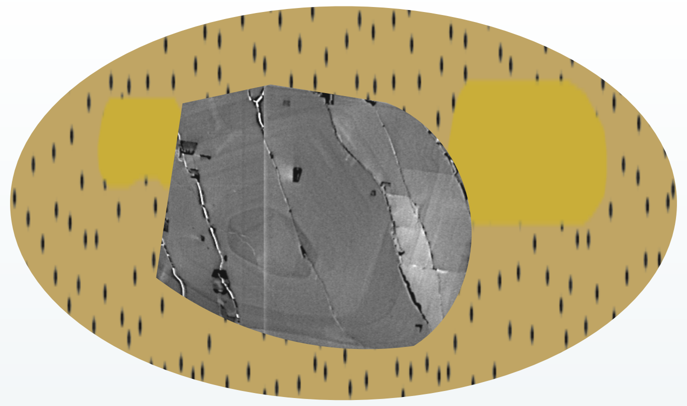


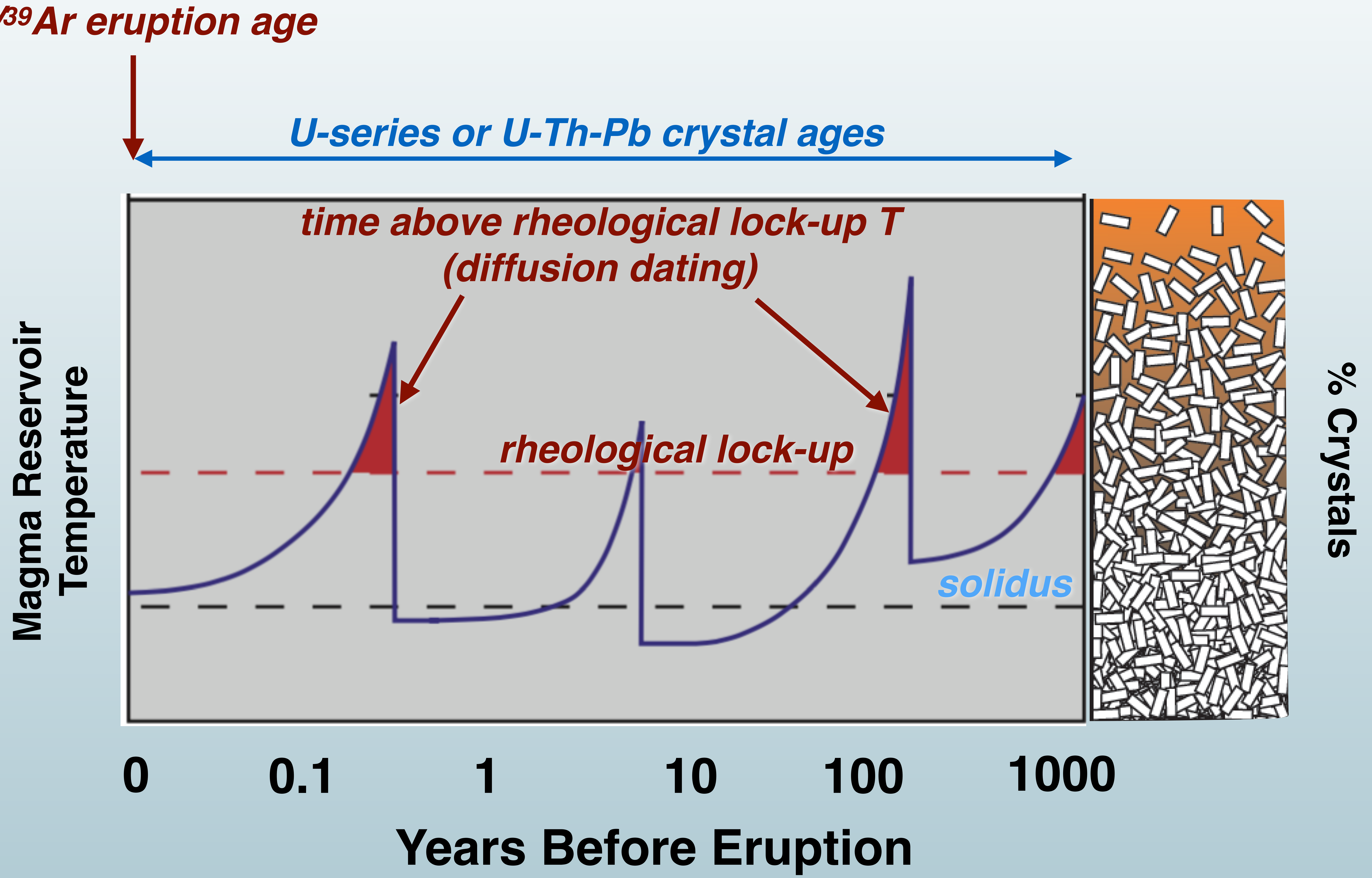
Clues from intracrystalline disequilibrium



Tom Shea (Next Lecture!)

Crystal spent a small % of its lifetime in a magma with <50% crystals





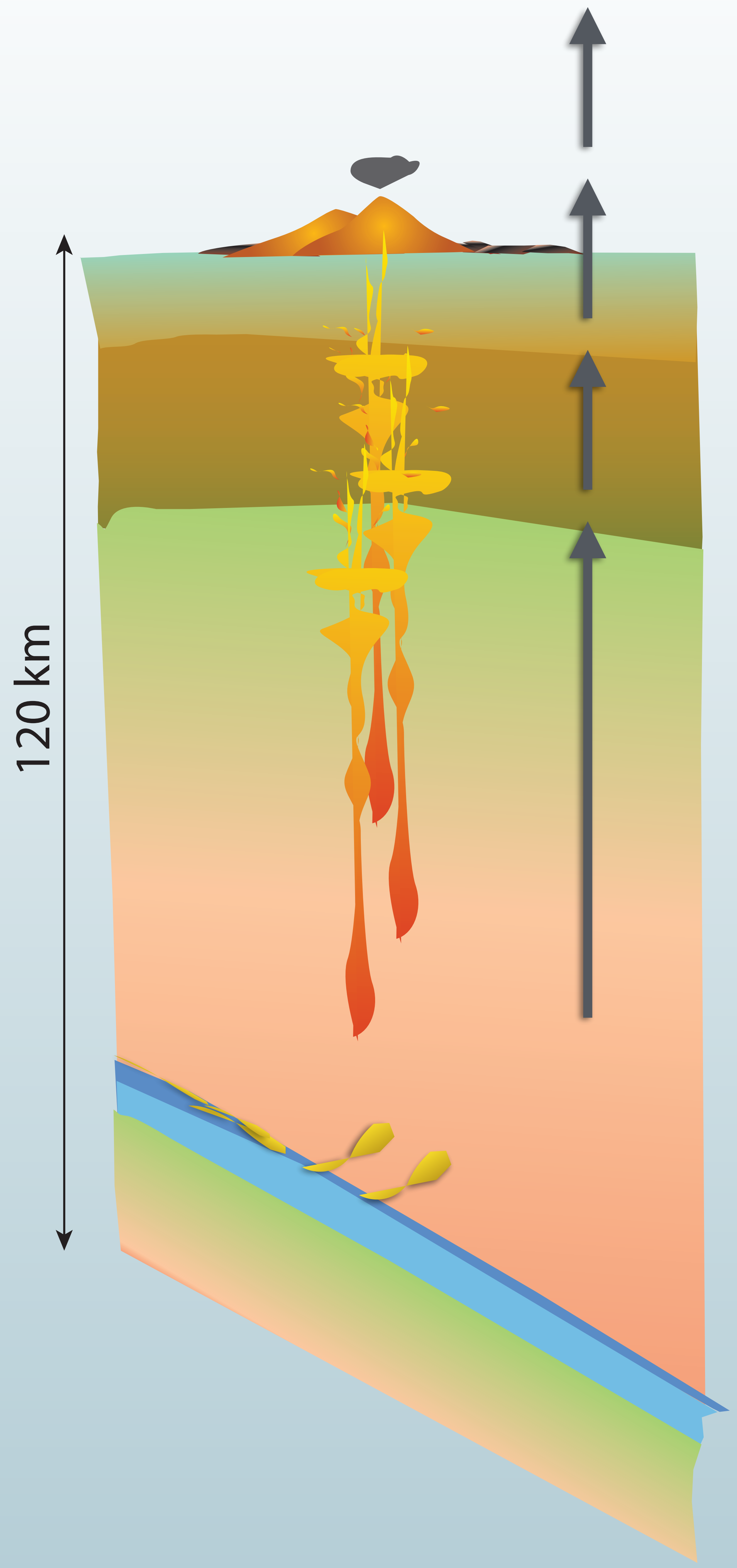
Cooper & Kent, 2014; Rubin et al., 2017

Goals For This Talk

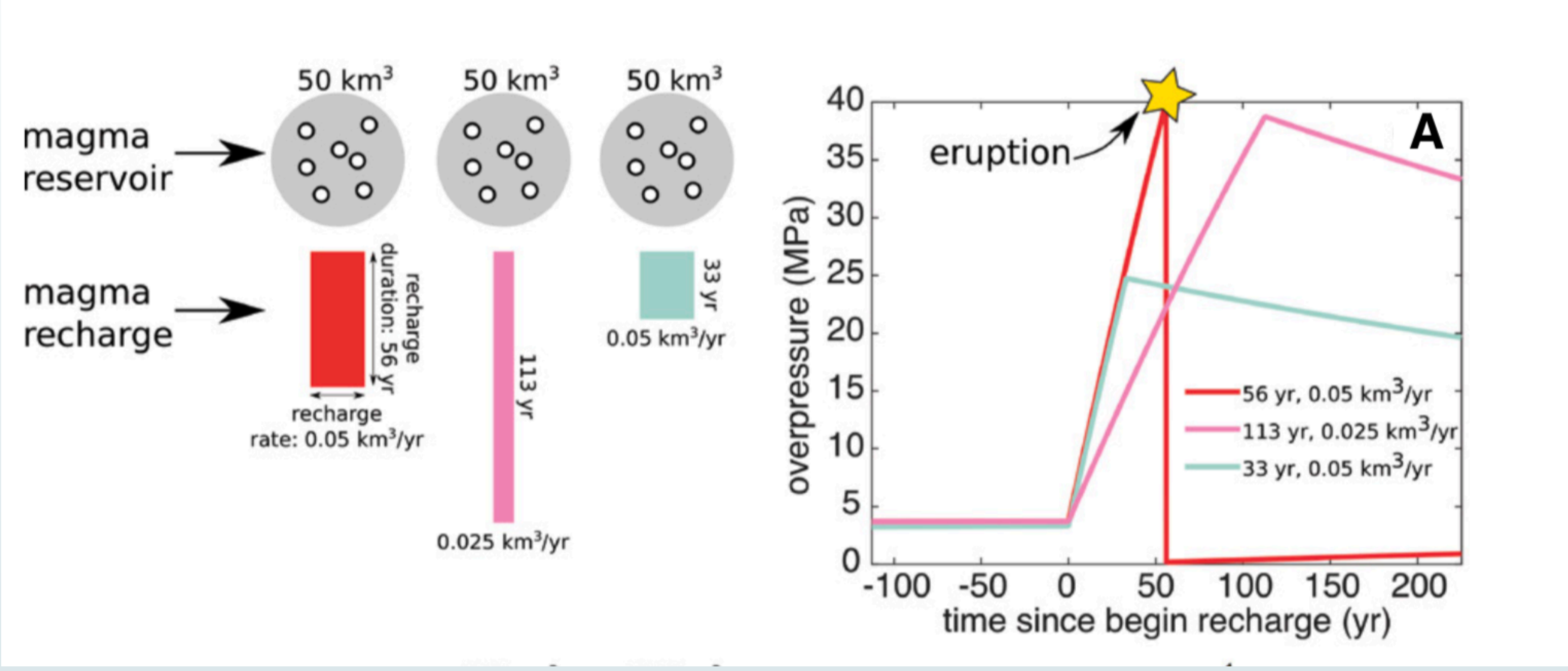
✓Transmagmatic system perspective

✓Reconstructing the P-T-X±t evolution of magmas in the crust

- Recent advances & exciting future directions
    - Causes of eruption initiation?
    - Causes of intra-arc diversity?

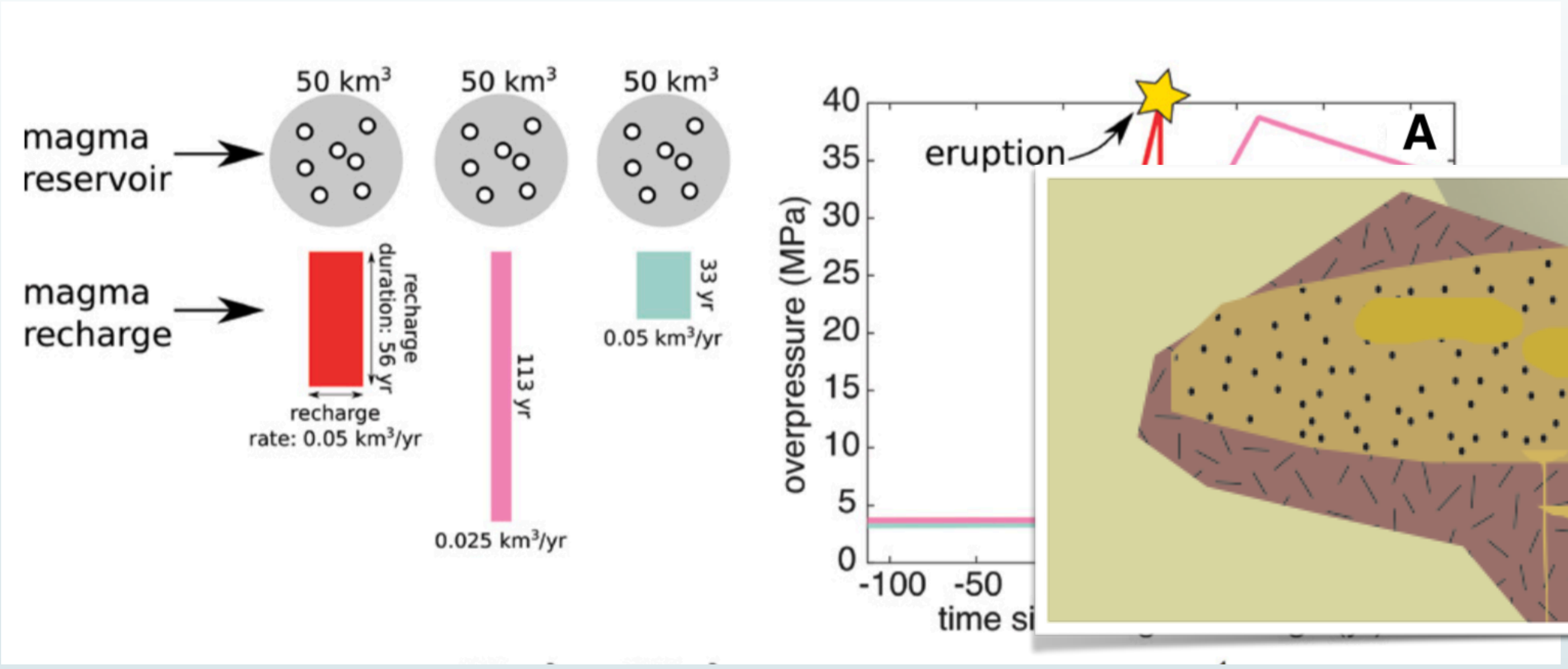


Cataloging eruption initiation via different crystal P-T-X-t paths

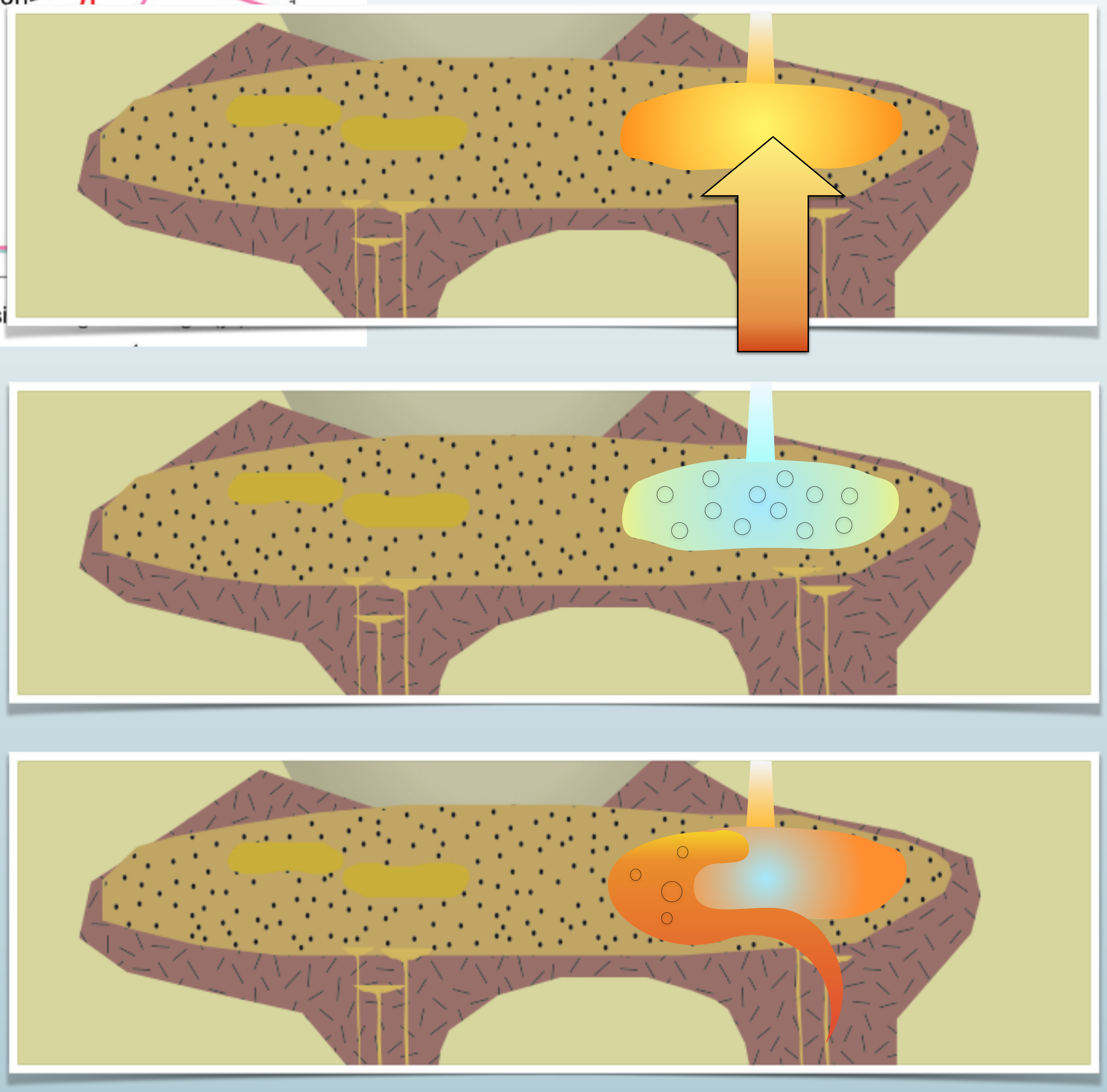


DeGruyter et al., 2015

Cataloging eruption initiation via different crystal P-T-X-t paths



DeGruyter et al., 2015

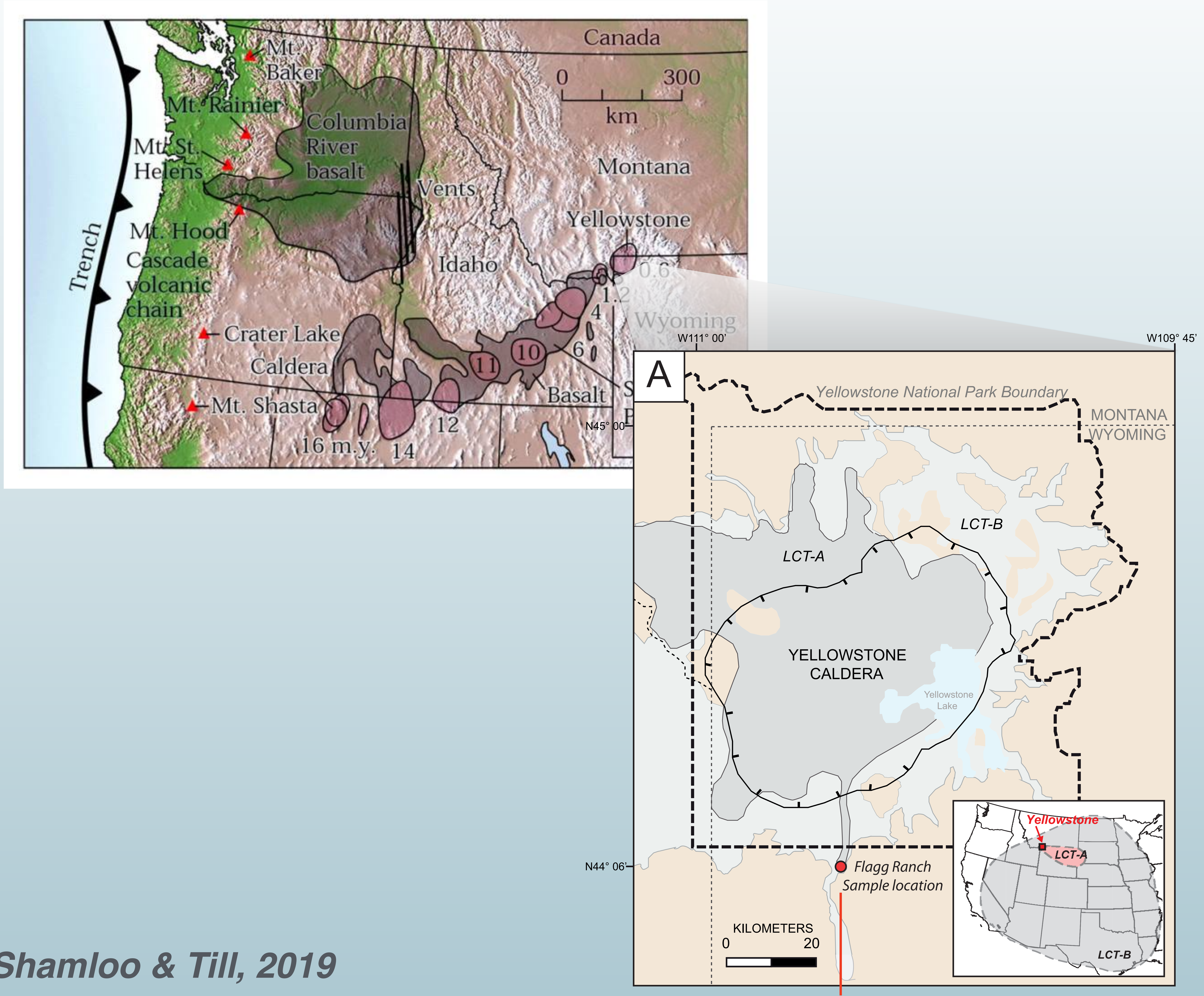


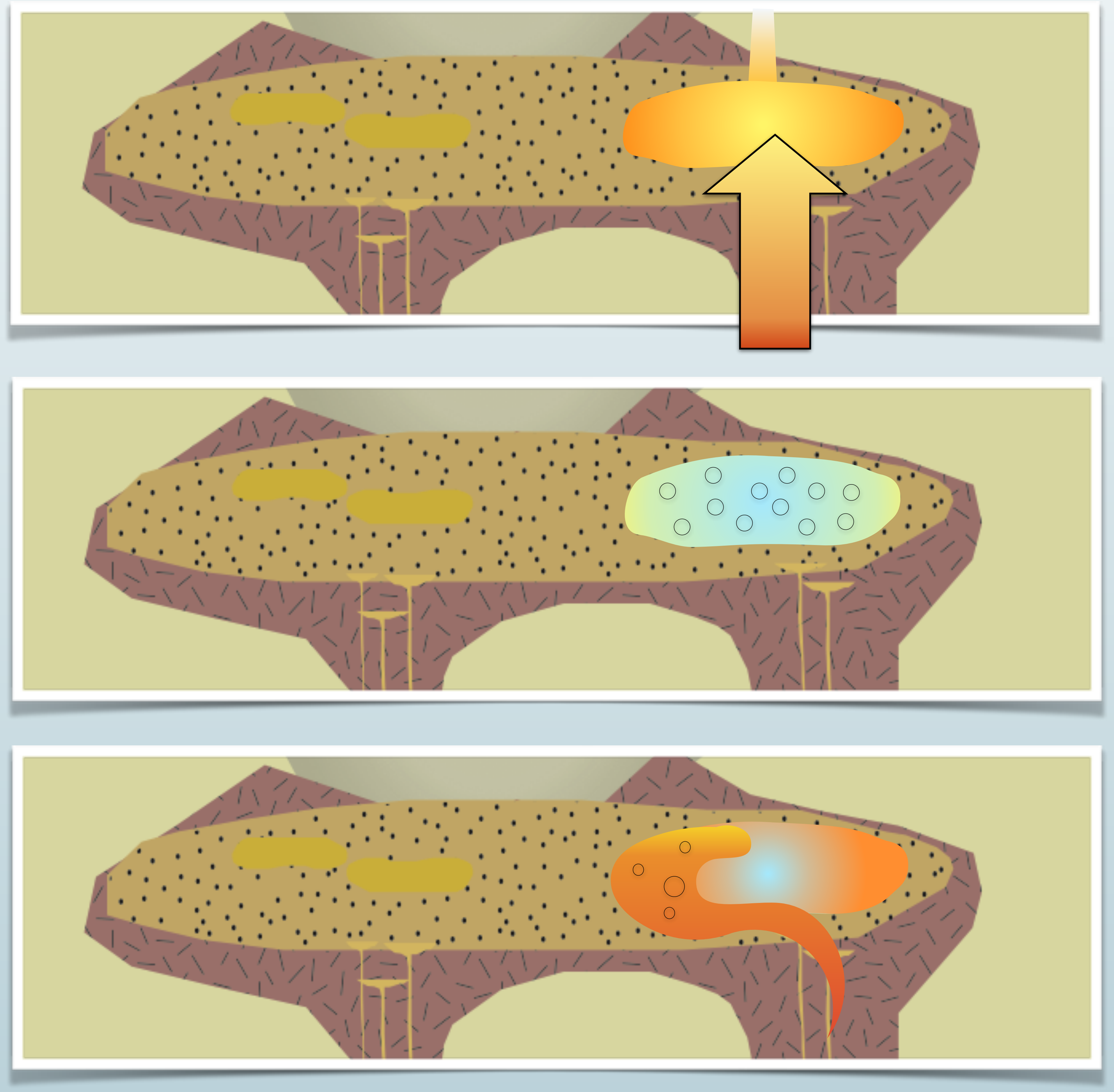
Injection Triggered

Volatile Overpressure Triggered

Magma Mixing Triggered

What Initiated Yellowstone's Lava Creek Tuff Eruption?

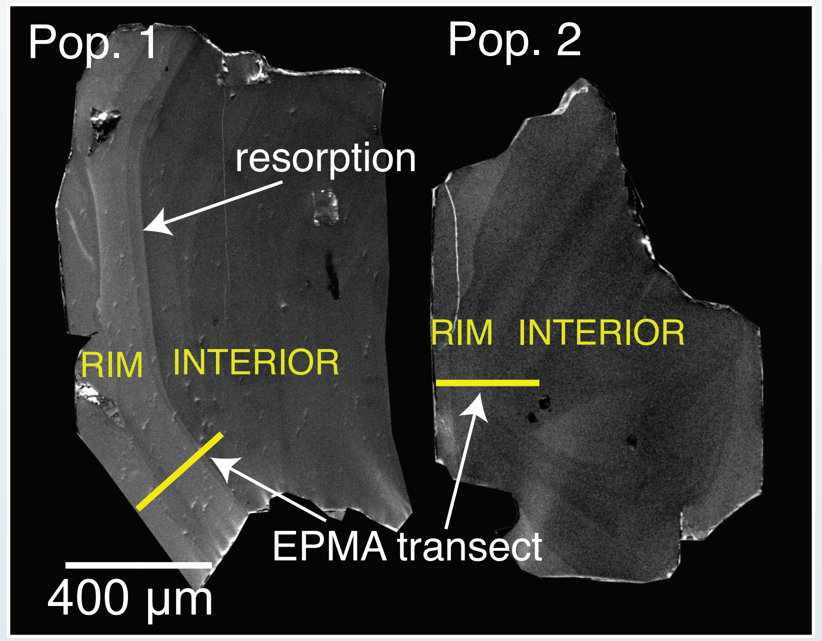


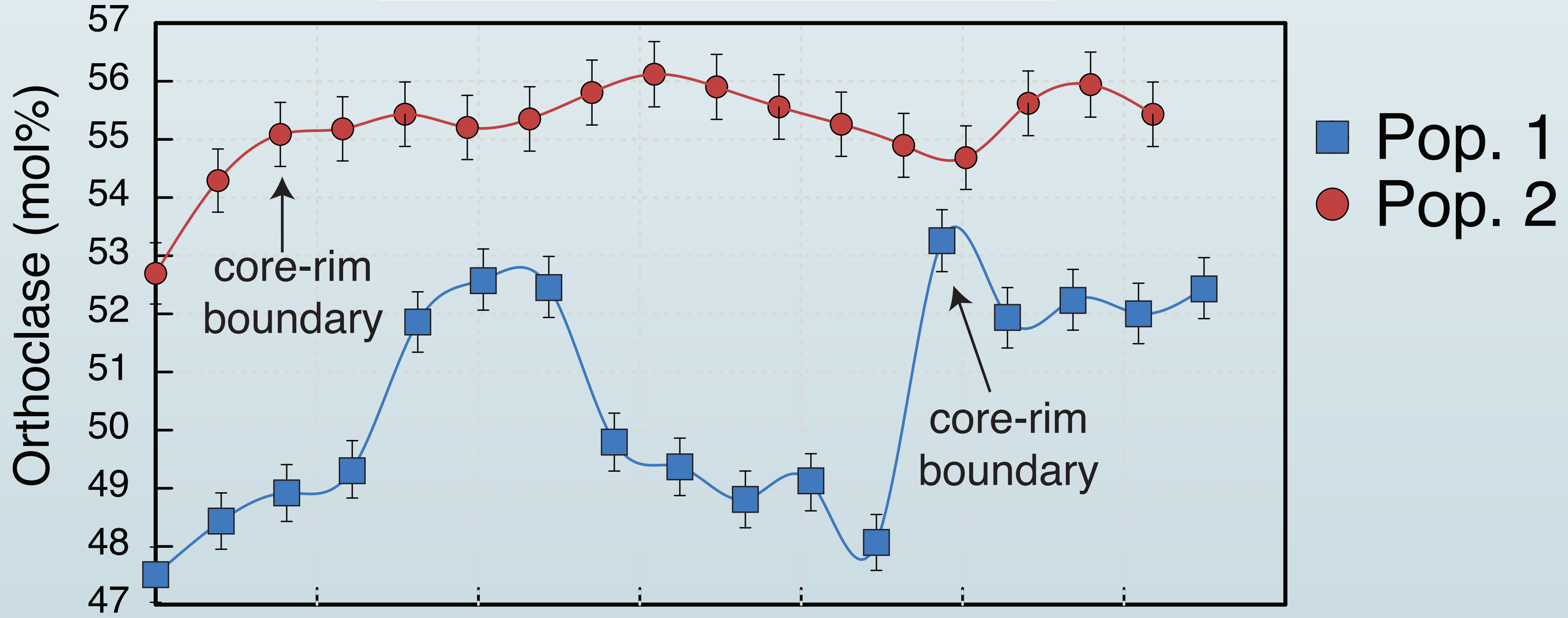


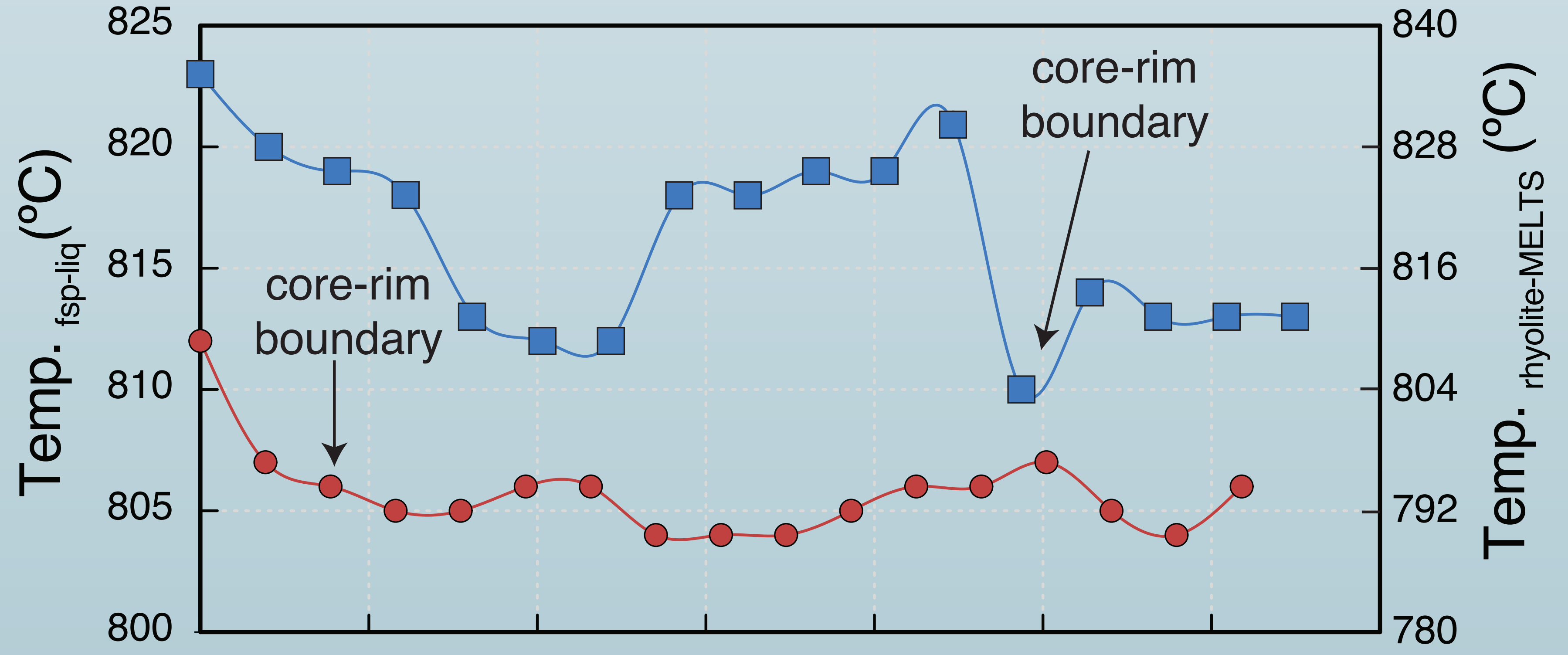
Shamloo & Till, 2019

What Initiated Yellowstone's Lava Creek Tuff Eruption?

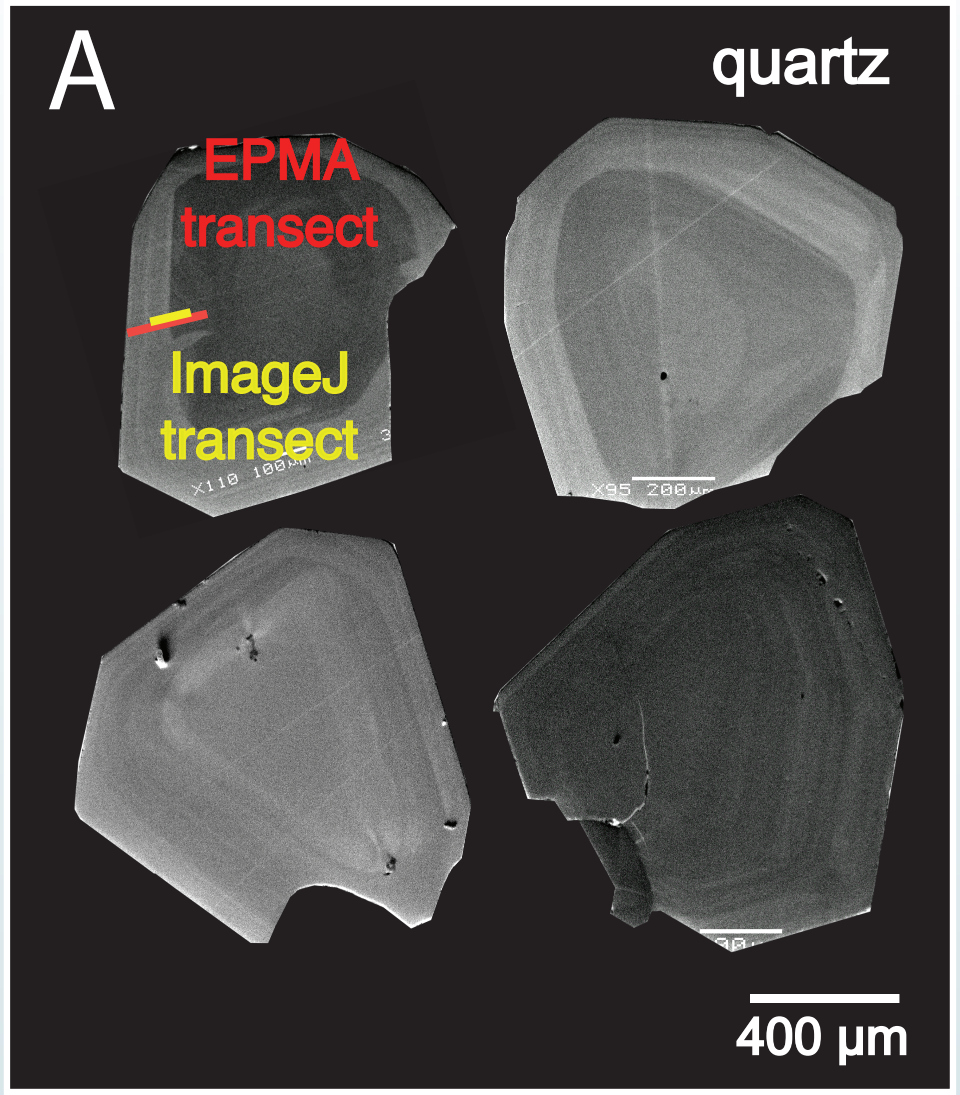
sanidine

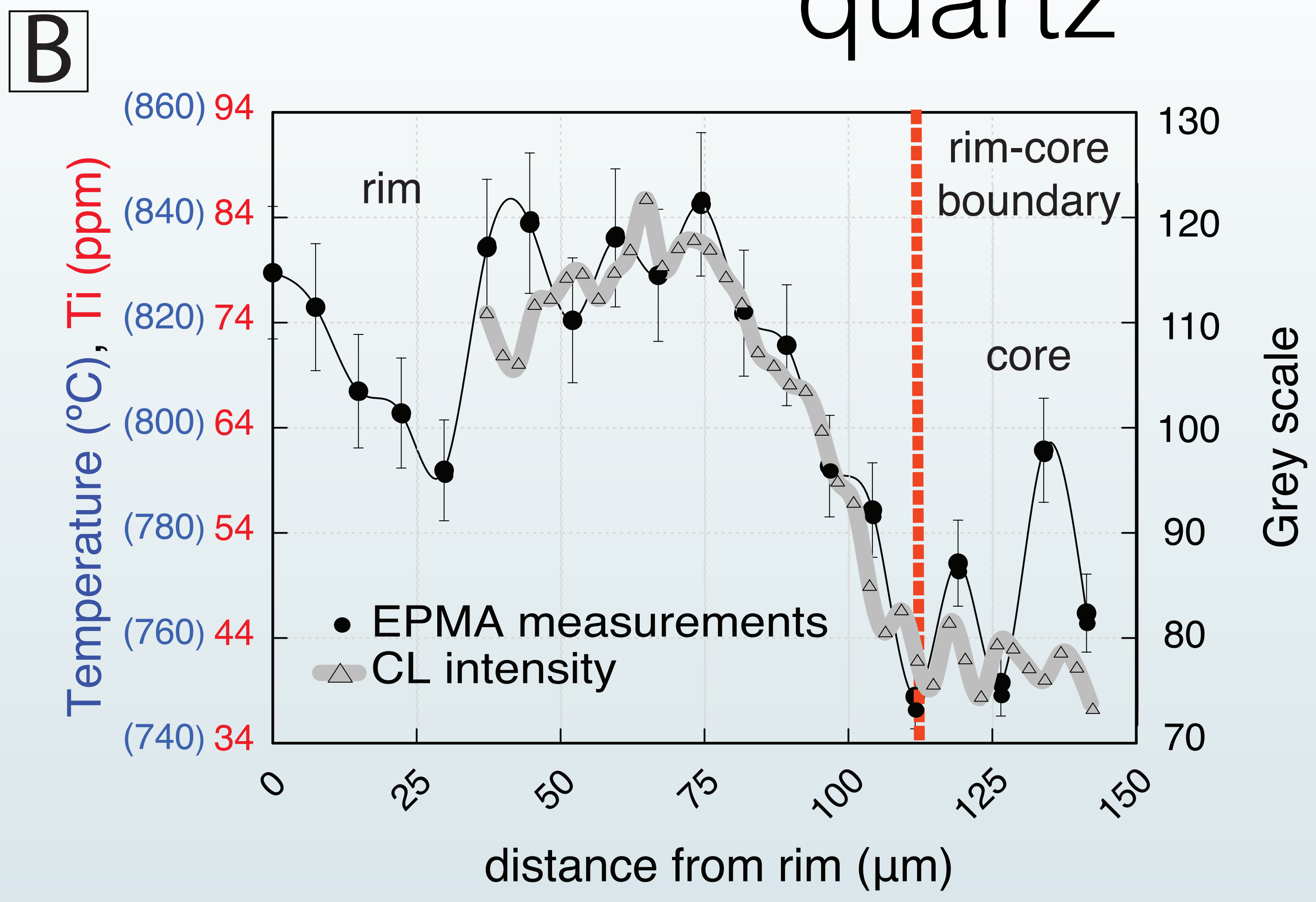




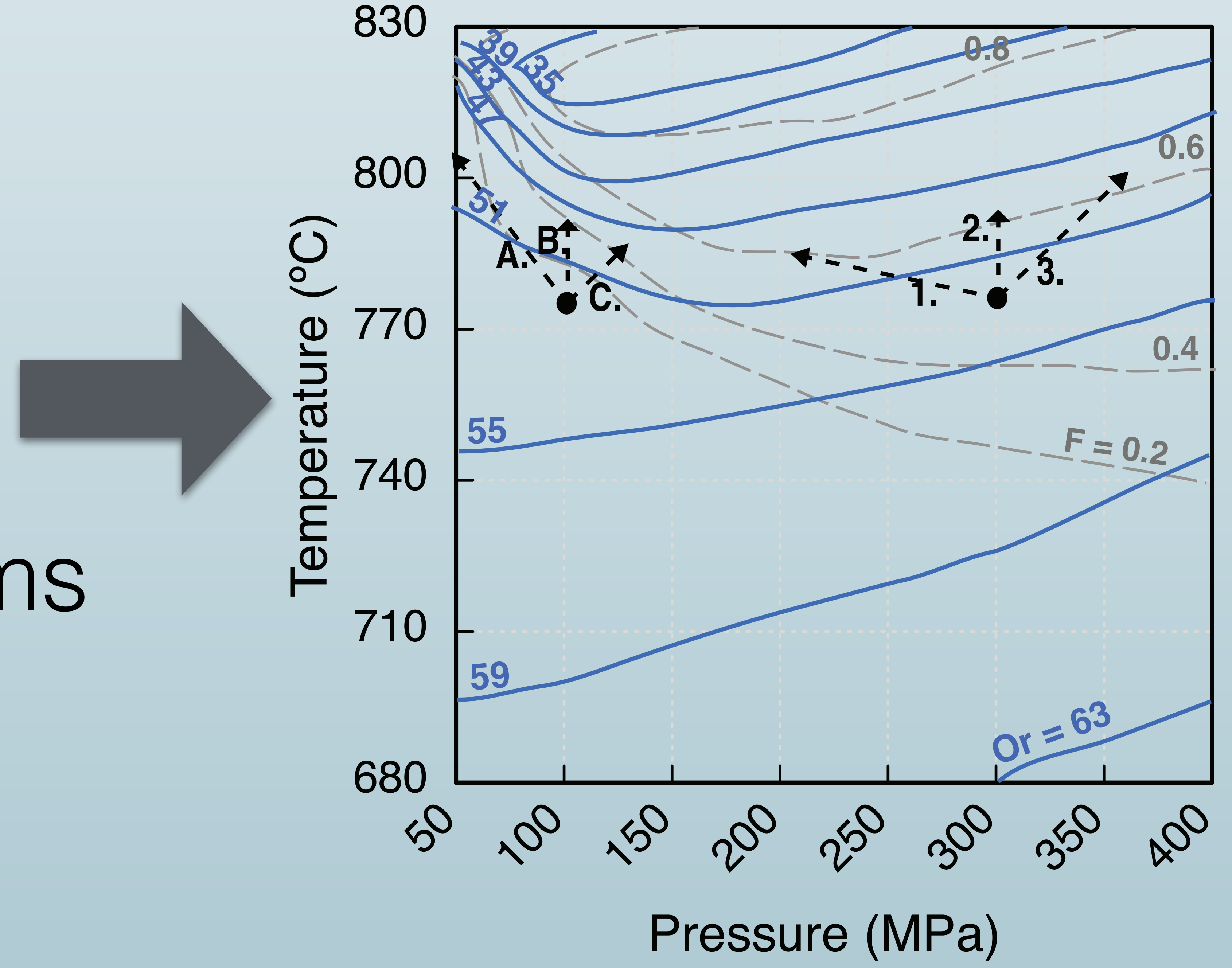


quartz





reconstruct P-T history recorded in phenocryst rims



Shamloo & Till, 2019

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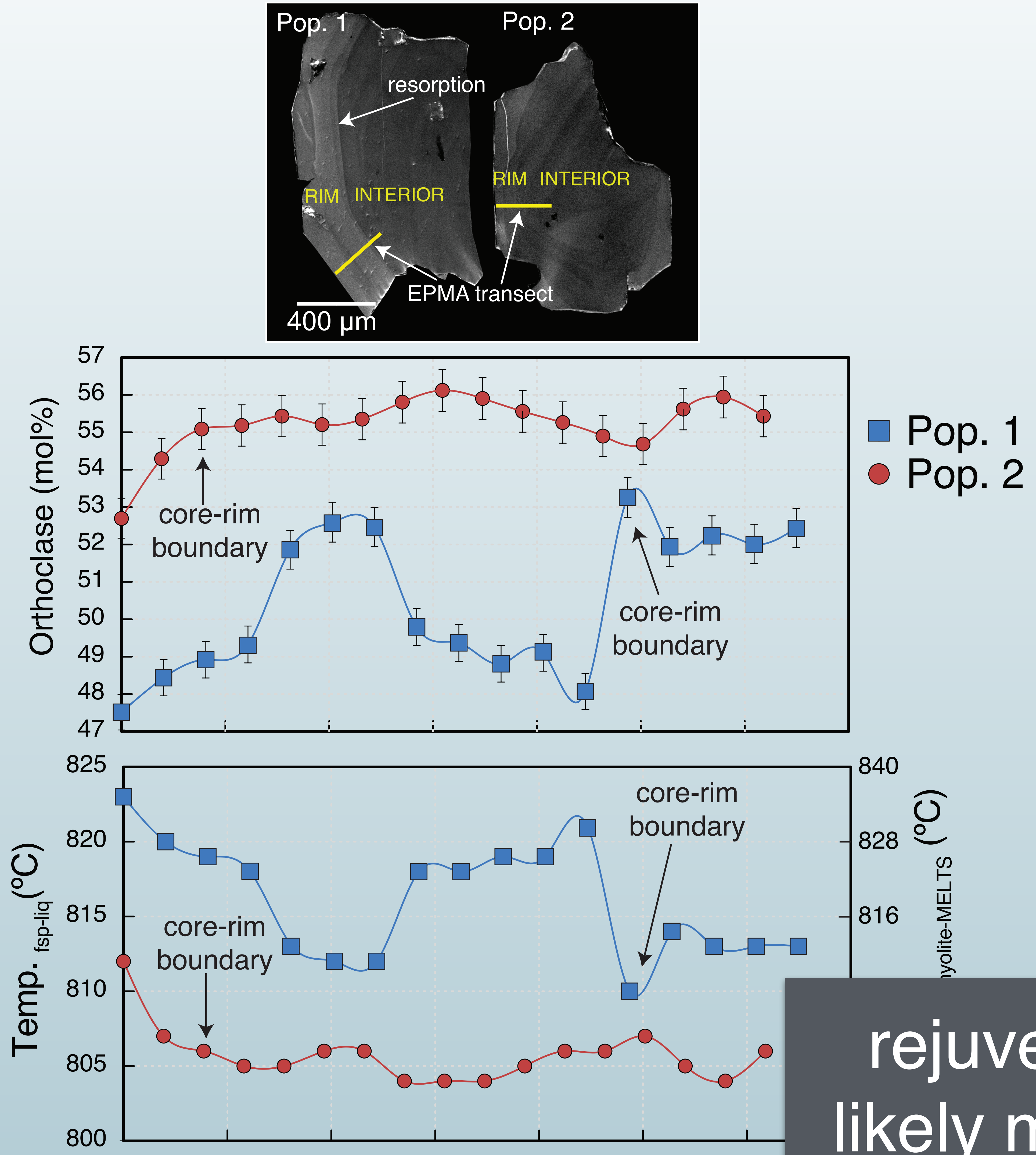
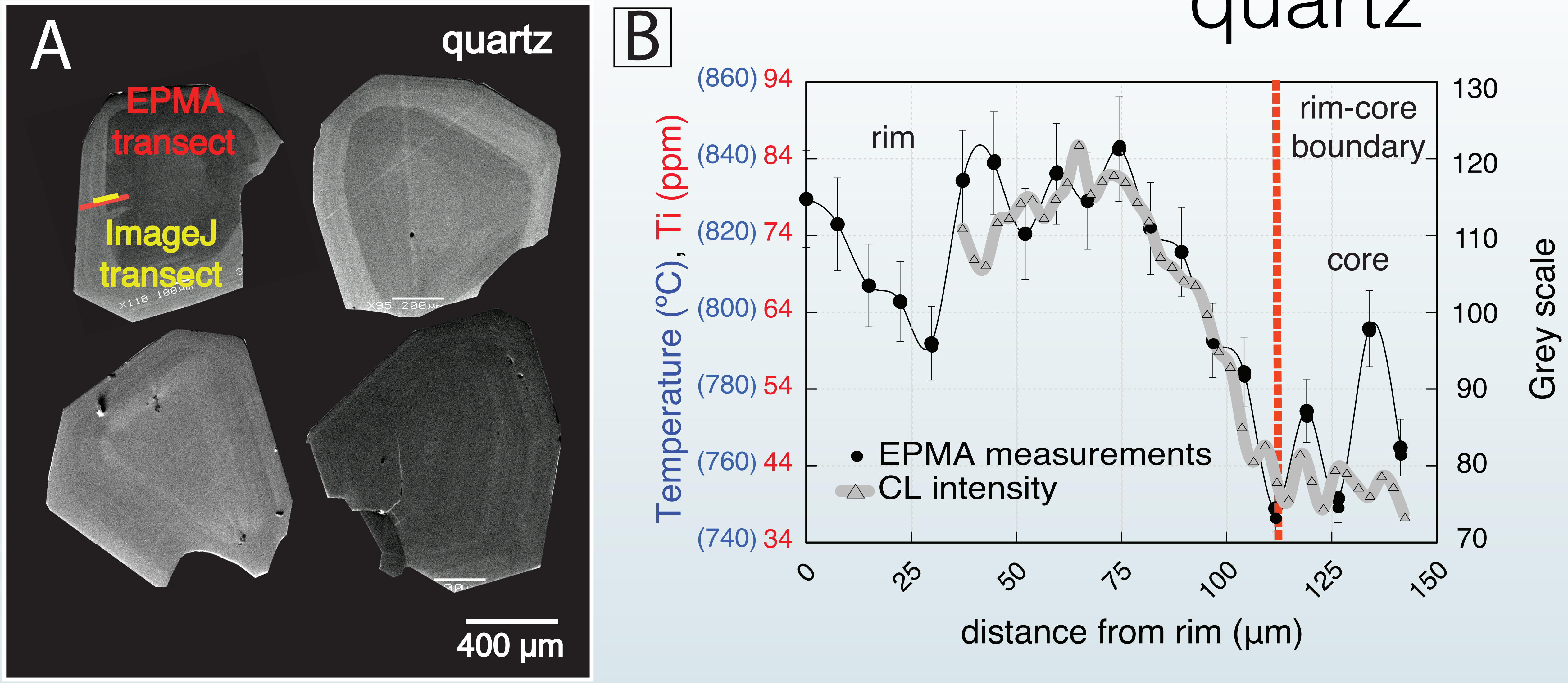
sanidine



quartz



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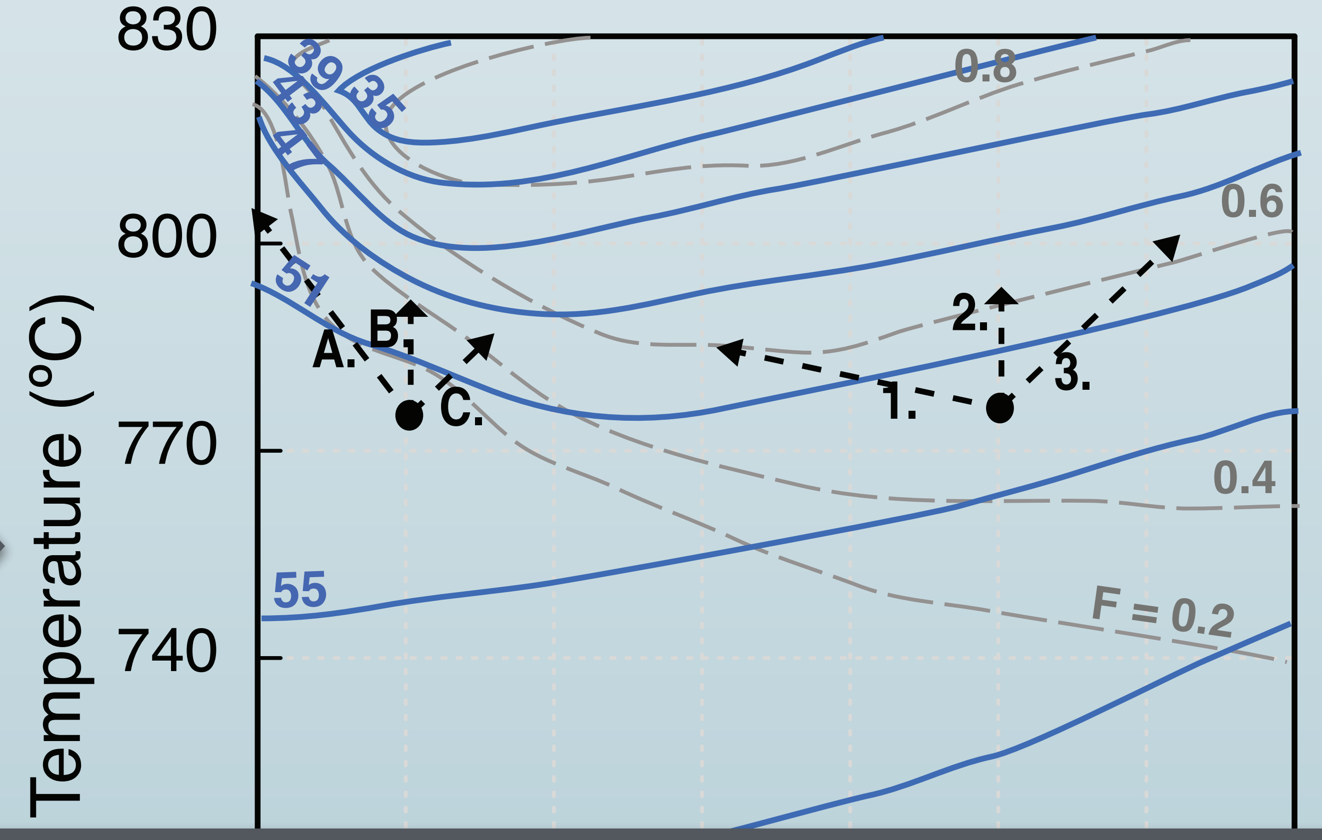
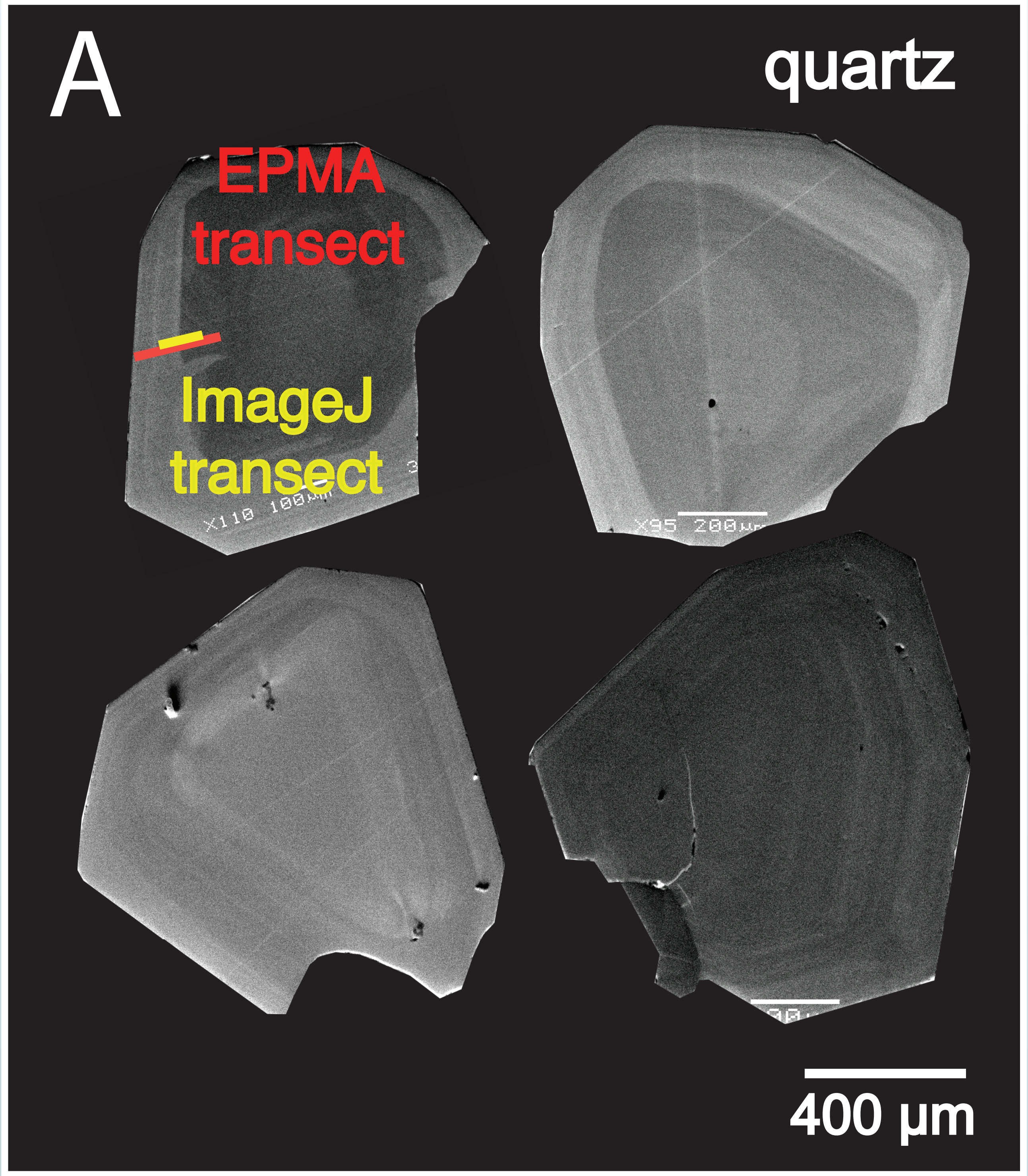
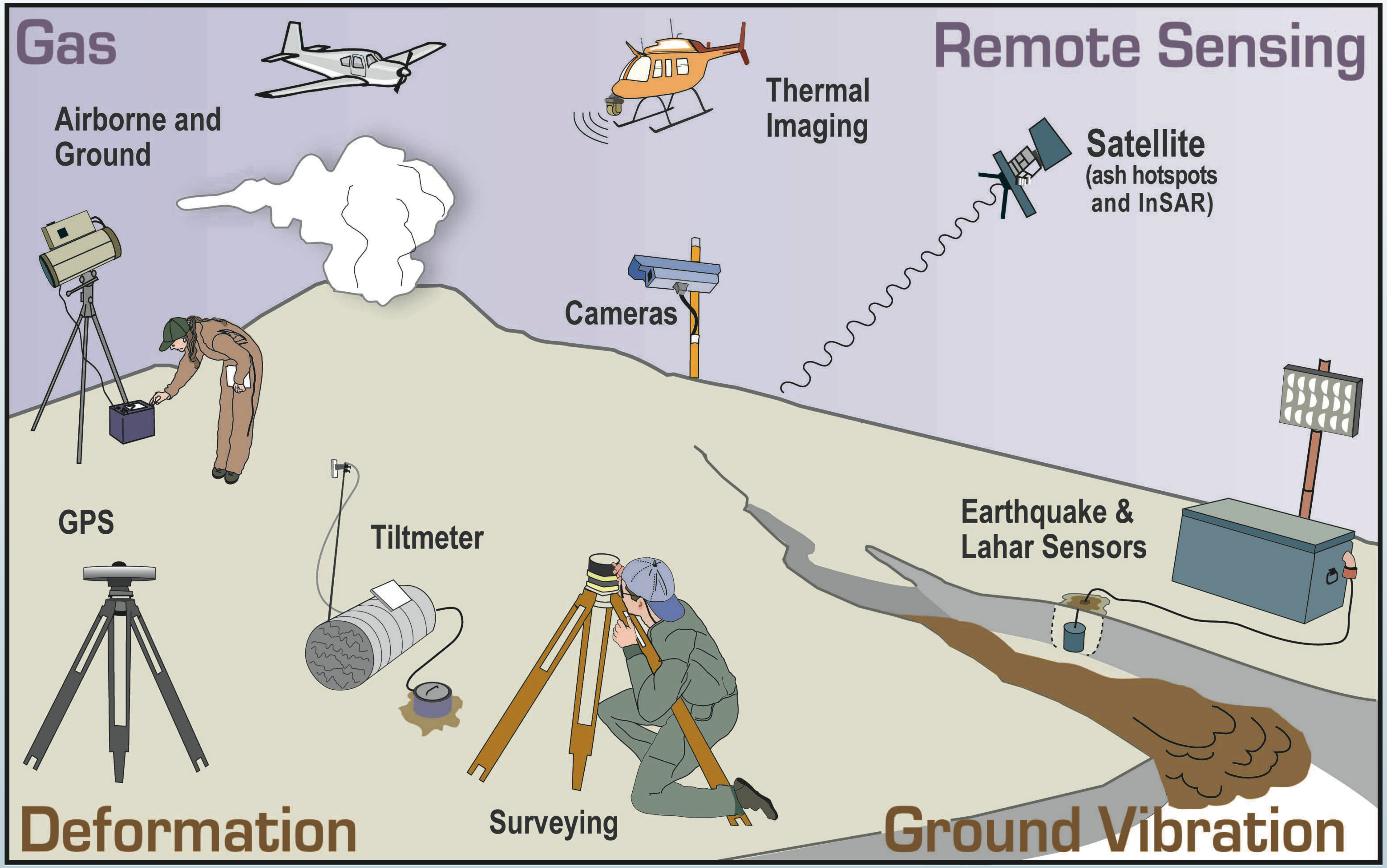


rejuvenation, within a decade of eruption, was the most likely mechanism to produce the overpressure required to trigger the LCT supereruption

Shamloo & Till, 2019

Tie patterns from volcanic deposits to volcanic hazard assessment

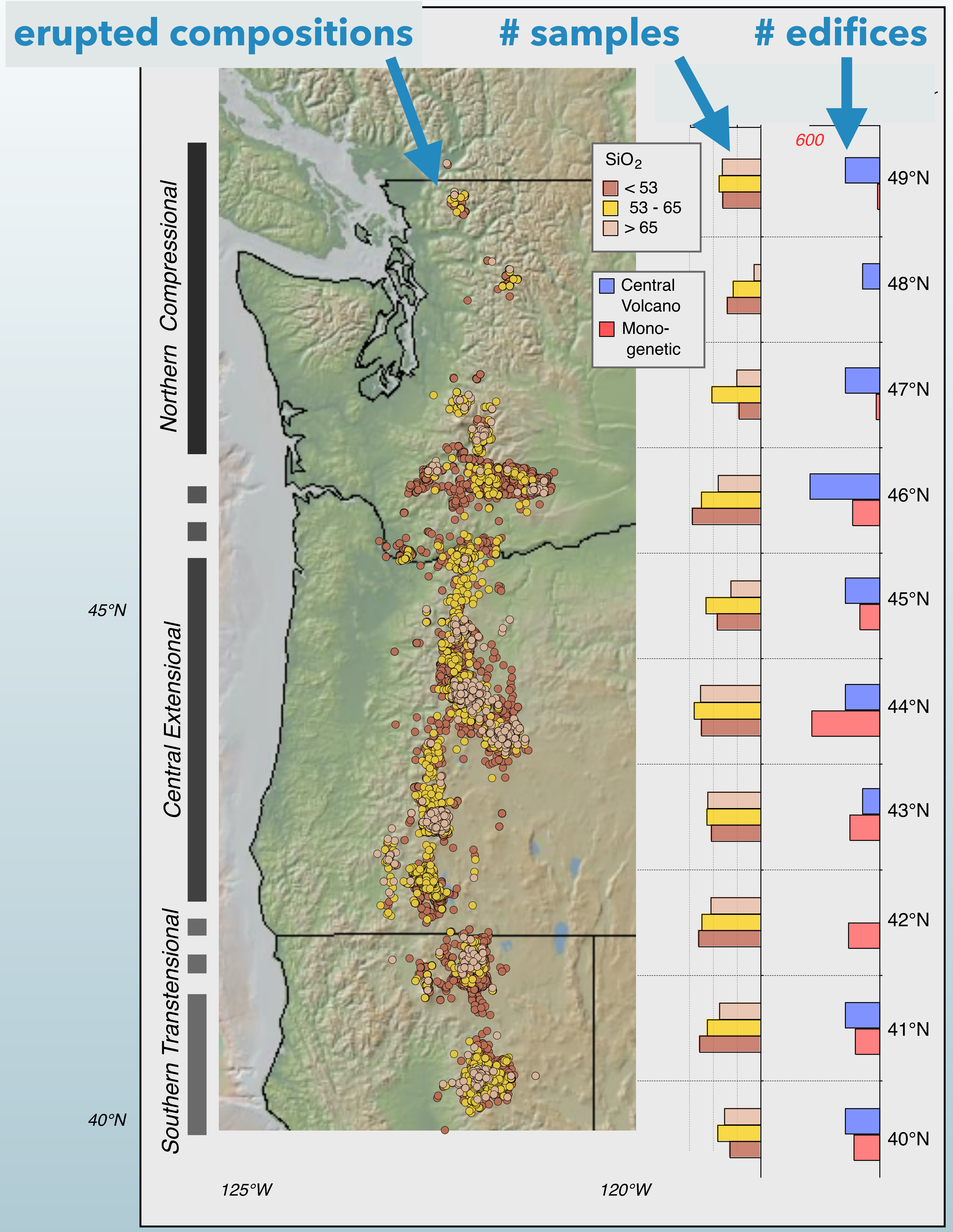




USGS.gov

How do we couple crystal records' view of magmatic processes with monitoring signals to better forecast eruptions?

Exciting Future Directions: What drives intra-arc diversity?



SiO_2
- < 53
- 53 - 65
- > 65

- Central Volcano
- Mono-genetic

Significant heterogeneity in erupted volumes, compositions & eruption style along strike. Why?

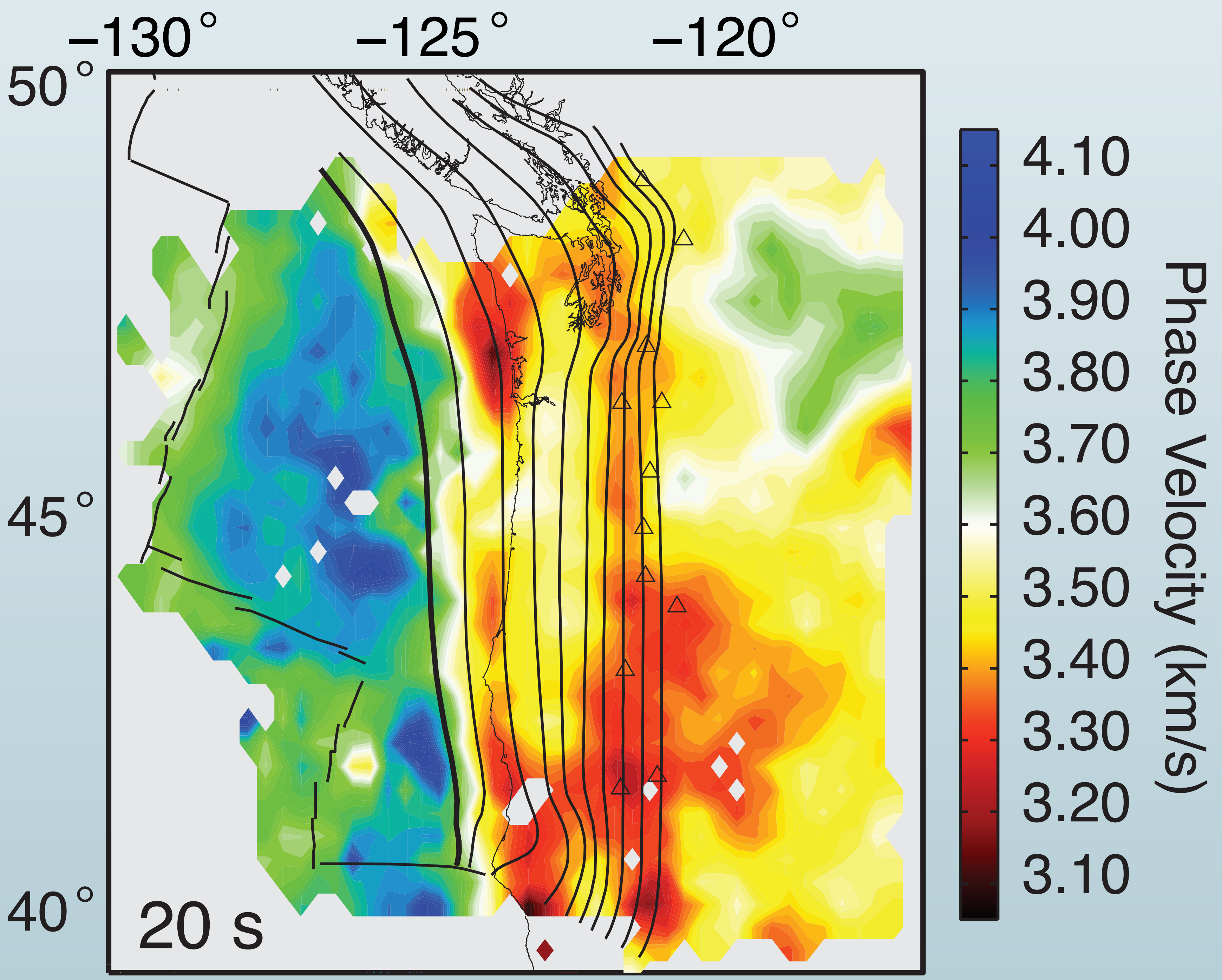
View West at 41.6° Latitude

Till et al., 2019

What Drives Intra-Arc Diversity?

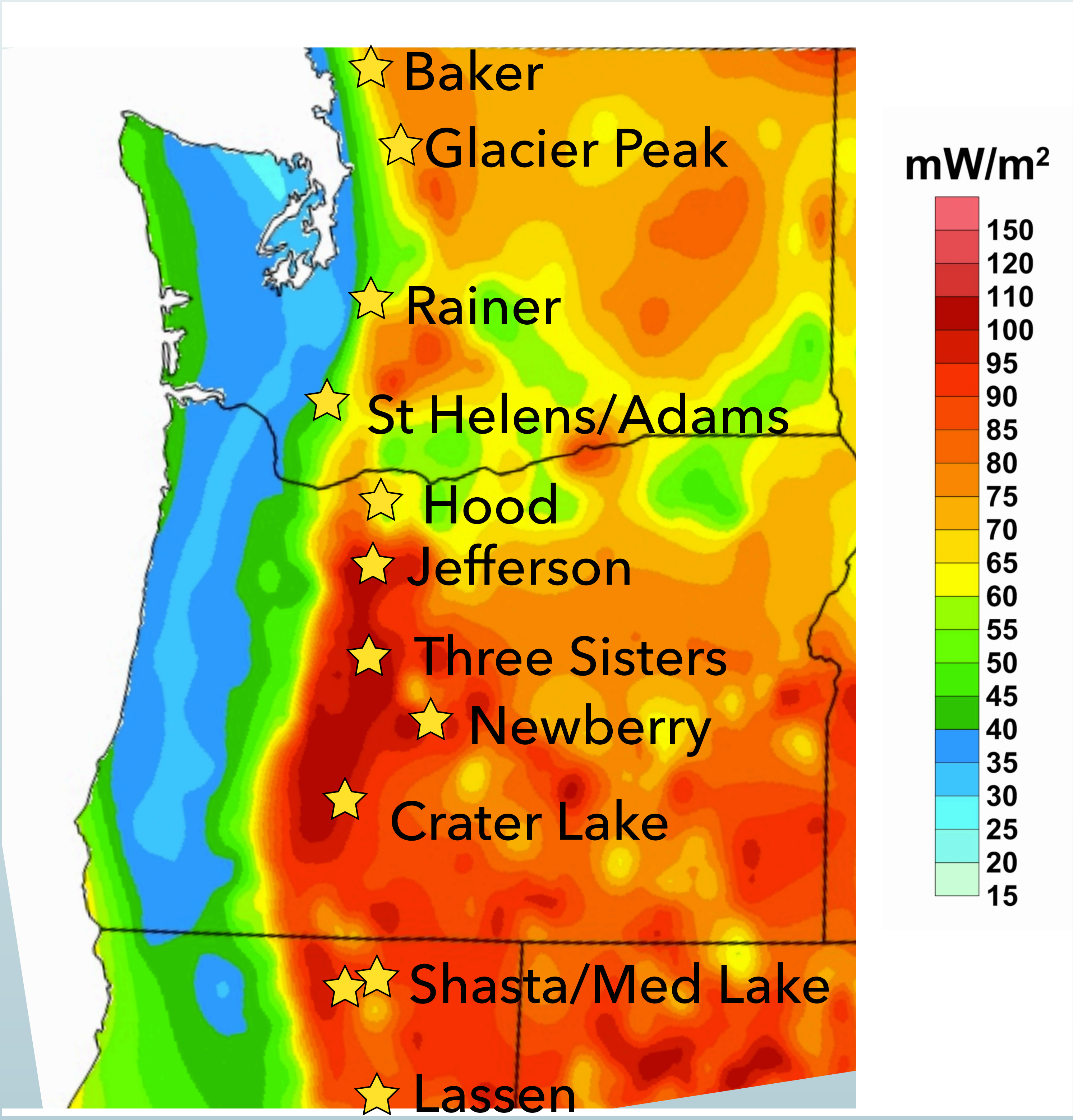
Significant heterogeneity in geophysical observables along strike. Why?

Lower Crust Depth Slice
Teleseismic Surface Wave Tomography



Janiszewski, Gaherty & Abers, 2019

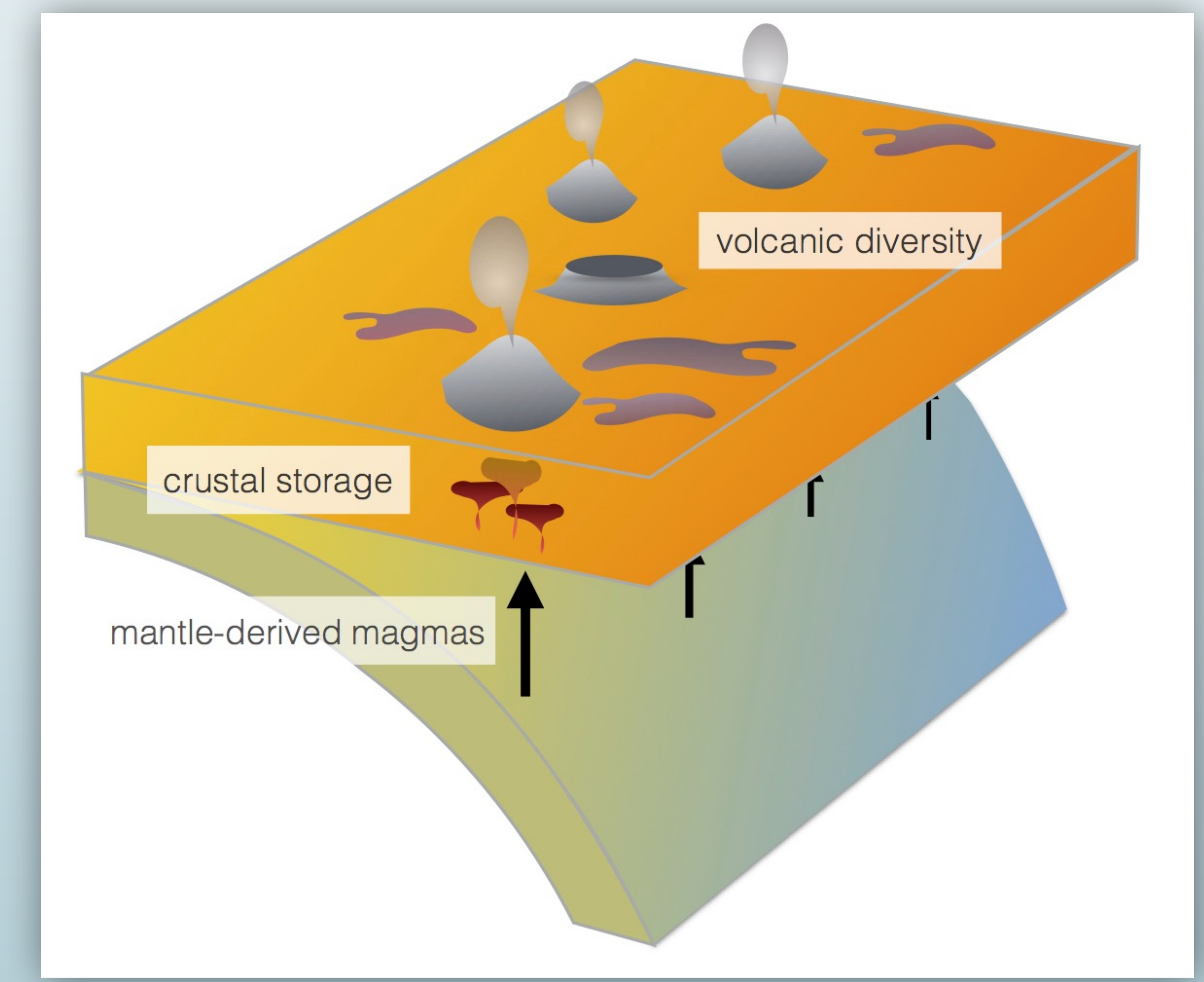
Measured Surface Heat Flow

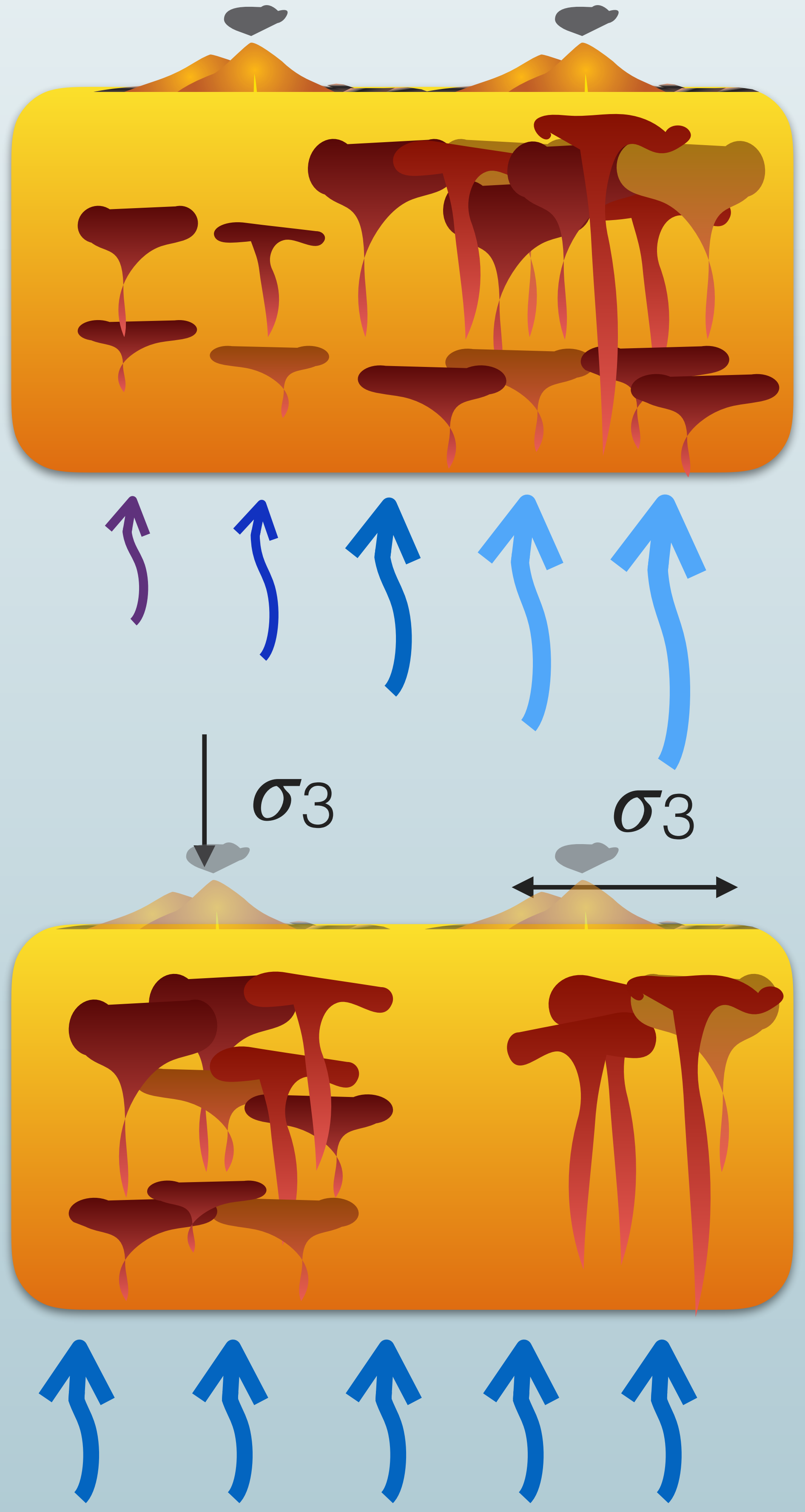


Blackwell et al., 2011

What Drives Intra-Arc Diversity?

What produces the along strike variations in erupted volumes and compositions the Cascades?





Mantle-driven model

heterogeneous mantle flux + compositions drive arc diversity

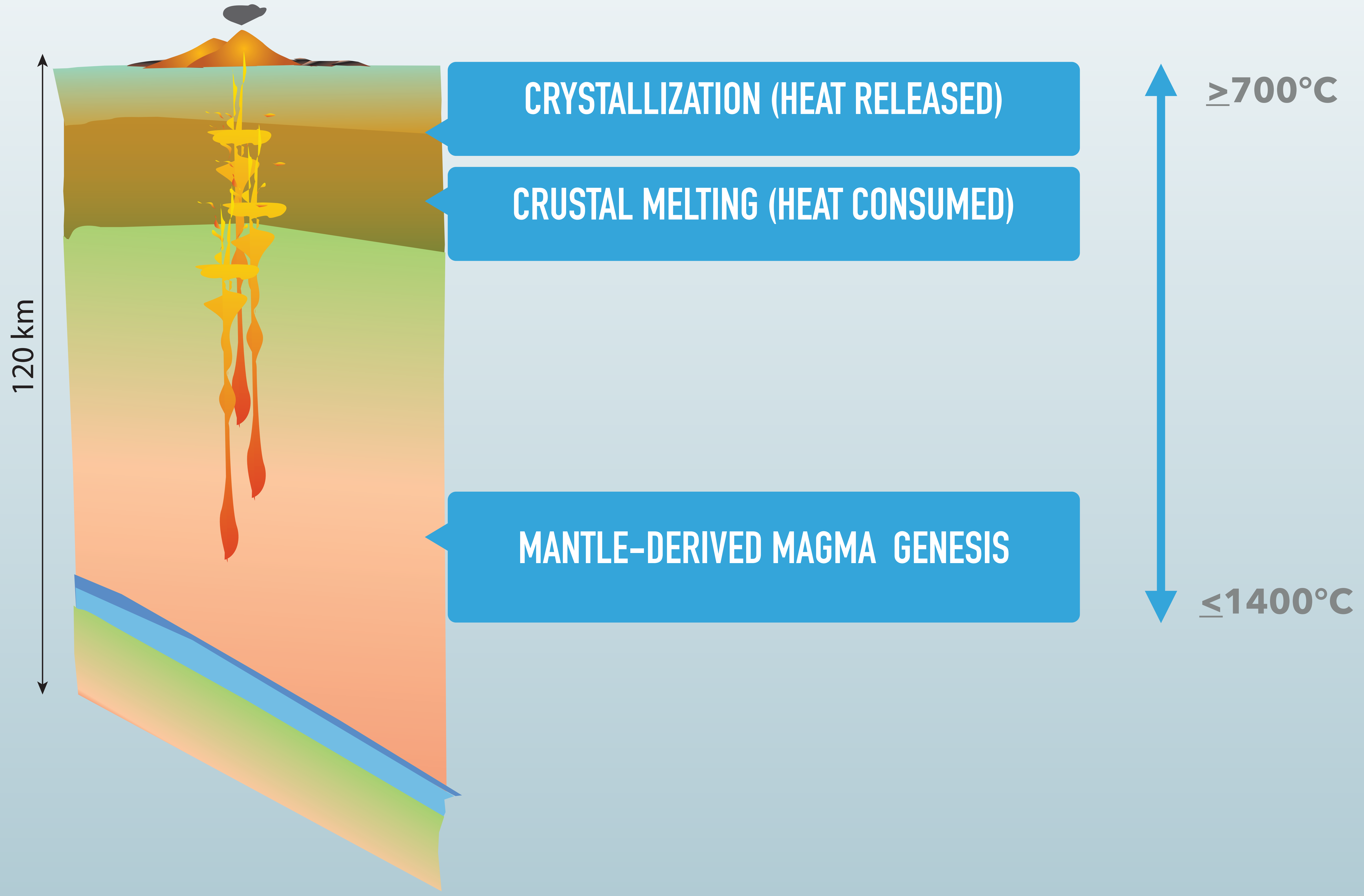
?

Crust-driven model

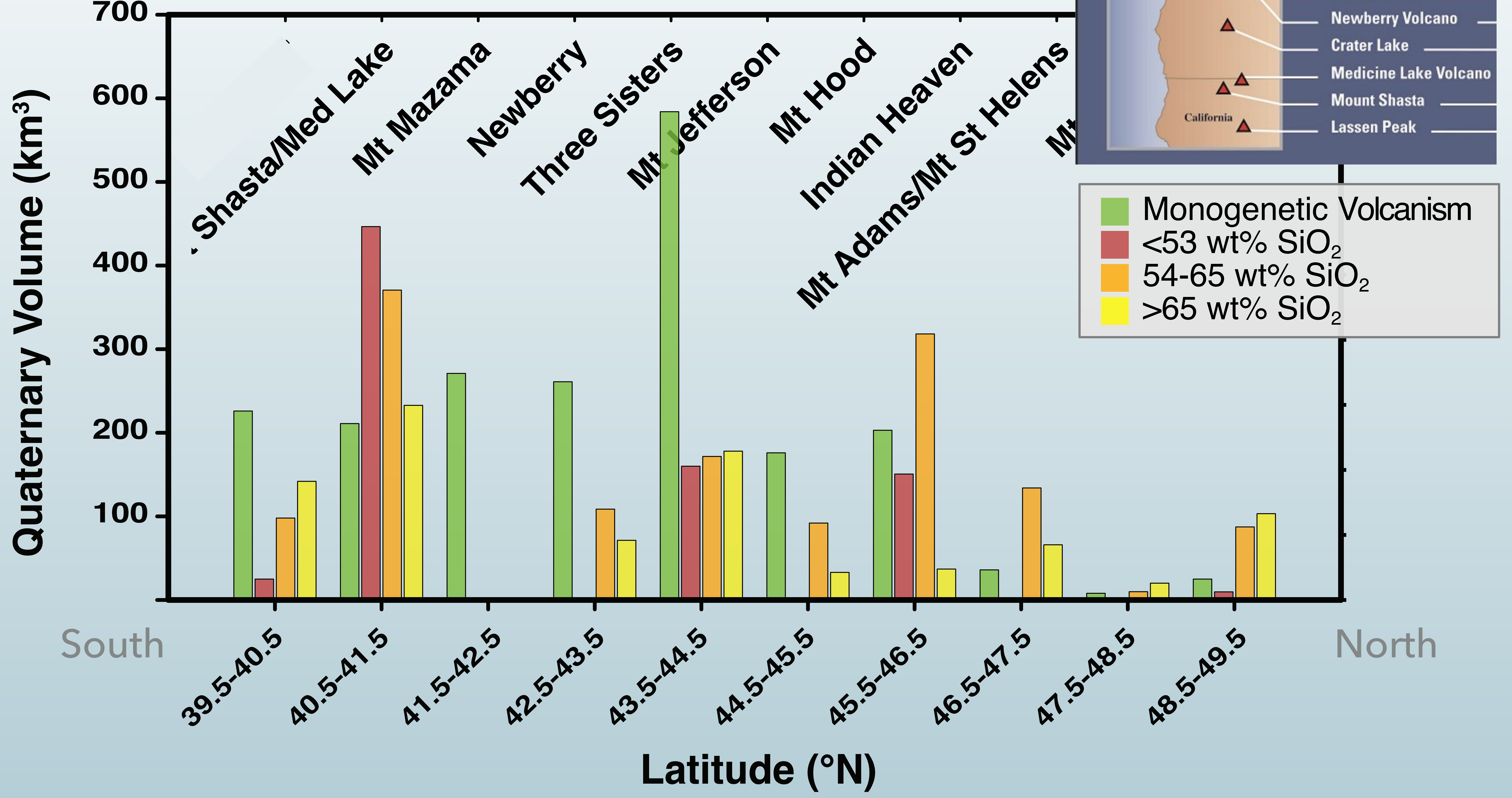
heterogeneous crustal structure & stress drive arc diversity

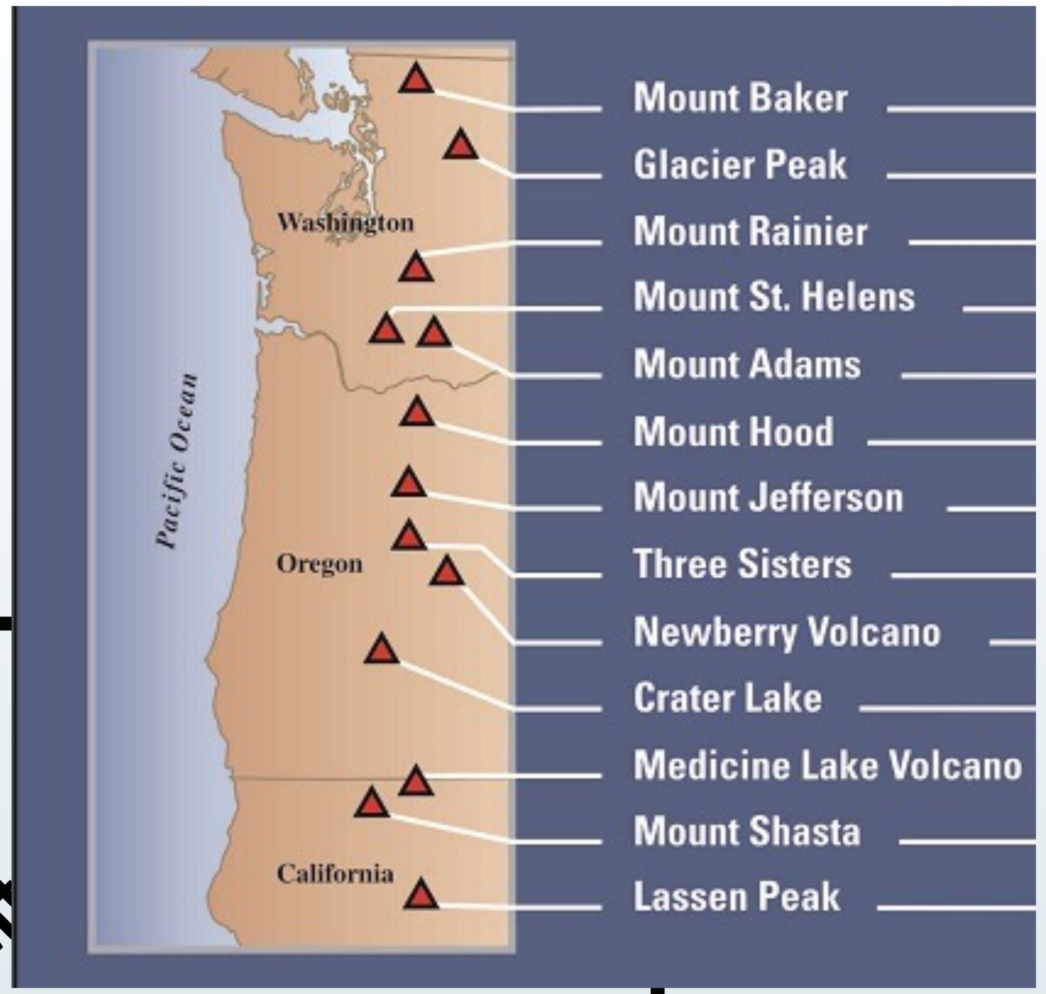
Heat Calculations

How much heat is released into the crust along strike to produce Quaternary Cascades volcanism?



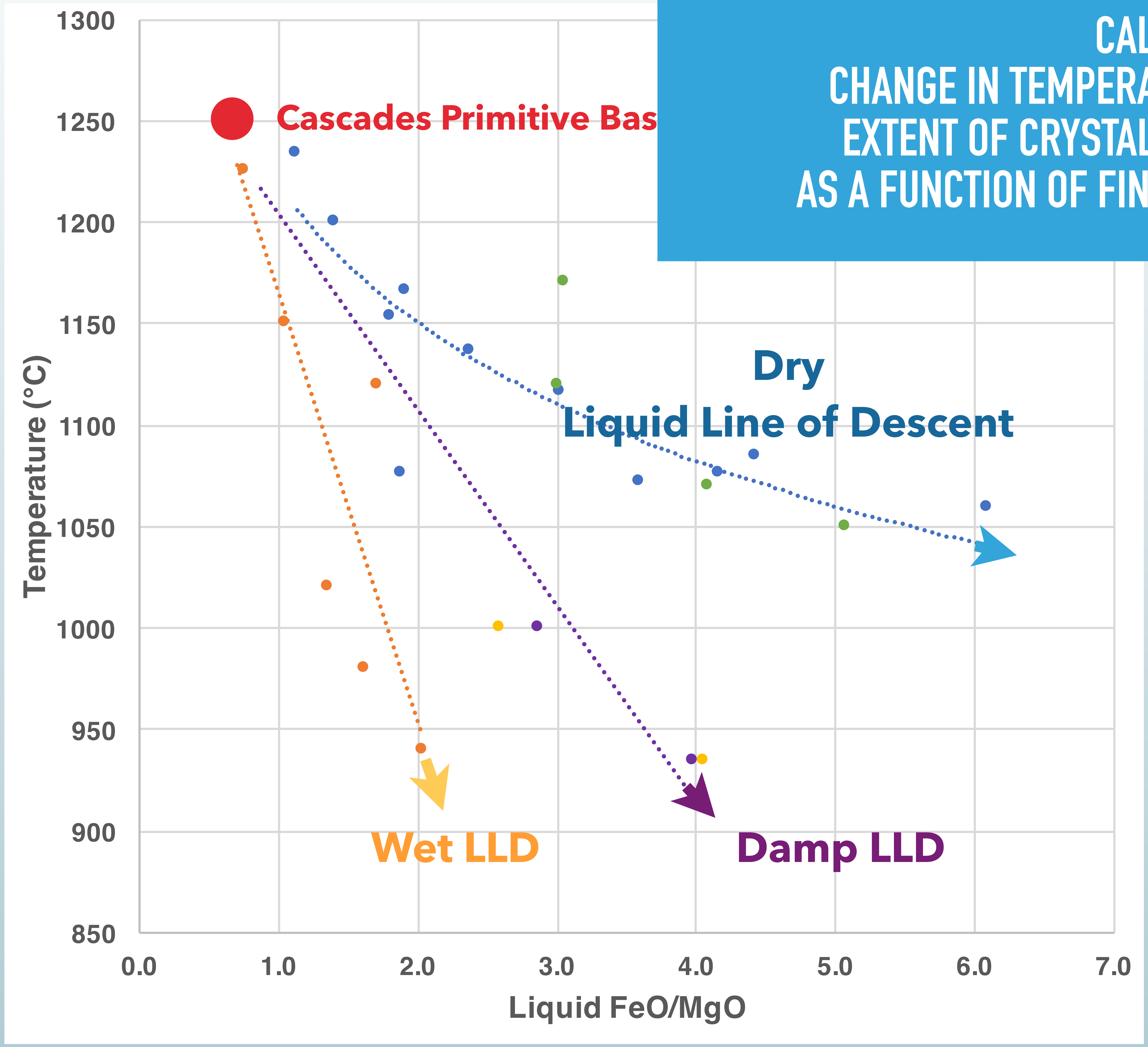
Volume of Quaternary Volcanism





Hildreth, 2007 & References Therein

Experimentally-Constrained Crustal Crystallization Paths (“Liquid Line of Descent”)



Till et al., 2019, Nat. Comm.

CALCULATE
CHANGE IN TEMPERATURE (SENSIBLE HEAT)+
EXTENT OF CRYSTALLIZATION (LATENT HEAT)
AS A FUNCTION OF FINAL ERUPTED COMPOSITION

position

DAMP:

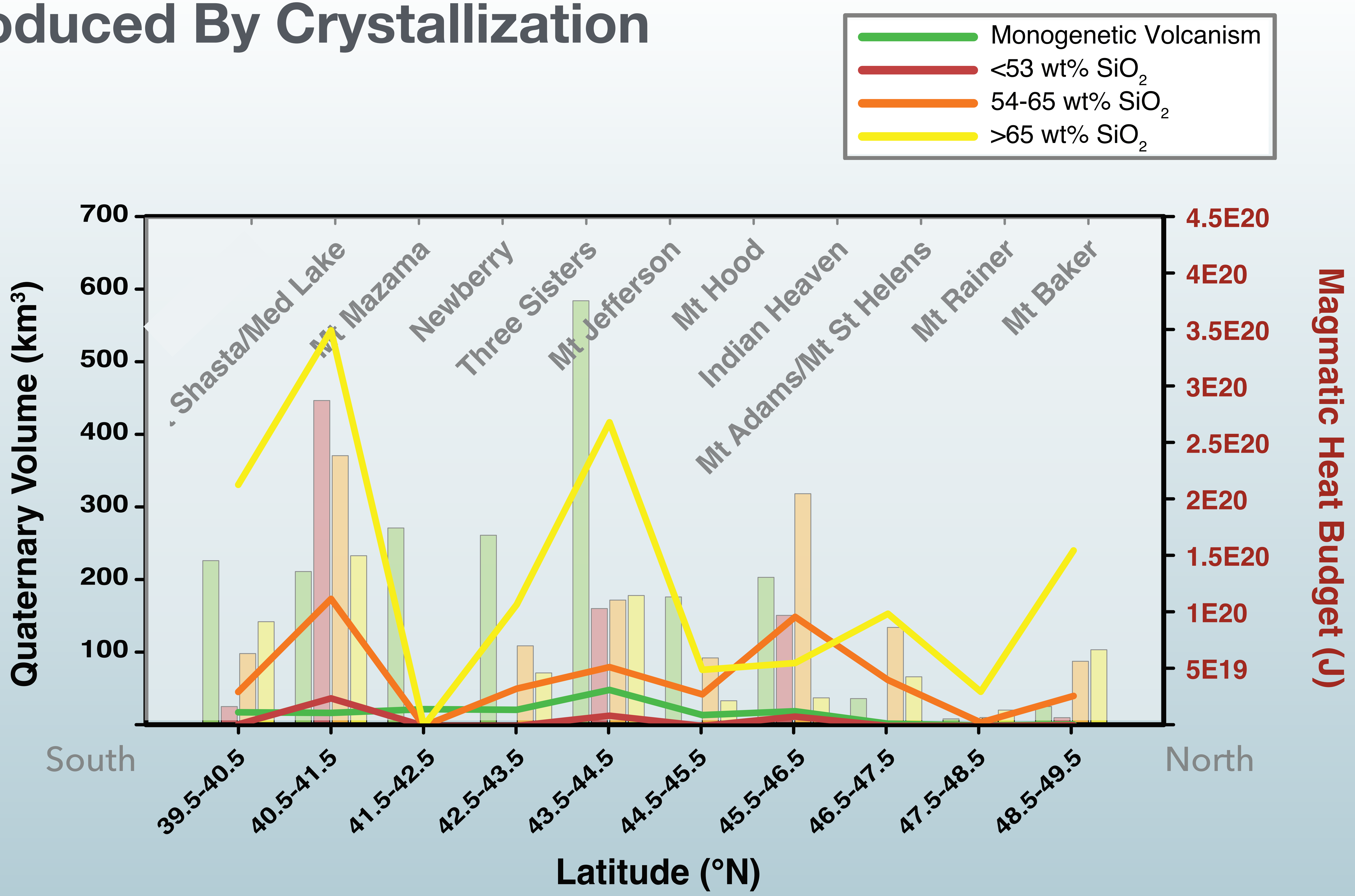
Blatter et al., 2013
Mt. Rainer starting composition
2 wt% H2O

Mandler et al., 2014
Newberry starting composition
0-3 wt% H2O

WET:

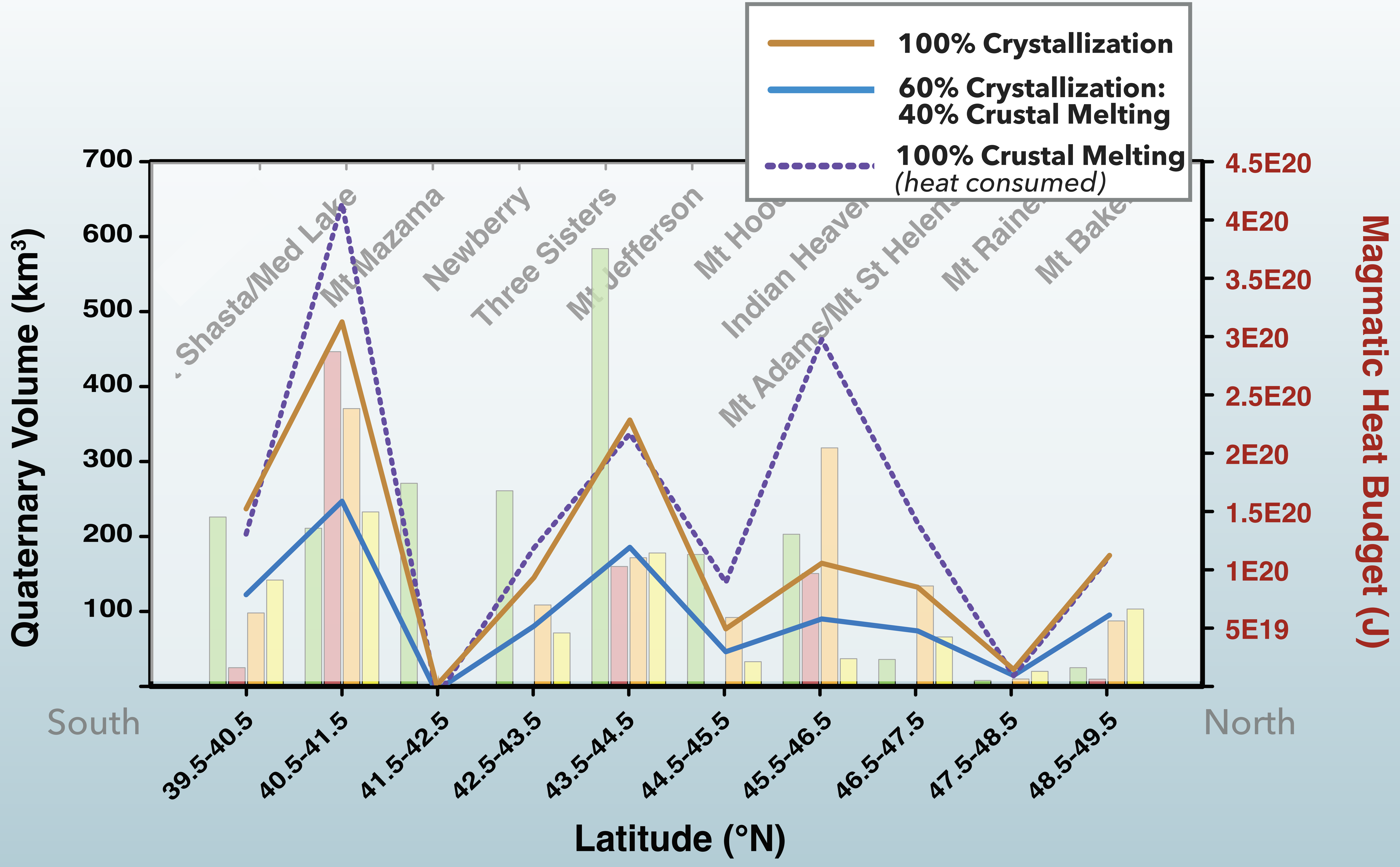
Grove et al., 2003
Mt. Shasta starting composition
>4.5 wt% H2O

Heat Produced By Crystallization



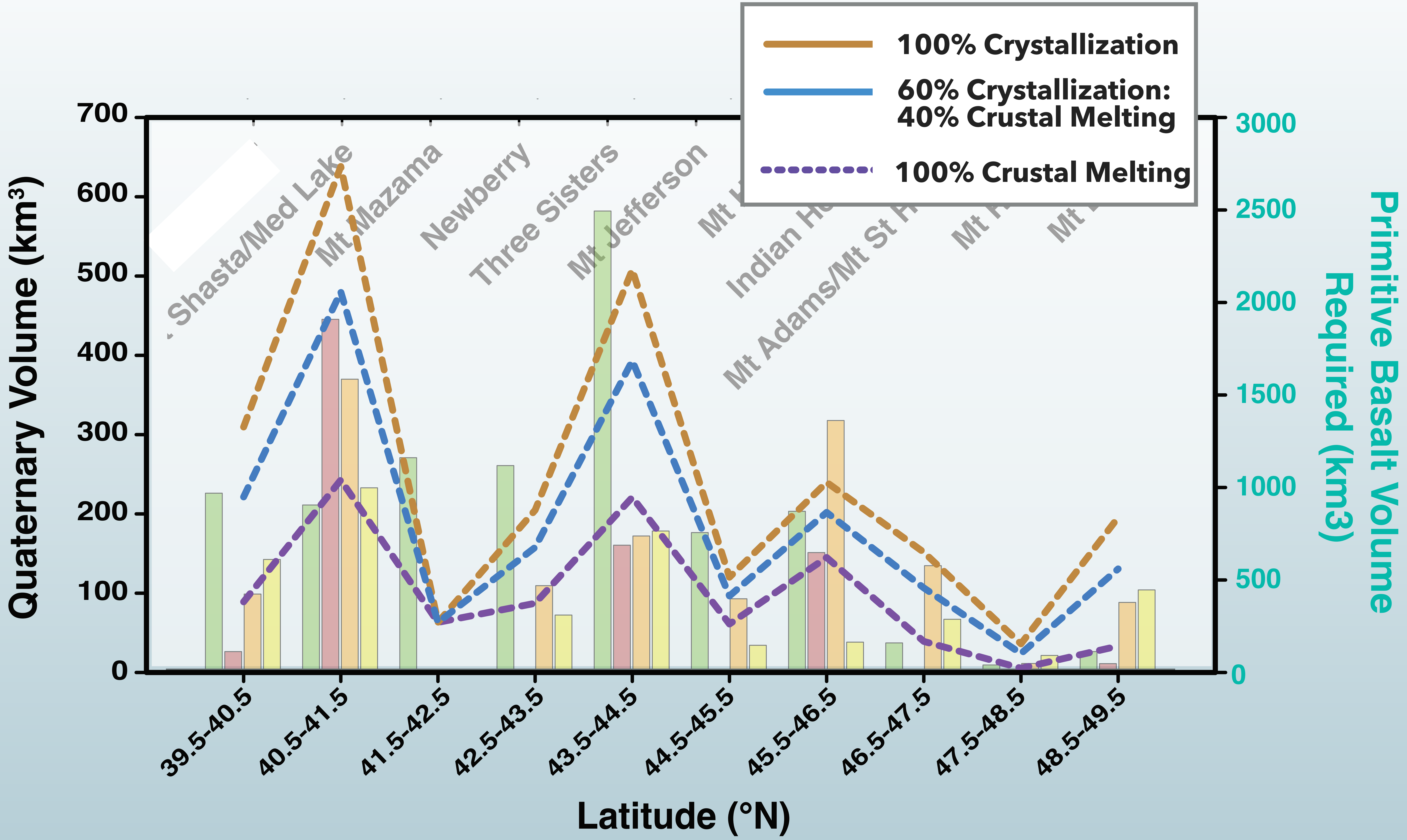
Till et al., 2019, Nat. Comm.

Total Magmatic Heat Released to Crust



Till et al., 2019, Nat. Comm.

Volume of Mantle Basalt Required



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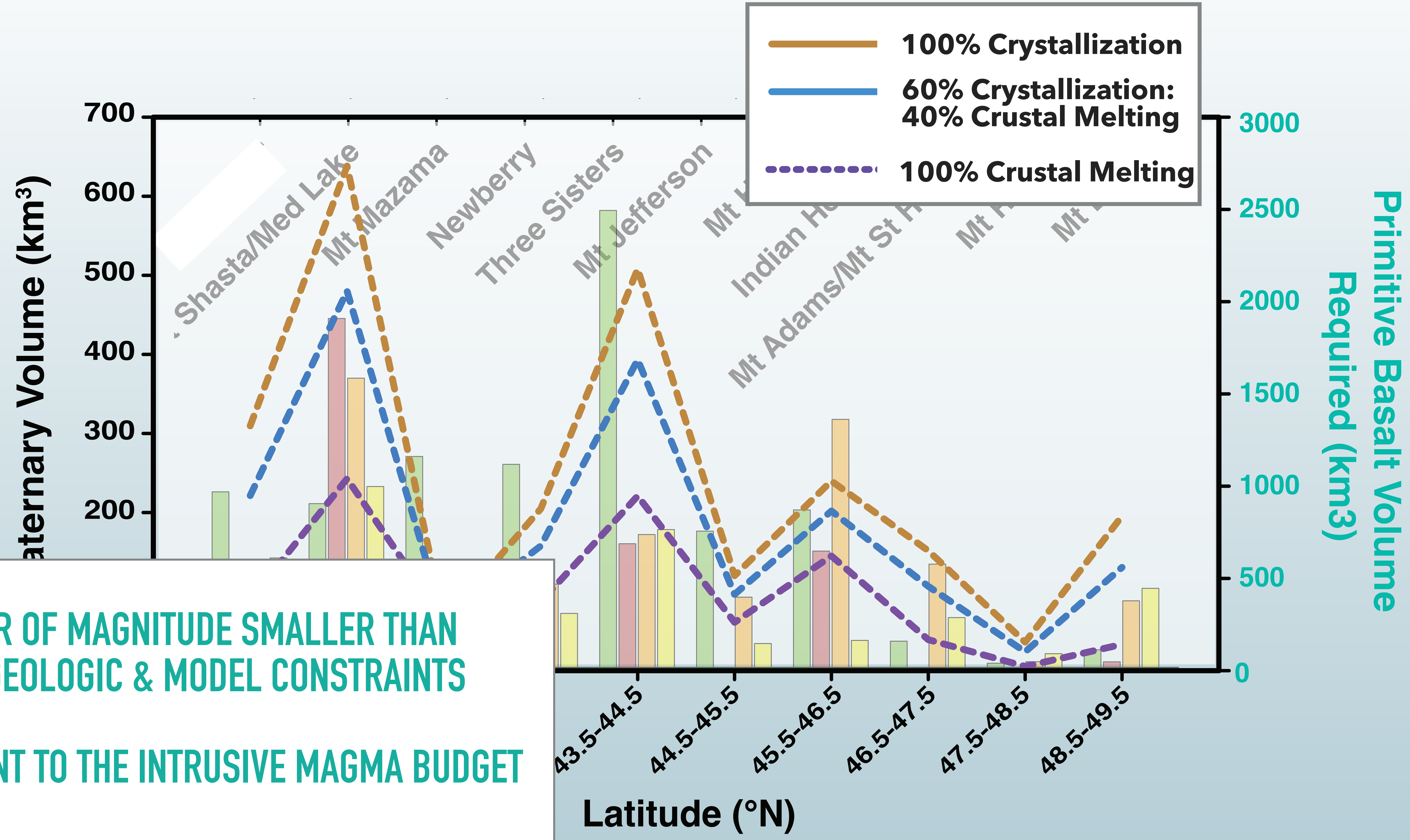
Volume of Mantle Basalt Required

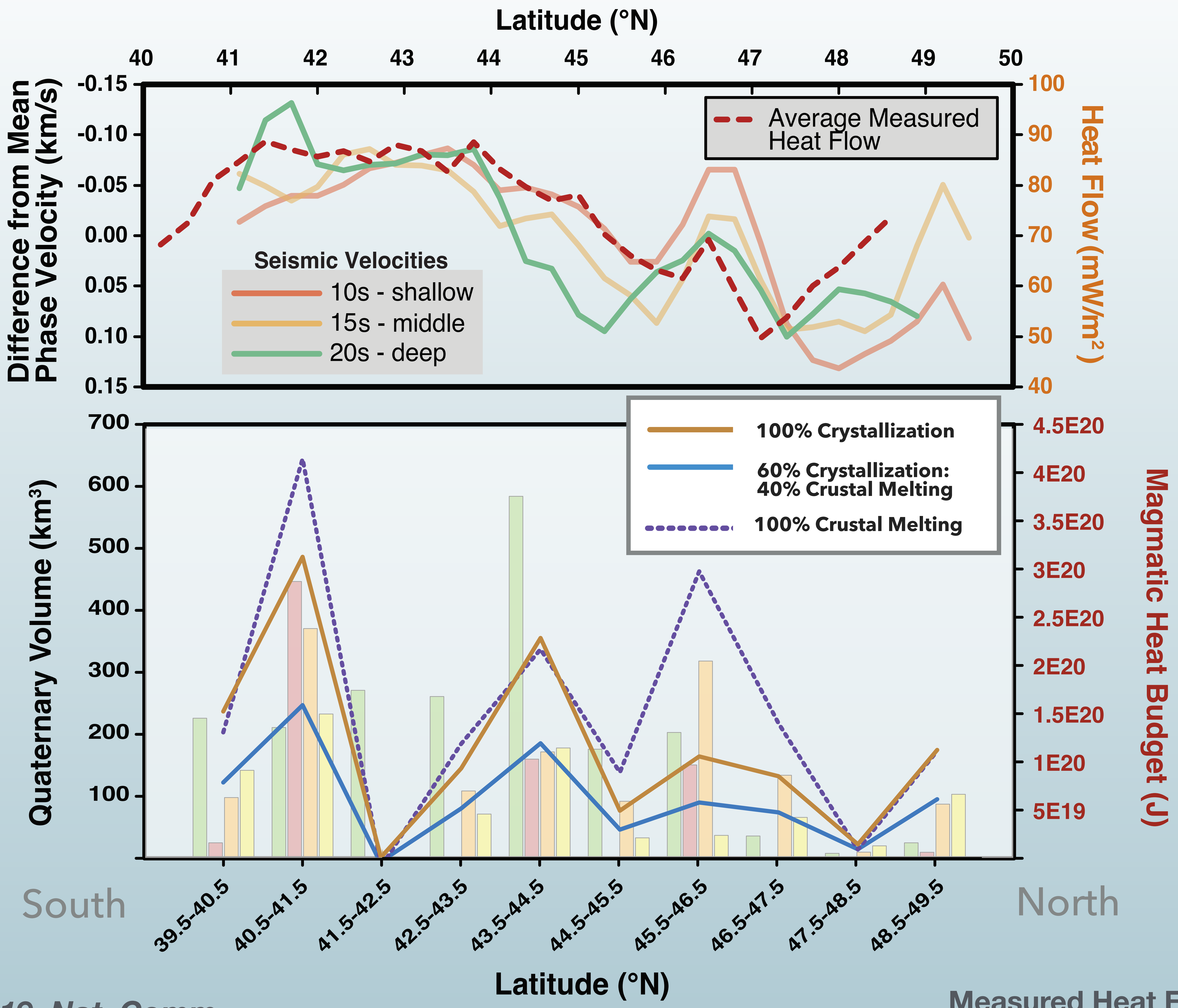


1 ORDER OF MAGNITUDE SMALLER THAN OTHER GEOLOGIC & MODEL CONSTRAINTS

~EQUIVALENT TO THE INTRUSIVE MAGMA BUDGET

Till et al., 2019, Nat. Comm.

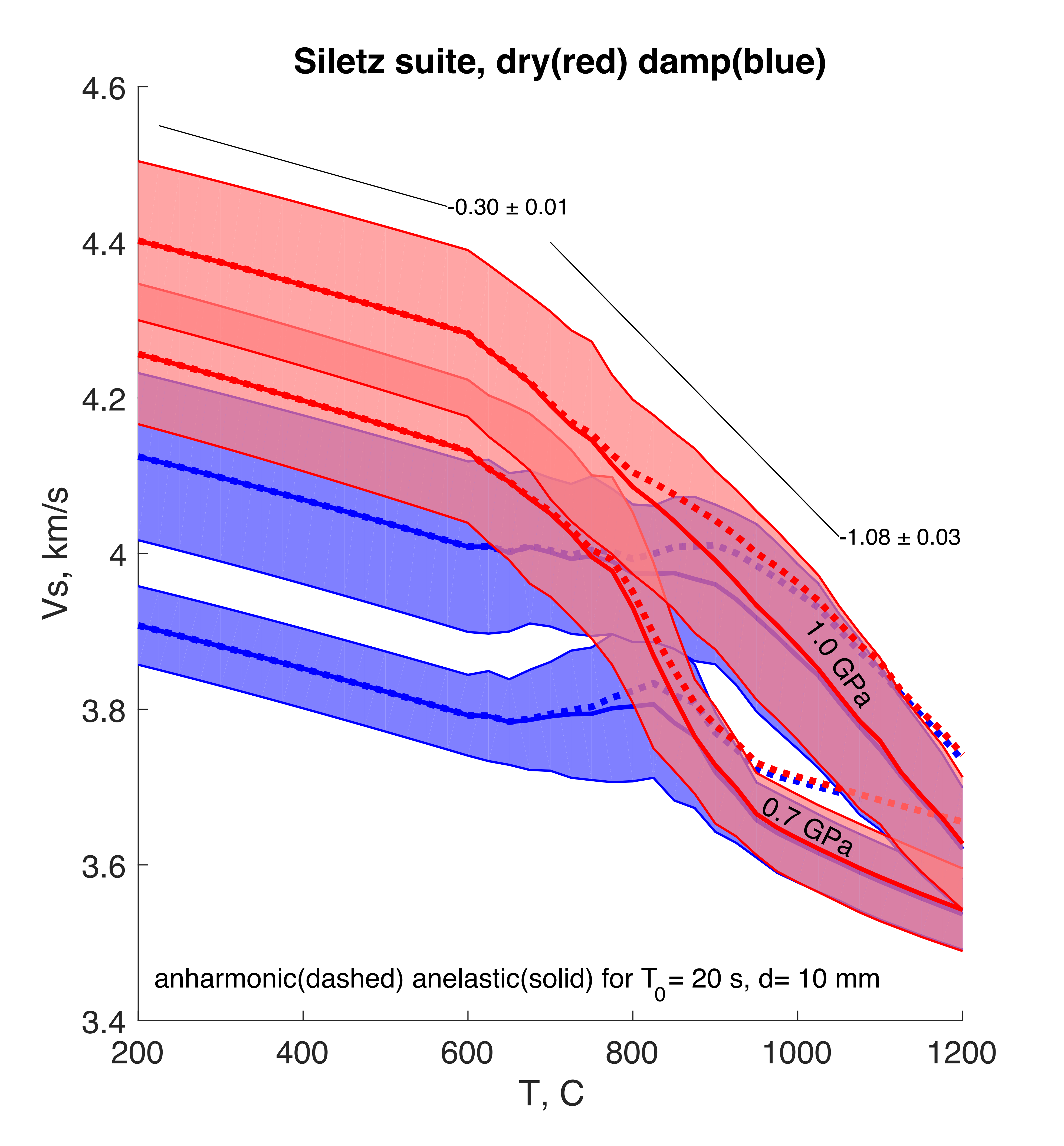
Statistical Correlation Between Magmatic Heat & Geophysical Observations



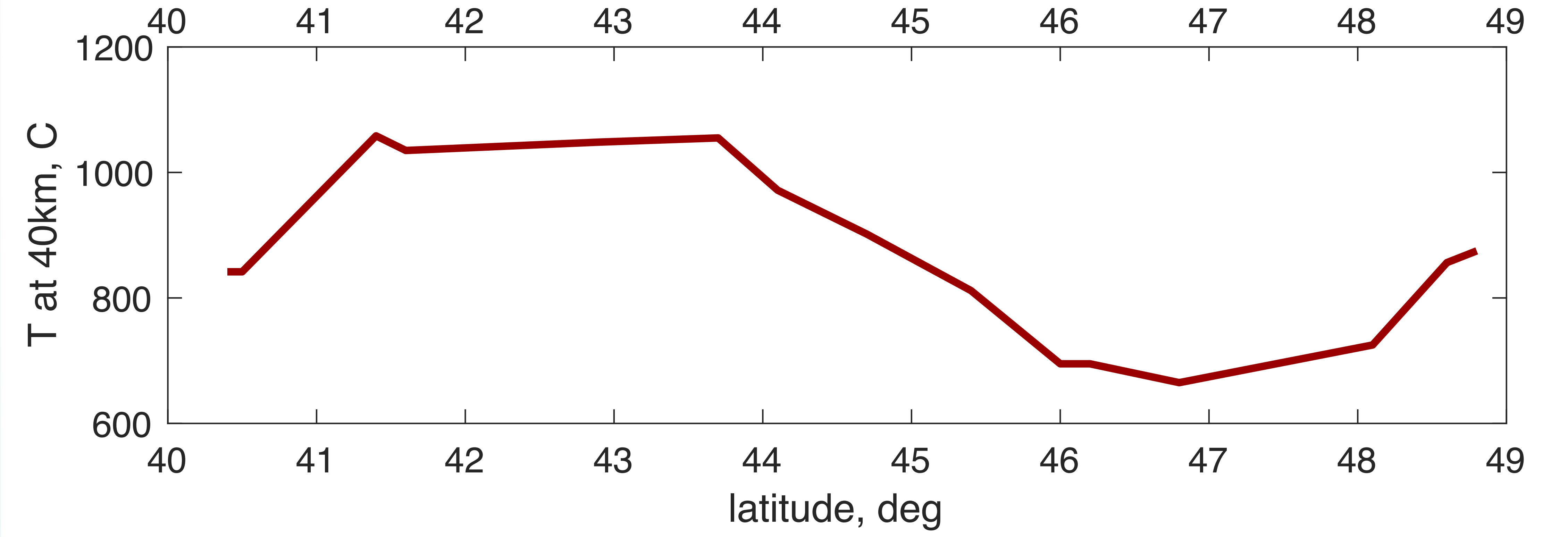
Till et al., 2019, Nat. Comm.

Measured Heat Flow: Ingebritsen & Mariner, 2010
Seismic Velocities: Janiszewski, Abers, Gaherty, 2019

1D Thermal Model to Interrogate the Geophysical Observations



Till et al., 2019, Nat. Comm.

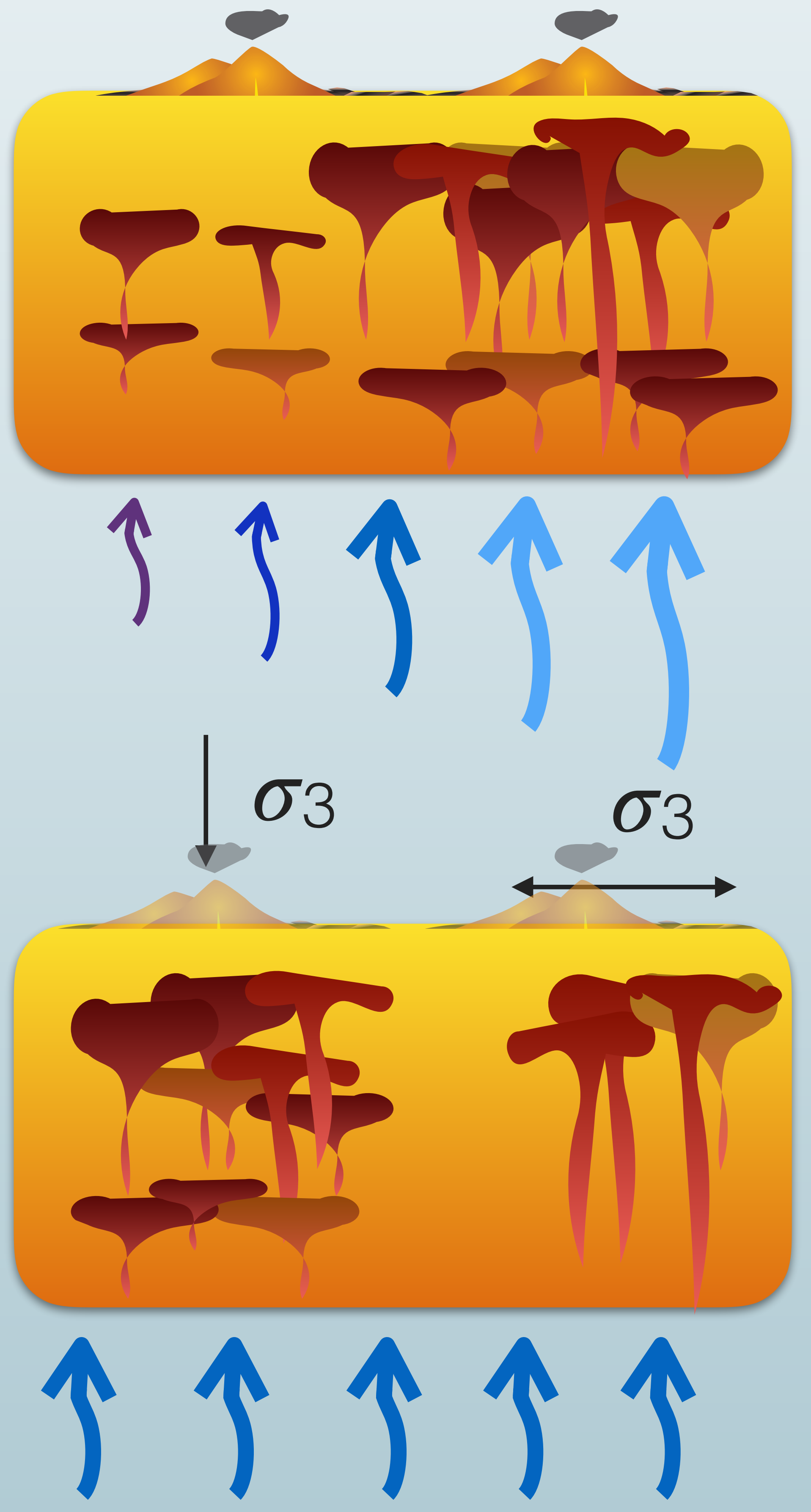


SEISMIC WAVE SPEEDS PREDICT A MAGMATIC INPUT OF 6–12 X 10^{21} J
INTO THE CRUST FOR EACH 100 KM ALONG STRIKE

COMPARED TO OUR VOLCANIC ESTIMATE OF 5 X 10^{19-20} J

Intriguing Results & Testable Hypotheses

The ≥2-fold variability in volume of basaltic magma & magmatic heat input regulates the observed volcanic activity



Mantle-driven model

heterogeneous mantle flux + compositions drive arc diversity

Crust-driven model

heterogeneous crustal structure & stress drive arc diversity

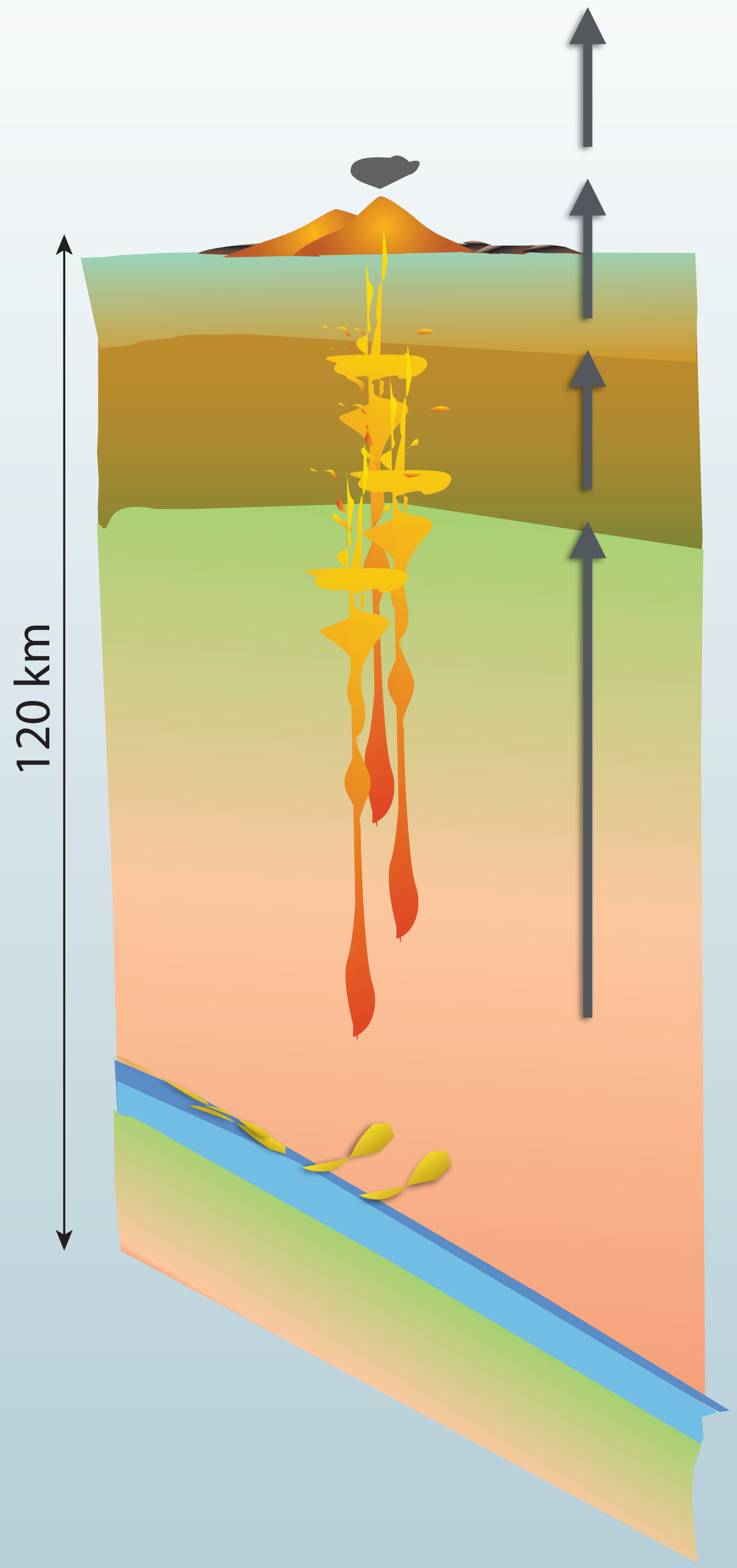
Goals For This Talk

✓Transmagmatic system perspective

✓Reconstructing the P-T-X±t evolution of magmas in the crust

✓Recent advances & exciting future directions

- Causes of eruption initiation?
- Causes of intra-arc diversity?




Questions?
christy.till@asu.edu