Origin and evolution of the Santiaguito lava dome complex, Guatemala

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Thesis submitted for the degree of Doctor of Philosophy

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ABSTRACT

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Subduction zone volcanoes are a major natural hazard, frequently endangering lives and livelihoods. The eruptive history of many subduction zone volcanoes includes the extrusion of blocky, silicic lava that forms domes or flows, but we do not yet understand what determines the duration of dome-forming behaviour, what path magma may take to the surface, or how these systems may change over time.

This thesis presents an investigation of the Santiaguito complex of lava domes and flows in Guatemala, which has been erupting continuously since its inception in 1922. The Santiaguito lavas are predominantly dacitic to andesitic, with a gradual reduction in SiO_2 content from ~66 wt% in the 1920s, to ~62 wt% in 2002. This is consistent with a ~15% decrease in the extent of fractional crystallization over that time. The compositions of plagioclase phenocryst cores indicate a diminished role for magma mixing after the 1940s.

I model the Santiaguito system as progressively extracting magma from an extensive, chemically-stratified storage zone. Petrological data are consistent with a storage zone extending from ~25 to ~12 km depth, and magma storage temperatures of ~940 to ~980°C. Phenocryst-hosted apatites suggest melt in this storage zone contained 401 to 1199 ppm S, 600 to 1300 ppm F, and 4100 to 6200 ppm Cl. Ascending magma may pass slowly through a conduit bottleneck, or plug, at shallow depths; groundmass texture suggests that melt rigidifies at or near the base this plug. Pre-eruptive melt volatile concentrations suggest time-averaged fluxes of 40 to 263 Mg d^{-1} SO_2, 32 to 145 Mg d^{-1} HF, and 247 to 708 Mg d^{-1} HCl, giving ratios of 0.6 to 0.8 HF/SO_2, and 2.7 to 6.2 HCl/SO_2. These results are consistent with the few direct measurements of SO_2 at Santiaguito, and with measured halogen emissions from other silicic dome-forming systems.

EXTENDED ABSTRACT

ORIGIN AND EVOLUTION OF THE SANTIAGUITO LAVA DOME COMPLEX, GUATEMALA

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Subduction zone volcanoes form one of the major hazards in the natural world; their eruptions frequently endanger lives and livelihoods, and can significantly impact on society, the environment, and the economy. The eruptive history of many subduction zone volcanoes includes the extrusion of blocky, silicic lava that forms domes or flows. In some cases, dome-forming activity may last only a few weeks to years; in others, it may persist for decades. What determines the duration, and intensity, of dome-forming behaviour is not yet understood; neither do we understand how explosive and extrusive behaviour can occur simultaneously, what path magma may take to the surface, or how these systems may change over time.

This thesis presents the results of a petrological and geochemical investigation of the Santiaguito complex of lava domes and flows in northwest Guatemala. Santiaguito began erupting in 1922, into the crater formed by the cataclysmic 1902 eruption of its parent stratocone, Santa María; today, after 90 years of continuous activity, it remains one of the most active volcanoes in the world. Despite this unusual longevity and prolific eruptive record, very little scientific research has been carried out at Santiaguito, with no petrological or geochemical studies since the initial survey in the 1960s.

In this thesis I present a detailed geochemical and petrological description of Santiaguito's rocks and examine how they have changed over time, I constrain the pressures and temperatures experienced by magma within the subsurface plumbing system, and estimate how much sulfur, fluorine, and chlorine may have been emitted by Santiaguito throughout its lifetime.

Fifty-five rock samples were obtained from Santiaguito, plus three from the 1902 pumice, and four from the prehistoric Santa María stratocone. Whole rock chemistry was analyzed using x-ray fluorescence (XRF) and inductively coupled plasma mass spectrometry (ICP-MS). Petrological data were obtained from thin sections using an optical microscope, the scanning electron microscope (SEM) and electron microprobe (EMP).

Whole rock analyses show that the earliest dome-forming Santiaguito rocks are geochemically and mineralogically identical to the dacitic 1902 pumice, except for the obvious differences in vesicularity associated with their very different eruptive styles. Erupted lavas have become progressively less evolved, with a decrease in whole rock SiO_2 from ~66 wt% in the 1920s to ~62 wt% by 2002. Such a decrease in SiO_2 over time could be caused by mixing with a progressively greater mafic component. Discrete enclaves of the mafic magma considered partly responsible for triggering the 1902 eruption, are present in early Santiaguito lavas; the bimodal compositional distribution of plagioclase phenocryst core compositions in early Santiaguito lavas also suggests they were strongly influenced by magma mixing. However, lavas erupted since the 1940s show a unimodal distribution of plagioclase phenocryst core compositions, which implies that the influence of magma mixing has decreased over time. Because the diminishing contribution of a mafic end member over time would increase silica content of lava, the observed decrease in whole rock SiO_2 is best explained by a decrease in the extent of fractional crystallization of the erupting lava. Geochemical modelling using whole rock trace element data constrains this decrease to ~15%.

I model the Santiaguito system as progressively extracting magma from an extensive, chemically-stratified storage zone thought to have formed during the ~25 ka of quiescence that preceded the 1902 eruption. All the hybridized dacite left from the 1902 eruption appears to have extruded by the 1940s; as extrusion continued at Santiaguito, drawdown of the stratified storage zone meant that ascending magma became progressively less evolved. This storage zone is thought to extend from at least ~25 km to ~12 km depth (from amphibole thermobarometry); amphibole chemistry suggests that stored magma experiences temperatures of ~940 to ~980°C, f_{O2} of NNO +0.4 to NNO +1.2, and crystal size distribution (CSD) data indicates a growth-dominated regime associated with phenocryst formation. Crystal nucleation overtook growth during microlite formation (from CSD analysis); since microlite crystallization is typically associated with ascent-related decompression at shallower levels, this suggests there is some distinction between slow ascent through Santiaguito's storage zone, and ascent to the surface. The rate of ascent is constrained by amphibole breakdown rims as ~27 to ~84 m hr^{-1}, although complete breakdown of amphibole in some samples suggests these constraints should be treated as maxima.

Ascending magma may slow just before reaching the surface, forming a conduit bottleneck, or plug. Based on matrix glass composition, microlite habit and aspect ratio, and plagioclase microlite abundances, I suggest that ascending melt undergoes rigidification at shallow levels, perhaps between ~200 and ~800 m; this corresponds with the base of the conduit plug. The preservation of vesicles, the lack of alignment of tabular microlites, the lack of correlation between groundmass textural parameters and distance of the sample from the vent, and the symplectic texture of glass decomposition are also consistent with rigidification prior to extrusion. In the uppermost ~200 m of the vent, matrix glass at Santiaguito undergoes progressive decay before extruding onto the surface as blocky lava. I suggest that experimental calibration of this decay process may provide a quantitative proxy for extrusion rate at Santiaguito.

Extruding lava units have been classified as either domes or flows according to their morphology, but no geochemical difference was found between dome and flow samples. This suggests that the morphological differences are caused by changes in the topography onto which lava is emplaced (with steeper topography promoting the formation of flows) and/or differences in the degree of vesicularity (with more vesicular magma fracturing more easily into blocks capable of granular flow).

The final part of the thesis provides constraints on the volatile emissions from Santiaguito. Few field measurements have been published to date, and the scarcity of appropriately-preserved melt inclusions in phenocrysts prevented use of traditional petrological methods to estimate degassing rates. Instead, I use measurements of S, F, and Cl in apatites that are fully enclosed by pyroxene phenocrysts, as they reflect the volatile concentrations in the melt prior to degassing. I use existing models to estimate temperature-sensitive S apatite-melt partition coefficients, and published, experimentally determined apatite-melt partition coefficients for F and Cl.

Prior to degassing, I estimate that Santiaguito melts contained 401 to 1199 ppm S, 600 to 1300 ppm F, and 4100 to 6200 ppm Cl. From the known long-term magma flux at Santiaguito, I estimate time-averaged sulfur emission rates of 40 to 263 Mg d^{-1} SO_2, consistent with the few direct measurements taken at Santiaguito. Estimated long-term average halogen degassing fluxes are 32 to 145 Mg d^{-1} HF (which gives HF/SO_2 of 0.6 to 0.8) and 247 to 708 Mg d^{-1} HCl (which gives HCl/SO_2 of 2.7 to 6.2). These results are similar to measured halogen emissions from other silicic dome-forming systems. The apatite-based petrological method may therefore provide a useful alternative for studying volatile degassing in the absence of viable melt inclusions.

The volcanic hazards associated with Santiaguito should be reassessed based on this new information, and the way Santiaguito is monitored can be tailored for greater efficiency. Further research to improve our understanding of this volcano is strongly encouraged.

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Sample preparation and analysis was made possible by Norman Charnley, Owen Green, Jeremy Hyde, Andrew Mason, John Watson, and Steve Wyatt. Phil Holdship and Seb Watt provided advice and assistance with processing analytical data. I am particularly grateful to Dave Sansom for teaching me to use Illustrator, and for turning my scruffy hand-drawn sketches into a truly spectacular poster.

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APPENDIX A

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Chapter 1: Introduction

Volcanic eruptions frequently endanger lives and livelihoods, and can significantly impact on society, the environment, and the economy. Subduction zone eruptions are particularly dangerous because they are often explosive, with numerous associated hazards including pyroclastic flows, lahars, and ash clouds (e.g. Schmincke, 2004). Notorious examples from recent years include the pyroclastic flows from Mont Pelée, Martinique that killed nearly 30000 people in 1902 (e.g. Tilling, 1985); the 1991 eruption cloud from Pinatubo, Philippines that caused a 0.5°C decrease in global mean surface temperature and substantial ozone depletion (e.g. Parker *et al*., 1996); and the 1980 eruption of Mount St Helens that cost the US economy more than $1 billion (e.g. Tilling *et al*., 1984).

The eruptive history of many subduction zone volcanoes includes the extrusion of blocky, silicic lava that forms domes or flows (e.g. Fink & Anderson, 1999). In some cases, dome-forming activity may only last a few weeks or years; in others, it may persist for decades. What determines the duration, and intensity, of dome-forming behaviour is not yet understood; neither do we understand how explosive and extrusive behaviour can occur simultaneously, what path magma takes to the surface, or how these systems may change over time. Nevertheless, our understanding of dome-forming systems has been greatly advanced by intensive study of a small group of volcanoes including Colima, Mexico (e.g. Luhr & Carmichael, 1980; Luhr, 2002), Mount St Helens, USA (e.g. Cashman, 1992; Rutherford & Hill, 1993), and Soufrière Hills, Montserrat (e.g. Barclay *et al*., 1998; Ryan *et al*., 2010). Studies like these suggest that domes often form in the aftermath of a Plinian eruption, so may represent degassed remnants of magma, and that dome-forming activity is often cyclic, with periods of quiescence (e.g. Luhr, 2002; Clarke *et al*., 2007; Scott *et al*., 2008).

This study focuses on the Santa María-Santiaguito complex in northwest Guatemala. The cataclysmic eruption of Santa María in 1902 was one of the largest of the 20^{th} century; it left a huge crater in one side of the stratocone. The Santiaguito dome and flow complex began extruding into that crater in 1922, and today, after 90 years of continuous activity, it remains one of the most active volcanoes in the world. This unusual longevity and prolific eruptive record makes Santiaguito an ideal place to study dome-forming processes, but very little scientific research has been carried out there, with no petrological or geochemical studies since an initial survey in the 1960s (Rose, 1972). Therefore, the major goal of this thesis was to provide a modern overview the Santiaguito volcanic system, in a format that could be of practical use to those monitoring the volcano, provide the basic information needed for more in-depth scientific study, and show the scientific community that Santa María-Santiaguito is an intriguing volcanic system worthy of their attention. Within this broader goal, the specific aims of the thesis are:

- To provide the first modern geochemical and petrological descriptions of Santiaguito's rocks;
- To place constraints on Santiaguito's magmatic plumbing system that may help other researchers better assess the hazards associated with this volcano and formulate the most effective monitoring strategies;
- To identify any geochemical or petrological changes over time at Santiaguito that may reveal potential influences that cannot be seen in the shorter or punctuated growth histories of most domes;
- To estimate the levels of SO_2, HF, and HCl in the Santiaguito system, so that other researchers might better assess the impact of these gases on the local environment.

With these objectives in mind, a comprehensive geological background and literature review is provided in Chapter 2, showing that pre-1970 Santiaguito lavas were plagioclase-dominated dacites. Lava units were classified as domes or flows based on their morphology; flows have become longer and more dominant over time (Rose, 1972). Chapter 3 details the rock samples used in this study and the methods used to analyze them. Magmatic storage conditions and ascent processes are constrained using various petrological methods in Chapter 4; the results suggest a storage zone extends from at least ~25 km to ~12 km beneath Santiaguito, and that rising magma rigidifies prior to extrusion.

In Chapter 5, the earliest erupted Santiaguito lavas are shown to be chemically and mineralogically identical to the dacite pumice erupted in 1902. Over time, the lavas become progressively less evolved, decreasing from ~66 wt% SiO_2 in 1922, to ~62 wt% by 2002; this is best explained by a decrease in the extent of fractional crystallization, rather than mixing of magmas. The data suggest that Santiaguito magma is sourced from a chemically-stratified lower crustal storage zone, as described in Chapter 4.

Measurements of S, F, and Cl in Santiaguito apatites are used alongside previously published apatite-melt partition coefficients to give pre-eruptive melt concentrations in Chapter 6. When combined with the total volume of magma erupted at Santiaguito, these data suggest that throughout its lifetime, Santiaguito has emitted 40 to 263 Mg d^{-1} SO_2, 32 to 145 Mg d^{-1} HF, and 247 to 708 Mg d^{-1} HCl. These petrological estimates are similar to measured emissions from other silicic dome-forming systems.

Finally, Chapter 7 presents a summary of this thesis, a possible mechanism allowing simultaneous explosive and effusive activity, comments on some of the issues raised in earlier chapters, and suggestions for further work.

To make this research more widely available, this thesis has been re-written in formats suitable for non-scientists; these can be downloaded free of charge from http://vhub.org/resources/2268 (booklet format) and https://vhub.org/resources/2329 (poster format).