# Machine Learning in Volcanology

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# Volcanoes deliver messages from depth

Tree not to scale...

Kola Superdeep Borehole SG-3: 12.2 km

From magma source to the surface

La Palma, October 2021

?

Our documents

1.5 cm

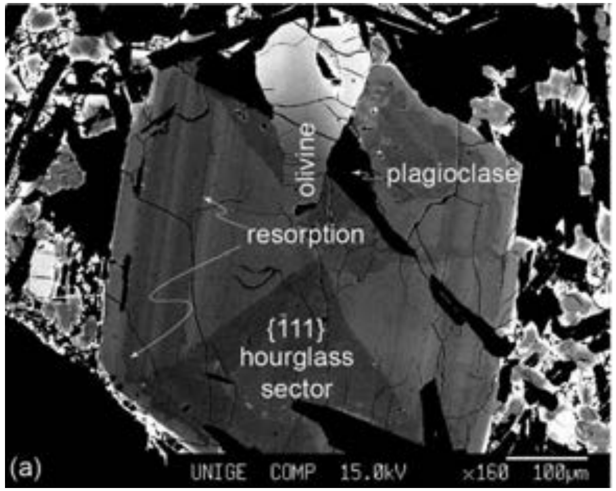
# How do we extract data?


Spatial resolution ∼ 1$\mu$m 😀

Analytical error ± 1 % relative 😀

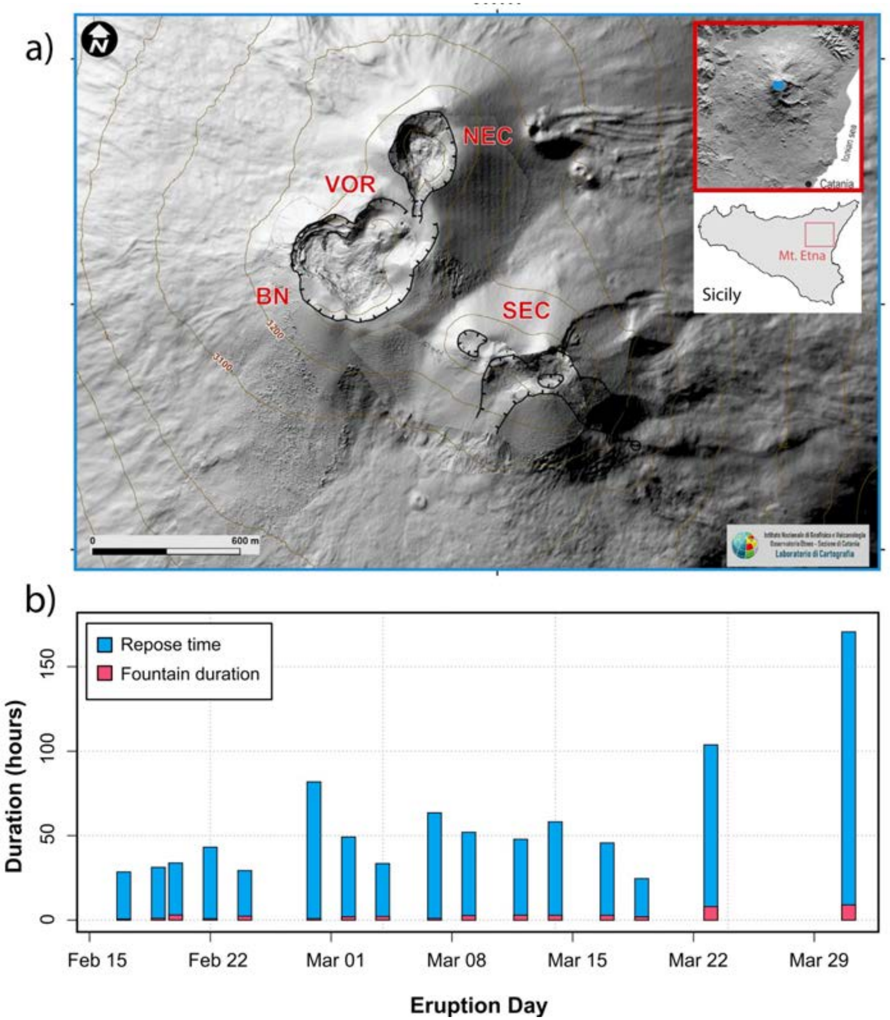
Expensive 😩

Clinopyroxene crystal




| | X | No. | SiO2.cpx | CaO.cpx | Na2O.cpx | MnO.cpx | FeO.cpx | MgO.cpx | NiO.cpx | Al2O3.cpx | Cr2O3.cpx | TiO2.cpx | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 151 | 49.76 | 23.51 | 0.4522 | 0.1000 | 6.50 | 14.34 | 0.0047 | 4.75 | 0.0890 | 1.9600 | 101.4658 |
| 2 | 2 | 152 | 49.21 | 23.09 | 0.4246 | 0.1397 | 7.12 | 14.22 | 0.0335 | 4.88 | 0.1537 | 2.2600 | 101.5315 |
| 3 | 3 | 153 | 47.69 | 23.26 | 0.7886 | 0.2158 | 7.98 | 12.48 | 0.0362 | 6.98 | 0.0342 | 2.6100 | 102.0748 |
| 4 | 4 | 154 | 47.79 | 23.08 | 0.6346 | 0.1374 | 7.26 | 13.27 | 0.0000 | 6.80 | 0.0192 | 2.6500 | 101.6412 |
| 5 | 5 | 155 | 48.63 | 23.00 | 0.6070 | 0.1066 | 7.16 | 13.70 | 0.0262 | 6.07 | 0.0372 | 2.2700 | 101.6069 |
| 6 | 6 | 156 | 48.09 | 23.33 | 0.5556 | 0.1019 | 7.18 | 13.57 | 0.0103 | 6.27 | 0.0561 | 2.4200 | 101.5838 |
| 7 | 7 | 157 | 48.79 | 23.48 | 0.5368 | 0.1417 | 6.98 | 13.87 | 0.0359 | 5.36 | 0.0744 | 2.2000 | 101.4688 |
| 8 | 8 | 158 | 45.61 | 23.20 | 0.6397 | 0.1649 | 7.45 | 12.28 | 0.0040 | 8.04 | 0.0386 | 3.2500 | 100.6771 |
| 9 | 9 | 159 | 49.65 | 23.51 | 0.4950 | 0.1363 | 6.83 | 14.42 | 0.0201 | 4.59 | 0.1330 | 1.9700 | 101.7544 |
| 10 | 10 | 160 | 48.55 | 23.15 | 0.5490 | 0.1398 | 7.12 | 13.93 | 0.0154 | 5.41 | 0.0872 | 2.3400 | 101.2914 |
| 11 | 11 | 161 | 47.02 | 23.30 | 0.8615 | 0.1989 | 8.50 | 11.78 | 0.0208 | 7.17 | 0.0572 | 2.7200 | 101.6283 |
| 12 | 12 | 162 | 47.31 | 23.19 | 0.9840 | 0.2026 | 8.94 | 11.66 | 0.0248 | 6.47 | 0.0355 | 2.4400 | 101.2569 |
| 13 | 13 | 163 | 48.15 | 23.42 | 0.7273 | 0.1397 | 7.19 | 13.10 | 0.0000 | 6.18 | 0.0537 | 2.5200 | 101.4807 |
| 14 | 14 | 164 | 48.29 | 23.49 | 0.6686 | 0.1460 | 7.12 | 13.56 | 0.0000 | 5.98 | 0.0276 | 2.5100 | 101.7922 |
| 15 | 15 | 165 | 49.58 | 23.62 | 0.5460 | 0.1387 | 6.44 | 14.21 | 0.0074 | 4.95 | 0.0877 | 2.1000 | 101.6797 |
| 16 | 16 | 166 | 47.80 | 23.71 | 0.5732 | 0.1224 | 7.12 | 13.26 | 0.0272 | 6.16 | 0.0516 | 2.7100 | 101.5343 |
| 17 | 17 | 167 | 47.85 | 23.63 | 0.6599 | 0.1344 | 7.54 | 13.09 | 0.0007 | 6.36 | 0.0090 | 2.4900 | 101.7639 |
| 18 | 18 | 168 | 49.13 | 23.46 | 0.6192 | 0.1500 | 6.84 | 14.10 | 0.0000 | 5.22 | 0.0487 | 2.0500 | 101.6179 |
| 19 | 19 | 169 | 45.45 | 22.96 | 0.5827 | 0.1079 | 7.69 | 12.66 | 0.0560 | 8.02 | 0.2962 | 3.4300 | 101.2528 |
| 20 | 20 | 170 | 46.25 | 23.03 | 1.1695 | 0.2966 | 10.61 | 10.32 | 0.0000 | 7.25 | 0.0231 | 2.6100 | 101.5592 |
| 21 | 21 | 171 | 45.76 | 22.99 | 1.0753 | 0.3462 | 10.60 | 10.20 | 0.0003 | 7.42 | 0.0068 | 2.8000 | 101.1985 |
| 22 | 22 | 172 | 44.77 | 23.19 | 1.0207 | 0.3026 | 10.34 | 10.34 | 0.0101 | 8.14 | 0.0000 | 3.1700 | 101.2833 |
| 23 | 23 | 173 | 46.84 | 22.94 | 1.1271 | 0.3400 | 11.20 | 10.44 | 0.0157 | 6.33 | 0.0000 | 2.0700 | 101.3027 |
| 24 | 24 | 174 | 45.93 | 23.01 | 1.1093 | 0.3453 | 10.49 | 10.50 | 0.0060 | 7.54 | 0.0056 | 2.7400 | 101.6761 |

# Unsupervised learning




Alessandro Musu

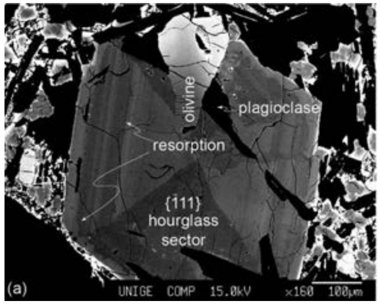
Bulletin of Volcanology (2023) 85:33
https://doi.org/10.1007/s00445-023-01643-2

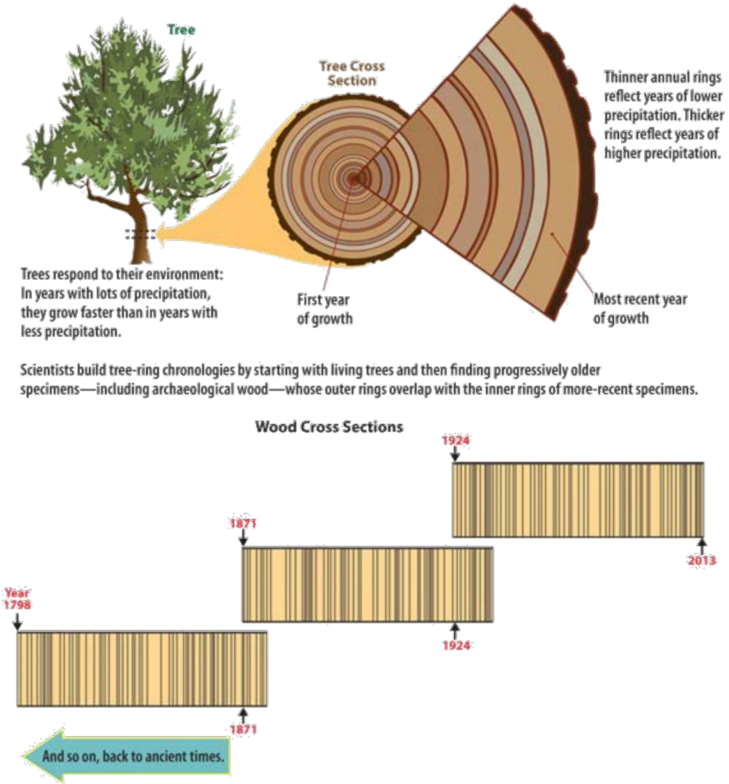
RESEARCH ARTICLE

**The magmatic evolution of South-East Crater (Mt. Etna) during the February–April 2021 sequence of lava fountains from a mineral chemistry perspective**

Alessandro Musu[1] · Rosa Anna Corsaro[2] · Oliver Higgins[3] · Corin Jorgenson[1] · Maurizio Petrelli[4] · Luca Caricchi[1]

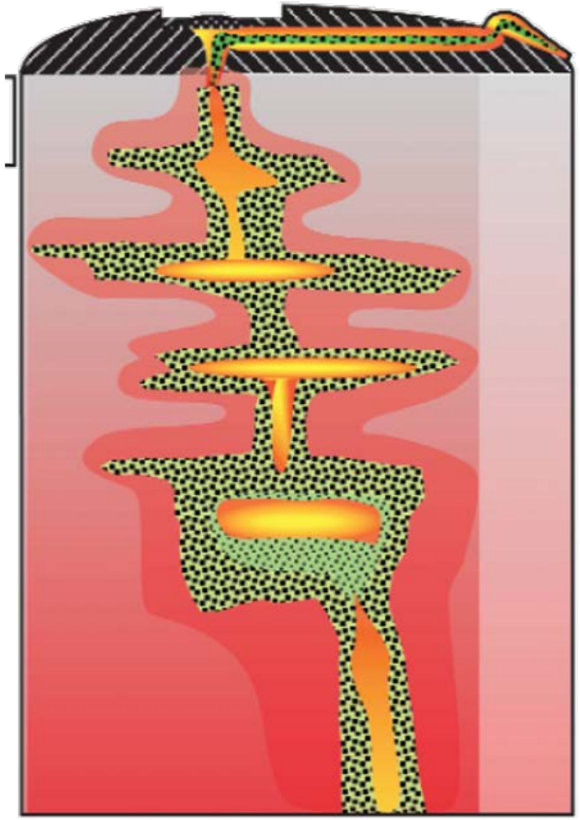
# Crystals are similar to trees…but not really



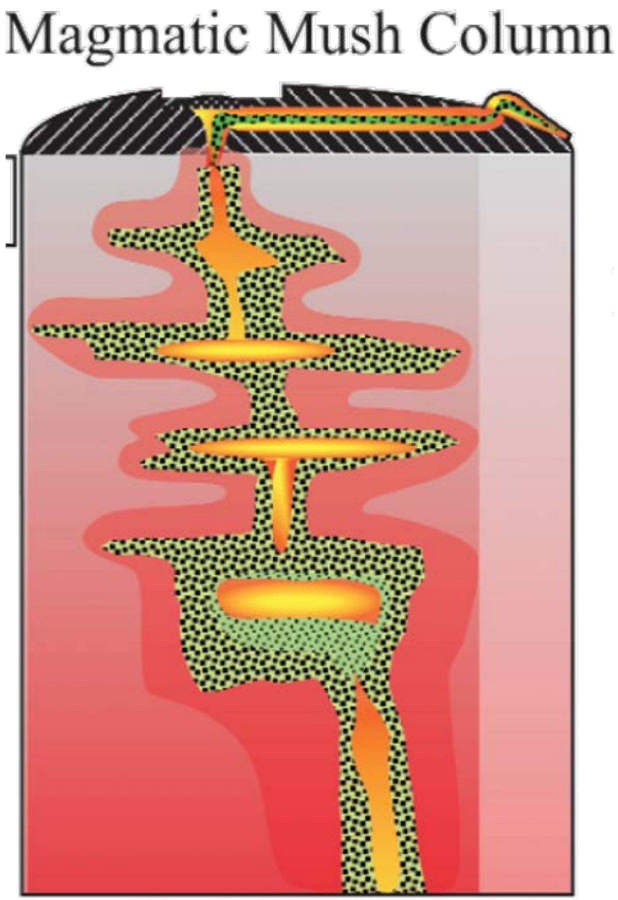

https://www.crowcanyon.org/index.php/dendrochronology

Magmatic Mush Column

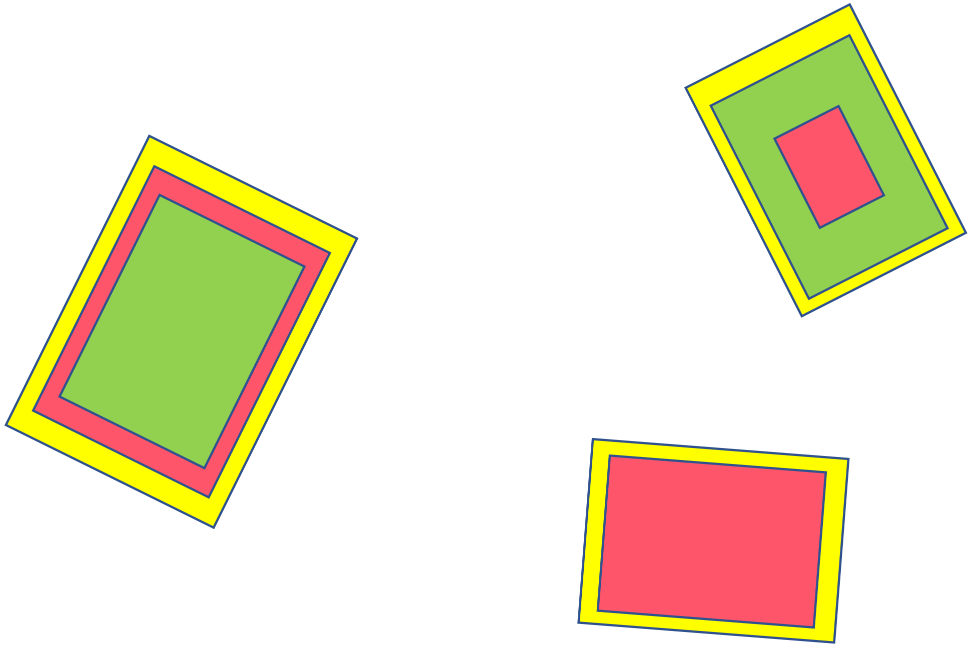


Marsh, 2004, EOS

# Pros and Cons




Marsh, 2004, EOS



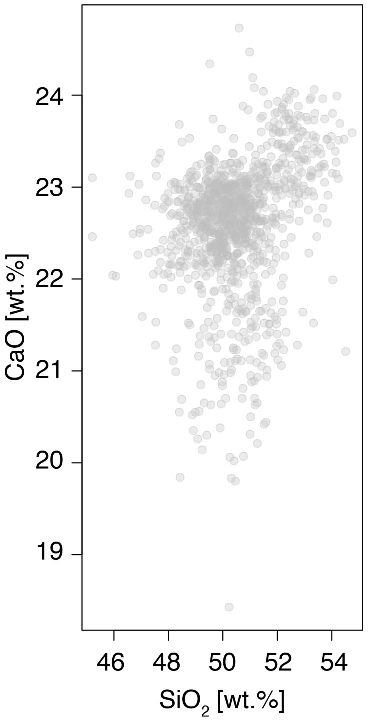
1. Each crystal is unique (i.e. might experience a different evolution of the conditions of growth over time) ☹️
2. Crystals provide representative samples of the distribution of intensive parameters within volcanic plumbing systems 😀

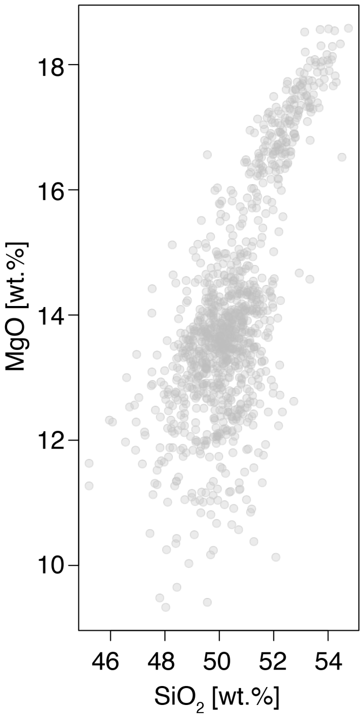
# Transformation: isometric log ratio

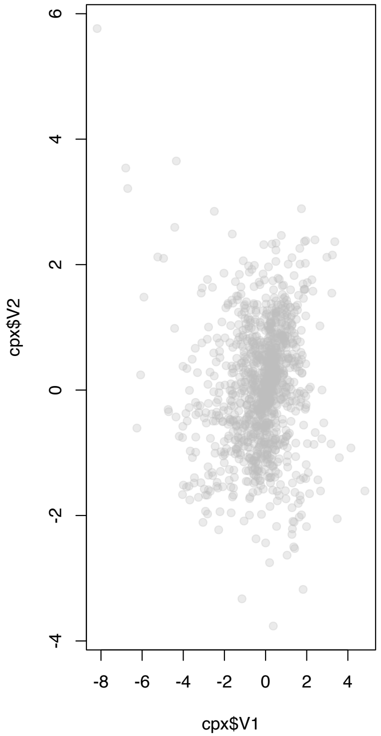
| | X | No. | SiO2.cpx | CaO.cpx | Na2O.cpx | MnO.cpx | FeO.cpx | MgO.cpx | NiO.cpx | Al2O3.cpx | Cr2O3.cpx | TiO2.cpx | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 151 | 49.76 | 23.51 | 0.4522 | 0.1000 | 6.50 | 14.34 | 0.0047 | 4.75 | 0.0890 | 1.9600 | 101.4658 |
| 2 | 2 | 152 | 49.21 | 23.09 | 0.4246 | 0.1397 | 7.12 | 14.22 | 0.0335 | 4.88 | 0.1537 | 2.2600 | 101.5315 |

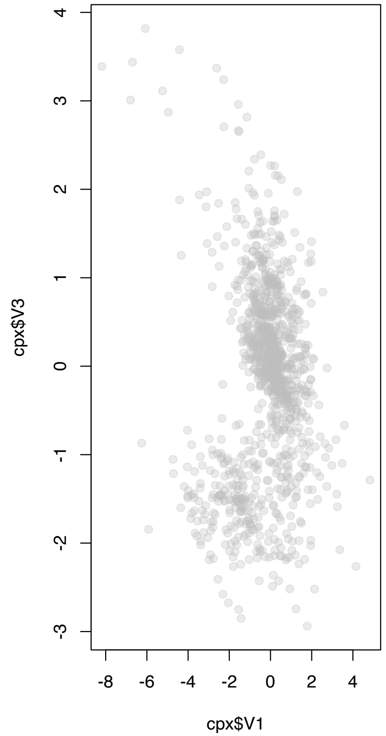
Geochemical analyses are ”closed datasets”, as their total should be always 100 wt.%

- This implies that the variables (e.g. $SiO_2$, $Al_2O_3$ etc…) are NOT independent

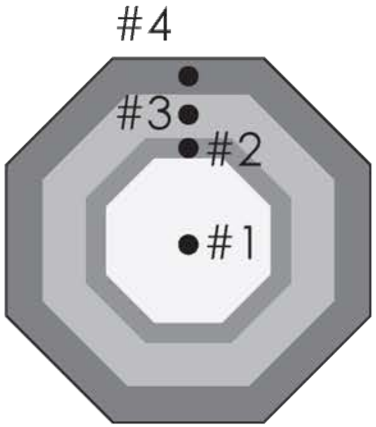


# Normalization and clustering

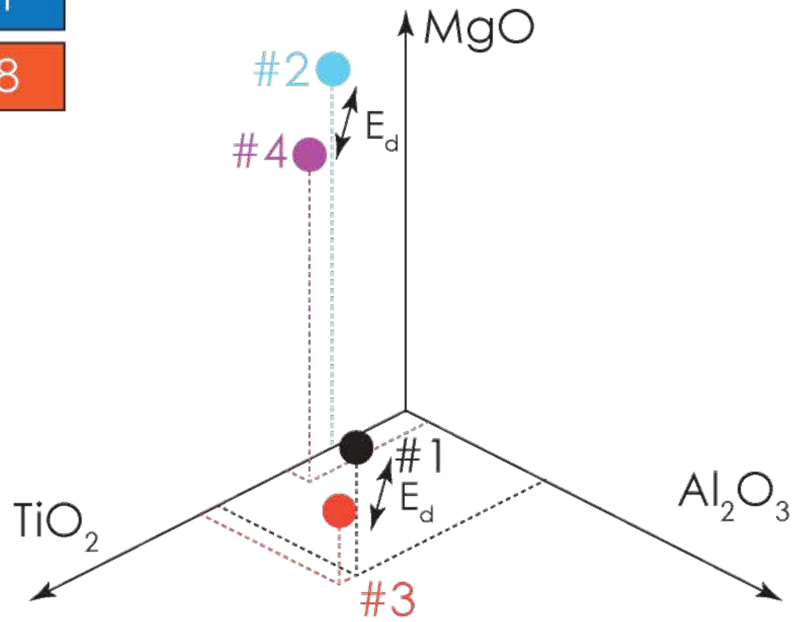



| spot analysis | $TiO_2$ | $Al_2O_3$ | $MgO$ |
|---|---|---|---|
| #1 | 0.9 | 0.6 | 0.3 |
| #2 | 0.3 | 0 | 1 |
| #3 | 1 | 0.6 | 0.1 |
| #4 | 0.6 | 0.1 | 0.8 |

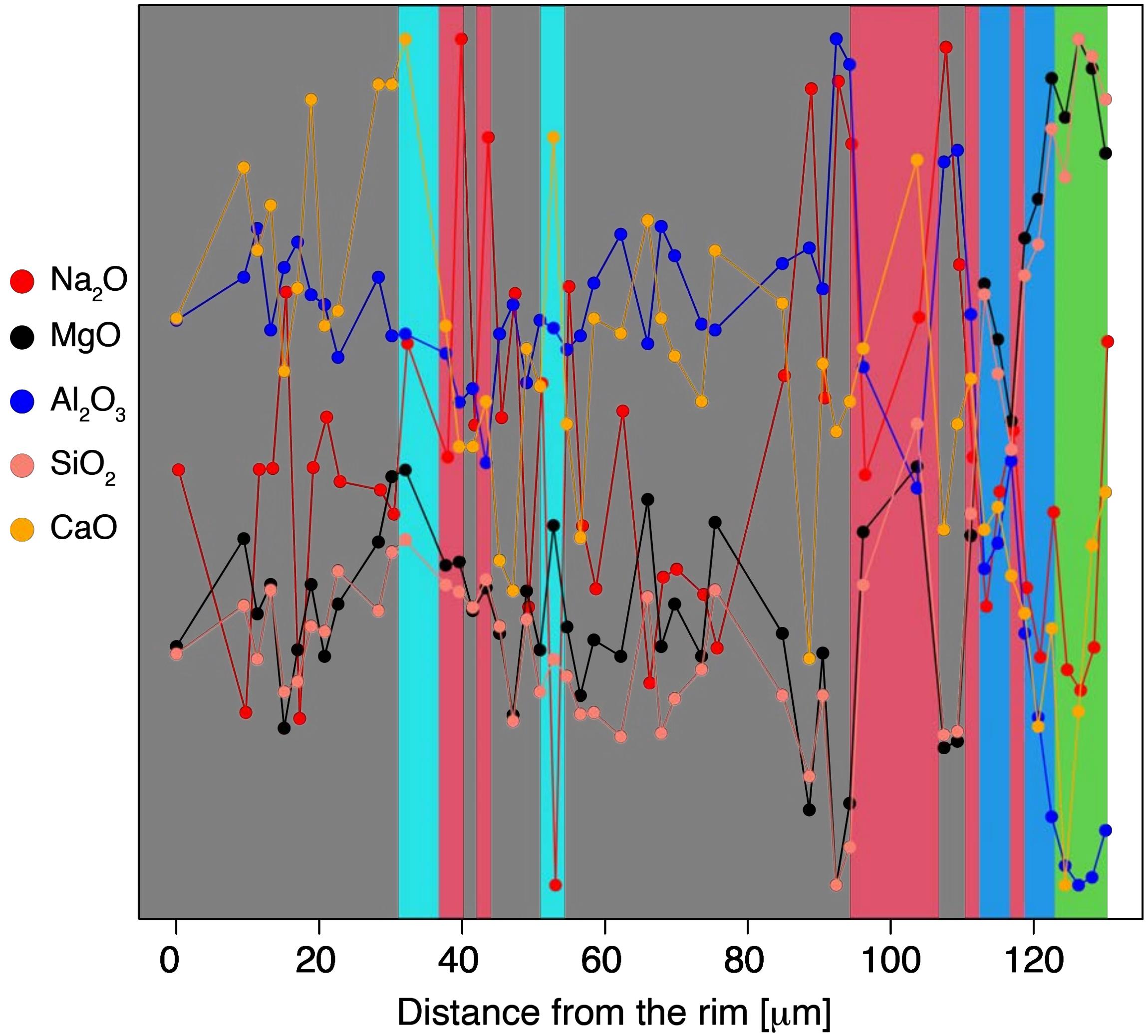
## Euclidean distance ($E_d$)

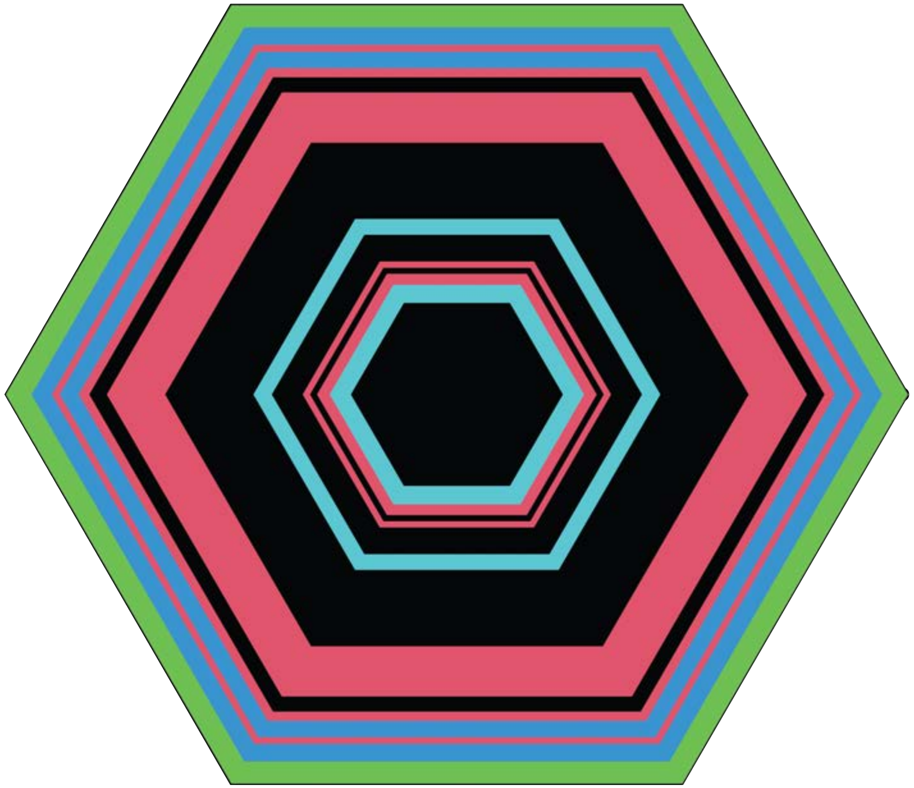
| | $TiO_2$ | $Al_2O_3$ | $MgO$ |
|---|---|---|---|
| #1 | 0.9 | 0.6 | 0.3 |
| #2 | 0.3 | 0 | 1 |

$$E_d^{\#1\,/\,\#2} = \sqrt{(0.9-0.3)^2+(0.6-0)^2+(0.3-1)^2}$$

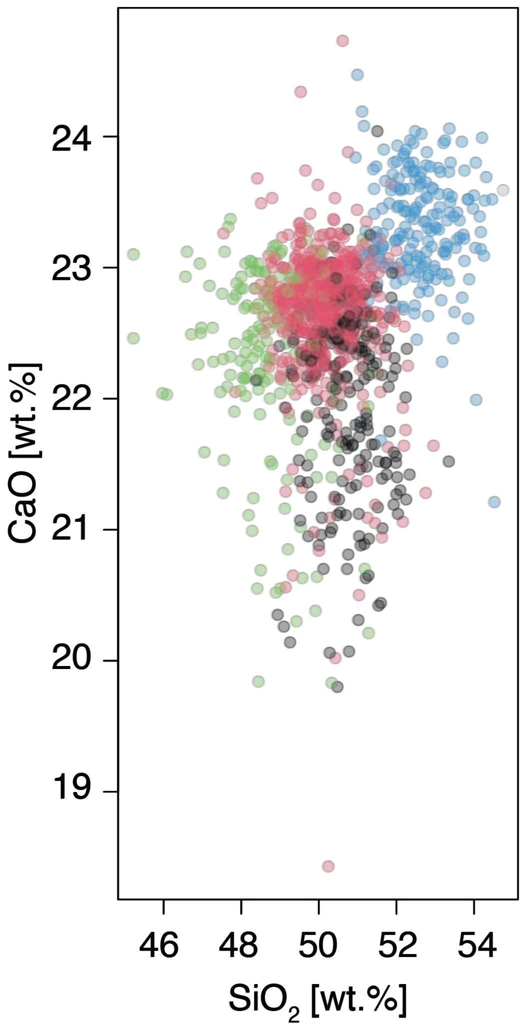


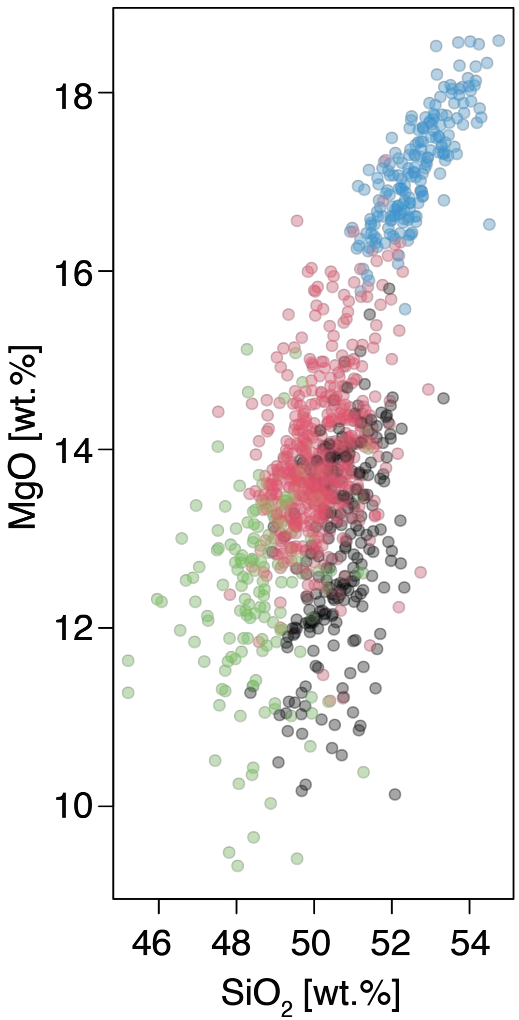
# Dimensionality reduction: a code bar for minerals

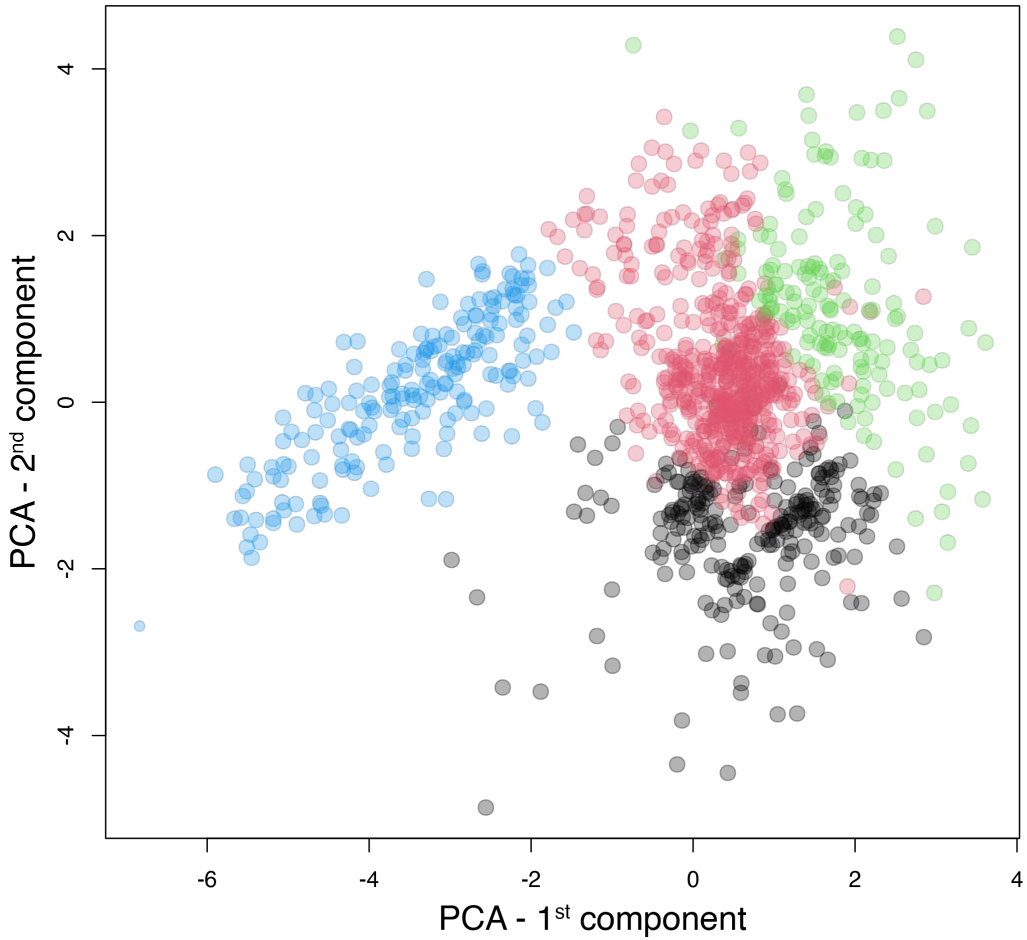


# Cross checks: How do we know the clustering is “correct”?

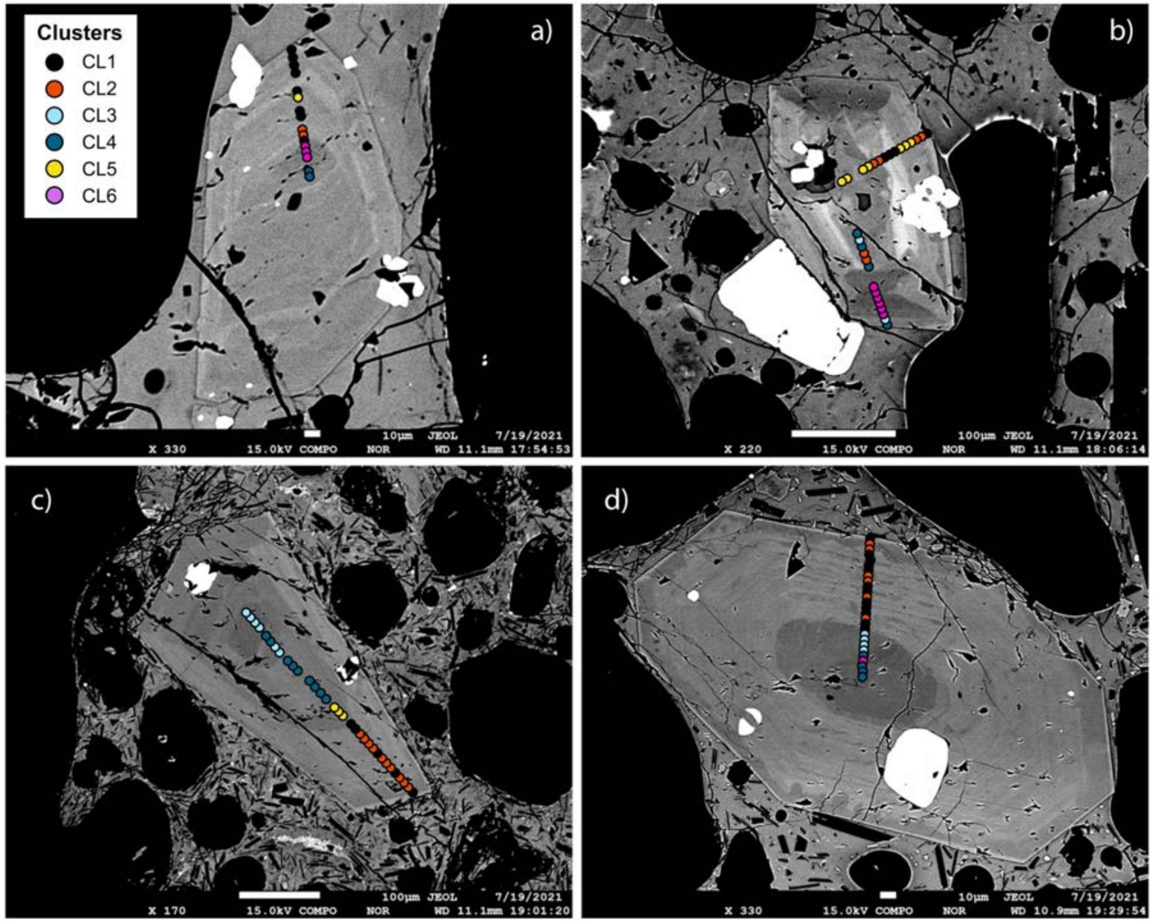


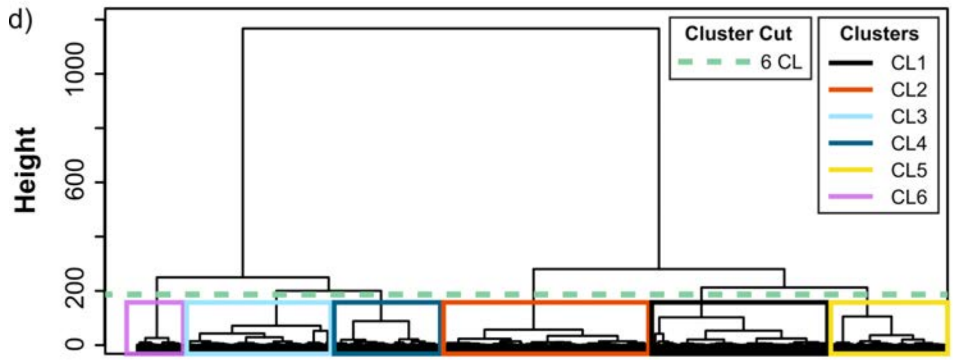



# Cross checks: How do we know the clustering is "correct"?

Textural check

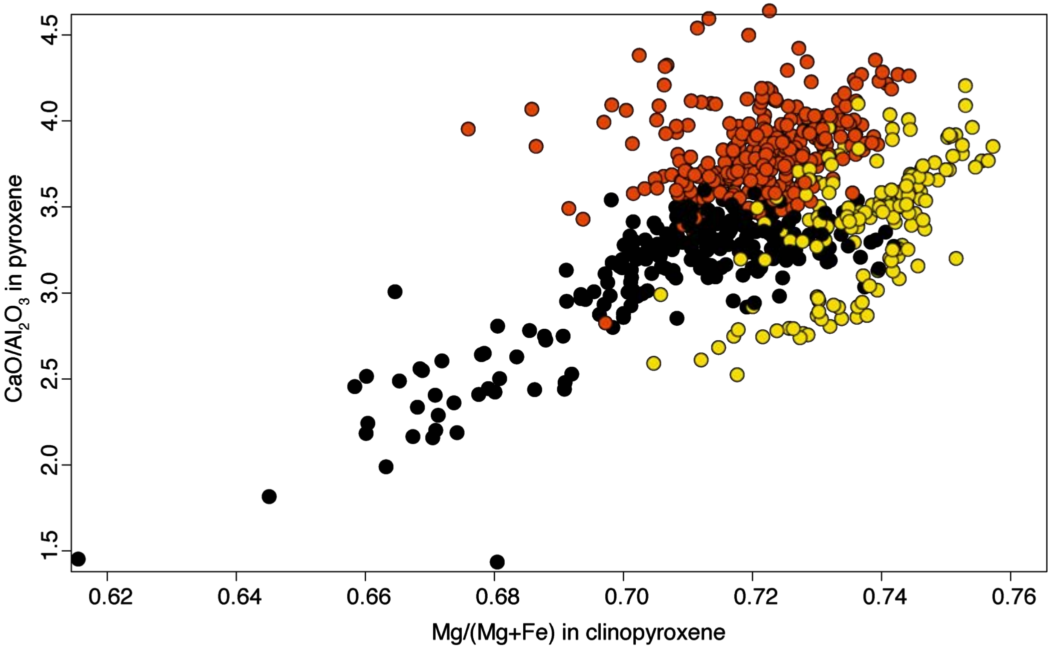



Dendrograms

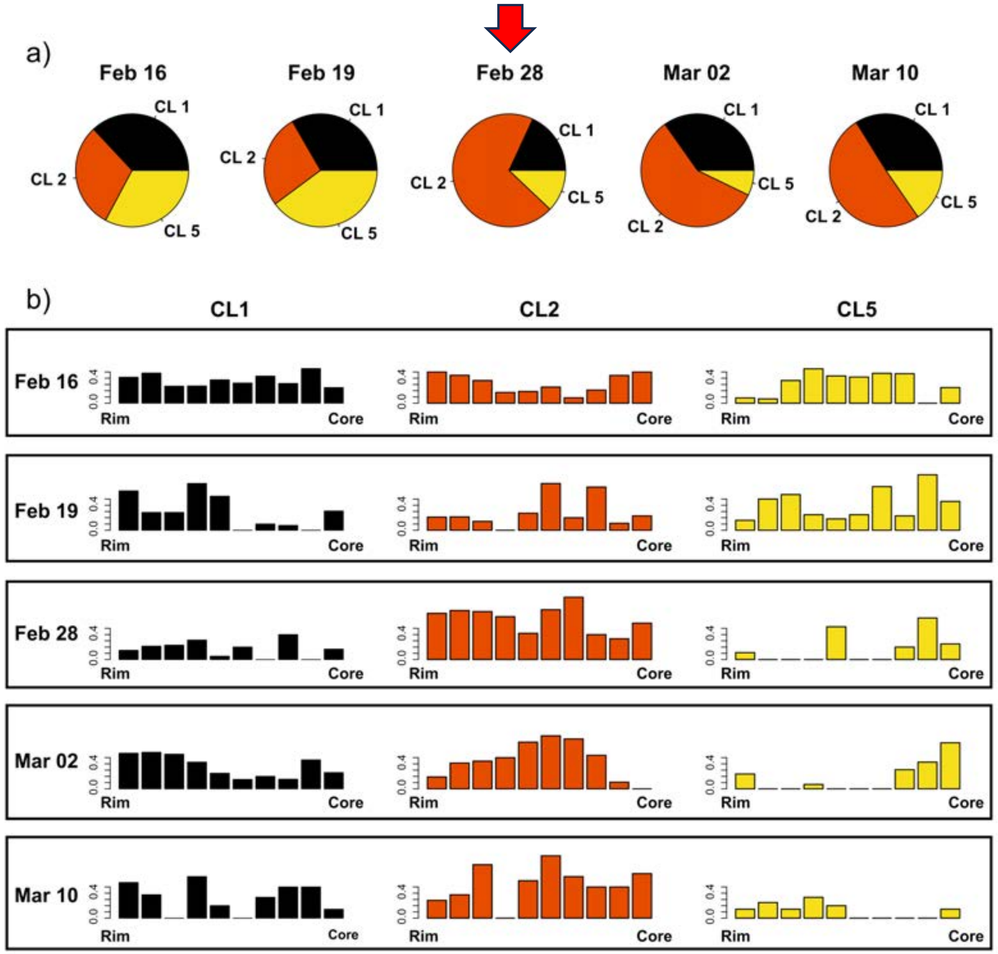



Musu et al., 2023; Bull. Volc.

# Application to Mt Etna

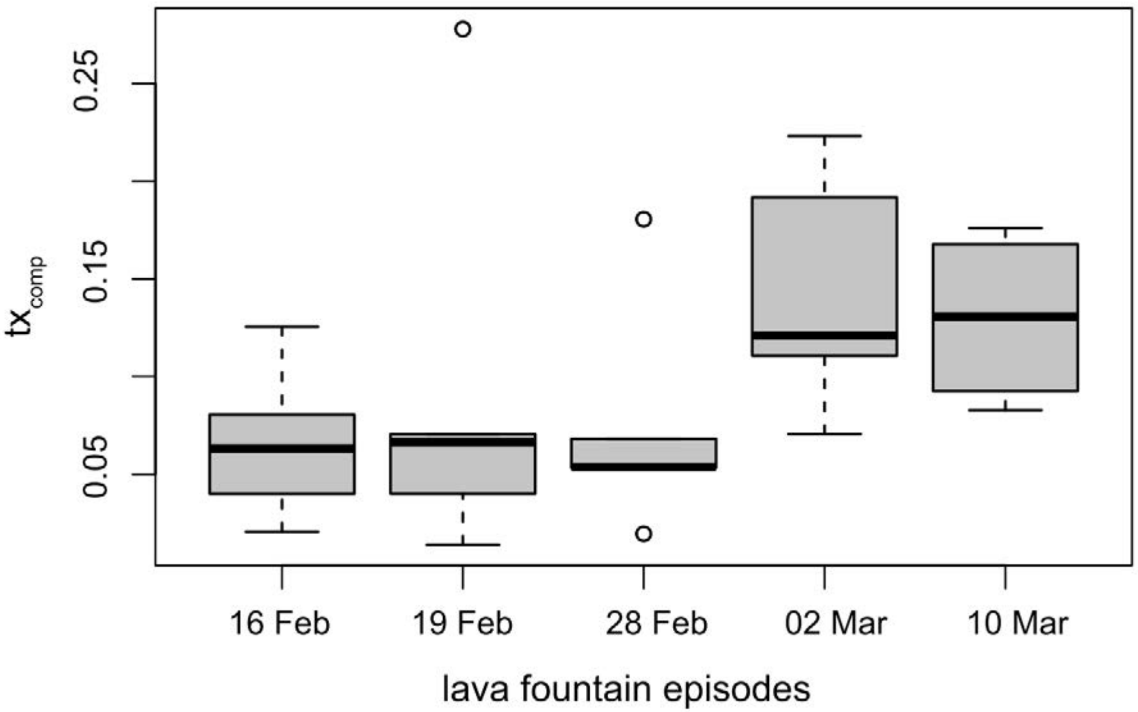


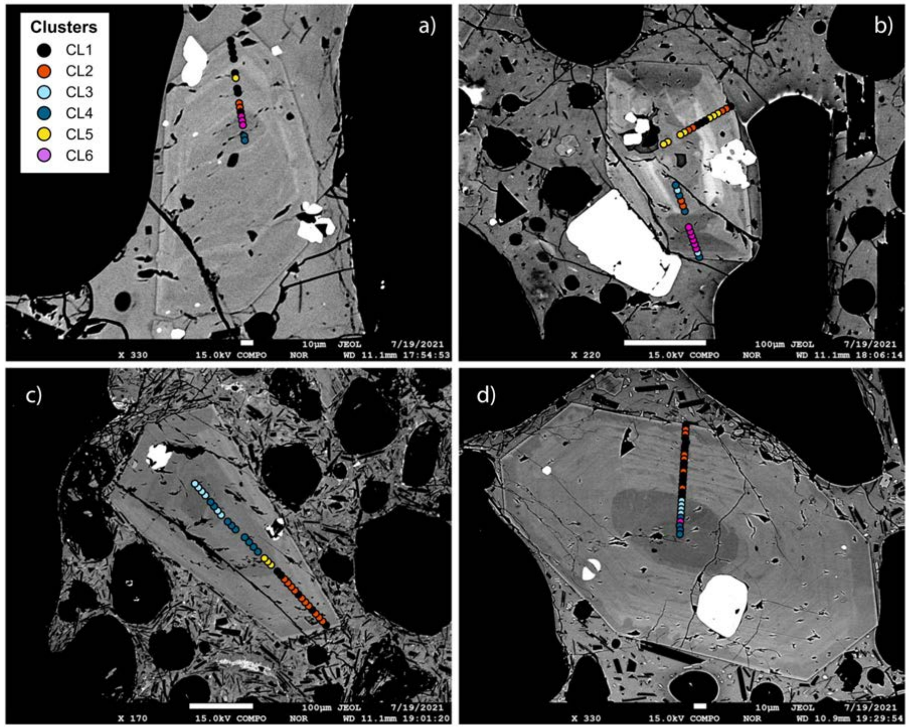

Most intense event




Musu et al., 2023; Bull. Volc.

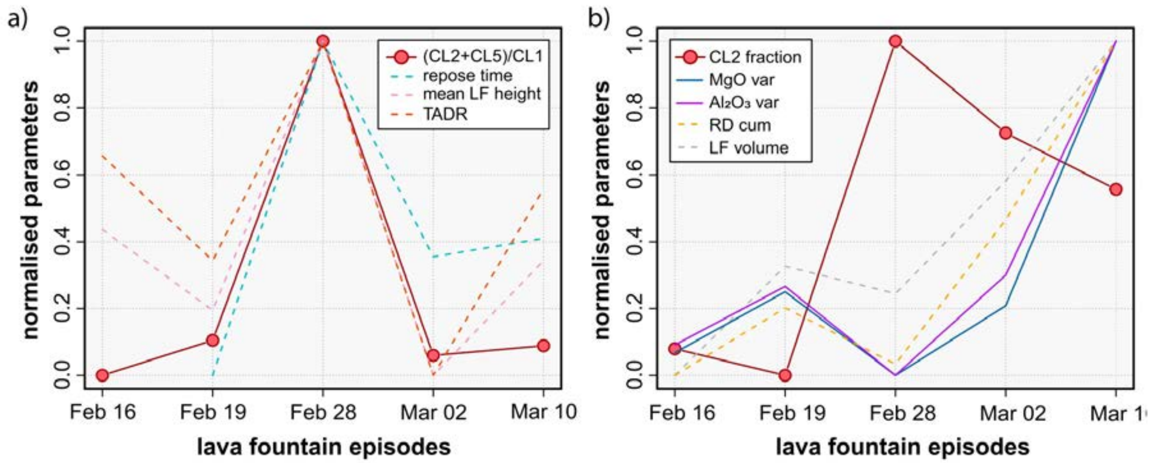
# Application to Mt Etna: Textural complexity

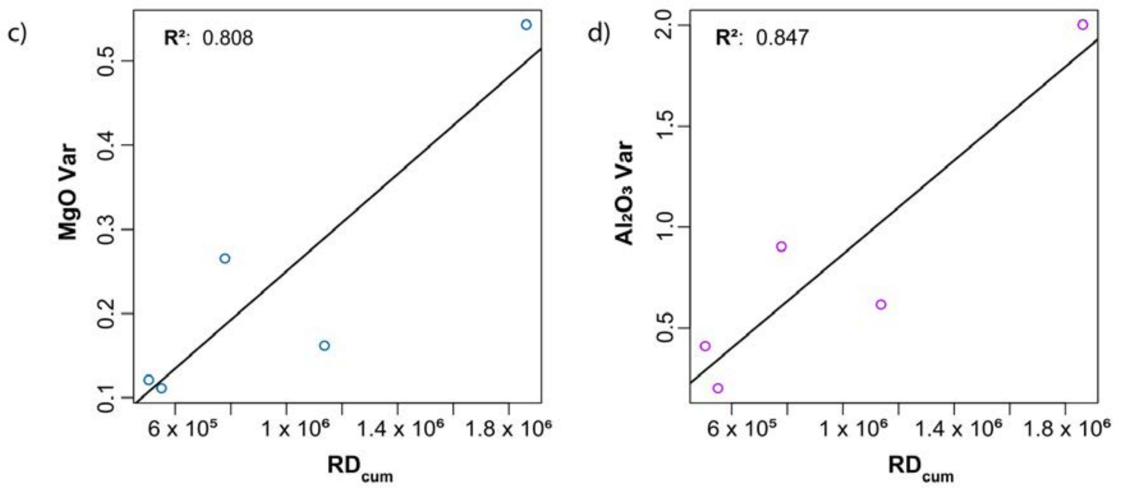



Musu et al., 2023; Bull. Volc.

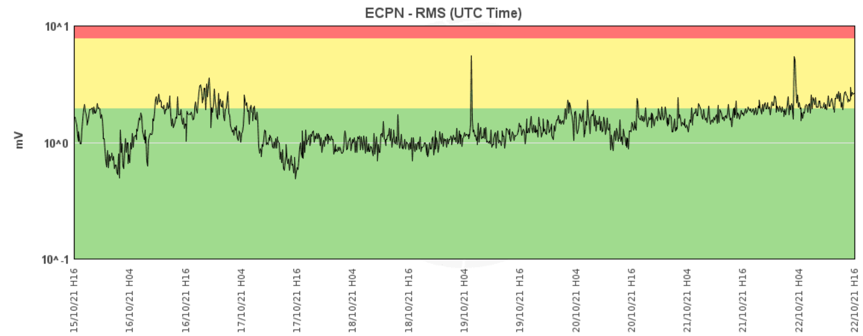
# Application to Mt Etna: Textural complexity




Musu et al., 2023; Bull. Volc.

$Rd_{cum}$=related to *Volcanic Tremor*




$LF_{volume}$=Volume Lava fountain

TADR=Time Averaged Discharge Rate

**Most intense event release:**

1. **The less chemically evolved crystals**
2. **The most texturally homogeneous and similar crystals**

**NEXT to address:**

- **Can we anticipate particularly intense eruptive events?**
- **Can we forecast the end of eruptions?**

**Sinergia project 'VAMOS'**

FNSNF SWISS NATIONAL SCIENCE FOUNDATION

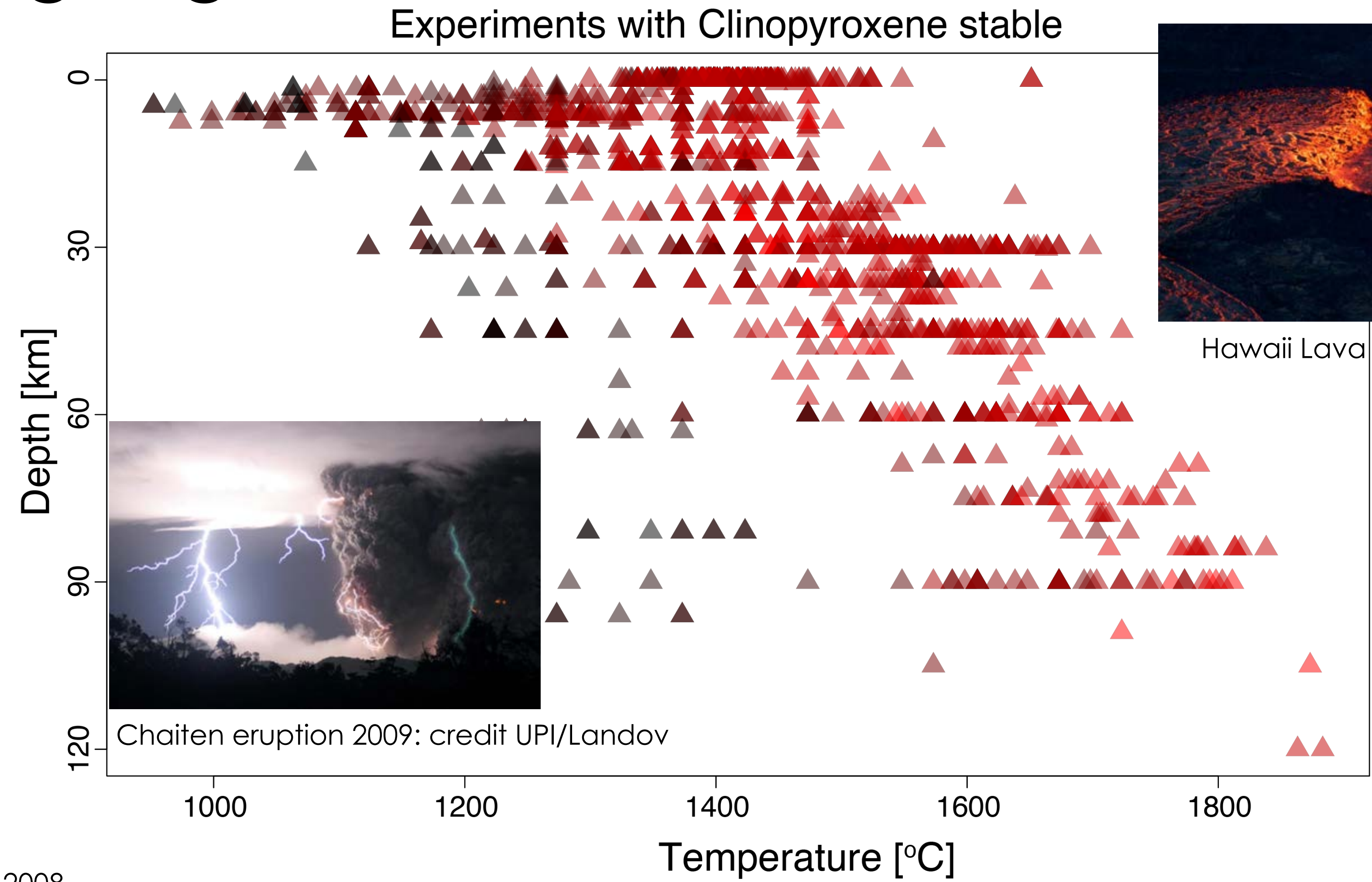
# Supervised Learning: Thermobarometry and chemometry

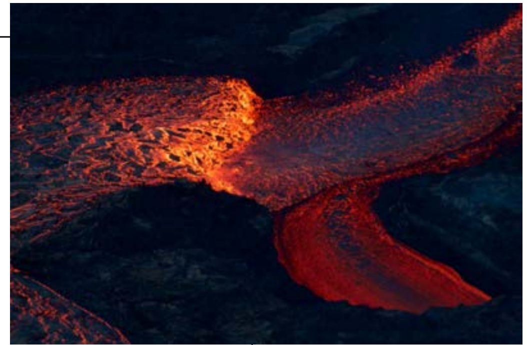
Oliver Higgins


Corin Jorgenson

Jorgenson et al., 2022 ; J. Geophysical Research
Higgins et al., 2022; Contribution Min. Pet.
Petrelli et al., 2020; J. Geophysical Research
Agreda-Lopez et al., submitted ; Computer and Geociences

# Experiments as a “Rosetta Stone” to translate the language of rocks



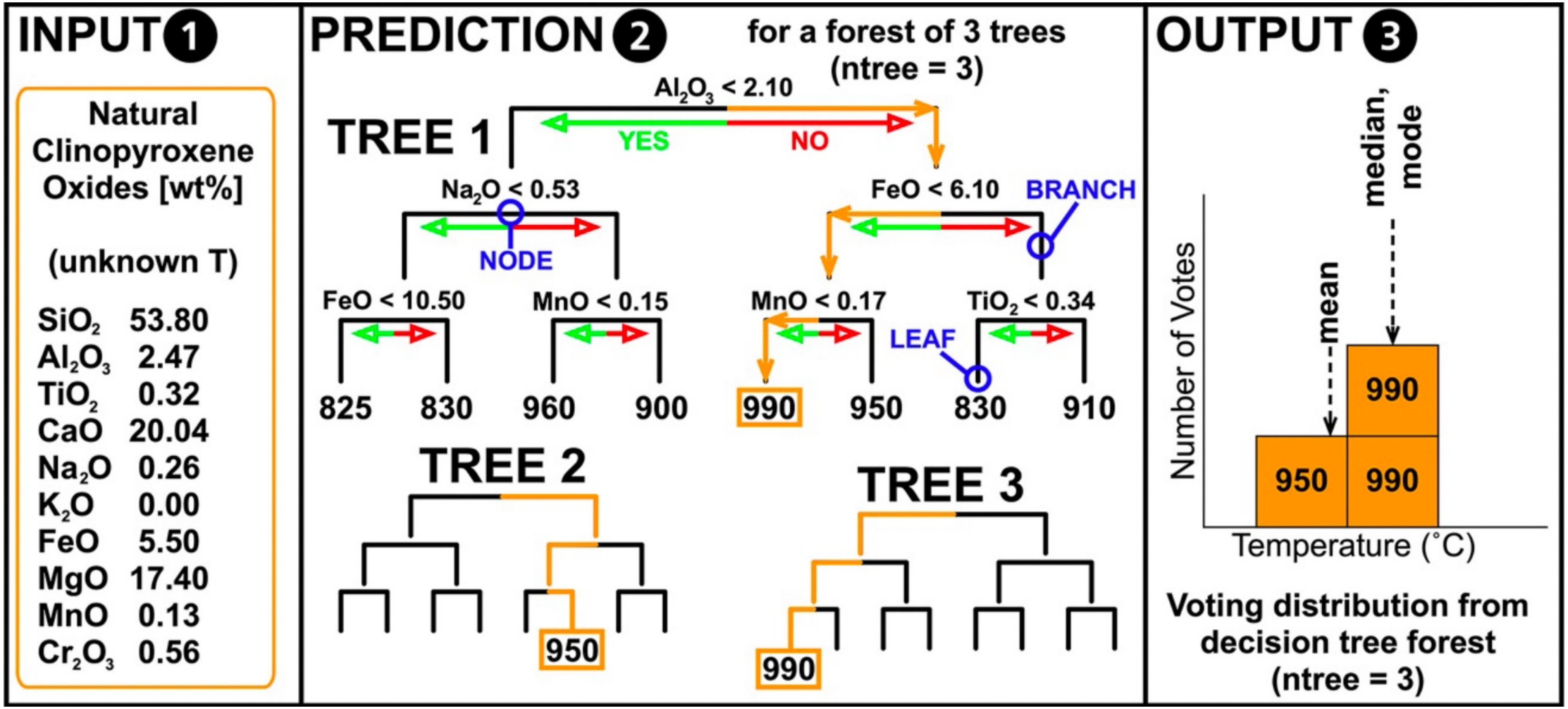



Hawaii Lava flow, credit: USGS

Chaiten eruption 2009: credit UPI/Landov

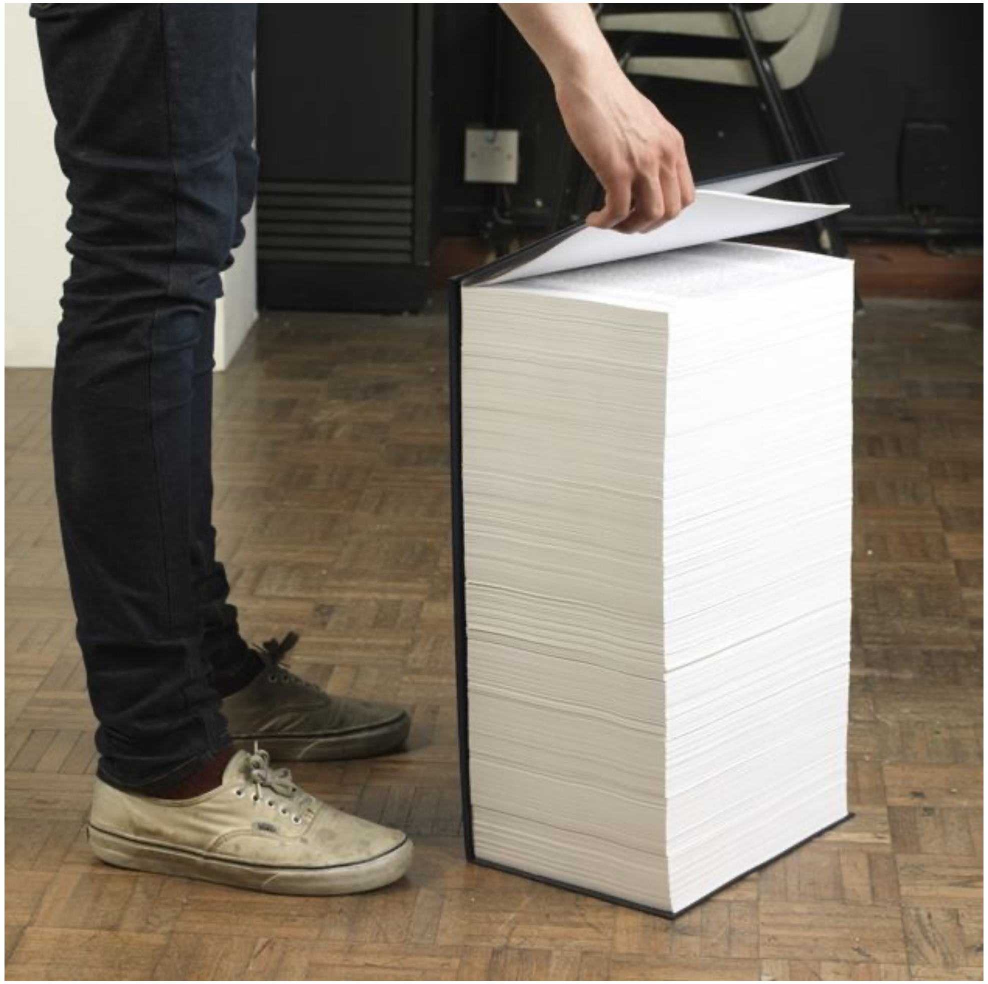
Hirschmann et al., 2008

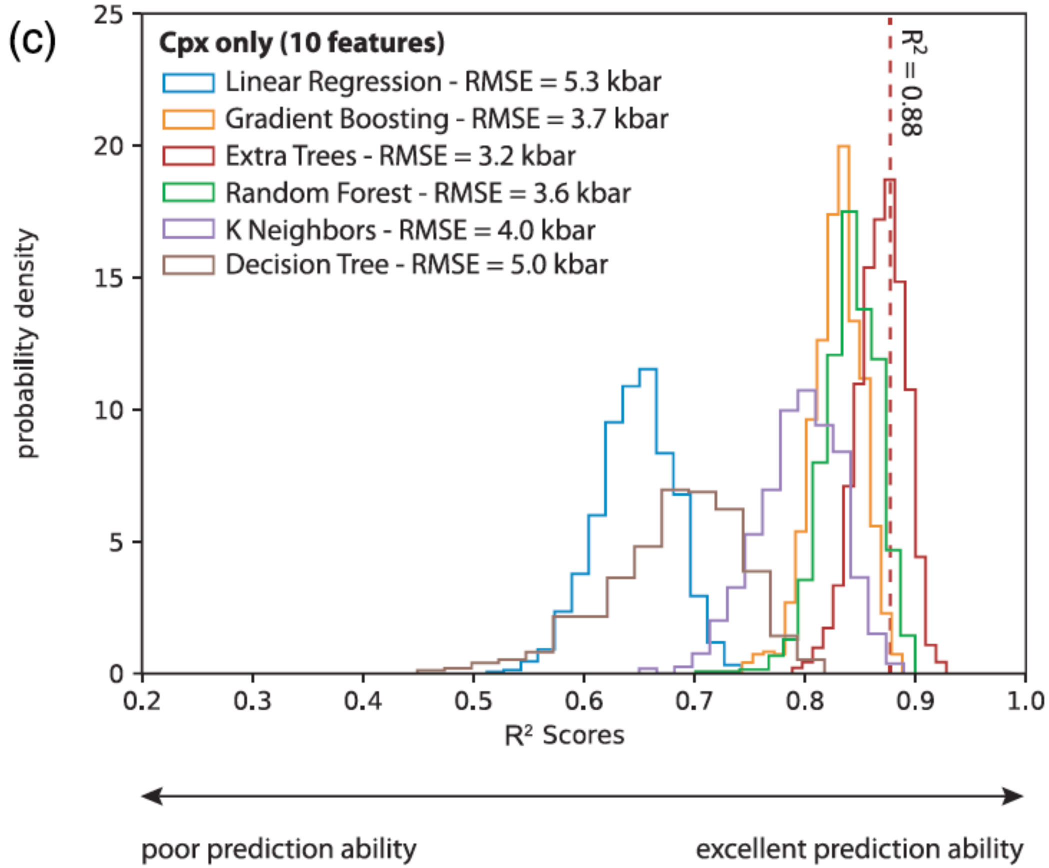
# Random Forest




Jorgenson et al., 2022; JGR

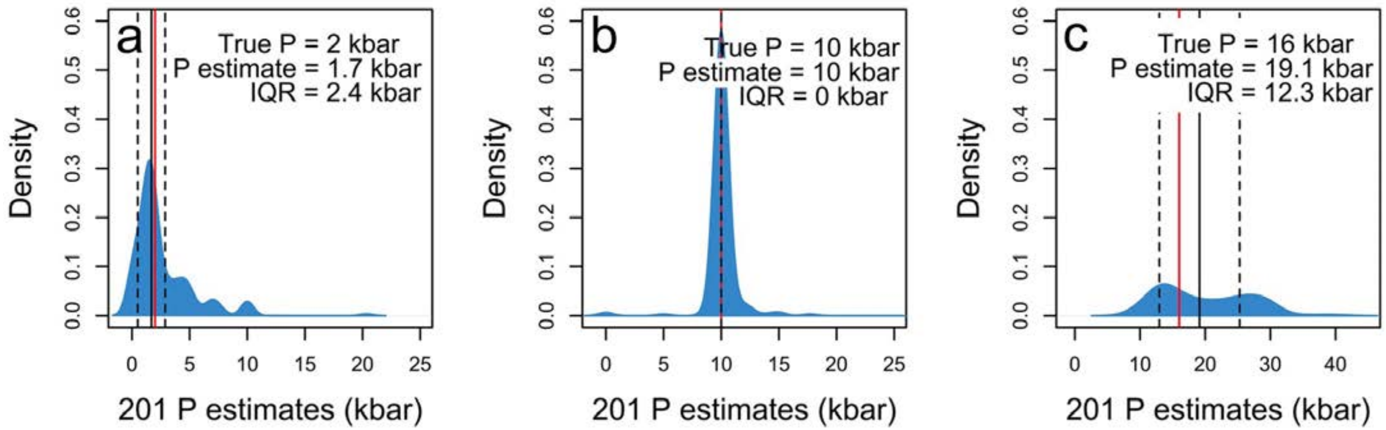
# Why random forest?

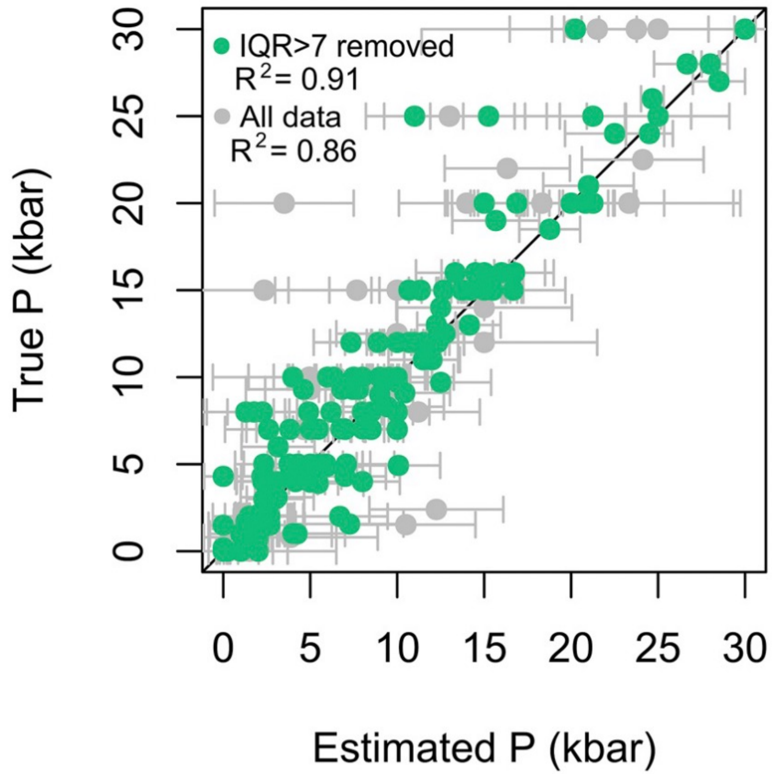


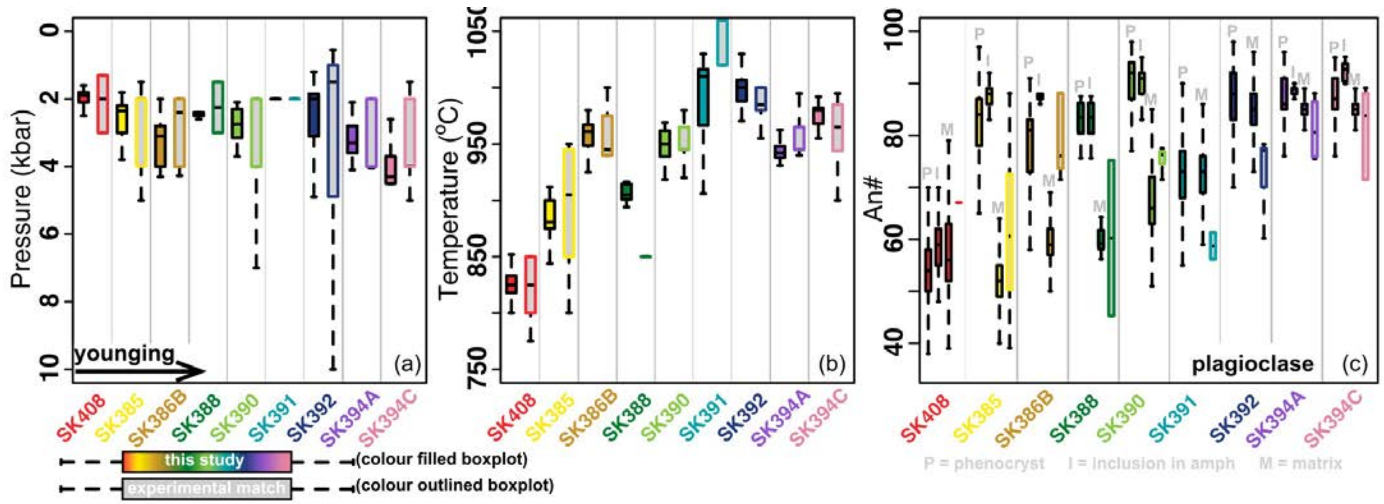



Petrelli et al., 2020

# Strategy to express uncertainty of the estimates

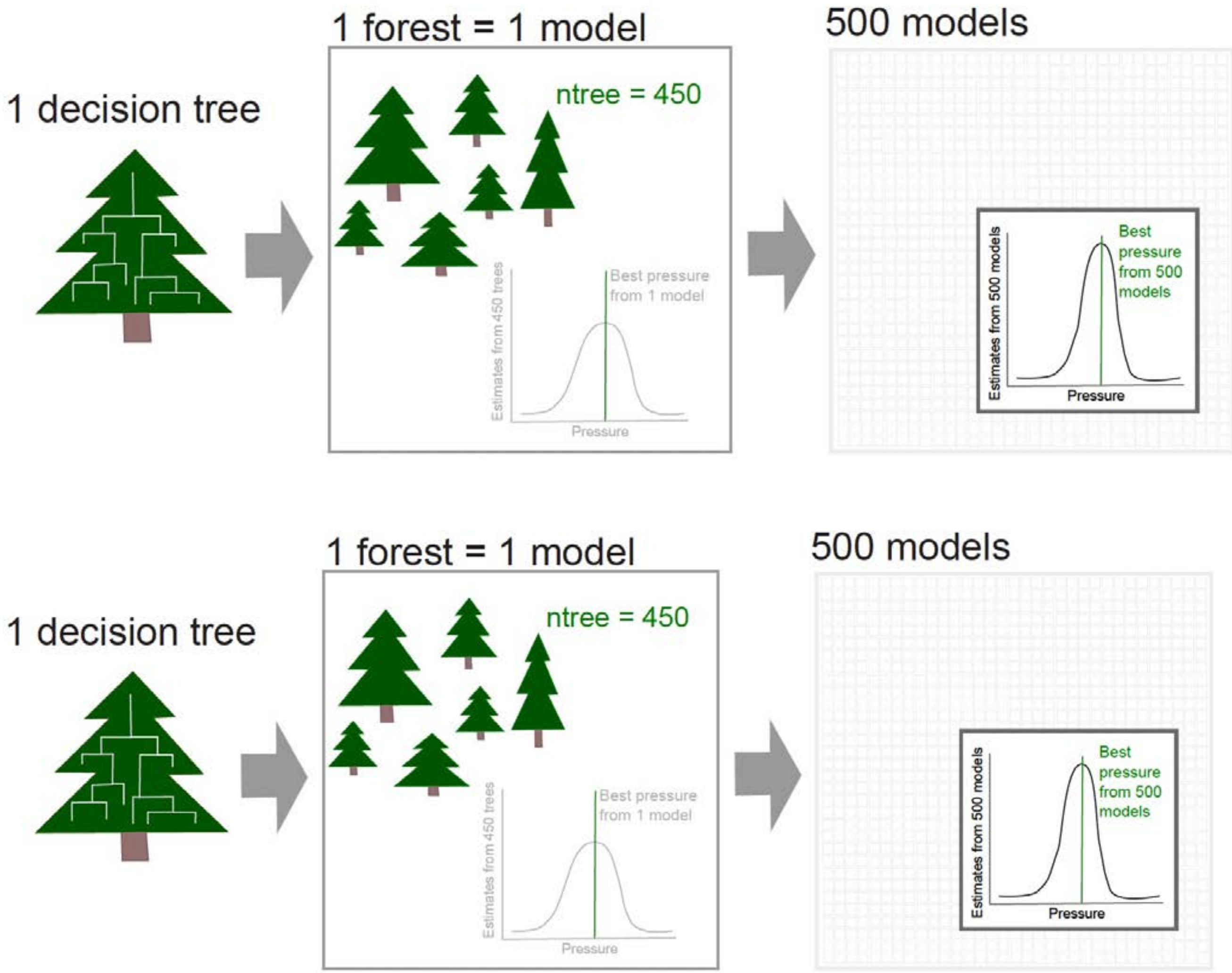



Jorgenson et al., 2022
Higgins et al., 2022

# Current architecture: Two layers of forests




**WORKFLOW**

1. Split the dataset in a Train and Test dataset (80-20%). 500 datasets slected using a Monte Carlo Approach

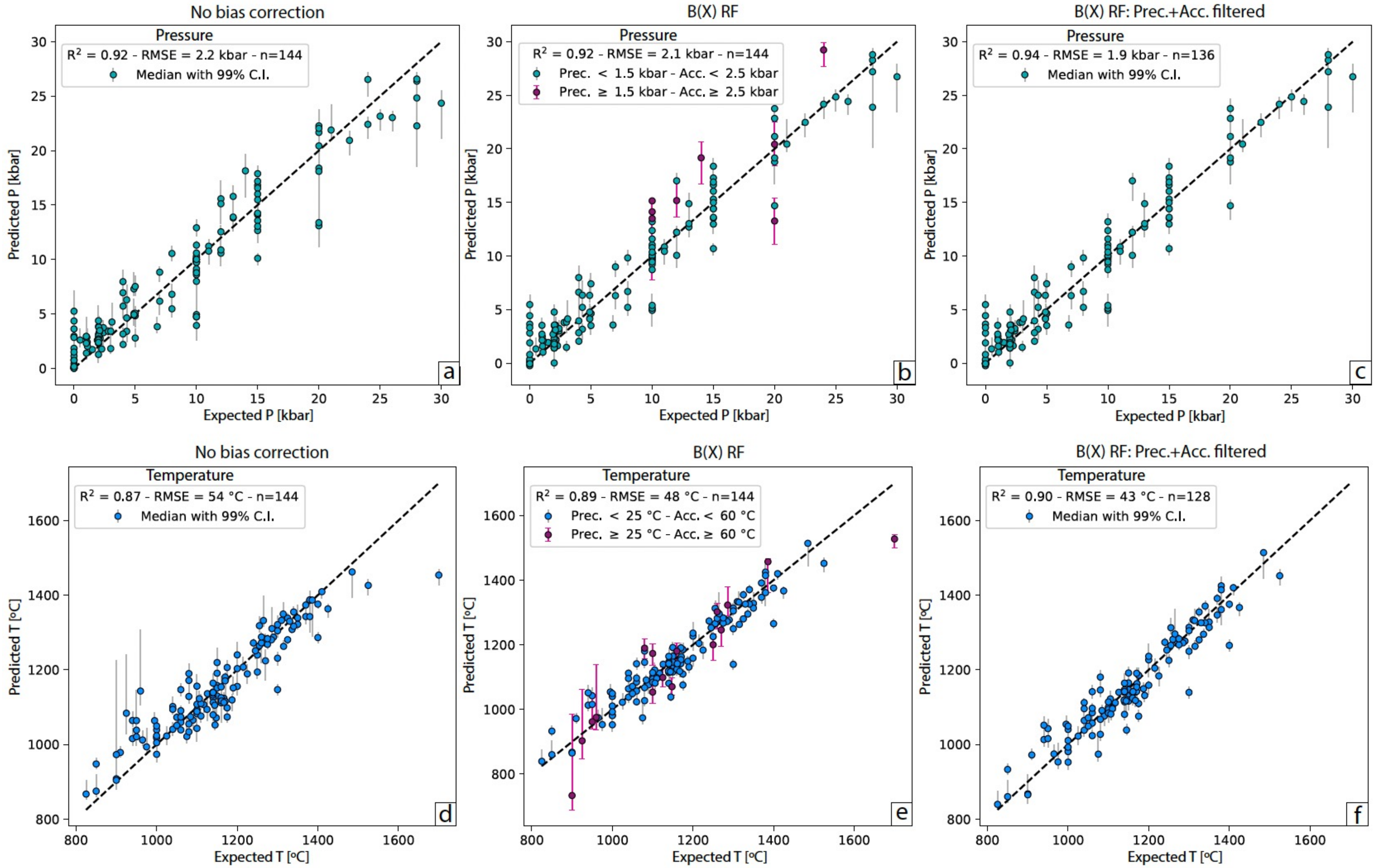
2. Split each Train dataset in a Train and Validation dataset (80-20%)

3. Run 500 forests to obtain 500 estimates for each analysis in the validation dataset

4. Compute the difference between the estimate and the actual value of P or T

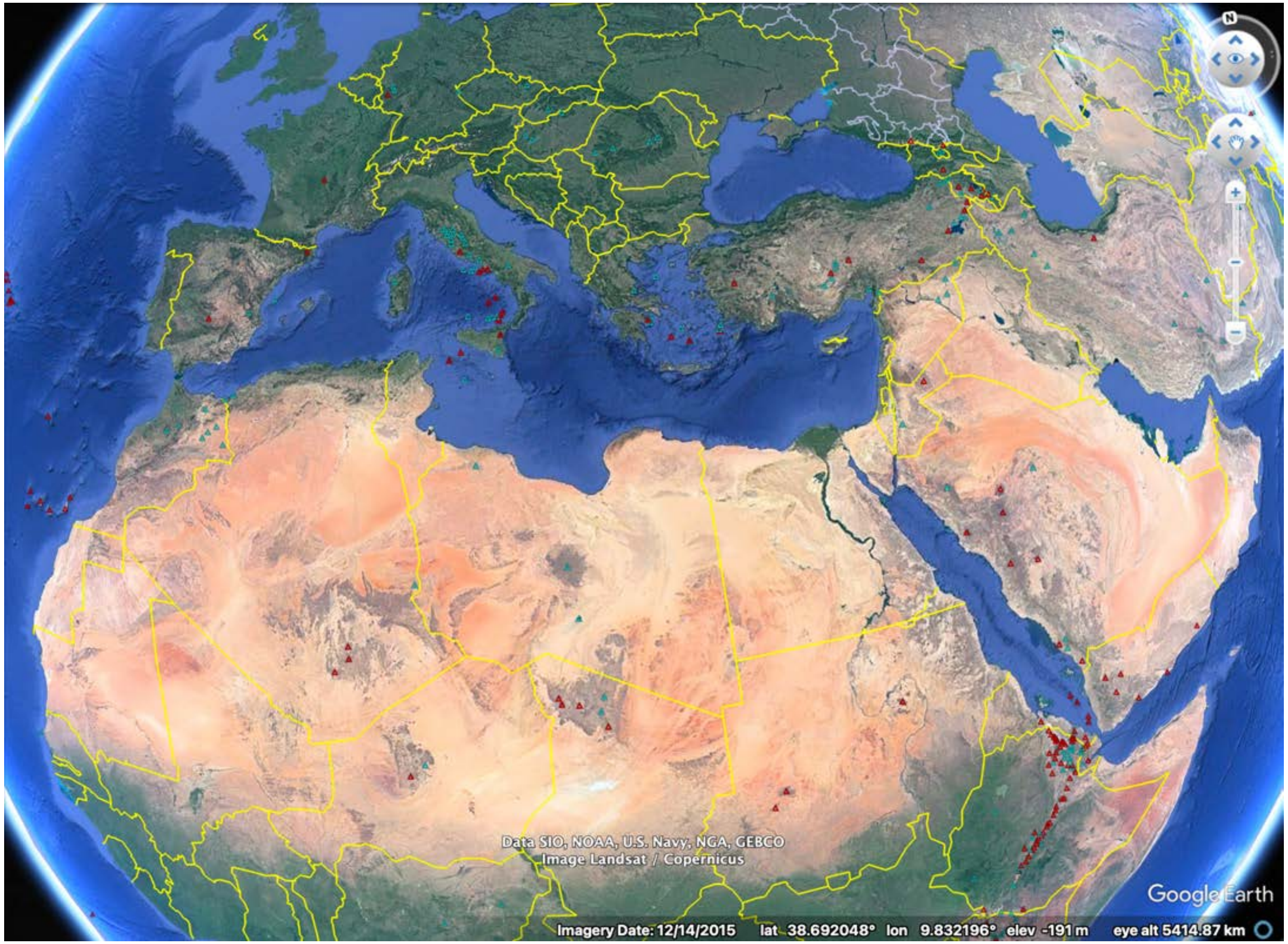
5. Train 500 forest to correct the bias related to the boundaries of the P and T space

# Current architecture: Two layers of forests




Agreda-Lopez et al., 2023; Computer and Geosciences

# A global perspective on volcanism

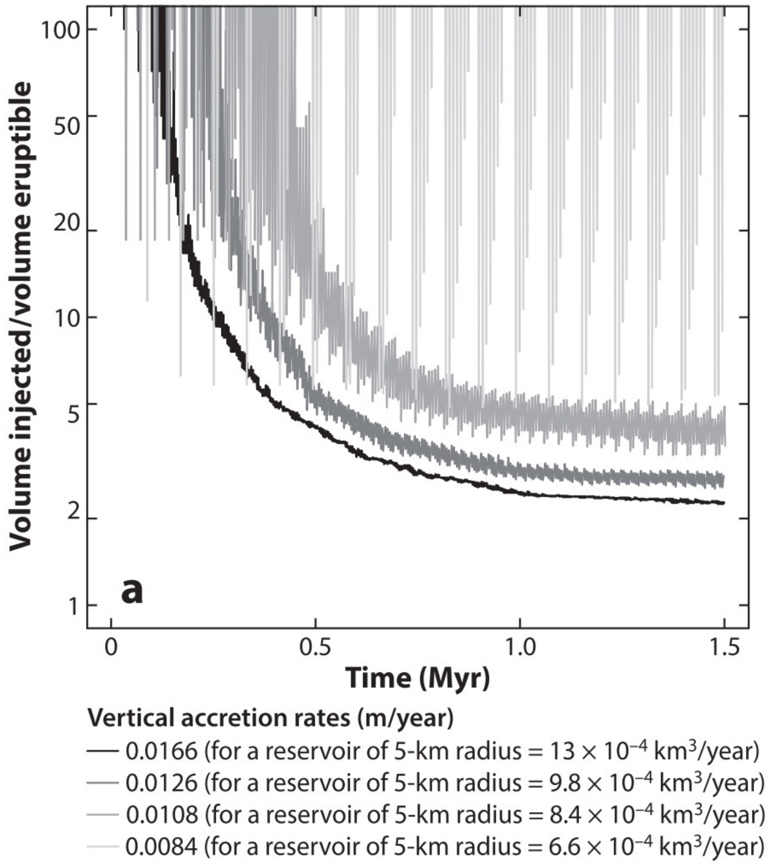



**1500 active volcanoes on Earth**

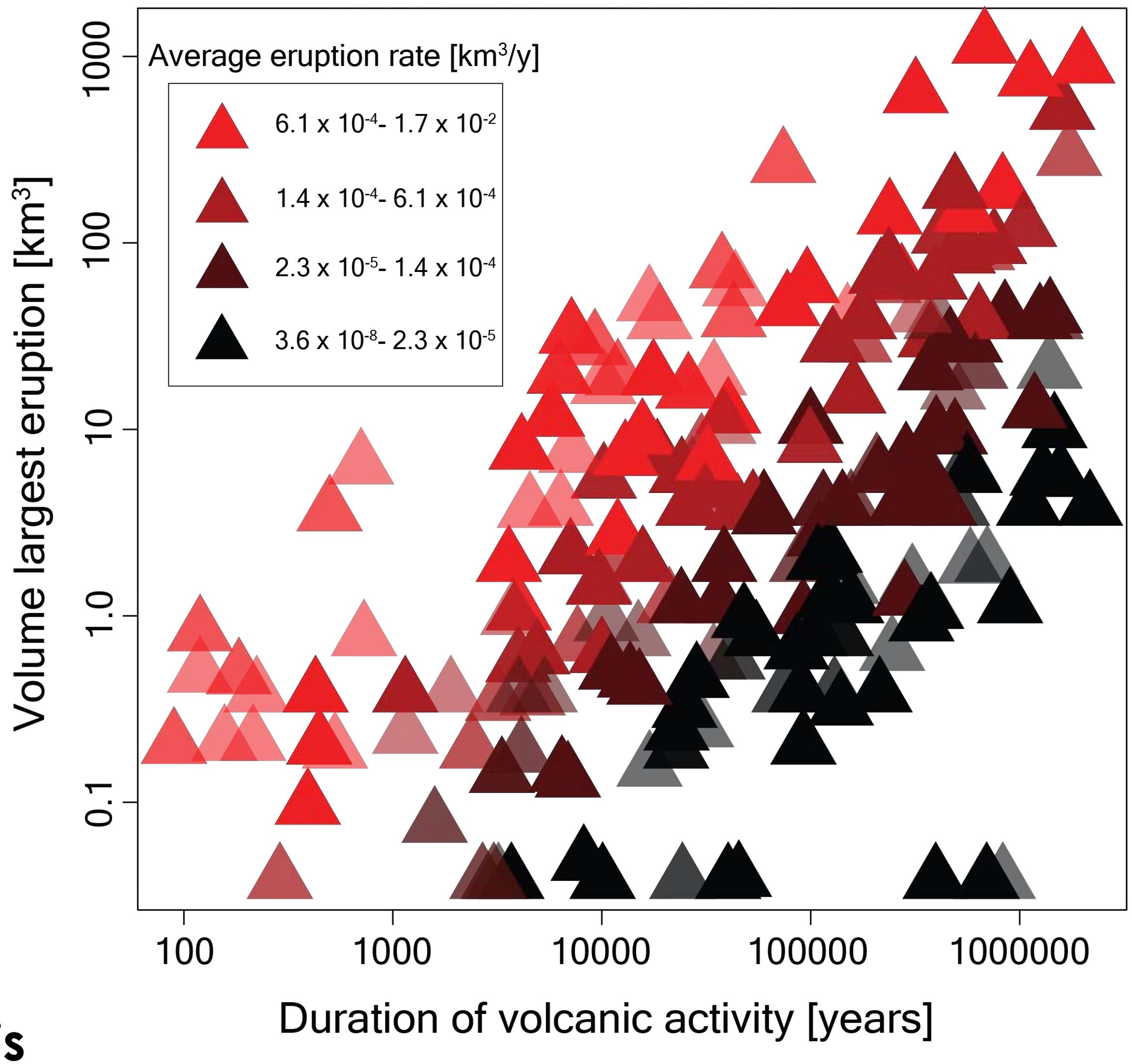
- **1 billion people live around active volcanoes**
- **we have a proper knolwedge for about 20%**

Higgins and Caricchi, 2023; Geology

# What can we do?




**Rate of magma input in the crust is fundamental**

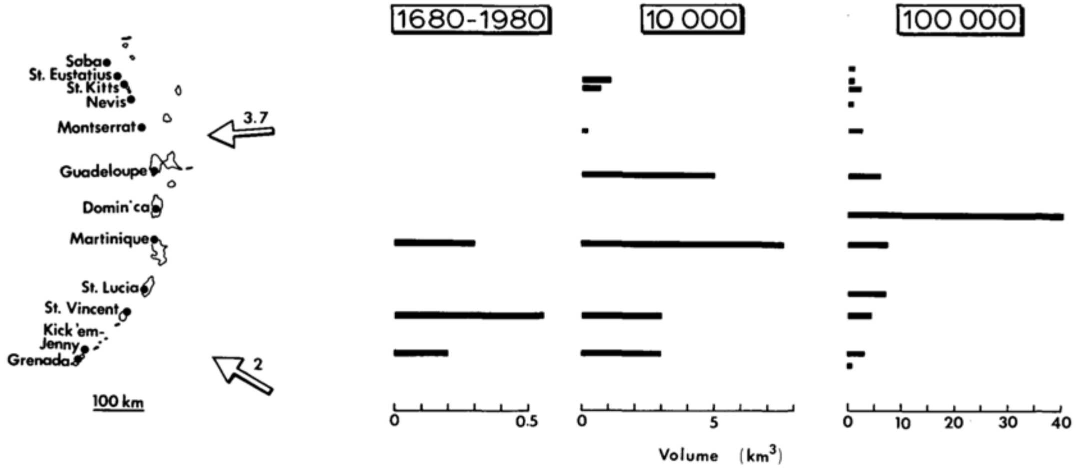


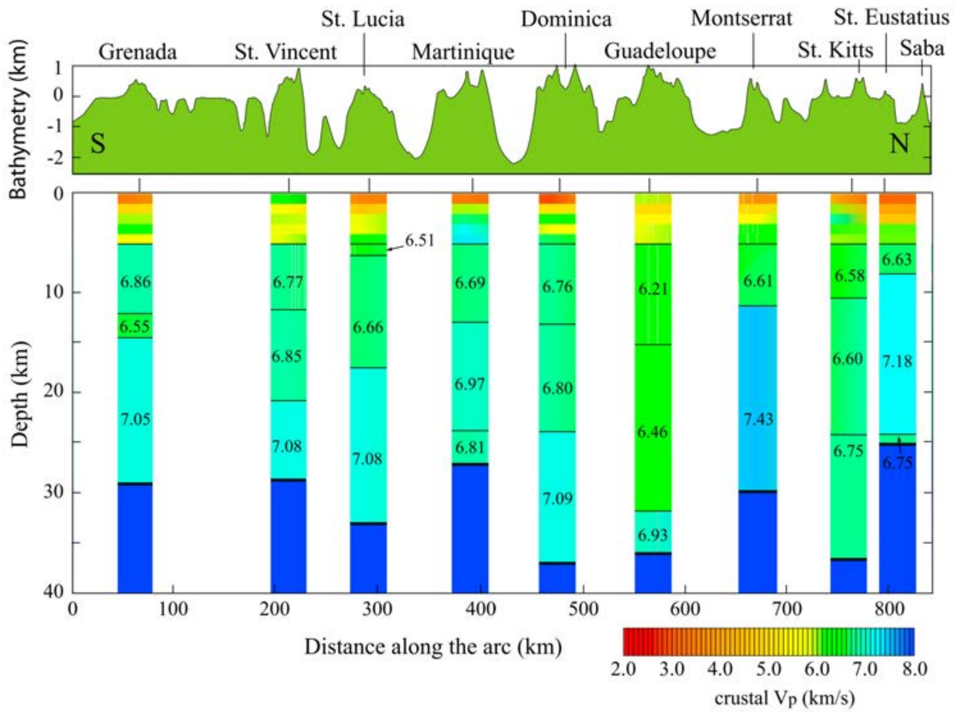

Giordano and Caricchi, 2022; Ann. Rev.Earth and Planetary Sciece

# How to quantify rates of magma input into the crust?

## Petrology, morphology and geophysics

## *Lesser Antilles arc*



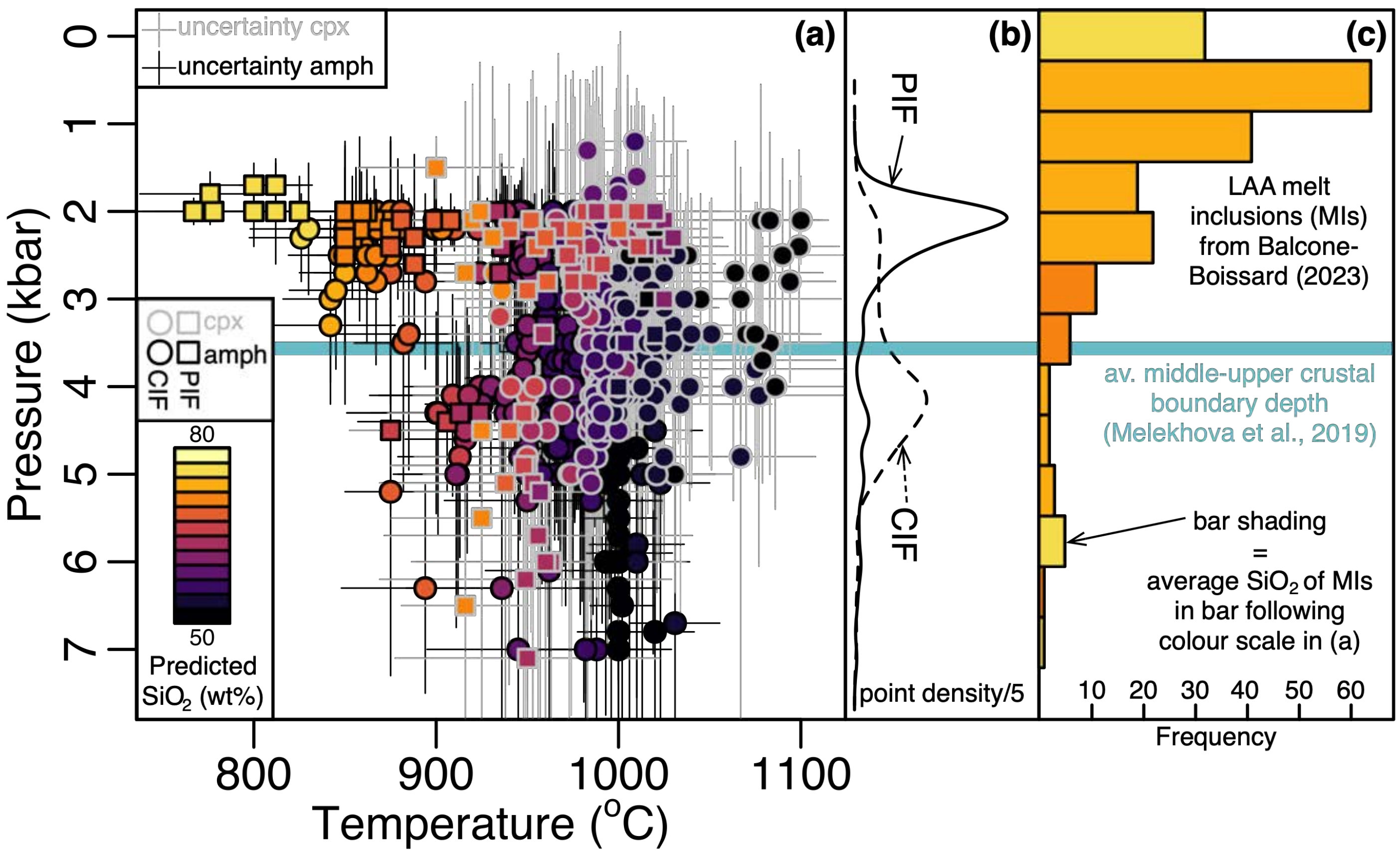

1. Availability of intrusive fragments and cumulates
2. Heterogeneity in magma eruption rates
3. Variable crustal structure

Wadge, 1984; Melekhova et al., 2019

# How to quantify rates of magma input into the crust?

# Thermobarometry and chemometry (amph and cpx)

***Lesser Antilles arc***




*PIF=Plutonic Intrusive Fragments*
*CIF=Cumulate Intrusive Fragments*

**OBSERVATIONS**

1. Relatively constant T over a large portion of the middle crust

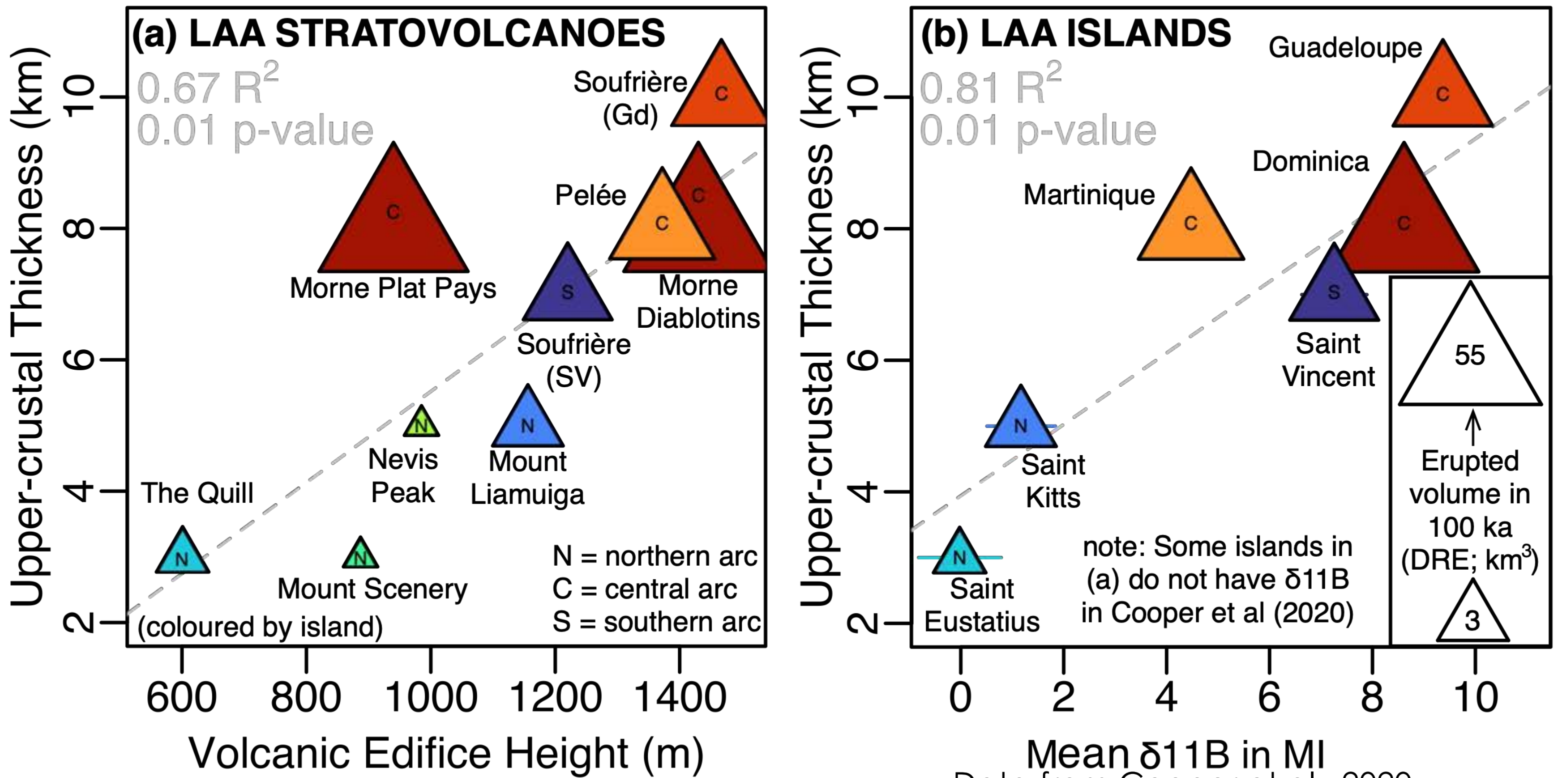
2. The most evolved melt reside in the upper crust

Higgins and Caricchi, 2023

# How to quantify rates of magma input into the crust?

## Petrology, volcano morphology and geophysics

### *Lesser Antilles arc*




Data from Cooper et al., 2020

**Thickness of the upper crust** (distance between layer 2 and 3 of Melekhova et al., 2019):

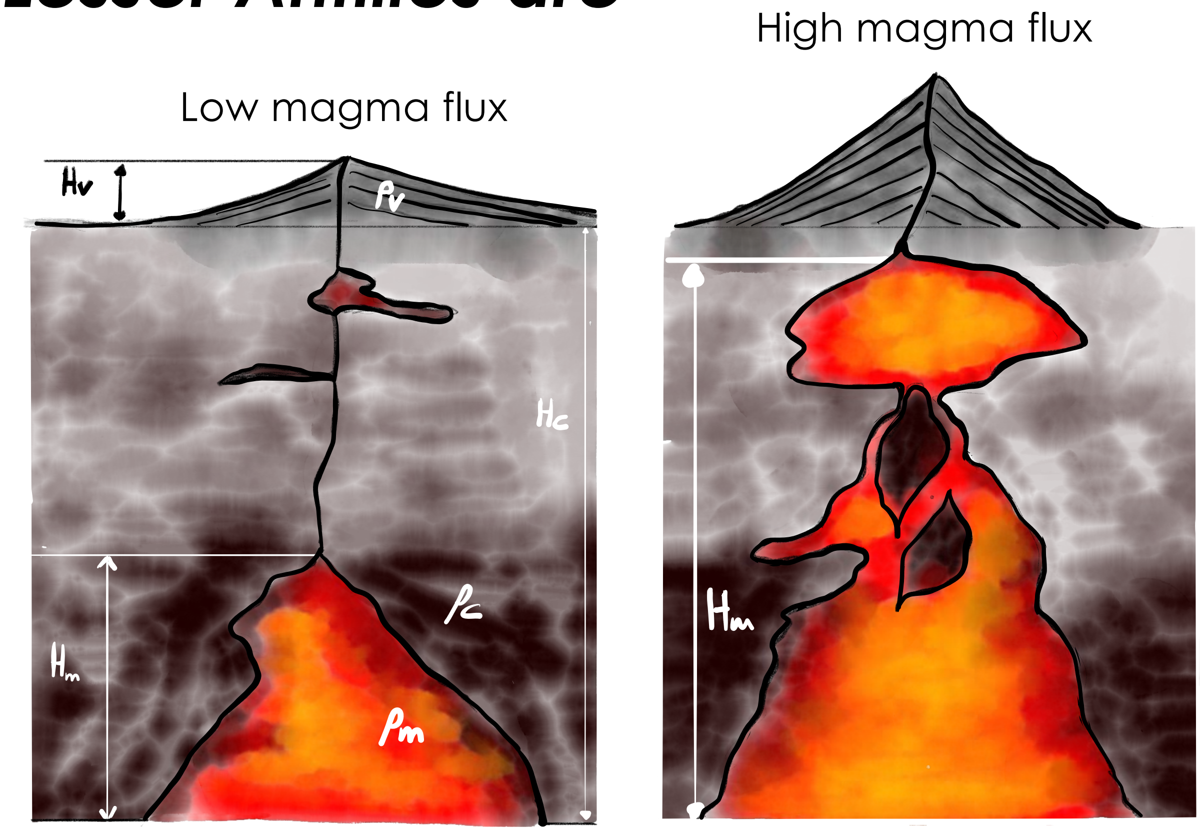
1. Scales with the height of the volcanic edifice
2. The volcanic output rate
3. The mean $\delta^{11}B$, a proxy for magma productivity in the mantle

Higgins and Caricchi, 2023

# How to quantify rates of magma input into the crust?

# Linking petrology, geophysics and volcano morphology

## *Lesser Antilles arc*




**Higher rates of magma input into the Earth's crust (i.e. higher heat supply to the crust):**

1. Lead to volcanic plumbing systems (VPS) extending to shallower depth in the upper crust which results in **taller volcanoes with higher eruption rate**.

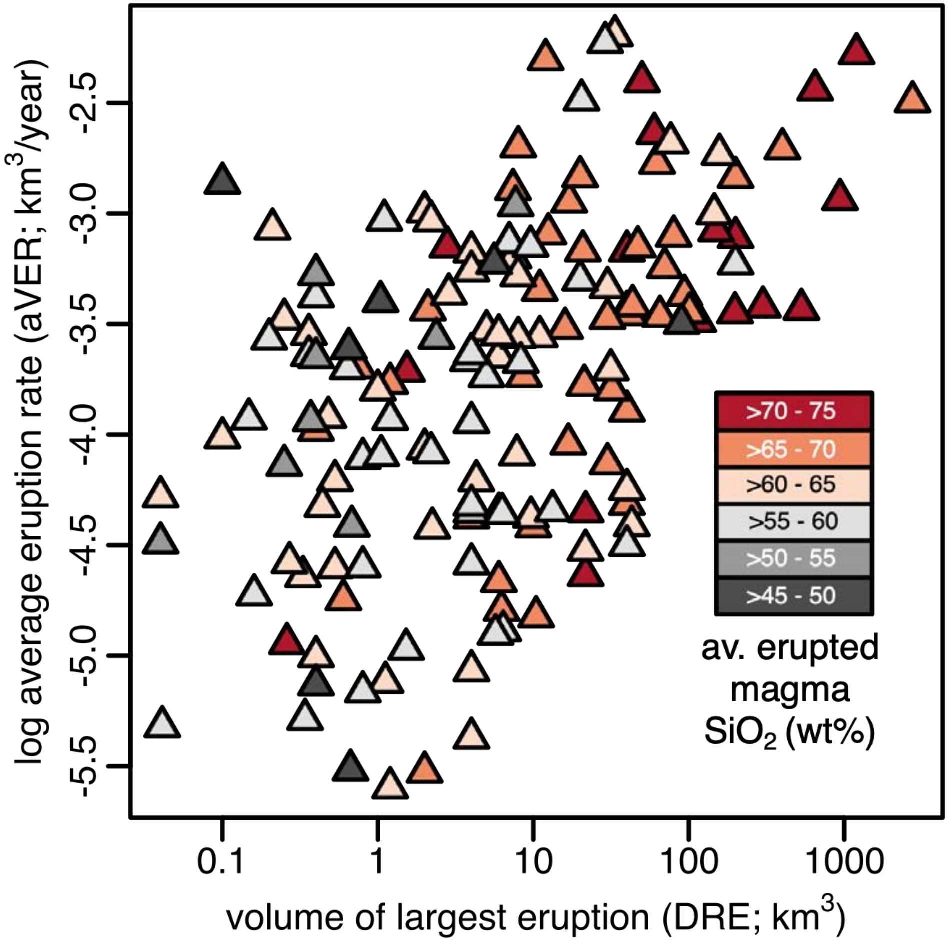
2. VPS extending to shallower depth tend to produce more chemically evolved magmas

Can we see this at the Global Scale?

$$\rho_c H_c = \rho_m H_m + \rho_c(H_c - H_m) + \rho_v H_v;\ H_v = \frac{H_m(\rho_c - \rho_m)}{\rho_v}$$

Castruccio et al., 2017; Higgins and Caricchi, 2023

# How to quantify rates of magma input into the crust?
# Global relationship and why do we care?



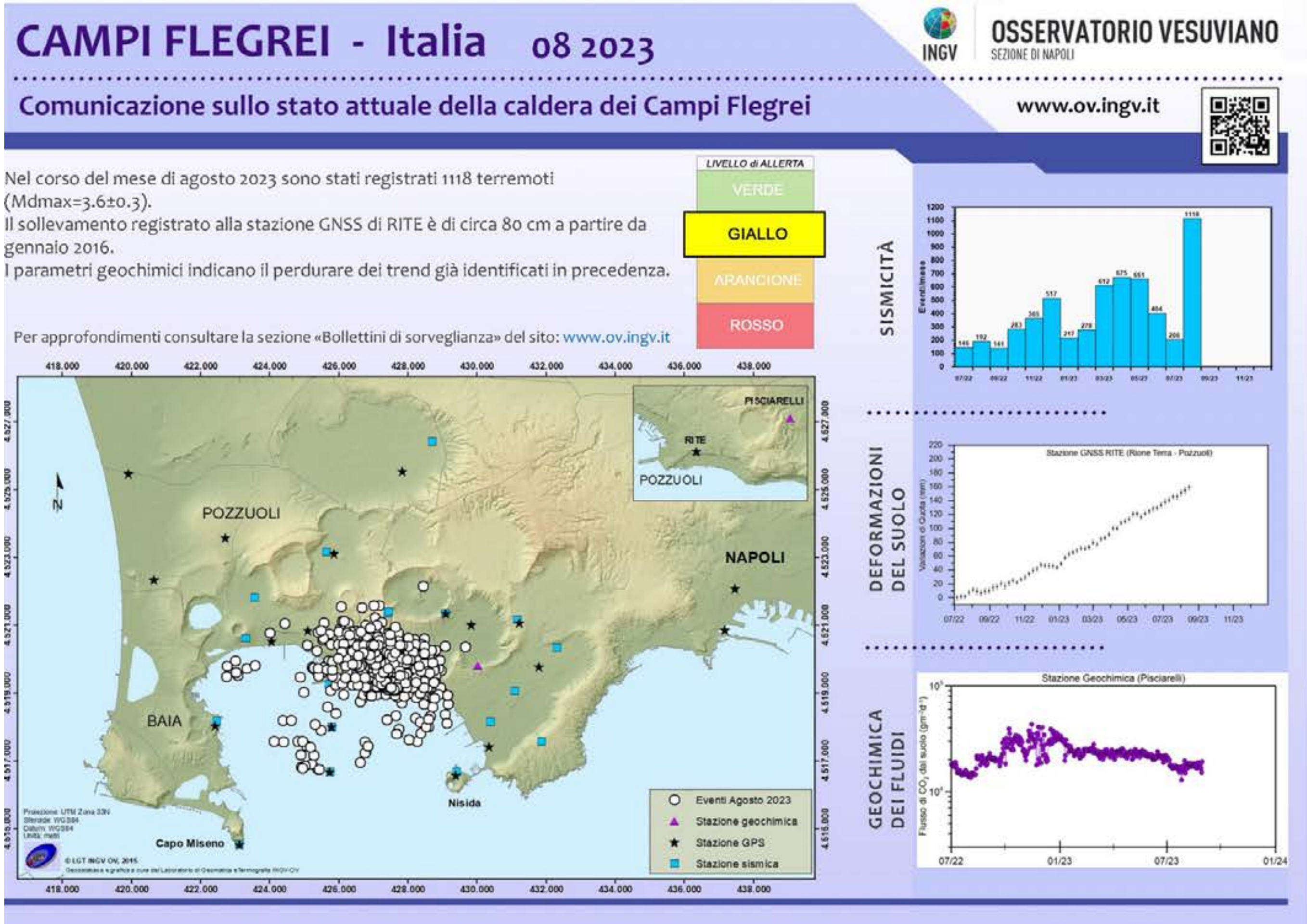

**We do not have information on 80% of the volcanoes currently active on Earth**

1. **Duration of volcanism**
2. **Volcano morphology**
3. **Dominant magma chemistry**

**Provide essential information to constrain the eruptive potential of poorly studied volcanoes**

Giordano and Caricchi, 2022; Higgins and Caricchi, 2023

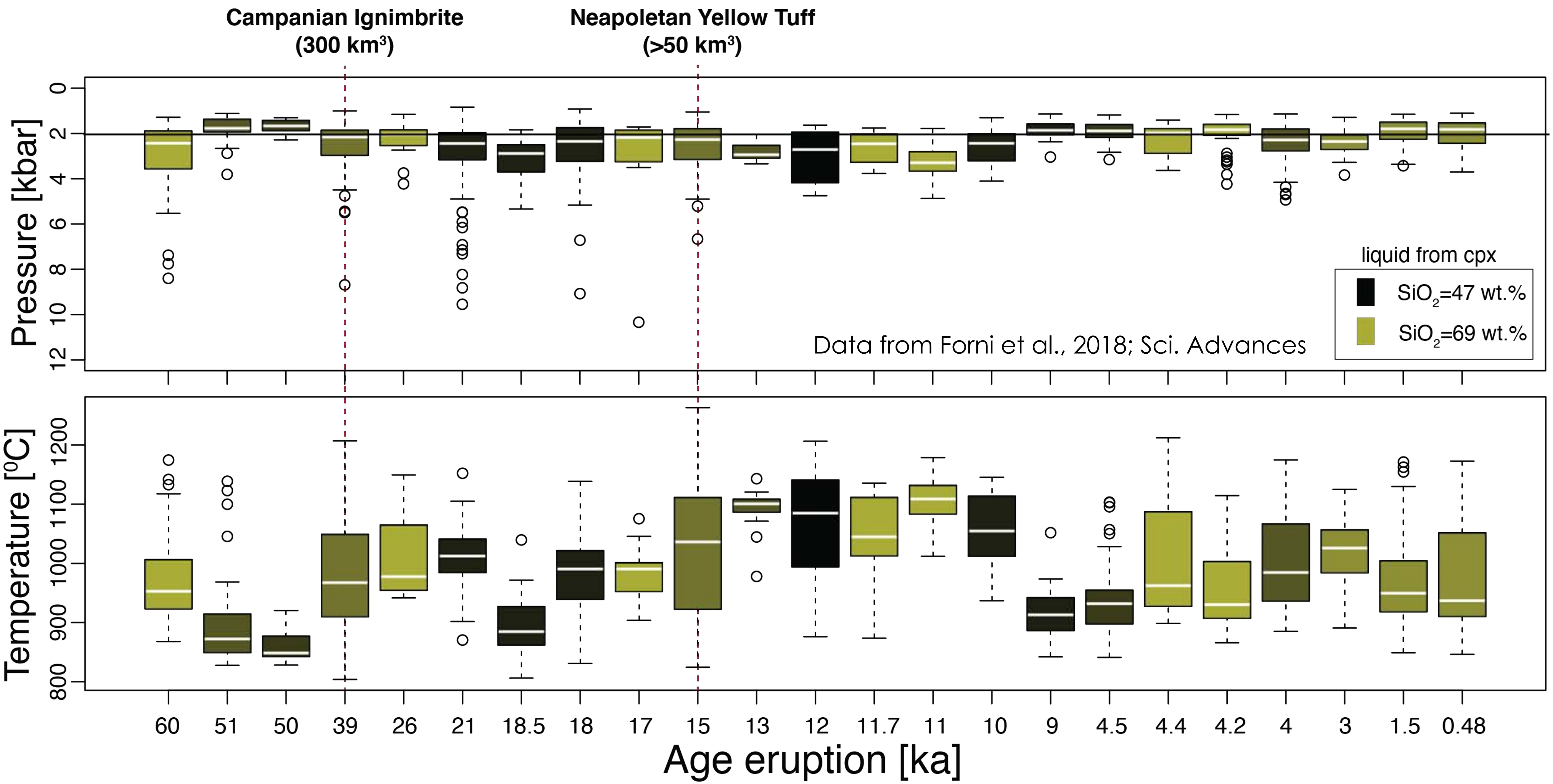
# Can we use ML to anticipate what will happen at Campi Flegrei?



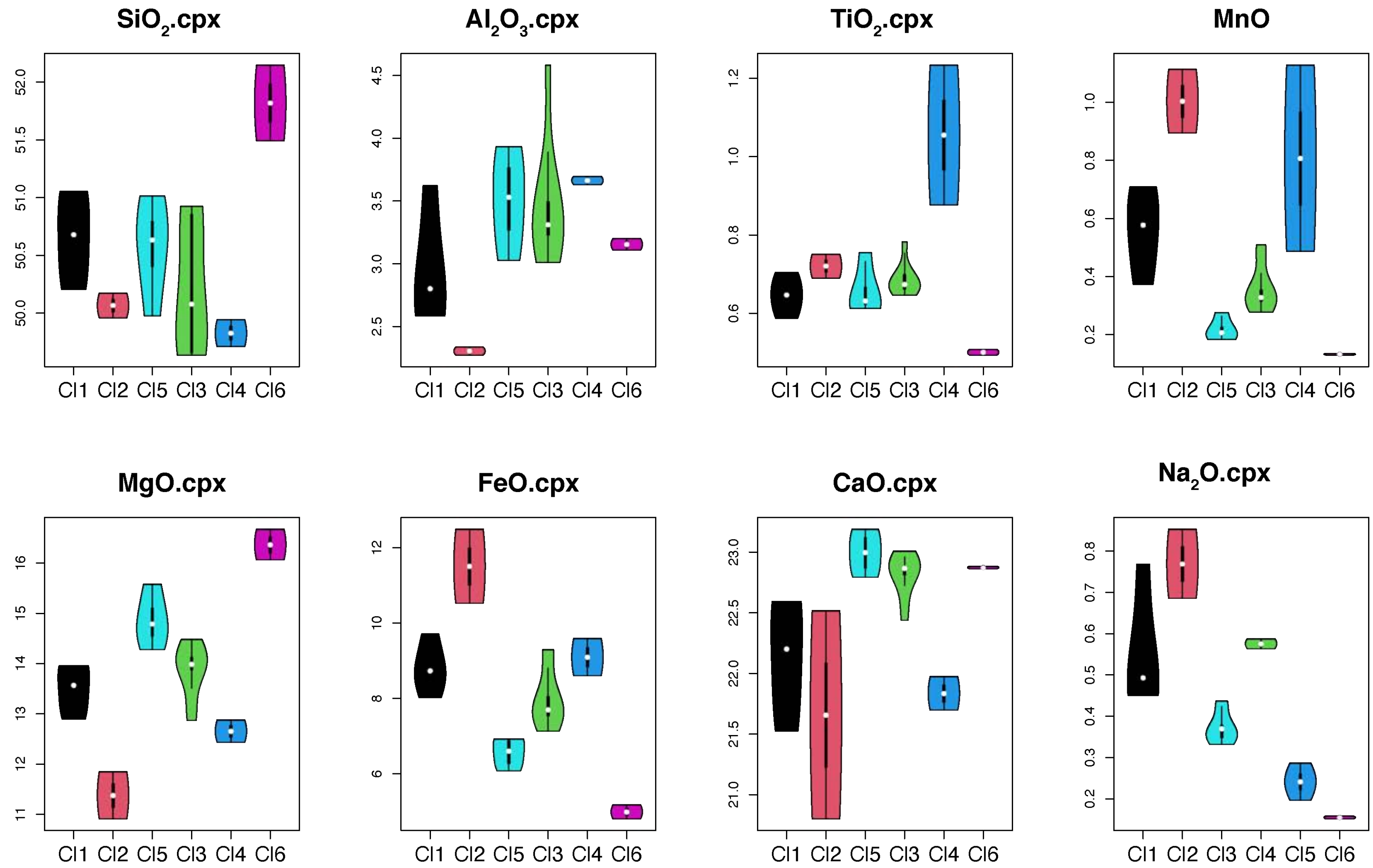


- **1118 earthquakes in August 2023 (1 Magnitude 4 at 2.7 km depth 2 days ago)**
- **Since January 2023, inflation of 15 mm/month**
- **T increase in the area of Pozzuoli**
- **$CO_2$ flux = 4000 t/day**

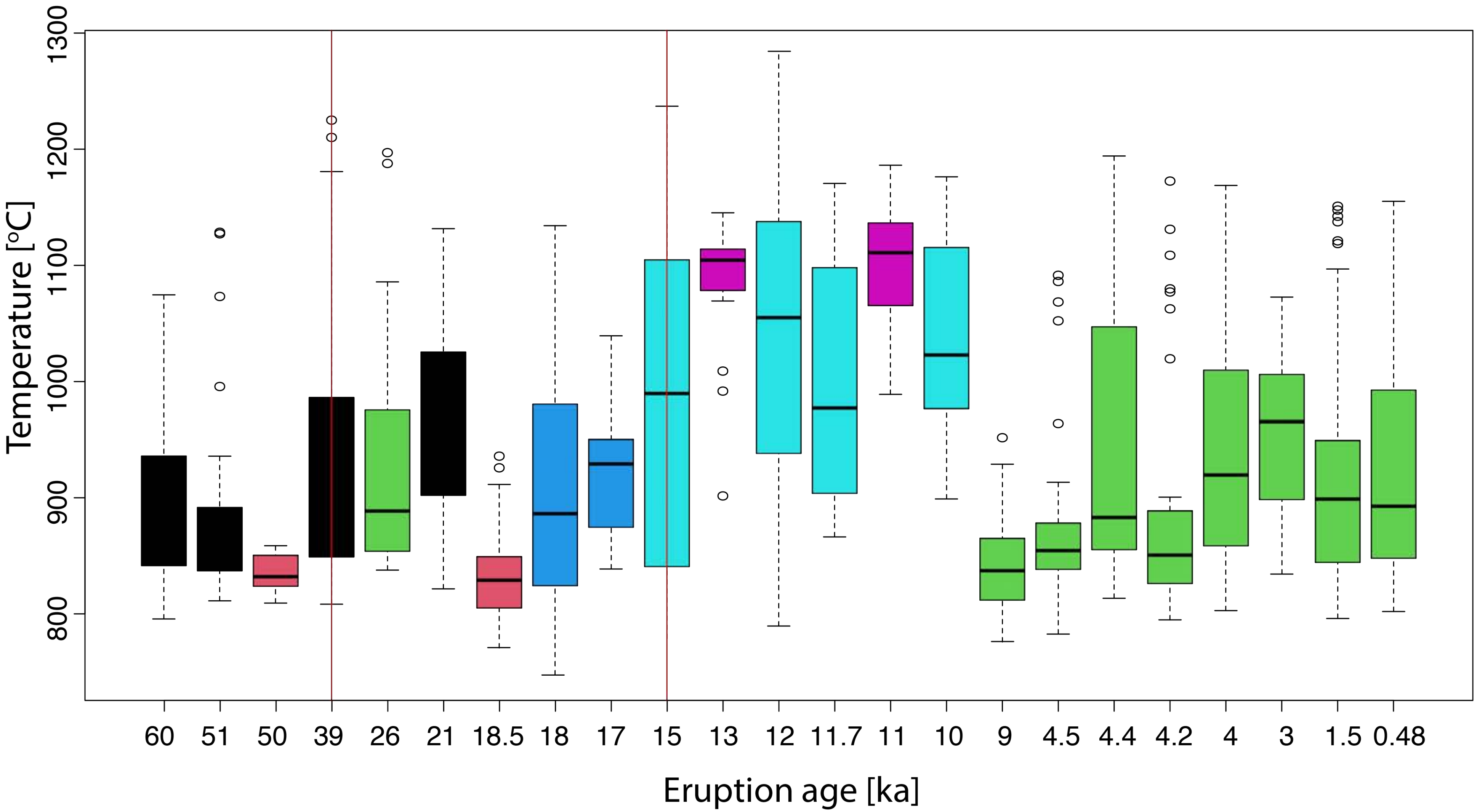
# Pressure-temperature-chemistry in time



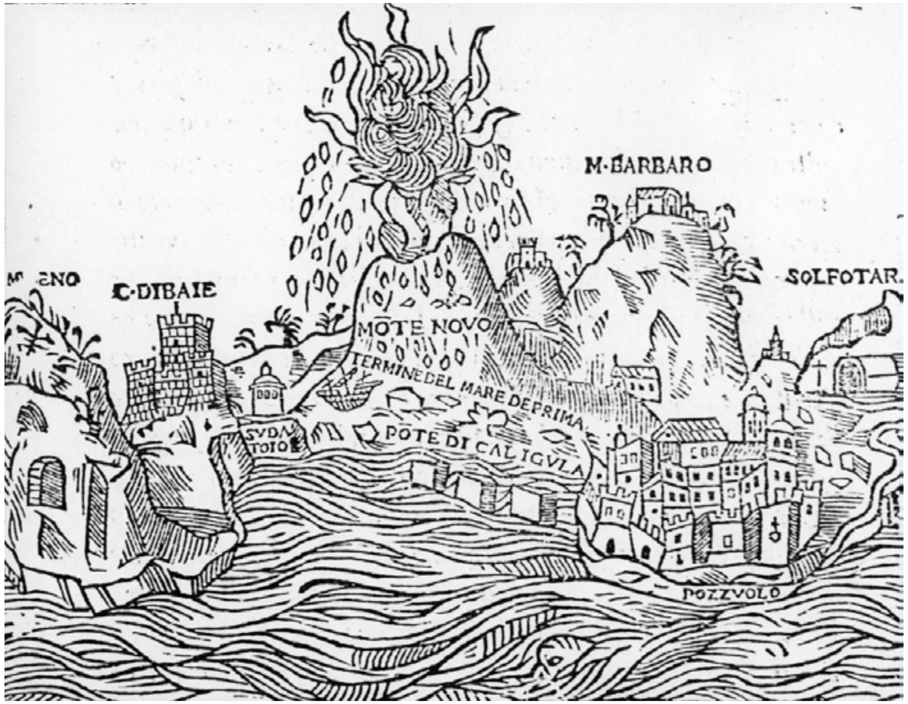
# How to define patterns of eruptive activity?



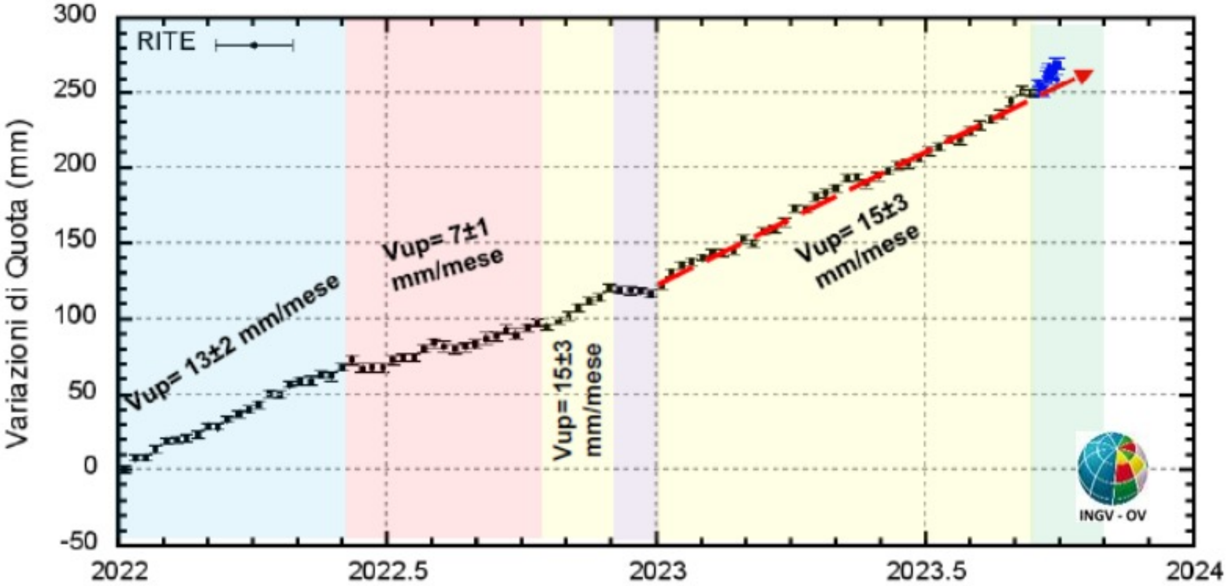
# How to define patterns of eruptive activity?

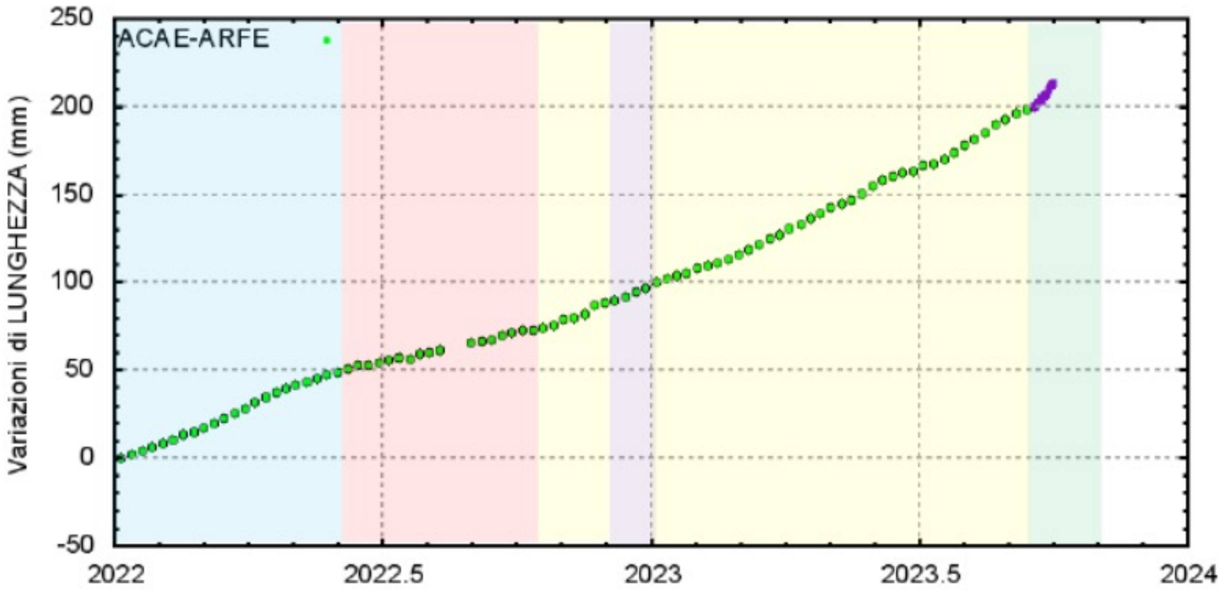


## Monte Nuovo eruption 1538




*Marco Antonio delli Falconi*



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FACULTY OF SCIENCE
Department of Earth Sciences

**We would like to discuss with you HOW TO:**

1. Filter of the calibration dataset for “non-equilibrium experiments”

2. How best to estimate the uncertainty of our approach

3. How to best look at time series?

1. Do you have any other idea? Please get in touch!