

SPECIAL COLLECTION: PERSPECTIVES ON ORIGINS AND EVOLUTION OF CRUSTAL MAGMAS

## Dynamics and thermodynamics of magma mixing: Insights from a simple exploratory model

FRANK J. SPERA<sup>1,\*</sup>, JASON S. SCHMIDT<sup>1</sup>, WENDY A. BOHRSON<sup>2</sup>, AND GUY A. BROWN<sup>3</sup>

<sup>1</sup>Department of Earth Science, University of California, Santa Barbara, California 93106, U.S.A.

<sup>2</sup>Department of Geological Sciences, Central Washington University, Ellensburg, Washington 98926, U.S.A.

<sup>3</sup>Rocking Hoarse Professional Services, 691 Chelham Way, Santa Barbara, California 93108, U.S.A.

### ABSTRACT

The mixing of magmas of distinct temperature, bulk composition, mineralogy, and physical properties plays a central role in explaining the diversity of magma types on Earth and in explaining the growth of continental and oceanic crust. Magma mixing is also of practical importance. For example, the mixing of distinct magmas has been cited as an important process in creation of economically important horizons in layered intrusions as well as a triggering mechanism for initiation of volcanic eruptions. The motivation for better quantifying the dynamics and thermodynamics of magma mixing and its attendant plutonic and volcanic products is clear. The degree of magma mixing, which spans a continuum from mingling to complete hybridization, depends upon initial and boundary conditions, magma properties, driving forces, and time available for mixing. Magma mingling produces a heterogeneous mixture of discrete clumps of the end-member magmas, whereas complete hybridization involves the thermodynamic equilibration of two distinct magmas to form a third. Qualitatively, mixing occurs via reduction in the size of compositional heterogeneities (i.e., clumps) through stretching and folding by viscous flow, followed by homogenization, once shear has reduced the size of compositional anomalies to diffusive length scales. Quantification of this process relies on two statistical measures: the linear scale of segregation ( $\Lambda$ ) defined as the spatial integral of the compositional correlation function related to the size-distribution of the segregated clumps within the mixture, and the intensity of segregation ( $I$ ) a measure that quantifies how much the composition at each location differs from the average. The mixing dynamics of a layered system are analyzed in terms of the parameters governing mixing (Rayleigh, Lewis, and buoyancy numbers and viscosity ratio) to estimate how the timescale for magma hybridization,  $\tau_{\text{H}}$ , compares to solidification, recharge, diffusive, and assimilation timescales. This analysis illustrates that hybridization times can be shorter than or comparable to thermal, solidification, and replenishment timescales; thus, formation of hybridized or nearly hybridized magmas is one anticipated outcome of mixing. The machinery of thermodynamics can be used to compute the hybrid magma state. An exploratory model for the thermochemistry of hybridization is developed based on binary eutectic phase relations and thermodynamics. Eight thermodynamic parameters define the phase diagram and associated energetics, and six parameters (initial temperatures, compositions, mass ratio of mixing magmas, and an enthalpy parameter) are necessary and sufficient to determine the state of hybrid magma uniquely. While relevant combinations of 14 thermodynamic and mixing parameters might suggest that the number of mixing outcomes (i.e., products) is too high to systematize, Monte Carlo simulations using the exploratory model document how millions of arbitrary initial states evolve into five possible final (mixed) states. Such an analysis implies that a magma mixing taxonomy that defines possible mixed product states can be developed and tied to petrologic indicators of mixing. Additional insights gained from this exploratory model that are supported by independent results from a multicomponent, multiphase thermodynamic model of magma mixing (Magma Chamber Simulator) include: (1) the proclivity of invariant point hybrid states, which may explain some instances of compositionally monotonous melts associated with mixed magma eruptions; (2) a surprising thermal effect such that the temperature of hybridized magma can be significantly less than the initial temperature of either of the mixing magmas. This type of magma mixing may result in crystal resorption, thus invalidating an assumption that resorption textures in crystals are typically the result of a magma heating event; (3) illustration of the differing effects of stoned block temperature and composition on hybrid magma temperature and phase state; and (4) illustration of a cessation of crystallization effect that may pertain to the MORB pyroxene “paradox.” Differences between adiabatic or R-hybridization and diabatic or RFC-hybridization are also explored. The model can be used to elucidate the thermodynamic principles underlying magma mixing in the hybridization limit. These principles are of general applicability and carry over to more compositionally complicated systems.

**Keywords:** Magma mixing, hybridization, thermodynamics, recharge