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The role of the volcano-tectonic structure on the seismic site response: An application in the northeastern sector of Mt. Etna volcano, Sicily, Italy

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Abstract: In this work, the author describes the results of a study aimed at verifying whether the technique of the spectral ratio *(Nakamura, 1989)* between horizontal and vertical components of an earthquake can also be applied to volcanic areas to estimate the site response.

Five earthquakes have been considered to achieve this objective. These were recorded at the digital seismic station, equipped with a 3D seismometer, situated at Vena in the northeastern sector of Etna, in an area where the volcanic rocks have a modest thickness and lay on the quaternary clays and on flysch. The epicenters of the seismic events are located roughly along an arc of 130°, with vertices at the Vena seismic station. By considering the S radiation in the frequency domain, a preliminary deconvolution of the recorded seismic signal was performed.

Then, the relationship $H_{(f)} = (h_u(f)^2 + h_v(f)^2)^{1/2}$ was calculated, which represents the transfer function of the seismic signal through several surface layers, or rather the site amplification. In the first instance, and on the basis of the obtained results, by analyzing only the effects related to five seismic events opportunely distributed with respect to the central axis of the magma uprise, one must conclude that this response shows an appreciable anisotropy, probably determined by the complex volcano-tectonic structure of the area where the seismic station is located.

Lastly, an analysis of the noise, to which the technique of the spectral ratio was applied, was performed in the frequency domain. Analogously to what was observed for the S waves, the amplification is markedly variable at the low frequencies and this, according to the author, is due to the temporal variation in the structure of the seismic signal.

Key words: Mount Etna, Nakamura, site response, spectral ratio, anisotropy

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1. Introduction

The importance of evaluating the ground movements in the short term, determined by relatively close seismic events, is largely owing to the great development of modest sized buildings in the territory. The generally adopted methods, since they are quicker, are based on recording micro-tremors, small oscillations ever present in the land determined both by natural, as well as anthrophic causes.

The analysis of micro-tremors begun by *Kanai and Tanaka (1961)* and saw successive developments through the use of *Nakamura's technique (1989)*, based on the spectral ratio of the horizontal and vertical component of the ground movement on the surface (H/V).

In general, the terrains analyzed with this method by other researchers that outcrop in sedimentary basins and more rigid formations, such as volcanic ones, have rarely been considered. The availability of numerous recordings of Etnean earthquakes at the Vena station, located in a sector of the volcano, where lava cover, on top of the quaternary clays, is not very thick (Fig. 1), has led the author of this work to verify whether the above methods are still applicable also in rigid terrains.

The problems encountered in the data analysis depend on the effect exercised on the site response by the large tectonic and volcano-tectonic structures, which are present and converge in the area, and by the peculiarity of the S wave propagation. The adopted technique is that of spectral ratios applied to the S waves and to the noise, which should ensure the absence of the effects due to the source and the attenuation of the medium in the site response.

2. Data analysis

The study of the recordings of Etnean earthquakes in time shows, depending on the relative position between the epicenter and the seismic station, that the waveform varies widely. Such a variation is also reflected in the trend of the seismic signal in the frequency domain; in fact, according to *Somerville et al. (1987)*, the lowest frequency band of the spectrum may be affected by the attenuation determined by the medium crossed by seismic

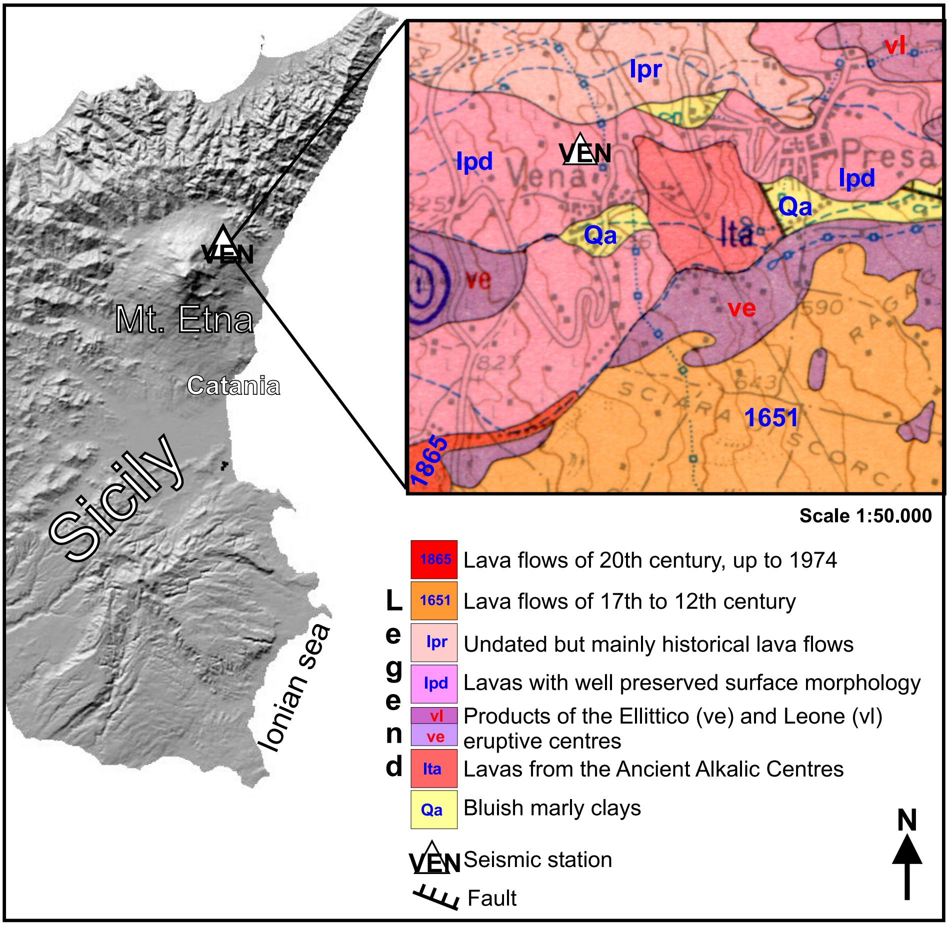


Fig. 1. Geological sketch map of the studied area and location of the seismic station (triangle).

energy along the source to station path and by the site response.

Frankel and Wennerberg (1989), when studying relatively distant ($\Delta \leq$ 50 km) earthquakes with modest magnitude, highlight that the structure of the spectrum is specific to each site and is due to a low Q coefficient value of the surface layers.

With the aim of testing if there is effectively a site response anisotropy, an analysis of the spectral content of five Etnean earthquakes recorded in the Vena region (740 m. a.s.l.), located in the north-eastern sector of Etna, (Fig. 1), was carried out. The seismic station works on "trigger" mode, digitizes the seismic signal with a sampling frequency equal to 62.5 Hz, and transfers the data to a suitably programmed memory; the sensor is a 3D seismometer with a natural frequency of 1Hz and a sensitivity of 400 V/m/s in the 0.5–100 Hz frequency band, fully comprising the analyzed seismic signal.

The two horizontal components were oriented in radial and transversal direction to the main conduit of the uprising magma, WSW–ENE and NNW–SSE respectively, and the earthquakes considered were chosen from a set of 26 events owing to their particular position (Fig. 2).

The epicenters, located by the National Geophysics and Volcanology Institute (INGV – Catania section) seismic network with ERH, ERZ$<$ 3 km, RMS$<$ 0.3 s, are 16–21 km from the Vena station, covering a roughly 130° circular sector that comprises the main axis of the magma uprise, and are more or less equidistant (Fig. 2). Through this particular station-epicenter geometry, it was hoped to verify the following:

- the interaction mode between geology and the site (Fig. 1) and the source of the wave which varies with the direction of the latter;
- the effect on the site response by the volcano-tectonic structures, known as "*Timpe della Naca*", which show a great morphological evidence in the examined zone (Fig. 2);
- the interaction between the S wave front and the central conduit of the magma uprise.

Figures 3a and 3b report the waveforms and the spectral content of the maximum amplitude stages (S wave) with respect to each of the five earthquakes, whose magnitude is less than 3.0.

The FFT of the S waves was performed in a four second window in which this phase showed the greatest energy; this latter generally has the maximum values in 1.0–5.0 Hz the frequency range and decreases substantially by 1.0 Hz $< f <$ 10.0 Hz.

However, in the No. 25 of 22/11/2001 earthquake (Fig. 3a) there are also considerable amplitudes for $f >$ 10.0 Hz, and it is believed they are mainly due to P type waves reconverted into S following refraction and reflection phenomena in the numerous discontinuities where the station is located.

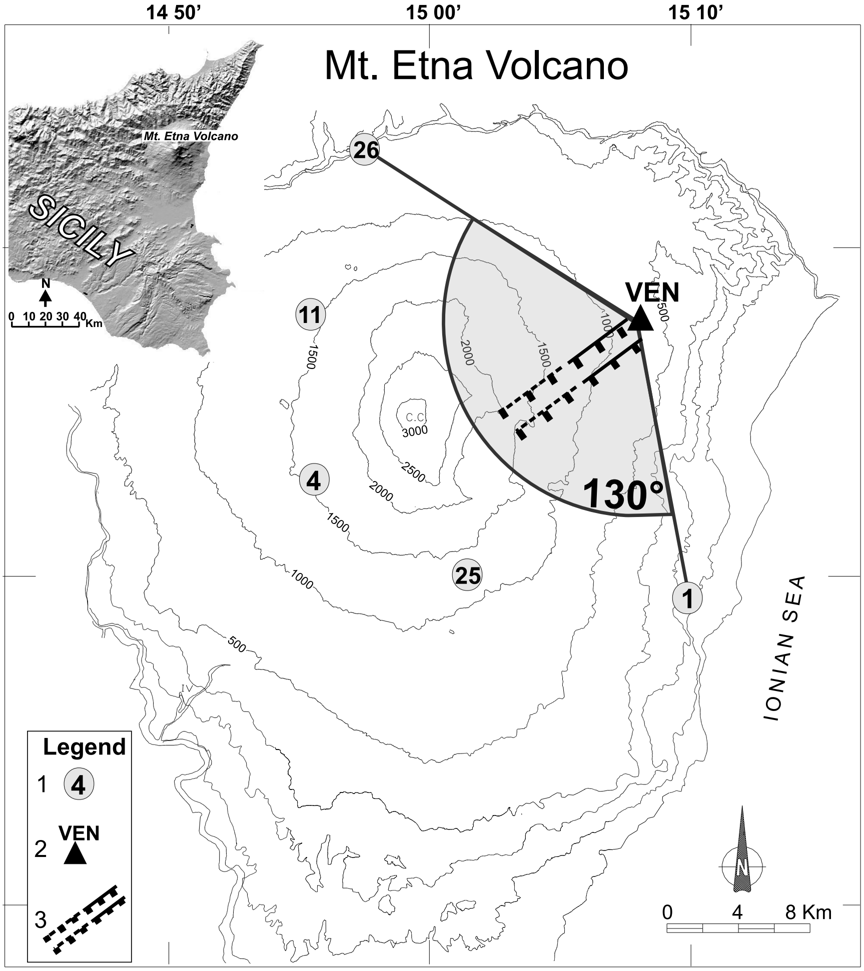
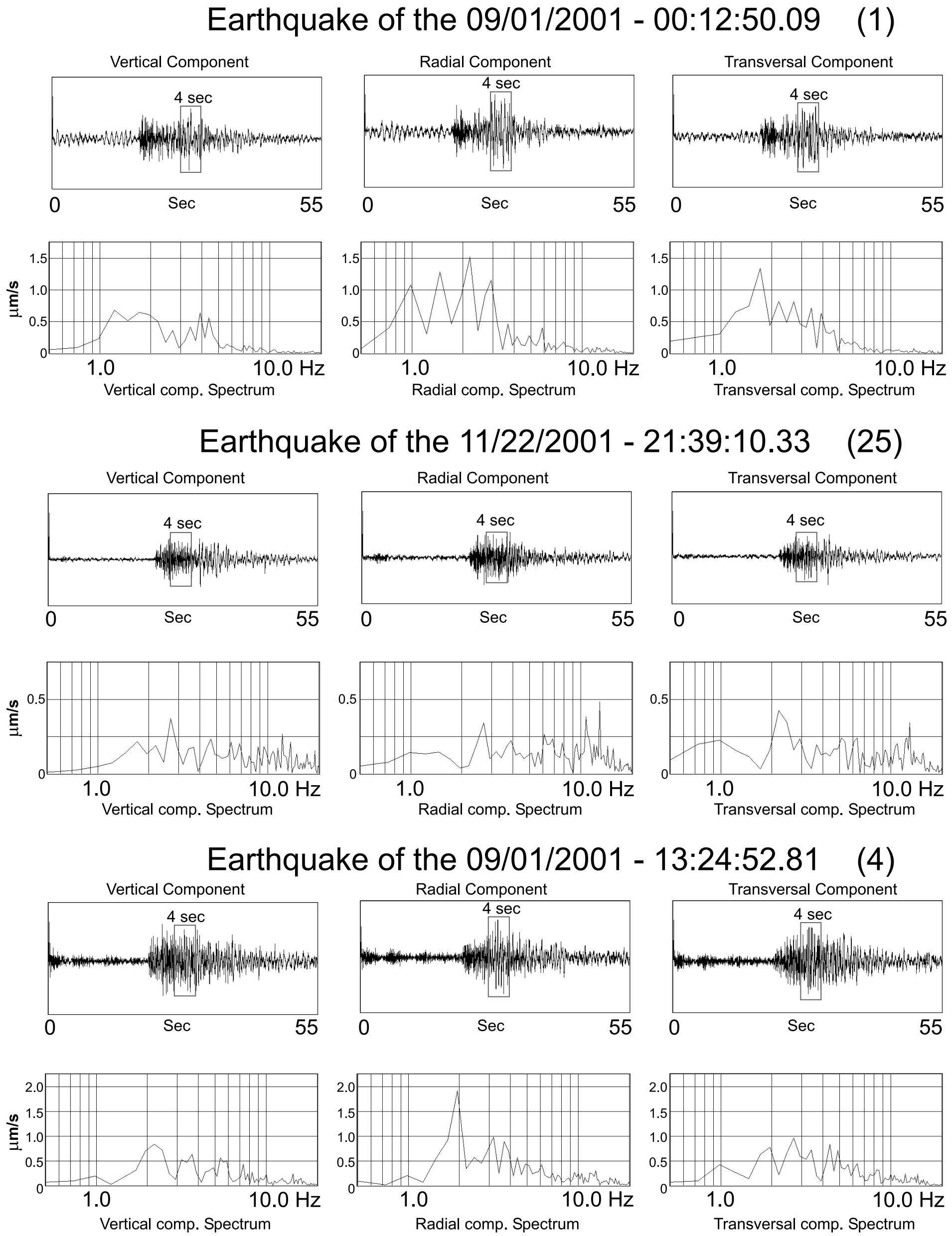


Fig. 2. Epicentral location of the seismic events studied. (1) epicenter; (2) seismic station; (3) volcano-tectonic structure denominated "Timpe della Naca".

After doing a smoothing of 5% on the amplitude spectra, we then proceeded to the relationship between the horizontal $H_s(f)$ and the vertical $V_s(f)$ component of the spectrum. Such a relationship, according to *Castro et al. (1997)*, represents the amplification of the site to various frequencies, given by the transfer equation:



Earthquake of the 09/01/2001 - 00:12:50.09 (1)

Earthquake of the 11/22/2001 - 21:39:10.33 (25)

Earthquake of the 09/01/2001 - 13:24:52.81 (4)

Fig. 3a. Waveform on the three components of the studied earthquakes and spectral analysis of the maximum amplitude phase, in a four second window.

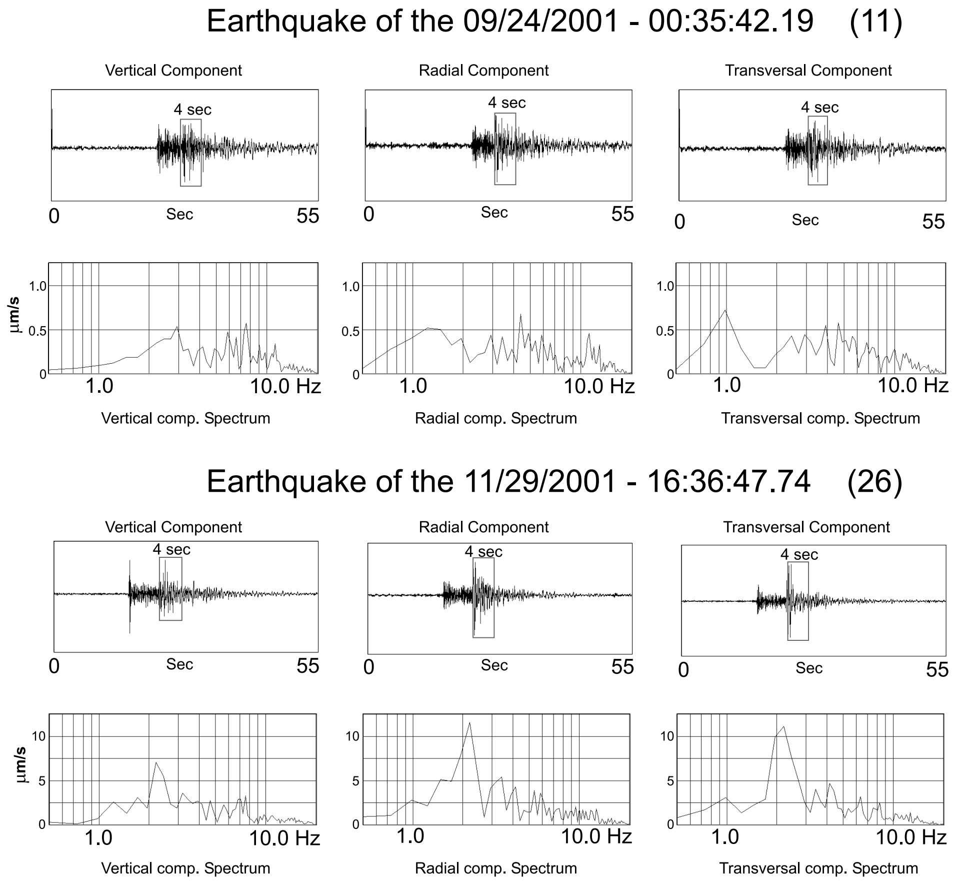


Fig. 3b. Waveform on the three components of the studied earthquakes and spectral analysis of the maximum amplitude phase, in a four second window.

$$H(f) = [h_v(f)^2 + h_u(f)^2]^{1/2},$$

where: $h_v(f) = V_s(f)/V_b(f)$; $h_u(f) = H_S(f)/H_B(f)$; $V_s(f)$, $V_b(f)$; $H_s(f)$ and $H_b(f)$ being the vertical and horizontal components of the earthquake on the surface and on top of the bedrock, respectively. In addition, $h_v(f)$ and $h_u(f)$ were given by the relations:

$$h_V(f) = \frac{S_V(f) \cdot T(f) \cdot Z_V(f)}{S_V(f) \cdot T(f)} = \frac{V_S(f)}{V_b(f)},$$

$$h_S(f) = \frac{S_u(f) \cdot T(f) \cdot Z_u(f)}{S_u(f) \cdot T(f)} = \frac{H_S(f)}{H_b(f)},$$

where:

$S_{v,u}(f)$ contains the contribution of the source on the vertical and horizontal component of the earthquake, respectively;

$T(f)$ contains the effects of the S wave path from the source to the top of the bedrock;

$Z_{v,u}(f)$ represents the amplification induced by the last layer in the vertical and horizontal component of the earthquake, respectively.

The relationship between $h_u(f)$ and $h_v(f)$ is given by the equation:

$$\frac{h_u(f)}{h_v(f)} = \frac{Z_u(f)}{Z_v(f)} = \frac{H_s(f)}{H_b(f)} \cdot \frac{V_b(f)}{V_s(f)}.$$

Castro et al. (1997) demonstrated that the vertical component of the earthquake does not undergo any amplification so that it is $Z_v(f) = 1$, moreover, if one assumes that it is

$$V_b(f) = H_b(f),$$

then:

$$h_u(f) = Z_u(f) = H_s(f)/V_s(f),$$

and thus the amplification of the site depends exclusively on the relationship between the vertical and horizontal components of the earthquake on the surface.

Naturally, this last assumption must be verified through well measurements that allow reaching the bedrock. Unfortunately, even if these exist in the area considered in this study, they are not suitable for the application of such methods.

The ratio $H_s(f)/V_s(f)$ obtained on average equals to 2, and generally falls between 1 and 3, would confirm what has been observed by other researchers. In fact, in soft sites it may exceed values of 4 *(Field and Jacob, 1993)*, while in sites with rigid rocks, as in our case, being relatively transparent to the higher frequencies (1.0–30.0 Hz), it shows lower amplifications *(Andrews, 1982; Hanks, 1982; Frankel and Wennerberg, 1989).*

Centamore et al. (1997) consider the mean value of the normalized seismic moments as the amplifications of three sites located in the eastern sector of Etna. The obtained results generally show an amplification lower than 2 to be attributed, probably, to a greater thickness of the more rigid layers. In agreement with *Aki (1988)*, the amplification factor largely depends on the frequency content of the ground movement.

In the 5 examined spectra, for frequencies below 1.5 Hz, such a factor may indeed exceed the value of 6 and vary generally between 3 and 5. Anomalies in site amplification of comparable entities, and dependent on frequency, were also found by *Patanè et al. (1994)* in some stations located on unaltered lava rocks.

These authors conclude, in accordance with *Tucker et al. (1984)* and *Cranswick (1988)* that this was owing to a distortion produced in the seismic signal by surface structures near to measurement stations located on rigid rocks. In our case, substantial differences in the site response are found between 0.5 and 1.5 Hz (Fig. 4), on altering the direction of the seismic radius; if the latter is closer to the *"Timpe della Naca"*, then the amplification is greater (events No. 11 and 25) (Fig. 4c,d).

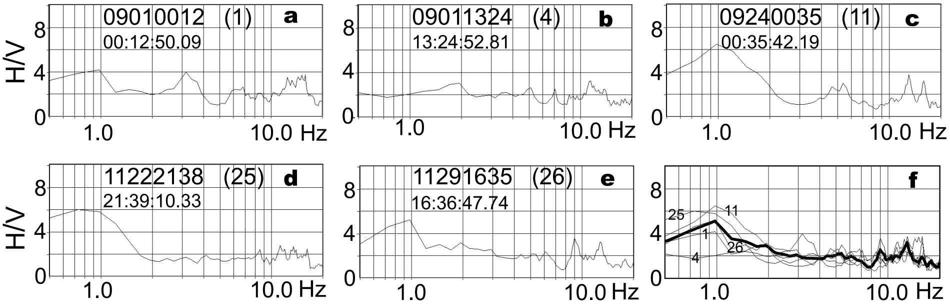


Fig. 4. Spectral ratios (a,b,c,d,e) between the horizontal components (H) and the vertical ones (V), relative to the studied earthquakes. In (f) are represented all spectral ratios and the bold line shows the average.

Below 1 Hz, however, the amplification shows a sharp decrease (less or equal to 2), when the epicenter of the earthquakes is at the antipodes of the Vena station with respect to the central conduit of the uprising magma (Fig. 2, Fig. 4b).

Lastly, the analysis, in the frequency domain, of the noise preceding the five studied seismic events was performed.

We considered 1 minute temporal windows of the seismic signal, choosing those samples in which anthrophic noise was completely absent, namely rather low frequency seismic transients and/or tremors caused by degassing processes within the volcanic conduit.

The trend of the spectral ratio H/V (Fig. 5) remained fairly stable and fluctuated between values of 1 and 2, in the 2.0-15.0 Hz frequency range.

For 1.5 Hz $< f <$ 2.0 Hz, H/V seems to increase and in particular between 0.5 Hz and 2.0 Hz, it assumes maximum values close to those found when considering the S waves. In detail, the values vary between 1.5 and 5.0 and this denotes a notable instability in the nature of the seismic signal, probably due to the nature of the kind of wave detected at different times.

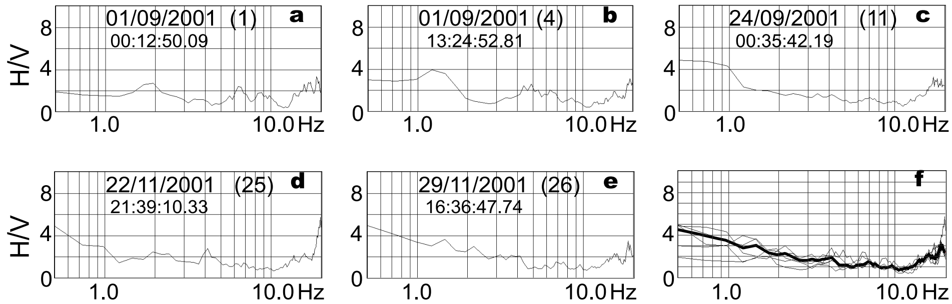


Fig. 5. Spectral ratios (a,b,c,d,e) between the horizontal (H) and vertical (V) components, relative to the noise samples. In (f) are represented all spectral ratios and the bold line shows the average.

3. Considerations and conclusions

The analysis of the seismograms of the 5 studied earthquakes in time clearly shows a substantial variation in the wave shape on altering the position with respect to the epicenter and the station.

The "Fast Fourier Transform" (FFT) carried out on the maximum amplitude phase shows in addition that most of the energy of the S wave is developed between 1 and 10 Hz; the spectral amplitudes are generally reduced for frequency values beyond this range. The H/V spectral ratios show that basically the mean value is circa 2 for $1.5 < f \leq 10$ Hz (Fig. 4f), which is the frequency range of greatest interest since most of the energy associated with S waves falls within it. However, the highest amplifications are for $f \leq 1$ Hz, even if the energy of the S phase is very modest in this frequency range.

In the case of event No. 4, the wave front crosses the central conduit of the rising magma before reaching the seismic station. This would appear to cause a drastic decrease in the amplitude of the horizontal component of the S wave and thus a lower H/V ratio value (Fig. 4b).

An overall picture of the observations carried out allows concluding that the seismic site response of Vena shows a clear anisotropy to the lower frequencies and a generally higher amplification. This anomaly seems to substantially depend on the direction taken by the wavefront of the S phase, with respect to the volcano-tectonic and/or tectonic structures outcropping in the area. In fact, these latter are probably responsible for the origin of surface waves, perhaps Rayleigh type, which may influence the H/V ratio.

The obtained results, analogous to those found by other researchers in sedimentary basins in a higher frequency range *(Yamanaka et al., 1994; Castro et al., 1997)*, demonstrate that the lava layer at Vena moderately affects the site response, which on average has a slightly higher amplification (circa + 0.5) with respect to that of other locations in fundamentally different geological-structural contexts.

In general, the trend of the H/V spectral ratios for the S waves and the noise are fairly similar and, in particular, one can see a considerable increase in the amplification for values below 1.0 Hz and above 15.0 Hz.

Nevertheless, the analysis of the noise in the 0.5-2.0 Hz frequency band shows a marked variability in the site response or, in other words, in H/V at different recording times.

This phenomenon may be attributed to the complex structure of the seismic signal, variable in time. In other words, the noise may be constituted by body (P and S) and shallow (Love and Rayleigh) waves, which to a differing extent can considerably alter the H or V component, and thus that which is generally considered to be the site amplification.

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