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Magma recharge patterns control eruption styles and magnitudes at Popocatépetl volcano (Mexico)

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ABSTRACT

Diffusion chronometry has produced petrological evidence that magma recharge in mafic to intermediate systems can trigger volcanic eruptions within weeks to months. However, less is known about longer-term recharge frequencies and durations *priming* magma reservoirs for eruptions. We use Fe-Mg diffusion modeling in orthopyroxene to show that the duration, frequency, and timing of pre-eruptive recharge at Popocatépetl volcano (Mexico) vary systematically with eruption style and magnitude. Effusive eruptions are preceded by 9–13 yr of increased recharge activity, compared to 15–100 yr for explosive eruptions. Explosive eruptions also record a higher number of individual recharge episodes priming the plumbing system. The largest explosive eruptions are further distinguished by an ~1 yr recharge hiatus directly prior to eruption. Our results offer valuable context for the interpretation of ongoing activity at Popocatépetl, and seeking similar correlations at other arc volcanoes may advance eruption forecasting by including constraints on potential eruption size and style.

INTRODUCTION

Intrusions of hot, volatile-rich magma can unlock stagnant, crystal-rich magma reservoirs and increase overpressure sufficiently to trigger volcanic eruptions (Sparks et al., 1977; Kent et al., 2010; Morgavi et al., 2017). Magma recharge is recorded by crystals in a magma reservoir as compositional zoning, and the time elapsed between injections and eruptions can be constrained by analyzing the extent of elemental diffusion between these compositional zones (e.g., Costa et al., 2008). Mixing-to-eruption time scales typically range from days to years for basaltic eruptions, and months to centuries for more evolved magma reservoirs (Costa et al., 2020). The large range in time scales for any given eruption reflects complex magma recharge and remobilization dynamics, including (1) individual crystals recording an injection at different times depending on their location in the magma reservoir (Cheng et al., 2020); and (2) multiple recharge episodes prior to an eruption. Pre-eruptive unrest signals such as repeated earthquake swarms (Tarasewicz et al., 2012) as well as crystals with multiple zoning (Petrone and Mangler, 2021) suggest that many plumbing systems are primed for eruptions by several recharge episodes rather than being triggered by a single intrusion. While not every erupted crystal would record every magma injection (Petrone et al., 2018; Cheng et al., 2020), the combined crystal cargo represents a record of pre-eruptive recharge patterns. Mixing-to-eruption time scales derived from crystal cargoes therefore track the long-term processes priming the plumbing system for eruption. Specifically, the timing, frequency, and duration of magma recharge leading to an eruption, hereinafter collectively referred to as the *priming pattern*, affects the state of the pre-eruptive magma reservoir and may therefore control eruption size and style. We explore this hypothesis by comparing the priming patterns of seven eruptions of different type and size at Popocatépetl volcano, Mexico (Fig. 1A).

POPOCATÉPETL'S DIVERSE CRYSTAL CARGO

Magma recharge and mixing is known to dominate both the magma petrogenesis and eruptive activity of Popocatépetl (Schaaf et al., 2005; Sosa-Ceballos et al., 2014). An andesitic-dacitic magma reservoir at 3–12 km depth (Straub and Martin-Del Pozzo, 2001) hosts a heterogeneous crystal mush comprising evolved plagioclase and pyroxene crystals grown *in situ* as well as several generations of mafic pyroxenes inherited from frequent mafic injections throughout the past centuries to millennia (Mangler et al., 2020). Most of Popocatépetl's eruptions in the past ~23.5 k.y. were fed from this reservoir and include a range of styles (effusive versus explosive) and sizes (volcanic explosivity index, VEI = 1–6; Fig. 1A). Lavas and pumices contain evolved and mafic pyroxene crystals of vast textural diversity, testifying to complex pre-eruptive recharge and mixing dynamics. In particular, pyroxene crystals with multiple compositional zones (Fig. 1C) as well as variably diffused mafic pyroxene cores (Fig. 1B) trace repeated injections prior to each eruption. We target this diverse pyroxene cargo to constrain the time scales of repeat mafic injections.

IRON-MAGNESIUM DIFFUSION IN ZONED ORTHOPYROXENE

Magmatic time scales were calculated by modeling Fe-Mg diffusion in orthopyroxene from three effusive and four explosive eruptions (Fig. 1A; Table 1; Items S1 and S2 in the Supplemental Material[1]). All suitable mafic and evolved, simply and multiply zoned crystals at various stages of diffusive re-equilibration were selected. Compositional transects across zoning boundaries were modeled using the non-isothermal diffusion incremental step model (NIDIS) of Petrone et al. (2016), which facilitates modeling of interior compositional zones. We used the diffusion coefficient, *D*, for Fe-Mg interdiffusion along the *a*-axis of orthopyroxene (D^{a}_{Fe-Mg}) of Dohmen et al. (2016), with temperatures (± one standard deviation) individually calculated for each compositional boundary

[1]Supplemental Material. Items S1 (full time scale datasets), S2 (diffusion model details), and S3 (priming durations for eruptions with published time-scale data). Please visit https://doi.org/10.1130/GEOL.S.17050340 to access the supplemental material, and contact editing@geosociety.org with any questions.

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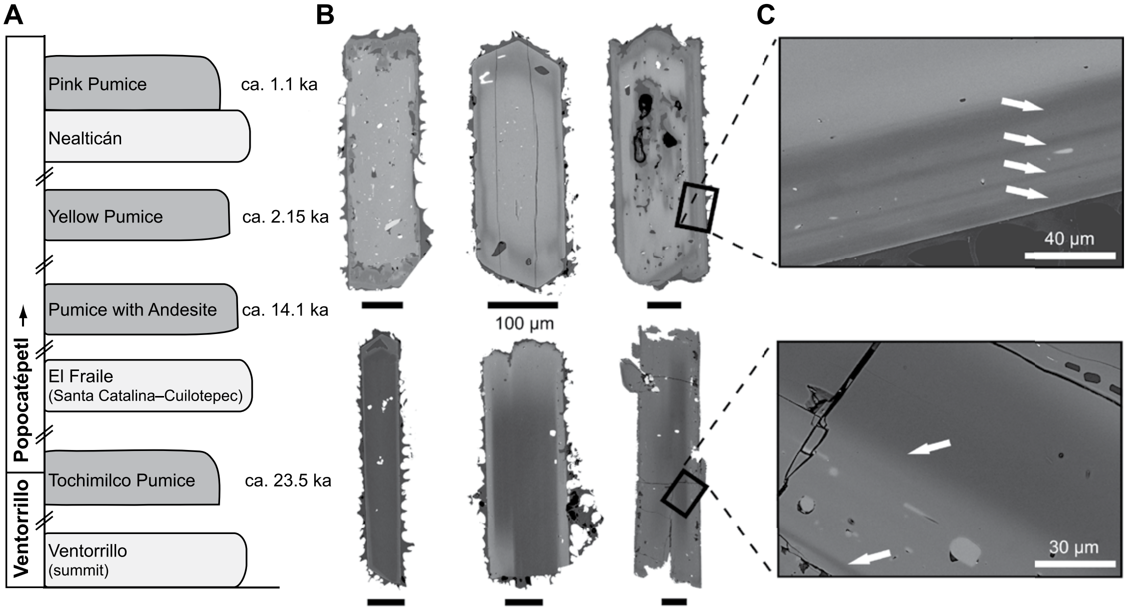

Figure 1. (A) Simplified eruptive history of Popocatépetl volcano (Mexico) in the past ~23.5 k.y. Break marks indicate the presence of other stratigraphic units that were not studied and were omitted for clarity. (B) Examples for textural variability of evolved (upper row) and mafic (lower row) pyroxene crystals. Note the varying degrees of diffusion between compositional zones. (C) Magnified view of crystals with several compositional zones (white arrows) indicative of multiple recharge episodes.

based on pyroxene compositions (Table S1 in the Supplemental Material; cf. Mangler et al., 2020) and oxygen fugacity f_{O2} = NNO + 0.7 (where NNO is Ni-NiO) (Table S2). The NIDIS script propagates uncertainties on temperatures (typically 20–30 °C) and errors on the model fit, resulting in uncertainties on individual time scales of 33%–100%. Between 16 and 37 time scales were modeled for each eruption.

PRE-ERUPTIVE TIME SCALES AT POPOCATÉPETL

Recharge Timing

The timing of recharge activity relative to eruption varies consistently with eruption type and size (Table 1; Table S1). Orthopyroxenes in the VEI 4–5 Pink Pumice and Tochimilco Pumice record magma recharge until days before the eruptions. By contrast, we find no evidence for magma influx <0.5–1 yr prior to eruption for the VEI 6 Pumice with Andesite and Yellow Pumice events, with the exception of a single time scale of 20 ± 8 d for the Yellow Pumice. The shortest time scales for effusive eruptions (Ventorrillo, El Fraile, and Nealticán) are ~1–2 mo.

Priming Duration

Minimum and maximum diffusion time scales (Table 1) indicate magma recharge durations of decades to centuries prior to eruptions of Popocatépetl, with no apparent systematic differences between styles and sizes. However, such overall ranges are dominated by rare, long time scales obfuscating real differences between eruptions: for Popocatépetl, time scales >10–30 yr typically constitute <20% of the data but 75%–95% of the total time-scale range (Fig. 2B). Data density begins to drop at different time scales for different eruptions (Fig. S1.1), implying that the scarcity of long time scales is petrologically significant rather than a mere artifact of sampling bias toward less-diffused crystals. We posit that these sporadic, long time scales reflect lower levels of recharge activity. In contrast, higher time-scale densities represent increased magma influx and mush remobilization, priming the magma reservoir for eruptions. To constrain the *priming duration* of each eruption, the low-data-density tails of the time-scale distributions need to be removed. To do so, we defined the time-scale density d as the slope between two neighboring data points in a cumulative frequency plot (Fig. 2B), which may be expressed normalized as the percent increase in cumulative frequency divided by the percent increase in time between the two data points. A cutoff threshold of $d = 1$ for the distribution tail yields results in agreement with visual assessment of our data (Fig. 2; Fig. S1.1) as well as published time-scale data sets (Table S3). We then defined the maximum priming duration for a given eruption as the total duration of all time scales with $d > 1$ (gray areas in Figs. 2 and 3). Priming durations thus derived for Popocatépetl correlate with eruption magnitude (Table 1; Fig. 3): VEI 6 events show longer priming durations (25–100 yr) than VEI 4–5 eruptions (15–19 yr), and effusive eruptions exhibit the shortest priming durations (9–13 yr).

TABLE 1. PRE-ERUPTIVE RECHARGE PATTERNS OF MAJOR ERUPTIONS OF POPOCATÉPETL VOLCANO (MEXICO) SINCE ca. 23.5 ka

Eruption	Year (ka)	Type	DRE (km^3)*	VEI	$T \pm 1SD$ (°C)†	SiO_2 (wt%)§	Crystallinity (vol%)	n#	Minimum time scale (d)	Maximum time scale(yr)	Priming duration (yr)**	Minimum recharge episodes during priming
Ventorrillo	Unknown	Effusive	<0.5	1	994 ± 26	66	30	25	37 ± 25	140 ± 71	11	3
El Fraile	Unknown	Effusive	1.6	1	989 ± 24	65	25	23	150 ± 91	34 ± 17	13	2
Nealticán	Unknown	Effusive	3.2	1	1004 ± 23	62	45	21	49 ± 29	88 ± 44	9	2
Tochimilco Pumice	23.5	Explosive	1.9	5	995 ± 23	62	10	33	3.7 ± 1.5	86 ± 42	15	5
Pink Pumice	1.1	Explosive	0.5	4	982 ± 30	62	10	37	8.0 ± 3.8	320 ± 160	19	4
Pumice with Andesite	14.1	Explosive	1.8	6	998 ± 24	60	10	16	320 ± 170	500 ± 250	100	4
Yellow Pumice	2.15	Explosive	1.0	6	988 ± 20	62	10	21	20 ± 7.8	90 ± 34	25	4

Note: Eruption dates, dense-rock equivalent (DRE), and volcanic explosivity index (VEI) for explosive eruptions are from Panfil et al. (1999), Siebe and Macías (2006), and Siebe et al. (2017). *T*—temperature; SD—standard deviation.

*Estimated using constraints on bulk volumes and vesicularities from Mangler et al. (2020) for units without published DRE.

†After Mangler et al. (2020).

§From Mangler et al. (2019).

#Number of modeled time scales.

**Total duration of episodes with time-scale density $d > 1$, calculated as (longest time scale + 1SD) – (shortest time scale – 1SD).

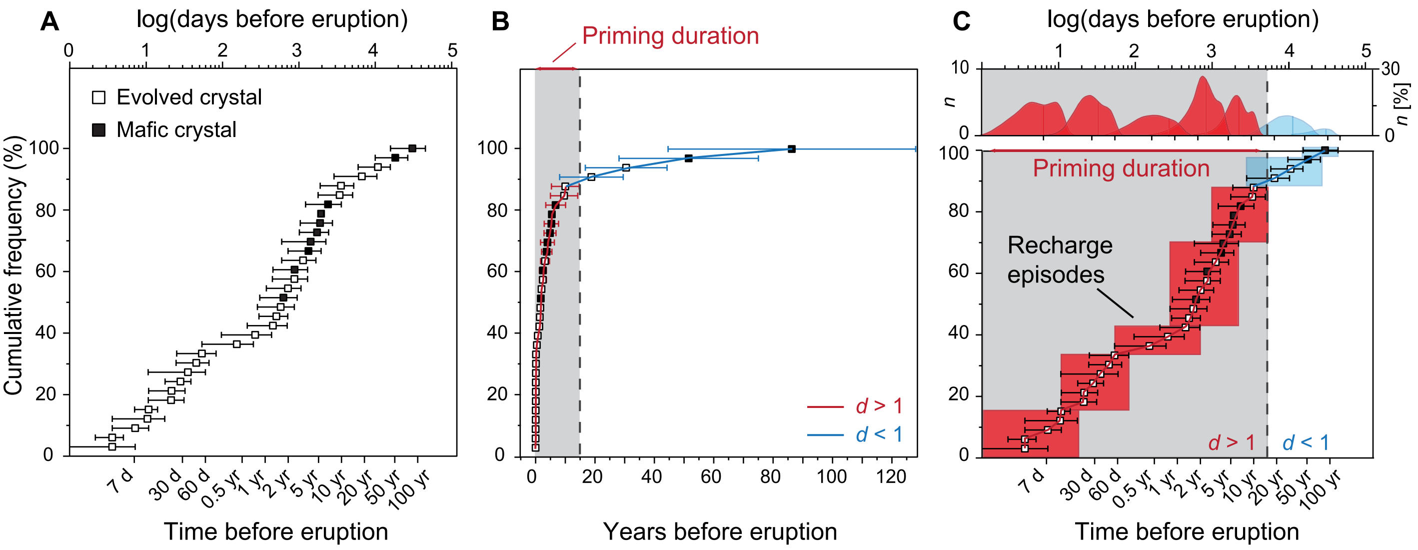

Figure 2. **Pre-eruptive time-scale distributions for Tochimilco Pumice eruption of Popocatépetl volcano, Mexico. (A) Cumulative frequency plotted against logarithmic time. Error bars are one standard deviation (1SD). (B) Same data plotted against linear time to illustrate the derivation of priming duration. Note the detached nature of the four oldest time scales. The slope of the line represents time-scale density *d*; priming duration (gray area) is defined as the total duration of time scales with *d* > 1 (red), calculated as (longest time scale + 1SD) – (shortest time scale – 1SD). (C) Same plot as in A, illustrating data clustering. Boxes outline individual recharge episodes defined by overlapping uncertainties. Upper panel shows kernel density functions for each episode where *n* is the number of time scales per recharge episode, which is converted into percent of total time scales per eruption on the right-hand vertical axis. See text for details.**

Multiple Recharge Episodes

Time-scale distributions for Popocatépetl's eruptions represent multiple recharge episodes and should therefore not be treated as single populations. Individual crystals with as many as four high-Mg zones (Fig. 1) and mafic pyroxene cores with large ranges in diffusion time scales (Table S1) are qualitative indicators for the frequency of mafic recharge, but they are too rare to allow a full reconstruction of the number of pre-eruptive injections. Similarly, uncertainties on time-scale data are too large to fully quantify the number, timing, and duration of individual recharge episodes, but they can be used to constrain the minimum number of injections for each eruption. For instance, a time scale of 20 ± 8 d is unlikely to describe the same recharge episode as one of 90 ± 34 yr, given that the data do not overlap within their uncertainties. Time-scale distributions may thus be subdivided into clusters of time scales with overlapping errors (i.e., individual recharge episodes). Data clustering starting at the shortest time scale (boxes in Fig. 2C and Fig. S1.1) yields a minimum estimate of distinct injections prior to an eruption; any other clustering approach results in an equal or higher number

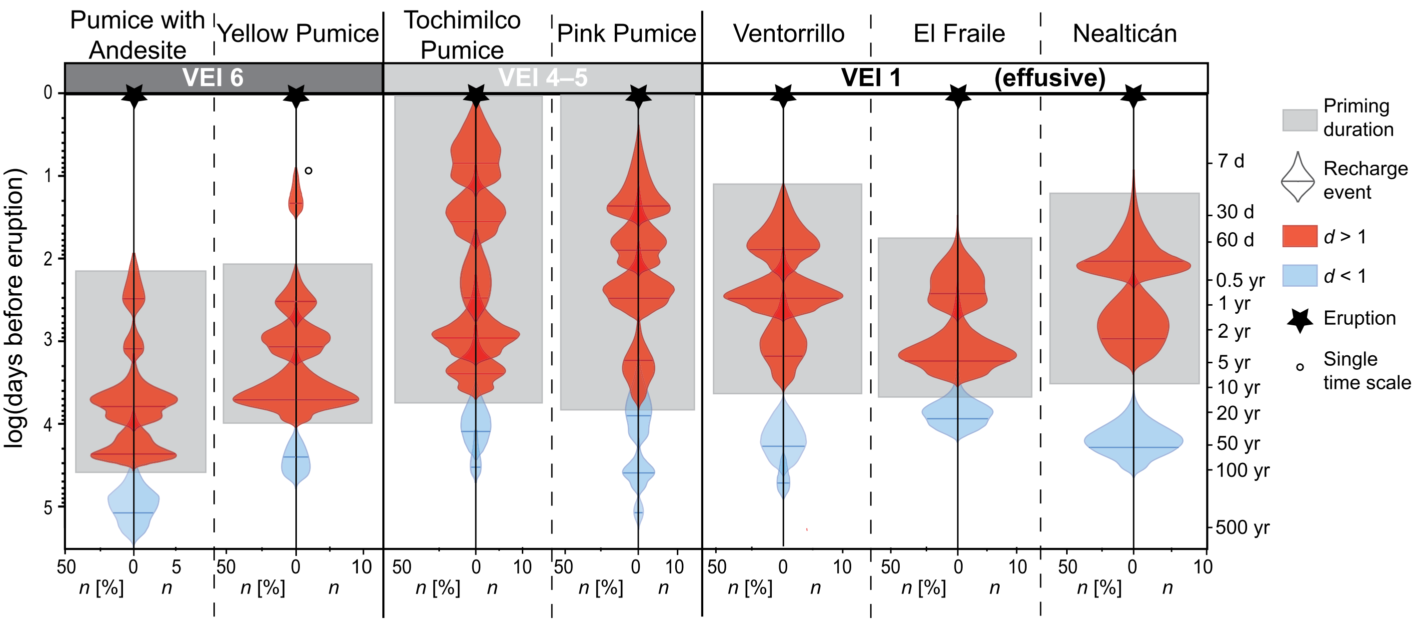

Figure 3. **Magma recharge patterns prior to eruptions of Popocatépetl volcano (Mexico) based on kernel density functions of individual recharge episodes (cf. Fig. 2), colorized to reflect time-scale density *d* and grouped by volcanic explosivity index (VEI). Horizontal axes denote the number of time scales per recharge episode, given as absolute number *n* and percent of total time scales per unit. Horizontal lines denote mean values for each recharge episode.**

of clusters (Fig. S1.2). At Popocatépetl, effusive eruptions are preceded by fewer recharge episodes (three to five) than explosive ones (five to seven; Fig. 3). If we consider only recharge during the priming duration (red in Figs. 2C and 3), the distinction between effusive (two to three injections) and explosive eruptions (four or more injections) is even clearer. While these estimates appear to be reasonable minima in light of the observed textural diversity, the minimum number of episodes derived using this approach depends on the model uncertainties. Larger uncertainties result in a lower minimum number of episodes; however, the pattern of relatively more recharge episodes for explosive than effusive eruptions remains.

PRIMING PATTERNS IMPACT ERUPTION STYLE AND SIZE

Consistent variations in recharge timing, priming duration, and injection frequency with VEI (Fig. 3) imply that priming patterns modulate eruptive style and magnitude at Popocatépetl.

Background Activity

Increased recharge activity priming the plumbing system commenced between 100 yr and 9 yr prior to individual eruptions (Table 1; Fig. 3). However, a small number of crystals record recharge episodes up to hundreds of years prior to each eruption, which clearly precede the priming of the plumbing system ($d < 1$; blue in Figs. 2 and 3). This highlights the long-term prevalence of magma recharge at Popocatépetl and its crucial role in replenishing the crystal mush, sustaining hot storage conditions of ~950 °C, and buffering whole-rock compositions (Mangler et al., 2019, 2020). However, these sporadic, long time scales do not coincide with any known eruptions in Popocatépetl's geological record. This suggests that the associated recharge activity was relatively minor, though individual injections may have produced small eruptions akin to Popocatépetl's present-day activity.

Effusive Eruptions

Effusive eruptions are characterized by the shortest priming durations and lowest number of pre-eruptive recharge episodes. Similar priming durations despite large differences in total erupted volumes (Table 1) suggest significant variations in recharge flux and remobilization rates.

Efficient pre-eruptive magma heating and mobilization in the presence of an exsolved fluid has been suggested to promote effusive eruptions by reducing magma viscosity and thus enhancing outgassing (Ruprecht and Bachmann, 2010; Degruyter et al., 2017). However, similar pre-eruptive temperatures for effusive and explosive eruptions (Table 1) do not imply such dynamics at Popocatépetl. Furthermore, the presence of exsolved volatiles would increase magma compressibility (Huppert and Woods, 2002), which in turn would favor *longer* recharge-mush interactions (Popa et al., 2019). This is at odds with our finding that priming durations are *shortest* for effusive eruptions. Instead, short remobilization time scales imply higher magma crystallinities and thus bulk viscosities (Costa et al., 2009), which have been suggested to favor effusive eruptions by reducing ascent rates and enhancing magma permeability (Parmigiani et al., 2017; Popa et al., 2020). Such a scenario is consistent with higher crystallinities for Popocatépetl lavas than for pumices (Table 1), and minimum mixing-to-eruption time scales for effusive eruptions of weeks to months (compared to days for the VEI 4–5 eruptions) likely trace slow magma ascent from the reservoir to the surface.

Explosive Eruptions

Priming patterns for explosive eruptions of different magnitudes are strikingly different (Fig. 3) and indicate distinct triggering mechanisms. For the VEI 4–5 eruptions, magma recharge remobilized and pressurized the reservoir over a period of ~15–20 yr. Injection and remobilization rates peaked 1–2 yr prior to the events (~52% and 68% of time scales for Tochimilco Pumice and Pink Pumice, respectively), which generated overpressure faster than the relaxation time scale of the crust (Degruyter and Huber, 2014), and eruptions ensued. In contrast, the VEI 6 events were preceded by longer priming durations followed by a near-complete absence of magma influx in the year or so prior to eruption (Fig. 3). At least three recharge episodes in the decades prior to each event did not immediately lead to eruptions, suggesting lower pressurization rates due to smaller recharge volumes, a more thoroughly locked crystal mush (Spera and Bohrson, 2018), or the presence of an exsolved volatile phase (Degruyter et al., 2017). The conspicuous pre-eruptive recharge hiatus rules out a ramping up in pre-eruptive recharge rates as eruption trigger, and instead indicates a critical role for crystallization-driven volatile exsolution. "Second boiling" in magmas with high viscosities may either directly trigger eruptions (Blake, 1984) or push the system to the brink of critical overpressure such that any subsequent melt- or gas-rich (Bachmann and Bergantz, 2006) injection can trigger an eruption without necessarily leaving significant petrological evidence (cf. the single data point weeks prior to the Yellow Pumice eruption in Fig. 3).

Toward Forecasting Eruption Style and Size

Our results offer new insight into deep magmatic controls on eruption style and size at Popocatépetl volcano, and they provide a new perspective on the present-day dome-building activity. Ongoing for 26 yr (Gómez-Vazquez et al., 2016), current activity exceeds the priming durations of past effusive and moderately explosive eruptions and most closely resembles those of the largest explosive eruptions known at Popocatépetl. Roberge et al. (2009) estimated that only ~0.3% of newly arrived magma erupts, suggesting that the current activity is essentially an intrusive event that may be pressurizing the plumbing system. On the other hand, efficient degassing pathways seem to be in place (Campion et al., 2018), and historical records suggest several eruptive episodes of similar type and duration in the past 800 yr (Martin-Del Pozzo et al., 2016). It is therefore plausible that present-day recharge activity corresponds to background activity. Nonetheless, our results call for heightened vigilance once the current eruption ends.

At present, comparison of recent recharge activity with past recharge patterns derived from diffusion chronometry has merely qualitative value. However, as more long-term monitoring data are gathered and advances in diffusion modeling decrease time-scale uncertainties (e.g., Mutch et al., 2021), direct comparison of monitoring-derived recharge histories with diffusion-derived priming patterns may help to assess the potential size and style of future eruptions. More studies of priming patterns for different eruption types at other volcanic systems are needed, including in other tectonic settings and with other magma compositions (e.g., Metcalfe et al., 2021), to test whether the correlation observed at Popocatépetl is of broader significance. If characteristic priming durations for specific eruption types are found elsewhere, they could present a unique opportunity for improving our ability to forecast volcanic eruptions.

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