The Origin of Large Zoned Ignimbrites: The Case of Aso Caldera, Japan

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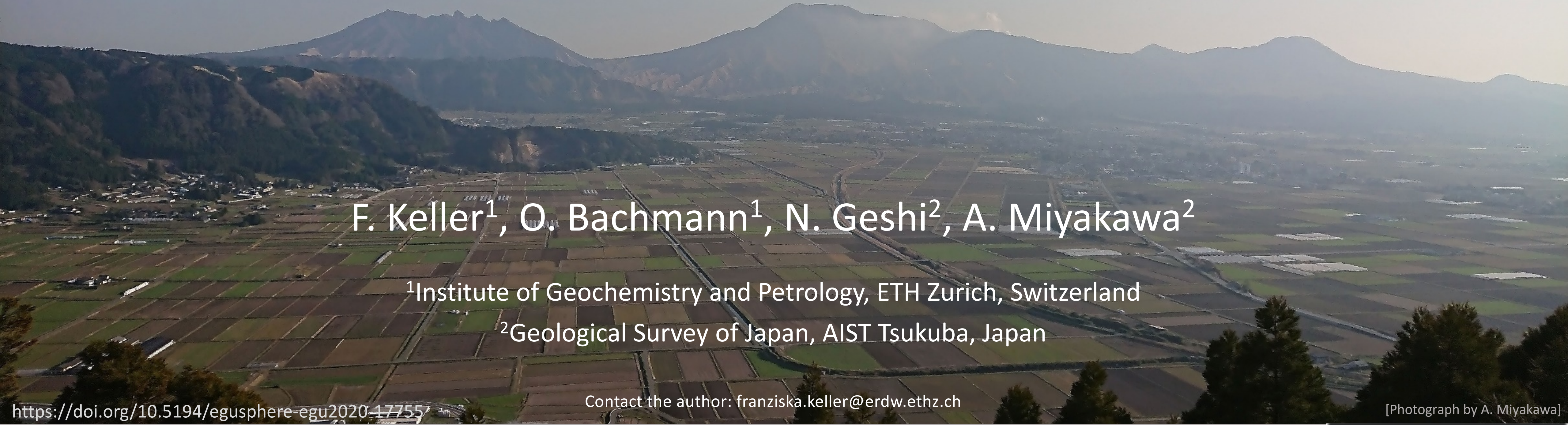

[Photograph by A. Miyakawa]

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Introduction: why do we study ignimbrite sheets?

- Large-volume ignimbrites = result of **large-scale caldera-forming eruptions** → evacuation of **enormous** (>10-100 km^3) **quantities** of magmas from subvolcanic (shallow) magma reservoirs in a **geological instant** (order of days)

- Caldera-forming eruptions **rare on a human timescale** but certainly more caldera eruptions occurring in the future, **threatening lives of millions of people** living around the volcanoes

- Ignimbrites characterized by compositional, mineralogical, and thermal **gradients from base to top** ("zoned ignimbrites") → exceptional opportunity to evaluate **magma storage conditions just prior to eruptions**

- Understanding the **origin of voluminous ignimbrites** can help improving the **understanding of the volcano-plutonic relation** of **silicic rocks**

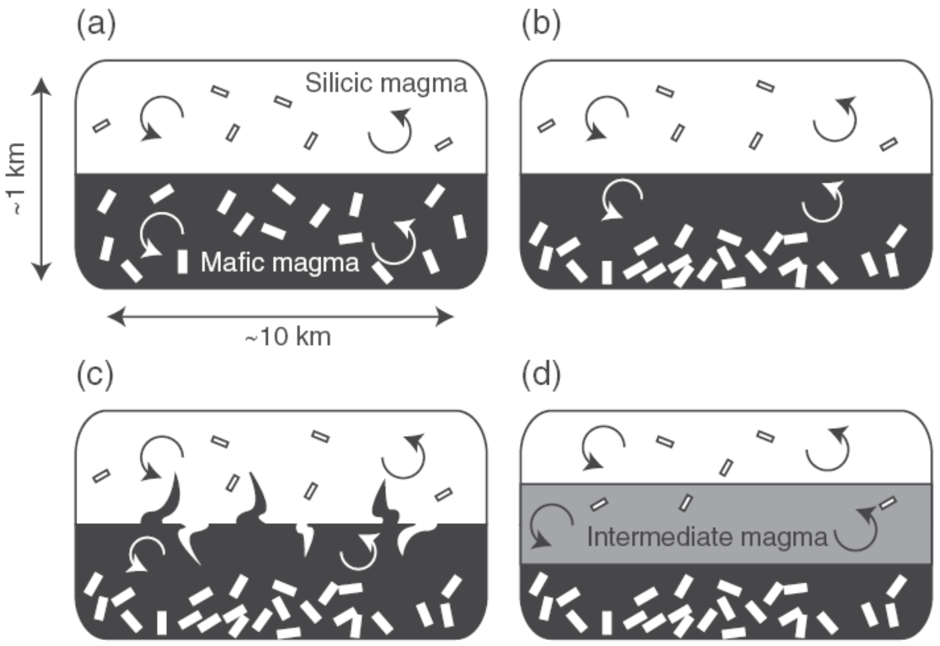
[Photograph by F.Keller]

Typical zoned ignimbrite produced during the 6800 BP Crater Lake eruption

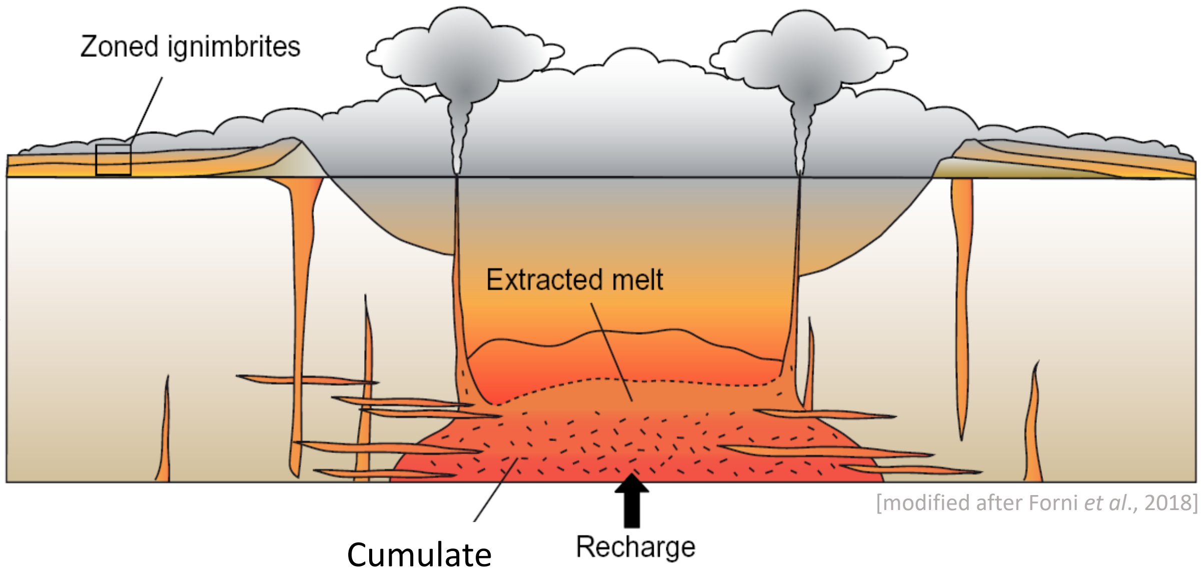
[Self, 2006; Bachmann *et al.,* 2014; Huber *et al.,* 2012; Forni *et al.,* 2016; Wolff *et al.,* 2020]

Introduction: why do we study ignimbrite sheets?

- The origin of zonation in ignimbrites still debated → 2 endmember scenarii:



[modified after Kaneko *et al.*, 2015]



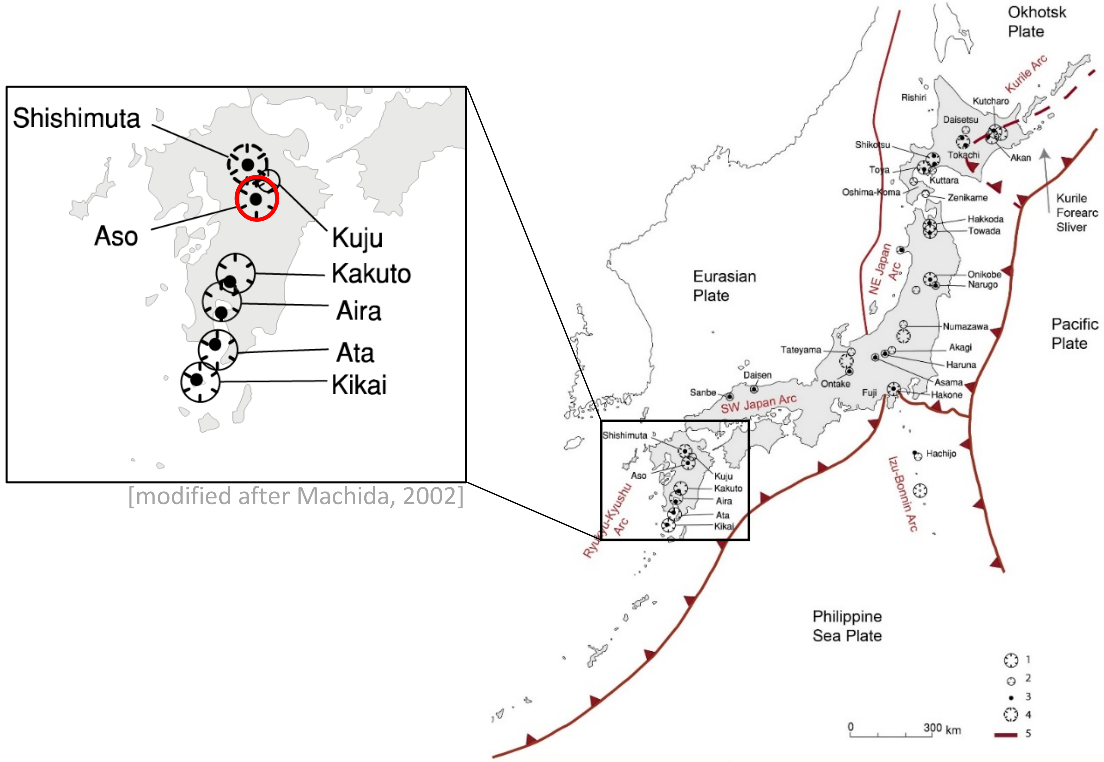
[modified after Forni *et al.*, 2018]

(1) mixing of two compositionally distinct magmas originating from different locations in the magmatic plumbing system

(2) in-situ differentiation in the subvolcanic reservoir, with eruption of extracted melt pockets and complementary cumulates

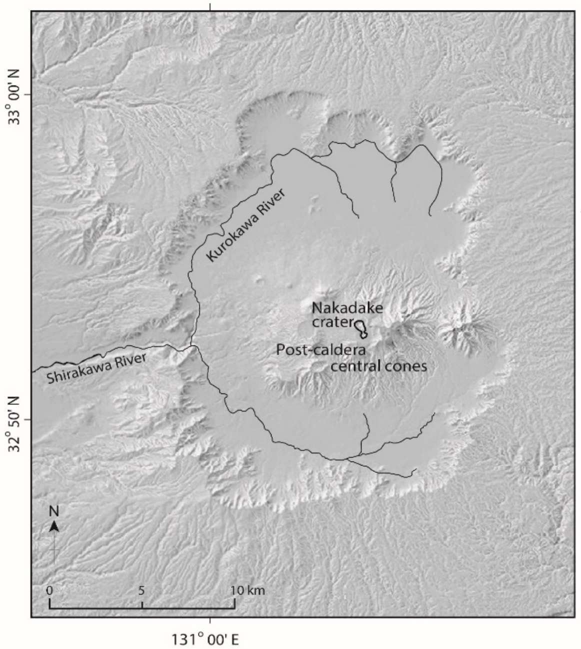
[Kaneko *et al.*, 2007; Huber *et al.*, 2012; Bachmann *et al.*, 2014; Forni *et al.*, 2016; Wolff *et al.*, 2020]

Introduction: Aso Caldera



[modified after Machida, 2002]

- Located in central Kyushu, SW Japan
- Second largest caldera in Japan (18x25 km)
- Multi-cyclic activity; 4 caldera-forming eruptions between ~266 ±14 ka and ~86 ±1.1 ka
- Youngest ignimbrite (Aso-4, 86 ±1.1 ka) one of first ever described compositionally zoned ignimbrites (ranging from rhyolite to (trachy-)basalt in composition)



[modified after Miyabuchi, 2011]

[Lipman, 1967, Kaneko *et al.*, 2007; Albert *et al.*, 2019]

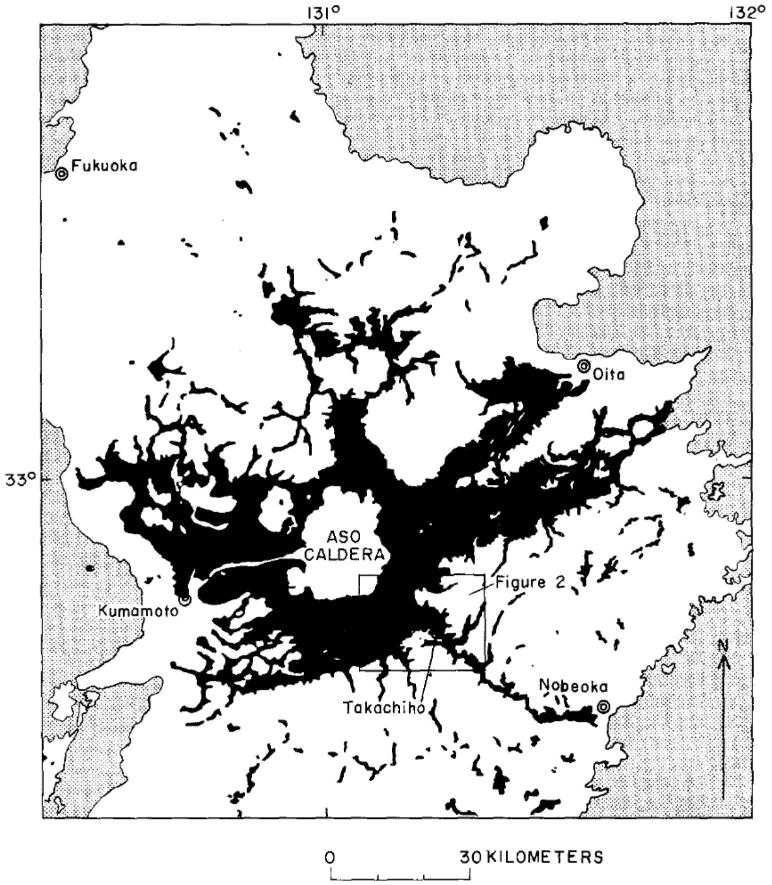
The Origin of the Zoned Aso-4 Deposits – Lipman, 1967

- One of the **first petrographic studies** on the Aso-4 ignimbrite, recognizing **compositional** and **crystallinity zonation** of the deposits.
- Zonation interpreted to reflect a **single, compositionally zoned magma chamber** erupted in a short geological sequence
- **3 endmember possibilities** to explain the **origin of the zonation (which may actually combine)**:

1) **Mixing of two compositionally distinct magmas** in the subsurface

1) **Differentiation (including potentially crystal fractionation and/or anatectic melting)** in a large "continuous" magma reservoir underlying the erupted portion

2) **Differentiation by vertical volatile transfer**



[modified after Lipman, 1967]

The Origin of the Zoned Aso-4 Deposits – Kaneko *et al.*, 2007

- Investigation of **pre-eruptive magma chamber configuration** and physical processes of Aso-4 caldera formation based on **whole rock chemistry**, **Sr isotopes**, and **phenocryst composition**

- Pre-eruptive magma chamber comprising **3 magma layers**:

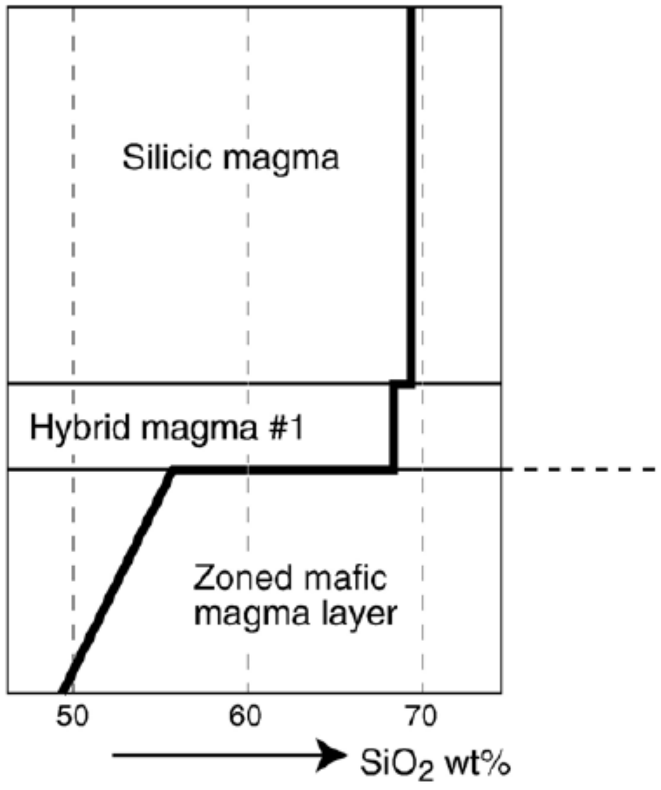
  1) **silicic magma** on top

  2) **mafic magma** at the bottom, showing increase of SiO_2 with decreasing depth

  3) **Hybrid magma #1** in between resulting from mixing of silicic magma and most silicic, upper part of the mafic layer

Hypothesis of magma mixing favored.

(a) Pre-eruptive magma chamber of the Aso-4 cycle

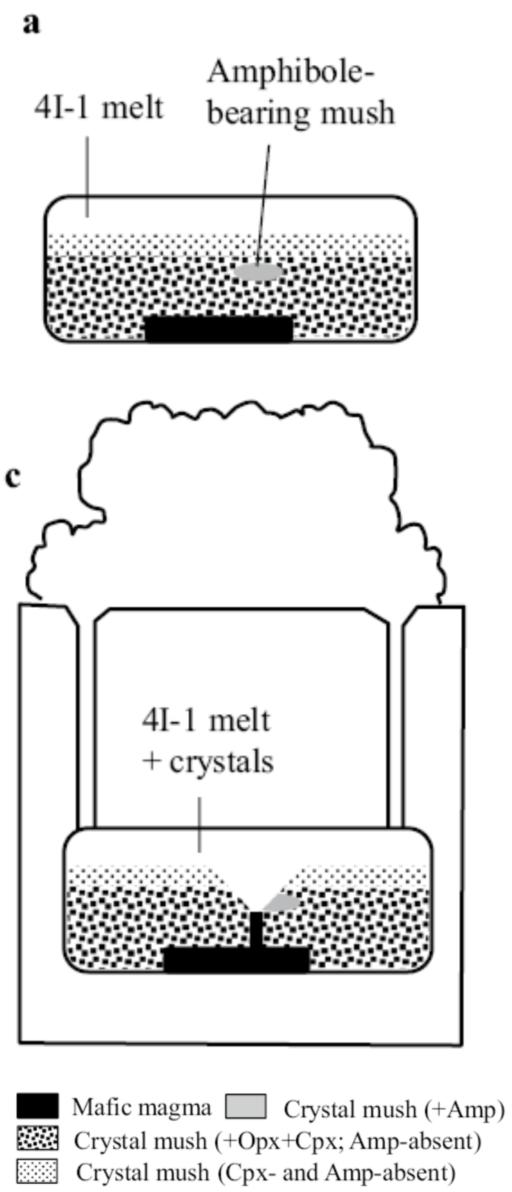


[modified after Kaneko *et al.*, 2007]

The Origin of the Zoned Aso 4 Deposits – Ishibashi *et al.*, 2018

- Evaluation of Aso 4 amphibole phenocryst composition and **amphibole-based quantification of P-T-SiO_2^{melt} conditions**
- **Disequilibrium** between Amphiboles and silicic groundmass melt → mostly crystallized from hydrous melt comprising **63-69 wt% SiO_2 at 910-950 °C**
- **Pre-eruptive system:**
  a) Complex magma reservoir comprising a **melt layer** underlain by **3 different layers of crystal mush**: (1) crystal mush +Opx, +Cpx, -Amph, (2) crystal mush -Cpx, -Amph, (3) crystal mush +Amph

  b) **Incorporation of amphibole** crystals into the melt **just prior to eruption** from underlying Amphibole - bearing mush due to **partial collapse** of the crystal mush triggered by **intrusion of mafic magma** from underneath



[modified after Ishibashi *et al.,* 2018]

Introduction: why do we re-evaluate the Aso-4 system?

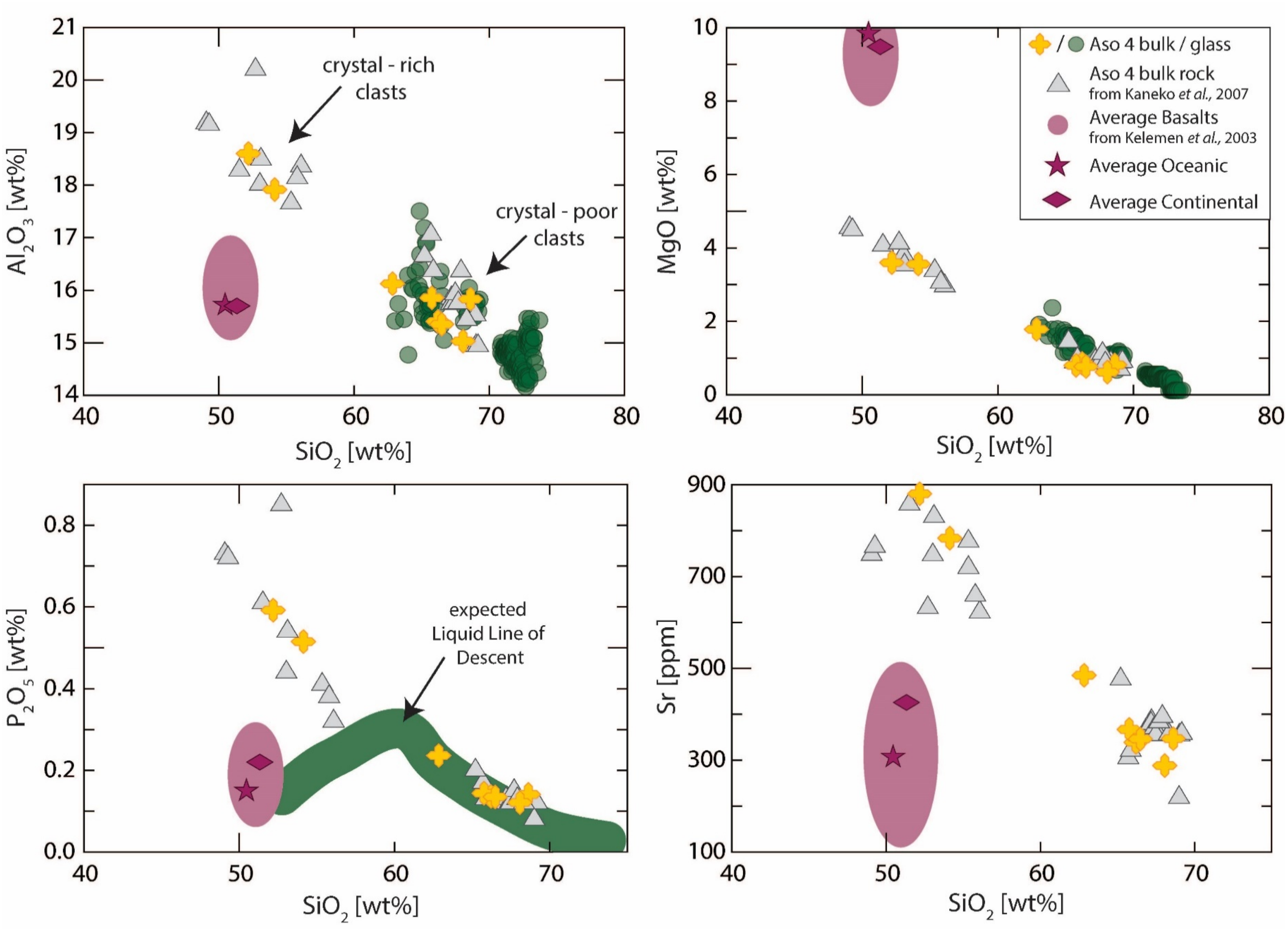
- Modern investigations → formation of zoned ignimbrites due to melt extraction from mushy, upper-crustal reservoirs and partial melting/reactivation of the cumulate mush by hot recharge (e.g. Carpenter ridge Tuff & Bishop Tuff, USA; Campanian Ignimbrite, Campi Flegrei, Italy, etc.)

- Can we find similar characteristics in the Aso-4 deposits (as well as in the pre-Aso-4 units)?

- Questions include:

  - Is **magma mixing** alone able to explain the **strong gradients** observed within the Aso-4 deposits?
  - Do we really have **3 distinct layers of crystal mush** with **locally limited amphibole crystallization** and are euhedral shaped amphiboles really in **disequilibrium** with the silicic host melt?
  - Do we see evidence for partial melting/reactivation of **cumulate mush** at depth?

Bulk Rock composition of selected elements:



- 2 types of pumices (crystal-poor and crystal-rich), with bulk-rock compositions separated by a compositional gap between SiO_2 57-63 wt%
- Marked deviation between Aso crystal-rich clasts („basalts“) and expected average basaltic compositions (from the compilation of Kelemen *et al.*, 2003) in several elements
- Can deviations be interpreted as possible indicators for crystal accumulation at depth dominated by plagioclase and apatite?

Major element modelling to predict extracted melt and cumulate compositions

- In order to test for possible indicators of crystal accumulation in late-erupted, crystal-rich clasts, major element modelling based on the examples of Deering and Bachmann, 2010 was conducted.
- Modelling was performed for P_2O_5 concentration, as the observed liquid line of descent (incompatible behavior until apatite saturation and then strongly compatible behavior in apatite) fulfills the optimal requirements to distinguish between cumulate residue and basaltic liquids (e.g., Lee and Bachmann, 2014)

Rayleigh Fractionation for extracted liquids:

$$\frac{C_L}{C_0} = F^{(D-1)}$$

Enrichment of elements in cumulates:

$$\frac{C_R}{C_0} = \frac{1 - F^D}{1 - F}$$

[After Rollinson, 1993]

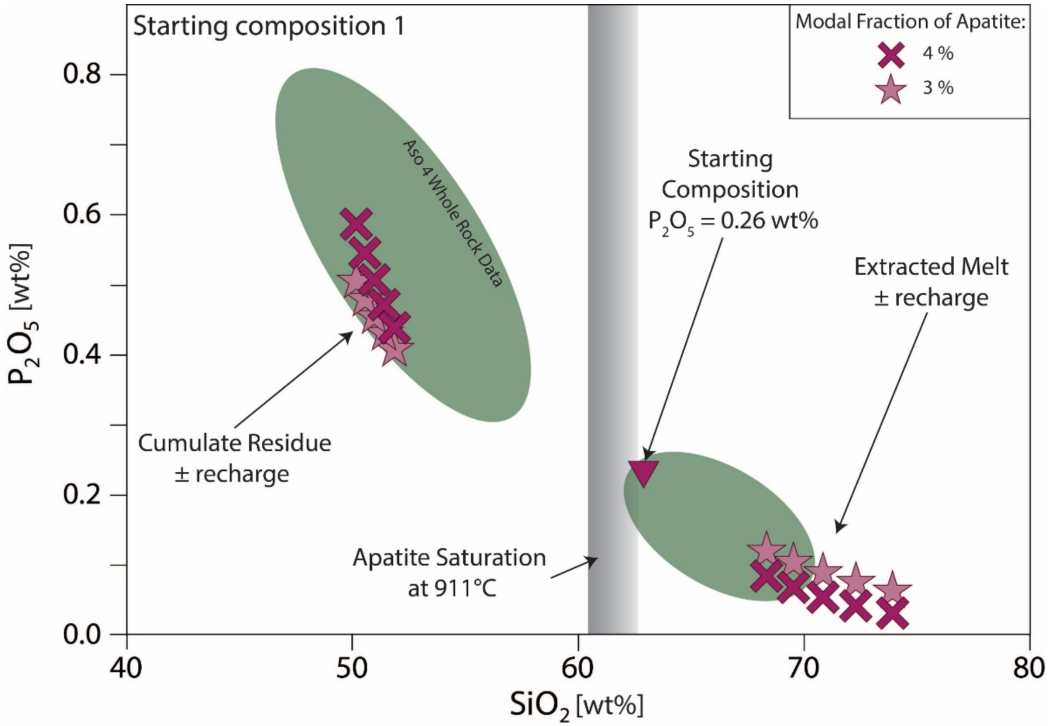
C_0 = weight concentration of element in the parental liquid

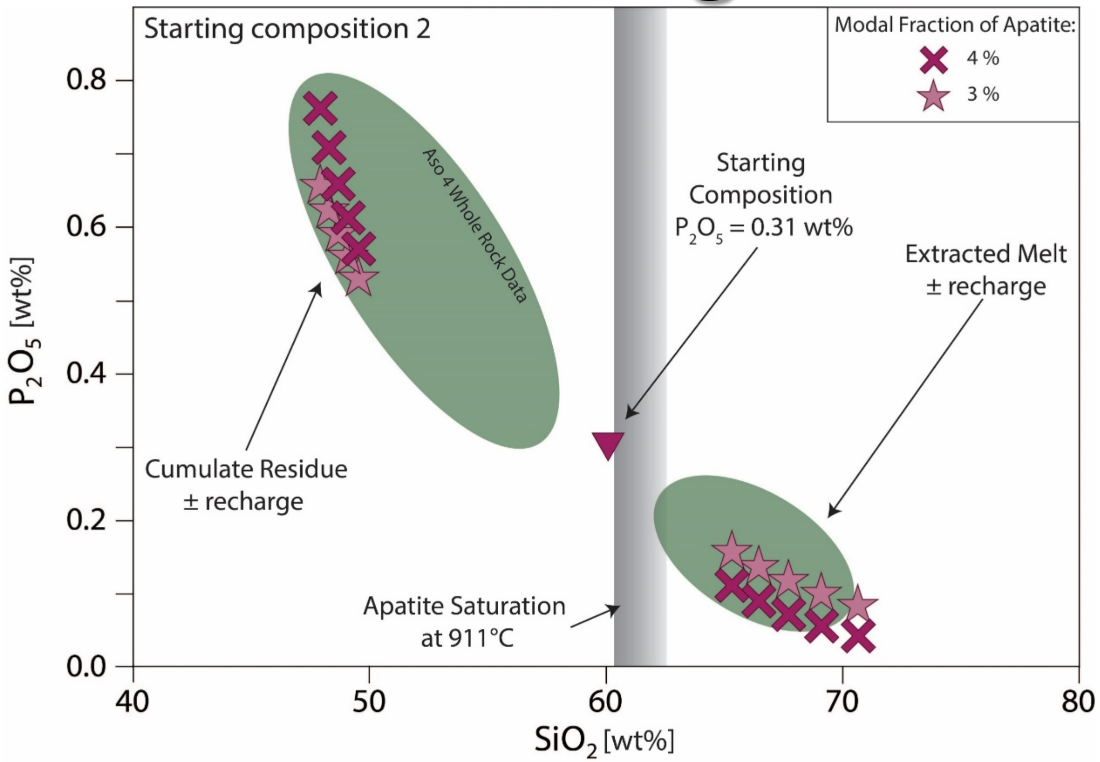
C_L = weight concentration of element in the liquid

D = Bulk distribution coefficient of the fractionation assemblage

F = Fraction of remaining melt

Results of major element modelling:





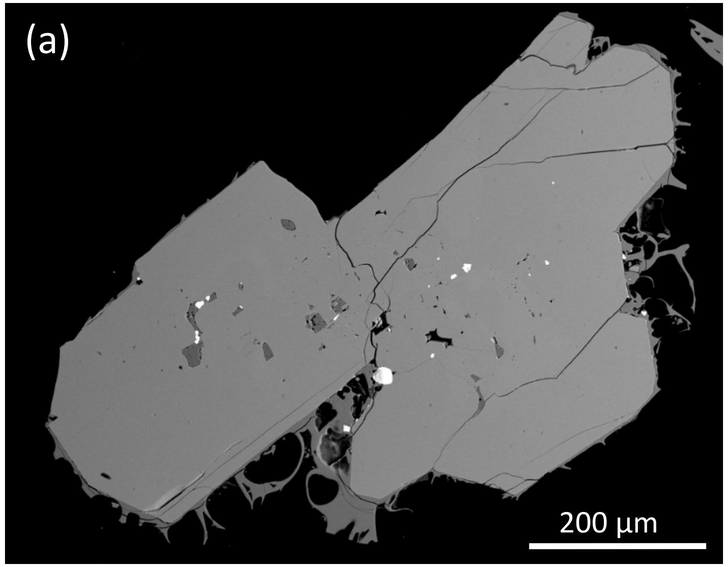
- First starting composition = least differentiated of crystal-poor clasts
- Results partly overlap with the bulk rock data, but modeled melts reach too high SiO_2 and modeled cumulates do not reach sufficiently high P_2O_5

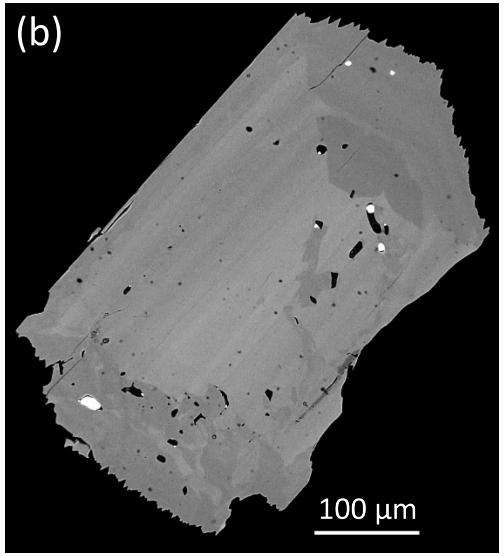
- Therefore second starting composition was chosen, located in the gap between crystal-rich and crystal-poor clasts
- Modelling results fit the range of bulk rock concentrations
- **Suggests cumulate signature in crystal-rich, late erupted clasts**

→ Similar modulations possible with other elements, however kinked liquid line of descent of P_2O_5 allows particular striking and useful results

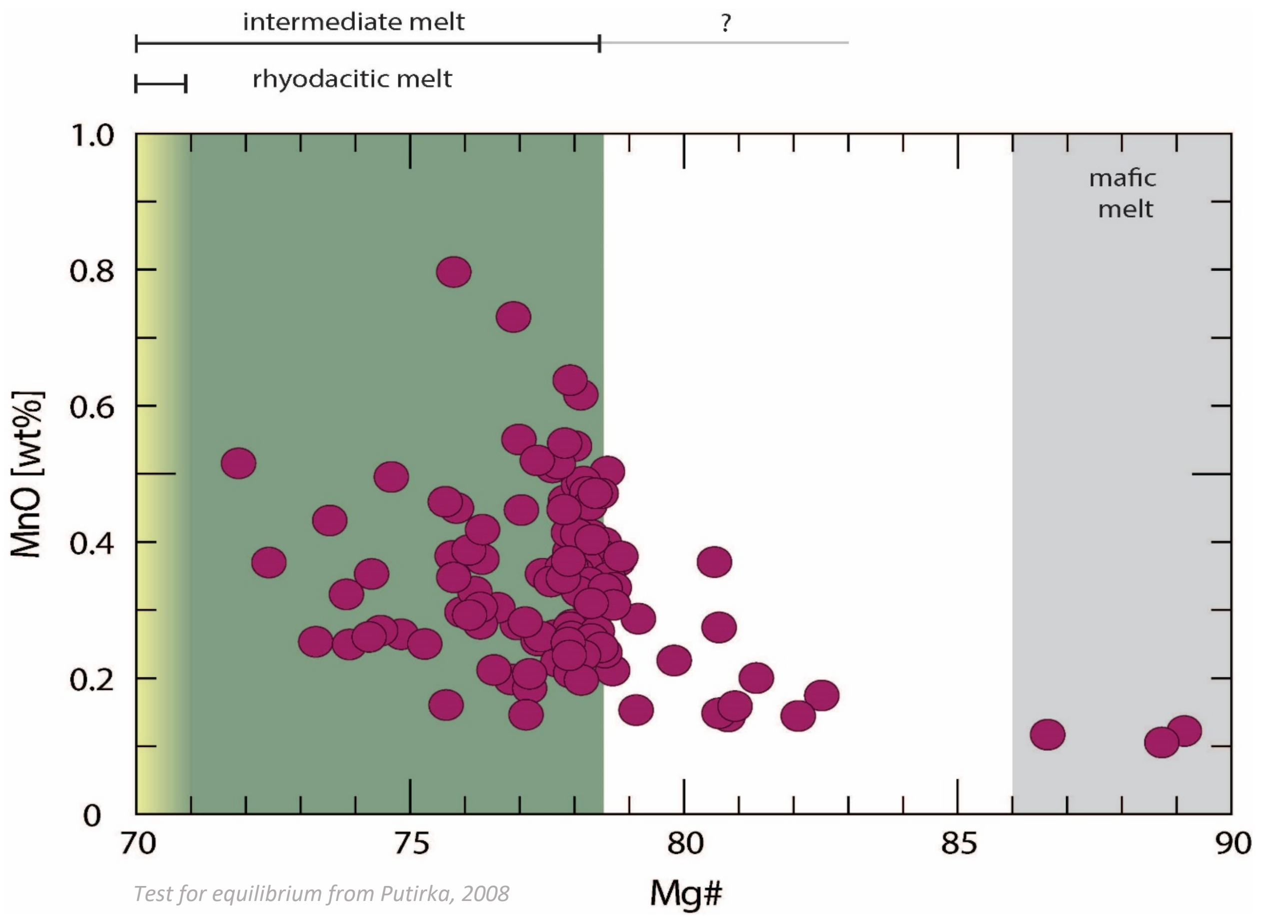
Mineral Chemistry - Clinopyroxene

- Mostly euhedral shape (rarely with resorpt rims (b))
- Poikilitic texture with inclusions of melt, Fe-Ti oxides and apatite
- 2 types of zonations observed:
  a) Largely unzoned crystals with a narrow compositional range of Mg# = 74-79
  b) Complexly zoned crystals from crystal-rich, deep units with a wide compositional range of Mg# = 72-89





Mineral Chemistry - Clinopyroxene



Test for equilibrium from Putirka, 2008

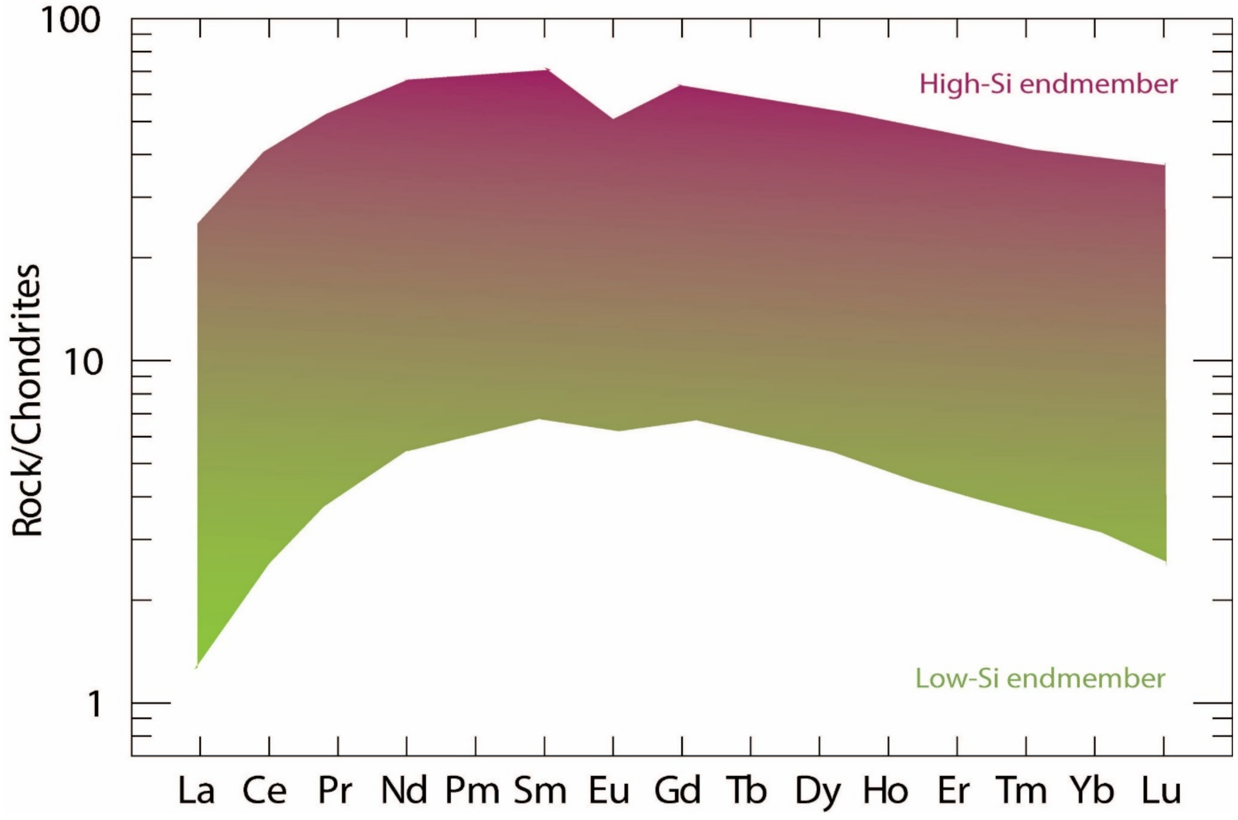
Mineral/ melt equilibria:

- Cpx tested for mineral/ melt equilibrium following the test of Putirka, 2008
  - Light green areas represent equilibrium fields with rhyodacitic host melt
  - Dark green areas represent equilibrium fields with intermediate melt measured in crystal-rich, cumulate clasts
  - Grey areas represent equilibrium fields with more mafic melt (basaltic andesite)
- Cpx largely in equilibrium with intermediate melts measured in crystal-rich clasts
- High Mg# crystals come from more mafic melt likely representing deep recharge

Mineral Chemistry - Clinopyroxene

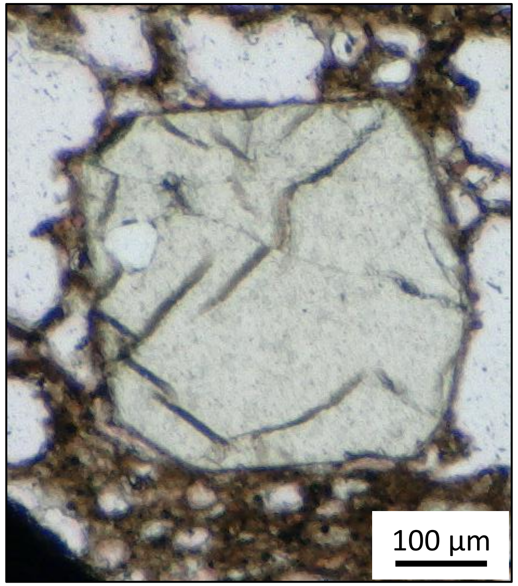
Trace elements in Cpx:

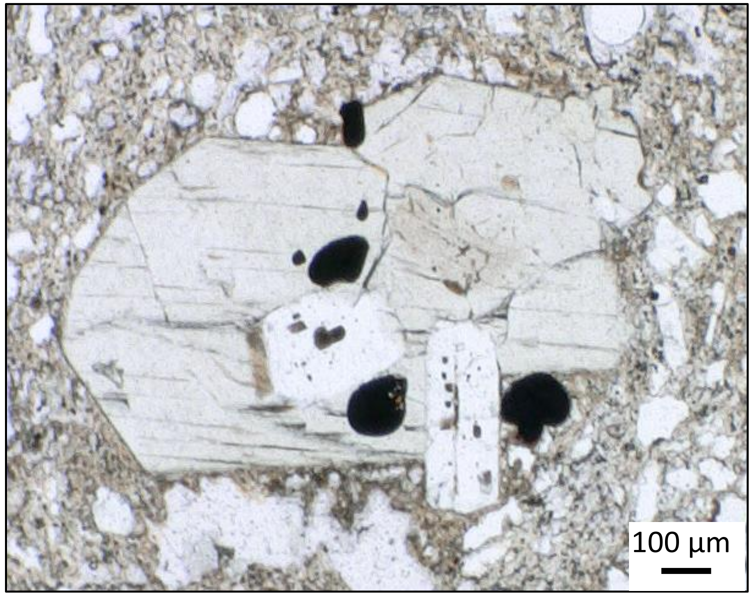
- High REE contents over a wide range of concentrations for crystals from intermediate melts (High-Mg# crystals not included in the plot)
- Progressively increasing Eu anomaly from low-Si endmember towards the high-Si endmember



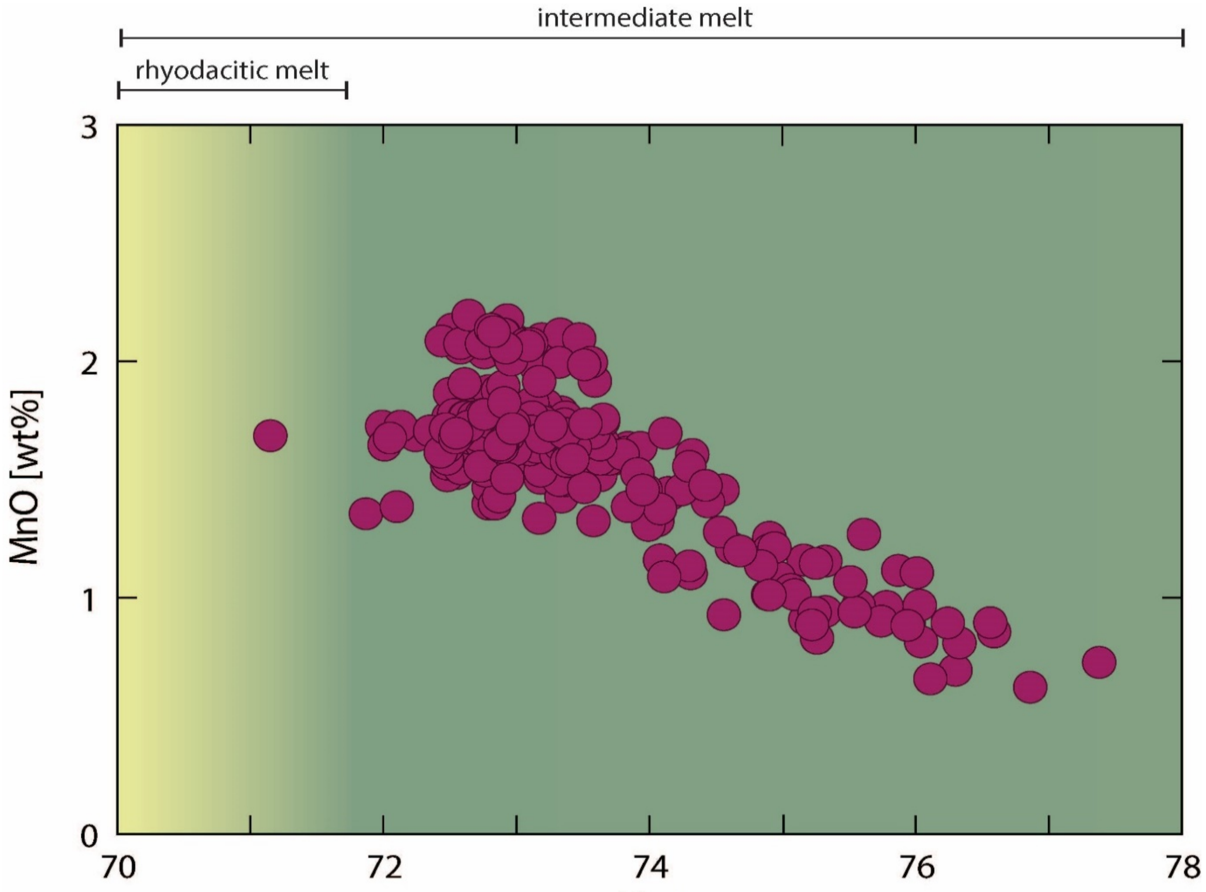
Mineral Chemistry - Orthopyroxene

- Mostly euhedral shape
- Poikilitic texture with many inclusions of plagioclase, Fe-Ti oxides, apatite, melt
- Relatively narrow compositional range (Mg# = 71-77)
- Largely unzoned appearance observed with individual crystals showing reverse zonation predominantly from deep, crystal-rich units





Mineral Chemistry - Orthopyroxene



Test for equilibrium from Putirka, 2008

Mineral/ melt equilibria:

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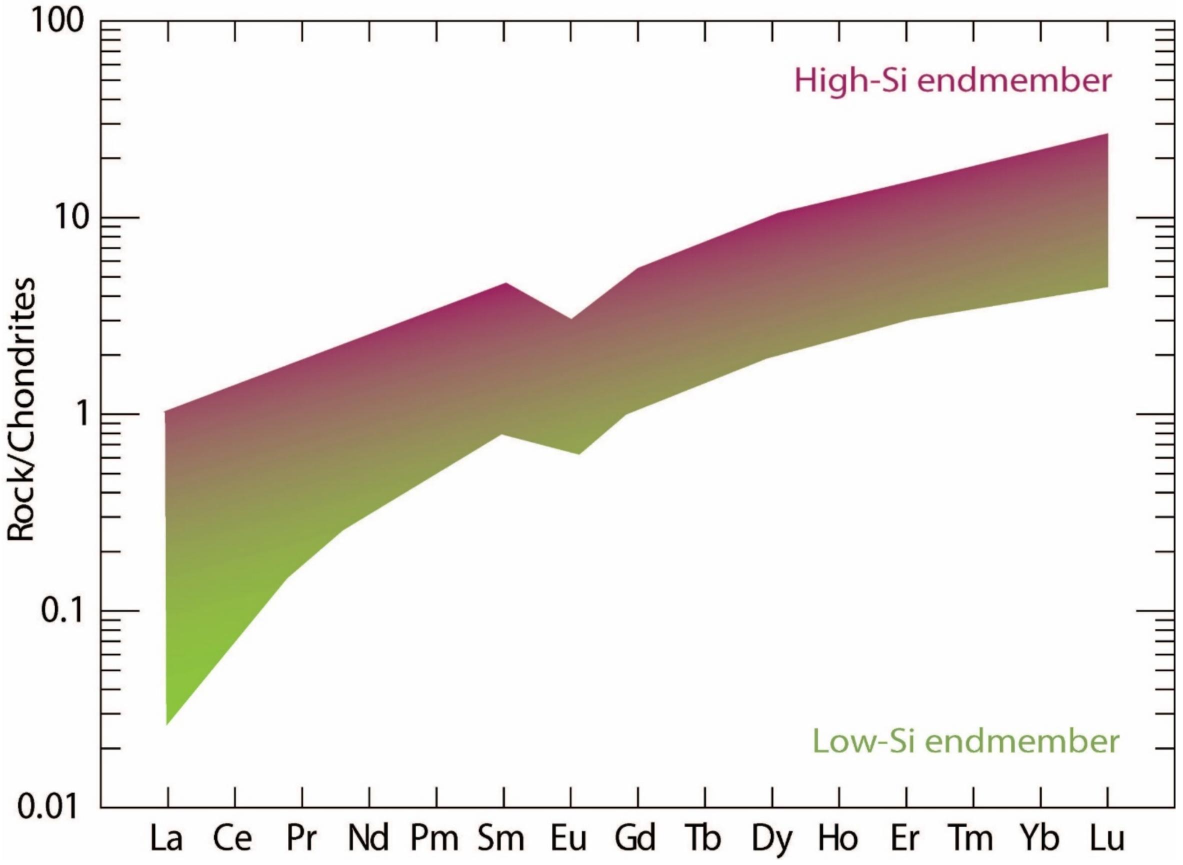
- Light green areas represent equilibrium fields with rhyodacitic host melt
- Dark green areas represent equilibrium fields with intermediate melt measured in crystal-rich, cumulate clasts

- Opx largely in equilibrium with intermediate melts measured in crystal-rich clasts

Mineral Chemistry - Orthopyroxene

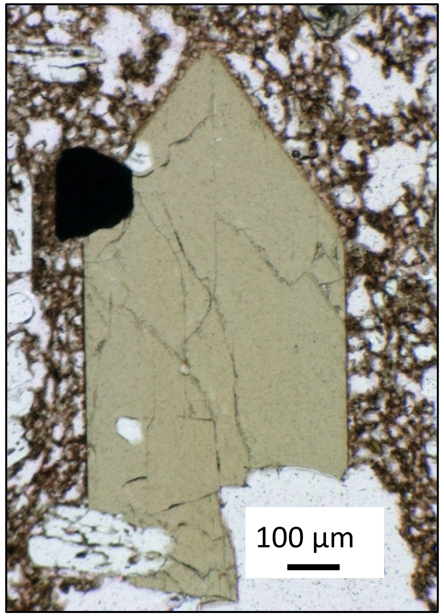
Trace elements in Opx:

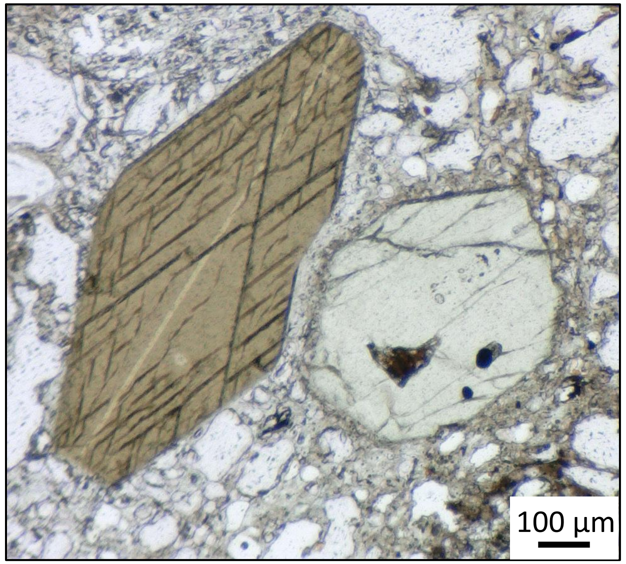
- High REE contents over a narrower range of concentrations
- Indicates crystallization over a narrower range than Cpx crystallization



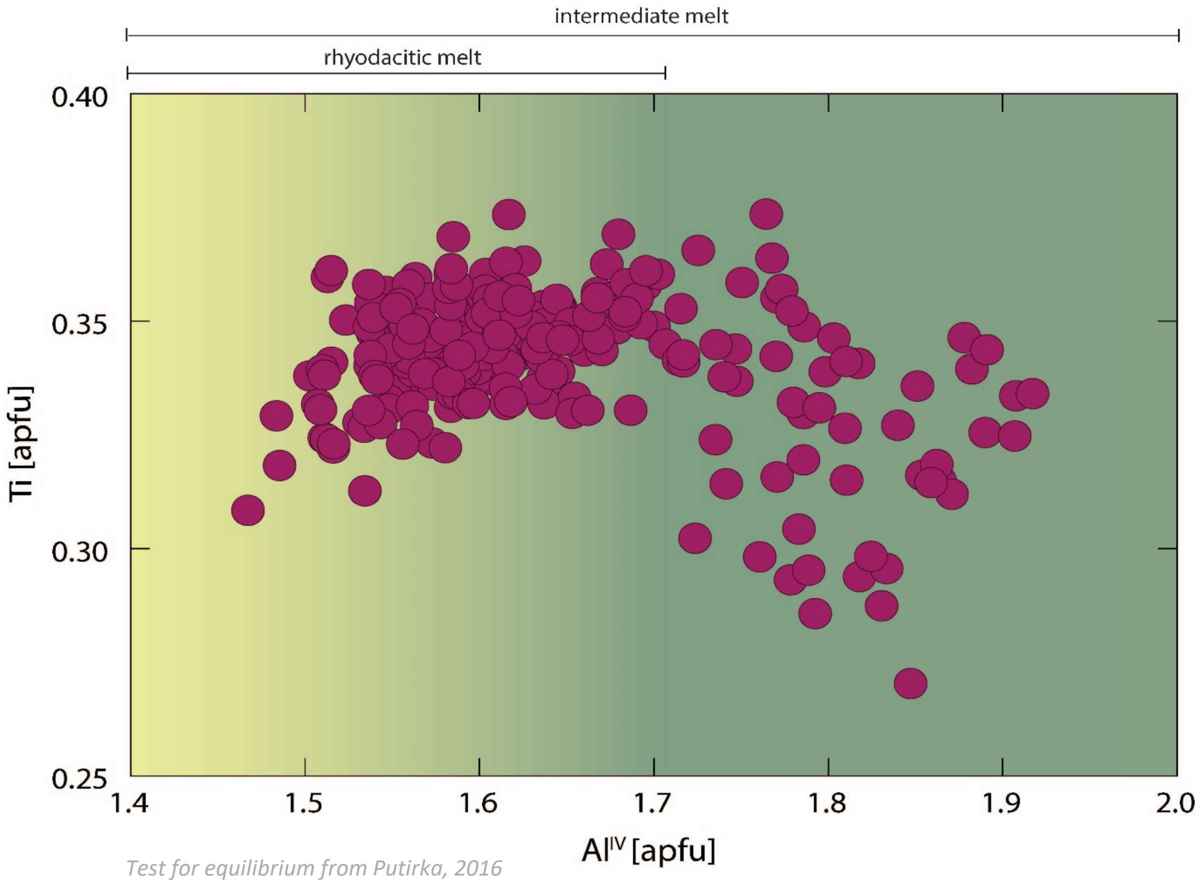
Mineral Chemistry - Amphiboles

- Amphiboles exhibit euhedral shape and are present in crystal-poor as well as crystal-rich clasts
- Rare inclusions of apatite, oxides, melt, opx and plagioclase
- Classified as Magnesio-Hastingsite
- Mostly unzoned with inter-grain chemical variations (T^{Al} = 1.5 – 1.9 apfu)





Mineral Chemistry - Amphiboles



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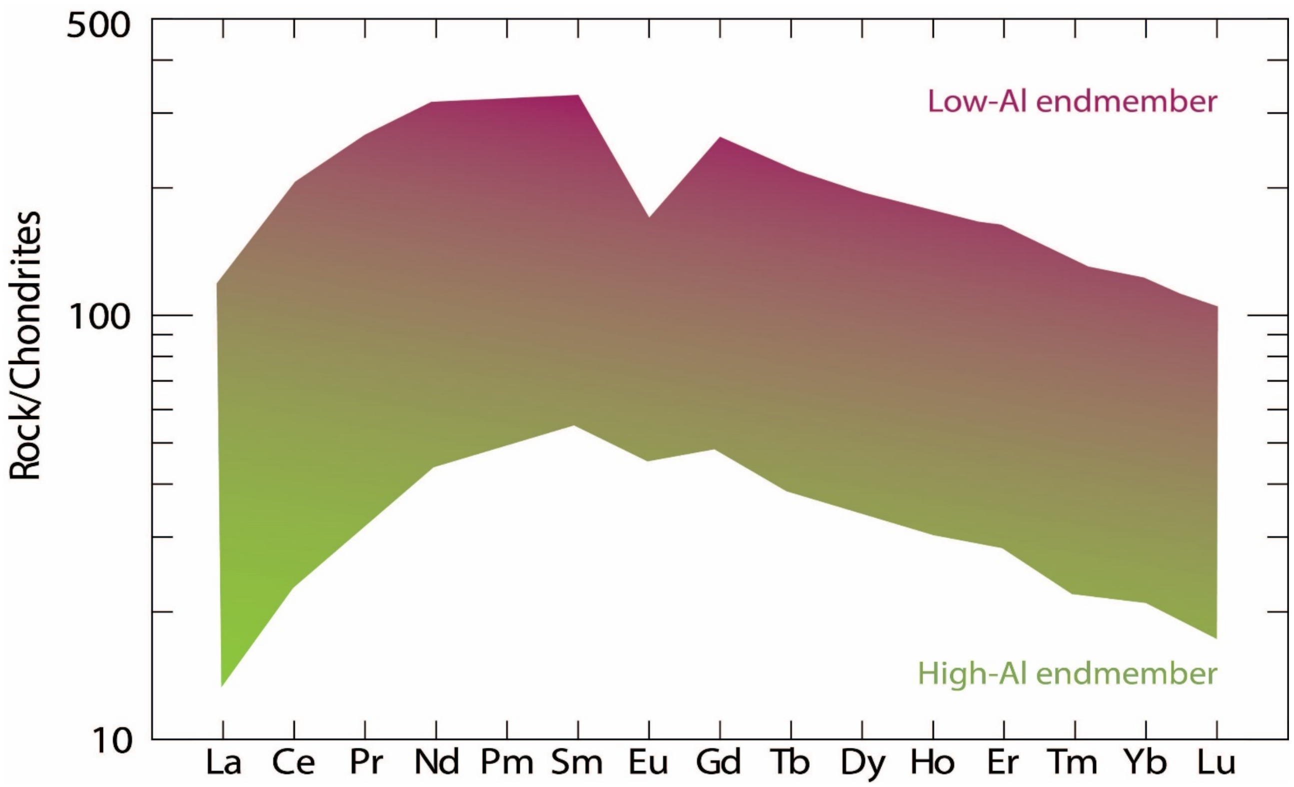
- Low-Al endmember in equilibrium with rhyodacitic melt measured in crystal-poor clasts

- High-Al endmember in equilibrium with intermediate melts measured in crystal-rich clasts

Mineral Chemistry - Amphiboles

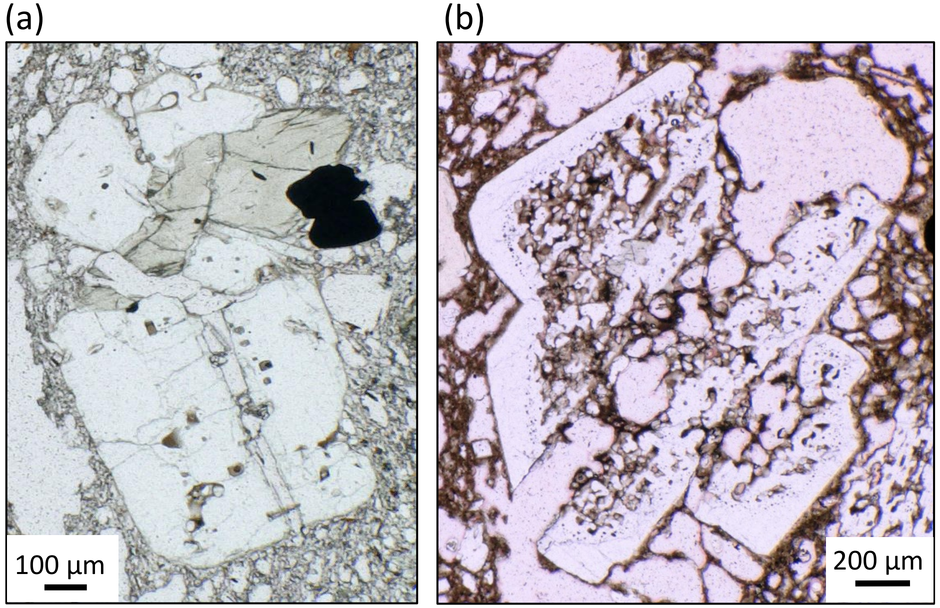
Trace elements in Amphiboles:

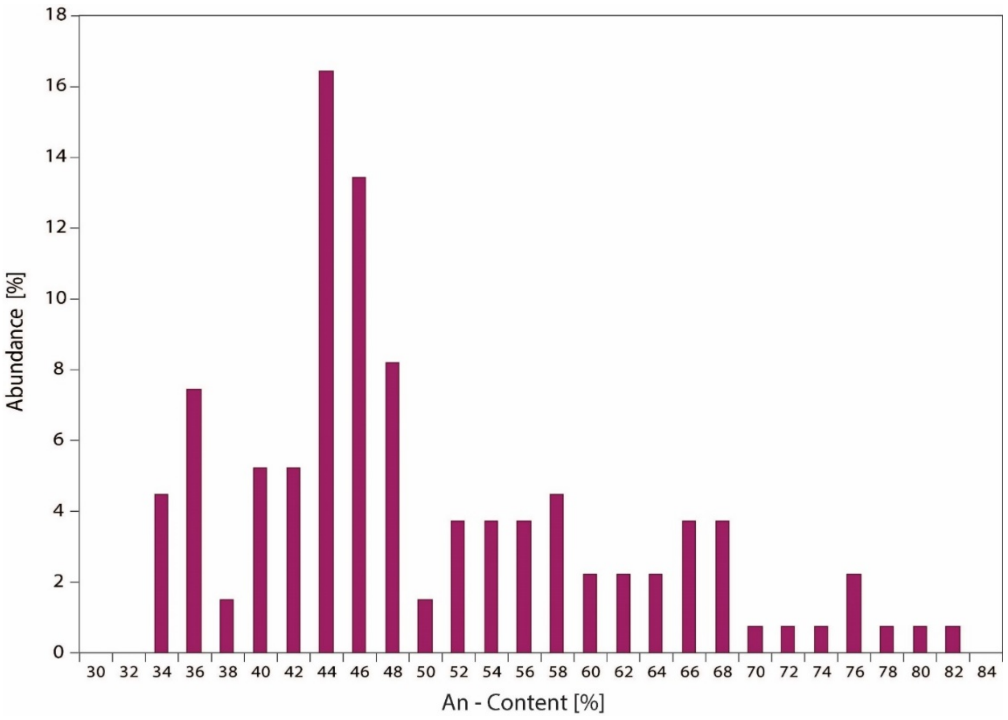
- High REE contents over a wide range of concentrations
- Increasingly negative Eu anomaly from the high-Al endmember towards the low-Al endmember



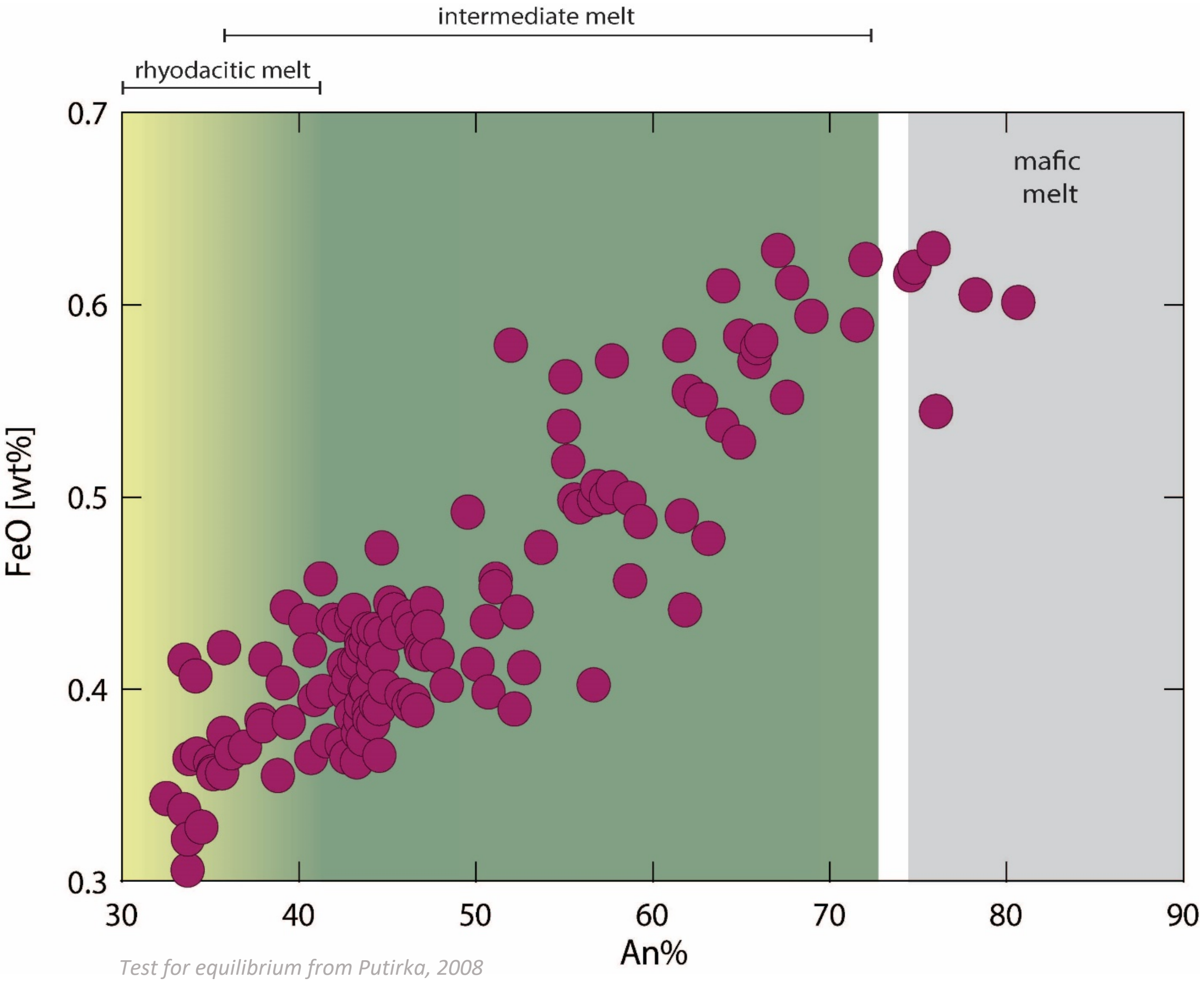
Mineral Chemistry - Plagioclase

- Crystallization of plagioclase in early erupted, crystal-poor units in euhedral shape (a); in late-erupted, crystal-rich units plagioclase often exhibits a sieved structure, sometimes (but not always) overgrown by rims with An50-55 (b)
- Inclusions of apatite, oxides, melt and opx
- Large compositional range (An30 - An80)
- largely unzoned crystals as well as oscillatory and normally zoned crystals present primarily in crystal-rich, deep units





Mineral Chemistry - Plagioclase



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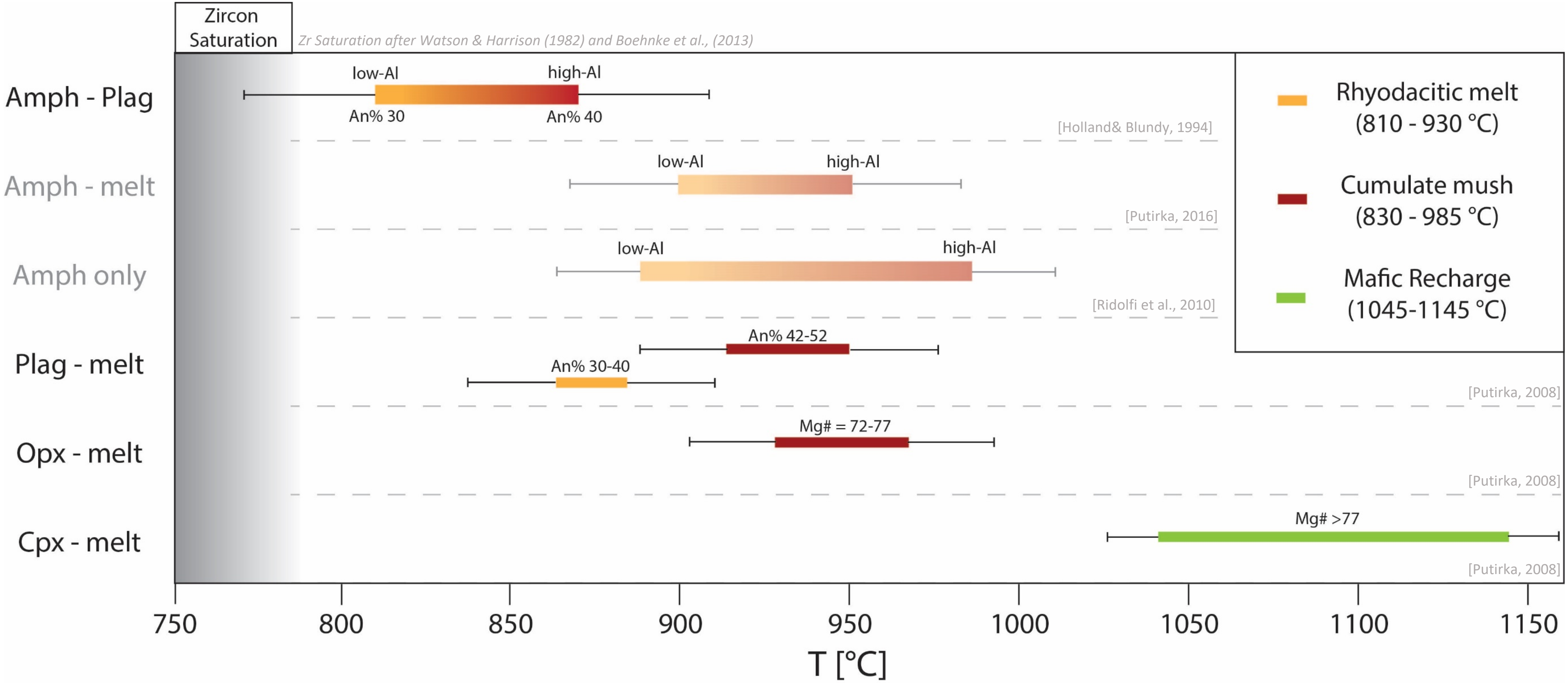
  - Grey areas represent equilibrium fields with more mafic (basaltic andesitic) melt
- Plagioclase largely in equilibrium with intermediate melts measured in crystal-rich clasts
- Individual crystals in equilibrium with a rhyodacitic melt measured in crystal-poor clasts
- others originate from a more mafic melt likely representing deep recharge melt

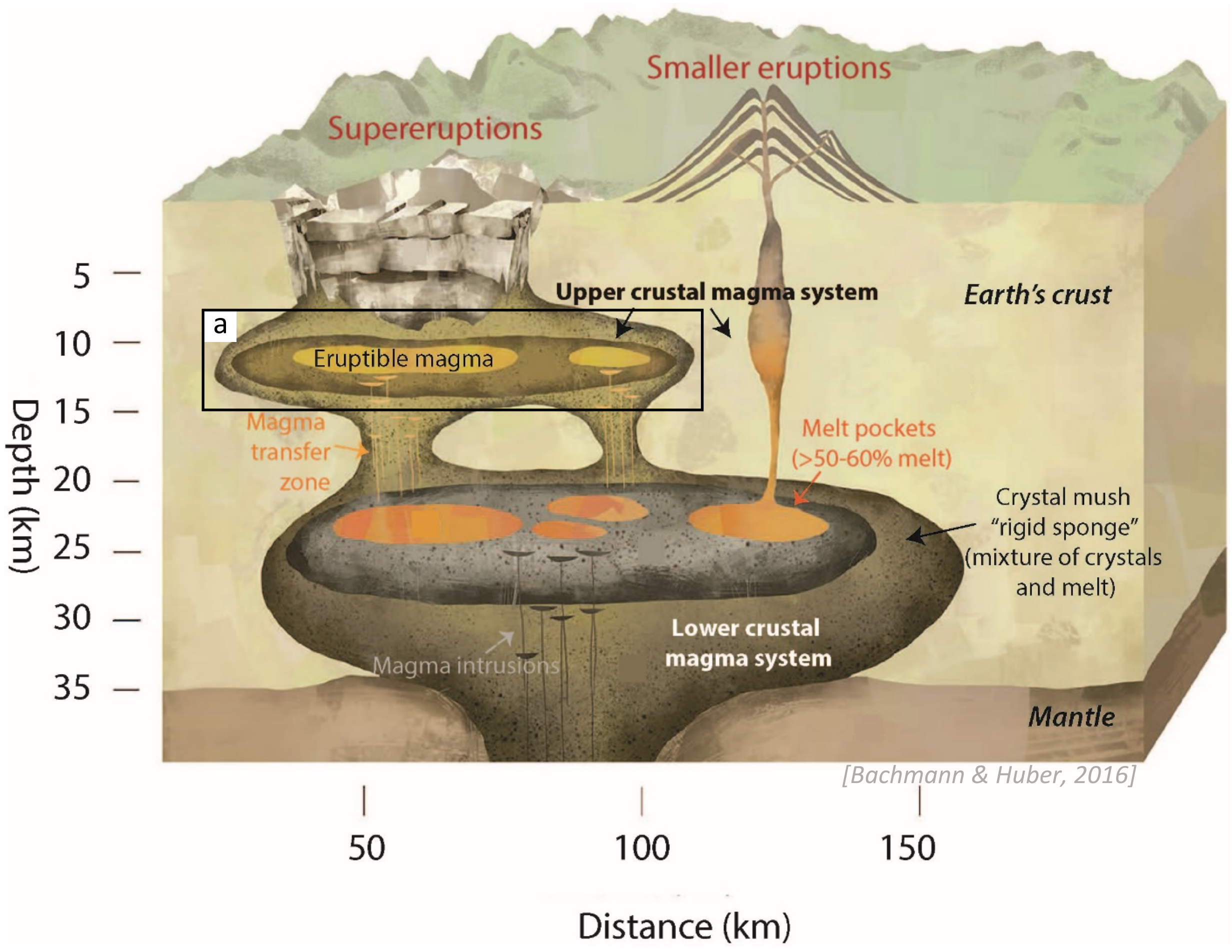
P = 1.22 – 2.52 kbar (±0.6 kbar)
H_2O = 4.4 – 4.7 wt% (± 0.35 wt%)

[P after Anderson & Smith, 1995;
H_2O after Waters & Lange, 2015]

Pre-eruptive Conditions - Thermometry



Pre-eruptive Magmatic System



[Bachmann & Huber, 2016]

General setup of a caldera systems extending through the whole crust, comprising different parts:

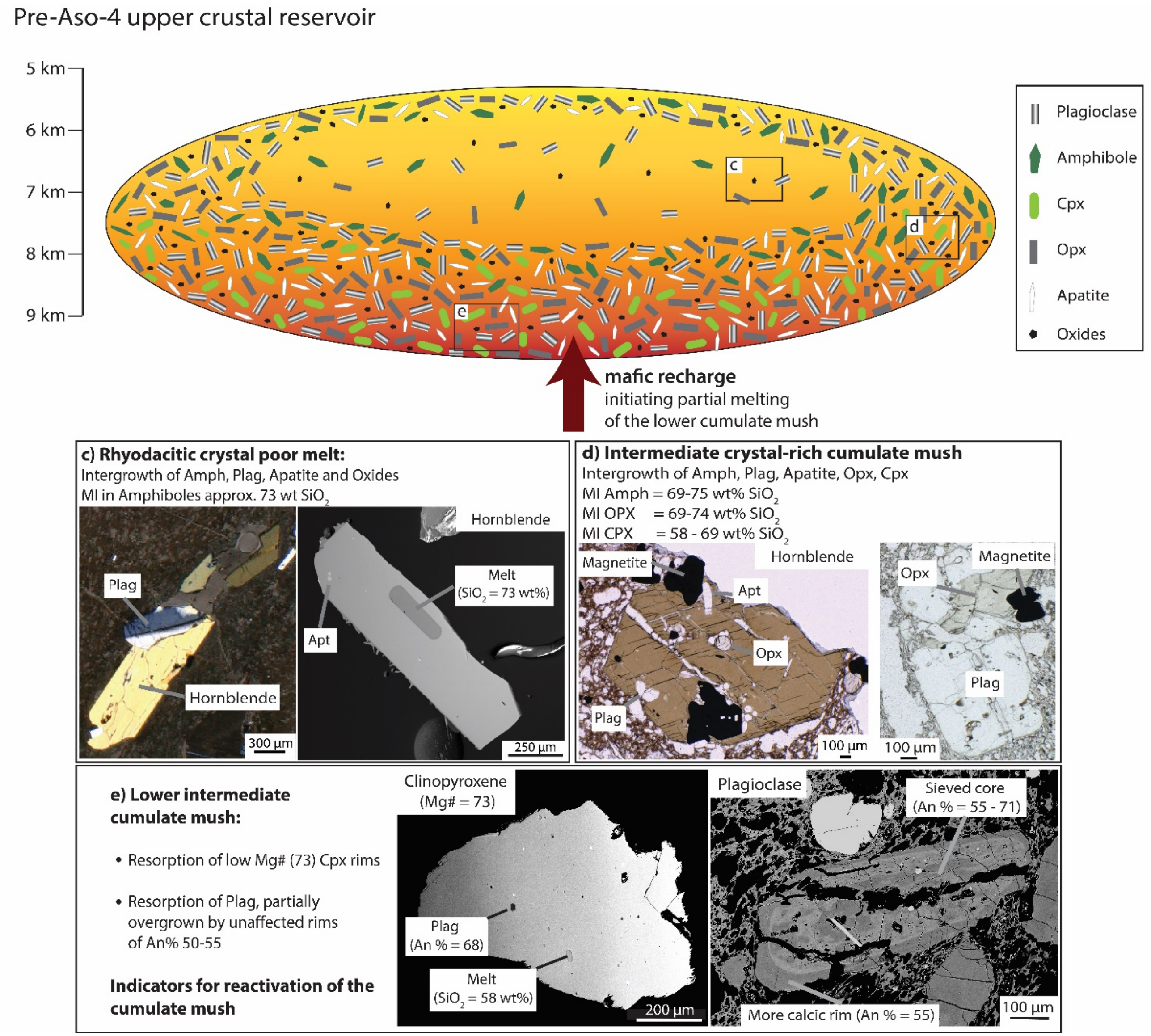
- A large lower crustal mush zone, fed by mantle melts, and producing magmas of intermediate compositions
- An upper crustal mush zone (a) showing melt-rich pockets extracted from the higher crystallinity regions of the reservoirs. The upper crustal reservoir is frequently recharged by variably differentiated input, mostly from the lower crustal mush zone
- Ignimbrite deposits represent a snapshot of the conditions of the upper crustal reservoir just prior to eruption, involving

  (1) crystal-poor, highly-evolved material

  (2) crystal-rich, partly cumulative material

  (3) Hotter recharge material, typically mixed in with the crystal-rich material

Pre-eruptive Magmatic System – The Aso 4 System



- We propose a similarly heterogeneous upper crustal reservoir built out of an intermediate cumulate mush hosting rhyodacitic melt pocket(s)
- Equilibrium mineral assemblages include:
  - Rhyodacitic melt: low-Al Amph, low-An Plag, Apatite and Fe-Ti oxides
  - Intermediate cumulate mush: high-Al Amph, Plag (An40-70), Opx, Cpx, Apatite and Fe-Ti oxides
- Presence of high Mg# Cpx and high-An Plag indicate more mafic/hotter recharge into the system, potentially initiating partial melting of the cumulate mush, mixing/ mingling and finally overpressurization of the reservoir, ultimately triggering the eruption

I am looking forward to further discussions! Please don‘t hesitate to contact me:

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[Photograph by A. Miyakawa]

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Methods

- Juvenile clasts of the Aso-4 caldera forming eruption were carefully collected and prepared for chemical analyses in the laboratories of ETH Zuerich and the Geological Survey of Japan (GSJ), AIST, Tsukuba.

- Bulk rock major element compositions were determined via X-ray fluorescence spectrometry (PANalytical Axios Advanced) at GSJ, AIST, Tsukuba

- Mineral major element compositions were measured via Electron Probe Microanalysis at ETH Zuerich (measurement conditions: 15 kV acceleration voltage, 20 nA beam current, a focused beam for pyroxene and a 10 µm defocused beam for amphibole and plagioclase measurements).

- Groundmass glass major element compositions were analyzed with an EDS-Calibrated Scanning Electron Microscope (Major elements were calibrated using EPMA standards, acceleration voltage was set to 15 kV with a dead time varying between 20-30% at a working distance of 10 µm, compositions were measured over wide areas with diameters between 20 – 50 µm).

- Mineral trace element compositions were measured via Laser Ablation Inductively-Coupled Spectrometry at ETH Zuerich (spot size 43 µm, output energy of the laser = 3.5 J/cm^2, data reduction based on Guillong *et al.*, 2008 (SILLS Software) using NIST 612 as external standards and appropriate EPMA major element analyses as internal standards)