Partitioning of trace elements among coexisting crystals, melt, and supercritical fluid during isobaric crystallization and melting

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ABSTRACT

The distribution of trace elements among coexisting crystals, melt, and supercritical fluid during melting and crystallization is a critical constraint for understanding the evolution of magmatic systems, including the origin and development of continental and oceanic crust. Although trace-element partitioning between crystals and melt during Rayleigh fractional crystallization or melting is well-known, partitioning among co-existing melt, crystals, and supercritical fluid during anatexis or crystallization is less explored despite the ubiquity of magmatic fluids. Here we develop the trace-element differential equations governing solid-melt-fluid equilibria for melting and crystallization under fluid-present conditions and provide analytical solutions for fractional and equilibrium crystallization and melting. A compilation of solid-fluid and melt-fluid distribution coefficients for about 30 trace elements in olivine, clinopyroxene, garnet, plagioclase, alkali feldspar, biotite, amphibole, apatite, and silicic melts is provided. Forward modeling demonstrates the conditions under which fluid-melt-solid partitioning will impact trace-element signatures in magmatic systems. We show that for trace elements soluble in aqueous fluids, the composition of a melt derived by fluid-present fractional crystallization or by fluid-present fractional melting will be significantly different than in otherwise comparable fluid-absent systems. Ignoring the partitioning of soluble elements into the fluid phase leads to large errors in concentrations (over 100%) and ratios and consequent misinterpretation of the trace-element character of source material and/or the processes of fractional crystallization and melting. Although significant in any setting involving fluid-present equilibria, this analysis may have a most profound influence on fluid-present subduction zone magma generation and the evolution of shallow level fluid-saturated silicic magmatic systems.

Keywords: Distribution coefficient, fluid-saturated magma, fluid-melt, solid-melt, trace element

INTRODUCTION

Magmatic processes including fractional or equilibrium crystallization or melting under isochoric or isobaric conditions, combined recharge-assimilation-fractionation, isentropic decompression melting, and volatile-fluxed melting are relevant to the eruption and intrusion of about 30 km3 of magma per year on Earth in various petrologic environments (e.g., White et al. 2006). Magmatism is one of the principal mechanisms of mass transfer among terrestrial geochemical reservoirs, and understanding the partitioning of elements during magmatic processes is a keystone for understanding global geochemical cycling. In particular, petrogenesis relies on quantitative analysis of the distribution of trace elements among coexisting crystals, melt, and supercritical fluids during phase transitions such as melting, crystallization, and fluid exsolution. It has been argued that water is essential for the formation of granite and, in turn, granite is essential for the formation of continents. Earth, the only terrestrial planet with abundant water, is the only planet with granitic cratons and continents (Campbell and Taylor 1983). Fluids are ubiquitous in the terrestrial crust and mantle and are essential components of magmatic-hydrothermal systems, which concentrate intrinsically low abundance trace elements (e.g., Cu, Mo, W, Sn, etc.) to form economic mineral deposits (Holland 1972; Burnham 1979; Candela 1989). Fluids also significantly influence magma transport and thermodynamic properties, and have dynamical consequences including contributing to explosive volcanic eruptions. Fluid components are recycled into the upper mantle by subduction of hydrated oceanic crust (sediments and altered mafic crust) and may enter the transition zone and lower mantle (Litovitz et al. 2003; Ohtani et al. 2004). Fluids derived from slab dehydration exert important constraints on the trace-element signatures of melts generated by anatexis of metasomatized (carbonated and hydrated) peridotite (McCulloch and Gamble 1991; Plank and Langmuir 1998; Stern 2002; Elliott 2003; Kelemen et al. 2003; Tatsumi 2005) or subducted lithospheric sources (Defant and Drummond 1990). Prouteau et al. (1999) have argued that slab melting in modern subduction zones occurs under fluid-present conditions at tem-