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# Evidence of low Q below Popocatépetl volcano, and its implication to seismic hazard in Mexico City

N.M. Shapiro, S.K. Singh, A. Iglesias-Mendoza, V.M. Cruz-Atienza, and J.F. Pacheco

Instituto de Geofísica, Universidad National Autónoma de México, México D.F., Mexico

**Abstract.** Seismograms recorded in Mexico City reveal that the amplitudes of seismic waves whose wavepaths pass below Popocatépetl, presently an volcano, before reaching the city are diminished by a factor of about one-third at frequencies greater than 1 Hz as compared to those which do not cross the volcano. The high attenuation of seismic waves below the volcano may be attributed to the presence of magma and partial melting of rocks. Q of shear waves below the volcano is roughly estimated as 60. A consequence of the large attenuation of high-frequency seismic waves is a decrease in the seismic hazard to low-rise buildings in Mexico City from intraplate earthquakes whose wavepaths cross the volcano.

## Introduction

Popocatépetl, a presently active volcano, poses a great hazard to Mexico City and to other nearby cities and towns from a possible major volcanic eruption. Since December, 1994 it has manifested significant seismic and fumorolic activity, coupled with minor eruptions. The volcano is, presently, well instrumented and is being carefully monitored. A study of seismicity shows that the tectonic earthquakes are concentrated in the depth range of 5 to 10 km and roughly define a volume of $25 \mathrm{km}^3$ [*Valdés-González and Gonzáles-Pomposo*, 1999]. A detailed tomography of the volcano, however, is still lacking. For instance, the quality factor, Q, below the volcano is not known.

An inspection of seismograms of a recent earthquake (June 15, 1999; depth=60 km; $M_W = 7.0$), located about 220 km SE of Mexico City (Fig 1), shows that the amplitude of seismic waves which pass through the volcano before reaching the city is significantly diminished as compared to those which do not cross the volcano. This suggets low Q below the volcano. This also implies reduced seismic hazard to Mexico City from earthquakes whose wavepaths cross Popocatépetl. In this paper, we analyze all available data to confirm high attenuation of seismic waves passing through the volcano and discuss its implication to the seismic hazard in the city.

## Analysis of the seismograms

Figs 2 and 3 show the earthquakes and the seismic stations used in this study. The earthquakes (Table 1) cover a magnitude range of 4.0 to 7.2 and depth range of 10 to 170 km. CUIG, YAIG, and PLIG are permanent broadband stations, equipped with velocity and acceleration sensors. CUIG is a hard site in the campus of National Autonomous University of Mexico, located in Mexico City. Stations YAIG and PLIG lie south of the Mexican volcanic belt

In Fig 2 we compare NS accelerograms of 11 earthquakes recorded at CUIG and YAIG. These accelerograms can be easily subdivided in two groups: (1) those with accelerations at CUIG equal to or higher than at YAIG (Fig 2b), and (2) those with accelerations at CUIG much smaller than at YAIG (Fig 2c). It is at once noted from Figs 2a and 2c that all events with much smaller accelerations at CUIG than at YAIG have the common feature that their wave paths cross Popocatépetl volcano. This strongly suggests that the smaller amplitudes at CUIG during these earthquakes result from higher attenuation of seismic waves crossing the volcano.

## Spectral ratios

To better understand the effect of Popocatépetl on wave propagation, we studied spectral ratio, SR(f), of ground motion at pairs of stations: CUIG and YAIG; CUIG and PLIG. Since the hypocentral distances to CUIG are greater than to YAIG and PLIG (Figs. 2 and 3), we reduced the observed spectra at YAIG and PLIG to the distance to CUIG. For this purpose, we used a regional spectral attenuation relation valid for south- central Mexico, namely:

$$\frac{\mathrm{e}^{-\pi \mathrm{fR}/\beta \mathrm{Q}_0(\mathrm{f})}}{\mathrm{R}^{0.5}} \tag{1}$$

where f is the frequency, R is the hypocentral distance, $\beta$ is the S-wave velocity, and $\mathrm{Q}_0(\mathrm{f}) = 273\mathrm{f}^{0.66}$ is the S-wave quality factor [*Ordaz and Singh*, 1992]. We take $\beta = 3.5$km/s. The results are shown in Fig. 3, where the events are grouped in two sectors. Sector 1 includes events whose wave paths to CUIG cross Popocatépetl, while the paths from events of sector 2 traverse entirely outside this volcano. There are two important features to be noted in Figs 3b and 3c. (1) Because the spectra are reduced to the same distance, the expected spectral ratio is about 1. The observed spectral ratios for events from both sectors, however, deviate significantly from 1. The explanation for this discrepancy lies in the response of CUIG, a site in the hill-zone of the Valley of Mexico, which is known to suffer amplification at f < 2Hz and deamplification at higher frequencies [*Singh et al.*, 1995; *Ordaz and Singh*, 1992]. (2) The median spectral ratio of CUIG with respect to YAIG and PLIG for sector 1 events is $\sim 1/2$ to $1/4$ of the corresponding spectral ratio for sector 2 events, in frequency range of 1 to 6 Hz. This unambiguously shows that seismic waves traversing the volcano are strongly attenuated. High seismic-wave attenu-



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**Table 1.** Events used in the study. $^1 - \mathrm{M_W}$, $^2 - \mathrm{M_b}$

| N | yyyy/mm/dd | Lat | Lon | H (km) | M |
|---|---|---|---|---|---|
| 1 | 1980/10/24 | 18.22 | -98.20 | 65 | $7.1^1$ |
| 2 | 1994/02/23 | 18.05 | -97.18 | 73 | $5.8^1$ |
| 3 | 1994/05/04 | 16.20 | -100.59 | 33 | $4.4^2$ |
| 4 | 1994/05/05 | 16.59 | -100.70 | 33 | $4.0^2$ |
| 5 | 1994/05/05 | 16.90 | -99.88 | 33 | |
| 6 | 1994/05/06 | 18.34 | -98.01 | 56 | $5.3^1$ |
| 7 | 1995/10/21 | 16.84 | -93.47 | 159 | $7.2^1$ |
| 8 | 1996/06/03 | 17.69 | -94.39 | 169 | $4.9^2$ |
| 9 | 1997/01/11 | 18.22 | -102.76 | 33 | $7.1^1$ |
| 10 | 1997/05/22 | 18.68 | -101.60 | 70 | $6.5^1$ |
| 11 | 1997/07/19 | 16.33 | -98.22 | 15 | $6.7^1$ |
| 12 | 1997/09/01 | 18.54 | -95.84 | 33 | $4.3^2$ |
| 13 | 1997/09/06 | 18.10 | -94.38 | 25 | $4.7^2$ |
| 14 | 1997/12/22 | 17.30 | -101.04 | 10 | $5.1^2$ |
| 15 | 1998/02/03 | 15.88 | -96.30 | 33 | $6.3^1$ |
| 16 | 1999/01/13 | 16.27 | -96.73 | 33 | $4.2^2$ |
| 17 | 1999/06/15 | 18.40 | -97.45 | 71 | $7.0^1$ |
| 18 | 1999/06/21 | 18.34 | -101.49 | 67 | $6.3^1$ |

ation below volcanoes is, probably, caused by the presence of magma bodies and partial melting of rocks.

Although the available data are insufficient to define the location and the depth of the highly-attenuating, low-Q body below the volcano, we can obtain a rough estimation of an average Q below Popocatépetl. Let the anomalous attenuation occur below the volcano over a distance of $\mathrm{R_V}$. Then the differential spectral ratio, $\Delta[\mathrm{SR(f)}]$, can be written as

$$\Delta[\mathrm{SR(f)}] = \mathrm{e}^{-\pi \mathrm{f} \mathrm{R_V}/\beta \mathrm{Q_V(f)}} \tag{2}$$

where $\mathrm{Q_V(f)}$ is the S-wave quality factor below the volcano. From Figs 3a and 3c, $\Delta[\mathrm{SR(f)}]$ varies from 0.6 at 2 Hz to about 0.25 at 6 Hz. Assuming $\mathrm{R_V} = 20$ km and $\beta = 3.5$km/s, we obtain $\mathrm{Q_V} \sim 60$. This value is in reasonable agreement with P-wave quality factor of 70 to 100 reported below active volcanos [*Ward and Yang*, 1980; *Sudo*, 1991; *Guilbert*, 1995].

## Discussion

We note that seismic waves from events in sector 2 pass through the active volcano of Nevado de Toluca before reaching CUIG. However, Figs 2 and 3 show that the attenuation suffered by the waves crossing the Nevado de Toluca is much less than the diminution of waves with paths through Popocatépetl. Although the volcanic edifice of the two volcanoes is similar in dimension, only one major eruption in the last 11,000 years has been reported for the Nevado de Toluca [*Macías et al.*, 1997]. On the other hand, six major eruptions have been documented for Popocatépetl in the same time period [*Siebe et al.*, 1996, 1997]. As mentioned before, since 1994 Popocatépetl has shown significant seismic and fumarolic activity, along with minor eruptions. In contrast, there are no detectable seismic and fumarolic activities associated with Nevado de Toluca. Thus a reasonable explanation for the relatively low attenuation of seismic waves crossing Nevado de Toluca is the quiescent state this volcano.

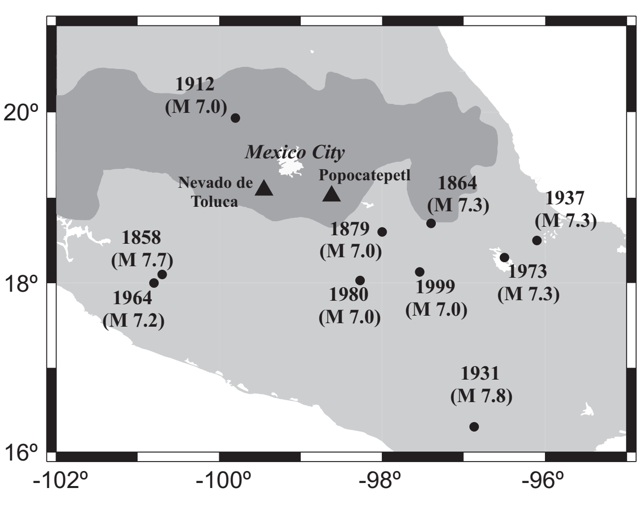


**Figure 1.** Map showing locations of intraplate earthquakes of the last two centuries (M $\geq$ 7.0) in southern and central Mexico. Gray area indicates the Mexican Volcanic Belt (MVB). Mexico City lies in the MVB and is surrounded by active volcanoes of Nevado de Toluca to the south-west and Popocatépetl to the south-east.

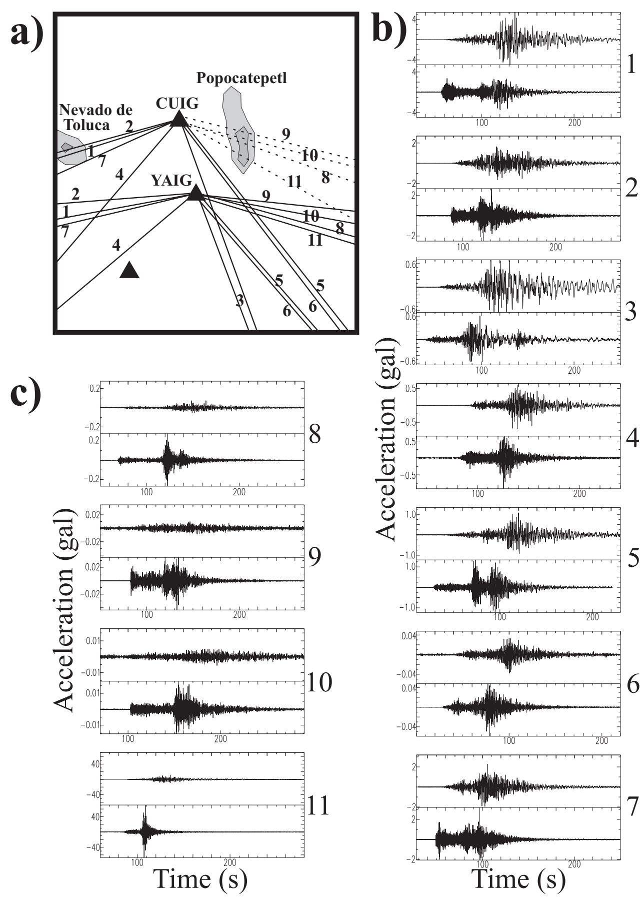


**Figure 2.** (a) Wave paths to CUIG and YAIG for different events. (b) N-S accelerograms at CUIG (upper frame) and YAIG (lower frame) for events 1 to 7. For this group of events, the wave paths to CUIG do not cross Popocatépetl and peak accelerations are nearly equal. (c) N-S accelerograms at CUIG and YAIG for events 8 to 11. For these events the wave paths to CUIG cross the volcano and the peak accelerations are much smaller than at YAIG.

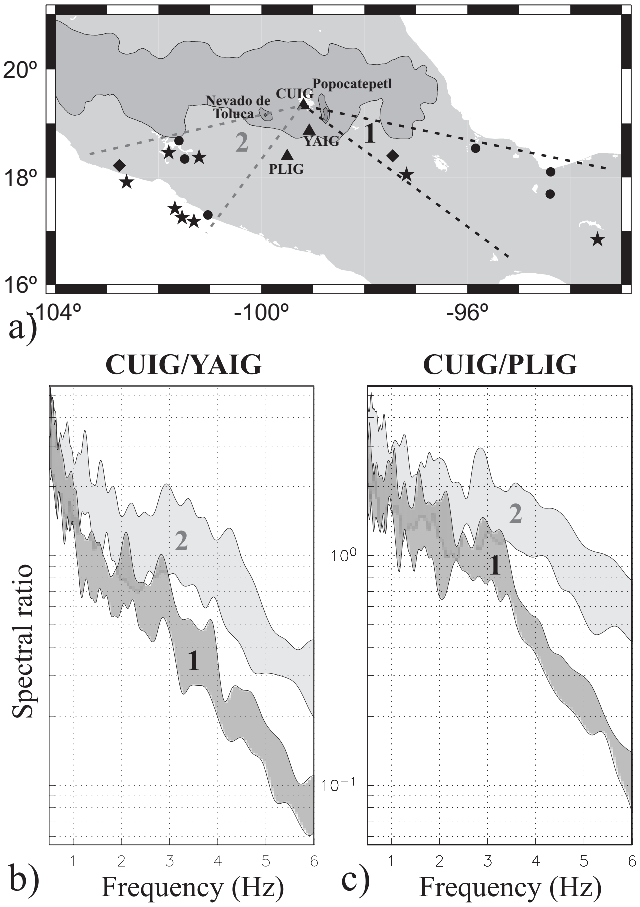


**Figure 3.** (a) Locations of earthquakes and stations (solid triangles) used in computing spectral ratios. Dots, stars, and diamonds indicate events recorded at YAIG, at PLIG, and at both stations, respectively. Dashed lines separate the events in two sectors. Wave paths to CUIG of sector 1 events cross Popocatépetl volcano but not the Nevado de Toluca volcano. Converse is the case for events of sector 2. (b) Spectral ratio of CUIG with respect to YAIG. Shaded area delineates ± one standard deviation range. (c) Spectral ratio of CUIG with respect to PLIG. Relatively small value of spectral ratio for sector 1 events as compared to sector 2 events strongly suggests high attenuation of seismic waves crossing Popocatépetl volcano.

We conclude that the presence of the active Popocatépetl volcano attenuates expected ground motions in Mexico City from earthquakes occurring towards SE of the city by a factor of about 2 to 4 at frequencies above 1 Hz. For a generally accepted constant stress drop, $\omega^2$-source model [*Aki*, 1967], the spectral amplitudes at frequencies above the corner frequency scale as $\mathrm{M}_0^{1/3}$, where $\mathrm{M}_0$ is the seismic moment. It follows that the ground motion in Mexico City at f > 1Hz from a sector 1 event roughly equals that from a sector 2 event located at equal distance whose seismic moment is 23 to 43 less, or, equivalently, whose magnitude is 0.6 to 1.2 unit less [*Kanamori*, 1977]. It may be argued that the ground motion at frequencies above 1 Hz is of no consequence to seismic risk in Mexico City since the damage results from extraordinary amplification of seismic waves in the soft subsoil of the lake-bed zone of city at the dominant period of the site which is around 2 sec [*Singh et al.*, 1988, 1995]. There is, however, reason to believe that large intraplate earthquakes, which occur in the subducted Cocos plate, can cause damage to low-rise structures which are sensitive to high-frequency ground motion. Figure 1 shows locations of large intraplate earthquakes ($\mathrm{M} \geq 7$) of the last two centuries which have occurred in south and central Mexico. We note that such earthquakes have reached $\mathrm{M} \sim 7.8$. According to historical reports, the 1858 earthquake ($\mathrm{M} \sim 7.7$) was one of the strongest to be felt in Mexico City, causing extensive damage. [*Singh et al.*, 1996] have shown that an earthquake similar to the 1858 earthquake in magnitude and location could result in total damage in Mexico City exceeding that estimated for the Michoacan earthquake of 1985 (Mw=8.0). This occurs because large damage is expected for low-rise construction, which constitute 80% of the total value. Our results show that the seismic hazard to the city may be significantly diminished from intraplate earthquakes if they originate in sector 1.

In retrospect, high attenuation of seismic waves traversing through Popocatépetl volcano is not a surprise. However, since Mexico City lies within the Mexican volcanic belt and since no diminution of ground motion has been detected for other paths, none had been suspected for the wave paths through the volcano. Thus Popocatépetl poses not only a great volcanic hazard to Mexico City but also provides some relief from damage which may result from strong ground motions. On the other hand, a large earthquake in the vicinity of the volcano may cause extensivbe damage to city from flank instability and ash emission.

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N.M. Shapiro, S.K. Singh, A. Iglesias-Mendoza, V.M. Cruz-Atienza, and J.F. Pacheco, Departamento de Sismología y Volcanología, Instituto de Geofísica, UNAM, C.P. 04510, México, D.F., México. (email: shapiro@ollin.igeofcu.unam.mx)

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