MELTS-constrained Bayesian Inversions of Magnetotelluric Data to Infer Magma Storage Conditions

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1. Introduction

--The melt fraction of a magma reservoir beneath a volcano is an important parameter which controls the rheology, viscosity, and eruptibility of the partial melt

--Magnetotelluric (MT) methods can constrain melt fraction using models of bulk resistivity (ρ_b)

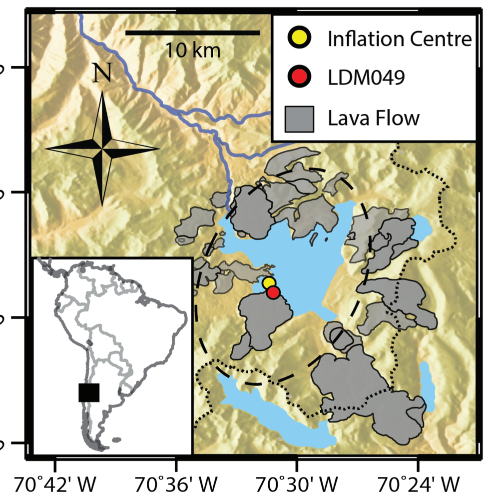
Problem #1: Standard deterministic inversions do not easily offer estimates of uncertainty in ρ_b

Problem #2: Converting from ρ_b to melt fraction relies on many inter-dependent variables, is non-unique, and can result in petrologically-inconsistent situations

--We use a trans-dimensional Bayesian inversion[1, 2] to address Problem #1

--We directly coupled the inversion to a MELTS[3] parameterization to address Problem #2

--As a test case, we apply this method to the restless Laguna del Maule Volcanic Field, central Chile[4], where regions of melt have been imaged using MT[5], seismic[6], and gravity[7] methods but with disparate estimates of melt fraction.



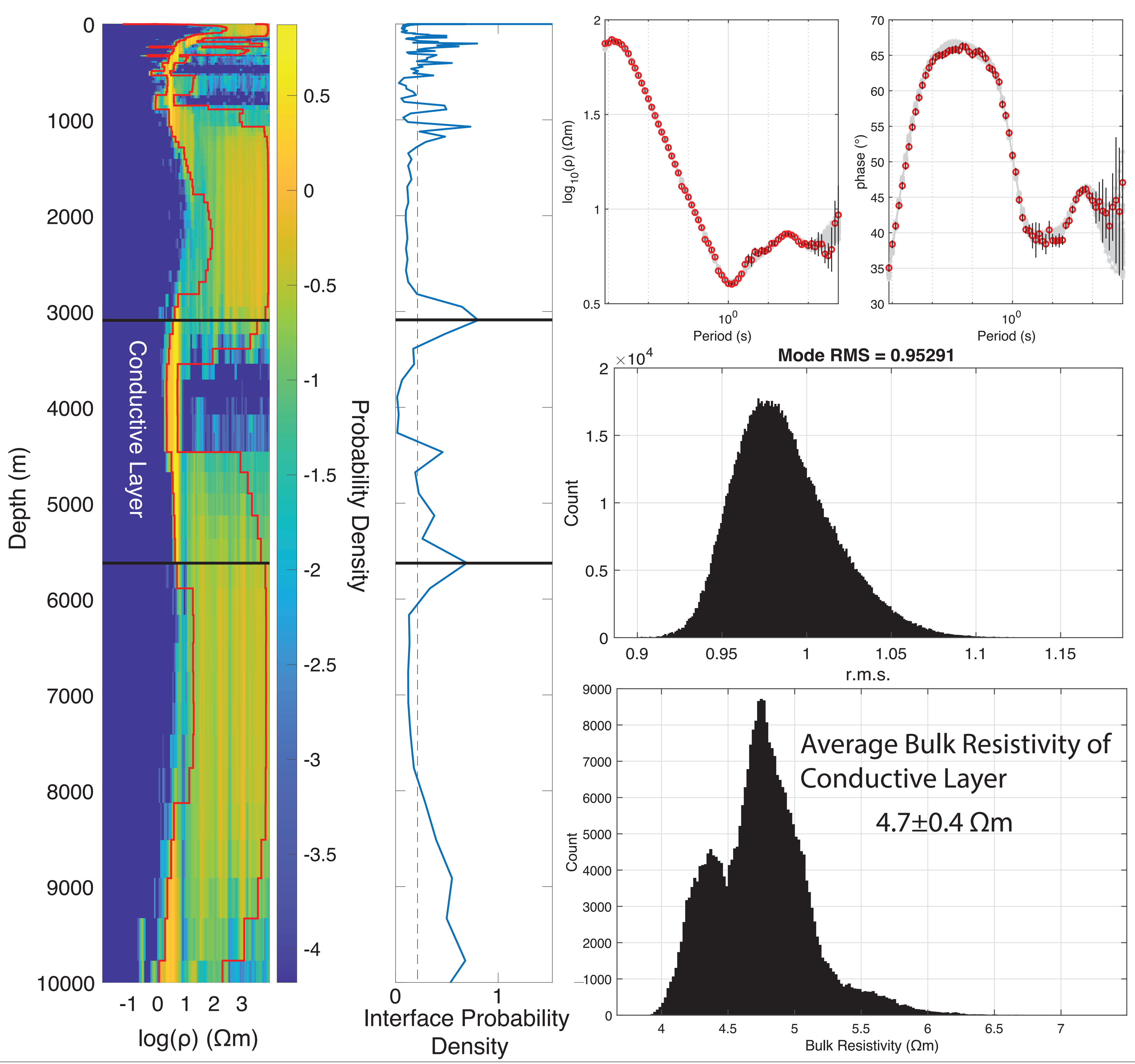
2. Incorporating Uncertainty in Bulk Resistivity

--Bayesian inversions formulate the inverse problem in terms of Bayes' Rule[1]

--Markov Chain Monte Carlo (MCMC) methods are used to efficiently sample the posterior

--This yields an ensemble of hundreds of thousands of models which adequately fit the data

--Site LDM049 was selected based on it's 1-D/2-D characteristics and proximity to the current inflation center. The sum-of-squares impedance was inverted which represents a bulk 1-D average which is less sensitive to galvanic distortion[8]



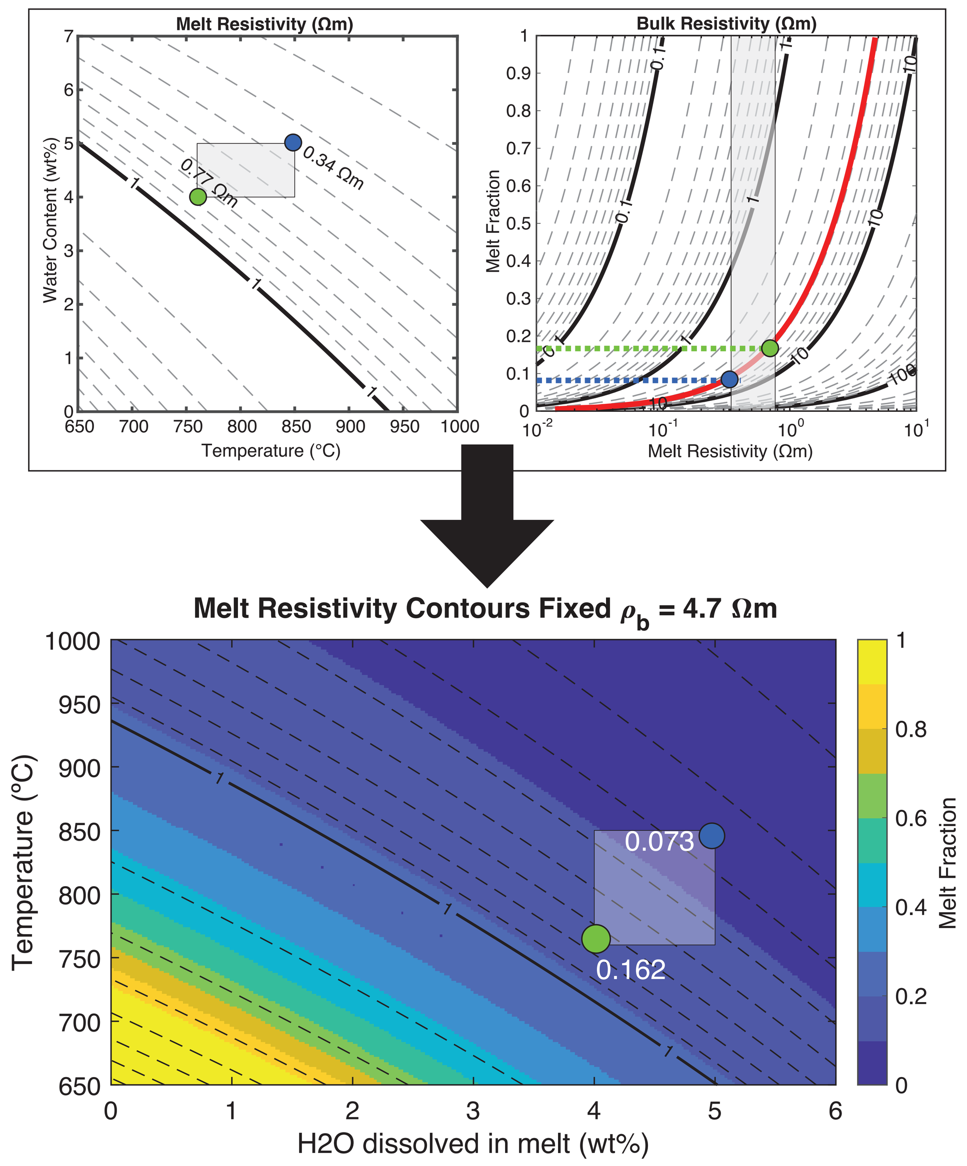
3. Illustration of the Problem

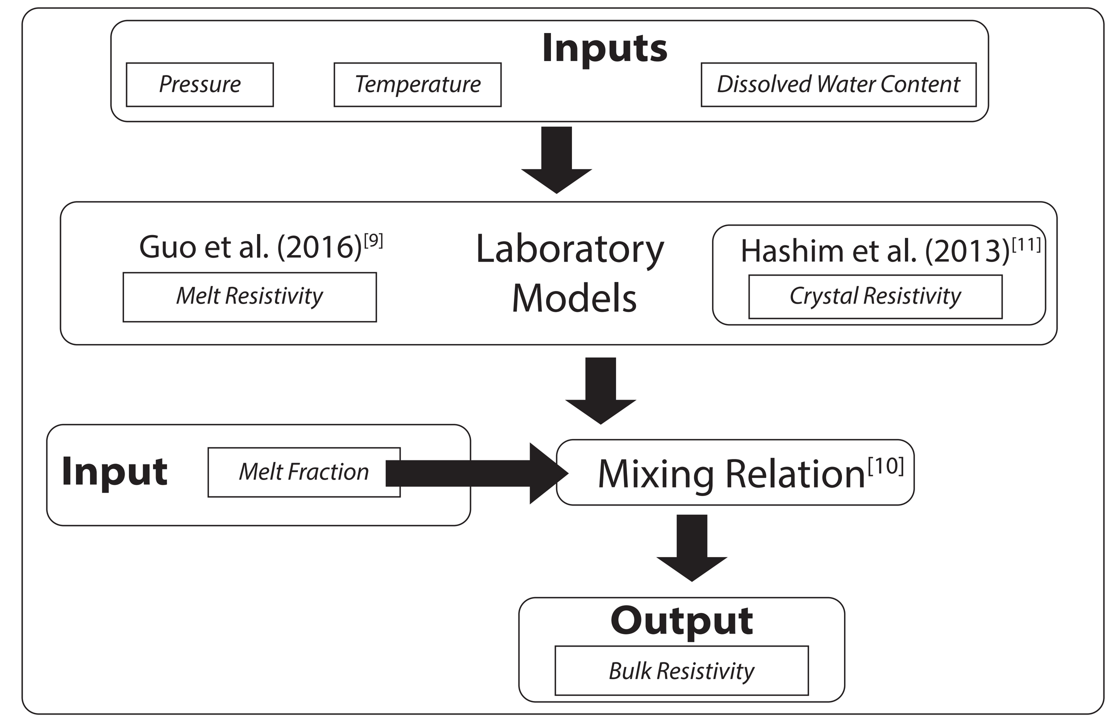
--Using a single bulk resistivity value of 4.7 Ωm at 3–5 km depth below surface, the melt fraction can be estimated

--The "standard" way assumes that melt resistivity and melt fraction are independent variables in a mixing relation

--Petrological studies[4] suggest magma storage at temperatures of 760-850°C and water contents of 4-5 wt% in the melt

--Melt resistivity[9] varies from 0.34–0.77 Ωm, yielding melt fractions[10] of 7 - 16 vol% using the standard approach





--Problem #1: Relying on a single ρ_b estimate ignores the uncertainty in ρ_b and hence uncertainty in melt fraction estimate

--Problem #2: Increasing temperature and/or water content lowers melt fraction estimates! This is the opposite of thermodynamically-consistent melting relationships, where melt fraction increases with increasing temperature/water content

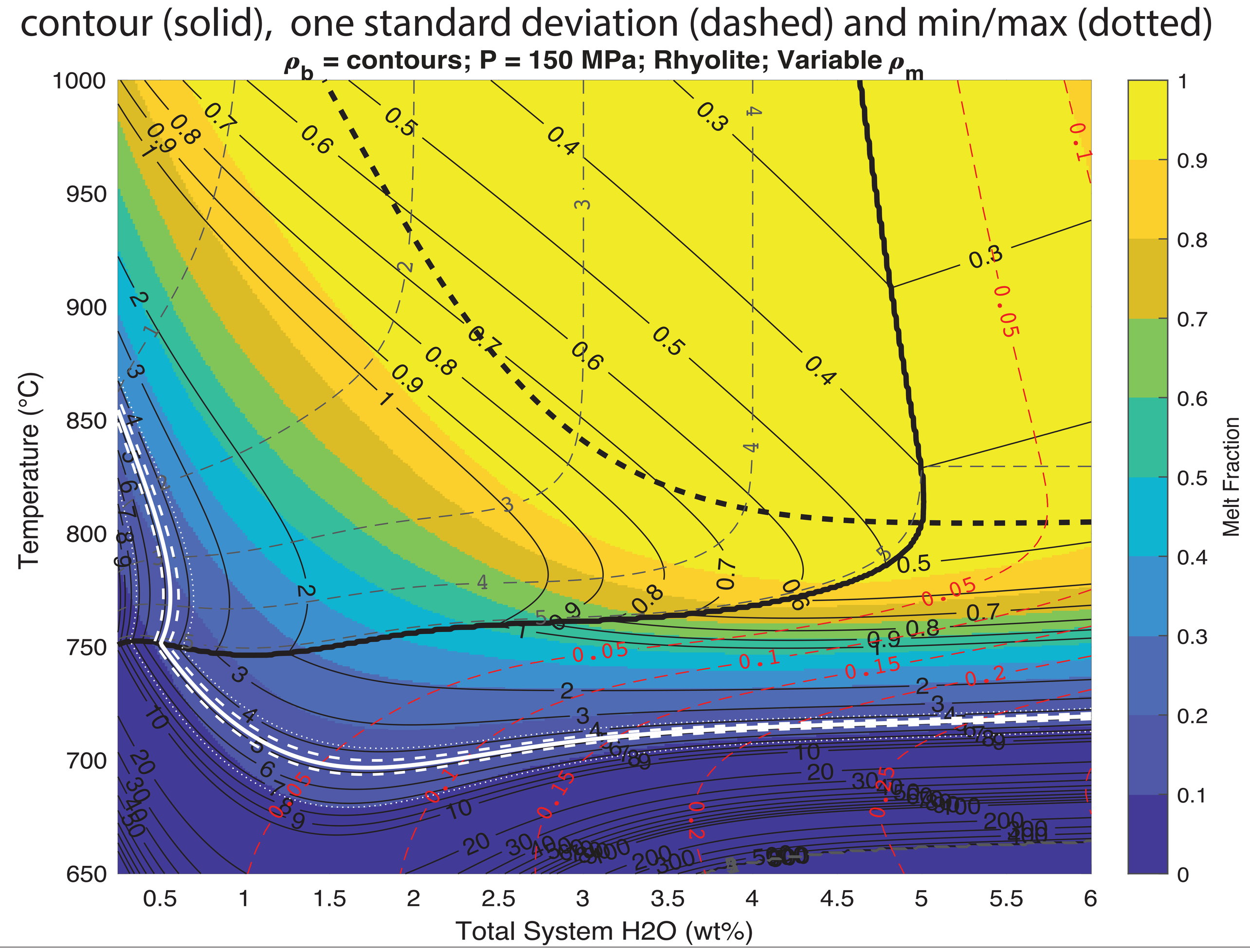
--Problem #3: No reference to saturation or volatile phases

4. Incorporating MELTS Thermodynamic Constraints

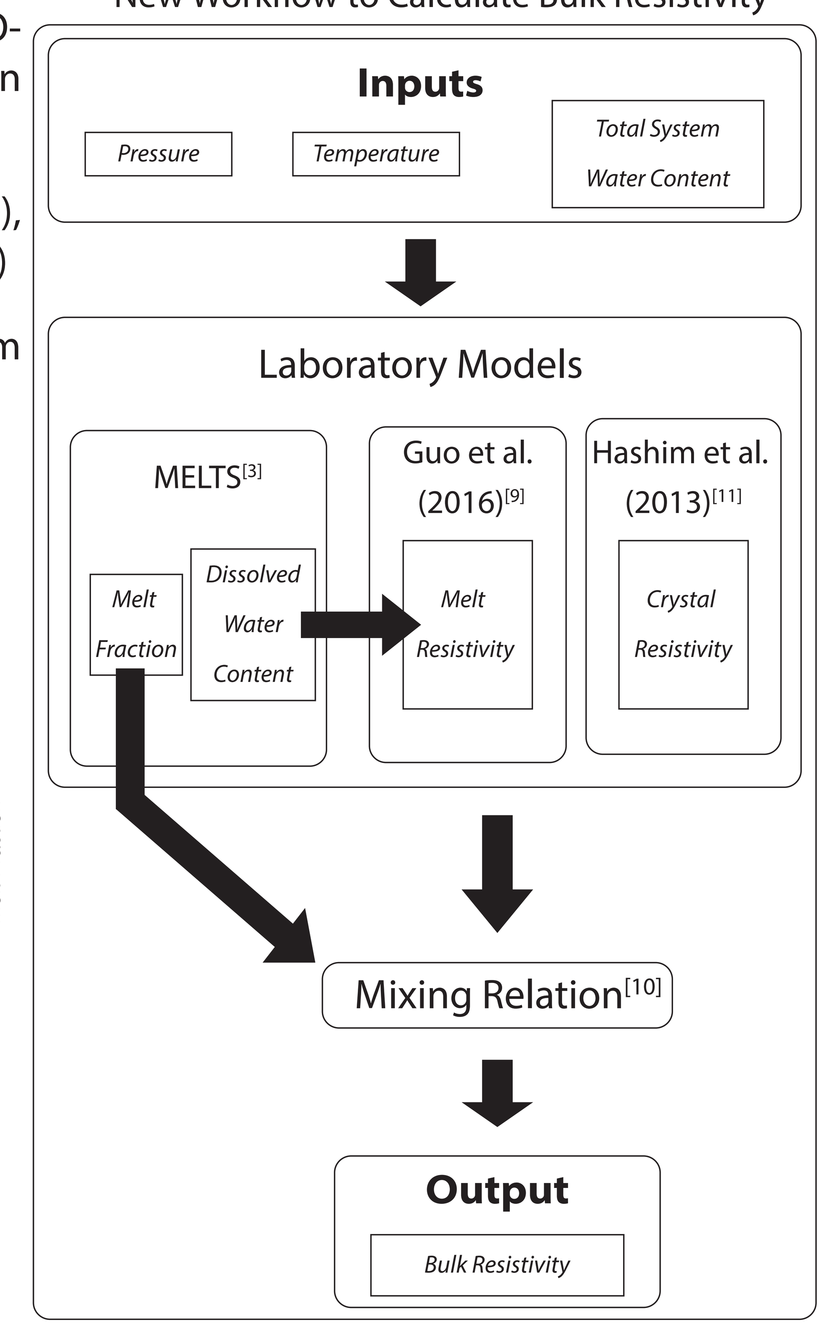
--We performed closed-system equilibrium crystallization simulations with rhyolite-MELTS[3] on an average Andean rhyolite composition from GEOROC[12]. The output was used to parameterize expressions for melt fraction and free fluid as a function of temperature, pressure and total H_2O.

--H_2O saturation curve[13] (thick black line), liquidus (thick dashed line), melt H_2O content (dashed grey lines), free fluid fraction (dashed red lines)

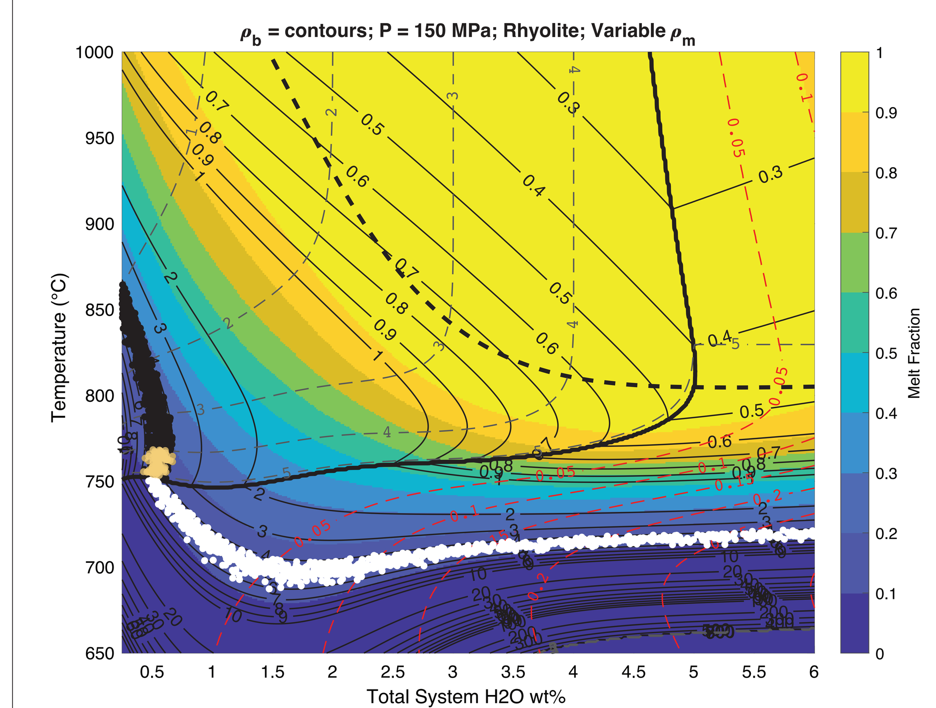
--Solid black contours are bulk resistivity. White lines shows the 4.7 Ωm contour (solid), one standard deviation (dashed) and min/max (dotted)

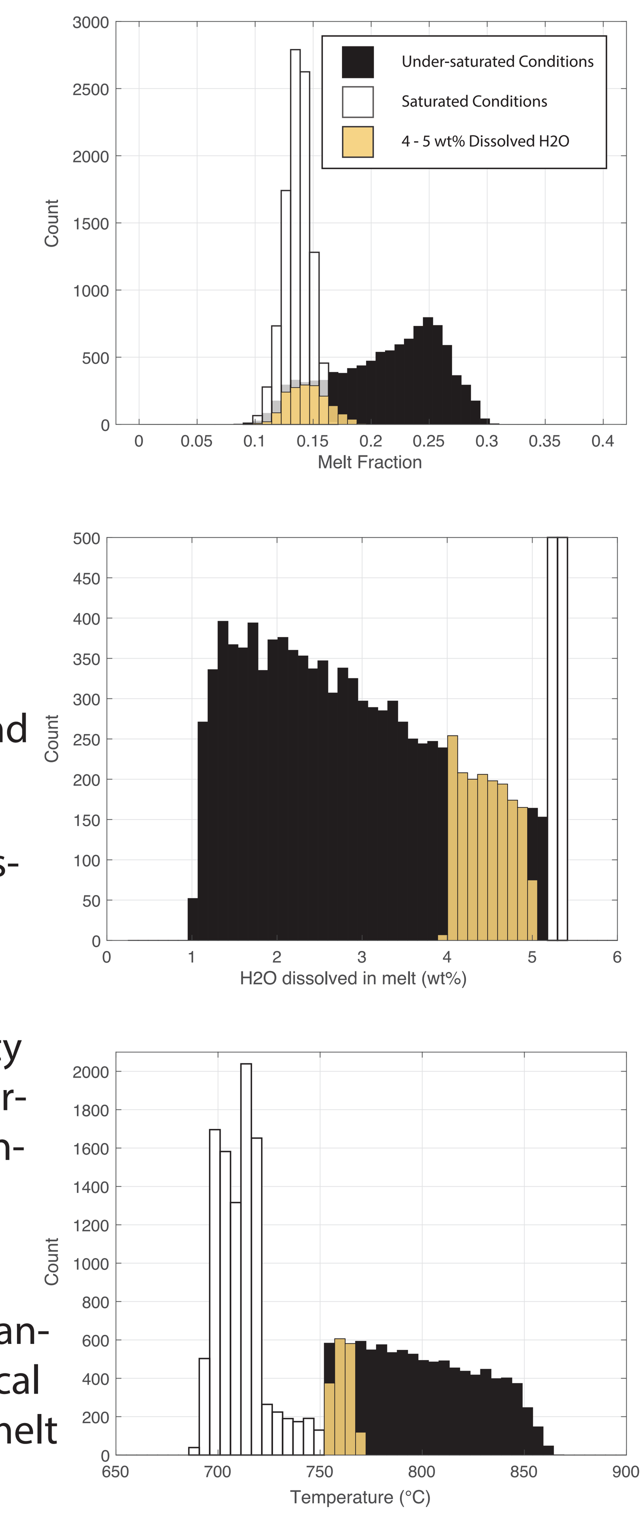


New Workflow to Calculate Bulk Resistivity



5. Estimates of Magma Storage Conditions





--Randomly sample the bulk resistivity distribution and uniform temperature and H2O distributions

--This suggests melt fractions between 9% to 31%, dissolved water content between 1.0 and 5.2 wt% , and temperatures >750°C for under-saturated conditions

--Comparing the conditions matching a bulk resistivity of 4.7 Ωm with petrological estimates[4] of magma storage at LdM suggests melt fractions of 9 -19 vol% at under-saturated or near fluid-saturated conditions and temperatures between 753°C to 769°C

--The melt fraction range is very similar to previous standard estimates, but the new method provides statistical bounds on physical state, melt volatile content, and melt fraction which are thermodynamically consistent

6. Conclusions and Additional Thoughts

--The bulk resistivity measured by MT and the estimates from MELTS align extremely well with the temperature and water content ranges suggested by petrological investigations of the LdM system. Future studies will investigate whether this approach can be applied other volcanic systems.

--Our novel method provides thermodynamically-consistent estimates of melt fraction, temperature, and water content for under-saturated magmas and avoids petrologically inconsistent interpretations.

--What about saturated magmas? Geophysical interpretations often avoid the complication of three-phase systems. If the volatile phase is resistive and super-critical, then melt fraction is well-constrained in the saturated regime, but total system water content is not. If the volatile phase is conductive brine, then the opposite is true. More work is needed to constrain the physical properties of the volatile phase.

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Acknowledgements

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