Implications of equilibrium and disequilibrium among crystal phases in the Bishop Tuff

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ABSTRACT

Eruption of the Bishop Tuff magma preserved equilibrium of exchange components and element concentrations among magnetite, ilmenite, biotite,apatite, zircon, and liquid. Orthopyroxene andclinopyroxene were not in exchange equilibrium with the other MgFe-bearing phases, but they appear to have been in equilibrium among themselves. Internally consistent temperatures recorded by the FeTi-oxide, Ti-in-quartz, and Δ40O quartz-magnetite thermometers, coupled with evidence for magmatic corrosion of quartz and sanidine, indicate that an initially low-T (∼700 °C), near-H2O-saturated, high-SiO2 rhyolite magma was heated up to ≥800 °C and its crystal cargo partially melted by recharge of hotter melt from below. Oxygen fugacity and compositions of biotite, ilmenite, magnetite, and silicate liquid initially adjusted by internal rearrangement of components and conservation of oxygen. Partial melting of feldspars liberated Sr and Ba back into the melt. Mixing during recharge eventually re-introduced compatible elements (e.g., Mg, Ba, Sr) as well as foreign crystals of euhedral ortho- and clinopyroxene, which evidently never totally re-equilibrated with the rhyolite liquid. Introduction of CO2 and accompanying reduction in the aH2O during recharge raised crystallization temperatures of quartz and sanidine in the rhyolite sufficient to allow marginal regrowth of these phases with enhanced contents Ti, Ba, and Sr.

Keywords: Bishop Tuff, Supervolcanoes, silicic magma, petrogenetic processes, disequilibrium

INTRODUCTION

Many studies on large silicic pyroclastic deposits (ignimbrites) have reported the preservation of original thermal gradients of 100–150 °C (700 to >800 °C) from early to late-erupted material (over length scales of tens to hundreds of meters; e.g., Lipman 1971; Hildreth 1979; Wolff et al. 1990; Mills et al. 1997; Matthews et al. 2012). These thermal gradients were revealed by microprobe analysis of the Fe-Ti oxides, which systematically change composition from the base to the top of stratigraphic sections. Assuming thermodynamic equilibrium, temperatures were estimated from these oxides using experimental/theoretical calibrations (Buddington and Lindsley 1964; Andersen et al. 1993; Ghiorso and Evans 2008). For the Bishop Tuff, however, the assumption of quenched Fe2+Ti3+ exchange equilibrium between ilmenite and magnetite, and consequently the reliability of extracted temperatures, was questioned (Lindsley et al. 1990, 1991; Ghiorso and Sack 1991; Frost and Lindsley 1992) on the following grounds: (1) the granite-minimum ("eutectic") assemblage (Qtz, San, Plag, L, V) close to H2O saturation could not be stable (as it appears to be) over the measured 100 °C temperature range, and (2) the compositions of FeTi-oxide minerals and pyroxenes failed to correlate in a manner appropriate for chemical equilibrium. Barometry based on the oxides + pyroxene + quartz assemblage produce a range of P values (from <0 to 5 kb) that are hard to reconcile with independent constraints. These authors concluded that the ilmenite had undergone late- or post-eruption re-equilibration and that oxide temperatures substantially below the 824 ± 15 °C two-pyroxene temperature were unreliable. Therefore, a sizeable thermal gradient may not have existed in the magma reservoir; it was instead an artifact of additional, poorly understood and late- or post-magmatic processes.

This paper presents a reassessment of thermodynamic equilibrium among the various Fe/Mg-bearing minerals of the Bishop Tuff (namely ilmenite, magnetite, biotite, orthopyroxene, and clinopyroxene) and the silicic melt using published data. We use Roozeboom plots, as commonly employed in metamorphic petrology, to assess thermodynamic exchange equilibrium among the coexisting phases. All selected oxide pairs used have passed the Hirschmann and Bacon (Mn/Mg) test (Hildreth and Wilson 2007). Hence, there is no a priori reason for rejecting or questioning the reliability of the temperature estimates based on Fe-Ti oxides (Fig. 1).

The Fe/Mg ratios of magnetite, ilmenite, and biotite, using analyses from Hildreth (1979) and Hildreth and Wilson (2007) plot in a manner strongly suggestive that these phases crystallized close to mutual element-exchange equilibrium (Fig. 2). Roozeboom plots ordinarily show curvature, and they terminate at 0:0 and 1:1. The Fe/Mg composition of the melt also appears to be in equilibrium with these minerals (Anderson et al. 2000). In contrast, orthopyroxene andclinopyroxene, found mostly in the late-erupted, hotter, and more crystal-rich parts in the deposits, fail to pass this test of exchange equilibrium with the FeTi oxides and biotite. The two pyroxenes show constant values of XMg2, while the oxide minerals and biotite exhibit positive correlations that extend in the case of the FeTi-oxides virtually to XMg = 0 (Fig. 2). Orthopyroxene and clinopyroxene do, however, appear to be in equilibrium with each other. The minor element compositions ofapatite and zircon vary consistently with temperature (Hildreth and Wilson 2007, p. 974), so we include them among the equilibrium minerals.

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In the following, we cite further reasons for considering that the pre-eruptive temperature range measured by Fe-Ti oxides in the Bishop Tuff is robust and reliable.

(1) Only chilled, unoxidized glassy samples with homogeneous oxide pairs were used for TdfO2 determination (Hildreth and Wilson 2007, p. 973).