Pure appl. geophys. 161 (2004) 1579–1596
0033 – 4553/04/071579 – 18
DOI 10.1007/s00024-004-2522-5

Pure and Applied Geophysics

Microtremor Analyses at Teide Volcano (Canary Islands, Spain): Assessment of Natural Frequencies of Vibration Using Time-dependent Horizontal-to-vertical Spectral Ratios

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Abstract — We use time-dependent horizontal-to-vertical spectral ratios (HVSR) of microtremors to determine the dominant frequencies of vibration of the geological structures beneath several recording sites in the vicinity of Teide volcano (Canary Islands, Spain). In the microtremors, the time-dependent HVSRs (ratiograms) are a useful tool to discriminate between the presence of real dominant frequencies linked to resonances of the subsurface structure and the spurious appearance of peaks due to local transients. We verified that the results are repeatable, in the sense that microtremors recorded at the same site but at different times yield a very similar HVSR function. Two types of results are found: (1) sites where there is no resonance of the propagating microtremors, and therefore no value of a dominant frequency can be assessed; and (2) sites where a stationary peak in the HVSR is found and a dominant frequency related to resonance of the shallow structure can be estimated. These resonant frequencies show substantial spatial variations even for nearby sites, which reflects the complexity of the shallow velocity structure in the Las Cañadas area. Large dominant frequencies occur near the caldera walls and also at a few locations that coincide with the intersections of the inferred rims of the three calderas forming Las Cañadas. Small dominant frequencies also occur near the caldera rim, and may be due to discontinuities in the caldera wall and/or to local velocity anomalies. Intermediate frequencies are mostly found in the eastern part of the caldera, where a tentative profile of the basement depth has been obtained. Intermediate frequencies have also been measured south of Ucanca and south of Montaña Blanca. In view of the present results, we conclude that the use of ratiograms constitutes an improvement of the HVSR method and provides an appropriate tool to investigate the shallow velocity structure of a volcanic region.

Key words: Surface geology, microtremors, resonant period, ratiogram, Teide volcano.

1. Introduction

The Canary Islands consist of seven islands and several islets located at about 28°N, 16°W in the Atlantic Ocean (Fig. 1). They lie in an intraplate setting on the northwestern African continental shelf. Several theories have been proposed to

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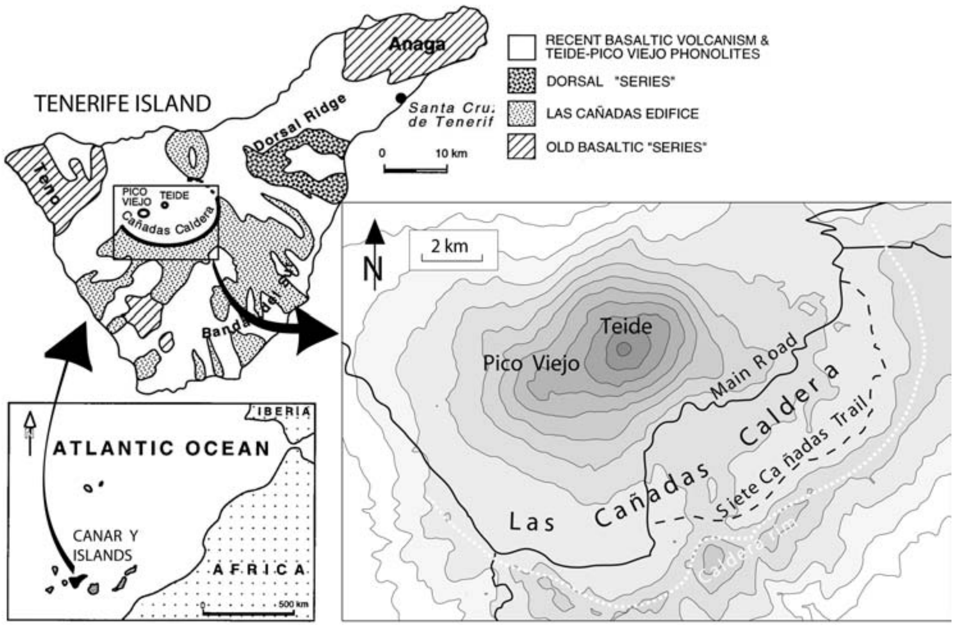

Figure 1
Composite map showing the region under study. (lower left) Position of the Canary Islands near the northwestern African coast. (upper left) Simplified geological map of Tenerife Island, showing the position of Teide volcano and Las Cañadas caldera. (lower right) Las Cañadas caldera. Microtremor records were obtained at several sites along the main road (solid black line) and at Siete Cañadas Trail (dotted black line). The dotted white line shows the approximate position of the caldera rim.

explain the origin of the Canarian volcanism (ANGUITA and HERNÁN, 2000), including a mantle hotspot (MORGAN, 1983; CARRACEDO *et al.*, 1998; DAÑOBEITIA and CANALES, 2000) and the uplift of tectonic blocks (ARAÑA and ORTIZ, 1991), among others. In Tenerife, subaereal volcanism started more than 12 Ma ago (ANCOCHEA *et al.*, 1990). The activity was concentrated mainly along the NE-SW and NW-SE faults that cross the center of the island, where a great volcanic edifice was built some 3 Ma ago (MARTÍ *et al.*, 1994). The collapse of this edifice, most likely by multiple collapses rather than by a single giant event (MARTÍ and GUDMUNDSSON, 2000) produced the Las Cañadas caldera, which constitutes one of the best exposed calderas in the world. It has an approximately elliptical shape, with dimensions of 16 and 9 km in east-west and north- south directions, respectively. The caldera floor has an elevation of about 2 km, and it is surrounded by walls clearly visible for 27 km. A gravitational failure of part of the north wall left the caldera open to the north. Subsequent episodes of volcanism on the northwest of caldera gave birth to the Teide-Pico Viejo stratovolcano (ABLAY and MARTÍ, 2000) and contributed to the filling of the caldera. There is also evidence of the importance of landslides in the volcanic evolution of Tenerife (ANCOCHEA *et al.*, 1990; ABLAY and HÜRLIMANN, 2000).

Teide is considered as potentially hazardous due to the proximity of populated areas such as the Orotava Valley. This may be one of the reasons for its selection as the Decade Volcano and the European Laboratory Volcano by the IAVCEI and the European Science Foundation, respectively. Several eruptions have occurred in Tenerife within historical times, for example in Siete Fuentes (1704), Fasnia and Montaña Arenas (1705), Montaña Negra (1706), Chahorra (1798), and Chinyero (1909) on the northwestern flank of the volcano. All these eruptions were preceded by premonitory seismicity (ARAÑA and CARRACEDO, 1978), which emphasizes the importance of a systematic geophysical monitoring.

The present study is intended to improve our understanding of the relationship between the shallow geological structure and microtremors in a volcanic environment. The experiments consisted of microtremor measurements at different points in the vicinity of the Teide volcano. These data are used to estimate the dominant frequencies of vibration of the structures beneath the recording sites, which may be used to characterize the local geological setting.

2. Instruments and Data

A single seismic station was used for the microtremor measurements. It was composed of a short-period, three-component seismometer with natural period of one second, a 24-bit A/D converter with GPS time, sampling each channel at 100 sps, and a laptop computer to control the system and store the data. We recorded data during three different surveys. Due to the rough topography and the difficult access to most parts of the Las Cañadas caldera, sites were generally selected on the basis of logistic ease. On July 2000, data were recorded at 56 locations along the main road and the Siete Cañadas trail crossing the Las Cañadas caldera (Fig. 1); record duration was set to three minutes. Additional data were obtained by recording 3-minute microtremor samples every hour during 24 hours near the Parador Nacional. The second survey was performed during July 2001, and consisted of a repetition of the 2000 survey to obtain new 3-minute microtremor records at the same 56 positions. Finally, in October 2001, 5-minute data samples were recorded at 28 sites in a denser grid on the eastern part of the Las Cañadas caldera. Measurements were repeated three times for one of the sites to control the stability of the results. Distances between nearby recording sites ranged between 0.5 and 1.0 km.

The microtremor spectrum contains energy basically below 10 Hz, with a main peak observed at 1 Hz. The main source of microtremors is most likely the oceanic microseismic noise, which usually peaks at periods of a few seconds. This kind of noise has been found to peak between 3 and 8 s at the oceanic islands of Hawaii (DAWSON *et al.*, 1998). At Tenerife, ALMENDROS *et al.* (2000) documented the presence of oceanic noise at frequencies below 1 Hz. The peak observed in our data probably corresponds to the shoulder of the microseismic noise filtered by our short-period instruments.

3. Method

3.1. The HVSR Technique

The horizontal-to-vertical spectral ratio (HVSR) method considers that the amplification produced by a surface layer can be obtained by evaluating the ratio between the horizontal and vertical spectral amplitudes of microtremors recorded at the site. This method is known as the Nakamura's technique since the publication of his paper (NAKAMURA, 1989). Nevertheless, the idea was introduced by NOGOSHI and IGARASHI (1971) who showed the coincidence between the lowest-frequency maximum of the HVSR of Rayleigh waves and the fundamental resonance frequency of the site. The method assumes that microtremors are composed of Rayleigh waves which propagate in a surface layer over a half-space (LERMO and CHÁVEZ-GARCÍA, 1994; DRAVINSKI *et al.*, 1996). The motion at the interface between the layer and the half-space is not affected by the source effect; moreover, the horizontal and vertical motions at the interface are approximately equal due to the ellipticity of the Rayleigh waves. Therefore the site effect can be computed by the spectral ratio of horizontal versus vertical components of motion at the surface, that is,

$$HVSR(f) = \frac{\sqrt{A_{\mathrm{east}}(f)^2 + A_{\mathrm{north}}(f)^2}}{A_{\mathrm{vertical}}(f)} \tag{1}$$

where A_C represents the spectral amplitude of the C component.

KONNO and OHMACHI (1998) extended the problem considering a multi-layered system; they reinforced the technique, which up to that moment had some theoretical gaps. Other studies have shown that the HVSR can reveal the fundamental resonant frequency of the structure beneath the site (LERMO and CHÁVEZ-GARCÍA, 1994; FIELD and JACOB, 1995; LACHET *et al.*, 1996; SEEKINS *et al.*, 1996; COUTEL and MORA, 1998). The method works reasonably well when the structure of the site under study can be approximated by a 1-D model. Recent works have investigated the applicability of this technique by the simulation of seismic waves in specific structures such as sedimentary basins (AL YUNCHA and LUZÓN, 2000; DRAVINSKI *et al.*, 1996). LUZÓN *et al.* (2001) performed a numerical study of the propagation of seismic waves in 2-D flat sedimentary basins, and concluded that the HVSR can reasonably predict the natural frequency when there is a high-impedance contrast between the sedimentary inclusion and the bedrock.

Despite its restrictions, Nakamura's method has become a widely used tool, with interest in seismological and engineering applications. For example, it has been used to map the thickness of sediments in the Segura Valley, Spain (DELGADO *et al.*, 2000), and the Lower Rhine Embayment, Germany (IBS-VON SEHT and WOHLENBERG, 1999); to characterize seismic hazards in small scale for seismic microzonation (see BARD, 1999 and references therein); or to estimate the topographical effects of ground shaking at mountains (ZASLAVSKY and SHAPIRA, 2000). The main reason for such a success is its simplicity both in field operations and data analysis. A few minutes of microtremor data is enough. Microtremors are ubiquitous in time and space, and it is not necessary to wait for the occurrence of earthquakes. A single three-component station is the only instrument required. Then, routine spectral techniques can be easily applied to obtain estimates of the dominant frequency of vibration of the underlying structure. These frequencies of vibration are strongly related to the physical properties of the site under study, i.e., layer thicknesses, densities, or wave velocities. Estimates of these frequencies could be thus useful to characterize the physical properties of a geological structure.

3.2. Application of the Method

The procedure generally used to calculate the HVSR consists in the application of eq. (1) to the average amplitude spectra of the three components of motion. However, we have tested that the routine application of this technique may lead to errors. Local perturbations of the wavefield may happen during the recording periods and be recorded together with the microtremor data. Usually, these transients are easily identified in the seismograms and/or spectra, and the analysis can be performed only on those data free of perturbations in order to obtain reliable results. But variations in the microtremor wavefields might be subtler in such a way that neither visual nor spectral analysis are able to reveal them. In this case, spurious peaks would appear in the average spectra. These peaks could be large enough to affect the spectral ratio and produce unrealistic results.

To avoid this problem, we used a different approach aimed to the estimate of a time-dependent HVSR. Our method consists in the application of eq. (1) to successive data windows along the traces. This procedure yields several HVSR functions that can be represented as a two-dimensional contour plot versus frequency and time. This plot, that we name ratiogram, represents the evolution of the HVSR in the same way that a spectrogram represents the evolution of the spectrum versus frequency and time.

Figure 2 shows an example of application of the HVSR method using the two approaches described above. Following the standard technique, average spectra are calculated (Fig. 2b, top) and the HVSR is obtained as the ratio between the horizontal and vertical spectral amplitudes (Fig. 2b, bottom); we can see the presence of a dominant peak at about 5 Hz and we could conclude that the site produces amplification for this frequency. However, the time-dependent HVSR with the second approach demonstrates that this peak is due to a single transient at about 60 s

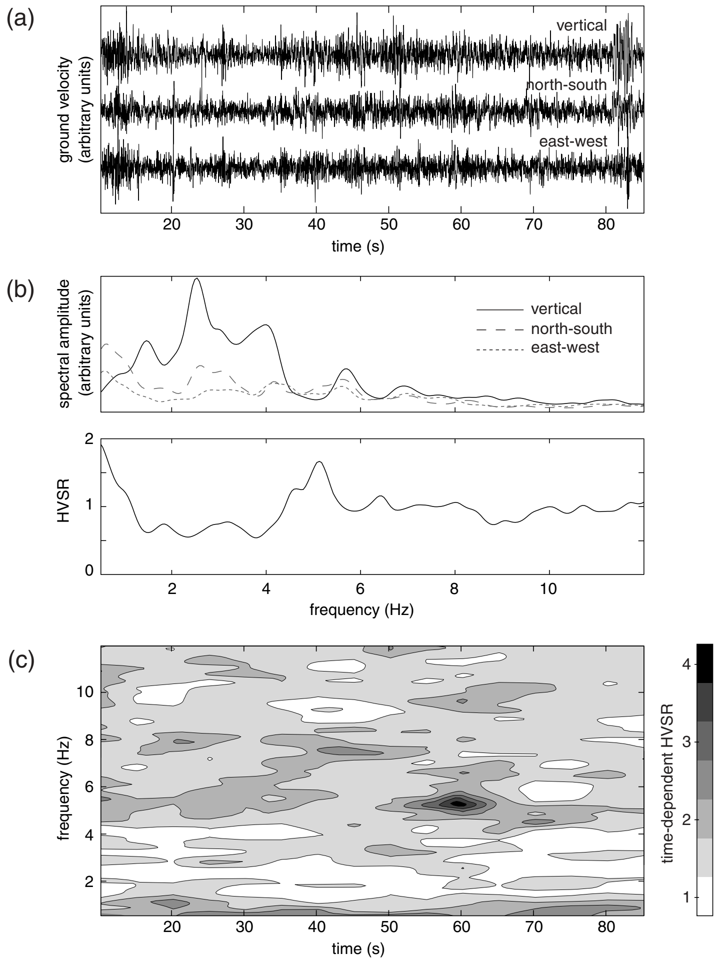

Figure 2
Example of the application of the HVSR method. (a) Three-component microtremor data. (b) Amplitude spectra of the three components (top) and HVSR (bottom) calculated using the standard procedure. (c) Ratiogram representing the HVSR as a function of frequency and time.

(Fig. 2c). This plot shows that the HVSR is not stationary at this site, at least at the time of our measurement, and therefore it makes no sense to estimate a value for the dominant frequency.

When the time-dependent HVSR is stationary, at least during particular time periods, an average HVSR can be obtained by stacking the corresponding HVSRs. This average usually coincides with the one calculated by the standard technique, except for problematic records as shown in Figure 2. The difference between the two techniques consists in the averaging procedure. In the standard method, we average the spectra corresponding to several windows along the traces, and then apply eq. (1)

just once to obtain the HVSR. In our approach, we apply eq. (1) several times to calculate the HVSR for each window, and then average them to obtain the site response. In our opinion, the second approach should be preferred since more stability is expected in the HVSR (that in theory depends only on the site structure) than in the microtremor amplitude spectra which can show temporal variations. Moreover, we take into account not only which peak of the average HVSR is highest, but also whether or not this peak appears stable in time in the ratiogram. A high peak that is not stationary is not considered in the assessment of the dominant frequency, something that is impossible to take into account in the standard approach.

We calculated HVSRs with the second approach described above. We select a window of 20.48 s and slide it at intervals of 5 s along the traces. For each window we calculated the amplitude spectra of the three components using an FFT algorithm, and smoothed using a 0.7-Hz Hanning window. Then we applied eq. (1) to obtain the HVSR. We repeated this procedure for successive time windows over the duration of the microtremor records to obtain a ratiogram for the site. In a ratiogram, the presence of a dominant frequency is marked by a horizontal, ridge-like structure. All noise-free HVSRs representing stable dominant frequencies were selected and averaged to yield the average HVSR, whose peak determines the dominant frequency for the site. Taking into account the response of our instrument and the frequency content of microtremors recorded in the Las Cañadas area, we restricted *a priori* the possible dominant frequencies to the range 1–10 Hz. This condition is not too restrictive, since this is the range of frequencies usually obtained in this kind of studies.

4. Results

Figure 3 shows examples of stationary ratiograms obtained at two different sites. In the first case (Fig. 3a), a clear dominant frequency of 3.6 Hz appears throughout the duration of the records. In the second case (Fig. 3b), the average HVSR does not present a resonant frequency but a flat response with an amplification level approximately equal to one. Ratiograms like these have been calculated for the entire data set using the method described in the last section.

The shape of the HVSR is usually repeatable; microtremors obtained at the same site at different times show similar HVSR functions. For example, Figure 4a shows average HVSRs of 24 data samples recorded hourly at the same site (July 2000 survey). A very stable peak at about 5 Hz is found. Two other peaks are also evidenced between 6 and 9 Hz, but their positions and values change slightly with time. Since the velocity structure under the recording site does not vary, these differences between HVSRs corresponding to different hours may suggest that the source effect has not been completely removed in the spectral ratio. Figure 4b shows

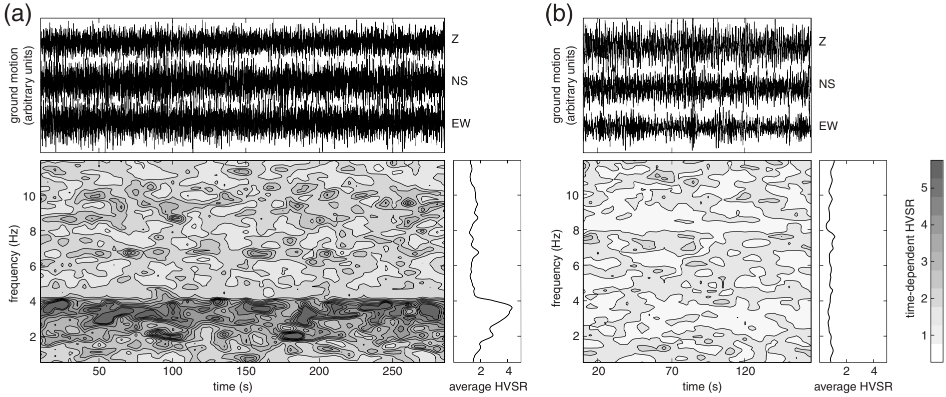

Figure 3
Two examples of ratiograms and average HVSRs obtained from microtremors recorded at sample locations. In each case, the top pannel shows the three-components of ground motion; the bottom pannel corresponds to the ratiogram calculated using the procedure described in the text; and the right pannel shows the average HVSR. The scale on the right represents the values of the time-dependent HVSR in both ratiograms. (a) Example with a stationary peak at a frequency of about 3.6 Hz. (b) Example with no resonant peaks.

another example of HVSRs calculated for data recorded at the same site during the October 2001 survey. Although the microtremors were recorded after lapses of several hours, a dominant frequency at about 3 Hz is clearly seen in the three cases. Finally, Figure 4c shows two examples of HVSRs for data recorded at the same sites with a temporal lapse of one year. The upper panel corresponds to a site where a dominant frequency could be determined at about 7 Hz. The bottom panel shows the average HVSR for a site where there is no vertical resonance of the propagating waves and therefore no dominant frequency could be established. In both cases, we find the same patterns for data recorded during the July 2000 and July 2001 surveys. This repeatability is the behavior observed at about 85% of the recording sites, for which both HVSR functions obtained during the July 2000 and July 2001 surveys at each site lead either to a flat amplification spectrum, or to the determination of the same values of dominant frequency within a limit of about 20%. There are a few cases, however, where we have found a flat HVSR for the July 2000 data and a more or less dominant peak for the July 2001 data, or *vice versa*. These inconsistencies could be attributed to near-site variations of the wavefield that have not been detected and have slipped in during the analysis.

The results corresponding to the dominant frequencies obtained for the three seismic surveys are summarized in Figure 5. The unfortunately large percentage of sites where no information could be obtained was mostly due to failure of a channel during the recording process and/or the presence of non-stationary noise in the vicinity of the recording site. Specifically, this happened at 12 of the 57 recording sites of the July 2000 survey; 21 of the 56 sites of the July 2001 survey; and 1 of the 28 sites

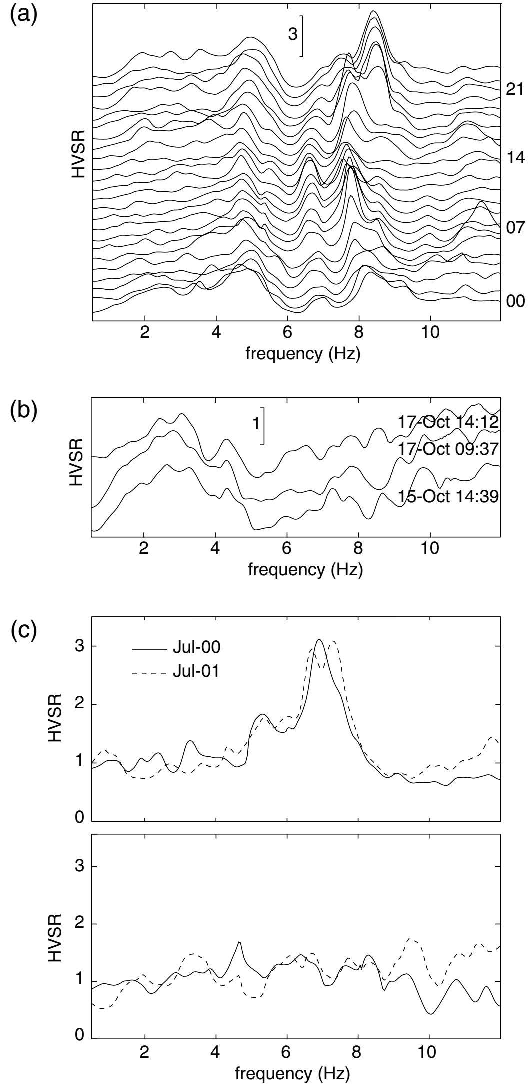

Figure 4
Average HVSRs obtained at the same site at different times: (a) from the analysis of microtremors recorded hourly for 24 hours during the July 2000 survey, (b) at three different times during the October 2001 survey, and (c) at the same sites during the July 2000 and July 2001 surveys.

of the October 2001 survey. Flat HVSRs, such as the example in Figure 3b, have been found at several recording sites during the July 2000, July 2001 and October 2001 surveys (for 16, 13 and 1 sites, respectively). The lack of stationary peaks can be interpreted as the absence of resonance of the structures under the recording sites, at least in the frequency range investigated. For the rest of the sites, the shallow

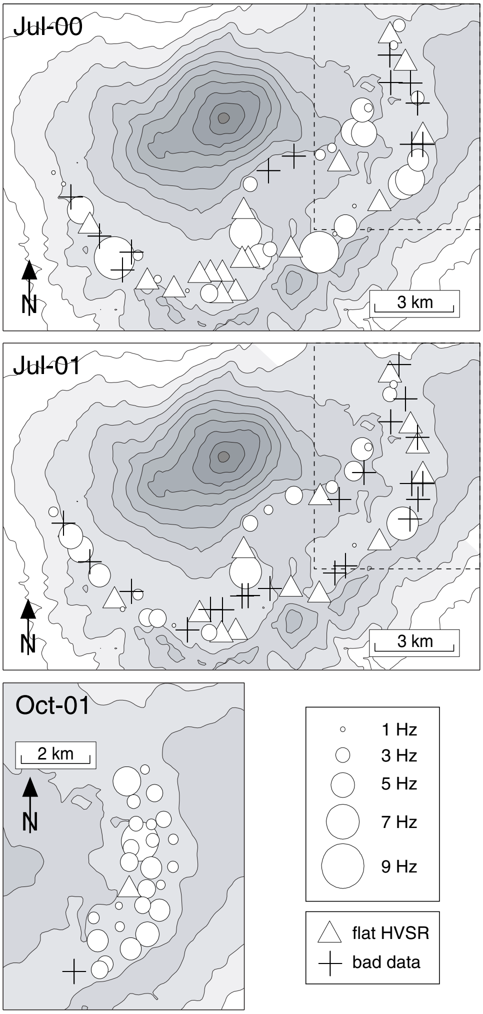

Figure 5
Maps of Las Cañadas caldera showing the results of the HVSR method for microtremor data obtained during the three surveys. Crosses indicate sites where no information could be obtained due to instrument failures or presence of non-stationary noise; triangles mark sites where flat response spectra were found. Finally, circles show those sites where dominant frequencies were determined. The region shown in the bottom left panel is marked by dashed lines on the top and middle panels.

structure beneath the station efficiently induces the resonance and stationary peaks are found. These HVSRs allowed us to assess values of a dominant frequency ranging from 1 to 8 Hz.

Figure 6 combines in a single plot the average values of the dominant frequency obtained at the different sites during the three surveys. The most striking characteristic of the distribution of dominant frequencies obtained is their high

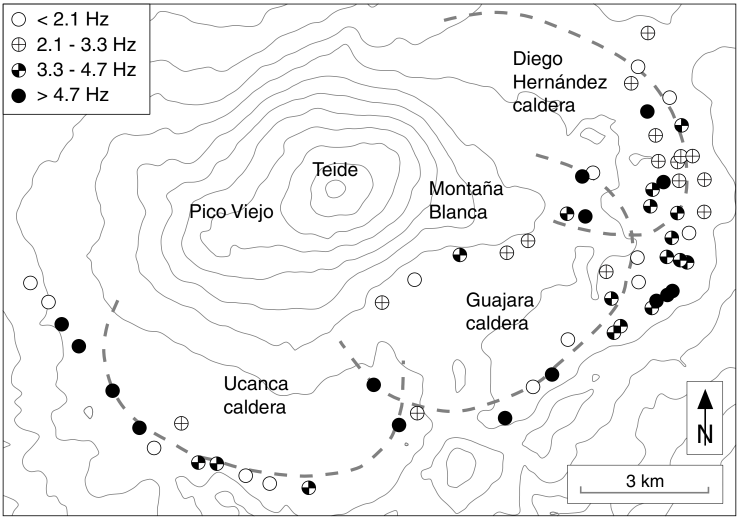

Figure 6
Map showing the average dominant frequencies measured during the three surveys (see Fig. 5). The dashed grey lines correspond to the inferred rims of the Ucanca, Guajara, and Diego Hernández calderas.

spatial variability. For example, in some cases there are very different frequencies at nearby sites located just 300 m apart.

5. Discussion

Several studies show the relationship between the velocity structure beneath the recording site and the dominant frequency obtained from HVSR analysis (see for example NAVARRO *et al.*, 2001). As a first-order approximation, we can apply a simple formula that relates the fundamental frequency to the thickness and seismic velocity of a medium composed of a single layer over a half-space:

$$f_0 = \frac{\beta}{4H} \; , \tag{2}$$

where β is the average *S*-wave velocity and *H* is the thickness of the layer. When the sites are located over the same structure we can assume that the *S*-wave velocity is approximately constant from site to site. This is usually the case in most sedimentary basins. The former relation thus yields a map of sediment thickness from estimates of the resonant frequency (e.g., IBS-VON SEHT and WOHLENBERG, 1999). Inversely, if we assume that in a certain region the surface layers have approximately a constant thickness, the dominant frequency at each point would be then related to an *S*-wave velocity and a map of surface velocities could be obtained.

However, in a volcanic environment like Las Cañadas caldera we cannot assume any of the former assumptions. Exhaustive studies of the surface geology in Las Cañadas (Ancochea *et al.*, 1990; Martí *et al.*, 1994; Ancochea *et al.*, 1999; Ablay and Martí, 2000) have produced detailed information about the composition, location, and extent of each exposed rock type and its role in the volcanic evolution of the region. Borehole data provide additional constraints on the subsurface structure of Las Cañadas. Current interpretations (e.g., Ablay and Martí, 2000) assume that the caldera fill is made by superposition of a variety of eruptive products originated at different vents related to the Teide-Pico Viejo edifice. These deposits are thick (> 500 m) in the central and eastern parts of the caldera, and thin (< 100 m) in the western part. Although, in principle, the different layers are assumed to be horizontal, no detailed information about thickness or horizontal extent is available. The diversity of volcanic materials which form the caldera prevents us from using the constant *S*-wave simplification; it would imply the assumption of a homogeneous velocity for the entire caldera, something that is not justified at all in view of the heterogeneities found by geological studies. Likewise, the absence of correlation between the observed dominant frequencies and the mapped geological units suggests that the constant depth simplification is not useful either. Even when we assume a smaller thickness of the volcanic deposits in the western caldera (Ablay and Martí, 2000) we find that some sites apparently located on the same geological structure show very different dominant frequencies.

In reality, it is likely that both *S*-wave velocity and layer thickness in Las Cañadas change considerably from site to site, over distance scales shorter than our sampling interval. This idea is consistent with the results shown in Figure 6. Dominant frequencies in the caldera vary sharply, even for nearby locations just a few hundred meters apart. Short-scale heterogeneity in the spatial distribution of dominant frequencies has been found in other volcanic areas as well. We have a clear example in the work by Mora *et al.* (2001), who applied the standard HVSR method to investigate the presence of site effects at the Arenal volcano, Costa Rica; they used a dense linear array (with a spacing of 150 m) and found that dominant frequencies may vary drastically in distances of just a few hundred meters, in correspondence with changes in the velocity structure.

The difficulty in the interpretation of this kind of results arises because we have to consider the effects of layer thickness and wave velocity simultaneously. To be able to interpret the measured values of dominant frequencies, further constraints on the shallow structure of the Las Cañadas caldera are required. In this sense, several geophysical studies have been carried out to investigate the structure and evolution of the Las Cañadas edifice. For example, gravimetric measurements have revealed the presence of density anomalies (Vieira *et al.*, 1986; Camacho *et al.*, 1991, 1996; Araña *et al.*, 2000; Ablay and Kearey, 2000); a shallow, low-density region is located under the Teide-Pico Viejo edifice in the northern part of the caldera. This anomaly could be due to the presence of a low-density caldera fill and the abundance of light materials erupted during recent volcanism. High-density anomalies are observed near the caldera walls. Gravity modeling suggests that these anomalies could extend several kilometers in depth (ABLAY and KEAREY, 2000) and be caused by the influence of dense materials related to the old basaltic shield (CAMACHO *et al.*, 1996). A dense fill could be also responsible for the positive gravity anomalies in the southern part (ABLAY and KEAREY, 2000). Magnetic surveys have revealed the existence of anomalies (BLANCO, 1997; GARCÍA *et al.*, 1997). A negative anomaly coinciding with the Teide summit has been interpreted as an effect of hydrothermal alteration due to fluids at high temperatures (ARAÑA *et al.*, 2000). The presence of volcanic fluids has been evidenced by measurements of gas emission rates (HERNÁNDEZ *et al.*, 2000). Another negative anomaly, coinciding with the Diego Hernández caldera, has been attributed to an accumulation of phonolitic materials infilling the caldera, which show very low magnetization compared with basalts (ARAÑA *et al.*, 2000). Seismic studies have been also performed to investigate the structure of Tenerife. Recent works have established the presence of a high-velocity zone southwest of Las Cañadas (WATTS *et al.*, 1997; CANALES *et al.*, 2000). This zone is coincident with a high-density body inferred from gravimetric studies and interpreted as the core of an old, large mafic volcano (CANALES *et al.*, 2000; ABLAY and KEAREY, 2000). The eastern part of Las Cañadas was the site of a seismic experiment by DEL PEZZO *et al.* (1997), who analyzed the coda of local earthquakes using two seismic arrays. They showed that the area is characterized by a highly heterogeneous shallow structure that produces strong scattering of the seismic waves. However, the locations of the scatterers could not be estimated.

All these studies constitute important contributions to our understanding of the general structure and volcanic evolution of Las Cañadas, although their resolution is too low for a direct comparison with the distribution of dominant frequencies. Nevertheless, they may help us understand the few patterns that we have been able to find in our results. For example, the largest dominant frequencies usually occur near the caldera rim (see the distribution of black dots in Fig. 6). Large frequencies are generally associated to thin layers (eq. (2)); therefore our observation is reasonable since we expect that the volcanic deposits become thinner when we move outward the eruptive centers and toward the caldera walls. There are two exceptions, one located south of Ucanca and another along the northeast caldera wall (Fig. 6). They may be attributed to a decrease in the seismic velocity that somewhat compensates the decrease in layer thickness, yielding moderate dominant frequencies. In support of this interpretation, both areas display loose pyroclastic deposits that would be characterized by low S-wave velocities. A few large dominant frequencies are measured within the caldera, far from the caldera walls (Fig. 6). They seem to correlate with the intersections of the ancient caldera rims (Ucanca-Guajara and Guajara-Diego Hernández) corresponding to the three inferred caldera collapses that formed Las Cañadas (MARTÍ *et al.*, 1994; MARTÍ and GUDMUNDSSON, 2000). If this is the case, our method would be sensitive to the presence of buried, compact remains of the Las Cañadas edifice. This might help us answer the question of whether the Cañadas caldera originated by a northward-directed landslide or by multiple vertical collapses (ANCOCHEA *et al.*, 1990; MARTÍ *et al.*, 1994; ABLAY and HÜRLIMANN, 2000; MARTÍ and GUDMUNDSSON, 2000). However, our sampling is too coarse to ensure a direct relationship. Further experiments with denser spatial sampling would be required. Very small dominant frequencies are likewise measured at several sites near the caldera rim (Fig. 6, white dots). They might correspond to discontinuities in the structure of the caldera wall, or local variations of the *S*-wave velocity of the caldera fill. Small-to-intermediate dominant frequencies are found in the central caldera, immediately south of Montaña Blanca (Fig. 6). This result is consistent with greater thickness of the volcanic deposits near the eruptive vents, as evidenced for example by the interpretation of borehole data (ABLAY and MARTÍ, 2000).

The easternmost region of Las Cañadas shows dominant frequency measurements that are more self-consistent and show less spatial variability than the rest of the caldera (Fig. 6). This may be due in part to the shorter sampling interval, which produces a clearer image of the distribution of dominant frequencies, and also to better conditions of the sites for application of the Nakamura method. For example, DEL PEZZO *et al.* (1997) speculated about the possibility of a strong velocity contrast between the uppermost and the underlying layers in the Diego Hernández area. A negative magnetic anomaly found in this part of the caldera (BLANCO, 1997; GARCÍA *et al.*, 1997) has been interpreted as a relatively thick deposit of phonolitic materials (ARAÑA *et al.*, 2000). Both results favor the generation of resonance and therefore the measurement of a dominant frequency.

Figure 7a shows a closer view of the results in the eastern caldera, where the spatial sampling is densest. Dotted lines surround regions where the measured dominant frequencies are similar. When we follow the AA' profile, we find a smooth variation of dominant frequencies, ranging in average between 2.7 Hz in zone I and 6.0 in zone III. If we assume a constant seismic velocity, our interpretation of these variations in dominant frequency is that the thickness of the volcanic deposits changes along the profile. Justification for this hypothesis comes from the fact that surface materials are far more homogeneous in this small region than in the caldera as a whole. They are mostly composed of phonolitic lavas and scorias (ABLAY and MARTÍ, 2000). Figure 7b shows the basement depth profile obtained from eq. (2) for an *S*-wave velocity of 1 km/s, that is the average velocity obtained from array measurements by DEL PEZZO *et al.* (1997). We obtain realistic basement depths between 40 and 95 m, approximately. The smallest layer thickness, corresponding to zone III, could correlate with the region where the ancient rims of the Guajara and Diego Hernández calderas would have intersected (Fig. 6). Alternatively, we could assume a constant thickness approximation to consider that the variations in dominant frequency are related to changes in the seismic velocity of the medium. This hypothesis is supported by the flatness of the caldera floor before the formation of the Teide-Pico Viejo edifice and subsequent filling of the caldera with new volcanic

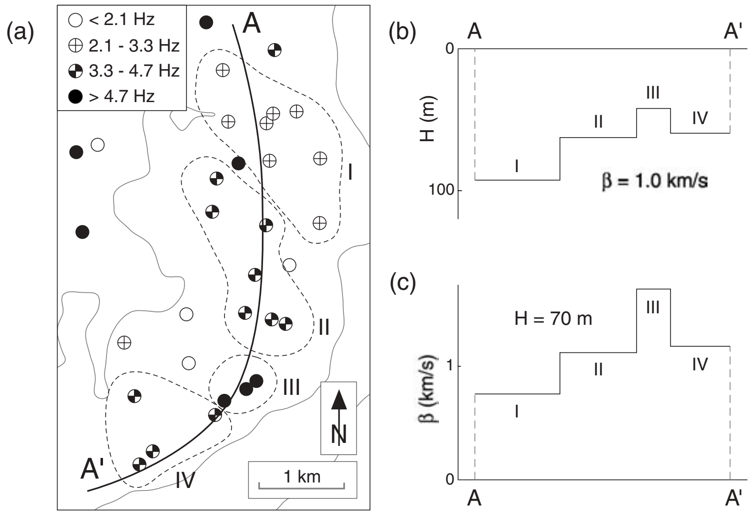

Figure 7
(a) Dominant frequencies obtained at the eastern part of the Las Cañadas caldera. Dashed lines identify regions where the measured dominant frequencies are similar. The solid line AA' represents a profile discussed in Figures 7b and 7c. (b,c) Interpretation of the dominant frequency data corresponding to the AA' profile for the simplified cases of constant *S*-wave velocity of $\beta = 1.0$ km/s (b), and constant layer thickness of $H = 70$ m (c).

materials (ABLAY and MARTÍ, 2000). In this case, eq. (2) yields the seismic velocity profile shown in Figure 7c, for a constant layer thickness of 70 m. However, there is no evident correspondence between these velocities and the surface geological units. Although the subsurface geology may be somewhat different from the exposed layer, the relative homogeneity of the materials in this region makes us think that the effect of layer thickness on the dominant frequencies might dominate over the effect of wave velocity. Therefore, we believe that the profile shown in Figure 7b may be closer to reality.

6. *Conclusions*

We have proposed a modification of Nakamura's method to microtremor data recorded near Teide volcano. This new approach consists of the calculation of time-dependent HVSR functions, or ratiograms, to investigate the temporal evolution of the spectral ratios and the effect of local perturbations. The interpretation of these ratiograms allows us to determine the dominant frequencies, excluding those cases where the time-dependent HVSRs are not stationary. In this way, we are able to discriminate between real resonant frequencies and spurious peaks due to local transients in the data. We performed various tests of the stability of our estimates of the average HVSR functions, checking the similarity between HVSRs for data recorded at the same site but at different times. We demonstrate that at a site, the HVSRs show similar shapes even when the measurements are separated by a time interval of a year. This fact is independent of the presence of resonant peaks, and suggests that the HVSRs depend basically of the geological structure at each recording location.

The application of the HVSR method provides new clues about the shallow velocity structure of the caldera. The distribution of dominant frequencies, although heterogeneous, may be approximately explained in terms of thickness and average seismic velocity of the volcanic deposits. However, some questions remain open, mostly due to lack of coverage. A finer sampling interval would be desirable for further applications of the method. From the results obtained in this study we conclude that ratiograms constitute an improvement of the HVSR method, due to their capability to help us understand the temporal evolution of the spectral ratio. This technique can be easily implemented, and may be applied not only to the problems or structures considered up to now by other authors, but to the characterization of the subsurface geology in volcanic ambients as well.

Acknowledgements

This work was partially supported by CICYT, Spain, under Grants AMB99-1015-CO2-02 and REN2001-2418-CO4-02/RIES. Additional support was provided by projects REN2001-3833/ANT, REN2001-2814-C04-04/RIES and REN2002-4198-C02-02/RIES, and by the research teams RNM-194 and RNM-104 of Junta de Andalucía, Spain. We thank the Teide Natural Park authorities and all institutions and individuals that collaborated in the microtremor experiments: Juan, Benito, and María José Blanco from Centro Geofísico de Canarias; Olga Muñoz; Benito Martín from Instituto Andaluz de Geofísica; and Serafín Limonchi and César F. Aguilera from Universidad de Almería. Ramón Ortiz provided useful hints for the interpretation of seismic data. We also acknowledge José Morales, Gerardo Alguacil, and Jesús Ibáñez for useful comments. We thank the Martín-Barry family for the review of the manuscript. The reviews of Joan Martí and an anonymous reviewer helped to improve this paper.

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(Received April 2, 2002, revised December 23, 2002, accepted January 31, 2003)