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The timing of compositionally-zoned magma reservoirs and mafic ‘priming’ weeks before the 1912 Novarupta-Katmai rhyolite eruption

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ABSTRACT

The June, 6, 1912 eruption of more than 13 km^3 of dense rock equivalent (DRE) magma at Novarupta vent, Alaska was the largest of the 20th century. It ejected >7 km^3 of rhyolite, ∼1.3 km^3 of andesite and ∼4.6 km^3 of dacite. Early ideas about the origin of pyroclastic flows and magmatic differentiation (e.g., compositional zonation of reservoirs) were shaped by this eruption. Despite being well studied, the timing of events that led to the chemically and mineralogically zoned magma reservoir remain poorly known. Here we provide new insights using the textures and chemical compositions of plagioclase and orthopyroxene crystals and by reevaluating previous U–Th isotope data. Compositional zoning of the magma reservoir likely developed a few thousand years before the eruption by several additions of mafic magma below an extant silicic reservoir. Melt compositions calculated from Sr contents in plagioclase fill the compositional gap between 68 and 76% SiO_2 in whole pumice clasts, consistent with uninterrupted crystal growth from a continuum of liquids. Thus, our findings support a general model in which large volumes of crystal-poor rhyolite are related to intermediate magmas through gradual separation of melt from crystal-rich mush. The rhyolite is incubated by, but not mixed with, episodic recharge pulses of mafic magma that interact thermochemically with the mush and intermediate magmas. Hot, Mg-, Ca-, and Al-rich mafic magma intruded into, and mixed with, deeper parts of the reservoir (andesite and dacite) multiple times. Modeling the relaxation of the Fe–Mg concentrations in orthopyroxene and Mg in plagioclase rims indicates that the final recharge event occurred just weeks prior to the eruption. Rapid addition of mass, volatiles, and heat from the recharge magma, perhaps aided by partial melting of cumulate mush below the andesite and dacite, pressurized the reservoir and likely propelled a ∼10 km lateral dike that allowed the overlying rhyolite to reach the surface.

1. Introduction

Knowledge of the processes that generate rhyolitic magma and drive its transport and eruption are paramount to understanding volcanic hazards as well as the evolution of earth’s crust (Hildreth, 1981; Jellinek and DePaolo, 2003; Self and Blake, 2008; Castro and Dingwell, 2009; Degruyter et al., 2016). A point in case is the 1912 Novarupta-Katmai eruption which has long propelled our understanding about how silicic pyroclastic deposits are produced (Hildreth and Fierstein, 2012). Moreover, the large range of magma compositions, and the chemical and mineralogical zonation of these deposits also fueled vigorous debate about the importance of crystallization–differentiation relative to assimilation and magma mixing (Fenner, 1926; Bowen, 1928). Modern field and geochemical data have since revealed that the rhyolite–dacite–andesite magmas were petrologically ‘contiguous’ (Hildreth, 1983; Hildreth and Fierstein, 2012) and stored at shallow depths between 3 and 6 km below the former Katmai edifice (Coombs and Gardner, 2001; Hammer et al., 2002). However, the origin of the compositional zoning has been debated (Eichelberger et al., 2000) and the intersection of a rhyolitic dike with an andesitic–dacitic magma reservoir has been proposed (Eichelberger and Izbekov, 2000). More recently, short-lived U-series isotope data (Reagan et al., 2003; Turner et al., 2010) reveal that the Novarupta-Katmai reservoir was built progressively by episodic input of mafic magma such that the crustal residence time of the rhyolite may have exceeded that of the dacite and andesite by thousands of years.

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Table 1

Sequence in eruption	1	2	3	4	5	6
Sample	K-1525	K-1490	K-131-d-r	K-1267-g	K-184	[a]K-224
SiO_2	77.19	67.72	58.72	65.52	59.47	76.52
TiO_2	0.18	0.57	0.72	0.67	0.72	0.21
Al_2O_3	12.28	15.10	16.86	15.69	16.77	12.5
FeO*	1.30	4.37	7.08	5.07	6.81	1.53
MnO	0.05	0.10	0.14	0.11	0.12	0.07
MgO	0.19	1.59	3.71	1.95	3.56	0.34
CaO	0.87	3.91	7.44	4.56	7.03	1.16
Na_2O	4.32	4.08	3.49	4.08	3.63	4.32
K_2O	3.17	2.03	1.31	1.78	1.35	2.94
P_2O_5	0.05	0.13	0.12	0.16	0.15	0.02
LOI	2.52	1.61	~	1.94	~	~
Original total	96.51	97.65	97.63	97.13	99.70	99.7
# plag xtals analyzed	8	9	7	10	13	14
# plag with calcic rims	0	2	5	7	5	3
# plag reverse zones in core	0	5	1	6	6	2
Reverse zoned opx?	0	0	1	3	6	0

The # of crystals listed with reverse zones are from surveys of a single thin section of each sample. Rim-to-core profiles of anorthite content for each crystal analyzed are in Supplementary Fig. 1.

[a] Sample is identical to RLS-214 in Hildreth and Fierstein (2012).

How volcanic unrest manifests prior to a rhyolitic eruption and how eruptions are primed and triggered remain obscure, largely because there are few historical examples. Recent studies of the rhyolitic to rhyodacitic eruptions in Chile at Chaiten in 2008 and Cordon Caulle in 2011 indicate periods of pre-eruptive unrest as short as months to days and rapid transport rates (Castro and Dingwell, 2009; Jay et al., 2014). However, the precursory seismic and deformation signals and petrological characteristics are ambiguous as to the processes that lead to silicic eruptions (e.g., Singer et al., 2014). There is some information about the period of unrest prior to the Novarupta-Katmai eruption. Eyewitnesses reported feeling earthquakes 5 days before the eruption began. Moreover, Katmai volcano—10 km to the east—collapsed above the partially emptied magma reservoir leading to the hypothesis that transport of rhyolitic magma to the surface was by a lateral sill or dike (Hildreth and Fierstein, 2000; Pinel and Jaupart, 2004). We use the textures, major and trace element zoning of plagioclase and orthopyroxene crystals, and reevaluate existing geochemical and U-series isotope data to address the questions of how and when the Novarupta magma reservoir became compositionally zoned. We integrate our results with recent modeling of the impacts that mafic recharge (Degruyter et al., 2016) and volatile accumulation (Parmigiani et al., 2016) have on crystal-poor rhyolites, to discuss how the rhyolitic magma was propelled toward the surface leading to seismicity in June, 1912, and the timing of the primer for the seismicity and eruption.

2. Eruption chronology, petrological background, samples and methods

After five days of increasingly severe earthquakes, on June 6, 1912 magma spanning a remarkably diverse range of composition including crystal-poor high-silica rhyolite (76.5–77.8% SiO_2), and a continuum of crystal-rich dacite through andesite (57.9–68.6% SiO_2) began to erupt. The eruption occurred from the Novarupta vent in three plinian episodes that produced 17 km^3 of fall de-

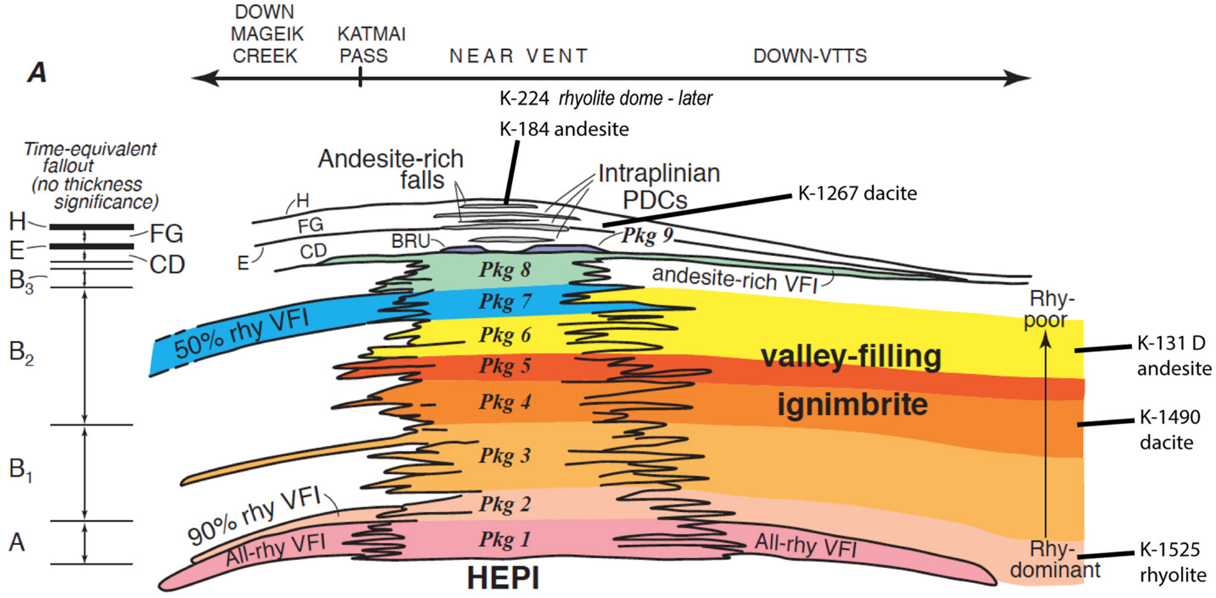

Fig. 1. Schematic diagram of relations among the 1912 pyroclastic deposits summarizing ignimbrite facies and time-equivalent fall deposits (Layers A through H). Rhyolite is abbreviated, rhy. Thicknesses not to scale; vertical dimension scaled to depict time equivalence. Positions of samples for this study are noted. VFI = Valley filling ignimbrite; HEPI = High energy proximal ignimbrite; PDC = pyroclastic density current deposit; BRU, block-rich flow units that dominate small-volume Package 9. Modified from Hildreth and Fierstien (2012).