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ACTIVITY AND Vp/Vs RATIO OF VOLCANO-TECTONIC SEISMIC SWARM ZONES AT NEVADO DEL RUIZ VOLCANO, COLOMBIA

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ABSTRACT

An analysis of the seismic activity for volcano-tectonic earthquake (VT) swarms zones at Nevado del Ruiz Volcano (NRV) was carried out for the interval 1985- 2002, which is the most seismic active period at NRV until now (2010). The swarm-like seismicity of NRV was frequently concentrated in very well defined clusters around the volcano. The seismic swarm zone located at the active crater was the most active during the entire time. The seismic swarm zone located to the west of the volcano suggested some relationship with the volcanic crises. It was active before and after the two eruptions occurred in November 1985 and September 1989. It is believed that this seismic activity may be used as a monitoring tool of volcanic activity. For each seismic swarm zone the Vp/Vs ratio was also calculated by grouping of earthquakes and stations. It was found that each seismic swarm zone had a distinct Vp/Vs ratio with respect to the others, except for the crater and west swarm zones, which had the same value. The average Vp/Vs ratios for the seismic swarm zones located at the active crater and to the west of the volcano are about 6-7% lower than that for the north swarm zone, and about 3% lower than that for the south swarm zone. We suggest that the reduction of the Vp/Vs ratio is due to degassing phenomena inside the central and western earthquake swarm zones, or due to the presence of microcracks inside the volcano. This supposition is in agreement with other studies of geophysics, geochemistry and drilling surveys carried out at NRV.

Key words: earthquake swarm, volcano-tectonic earthquakes, volcanic activity, Vp/Vs ratio, volcanic eruption.

RESUMEN

Se llevó a cabo un análisis de a actividad para zonas de enjambres sísmicos tipo volcano-tectónico (VT) en el Volcán Nevado del Ruiz (VNR), para el período 1985-2002, que fue el período sísmicamente más activo hasta el 2010. Los enjambres sísmicos se localizaron en fuentes muy bien definidas alrededor del cráter. La fuente sísmica localizada en el cráter, fue la más activa durante este tiempo. La zona ubicada al W del cráter, parece tener una relación con crisis volcánicas posteriores, permaneciendo activa antes de las erupciones de noviembre de 1985 y septiembre de 1989. Se cree que la ocurrencia de sismicidad en esta zona sísmica, puede ser usada como premonitorio de actividad volcánica en el VNR. Para cada zona sísmica se calculó el Vp/Vs agrupando sismos y estaciones para cada una de ellas. Se encontró que cada zona sísmica tiene un valor Vp/Vs diferente de las otras. Las zonas cráter y oeste (W) presentaron el mismo valor de Vp/Vs. El valor de Vp/Vs para la zona cráter y W, fue un 6-7% menor el de la zona norte, y un 3% menor que el de la zona sur. Se interpreta que la disminución del Vp/Vs es debido a desgasificación producida en las zonas sísmicas del cráter y al occidente del volcán, o a la presencia de microgrietas en

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el interior del volcán. Esta suposición esta soportada en otros estudios geofísicos, geoquímicos y de datos de pozos geotérmicos, llevados a cabo en el VNR.

Palabras clave: enjambre sísmico, sismos volcán - tectónicos, actividad volcánica, proporción Vp/Vs, erupción volcánica

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1. Introduction

In many volcanoes around the world, volcano-tectonic (VT) earthquakes are directly or indirectly associated with volcanic activity. In some cases they are associated with magmatic intrusions and rock fracturing (Karpin and Thurber, 1987). This earthquakes are also known as high-frequency events, and they are thought to be produced by shear failure or slip on faults in the volcano edifice. The only difference with tectonic earthquakes, is their pattern of occurrence. In volcanoes, they occur in swarms, that is a group of many earthquakes of about same size and location with no dominant shock (McNutt, 2000).

The Nevado del Ruiz Volcano (NRV) (Fig. 1) began the last eruptive period in December 1984; after this event the most important eruptive processes have been those of November 13, 1985 and September 1, 1989 (Bohorquez, 1993). At NRV the VT seismic activity sometimes increased several days before the volcanic crises (eruptions, ash emissions, etc.). VT earthquakes occurred both in a swarm-like pattern and as isolated earthquakes, but mainly in swarm-like pattern (Muñoz *et al.*, 1990).

Several studies of the VT activity at NRV have been carried out with the aim of finding relationships with volcanic activity. All these studies have been done for VT seismicity in NRV but only over short periods of time (e.g., Nieto and Muñoz 1988; Nieto *et al.,* 1990; Bohorquez 1993; Londono and Kobayashi, 1994; Londoño 1996, Londono and Sudo, 2001).

Nieto *et al.* (1990) found clusters of VT earthquakes based on the hypocenters obtained for the period July 1985 - December 1986. They associated such clusters with a possible ascent of magma. Muñoz *et al.* (1990) identified some geologic features in the area around NRV analyzing hypocenters and composite focal mechanism of VT swarms

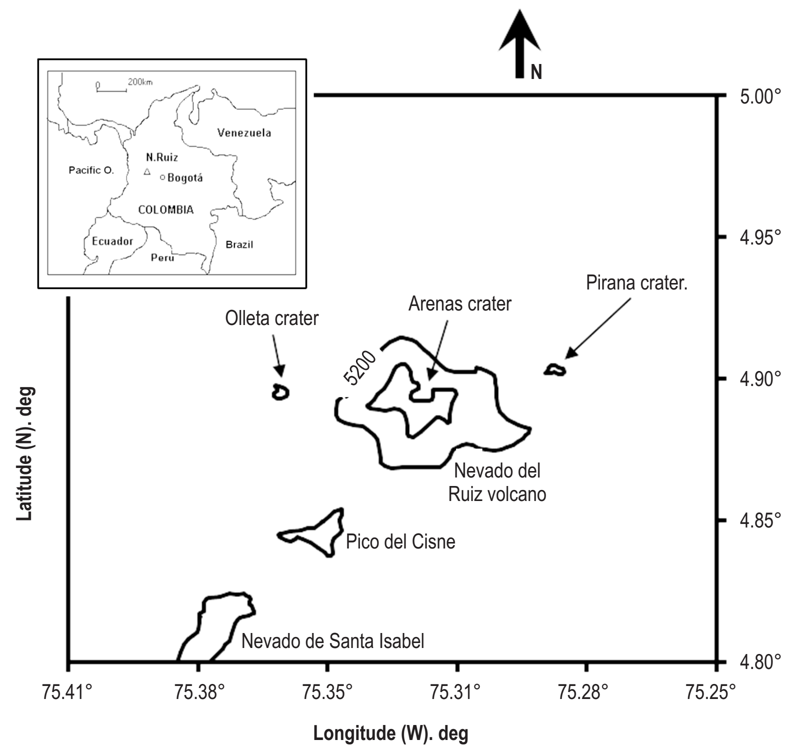

Figure 1. Location map of the Nevado del Ruiz Volcano (NRV). The topographic curves of 5200 and 5000 m are shown as reference.

from 1986-1987. They conclude that the magma chamber of NRV has a very complex geometry. Zollweg (1990) studied VT seismicity from December 1985 to May 1986, examining spatial patterns and information on the orientation of local tectonic stress. He also concludes that these kind of earthquakes are related with a magma-transport process. Muñoz (1992) made a study of lateral variations of P wave velocity by using a tomographic technique. The preliminary results obtained with this 3D model suggested that there are several regions of low velocity beneath the active crater and northwest of it. Bohorquez (1993) analyzed arrival times of P and S waves, polarity of the P wave, spectra of frequencies and particle motion of VT earthquake swarms occurred at August - October 1990. She found spatial concentrations of VT around NRV similar to those found by Muñoz *et al*. (1990). Londono and Kobayashi studied the VT swarms occurred during 1990 at NRV, by using a portable seismic network of 3-components. They found different seismic sources with different spectral characteristics. Londono and Sudo (2001) developed a method to determine spectral characteristics of seismic zones at NRV, by using main part of spectra of P and S waves.

The calculation of the Vp/Vs ratio in volcanic regions is another interesting subject to study. Although today the 3D tomographic technique for calculation of Vp/Vs is a powerful tool to find its wide spatial distributions, the Modified Wadati diagram (Chatterjee *et al.*, 1985) is also a useful and simple technique to find differences in Vp/Vs between small earthquake swarm regions. In that technique, the study area is divided in several sectors, and for each earthquake swarm region a group of earthquakes and stations are choose carefully to calculate the Vp/Vs ratio, to avoid mixing propagation effects between regions.

It is known that changes in Vp/Vs ratio may be related to changes in the physical and chemical properties of the medium, such as partial saturation of rocks, changes in temperature, density, and steam content (Birch, 1961; Ito *et al.*, 1979; Toksoz *et al.,* 1976). In this study we made an evolutionary study of the whole seismicity of swarm-like VT earthquakes, covering the most active periods of activity of NRV from 1985 to 1999, in order to find some relationships with volcanic activity through time. On the other hand, we calculated the Vp/Vs ratio for each VT swarm zone in order to determine if there are differences between the swarm zones. This paper does not pretend to map the distribution of Vp/Vs ratios at NRV area as a whole. Since only few specific and small zones around the volcano were investigated, we consider that for the purpose of this study the modified Wadati diagram is suitable for Vp/Vs calculation.

2. Data and processing

We used VT earthquakes recorded by the telemetered local network at NRV area (Fig. 2); the stations feature vertical component seismometers with a natural frequency of 1 Hz, model L-4C. The hypocenters of VT earthquakes for each swarm zone were selected from the database of the Volcanological Observatory of NRV for the period 1985 - 2002. Since that year the NRV has not shown swarm like seismic activity until now. We relocated the earthquakes by using the earthquake location program HYPO71 (Lee and Lahr 1985). We used a P velocity model proposed by Zollweg (1990) for NRV (Table 1). The arrival times of P phases were accurate to 0.05s and those of S phases to 0.1s. We selected those earthquakes which were recorded at five or more stations, with clear onset of P and S phases. The parameters for the selection of the earthquake locations in this analysis were: residual times less than 0.10s,

Table 1. Velocity model for P waves used for earthquake location (Zollweg, 1990)

Velocity (km/s)	depth at bottom of the layer (km)
3.6	0.00
4.6	0.95
5.5	1.95
6.1	4.00
6.6	14.00
7.8	30.00

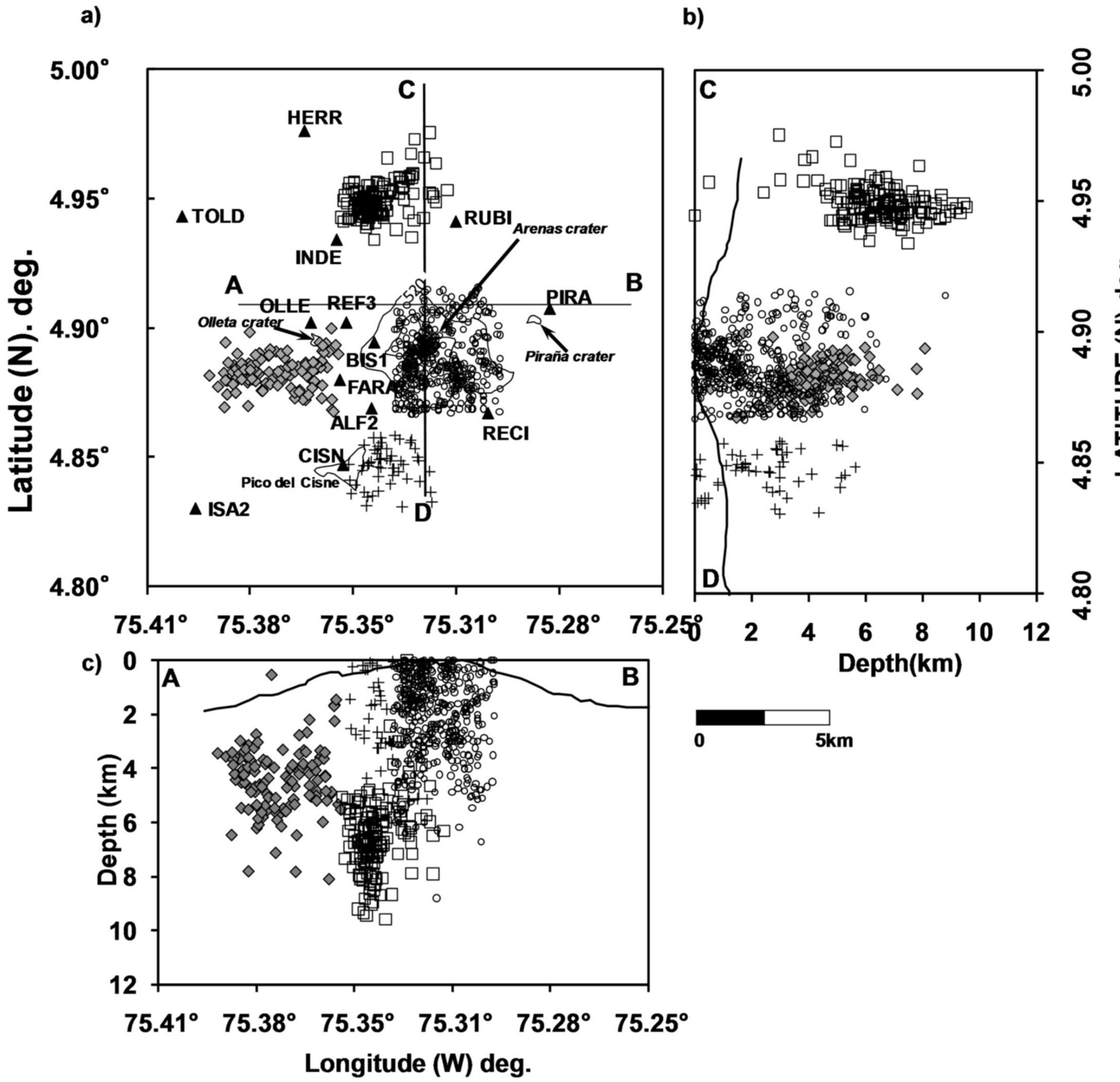

Figure 2. Epicentral and hypocentral location of the earthquake swarms and the stations used in this study. Each VT seismic zone is identified with a symbol (circles=crater zone; squares =North zones; filled rhomboids=west zone; crosses=South zone). Filled triangles represent seismic stations. The topographic curves of 5200 and 5000 masl are plotted as reference. Active crater (Arenas) and extinct craters (Olleta and Piraña) of NRV are indicated as well.

vertical errors less than 0.5km, and horizontal errors less than 0.3km.

A total of 600 high-quality earthquakes were used for the analysis. Figure 2 shows the hypocenters of these earthquake swarms as well as the seismic stations used in this study. We calculated the seismic energy for the VT selected and correlated the resulting values with volcanic activity. The seismic energy (E) was calculated from the following expressions:

$$Log\ E = 9.9 + 1.9\ M_L - 0.024\ M_L^2 \quad \text{(Richter, 1958)}$$

$$M_L = 2.82\ \log(duration) - 2.59 \quad \text{(Nieto \textit{et al.}, 1990)},$$

where M_L is the local magnitude for VT earthquakes at NRV. A modified Wadati diagram was used for the calculation of Vp/Vs ratios using selected groups of stations for each earthquake swarm zone in order to see differences among them (Chatterjee *et al.,* 1985). Instead of plotting the S-P as ordinate versus travel time of P (Tp) as the abscissa used in the normal Wadati diagram (1933), we plotted the travel time of S (Ts) as the ordinate. Assuming the Poisson's ratio to be constant along the ray path, the Tp versus Ts relation is a straight line through the origin with slope equal to the Vp/Vs ratio. A linear least square fit was made using Tp versus Ts data. The Vp/Vs ratio for each earthquake swarm was calculated with a confidence interval of 90% (Press *et al.,* 1992). Figure 3 shows some examples of the typical seismograms used in this study.

3. Analysis

Sources of error

Several sources of error are probably involved in the analysis of the evolution of VT seismicity in this study. Uncertainty about the earthquake location as well as the origin time are perhaps two of the most important sources of error. The readings of the arrival times of P phase and S phase are also possible sources of error for both Vp/Vs ratio calculation and analysis of the seismicity. As we are using only the arrival time of the S phase on the vertical component, it is possible to have some error, such as P-to-S conversion, leading to a mispicking of S wave but this possibility is low. Although we selected only very clear S phases, we assume an error of 0.5 sec in the arrival time of S phase and it is included in the error of earthquake location and Vp/Vs calculation. The velocity structure considered for hypocenter location is also a possible source of error, but some tests made previously using controlled blasts showed that the crustal model used for the hypocenter determination at NRV is well constrained. Moreover, as Zollweg (1990) pointed out, assuming a 1 km/s error in the P velocity model for NRV and an average travel time of 1 sec, the additional error in the location is less than 1km. This systematic error is smaller than a typical 95% confidence ellipsoid major axis lengths that is 1-3km.

Evolution of the VT seismicity and its relationship with volcanic activity

The most recent volcanic activity of NRV started in November 1984. One year later, in November of 1985, a phreato-magmatic eruption occurred, melting about 5% of the ice cap of the volcano. This produced a mudflow, which destroyed Armero City located in the eastern part of the volcano, killing about 25000 people. The volume of the eruption was calculated to be about $3.8x10^7$ m^3 (Naranjo *et al.*, 1986). From 1985 to 1989, several ash emissions occurred. On September 1, 1989 a new phreato-magmatic eruption took place. It was smaller in size than the eruption of November 1985, with a volume of about $1.6x10^6$ m^3 (Mendez and Patiño 1993). More than 1100 earthquakes occurred in only one day.

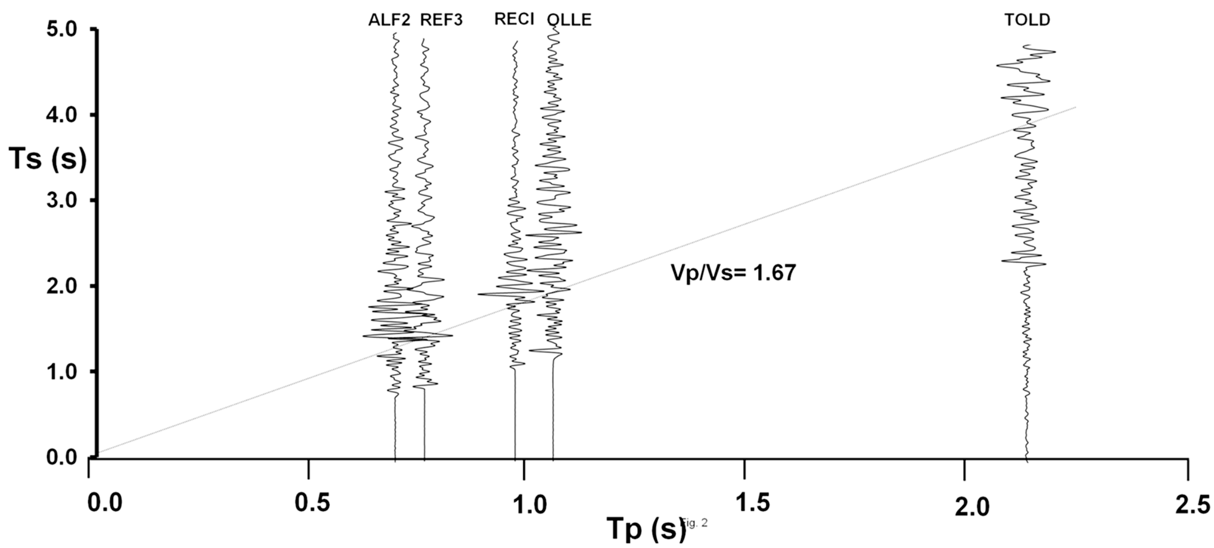

Figure 3. Example of typical seismograms of volcano tectonic earthquake at NRV. The seismograms correspond to an earthquake of crater swarm zone. The line shows the Vp/Vs ratio for the crater swarm zone.

Ash continued falling for several days and a small lahar formed. Londoño *et al.,* (1998) found a temporal change of coda Q before and after these two volcanic eruptions.

After the last eruption, the volcanic activity started to decrease gradually. Since then, few ash emissions have been observed. Table 2 shows a summary of the most relevant volcanic crises of NRV from 1985 to 1999. It seems that a change in the volcanic activity started in 1992. The substantial and continuous decreasing in the VT seismicity is remarkable after that year, compared with previous years. The total energy release for long period (LP) events as well as for all VT earthquakes including those not occurring during swarms is depicted in Figure 4. It is clear that as a general tendency, the seismic activity of NRV has decreased gradually since 1992 (except on some particular dates associated with minor volcanic crises), without ash emission or volcanic eruptions.

There are two seismic swarm zones that displayed some recurrence in time, but both were low in seismic energy release, and were associated with few volcanic crises. A swarm zone NW far away of the crater exhibited activity a few times, not related with volcanic crises, and was the lowest in seismic energy release. Therefore, this swarm zone is not included in this study. There is a seismic swarm zone that has been associated with some of the most important crises at NRV, that is, the eruptions of November 1985 and Sep-

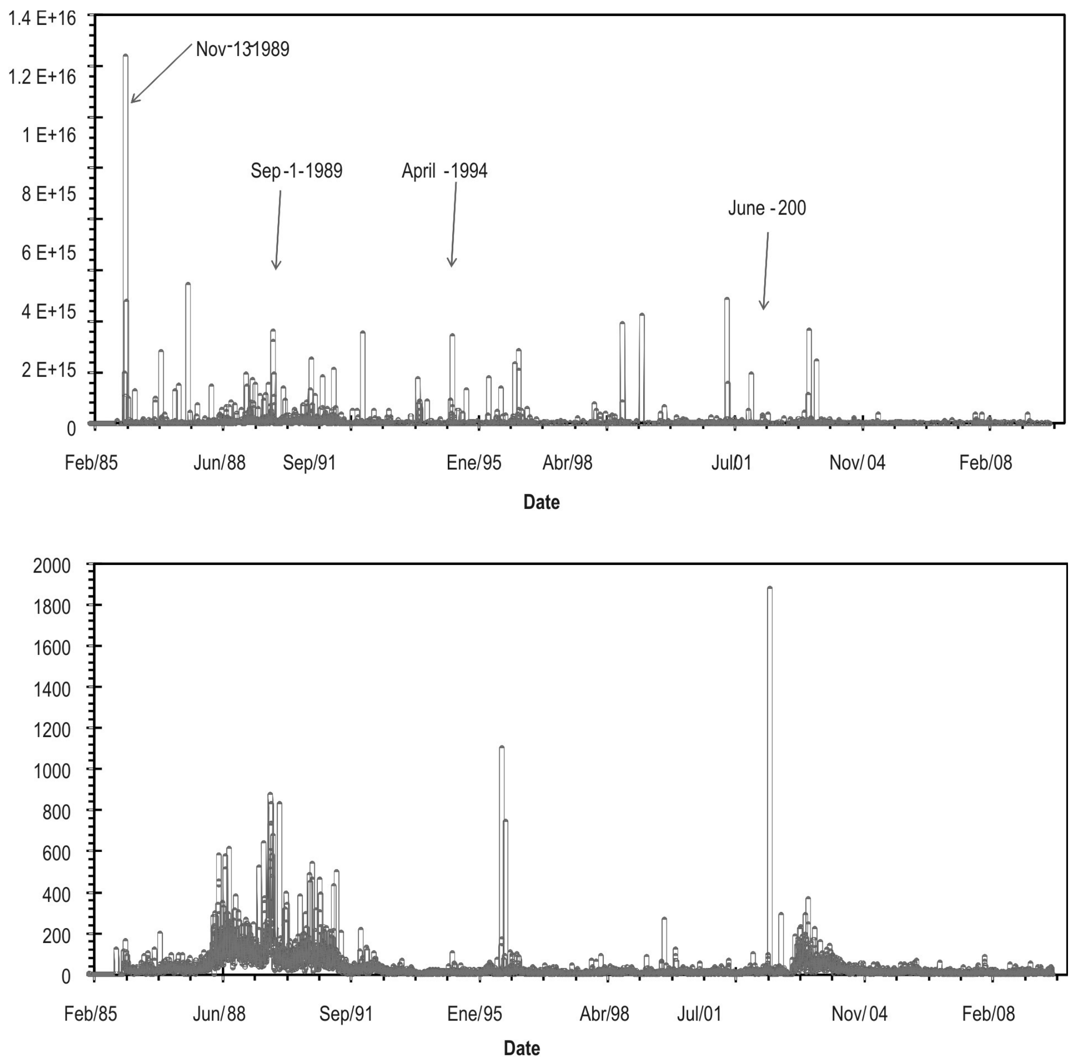

Figure 4. Daily total energy (in ergs) releasing (VT and long-period earthquakes) and daily number of VT earthquakes at NRV from 1985 to 2009. Asterisks represent volcanic crises.

Table 2. Main volcanic crises at NRV from 1985 to 1999. This list includes phreatic eruptions, phreato-magmatic eruptions as well as strong seismic activity. (Lp=Long- period earthquakes; VT=volcano-tectonic earthquakes).

No	Activity	DATE
1	Small phreatic eruption	September 1985
2	Phreato-magmatic eruption	13 November 1985
3	Small phreatic eruption	January 1986
4	Small phreatic eruption	May 1986
5,6	Small phreatic eruption	July 1986
7	Small phreatic eruption	June 1987
8	Small phreatic eruption	March 1988
9	Intense Seismic Activity (Lp)	February 1989
10	Intense Seismic Activity (VT)	May 1989
11	Intense Seismic Activity (VT + Tremor)	June 1989
12	Intense Seismic Activity (VT + Lp+Tremor)	August 1989
13	Phreato-Magmatic eruption	1 September 1989
14	Small phreatic eruption	April 1991
15	Small phreatic eruption	May 1991
16	Intense Seismic Activity (Lp + Tremor)	April 1994
17	Intense Seismic Activity (VT + Lp + hybrids)	July-September 1995

tember 1989. This western swarm-like activity occurred before and after both volcanic eruptions. Although this seismic activity recurred only on rare instances, the level of energy was low compared with those recorded before and after both the eruptions mentioned above (Figure 5). Therefore, it is important to note that not all these VT swarms are related with subsequent volcanic activity. Sometimes this was low in energy and in number of events but it was related with a posterior phreatic eruption (Fig. 4). In February 1998, another swarm in the western part was recorded. Although this swam zone was more energetic than previous mentioned, it did not correlate with any surface volcanic activity (Fig. 5). The earthquakes located to the north and to the west were the deepest (4-8 km), while those located beneath the crater and to the south were the shallowest (0-3 km) (Figure 2). As is noticed in Figure 4, most of the volcanic crises occurred between 1985 and 1992. Only two volcanic crises have occurred since 1992. Seismic swarm-like activity also occurred concurrently. VT seismicity of this type located in the crater area has been recorded quite continuously after 1992, but it is very low in energy compared to previous years. *Vp/Vs ratios for each VT swarm zone at NRV* With the aim to obtain well constrained Vp/Vs ratios for each VT swarm zone and to avoid mixing propagation effects, we calculated the Vp/Vs ratio for each swarm zone using different groups of stations for each swarm (Figures 2, 6).

In order to detect temporal changes of Vp/Vs for each swarm zone, the Vp/Vs ratio was calculated for each swarm zone. The Figure 7 shows the results. From this figure it is possible to observe that there are some temporal changes in Vp/Vs with time at NRV for some regions, mainly for crater and west zones.

The Vp/Vs ratios showed low values at the crater and west swarm zones, with Vp/Vs ratios of 1.67±0.01 and 1.67±0.03 respectively. The Vp/Vs ratio for the earthquake

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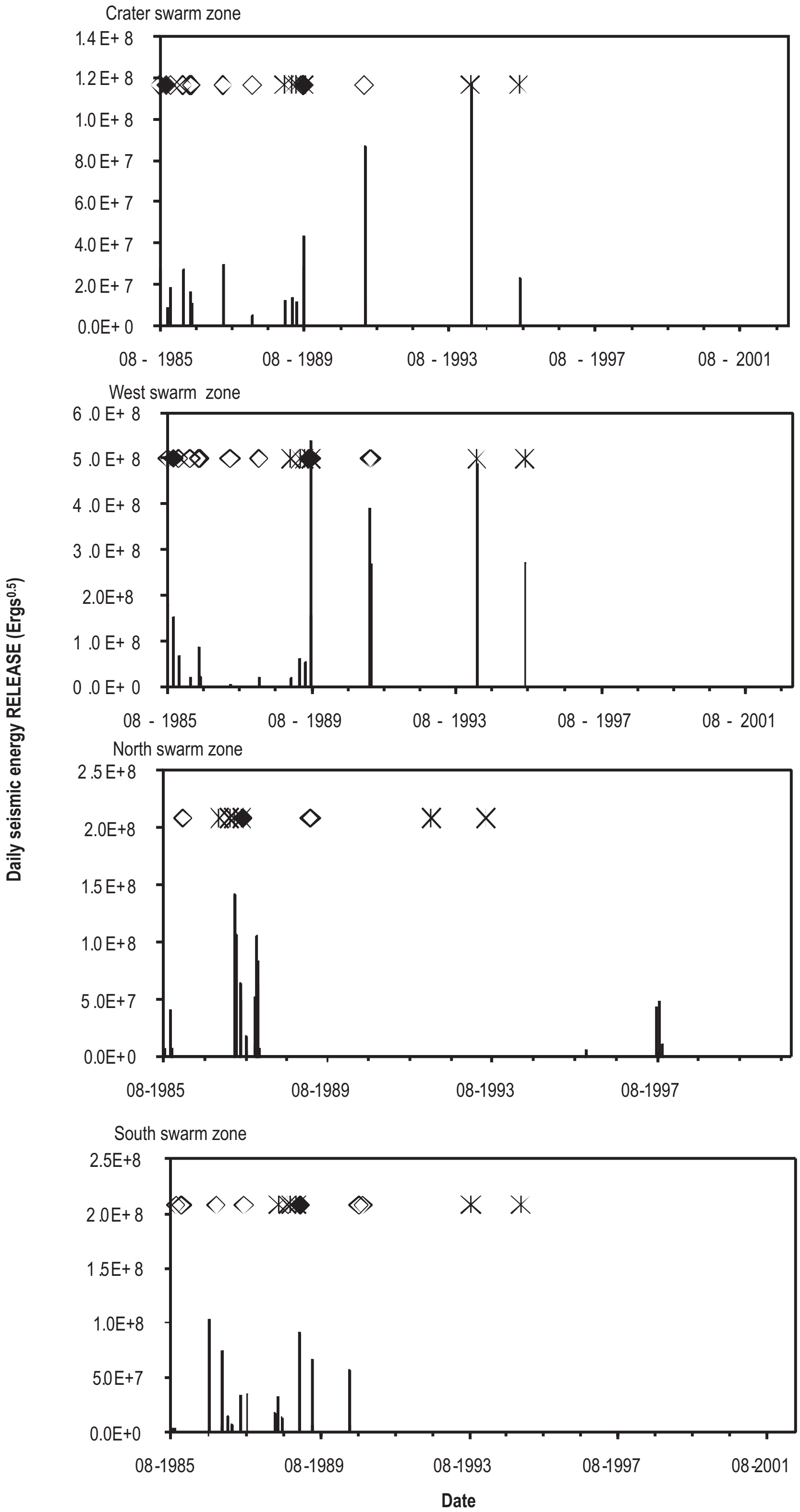

Figure 5. Energy release for each VT swarm (1985-2002).

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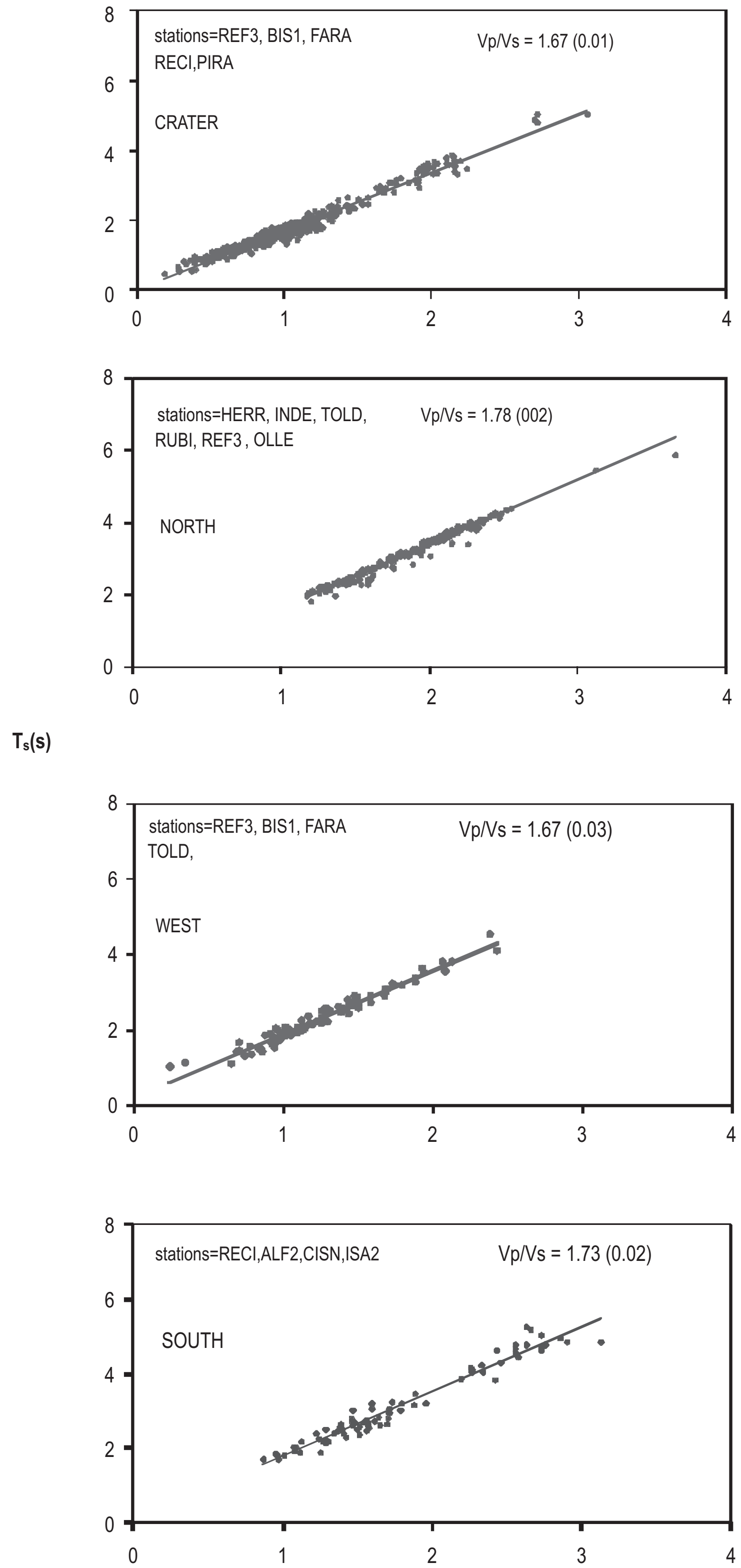

Figure 6. Modified Wadati diagrams for each seismic swarm zone. The group of stations used for Vp/Vs calculation for each swarm zone and the Vp/Vs ratio and its error are listed.

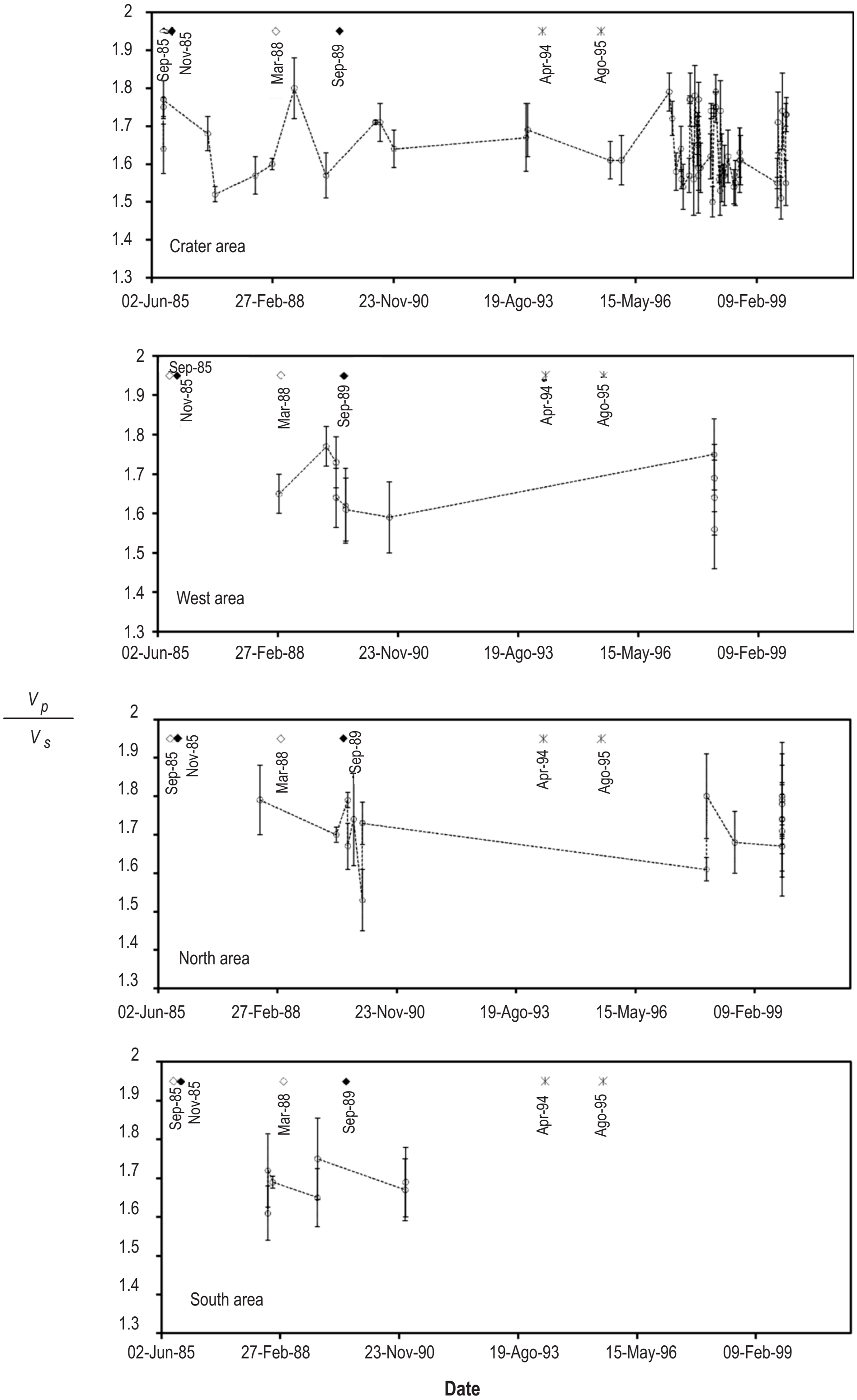

Figure 7. Temporal variation of Vp/Vs for each seismic swarm zone at NRV. Asterisks represent volcanic crises. Vertical lines represent standard error.

swarms located to the south was 1.73±0.02, and for those swarms located to the north was 1.78±0.02. The Vp/Vs ratios were reduced about 6% for the west and crater swarm zones with respect to the north swarm, and 3% with respect to the south swarm zone. The error bars show that the estimated Vp/Vs ratios are significantly different among swarm regions, except for the west and crater swarms, whose values of Vp/Vs are indistinguishable (Figure 8). Some of the stations used to calculate the Vp/Vs ratio for the north and the west earthquake swarm zones were the same (Figure 6). These two seismic zones were the deepest, as mentioned before.

4. Discussion and concluding remarks

VT seismic activity is closely related to the volcanic activity at NRV from 1985 to 2002. The swarm-like VT seismic activity was one of the most remarkable phenomena associated with the volcanic crises, occurring before, during or after the crises, although other phenomena such as LP earthquakes and tremor were also associated. The continuous decreasing of seismic activity related to the decrease in volcanic activity for more than 17 years, can suggest that a period of quiescence or calm has occurred since 1992, with some sporadic increment of activity that has not affected the stability of the volcanic system.

VT seismic activities located beneath the crater zone and to the west of the volcano were related with the two phreato-magmatic eruptions that had occurred to date at NRV (Londoño and Sudo, 2001). It is possible that such seismic pattern can be used as a premonitory tool for the major volcanic crises. Another volcanic eruption has not occurred yet to confirm this supposition, but we argued, that the level of energy and the conditions of the volcano must be taken into account. It seems that after a certain level of seismic energy release is reached in the western zone, depending on the conditions of the volcano, monitoring of VT becomes an important tool for the surveillance of NRV activity, as is seen on Figure 5, where only those dates with high seismic energy release at western zone, are related with phreato-magmatic activity.

We suggest that the reduction of 6% of the Vp/Vs ratio between the north and the west swarm zones is due to the differences in travel path between them. Moreover, although it is known that there is a strong relationship between the Vp/Vs ratios and the depth of the earthquakes, it is interesting to notice that the lowest Vp/Vs ratios are those for the crater and west zones, which are the shallowest and the deepest seismic zones, respectively. On the other hand, surface geology of NRV around the active crater is fairly homogeneous, consisting mainly of lava flows. Based in this, we think that the surface geology did not affect too much the

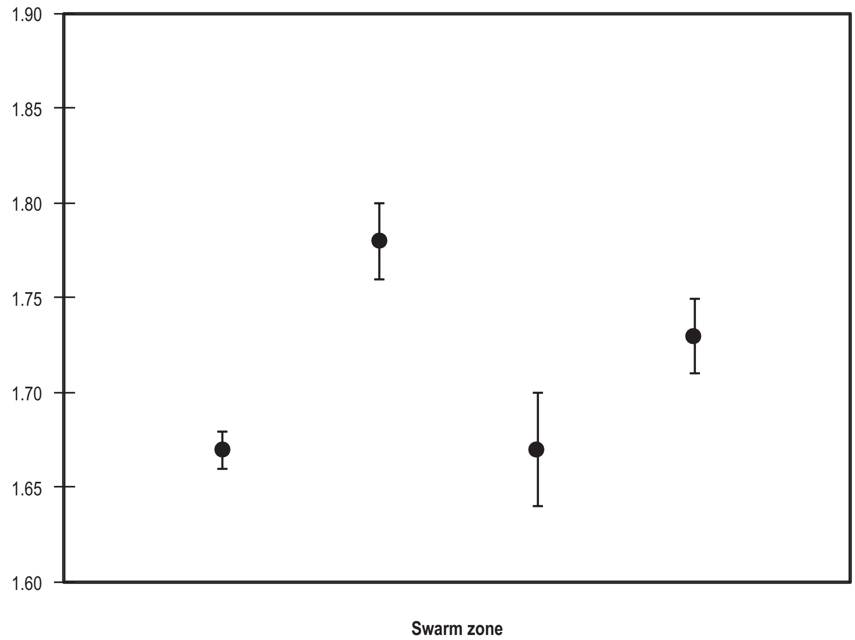

Figure 8. Comparison of Vp/Vs for each VT swarm zone at NRV. Vertical lines represent standard error.

Vp/Vs ratios. From these results, we suggest that the low Vp/Vs ratios found in the crater and west zones are the manifestations of different material beneath the volcano. Probably these zones have different physical-chemical characteristics from those of the surrounding zones. Previous studies carried out in different materials show that factors such as porosity, density, temperature and composition can affect the Vp/Vs ratio (Birch 1961, Ito *et al.*, 1979, Toksoz *et al.,* 1976). It is possible that such factors affected the Vp/Vs ratios inside NRV. Material such as gas or steam changes the properties of the medium, reducing the Vp/Vs ratio as was pointed out by Chatterjee *et al*. (1985) who suggested that the low Vp/Vs ratios in the Yellowstone region are due to the presence of steam or gas. We suggest that in the crater and west zones of NRV probably there are more gas available due to continuous degassing of rocks, that affect the Vp/Vs ratio as well as the volcanic activity. Moreover, the temporal changes of Vp/Vs ratio could be related to temporal changes in gas content inside the volcano. South and North seismic zones did not show any remarkable temporal variation of Vp/Vs ratio, while west and crater seismic zones did it. On the other hand, the last two seismic zones showed more activity through time (Figure 4).

The Vp/Vs ratio found in this study for almost all the VT swarm zones at NRV are rather low. The release of gas or steam from 1985 to 2002, was continuous at NRV, making it possible to observe many fumaroles inside the active crater and huge vapor columns almost daily. On the other hand, a geothermal exploration well, almost 1500m deep was drilled in the NRV area in 1998. The results suggested that: boiling processes are occurring in some places inside the volcano, there is a big hydrothermal system, and the temperatures are higher than 200 °C (Monsalve *et al.*, 1998). Giggenbach *et al.* (1990) suggested that there is a huge hydrothermal system in NRV based on petrological and geochemical data. These results support the hypothesis that there is a huge amount of gas or steam inside NRV that affects the Vp/Vs ratios. This supposition is also in agreement with the idea that there are degassing rocks benath the crater and to the west sectors of the volcano (Giggenbach *et al.*, 1990). Studies elsewhere suggest that presence of hydrothermal systems at the water-steam transition can explain the reduction of the mean value of the Vp/Vs ratio (Chatterjee *et al*. 1985; Zimmer *et al*, 2002; Maheswar and Kalachand, 2007). We think that this is the most likely process occurring at NRV as well. Another possible explanation of the low values of Vp/Vs found in the crater and west swarm zones of NRV compared with the higher values of the north and south zones, is the presence of melting material inside the volcano, or different mechanical properties of the rocks, due probably to the presence of microcracks inside the volcano. A detailed local tomography done at NRV area by Londoño and Sudo (2002a) seems to support this supposition. They found two low velocity zones to the west and beneath the active crater at NRV. They associated these zones with the presence of degassing magma bodies. No low velocity zones were found at Norrh of the volcano. On the other hand, Londono and Sudo (2002b), modeled the seismic waves attenuation at NRV due to gas content changes through time. They concluded that the gas content is the responsible for phreato-magmatic activity at NRV. Therefore, the supposition that the gas content in space and time, is probably one the main causes of spatial and temporal variation of Vp/Vs ratio at NRV, seems to be reasonable.

The relationship between both swarm-like VT seismic zones, the crater and the west zones at NRV, not only with respect to the volcanic activity, but also with respect to the similarity of Vp/Vs ratios, suggests that these two zones are important for the surveillance and monitoring of the volcano. We think that attention should be raised when VT seismic activity occurs in these places, and when the level of seismic energy release reaches certain levels. Of course, it is necessary to correlate such VT seismic activity with other seismic phenomena such as the occurrence of LP earthquakes and tremors, and the conditions of the volcano in order to be more confident about a prediction of volcanic crisis at NRV.

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