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# The magmatic and eruptive response of arc volcanoes to deglaciation: Insights from southern Chile

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## ABSTRACT

**In tectonic settings where decompression melting drives magmatism, there is compelling evidence that changes in ice loading or water loading across glacial-interglacial cycles modulate volcanic activity. In contrast, the response of subduction-related volcanoes remains unclear. A high-resolution postglacial eruption record from a large Chilean stratovolcano, Mocho-Choshuenco, provides new insight into the arc magmatic response to ice-load removal. Following deglaciation, we identify three distinct phases of activity characterized by different eruptive fluxes, sizes, and magma compositions. Phase 1 (13–8.2 ka) was dominated by large dacitic and rhyolitic explosive eruptions. During phase 2 (7.3–2.9 ka), eruptive fluxes were lower and dominated by moderate-scale basaltic andesite eruptions. Since 2.4 ka (phase 3), eruptive fluxes have been elevated and of more intermediate magmas. We suggest that this time-varying behavior reflects changes in magma storage time scales, modulated by the changing crustal stress field. During glaciation, magma stalls and differentiates to form large, evolved crustal reservoirs. Following glacial unloading, much of the stored magma erupts (phase 1). Subsequently, less-differentiated magma infiltrates the shallow crust (phase 2). As storage time scales increase, volcanism returns to more evolved compositions (phase 3). Data from other Chilean volcanoes show a similar tripartite pattern of evacuation, relaxation, and recovery, suggesting that this could be a general feature of previously glaciated arc volcanoes.**

## INTRODUCTION

Volcanism exerts a major influence on Earth's atmosphere and surface environments (e.g., Schmidt et al., 2015). Understanding feedbacks between climate and long-term changes in rates or styles of volcanism is important, but unresolved. In regions dominated by decompression melting (e.g., oceanic ridges and some continental volcanic fields) there is mounting evidence that unloading by ice removal or changing sea level influences the amount of mantle melting and magmatic fluxes into the crust (e.g., Jull and McKenzie, 1996; Nowell et al., 2006; Crowley et al., 2015). Arc volcanoes account for 90% of subaerial eruptions (Siebert and Simkin, 2014) and are the predominant source of volcanic gases and tephra to the atmosphere. Huybers and Langmuir (2009) proposed that from 12 to 7 ka, a global pulse of activity of once-glaciated volcanoes contributed to increasing atmospheric $CO_2$, accelerating early Holocene warming and deglaciation. However, empirical data on arc eruption rates through time remain ambiguous, and attempts to identify whether, or how, subduction-related volcanoes respond to ice-unloading remain inconclusive (e.g., McGuire et al., 1997; Singer et al., 2008; Watt et al., 2013).

In arc settings, the crust is typically thick, and mantle melting is dominated by flux melting (e.g., Grove et al., 2012). Consequently, glacial unloading may primarily affect the crustal stress regime and magma movement within the crust, rather than melt generation (e.g., Nakada and Yokose, 1992; Jellinek et al., 2004; Singer et al., 2008; Kutterolf et al., 2013; Watt et al., 2013).

The sparse nature of current data sets makes it difficult to distinguish whether the limited evidence of an arc volcanic response to deglaciation reflects its absence or the incompleteness of the eruption records (Watt et al., 2013). Arc volcanoes present particular challenges when compiling regional eruption archives. Records of effusive eruptions from long-lived systems are difficult to reconstruct and date, and deposits from the explosive eruptions that dominate arc records are prone to erosion and reworking (Fontijn et al., 2014). Many prior studies have focused on changes in explosive eruption frequency, rather than eruptive flux. Eruption frequency records are prone to temporal bias (as preservation potential typically declines with time), and consider different sized eruptions to be equally significant. Detailed characterization of preserved eruptive products is essential to reconstruct a sufficiently complete eruptive history to investigate arc-scale volcanic responses to deglaciation.

Here we investigate the response of arc volcanoes to deglaciation by detailed analysis of one representative volcano, Mocho-Choshuenco (Chile). It is a large, late Quaternary (younger than 350 ka) stratovolcano that was draped by as much as ~1 km of ice until ca. 18 ka (Porter, 1981; Glasser et al., 2008). It has been one of the most active volcanoes in Chile during postglacial time, with at least 34 explosive eruptions of basaltic andesite to rhyolite magma. The 18-k.y.-long postglacial eruption record has been reconstructed through detailed field work and radiocarbon dating (Rawson et al., 2015); there has been no detailed study of the effusive deposits. Analyses of erupted glasses and Fe-Ti oxides provide complementary evidence for temporal changes in magma composition and temperature; pressures were not estimated because geobarometers suitable for amphibole-free magmas have insufficient resolution. These data provide critical information on postglacial eruptive fluxes and crustal magma storage, allowing us to investigate the volcanic response to unloading.

## RESULTS

Analysis of tephra deposits at Mocho-Choshuenco constrains the cumulative erupted magma volume through time (Fig. 1A; Rawson et al., 2015), showing that magmatic output has varied considerably in postglacial time. We identify three phases of activity, with distinct time-averaged eruptive fluxes, eruption sizes, magma compositions, and temperature ranges (Fig. 1): phase 1 (13.0–8.2 ka), phase 2 (7.3–2.9 ka), and phase 3 (2.4 ka to present; age range given by mean eruption ages bounding the phase).

Phase 1 included several large eruptions (magnitude ≥5; erupted volumes >1 km$^3$ dense rock equivalent, DRE) of dacite and rhyolite melt

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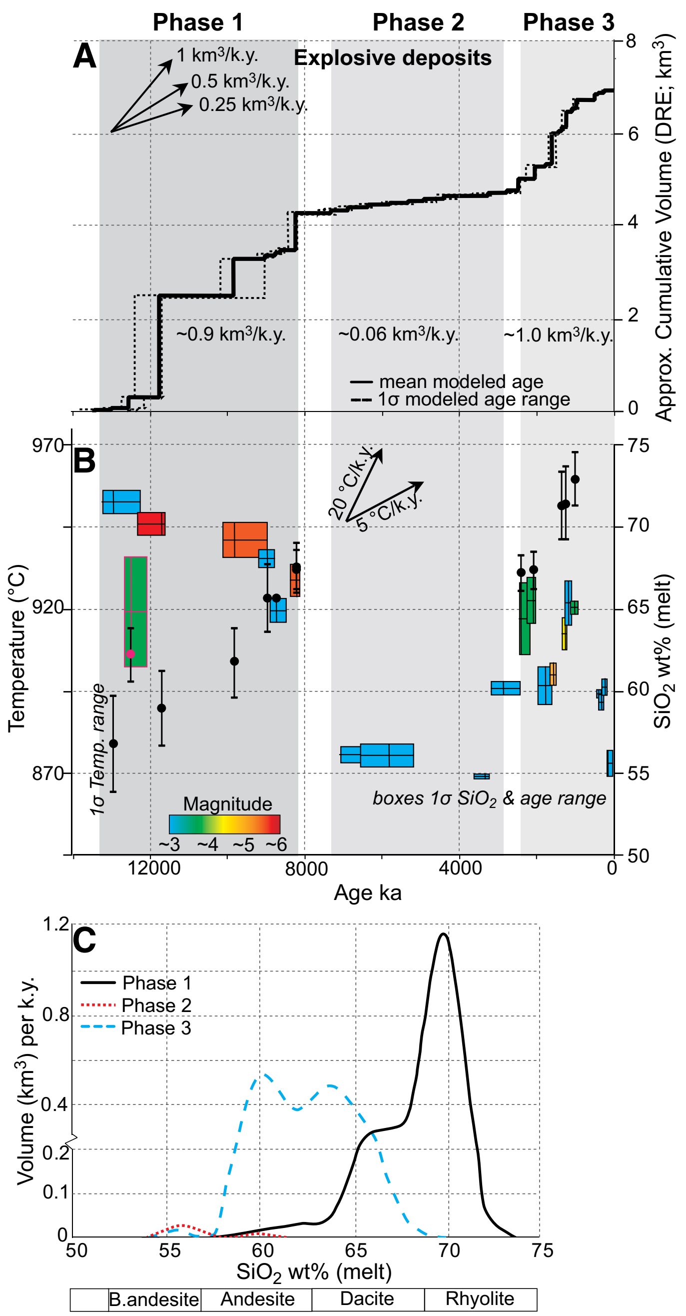


**Figure 1. Observations and analyses of explosive eruptions of Mocho-Choshuenco volcano, Chile. A: Cumulative dense rock equivalent (DRE) volume of tephra through time. The thick line is the mean age; dashed lines show 1σ uncertainty, from the age model. B: Temporal trends in magmatic temperature (from Fe-Ti oxide pairs; black circle with 1σ error bars and plotted against mean age) and mean erupted melt $SiO_2$ content (box shows 1σ range for both $SiO_2$ and age, colored by eruption magnitude). For deposits with both temperature and $SiO_2$ data the circle aligns (by age) with the center of the corresponding cross. The pink symbol corresponds to the one unit formed by mixing rather than fractional crystallization (see the Data Repository [see footnote 1]). Fe-Ti oxide pairs were not stable during phase 2. C: Comparison of the ranges of melt compositions erupted during each phase of postglacial activity, based on glass composition for each phase, normalized by both eruption volume and phase duration. Deposit ages were determined by dating charcoal within paleosols bounding the tephra deposits; these are calibrated and combined with the stratigraphy in a Bayesian age model to calculate the probability distribution for the age of each deposit (Rawson et al., 2015). B.andesite—basaltic andesite.**

composition, and is characterized by an elevated eruptive flux (0.9 km³/k.y. DRE) but low eruption frequency (1.9 eruptions/k.y.) (Fig. 1). During phase 1, magma temperatures increased systematically with time (from ~860 °C to ~930 °C; Fig. 1B). During phase 2, the eruptive flux was lower (0.06 km³/k.y. DRE). The eruption frequency was similar to phase 1 (2.0 eruptions/k.y.) but comprised smaller eruptions (magnitude ~3; volumes ~0.01 km³ DRE) of basaltic andesite melts (Fig. 1). Phase 3 is typified by a higher eruptive flux (1.0 km³/k.y. DRE) and frequency (6.3 eruptions/k.y.). Eruptions spanned a range of sizes (magnitude 3–5) and predominantly intermediate melt compositions (andesite and dacite) with magmatic temperatures ranging from ~930 °C to ~960 °C (Fig. 1).

Figure 1 includes the flux of explosively erupted magma. There are few age data for effusive eruptions at Mocho-Choshuenco, so we use the edifice volume (~160 km³) and $^{40}Ar/^{39}Ar$ dates for the oldest exposed lavas (ca. 350 ka; Moreno and Lara, 2007) to estimate the time-averaged DRE effusive magma flux as ~0.5 km³/k.y. Mantle melts that differentiate on their ascent through the crust beneath arc volcanoes leave plutonic cumulates. We estimate the mass of such cumulates by assuming that the spectrum of erupted melt compositions was generated by fractional crystallization (Rawson et al., 2015), taking the Mg# [= 100 × Mg/(Mg + Fe)] of the primary melts as 50–70 (e.g., Workman and Hart, 2005; Grove et al., 2012) and assuming that potassium behaves perfectly incompatibly, so is a proxy for the extent of crystallization (for further discussion, see the GSA Data Repository[1]). By summing the extrusive and cumulate mass (per k.y.) and assuming a primary magma density of 2830 kg/m³, we estimate the minimum magma supply rate required to sustain the eruptive fluxes (see the Data Repository). Phase 1 has the highest magma supply rate (3–24 km³/k.y.), and the smallest fraction that erupts (5%–50%); phase 2 has the lowest magma supply rate (1–6 km³/k.y.), and the largest erupted proportion (10%–70%); phase 3 has the median magma supply rate (2–17 km³/k.y.), and the median fraction that erupts (5%–65%).

## DISCUSSION

There are considerable variations in the observed eruption fluxes (0.06–1 km³/k.y. DRE; Fig. 1A) and estimated magma supply rates (1–5 km³/k.y.; for primary melt Mg# of 60) between different phases of the Mocho-Choshuenco postglacial eruptive history. These imply changes in the magma flux either into the crust from the mantle, or from the crust to the surface, i.e., time scales of magma storage within the crust. Arc-front magmatism is dominated by flux melting (e.g., Grove et al., 2012), with rates governed primarily by subduction inputs and parameters (e.g., convergence rate and sediment thickness). Changes in these are generally detected in erupted magma composition on time scales of hundreds of thousands of years (e.g., Turner and Hawkesworth, 1997). It is not known how quickly a mantle-melting response to unloading would be reflected in erupted arc magma composition, because melt extraction velocity and transport rate through the crust are poorly constrained (e.g., Zellmer et al., 2005). Given the relatively short time scales (~10 k.y.) considered here, we assume that magma fluxes into the crust are quasi-steady, and consider how the storage time scales within the crust might change.

Magma residence time in the crust depends upon the ratio between the stored volume and erupted flux (Fig. 2). One major control on eruptive flux is the regional crustal stress field, which influences dike formation. This is sensitive to (un)loading of ice sheets (e.g., Jellinek et al., 2004). At the last glacial maximum, the ice sheet around Mocho-Choshuenco extended ~100 km perpendicular to the arc and was ~1 km thick (e.g., Porter, 1981). Considering the lithosphere as an elastic half-space, unloading this ice sheet alone causes a maximum decrease in lithostatic crustal

[1]GSA Data Repository item 2016077, additional details on the methodology for estimating eruptive flux, magma supply rates and stress change, and cumulative volume plots of non-glaciated volcanoes, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

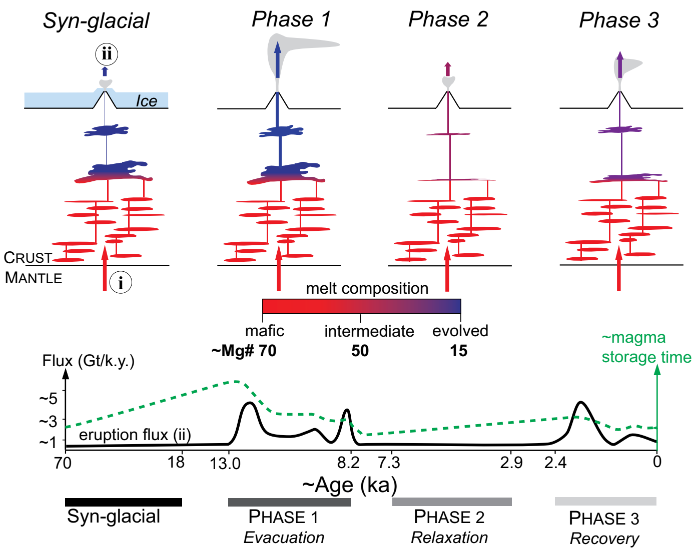


**Figure 2. Illustration of changes to the magmatic system of Mocho-Choshuenco (Chile) from glacial time to the present day. During glacial time, eruption fluxes (ii) are low and magma storage times, τ, are high [τ will depend on the ratio between the stored volume, *V*, and erupted flux, *F* (ii); low *F* leads to large *V*/*F* and large τ]. Magma fluxes into the crust (i), accumulates and evolves. During phase 1, large eruptions rapidly drain the stored evolved magma. During phase 2, the system recharges with mafic magmas; eruption fluxes are low. During phase 3, the system returns to steady-state behavior as the system has relaxed. The lower panel shows eruptive flux, determined by summing the effusive and explosive masses in 0.5 k.y. bins, using the deposit volumes and age probability distributions (see the Data Repository [see footnote 1]). The magma storage time (shown in green; *V* will follow the same general trend) represents the average time magma spent in the crust prior to eruption; this is inferred from the prior eruptive fluxes and erupted melt composition (see the Data Repository). Low prior eruption fluxes (i.e., during the glacial period) and evolved melts imply that magmas erupted in phase 1 had a long magma storage time. The processes governing the change from phase 2 to phase 3 are not clear, but could be related to factors such as the thermal state of the crust (e.g., Bacon and Lanphere, 2006).**

stress of ~6 MPa at ~16 km depth (i.e., in the mid-crust) over the entire period of deglaciation (see the Data Repository). This stress change is the same order of magnitude as that typically involved in dike formation (e.g., Nakada and Yokose, 1992). Thus, unloading during deglaciation might promote dike formation, and hence increased eruptive fluxes and reduced crustal magma storage times (Jellinek et al., 2004). We suggest that large volumes of magma were able to accumulate and differentiate in the crust during the last glaciation. Following deglaciation, dike formation enabled these stored magmas to erupt in phase 1 (Fig. 1). Ice retreat would have been accompanied by an increase in physical erosion rate (e.g., Koppes et al., 2015), contributing further to rates of unloading, while local faults may accommodate part of the stress change (see the Data Repository).

Our hypothesis that variations in magma storage time scales explain the variable postglacial eruption flux at Mocho-Choshuenco is consistent with observed trends in magma chemistry. Erupted melt compositions vary temporally from evolved (phase 1) to mafic (phase 2) and then to intermediate (phase 3; Fig. 1C). Because the compositional diversity of magmas at Mocho-Choshuenco is primarily generated by fractional crystallization (Rawson et al., 2015), melt composition is a proxy for crustal storage time (e.g., Hawkesworth et al., 2004). Therefore, evolved magmas erupted during phase 1 have the longest crustal residence time, and the lowest magmatic temperatures (Fig. 1B). This is consistent with our hypothesis that magmas accumulated, cooled, and differentiated in the crust during the glacial period. Large eruptions during phase 1 drained the crustal storage system, reducing the volume of stored melt. Phase 2 was dominated by mafic melt compositions, reflecting a limited crustal storage time. Then during phase 3, as stored magma volumes increased, so did crustal storage times. Phases 2 and 3 plausibly reflect the evolution of the crustal magmatic system following phase 1; i.e., this later activity maybe an indirect response to deglaciation. These changes in the magmatic system from glacial to recent time can be broadly characterized in terms of three phases, evacuation, relaxation, and recovery (summarized in Fig. 2).

## Evidence From Other Arc Volcanoes

We propose that variations in magma storage time scales related to changes in crustal stresses following ice unloading can explain the pattern of postglacial eruptive fluxes at Mocho-Choshuenco. By analogy, similar trends should be observed at other large previously glaciated arc volcanoes. The magnitude and tempo of variations (e.g., in eruptive flux and magma composition) may differ between volcanic centers, depending on the local stress regime, edifice size, and the nature of the magmatic plumbing system. In the Andean Southern Volcanic Zone (SVZ), only 3 of the ~60 other volcanic centers active in the Holocene, Calbuco, Puyehue-Cordón Caulle, and Villarrica, have sufficiently complete data sets to reconstruct the cumulative volumes of their postglacial eruptions (Fig. 3). Although the eruptive records for these other volcanoes are not as complete as for Mocho-Choshuenco, they appear to exhibit similar temporal changes in eruption rate (Fig. 3). The age of the earliest known eruptions and the timing of later eruptive phases decrease with increasing latitude. This may reflect the differential timing of ice retreat with latitude (e.g., Glasser et al., 2008; Watt et al., 2013), and implies a lag of a few thousand years (~5 k.y. at Mocho-Choshuenco) between deglaciation and the onset of large-scale explosive eruptions. This lag may imply that the crust has an inelastic viscous part (e.g., Jellinek et al., 2004) or that the early postglacial eruption record is incomplete (tephra deposits may not have been preserved until terrestrial soils had become established after ice retreat; e.g., Fontijn et al., 2014). The synchronization of eruptive behavior at these four volcanoes supports our inference that this is a volcanic response to deglaciation; there are no other external forces that could account for this over these spatial (>200 km) and temporal (millennia) scales. There are insufficient data to establish whether Calbuco, Puyehue-Cordón Caulle, and Villarrica also show temporal trends in erupted melt composition. Detailed eruption records exist for some other SVZ volcanoes (e.g., Lonquimay and Llaima; Schindlbeck et al., 2014; Gilbert et al., 2014); both these studies find that eruption frequency varies through time,

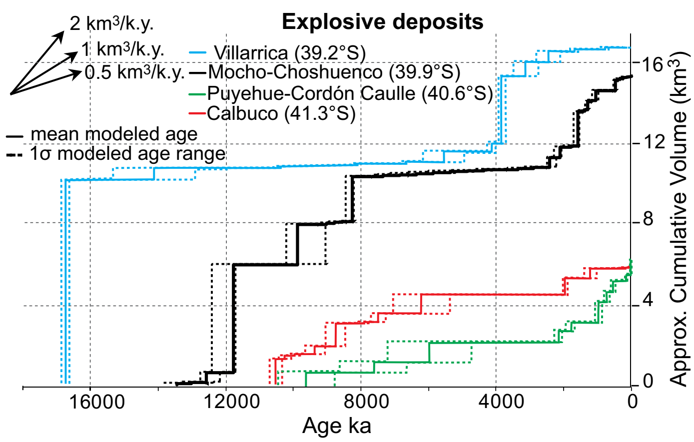


**Figure 3. Cumulative tephra volume (bulk) estimates from Villarrica, Puyehue-Cordón Caulle, and Calbuco compared to Mocho-Choshuenco (Chile). Like Mocho-Choshuenco, these three volcanoes appear to show three phases of postglacial activity. Thick lines are mean ages, and dashed lines show the 1σ uncertainty in age from Bayesian modeling of published radiocarbon dates (Fontijn et al., 2014; see the Data Repository [see footnote 1]).**

and suggest that this is driven by changes in the crustal stress fields and tectonic conditions (neither constrain eruption volumes and so cannot be added to Figure 3). There are hints of similar temporal trends at volcanoes from other formerly glaciated arcs (e.g., Kamchatka; Watt et al., 2013), but the lack of data on eruption chronology, magnitude, and composition hampers comparison (e.g., the Cascades; Hildreth, 2007). Well-studied arc volcanoes that were not extensively glaciated do not display similar temporal trends (see the Data Repository), but further study of other previously glaciated arc volcanoes is needed to test the wider applicability of our hypothesis. Records that preserve evidence for synglacial volcanic activity would offer important new insight. In southern South America, only one such record is known (Potrok Aike lake sediment sequences at 52°S, 70°W; Wastegård et al., 2013), but this contains numerous reworked tephras so the available data are not suitable to test our hypothesis.

## IMPLICATIONS AND CONCLUSIONS

Analysis of high-resolution eruption records from a previously glaciated arc stratovolcano (Mocho-Choshuenco, Chile) suggests a transient volcanic response to deglaciation over millennial time scales. Mocho-Choshuenco and some other southern Andean volcanoes show considerable variations in eruptive flux and in the composition and size of eruptions following deglaciation. These observations are consistent with a mechanism by which unloading affects the magma storage time scales via changes in crustal stress regime, rather than changes in mantle melting rates. Such a response may be a general feature of previously glaciated arc volcanoes. These observations have wider implications for the potential impact of postglacial volcanic activity on the release of tephra and volcanic gas to the atmosphere, and subsequent impact on global climate.

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