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Crystallization conditions and petrogenesis of the lava dome from the ~900 years BP eruption of Cerro Machín Volcano, Colombia

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ABSTRACT

The last known eruption at Cerro Machín Volcano (CMV) in the Central Cordillera of Colombia occurred ~900 years BP and ended with the formation of a dacitic lava dome. The dome rocks contain both normally and reversely zoned plagioclase (An_{24-54}), unzoned and reversely zoned amphiboles of dominantly tschermakite and pargasite/magnesio-hastingsite composition and olivine xenocrysts ($Fo = 85-88$) with amphibole/clinopyroxene overgrowth, all suggesting interaction with mafic magma at depth. Plagioclase additionally exhibits complex oscillatory zoning patterns reflecting repeated replenishment, fractionation and changes in intrinsic conditions in the magma reservoir. Unzoned amphiboles and cores of the reversely zoned amphiboles give identical crystallization conditions of 910 ± 30 °C and 360 ± 70 MPa, corresponding to a depth of about 13 ± 2 km, at moderately oxidized conditions ($f_{O_2} = +0.5 \pm 0.2$ ΔNNO). The water content in the melt, calculated based on amphibole chemistry, is 7.1 ± 0.4 wt.%. Rims of the reversely zoned amphiboles are relatively enriched in MgO and yield higher crystallization temperatures ($T = 970 \pm 25$ °C), slightly lower melt H_2O contents (6.1 ± 0.7 wt.%) and overlapping pressures (410 ± 100 MPa). We suggest that these rims crystallized following an influx of mafic melt into a resident magma reservoir at mid-crustal depths, further supported by the occurrence of xenocrystic olivine. Crystallization of biotite, albite-rich plagioclase and quartz occurred at comparatively low temperatures (probably <800 °C) during early stages of ascent or storage at shallower levels. Based on amphibole mineral chemistry, the felsic resident melt had a rhyolitic composition (71 ± 2 wt.% SiO_2), whereas the hybrid magma, from which the amphibole rims crystallized, was dacitic (64 ± 3 wt.% SiO_2). The bulk rock chemistry of the CMV lava dome dacites is homogenous. They have elevated $(La/Nb)_N$ ratios of 3.8–4.5, typical for convergent margin magmas, and display several geochemical characteristics of adakites. Both Sr and Nd isotope compositions ($^{87}Sr/^{86}Sr$ ~0.70497, $^{143}Nd/^{144}Nd$ ~0.51267) are among the most radiogenic observed for the Northern Volcanic Zone of the Andes. They are distinct from oceanic crust that has been subducted in the region, pointing to a continental crustal control on the isotope composition and hence the adakitic signature, possibly in a crustal "hot zone".

1. Introduction

Cerro Machín Volcano (CMV), a composite volcano located in the Colombian Central Cordillera (Fig. 1A), is considered to be one of the most dangerous active volcanoes in Colombia due to its proven ability to produce large explosive eruptions and its location in a strategic region for the country (Cortés, 2001; Murcia et al., 2008, 2010). In the last 5000 years, CMV has produced at least six major dacitic eruptions, four plinian – sub-plinian and two vulcanian, with volcanic activity generating pyroclastic flows, pyroclastic surges, pyroclastic falls and lahars (Cortés, 2001; Rueda, 2005; Murcia et al., 2008, 2010). Eruptions were dated at ~5000, ~4600, ~3600, ~2600, ~1200 and ~900 years BP based on averages of several individual ^{14}C radiometric ages (Méndez et al.,

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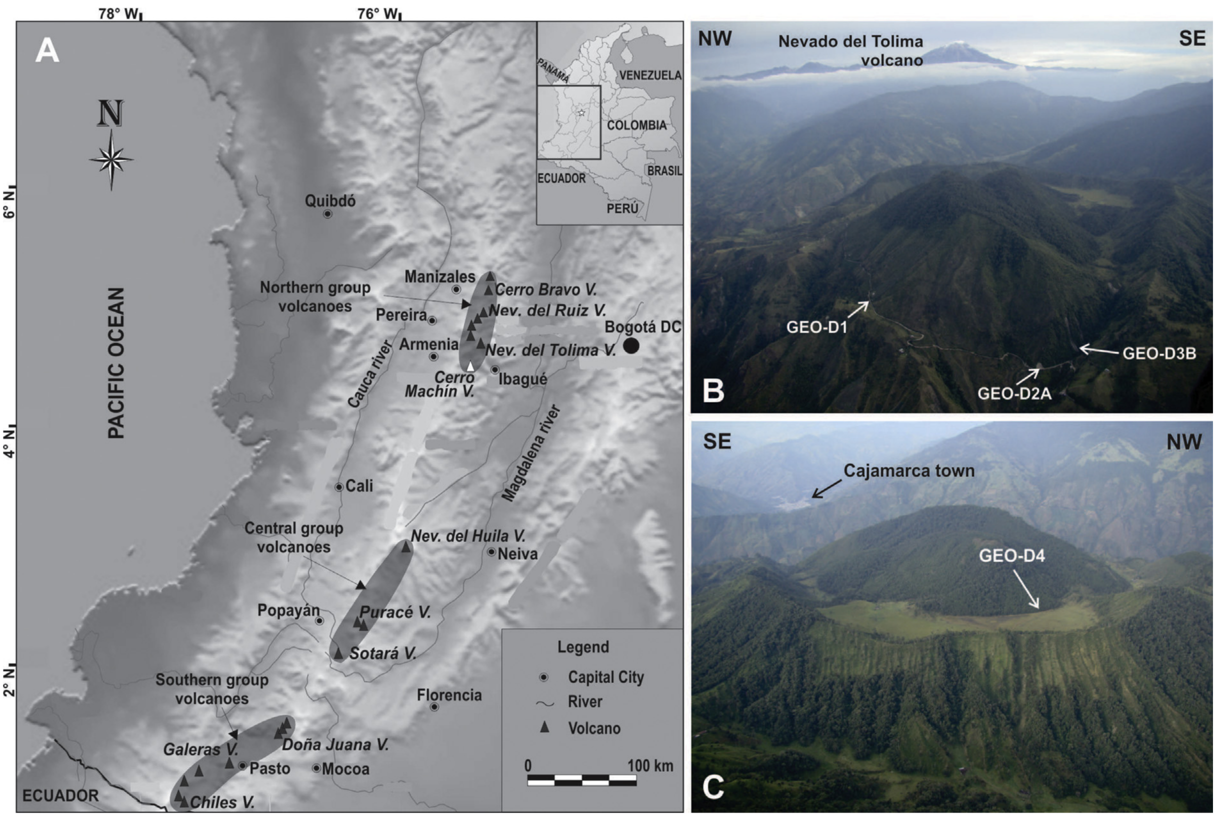

Fig. 1. Map and photographs of Cerro Machín Volcano. A) Map of the western part of Colombia with three groups of active volcanoes. CMV is situated at the southern end of the northern group, about 20 km west of Ibagué. B) Crater and lava dome of CMV in viewing direction NE with sample locations GEO-D1, -D2A and -D3B. Nevado del Tolima Volcano is seen in the distance. C) View onto CMV towards the SW with sample location GEO-D4 and Cajamarca in ∼6 km distance.

2002; Rueda, 2005). The last eruption of CMV, ∼900 years BP, produced pyroclastic flows associated with a vulcanian eruption that terminated with the emplacement of an intra-crater dacitic dome (Thouret et al., 1995; Rueda, 2005; Murcia et al., 2010). Five of the major eruptions have generated lahars, the biggest of which reached distances of more than 100 km from the volcano edifice (Cepeda et al., 1995, 1999; Cortés, 2001; Cortés et al., 2006; Murcia et al., 2008). Today, similar eruptions would affect nearly 1 million inhabitants (Méndez et al., 2002; Murcia et al., 2008) in an area of ∼2000 km^2, including the town of Ibagué in the West, where pyroclastic deposits of previous eruptions have been found. From 2000 to 2010, seismic activity has increased at CMV, reaching up to 9000 volcano-tectonic (VT) earthquakes per year in 2010 (Londoño, 2011). 6500 and about 2000 VT earthquakes were recorded in 2011 and 2012, respectively. Two VT earthquakes on the 7th of October 2012 reached magnitudes of 4.7 and 4.1 (Londoño, 2011). Hypocenter locations clearly show three main seismic zones; one located beneath the central dome at 3–5 km depth; the second one, located to the SE of the central dome (5 km away) at 5–8 km depth; and the last, located 8–10 km to the SE of the central dome at 12–18 km depth (Londoño, 2011). It seems that these seismic sources can represent a fault/dyke system related to the main path of magma ascent at CMV (Londoño, 2011). At the time of writing (February 2013), swarms of volcano-tectonic events continue to occur under the volcano. Moreover, ground deformation, changes in composition and temperature of hot springs and fumarolic activity with radon outputs were observed, suggesting that the volcano has been gradually increasing its activity (Londoño et al., 2007), and this constitutes a potentially increasing threat to the local population (Murcia et al., 2008). A better understanding of the CMV magmatic system is therefore particularly urgent, given the recent observation that ascent of hydrous felsic magmas can occur rapidly and lead to unexpected explosive eruptions (e.g., Castro and Dingwell, 2009).

For an assessment of volcanic hazards in the case of future eruptions, it is essential to understand past volcanic eruptions and the dynamics of a given magmatic system (Sparks, 2003). Critical information about volcanic eruptions includes knowledge about magma storage conditions, manner and rate of magma ascent, volatile concentrations and eruption trigger processes (e.g., Bachmann et al., 2002; Browne and Gardner, 2006; Pallister et al., 1992; Rutherford and Devine, 2003; Prouteau and Scaillet, 2003; Savov et al., 2008). Geothermobarometers can be used to determine P–T-conditions during magma storage and ascent, and they provide information about water contents and oxygen fugacities of the erupted magmas (Putirka, 2008). Amphibole is a particularly important phenocryst phase in many convergent margin magmas and its composition can provide information about magma storage and ascent (Thornber et al., 2008; Browne and Gardner, 2006; Bachmann and Dungan, 2002; Sato et al., 1999; Savov et al., 2008). Combined with seismic observations, petrologic constraints on the magmatic system of a volcano are a powerful tool to understand magma dynamics and eruption triggering processes in more detail. Magma mixing, where fresh magma batches interact with residual magma and cause an increase in heat flux and volatile contents, is of particular importance for explosive eruptions (Sparks et al., 1977; Eichelberger, 1980, 1995). Magma mixing appears to be a ubiquitous process in many ancient and recent eruptions (e.g., Bachmann et al., 2002; Browne et al., 2006; Di Muro et al., 2008; Gourgaud and Thouret, 1990; Swanson et al., 1994),