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A fresh look at crystals in the Bishop Tuff

MICHEL PICHAVANT

Institut des Sciences de la Terre d'Orléans, Orléans, France
pichavan@cnrs-orléans.fr

Crystals are essential components of magmas. Igneous rock series are often distinguished from the nature of the crystals they carry. With the continuing development of analytical capabilities, crystals are receiving increasing attention as sources of information on igneous processes. Certain types of crystals provide absolute ages. Others record chemical gradients that relate to magmatic timescales. Equilibria between crystals enable magmatic conditions, such as pre-eruptive temperatures, to be precisely determined. Crystal textures reveal discrete igneous processes such as growth, dissolution and mixing, among others. One could say that the ecology of crystals in magmas is very rich, including phenocrysts, microlites, xenocrysts and antecrysts, to name just a few types. To assess the significance in igneous systems of any given crystal, or crystal population, is clearly a difficult task.

The Bishop Tuff (eastern California) is the product of one of the greatest Quaternary eruptions. Studies in the last 30 years have established the Bishop Tuff as the reference system for zoned large volume rhyolitic eruptions Due to the influential work by Hildreth (1979), Bishop Tuff eruption products have been scrutinized using new approaches and techniques. Models for the pre-eruptive evolution of the Bishop Tuff have been and are still being refined. Several aspects of the Bishop Tuff magma chamber continue to challenge scientific understanding such as, for example, the anticorrelation between crystallinity and temperature, and the marked fO_2 zonation frozen in the deposits. As an example, the validity of the $\geq$ 100°C pre-eruptive temperature gradient in the Bishop Tuff magma chamber has been questioned on the basis that Fe-Ti oxide crystals were re-equilibrated at low temperatures (Frost and Lindsley, 1992; Ghiorso and Sack, 2001).

In a recent issue of American Mineralogist, Evans and Bachmann (2013) take a fresh look at crystals in the Bishop Tuff. They present a reassessment of thermodynamic equilibrium between the different ferromagnesian crystals present in the rhyolitic magma. They show that the composition of magnetite, ilmenite and biotite is consistent with mutual Fe/Mg equilibrium. The interstitial rhyolitic melt also appears to be in equilibrium with those crystals. In contrast, orthopyroxene and clinopyroxene show constant Fe/Mg, uncorrelated with those of the other ferromagnesian minerals. Evans and Bachmann (2013) conclude that the pyroxenes in the Bishop Tuff are not in chemical equilibrium with the oxides, and that they should not be incorporated into any sort of test of Fe-Ti oxides temperatures. The Bishop Tuff thus appears to include a volumetrically dominant crystal-melt fraction at near-chemical equilibrium and a minor population of out-of-equilibrium crystals. This is a case of partial equilibrium typical of most silicic-intermediate magmas (Pichavant et al., 2007).

One important practical conclusion of the results of Evans and Bachmann (2013) is that the reliability of temperature estimates based on Fe-Ti oxide pairs is reinforced. This in turn supports the existence of a strong thermal zonation in the pre-eruptive rhyolitic magma body, from ~ 700°C to ~ 830°C (Hildreth and Wilson, 2007). Evans and Bachmann (2013) note that the Fe-Ti oxide data are consistent with other independent thermometric evidence from Ti in quartz and $^{16/18}O$ quartz-magnetite partitioning. The lowest estimated temperatures (~ 700°C) fit well with experiments on the early plinian fall by Scaillet and Hildreth (2001). Such a temperature range for the upper portion of the magma body requires H_2O-rich conditions (5-6 wt%), in agreement with independent evidence from melt inclusions and equilibria involving biotite. It is worth stressing here that, for a given pressure (e.g., 2 kbar), temperatures of equilibration of a quartz-sanidine-plagioclase-melt assemblage can vary by > 100°C (see for example Dall'Agnol et al., 1998) depending on the melt H_2O content and, to a lesser extent, on the melt Na/Ca or plagioclase An content. Therefore, there is no necessity that quartz-sanidine-plagioclase-melt assemblages indicate temperatures of ~ 700°C.

Evans and Bachmann (2013) place their results in the context of the recharge model of Hildreth and Wilson (2007) and Wark et al. (2007). The temperature zonation in the Bishop Tuff magma chamber, and its preservation for significant timescales, is driven by the episodic remobilization of a batholitic-scale crystal mush from which rhyolite magma batches are periodically extracted and mixed with previously segregated magmas. The temperature zonation recorded in the Bishop Tuff deposits is therefore a transient feature (Hildreth and Wilson, 2007; Evans and Bachmann, 2013) imposed by the fluid dynamics of the periodically remobilized and recharged reservoir.

Although this model accounts well for most data and observations, certain aspects may require further clarification, such as the strong pre-eruptive fO_2 gradient ($\geq$ 1 log unit relative to the NNO buffer). Evans and Bachmann (2013) provide an elegant explanation of this puzzling observation. They argue that a relative fO_2 increase of 1 log unit as seen in the deposits is perfectly consistent with a temperature increase of 100°C of the magma. In other words, the fO_2 gradient would be the consequence of the thermal zonation of the reservoir. Their analysis is, however, based on an oxygen conservative, closed-system, re-equilibration mechanism upon heating, a critical assumption that may well require confirmation. Mutual compatibility between the closed-system re-equilibration and recharge models is yet to be demonstrated. The Bishop Tuff rhyolitic magma is also characterized by marked H_2O and CO_2 concentration gradients, implying mobility of volatiles at the scale of the reservoir. Intuitively (assuming constant fH_2 across the entire chamber), the H_2O-rich upper rhyolitic cap would be expected to be more oxidized than the drier CO_2-fluxed mush, ie, the reverse to what is actually observed. Additional studies on these and other questions would certainly continue to foster interest about the Bishop Tuff, this fascinating natural laboratory.

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