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# Twenty years (1990–2010) of geodetic monitoring of Galeras volcano (Colombia) from continuous tilt measurements

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## ABSTRACT

Galeras – an andesitic stratovolcano part of the Galeras Volcanic Complex – is one of the most active volcanoes in Colombia. Historic activity is centered on a small-volume cone inside the youngest amphitheater, which breaches the west flank of the volcano. At least 30 confirmed eruption periods have been recorded in the past 480 years, with episodes of unrest ranging from weak fumarolic activity and ash emissions to larger explosive events. The most recent eruption periods, recorded instrumentally since 1988, have been characterized by minor explosive eruptions, and the emplacement of three crater domes and small pyroclastic flow deposits. In this paper, we discuss the evolution of volcanic activity using a 20-year-long record of tilt measurements. In particular, we focus on three episodes of unrest occurred in 1991, 2006 and 2008, when the deformation was clearly associated with shallow magma intrusions, and the emplacement and destruction of crater domes. The depth of the intrusions varied from a few hundred meters (August 2005) to two kilometers (January 2009), while the volume change ranged from  $10^4$  m<sup>3</sup> (May–October 2009) to  $10^6$  m<sup>3</sup> (January 2009). A comparison with seismic data indicates that the deformation sources were located within the cloud of hypocenters of the volcano-tectonic events. The lack of a clear correlation between the volume change (and depth) of the sources and the total SO<sub>2</sub> flux could indicate that the unrest at Galeras was related to a larger intrusive event with only a small part of the magma erupted in the form of tephra and lava domes.

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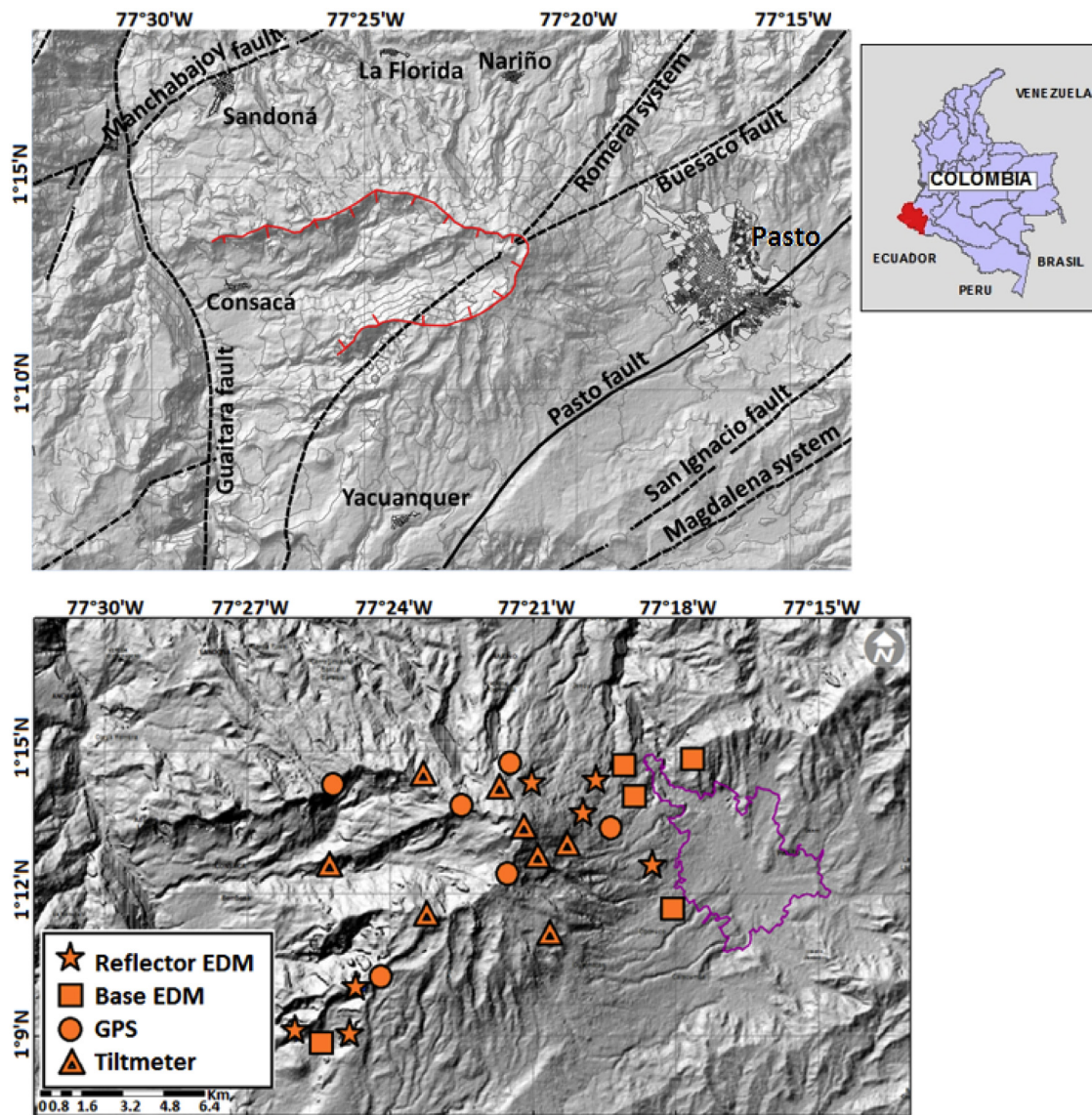
## 1. Introduction

Galeras – an andesitic stratovolcano part of the Galeras Volcanic Complex (GVC) – is one of the most active volcanoes in Colombia. It is located 9 km west of the City of San Juan de Pasto and around it are eight municipalities with a total population of about 400,000 inhabitants. The GVC geological record shows evidence of large, hazardous eruptions although the most recent eruptions (<5000 years) have been of small scale (Calvache, 1995). Historic activity has been centered on a small-volume cone inside the youngest amphitheater, which breaches the west flank of the volcano (Fig. 1, top). Since the establishment of Pasto in 1537, Galeras has had 30 confirmed eruptive periods with an average recurrence time of 16 years. During these periods, at least 63 episodes of unrest have been recorded ranging from weak fumarolic activity and ash emissions to larger explosive events (Global Volcanism Program, Smithsonian Institution; Cardona, 1997).

The Volcano Observatory of Pasto has a long and continuous monitoring record of tilt at Galeras. Monitoring of the deformation at Galeras began in 1990 with the installation of two electronic tiltmeters at the summit of the volcano, and some additional measurements of tilt using leveling routes <100 m long, located in different parts of the flanks of the volcano (Ordóñez and Rey, 1997). By 2004, leveling was abandoned and the Pasto observatory began strengthening the deformation monitoring network with the installation of electronic tiltmeters; in 2011 the observatory installed the first network of permanent Global Navigation Satellite System (GNSS) sites and in 2013 an Electronic Distance Meter (EDM) network. At the end of 2014, the geodetic monitoring networks of Galeras included 8 telemetric electronic tiltmeters, 6 permanent GNSS and 11 EDM points, covering a large part of the volcano's flanks (Fig. 1, bottom).

Electronic tiltmeters are very sensitive and can measure changes in ground deformation of a few  $\mu$ rad that would go unobserved by GPS or other monitoring techniques. This characteristic makes tiltmeters very effective in monitoring transient deformation episodes that may be associated with shallow processes of inflation or deflation of the volcano, caused by volume changes in magma reservoirs or geothermal aquifers (Dvorak et al., 1981; Dzurisin et al., 1983; Dzurisin, 1992;

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**Fig. 1.** (Top) Map showing the location of Galeras volcano. The crater is located at the center of the panel. The black lines represent the main faults crossing the volcano (Romeral Fault Zone system) and the red line the caldera. (Bottom) Map showing the volcano monitoring networks in 2014. The purple line is the perimeter of the city of San Juan de Pasto located 9 km east of the volcano. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Dzurisin, 2003; Voight et al., 1998; Agnew, 1986; Powell and Pheifer, 2000; Gambino, 2004).

In this article we present first the record of continuous tilt monitoring of the Galeras volcano for the period 1990–2010, see Fig. 2. Next, we focus on three episodes of unrest happened in 1991, 2006 and 2008, when the deformation recorded by the tiltmeters was clearly associated with magma intrusion and the emplacement of crater domes. Then we model the deformation using a spherical source to get an estimate of the depth and volume change of the magma intrusions. Our results indicate that during the evaluated period (1990–2010) of volcanic activity, the depth and volume change of the magma intrusions preceding the domes emplacements were wide-ranged. The depth of the intrusion went from a few hundred m (August 2005) to two km (January 2009), while the volume change changed from a minimum of  $10^4 \text{ m}^3$  (May–October 2009) to a maximum of  $10^6 \text{ m}^3$  (January 2009).

## 2. The Galeras Volcanic Complex

The Galeras Volcanic Complex (GVC), located in the Department of Nariño (southern Colombia; Fig. 1), reaches an altitude of 4276 m

above sea level at its main crater. Its most notable morphological feature is the large amphitheater (approximately 1250 m in diameter) on its west flank, the result of eruptions, landslides and flank collapse (Calvache, 1995). Inside the amphitheater, we find the active cone of the Galeras volcano with an approximate height of 150 m, a crater of about 300 m in diameter and several secondary craters located around it (Fig. 1). The GVC has erupted lavas and pyroclastic flows, with magma compositions ranging from basaltic andesite to dacite (Calvache and Williams, 1997a, 1997b).

The GVC has a complex evolutionary history that includes two caldera-forming eruptions (560 ka and 40 ka ago) and a summit collapse between 12 and 5 ka ago. The approximately  $4 \text{ km}^3$  of material missing from the top of the volcano is found today in the debris avalanche deposits near Consacá. The migration of the eruptive centers towards the east suggests that the location of eruptive centers and eruption rates may be controlled by tectonic constraints such as the Romeral Fault Zone system (Fig. 1; Calvache, 1995).

About 30 eruptive periods have been confirmed in the 480 years of recorded history at Galeras: twenty were brief vulcanian eruptions (VEI 1 and VEI 2); ten were more powerful (VEI 3) but still modest in

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