# Phosphorus Zoning in Olivine: An Additional Constraint on Magmatic Processes in Arc Volcanism

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## Introduction/Context

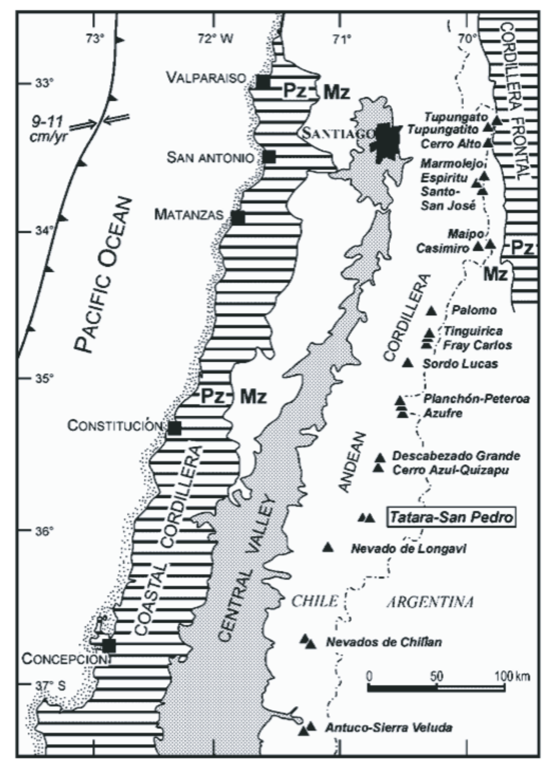
Arc lavas contain abundant evidence of disequilibrium processes, in the form of concentration profiles, reaction rims, and dissolution features. Many of these disequilibrium features can be used to determine the time scales of the magmatic events resulting in their formation. Previous studies have used zoning in plagioclase and/or olivine, reaction rims on olivine, and amphibole break down rims to infer the time from the disequilibrium event to eruption.

Previous work by Fidel Costa used zoning in olivine or plagioclase to infer the time scales of magmatic processes. Costa and Chakraborty (2004) looked at Fe-Mg zoning in olivine to calculate the time scales of olivine incorporation into dacite and andesite magmas. They focus on four lavas from Volcan San Pedro in the Southern Volcanic Zone of Chile (a and b). The lavas are three dacites (Qcf1, Qcf2, and Qcf3) and one andesite (Qcf4). None of these magmas lie in the low-pressure olivine phase volume so its presence is assumed to be the result of magma mixing with a more mafic magma (i.e, basaltic andesite, Costa and Chakraborty, 2004) or assimilation of mafic to ultramafic lithologies (Costa and Dungan, 2005). The Fo (or Mg#) profiles in olivine reported in Costa and Chakraborty (2004) are reproduced for each of the studied olivines. As illustrated the Fo (Mg#) zoning can be complicated, but their model focused on the outer-most zone developed during the last stage prior to eruption. The time scales calculated for olivine incorporation range from less than a year for Qcf1 to 0.8 to 91 years for Qcf2, Qcf3, and Qcf4.

Recent studies of zoning in olivine suggest that just focusing on the major elements such as FeO and MgO maybe insufficient. Certain trace elements such as the slower diffusing $P_2O_5$, $Al_2O_3$ and $Cr_2O_3$ may record important information about the olivine growth history that is not retained by the faster diffusing species. Milman-Barris et al. (2006) described complex zoning of $P_2O_5$, $Al_2O_3$ and $Cr_2O_3$ in natural olivines from Hawaiian lavas, komatiites and a Martian meteorite. In addition, their linear cooling rate experiments on a Hawaii bulk composition produced olivine with strong zoning in $P_2O_5$, $Al_2O_3$ and $Cr_2O_3$. They attributed the $P_2O_5$, $Al_2O_3$ and $Cr_2O_3$ zoning to rapid growth of the olivine.

The purpose of this study is to examine olivine from arc lavas for zoning in $P_2O_5$, and to explore the effects this zoning will have on the model and time scales estimated by Costa and Chakraborty (2004).

a)

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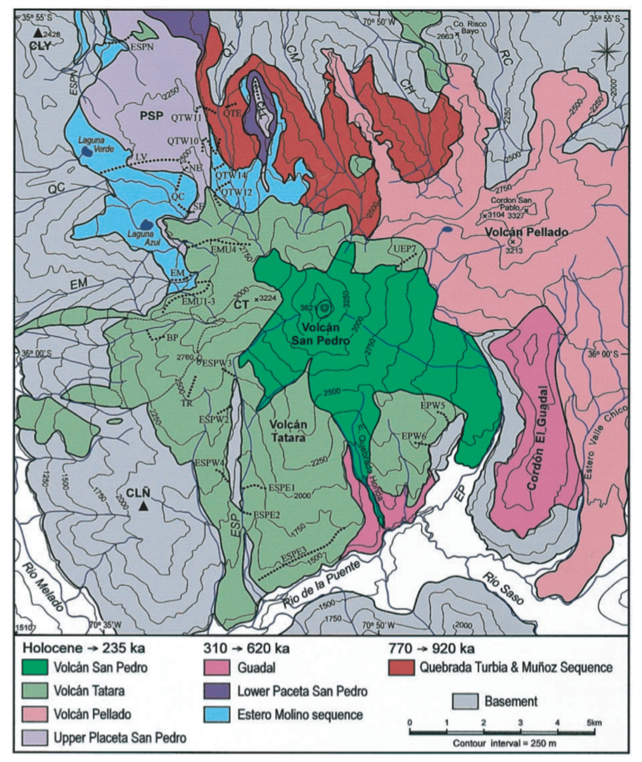
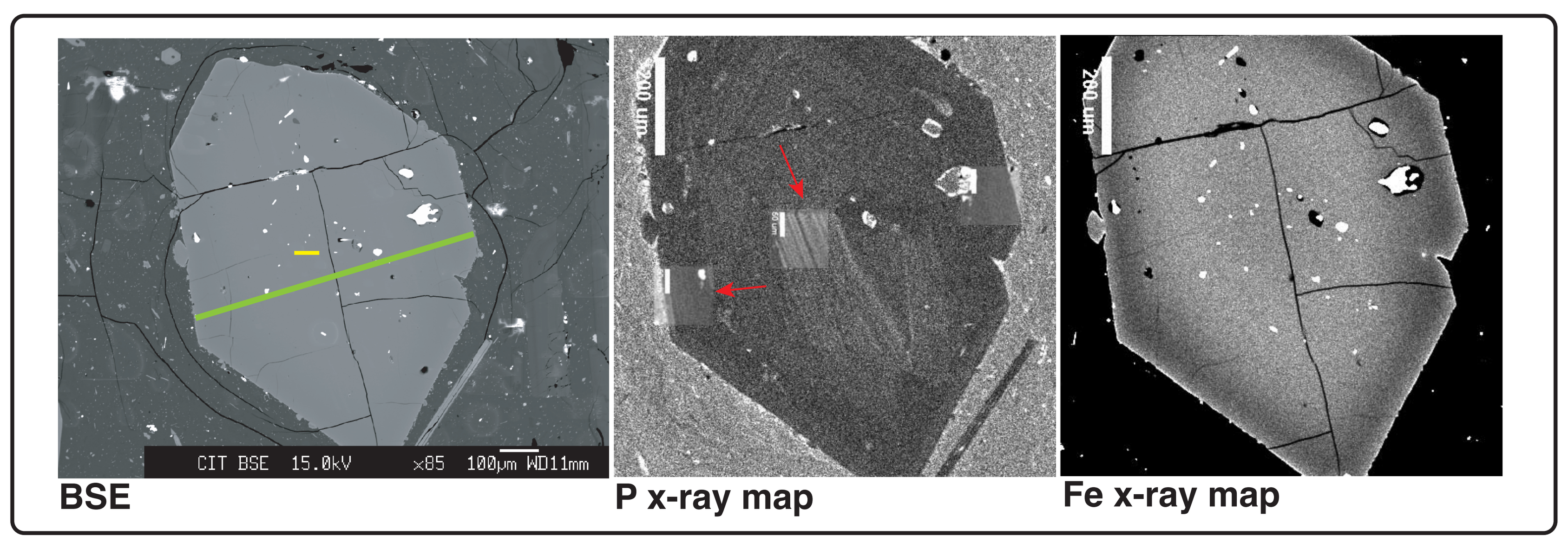
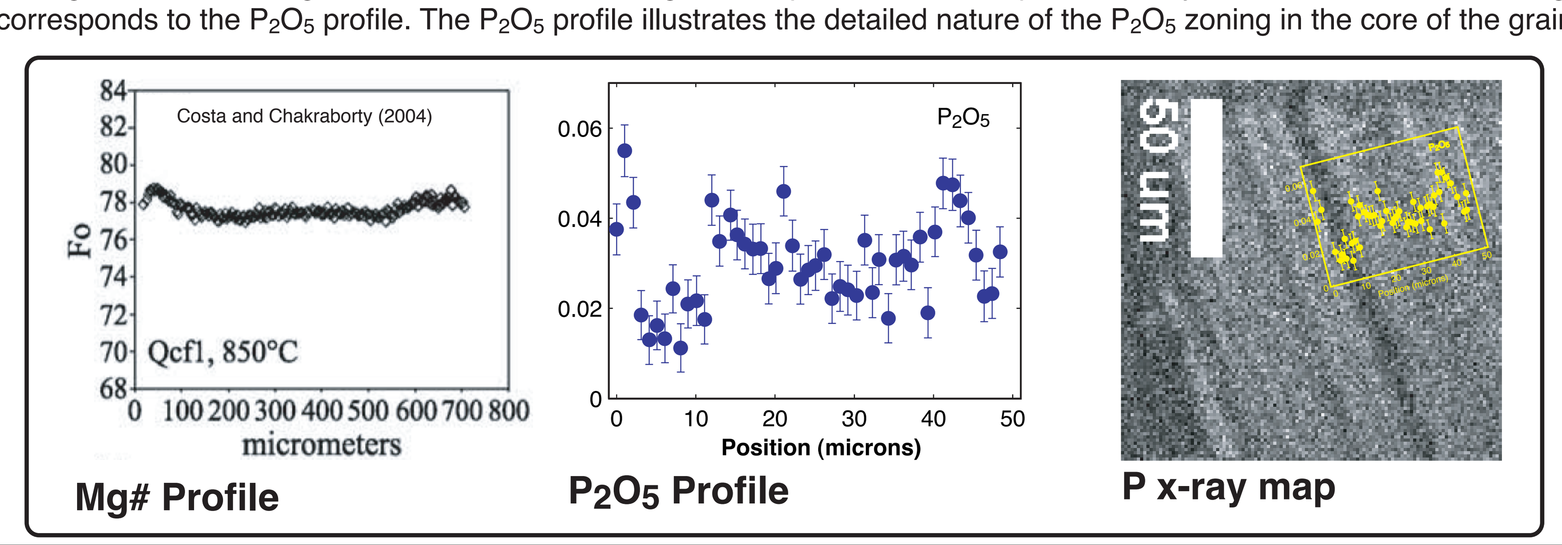


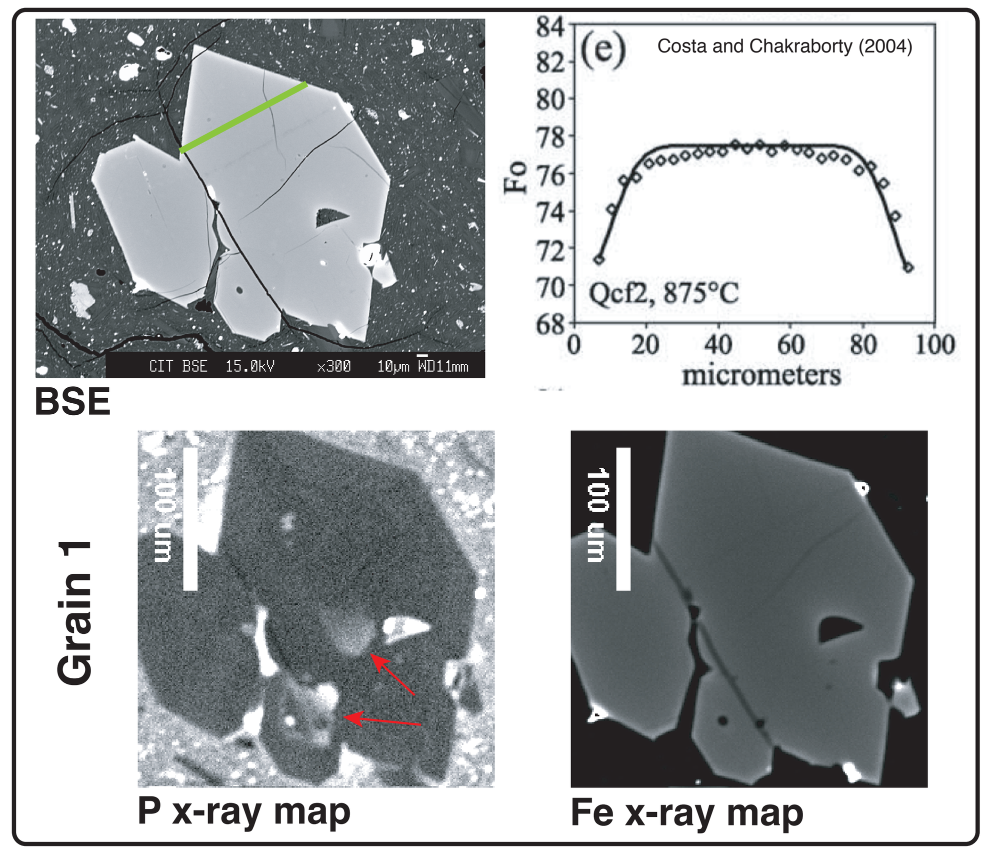

## Qcf1: Dacite, $SiO_2$ = 65.8%, T = 850 C

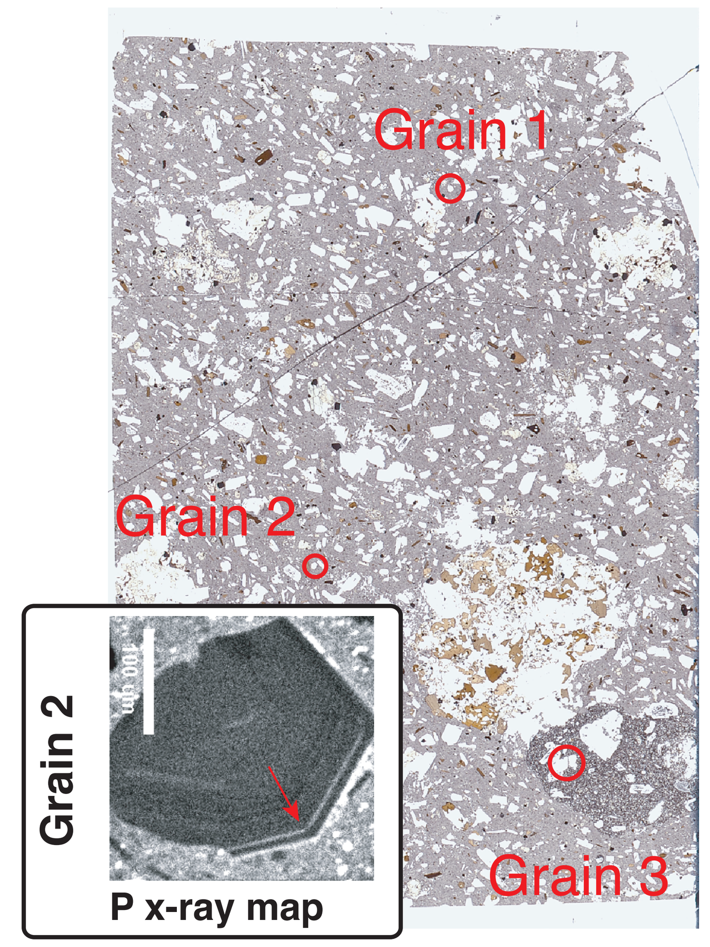



This olivine has two distinct zoning features: complex banding of $P_2O_5$ in the core of the grain (P x-ray map) and a 100 micron band of higher Mg (lower Fe) concentration (Fe x-ray map and Mg# profile) in which $P_2O_5$ zoning is absent. The red arrows on the P x-ray map point to $P_2O_5$ zoning in the core and the region near the rim of the grain where $P_2O_5$ zoning is absent. The green line on the BSE image corresponds to the Fo profile. The yellow line on the BSE image corresponds to the $P_2O_5$ profile. The $P_2O_5$ profile illustrates the detailed nature of the $P_2O_5$ zoning in the core of the grain.




## Qcf2: Dacite, $SiO_2$ = 64.5%, T = 875 C

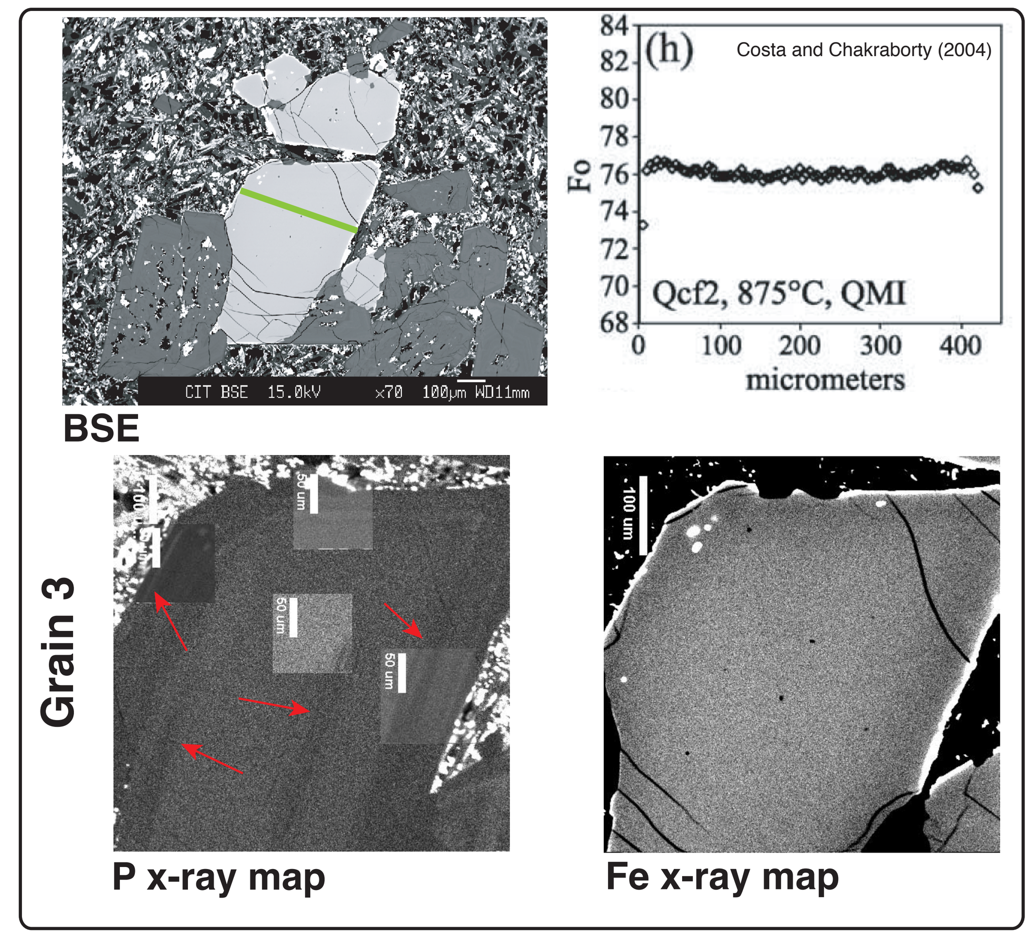


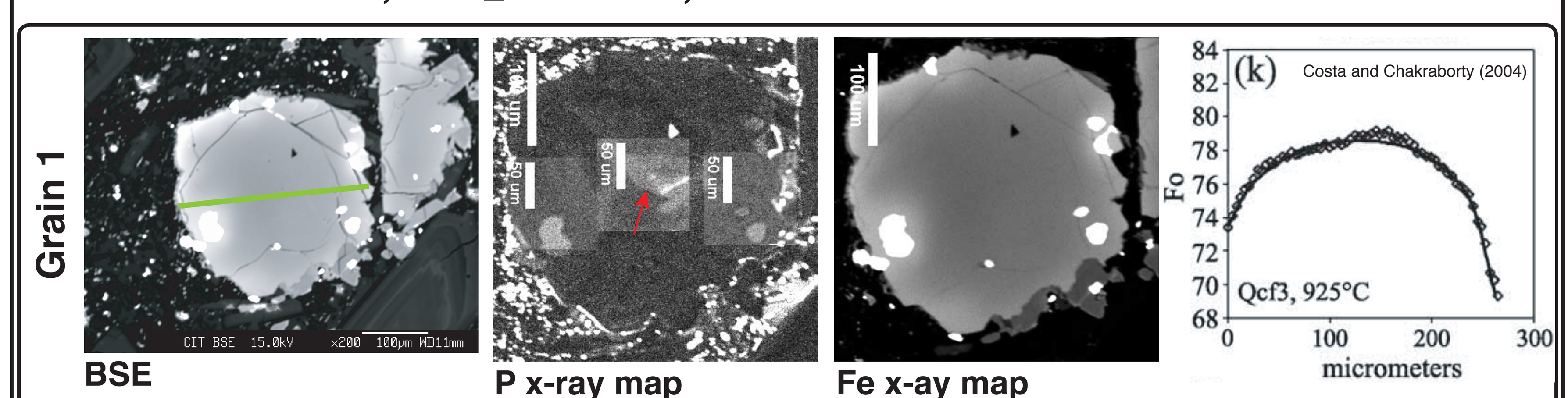

Grain 1: This olivine has two distinct zoning features: a higher Fe concentration rim (outer 10 microns, Fe x-ray map) where $P_2O_5$ zoning is absent and $P_2O_5$ rich zoning in the interior of the grain. The red arrows on the P Xray Map point to $P_2O_5$ zoning in the core of the grain. The green line on the BSE image corresponds to the Fo profile.

Grain 2: The $P_2O_5$ zoning in this olivine grain occurs as bands parallel to the crystal faces.

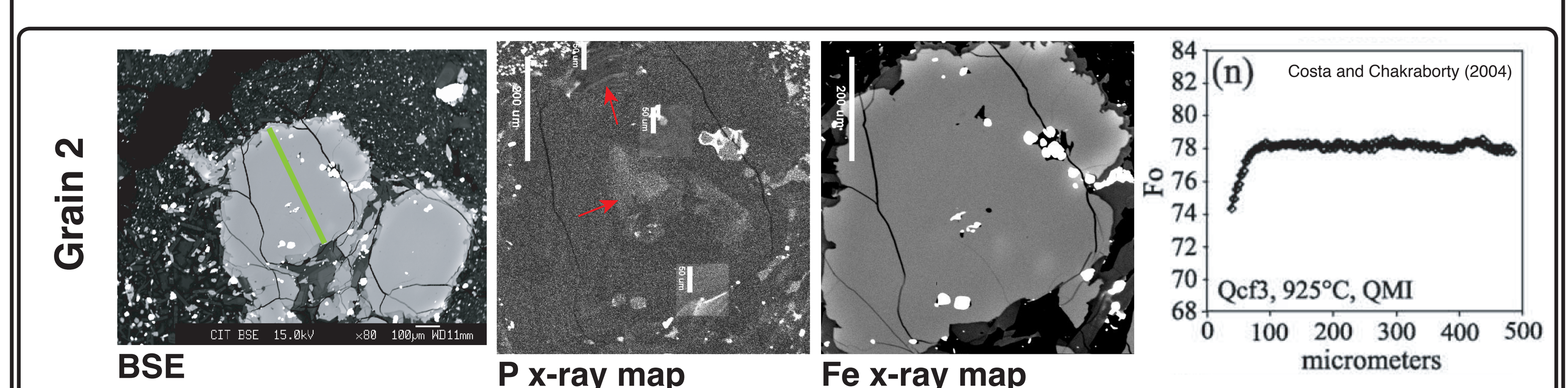
Grain 3: This grain occurs in a more mafic inclusion in the dacitic magma. The $P_2O_5$ zoning in this olivine is combination of patchy $P_2O_5$-rich zones in the interior and a faint band parallel to the crystal face. Similar to the Qcf1, there is a 100 micron band near the outer edge of the grain with lower FeO (higher Fo, Mg# profile) and an abence of $P_2O_5$ zoning. The red arrows on the P x-ray map point to features in the $P_2O_5$ zoning region. The green line on the BSE image corresponds to the Fo profile.



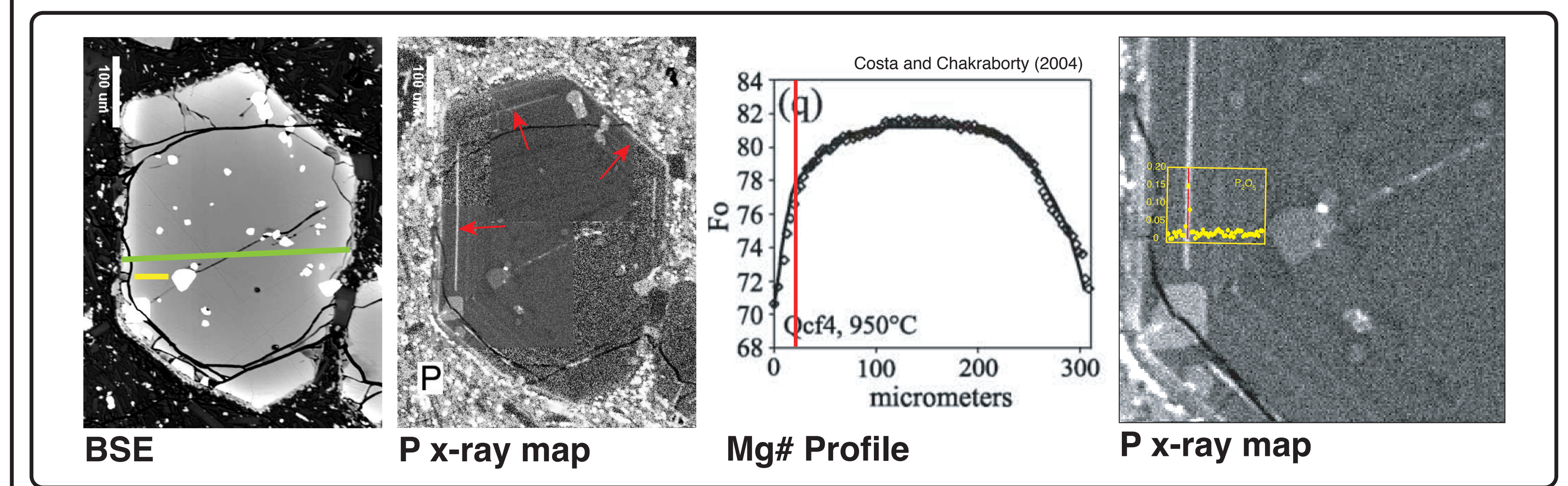

## Qcf3: Dacite, $SiO_2$ = 63.6%, T = 925 C

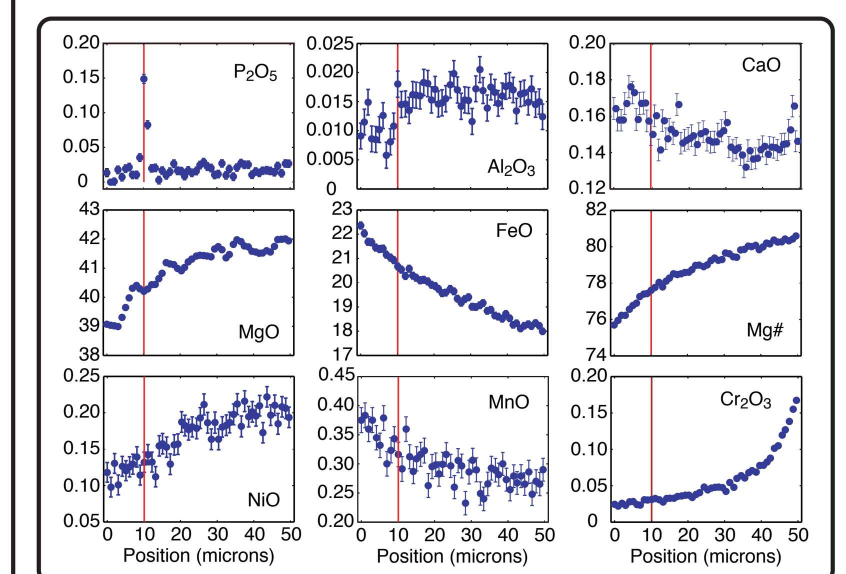



These grains do not have good crystal faces. The red arrows on the P x-ray map point to features in the $P_2O_5$ zoning region. The $P_2O_5$ zoning is patchy in the interior of the grain (Grains 1 and 2); grain 2 also has a suggestion of $P_2O_5$ banding near the edge of the crystal. The green lines on the BSE images correspond to the Fo profiles.



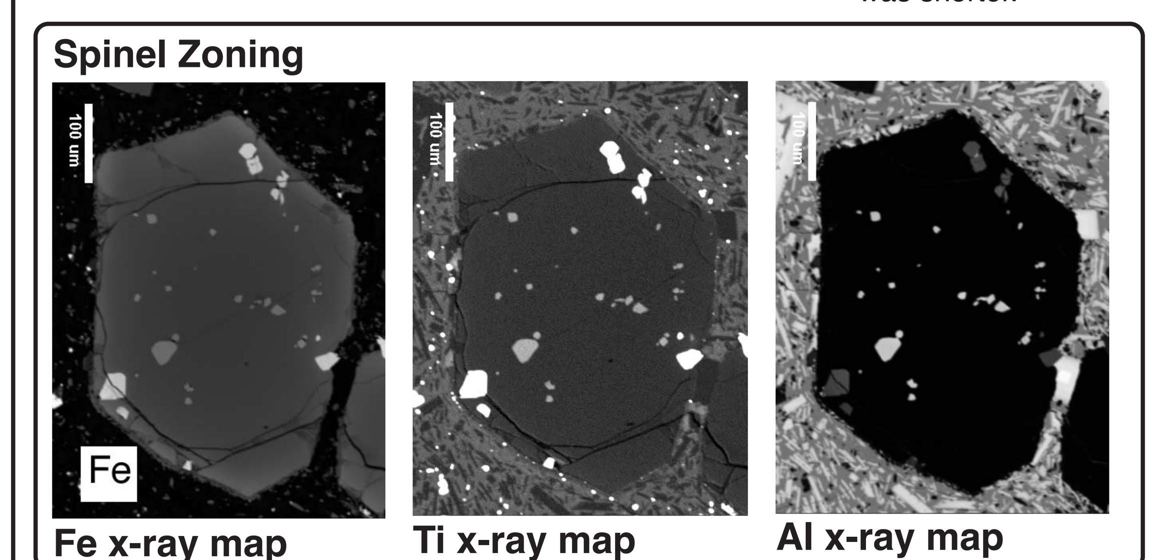

## Qcf4: Andesite, $SiO_2$ = 61.4%, T = 950 C

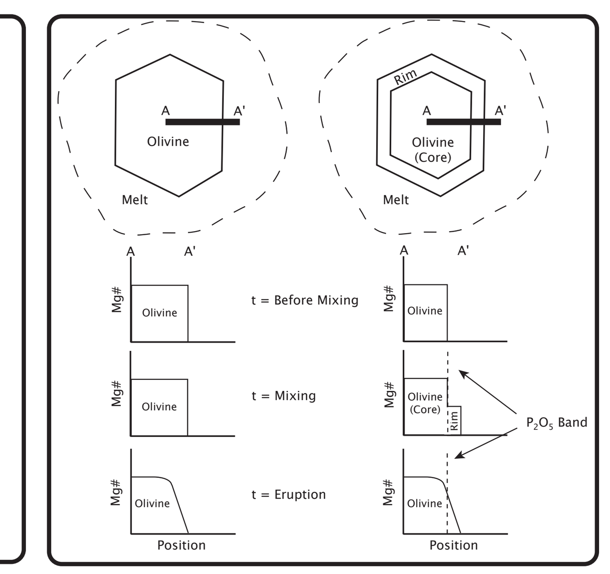



Like Qcf2 grain 2, the primary $P_2O_5$ zoning in this grain is $P_2O_5$ rich bands parallel to the crystal faces. The red arrows on the P x-ray map point to strong $P_2O_5$ bands. The green line on the BSE images corresponds to the Fo profiles. The red line on the Mg# Profile marks the position of the $P_2O_5$ rich band relative to the Fo profile. This suggests that (at least for this case) the interpretation of Costa and Chakraborty (2004) that the zoning in Fe-Mg is the result of simple diffusive exchange between the olivine and the host liquid is not correct. Instead we suggest that a new rim of olivine with a different Fo content (marked by the $P_2O_5$ rich band) grew on a pre-existing olivine crystal. Diffusive exchange between the new olivine rim, the pre-existing core and the host magma resulted in the observed Fo profile. However, the concentration of slower diffusing species such as $P_2O_5$ and $Al_2O_3$ did not change significantly. This suggests that the time scales estimated by Costa and Chakraborty (2004) are over estimates and the actual time was shorter.

### Spinel Zoning




The magnified P x-ray map illustrates the $P_2O_5$ banding, on which I've superimposed a quantitative profile taken across a portion of the crystal. The quantitative profile illustrates the $P_2O_5$ concentrations that are qualitatively described by the x-ray map.

Additional evidence for our hypothesis of a later stage rim on the olivine comes from spinel inclusions hosted within the olivine grain. The Fe, Ti, Al and P x-ray maps illustrate that spinel inclusions on the outer edge of the grain have high Fe, Ti and P and low Al relative to spinel inclusions in the core of the olivine.

## Summary/Future Work:

As with previously examined olivine from other tectonic environments (Milman-Barris et al., 2006), olivines from arc lavas contain complex zoning in $P_2O_5$. The types of $P_2O_5$ zoning in olivine we have observed are bands parallel to the crystal faces (Qcf2 grains 1 and 2, Qcf3 grain 2, and Qcf4), bands in the interior of the grain (Qcf1), and irregular patches in the interior of the grain (Qcf2 grain 1, and Qcf3). Ultimately, the complex zoning will better constrains the growth histories of the olivine and lead to a greater understanding processes involved the timing of mixing and eruption events in arc lavas. However, in the shorter term the $P_2O_5$ zoning coupled with Fe-Mg zoning can be used to refine models and estimates for olivine residence times in lavas, as is illustrated with Qcf4.

The next step of this study is to collect P x-ray maps for a population of different olivine in the same section to characterize the $P_2O_5$ zoning for each lava. Are the types of $P_2O_5$ zoning in olivine distinct for a given lava or is there a continuum of $P_2O_5$ zoning common to all of the lavas?

In addition, we will modify the model used by Costa and Chakraborty (2004) to estimate the olivine residence times to include a rim of new olivine similar to Qcf4. What is the effect on time estimates when a rim of new olivine is added to a pre-existing olivine? Are the changes to the olivine residence times consistent for all olivine in a given lava?

References:
Costa, F., Chakraborty, S. (2004), Decadal time gaps between mafic intrusion and silicic eruption obtained from chemical zoning patterns in olivine, *Earth Planet. Sci. Lett.*, 227, 517-530.
Costa, F., Dungan, M., (2005), Short time scales of magmatic assimilation from diffusion modeling of multiple elements in olivine, *Geology*, 33, 837-840.
Milman-Barris, M.S., Hofmann, A.E., Beckett, J.R., Morgan, Z., Baker, M.B., Daniel Vielzeuf, D., Stolper E.M., (2006), Zoning of phosphorus in magmatic olivine, Abstract, *Geol. Soc. Amer.*.