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SPATIAL MAPPING OF THE B-VALUE AT GALERAS VOLCANO, COLOMBIA, USING EARTHQUAKES RECORDED FROM 1995 TO 2002

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ABSTRACT

The catalog of volcano-tectonic earthquakes at Galeras volcano, Colombia, was analyzed to determine the magnitude of completeness of the seismograph network and to explore the subsurface structure by mapping the b-value of the frequency-magnitude distribution. By using 8,435 well-located earthquakes between 1989-2002 we found the catalog to be complete above MD=0.26. The average b-value of 0.71 was found to be the result of an unintentionally stretched magnitude scale. The two- and three-dimensional mapping of b-value illuminates a vertically elongated structure beneath the active crater of Galeras down to a depth of 6 km, which may be associated with a conduit, or alternatively, with a shallow region of temporary magma storage. A structure with this geometry and location has not been found before in previous studies of b-value on volcanoes around the world.

Key words: seismology, Galeras volcano, b-value, earthquarques.

RESUMEN

El catálogo de Sismosº Vulcanotectonicos en el Volcan Galeras, Colombia, fué analizado para determinar la magnitud de completitud, de la red sismografica y explorar las estructuras del sub-suelo mapeando los valores b, asociados a la distribución frecuencia - magnitud.

Utilizando 8.435 eventos bien localizados, para el periodo 1989 -2002 se encontró que el catalogo estaba completo por encima de Md=0.26. El valor promedio b=0.71 fué encontrado mediante un no- intencionado estiramineto de escala de magnitudes.

El mapeo bidimensional y tridimensional del parametro b discrimina una estructura verticalmente elongada debajo del crater activo del Galeras a una profundidad de 6 Km, que estaria asociada con un conducto ó con un almacenamiento temporal de de magma en una zona somera. Una estructura con esa simetría y localización no ha sido reportada antes en estudios previos del valor b en Volcanes alrededor del mundo.

Palabras Claves: Sismología, volcan Galeras, Valor b, terremotos.

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INTRODUCTION

Galeras volcano is located in southwestern Colombia, 9 km from the city of San Juan de Pasto (pop. ~ 350,000) and it is one of the most active volcanoes in the region, with major eruptions over the last 4,500 yr (Calvache, 1990). In 1988 Galeras showed signs of unrest and erupted explosively in 1989; an andesitic lava dome was emplaced during September-November 1991, and explosive activity took place again during 1992-1993. The last explosive eruption occurred on June 7, 2002 (Global Volcanism Network, 2003).

Between 1989 and 2002 The Observatorio Vulcanológico y Sismológico de Pasto (OVSP) has compiled an important catalog of earthquakes locations and this offers the possibility of determining the magnitude of complete detection and spatially mapping the b-value to explore the internal structure of the volcano down to a depth of 10 km. Between 1991 and 1992 the seismicity at Galeras was characterized by the occurrence of long-period events (LP) but also volcano-tectonic earthquakes (VT) were recorded (Gil-Cruz and Chouet, 1997). Both types of events, however, form the background seismicity at the volcano from 1993 until present. In this work we focus on the VT earthquakes. These earthquakes usually show sharp and distinct arrivals of P and S waves to the various seismograph stations, and broadband spectra, commonly above 5 Hz (Lahr et al, 1994). The sharp arrivals of P and S waves allow reliable location of the earthquakes. From 1993, the locations of VT earthquakes around Galeras illuminate several particularly active regions north of the active crater (Figure 1).

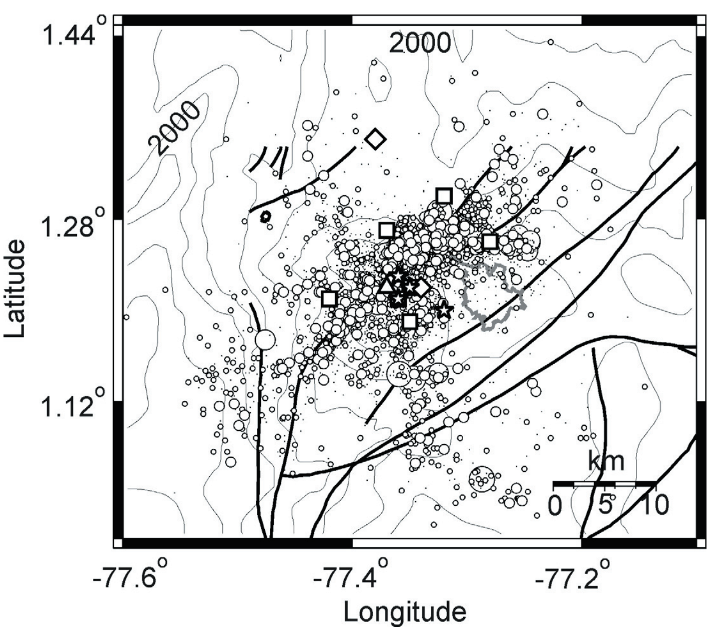

Figure 1. Map of Galeras volcano. Topographic contours drawn every 500 m. Circles represent epicenters of VT earthquakes recorded between 1989-2002, with magnitudes ranging between 1 – 3.8. The triangle marks the active crater. Thick solid lines cutting through topography are fault segments and the thick gray contour southeast of Galeras marks the limits of the city of San Juan de Pasto. Squares- seismograph stations equipped with short-period, vertical component seismometers; diamonds- short-period, three component stations; stars- broadband stations.

The distribution of earthquakes sizes in a region can be described by a law identified by Ishimoto and Iida in 1939, and later by Gutenberg and Richter in 1944:

$$\text{Log } N = a - bM \qquad (1)$$

where N is the cumulative number of earthquakes with magnitude larger than or equal to M, and a, b are constants that describe the activity of a seismogenic region and the relative distribution of earthquakes sizes, respectively. When plotting the cumulative number of earthquakes versus their magnitudes (frequency-magnitude distribution, FMD), b represents the slope of the best-fitting line for a certain magnitude range and is inversely proportional to the average size of faults that rupture during earthquakes (Aki, 1965). Values of b are close to 1.0 in the Earth's crust (Frolich and Davis, 1993) but in volcanic regions b is commonly higher than 1.0 (Wiemer and McNutt, 1997; Wyss et al., 2001, Sánchez et al., 2004). This anomalously high b-value at volcanoes has been attributed to excessive material heterogeneity (Mogi, 1962), decreased applied stress (Scholz, 1968), decreased effective stress (high pore pressure) (Wyss, 1973), or alternatively, elevated thermal gradients (Warren and Latham, 1970). In this work we determine the magnitude of completeness (Mc) of the seismograph network and then we select a subset of data that is optimal for spatial mapping of b.

DATA

From 1989 the seismic activity at Galeras has been monitored with a 3 to 9-stations seismograph network. (Figure 1). The network is equipped with five L-4 Mark Products vertical-component seismometers (flat response between 1 - 10 Hz) with one Hertz natural frequency, two L-22 Mark Products three-component seismometers (flat 2 to 20 Hz) with 2 Hertz natural frequency; and four Broadband, three-component seismometers (two Guralp CMG-40T and two Strekeissen STS-2, flat 0.02 to 50 Hz) with 0.01 Hz natural frequency.

Earthquakes are located by reading the arrival times of P and S-waves to several seismograph stations and using the iterative computer program HYPO71 (Lee and Lahr, 1975). A one-dimensional model consisting of five layers over a half-space, with velocities increasing with depth, and constant Vp/Vs = 1.78 is used as approximation to the distribution of velocities in the Galeras area. Table 3.1 lists the parameters of the velocity model.

Table 1. Velocity model used for the locations of earthquakes at Galeras volcano.

Depth of top of layer (km)	P-wave velocity (km/s)
0.0	3.5
2.0	3.7
4.0	4.0
8.0	6.0
26.0	6.8
44.0	8.0

The VT earthquakes occur close to the active crater with an apparent tendency to align with the active faults mapped in the region of Galeras, particularly in direction SW-NE, although there are also earthquakes that align in direction SE-NW (Figure 1). The depths of earthquakes vary, but we observe a dominance of hypocenters between the summit and 10 km depth (Figure 2). We also observe that between 1989 and mid-1995 the seismicity rates vary quite frequently because of intense swarm activity. After August 1995 the distribution and rates of earthquakes are more representative of background-like seismicity.

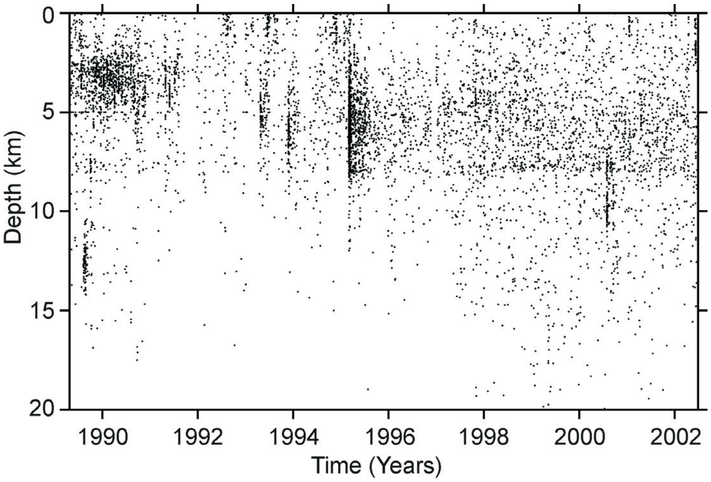

Figure 2. Time-Depth plot for VT earthquakes at Galeras for earthquakes recorded between 1989-2002. Depths are referenced to the volcano's summit, which is 4,200 meters above sea level. Seismicity prior to August 1995 is characterized by swarm activity, and during subsequent years the seismicity is more representative of a background-like activity.

We use the catalog of earthquakes and map the b-value to recognize the regions where the production of small earthquakes is statistically higher or lower than average. This is of interest because several workers at volcanoes elsewhere have suggested a relationship between high b-values, and possible regions of high material heterogeneity, high pore pressure, decreased applied stresses and high thermal gradients; which are conditions that intuitively are expected near magma conduits or reservoirs.

On average, the number of stations used routinely for locations of VT earthquakes shows a clear tendency to increase with time (Figure 3), which also prompted us to use the more recent data since 1995. The original catalog compiled by OVSP 8,435 earthquakes with magnitudes in the range -1.2 to 4.5. The original magnitudes are duration magnitudes (M_D) estimated from the duration of shaking, starting from the onset of the P-waves until the coda waves are roughly equal in amplitude to the background noise. We discarded earthquakes without magnitude computation or with no estimates of the location errors.

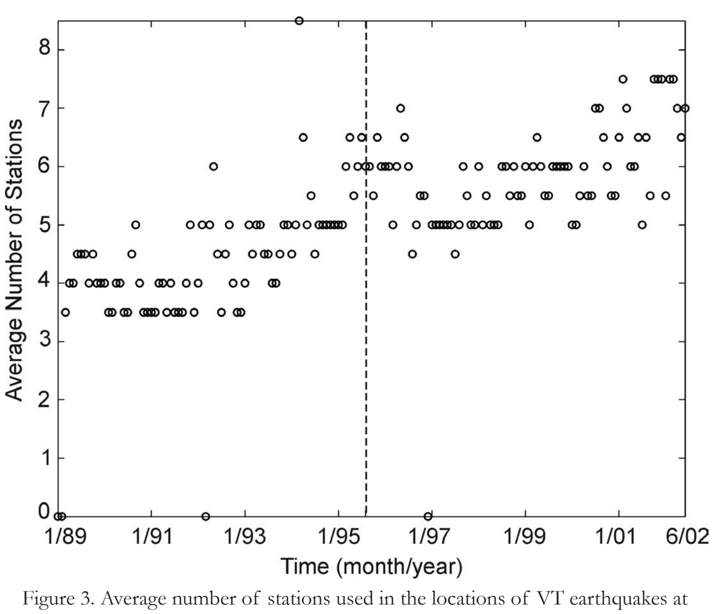

Figure 3. Average number of stations used in the locations of VT earthquakes at Galeras. The vertical dashed line indicates the date August 1995. Values of zero were assigned whenever the catalog did not have locations during a particular month.

We computed preliminary estimates of the M_c and b-values using the original M_D of earthquakes and found that the average M_c and b-value were 0.26 and 0.71, respectively. This suggests that the magnitude scale is unintentionally stretched and implies that in terms of the usual b-values (b~1) our anomalous volumes have low values. Thus we could argue that it is still possible to map volumes of high b, relative to "normal" (what we define as the average b in our catalog). Although it is difficult to devise a magnitude scale that is identical to that originally defined, we used amplitude data for 147 earthquakes recorded at the four broadband stations between April 2002 and September 2003, and duration data for the same set of earthquakes recorded by the short-period network to derive a regression equation to convert all magnitudes in the catalog from M_D to M_L (Figure 4). This implies that our new magnitudes will be scaled up by some amount and produce Mc and b-values that look comfortably similar to those in other areas. We feel, however, that we still cannot directly compare b-values in one local catalog to those in another and recommend that the results of this work be cautiously used and with comparison purposes in the Galeras area only, without attempting to derive conclusions on the absolute value of b.

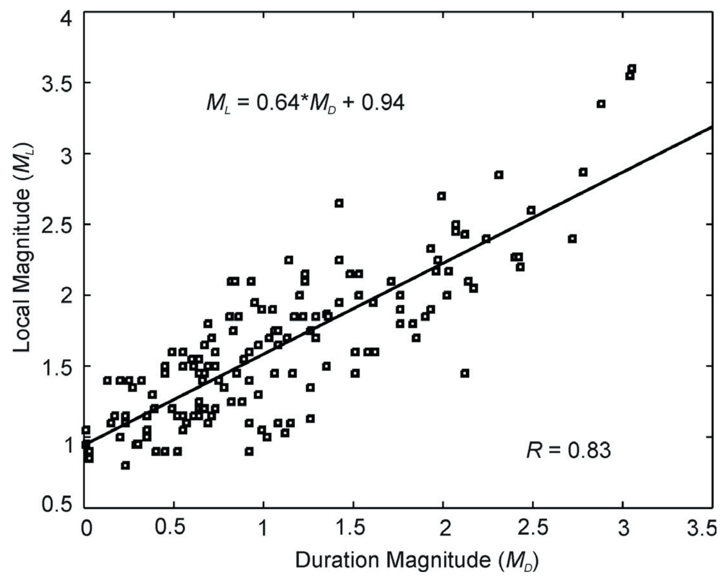

Figure 4. Regression equation for ML. Plot of duration magnitude versus local magnitude for 147 VT earthquakes simultaneously recorded by the broad band and short period subnetworks. The solid line is the best fit to the data. The regression equation is used to re-compute all duration magnitudes used in the mapping of b-values at Galeras. The change of magnitude scale results in a positive shift of the average magnitude of completeness and b-value of Δ Mc = 0.94 and Δ b = 0.44, respectively.

The histogram of the number of events versus magnitudes shows a simple distribution (Figure 5a), with some peaks, but in general uniform. The maximum in number of earthquakes occurs in the magnitude range 1 to 1.5, which is a first indication of the value of M_c of the catalog. Indeed, an automatic estimate, based on least squares, shows M_c = 1.2. The slope of the line that best fits the FMD for earthquakes with M_L > 1.2, is b = 1.15 (Figure 5b).

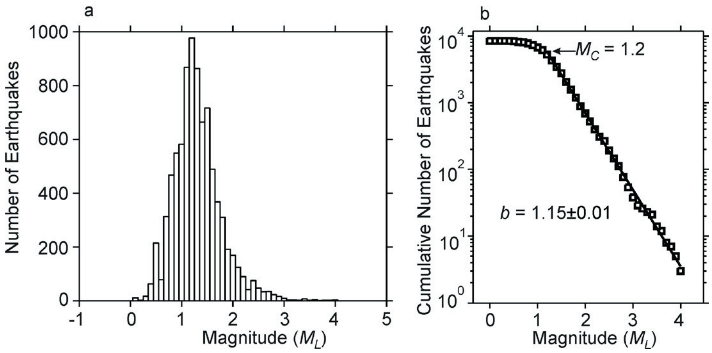

Figure 5. Average magnitude of completeness. (a) Histogram of the number of events versus magnitudes for the original catalog compiled by OVSP. The magnitude bins are equal to 0.1. (b) The frequency-magnitude distribution (FMD) for earthquakes at Galeras. The solid line shows the least squares best fit.

The formal errors in locations of earthquakes used here, as estimated by the computer program HYPO71 (Lee and Lahr, 1975), are on average 1 and 2 km in the horizontal and vertical directions, respectively. The errors in depth decrease to 1 km after August 1995, which may reflect the improvement of the monitoring network.

Because the M_c varies with time as a result of factors such as changes in seismograph network configuration and detection systems, instrumental failures, increased awareness and level of detail during times of volcanic unrest, and also temporal changes introduced by different human analysts during routine locations; we study the magnitude of completeness of the Galeras catalog by using a moving windows technique. For the catalog ordered sequentially in time, the detection threshold is calculated for the first 300 events by using the FMD, then the window is moved forward in time by 5 events and the computation is repeated, proceeding systematically until the end of the catalog. In this fashion we obtain a smoothed graph of M_c versus time (Figure 6).

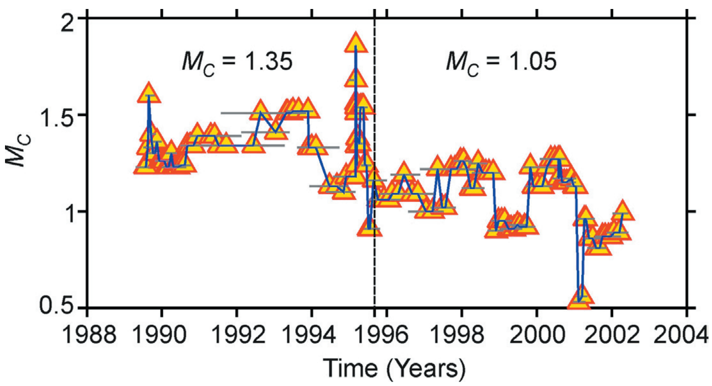

Figure 6. Magnitude of completeness (Mc) vs. time. The detection threshold is computed in moving windows with 300 earthquakes each, stepping 5 events. Triangles indicate the Mc for any particular window; horizontal lines show the window width (in time) of each group of 300 earthquakes. The average values of Mc before and after mid 1995 (vertical dashed line) are given.

We decided to divide the catalog of VT earthquakes at Galeras into two periods: pre- and post-August 1995. Because the activity prior to August 1995 was characterized by swarm activity we use only 1918 earthquakes with $M_L > 1.2$ recorded between September 1995 - June 2002 that represent better the background seismicity. This decision is based on the temporal characteristics of the VT activity (Figure 2), the gradual improvement of the seismograph network that resulted in a higher number of stations being used for the locations (Figure 3); and on average, a lower M_c (Figure 6), which allows expanding the range in magnitudes for analysis and maximizes the usable number of earthquakes. We note that the error estimates of our earthquake data are within the uncertainties that are usually expected for locations obtained from arrival times to stations in a sparse network. Our mapping of b-values is based on grids with nodes separated accordingly.

METHOD

To compute the b-value, we apply the method of Maximum Likelihood (Aki, 1965),

$$b = 2.3/(M_{avg} - M_o) \qquad (2)$$

where Mavg is the mean magnitude and $M_o = M_c - 0.05$ (0.05 is a half of the magnitude bin unit of 0.1). Because $M_{avg} - M_o$ and b are inversely proportional, whenever we measure b, we are also measuring M_{avg}.

To map b we use the method of Wiemer and Benoit (1996), Wyss et al., (1997), and Wiemer et al., (1998). Briefly, the b-values are calculated in two and three dimensions at grid nodes that are 2 km apart (horizontally and vertically), using a fixed number of earthquakes (n = 100) without limiting the size of the sampling volumes. During this mapping we observed that the radius of sampling varied between 1 and 6 km. In two dimensions, the nearest 100 earthquakes are selected according to their distances projected onto a vertical (cross-section) or horizontal (map-view) plane; therefore the sampling volumes are cylinder-shaped and varying in height. In the case of three-dimensional mapping the sampling volumes have the shape of spheres. To verify that the results are independent of the method used, we computed b-values using two methods: Maximum Likelihood (ML) and Weighted Least Squares (WLS). Because the spatial patterns in b-values were invariant, we only show the maps obtained using the ML method. For a detailed discussion on the different methods used to estimate b and a comparison of results, the reader is referred to Centamore et al., 1999.

RESULTS

The average b-value (ML > 1.2) between September 1995 and June 2002 starts at b = 1.46 at shallow depths, decreases gradually to b = 1.0 at 7 km depth, then decreases rapidly to b = 0.7 at a depth of 8 km and below this depth the b-values oscillate between b = 0.7 and b = 0.9. Below 14 km depth the amount of earthquakes is not enough to estimate reliably the b-values (Figure 7). In map view and cross-section trough the active crater (Figure 8a, b) we see that regions of low b-value are common and that the region located adjacent and beneath the active crater shows the highest b-values, this region extends from the summit of the volcano down to a depth of 5 km.

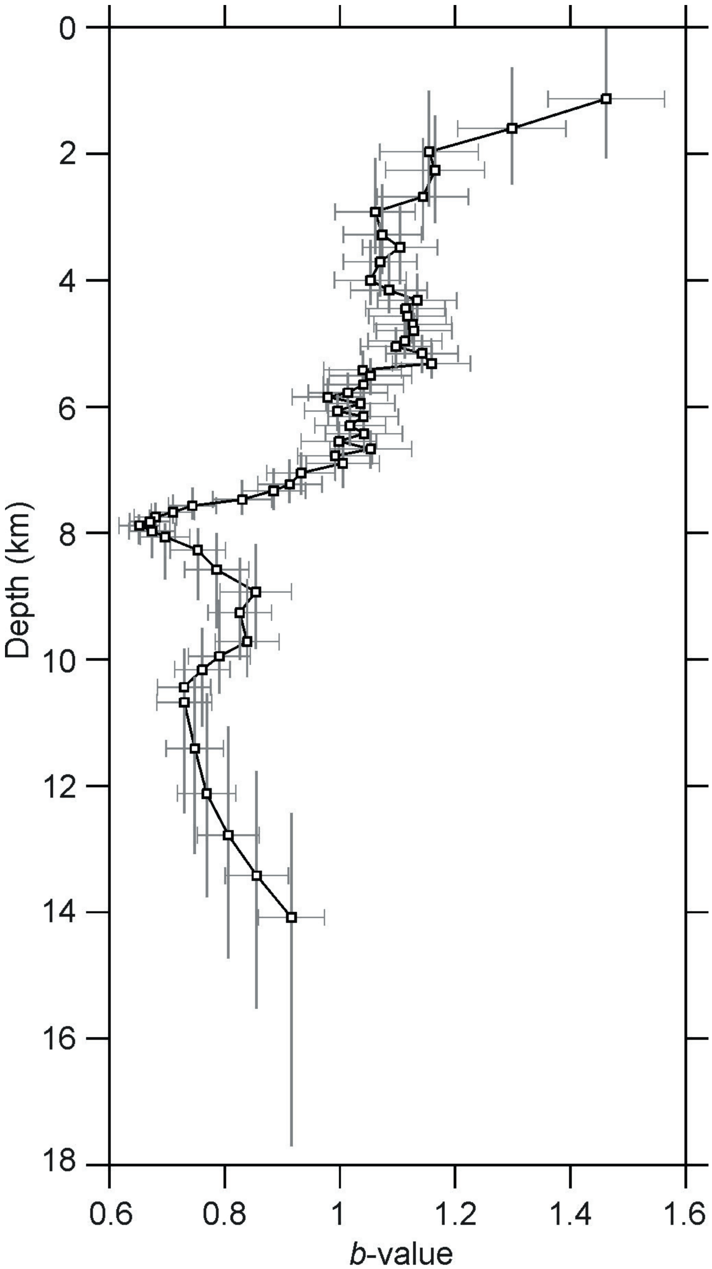

Figure 7. Average b-values versus depth at Galeras. To compute b we used mobile windows of 300 earthquakes each, stepping 5 events. Squares mark the center of the window, vertical lines show the window size and horizontal lines show the standard deviation.

These spatial patterns persisted when we mapped b under the assumption that Mc varies spatially at each sampling node; assuming that Mc is constant through the region; or changing the sampling method by using constant radius of 2 km and letting the number of earthquakes float. The differences in b-values among spatially different volumes are significant because the estimated probabilities that samples taken from contrasting regions come from the same population (Utsu, 1992) are low (Figure 8c). The three-dimensional mapping of b for Galeras volcano (Figure 9) confirms that the high b-values region is located beneath the active crater and vertically elongated down to 5 km depth.

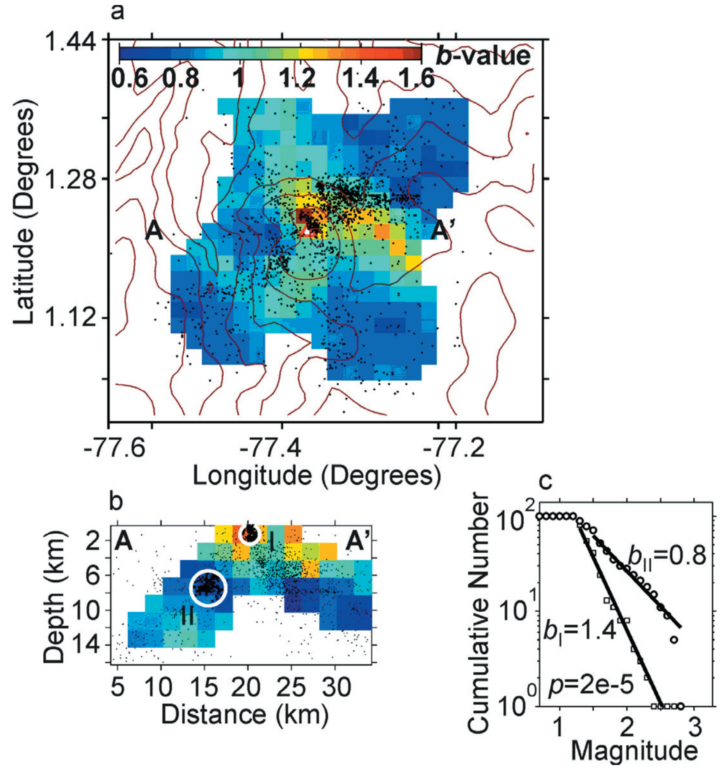

Figure 8. 2D mapping of b-values. (a) Map view showing the b-values at Galeras. Blue and reddish colors indicate low and high b-values, respectively. Nodes separated by 2km. A-A' indicates the length and orientation of the cross section. The white and red triangle marks the active crater. Other conventions as in Figure 1. (b) WE cross-section through the vent, showing the b-values at Galeras volcano. White circles labeled "I" and "II" enclose samples for which b-values are compared, selected earthquakes are marked by "x" and black dots mark other earthquake hypocenters. (c) . Frequency-magnitude distribution for selected samples in (b). The value p indicates the probability that the two samples being compared come from the same population (Utsu, 1992).

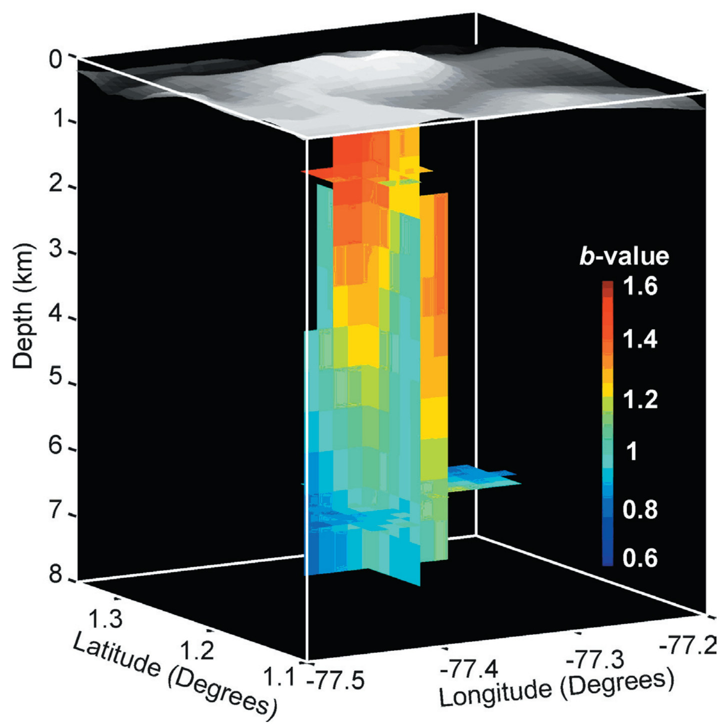

Figure 9. Three-dimensional view of b-values at Galeras volcano. The mapping of b is performed in a 2km x 2km x 2km grid (Lat., Lon., Depth) selecting the nearest 100 earthquakes to each node. The two vertical slices are mutually orthogonal and intersect at the vent in WE and NS directions. Two additional horizontal slices are shown at depths of 1.5 and 6.5 km. The light and dark tones of gray represent the topography (lighter colors are topographic highs).

DISCUSSION

The b-values calculated in this study are similar to those found by Eraso and Guerra (2002) in their study of the seismogenic regions around Galeras. They found that shallow sources that are close to the crater show b-values that are higher than those for deeper sources away from the vent. Because the absolute value of b depends on the magnitude scale used (Zúñiga and Wyss, 2001) we suggest that our estimates be taken with caution and used only for comparison purposes within the Galeras region. The contrast in b-value among different volumes that we document here is robust because the statistical tests indicate low probabilities that samples taken from contrasting regions are the same; and the spatial pattern of anomalies in b-values persists, independent of the methods used in sampling of earthquakes and estimating b.

Wiemer (1996) put forward the idea that restricted volumes of anomalously high b-values exist at volcanoes. This hypothesis has been tested at a number of volcanic regions: Mt. St. Helens, Washington, and Spurr, Alaska (Wiemer and McNutt, 1997); Off-Ito, Japan (Wyss et al., 1997); Long Valley, California (Wiemer et al., 1998); Soufriere Hills, Montserrat (Power et al., 1998); Katmai, Alaska (Jolly and McNutt, 1999), Etna, Italy (Murru et al., 1999); Kilauea, Hawaii (Wyss et al., 2001); and Mt. Pinatubo, Philippines (Sánchez et al., 2004). Thus, high b-value anomalies seem pervasive and independent of the type of volcano, although the pattern of the anomalies does vary.

There are many possible causes for higher-than-normal b-values at volcanoes. At Galeras, the high material heterogeneity was highlighted as likely by Eraso and Guerra (2002) and related to the high b-values calculated for sources beneath and west of the vent. A possibility for the material heterogeneity close to the crater could be the fracturing of a semi-brittle magma body. When rapidly deformed, these bodies can fracture just as seen on the surface of lava domes, and the earthquakes thus generated would be relatively small (C. Newhall, Pers. Comm., 2003, Sánchez et al., 2004). Because Galeras has shown frequent eruptive activity, including emplacement of a lava dome (Calvache and Williams, 1997), we speculate that the high b-values found beneath the active crater may correspond to the regions adjacent to a conduit, the remnants of a semi-crystallized intrusion, or a shallow and temporary magma reservoir.

The total volume of the dome and its conduit system emplaced at Galeras between 1990-1992 was estimated as 8.4 x 106 m3 by Calvache and Williams (1997), the b-value anomaly that we report here is larger, ~ 32 x 106 m3, which makes sense, if it surrounds a shallow semi-crystallized magma body.

Temporal changes in b-values at Galeras have been studied with some detail (Torres and Gómez, Pers. Comm., 2004). The b-values on the most active seismogenic sources at Galeras are also in the range 1.0 – 1.4 and it is speculated that the variations in b are related to changes in the volcano's eruptive activity. In this work, however, we limit our analysis to spatial changes and suggest, as future work, the refining of the study of temporal variations by using a differential mapping technique (Wiemer et al., 1998).

Galeras is not the exception among other volcanoes where b has been mapped, and several other possibilities for the generation of higher-than-normal b-values remain an open question. The location and apparent configuration of the anomaly found here, however, illuminates a new feature that has not been mapped by this method before (Figure 9). Perhaps the application of earthquakes-relocation techniques and mapping using other approach (P-and S-wave velocity tomography) can put our results to the test.

CONCLUSIONS

The relative distribution of VT earthquakes magnitudes at Galeras volcano, Colombia has been mapped to a depth of 8 km below the summit. We found relatively higher b-values in an elongated region below the vent and down to a depth of 5 km. This indicates the occurrence of earthquakes that are smaller than average. The higher-than-normal b-values can result from high pore pressure, repeated intrusions and eruptions, or alternatively, from high material heterogeneity (as produced by many fractures). There exists the possibility that we are illuminating the region adjacent to the conduit, a shallow magma reservoir, or the remnants of a semi-crystallized intrusion.

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