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## Leveraging crystal-scale data to constrain the conduit flow regime in persistently active volcanoes

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Persistently active volcanoes are often closely monitored, yielding a rich archive of observational data. The availability of varied observations provides a unique opportunity for improving theoretical models of magma dynamics, but data and model can be difficult to compare directly. Geophysical observations like seismicity or geodetic measurements often operate at similarly large scales as many models, but they only provide indirect and non-unique testimony of the processes occurring at depth. In contrast, crystals in erupted tephra or scoria samples record at least some aspects of the pre-eruptive condition in the volcanic conduit directly, but refer to spatial scales that are much smaller than most models resolve.

The goal of this paper is to demonstrate the potential of crystalline-scale data for distinguishing directly between different conduit-flow models. As a proof of concept, we focus on the preferential alignment of olivine crystals from tephra erupted at Kilauea Iki in 1959. Prior petrographic analysis suggests that these olivine glomerocrysts formed through synneusis of individual crystals. To evaluate the fluid-dynamical conditions under which both crystal synneusis and preferential crystal alignment would occur, we compare two broad classes of conduit flow models, unidirectional and bidirectional models.

We hypothesize that the observed preferential alignment of olivine crystals is created by a pronounced, nearly stationary wave at the interface that separates the ascending and descending magmas in bidirectional flow models. Crystals in bidirectional flow are hence exposed to a superposition of wave and shear, while crystals in a unidirectional, laminar flow experience approximately constant shear strain during ascent. To test our hypothesis, we quantify the crystal alignment resulting from a pure shear flow and from the superposition of a stationary wave on shear flow through two complementary model approaches. We first derive an analytical model for when crystals align under the joint influence of a wave and shear flow. We then use direct numerical simulations to quantify how crystal-crystal interactions modulate the analytically predicted preferential alignment of crystals.

We find that the formation of glomerocrysts with preferential aligned olivine crystals is consistent with bidirectional flow models, but unlikely to form in a unidirectional model. We emphasize that the imprint of the conduit flow on the crystals is subtle, suggesting that both clustering or alignment in isolation would be compatible with a much wider range of flow conditions than the

observed conjunction of both attributes in the Kilauea Iki olivines. To our knowledge, these observations provide the first direct evidence of bidirectional flow in volcanic conduits.