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Volatiles and the tempo of flood basalt magmatism

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ABSTRACT

Individual flood basalt lavas often exceed 10^3 km^3 in volume, and many such lavas erupt during emplacement of flood basalt provinces. The large volume of individual flood basalt lavas implies correspondingly large magma reservoirs within or at the base of the crust. To erupt, some fraction of this magma must become buoyant and overpressure must be sufficient to encourage failure and dike propagation. The overpressure associated with a new injection of magma is inversely proportional to the total reservoir volume, and as a large magma body heats the surrounding rocks thermally activated creep will relax isotropic overpressure more rapidly. Here, we examine the viability of buoyancy overpressure as a trigger for continental flood basalt eruptions. We employ a new one-dimensional model that combines volatile exsolution, bubble growth and rise, assimilation, and permeable fluid escape from Moho-depth and crustal chambers. We investigate the temporal evolution of degassing and the eruptibility of magmas using the Siberian Traps flood basalts as a test case. We suggest that the volatile inventory set during mantle melting and redistributed via bubble motion controls ascent of magma into and through the crust, thereby regulating the tempo of flood basalt magmatism. Volatile-rich melts from low degrees of partial melting of the mantle are buoyant and erupt to the surface with little staging or crustal interaction. Melts with moderate volatile budgets accumulate in large, mostly molten magma chambers at the Moho or in the lower crust. These large magma bodies may remain buoyant and poised to erupt—triggered by volatile-rich recharge or external stresses—for $\sim 10^6$ yr. If and when such chambers fail, enormous volumes of magma can ascend into the upper crust, staging at shallow levels and initiating substantial assimilation that contributes to pulses of large-volume flood basalt eruption. Our model further predicts that the Siberian Traps may have released 10^{19}–10^{20} g of CO_2 during a number of brief ($\sim 10^4$ yr) pulses, providing a plausible trigger for warming and ocean acidification during the end-Permian mass extinction. The assimilation of carbon-rich crustal rocks strongly enhances both flood basalt eruptibility and CO_2 release, and the tempo of eruptions influences the environmental effects of CO_2, SO_2, and halogen degassing. The eruptive dynamics of flood basalts are thus inextricably linked with their environmental consequences.

1. Introduction

Flood basalts are voluminous outpourings of basaltic lava that likely erupt as a result of magmatic processes that are distinct from those occurring at plate boundaries (Richards et al., 1989). Flood basalt provinces can encompass several million cubic kilometers of magma, with hundreds of stacked flows that reach kilometers of total thickness (e.g., Bryan et al., 2010). Individual eruptive episodes during flood basalt emplacement last decades or more, separated by hiatuses of 10^3–10^5 yr (Self et al., 2014); in total, flood basalt provinces can span 10^5–10^7 yr (e.g. Kamo et al., 2003; Blackburn et al., 2013; Schoene et al., 2015), with active flood basalt provinces recurring at intervals of $\sim 10^7$ yr somewhere on Earth (Courtillot and Renne, 2003).

Even as debate continues regarding the deep genesis of flood basalt magmas (e.g. Richards et al., 1989; Campbell and Griffiths, 1990; Elkins-Tanton and Hager, 2000; DePaolo and Manga, 2003; Foulger and Natland, 2003), a clearer picture of flood basalt lithospheric plumbing systems is gradually emerging. Abundant physical and geochemical evidence supports widespread interaction with crustal material (e.g., Cox, 1980; Wooden et al., 1993; Kontorovich et al., 1997; Bryan et al., 2010; Black et al., 2014a). On the other hand, most flood basalt provinces also host alkaline lavas that may have interacted with mantle lithosphere but show little evidence for protracted crustal residence (Arndt et al., 1998).

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Many flows within flood basalt provinces are highly homogeneous and combine to form coherent geochemical sequences, consistent with eruption from a large centralized magmatic system (Wolff et al., 2008). This geochemical homogeneity has been interpreted as evidence for processing in long-lived magma reservoirs undergoing Recharge, Tapping via eruptions, Fractionation, and Assimilation (O'Hara, 1977; Cox, 1988; Arndt et al., 1993; Wooden et al., 1993), also known as RTFA processes. Intercalated low-Ti and high-Ti lavas in the Siberian Traps have been interpreted as the result of dual plumbing systems (Arndt et al., 1998), each erupting repeatedly. The evidence for large, well-integrated, episodically erupting plumbing systems underscores a fundamental question: how and why do flood basalts erupt?

Eruptions occur when magmas are buoyant and mobile (e.g., Marsh, 1981), and when external stresses or magmatically-generated stresses around an overpressured chamber are sufficiently large to allow dike propagation (e.g., Tait et al., 1989). Large volume magma chambers resist eruption, for at least two reasons. First, the overpressure associated with injection of a new volume of magma—a process thought to be key to relatively small volcanic eruptions—is inversely proportional to the total reservoir volume (Jellinek and DePaolo, 2003; Karlstrom et al., 2010; Caricchi et al., 2014). Second, large masses of resident magma will heat the crust, expediting viscoelastic relaxation and relieving overpressures from volume change (Jellinek and DePaolo, 2003). Consequently, injection alone is probably an inadequate trigger for rare, explosive super-eruptions. Instead, roof failure (e.g., de Silva and Gregg, 2014) and buoyancy overpressure (e.g., Caricchi et al., 2014) have been invoked to trigger caldera-forming silicic eruptions.

In some respects, continental flood basalt eruptions are even more difficult to explain than large silicic eruptions. The episodic tempo of flood basalt volcanism and the large volumes attained by individual lava flows and magmatic pulses (e.g., Chenet et al., 2008, 2009; Bryan et al., 2010; Pavlov et al., 2011) are consistent with accumulation in immense reservoirs prior to main phase eruptions. While the factors that control the inception of magma reservoirs are poorly understood, we expect the rheological structure of the continental lithosphere to influence the depths of magma accumulation. If the geothermal gradient is shallow and the lower crust is fluid-saturated, the lower crust will be weaker than both the upper crust and lithospheric mantle (e.g., Bürgmann and Dresen, 2008), encouraging growth of lower crustal magma reservoirs. If the lower crust is dry and the geothermal gradient is steep (as expected when a mantle plume arrives), the uppermost mantle may be much weaker than the crust (e.g., Bürgmann and Dresen, 2008), encouraging growth of magma reservoirs at the Moho. In either case, continental flood basalt magmas encounter a mechanical barrier to ascent at the base of the crust or in the lower to middle crust, which is compounded by a possible density barrier due to the high densities of volatile-free flood basalt magmas (relative to the upper continental crust).

Lange (2002) and Karlstrom and Richards (2011) have invoked gas exsolution and the resulting buoyancy to overcome this density barrier. H_2O, sulfur species, and halogens are relatively soluble in basaltic melts up until shallow crustal pressures (e.g. Gerlach, 1986). However, significant quantities of CO_2 may exsolve even at Moho depths (Karlstrom and Richards, 2011).

In this study, we build on ideas proposed by Lange (2002) to investigate buoyancy produced through magmatic volatile exsolution at depth. We propose that, in addition to allowing mafic magmas to surmount the crustal density barrier, such buoyancy may also be an important trigger for failure of large magma reservoirs surrounded by warm wall rocks at lower crustal or Moho depth. To explore the consequences of magmatic volatile exsolution for the tempo of flood basalt eruptions, we couple one-dimensional models for thermal evolution, assimilation, gas exsolution and bubble population dynamics in a magma chamber with permeable gas transfer through the overlying crust. While our model is designed to capture the eruptive dynamics of flood basalts generally, we consider the Siberian Traps as a useful case study. Our model can explain the most distinctive features of flood basalt eruptions in the Siberian Traps and elsewhere, including eruptibility despite large magma chamber volumes, the buoyancy of mafic magmas, and repeated, sustained eruptive episodes punctuated by long hiatuses.

Flood basalt eruptions and volatile degassing have been hypothesized to have severe environmental repercussions. Geochronologic evidence suggests that flood basalt eruptions overlapped temporally with the end-Guadalupian, end-Permian, end-Triassic, and end-Cretaceous mass extinctions (Zhou et al., 2002; Courtillot and Renne, 2003; Blackburn et al., 2013; Burgess et al., 2014; Schoene et al., 2015; Renne et al., 2015; Burgess and Bowring, 2015). The flux of gases to the atmosphere critically determines the severity of magmatically-induced acid rain, ozone depletion, and surface temperature changes (e.g., Caldeira and Rampino, 1990; Black et al., 2012, 2014b; Schmidt et al., 2015). Most studies of volatiles in melt inclusions focus on degassing at the vent and in shallow conduits and chambers (Métrich and Wallace, 2008). However, the preponderance of CO_2 will exsolve at depth. In some cases large quantities of CO_2 may also be released in the subsurface through metamorphism of carbon-rich sedimentary rocks (Svensen et al., 2009). Such CO_2 may be trapped at depth as a fluid, or it may react with water and feldspars in the crust to form hydrated minerals (Bredehoeft and Ingebritsen, 1990). Alternatively, CO_2 can be dissolved in groundwater (e.g., James et al., 1999), or may reach the atmosphere through permeation and passive degassing or during an eruption that breaches a magma chamber that hosts a significant mass of exsolved CO_2. This exsolved CO_2, which would not be recorded directly in melt inclusions (Wallace et al., 2015), may be distilled from larger volumes of magma than those of the lavas that erupt. The total flux of CO_2 to the atmosphere or surface environments—a critical variable for understanding the climatic consequences of flood basalts—is therefore difficult to determine.

Here, we propose that the evolution of magmatic CO_2, eruption tempo, and environmental consequences are all interrelated. Episodic surface volcanism reflects rheological and density barriers to magma ascent into the crust, and results in expulsion of CO_2 and SO_2 to the atmosphere in brief pulses. These dynamics may help to explain the profound climate and carbon cycle perturbations that seem to coincide with the emplacement of some flood basalt provinces.

2. Model description

2.1. Overview

The features of flood basalt plumbing systems dictate the structure of our model. Flood basalt magmas originate in the mantle, most likely where mantle plumes arrive at the base of the lithosphere (Richards et al., 1989). The arrival of a plume may lead to a swell in melt production (Richards et al., 1989; Hooper et al., 2007). As described in the previous section, we expect this melt to rise towards the base of the crust, where rheological and density contrasts may cause the melt to pond and form large primitive magma chambers (Ridley and Richards, 2010; Farnetani et al., 1996). The number of such chambers will be governed in part by the compaction length, which describes the volume of crystalline matrix from which melt can be extracted (Keller et al., 2013). When the magma in these lower crustal or Moho-depth chambers is buoyant and overpressures are high enough to cause the overlying crust to fail, magmas will ascend via dikes.

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