GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G48697.1

Manuscript received 7 December 2020
Revised manuscript received 18 February 2021
Manuscript accepted 23 February 2021

Eruption risks from covert silicic magma bodies

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ABSTRACT

Unintentional encounters with silicic magma at ~2–2.5 km depth have recently occurred during drilling at three volcanoes: Kilauea (Hawaii), Menengai (Kenya), and Krafla (Iceland). Geophysical surveys had failed to warn about shallow magma before each encounter, and subsequent surveys at Krafla have been unable to resolve the size or architecture of its silicic magma body. This presents a conundrum for volcano monitoring: Do such shallow "covert" magma bodies pose an eruption risk? Here, we show that Krafla's most recent explosive eruption, a mixed hydrothermal-magmatic event in 1724 C.E. that formed the Víti maar, involved rhyolite essentially indistinguishable in composition from magma encountered during drilling in 2009. Streaks of quenched basalt in some Víti pumices provide direct evidence for interaction between co-erupted rhyolitic and basaltic magmas, but crystals in these pumices show no evidence for late-stage heating or re-equilibration with more mafic melt, implying mixing time scales of at most several hours. Covert silicic magma thus presents an eruption risk at Krafla and may be mobilized with little warning. Difficulties in resolving magma bodies smaller than ~1 km^3 with geophysical surveys mean that covert silicic magma may exist at many other volcanoes and should be considered in hazard and risk assessments.

INTRODUCTION

Eruptions from mature magmatic systems have traditionally been thought to tap large bodies of melt-dominant magma in the middle to upper crust ("magma chambers"; Marsh, 1989). However, it is increasingly recognized that eruptible magma can be much more distributed than previously thought, and recent petrologic evidence suggests that some eruptions tap small and discrete magma bodies from a range of depths rather than a single chamber (e.g., Cashman and Giordano, 2014; Sparks et al., 2019). Such distributed magmatic systems present a challenge for volcano monitoring because magma bodies up to ~1 km^3 are difficult to detect with geophysical surveys. Seismic waves used to image volcanoes typically have wavelengths ranging from several hundred meters to kilometers, with inherent difficulties in resolving features with sub-wavelength dimensions. For example, seismic tomography will smear boundaries of real velocity anomalies so that their outlines may not be mapped with resolution better than 1–2 km (e.g., Schuler et al., 2015). Similarly, sensitivity testing suggests that a 1 km^3 magma body could go undetected by magnetotelluric (MT) observations (Lee et al., 2020). Recent unintentional encounters with shallow (≤2.5 km depth) silicic magmas in boreholes at Kilauea, Hawaii (dacite; Teplow et al., 2009); Menengai, Kenya (trachyte; Mbia et al., 2015); and twice at Krafla, Iceland (dacite to rhyolite; Mortensen et al., 2010; Elders et al., 2011) underline the problem. In each case, pre-drilling geophysical surveys failed to detect or warn about shallow silicic magma.

To better understand the covert silicic magma at Krafla, we studied juvenile products from seven eruptions spanning the system's known history of rhyolitic volcanism and compared them with magma sampled during drilling. Our methods are outlined in the Supplemental Material[1]. Krafla is a predominantly basaltic system, consisting of an ~8 × 10 km caldera (65.73°N, 16.78°W) transected by an ~100-km-long fissure swarm (Sæmundsson, 1991). Silicic melt was first encountered during drilling in 2008 in well KJ-39 (Fig. 1; drilled by Landsvirkjun), where quenched glass (Fig. S1 in the Supplemental Material) was found to comprise up to 30% of cuttings from the well base (2571 m depth; Mortensen et al., 2010). Pre-drilling seismic and geodetic observations had revealed magma interpreted to lie in the 3–7 km depth range (Einarsson, 1978; Tryggvason, 1986), but these findings were interpreted in the context of the 1975–1984 Krafla Fires basaltic eruptions (e.g., Wright et al., 2012). In 2009, silicic magma was again intercepted in well IDDP-1, the first well of the Iceland Deep Drilling Project (Fig. 1). The well was intended to reach the margin of the large basaltic storage zone, inferred from MT observations to reside at depths of ≥4–4.5 km (Friðleifsson et al., 2014), but drilling ceased when magma was encountered at 2096 m. Cuttings from ~30–80 m above the magma consisted of fresh fine-grained mafic ("diabase") and felsic ("felsite") intrusive material (Zierenberg et al., 2013). Circulation loss prevented sampling of the 30 m interval above the magma, but quenched rhyolitic glass hosting <3 modal% crystals and occasional intrusive fragments were sampled from the magma. Further details of these drilling encounters and the geology of Krafla are given in the Supplemental Material.

VÍTI–IDDP-1 LINK

Our petrologic data reveal a link between the IDDP-1 rhyolite and Krafla's youngest rhyolitic products, erupted in 1724 C.E. during the Mývatn Fires rifting episode. The eruption formed Víti, a small (~300-m-diameter) maar ~500 m northeast of IDDP-1 (Fig. 1). Approximately 0.45 km^3 of basaltic lava effusion followed from fissures ~2 km to the west in 1727–1729 (Grönvold, 1984). Víti ejecta are mainly altered country

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[1]Supplemental Material. Details of methods, an outline of the geology of Krafla, supplemental details of the drilling encounters with magma, supplemental figures, and a spreadsheet containing all compositional data collected from Víti pumice samples. Please visit https://doi.org/10.1130/GEOL.S.14346863 to access the supplemental material, and contact editing@geosociety.org with any questions.

CITATION: Rooyakkers, S.M., et al., 2021, Eruption risks from covert silicic magma bodies: Geology, v. 49, p. , https://doi.org/10.1130/G48697.1

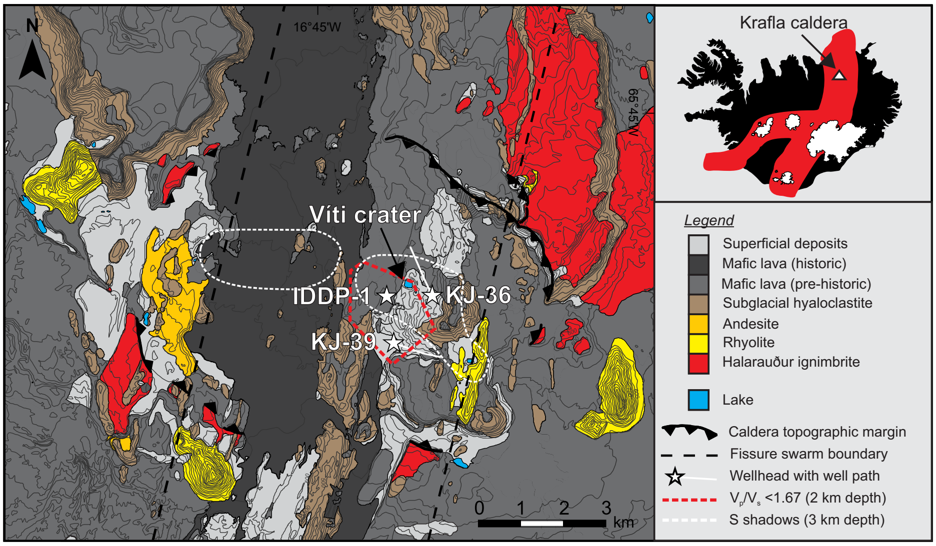

Figure 1. Geologic map of the Krafla caldera (Iceland), modified after Sæmundsson et al. (2012). Inset shows location of the caldera in Iceland's neovolcanic zone. White areas are glaciers. Low V_p/V_s zone is after Schuler et al. (2015); S-wave shadows are after Einarsson (1978).

rock fragments, consistent with a predominantly hydrothermal eruption, but occasional juvenile basaltic scoria and rhyolitic pumice clasts imply a magmatic trigger. IDDP-1 glass major-element compositions resemble glasses in erupted Krafla rhyolites and largely overlap with Víti pumice glasses (Fig. S1). More revealing are the trace elements (Fig. 2); Víti and IDDP-1 bulk and glass compositions almost completely overlap and are distinct from other Krafla rhyolites, with similar highly incompatible element ratios implying a common source.

The IDDP-1 and Víti crystal populations also show similarities. Anorthite (An) contents for IDDP-1 rhyolite plagioclase cores and rims (Masotta et al., 2018) overlap with the primary modes for Víti (Fig. 3A), while trace elements La, Ce, and Eu overlap with the lower end of the Víti range (Fig. 3B). Major-element compositions of Víti augites strongly overlap with those from the IDDP-1 rhyolite and felsite (Fig. 3C), while their trace-element contents closely match those produced in crystallization experiments on the IDDP-1 rhyolite (Masotta et al., 2018; Fig. S2). Similarly, IDDP-1 pigeonite compositions overlap with the more magnesian grains from Víti (Fig. 3C) and have similar rare earth element (REE) patterns. Subtle differences and the narrower range of IDDP-1 crystal compositions may point to a real difference between the rhyolites, but they could also be an artifact of the lower number of published analyses from IDDP-1 and/or the small magma volume sampled during drilling.

Based on similarities between the rhyolite and experimental melts of IDDP-1 felsite, Masotta et al. (2018) proposed that the IDDP-1 rhyolite was produced by high-degree (>70%) felsite remelting, and they conceptualized the crust around IDDP-1 as hosting a plexus of small felsite bodies that may be remobilized by new

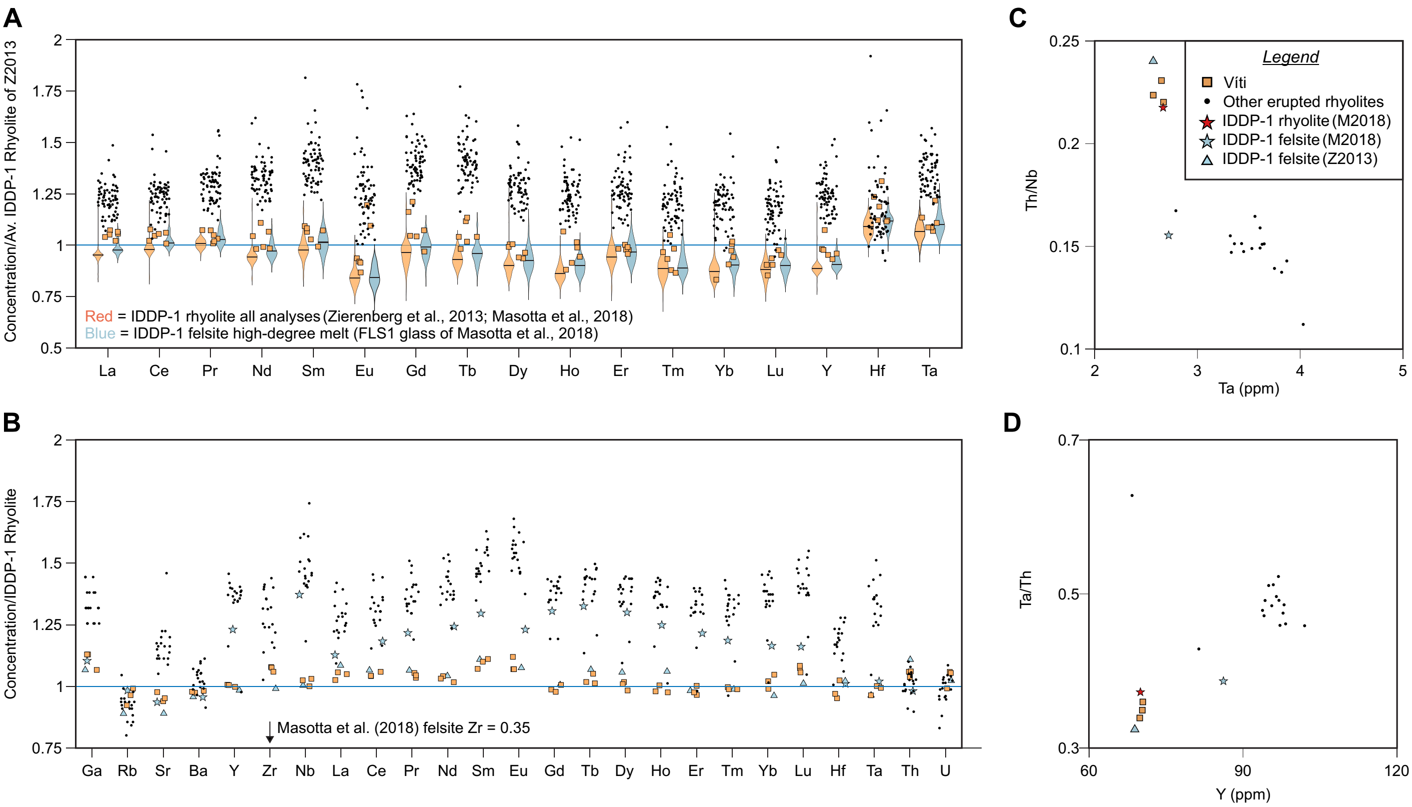

Figure 2. Comparative trace-element plots for Krafla (Iceland) rhyolites. (A) Glass compositions measured by laser-ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS), normalized to average well IDDP-1 rhyolite glass of Zierenberg et al. (2013). Horizontal bars on violin plots are medians. Felsite glasses (blue violins) are type FLS1 glass of Masotta et al. (2018), which correspond with ~70% partial melting of their bulk felsite composition. (B) Bulk compositions determined by solution ICP-MS, normalized to average IDDP-1 rhyolite bulk composition of Masotta et al. (2018). (C,D) Selected bulk trace-element plots. Z2013—Zierenberg et al. (2013); M2018—Masotta et al. (2018).

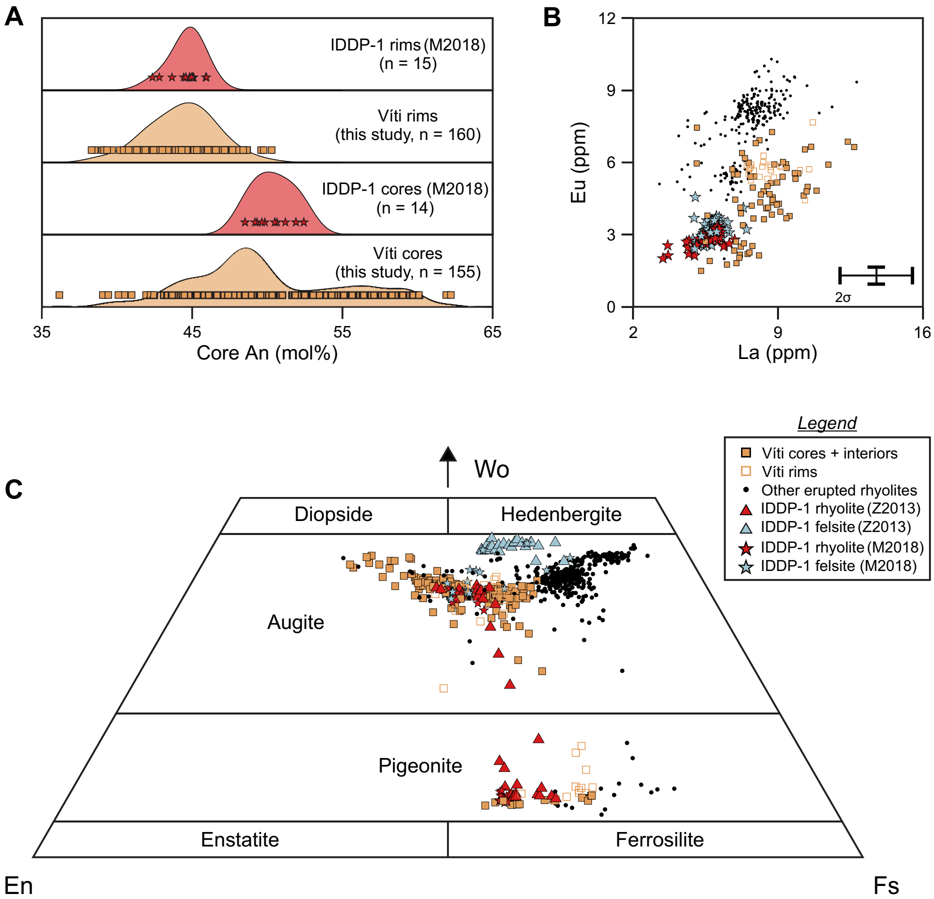

Figure 3. Comparisons of Víti and IDDP-1 crystals from the Krafla caldera in Iceland). Z2013—Zierenberg et al. (2013); M2018—Masotta et al. (2018). (A) Kernel density estimates for plagioclase core and rim anorthite (An) contents. (B) Plagioclase Eu versus La. (C) Pyroxene ternary diagram: En—enstatite; Wo—wollastonite; Fs—ferrosilite.

intrusions. Textural evidence for partial melting and felsite assimilation at the roof of the IDDP-1 magma body is consistent with such a scenario (Zierenberg et al., 2013; Saubin et al., 2021). Features of the Víti crystals also suggest some degree of felsite recycling; macrocrysts commonly host internal resorption surfaces with only slight compositional shifts across them (e.g., Figs. 4B and 4D), consistent with assimilation followed by overgrowth on resorbed cores. Further, mixing of at least two crystal populations, which may derive from distinct felsite bodies, is suggested by two distinct modes in Víti plagioclase core An content (Fig. 3A), a scattered relationship between plagioclase core An and Sr content (Fig. S3), and a bimodality in titanomagnetite V and Cr contents (Fig. S4). Evidence for felsite recycling raises the possibility that the similarities between the rhyolites could be explained by freezing and later remelting of Víti magma. However, because both rhyolites have essentially indistinguishable bulk trace-element contents, explaining the link between them in this way requires near-complete and closed-system melting to prevent trace-element fractionation.

A simpler alternative is that the Víti and IDDP-1 rhyolites reflect the same magma body, which remained molten between 1724 and 2009. In this case, the similar crystal contents of both magmas require negligible cooling over almost 300 yr. Axelsson et al. (2014) calculated that a sill of IDDP-1 magma cooling by conduction would have to be >50 m thick to remain molten since the 1975–1984 Krafla Fires eruptions. Using the same parameters, we calculated that sills thicker than ~250–300 m could remain largely molten from 1724 to 2009 (Fig. S5). Alternatively, the IDDP-1 magma may rest above hot mush or nearby basaltic intrusions, in which case a thinner body could be buffered at near-liquidus temperatures.

Distinguishing between these scenarios is difficult because the size and architecture of the IDDP-1 magma body are poorly resolved. Felsite intrusions meters to tens of meters thick are common in Krafla wells, and in some cases form swarms up to several hundred meters thick, but continuous bodies >200 m thick also occur (Mortensen et al., 2015). A recent three-dimensional (3-D) MT inversion study failed to image the IDDP-1 magma, but the inversion was shown to be insensitive to bodies as large as 1 km^3 (Lee et al., 2020). Postdrilling seismic tomography (Schuler et al., 2015) showed a pronounced low V_p/V_s anomaly at ~2 km depth, interpreted as either magma or superheated steam above magma, that extends beneath IDDP-1 and KJ-39 (Fig. 1). The footprint of this anomaly partially overlaps with one of the two bodies of seismic attenuation at ~3–7 km depth (Fig. 1; Einarsson, 1978), but its real spatial extent cannot be resolved more accurately than the ~1 km node spacing of the velocity model, and it thus remains unclear it reflects a single magma body or separate bodies. A prominent seismic reflector near the base of IDDP-1 (Kim et al., 2020), interpreted as either magma or magmatic fluids, extends at least 1 km westward from the well but has yet to be mapped out in 3-D. High bottom-hole temperatures and corrosive gases encountered north of Víti in well KJ-36 (depth 2501 m) also imply proximity to magma. If both KJ-36 and KJ-39 approached the margins of the same body encountered by IDDP-1, an area as large as ~3.5 km^2 may be underlain by shallow rhyolitic magma (Eichelberger, 2020).

BASALT TRIGGERING OF THE VÍTI ERUPTION

Streaks or blebs of quenched basalt in some rhyolitic pumices provide evidence for interaction between the magmas co-erupted from Víti (Fig. 4A). However, crystals in these pumices almost exclusively have compositions appropriate for equilibrium with silicic melts (Fig. S6), and crystals matching those in Mývatn Fires basalts are either absent (olivine) or very rare ($An_{60–70}$ plagioclase, Mg# 64–74 augite; cf. Grönvold, 1984). Furthermore, all plagioclase crystals in the pumices are euhedral (excluding scarce resorbing felsite clots), lacking the rim resorption typical of other mixed basalt-rhyolite Icelandic eruptions (Sigurdsson and Sparks, 1981; Charreteur and Tegner, 2014). Evidence for basaltic recharge is also absent within plagioclase crystals (Fig. 4E), and most crystals show normal core-rim zoning (Fig. 4C); a minority with internal resorption surfaces show reverse-zoned overall, but their outer mantles are normally zoned (Fig. 4B). Reverse zoning is also absent in Víti pyroxenes (Fig. 4E), while titanomagnetites, which partially re-equilibrate within hours to days in response to mafic-felsic mixing (e.g., Tomiya et al., 2013), are unzoned except for a single grain (Fig. 4F; Fig. S7). The absence of reverse zoning or resorption at the rims of most crystals rules out thermal remobilization of the Víti rhyolite shortly before eruption, instead indicating that the rhyolite was dominantly liquid when it was encountered by the basalt.

We thus infer that the Víti eruption was triggered by a basaltic dike intercepting a near-liquidus rhyolite body and its overlying hydrothermal system, and that interactions between the magmas were too short for significant crystal exchange or reaction. Similar mafic-felsic interactions too short to be recorded by crystals

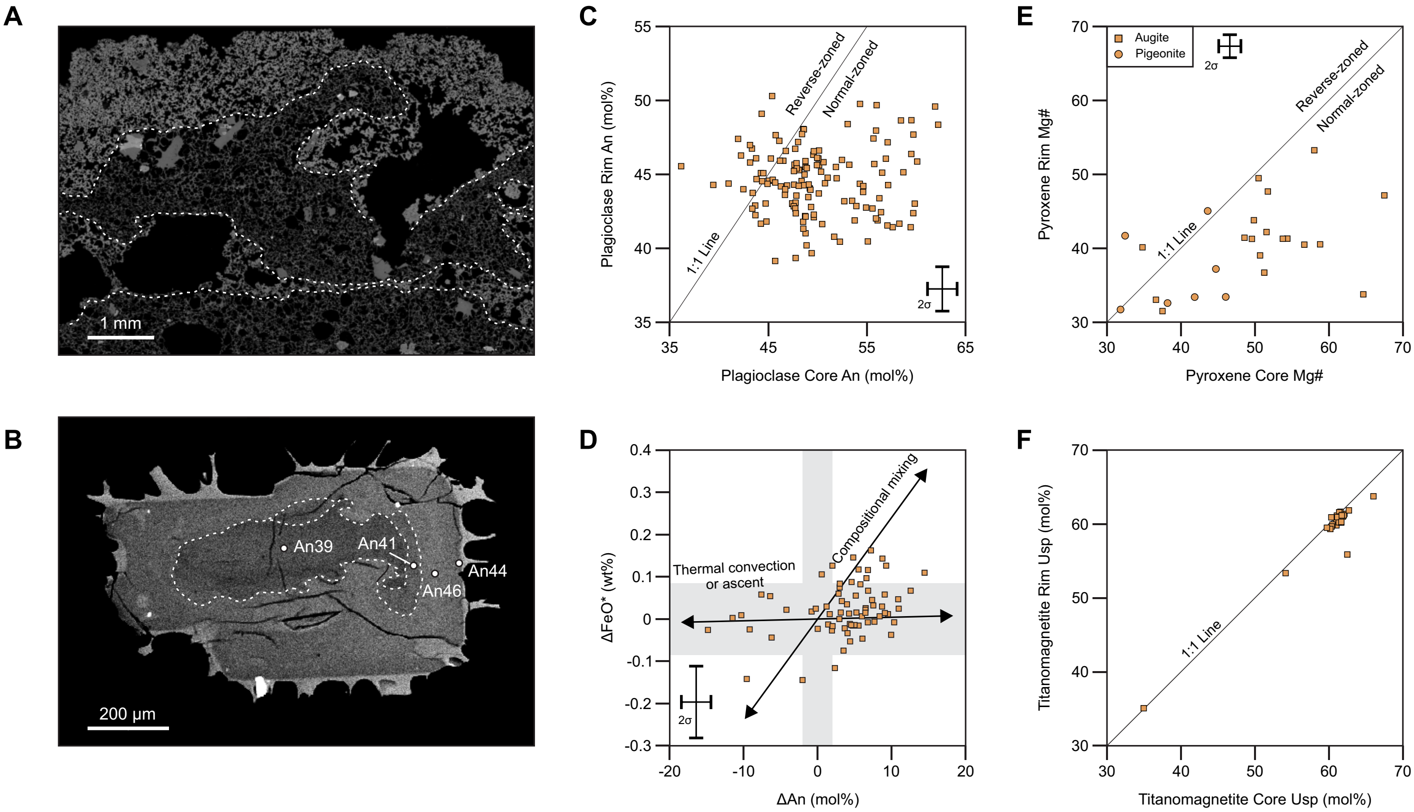

Figure 4. (A) Backscattered-electron (BSE) image mosaic showing basalt-rhyolite mixing in Víti pumice clast (from Krafla caldera, Iceland). White dashes separate rhyolitic glass (dark gray) and sparse crystals from basalt (light gray) with abundant quench crystals. (B) BSE image of plagioclase in rhyolitic glass (bright spines). Internal resorption surfaces are dashed. Grain is reverse-zoned, but outer mantle shows subtle normal zoning. (C) Rim versus core anorthite (An) content for plagioclase from Víti pumices. (D) Compositional changes across plagioclase internal resorption surfaces. ΔAn = change in An (mol%; outer – inner zone). ΔFeO* = change in total Fe expressed as FeO (wt%; outer – inner zone). Mixing and thermal convection or ascent vectors are after Ruprecht and Wörner (2007). Changes that plot in gray fields are <2σ analytical uncertainty. (E) Rim versus core Mg# for pyroxenes from Víti pumices. (F) Rim versus core ulvöspinel (Usp; mol%) for Víti titanomagnetite.

are known from the 1912 C.E. Novarupta-Katmai (Alaska) eruption, where they are regarded as syneruptive processes (Singer et al., 2016). In other eruptions, interactions as short as ∼7–9 h have been modeled from diffusion profiles at titanomagnetite rims (Tomiya et al., 2013; Allan et al., 2017). The lack of such gradients in Víti titanomagnetites suggests even shorter time scales. At mid- to upper-crustal ascent rates similar to the 2014–2015 Holuhraun eruption in Iceland (0.1–0.3 m s^{-1}; Hartley et al., 2018), a dike from the shallow basaltic storage region beneath Krafla (∼3–4 km depth; Einarsson, 1978) could reach the surface in ∼3–8 h, comparable to the shortest time-scale estimates from these diffusion studies. Hence, we suggest that basalt-rhyolite interactions in the Víti event occurred mainly during ascent (Snyder et al., 1997).

HAZARD IMPLICATIONS

Krafla is one of the most intensely monitored volcanoes in the world. Yet, if not for accidental drilling encounters, its active shallow silicic magma body would have gone unnoticed. Our discovery of a previous eruption involving this magma body or intrusive complex and its rapid mobilization by basaltic diking serves as a stark warning for possible future eruption scenarios. An explosive eruption involving the IDDP-1 rhyolite and/or its overlying hydrothermal system should be considered an immediate possibility if dike intrusion is detected in the area.

Resolution limits of geophysical methods mean that silicic magma bodies as large as 1 km^3 may exist unrecognized beneath many volcanoes. In principle, the largest such bodies may produce eruptions with regional or hemispheric effects. The 1875 C.E. rhyolitic eruption of Askja, ∼100 km from Krafla and also triggered by basalt (Sigurdsson and Sparks, 1981), serves as a useful analogy. This event ejected ∼0.3 km^3 of rhyolite, producing thick fallout across Iceland, ash fall in continental Europe, and caldera collapse. Despite these impacts, there is a distinct possibility that this magma would not have been detected by modern geophysics. More recent events involving covert silicic magma include the 2010 Eyjafjallajökull eruption, when silicic magma residual from its 1821–1823 eruption was remobilized and mixed with ascending basalt (Sigmarsson et al., 2011), and the 2005 rhyolitic eruption at Dabbahu (Ethiopia) triggered by rifting and basaltic diking (Wright et al., 2012).

We contend that covert silicic magma should be considered in hazard and risk assessments. Scrutiny is especially warranted for systems where small silicic eruptions have occurred historically and may have left residual magma hidden at depth. In the event of unrest, possible remobilization of shallow covert silicic magma by ascending recharge magmas may present a considerable hazard in such systems (e.g., current unrest in the Phlegrean Fields, Italy, where silicic eruptions occurred in 1302 and 1538 C.E.; Di Vito et al., 2016; Selva et al., 2019). Efforts to improve resolution for detecting and imaging magma bodies, such as use of extremely dense geophone arrays, may be warranted to maximize the chance of detecting covert silicic magma at volcanoes that threaten large populations or before costly drilling campaigns. Endeavors to improve magma imaging and drilling capabilities may eventually allow sensors to be placed around covert magma bodies for in situ monitoring (a present goal at Krafla; Eichelberger, 2019).

ACKNOWLEDGMENTS

We thank Landsvirkjun (National Power Company of Iceland) for hosting us during fieldwork; S. Mollo and M. Masotta for providing well IDDP-1 whole-rock data for select elements not reported in their published work; and D. Baker and J. Eichelberger for helpful comments on an early version of this work. J. Stix acknowledges a Discovery grant from the Natural Sciences and Engineering Research Council of Canada. K. Berlo acknowledges a Fonds de Recherche du Québec–Nature et Technologies Nouveau Chercheur grant. We also thank J. Troch, G. Giordano, and an anonymous reviewer for helpful suggestions, and editor G. Dickens.

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