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Cannibalization Processes in Hotspot Rhyolites as Deduced from the Kimberly Rhyolite,
Central Snake River Plain, Idaho, USA

Danielle Jeannette Spencer

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Master of Science

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ABSTRACT

Cannibalization Processes in Hotspot Rhyolites as Deduced from the Kimberly Rhyolite, Central Snake River Plain, Idaho, USA

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Master of Science

The 7.7 Ma Kimberly Member of the Cassia Formation is part of a succession of A-type rhyolites associated with the Yellowstone hotspot track. It was sampled by the Kimberly core that was drilled on the Snake River Plain as part of Project HOTSPOT (Shervais, et al., 2013). The Kimberly Member is a 170 m thick high-silica rhyolite lava flow containing quartz, plagioclase, anorthoclase, sanidine, augite, pigeonite, magnetite, ilmenite, zircon, and apatite. δ18O of zircon ranges from 0 to 4.9‰ (Colón et al., 2018), typical low values for the Snake River Plain. Quartz is intensely embayed. Exsolved and resorbed pigeonite cores are mantled by augite. REE-poor apatite cores are resorbed and oscillatory zones truncated by rims with SiO2 as high as 12.8 wt% and LREEtot up to 4.7%. There are three chemically distinct feldspars. Rounded and pitted anorthoclase (Or21 Ab64 An15) mantles plagioclase (An20 to An40) cores. Sanidine (Or47 Ab48 An05) forms thin, subhedral drapes on the outer edges of anorthoclase. Sanidine also fills some of the sieved holes in plagioclase and anorthoclase. There are two chemically distinct glasses, a light glass (~95%) and a dark glass (~5%). Relative to the light glass, the dark is enriched in Al2O3, CaO, and Na2O and depleted in Fe2O3 and K2O. The dark glass is depleted in Rb and enriched in Sr and Ba, but they have similar concentrations of the high field strength elements (Y, Zr, Nb, Hf, and Ta). LREE are slightly more enriched in the dark glass than in the light glass. Temperatures of 926°C (magnetite-ilmenite thermometry with QUILF), 894°C (pigeonite-augite pairs with QUILF), and 889°C (zircon-saturation) are calculated for the magma.

Although Fe-Ti oxides appear to have equilibrated with melt before eruption, most of the other phases preserve strong evidence of disequilibrium. These complex mineral textures also indicate assimilation and mixing processes. We propose a pigeonite-bearing, dry, metasomatized, A-type granite was fragmented and assimilated by the Kimberly member, mantling exsolved pigeonite with augite. Also incorporated into the Kimberly member were volcanic xenocrysts indicative of rhyolite assimilation or magma mixing. These components are embayed volcanic quartz, and composite plagioclase-anorthoclase grains (mantled by sanidine upon assimilation). Complex zircon grains could be sourced from metasomatized rhyolite or intrusion, and complex apatite grains could be due to mixing or assimilation. We propose the distinct glass types are caused by mingling of the Kimberly magma with the melted metasomatized assimilant. This scenario demonstrates the complexity of open system processes involved in some Snake River Plain magmas.

Keywords: Yellowstone, Kimberly Member, Project HOTSPOT, assimilation, cannibalization, rhyolite, lava
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INTRODUCTION

Assimilation and magma mixing have been confirmed processes in a variety of volcanic and plutonic systems. Tracing these processes is critical for a complete understanding of a magma’s history, but volcanic rocks often hold only partial evidence of pre-eruptive interactions, making interpretation difficult. Textural and chemical characteristics of magmatic crystals provide details about these processes that cannot be gleaned from whole-rock data alone. Zircon is an important mineral hallarking mixing and assimilation processes because its resistance to alteration allows for preservation as xenocrysts and antecrysts. Beyond zircon, other minerals in the crystal cargo may be antecrystic or xenocrystic when open system processes are involved as proposed by Davidson, et al. (2004).

Colón et al. (2018) showed that zircon in many rhyolites from the central Snake River Plain have diverse compositions with large ranges of $\delta^{18}$O and $\varepsilon$Hf values, as well as U-Pb ages, indicating they were cannibalized from older silicic rocks and incorporated into the rhyolite magma before eruption. Here, we show that diverse compositions and disequilibrium textures extend to most of the crystal cargo in at least one of these rhyolites—the Kimberly Member of the Cassia Formation (as defined by Knott et al., 2016). This is the first report of such wide-ranging diversity in a Snake River Plain Yellowstone rhyolite; it gives further support to the cannibalization hypothesis (e.g. Bindeman and Simakin, 2014) and also reveals important characteristics of the assimilated materials. The Kimberly Member’s unique mineral assemblage and textures provide an opportunity to explore the effects of assimilation and magma mixing on Yellowstone Hotspot rhyolites. Study of the Kimberly Member increases understanding of how assimilation and other processes may effect geochemistry, textures, and crystal cargo of erupted products.
THE KIMBERLY MEMBER

The Kimberly well is one of three ~2 km deep holes drilled by Project Hotspot (Shervais et al., 2013; Supplementary Fig. 1, 2). The Kimberly site was selected to penetrate through the basaltic lava and into underlying rhyolites. The drill site lies on the southern margin of the Twin Falls eruptive complex, a 10-6 Ma Yellowstone-scale volcanic field that underlies the Central Snake River Plain (Ellis et al., 2010; Pierce and Morgan, 1992). Christiansen et al. (2013) concluded that the core penetrated an intracaldera section with a thick (~1400 m) basal intracaldera tuff, and a caldera fill sequence (~600 m) of lake sediment, rhyolite lava, loess and basalt (Supplementary Fig. 1). Inclinations of paleomagnetism, mineral assemblages, textures, O-isotopic and chemical compositions, and U-Pb zircon ages reveal three rhyolite units (Supplementary Fig. 1, 3; Christiansen et al. 2013; Knott et al., 2016; Colón et al., 2018). The bottom ignimbrite and top rhyolite lava in the core have been correlated with the Castleford Crossing Member (7.96 +/- 0.12 Ma; Colón et al., 2018) and the Shoshone Rhyolite (6.06 +/- 0.08 Ma; Colón et al., 2018), respectively (Knott et al., 2016). The Kimberly Member, the middle rhyolite, is not exposed anywhere and is the subject of this paper.

The Kimberly rhyolite is a viscous lava flow that erupted 7.70 Ma (Colón et al., 2018). It lacks eutaxitic fabrics and broken phenoclasts and has contorted flow foliations and vitrophyric breccias at the top and bottom. In contrast to the other two rhyolites in the Kimberly core, the middle lava has dramatically embayed quartz and is a high-silica rhyolite with low Fe₂O₃ and TiO₂ (Supplementary Fig. 3). Whole rock compositions are fairly uniform in the 17 freshest samples we have analyzed. For example, TiO₂ varies only from 0.35 to 0.41 wt% and SiO₂ from 74.3 to 75.2 wt%. The Kimberly Member has 13% phenocrysts consisting of quartz, plagioclase, anorthoclase, sanidine, augite, pigeonite, and accessory magnetite, ilmenite, apatite, and zircon.
In this paper, phenocrysts are defined as any pre-eruptive crystal which may include antecrytsts and xenocrysts. As expected for the central Snake River Plain, magmatic $\delta^{18}O$ values are low, with 3.7‰ in quartz, 3.0‰ in feldspar, and about 2‰ to nearly 0‰ in zircon showing the $\delta^{18}O$ of magma was also low, less than 3.7‰ (Bindeman, et al., 2007; Watts et al., 2010, 2011, 2012; Boroughs et al., 2005; 2012; Ellis and Wolff, 2012).

MINERAL CHEMISTRY AND TEXTURES

All phases in the Kimberly Member, with the exception of Fe-Ti oxides, have textures, geochemical characteristics, or both that indicate disequilibrium. Here we present these textures, as well as calculated temperatures for the magma.

Zircon

Zircon in the Kimberly Member is diverse. Colón et al. (2018) report the in situ isotopic compositions and U-Pb ages of zircon range widely. $\delta^{18}O$ extends from 0 to 4.9‰, $\epsilon$Hf varies from -7.1 to 1.3 (with one outlier at 6.6), and ages range to as much as 1.5 m.y. older than the eruption age. Moreover, zircon cores and rims have distinct Hf and O isotopic compositions, indicating different sources. We calculated zircon saturation temperatures of 889° from whole rock and 839° from glass composition of sample A2-1946 using the method from Watson (1979).

Fe-Ti oxides

In the Kimberly rhyolite, magnetite is euohedral to subhedral and often forms in clots with pyroxene, although some is isolated in glass or attached to feldspar. Ilmenite is euohedral but rare. Based on euohedral shape, compositional similarity from sample to sample, and a lack of reaction rims or zoning, we conclude the oxides are not xenocrystic. Since both appear to be native to the magma and because of their rapid equilibration with silicate melt (Evans et al., 2016), we use
their compositions (Supplementary Fig. 7) to calculate temperature and $fO_2$. QUILF (Andersen, et al., 1993) yielded an average temperature of $926^\circ C \pm 11^\circ$ and a log $fO_2$ of $-12.3 \pm 0.2$ (0.2 $\Delta$QFM) (Appendix 5b). Such high temperatures and low oxygen fugacities are typical of the hot, reduced rhyolites of the Snake River Plain Yellowstone province (Honjo et al., 1992; Cathey and Nash, 2009; Andrews et al., 2006; Almeev et al., 2012).

**Quartz**

Quartz in the Kimberly rhyolite is very distinctive. Large (0.6-2.5 mm) quartz grains are rounded, intensely embayed on their outer edges, and have numerous subcircular holes unconnected to matrix glass (from a 2D thin section perspective). Single grains have 15-20 of these irregularities (Fig. 1, Appendix 8). The glass filled holes lack shrinkage bubbles, so it is unlikely that they were trapped as melt inclusions but instead they probably have connections to the matrix glass through broad channels. Very few of the embayments have narrow necks and many taper inward (unlike those documented by Loewen et al. (2017) for the Summit Lake rhyolite lava at Yellowstone). None of the crystals have hopper-shaped exteriors with “Christmas tree” extensions indicative of rapid growth. Facets of the crystals are essentially absent and most are rounded or extremely irregular in shape. None of the grains have undulatory extinction.

Cathodoluminescence images reveal faint oscillatory growth zones in almost all grains (Appendix 8). Embayments and holes commonly cut growth zones. In a few of the grains,
Figure 1. Petrographic summary of textures in the Kimberly rhyolite

A. Mantled feldspar (plagioclase, anorthoclase, sanidine) in cross polarized view
B. Mantled feldspar in colored K element map
C. Mantled pyroxene (embayed and exsolved pigeonite core mantled by augite) in cross polarized image
D. Mantled pyroxene in BSE image
E. Embayed quartz grain in CL image
F. Zoned apatite in BSE image with dark REE-poor core, truncated oscillations, and bright REE-rich rim
G. Mantled feldspar (anorthoclase, sanidine), dark glass, and light glass in cross polarized image
brighter cores were embayed and then infilled by later generations of quartz with lower CL intensity. These mantles around the cores are also embayed, and some embayments cut core-mantle boundaries.

The average Ti content in quartz is 202 +/- 26 ppm (based on 27 analyses of quartz cores and rims in two samples; Supplementary Table 2). We calculate average Ti-in-quartz temperatures of 1044°C (Huang and Audéat, 2012) and 814°C (Thomas et al., 2010) using $aTiO_2 = 0.26$ based on the composition of the glass and the formulas of Kularatne and Audéat (2014). Temperatures from the Thomas et al. (2010) thermometer are ~90°C less than predicted by other geothermometers and are typically lower than magmatic temperatures (e.g., Dailey et al., 2018; Wilson et al., 2012). Temperatures calculated using Huang and Audéat’s (2012) model are usually close to magmatic temperatures inferred by other means, but here it predicts a high and unlikely temperature as discussed below.

**Apatite**

Apatite grains are typically euhedral to subhedral and up to 50 μm in diameter. They are found attached to or included in other mineral phases (magnetite and clinopyroxene) and also isolated in the glass matrix. BSE images of apatite grains show textural variety and EMP and LA analyses reveal strong compositional zoning. Most apatite grains imaged have euhedral oscillatory zoning. Additionally, many grains have oscillatory zoned dark cores truncated and then mantled by brighter rims (Fig. 1, Appendix 9) that have high REE and SiO$_2$ contents. SiO$_2$ is as high as 12.8 wt% and LREE$_{tot}$ reaches 4.7% in the bright rims (Supplementary Fig. 6)

**Pyroxene**

The Kimberly rhyolite has two Fe-rich pyroxenes, augite and pigeonite, that form single compositional populations [(Fig. 2b, Supplementary Fig. 5); cf. Cathey and Nash, 2004, Ellis and
Wolff, 2012, and Ellis et al., 2014 who found multiple populations of both augite and pigeonite in Snake River Plain rhyolites. Augite forms some uniform, euhedral phenocrysts but commonly it mantles pigeonite that is raggedly embayed and infilled by augite (Fig. 1, Appendix 7). The pigeonite cores have exsolution lamellae of augite as much as 2-3 um wide. Pigeonite rarely forms isolated crystals without augite mantles. The intermediate compositions between the augite and pigeonite clusters (Fig. 2b) is explained by the presence of exsolution lamellae with thicknesses less than the electron beam diameter (~2 µ) resulting in mixed compositions. Qualitative observation of WDS maps and BSE images show the augite lamellae are close in composition to the augite mantles. Since the compositions of mantled and unmantled pigeonite grains are the same, both were used with augite to calculate an average temperature of 894 +/- 7°C using QUILF (Andersen, et al., 1993) (Appendix 5a). These temperatures are comparable to the 926°C for the magnetite-ilmenite pairs and 899°C for whole-rock zircon saturation temperatures.

**Feldspar**

In the Kimberly rhyolite, three feldspars—plagioclase, anorthoclase, and sanidine—form composite grains with complex mantling relationships (Fig. 1, Supplementary Fig. 4, Appendix). Plagioclase is found exclusively in the center of mantled feldspar, has ragged edges, and sieve textured interiors. The plagioclase ranges from An_{20} to An_{40} (Fig. 2a) and has an Or range of 0.04-0.10. Anorthoclase (Or_{21} Ab_{64} An_{15}) mantles plagioclase cores, but is rounded and
Figure 2. Geochemistry of feldspar and pyroxene
a. Feldspars in the Kimberly Member plot in a continuum from oligoclase to andesine, in an anorthoclase cluster, and in a sanidine cluster (label on photos). Solvus lines from SOLVCALC (Wen and Nekvasil, 1994). Each feldspar type plots on a different solvus, indicating disequilibrium between plagioclase, anorthoclase, and sanidine.
b. Pyroxenes are augite and exsolved pigeonite, which are frequently in mantling relationships. The intermediate compositions are the microprobe beam hit a narrow exsolution lamellae.
sometimes pitted. Sanidine (Or$_{47}$ Ab$_{48}$ An$_{05}$) forms thin, subhedral drapes on the outer edges of anorthoclase. Sanidine also fills some of the sieved holes in plagioclase and anorthoclase.

**Glass**

In the Kimberly rhyolite, the matrix glass is perlitic in samples that are not devitrified. There are two distinct colors of glass--light tan and a darker brown (Fig. 1, Supplementary Fig. 8) The darker brown glass is subordinate (<5%) and forms 1 to 5 cm long lenses with swirled, ductile morphologies and is embedded in the light glass. At boundaries between the dark and light glass, there are alternating mingled bands of the two colors of glass. The dark glass contains abundant microcrystals (30 μm and smaller) of quartz, pyroxene, and feldspar but no larger phenocrysts. In A2-1946, a composite (anorthoclase and sanidine) feldspar grain is engulfed by darker glass, but has attached tendrils of the lighter glass around it (Fig. 1).

Both types of glass are high-silica rhyolite. The dominant light-colored glass has a major element composition typical of most rhyolite glass with ~77% SiO$_2$ and low concentrations of TiO$_2$, MgO. The dark glass is more variable in composition and has a more unusual composition (Fig. 3; Supplementary Fig. 9, 10; Appendix 2b, 3b). Relative to the light glass, it is enriched in Al$_2$O$_3$ (by ~0.7%), CaO (by ~0.5%), and Na$_2$O (by ~2%) and depleted in Fe$_2$O$_3$ (by 0.5%) and K$_2$O (by 2.9%). Laser ablation analyses show the dark glass is depleted in Rb (33 versus 204 ppm) and enriched in Sr (57 versus 10 ppm) and Ba (1032 versus 395 ppm), but they have similar concentrations of the high field strength elements (Y, Zr, Nb, Hf, and Ta). LREE are slightly more enriched and HREE depleted in the dark glass than in the light glass (Fig. 3). Low concentrations of HREE in dark glass are often below detection limits.

**CANNIBALIZATION AND MIXING IN THE KIMBERLY RHYOLITE**
The textures and compositions outlined above provide strong evidence for nonequilibrium, open-system processes in the evolution of the Kimberly rhyolite. In the following section, we outline basic interpretations of these complexities by beginning with the composite feldspars, proceeding through the other phases, and then develop a hypothetical model for the origin of the rhyolite.

Embayment and mantling of plagioclase, anorthoclase, and sanidine could be due to several processes, including decompression, assimilation, magma mixing, or thermal and chemical evolution of a single magma. A closed system explanation for resorption of plagioclase in magma systems is decompression (e.g., Nelson and Montana, 1992), but this does not predict mantling by anorthoclase as seen here. Instead, the mantling suggests a temperature or composition change. Closed system cooling of magma could perhaps produce resorption of plagioclase and appearance of two different feldspars (plagioclase and sanidine) in equilibrium (Nekvasil, 1992). However, the three feldspars plot on different isotherms in a feldspar ternary (Fig. 2). In accord with the embayment and mantling textures, this indicates these feldspars did not co-precipitate and were not in equilibrium with one another. Moreover, the solvus temperature for each feldspar does not decrease in the same sequence as the mantling sequence: plagioclase (800°), anorthoclase (950°), sanidine (900°). In a closed-system cooling model, plagioclase would crystallize at a higher temperature than anorthoclase and sanidine.

Disequilibrium is also indicated by an unreasonably high partition coefficient for Eu in plagioclase ($D_{Eu}$). With an average concentration of 8 ppm Eu in plagioclase, and an average of 0.78 ppm Eu in glass, the calculated $D_{Eu}$ is 10.9. The lowest $D_{Eu}$ reported on GERM
Figure 3. REE glass composition
The dark glass in the Kimberly rhyolite has elevated concentrations of LREE. These distinctions demonstrate the two glasses are from different magmas that mingled shortly before eruption. Concentrations are normalized to chondrite (McDonough and Sun, 1995).
(EarthRef.org) in a rhyolite is 2 (Bacon and Druitt, 1988) and the highest is 7.9 (Nash and Crecraft, 1985), in an evolved, low-T rhyolite. Therefore, plagioclase in the Kimberly member probably was not in equilibrium with the glass since it seems to fall outside the range of reported partition coefficients for Eu in plagioclase.

Thus, we conclude the feldspars precipitated sequentially to form composite grains and were not in equilibrium with one another based on textures and compositions. The inferred sequence is crystallization of sodic plagioclase in an evolved lower-temperature (800°C) rhyolite, followed by resorption. We interpret this to be the result of mixing of the plagioclase into hotter (950°C) magma in which anorthoclase nucleated on and mantled the plagioclase. This was followed by a second episode of resorption, and finally sanidine precipitation (900°C) in equilibrium with the erupted melt. This second resorption episode could represent another magma mixing event, but we speculate that it is the result of cannibalizing the mantled grains from solid rhyolite into the silicic melt from which sanidine crystallized to mantle and infill the resorbed composite grains at about 900°C.

Pyroxenes provide additional constraints on what kinds of rocks were cannibalized by the Kimberly rhyolite. The exsolved pigeonite cores must have experienced slow intrusive cooling in order to exsolve augite lamellae. The ragged boundaries between the exsolved pigeonites and their augite mantles indicate pigeonite was resorbed and followed by augite crystallization. We propose that pigeonite was resorbed when the Kimberly magma assimilated a dry A-type intrusive host of the Fe-rich exsolved pigeonite. The pigeonite cores were spared total resorption by their augite mantles. The augite mantles appear to have equilibrated with the melt in the same way that the sanidine mantles did.
The isotopic variations in zircon likewise indicate multiple sources and cannibalization of already crystallized granite or rhyolite at a shallow level. It is unlikely that the older (xenocrystic) zircons in the Kimberly Member are the result of magma mixing. The xenocrystic cores were mantled by newly crystallized zircon in equilibrium with melt. Their isotopic diversity (\(\delta^{18}O\) from 0 to 4.9‰ and \(\varepsilon\)Hf from -7.1 to 1.3) and range of U-Pb ages (as much as 1.5 m.y. older than the eruption age of 7.70 +/- 0.10 Ma) make it more likely the zircon was derived from already-solid rhyolite or granite that was cannibalized by the Kimberly Member. They may have come from the same intrusion(s) that supplied the exsolved pigeonite cores now mantled by augite or from the rhyolite with the Pl-Anor composite grains.

Like the feldspars, pyroxene, and zircon, cores of apatite are probably xenocrysts from an assimilated granite/rhyolite. The truncation of oscillatory zones in the dark cores demonstrates that there was a resorption event between crystallization of the BSE-dark, REE-poor cores and crystallization of the bright, REE-rich rims. The best explanation for the compositional disparity is that dark cores are xenocrysts that were mantled by apatite in equilibrium with the host melt. (Watson and Green (1981) found that diffusion of REE elements in apatite is sufficiently slow for REE compositions of apatite xenocrysts to be preserved for millions of years.) The textures and compositions could be explained by either magma mixing (e.g., Bruand et al., 2014) or cannibalization of solid rock—either one could result in the incorporation of REE-poor apatite into a different melt, causing resorption of xenocrystic apatite and cross-cutting of the oscillatory zones followed by crystallization of the bright euhedral rims in equilibrium with the new melt. The high concentrations of LREE (and charge compensating substitution of Si for P) in the bright rims are consistent with equilibrium with the erupted melt. Partition coefficients as high as 113 (La), 140 (Ce), and 209 (Nd) are required to explain the rim compositions. Padilla and
Gualda (2016) report partition coefficients of 109 (La), 133 (Ce), and 239 (Nd) for apatite in the Peach Springs Tuff, very similar to what we have found in the Kimberley rhyolite and consistent with late crystallization of apatite in equilibrium with melt right before eruption.

The characteristics of quartz also point to a history of assimilation and resorption. Multiple embayments that cut oscillatory growth zones, high Ti-quartz temperatures, and rounded cores with mantles, hallmark a complex history of quartz growth and resorption. The Ti-in-quartz thermometer we take to be most accurate (Huang and Audétat, 2012) gives a temperature of ~1044°C. There is a large disparity between this value and temperatures calculated from pyroxene, Fe-Ti oxides, and zircon saturation (~900°C). We propose this large disparity exists because quartz grains were not in equilibrium with the Kimberly Member magma, and thus yield this inaccurate temperature. Since Huang and Audétat’s thermometer for Ti-in-quartz is dependent on melt composition, if the quartz were in equilibrium with the Kimberly magma, we would expect the thermometer to yield a temperature around 900°C. Since the temperature was not around 900°C, we use Ti-in-quartz thermometry as further evidence quartz was not a stable phase in the Kimberly magma. We propose that the embayments in quartz are the result of destabilization and resorption of xenocrystic quartz and not as a result of rapid growth. Loewen et al. (2017) discount the formation of narrow-necked quartz embayments forming through dissolution in the Summit Lake rhyolite lava at Yellowstone. They conclude that secondary healing of skeletal, hopper-shaped crystals caused narrow-necked embayments and were indicative of rapid cooling and growth. In the Kimberly rhyolite, (1) quartz embayments and holes crosscut growth zones and core-mantle boundaries, (2) external hopper shapes are absent, (3) embayments are wide and narrow necks are rare, (4) faceted crystals are absent, (5) glass in subcircular holes lack vapor bubbles, and (6) Ti-in-quartz temperatures are
unreasonably high. Consequently, we interpret the embayments to be produced by resorption and that quartz was not stable.

An experimental study by Almeev et al. (2012) puts some constraints on quartz stability for Snake River Plain rhyolites similar to the Kimberly Member. At 200 MPa and 900°C, quartz (along with Px, Sa, Pl, and oxides) is stable, if the water content is less than 1.5%. If water content exceeds 1.5%, quartz is unstable. Sanidine is stable until H₂O exceeds about 2.2%. An additional experimental study by Bolte et al. (2015) on the more silicic Blacktail Creek Tuff found quartz is stable at 200 MPa and 900°C with less than 2% water. Thus, if quartz xenocrysts were incorporated in rhyolite magma with more than about 1.5 to 2.0 wt% H₂O, it should become resorbed. Both experimental studies also show that an increase in temperature or decrease in pressure would destabilize quartz and could cause it to become embayed. However, the high Ti content and inferred temperature that is higher than the host melt temperature indicate a temperature increase did not play a role here. Moreover, decompression should not increase the Ti content of the dissolving quartz grains. We conclude that xenocrystic quartz dissolved partially as a result of its incorporation in a wetter magma. In short, the embayed quartz indicates assimilation of quartz from rock or mixing of disparate magmas—quartz formed in one magma became unstable when it was mixed in with the Kimberly rhyolite right before eruption.

Consistent with the other open-system characteristics, we propose that the light and dark glasses in the Kimberly rhyolite represent distinct magmas that mingled. The fluidal textures suggest that the dark glass was molten when it mixed with the dominant light glass. Lava flow emplacement apparently stretched and deformed small bits of dark glass magma into lenses. Mingling must have occurred shortly before eruption of the rhyolites because the glass did not
mix completely. An anorthoclase with a sanidine rim enclosed in dark glass (Fig. 1) is evidence that the mingling event happened after sanidine was stabilized in the dominant volume, in the latter part of the magma’s multi-stage history.

In addition to distinguishing the two magmas from each other, the elemental compositions may illuminate the origin of the small volume of dark glass. The dark component is still glassy and is embedded in unaltered light-colored glass suggesting the differences are not the result of post-eruptive hydrothermal metasomatism. Rather, to explain its odd composition, we propose the dark glass formed from a melt of a hydrothermally altered rhyolite or granite and that the fine crystals it contains are residual solids. MELTS (Ghiorso and Sack, 1995; Gualda and Ghiorso, 2015) calculations involving melting a hydrothermally altered rhyolite or granite yield compositions similar to the dark glass (Supplementary fig. 9, Appendix 4). The parent rock was assumed to be similar to the average composition of the most altered parts of the low-silica rhyolite ignimbrite (the Castleford Crossing Member) from the Kimberly core. It erupted and cooled shortly before the Kimberly rhyolite (7.96 +/- 0.12 Ma vs 7.70 +/- 0.10 Ma; Colón et al., 2018). It is more oxidized and somewhat enriched in Al₂O₃, CaO, and Na₂O and depleted in K₂O compared to fresh samples of the ignimbrite (Appendix 4). Partial melting at 880°C with water content 3.75 wt% (based on LOI of samples) produces >95% liquid which has a composition like that of the dark glass (Supplementary Fig. 14) and residual plagioclase, pyroxene, and oxides. Thus, the last stage of the Kimberly Member’s history includes mingling with a small amount of melt derived from a fluid-metasomatized rhyolite or granite. Incorporation of this exotic melt seems to have accompanied resorption of xenocrysts of quartz, pyroxene, feldspar, apatite, and zircon suggesting all are related to the same processes. Further the possible link to the Castleford Crossing Member to the dark glass in the Kimberly Member is significant given the two units’
close ages (see above). This lends further weight to the cannibalization model of Yellowstone Snake River Plain magmas.

In spite of all these textural and compositional complexities, some phases appear to have been in equilibrium with the light colored glass and with one another before eruption. For example, Fe-Ti oxides do not appear to be xenocrystic, because of their euhedral shapes, uniform compositions and single compositional populations (Supplemental Fig. 7). The 926°C ilmenite-
magnetite temperature, discussed above, may then be a good estimate of magmatic temperature of the Kimberly rhyolite. In addition, sanidine, zircon, and two-pyroxenes appear to have reached exchange equilibrium with melt (the light-colored glass) and each other before eruption and yield similar temperatures.

**MAGMA MIXING, GRANITE ASSIMILATION, AND MAGMA EVOLUTION**

The observations and interpretations provide the conceptual framework for understanding the origins of the diverse textures and mineral compositions in the Kimberly rhyolite, part of a multicyclic collapse caldera with an extended life time (10 to 6 Ma). We invoke a cannibalization scenario that involves partial melting of hydrothermally altered rock and magma mixing in a caldera setting, which create episodes of resorption punctuating crystallization (Fig. 4).

At least five different magmatic components are required to explain our observations: 1. Rhyolite magma with sodic plagioclase at about 800°C, 2. Rhyolite (magma or rock) with anorthoclase and quartz that crystallized at about 950°C, 3. A completely solidified A-type granite, 4. The host rhyolite magma with a temperature of about 900°C, and 5. A partial melt derived from a hydrothermally altered version of 2 or 3.
Figure 4. Conceptual model outlining the assimilation of solid rhyolite and granite by the Kimberly rhyolite. A rhyolite with composite plagioclase-anorthoclase grains and quartz and a slowly-cooled, pigeonite-bearing A-type granite intrusion are hydrothermally altered. Both are subsequently intruded by the hot Kimberly Member, causing partial melting and incomplete digestion of the granite and rhyolite to produce a variety of disequilibrium textures and compositions followed by eruption of the lava floor onto the floor of a slightly older caldera.
A first step involved, mixing of two rhyolite magmas (1 and 2) to make composite plagioclase-anorthoclase feldspars with resorption interfaces between the two types of feldspar coexisting with high Ti-quartz. We infer a volcanic origin for these phases because the quartz does not have undulatory extinction like typical plutonic quartz, the plagioclase has high Or contents (0.04-0.10) unlike slowly cooled reequilibrated plagioclase in granite, and the anorthoclase shows no microcline twinning or perthitic exsolution unlike alkali feldspars in hypersolvus intrusive rocks. The fact that the anorthoclase and plagioclase do not appear to have been in equilibrium with one another (Fig. 1) implies that at least two different rhyolites were involved. This mixed magma either erupted and crystallized as a caldera-filling deposit or remained molten until it mixed with hotter rhyolite (4). This sequence produces the composite plagioclase-anorthoclase-sanidine grains which ultimately erupt in the Kimberly rhyolite.

Another component is an early formed dry A-type granite (3) that was eventually partially digested by the younger mixed rhyolite (4). The intrusive character of the cannibalized granite is inferred from the exsolution lamellae in pigeonite which indicate slow, subsolidus cooling of a pluton. The Fe-rich pigeonite implies it was a dry, chemically evolved, silicic A-type granite such as would be expected to form from a subcaldera magma chamber along the track of the Yellowstone hotspot. Granite (3) may also have been a source of REE-poor apatite. Additionally, granite (3) is a possible source for diverse zircon with ages as much as 1.5 m.y. older than the eruption age of 7.70 Ma, varying $\varepsilon$Hf, and $\delta^{18}$O which provide evidence for previous episodes of contamination.

Crystalline phases from 1, 2, and 3 were partially digested by another rhyolite magma, the fourth and major component of the Kimberly rhyolite. This near-liquidus rhyolite must have been generated at greater depth than the assimilated components, with a temperature of about
900°C (as estimated from magnetite-ilmenite pairs, sanidine, pyroxenes, and zircon saturation) and then intruded granite and rhyolite(s) in a subcaldera setting. One or all of these components was hydrothermally altered, modifying its delta $^{18}$O, its oxidation state, and its mobile element composition. Less mobile elements such as the high field strength elements (Y, Zr, Nb, Hf, and Ta) were probably less impacted by hydrothermal alteration. As modeled by Bindeman and Simakin (2014), the hot rhyolite magma (4) appears to have induced nearly complete melting of the altered rocks. This released silicic melt, preserved as the wisps of dark glass (5), disaggregated and partially resorbed crystals, and mixed them into the host rhyolite.

The cannibalized grains included exsolved pigeonite from the granite (3), resorbed quartz from 2, composite grains of plagioclase (1) and anorthoclase (2), and also diverse zoned zircon and apatite from 1, 2, or 3 that became more or less resorbed. Although quartz remained unstable, pigeonite was mantled with newly crystallized augite, apatite with REE-rich apatite, zircon by younger and isotopically homogenous rims, and plagioclase-anorthoclase clots by sanidine as the melt evolved and cooled. Lenses of melt and the partially disaggregated crystal load were mixed into the melt shortly before eruption. There was sufficient time for equilibration of Fe-Ti oxides, resorption of quartz and other minerals, and growth of mantling rims on zircon, apatite, feldspar, and pyroxene, but insufficient time for homogenous phenocrysts to form or for the two melts to mix completely before eruption as an intracaldera lava flow and quenching.

CONCLUSIONS

The diverse and texturally complex crystal cargo in the Kimberly Member consisting of quartz, sanidine, anorthoclase, plagioclase, pigeonite, augite, zircon, apatite, magnetite, and ilmenite, as well as two glass compositions, requires processes beyond simple equilibrium crystallization. At least six of the phases in the rhyolite were foreign to it. Some (plagioclase,
anorthoclase) crystallized earlier in different magma(s) which mixed with the Kimberly rhyolite. Other phases came from solidified granite and rhyolite, and then reacted with the magma to be erupted with the rhyolite 7.7 Ma. Such textural and chemical evidence underlines the importance of magma mixing, assimilation, shallow melting, and upper crustal cannibalization even in high-silica rhyolites.

Cognizance of these chemical and textural features aids in recognition of open system processes in Snake River Plain Yellowstone rhyolites and other rhyolites. Multiple rhyolites on the Snake River Plain are low $\delta^{18}$O and have diverse $\delta^{18}$O and $\varepsilon$Hf values and U-Pb ages in zircon, which indicates assimilation of hydrothermally altered rock. Despite the common nature of these isotopic characteristics, the crystal cargo of such rhyolites does not often preserve evidence of the assimilation process with the exception of zircon. The Kimberly Member is unique and valuable to understanding assimilation in Snake River Plain Yellowstone rhyolites because its crystal cargo has preserved a snapshot of the magma in the process of assimilation. Its disequilibrium mineral assemblage provides critical knowledge of what components may be involved in assimilation, and effect on the magma. Further, recognition of common disequilibrium textures related to assimilation is critical for understanding the meaning of whole-rock compositions and in estimating equilibrium temperatures and pressures in future Snake River Plain Yellowstone magma studies. Additionally, knowledge of these processes in Yellowstone Snake River Plain rhyolites provides more complete models for the deeper cannibalistic mechanisms for magma evolution along the Yellowstone Hotspot. Particularly useful is the potential evidence of assimilation of plutonic and volcanic components preserved in the Kimberly Member. This evidence even lends itself to identifying the pre-assimilation composition of components, such as in the case of the dark glass of the Kimberly Member that
could come from the closely aged Castleford Crossing Member or a similar, deeper unit. Thus, study of this unique rhyolite gives insight into the role open system processes may play in the larger context of the Yellowstone Hotspot track.

REFERENCES

Andersen, D. J., Lindsley, D. H., and Davidson, P. M., 1993, QUILF: A Pascal program to assess equilibria among Fe, Mg, Mn, Ti oxides, pyroxenes, olivine, and quartz: Computers & Geosciences, v. 19, no. 9, p. 1333-1350.


Earthref.org, Geochemical Earth Reference Model, Partition Coefficients:

https://earthref.org/KDD/


SUPPLEMENTARY FIGURES

(Supplementary figures available in the attachments tab)

APPENDIX A1-METHODS
APPENDIX A2 – A5-DATA TABLES
APPENDIX A6-FELDSPAR ELEMENT MAPS AND CATHODOLUMINESCENCE IMAGES
APPENDIX A7-PYROXENE ELEMENT MAPS AND BACKSCATTER IMAGES
APPENDIX A8- QUARTZ CATHODOLUMINESCENCE IMAGES
APPENDIX A9-APATITE BACKSCATTER IMAGES
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