EARTH SCIENCES
RESEARCH JOURNAL

Earth Sci. Res. J. Vol. 8, No. 1 (Dec. 2004): 19 - 24

TEMPORAL VARIATION OF CODA-Q AT GALERAS VOLCANO, COLOMBIA

Édgar Moncayo[1], Carlos Vargas[2] and Juan Durán[3]
[1]*Universidad Nacional de Colombia. E-mail cavargasj@unal.edu.co*
[2]*Universidad Nacional de Colombia. E-mail cavargasj@unal.edu.co*
[3]*Instituto de investigaciones geológico mineras- Ingeominas.*

ABSTRACT

The Temporal variation of coda-Q was analyzed for Galeras volcano, located in the Andes of southwestern Colombia. The Q^{-1} value was calculated using the Single Back Scattering (SBS) model working with seismograms filtered in frequency bands centered in 1.5, 3.0, 6.0 and 12.0 Hz. The analysis was done in 1990-2002 period, using the URCR station and the frequency dependence $Q = Qo\, f^{-n}$ was calculated before and after some eruptions. We used volcano tectonic events with magnitude lower than 1.5 and RMS, GAP, vertical and horizontal errors lower than 0.1s, 180 and 1km.
The temporal change of attenuation occurred in two stages, the first in 1989-1992 period, when the Q^{-1} value increases from 0.015 to 0.070. The second is the 1992-2002 period that is characterized by a decreasing Q^{-1} value. Before July 1992 eruption the attenuation increase is associated with the extrusion of an andesitic dome, after this eruption the dome was destroyed and the Q^{-1} value drops. Starting from 1994 low attenuation values was associated with low Galera's activity. The analysis shows that Q value increases before an eruption and decreases after it.

Key words: attenuation, coda-Q, scattering, Colombia, Galeras volcano.

RESUMEN

La variación temporal de Coda Q fue analizada en el Volcán Galeras ubicado en el sureste de los Andes colombianos. El valor Q^{-1} fue calculado usando el modelo "Single Back Scattering" (SBS) trabajando con sismógrafos filtrados en bandas de frecuencia centradas en 1.5, 3.0, 6.0 y 12.0 Hz. El análisis fue hecho durante el periodo 1990-2002, usando la estación URCR y las frecuencias dependientes $Q = Qo\, f^{-n}$ fueron calculadas antes y después de algunas erupciones. Usamos eventos Vulcano tectónicos con magnitud menor que 1.5 y RMS, GAP, vertical y horizontal con un margen de error menor que 0.1s, 180 y 1km.
Los cambios temporales en la atenuación se dieron en dos etapas, la primera en el periodo 1989-1992 donde el valor Q^{-1} se incremento desde 0.015 a 0.070. El segundo en el periodo de 1992-2002, caracterizado por un decrecimiento del valor Q^{-1}. La atenuación se incrementa antes de la erupción de julio de 1992. Esta erupción está asociada a la extrusión de la cúpula de los Andes. Después de esta erupción la cúpula se destruyó y cayo el valor Q^{-1}. Iniciando en 1994, los bajos valores de atenuación fueron asociados a la baja actividad del volcán Galeras. El análisis muestra que el valor Q se incrementó antes de la erupción y decreció después.

Palabras clave: atenuación, coda-Q, dispersión, Colombia, volcán Galeras.

Manuscript received April 2004
Paper accepted October 2004

INTRODUCTION

Galeras volcano (Lat. 1°14’N, Lon. 77°22’W) is 4200m-high andesitic volcano in the Andes of southwestern Colombia and is the most recent active center of Galera’s volcanic complex (Cepeda, 1986). The active cone has 320 m in diameter and lies within a caldera that is breached to the west. Galeras is historically characterized by Vulcanian type explosions (Calvache, 1990). The most important one recorded, in 1936, generated a pyroclastic flow to the northeast of the volcanic structure. The volcano lies 8 km from Pasto city and various

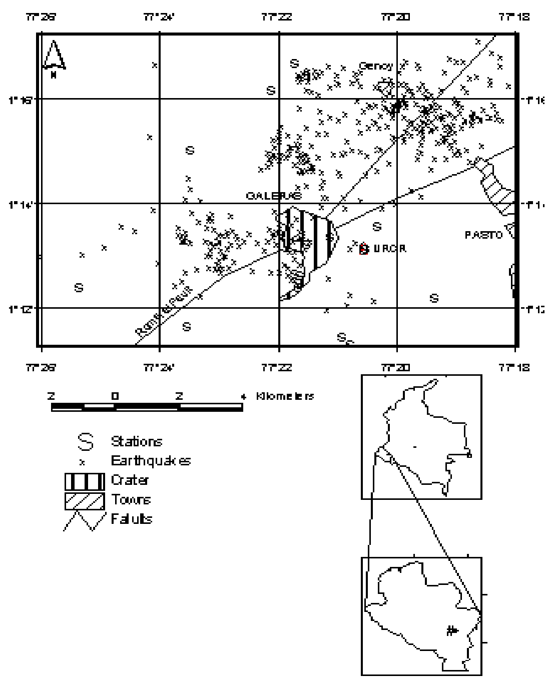

Figure 1. Location of Galeras volcanic complex area, and the earthquakes (circles) and stations (S) used for determinations.

other towns locate on its flanks. In total, 400.000 people live close to the volcano, inside this hazard zone. Since 1988, when Galeras was reactivated, after 50 years of repose, it entered in a fumarolic and degassing stage, with seven eruptions between 1989 and 1993. An andesitic dome was extruded in September 1991 and destroyed during July 1992 eruption. Since 1994 Galeras is in calm stage with lesser explosions and seismic crises in 1995, 1982, 2000 and 2002.Many studies have been done since Cepeda (1986) and Calvache (1990).

The latter made a stratigraphic correlation based on C^{14} in the 1990-1993 period Galeras was declared the volcano of the decade and much research was done. On 1993 January 14 during an international workshop while a fieldwork was in progress in the crater, there was an eruption where several scientists died and others resulted injured.
Many works were published about Galeras in different disciplines: Calvache et al., (1997) worked the stratigraphy and evolution of the volcano, a model of degassing was proposed by Stix et al., (1993) and geochemistry studies were done by Zapata et al., (1997). In the seismology field, the works of Gómez and Torres (1997) and Narvaéz et al., (1997) analyzed the tornillo-type signals whereas the different features seismic sources has been analyzed by Ortega et al., (2002).
Any investigation about temporal variation of the attenuation hasn’t been done, so this is an innovative study that enlarges the knowledge about Galeras Volcano.

Geological Setting

Galeras is located in southwestern Colombia, a region with a metamorphic rocks basement of Precambrian and Paleozoic ages. The basement is overlaid by metamorphic rocks of Cretacic age with low and medium grade associated with amigdular metabasalts. All of this is covered by volcano sedimentary units of Tertiary age that made a plateau, over which the Pleistocenic and Holocenic volcanoes have emerged.
The tectonic plate of this region is very complex, as a result of the collision between the Nazca and southamerican plates. This causes the uplift of the Andes and the volcanism in the region. The structural trend is N40°E and the principal tectonic feature is the Romeral Fault Zone, which has been interpreted as the limit between continental crust to the East and the oceanic crust to the West (Barrero, 1979). This system includes the Silvia-Pijao and Buesaco faults, both of which cross under Galeras, and are associated with many old caldera systems (Figure 1).

METHOD

We follow the Single Back Scattering (SBS) model of Aki and Chouet (1975) for calculating Q^{-1} from the ending portion of the records of local earthquakes, or coda waves. The Q factor contains information about seismic energy for two reasons: intrinsic losses (Qi) and radiation losses (Qr).

The method assumes that local earthquake coda is composed by the sum of secondary S waves produced by heterogeneities inside a propagation medium. In this context, coda is the portion of seismogram corresponding to back-scattered S-waves, whose travel times are assumed to be twice the S-wave travel time taken from the origin of the earthquake. We assume that the coda portion finishes when the signal-noise ratio is lower than approximately 2 (Aki and Chouet, 1975).

The SBS model considers the back-scattered S-waves produced by in homogeneities (scatterers) distributed randomly and uniformly in the lithosphere. The basic and simplified equation is:

$$\ln [\, t^2 A_{obs} (f \,|\, r, t)] = C - Q^{-1}\, 2\pi f t \qquad (1)$$

Where C is a constant, $A_{obs} (f \,|\, r, t)$ is the squared amplitude of the record, f is the frequency, t is the time and Q is the quality factor, which contains information about the attenuation of seismic energy.

Equation (1) has the form $\mathbf{Y} = b\mathbf{X} + C$ where:

$$\mathbf{Y} = \ln [\, t^2 A_{obs} (f \,|\, r, t)]$$

$$\mathbf{X} = 2\pi f t$$

$$b = Q^{-1} \qquad (2)$$

Thus from this model it is possible to calculate Q^{-1} from the slope b, using least-squares techniques.

DATA AND PROCESSING

The seismic data used in this study covered the period between September 1989 and June 2002. The seismograph network installed at Galeras is composed of 31 stations equipped with vertical component L-4C seismometers with 1second natural period. The ground motions were telemetric from an observatory located at Pasto city and the information taken was signals sampled at a rate of $100s^{-1}$. However, seismograph stations have not operated continuously because of changes on network configuration, we used earthquakes with magnitude less than 1.5 to avoid clipping. A total of 435 earthquakes were selected for this study. For hypocenter determinations we used the HYPO71 computer program (Lee and Lahr, 1975).

Table 1. VELOCITY MODEL USED TO LOCATE THE HYPOCENTERS

Depth at top of the layer (km)	**P-wave velocity (km/s)**
0.0	3.50
2.0	3.70
4.0	4.00
8.0	6.00
26.0	6.80
44.0	8.00
Vp / Vs	1.78

Defined to use regional seismic reflection profiles and based in the work by Meissner Et al., (1977). We carefully selected seismograms of located earthquakes with root mean square residuals of calculated travel times and observed times (RMS) less than 0.1s, azimuthal separation between stations (GAP) less than 180°, and formally computed horizontal and vertical errors in locations of less than 1 km. Figure 1 shows the location of the seismograph stations and selected earthquakes. The coda-Q was calculated for four frequency bands centered at 1.5, 3.0, 6.0 and 12.0 Hz, (see Figure 2),

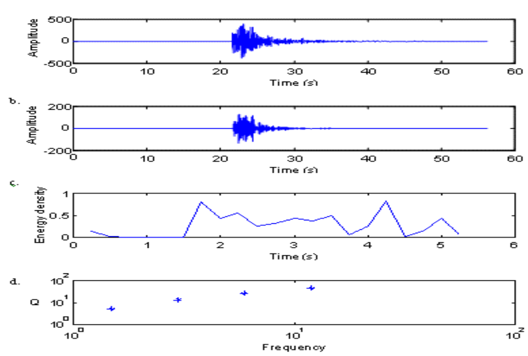

Figure 2. Data processing example a. Raw seismogram b. Band-pass filtered seismogram with centered band at 12 Hz c. Energy density d. Q^{-1} values.

We used the velocity model adopted by the Pasto Volcano Observatory (Table 1), using the SBS model with a variation of the in-house routine for MATLAB developed by Vargas and Mora (2000) with a 10 seconds window. Because variations in Q can be introduced by changes in the spatial location of the earthquakes and be misinterpreted as a temporal variation, we show in Figure 3. that the hypocenters did not shift through time.

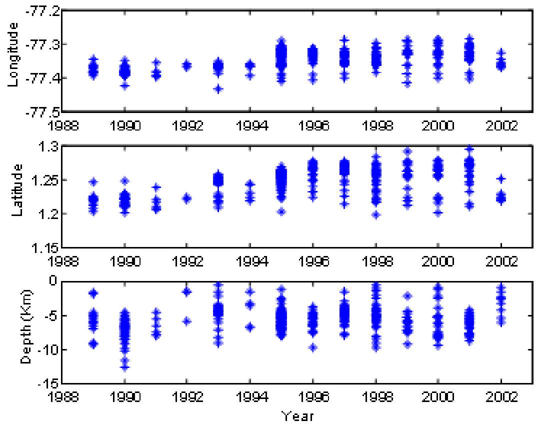

Figure 3. Space-time and depth-time plots of the selected earthquakes. Note that the hypocenters did not shift significantly with time, suggesting that any change in Q^{-1} could be due to temporal changes rather than spatial changes associated with earthquakes' locations.

We used Q-values at all stations because we note that during the entire 1989-2002 period the station were not operated, and finally find that these present a similar behavior. Additionally we worked with the URCR station, because it has the best record and a wide number of records through the time.

ANALYSIS AND RESULTS

The coda-Q was analyzed for frequency bands centered in 6 and 12 Hz. Figure 4 shows that Q^{-1} values for the 12 Hz band show a clear change in time, maybe contribution of intrinsic absorption to the total attenuation is higher at 12 Hz that at 6 Hz for Galeras volcano. The temporal variations of Q -1 value obtained by the SBS model show clear tendencies that follow the changes in volcanic activity. To find the frequency dependence of Q^{-1}, we fit the values of Q^{-1} for each frequency band ($Q = Q_o f^{-\eta}$). Table 2 shows the results obtained from Q_o and for each eruption (pre and post-eruptive periods). There is a clear difference before and after each eruption.

Temporal changes can be separated in two stages, the first, before July 1992 eruption, shows a fast rise of Q that begins in October 1991 and reaches a maximum value before the eruption. The second stage begins after this eruption, since this date, a long-lasting drop in Q is registered, in a short time a little raise happening before June 1993 eruption, and from

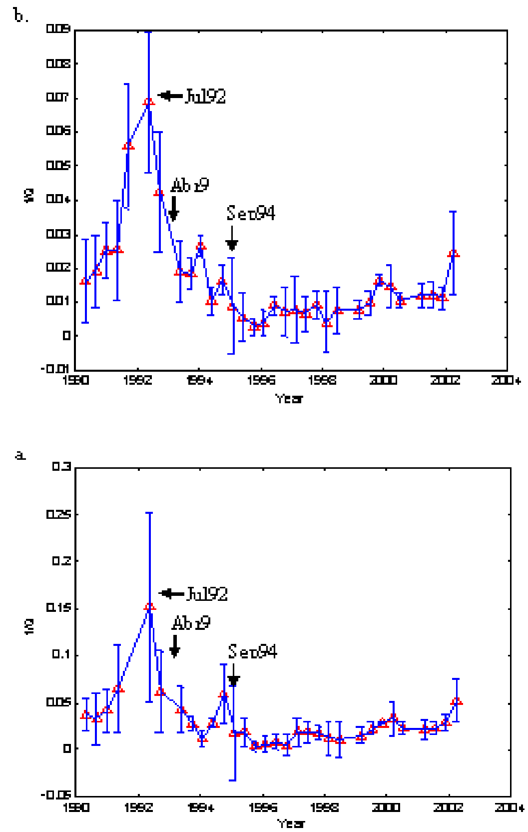

Figure 4. Result of Q^{-1} analysis a. 6, b. 12 Hz. Notice the temporal changes at 12 Hz. The Q^{-1} values for 6 Hz show scatter. Arrows mark the dates of eruptions and periods of unrest at Galeras volcano.

TABLE 2. FREQUENCY DEPENDENCE PARAMETERS BEFORE AND AFTER OF SOME GALERAS ERUPTIONS

Period	Q^{-1}	η
Before Jul.-92 eruption	2.8290 ± 1.32	0.8229 ± 0.12
After Jul.-92 eruption	3.2837 ± 1.31	1.4565 ± 0.44
Before 16 Apr.-93 eruption	5.4490 ± 1.43	0.8541 ± 0.15
After 16 Apr.-93 eruption	6.0613 ± 2.60	0.9271 ± 0.15
Before Jun.-93 eruption	5.2673 ± 1.98	0.9840 ± 0.13
After Jun.-93 eruption	6.0890 ± 1.67	1.2225 ± 0.10

1994 to 2002 there were not important changes. The frequency dependence parameters (Table 2) show an increase before eruptions and a fall after these, a similar trend shows the Q^{-1} value Figure 5.

DISCUSSION AND CONCLUSION

Evident changes in Q^{-1} occurred in 1990-2002 period. These changes cannot be ascribed to spatial changes in earthquakes hypocenters (Figure 2). We concluded that these differences are attributed to changes in the volcano activity and discarded changes related to spatial variations.

The values obtained in this work show two stages separated by July 1992 eruption. This date marks an important change at Galeras activity, because before this date the attenuation had a clear upward tendency, and after it, the Q^{-1} value decreased, with no similar values being recorded since. Finally, the Q^{-1} values show a slow recovery since 1995 to 2002 with a steep increase at the end.

Our results are according to the study by Londoño Et al., (1998) about Nevado del Ruiz Volcano, Colombia. They observed a systematic decrease in the Q^{-1} values before and after two phreatomagmatic eruptions in 1985 and 1989.

At Galeras, the temporal variation shows that 12 Hz is the best frequency value to discern changes in the activity. These variations in Q^{-1} are clearly associated with changes in the volcanic activity as follows: The fall in the attenuation between 1990 and 1991 can be associated with a degassing process that begins after 1989 eruption. The rise between October 1991 and July 1992 is related to an important change in volcanic activity, such as the extrusion of an andesitic dome with accompanying shallow deformation, increase in the rates and amplitudes of long-period seismic events, and a decrease in the SO_2 flux. This suggest that the conduit was partially blocked because the viscous magma in the dome acted like a seal that stopped the gas flux, this caused an increase in pressure and attenuation that ended on July 1992 eruption. After this explosive eruption the dome was destroyed and the gas released. For this reasons the pressure drops and attenuation appears. Before June 1993 eruption a little rise took place. We suggest this can be caused by small plugs formations that are destroyed in subsequent eruptions. For that reason we didn't have enough data to get consistent results. Attenuation parameters were analyzed on July 1992, April 1993, and June 1993 eruptions. Although the error bars are superimposed, (Figure 5), the frequency dependence of Q shows a similar tendency because we observe three cases in which the attenuation (Q^{-1}) exhibits a decrease in value before and after each eruption. The parameters also show a long-term decreasing tendency that is according to the fall in the Q^{-1} value during the 1992-1994 periods.

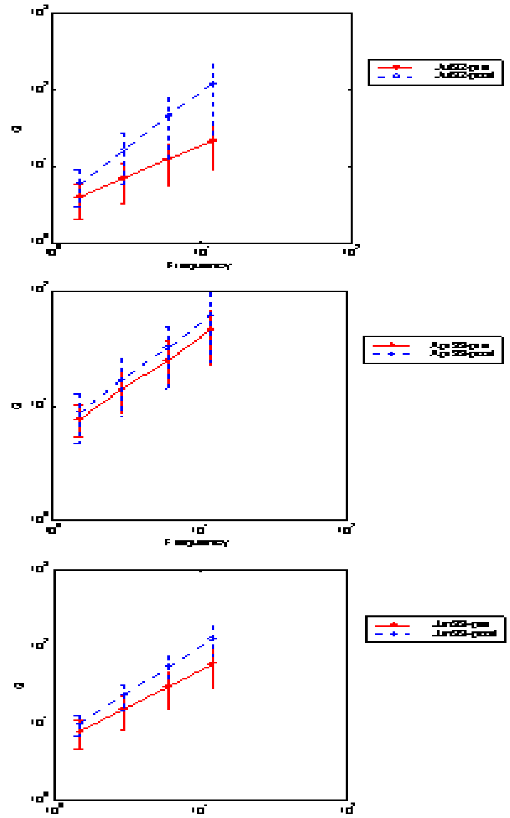

Figure 5. Changes in Q^{-1} values before and after some eruptions. Note the decrease of Q^{-1} values after eruption.

In 1994-2002 period the Q^{-1} value were stable. We suggest that it may be associated with repose of the volcano, because it reached an equilibrium state after 1993 eruptions. In this stage little rises in the Q^{-1} value took place. These could be related to minor explosions and ash emissions possibly caused by small gas accumulations (i.e., during June 2002).

The changes in the Q^{-1} values show that this parameter can be used as an important tool at Galeras volcanic surveillance, because is clearly related to the activity changes, especially before the eruptions. We suggest implementing an attenuation monitoring system. Measure by Q^{-1}, can be a good complement to the information currently used, for instance, number of seismic events, deformation measurements, and fumaroles gas geochemistry thus helping improve the monitoring. Finally we recommend more detailed studies that investigate a possible use of Q^{-1} for forecasting.

ACKNOWLEDGEMENTS

We thank INGEOMINAS-CORP for technical support in this study. We also thank the comments of our colleagues from Volcanological and Seismological Pasto Observatory, OVSP. Specially thanks to R. Torres for suggestions and comments.

REFERENCES

Aki, K., Chouet, B., (1975). Origin of coda waves: source, attenuation and scattering effects. Journal of Geophysical Research, 80: 615-631.

Barrero, D. (1979). Geology of central western cordillera west of Buga and Roldanillo, Colombia. Informe Ingeominas, Bogotá (Colombia).

Calvache, M. (1990). Geology and Volcanology of the recent evolution of Galeras volcano, Colombia. M.S. Thesis, Louisiana State University.

Calvache, M., Cortés, P., Williams, S. (1997). Stratigraphy and chronology of the Galeras Volcanic Complex, Colombia. Journal of Volcanology and Geothermal Research, 77: 5-19.

Cepeda, H. (1986). Investigaciones petrológicas en el ámbito de las planchas 429-Pasto y 410-La Unión, con especial énfasis en el Complejo Volcánico del Galeras. Informe Ingeominas, Medellín (Colombia).

Gomez, D., Torrres, R. (1997). Unusual low-frequency volcanic seismic events with slowly decaying coda waves observed at Galeras and other volcanoes. Journal of Volcanology and Geothermal Research, 77: 173-193.

Lee, W. H., Lahr, J. C. (1975). HYPO71: A computer program for determining hypocenter, magnitude, and first motion pattern of local earthquakes. U.S. Geological Survey. Open-File report 75-311.

Londoño, J. M., Sánchez, J. J., Toro, L. E., Gil-Cruz, F, and Bohórquez, O. P. (1998). Coda Q before and alter the eruptions of 13 November 1985, and 1 September 1989, at Nevado del Ruiz Volcano, Colombia, Bulleting of. Volcanology, 59: 556-561.

Meissner, R., Fluedh, E., Stibane, F., y Berg, E., (1977), Dinámica del límite de placas activo en el SW de Colombia, de acuerdo a recientes mediciones geofísicas. En: Proyecto Cooperativo Internacional Nariño "La Transición oceáno-continente en el suroeste de Colombia": 169-199.

Narváez, L., Torres, R., Gómez, D., Cortés, P., Cepeda, H., Stix, J. (1997). “Tornillo”-type seismic signals at Galeras volcano, Colombia, 1992–1993. Journal of Volcanology and Geothermal Research, 77: 159-171.

Ortega, A, Torres, R., Gómez, D. (2002). Caracterización de fuentes sismogénicas de eventos volcano-tectónicos (VT) en el complejo volcánico Galeras. Memorias. Primer Simposio Colombiano de Sismología.

Stix, J., Zapata, J., Calvache, M., Cortez, G., Fischer, T., Gómez, D., Narváez, L., Ordoñes, M., Ortega, A., Torres, C., Williams, S. (1993). A model of degassing at Galeras Volcano, Colombia, 1988-1993. Geology, 21: 963-967.

Vargas, C, Mora, P. (2000), Conceptos sobre atenuación de ondas coda. Red Sismológica Regional del Eje Cafetero–Viejo Caldas y Tolima: 37-43.

Zapata, J., Calvache, M., Cortés, P., Fischer, T., Garzón, G., Gómez, D., Narváez L., Ordóñez, M., Ortega, A., Stix, J., Torres, R., Williams, S. (1997). SO_2 fluxes from Galeras Volcano, Colombia, 1989–1995: Progressive degassing and conduit obstruction of a Decade Volcano. Journal of Volcanology and geothermal research. 77: 195-208.