Study of seismic site effects using H/V spectral ratios at Arenal Volcano, Costa Rica

Mauricio M. Mora, Philippe Lesage, Jacques Dorel, Pierre-Yves Bard,
Jean-Philippe Métaxian, Guillermo E. Alvarado, Carlos Leandro

▶ To cite this version:

Mauricio M. Mora, Philippe Lesage, Jacques Dorel, Pierre-Yves Bard, Jean-Philippe Métaxian, et al.. Study of seismic site effects using H/V spectral ratios at Arenal Volcano, Costa Rica. Geophysical Research Letters, American Geophysical Union, 2001, 28, pp.2991-2994. 10.1029/2001GL013049 . insu-03606672

HAL Id: insu-03606672
https://hal-insu.archives-ouvertes.fr/insu-03606672

Submitted on 12 Mar 2022

GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 15, PAGES 2991-2994, AUGUST 1, 2001

Study of seismic site effects using H/V spectral ratios at Arenal Volcano, Costa Rica

Mauricio M. Mora,[1,2] Philippe Lesage,[1,3] Jacques Dorel,[3,4] Pierre-Yves Bard,[5]
Jean-Philippe Métaxian,[1,6] Guillermo E. Alvarado,[2,7] and Carlos Leandro[7]

Abstract. By using data obtained with a linear array at Arenal volcano, we show that the H/V spectral ratio method can be profitably applied to detect site effects on volcanoes. Similar results are obtained when calculating spectral ratios with different types of seismo-volcanic signals (tremor, ambient noise, explosion quakes, LP events). We compare the H/V ratios with theoretical S-wave transfer functions calculated using velocity models obtained from seismic refraction studies. There is a good agreement when the H/V ratios display sharp peaks, indicating a close relationship between the ratios and the transfer function of the shallow structure. Furthermore, the main peaks of the spectral ratios are consistent with local amplification of seismic waves observed at the corresponding frequencies.

Introduction

Volcanoes are complex heterogeneous structures including hard rock and poorly consolidated material. The propagation of seismic waves is thus affected by complex phenomena, which can locally modify their amplitude, polarization, incidence angle, or their propagation direction and velocity (e.g. Neuberg and Pointer, 2000). In particular, local amplifications of volcanic tremor at some frequencies have been observed at several volcanoes : Stromboli, Italy (Del Pezzo et al., 1974 ; Falsaperla et al., 1992 ; Ntepe & Dorel, 1990), Klyuchevskoy, Kamchatka (Gordeev et al., 1989 ; 1990) and Sakurajima, Japan (Tsuruga et al., 1997). Those site effects can be pointed out and distinguished from source effects by comparing spectra obtained at spatially separated seismic stations. However, they are generally not studied in detail in volcanic contexts, even though it is important to detect and characterize them in order to avoid misinterpretations. On the other hand, site effects have been widely studied in the framework of earthquake hazard reduction programs, and several methods, either experimental, empirical or numerical, have been proposed for this purpose (Bard, 1999). One of them, the H/V spectral ratio method, is based on the ratio of the horizontal and vertical components spectra of the microtremor recorded at a single station (Nakamura, 1989). While its theoretical basis has been controversial (Bard, 1999), many works have demonstrated that the H/V ratio gives good measurements of the fundamental resonance frequency of the local structure (e.g., Lermo & Chávez-García, 1994; Theodulidis et al., 1996; Lachet et al., 1996), although not producing reliable determination of the amplification at the resonance frequency (Lachet and Bard, 1994).

In this paper, we present an application of the H/V spectral ratio method for the identification and characterization of site effects at Arenal volcano, Costa Rica. By using records from a linear array, we verify that reliable and similar results are obtained when calculating H/V spectral ratios with different types of seismo-volcanic signals. The H/V ratios are also compared to the theoretical S-wave transfer functions calculated by using velocity models obtained from seismic refraction surveys.

Seismic arrays and data

Arenal is a 1640 m o.s.l. high volcano located at the north of Costa Rica (10°28' N – 84°42' W, Figure 1). Since the large 1968 eruption, Arenal has permanent activity characterized by strombolian explosions, gas emanations, lava flows and sporadic pyroclastic flows. Seismic activity includes signals such as harmonic and spasmodic tremors,

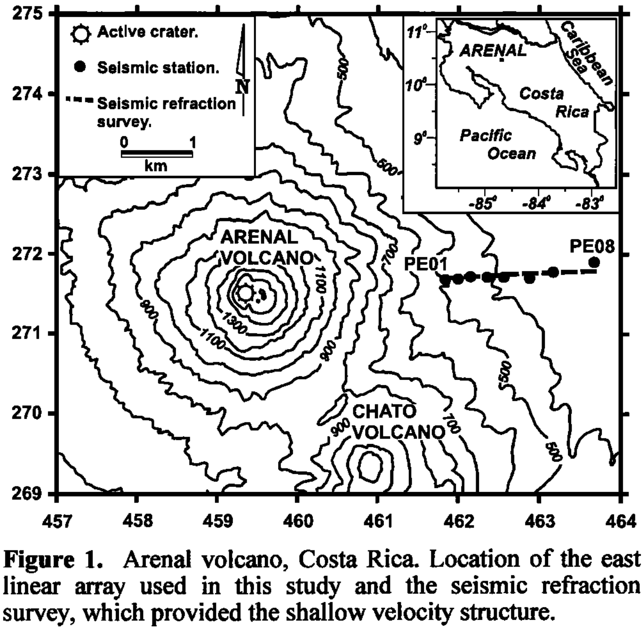

Figure 1. Arenal volcano, Costa Rica. Location of the east linear array used in this study and the seismic refraction survey, which provided the shallow velocity structure.

---

[1] Laboratoire de Géophysique Interne et Tectonophysique, Université de Savoie, Le Bourget-du Lac, France.

[2] Escuela de Geología, Universidad de Costa Rica, San José, Costa Rica.

[3] Centre de Recherches Volcanologiques (CNRS).

[4] Observatoire de Physique du Globe, Clermont-Ferrand, France.

[5] Laboratoire de Géophysique Interne et Tectonophysique, Grenoble, France.

[6] Institut de Recherche pour le Développement, France.

[7] Area de Amenazas y Auscultación Sismovolcánicas, Instituto Costarricense de Electricidad, San José, Costa Rica.

Paper number 2001GL013049.
0094-8276/01/2001GL013049$05.00

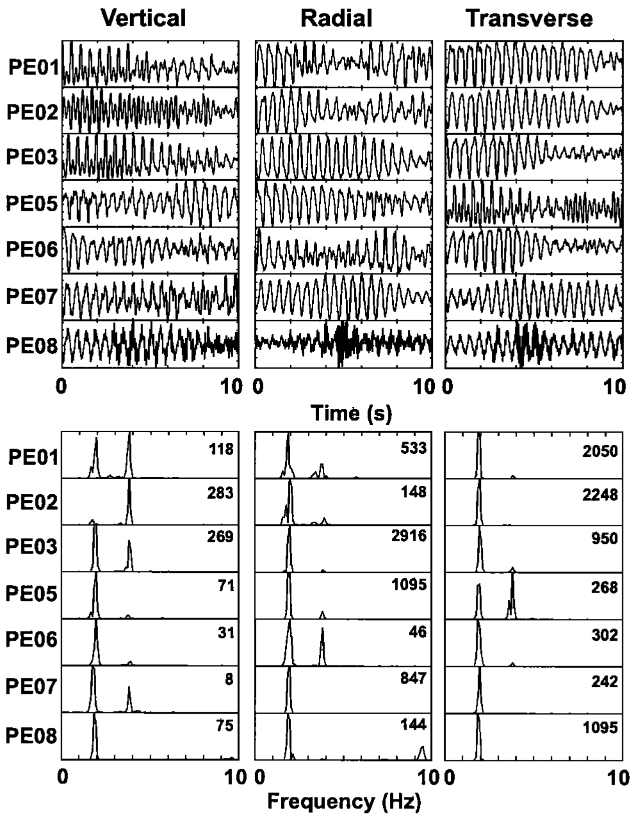

Figure 2. Three components waveforms (top) and corresponding normalized power density spectra (bottom) of a harmonic tremor section recorded along the east linear array. Numbers at the upper right corner of the spectra corresponds to the maximum amplitude. No records are available at station PE04 because of a recorder failure.

explosions and long-period (LP) events. The corresponding seismic sources are localized beneath the active crater (Hagerty et al., 2000 ; Métaxian and Lesage, 2001). A seismic experiment was carried out in 1997 in order to study the sources and wavefield of the tremor and LP events. Several dense arrays with various configurations were set up at different places around the volcano. In this paper, the discussion will focus on the data obtained with a linear array deployed on the east flank (Figure 1). It is a 1.9 km long radial array composed of 8 stations located 150 to 500 m apart with the first station situated at about 2.5 km from the active crater. Stations include 3-components 2 Hz L22 seismometers, with the N-S component oriented radial to the active crater. Sismalp3 LEAS recorders were operated in continuous mode with a sample rate of 100 Hz.

In a second stage of the experiment, a seismic refraction profile and a geoelectric survey were carried out along the linear array (Figure 1). A detailed 2D velocity model has been obtained down to about 100 m deep (Leandro and Alvarado, 1999). Four main units are generally identified. The first and shallower layer is thin (5-15 m) with P-wave velocities varying between 0.2 and 0.8 km/s ; it corresponds to recent epiclastic and pyroclastic deposits. The second layer, with thickness of 10 to 45 m and V_P in the range 0.9-1.6 km/s, includes low-consolidated deposits (fine to medium tephra interbedded with paleosoils). The third layer, with V_P between 2.1 and 2.8 km/s, is 15 to 60 m thick and is correlated with breccias and tuffs. A fourth unit, up to 100 m thick with velocities of 2.8 to 3.9 km/s, is associated with lava. Two geophysical anomalies are detected along the profile and seem to be related to faults. The thickness and physical properties of the layers present large variations even between sites located a few hundreds of meters apart.

Figure 2 displays three components seismograms and spectra of harmonic tremor. Strong variations of the relative amplitude of the spectral peaks are observed between stations close to each other. For instance, the relative amplitude of the vertical component spectral peak at 1.9 Hz is very low at station PE02. Likewise, the amplitude of the 3.8 Hz peak is much smaller at PE05, PE06 and PE08 than at the other stations. These local amplitude variations induce important distortions in energy as a function of distance, which should normally be a smooth decaying curve (Figure 3). For example, there is a strong amplification of the transverse component at station PE05 in the 3-5 Hz spectral band. While the regularly spaced peaks in the spectra are source effects (Benoit and McNutt, 1997 ; Hagerty et al., 2000), the local variations of the peak amplitude are probably site effects.

Methods and Data Processing

Several sets of high quality records of various types (harmonic tremor, spasmodic tremor, noise, explosions and LP events) were selected. The Fourier transforms of 20 s long signal slices were calculated and smoothed by a 0.4 Hz wide moving window. The horizontal term in the H/V ratio is the geometrical average of the two horizontal components spectra. Then, assuming a log-normal distribution of spectral ratios (Field and Jacob, 1995), the logarithmic average and the corresponding standard deviation were calculated.

The theoretical transfer functions of the local structure at each station were computed for vertically incident S-waves by using the reflectivity method (Kennett and Kerry, 1979). One-dimensional P-wave velocity models were obtained from the seismic refraction and geoelectric surveys. S-wave velocities were derived taking V_P/V_S ratios characteristic of low consolidated materials (2.0 and 3.0 for dry and saturated layers, respectively). A S-wave velocity contrast of about 2 determines the limit between the soft resonating layers and the competent underlying half space of the models.

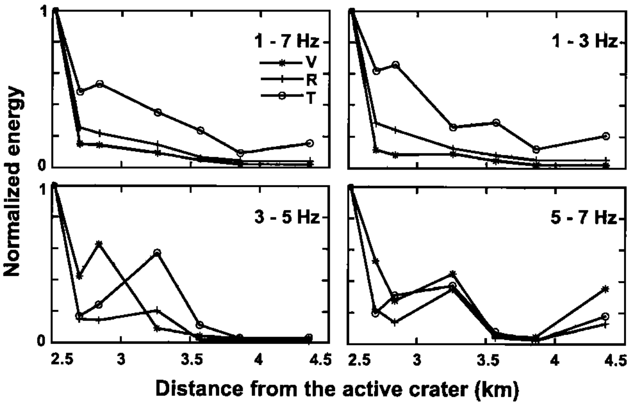

Figure 3. Tremor energy as a function of the distance from the active crater along the radial array, in several frequency bands. All the calculated energies are normalized by the corresponding values at station PE01. V: vertical, R: radial, T: transverse component.

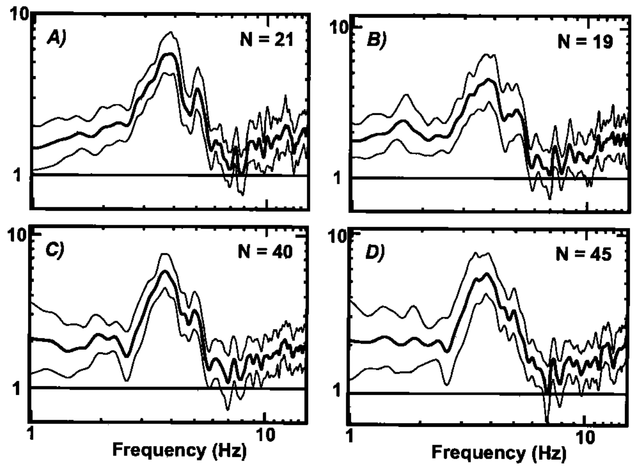

Figure 4. Mean H/V spectral ratios (solid lines) and mean ratios ± 1 standard deviation (thin lines) at station PE05, calculated by using different types of signal : a) seismic noise, b) long-period events and explosions, c) spasmodic tremor, d) harmonic tremor. N in the upper right corner is the number of signal sections used for computing the average and the standard deviation.

Results

The mean H/V ratios calculated with the different types of signal display similar shape. At station PE05, for example, the ratios are all characterized by a large peak near 3.5 Hz (figure 4). This shows that reliable H/V ratios can be obtained by using the different types of events generated in volcanoes. It is consistent with the conclusions of Lachet and Bard (1994) who demonstrated, using numerical simulations, that the fundamental peak frequency in the H/V ratios does not depend on the source. Furthermore, the moderate values of the standard deviations indicate that the H/V ratio computations are stable with respect to the selected signals. However, standard deviations are lower when using noise and are higher for the harmonic tremor, indicating that the ratio dispersion is smaller for signals with broad spectra than for signals with limited bandwidths.

Figure 5 displays the H/V spectral ratios, obtained with seismic noise, and the corresponding theoretical transfer functions for all the stations. The large variations observed along the array reflect the heterogeneous nature of the underlying geological structure. Several H/V ratios exhibit a low frequency peak indicative of a resonance effect in the poorly consolidated layers. In some cases, there are peaks at higher frequency suggesting that the resonance of individual thin layers can also occur, probably when the impedance contrast with the surrounding material is large enough. The fundamental frequency is generally in the range 1.8 to 2.2 Hz, with the exception of station PE05 that exhibits a large peak at 3.5 Hz. In the case of PE06 and PE07, the corresponding peak has very low amplitude, which indicates the lack of pronounced discontinuity between the shallow soft deposits and the deep competent materials.

The fundamental peak frequency of the theoretical transfer function is in good agreement with the H/V ratio peak at stations PE02, PE03 and PE05, while a clear discrepancy is observed at PE01. At PE06, PE07 and PE08, the transfer functions do not contain any peak at frequencies lower than 5 Hz, reflecting the shape of the corresponding H/V ratios. On the other hand, at most stations, the transfer functions exhibit high frequency peaks that do not always coincide with H/V ratio peaks. Reasons for the agreements and discrepancies are discussed in the following section.

Discussion

The peaks in the H/V ratios are often associated with the amplification of the horizontal components of the seismic waves and resonance effects of the shallow structure. Thus the transfer function of vertically incident S-waves usually presents peaks at the same frequencies as those found for the ratios. In this study, the agreement between the fundamental resonance frequency obtained by both the H/V ratios and the theoretical transfer functions is correct only when the corresponding peak is sharp. This feature is probably associated with a strong impedance contrast at an interface in the shallow structure, which produces a resonance effect. Such a discontinuity is also easy to detect by seismic refraction, leading to reliable velocity models. This supports the close relationship between the spectral ratios and the structure. For other stations the agreement is not as good. It can be partly due to poorly constrained velocity models, as these stations are either at an end of the seismic refraction profile (PE01, PE08) or are about 100 m distant from the line (PE06, PE08). Lateral heterogeneities and topography effects

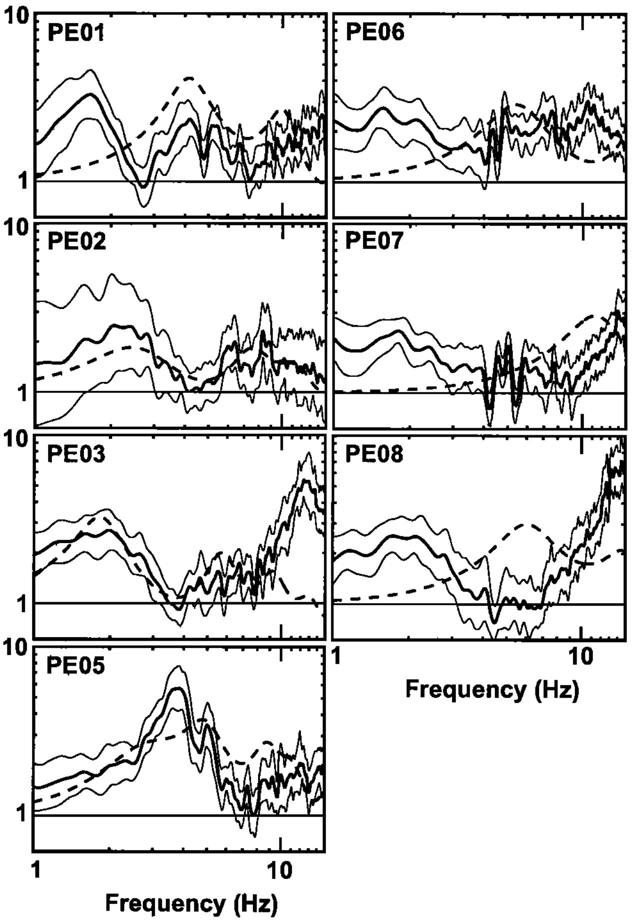

Figure 5. Mean H/V ratios (solid lines), calculated with 21 slices of ambient noise, mean ratios ± 1 standard deviation (thin lines) and theoretical S-wave transfer functions (dashed lines) for the stations of the linear array.

can produce complex perturbations of the wave field. Nevertheless, the topography along the east profile is relatively smooth, so its effect would be weak. Most of the discrepancies probably result either from bad estimates of the velocity contrasts at the interfaces that determine the resonating set of layers, or from strong lateral heterogeneities. The H/V spectral ratios obtained in this study reveal site amplifications that can explain the irregularities of the curves of energy as a function of distance. In particular, the large 3.5 Hz peak of the spectral ratio at PE05 (Figure 5) is consistent with a strong amplification of the horizontal component in the 3-5 Hz frequency band (Figure 3).

Conclusions

An increasing number of studies aim at obtaining detailed features of the seismic wavefield in volcanoes, e.g. amplitude decay, polarization, propagation direction and velocity, incidence angle, which in turn can provide information on the seismic sources. Strong velocity variations in the shallow volcanic structures can produce large site effects that perturbate the wavefield. This can lead to misinterpretations if this phenomenon is not properly detected and characterized. The Nakamura's method is cheap, easy-to-use and efficient in measuring the fundamental resonance frequency of the structure, although it does not provide correct estimates of the corresponding amplification. In this work, we have shown that reliable calculations of the H/V spectral ratios can be obtained for all types of seismo-volcanic signal. Several peaks of the spectral ratios are consistent with local amplifications observed in the corresponding spectral bands and are clearly related to the shallow geological structure. Hence, it seems necessary to calculate the H/V spectral ratio for any seismic station set up on a volcano.

Acknowledgments. We thank the staff at the Instituto Costarricense de Electricidad and Observatorio Sismológico y Vulcanológico de Miravalles for their logistical support during the field work and for the seismic refraction and electric surveys they carried out. We also thank the Arenal Conservation Area staff for the facilities provided during the field work. The manuscript was improved thanks to the remarks of two anonymous reviewers. This study was supported by the Programme Régional pour la Prévention du Risque Volcanique en Amérique Centrale (PREVO-MAE), the Programme National de Recherche sur la Prévision et la Prévension des Risques Naturels (PNRN-INSU), the Centre de Recherches Volcanologiques (CRV-CNRS), the Université de Savoie and the Institut de Recherche pour le Développement.

References

Bard, P-Y., Microtremor measurements: a tool for site effect estimation? State-of-the-art paper presented at Second International Symposium on the Effects of Surface Geology on seismic motion, Yokohama, December 1-3, 1998, Volume n°3, 1251-1279, 1999.

Benoit, J. P., and S. R. McNutt, New constraints on source processes of volcanic tremor at Arenal Volcano, Costa Rica, using broadband seismic data, *Geophys. Res. Lett.*, *24*, 449-452, 1997.

Del Pezzo, E., I. Guerra, A. Lo Bascio, G. Luongo, G. Nappi, and R. Scarpa, Microtremors and volcanic explosions at Stromboli, *Bull. Volcanol.*, *38*, 1023-1036, 1974.

Falsaperla, S., B. Martinelli, and R. Schick, Seismic activity at Stromboli (Southern Italy) for the period 1983-1986, in *Volcanic Seismology*, edited by P. Gasparini, R. Scarpa, and K. Aki, 267-278, Springer-Verlag, Berlin, 1992.

Field, J.E., and H. Jacob, A comparison and test of various site-response estimation techniques, including three that are not reference-site dependent, *Bull. Seismol. Soc. Am.*, *85*, 1127-1143, 1995.

Gordeev, E., Y. Melnikov, V. Sinitsy, and V. Chebrov, Volcanic tremor of Kliuchevskoi volcano (1984 Eruption), in *Volcanic Hazards, Assessment and Monitoring*, edited by Latter, J.H., 486-503, Springer-Verlag, Berlin, 1989.

Gordeev, E., V. Saltykov, V. Sinitsyn, and V. Chebrov, Temporal and spatial characteristics of volcanic tremor wavefields, *J. Volcanol. Geotherm. Res.*, *40*, 89-101, 1990.

Hagerty, M.T., S.Y. Schwartz, M.A. Garcés, and M. Protti, Analysis of seismic and acoustic observations at Arenal Volcano, Costa Rica, 1995-1997, *J. Volcanol. Geotherm. Res.*, *101*, 27-65, 2000.

Kennett, B.L.N., and N.J. Kerry, Seismic waves in a stratified half-space, *Geophys. J. Roy. Astr. Soc.*, *57*, 557-583, 1979

Lachet, C., and P.-Y. Bard, Numerical and theoretical investigations on the possibilities and limitations of Nakamura's technique, *J. Phys. Earth*, *42*, 377-397, 1994.

Lachet, C., D. Hatzfeld, P.-Y. Bard, N. Theodulidis, C. Papaioannou, and A. Savvaidis, Site effects and microzonation in the city of Thessaloniki (Greece) : comparison of different approaches, *Bull. Seismol. Soc. Am.*, *86*, 1692-1703, 1996.

Leandro, C., and G. Alvarado, Geological – Geophysical study of a Eastern and Western section in the Arenal volcano, *Boletín del Observatorio Sismológico y Vulcanológico de Arenal y Miravalles*, *20-21*, 48-58, 1999.

Lermo, J., and J.F. Chávez-García, Are microtremors useful in site response evaluation?, *Bull. Seismol. Soc. Am.*, *84*, 1350-1364, 1994.

Métaxian, J.-Ph., and Ph. Lesage, Locating sources of volcanic tremor and emergent events by seismic triangulation : Application to Arenal volcano, Costa Rica, *J. Geophys. Res. (submitted)*, 2001.

Nakamura, Y., A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface, *Quarterly Report of Railway Technical Research Institute*, *1*, 25 - 33, 1989.

Neuberg, J., and T. Pointer, Effects of volcano topography on seismic broad-band waveforms, *Geophys. J. Int.*, *143*, 239-248, 2000.

Ntepe, N., and J. Dorel, Observations of seismic volcanic signals at Stromboli volcano (Italy), *J. Volcanol. Geotherm. Res.*, *43*, 235-251, 1990.

Theodulidis, P., P.-Y. Bard, R. Archuleta, and M. Bouchon, Horizontal-to-vertical spectral ratio and geological conditions: the case of Garner Valley downhole array in Southern California, *Bull. Seismol. Soc. Am.*, *86*, 306-319, 1996.

Tsuruga, K., K. Yomogida, S. Honda, H. Ito, T. Ohminato, and H. Kawakatsu, Spatial and temporal variations of volcanic earthquakes at Sakurajima volcano, Japan, *J. Volcanol. Geotherm. Res.*, *75*, 337-358, 1997.

G. E. Alvarado and C. Leandro, Area de Amenazas y Auscultación Sismovolcánicas, Instituto Costarricense de Electricidad, Apartado Postal 10032-1000, San José, Costa Rica (gainduni@cariari.ucr.ac.cr, cleandro@icelec.ice.go.cr).

P-Y. Bard, Laboratoire de Géophysique Interne et Tectonophysique, Université Joseph Fourier B.P. 53 X – 38041 Grenoble, Cedex, France (Pierre-Yves.Bard@lgit.obs.ujf-grenoble.fr)

J. Dorel, Observatoire de Physique du Globe, 24 Avenue des Landais, Complexe des Cezeaux, 63170 Aubiere, Clermont-Ferrand, Cedex, France (J.Dorel@opgc.univ-bpclermont.fr).

P. Lesage, J-P. Métaxian, and M. M. Mora, Laboratoire de Géophysique Interne et Tectonophysique, Université de Savoie, 73376 Le Bourget-du-Lac, Cedex, France (lesage@univ-savoie.fr, metaxian@univ-savoie.fr, mmora@cariari.ucr.ac.cr)

(Received: February 16, 2001; revised: April 17, 2001;
accepted: May 23, 2001.)