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P–T–X evolution of the 1280 AD Quilotoa dacite

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ABSTRACT

The pre-eruptive storage conditions and volatile budgets were constrained for magma erupted with Plinian intensity from Quilotoa volcano in Ecuador in AD 1280. Geothermobarometry, solubility modeling, and petrologic observations were combined to estimate magma temperature, pressure, oxygen fugacity and concentrations of H_2O, CO_2 and S in the melt phase. The moderately oxidized (NNO + 1.63) magma was found to have resided between 4 and 11 km, under associated pressures of ~130–340 MPa and a temperature of 780 ± 20 °C. Variability in estimated storage pressures, melt volatile concentrations (4.8 ± 1.5 to 8.8 ± 2.8 wt.% H_2O and 0 to 447 ± 170 ppm CO_2), Na_2O–MgO–H_2O trends and a decrease in vapor bubble volumes in the glass inclusions suggest that the magma under Quilotoa concomitantly degassed and crystallized in the early stages of magma ascent, with maintained high H_2O suppressing crystallization thereafter. H_2O concentrations may have been partly buffered with volatile input from a deeper reservoir of chemically similar magma prior to the AD 1280 eruption. The Quilotoa deposits are thus thought to represent a homogenous chemically-buffered zone within an even larger-volume intermediate body that periodically erupts geochemically uniform deposits in a volatile-oversaturated system.

1. Introduction

In AD 1280 Quilotoa volcano in Ecuador erupted with Plinian intensity (VEI 6), expelling 18.3 km^3 DRE (Dense Rock Equivalent) volume of crystal-rich dacitic tephra in an event that formed a 2.9 km diameter caldera (Mothes and Hall, 2008). Quilotoa is located at the southern end of the Western Cordillera in Ecuador, one of the two parallel N–S-oriented cordilleras forming part of the Northern Volcanic Zone associated with the young (~20 Ma; Stern, 2004) Colombian–Ecuadorian subduction zone.

Previous work by Mothes and Hall (1998, 2008), Hall and Mothes (2008) and Di Muro et al. (2008) documents the field relations and physical characteristics of the most recent (AD 1280) ignimbrite and the laterally extensive, co-eruptive air-fall tephra blanket. In addition to the AD 1280 event, these workers recognized 8 other previous eruption cycles at Quilotoa, each one approximately 10,000–15,000 years apart. The Quilotoa deposits are all dominated by plagioclase, with subordinate amounts of hornblende, biotite, quartz, Fe–Ti oxides, and apatite (Hall and Mothes, 2008) as well as rare zircons.

As a calc-alkaline dacite from a subduction-related setting, the AD 1280 Quilotoa magma shares mineralogical similarities with other oxidized arc dacites including Mount St Helens 1980 (Rutherford et al., 1985; Rutherford and Devine, 1996), Novarupta 1912 (Hammer et al., 2002; Gonnermann and Houghton, 2012), San Pedro (Costa et al., 2004), Santa Maria 1902 (Singer et al., 2013), Unzen 1991–1995 (Holtz et al., 2005; Nishimura et al., 2005), and in particular Pinatubo 1991 (Pallister et al., 1996; Rutherford and Devine, 1996; Scaillet and Evans, 1999; Prouteau and Scaillet, 2003).

The latest Quilotoa eruption stands apart as having the largest volume of this group (compared to 13 km^3 erupted by Novarupta, and just 0.2–5 km^3 by the other eruptions listed above), and an unusual deposit homogeneity during its eruption history (Hall and Mothes, 2008; Mothes and Hall, 2008). An exception is Pinatubo, which has erupted repeatedly (6–12 events) over 35 ka, producing an explosive phase of mineralogically similar dacite magmas each time, and whose past erupted DRE volumes are estimated to have been at up to 15 km^3 for a single eruption (Newhall et al., 1996). In contrast to Quilotoa however, the 1991 eruption of Pinatubo is thought to have been triggered by the injection and mixing of basalt and dacite and associated fluids (Pallister et al., 1992, 1996, Hattori and Sato, 1996; Borisova et al., 2014), though whether Pinatubo's other eruptions were triggered this way is unknown.

Quilotoa's repetitive history of ignimbrite-producing dacite eruptions is similar not only to that of Pinatubo, but also to the latter half of Cerro Galán's rhyodacite-erupting history, for which Folkes et al. (2011) have proposed the existence of a magmatic zone of geochemical buffering situated between the incoming magma and the stored magma in the upper crust.

Mineralogical homogeneity of deposits occasionally occurs in much larger silicic systems such as the 5000 km^3 DRE Fish Canyon Tuff (a continental magmatic arc volcano). Christiansen (2005) has put forward a model of 'progressive growth at a shallow level with repeated input of

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intermediate to silicic magma' for the process involved in forming these deposits, emphasizing that the high viscosity of these crystal-rich dacite magmas prevents the crystal–liquid separation that occurs in rhyolites. Similarly, Huber et al. (2009) postulate that growth in volume of the dacite magmas by additions of magma batches compositionally similar to that in the upper crustal chamber would augment a primary homogenization mechanism of latent heat buffering, which rapidly equilibrates the magma and drives it towards a higher crystallinity 'mush'. A mechanism of transport would thus require an eruption conveyance of frictional heating by conduit shearing to lubricate and sustain the magma ascent on eruption. Evidence of this has been highlighted in multiple studies (Polacci et al., 2001; Polacci, 2005; Rosi et al., 2004), which identified gray pumice in Quilotoa's deposits (also observed in this study) with the same bulk rock composition as the white pumice.

Although the first steps have been made towards identifying equilibration pressures and temperatures of Quilotoa's pre-eruptive magma based on its phenocryst assemblage, current estimates carry much uncertainty and specific volatile budgets driving Quilotoa's most recent eruption remain to be conclusively determined. (cf., e.g., Rosi et al., 2004; Hall and Mothes, 2008). Our investigation therefore aims to provide further and concise constraints on magmatic intensive variables and volatile contents, in addition to providing a model of magma degassing and ascent that reconciles data on the pre-eruptive storage conditions from volatile solubility modeling and geothermobarometry as well as mineralogical features observed in the phenocrysts.

2. Methods

2.1. Samples and bulk rock composition analysis

Samples in this study were collected from the Plinian fall unit of the AD 1280 deposit at Chugchilán, specifically the mid-to-lower portion of the ~1.4 m thick unit. We selected between 5 and 20 pyroclasts from individual fall layers positioned approximately 6–10 m above the base of the AD 1280 'Q1' deposit, (as per Figure 2 in Mothes and Hall, 2008). The Chugchilán collection site is marked on Fig. 1. The outcrop at Chugchilán is shown in Fig. 2.

The bulk rock major- and trace-element composition of the Quilotoa pumice was measured by X-ray Fluorescence (XRF). For each sample, 4 pumice pyroclasts were separately milled in a 200 rpm Fritsch Pulverisette 5 Planetary Mill. A homogenizing flux was added to half of the resultant powders, those of which were made into glass pellets for bulk rock analysis by re-melting at 1000 °C in a Cimrex 10 Vulcan Fusion Machine followed by rapid quenching in ambient air. XRF on the pellets was run in a Phillips MagiX PRO with PW 2540 VRC sample changer, at 3.2 kW excitation power, 18–48 s runtime, and element detection limit of 1 μg/g. The bulk rock compositions are given in Table 2. All analytical facilities, including the XRF equipment are located in the Institute for Geosciences at the Johannes Gutenberg University (Mainz, Germany).

2.2. Phenocryst rim and matrix glass compositions

Plagioclase and hornblende phenocrysts in contact with glass matrix were selected from lightly crushed pumice and prepared for Electron Micro-Probe Analysis (EMPA). Mineral grains were set in epoxy mounts, or analyzed within thin sections that were polished and carbon-coated. The major element compositions of the phenocryst cores and rims were determined by Wavelength-Dispersive Spectroscopy (WDS) with a JEOL JXA-8900RL WD/ED combined microanalyser Superprobe. Measurement conditions are as follows: 15 kV power, 12 nA beam current, 12 μm beam diameter, and 20 peak counts per element. Standards used were wollastonite (Si and Ca), albite (Na), orthoclase (K), corundum (Al_2O_3), MgO, $MnTiO_3$, Cr_2O_3, and Fe_2O_3. Matrix glass (15 spots in

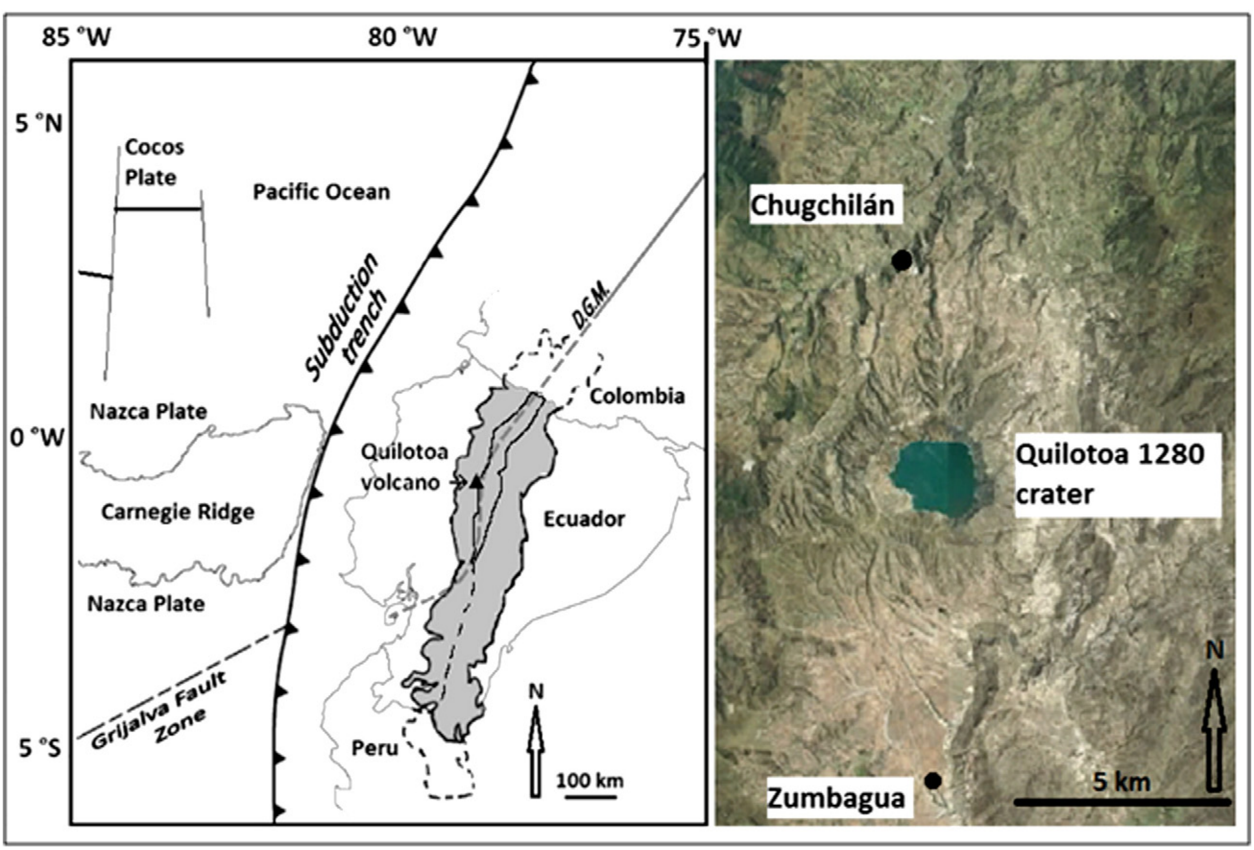

Fig. 1. Left: simplified geological map of Ecuador with location of Quilotoa, after Hall et al. (2008). Right: Satellite view of Quilotoa from Google Earth, the Chugchilán collection site is marked.