**The Grizzly Lake Complex (Yellowstone Volcano, USA):
Mixing between Basalt and Rhyolite Unravelling by
Microanalysis and X-ray Microtomography**

**Daniele Morgavi¹, Fabio Arzilli^{2,3}, Chad Pritchard⁴, Diego Perugini¹, Lucia
Mancini², Peter Larson⁵, Donald B. Dingwell⁶**

¹ *Dept. Physics and Geology, University of Perugia, Piazza Università, 06100 Perugia, Italy.*

² *Elettra-Sincrotrone Trieste S. C.p.A., SS 14, Km 163.5 in Area Science Park, 34149 Basovizza
(Trieste), Italy*

³ *School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Oxford
Road, Manchester, M13 9PL, UK*

⁴ *Dept. of Geology, Eastern Washington University, Cheney, WA, USA 99004*

⁵ *School of the Environment, Washington State University, Pullman, WA 99164*

⁶ *Earth and Environmental Sciences, LMU Munich, Theresienstrasse 41/III, 80333 Munich,
Germany.*

Corresponding author: Daniele Morgavi

e-mail: daniele.morgavi@unipg.it

Tel.: +39 075 585 2609

Fax: +39 075 585 2603

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 characterised 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.

Key words: magma mixing, X-ray computed microtomography, Yellowstone, rhyolite, basalt.

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, 1998; Leonard et al., 2002; Perugini & 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) physico-chemical 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 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., 2010). 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., Perugini et al., 2006; 2008; De Campos et al., 2011; Perugini et al., 2012; Perugini and Poli, 2012; Morgavi et al.

2012; Morgavi et al. 2013a,b). 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,b).

The Yellowstone Plateau Volcanic Field (YVF) hosts at least four mixed magma complexes (Wilcox, 1944; Christiansen et al. 2007; Pritchard et al., 2013). 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 and 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, b; Iglauder et al., 2012; Blunt et al., 2013; Füsseis 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 hybridisation 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 km³ of high-silica (≤ 76 wt. % SiO₂) pyroclastic material over an immense area (Christiansen et al., 2001). The most recent caldera-forming eruption deposited the Lava Creek Tuff, 640 ± 2 ka with a caldera size of over 50 km (Christiansen et al., 2001 & Lanphere et al., 2002). Smaller volume rhyolites (< 100 km³ 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 (Struhsacker, 1978; Christiansen, 2001) 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 km³; Christiansen et al., 2001) and, to a lesser extent, basalt (of the order of 250 km³; Christiansen et al., 2001) erupted in the Yellowstone Plateau Volcanic Field, occasional, if not continuous interaction between rhyolitic and basaltic magmas should to be expected. The study of Pritchard et al. (2013) suggests the presence of volumes of rhyolites and basalts at temperatures of ca. 900°C and 1150°C respectively. An array of processes have been proposed for the formation of magma in the Yellowstone area, including magma mixing between mantle-derived melts possibly in concert with fractional crystallization (Hildreth et al., 1991; Leeman et al., 2008; Girard and Stix, 2009; Vazquez et al., 2009; Pritchard and Larson, 2012; Stelten et al., 2013).

The extracaldera mixed complexes, mapped as part of the Plateau Rhyolite (e.g., Christiansen, 2001), formed following the most recent caldera formation. The mixed magmas are some of the youngest volcanic deposits in the YVF and are divided into: Crystal Spring flow at 80 ± 3 ka, Grizzly Lake at 263 ± 3 ka, Gardner River at 301 ± 3 ka, and Appolinaris Spring dome at 316 ± 2 ka (Nastanski, 2005; Christiansen et al., 2007; Pritchard et al., 2013). The mixed magma complexes are located approximately at 10 km north of the caldera along the Norris-Mammoth corridor (Fig. 1) and in the active East Gallatin-Washburn fault zone (Christiansen et al., 2007; White et al., 2009). Similarities between other basalt-rhyolite systems located in extensional regimes and physical

modelling by Woods and Cowan (2009) lead Pritchard et al. (2013) to ascribe mixing to coeval eruption along pre-weakened fault planes, as the less viscous basalt intruded into the cooler rhyolitic magma chamber with higher viscosity.

2.2 Outcrop description

The Grizzly Lake Complex was emplaced as a relatively small volume lava flow, relative to other volcanic deposits in the YVF. The lava flow has a length of ca. 3.0 km and a width of ca. 1.0 km, thickness ranging from 70 to 150 m. The lava flow covers an area of about 3.0 km²; the basal portion of the flow is not visible because of vegetation and inaccessible areas.

The Grizzly Lake outcrop consists approximately of 11% basalt, 24% hybrid magmas and 65% rhyolitic magma (see below for a more detailed definition of lithologies). Outcrops commonly display flow banding and mineral alignment due to flow and, occasionally, brecciation, indicating that the magmatic mass was emplaced as a lava flow. In the following description of mixing structures we refer to the terminology proposed by Perugini and Poli (2012).

The outcrops appear very heterogeneous in terms of magmatic structures generated by the mixing process. An example of this structural variability can be seen on the outcrop-scale picture shown in Fig. 2. In particular, the figure shows a quite continuous transition between an outcrop portion dominated by the rhyolite (sample location 1), through a hybrid zone (sample location 2), to a portion where the basalt is the dominant lithology (sample location 3).

184 In general, the Grizzly Lake basaltic-rhyolite complex displays angular to round
185 inclusions of basalt in the rhyolite (previously described as enclaves or pillows; Wilcox,
186 1944), irregular fringes and dikelets of rhyolite intruded into the basalt and complex
187 intermingling of basalt and rhyolite, the latter forming convoluted filaments (previously
188 defined as emulsion rocks and net-veining by Walker and Skellhorn, 1966). The most
189 complex mixing structures tend to occur toward the centre of the outcrop, whereas
190 rounded enclaves mainly occur toward the external portions (Pritchard et al., 2013).

191 A detailed investigation of outcrop features highlights the presence of a large variety
192 of mixing structures. Some representative structures are shown in Fig. 3 a-f. In particular,
193 Fig. 3a shows the occurrence of basaltic enclaves (grey to brownish colour, marked by
194 white lines) and hybrid filaments (dark grey/bluish colour) dispersed within the rhyolitic
195 mass (light grey/whitish colour). Fig. 3b shows a rounded shape basaltic enclave
196 surrounded (brownish colour) by hybrid magma. Fig. 3c displays a basaltic enclave
197 (white line) with an elongated shape, surrounded by alternated filaments of hybrid and
198 rhyolitic composition; compared to the other two cases (Fig. 3a) this portion of the
199 outcrop appears dominated by a magma having an intermediate composition. Fig. 3d
200 shows the deformation of rhyolitic and hybrid filaments against a hybrid mass having a
201 cusate termination pointing toward the right side of the picture and containing a basaltic
202 enclave. In Fig. 3e the basaltic magma appears to invade a small volume of rhyolitic
203 magma (marked by a black dotted line); a hybrid portion occurs on the top of the picture
204 at the contact between them and appears to fade out from the basaltic mass. Two basaltic
205 enclaves (marked by white lines) are also present in this section of the outcrop. Fig. 3f
206 shows a section of the outcrop where the basaltic magma is the main component and the

rhyolite occurs only as filaments with very irregular margins (finger-like boundaries). Hybrid filaments are also present and are characterized by variable composition from rhyolite to andesite.

Noteworthy is the fact that the mixing structures described before tend to be replicated from meso- to micro-scales. This is shown in Fig. 4 representing a zoomed-in view of a portion of the outcrop. Here we observe the occurrence of the same (statistically speaking) mixing structures characterized by a continuous inter-fingering of portions of rhyolite and basalt from the decimetre to the micron length scale. This suggests, as already pointed out by other authors (e.g. Perugini & Poli 2012 and Morgavi et al., 2013), that the mixing process propagated at different length scales with approximately the same efficiency defining scale-invariant structures and leading to the generation of fractal domains. This being so the Grizzly Lake outcrop can be analysed at any length-scale (from μm - to cm-sized samples) and should provide statistically the same reliable information (Perugini and Poli, 2012). As for Fig. 4, at the centimetre length-scale (Fig. 4a) the transition between the different lithologies appears generally abrupt over distances of the order of a few millimetres. However, at smaller length-scales (Fig. 4b and c) contacts between the basaltic and rhyolitic portions become less obvious (Fig. 4b and c) with the occurrence of a continuous gradation and the presence of crystals passing from one lithology to the other.

Optical microscopy analysis of mineralogical associations indicates that Grizzly Lake rocks can be divided into three general groups: basaltic, rhyolitic, and hybrid. Basaltic lithologies can be further divided into two sub-groups: basaltic enclaves and basaltic portions. Basaltic enclaves are characterized by the occurrence of phenocrysts of

plagioclase, olivine and clinopyroxene; the groundmass, completely crystallized, is composed of microlites of plagioclase and clinopyroxenes. Basaltic enclaves do not show any sign of crystal exchange with the rhyolitic magma, suggesting that they experienced little, if any, mass transfer processes during mixing. Basaltic portions contain the same minerals as the basaltic enclaves with the difference that in these lithologies resorbed crystals of quartz and sanidine, likely transferred from the rhyolitic magma during mixing, are common. The rhyolitic lithologies show a glassy groundmass in which phenocrysts of k-feldspar (sanidine) and quartz occur; crystals of olivine and plagioclase, likely transferred from the basaltic magma during mixing and commonly surrounded by clinopyroxene coronae, are commonly found. The hybrid portions contain phenocrysts of plagioclase, olivine, quartz and sanidine embedded in a glassy groundmass where microcrystals of clinopyroxene and oxides occur.

3. Materials and methods

3.1. Sample selection and description

Multiple samples were collected to analyse in detail both the chemical compositions of melts and crystals and their textures and mineral associations. Chemical analyses were performed to quantify the different compositions of glasses and the compositional zoning of minerals in the rocks to better constrain how the magma mixing had occurred. Mixing textural features from a representative sample were observed and analysed through two-dimensional (2D) Back Scattered Electron (BSE) images, but the intrinsic limitation of a 2D approach drove us to the use of X-ray computed microtomography (microCT) techniques for a three-dimensional (3D) non-destructive characterization of the samples.

Three representative samples were selected for microCT analysis (sample location 1, 2 and 3 in Fig. 2), to be representative of the architecture of mixing and mingling of rhyolite and basaltic magmas. The first sub-sample YMRBW6 (Fig. 5) was chosen as representative of the contact between a basaltic enclave and a hybrid filament. This sample clearly shows the interaction between the two different magmas represented by the mutual transfer of crystals and different degree of crystallization and vesiculation. The shape of YMRBW6 is approximately parallelepiped and its dimensions are reported in Table 1. The other two sub-samples YMRBW7 and YMRBW1 (Fig. 6 and 7) were selected as representative specimens illustrating the complex architecture of the rhyolitic filaments penetrating into the basaltic portion. The shape of YMRBW1 is cylindrical, whereas that of YMRBW7 is parallelepiped. Their dimensions are reported in Table 1. In particular, the sample YMRBW7 is a sub-volume of sample YMRBW1 appropriately selected to investigate in detail the morphology of the contact between the two end-member magmas (see below).

3.2 Electron microprobe

Concentrations of major elements and BSE images were acquired through a Cameca SX100 electron microprobe (EMP) (Department of Earth and Environmental Sciences, LMU-Munich, Germany). The operating conditions were 15 kV acceleration voltage and 20 nA beam current. A defocused 10- μ m beam was used for all elements in order to avoid alkali loss. Synthetic wollastonite (Ca, Si), periclase (Mg), hematite (Fe), corundum (Al), natural orthoclase (K), and albite (Na) were used as standards, and matrix

correction was performed by the PAP procedure (Pouchou and Pichoir, 1984). Standard deviations were lower than 2.5% for all analyzed elements.

3.3 The X-ray computed microtomography (microCT) technique

The X-ray microCT experiments have been carried out using both a third generation synchrotron X-ray source and a laboratory microfocus instrument (for more details see the electronic supplemental appendix).

Synchrotron X-ray microCT experiments on samples YMRBW6 and YMRBW7 (Table 1) were performed at the SYRMEP beamline of the Elettra - Sincrotrone Trieste Laboratory (Basovizza, Italy) (<http://www.elettra.trieste.it/elettra-beamlines/symep.html>; Tromba et al., 2010). In our experiments a monochromatic, nearly-parallel X-ray beam has been employed whose energy has been set to 35 keV. The pixel size of the detector has been fixed to 9.0 μm (2×2 binning) and, for each sample, 1800 radiographic images (or projections) have been acquired with equiangular steps over a total range of 180° . The sample-to-detector distance was set to 200 mm. The scan duration was on the order of one hour. The custom software Syrmep_tomo_project 4.0 and the GRIDREC algorithm (Dowd et al., 1999) were used to reconstruct the 2D axial slices (Fig. 5a and 6a) of the samples with anisotropic voxel size of 9.0 μm .

Sample YMRBW1 was imaged at the TomoLab station of Elettra (Polacci et al., 2009; Zandomenighi et al., 2010; Baker et al., 2012b). In our experiments a 2×2 binning was applied. The source-to-sample and source-to-detector distances were set to 10 mm and 25 mm, respectively, resulting in an equivalent pixel size of 10.0 μm . A “local tomography” protocol was used during data collection (Lak et al., 2008). From the 2400 tomographic

projections acquired by the detector during a 360° rotation of the sample, a set of 2D axial slices (Fig. 7a) was reconstructed with the commercial software package COBRA (Exxim) based on the Feldkamp algorithm (Feldkamp et al., 1984; Kak and Slaney, 1987). The same software was employed to reduce beam-hardening artefacts from the reconstructed slices.

3.4 Image processing

The reconstructed volumes for the different sub-samples (YMRBW6, YMRBW7 and YMRBW1) have been processed and analyzed by the Pore3D software library (Brun et al., 2010) in order to obtain a quantitative description of the morphology and topology of the sample components operating directly in the 3D domain. The visualization of the reconstructed and processed volumes for all samples has been obtained with the commercial software VGStudio MAX 2.0, selecting a volume rendering procedure.

A Volume Of Interest (VOI) has been selected for each sample to visualize the main features of mixing textures. The VOIs of the samples YMRBW6 and YMRBW7 correspond roughly to the whole imaged volumes (Table 1), where only a small part of the volume, close to the external borders of the sample, has been cropped. The VOI of the sample YMRBW1 (Table 1) was selected in the central part of whole imaged volume in order to avoid artefacts of the cone beam reconstruction.

After the extraction of the VOI, the volume was pre-processed with filters to facilitate the processing of images (for more details see the electronic supplemental appendix), i.e. reducing noise and potential artefacts, to enhance the edges of objects and better

distinguish the different phases of interest (e.g. the rhyolitic glass, the basaltic portion, mafic and felsic crystals and bubbles).

The next step was obtaining binary volumes optimised for the different phases of interest. Since several phases of interest were present in our samples, a 3D Multi Otsu's thresholding was applied. This multi thresholding approach allowed us to segment the phases of interest with complex backgrounds; therefore we were able to separate crystals (mafic and felsic) and bubbles from the glass matrix (rhyolitic to basaltic). Further details about the methodology are given in the electronic supplemental appendix.

4. Results and discussion

4.1 X-ray microCT data

The specific regions of the original datasets selected as VOI are reported for each imaged sample in Table 1. The analysis of sample YMRBW6 allowed the 3D visualisation of the contact between a basaltic enclave and a hybrid portion (Fig. 5 and 8a-d). Figures 5 and 8a, c show that the basalt is completely crystallized and characterized by phenocrysts of plagioclase, olivine and clinopyroxene; the groundmass is composed of microlites of plagioclase and clinopyroxenes. The hybrid portion shows phenocrysts of plagioclase, olivine, quartz and sanadine. Its groundmass is mainly constituted by glass with microcrystals of clinopyroxene and oxides. The vesicle populations are distinct between the basaltic enclave and the hybrid portion in terms of size and quantity. In particular, the hybrid portion has nearly no vesicles. Vesicle number increases at the contact between the hybrid and basaltic enclave. These vesicles are very small (50-60 μm in diameter) and distributed along the contact. Vesicles in the basalt are

bigger (up to 1.5 mm) but lower in number. Using 3D images we measured the bubble fraction and crystallinity of mafic minerals in both magmatic portions (using Pore3D software). We chose to trace the mafic minerals on our sample to show their spatial distribution and, therefore, to better understanding the mechanism of crystal exchange between mafic and felsic magmas. In detail, the basaltic enclave has a volume of 44% of mafic minerals and 11% of bubbles (Fig. 8; Supplementary Movie 1). The bubbles are spherical with diameters ranging from 10 to 1500 μm (Fig. 8b, d). The hybrid filament contains 20% of mafic minerals and ca. 1.0% bubbles. The contact between the basaltic enclaves and the hybrid portion is irregular, characterized by a transition zone, where crystals pass from the basalt to the hybrid melt (Supplementary Movie 1). In this case bubbles were not able to cross the contact and remained along the hybrid/basalt interface (Fig. 8b, d and Supplementary Movie 1).

We attempted to study the morphology of rhyolitic filaments in the basaltic magma using X-ray microCT in cone-beam geometry. To this purpose a large cylindrical sample (sample YMRBW1; Fig. 7 and Table 1) was scanned using the TomoLab station at Elettra. This device is characterized by a larger energy range with respect to the SYRMEP beamline. The use of this equipment was fundamental to scan in 3D the texture of a larger sample (Table 1) and determine the spatial distribution of the different lithologies at a larger length-scale. This helped to evaluate the best volume to be scanned at high-resolution at the SYRMEP beamline. Although in principle 3D observations could be made using the TomoLab 3D scans, the quality of the images obtained with the microfocus source was not high enough to discriminate fine details in the mixing structures (Figs 7a and b). This was mainly due to the fact that the rhyolitic filament

displays grey values similar to those associated with feldspars; the isolation of the filament itself, therefore, is not accurate enough (Fig. 7b). Therefore, a selected volume of the sample (YMRBW7) was extracted from the larger sample and scanned using the SYRMEP beamline (Figs 6 and 9).

Sample YMRBW7 (Figs 6 and 9) allowed us to focus on a rhyolitic filament passing through the basaltic portion and to study the characteristics of this filament (see Fig. 9 and Supplementary Movie 2 and 3). In particular, Fig. 6 shows a 3D view of the structure where the rhyolite interacts through a complex interface with the basaltic magma. In Fig. 9a the sample is segmented to highlight the occurrence and location of mafic minerals (olivine and clinopyroxene). In order to better observe the distribution of mafic minerals, Fig. 9b shows the same sample in which the groundmass of the basaltic portion has been removed. The figure shows that the contact between the two magmas is populated by mafic minerals that tend to disrupt the contact itself allowing the transfer of minerals from the basalt to the rhyolite. This is evident by the presence of mafic minerals within the rhyolitic glass (Fig. 9b). In Fig. 9c the rhyolitic filament is segmented and the whole basaltic portion (groundmass plus minerals) has been removed in order to display the morphological characteristics of the rhyolite/basalt interface. The figure shows a complex mutual interpenetration of the two melts where fingers of basalt displace the rhyolitic mass increasing the contact surface between the two and potentially increasing mass exchange processes by both chemical diffusion and crystal transfer, as indeed observed in Fig. 9b.

In summary, the use of tomographic techniques allowed us to investigate in greater detail the development of mass transfer exchanges during magma mixing focusing on the

three dimensional visualization of the contact interfaces of the magmas and the transfer of crystal from one magma to the other. This high-resolution information is difficult to achieve using two-dimensional pictures, such as BSE or optical images, where stereological aberrations are necessarily associated with the lack of the third dimension, preventing a thorough analysis of sample complexity. Noteworthy is the fact that the comparison between the images obtained using a conventional source (TomoLab) and those obtained with synchrotron radiation (SYRMEP) (Figs 5, 6 and 7) shows that the use of a synchrotron X-ray beam results in a better definition of the 3D sample morphology and texture. Despite the fact that the nominal spatial resolution of the two microCT systems is quite similar, the X-ray beam monochromaticity, the parallel geometry and the high spatial coherence of the X-ray beam in synchrotron X-ray imaging play a crucial role in the segmentation of these multiphase materials.

4.2 Geochemical features of Grizzly Lake rocks

As reported above we divided the Grizzly Lake rocks into three major groups: rhyolitic, hybrid and basaltic; accordingly, the presentation and discussion of geochemical data will be done following, when possible, this lithological division. It should be kept in mind however that these three groups do not represent completely separate lithologies, but fade continuously one into the other in terms of both geochemical and textural features.

Electron microprobe spot analyses were performed (using Cameca SX100 electron microprobe with a spot analysis of 20- μm) on the interstitial glass of the rhyolitic and hybrid magmas. In particular, given the presence of spherulites in the rhyolitic rocks (see

below), microprobe analyses we performed far away from them to avoid any possible effect of post-mixing crystallization on geochemical data. Microanalysis of the glass of basaltic lithologies was not possible because of their fully crystallized groundmass. We decide therefore to use as a representative basaltic end-member the average composition of basalts present in the Yellowstone volcanic field with MgO larger than 9.0% (Fenner 1938; Hildreth et al., 1991; Christiansen, R.L., 2001; Bennet 2006 and Pritchard et al. 2013). The Grizzly Lake rocks are basaltic and rhyolitic in composition (Fig. 10), whereas the intermediate products range from basaltic-andesite to dacite and trachydacite (Fig. 10). To better visualize the chemical variation in the analysed rocks, binary inter-elemental plots of representative major elements measured in the hybrid and rhyolitic interstitial glasses are displayed in Fig. 11. The plots also contain element concentrations for each of the end-members (white and black stars). The dashed line connecting the end-members represents the classic binary mixing model, which is commonly applied in dealing with mixing processes (Fourcade and Allègre, 1981). This model states that linear correlations must be observed in any inter-elemental binary diagrams, irrespective of the chosen pairs of elements. This appears not to be the case for the Grizzly Lake mixed complex; indeed, some elements deviate strongly from this simple pattern, as also observed by Pritchard et al. (2013).

As for the rhyolitic portions, major element data show a limited variability for SiO₂, MgO, CaO and Al₂O₃ (Fig. 11a, c and f). The major exceptions are Na₂O and K₂O, which exhibit the largest variations. As for the other samples (hybrid portions), they show a much larger chemical variability. These samples correspond to analyses performed at the contact area between the hybrid filaments and the basaltic enclaves.

Data points measured at the interface between the hybrid and rhyolitic portions, as well as on the hybrid enclaves in the rhyolite, show chemical variations ($74 \leq \text{SiO}_2 \leq 81$ wt.% and $1 \leq \text{Na}_2\text{O} \leq 5$ wt.%) similar to those measured in the rhyolitic end-member. The hybrid portions, for most of the major elements (e.g., SiO_2 vs. MgO , SiO_2 vs. CaO , SiO_2 vs. Al_2O_3 and SiO_2 vs. FeO_{tot}), tend to define complex compositional patterns with data points ranging from the basaltic-andesitic to the rhyolitic composition. This is particularly evident for elements such as Na_2O and to some extent K_2O (Fig. 11d, f). In particular, Na_2O defines a curved bell-shape pattern moving from the rhyolites towards the basaltic end-member. Noteworthy is the fact that these types of inter-elemental relationships in binary plots in magma mixing systems have been already documented in natural rock samples (Perugini et al., 2006), numerical simulations and experiments (e.g., Perugini et al., 2008; De Campos et al., 2008, 2011; Morgavi et al. 2012; Morgavi et al. 2013a,b). In particular, these variable correlations have been related to the onset of a diffusive fractionation process triggered by the combined action of chaotic flow fields and chemical diffusion. Such a process appears responsible for a highly variable scattering in inter-elemental binary plots and non-linear trends due to the different mobility of chemical elements (i.e. their ability to spread in the magmatic system by diffusion in the melts). We infer, therefore, that the variable correlations between pairs of major elements in the plots of Fig. 11 could be imputed, to a first approximation, to the different mobility of the chemical elements during the interaction of the rhyolitic and basaltic magma.

Magma mixing, however, not only occurs only between melts but also as a result of the transfer of mineral phases from one magma to the other eventually leading to the

development of disequilibrium texture due to dissolution and/or recrystallization (Hibbard 1981; Baxter and Feely 2002; Coombs and Gardner, 2004; Martin et al. 2006). That transfer of minerals between magmas occurred during mixing is evident in the detailed 3D observation of Grizzly Lake samples reported above; therefore, a detailed analysis of mineral phases is necessary to understand the role played by mineral dissolution/crystallization during mixing at Grizzly Lake. This is reported in the following sections focusing on the three major group of lithologies defined above.

4.3 Rhyolitic portions

The rhyolitic portions (Fig. 12 and 13) are composed of glass, sanidine, quartz, olivine, pyroxene and plagioclase. Post-mixing spherulites of feldspar and quartz (compositional equivalent) are present as secondary phases (Fig. 13). Microprobe analysis indicates the presence of labradoritic plagioclase xenocrysts (An_{60-70}) (Fig. 14). These are characterized by resorbed rims (Fig. 13) indicating that this phase underwent disequilibrium conditions. Sanidine phenocrysts of 1-2 mm (Or_{40-60} ; Fig. 13 and Fig. 14) and augite crystals (typically smaller than 30-40 μm) are also identified (Fig. 15). The majority of clinopyroxenes are enriched in Mg although some Fe-rich crystals occur (Fig. 15). Olivine commonly showing resorption textures is typically zoned with cores having forsteritic composition (Fo_{70-80}) and thin (50-60 μm) fayalitic rims (Fa_{95}) (Fig. 16). In several portions of the rhyolitic mass a glass having an andesitic to dacitic composition and containing the above-described minerals, smaller in size, is also observed (Fig. 13). From the above description it is clear that only sanidine and quartz are the products of crystallization of the rhyolite. The other minerals, due to their more mafic compositions,

which are incompatible with crystallization from the rhyolitic melt, were likely transferred from the basalt to the rhyolite during the mixing process (Wilcox, 1944; Christensen, 2001; Pritchard et al., 2013).

4.4 Basaltic portions/Basaltic enclaves

As introduced above we divide the basaltic magma in two sub-groups showing a different style of interaction with the rhyolitic end-member (e.g. Fig. 4): basaltic portions and basaltic enclaves. Basaltic portions are larger in size, amoeboid in shape and display evidence of compenetration with the rhyolitic magma. In particular, they are characterized by the presence of xenocrysts transferred from the rhyolitic magma (sanidine and quartz) and are pervaded by hybrid filaments with compositions ranging from andesite to rhyolite. Basaltic enclaves, on the contrary, are smaller in size, rounded in shape and do not show any significant interaction with the rhyolitic magma. In general, the mineral assemblage of both basaltic portions and enclaves comprises: phenocrysts of labradoritic plagioclase (An_{60-70}) up to 3 mm, (Fig. 14 and 17), forsteritic olivine up to 1 mm (Fo_{70-80}) (Fig. 16 and 17) and clinopyroxene mostly having augitic composition (up to 1 mm; Fig. 15 and 17). Furthermore, the basaltic portions typically contain rhyolitic filaments (Fig. 9), hybrid portions (Fig. 17), and phenocrysts of sanidine (Fig. 17) and quartz (Fig. 17). Hybrid portions are commonly located around the rhyolitic portions, representing areas where interaction between the rhyolitic and basaltic magmas mainly occurred. Sanidine and quartz occurring in the basaltic portions show resorbed rims (Fig. 17) indicating a disequilibrium process suffered by these minerals once transferred from the rhyolitic magma to the basaltic one. The groundmass of the basaltic portions and

basaltic enclaves is fully crystallized, being constituted by labradoritic plagioclase, clinopyroxene and Fe-Ti oxides. However, crystal morphologies are different in the two sub-groups. In particular, euhedral microlites of plagioclase and clinopyroxene are present in the large basaltic portions (Fig. 17), whereas dendritic crystals of the same minerals characterize the groundmass of basaltic enclaves (Fig. 18 and Supplementary Fig. 1). A distinctive feature of basaltic enclaves is the presence of miarolitic cavities containing secondary quartz (cristobalite), crystallized from a vapor phase (Fig. 18) (Christiansen and Venchiarutti, 1990; Horwell et al., 2013; Schipper et al., 2015). These quartz-bearing miarolitic cavities represent less than 1.0% in volume of basaltic enclaves.

4.5 Hybrid portions

Hybrid portions represent those areas where the mixing process between the basaltic and rhyolitic end-member occurred with the highest efficiency due to the generation of wide contact surfaces between the rhyolite and the basaltic portions/enclaves (Fig. 9 and 11). Hybrid portions contain interstitial glasses ranging in composition from andesite to rhyolite (Fig. 10). The crystal assemblage is composed of small crystals (2-200 μm) of augites and Fe-Ti oxides (Fig. 17 and 18), large crystals (from 200 μm to 3 mm) of plagioclase (Fig. 17 and 18) with highly variable composition (An_{20-70} ; Fig. 14), anorthoclase, olivine (Fig. 17 and 18), sanidine (Fig. 17) and quartz (Fig. 17). In the hybrid portions, both mafic and felsic phenocrysts show disequilibrium textures represented by resorptions and regrowth rims (Fig. 17 and 18; Supplementary Fig. 2). Alkali feldspar phenocrysts with composition Or_{40-60} (Fig. 14) coexist with anorthoclase and plagioclases (Fig. 14). Disequilibrium textures in augite and Fe-Ti oxide are not

present indicating that these phases are in equilibrium with the hybrid magma. The diagram in Fig. 15 shows that most of clinopyroxene is augite with a few crystals having pigeonite and enstatite composition. Olivine crystals have wide ranging compositions (Fo₅₋₈₃) (Fig. 16) with their cores displaying the highest forsteritic contents.

4.6 Insights into mixing mechanisms and dynamics at Grizzly Lake

The compositional and textural evolution of the magmatic masses forming the Grizzly Lake complex are dominated by the interaction of basaltic and rhyolitic melts. This process generated an extraordinary complexity of lithologies recognisable at different length-scales and characterized by mass exchange processes between the two melts. The different lithologies can be viewed as snapshots of the development of the mixing process frozen in time by the eruption. This led us to select a representative number of samples, which were analysed through a variety of conventional and innovative techniques providing high-resolution insights on the mechanisms and dynamics governing the evolution of the magmatic system in time. In particular, MicroCT data on selected 3D samples were essential to highlight the complexity of the process allowing us to observe and quantify structural and textural patterns arising from the mixing process that would have been difficult to be observed and quantified properly using conventional petrographic techniques.

Our results indicate that the main mechanism triggering the mutual dispersion of the two magmas is represented by stretching and folding dynamics that generated an increase of contact surfaces between the two magmas and allowed for an extensive mass exchange by both chemical diffusion and reciprocal transfer of mineral phases. 3D observations

and analyses allowed us to observe in three dimensions the stretching and folding process generating magma domains where both chemical interaction and transfer of mineral phase (and relative disequilibrium phenomena) produced magma portions having compositional and textural features spanning the entire range from the basaltic to rhyolitic end-members. Furthermore, the occurrence of a self-similar cascade of structures/textures from the outcrop to the millimeter length scale suggests the generation of fractal structures, a typical feature of the development in space and time of stretching and folding processes (i.e. chaotic dynamics; Perugini and Poli 2012). Numerical simulations of mixing systems and their experimental reproduction using high-temperature and high-viscosity natural melts confirmed the important role played by chaotic dynamics (stretching and folding processes between melts) in defining the textural features of mixed igneous rocks. Up to now these characteristics have been mostly documented in igneous outcrops where mixing occurred between crystal-poor magmas. However, in the Grizzly Lake outcrop an increase of complexity of the mixing process is provided by the occurrence of minerals in the two interacting melts and their mutual exchange.

From the results reported above it is apparent that numerous mineral phases display a range of disequilibrium features, such as resorption morphologies, wide ranges of mineral composition and mismatching (disequilibrium) mineral-matrix pairs. Examples are the co-existence of forsteritic olivine, sanidine and quartz in the same magma portions. This provides unequivocal evidence of physical/chemical exchanges between the end-members and the inability of the magmatic system to reach equilibrium conditions.

The presence of mineral phases in both end-member 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 (e.g. Perugini et al., 2003, *Mineralogy and Petrology* Sithonia). The first process, i.e. mass exchange between end-members by chemical diffusion, is evident in the strong compositional variability observed in the composition of analysed glasses in all rock types (Fig. 10 and 11). The second process, i.e. crystal transfer between magmas, is evident in the occurrence of mineral phases that are not in equilibrium in the rhyolites and the basaltic portions (Fig. 11-18). The micro-CT 3D images were fundamental to better appreciate this process of crystal transfer between magmas during mixing. For example, Fig. 8a, c (and Supplementary Movie 1) show a mechanical disaggregation of the basalt and a subsequent dispersion of phenocrysts of plagioclase, olivine and clinopyroxene in the hybrid magma that was previously rhyolitic; this process, also described by Hibbard (1981), Bindeman and Bailey (1994), and Baxter and Feely (2002), can enhance the mixing efficiency breaking the contact interfaces between the two magmas, and dissolving into compositionally different melts while end-members magma undergo mutual compenetration (Kouchi and Sunagawa; 1985).

Minerals transferred from one magma to the other (i.e. olivine, pyroxene, labradoritic plagioclase from the basalt to the rhyolite; mainly sanidine and quartz from the rhyolite to the basalt) might have contributed, therefore, to increase the complexity of the compositional variation of the liquid phase (the analysed glass). Discriminating the relative role played by mass exchange by chemical diffusion between compositionally

different melts and the chemical variability triggered by dissolution/recrystallization in the liquid phase is not easy. The complication of this operation is even more difficult when the chemical diffusion process occurs between melts undergoing chaotic advection with chemical elements having different mobility, as in the case of Grizzly lake outcrop. Nevertheless, some discussion can be made on the basis of the observed textures and mineral chemistry.

From the textural and chemical analysis we have shown that augite form coronae surrounding the mafic minerals that are in dissolution in the rhyolitic portion (Fig. 12 and zoom in Fig. 13). The same mineral represents the main component in the hybrid magma; it is present as phenocrysts, as well as in the groundmass, in the basaltic magma.

Chemically, the basaltic magma is characterized by higher abundance of CaO and MgO (~12 wt.% and ~10 wt.%, respectively) compared to the rhyolitic end-member (Fig. 11), fostering the crystallisation of Mg-rich augite. As CaO and MgO (0.40 wt.% and 0.20 wt.%, respectively) are low in the rhyolitic magma (Fig. 11a, c), a significant amount of Mg-rich augite should not be expected; rather, a minor amount of Fe-rich augite (as shown in Fig. 15) should be present, in agreement with the experimental results of Almeev et al. (2012). Concerning olivine crystals in the rhyolite, they were likely transferred from the basaltic magma into the rhyolitic one during mixing. This is evidenced by the presence of Fe-rich rims reaching fayalitic compositions that are the consequence of olivine crystallization from a highly evolved melt. Furthermore, the abundance of textural disequilibrium in Mg-rich augite and forsteritic olivine in the rhyolitic melts is likely due to the transfer of these minerals from the basaltic magma. Their instability in the new host triggered their partial resorption, contributing to the

618 “hybridization” of the rhyolitic melt (e.g. Vance, 1965; Barbarin, 1990; Freundt and
619 Schmincke, 1992; Andersson and Eklund, 1994; Bindeman and Bailey, 1994; Ginibre et
620 al., 2002; Baxter and Feely, 2002; Coombs and Gardner, 2004; Mueller et al., 2005;
621 Pritchard et al., 2013). The experiments of Donaldson (1990) have shown that olivine can
622 dissolve on the order of days in superheated rhyolitic melts, allowing us to put forward
623 the hypothesis that the chemical contamination of the rhyolite may have occurred also
624 through dissolution of mafic minerals transferred from the basaltic magma. Furthermore,
625 in the case of the Grizzly Lake complex, also the dissolution of labradoritic plagioclase
626 crystals might have contributed to the “hybridization of the rhyolite”, generating volumes
627 of magma with dacitic, trachydacitic and andesitic composition. Therefore, we consider
628 that the crystallization of augite microlites around the mafic phenocrysts may have
629 occurred in those hybrid melts (originally rhyolitic in composition) where the dissolution
630 of labradoritic plagioclase and mafic phenocrysts had also occurred. Such textures have
631 been recognised in other rhyolites (e.g., Freundt and Schmincke 1992). According to
632 many authors the coronae of clinopyroxenes crystallized in the hybrid melt around
633 dissolved phenocrysts (Fig. 17a, e, and f) argue in favour of magma mixing (e.g. Wilcox,
634 1944; Hibbard, 1981; Bindeman and Bailey, 1994; Baxter and Feely, 2002; Coombs and
635 Gardner, 2004; Pritchard et al., 2013). Furthermore, andesitic and dacitic melts can
636 produce Mg-rich augites (Eichelberger, 1975; Sakuyama, 1979) enabling the growth of
637 microlites of clinopyroxenes from hybrid melts during and/or after the mixing process.
638 Therefore, in the rhyolitic portions these anomalous clusters of mafic minerals showing
639 textures of dissolution represent the evidence of the influx of mafic magma into the
640 rhyolitic one. Obviously, together with the transfer of minerals, also the melt of the

intruding basalt should have penetrated into the rhyolite leading to its contamination by both chemical diffusion between melts and dissolution of mineral phases. The geochemical evidence of the overlapping role played by chemical diffusion between melts (enhanced by the stretching and folding dynamics), crystallization and dissolution can be seen in Fig. 11. For example, the change in the compositional trend in the MgO and FeO vs. SiO₂ plots at about SiO₂=65% can be interpreted as due to the crystallization of clinopyroxene in the hybrid magma producing a decreasing of MgO and FeO in the hybrid melt (Fig. 11a, b). Also during mixing, the dissolution of plagioclase produces an increasing of Al₂O₃ and CaO in the same melt (Fig. 11f). The quantity of CaO released in the hybrid melt during the dissolution of plagioclase, however, is balanced by the request of CaO from the clinopyroxene crystallization. Therefore, it can be inferred that the correlation between CaO and SiO₂ (Fig. 11c) can be due to the combination of chemical diffusion between melts, crystallization and dissolution of mineral phases. Na₂O and K₂O appear to be less influenced by crystallization and dissolution and probably most of their variability is mostly due to the chemical inter-diffusion of the two melts in the end-members magmas.

The study of the magma filaments generated by the stretching and folding dynamics of magma mixing (Fig. 3 and 4) reveals the real spatial evolution of the mixing and its complexity. The 3D images provide further evidence that most of basaltic magma (except enclaves, see below) and rhyolitic magmas were at least partially liquid at the moment of interaction, further corroborating the idea that the compositional variations observed in this suite of rocks are likely the result of the overprint of at least two processes

developing during mixing: chemical diffusion between melts and crystal exchange (Fig. 9 and Supplementary Movie 2).

During magma mixing, the interface between the magmatic end-members is changing in time, generating progressively more irregular interfaces (Perugini et al., 2005). The contorted 3D morphologies shown in Fig. 9 (and Supplementary Movie 2) reveal that the mixing process must have been protracted for a sufficient time to produce these complex structures in the rhyolitic filaments, in agreement with the chemical heterogeneities found in mafic minerals hosted in the rhyolite and at the contact between the rhyolite and the basalt.

The formation of the hybrid filaments appears, hence, to be a process of prodigious complexity in terms of its physics and petrological consequences, regardless of whether it derives from the hybridization of the rhyolite or from the hybridization of the basalt. We suggest that the formation of the hybrid magma (Fig. 6, 8, 17, 18) is the result of a two-stage process: the intra-contamination between the basaltic and rhyolitic magma by chemical diffusion, and the contamination by crystals that have migrated into the rhyolite from the basaltic magma and therein dissolved. However, it is also possible to find sanidine and quartz phenocrysts that have been transferred into outcrop volumes where the more voluminous lithology is represented by the basaltic portions (Fig. 17).

The compositional heterogeneity of hybrid magmas ranging from andesite, trachyandesite and trachydacite (Fig. 10) can justify the presence of anorthoclase, sanidine and plagioclase with An₂₀₋₇₀ only in these portions (Fig. 14). These minerals, in fact, are equilibrium phases in magma compositions ranging from andesite and dacite (Johannsen, 1958; Briggs, 1986).

The textural observations made from the outcrop, micro-CT and BSE images enable us to identify large portions of basaltic magma hosting large filaments of rhyolitic magma and basaltic enclaves. According to the textural features of basaltic portions and enclaves reported above, these two lithologies are likely to represent batches of the basaltic magma that interacted with the rhyolite at different times and experiencing different histories of cooling and crystallization. The fact that basaltic enclaves show no sign of internal contamination from the rhyolite can be interpreted, in fact, as an indication that basaltic enclaves behaved essentially as solid bodies. This can be related to the initial stages of the invasion of the felsic magma by the basaltic magma. In particular, at the beginning of the interaction process it is likely that the two end-members had strongly different temperature contrasts, with the basalt having higher temperature relative to the rhyolite (e.g. Sparks and Marshall 1986). According to Giordano et al. (2004) this temperature difference leads to quenching of the basalt and the generation of solid basaltic enclaves having a microcrystalline groundmass due to the very rapid cooling. This is supported by the textural feature of the groundmass of the studied basaltic enclaves that is composed of dendritic plagioclases and pyroxenes. These crystalline textures are not typically formed under isothermal conditions (e.g., Agostini et al., 2013); on the contrary they are typical of rapid cooling and a high degree of undercooling (Conte et al., 2006). During this process the basalt is losing heat in the rhyolitic magma. This way the temperature of the rhyolite is increased and the viscosity contrast between the rhyolite and the new volumes of intruding basaltic magma decreases. As viscosity contrasts decrease, the probability of mixing increases (e.g., Perugini and Poli, 2012). In particular, at low viscosity contrasts the development of stretching and folding dynamics, promoting the mutual dispersion of

the two magmas, is strongly favoured (e.g. Perugini et al., 2003). This leads to the generation of an increase of contact surfaces between magmas through which chemical exchanges via chemical diffusion and transfer of crystals can occur with increasing efficiency. Transfer of mineral phases from the rhyolitic magma to the basaltic magma is evident in the basaltic portions, for example, by the presence of strongly resorbed alkali feldspar and quartz crystals (Fig. 17e; Supplementary Fig. 2; Freundt and Schmincke, 1992). Resorbed alkali feldspar and quartz with smooth shapes (Fig. 17e and f respectively) highlight their disequilibrium conditions suffered when passing from the rhyolitic to the basaltic magma. This supports the hypothesis that basaltic portions represent those volumes of basaltic magma that intruded at later times into the rhyolite when the viscosity contrast between the two magmas was lower, allowing for mutual dispersion of magmas.

In conclusion, we hypothesize that the magma mixing process at Grizzly Lake was triggered by batches of basaltic magma intruding into a rhyolitic magma chamber, causing overheating of the rhyolite. As shown by our results, the interaction between the two magmas mostly occurred while they were still behaving as deformable bodies (liquid plus crystals in both magmas) and at different temperature. This resulted in portions of hybrid magma that are texturally and chemically heterogeneous due to the development in space and time of stretching and folding of magma volumes leading to the production of numerous melts with intermediate compositions (in agreement with experimental studies of Morgavi et al., 2012 and 2013a-b). Stretching and folding processes might have been occurred at any time after the two magmas come into contact, from their migration from the plumbing system to their eruption (e.g. Perugini and Poli, 2012). The

chemical heterogeneity of rocks from the Grizzly Lake complex was also increased by the dissolution/crystallization of mafic and felsic minerals during the mixing process. As a whole, the eruption of the Grizzly Lake complex exemplifies the great complexity of magma mixing processes that might occur between crystal-bearing basaltic and rhyolitic magmas.

5. Summary and conclusions

We presented the first combined study of high-resolution microanalysis and 3D micro-CT data on magma mixing between basaltic and rhyolitic magmas. Results indicate that the mixing process was mostly governed by the development of stretching and folding dynamics between two crystal-bearing magmas. This produced volumes of magmas exhibiting a wide variety of compositional patterns and textures depending upon the relative mass exchanges, in terms of both chemical diffusion and crystal transfer, between the two end-members. These variable patterns represent snapshots of the mixing process fossilized in time due to the eruption of the magmatic mass.

Chemical variations in the rhyolitic, hybrid, and basaltic portions were quantified by EMP measurements of glass and mineral phases. The use of 3D micro-CT analysis was fundamental to unravel the extraordinary complexity of structures generated by magma mixing and allowed us to study their real morphologies and architecture. This was an essential approach to identify the mechanisms acting during magma mixing, especially the transfer of mineral phases from one magma to the other. The mineral exchange between magmas is identified as a process that, acting in combination with the chaotic dynamics characterizing the redistribution of melts in space and time, can enhance

chemical exchanges and influence the geochemical evolution of the mixing system due to dissolution/recrystallization on minerals.

Further research needs to be focused on the impact of magma mixing on the generation of extreme compositional variations and the variety of disequilibria in minerals in petrogenetic systems whose evolution is governed by the interaction between compositionally different magmas. The approach presented here combining high-resolution geochemical analyses and 3D observations appears promising to gain further insight about the process of magma mixing, which is probably one of the most complex, yet poorly known, petrogenetic processes. Additional insights about the complexity of this process can be gained through high-temperature experiments in which natural crystal-bearing magmas are mixed in different proportions and for different experimental durations. Such experiments, analysed using the same techniques used in this work, might provide unprecedented information about the time and space evolution in magma mixing processes and their impact on the modulation of the development of the geochemical variability trigger by magma mixing both in the melt phase and minerals.

Acknowledgements

This research was funded by the European Union's Seventh Programme for research technological development and demonstration under grant agreement No 282759 - VUELCO; by the ERC Consolidator Grant 612776 – CHRONOS, by advanced Grant 247076 EVOKEs as well as by the National Science Foundation Grant #EAR-0609475. The Authors acknowledge the editor Nelson Eby, Eric H. Christiansen and an anonymous reviewer for the detailed and constructive comments that greatly helped the authors in

improving the manuscript. Sampling permits were issued to Dr. Peter Larson by Yellowstone National Park, Research Permit Office, with help from Christie L. Hendrix.

References

Agostini, C., Fortunati, A., Arzilli, F., Landi, P., Carroll, M., R., 2013. Kinetics of crystal evolution as a probe to magmatism at Stromboli (Aeolian Archipelago, Italy). *Geochimica et Cosmochimica Acta* 110, 135–151.

Almeev, R.R., Bolte, T., Nash, B.P., Holtz, F., Erdmann, M., Cathey, H.E., 2012 High-temperature, low-H₂O silicic magmas of the Yellowstone hotspot: an experimental study of rhyolite from the Bruneau– Jarbidge Eruptive Center, Central Snake River Plain, USA. *Journal of Petrology* 53, 1837–1866.

Anderson, A.T., 1976. Magma mixing: Petrological process and volcanological tool. *J. Volcanology Geothermal Research* 1, 3-33.

Baker, D.R., Brun F., O'Shaughnessy, C., Mancini, L., Fife J.L., Rivers, M., 2012a. A four-dimensional X-ray tomographic microscopy study of bubble growth in basaltic foam: *Nature Communications*. 3, 1135.

Baker, D.R., Mancini, L., Polacci, M., Higgins, M.D., Gualda, G.A.R., Hill, R.J., Rivers, M., 2012b. An introduction to the application of X-ray microtomography to the three-dimensional study of igneous rocks. *Lithos*, 148, 262-276.

Baxter, S., and Feely, M. 2002. Magma Mixing and mingling textures in granitoids: examples from the Galway Granite, Connemara, Ireland. *Mineralogy and Petrology*, 76 63-74.

800 Bennett, M.K., 2006. Petrogenesis of Pleistocene basalts in the Norris-Mammoth
801 Corridor, Yellowstone National Park. [M.S. Thesis] University of Nevada, Las
802 Vegas.

803 Bindeman, I.N., and Bailey, J.C. (1994) A model of reverse differentiation at Dikii
804 Greben' Volcano, Kamchatka: progressive basic magma vesiculation in a silicic
805 magma chamber. *Contributions to Mineralogy and Petrology*, 117, 263–278.

806 Blunt, M.J., Bijeljic, B., Dong, H., Gharbi, O., Iglauer, S., Mostaghimi, P., Paluszny, A.,
807 Pentland C., 2013. Pore-scale imaging and modeling: *Advances in Water Resources*.
808 51, 197-216.

809 Brun, F., Mancini L., Kasae, P., Favretto, S., Dreossi, D., and Tromba, G., 2010. Pore3D:
810 A software library for quantitative analysis of porous media: *Nuclear Instruments*
811 *and Methods in Physics Research A*. 615, 326–332.

812 Carlson, W.D., 2006, Three-dimensional imaging of earth and planetary materials: *Earth*
813 *and Planetary Science Letters*. 249, 133–147.

814 Christiansen, E.H.; Venchiarutti, D.A., 1990, Magmatic inclusions in rhyolites of the
815 Spor Mountain Formation, western Utah: limitations on compositional inferences
816 from inclusions in granitic rocks. *Journal of Geophysical Research*. 95, 17717-
817 17728.

818 Christiansen, R.L., Lowenstern, J.B., Smith, R.B., Heasler, H., Morgan, L.A., Nathenson,
819 M., Mastin, L.G., Patrick Muffler, L.J., Robinson, J.E., 2007, Preliminary
820 Assessment of Volcanic and Hydrothermal Hazards in Yellowstone National park
821 and Vicinity: US Geological Survey Open-File Report .2007-1071, 94 p.

822 Christiansen, R.L.,1999, Digital geologic map for Yellowstone National Park, Idaho,
823 Montana, and Wyoming and vicinity: US Geological Survey Open-File Report. 99-
824 0174

825 Christiansen, R.L., 2001 The Quaternary and Pliocene Yellowstone Plateau Volcanic
826 Field of Wyoming, Idaho, and Montana. US Geological Survey Professional Paper
827 729-G

828 Conte, A., Perinelli, C. and Trigila, R. 2006. Cooling kinetics experiments on different
829 Stromboli lavas: Effects on crystal morphologies and phases composition. Journal of
830 Volcanology and Geothermal Research 155, 179– 200.

831 Coombs, M. L., Eichelberger J. C., Rutherford, M. J., 2002. Experimental and textural
832 constraints on mafic enclave formation in volcanic rocks. Journal of Volcanology
833 and Geothermal Research 119, 125-144.

834 Coombs, M. L., and Gardner, J. E., 2004. Reaction rim growth on olivine in silicic melts:
835 Implications for magma mixing. American Mineralogist, Volume 89, pages 748–
836 759.

837 Couch, S., Sparks, R. S. J., Carroll, M. R., 2001. Mineral disequilibrium in lavas
838 explained by convective self-mixing in open magma chambers. Nature 411, 1037-
839 1039.

840 De Campos, C.P., Perugini, D., Dingwell, D.B., Civetta, L., Fehr, T.K., 2008.
841 Heterogeneities in Magma Chambers: insights from the behavior of major and minor
842 elements during mixing experiments with natural alkaline melts. Chemical Geology
843 256, 131–145.

844 De Campos, C. P., Perugini, D., Ertel-Ingrisch, W., Dingwell, D. B., Poli, G., 2011.

845 Enhancement of Magma Mixing Efficiency by Chaotic Dynamics: an Experimental
846 Study. *Contribution to Mineralogy and Petrology* 161, 863-881.

847 Donaldson, C. H., 1990. Forsterite dissolution in superheated basaltic, andesitic and
848 rhyolitic melts. *Mineralogical Magazine*, 54, 67-74.

849 Dowd, B.A., Campbell, G.H., Marr, R.B., Nagarkar, V.V., Tipnis, S.V., Axe, L., Siddons,
850 D.P., 1999. Developments in synchrotron X-ray computed microtomography at the
851 National Synchrotron Light Source. *SPIE's Int. Symp. Opt. Sci. Eng. Instrum.*, 224-
852 236.

853 Eichelberger, J. C., 1975. Origin of andesite and dacite: Evidence of mixing at Glass
854 Mountain in California and at other circum-Pacific volcanoes. *Geological Society of
855 America Bulletin* 1975; 86, 10;1381-1391

856 Feldkamp, L.A., Davis, L.C., and Kress, J.W., 1984. Practical cone-beam algorithm:
857 *Journal of the Optical Society of America* 1, 612–619.

858 Flinders, J., Clemens, J.D., 1996. Non-linear dynamics, chaos, complexity and enclaves
859 in granitoid magmas. *Trans. R. Soc. Edinburgh Earth Science* 87, 225-232.

860 Fenner, C.N., 1938. Contact relations between rhyolite and basalt on the Gardiner River,
861 Yellowstone Park. *Geological Society of America Bulletin* 49, 1441–1484

862 Fourcade, S., Allegre, C. J., 1981. Trace element behaviour in granite genesis: a case
863 study the calc-alkaline plutonic association from the Querigut Complex (Pyrenees
864 France). *Contribution to Mineralogy and Petrology* 76, 177-195.

865 Freundt, A., Schmincke, H. U. 1992. Mixing of rhyolite, trachyte and basalt magma
866 erupted from a vertically and laterally zoned reservoir, composite flow P1, Gran
867 Canaria. *Contribution to Mineralogy and Petrology* 112, 1–19.

868 Fusseis, F., Xiao, X., Schrank, C., De Carlo, F., 2014. A brief guide to synchrotron
869 radiation-based microtomography in (structural) geology and rock mechanics.
870 Journal of Structural Geology 65, 1-16.

871 Giordano, D., Romano, C., Papale, P., & Dingwell, D. B. (2004). The viscosity of
872 trachytes, and comparison with basalts, phonolites, and rhyolites. Chemical Geology,
873 213(1), 49-61.

874 Girard, G., Stix, J., 2009, Magma recharge and crystal mush rejuvenation associated with
875 early post-collapse Upper Basin Member Rhyolites, Yellowstone caldera, Wyoming:
876 Journal of Petrology 50, 2095-2125.

877 Gualda G.A.R., Pamukcu A.S., Claiborne L.L. and Rivers M.L. 2010. Quantitative 3D
878 petrography using X-ray tomography 3: Documenting accessory phases with
879 differential absorption tomography, Geosphere 6, 782-792.

880 Hibbard, M.J., 1981. The magma mixing origin of mantled feldspar. Contribution to.
881 Mineralogy and Petrology. 76, 158-170.

882 Hibbard, M.J., 1995. Petrography to petrogenesis. Prentice Hall 587

883 Hildreth, W., Halliday, A.N., Christiansen, R.L., 1991, Isotopic and chemical evidence
884 concerning the genesis and contamination of basaltic and rhyolitic magma beneath
885 the Yellowstone Plateau Volcanic Field: Journal of Petrology 32 63-138.

886 Horwell, C.J.; Williamson, B.J.; Llewellyn, E.W.; Damby, D.E. Le Blond, J.S., 2013, The
887 nature and formation of cristobalite at the Soufriere Hills, volcano, Montserrat:
888 implications for the petrology and stability of silicic lava domes: Bulletin of
889 Volcanology 75, 696-715.

890 Kak, C., and Slaney, M., 1987, Principles of Computerized Tomographic Imaging: New
891 York, IEEE Press.

892 Ketcham, R.A., 2005, Computational methods for quantitative analysis of three-
893 dimensional features in geological specimens: *Geosphere*, 1, 32–41.

894 Ketcham, R.A., and Carlson, W.D., 2001, Acquisition, optimization and interpretation of
895 X-ray computed tomographic imagery: Applications to the geosciences: *Computers*
896 *& Geosciences*, 27, 381–400.

897 Kouchi, A., and Sunagawa, I., 1985. A model for mixing basaltic and dacitic magmas as
898 deduced from experimental data. *Contribution to Mineralogy and Petrology* 1985 89,
899 17-23.

900 Kratzmann, D.J., Carey, S., Scasso, R., Naranjo, J.A., 2009. Compositional variations and
901 magma mixing in the 1991 eruptions of Hudson volcano, Chile. *Bulletin of*
902 *Volcanology* 71, 419-439.

903 Lak, M., Néraudeau, D., Nel, A., Cloetens, P., Perrichot, V., Tafforeau, P., 2008. Phase
904 contrast X-ray synchrotron imaging: opening access to fossil inclusions in opaque
905 amber. *Microsc. Microanal.* 14, 251-259.

906 Lanphere, M.A., Champion, D.E., Christiansen, R.L., Izett, G.A., Obradovich, J.D., 2002,
907 Revised ages for tuffs of the Yellowstone Plateau volcanic field: Assignment of the
908 Huckleberry Ridge Tuff to a new geomagnetic polarity event. *Geological Society of*
909 *America Bulletin* 114, 559-568.

910 Leeman, W.P., Annen, C., Dufek, J., 2008, Snake River plain-Yellowstone silicic
911 volcanism: implications for magma genesis and magma fluxes, *In*: Annen C, Zellmer

912 GF (eds.) Dynamics of Crustal Magma Transfer, Storage and Differentiation.
 913 Geological Society of London 305, 325-259.

914 Leonard, G. S., Cole, J. W., Nairn, I. A., Self, S., 2002 Basalt triggering of the c. AD
 915 1305 Kaharoa rhyolite eruption, Tarawera volcanic complex, New Zealand Journal
 916 of Volcanology and Geothermal Research 115, 461-486.

917 Martin, V. M., Holness, M. B., Pyle, D. M., 2006 Textural analysis of magmatic enclaves
 918 from the Kameni Islands Santorini, Greece. Journal of Volcanology and Geothermal
 919 research 154 89-102.

920 Mees, F., Swenner, R., Van Geet, M., and Jacobs, P., 2003, Application of X-ray
 921 computed tomography in the Geosciences, in Mees, F., Swenner, R., Van Geet, M.,
 922 and Jacobs, P., eds., Application of X-ray computed tomography in the Geosciences:
 923 Geological Society, London, Special Publication 215, 1–6.

924 Morgavi, D., Perugini, D, De Campos, C. P., Ertl-Ingrisch, W., Lavallée, Y., Morgan, L.,
 925 Dingwell D. B. 2012. Interactions between rhyolitic and basaltic melts unraveled by
 926 chaotic mixing experiments. Chemical Geology 346, 199–212.

927 Morgavi, D., Perugini, D, De Campos, C. P., Ertl-Ingrisch, W., Dingwell, D. B. 2013.
 928 Morphochemistry of patterns produced by mixing of rhyolitic and basaltic melts.
 929 Journal of Volcanology and Geothermal Research 253, 87–96

930 Morgavi, D., Perugini, D, De Campos, C. P., Ertl-Ingrisch, W., Dingwell, D. B. 2013.
 931 Time evolution of chemical exchanges during mixing of rhyolitic and basaltic melts.
 932 Contribution to Mineralogy and Petrology 166, 615–638.

933 Murphy, M.D., Sparks, R. S. J., Barclay, J., Carrol, M. J., Lejeune, A-M., Brewer, T. S.,
 934 Macdonald, R., Black, S., Young, S., 1998 The role of magma mixing in triggering

935 the current eruption of the Soufriere Hills volcano Montserrat, West indies V., 25 18,
 936 3433-3436.

937 Nastanski, N.M., 2005, Petrogenesis of extracaldera rhyolites at Yellowstone volcanic
 938 field. [M.S. Thesis] University of Nevada, Las Vegas.

939 Otsu, N., 1979. A threshold selection method from gray level histograms. IEEE Transactions
 940 on Systems, Man and Cybernetics 9, 62-66, CODEN: ISYMAW, ISSN 0018-9472

941 Pierce, K.L., and Morgan, L.A.,. 2009. Is the track of the Yellowstone hotspot driven by
 942 a deep mantle plume? Review of volcanism, faulting, and uplift in light of new data.
 943 Journal of Volcanology and Geothermal Research. 188,1-25.

944 Perugini, D., De Campos, C. P., Dingwell, D. B., Petrelli, M., Poli, G., 2008. Trace
 945 element mobility during magma mixing: preliminary experimental results. Chemical
 946 Geology 256, 146-157.

947 Perugini, D., De Campos, C.P., Ertel-Ingrisch, W., Dingwell, D.B., 2012. The space and
 948 time complexity of chaotic mixing of silicate melts: implications for igneous
 949 petrology. Lithos 155, 326–340.

950 Perugini, D., Petrelli, M., Poli, G., 2006. Diffusive fractionation of trace elements by
 951 chaotic mixing of magmas. Earth Planetary Science letter 243, 669-80.

952 Perugini, D., Poli G., Mazzuoli, R. 2003. Chaotic Advection, Fractals and Diffusion
 953 During Mixing of Magmas: Evidence from Lava Flows. Journal of Volcanology and
 954 Geothermal Research 124, 255-279.

955 Perugini, D., Poli, G., 2000. Chaotic dynamics and fractals in magmatic interaction
 956 processes: a different approach to the interpretation of mafic microgranular enclaves.
 957 Earth and Planetary Science Letters. Volume 175, Issues 1–2, 30, 93–103.

958 Perugini, D., Poli, G., 2005. Viscous fingering during replenishment of felsic magma
 959 chambers by continuous inputs of mafic magmas: field evidence and fluid-
 960 mechanics experiments. *Geology* 33, 5-8.

961 Perugini D., Poli G. 2012. The mixing of magmas in plutonic and volcanic environments:
 962 analogies and differences. *Lithos*, 153, 261–277.

963 Perugini, D., Poli, G., Gatta, G., 2002. Analysis and Simulation of Magma Mixing
 964 Processes in 3D. *Lithos*, 65, 313-330.

965 Perugini, D., Ventura, G., Petrelli, M., Poli, G., 2004. Kinematic significance of
 966 morphological structures generated by mixing of magmas: a case study from Salina
 967 Island (Southern Italy). *Earth Planetary Science Letter* 222, 1051-1066.

968 Petrelli, M., Perugini, D., Poli, G., 2011. Transition to chaos and implications for time-
 969 scales of magma hybridization during mixing processes in magma chambers: *Lithos*
 970 125, 211–220.

971 Polacci, M., Burton, M.R., La Spina, A., Murè, F., Favretto, S., Zanini, F., 2009. The role
 972 of syn-eruptive vesiculation on explosive basaltic activity at Mt. Etna, Italy: *Journal*
 973 *of Volcanology and Geothermal Research*, 179,

974 Poli, G., Perugini D., 2002. Strange Attractors in Magmas: Evidence from Lava Flows.
 975 *Lithos* 65, 287-297.

976 Pouchou, L., Pichoir, F., 1984. A new model for quantitative X-ray microanalysis: Part I:
 977 Applications to the analysis of homogeneous samples. *Rech Aerosp* 3, 13-38.

978 Pratt, W.K., 2007, *Digital Image Processing*: Hoboken, New Jersey, John Wiley and Sons
 979 782

980 Pritchard, C.P., Larson, P.B., 2012. Genesis of the post-caldera eastern Upper Basin
 981 Member rhyolites, Yellowstone, WY, from volcanic stratigraphy, geochemistry, and
 982 radiogenic isotope modeling. *Contributions to Mineralogy and Petrology*. 164, 205-
 983 228.

984 Pritchard, C.J., Larson, P.B., Spell, T.L., Tarbert, K.D., 2013, Eruption-triggered mixing
 985 of extra-caldera basalt and rhyolite complexes along the East Gallatin-Washburn
 986 fault zone, Yellowstone National Park, WY, USA. *Lithos*, v. 175-176, 163-177.

987 Rothstein, D., Henry, E., Gollub, J. P., 1999. Persistent patterns in transient chaotic
 988 fluid mixing. *Nature*, 401, 770-772.

989 Sakuyama, M. 1979 Evidence of magma mixing: petrological study of Shir- ouma-Oike
 990 calc-alkaline andesite volcano, Japan. *Journal of Volcanology and Geothermal*
 991 *Research*, 5, 179–208.

992 Sparks, R. S. J., Marshall, L. A., (1986). Thermal and mechanical constraints on mixing
 993 between mafic and silicic magmas. *Journal of Volcanology and Geothermal*
 994 *Research* 29 (1), 99-124.

995 Sparks, R. S. J., Pinkerton, H., Macdonald, R., (1977). The transport of xenoliths in
 996 magmas. *Earth and Planetary Science Letters* 35 234-238.

997 Stelten, M.E., Cooper, K.M., Vazquez, J.A., Reid M.R., Barfod, G.H., Wimpenny, J.,
 998 Yin, Q., 2013, Magma mixing and the generation of isotopically juvenile silicic
 999 magma at Yellowstone caldera inferred from coupling ^{238}U - ^{230}Th ages with trace
 1000 elements and Hf and O isotopes in zircon and Pb isotopes in sanidine: *Contributions*
 1001 *to Mineralogy and Petrology* 166 587-613.

1002 Struhsacker, D.W., 1978. Mixed basalt-rhyolite assemblages in Yellowstone National
1003 Park. [M.S. Thesis] University of Montana, Missoula.

1004 Szymanowski, D., Ellis, B.S., Bachmann, O., Guillong M., Phillips, W.M. 2015.
1005 Bridging basalts and rhyolites in the Yellowstone-Snake River Plain volcanic
1006 province: the elusive intermediate step. *Earth and Planetary Science Letters*. 415, 80-
1007 89.

1008 Tromba, G., Longo R., Abrami, A., Arfelli, F., Astolfo, A., Bregant, P., Brun, F., Casarin,
1009 K., Chenda, V., Dreossi, D., Hola, M., Kaiser, J., Mancini, L., Menk, R.H., Quai, E.,
1010 Quaia, E., Rigon L., Rokvic, T., Sodini, N., Sanabor, D., Schultke, E., Tonutti, M.,
1011 Vascotto, A., Zanconati, F., Cova, M., Castelli, E., 2010. The SYRMEP Beamline of
1012 Elettra: Clinical Mammography and Bio-medical Applications: AIP Conference
1013 Proceedings 1266 (1),18-23.

1014 Vazquez, J.A., Kyriazis, S.F., Reid, M.R., Sehler, R.C., Ramos, F.C., 2009.
1015 Thermochemical evolution of young rhyolites at Yellowstone: Evidence for a
1016 cooling but periodically replenished post caldera magma reservoir. *Journal of*
1017 *Volcanology and Geothermal Research* 188, 186-196.

1018 Voltolini, M., Zandomenighi, D., Mancini, L., Polacci M., 2011. Texture analysis of
1019 volcanic rock samples: quantitative study of crystals and bubbles shape preferred
1020 orientation from X-ray microtomography data. *Journal of Volcanology and*
1021 *Geothermal Research* 202, 83-95.

1022 Walker, G.P.L., Skelhorn, R.R., 1966, Some associations of acid and basic igneous rocks.
1023 *Earth-Science Reviews* 2, 93-109.

- White, B.J.P., Smith, R.B., Husen, S., Farrell, J.M, Wong, I, 2009. Seismicity and earthquake hazard analysis of the Teton-Yellowstone region, Wyoming. *Journal of Volcanology and Geothermal Research* 188, 277-296.
- Wiebe, R. A., 1994. Silicic magma chambers as traps for basaltic magmas: the Cadillac mountain intrusive complex, Mount Desert island, Maine. *Journal of Geology* 102, 423-427.
- Wilcox, R.E, 1944. Rhyolite-basalt complex of Gardiner River, Yellowstone Park, Wyoming. *Geological Society of America Bulletin* 55,1047-1080.
- Woods, A.W., Cowan, A., 2009. Magma mixing triggered during volcanic eruptions. *Earth and Planetary Science Letters*, 288, 132-137.
- Zandomeneghi, D., Voltolini, M., Mancini, L., Brun, F., Dreossi, D., Polacci, M., 2010. Quantitative analysis of X-ray microtomography images of geomaterials: Application to volcanic rocks. *Geosphere* 6, 793-804.

Figure Captions

Figure 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).

Figure 2: General picture of Grizzly Lake outcrop showing in square dashed lines the location of samples studied in the this work.

Figure 3: Detailed images of the mixing features present at Grizzly Lake. a) Large area of rhyolitic magma (white colour) with basaltic enclaves (light grey/brownish marked in white lines) surrounded by hybrid filaments (blue/dark gray colour). b) Basaltic enclave surrounded by hybrid magma (highlighted with a white line). c) Exhibits at the centre a basaltic enclave (white line) with an elongated shape. d) Stretching and folding of hybrid magma (dark grey) into a rhyolitic portion (white). e) Rhyolitic magma (white, highlighted with black dots) has apparently intruded into the basaltic magma; hybrid portions are present at the contact between the two end-members and show a single filament intruding the rhyolite (top left). Two large basaltic enclaves are visible at the bottom left and at the centre right (white lines). f) Section of the outcrop where the basaltic magma is the main component and the rhyolite appears only as small finger-like filaments.

Figure 4: Magma mixing structure at Grizzly Lake outcrop shown at different magnifications.

Figure 5. Synchrotron X-ray microCT images of sample YMRBW6. (a) Reconstructed 2D coronal slice. (b) Volume rendering of the imaged VOI; the size of the VOI along the z axis is 18.8 mm.

Figure 6. Synchrotron X-ray microCT images of sample YMRBW7. (a) Reconstructed 2D coronal slice and (b) Volume rendering of the VOI reported in Table 1.

Figure 7. Conventional X-ray microCT image of sample YMRBW1. (a) Reconstructed 2D axial slice and b) after a binary thresholding, attempting to segment the rhyolitic filament.

Figure 8. Two different 3D views of sample YMRBW6, where in (a) and (c) the mafic crystal have been coloured in yellow; bubbles have been coloured red after segmentation. In (a-b) the size of the VOI along the z axis is 18.8 mm. In (c-d) the slices of the VOI along the z axis are in total 980.

Figure 9. Volume renderings of sample YMRBW7. Renderings (a-c) show the spatial distribution of rhyolitic filaments and mafic crystals into the basaltic portion. In (a) rhyolitic filaments (gray/white) and mafic crystals (yellow) have been coloured after segmentation. In (b) rhyolitic filaments and mafic crystals are shown. Isolated rhyolitic filaments from basaltic portion are shown (c). The vertical size of the VOI is 10.7 mm.

Figure 10. Total alkalis vs. SiO_2 (TAS) classification (Le Bas et al., 1986), for the interstitial glass for the rhyolitic portion, the hybrid portion and the basaltic/rhyolitic end-member. Data are normalized to 100%. The basaltic and rhyolitic end-members are reported as white and black star, respectively.

Figure 11. Representative binary plots showing the variable correlation between pairs of major elements measured in the glass of the rhyolitic and hybrid portion. The mixing line connecting the two end-members is also reported. Average mafic and felsic end-member compositions are reported as white and black star, respectively. The grey area represents the chemical variability for basalts in the Yellowstone volcanic field with MgO larger than 9.0% (data are normalized to 100%).

Figure 12. Back-scattered electron (BSE) image of a section of the mixed rock showing analysis locations on the basaltic portion, the hybrid portion and the rhyolitic portion. The basalt is at the bottom left and is marked by a dashed line. The hybrid portion is marked by a dotted line and the rhyolite portion is from the center to the right of the figure. a) quartz in the hybrid portion; b) rhyolitic glass; c) olivine in the rhyolitic magma; d) alkali feldspar; e) labradoritic plagioclase. The area marked with a dashed square is magnified in Fig. 13.

Figure 13: Back-scattered electron (BSE) image, showing the rhyolitic portion. a-b-c) Clusters of pyroxene; d) olivine in the rhyolitic magma; e-f-g) labradoritic plagioclase in the rhyolitic magma; h) pyroxene crystals around a plagioclase; i) spherulite; j) alkali feldspar; k) quartz.

Figure 14: Ternary diagram of feldspar crystals. The diagram shows the chemical composition of feldspar in the basaltic, hybrid and rhyolitic portion. Or: orthoclase; Ab: albite; An: anorthite.

1115

1116 Figure 15: Diagram of pyroxenes. The diagram shows the chemical composition of
1117 pyroxenes in the basaltic, hybrid and rhyolitic portion.

1118

1119 Figure 16: Binary diagram of olivines. The diagram shows the chemical composition
1120 of olivines in the basaltic, hybrid and rhyolitic portion. Fo: forsterite; Fa: fayalite.

1121

1122 Figure 17: Back-scattered electron (BSE) image of an outcrop section showing the
1123 contact between the basaltic and hybrid portion. a) Labradoritic plagioclase; b) olivine; c)
1124 clino-pyroxene; d) matrix; e) alkali-feldspar; f) quartz; g) micro clino-pyroxene; h)
1125 olivine; i) labradoritic plagioclase; j) alkali feldspar; k) quartz.

1126

1127 Figure 18: Back-scattered electron (BSE) image of an outcrop section showing the
1128 contact between the basaltic enclave and the hybrid portion. The basaltic magma in this
1129 section of the outcrop preserves its original features such as bubbles and mineral
1130 assemblage. a) Vesicles; b) labradoritic plagioclase; c) olivine; d) pyroxene; e) quartz as
1131 vapor phase; f) micro bubble; g) clino-pyroxene; h) labradoritic plagioclase; i) olivine.

1132

1133 Table 1: Summary of experimental conditions and details of the analysed Volumes of
1134 Interest (VOI) for the investigated samples. Samples YMRBW6 and YMRBW7 have a
1135 parallelepiped shape; their size is reported (in pixel unit) in the column named Imaged
1136 volume. The sample YMRBW1 has a cylindrical shape; (diameter 1800 pixels and the
1137 number of reconstructed slices 1270) are reported in the column Imaged volume.

Figure 1

Figure 2

Figure 3

Figure 4

Hybrid Contact
Magma

Basaltic Enclave

1 mm

Rhyolitic Portion

Basaltic Portion

1 mm

Figure 7

Figure 8

a

b

c

d

a

b

c

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16

Figure 17

Figure 18

Table 1

1 Table 1: Summary of some experimental conditions and details of the analysed Volumes
2 of Interest (VOI) for the investigated samples. Samples YMRBW6 and YMRBW7 have a
3 parallelepiped shape and in the column named *Imaged volume* we report their size in
4 pixel unit. The sample YMRBW1 has a cylindrical shape and in the column *Imaged*
5 *volume* we report the diameter (1800 pixels) and the number of reconstructed slices
6 (1270).

Sample	Instrument	Isotropic voxel size (μm)	Imaged volume (pixels)	Imaged volume (mm^3)	Analysed VOI (mm^3)
YMRBW6	SYRMEP	9.0	490x590x2240	472.1	376.34
YMRBW7	SYRMEP	9.0	530x552x1195	254.86	245.69
YMRBW1	TomoLab	10.0	1800x1270	3230.12	1228