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Assessing eruption column height in ancient flood basalt eruptions ☆

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ABSTRACT

A buoyant plume model is used to explore the ability of flood basalt eruptions to inject climate-relevant gases into the stratosphere. An example from the 1986 Izu-Oshima basaltic fissure eruption validates the model's ability to reproduce the observed maximum plume heights of 12–16 km above sea level, sustained above fire-fountains. The model predicts maximum plume heights of 13–17 km for source widths of between 4–16 m when 32% (by mass) of the erupted magma is fragmented and involved in the buoyant plume (effective volatile content of 6 wt%). Assuming that the Miocene-age Roza eruption (part of the Columbia River Basalt Group) sustained fire-fountains of similar height to Izu-Oshima (1.6 km above the vent), we show that the Roza eruption could have sustained buoyant ash and gas plumes that extended into the stratosphere at ∼45° N. Assuming 5 km long active fissure segments and 9000 Mt of SO_2 released during explosive phases over a 10–15 year duration, the ∼180 km of known Roza fissure length could have supported ∼36 explosive events/phases, each with a duration of 3–4 days. Each 5 km fissure segment could have emitted 62 Mt of SO_2 per day into the stratosphere while actively fountaining, the equivalent of about three 1991 Mount Pinatubo eruptions per day. Each fissure segment could have had one to several vents, which subsequently produced lava without significant fountaining for a longer period within the decades-long eruption. Sensitivity of plume rise height to ancient atmospheric conditions is explored. Although eruptions in the Deccan Traps (∼66 Ma) may have generated buoyant plumes that rose to altitudes in excess of 18 km, they may not have reached the stratosphere because the tropopause was substantially higher in the late Cretaceous. Our results indicate that some flood basalt eruptions, such as Roza, were capable of repeatedly injecting large masses of SO_2 into the stratosphere. Thus sustained flood basalt eruptions could have influenced climate on time scales of decades to centuries but the location (i.e., latitude) of the province and relevant paleoclimate is important and must be considered.

1. Introduction

There is an intriguing age correlation between several continental flood basalt (CFB) provinces emplaced in the past 300 Ma with mass extinction events (e.g., Wignall, 2001; Courtillot and Renne, 2003; Kelley, 2007). The link between CFB volcanism and mass extinctions may be due to gas release from the magmas or magma–sediment interactions potentially leading to environmental changes (Self et al., 2014; Schmidt et al., in press). Recent studies have shed light on variations in eruption rate over time and the spatial distribution of eruptive vents for the 14.7 Ma Roza Member of the Columbia River Basalt Group (CRBG) (e.g., Brown et al., 2014). These new data allow more robust assessment of magmatic gas contributions to the atmosphere by CFB volcanism.

The effects of volcanism on climate are complex and occur over a range of time scales, from days to possibly centuries (Robock, 2000; Timmreck, 2012). Sulfur species (sulfur dioxide, SO_2, and hydrogen sulfide, H_2S) are the primary volcanic volatiles known to impact climate. Most basaltic eruptions release SO_2 (Sharma et al., 2004) and most is known about its relevance to climate when injected into the stratosphere. Sulfuric acid (H_2SO_4) aerosols derived from SO_2 and H_2S can have long residence times (1–3 years) in the stratosphere, where these particles scatter and absorb incoming solar and thermal infrared radiation, resulting in a net cooling at the surface (e.g., Robock, 2000). Release of volcanic CO_2 may have a limited effect on climate (Self et al., 2006). However, magmatic interaction with sediments, may also play a role.

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Examples of large, historic, silicic explosive eruptions that have impacted climate on the 1–2 year timescale through the injection of large amounts of SO_2 into the stratosphere include Tambora (1815), Krakatau (1883), Agung (1963), El Chichón (1982), and Pinatubo (1991). The high-latitude (65° N) basaltic fissure eruption of Laki in 1783–1784 (Thordarson and Self, 1993; Schmidt et al., 2010) injected SO_2 into the upper troposphere and lower stratosphere through repeated sub-Plinian explosive phases over a period of eight months, affecting climate in the northern hemisphere for up to two years (Thordarson et al., 1996; Highwood and Stevenson, 2003; Thordarson and Self, 2003; Oman et al., 2006a, 2006b; Schmidt et al., 2012).

Masses of SO_2 injected into the atmosphere by historic explosive volcanic eruptions range from ∼7 Mt (= 7 Teragram) by El Chichón in 1982 (Bluth et al., 1992), to ∼20 Mt by Pinatubo in 1991 (Bluth et al., 1992), and ∼60 Mt by Tambora in 1815 (Self et al., 2004). Up to 122 Mt of SO_2 was emitted by the Laki eruption (Thordarson et al., 1996), with over 90 Mt injected into the upper troposphere and lower stratosphere over a 5 month period. Volcanic eruptions are also capable of redistributing large volumes of water from the lower atmosphere into the stratosphere (Glaze et al., 1997). Models indicate that a 25 km-high eruption column rising through a wet, tropical atmosphere can transport up to 4 Mt of H_2O per hour. ("Plume" describes the vertical eruption column and downwind ash/gas cloud.) In this case, ∼30% of the water vapor in the plume at its maximum height is derived from the erupted magma and ∼70% is entrained while passing through the moist lower atmosphere (Glaze et al., 1997).

Based on the atmospheric and environmental impacts observed following the Laki eruption, some have speculated that large CFB eruptions (e.g., CRBG, peak 16–15 Ma; Deccan Traps peak ∼67–65 Ma) may have supplied large masses of SO_2 and other gases to the upper troposphere, or possibly even the stratosphere (e.g., Stothers et al., 1986; Woods, 1993a; Thordarson and Self, 1996; Chenet et al., 2005; Self et al., 2005). Early attempts by Stothers et al. (1986) and Woods (1993a) at modeling CFB plumes suggested that near-stratospheric heights could be attained by high-intensity basaltic eruptions but there were many simplifications. CFB lava flow-fields, each the product of one sustained eruption over decadal time-scales, are made up of multiple lava flows that are proposed to have erupted with volumetric flow rates similar to the maximum estimated for Laki (e.g., Self et al., 1998, 2006). Long-duration effusive basaltic eruptions, such as the current > 30 year eruption of Pu`u `Ō`ō, Hawaii, are consistent with much larger CFB events that may have been active over decades to possibly hundreds of years. These larger CFB events may have injected as much as 1000 Mt of SO_2 into the atmosphere annually (Self et al., 2005). Despite the long overall duration of CFB province emplacement (1 to a few Ma), it is likely that this activity was characterized by long periods of inactivity, punctuated by shorter duration eruptive phases lasting decades to possibly centuries.

We investigate the possible delivery of climate-relevant gases (SO_2 and H_2O) into the atmosphere from CFB eruptions by combining numerical modeling and volcanological datasets for the 14.7 Ma Roza flow of the CRBG (Thordarson et al., 1996; Brown et al., 2014). In particular, we place constraints on the mass of SO_2 that such eruptions could have injected into the stratosphere. This is the first application of a buoyant plume model to ash and gas plumes sustained above a fire-fountain.

2. Basaltic gas–ash plumes

The key to having an impact on climate for a basaltic eruption is the ability to loft climate-relevant gases into the stratosphere and to sustain the supply over many years, even intermittently. Although not common, sustained buoyant plumes associated with large basaltic fire-fountain events have been observed. An example is the Pu`u `Ō`ō eruption at Kilauea, Hawaii (Fig. 1); early episodes of the eruption in 1983 and 1984 generated fire-fountains, with typical heights of 100–200 m, and occasionally as high as ∼400 m (Wolfe et al., 1988), which sustained gas and ash plumes of 5–7 km height above sea level (ASL). The 1984 eruption of Mauna Loa, Hawaii, produced somewhat larger fire-fountains (up to 500 m high) along a 2 km-long active fissure that generated a buoyant plume estimated to rise to 11 km ASL (7.5 km above the vent) (Smithsonian Institution, 1984). Much larger fire-fountains were documented during the 1986 eruption of Izu-Oshima, Japan, and, indirectly, the 1783–1784 eruption of Laki, Iceland. At Izu-Oshima, fire-fountains 1.6 km high were observed to feed an ashy sub-Plinian plume that reached 16 km ASL (Endo et al., 1988; Sumner, 1998; Mannen and Ito, 2007). Miyakejima, Japan, also produced 12-km-high plumes during a basaltic fissure eruption in 1983, but the exact source of the plumes is not known (Aramaki et al., 1986). Fire-fountains at Laki, estimated to have reached 0.8–1.4 km in height, were observed from afar to sustain eruption columns of up to 15 km altitude (Thordarson and Self, 1993; Oman et al., 2006a). These historic eruptions can be used to evaluate plume-rise models for application to convecting, buoyant ash plumes sustained above fire-fountains.

Fig. 1. Lava fountain from Pu`u `Ō`ō on September 19, 1984. Fire fountain extends to 450 m high and sustains an ash and gas plume. Note how ash plume separates from fountain before apex. See text for discussion. Photograph taken by C. Heliker.