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Flank collapse scenarios at Volcán de Colima, Mexico: A relative instability analysis

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ABSTRACT

Previous studies on debris avalanche deposits of Volcán de Colima suggest a cyclic process of repetitive flank collapses triggered by major eruptions (VEI>4). The recurrence interval of major collapse events during the last 10,000 years is calculated here using a stochastic approach, yielding a mean recurrence interval of 2698 yr, with an uncertainty range of 180 yr. The analysis yields an increased probability of flank collapse in the interval between −110 yr and +345 yr from the present. This generates a series of scenarios ranging from optimistic, considering a collapse within the next 345 years, to pessimistic, derived from the 110 year delay. The analysis of relative mass/volume deficit in the volcano structure, made using the new VOLCANOFIT 2.0 software, and a limit equilibrium analysis on the volcano flanks point to the SW quadrant as potentially the most unstable sector of the edifice under a wide range of scenarios. The TITAN2D numerical model is also used to simulate the extent of debris avalanches caused by failure of the SW flank. This approach may be applied to any volcano with a potential for flank collapse.

1. Introduction

The 1980 sector collapse and debris avalanche at Mount St. Helens triggered the recognition of characteristic hummocky deposits in many similar debris avalanche deposits worldwide (Siebert, 1984; Ui and Glicken, 1986; Siebert et al., 1987; Francis and Wells, 1988; Vallance et al., 1995; Capra et al., 2002). Since then, several studies have revealed that many volcanoes are susceptible to failure caused by exogenous or endogenous processes (McGuire, 1996), and that the associated deposits can completely change the topography around the volcano with important secondary effects, particularly on the hydrographic network (Swanson et al., 1986; Capra and Macías, 2002; Capra, 2007).

Instability of a volcanic edifice may be caused by many factors, either directly related to volcanic activity or to exogenous processes such as weathering. These factors include direct magmatic intrusion into the edifice (Bezymianny-type activity, Gorshkov, 1962) or into the sub-volcanic crust (Day, 1996; Elsworth and Voight, 1996), deposition of voluminous pyroclastic deposits on steep slopes (McGuire, 1996), hydromagmatic processes (Dzurisin, 1998), and phreatomagmatic activity (Bandai-type activity, Moriya, 1980). In some cases faulting may trigger collapse (McGuire, 1996), and the tectonic setting of the volcano may also influence the direction of the failure (Siebert, 1984). In addition, the mass of the volcano can induce isostatic flexure, compaction, and deformation that can lead directly to collapse (Borgia et al., 1992; van Wyk de Vries and Borgia, 1996). Although simple gravitational failure may occur in response to progressive weakening of an edifice, discrete triggering mechanisms are commonly independent of the processes producing edifice instability. Keefer (1984) established that numerous large landslides during historic time were triggered by earthquakes. Other triggering mechanisms include phreatic explosions and precipitation. Hurricane-induced rainfall triggered a flank collapse at the Casita volcano in Nicaragua in 1998, killing 2,500 people (Sheridan et al., 1999; Scott et al., 2005).

Two different approaches have been used to model volcano instability; scaled analog experiments, and numerical simulation. i) Analog models have been widely used to simulate sector collapses of volcanoes, mostly focused on reproducing the direction of the collapse with respect to the stress field affecting the volcano. Experiments of volcanic spreading have been performed to predict deformation, taking a volcano as a function of its height and the brittle-ductile ratio of the substratum, in extension and strike-slip settings (e.g. Merle and Borgia, 1996; van Wyk de Vries and Merle, 1996; van Wyk de Vries et al., 2003; Acocella, 2005; Norini and Lagmay, 2005). In addition, cryptodome intrusion has also been modeled attempting to reproduce the volcano deformation prior to the 1980 Mt. St. Helens collapse (Donnadieu and Merle, 1998; Donnadieu et al., 2001). ii) Numerical simulations have been used to understand how the stability of a volcano is affected by the increase of internal magmatic pressure (Dietrich, 1988; Russo et al., 1997), excess pore pressures due to intrusion (Voight and Elsworth, 1997; Elsworth and Day, 1999; Elsworth and Voight, 2001), hydrothermal alteration (Zimbelman et al., 2004) and even in magmatically

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inactive volcanoes with significant mass resting over a weak substratum (Borgia, 1994; van Wyk de Vries and Matela, 1998).

The Colima volcano (3860 masl), also known as Volcán de Fuego, is an active composite cone with a maximum age of about 50,000 yr (Robin and Boudal, 1987) and is the youngest edifice of the Colima Volcanic Complex (CVC), located in the western limit of the Trans-Mexican Volcanic Belt (Fig. 1). The older part of the edifice, Paleofuego, (the ancestral Colima volcano), consists of a south-facing horseshoe-shaped crater surrounding the present active cone. Luhr and Prestegaard (1988) describe a main debris avalanche deposit exposed south of the edifice, up to 70 km from the source, with an age of 4280 ± 110 yr BP, contrasting with the age reported by Robin and Boudal (1987) of 9370 ± 400 yr BP for the same deposit. Despite the difference in age determinations, both groups of authors agree that the deposit corresponds to a single event. In contrast, Komorowski et al. (1997) suggest that collapses have occurred at least 12 times in the last 45,000 years and perhaps as much as 9 times at the younger edifice. Table 1 presents the radiocarbon ages related to these collapse events. Recently, Cortes et al. (2010) have described in great detail some of the more recent collapse events, as well as a 3600 yr BP collapse on the western flank of the edifice emplacing a 1 km^3 debris avalanche deposit. Similar to older deposits (Capra and Macías, 2002; Capra, 2007), this debris avalanche deposit obstructed the Armería river, forming a temporary dam that then failed, producing a voluminous debris flow. Such secondary effects are caused by the walls of the N-S tectonic graben in which Colima is settled, acting as topographic barriers where the voluminous debris avalanches stop (Fig. 1).

Modern activity of the volcano has been characterized by explosive phases, including two major Plianian eruptions such that occurred in 1818 and 1913 (Saucedo et al., 2010). Since the 1913 Plinian event, the volcano has had several eruptive phases. Its activity has been more persistent since 1998, with explosions and lava and dome extrusions (Saucedo et al., 2005). The collapse of summit domes and lava flow fronts has produced several block and ash flow deposits. Such deposits are up to several meters thick in the proximal area with filled proximal drainages up to 6 km from the vent. The block-and-ash flows at the Colima volcano consist of unwelded deposit with clasts embedded in a silty to sandy matrix. During the last 15 yr the volcano had several eruptive episodes; in 1991, 1994, 1998–1999, 2001–2003, 2004 and 2005. Despite this persistent eruptive activity, the emitted products have not significantly affected the surrounding inhabited area. During heavy rains, which usually occur from June through October at this latitude, these deposits are often remobilized, producing lahars (Capra et al., 2010).

Although numerous studies on the textural characteristics of the avalanche deposits have been published, we are not aware of any results concerning the edifice conditions prior to the failure or the possible triggering mechanism. Considering the present condition of the active cone, it is extremely important to understand its stability and recognize which sector could be destabilized by any endogenous or exogenous triggering process.

The aim of the present work is to evaluate the relative flank instability of the Colima volcano using a set of new tools; recurrence intervals of cyclic debris avalanche events, the analysis of mass/volume deficit with respect to a homogeneous stable reference shape, and a limit equilibrium method (LEM); and to evaluate the possible debris avalanche scenario after estimation of potential volume of the Debris Avalanche Events (DAE).

2. Materials and methods

2.1. Recurrence time of Debris Avalanche Events (DAE)

The published average ages (BP) and associated uncertainties for each DAE in the Colima Volcanic Complex (Komorowski et al., 1997; Cortes et al., 2005, 2010) are listed in Table 1. The number of DAE is indeed much lower than the number of explosive events. De la Cruz-Reyna (1993) established a Poissonian model for the recurrence intervals and occurrence frequency of explosive eruptions, and Mendoza-Rosas and De la Cruz-Reyna (2008) analyzed the distribution of events with VEI > 4, which may be related to large DAE, finding an 85% probability of a VEI > 4 event within the next 500 yr, and an average recurrence time for VEI > 5 over 2500 yr. The fundamental problem for VEI > 4 events derives from the reduced number and reliability of event dating.

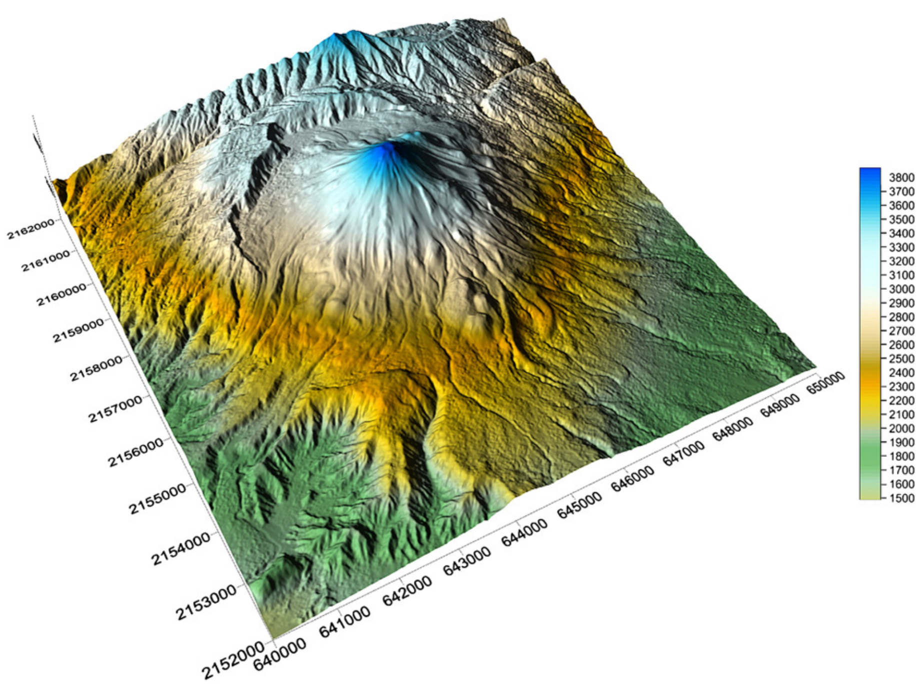

Fig. 1. Colima Volcan de Fuego. DEM.