Lithos 236–237 (2015) 275–286

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

Invited review article

Remelting of cumulates as a process for producing chemical zoning in silicic tuffs: A comparison of cool, wet and hot, dry rhyolitic magma systems

J.A. Wolff [a,*], B.S. Ellis [b], F.C. Ramos [c], W.A. Starkel [a], S. Boroughs [a], P.H. Olin [d], O. Bachmann [b]

[a] School of the Environment, Washington State University, Pullman, WA 99164, USA
[b] Institute of Geochemistry and Petrology, ETH Zurich, NW Clausiusstrasse 25, 8092 Zurich, Switzerland
[c] Department of Geological Sciences, New Mexico State University, Las Cruces, NM 88003, USA
[d] CODES Center of excellence and School of Physical Sciences, University of Tasmania, Private Bag 79, Hobart, TAS 7001, Australia

ARTICLE INFO

Article history:
Received 15 April 2015
Accepted 2 September 2015
Available online 8 September 2015

Keywords:
Silicic magma
Compositional zoning
Trace elements
Recharge
Cumulate melting

ABSTRACT

We review petrological and geochemical features of silicic pyroclastic deposits of dominantly low to moderate (0–25%) crystallinity, and volumes in the range of 5–1000 km^3, erupted from caldera volcanoes. Chemical gradients in zoned deposits with compositions near the water-saturated granite minimum, for example the Bishop and Bandelier Tuffs, are consistent with mineral/melt partitioning predicted from the observed phenocryst assemblages, and are inconsistent with mixing with more mafic magma. Smaller volume alkaline (phonolite and pantellerite) systems show similar behavior. In contrast, high-temperature ignimbrites of the 'Snake River'-type typically lack compositional zoning. Internal isotopic variations are weak or absent from whole rocks in both types of rhyolite, even in systems where associated volcanic rocks exhibit wide isotopic variation and strong contrasts exist between the isotopic compositions of mantle and crust. An exception to this is $^{87}Sr/^{86}Sr$ variations in high-silica rhyolite systems, where Sr has been depleted to subchondritic concentrations and is exceptionally sensitive to open-system processes. Both types of ignimbrite commonly contain crystal aggregates, interpreted as fragments of cumulate mush. In zoned systems, these aggregates exhibit evidence for partial resorption of early-formed crystals. We infer that chemical zoning is a near closed-system process and propose that it arises through melting of cognate cumulate mush beneath a crystal-poor body of melt due to heating by invading mafic or intermediate magma with little mass transfer to the eruptible magma. If the crystal mush is fusible (e.g. dominated by sanidine + quartz), part of it melts to yield mobile, water-poor rhyolite that pools at the interface between the mush and overlying rhyolitic liquid. This new, eruptible melt has a cumulate composition and is thus less evolved than the original supernatant melt lens. The result is a chemically zoned crystal-poor rhyolitic magma produced with little mass contribution from the invading magma. This model reconciles evidence for thermal rejuvenation, preserved in crystals, with evidence for the production of zoning by crystallization-differentiation, apparent in whole-rock chemistry. Fusibility of the cumulate is key to the process; high-temperature 'Snake River'-type rhyolites are not zoned because their cumulates are dominated by a refractory assemblage of pyroxene, plagioclase, and Fe–Ti oxides. Previous models of compositional zoning have envisaged a pot of silicic magma undergoing slow cooling towards thermal senescence. In contrast, we contend that zoning records a history of thermal rejuvenation in which any one recharge event has the potential to trigger a caldera-forming eruption.

Contents

* Corresponding author.
E-mail address: jawolff@mail.wsu.edu (J.A. Wolff).

http://dx.doi.org/10.1016/j.lithos.2015.09.002
0024-4937/

1. Introduction

It has long been recognized that individual volcanic deposits have internally variable compositions, indicating the co-existence of contrasting magmas in the systems that produce them. Compositional variability may result from magma mixing and recharge (Anderson, 1976; Blake et al., 1965; Sparks et al., 1977) and the products, such as banded glasses, disequilibrium phenocryst assemblages, or a marked change in magma type through an eruption sequence are usually petrographically obvious. In contrast, many silicic pyroclastic units exhibit little internal variation in major element composition, hence are not the products of mixing with mafic magma, but possess strong upward gradients in trace elements and magma temperatures indicated by geothermometry (Hildreth, 1979; Lipman, 1971; Smith and Bailey, 1966). Such eruptives are usually pyroclastic, silicic (rhyolitic, trachytic or phonolitic), frequently associated with calderas, and constitute a distinct category of heterogeneous volcanic rock. We refer to these as 'Bishop-type' zoned tuffs, in recognition of the central role occupied by the Bishop Tuff (Long Valley, eastern California), the subject of many studies starting with the landmark paper by Hildreth (1979). The major element compositions of Bishop-type rhyolites are usually close to the water-saturated granite minimum at upper crustal pressures, with magma temperatures below 800 °C and magmatic water contents of ~4% to ~6% by weight. Phenocryst assemblages are dominated by alkali feldpar and quartz. Erupted volumes are typically a few hundred cubic kilometres. Alkaline examples such as the zoned phonolitic tuffs of Laacher See (Wörner and Schmincke, 1984) and Tenerife (Edgar et al., 2007; Wolff and Storey, 1984), although significantly smaller with typical magmatic volumes of the order of 10 km^3, similarly plot near the water-saturated phonolitic minimum in Petrogeny's residua system and we consider them analogous to the larger Bishop-type systems. Their phenocryst assemblages are also dominated by alkali feldspar, with varying amounts of feldspathoids and accessory quantities of mafic minerals.

It is assumed from the principle of superposition that the zoned sequence preserved in Bishop-type tuffs represents, at least qualitatively, the inverted sequence in the magma chamber prior to eruption. Different mechanisms have been proposed for producing vertical compositional zoning in Bishop-type magma chambers. Following early interest in chemical differentiation by thermogravitational diffusion (Hildreth, 1979, 1981), a consensus emerged that crystal–liquid processes are responsible for producing the compositional range observed in zoned silicic systems. A key observation leading to this conclusion is that element covariations, which differ considerably between zoned systems of differing silica- and alumina-saturation, are predictable on the basis of element partitioning between melt and observed phenocrysts (Cameron, 1984; Cameron and Cameron, 1986; Michael, 1983; Wolff and Storey, 1984). The stabilities of many trace phases such as allanite, chevkinite, titanite and zircon are dependent on melt compositional and structural parameters, and these phases play an especially important role in producing distinctive patterns of enrichment and depletion in rare earth and high field strength elements in zoned silicic systems.

In contrast to Bishop-type tuffs, 'Snake River-type' rhyolites (Branney et al., 2008) represent hot (>850 °C), and relatively dry (<3.5% H_2O) silicic magmas. High magmatic temperatures coupled with limited adiabatic cooling during eruption result in high emplacement temperatures; consequently these tuffs are intensely welded, rheomorphic, and lava-like. They are notable for almost completely lacking chemical zonation, despite having volumes in the same range (10^2–10^3 km^3) as Bishop-type rhyolites (Ellis et al., 2013). It is a major contention of this paper that the contrasting behaviors of cool, wet and hot, dry felsic magmas provide an important clue to the processes causing zoning. We suggest that a single mechanism of cumulate melting by recharge can explain all essential features of Bishop-type zoning, and that the susceptibility of felsic magma to zoning development depends on its thermal condition and the fusibility of its cumulate assemblage.

2. Examples of zoned systems

Much recent debate on the origins of zoning, especially in the case of the Bishop Tuff (Chamberlain et al., 2014a,b; Evans and Bachmann, 2013; Gardner et al., 2014; Gualda and Ghiorso, 2013), has focused on mineral phases and evidence for temperature and pressure gradients in the magmas prior to eruption. Here, we are more concerned with the chemical expression of zoning, largely seen in trace element abundances. Zoning style and magnitude can be summarized by enrichment diagrams (Hildreth, 1979), in which the composition of early-erupted material is divided by (normalized to) that of late-erupted magma, assumed representative of the deepest level tapped by the eruption, from the same unit (Fig. 1). These diagrams are thus similar in type to the familiar normalized trace element 'spider' diagrams employed in characterising basalts. Ideally, for pyroclastic units, compositions are those of single whole pumice clasts, or an average of several clasts. In the case of densely welded tuffs, however, whole rocks are usually analyzed due to the difficulty of separating or, in the case of the Snake River rhyolites, even identifying fiamme that represent original pyroclasts. Volumes quoted below are dense rock equivalent.

Many tuffs show compositional variations that have no systematic relationship to internal stratigraphy, even though the most strongly differentiated compositions have the lowest calculated magmatic densities within the system and can be argued to have erupted from zoned systems. Several plausible processes, such as overturn driven by gas exsolution or thermal disturbance before eruption (Bachmann and Bergantz, 2006; Burgisser and Bergantz, 2011), preferential extraction effects during eruption (Blake and Ivey, 1986a,b; Trial et al., 1992), non-sequential deposition (Branney and Kokelaar, 2002; Torres et al., 1996) as well as poor field exposure may limit, scramble or obscure preservation of spatial zoning in the final deposits. It is also possible that zoning could develop such that the most differentiated