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The Grizzly Lake complex (Yellowstone Volcano, USA): Mixing between basalt and rhyolite unraveled by microanalysis and X-ray microtomography

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ABSTRACT

Magma mixing is a widespread petrogenetic process. It has long been suspected to operate in concert with fractional crystallization and assimilation to produce chemical and temperature gradients in magmas. In particular, the injection of mafic magmas into felsic magma chambers is widely regarded as a key driver in the sudden triggering of what often become highly explosive volcanic eruptions. Understanding the mechanistic event chain leading to such hazardous events is a scientific goal of high priority. Here we investigate a mingling event via the evidence preserved in mingled lavas using a combination of X-ray computed microtomographic and electron microprobe analyses, to unravel the complex textures and attendant chemical heterogeneities of the mixed basaltic and rhyolitic eruption of Grizzly Lake in the Norris-Mammoth corridor of the Yellowstone Plateau volcanic field (YVF). We observe evidence that both magmatic viscous inter-fingering of magmas and disequilibrium crystallization/dissolution processes occur. Furthermore, these processes constrain the timescale of interaction between the two magmatic components prior to their eruption. X-ray microtomography images show variegated textural features, involving vesicle and crystal distributions, filament morphology, the distribution of enclaves, and further textural features otherwise obscured in conventional 2D observations and analyses. Although our central effort was applied to the determination of mixing end members, analysis of the hybrid portion has led to the discovery that mixing in the Grizzly Lake system was also characterized by the disintegration and dissolution of mafic crystals in the rhyolitic magma. The presence of mineral phases in both end member, for example, forsteritic olivine, sanidine, and quartz and their transport throughout the magmatic mass, by a combination of both mixing dynamics and flow imposed by ascent of the magmatic mass and its eruption, might have acted as a "geometric perturbation" of flow fields further fuelling mass exchange between magmas in terms of both chemical diffusion and crystal transfer. These results illuminate the complexity of mixing in natural magmatic systems, identifying several reaction-related textural factors that must be understood more deeply in order to advance our understanding of this igneous process.

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1. Introduction

Magma mixing is a geological process that initiates when two or more magmas physically mingle leading to mutual chemical adaptation (e.g., Flinders and Clemens, 1996). Mixing plays a fundamental role in influencing petrological processes such as fractional crystallization, assimilation, and partial melting, causing both chemical and thermal disequilibrium (Anderson, 1976). Furthermore, the injection of mafic magmas into felsic magma chambers is regarded as a key process in triggering highly explosive volcanic eruptions (e.g., Sparks et al., 1977; Murphy et al., 1998; Leonard et al., 2002; Perugini and Poli, 2012). The main evidence of mixing in igneous rocks is commonly preserved as textural heterogeneities, such as (i) flow structures, (ii) magmatic enclaves, and (iii) physicochemical disequilibria in melt and crystals (e.g., Perugini and Poli, 2012; Murphy et al., 1998; Couch et al., 2001; Morgan and Blake, 2006). From the geochemical and mineralogical point of view, quantitative and qualitative analyses of chemical and textural heterogeneity in mixed rocks highlight the important role of mixing dynamics in producing geochemical complexities and

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heterogeneities (Kratzmann et al., 2009). Zoned crystals and complex mineralogical associations are also often considered as evidence for mixing (e.g., Murphy et al., 1998; Couch et al., 2001; Davidson et al., 2001; Morgan et al., 2004; Costa et al., 2008). The generation of complex textural features and mineralogical associations implies the development of large contact interfaces between interacting melts through which chemical and crystals exchanges may be strongly amplified. This, in turn, leads to highly variable degrees of homogenization depending on the mobility of different chemical elements in the melts (e.g., De Campos et al., 2011, Morgavi et al., 2012, Morgavi et al., 2013a, 2013b, Perugini and Poli, 2012, Perugini et al., 2006, 2008, Perugini et al., 2012). Despite the abundant literature regarding magma mixing processes, a few studies have focused on describing and quantifying the inter-relationship between the morphology of mixing patterns and the geochemical variability in mixed rhyolitic and basaltic complexes (Freundt and Schmincke, 1992; Morgavi et al., 2012; Morgavi et al., 2013a, 2013b).

The Yellowstone Plateau volcanic field (YVF) hosts at least four mixed magma complexes (Christiansen et al., 2007; Pritchard et al., 2013; Wilcox, 1944). This work focuses on the well-exposed Grizzly Lake complex where mixed rocks appear to preserve evidence of significant complexity of the mixing process. Mixed eruptions such as those studied in this work are both rare yet vital resources for providing substantial information on the evolution of complex large bimodal magmatic systems.

Here we conducted a substantial micro-analytical program of chemical measurements to characterize both chemical exchanges and transfer of minerals between magmas at Grizzly Lake in order to evaluate the degree of chemical and textural disequilibrium triggered by the mixing process. In addition, to study the chemistry and texture of mixed rocks, we combined the electron microprobe analyses with the X-ray computed microtomography (microCT) technique. The microCT technique, either using conventional or synchrotron sources, is able, in fact, to provide three-dimensional (3D) information on rock samples and to couple geochemical and textural investigations to gain new insights about the textures arising during complex rock forming processes (Ketcham and Carlson, 2001; Mees et al., 2003; Ketcham, 2005; Carlson, 2006; Gualda et al., 2010; Polacci et al., 2010; Voltolini et al., 2011; Baker et al., 2012a, 2012b; Blunt et al., 2013; Fusseis et al., 2014). Despite its potential, however, the application microCT to characterize textures generated by magma mixing is still lacking. In this work, we present the first 3D imaging of magma mixing morphologies, achieved using advanced X-ray microCT techniques, to characterise the complex multi-scale character of magma mixing and hybridization processes. We show that the integration of microanalysis techniques and 3D microCT images can provide the most complete picture for understanding the development of magma mixing processes and gaining new insights on one of the most recent eruptions at Yellowstone volcano.

2. Geological setting

2.1. The Yellowstone Plateau volcanic field

The Yellowstone Plateau volcanic field is located in northwest Wyoming and southeast Idaho, USA (Fig. 1). It is well known for three major caldera-forming eruptions that deposited 250 to 2500 km^3 of high-silica ($\leq$76 wt.% SiO_2) pyroclastic material over an immense area (Christiansen, 2001; Pierce and Morgan, 2009). The most recent caldera-forming eruption deposited the Lava Creek Tuff, 640 $\pm$ 2 ka with a caldera size of over 50 km (Christiansen, 2001 & Lanphere et al., 2002). Smaller volume rhyolites (<100 km^3 of erupted material) that are younger than 640 ka have been grouped as the Plateau Rhyolite and can be found in the caldera (intracaldera) and outside the caldera (extracaldera). Numerous basalts are also present in the YVF but have only been found in the extracaldera setting. Volcanism of intermediate composition appears to be absent except for those basalts displaying crustal contamination (Christiansen, 2001; Struhsacker, 1978) and the four extracaldera mixed basaltic–rhyolitic complexes (Pritchard et al., 2013). Since the extracaldera system contains some of the youngest volcanism in the Yellowstone volcanic field (Nastanski, 2005; Bennet, 2006; Christiansen et al., 2007), these volcanic units are important, together with the current geophysical unrest signals, to provide relevant information for the possible reactivation of the Yellowstone volcano.

Considering the large volumes of rhyolite (of the order of 2500 km^3; Christiansen, 2001) and, to a lesser extent, basalt (of the order of 250 km^3; Christiansen, 2001) erupted in the Yellowstone Plateau

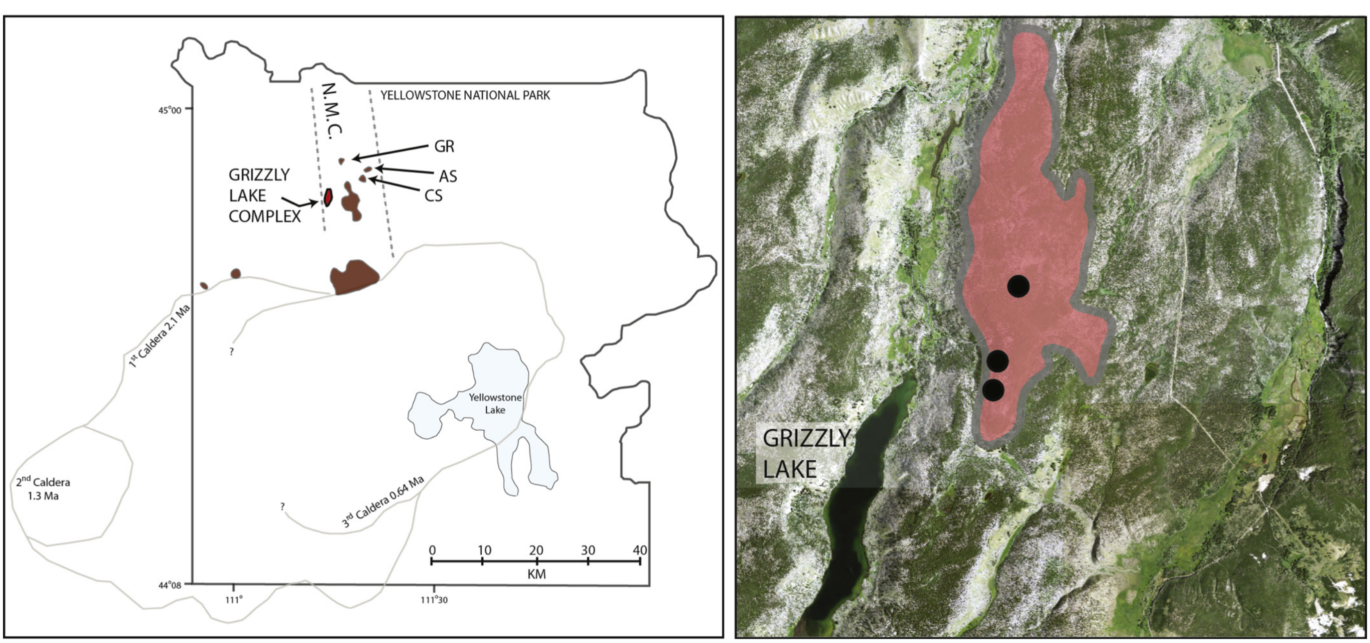

Fig. 1. Left map of Yellowstone Park showing the three calderas of Yellowstone, most recent resurgent domes. N.M.C.: Norris Mammoth Corridor; G.R.: Gardiner River complex; C.S.: Crystal Spring complex; and A.S.: Appolinaris Spring complex. Right map zoom of the N.M.C. and Grizzly Lake extra-caldera complex (red) showing sampling localities. Maps modified from Christiansen (1999 and 2001) and Pritchard et al. (2013).

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