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A generalized multi-phase theory for reactive transport in magmatic and volcanic systems

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Many pertinent processes in magmatic and volcanic systems involve mechanical and thermodynamic interactions between multiple material phases, including solids, liquids, and gases. These phases are typically present as microscopic structures including crystals, melt films, bubbles, and melt droplets. The direct modeling of interactions at the local scale of individual interfaces is impracticable if the system-scale behavior of interest is many order of magnitude larger. In these instances it may be favorable to formulate mixture models, that represent reactions and transport for multi-phase materials as continuum fields of spatially averaged phase quantities. This approach has been used successfully to model melt transport in the mantle by two-phase porous flow, and to model settling of crystals by two-phase suspension flow. However, these end-member models are limited to their special case and do not generalize readily to different phase proportions or material properties, or indeed more than two phases, all of which may be called for in certain magmatic and volcanic systems.

Here, we derive a generalized multi-phase theory for reactive transport in magmatic and volcanic systems formulated for mixtures of arbitrary number and type of material phases, and chemical compositions. Based on general conservation laws for mass, momentum and energy in a n-phase, m-component mixture, we use the entropy principle to constrain permissible constitutive relations for averaged phase interactions, diffusive fluxes, and source terms. While we follow canonical choices for the latter two, we present a new way to formalize the former phase interaction or transfer rate terms. These govern the processes of thermal equilibration, chemical reaction, segregation, and compaction. They are each controlled by phase interaction coefficients, which need to be further constrained by analogue experiments, direct numerical modelling, or mathematical homogenization of idealized microstructural models. This new theoretical framework for building models of reactive multi-phase flows in magmatic and volcanic systems elucidates the common features of diverse multi-phase processes, such as porous and suspension flows, which are special limits of this generalized theory.