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Lahar hazard assessment in the southern drainage system of Cotopaxi volcano, Ecuador: Results from multiscale lahar simulations

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ABSTRACT

The ice-capped Cotopaxi volcano is known worldwide for the large-scale, catastrophic lahars that have occurred in connection with historical explosive eruptions. The most recent large-scale lahar event occurred in 1877 when scoria flows partially melted ice and snow of the summit glacier, generating debris flows that severely impacted all the river valleys originating from the volcano. The 1877 lahars have been considered in the recent years as a maximum expected event to define the hazard associated to lahar generation at Cotopaxi. Conversely, recent field-based studies have shown that such debris flows have occurred several times during the last 800 years of activity at Cotopaxi, and that the scale of lahars has been variable, including events much larger than that of 1877. Despite a rapid retreat of the summit ice cap over the past century, in fact, there are no data clearly suggesting that future events will be smaller than those observed in the deposits of the last 800 years of activity. In addition, geological field data prove that the lahar triggering mechanism also has to be considered as a key input parameter and, under appropriate eruptive mechanisms, a hazard scenario of a lahar with a volume 3-times larger than the 1877 event is likely. In order to analyze the impact scenarios in the southern drainage system of the volcano, simulations of inundation areas were performed with a semi-empirical model (LAHARZ), using input parameters including variable water volume. Results indicate that a lahar 3-times larger than the 1877 event would invade much wider areas than those flooded by the 1877 lahars along the southern valley system, eventually impacting highly-urbanized areas such as the city of Latacunga.

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1. Introduction

Lahars, or volcanic debris flows, consist of high-concentration, sediment-loaded flows that occur on volcanic terrains. They may be a primary phenomenon directly triggered by eruptive activity (e.g. the 1985 Nevado del Ruiz event in Colombia; Pierson et al., 1990) or they may result from the post-eruptive mobilization (secondary lahars) of volcanic debris (e.g. the 1991 eruption of Mt. Pinatubo, Philippines; Rodolfo et al., 1996). Lahar generation requires a combination of three main factors including: (i) a triggering mechanism that rapidly makes available an adequate water source; (ii) the availability of abundant, unconsolidated debris; and (iii) steep slopes (Vallance, 2000). Due to water incorporation and volume increase, lahars can easily overflow lateral banks and spread over areas of low gradient. This can produce catastrophic consequences for the communities living along the areas, which can be inundated unexpectedly by lahars — as recently shown by the Pinatubo, Mayon and Nevado del Ruiz events (Pierson et al., 1990; Voight, 1990; Rodolfo, 1995; Newhall and Punongbayan, 1996; Tanguy et al., 1998).

According to Varnes (1978), we include here with the term 'lahars' not only debris flows but also hyperconcentrated mudflows (Smith and Lowe, 1991). Although the term has sometimes been used to refer to the deposits of such flows, Smith and Fritz (1989, p. 375) dismiss this meaning stating that "lahar is an event that can refer to one or more discrete processes, but does not refer to a deposit". Small debris flows occur daily on the flanks of many active and inactive volcanoes; although traditionally the term 'lahar' has generally been restricted to those events which can generate a hazard to populations (Scott, 1988), nowadays lahar is fairly broadly used regardless if the event poses hazard to population or not (Manville et al., 2009). In the following, we will use lahar to refer to the process, and as a synonym of debris flow.

Lahars can be generated at crater lakes, following crater failures (Bornas et al., 2003; Manville and Cronin, 2007; Manville, 2010; Massey et al., 2010), or explosive expulsion of water (Zen and Hadikusumo, 1965; Nairn et al., 1979; Suryo and Clarke, 1985; Thouret et al., 1998; Németh et al., 2006; Kilgour et al., 2010) or by heavy rainfall on freshly deposited tephra or loose material on volcano slopes, as in the case of the 1991 eruption of Mt. Pinatubo (Rodolfo, 1989; Pierson et al., 1992; Arboleda and Martinez, 1996; Rodolfo et al., 1996). Lahars are also

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generated by the rapid melting of snow or ice on ice clad volcanoes, due to the interaction of eruptive products with the ice cap (Major and Newhall, 1989). As demonstrated by the 1985 Nevado del Ruiz event in Colombia, even small volcanic eruptions can trigger catastrophic lahar events when pyroclastic material interacts with a summit glacier (Pierson et al., 1990; Voight, 1990; Tanguy et al., 1998), especially if combined with seismic shaking and intense scouring of the ice (with consequent channeling of the lahar).

During the past 30 years, lahar-related disasters have been documented worldwide in the volcanological literature (Voight, 1990; Hall, 1992; Rodolfo, 1995; Newhall and Punongbayan, 1996; Tanguy et al., 1998; Wood and Soulard, 2009). In the last century, about 30,000 casualties were reported in relation to the occurrence of lahar events (Witham, 2005); about 80% of this terrific quota is related to a single event (the devastation of the village of Armero, following the 1985 eruption of Nevado del Ruiz). Continuous growth of buildings and settled areas in lahar flow paths demonstrates that better risk perception, land-use planning and rapid evacuation plans may combine in reducing damage and loss of life from future lahars (Wood and Soulard, 2009).

Cotopaxi volcano is well known for the potential destructiveness of its lahars, and models of lahar invasion have been recently applied to the northern and southern drainages (Barberi et al., 1992; Aguilera et al., 2004). Inundation areas for future lahars have also been partially explored by several authors (Miller et al., 1978; Hall and von Hillebrandt, 1988a, 1988b; Mothes et al., 2004; Mothes, 2006) who presented maps of lahar inundation areas related to the last (1877) eruptive event and for future lahar-generating events of similar size. Modeling procedures were not presented in detail in these papers so that a more in-depth discussion on the potential of lahar inundation at Cotopaxi and the mapping of the related hazard are elements of considerable importance.

In this work, we concentrate on lahar hazard assessment in the Río Cutuchi system, which conveys all the main drainages of west and south of the Cotopaxi cone (Fig. 1). The Cutuchi valley hosts several human settlements, most of which lie on recent lahar deposit terraces, only a few meters above the present river bed. Further south, the Río Cutuchi crosses the large urban settlement of Latacunga (43 km SE of the volcano, Fig. 1), with a population of 52,000 inhabitants. Its path is generally parallel to the Pan American Highway, the major state road connecting the country from north to south. Many small-scale lahars have followed this drainage in the past (<100 million m^3), as well as some large-scale historical flows that severely impacted the population.

We present lahar simulations with different starting volumes performed with a GIS-based semi-empirical model (LAHARZ; Iverson et al., 1998) in order to evaluate the inundating potential of Cotopaxi lahars and to assess the inundation hazard in the southern part of the volcano towards the city of Latacunga. The manuscript is arranged with a section (Section 2) in which we briefly describe the geological data relevant to this study (recent Cotopaxi activity, lahar deposits, lahar triggering mechanisms, and the factors which control lahar volume). In Section 3 we introduce and discuss lahar modeling approaches and strategies (limitations, model used for simulations); used input

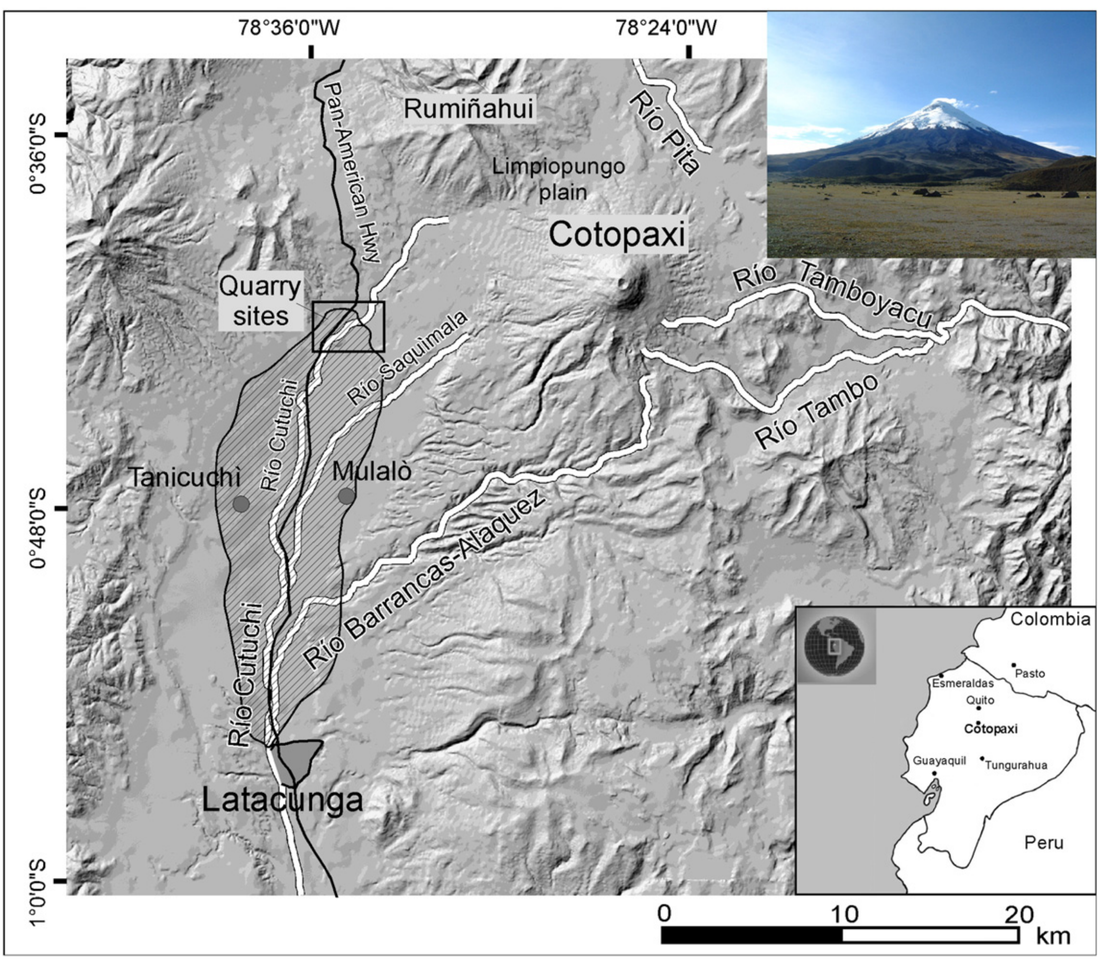

Fig. 1. Shaded relief map of Cotopaxi volcano and surrounding areas with main drainage systems and locations indicated in the text. The main geographic locations are shown in the bottom inset. The black box indicates the quarry site. Black striped area refers to the zone of intense farming and cultivation. In the upper inset, Cotopaxi volcano seen from the north. In the foreground the Limpiopungo plain, with blocks carried by recent lahars.

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