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A seismic attenuation zone below Popocatépetl volcano inferred from coda waves of local earthquakes

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RESUMEN

Utilizando un modelo de dispersión simple, los promedios pesados del factor de calidad $<Q_c>$ fueron estimados a 6 Hz para ventanas de ondas coda de 25s después de la llegada de la onda S con profundidades en el rango de 2 a 10 km y magnitudes entre 2 y 3. Considerando Q_c^{-1} como atenuación intrínsica, encontramos una zona de atenuación sísmica entre los 6 y 8 km de profundidad atribuida a la presencia de magma y al derretimiento parcial de roca.

PALABRAS CLAVE: Ondas coda, volcán Popocatépetl, coda Q, factor de calidad, atenuación.

ABSTRACT

Using a single scattering model, weighted averages of the quality factor $<Q_c>$ were estimated at 6 Hz for coda wave windows 25s after S-wave arrival at depths ranging from 2 to 10 km and magnitudes between 2 and 3. Considering Q_c^{-1} as intrinsic attenuation, we find a zone of seismic wave attenuation between 6 and 8 km depth attributed to the presence of magma and partial melting of rock.

KEY WORDS: Coda waves, Popocatépetl volcano, coda Q, quality factor, attenuation.

INTRODUCTION

Popocatépetl volcano (Popo) is one of the most active volcanoes of Mexico. It represents a hazard to Mexico City and towns located near the volcano in the states of Puebla and Morelos with a combined population of more than 25 million people within 60 km from its summit. Since December 1994, Popo has shown a significant increase of seismic, fumarolic and ash emission activity as well as minor and medium eruptions (Arciniega-Ceballos *et al*., 1999). Most of the tectonic earthquakes are located in the depth range of 5 to 10 km under the summit of Popo (Valdés-González and González-Pomposo, 1999).

We use the single scattering model of Aki and Chouet (1975) to analyze the quality factor of coda waves (Q_c) of local earthquakes recorded by the Popo seismic network during 1995 (Figure 1a). The seismic network is described in Martínez-Bringas (1998). The activity at Popo in early 1995 was related to the volcanic eruption of 21 December 1994. The following three months presented a continuous tremor with amplitude between 1 and 8 mm, and volcano-tectonic earthquakes with magnitudes between 2 and 3 located at depths between 1 and 9 km (Figure 1b). From April to December 1995, the main volcanic activity consisted of ash and gas emissions (Valdés-González and González-Pomposo, 1999).

Variations of Q_c have been studied in several tectonic environments (Novelo-Casanova *et al*., 1985, 1990; Jin and Aki, 1988; Zúñiga and Díaz, 1994; O' Doherty and Bean, 1997). Amplitudes of coda waves are frequency-dependent and their decay rate is independent of the path and source-to-receiver distance (Aki and Chouet, 1975; Rautian and Khalturin, 1978). Q_c values change regionally with tectonic activity and gradually increase from active to stable areas (Pulli and Aki, 1981; Singh and Herrmann, 1983).

Spatial or temporal variations in coda decay rate could indicate changes in seismic properties, such as attenuation and the state of stress. Variations in coda decay rate have been suggested as earthquake precursors (Jin and Aki, 1986; Sato, 1988). It has been observed that *b*-value and Q_c variations have the same trend around major earthquakes and an opposite trend around volcanic eruptions (Wyss, 1985; Novelo-Casanova *et al*., 1985; Sato, 1986; Jin and Aki, 1986). The *b*-value gives an indication of the ratio of small magnitude events to large magnitude events. Thus, *b* might increase or decrease with the closing of crustal cracks according to the change of stress (Herraiz and Espinosa, 1987). If the in-

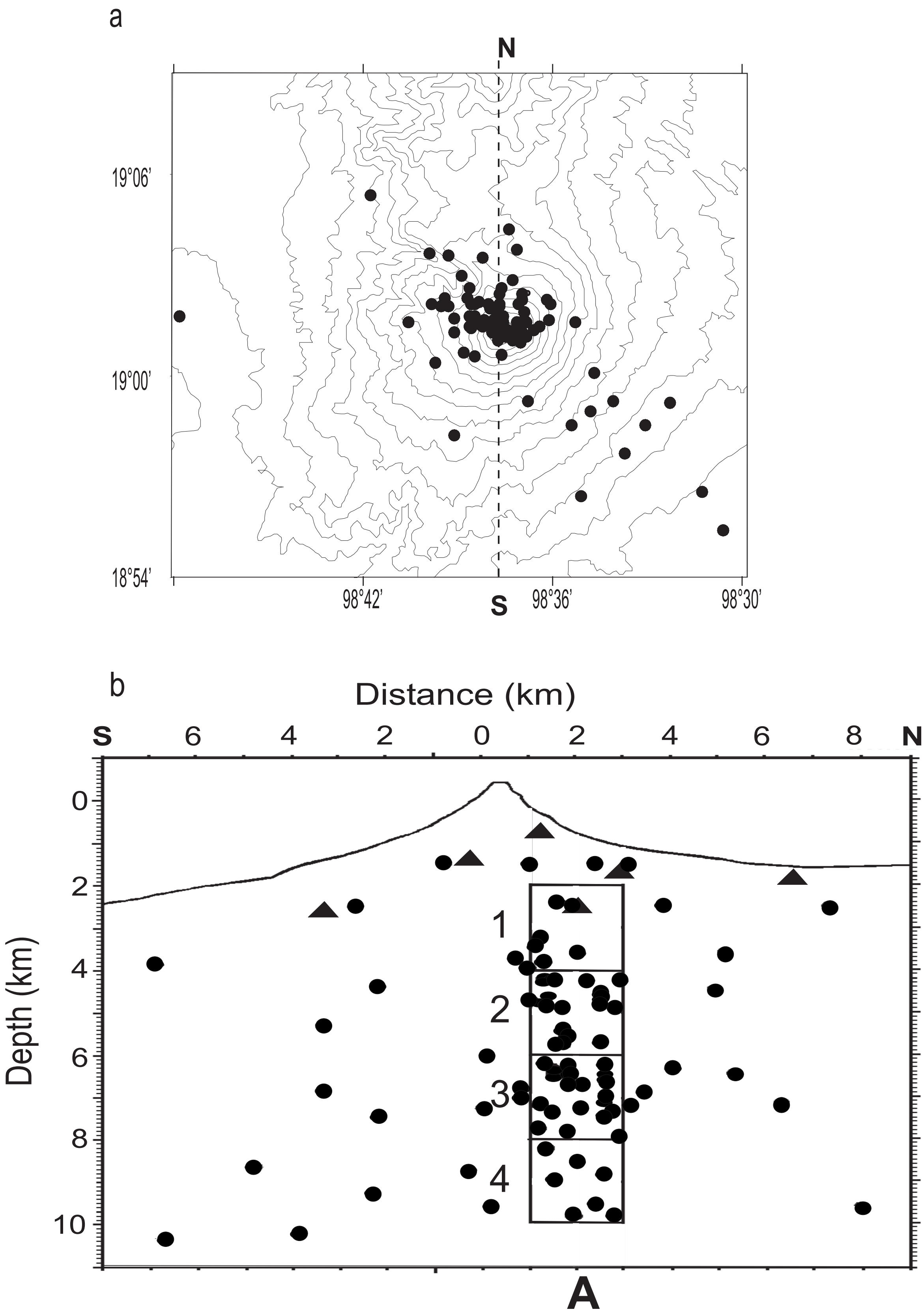


Fig. 1. (a) Epicentral distribution of the analyzed earthquakes. The direction of the NS profile along which the earthquake depth distribution was projected is shown. (b) Earthquake depth distribution. Coda *Q* was calculated for sources in the four blocks along Section A. The solid triangles indicate the location of the recording seismic stations.

crease of Q_c is related to the closing of cracks, this parameter might be a more reliable indicator of tectonic stress than the *b*-value (Aki, 1985).

Temporal variations of Q_c before major earthquakes, however, are not always present. Got *et al*. (1990), analyzing doublets before the Coyote Lake earthquake (August 1979, M=5.9), reported no major change in coda attenuation in the crust. Hellweg *et al*. (1995) reported that Q_c in two frequency bands from a tight cluster of 26 events in the Parkfield, California, region, was stable before and after two earthquakes of magnitude 4.6 and 4.7.

In geothermal areas such as Etna (Del Pezzo *et al*., 1987), Campi Flegrei (Castellano *et al*., 1984; De Natale *et al*., 1987), and Kilauea (Chouet, 1976) Q_c^{-1}showed higher and approximately constant values for frequencies above a certain critical value, as compared to other tectonically active regions. In the Long Valley caldera, eastern California, O'Doherty and Bean (1997) found a high attenuation anomaly ($Q_s \sim 125$) under the caldera compared with $Q_s \sim 220$ outside the caldera. They suggest that these variations may be related to magma accumulation, geothermal activity or an area of high temperature. Havskov *et al*. (1989) reported that coda *Q* at Mount St. Helens is significantly lower than in surrounding areas.

Models with a more realistic distribution of scatterers and seismic-wave velocities have been considered (Gusev, 1995; Hoshiba, 1997; Margerin *et al*., 1998). Margerin *et al*. (1999) and Campillo *et al*. (1998) studied the effect of the Moho on the coda envelope, by solving the radiative transfer equations in a model containing a heterogeneous layer overlying a transparent half-space. They found that at high frequencies ($f > 10$ Hz), Q_c is dominated by intrinsic absorption, while at frequencies around 1 Hz, by the effect of leakage of diffuse seismic energy in the mantle. Thus at frequencies ~ 1 Hz, Q_c depends strongly on the mean free path of the seismic waves in the crust and on the crustal thickness. Also, Q_c at 1 Hz is a function of the reciprocal of the total scattering coefficient. Q_c at low frequencies is therefore expected to have strong regional variations, correlated with heterogeneity of the crust and crustal thickness. The heterogeneities responsible for the development of Q_c may be caused by velocity and/or density perturbations, and presence of cracks and faults. Shapiro *et al*. (2000a), using a small-aperture seismic array experiment in Mexico, showed the diffusive regime of the seismic coda.

In this study, from variations of Q_c^{-1} at 6 Hz we found a zone of high seismic wave attenuation between 6 and 8 km depth below Popo volcano. Our interpretations are based on the assumption that Q_c^{-1} represents intrinsic attenuation. The results are consistent with Cruz-Atienza *et al*. (2001) who identified a low velocity zone at approximately the same depth interval from receiver function analysis of broadband records from a station located near this volcano. High attenuation below Popo was also reported by Shapiro *et al*. (2000b).

ESTIMATION OF CODA Q

To estimate coda *Q*, we used the single-backscattering model developed by Aki and Chouet (1975). According to this model, the displacement envelope $A(f,t)$ of coda waves from body waves in a frequency band around *f* can be expressed as:

$$log_{10}\,[A(f,t)t] = C(f) - [(log_{10}\,e)\,\pi f\,/\,Q_c(f)]\;t\;, \qquad (1)$$

where *C* is the coda source factor which is dependent only on the frequency *f*; *t* is time measured from the earthquake origin time. $Q_c(f)$ is determined from the slope of equation (1) by a least-squares solution. We assume that the source and receiver are at the same point and that the radiation is spherical. Therefore, the model is valid for signals which arrive long after the primary *S* wave.

Seismograms were bandpass-filtered using a recursive 8-pole, zero phase Butterworth filter at the center frequency of 6 Hz with a bandwidth of 4 Hz. We did not use frequencies larger than 6 Hz because the Q_c estimates at these frequencies had very large errors. Figure 2 shows the filtered seismograms at 6 Hz and the window of 25s from which Q_c was estimated for an earthquake of M= 2 and another of M= 3.

Values of Q_c were estimated using the coda *Q* program developed by Valdés and Novelo Casanova (1989). Average values ($<Q_c>$) were determined by weighting each individual measurement by the inverse of its variance (Hellweg *et al*., 1995):

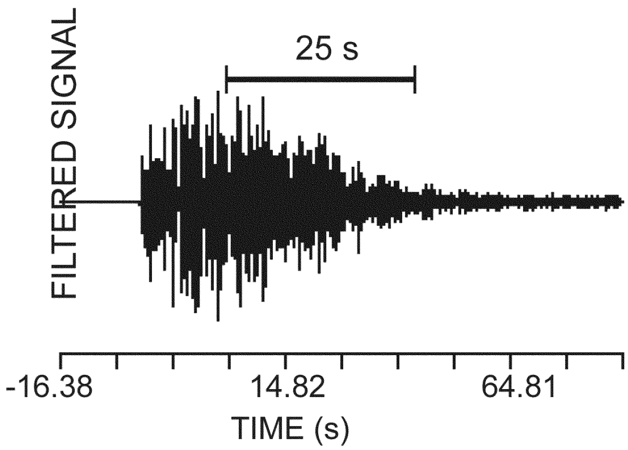
$$<Q_c> = [\,\textstyle\sum (Q_{ci}/\sigma_i^2)]\,/\,[\,\textstyle\sum (1/\sigma_i^2)]\;. \qquad (2)$$

The variance of the mean was calculated by

$$\sigma_m^{\;2} = \textstyle\sum [(1/\sigma_i^2)\,(Q_{ci} - <Q_c>)^2]\,/\,[(n-1)\textstyle\sum(1/\sigma_i^2)]\;. \qquad (3)$$

Using equation (2), we calculated weighted Q_c^{-1} values from at least three stations for events located at 2 km depth intervals along the four blocks of Section A shown in Figure 1b. By grouping data from many earthquakes within the same area (2 x 2 km²), we are estimating $<Q_c>$ for a common range of lapse times.

By using the same coda window we may directly compare Q_c^{-1} variations from events with similar hypocenters. Using a start time of $2t_s$ and window length of 25s, we are



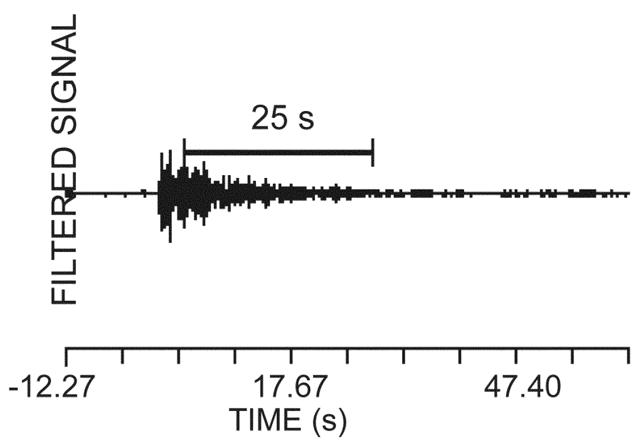


Fig. 2. Seismograms filtered at 6 Hz for an earthquake of M= 3 (top) and another of magnitude 2 (bottom). The coda window of 25s for which Q_c is estimated, is shown.

not sampling direct *S*-waves, and the Q_c values will correspond to a minimum sampling volume. We visually verified that for each Q_c estimate, the filtered seismograms had a high signal-to-noise ratio at the coda end.

We estimated coda *Q* for 107 local earthquakes located in the vicinity of Popo volcano (Figure 1a) during 1995, with depths ranging from 2 to 10 km (Figure 1b) and magnitudes between 2 and 3. The quality of locations and the seismic velocity model are discussed by Valdés *et al*. (1997).

In the single-scattering model of Aki and Chouet (1975), for any given lapse time *t*, the seismic coda waves sample an ellipsoidal volume related to the source-receiver separation (Pulli, 1984). The surface projection of this ellipsoid onto the Earth´s surface is defined by the equation

$$x^2 / [(vt/2)^2] + y^2 /[(vt/2)^2 - R^2/4] = 1. \quad (4)$$

Here, *R* is the surface source-receiver distance, *v* is the *S*-wave velocity, and *x* and *y* are the surface coordinates (Pulli, 1984). In this study *R*= 0 km since practically all analyzed events are recorded just below the recording network. Also, 1.7 km/sec is the *S*-wave velocity for Popo volcano as proposed by Valdés *et al*. (1997). Figure 3 shows the theoretical horizontal and vertical projections of the ellipsoid calculated using a source-receiver distance of 0 km with a lapse time of 25s. The coda waves sample a maximum zone of about 40 km in extent and 20 km in depth.

In the scalar single scattering approximation of Aki and Chouet (1975) the seismic coda is composed of first-order scattered *S*-waves and the coda quality factor is given by

$$Q_c^{-1} = Q_i^{-1} + Q_s^{-1} \ , \quad (5)$$

where Q_i and Q_s are intrinsic and scattering quality factors. Scattering redistributes wave energy within the medium but does not remove energy from the overall wavefield. Conversely, intrinsic attenuation refers to various mechanisms that convert vibration energy into heat through friction, viscosity and thermal relaxation (Sato and Fehler, 1998).

Based on the previous studies reported above and on our experiment characteristics, we consider that our measured Q_c is dominated by intrinsic mechanisms. Under these conditions, the estimated Q_c^{-1} at 10 km (Z_{10}) will be an average value for the ellipsoidal region at that depth. Q_c^{-1} at 8 km (Z_8) corresponds to the average Q_c^{-1} value for the ellipsoid at 8 km. At Z_6 = 6 km, Q_c^{-1} is an average for the projections above 6 km and so on. Thus, to estimate the variation of Q_c^{-1} (VQ_c^{-1}) at any given depth interval (z_2-z_1), we subtract the Q_c^{-1} value of the shallowest depth (z_1) from the Q_c^{-1} value of the deepest depth (z_2):

$$VQ_c^{-1} \text{ (between } z_2 - z_1) = Q_c^{-1} (z_2) - Q_c^{-1} (z_1) \text{ (for } z_2 > z_1) . \quad (6)$$

To determine whether the changes of VQ_c^{-1} are statistically significant for the different blocks along Section A (Figure 1b), we applied Student's *t*-test (Mendenhall, 1975, p. 222):

$$t = (\langle VQ_c^{-1}\rangle_1 - \langle VQ_c^{-1}\rangle_2)/(\sigma_1^2/n_1 + \sigma_2^2/ n_2)^{1/2} \quad (7)$$

$\langle VQ_c^{-1}\rangle_1$ and $\langle VQ_c^{-1}\rangle_2$ are calculated from the n_1 or n_2 individual component values of Q_{ci}^{-1} (equation 2) which make up all events in each area. In the denominator, σ_1 and σ_2 are the standard deviations of the two populations. For σ_1^2/n_1 and σ_2^2/n_2, which represent the variances of the means, we use the values calculated using equation (3). Values of *t*

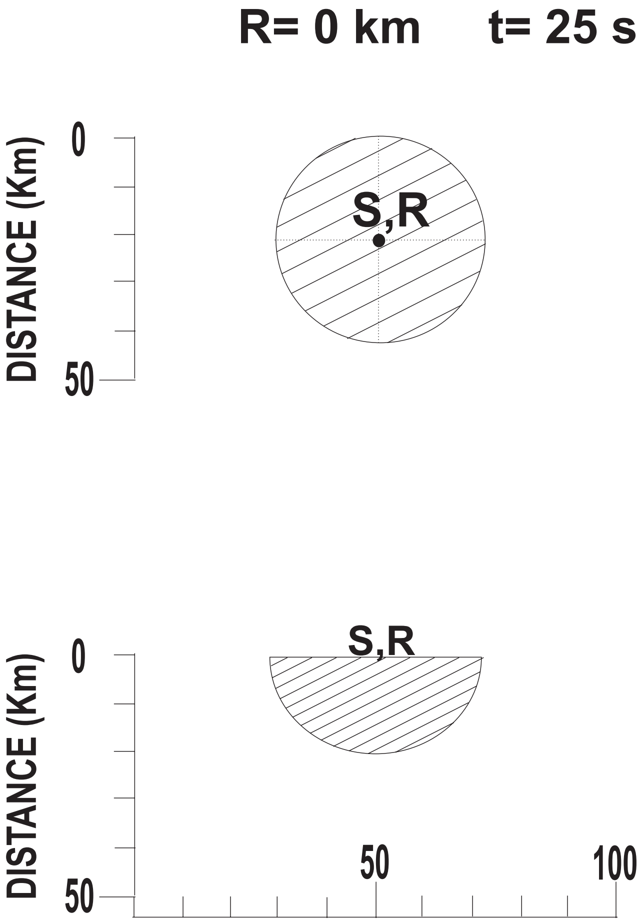


Fig. 3. Theoretical horizontal (top) and vertical (bottom) projections of the ellipsoidal region for coda waves estimated for a source-receiver distance of 0 km and a lapse time of 25s (equation 4) which are similar to our experiment conditions. Coda waves sample a maximum zone of about 40 km in extent and 20 km in depth.

greater than 1.64 and 2.58 indicate differences between two areas at 90 and 99% confidence levels, respectively.

RESULTS AND DISCUSSION

Figure 4 shows the Q_c^{-1} estimates at 2 km depth intervals using the events located within each block of Section A (Figure 1b). According to the procedures indicated above, the corresponding vertical theoretical ellipsoid where the intrinsic attenuation occurs is also displayed.

Wu (1985), Abubakirov and Gusev (1990) and Hoshiba (1991) using the Monte Carlo method, a constant background velocity and a homogeneous distribution of scatterers concluded that Q_c is dominated by intrinsic absorption and that this absorption exhibits a strong frequency dependence. Fehler *et al*. (1992), using measurements of *S*-wave energy versus hypocentral distance, found that intrinsic attenuation is larger than scattering attenuation over three frequency bands: 1-2, 2-4, and 4-8 Hz. Wennerberg (1993), based on the observation that $Q_c^{-1} > 0$ in field data, also concluded that the close agreement between Q_s^{-1} and Q_c^{-1} reported by Aki (1980) implies that *S*-wave attenuation is dominated by intrinsic mechanisms.

Gao (1992) also supports our assumption that our measured Q_c^{-1} represents intrinsic attenuation. He reported that for the single scattering technique, when the receiver is set very close to the source, the coda decay rate is dominated by intrinsic absorption. As the distance increases between source and receiver, the scattering attenuation becomes important in the decay rate of coda. In our case, the sources are located to a maximum depth of about 9 km below the receiver (Figure 1b). Physical model simulation of wave propagation trough cracked media has also been conducted. Matsunami (1991) measured ultrasonic wave propagation through a plate with many holes. Changing the number of holes and frequency of incident waves, he found a strong correlation between the strength of scattering attenuation and the excitation of coda level in 2-D. He also concluded that there is a large contribution of intrinsic attenuation to coda attenuation. Considering that intrinsic absorption is very sensitive to changes in temperature, microfractures and the content of fluid within the pores, then, coda waves are a good detector of these changes within magmatic systems.

Multiple scattering cannot be totally ruled out, but our research is focused on analyzing and comparing the variations of Q_c instead of their absolute values. Besides, because the recording seismic stations are located practically above the hypocenters (Figure 1b), the effect of the shallowest layers and topography should be the same for all earthquakes. From previous studies any observed change in Q_c^{-1} is related to the intrinsic attenuation from the hypocenter position. The

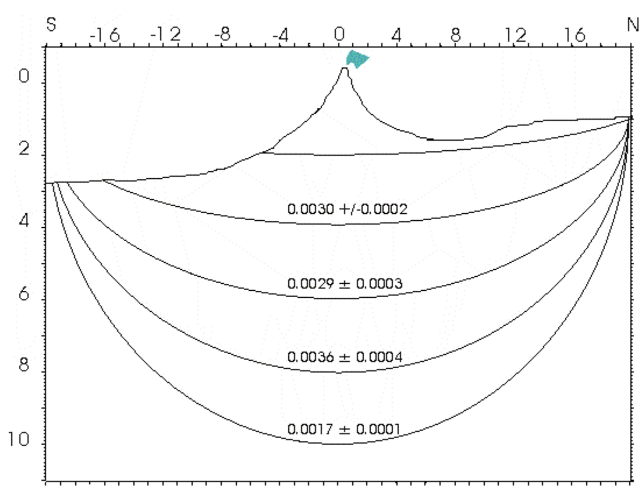


Fig. 4. Vertical theoretical ellipsoid projection where intrinsic attenuation occurs along the fours blocks of Section A (Figure 1b). The values in each ellipsoid are the corresponding estimates of Q_c^{-1} calculated from the group of events in each block.

method of Aki and Chouet (1975) yields an apparent Q_s, called Q_c, which is a useful datum for any discussion of coda properties. The derived Q_c can be compared with other Q_c values in the same area to observe its relative variations.

Figure 5a shows the estimated VQ_c^{-1} depth distribution (equation 6). From Figure 4 and Figure 5a, Q_c^{-1} and VQ_c^{-1} are approximately constant up to 6 km depth. Thus, VQ_c^{-1} increases between 6 and 8 km and then decreases below this depth.

Using equation (7), Table 1 shows the Student's *t*-test results applied to the VQ_c^{-1} estimates for the different studied blocks (Figure 1b). Negative values in Table 1 indicate a decrease of VQ_c^{-1}. The values of VQ_c^{-1} increase between 6 and 8 km and decrease between 8 and 10 km depth at the 99% confidence level. Based on these results, we consider that the high seismic wave attenuation zone (high VQ_c^{-1}) observed between 6 and 8 km depth below Popo volcano is statistically significant.

Cruz-Atienza *et al*. (2001) reported for Popo volcano a low velocity zone between 6 and 7.5 km depth (Figure 5b). They inverted waveforms of ten explosions to estimate the depth, duration, magnitude and direction of the single force using data from a broadband seismic station located 5 km north of the volcano. Shapiro *et al*. (2000b) also reported a low Q below Popo volcano. They estimated a Q value of shear waves roughly around 60 from events recorded in Mexico City whose wavepaths pass below the volcano. They

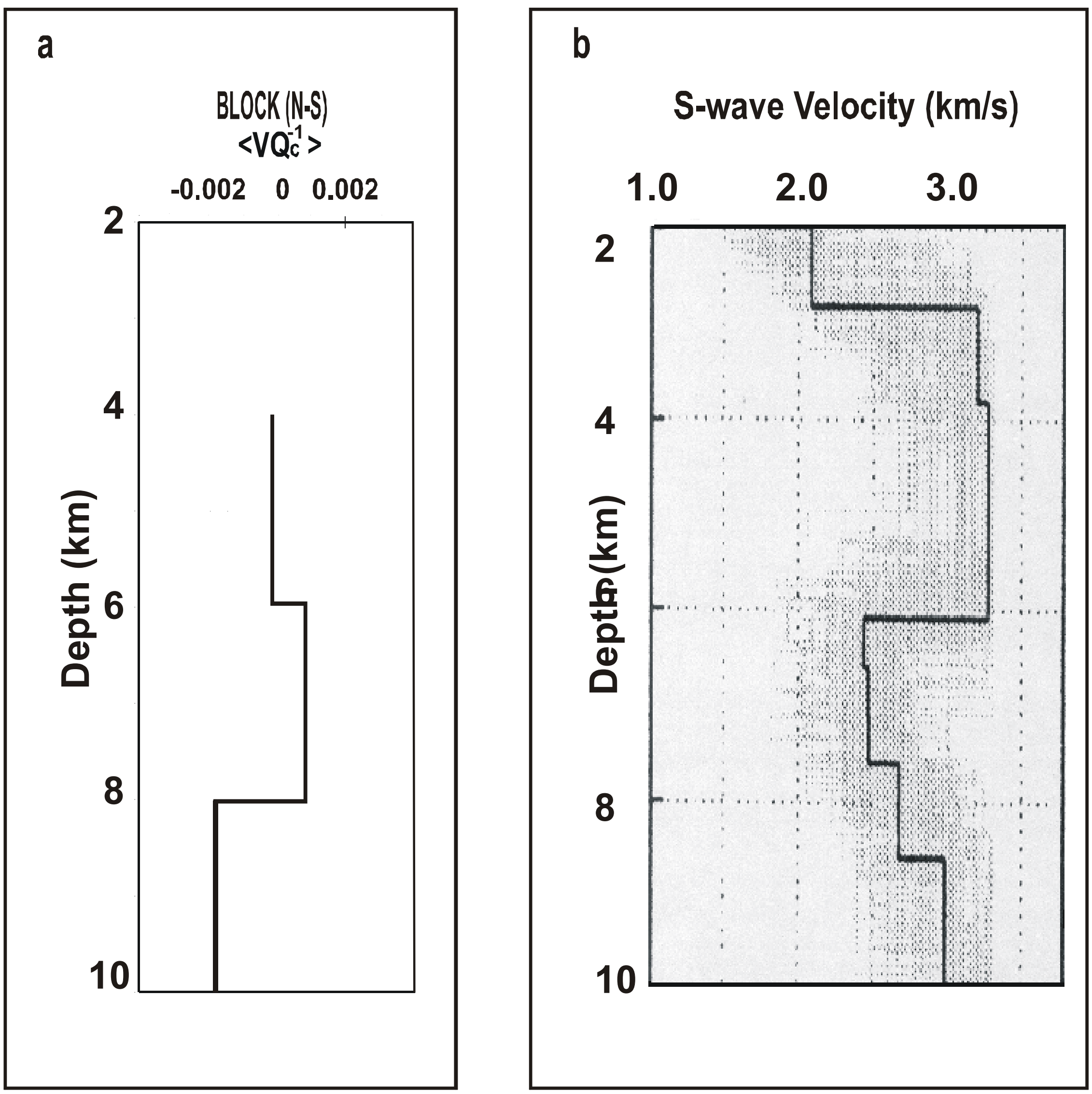


Fig. 5. (a) VQ_c^{-1} (equation 6) distribution with depth along the four blocks of Section A (Figure 1b). (b) *S* -wave velocity distribution with depth estimated for Popo volcano by Cruz-Atienza *et al*. (2001).

Table 1

Student's *t*-test applied to the VQ_c^{-1} values of Figure 5a

Block	Depth Interval (km)	Q_c^{-1}	VQ_c^{-1}	*t*-test	Interpretation
1	2-4	0.0030 ± 0.0002			
2	4-6	0.0029 ± 0.0003	-0.0001	-0.04	The attenuation decrease from Block 1 to Block 2 is not statistically significant
3	6-8	0.0036 ± 0.0007	0.0007	6.09	The attenuation increase from Block 2 to Block 3 is statistically significant at the 99% confidence level
4	8-10	0.0017 ± 0.0001	0.0019	-12.7	The attenuation decrease from Block 3 to Block 4 is statistically significant at the 99% confidence level

concluded that the amplitudes of seismic waves are diminished by a factor of about one-third at frequencies greater than 1 Hz as compared to those which do not cross under the volcano.

The low velocity zone identified below Popo volcano by Cruz-Atienza *et al*. (2001) might be related to the zone of high attenuation (high VQ_c^{-1}) measured from coda waves in this study. However, measurements of coda characteristics may be more sensitive to small spatial and temporal changes than measurements of velocity or attenuation using direct waves which sample a 1-D ray path between the source and the receiver (Aki, 1985). The zone of high attenuation reported here, could be created by magma accumulation between 6 and 8 km depth.

O'Doherty and Bean (1997) obtained a coda wave imaging of the Long Valley caldera (LVC). They reported a low Q_c^{-1} in the west-central area of the LVC. Using direct *S*-wave attenuation patterns, Ryall and Ryall (1981) suggested anomalous attenuation of *S*-waves in the south-central area at 4-5 or 7-8 km depth in this volcano. Havskov *et al*. (1989) reported that Q_c is much lower in the immediate vicinity of Mount St. Helens than its surroundings. Matsumoto and Hasegawa (1989) reported large Q_c^{-1} near active volcanoes and the coast of the Japan sea where the *S*-wave velocity is relatively low. These reports of high attenuation of coda and *S* waves from different volcanic systems are coincident with the present observations at Popo volcano.

The observed variations of VQ_c^{-1} (Figure 5a) may be associated to the magma chamber. Many investigators have concluded that Q_c^{-1} reflects mainly intrinsic absorption of the medium (Wu, 1985; Abubakirov and Gusev, 1990; Hoshiba, 1991, 1993; Matsunami, 1991; Fehler *et al*., 1992; Gao, 1992; Wennerberg, 1993; Campillo *et al*., 1998; Margerin *et al*., 1999).

Our measured Q_c^{-1} is sampling a region that contains viscous fluid, molten bodies, cracks and pores. Variations of VQ_c^{-1} reflect changes in the interior of the volcano that may be directly related to the magma and rock composition. In any case, the result of magmatic processes is a wide spatial variation in chemical composition and mechanical properties of the rocks (Sato and Fehler, 1998).

Predicting future eruptions at Popo volcano may require a hybrid approach based on a detailed knowledge of its past eruptive history, the physical-chemical properties of the magma, and the geometry of the feeding magmatic system.

CONCLUSIONS

We have used the coda wave theory of Aki and Chouet (1975) to measure Q_c^{-1} variations with depth at Popocatépetl volcano, considering Q_c^{-1} estimates as average values of intrinsic attenuation. Our results are highly dependent on our assumptions and on the validity of this model. The mapping of Q_c^{-1} variations allows us to estimate the depth (6-8 km) of the highly-attenuating body below Popo volcano. This high attenuation could be due to the presence of magma.

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