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Volcanic hazard zonation of the Nevado de Toluca volcano, México

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ABSTRACT

The Nevado de Toluca is a quiescent volcano located 20 km southwest of the City of Toluca and 70 km west of Mexico City. It has been quiescent since its last eruptive activity, dated at ~3.3 ka BP. During the Pleistocene and Holocene, it experienced several eruptive phases, including five dome collapses with the emplacement of block-and-ash flows and four Plinian eruptions, including the 10.5 ka BP Plinian eruption that deposited more than 10 cm of sand-sized pumice in the area occupied today by Mexico City. A detailed geological map coupled with computer simulations (FLOW3D, TITAN2D, LAHARZ and HAZMAP softwares) were used to produce the volcanic hazard assessment. Based on the final hazard zonation the northern and eastern sectors of Nevado de Toluca would be affected by a greater number of phenomena in case of reappraisal activity. Block-and-ash flows will affect deep ravines up to a distance of 15 km and associated ash clouds could blanket the Toluca basin, whereas ash falls from Plinian events will have catastrophic effects for populated areas within a radius of 70 km, including the Mexico City Metropolitan area, inhabited by more than 20 million people. Independently of the activity of the volcano, lahars occur every year, affecting small villages settled down flow from main ravines.

1. Introduction

The Quaternary Mexican volcanism is concentrated along the Trans-Mexican Volcanic Belt (TMVB) (Fig. 1A), a continental volcanic arc that has been active since 14 Ma (Ferrari et al., 1994). At least 14 active volcanoes are present in Mexico, and most of these are located along the TMVB (Fig. 1A). At present, only Volcán de Colima and Popocatépetl exhibit persistent activity, with small eruptive columns (up to 5–8 km in each case) and short-runout pyroclastic flows that have not affected populated areas (Saucedo et al., 2005; Macías and Siebe, 2005; Macías et al., 2006). The other volcanoes, including Nevado de Toluca (hereafter, NdT), are quiescent and apparently represent no threat to the surrounding populations. However, the sudden reactivation of El Chichón volcano in 1982 after a 550 yr quiescence period killed over 2000 people (Macías et al., 2008), suggesting that long-term dormant volcanoes can become active in a very short time, with catastrophic consequences due to previous dearth of basic studies, hazard maps, emergency information programs, etc. The Popocatépetl and Colima volcano hazard maps were the first maps prepared in Mexico as a consequence of the eruptive crises that occurred in these volcanoes in 1994 and 1991, respectively (Macías et al., 1995; Del Pozzo et al., 1996; Sheridan et al., 2001a; Navarro et al., 2003). More recently, Sheridan et al. (2001b, 2004) produced a hazard map for the Pico de Orizaba volcano in which the hazard delineation was based primarily on flow simulations that took into account the more recent eruptive activity. At present, these maps represent a fundamental scientific document that civil defense authorities use in case of future volcanic crises. For the case of Nevado de Toluca, the only available hazard map was reported by Capra et al. (2000, 2004) and Aceves Quesada et al. (2007). These maps were mostly based on the stratigraphic record and morphology of the volcano.

The Nevado de Toluca is a quiescent volcano, located 20 km southwest of Toluca, and 70 km west of Mexico City (Fig. 1B). The volcano has been silent since its last eruptive activity, dated at ~3.3 ka BP (Macías et al., 1997), although minor fumarolic activity was reported during the nineteenth century (Bloomfield and Valastro, 1977). The reactivation of NdT could threaten more than 20 million people, including the Mexico City metropolitan area, that some 10.5 ka years ago was blanketed by more then 10 cm of pumice from the Upper Toluca Pumice eruption, one the most violent Plinian eruption occurred during the Holocene (Fig. 1B) (Cas and Wright, 1988; Arce et al., 2003). The aim of this work is to present a hazard assessment that includes future eruptive scenarios deduced from a detailed geological map (Garcia-Palomo et al., 2002; Bellotti et al., 2004; Norini, 2006) coupled with computer flow simulations for debris avalanches, block-and-ash flows, falls, and lahars. All simulations were carefully tested based on spatial distributions and thickness of past flows, and in some cases the paleotopography was restored in digital elevation models (DEMs) to better reproduce past events. The resulting hazard zonation benefits from accurate calibration and validation of the numerical

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Fig. 1. A) Map of the Trans-Mexican Volcanic Belt (TMVB) showing the location of the Nevado de Toluca and other active volcanoes. Abbreviations are: Ce: Ceboruco; CVC: Colima Volcanic Complex; Pa: Parícutin; NT: Nevado de Toluca; Jo: Jocotitlán; Mx: Mexico City; Iz: Iztaccíhuatl; Po: Popocatépetl; PdO: Pico de Orizaba; CdP: Cofre de Perote. B) Landsat image (RGB combination) of the central sector of the TMVB. Mexico City is located 70 km northwest of Nevado de Toluca and 40 km northeast of Popocatépetl, both active volcanoes. White dotted lines refer to the 10-cm isopach map of three mayor plinian eruptions occurred at the Nevado de Toluca volcano: the Lower Toluca Pumice (LTP, at 21 ka BP), the Middle Toluca Pumice (MTP, at 12.5 ka B.P.) and the Upper Toluca Pumice (UTP, at 10.5 ka BP) that covered the area occupied today by Mexico City. Abbreviations are: TF: Tenango Fault; TLF: Tenango Lava Flow; CVF: Chichinautzin Volcanic Field; CR: Las Cruces Range. Black dotted line refers to the main Tenango fault intersecting Nevado de Toluca Volcano.

models coupled with high-resolution geological data and reliable computer flow simulations. This compiled methodology can better predict the extent of products of future volcanic activity in contrast to previous research, which tended to be based either on numerical modeling or on geological mapping (Waythomas and Waitt, 1998; Moreno, 2000; Sheridan et al., 2004; Sofield, 2004).

2. The Nevado de Toluca volcano

2.1. Morphostructural features

The Nevado de Toluca is 4680 m high and is characterized by an open crater, 1.5 to 2 km in diameter, E–W elongated, which developed in response to intense tectonic activity (Tenango Fault System, Fig. 2; García-Palomo et al., 2000, Norini et al., 2004; Bellotti et al., 2006; Norini et al., 2006). The Ombligo dome, residing in the crater's interior, separates two lakes (Moon Lake and Sun Lake, Fig. 3A).

The volcano shows striking morphological differences on its flanks and two main morphological domains can be defined (Norini et al., 2004). The southern flank of Nevado de Toluca volcano has an irregular morphology, relatively flat and dissected by deep rectilinear valleys with NNW–SSE strikes associated to the Taxco–Queretaro Fault System (García-Palomo et al., 2000; Bellotti et al., 2006). The altitude of the this flank varies between 3800 and 2500 m a.s.l. and more than 50% of this area has slopes greater than 20° (Norini et al., 2004). Ravines are deeply eroded with depths up to 450 m (Barranca del Muerto, Fig. 2). All these features led previous authors to consider this area as the remains of an older volcanic structure called Paleonevado (Cantagrel et al., 1981; García-Palomo et al., 2000). The western, northern, and eastern NdT flanks, in conjunction with the crater area, depict the second morphological domain, and constitute the present active cone of the NdT volcano. The northern and northwestern sectors of the volcano are gentle, with slopes of 6–8°, mostly formed by pyroclastic fans (Fig. 3B,C) on the Toluca basin. The main drainages are radial with respect to the cone. The eastern sector has a gentler slope but is more dissected, with ravines up to 70 m deep (Arroyo Grande ravine, Fig. 2) due to the presence of the Tenango Fault System (García-Palomo et al., 2000), an active left-lateral transtensive structure (Norini et al., 2006).

The present morphological arrangement of the volcano may have a great influence on the hazard assessment, because the distribution and runout distances of volcanic flows will depend primarily on the flow dynamics and topography.

2.2. Stratigraphic record

The volcano started to grow at ~2.6 Ma with andesitic to dacitic effusive activity that ended at 1.1 Ma and led to the formation of Paleonevado edifice (Cantagrel et al., 1981; Garcia-Palomo et al., 2002; Martínez-Serrano et al., 2004). After an intense erosive stage that originated the emplacement of voluminous epiclastic sequences, including two sector collapses (Capra and Macías, 2000), magmatic activity was renewed ~42 ka ago whit the formation of the recent active cone of the NdT and the emplacement of the Pink Pumice Flow (PPF) deposit (Macías et al., 1997). Fig. 4 shows a detailed geological map compiled from previous works (Garcia-Palomo et al., 2002; Bellotti et al., 2004; Norini, 2006), representing the last 50 ka of volcanic activity that was characterized by different eruptive phases (Fig. 5), including five dome collapses dated at 37, 32, 28, 26.5, and 13 ka (Macías et al., 1997; Garcia-Palomo et al., 2002), at least three lateral collapses (Macías et al., 1997; Norini, 2006), and four Plinian eruptions at 36 ka (Ochre Pumice) (Garcia-Palomo et al., 2002), 21.7 ka (Lower Toluca Pumice, LTP) (Bloomfield et al., 1977; Capra et al., 2006), 12.1 ka (Middle Toluca Pumice, MTP) (Arce et al., 2005), and 10.5 ka (Upper Toluca Pumice, UTP) (Macías et al., 1997; Arce et al., 2003). The eruptive sequence is crowned by a phreatomagmatic surge deposit dated at ~3.3 ka BP (Macías et al., 1997).

2.3. Origin, distribution and magnitude of major volcanic events

We next describe in detail past eruptions and associated deposits related to the activity of the active cone of NdT (<50 ka), to illustrate expected events in case of renewed volcanic activity. The activity of the Paleonevado, characterized by voluminous lava flows, ended approximately 1.2 Ma ago, a time interval too long to be considered as a possible locus of a new eruption.

Dome collapse events have been characterized by summit dome growth and destruction, associated or not with an explosive component. The 37- and 28-ka events correspond to major dome-destruction episodes that originated lithic-rich block-and-ash flow deposits that traveled up to 20 km from the source emplacing up to 30 m thick deposits (Fig. 6A). These deposits are grouped in the map in one unit because they usually represent vertical sections, being impossible to lay out their individual distribution on the geological map. Main outcrops are limited to quarries where material is extracted for construction (Fig. 3C); it is thus difficult to determine