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Eruption mechanisms and short duration of large rhyolitic lava flows of Yellowstone

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ABSTRACT

Large-volume effusive rhyolite lava flows are a common but poorly understood occurrence from silicic volcanic centers. We integrate characterization of lava flow topographic morphology and petrographic textures and zoning of crystals with physical models of viscous fluid flow in order to interpret the eruption durations and discharge rates for the most recent effusive volcanic eruptions from Yellowstone. These large-volume (10–70 km^3) crystal-poor rhyolite lavas erupted within the Yellowstone caldera as 100–200 m thick flows and have a cumulative erupted volume of 650 km^3 that is similar to less frequent caldera-forming events, but occur as individual eruptions spread over ∼100 ka. Most of this work is focused on the axisymmetric 124 ka, ∼50 km^3 Summit Lake flow. We examined crystallinity, major and trace element concentrations, oxygen and hydrogen isotopic values, and quartz morphology and zoning in samples from the center to margin of this flow. Water contents down to 0.1 wt.% and δD values of −110‰ are low and require closed-system degassing until near-surface lithostatic pressure, while major elements are consistent with water-undersaturated pre-eruptive storage and crystallization at ∼4–8 km depth. We found some evidence for subtle km-scale zoning within the lavas but describe significant microscopic scale compositional diversity including sharp boundaries between high-Ti cores and ∼200 μm thick rims on quartz phenocrysts. Embayed quartz external morphology and rim growth may be the result of undercooling during coalescence of magma bodies during shallow transport between dikes and sills. Modeling the emplacement of the lava flow as a simple viscous fluid suggests that emplacement of rhyolite lava at ∼800 °C occurred over ∼2 to 5 yrs with high discharge rates >100 m^3/s. Such high magma discharge rates are accommodated through ∼6 km-long fissures that allow for slower magma ascent velocities of <1 cm/s required for eruptions to remain dominantly effusive. Lower temperatures will result in >10 yr flow durations and significant cooling of the flow front that should result in a more complex compound flow morphology than observed. Higher temperatures require unrealistically wide (>50 m) dike widths to accommodate large discharge rates. Petrographic and isotopic evidence from crystals suggests recharge and merger of individual magma batches occurs on a similar timescale to the eruption duration and may directly cause overpressure and emplacement of these rhyolite lava flows from a shallow, ephemeral magma chamber. Large-volume rhyolitic lavas are able to erupt effusively through elongate fissures that utilize preexisting zones of crustal weaknesses such as ring fractures. Less-common explosive eruptions at Yellowstone may result when ascending magmas are forced through narrower conduits or when recharge rates are especially high. The results of this study provide a unique "top-down" constraint on effusive eruption rates, make new interpretations of common petrographic textures, and presents a comprehensive model for eruption control.

1. Introduction

Large centers of rhyolitic volcanism receive a great deal of attention for their caldera-forming "supereruptions." These largest eruptions may be responsible for major climate perturbations in the Earth's history (e.g., Self and Blake, 2008). Their underlying magma systems play a critical role in development and evolution of the Earth's crust (e.g., Hildreth and Moorbath, 1988; Huppert and Sparks, 1988). Many recent studies have focused on the eruption mechanisms and triggers of these largest caldera-forming tuffs (e.g., Gregg et al., 2015), while less attention has been devoted to the eruption mechanisms of more common but less publicized effusive rhyolite flows from these volcanic centers.

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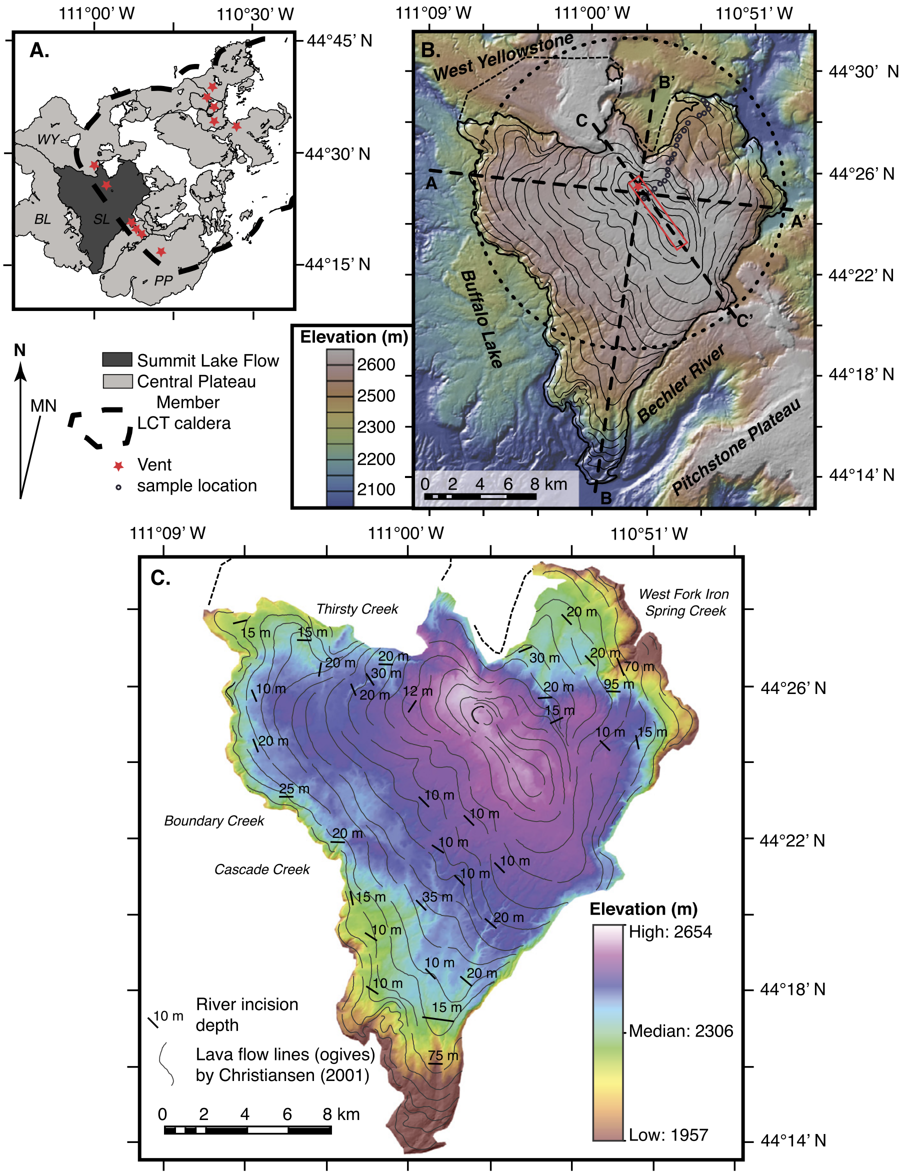

Fig. 1. **(A)** Overview map outlining Yellowstone Central Plateau Member rhyolite lava flows, vent locations, and the Lava Creek Tuff caldera margin. **(B)** Elevation map of the Summit Lake and nearby lavas. Approximate symmetrical dotted circle in line with the A–A′ section has the same area (400 km^2) as the mapped flow surface area. Thin flow morphology lines are shown from Christiansen (2001). A potential 6 km long fissure, is indicated by a thick line that focused to a final vent location at the intersection of A–A′, B–B′, and C–C′. Topography is from 10 m resolution ASTER data plotted using GeoMapApp (Ryan et al., 2009). **(C)** Detailed elevation map for the surface of the Summit Lake flow, with measured river incision depths.

While direct observations exist for small-volume rhyolite eruptions and many silicic domes, primarily in arc volcanic settings (e.g., Castro and Dingwell, 2009; Pallister et al., 2013; Tuffen et al., 2013), eruption of large-volume rhyolitic lavas have never been observed. Therefore, interpretation of the eruption processes for large-volume rhyolite lava flows is constrained only by the observed physical features of prehistoric flows (de Silva et al., 1994; Manley, 1996; Fink and Griffiths, 1998). In recent years significant progress of lava flow simulations was achieved starting from analytical solutions (Huppert, 1982) to fully 3D non-isothermal lava flow models (Hidaka et al., 2005). In the case of prehistoric lava flows with parameters that are hard to constrain, including discharge rate, vent shape, and emplacement temperature, an obvious solution is to use a simple modeling strategy to gain first order constraints on eruption dynamics.

The Yellowstone Plateau is one of the largest and most well-recognized centers of rhyolitic volcanism in the world, most noted for its massive caldera-forming "supereruptions" such as the most recent 630 ka Lava Creek Tuff. Since this eruption the caldera has been filled with numerous effusive lava flows, including the products of the most recent Central Plateau Member (CPM) period of volcanism from 180–70 ka. These flows have volumes up to 70 km^3, with 16 individual flows of over 2 km^3, and only 2 mapped occurrences of significant tuff deposits (Christiansen et al., 2007; Fig. 1A). The cumulative 650 km^3 volume of these flows is comparable to that of a large caldera-forming supereruption, and thus the CPM has sometimes been considered a "fourth" caldera cycle with a series of voluminous flows occurring over a 100 ka period instead of as a single catastrophic caldera-forming eruption (Christiansen and Blank, 1972; Hildreth et al., 1984). The CPM rhyolites provide an ideal setting to test models of rhyolite lava eruption mechanisms with some of these largest and most exceptional examples of rhyolite flows on earth.

In this contribution we are interested in understanding the eruption mechanics of these large-volume rhyolite lava flows. We constrain eruption timescales and temperature by integrating ob-

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