PhD Proposal

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Motivation

Background

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The Ora Ignimbrite (277 +/- 2 Ma) is a welded crystal-rich supereruption-
sized deposit located in the southern Alps of northern Italy.  Ora
represents the final eruptive pulse of the Athesian Volcanic Group (285-274
Ma), a slab-rollback ignimbrite flareup resulting from the oblique
subduction of the Paleo-Tethys ocean under Eurasia in the Permian (Marocchi
et al., 2008; Best et al., 2016).  This volcanic terrain escaped alpine
deformation and has been scoured by glacial incision, exposing intracaldera
deposits reaching thicknesses of 1350 m.  Outflow deposits are less than 250
m thick and are stratigraphically similar to the late-erupted deposits
(Willcock et al., 2013) (Fig 1).  The Ora eruption is interpreted to have
had an early caldera collapse, based on the large amount of intracaldera
fill and the fact that the outflow correlates with the late-erupted units of
the intracaldera deposit (Willcock et al., 2013).  Furthermore, Willcock et
al. (2015) identify two discrete collapse calderas (northern and southern)
and variations in bulk rock compositions and biotite content between the two
calderas suggest that multiple magma chambers were evacuated to form the Ora
Ignimbrite.
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Figure 1: A map of the field location. The four fiamme types identified in Chiaro et al. (in prep) are listed with their corresponding vitrophyre locations.

Table 1: Samples collected in Fall 2017 and Spring 2019. Sample locations are shown in Fig. 1. The number of bulk tuff samples and fiamme are listed.

Samples: Location: Type: Bulk Tuff: Fiamme: ORA 2 Outflow Vitrophyre Vitrophyre 1 x ORA 3 Northern Intracaldera Bulk Tuff 1 1 ORA 4 Odorizzi Quarry Bulk Tuff 2 50 ORA 5 Intracaldera Vitrophyre Vitrophyre 1 x ORA 6 Northern Intracaldera Rhyolite Dike 4
ORA 7 Base of Northern Intracaldera Bulk Tuff 1
ORA 8 Northern Intracaldera Bulk Tuff 1
ORA 9 NW Outflow 1 Biotite-Rich Fiamme x ORA 10 NW Outflow 2 Medium-Grained Fiamme x ORA 11 Castel Firmiano Ash/Ignimbrite Contact 3
ORA 12 Rhyolite Dike Granite Dike 4
ORA 13 Rhyolite Dike Potential Fiamma 1 ORA 14 Caldera Rim Cutting Dike Porphyritic Coarse-Grained Dike 1
ORA 15 Caldera Rim Cutting Dike Medium-Grained Dike 1
ORA 16 Cava Flor Quarry Fine and Coarse-Grained Fiamme 4 ORA 17 NW Outflow 3 Fine to Medium-Grained Fiamme x ORA 18 Magdalena Hike Pseudotachylite 1
ORA 19 Magdalena Hike @ Sculpture Fine and Coarse-Grained Dikes 1

Recent work has attempted to understand the pre-eruptive architecture of the Ora system by using textural, mineralogical, and geochemical features of fiamme (Chiaro et al., in prep). Fiamme were collected from two vitrophyre horizons: an early-erupted intracaldera deposit and a late-erupted outflow deposit in order to find well-preserved glass. These fiamme were initially grouped into four types based on crystal content and biotite content (Table 2). Glass major elements further verified the categorization scheme.

Table 2: The four fiamme types and their location, crystal content, maximum phenocryst size, and mafic content (Chiaro et al., in prep).

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Glass trace elements illuminate at least three distinct populations for both
the VCCR and MG fiamme, suggesting the presence of multiple magma batches
within the Ora system (Fig. 2).
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Figure 2: Rare earth element diagrams and a plot of strontium vs. barium illustrate the six discrete glass populations in the Medium-Grained (MG) and Very Coarse-Grained Crystal-Rich (VCCR) fiamme.

Pre-eruptive storage pressures were calculated using the Rhyolite-MELTS (Q2F) geobarometer.

Different fiamme types were stored at different pressures in the crust, with a progression of erupting shallower to deeper magmas through time.

Silica content vs. pressure shows variable storage depths for the fine-grained crystal-poor melt, suggesting that there were multiple, small melt bodies located at different depths throughout the magma chamber.

Figure 3: (from Chiaro et al., in prep)

This work suggests that there were two potential scenarios for the pre-eruptive architecture of the Ora magma system. There were either two distinct mush zones that were at slightly different depths within the crust, or a continuous crystal mush with multiple heterogeneous zones located throughout.

Approach

Building on the work from Chiaro et al. (in prep), we propose to use mineral compositions in order to apply this characterization scheme to the entire Ora deposit. Since unaltered glass is only present in the vitrophyre horizons, we plan to use mineral compositions to classify each fiamma. We will collect trace and major elements of plagioclase, alkali feldspar and biotite in fiamme. Preliminary work shows that biotite and plagioclase major elements can be used to differentiate intracaldera vs. outflow fiamme. Furthermore, biotite major element compositions can be used to infer both fiamme type and population (Fig. 4).

Figure 4: Biotite and plagioclase major element compositions from fiamme. Fiamme are divided into population based on hue. Both plagioclase and biotite can be used to determine fiamme type, and biotite can also determine fiamme population (from Chiaro et al., in prep).

Hierarchical Clustering and Machine Learning in Python:

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The foundation for this project involves obtaining mineral compositions for
the entire crystal.  After creating biotite and feldspar EDS maps and
collecting trace element profiles, I plan to utilize a hierarchical
agglomerative clustering algorithm for major elements in order to
statistically determine how many clusters of minerals are present in the
fiamme.  Another clustering algorithm will be run using trace elements and
we will compare the results.  Once the clusters are identified, we can
observe whether they correlate with fiamme type and population (Chiaro et
al., in prep).  If we see a correlation, we can confidently use mineral
populations to classify fiamme throughout the Ora Ignimbrite.  We can also
use the mineral maps to visualize core to rim cluster evolution (Fig. 5).
By visualizing where the clusters occur in each mineral and by looking at a
large enough population of core to rim clusters, we can infer whether
crystals experienced similar histories.  This approach may reveal
information regarding the magmatic processes which occurred prior to the Ora
eruption (injection, decompression-driven growth, etc).
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Figure 5: (A-C) BSE and EDS scans of a clinopyroxene phenocryst from the Holuhraun-Bardarbunga eruption in 2014-2015. The circles show the location of the electron microprobe analysis and the color indicates the corresponding cluster from major element analysis. (D) Trace element profiles from A-B. The colors and numbers at the bottom indicate the corresponding cluster identified with major elements. (E) The same as D, but for another crystal that is not shown (from Luca Caricchi).

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We are also interested in identifying the mineral populations that are
present in the ignimbrite matrix and seeing whether this varies throughout
the deposit.  Machine learning algorithms are becoming widely incorporated
in scientific studies, and they provide an opportunity to make tedious
point-counting obsolete.  By utilizing previously determined mineral
clusters (major element-based clustering), we can train a machine to
classify each mineral in a thin section EDS scan into its associated
population.  Furthermore, this automatic clustering can be applied to
multiple large thin sections, allowing for an estimation of bulk eruptive
material.  Initial formulation will involve training a supervised machine
learning algorithm to identify feldspars.  If successful, we will work to
develop an unsupervised neural network algorithm.  The unsupervised neural
network algorithm will effectively create clusters automatically via self-
organizing maps and then it will tag each mineral with its identified
population.
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Spatial Statistics in ArcGIS:

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The spatial distribution of fiamme types and populations has the potential
to reveal the locations of eruptive vents that were destroyed during the
eruption.  Multi-distance spatial cluster analysis (Ripley's k-function) in
Arc-GIS investigates the clustering of features over a defined study area.
Similarly, this may provide insight on the pre-eruptive magmatic
architecture.  For example, if the Ora system had two laterally juxtaposed
magma chambers that were tapped by different eruptive conduits, we would
expect to find two separate clusters with discrete fiamme populations.
Integrating spatial statistics and petrology can help us determine how magma
was stored in the crust prior to eruption (single chamber, multiple
chambers?) and the approximate locations of storage in the x-y plane.  If we
combine our previously obtained Rhyolite-MELTS data to this model, we can
elucidate pre-eruptive storage conditions in three-dimensions.
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Sequence Stratigraphy and Ar-Ar Age Dating:

We propose to investigate whether fiamme type and population change as a supereruption progresses. Our approach will take advantage of the previous work done by Willcock et al. (2013) in which they correlated stratigraphic logs throughout the deposit with observed changes in volcanic lithofacies for 13 intracaldera and 7 outflow stratigraphic sections. More detailed efforts to ascertain the temporal changes of the Ora eruption involved plotting the bulk rock compositions, biotite crystal content, and total crystal content as they varied stratigraphically (Willcock et al., 2015) (Fig. 6). We have identified potential horizons of interest that may signify a change in eruptive material (Fig. 6). By sampling the fiamme types present at these locations, we hope to discover whether there are gradual or instantaneous changes in the fiamme types or populations. Similar to the methodology employed in sedimentary strata with fossil assemblages, we may be able to observe fiamme “extinction horizons” representing the depletion of a magma chamber. We will also utilize this workflow on samples of the ignimbrite matrix with a machine learning algorithm to determine whether we see a change in mineral populations with time. These methods will allow us to extract relative timescales for magmatic events taking place during the Ora supereruption.

Figure 6: Bulk rock compositions, biotite crystal content (Bt), and total crystal content (CF) variation through time. The yellow stars indicate horizons of interest that could show potential changes in eruptive material. Locations 3 and 8 are intracaldera deposits and correlate with Ora 3 and Ora 8. We have yet to sample from location 20, which is just south of the Ora 2 vitrophyre unit. Figure is modified from Willcock et al., 2015.

There has not been much work done regarding age dating for the Ora Ignimbrite. Marocchi et al. (2008) obtained single zircon ages for Ora Ignimbrite of 277 +/- 2 Ma for the intracaldera fill and 274.1 +/- 1.6 Ma for the outflow. These suggest a time break in the eruptive record. Willcock et al. (2015) suggests that Ora experienced a two-stage eruptive history: the southern caldera collapsed first and the northern caldera followed. However, there is no evidence for paleosols or reworked contacts, suggesting that the eruptions were closely spaced in time. The zircon ages are in contrast with the inferred eruption timescale based on stratigraphic evidence. In order to determine whether the Ora eruption lasted for millions of years or was constrained to a shorter time period, we plan to obtain Ar-Ar sanidine ages. Argon is trapped upon eruption so these will provide eruptive ages. We will first determine eruption ages for the intracaldera vitrophyre and the outflow vitrophyre to see if we can resolve discrete ages. If so, Ar-Ar sanidine ages provide a methodology to “deconstruct” a supereruption into distinct volcanic pulses (Kay, 2011). Combined with our work on fiamme type distribution for a stratigraphic column, we may be able to resolve maximum timescales of magma chamber depletion for the Ora system.

References