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Impact of tephra falls on Andean communities: The influences of eruption size and weather conditions during the 1999–2001 activity of Tungurahua volcano, Ecuador

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ABSTRACT

Repeated ash fall events have occurred during the 1999-ongoing eruption of Tungurahua volcano, Ecuador, notably during the late 1999 and August 2001 eruptive phases. While the eruptive styles were similar, these two phases had different impacts on nearby rural and urban Andean populations: ash falls in late 1999 had limited effects on human health and farming, whereas the 2001 phase resulted in medical problems, death of animals in livestock, and damages to houses and crops. Here we investigate the origin of this difference by estimating the size of the August 2001 event (VEI, magnitude, intensity), and by comparing monitoring information of the 1999 and 2001 phases (duration, explosion rate, column height, SO_2 output rate). The results show that both phases ranked at VEI 3, although the longer 1999 phase was likely larger than the 2001 phase. Mass magnitude (M) and intensity (I) indexes calculated for the 2001 phase reach $M \approx 2.7$ and $I \approx 6.5$ when based on ash fall layer data, but increase to $M \approx 3.2$ and $I \approx 7.0$ when ballistic products are included. We investigated the influence of rain fall and wind flow regimes on ash dispersion, sedimentation and remobilization. The analysis indicates that the harmful effect of the 2001 phase resulted from unfavorable conditions that combined volcanological and seasonal origins, including: a) a low elevation of the ash plume above rural regions owed to a usually bent-over column, b) ash sedimentation in a narrow area west of the volcano under sub-steady wind directions, c) anticipated ash settling by frequent rain flushing of low intensity, and d) formation of a wet cohesive ash coating on buildings and harvests. Conversely, the stronger 1999 phase injected a large amount of ash at higher elevation in the dry season; the ash was widely disseminated across the whole Ecuadorian territory and beyond, and was frequently removed by rain and winds. In summary, our study illustrates the influences of eruption size and weather conditions on the impact of volcanic activity in a tropical setting and puts emphasis on the necessity to merge volcanological and meteorological monitoring duties for hazard assessment and alert level definition, in order to mitigate the effect of ash falls in the Andes and elsewhere.

1. Introduction

Most explosive andesitic eruptions produce substantial amounts of ash which may impact air traffic, as illustrated by recent eruptions in Iceland and Chile. It may also have significant effect on health, infrastructure and economy at local to multi-provincial scales. Understanding the wide range of hazards associated to transport and deposition of volcanic ash is thus an important issue that has received increasing attention from the international scientific community in the past two decades (e.g. Cronin et al., 1998; Connor et al., 2001; Casadevall, 2003; Horwell and Baxter, 2006; Stewart et al., 2006; Beddington et al., 2008; Prata, 2009).

Volcanic cloud dispersal and ash fall events have repeatedly taken place near Tungurahua volcano, Ecuador, during the long-lived 1999-ongoing eruptive episode. The eruption has consisted of successive eruptive phases of uneven size and intensity, alternating with periods of relative to complete quietness. As these phases had different impact on nearby Andean communities, we newly introduce here a distinction between *Large* (L), *Moderate* (M) and *Small* (S) *type* phases as useful proxies to describe the size of the events in the context of the 1999-ongoing episode. The most violent *L-type* phases occurred in July and August 2006, February 2008, and May and December 2010, lasted several hours or days, and comprised pyroclastic flow-forming activity and tall eruptive columns (5–13 km above the crater,

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itself located 5 km above sea level, asl) accompanied by scoria and ash falls. The activity was dominated by violent Strombolian to Vulcanian eruptive styles and scoria flow emplacement. These events implied hurried evacuations and resulted in 2006 in six fatalities and severe damages to buildings and farming (BGVN, 1999–2010; Kelfoun et al., 2009; Samaniego et al., 2011). The *M-type* phases typically lasted several days to weeks (e.g. in late 1999, August 2001, October 2003, June 2004 etc.), and consisted of intense degassing with Strombolian to violent Strombolian explosions, lava jets and fountains, and sustained ash emissions, with eruptive columns rising 2–8 km above the crater, but without generation of any pyroclastic flows. However, some *M-type* events had severe impact on economic activities, notably on agriculture and tourism, and occasionally required rerouting of air traffic in central Ecuador. Many other small *S-type* phases had limited or no impact on human activities, when explosions and ash emissions (column height lower than 2.5–3 km above the vent) were too small to affect the populated and cultivated areas.

While the societal outcomes of the 1999–2001 activity has received ample attention (e.g. Lane et al., 2003; Tobin and Whiteford, 2002, 2004; BGVN, 1999–2010; 1999, 2000 and 2001 issues), the volcanology of these distinct eruptive phases has remained poorly known. The size of some *L-type* phases has been estimated and discussed in the literature (e.g. Eychenne et al., 2012), but the characteristics of *M-* and *S-type* events are still insufficiently documented. However, establishing the eruptive conditions by determining the magnitude, intensity and style of these events, and examining the influence of non-volcanic factors such as weather conditions are important issues to address for understanding the cause of ash impact on rural and urban communities in the Andes in the context of hazard assessment, volcano monitoring, and alert level definition. Here we present the results of such investigation by determining the magnitude and the intensity of the August 2001 phase from ground-based information, and by comparing monitoring data of the 2001 phase with those obtained during the 1999 phase. In addition, we appraise the influence of rain fall and wind flow regimes to gain insights into the cause of the particularly severe impact of the August 2001 eruption.

2. Tungurahua volcano and the 1999–2001 eruptive phases

Tungurahua volcano is located in the southern area of the eastern volcanic row of Ecuador (Hall et al., 2008; Fig. 1). The steep-sided, cone-shaped edifice rises 3 km above the metamorphic basement of the Eastern cordillera, which defines north–south topographic ridges peaking at elevations of ~3.5 km asl. The volcano experienced a major

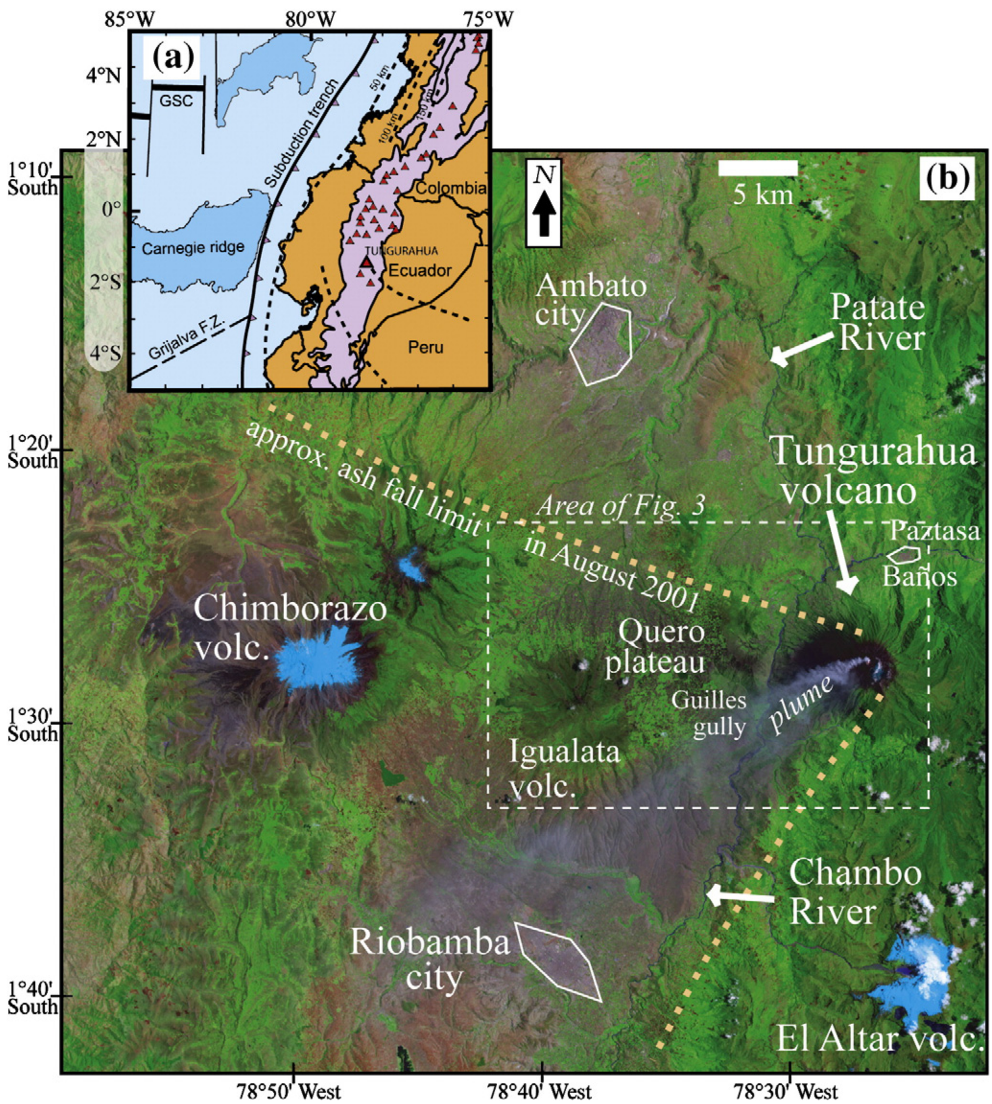

Fig. 1. (a) Location map of Tungurahua volcano in the Ecuadorian volcanic arc. Triangles are quaternary volcanic centers, dashed lines indicate the depth of the Benioff plan, GSC is the Galapagos Spreading center, and G.F.Z. is the Grijalva Fault Zone. (b) Landsat 7's Enhanced Thematic Mapper Plus (ETM+) sensor image of the Tungurahua area during the 2001 eruption. Place names cited in the text are indicated. The dashed box is the study area shown in Fig. 3.