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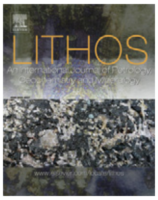

Eruption-triggered mixing of extra-caldera basalt and rhyolite complexes along the East Gallatin–Washburn fault zone, Yellowstone National Park, WY, USA

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ABSTRACT

Though mixing and commingling of magmas is common, mixing between rhyolite and basalt magmas is not commonly preserved in volcanic rocks. The presence of at least four mixed magma complexes at Yellowstone National Park suggests that mingling is not due to random intersections of feeder dikes, geochemical analyses also show that though these magmas appear to be commingled, there is mixing between the two disparate end members. Our model combines previous work on the Grizzly Lake, Gardner River, Crystal Spring, and Appolinaris Spring mixed magma complexes with results from new analyses, recent mixing experiments, and regional structural geology. Coeval extensional tectonism, as seen in the East Gallatin–Washburn fault zone, is also present in other areas of basalt and rhyolite mixing/mingling (*e.g.* Iceland). The central portions, or core, of the complexes contain increased concentrations of emulsion rock, occasional basaltic pillows in a rhyolite matrix, net veining, and mixed magma with highly variable geochemistry (SiO_2 ranges from 50 to 78 wt.%). Phenocrysts have been transferred between mafic and felsic portions of the complexes and suggest that these mixed magmas did not have enough time, or energy (*e.g.* heat), to thoroughly mix into complete hybrid intermediate magmas. This implies that mixing occurred during eruption. Furthermore, analyses at the micron-scale suggest that zones of chaotic mixing between basalt and high-silica rhyolites may be more complete than previously thought during mixing of high silica rhyolites and basalts with greater than 4 wt.% MgO. The temperature of the rhyolitic magmas was approximately 850 °C with a viscosity between 1×10^6 and 3×10^6 Pas. The basalt was approximately 1070 °C with a viscosity of 2×10^2 to 9×10^3 Pas prior to mixing. Mixing of these two extreme end members may have required decompression of the lower basaltic magma chamber during eruption of the overlying rhyolitic magma chamber into through structurally weakened zones of the upper crust. The decompression induced mixing was facilitated by coeval extensional tectonics and structures in the Norris–Mammoth Corridor. Extra-caldera rhyolites are some of the first volcanics following the collapse of the current caldera and also some of the youngest volcanics in the Yellowstone Plateau and require further understanding of volcanism in the Yellowstone Plateau.

1. Introduction

Magma mixing and commingling are igneous processes that are found worldwide, in an array of rocks; however, there are distinct differences between mixing in the plutonic versus volcanic settings (Perugini and Poli, 2012). Most commonly mixed magmas include host magma, or enclaves, that have intermediate compositions and are generally associated with arc magmatism (*e.g.* Bacon, 1986; Bacon et al., 1997; Bergantz and Breidenthal, 2001; Clynne, 1999; Kouchi and Sunagawa, 1985; Murphy et al., 1998; Perugini et al., 2010) or plutonic rocks (*e.g.* Perugini and Poli, 2005; Sparks and Marshall, 1986; Waight et al., 2001). Few mixed or commingled volcanic rocks preserve such explicit evidence of mixing basalt and rhyolite as those found in Yellowstone. One reason for this may be that basaltic portions conduct heat when put in contact with cooler rhyolitic magma (Sparks and Marshall, 1986), thus inhibiting complete mixing when the system is not controlled by large amounts of mafic magma. However, recent experimental studies suggest that more evolved mixing may continue on a small scale due to chaotic mixing in experimental conditions (*e.g.* De Campos et al., 2011; Morgavi et al., 2013). Basalt and rhyolite mixing in volcanic rocks is described in tensile stress regimes such as Iceland and in plutonic rocks from Scotland and England (Hawkes, 1945). Magma mixing has also

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been described in alkaline systems, which have substantially different viscosities and mixing dynamics than Yellowstone (*e.g.* Wiesmaier et al., 2011). Syn-extensional magma mixing is also described in Miocene plutonic rocks from Arizona (Metcalf et al., 1995) The relationship between magmatism and crustal extension has been well documented (*e.g.* Smith et al., 1998). Here, we link shallow mixing of bimodal end members that has been facilitated by extension.

In some cases it appears that magma mixing triggered eruptions (Murphy et al., 1998; Sparks et al., 1977). However, recent physical experimental studies suggest that shallow eruptions may lead to decompression induced magma mixing as decreased pressure allows volatiles to exsolve, thus decreasing the density of magma in the underlying chamber during an eruption. This concept of decompression induced mixing has been used to demonstrate how, in extreme conditions, bi-modal magma chambers can become inverted during an eruption (Woods and Cowan, 2009).

The Yellowstone Volcanic Field is located in northwest Wyoming (Fig. 1) and is classically known for the three major caldera-forming eruptions that deposited high-silica ($>$77 wt.% SiO_2) rhyolite tuffs over an area of $>$65,000 km^2 (Christiansen, 2001). Lesser known are the basalts that erupted outside of the caldera, the extra-caldera basalts, where the mixed units are also found. Extra caldera rhyolites have distinct geochemistry, including distinctly low epsilon-Nd values when compare to most other Yellowstone rhyolites, suggesting a stronger crustal influence during formation (Hildreth et al., 1991; Pritchard and Larson, 2012). Geologic research in Yellowstone has been documented since the late 1800's during the US Geological and Geographical Survey of the Territories (*e.g.* Holmes, 1883a,b), and has led to an extensive amount of nomenclature and ever evolving unit descriptions. Rhyolites that erupted following the most recent caldera collapse, post 640 ± 2 ka (Lanphere et al., 2002), are grouped in the Plateau Rhyolite. The intracaldera portion of the Plateau Rhyolite has been divided into the Upper Basin Member and the Central Plateau Member. These post-collapse rhyolites erupted over about the same time span as did the mixed magmas (Christiansen et al., 2007). The extra-caldera portions of the Plateau Rhyolite are divided into the Roaring Mountain Member and Obsidian Creek Member (Christiansen and Blank, 1972). Division of the extra-caldera members is based upon petrography, where the Roaring Mountain Member is mostly aphyric and the Obsidian Creek Member contains abundant quartz, sanidine, and plagioclase phenocrysts (Christiansen and Blank, 1972). The aphyric nature of the Roaring Mountain Member shows that the magmas were emplaced at, or above, the magma liquidus (Christiansen et al., 2007). Units from each member and proximal basalt lava flows are listed in Table 1. The youngest mixed magma, and one of the youngest volcanic deposits associated with the Yellowstone Caldera, is the Crystal Spring flow, 80 ± 3 ka, based on K–Ar sanidine age measurements (Obradovich, 1992). Other mixed magmas yield $^{40}Ar/^{39}Ar$ age determinations that include: Grizzly Lake at 263 ± 3 ka, Gardner River at 301 ± 3 ka, and Appolinaris Spring dome at 316 ± 2 ka (Christiansen et al., 2007; Nastanski, 2005). The Gardner River complex name was officially changed in 1979, during the US Geological Survey geographic names phase I data compilation (1976–1981). Therefore, publications prior to 1979 refer to the complex as the Gardiner River.

We have used the outcrop descriptions of Walker and Skelhorn (1966), although the common parlance "mafic and felsic" is preferred to their "basic and acidic". We attempted to apply their classic descriptions as much as possible. Walker and Skelhorn (1966) describe *basic inclusions* as abrupt boundaries between mafic enclaves and rhyolite matrix (Fig. 2A). *Basic pillows* are mafic enclaves that are larger than approximately 50 cm and commonly as shed layers into the rhyolitic portion (Fig. 2B). *Emulsion rock* is a complex intertwining of the two portions, although generally during this stage there seems to be an increased portion of mixed magma with a general composition of andesite (Fig. 2C). *Net-veined complex* consists of mafic enclaves that contain veins of rhyolitic material that are generally associated with margins of basic pillows (Fig. 2B and D). Finally, crenulated margins were observed between the two magmas and the hybrid magmas, generally requires a hand lense to observe the undulatory boundaries (Fig. 2E).

Extra-caldera volcanism is also important in understanding some of the youngest volcanism associated with the Yellowstone Caldera. Weakening of the crust in the Norris–Mammoth Corridor by the East Gallatin–Washburn fault zone has been acknowledged by Christiansen et al. (2007). Though preliminary assessments have generally not addressed the potential of future volcanism in the Norris–Mammoth Corridor geophysical surveys have measured and imaged the highest amount of uplift in the Norris area (Chang et al., 2007).

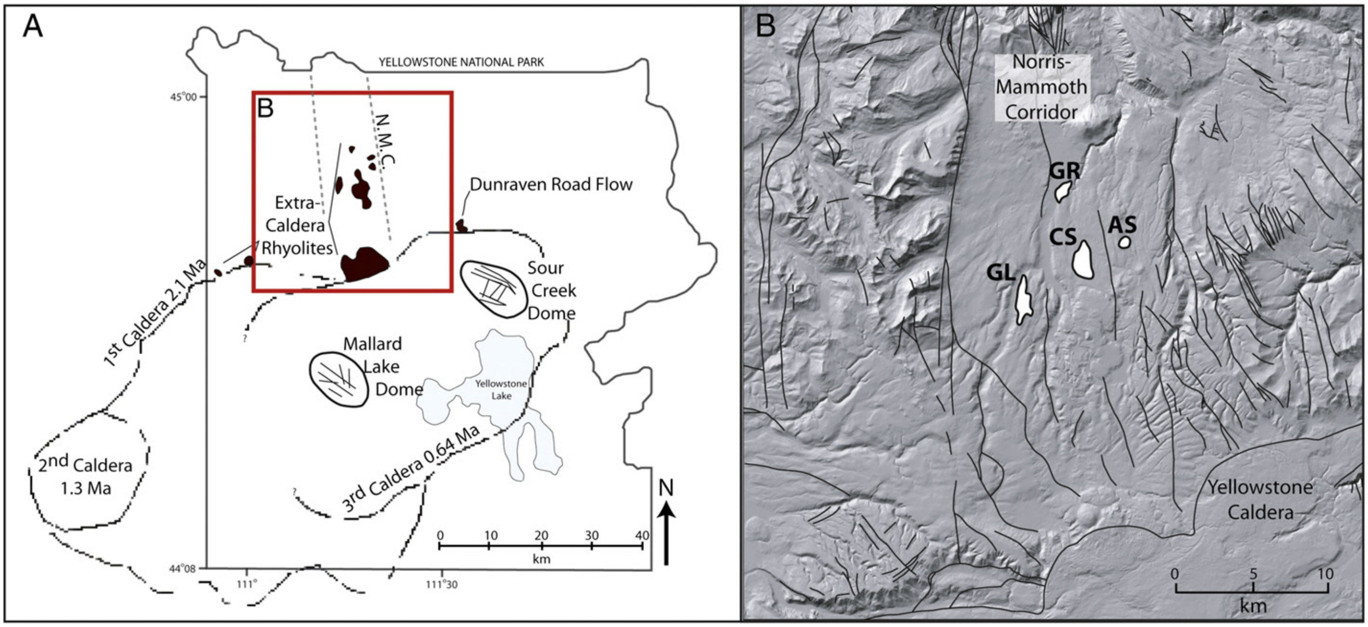

Fig. 1. A. Map of Yellowstone National Park showing the three calderas of Yellowstone, most recent resurgent domes, and sites of extra-caldera volcanism. N.M.C. — Norris–Mammoth Corridor. B. Close up of the N.M.C. illustrating faults from the East Gallatin–Washburn fault zone and the four mixed magma complexes: GL — Grizzly Lake, GR — Gardner River, CS — Crystal Spring, and AS — Appolinaris Spring, black lines represent faults. Maps modified from Christiansen (1999, 2001).