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Patterns of crustal magma transport in arcs revealed by comparing geophysical observations with volcanic topography

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Understanding magma migration beneath Earth's surface is a key barrier to predicting volcanic eruptions and associated human hazards. However, the multiscale and subsurface nature of crustal magma transport makes it challenging to study. Cycles of eruptive phenomena at long-lived volcanic centers may span 10s of kyr, longer than any direct observational record. But active monitoring does constrain a diversity of subsurface magmatic activity that can test generic models of magma transport. Here we use geophysical data to examine one hypothesis, that surface volcanic topography encodes the spatial patterning of deeper magma transport in arcs. We present and analyze two datasets at different spatial scales: 1) A global compilation of 67 magma chamber centroids beneath arc stratovolcanoes inferred from published ground deformation and seismic/magnetotelluric tomography studies, and 2) A compilation of 3000 Quaternary vents from the Cascades, USA, that contains locations, vent types, and Geologic epoch of the last known eruption, along with arc-scale seismic tomography, heat flow, and GPS-derived strain rate. Alongside geophysical data, we quantify the topographic expression of volcanic edifices associated with vents or deeper magma chambers by analyzing digital elevation models (DEMs).

At volcano scales, our compilation reveals that magma chambers can be significantly laterally offset from overlying volcanic edifices. While many magma chambers are centrally located, >20% of all imaged magma chambers lie further than one edifice radius away from the topographic centroid of the volcano. Edifice height generally correlates with magma chamber depth, despite diversity in edifice type, average composition, and subduction zone parameters. Viewed globally, shallow (<15 km depths) magma storage beneath long-lived arc volcanoes tends not to reflect 'textbook' vertical plumbing but rather a distributary system that appears roughly predictable based on overlying edifice dimensions. We hypothesize that the evolving thermal and stress history of crust under a given volcano – and the history of magma transport itself – determines the lateral extent of crustal transport pathways.

At the scale of the Cascades arc, volcanic topography is most naturally compared with regional-scale geophysical imaging. Topographic analysis of DEMs, using a closed-contour approach to extract volcanic edifices, gives a spatially averaged Quaternary extrusion rate for the northern Cascades of ∼59 km3/Myr, while for the southern Cascades the extrusion rate is ∼699 km3/Myr. This major N-S dichotomy in eruption rates mirrors arc-scale variations in the spatial patterning of edifices, surface heat flow, 1-10 km depth average shear velocity perturbation, and GPS-derived strain rate magnitudes. Holocene vents exhibit stronger correlations with geophysical anomalies than early Pleistocene vents. This suggests that subsurface transport pathways migrate significantly on Myr timescales in concert with surface vents, modulo local magma chamber lateral offset from individual volcanoes. Topographic form in volcanic provinces may thus encode the spatial patterning of subsurface magma transport.