Journal of Volcanology and Geothermal Research 301 (2015) 148–158

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Three-dimensional velocity structure of the Galeras volcano (Colombia) from passive local earthquake tomography

Carlos Alberto Vargas [a,*], Roberto Torres [b]

[a] Department of Geosciences, Universidad Nacional de Colombia at Bogotá, Colombia
[b] Colombian Geological Survey, Volcanological Observatory of Pasto, Colombia

ARTICLE INFO

Article history:
Received 10 October 2014
Accepted 8 May 2015
Available online 23 May 2015

Keywords:
Galeras volcano
Volcano-tectonic earthquakes
Local seismic tomography
3D velocity structure
Volcanic activity

ABSTRACT

A three-dimensional estimation of the Vp, Vs and Vp/Vs ratio structure at Galeras volcano was conducted by means of passive local earthquake tomography. 14,150 volcano-tectonic events recorded by 58 stations in the seismological network established for monitoring the volcanic activity by the Colombian Geological Survey – Pasto Volcano Observatory between the years 1989 and 2015, were inverted by using the LOTOS code. The seismic events are associated with shear-stress fractures in solid rock as a response to pressure induced by magma flow. Tomography resolution tests suggest a depth of imaging that yield 10 km from the summit of the main crater, illuminating a large portion of the volcanic structure and the interaction of tectonic features like the Buesaco and Silvia-Pijao faults. Full catalog tomographic inversion, that represents the stacked image of the volcanic structure or the most permanent features underneath the volcano, shows vertical structures aligned with seismicity beneath the main crater. We hypothesize that these structures correspond to a system of ducts or fractures through which magma and fluid phases flow up from deeper levels toward the top and related with the intersection of the surface traces of the Silvia-Pijao and Buesaco faults.

1. Introduction

The active crater of the Galeras volcano is located in SW Colombia, approx. 9 km W of the city of San Juan de Pasto, and near to other 9 small towns (total population of 500,000 inhabitants) (Fig. 1). This volcano is part of the Galeras Volcanic Complex (GVC), which consists of stages and has been evolving for over one million years (Cepeda, 1985). According to Murcia and Cepeda (1991), the GVC consists mostly of lava flow deposits, pyroclastic flow deposits, ash fall deposits, debris avalanche deposits and mud flow deposits (Fig. 2). As shown in Figs. 1 and 2, the GVC is formed on one of the traces of the Romeral Fault System (RFS), which has an approximate orientation of 45° NE in this sector. This system separates a basement to the W formed from oceanic basalts and Cretaceous meta-sediments of Paleozoic metamorphic rock to the E. This resulted from a compressive system related to the subduction of the Nazca plate with respect to the South American plate (Barrero, 1979). The Buesaco and Silvia-Pijao faults are associated with this system, and complexes of calderas in the traces of these faults are common. The evolution of the GVC included the formation of two calderas, with one forming approximately 560,000 yr bp and the other forming between 150,000 and 40,000 yr bp. A summit collapsed by instability related to hydrothermal alterations generated a steep slope along the W side of the volcanic edifice between 12,000 and 5000 yr bp. In addition, explosive eruptions and lava flows resulted in the nowadays stratovolcano structure (Calvache, 1995).

The Galeras volcano composed mostly of andesite is 4500 years old, corresponding to the last of the GVC states. Six identified periods of major eruptions generated pyroclastic flows and fallout and lava flows (Calvache, 1990; Calvache and Williams, 1997). According to Espinosa (2001), sixty-three eruptions between the years 1535 and 1936 have been found in historical records. Permanent monitoring of the Galeras volcano was initiated by the Colombian Geological Survey – Pasto Volcano Observatory (SGC-OVP by name in Spanish) in 1989, and since then to May, 2015, approx. 130 eruptive events have been reported (see Annex T1, Table of eruptive events of the Galeras volcano). Many of these correspond to explosive eruptions categorized as vulcanian type; these eruptions had eruptive columns that did not surpass 12 km in height, and they produced small deposits of pyroclastic material.

Four stages of activity between Jan. 2004 and Dec 2010 have been identified due to representative monitoring from increased instrumentation on the Galeras volcano. Fig. 3 shows the cumulative number of seismic events along the instrumental history of the volcano as well as a histogram of the daily occurrence of volcano-seismic signals highlighting these stages. The first is the "resting stage," and it is characterized by low levels of seismic activity, gas emissions and released seismic energy without deformations to the volcanic edifice. The second stage is the "clean-up and conduit opening stage," where an increase of diverse

* Corresponding author. Tel.: +57 3002146420.
E-mail address: cavargasj@unal.edu.co (C.A. Vargas).

http://dx.doi.org/10.1016/j.jvolgeores.2015.05.007
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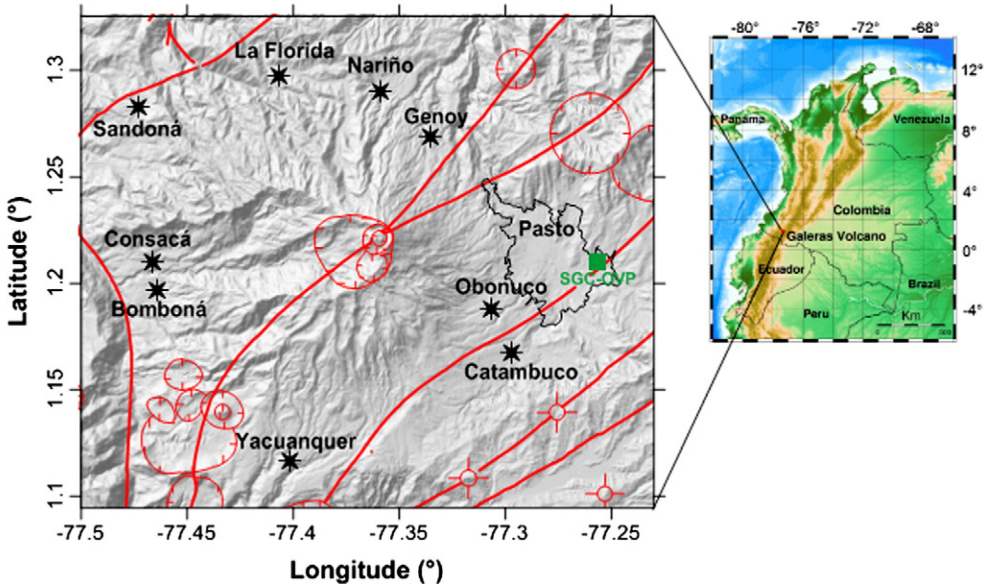

Fig 1. Location of the Galeras volcano. The perimeter of the city of San Juan de Pasto to the E of the volcano is marked with a black line, and other small towns are marked with black stars. The crater is located at the center of the panel. The green rectangle shows the location of the Data Collection Center of the Volcano Observatory (SGC-OVP). Main faults that are crossing the area of study, as well as other old craters and calderas are presented with red lines.

volcano-seismic signals and of the amount of released energy occurs. Among these signals are volcano-tectonic (VT) earthquakes associated with fragile shear-stress fractures in the rock, long-period seismic events (LPS) related to transient pressure perturbations caused by flow transport or volumetric changes, hybrid earthquakes (HYB) that manifest as combined VT and LPS, and tremor (TRE) signals associated with sustained pressure perturbations related to fluid flows (Chouet, 1988). In this stage, emissions of gas, ash and explosive eruptions of non-juvenile magma occur, where the hydrothermal system plays a fundamental role. The third stage is the "dome intrusion and/or construction stage", this is characterized by an increasing deformation of the volcanic edifice and volcano-seismic signals that are associated with the activity of volcanic flows and an increase of emissions of sulfur dioxide. In this stage, the hydrothermal system has dried out, there are minor eruptions, predominantly of ashes, and it generally ends with the emplacement of a lava dome at the surface. The fourth stage is the "dome destruction stage" and it begins with a decrease in volcano-seismic signals. In addition, there are no manifestations of progressive volcanic deformations (except during major eruptions, where a fast deformation occurs), and there is a low emission of gases preceding explosive eruptions with a predominant magma component. In general and in the long term, the drastic changes in the evolution of VT events are a manifestation of new phases of fracturing as the consequence of tectonic perturbation related to magmatic or fluid pressure that

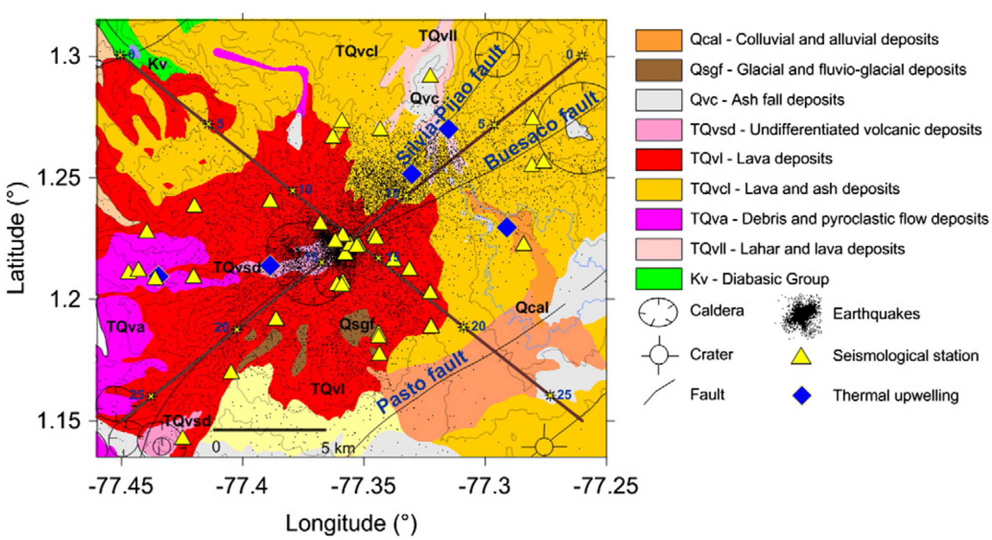

Fig. 2. Geological map that includes the Galeras Volcanic Center (GVC). The crater of the Galeras volcano is located at the coordinates 1.22 N and 77.36 W. Geologic units make reference to the host-rock (older unit, Kv) and the main products of the GVC (modified from Murcia and Cepeda, 1991). Thermal upwelling occurrences are expressed with blue diamonds. Seismological stations are represented with yellow triangles. Brown lines with reference distances represent the tomographic profiles estimated in this work. Small black dots correspond to seismic events used for the 3D velocity inversion.