Can we relate diffusion timescales to magmatic flux and crustal permeability? The case of Villarrica and Osorno volcanoes (Chile)

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1. Background

Villarrica and Osorno are two active stratovolcanoes in the Central Southern Volcanic Zone of the Andes (see map). Both volcanoes share near-primary, tholeiitic parent magmas (50-53 wt. % SiO_2), overlap in major/trace element trends, and comparable magmatic storage conditions [1-4].

Yet Villarrica is an open-vent volcano with an active lava lake that produced ~100 moderate-intensity, Strombolian eruptions since 1579. By contrast Osorno is a closed-vent volcano with 10x less eruptions compared to Villarrica for the same period. In this study, we seek to answer the following questions:

1. Why is there a difference in eruptive style between the two volcanoes?
2. Could this difference be related to crustal permeability and/or magmatic flux?

To answer these questions, we analyzed the olivine textures and chemistry from tephra ejected by the 2015 eruption of Villarrica and the 1790 eruption of Osorno. We modelled timescales from diffused Fe-Mg growth zoning in olivine.

Our Hypothesis

Differences in eruptive style and frequency could stem from differences in the crustal permeability under Villarrica relative to Osorno (either from higher permeability of conduit walls, complex fracture network, or both).

Main Message:

Olivine from **Villarrica** display textures that reflect magma recharge, mixing and/or convection.

vs.

Olivine from **Osorno** display textures that mostly reflect fractional crystallization, mush disaggregation, and entrainment.

Timescales of processes overlap between the two volcanoes.

2. Methods and model inputs

1. Olivine crystals 100 µm < x < 1 mm in size were isolated by sieving and heavy mineral separation with bromoform at U. of Liège, and were oriented and then set in grain mounts.

2. **Textural and compositional characterization** of olivine crystal populations were conducted on the SEM and EPMA at KU Leuven. From this we selected olivine populations from each volcano for modelling

3. We obtained **crystallographic a-, b-, and c-axes orientations** using EBSD, and element concentration maps using EDS mode on the SEM at Ruhr-Universität Bochum, Germany.

4. Olivine Mg-Fe diffusion chronometry

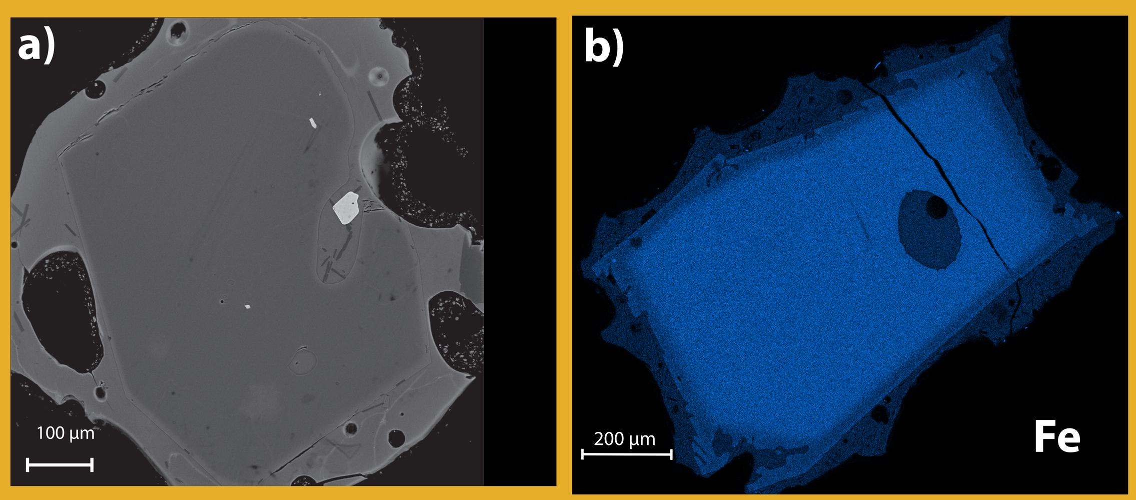
Timescales were obtained from diffused growth zones in olivine were **modelled numerically** using a finite difference method based on **Fick's 2nd law**:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$$

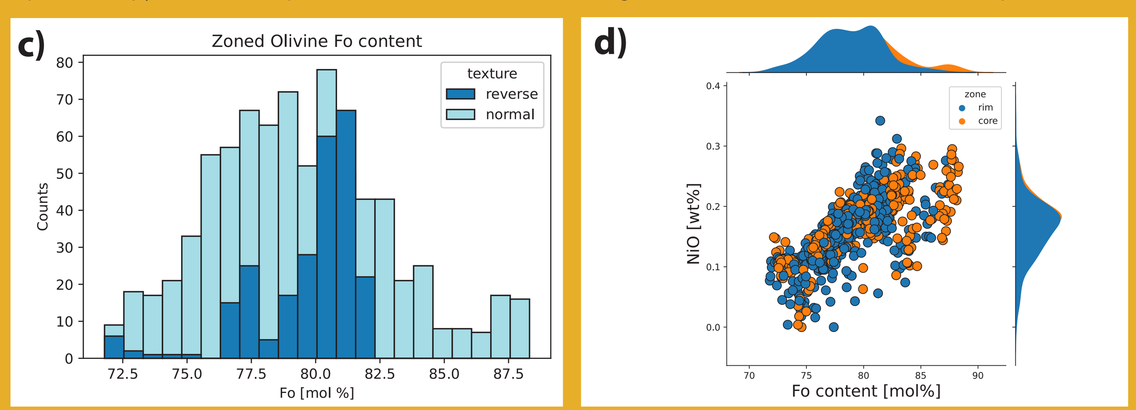
C is concentration or Fo content (Fo = [Mg]/[Mg+Fe^{2+}] in mol. %), D is the diffusion coefficient in m^2/s, t is time in s, and x is diffusion length in m. We used the following input values for diffusion modelling of both volcanoes [4,5]:

Variable.	Value.	Units
T	1114 (normal) / 1140 (reverse)	°C
P	200	MPa
fO_2	NNO buffer	

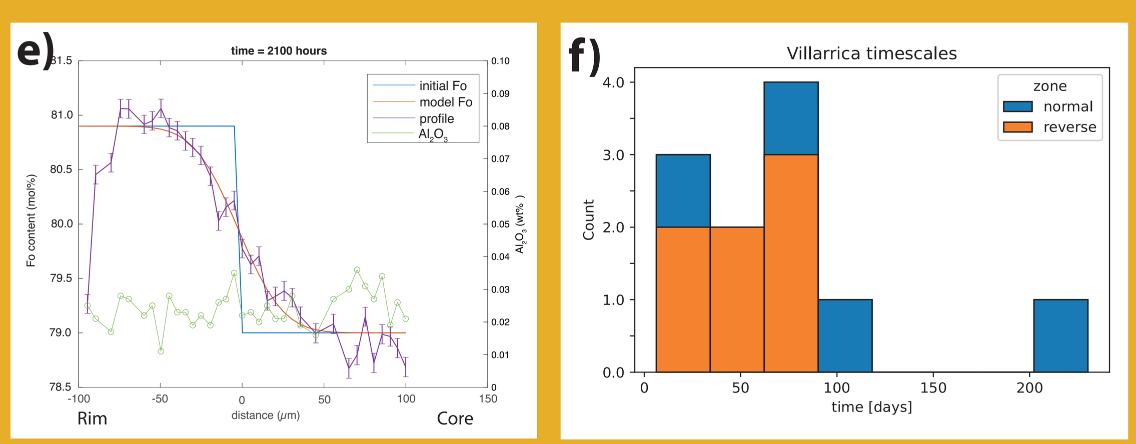
3. Results: crystal zoning, compositional profiles, and diffusion timescales



a) Backscattered electron (BSE) image of a crystal with normal zoning of <10 µm. b) Energy Dispersive Spectroscopy (EDS) Fe maps for olivine with reverse zoning (ΔFo content +10 mol. % over ~50 µm).

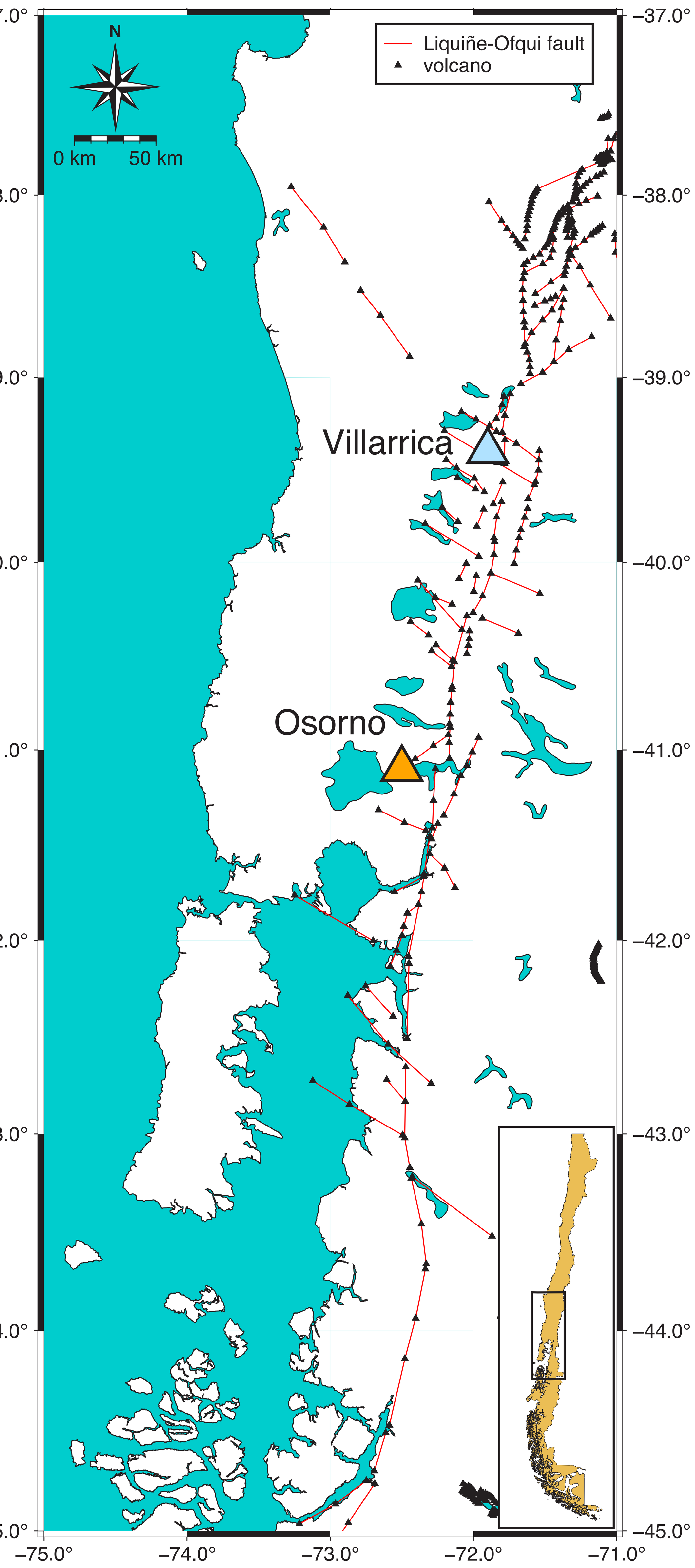


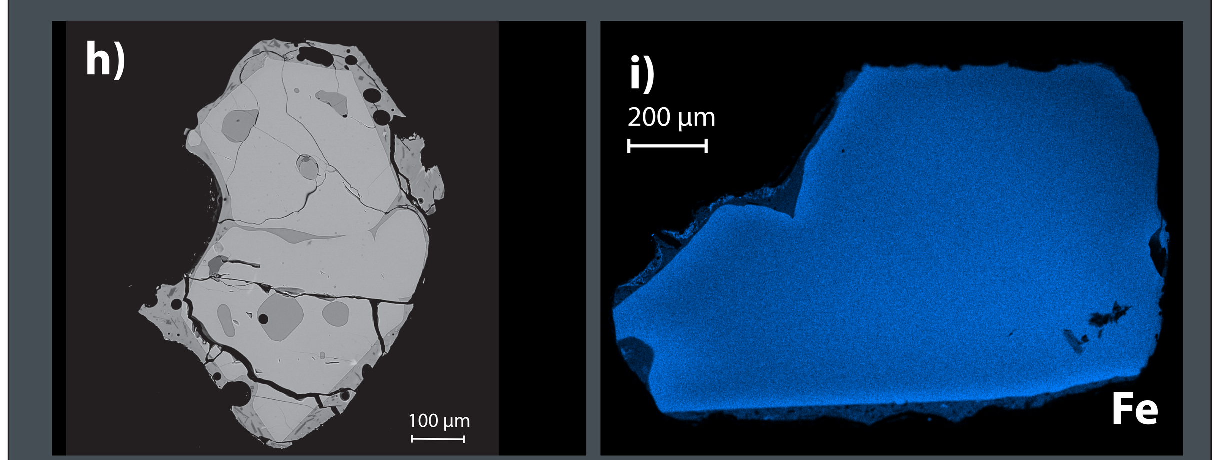
c) Histogram of Fo content of crystals from Villarrica divided by type of zoning. d) Scatter plot of Fo content vs. NiO of zoned crystals, divided into type of zoning and growth zone.



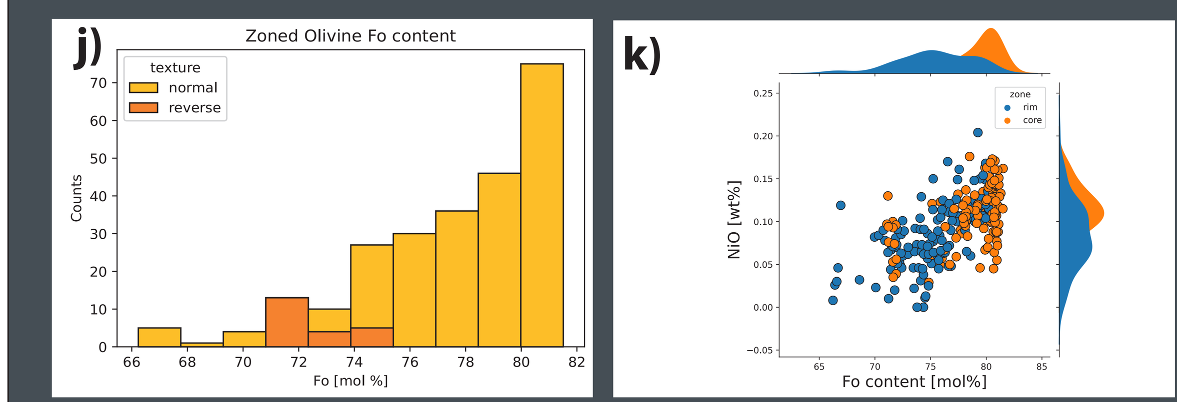
e) We show that Fe-Mg interdiffusion produced the profile observed, which we then modelled for timescale (83 days). f) Histogram of timescales, split into zoning type.

g) Map of the Central Southern Volcanic Zone of the Andes, with Osorno (orange triangle) and Villarrica (light blue triangle). The Liquiñe-Ofqui fault and other volcanoes are also shown here. Inset map at the bottom right shows the country of Chile with the map region bound by a black rectangle.

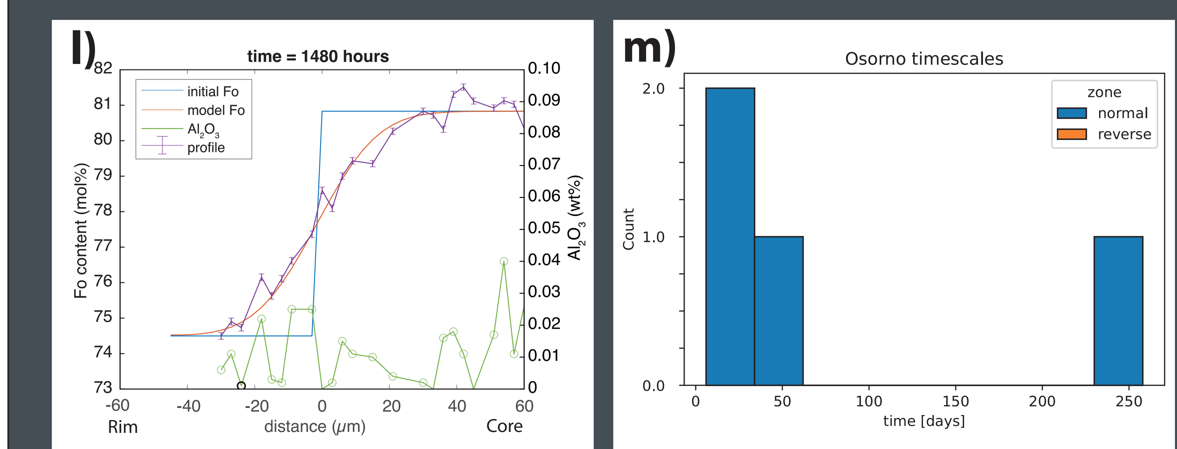




h) BSE image of an unzoned crystal with rounded edges, and melt and mineral inclusions. i) EDS Fe map of a crystal with normal rim zoning (ΔFo content -5 mol. % over ~75 µm).



j) Histograms of compositional variability in the olivine population. k) Scatter plot of Fo content vs. NiO of zoned crystals, divided into type of zoning and growth zone.



l) We show that Fe-Mg interdiffusion produced the profile observed, which we then modelled for timescale (60 days). m) Histogram of timescales for Osorno.

4. Discussions and preliminary interpretations

Villarrica olivine crystals (Fo_{72-87}) display textures e.g. resorbed edges and no/normal/reverse growth zones. These textures reflect processes occurring in the reservoir, such as magma recharge, mixing, and convection. Hence the crystal population crystallized in the magmatic reservoir likely as part of a magma mush, but can also move to the lava lake before eruption. Timescales of processes are 6-229 days.

Osorno olivine crystals (Fo_{66-82}) display a limited range of textures such as thin normal zoning (< 10µm) and resorbed edges. Uncommon textures include growth zones >10 µm, and reverse zoning. As Osorno is a closed-vent volcano, the olivine population crystallized in the magmatic reservoir prior to eruption. These textures reflect processes including fractional crystallization, disaggregation, and/or entrainment. Timescales of processes are 6-250 days

Although the types of processes differ, the timescales from Villarrica and Osorno olivine populations overlap suggesting a similar degree of crustal permeability below both volcanoes. More timescales are needed to better understand the link between timescales, crustal permeability, and magma flux.

5. Future directions

1. Target samples that record processes in the magma reservoir:
   a) Model diffused profiles using calibrated grayscale maps
   b) Consider modeling diffusion of trace elements e.g. Ni, Mn

2. Analyze olivine crystals from multiple eruptions to gain statistically significant populations.

3. Relate timescales to crustal permeability and magmatic flux for both volcanoes.

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