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A comparative analysis of the quality factor Q for the regions of Guerrero and Oaxaca, Mexico

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RESUMEN

Estimaciones del factor de calidad Q_s de las ondas S reportadas para las regiones de Oaxaca y Guerrero, México, muestran que la atenuación en Oaxaca es entre 3.7 y 5.0 veces mayor comparada con la de Guerrero en la banda de frecuencias de 1 a 30 Hz. Esta importante diferencia en la atenuación de estas regiones vecinas no puede ser completamente explicada por las características petrológicas de estas regiones.

Cuando los valores de Q_s observados en Oaxaca y Guerrero se comparan con otros parámetros, tales como la edad de las rocas y el flujo de calor, resulta que la atenuación en Oaxaca es mayor de lo esperado en relación con Guerrero. Esto sugiere que el mecanismo más viable para explicar las diferencias de Q_s observadas puede relacionarse con el estado de esfuerzos prevalentes cuando los valores de Qs fueron medidos. Los altos valores de Q_s estimados para Guerrero pueden ser el resultado del esfuerzo tectónico acumulado en esta región y a que la corteza está posiblemente menos fracturada que en Oaxaca.

PALABRAS CLAVE: Guerrero, Oaxaca, atenuación, Q.

ABSTRACT

Estimates of the quality factor Q_s of S waves reported for the regions of Oaxaca and Guerrero, Mexico show that the attenuation in Oaxaca is 3.7 to 5.0 times greater than that in Guerrero for the frequency band from 1 to 30 Hz. This important difference in attenuation of these neighboring regions cannot be completely explained by petrological difference.

When the observed values of Q_s for Oaxaca and Guerrero are compared with the age of the rocks and the heat flow, it turns out that the attenuation in Oaxaca is greater than expected relative to that in Guerrero. This suggest that the most likely mechanism to explain the observed differences in Q_s may be related to the state of stress prevailing when Q_s was measured. The high values of Q_s estimated for Guerrero can be the result of a less fractured crust and tectonic stress accumulated in this region.

KEY WORDS: Guerrero, Oaxaca, attenuation, Q.

INTRODUCTION

It has been recognized from many studies of attenuation and laboratory measurements of rocks (e.g. Johnston *et al.*, 1979; Stewart *et al.*, 1983; among others) that the quality factor Q implicitly contains information on the properties of the lithosphere. Several correlations between Q and physical conditions such as stress (Lockner *et al.*,1977) and pressure (Toksoz *et al.*, 1979) and other geophysical parameters such as heat flow (Archambeau *et al.*, 1969) and crustal age (Sipkin and Jordan, 1980) have also been reported in the literature.

Recent estimates of Q of S-waves (Q_s) for Guerrero (Castro *et al.*, 1990 and Ordaz and Singh, 1992) and Oaxaca, Mexico (Castro and Munguía, 1993) show very distinct differences. The purpose of this paper is to discuss the possible origin of the differences in attenuation between these two neighboring segments of the North American plate.

ATTENUATION ESTIMATES REPORTED

Several estimates of attenuation have been made in the region of Oaxaca using aftershocks of the 1978 Oaxaca earthquake (M=7.8). Castro and Munguía (1993) showed that Q_s is very similar to previous estimates of coda Q (Acosta, 1980 and Rodríguez, 1985). Figure 1, modified from Castro and Munguía (1993) shows the values of Q_s and coda Q (Q_c) estimated for this region. The straight line in Figure 1 was obtained using the values of Q_s shown. However, this function also approximates the frequency dependence of Q_c fairly well. The dashed line in Figure 1 was obtained by Canas *et al.* (1988) using Lg waves. More recently, Chavez *et al.* (1993) obtained values of Q_c for the eastern side of Oaxaca that are comparable with those obtained in previous studies (see Table 1).

The attenuation of S waves in Guerrero has been estimated mainly using records from the Guerrero Accelerograph Array (Singh *et al.*, 1990; Castro *et al.*, 1990; Ordaz and Singh, 1992; Humphrey and Anderson, 1992) and using seismograms from aftershocks of the 1979 Petatlán earthquake (Rodríguez *et al.*, 1983; Mahdyiar, 1984; Novelo-Casanova *et al.*, 1985 and Valdés, 1993) (see Table 2). Figure 2 shows the values of Q_s estimated by Castro *et al.* (1990) and the least-squares fit, $Q_s(f) = 278 f^{0.92}$, obtained. For comparison, this figure also shows the Q_s-

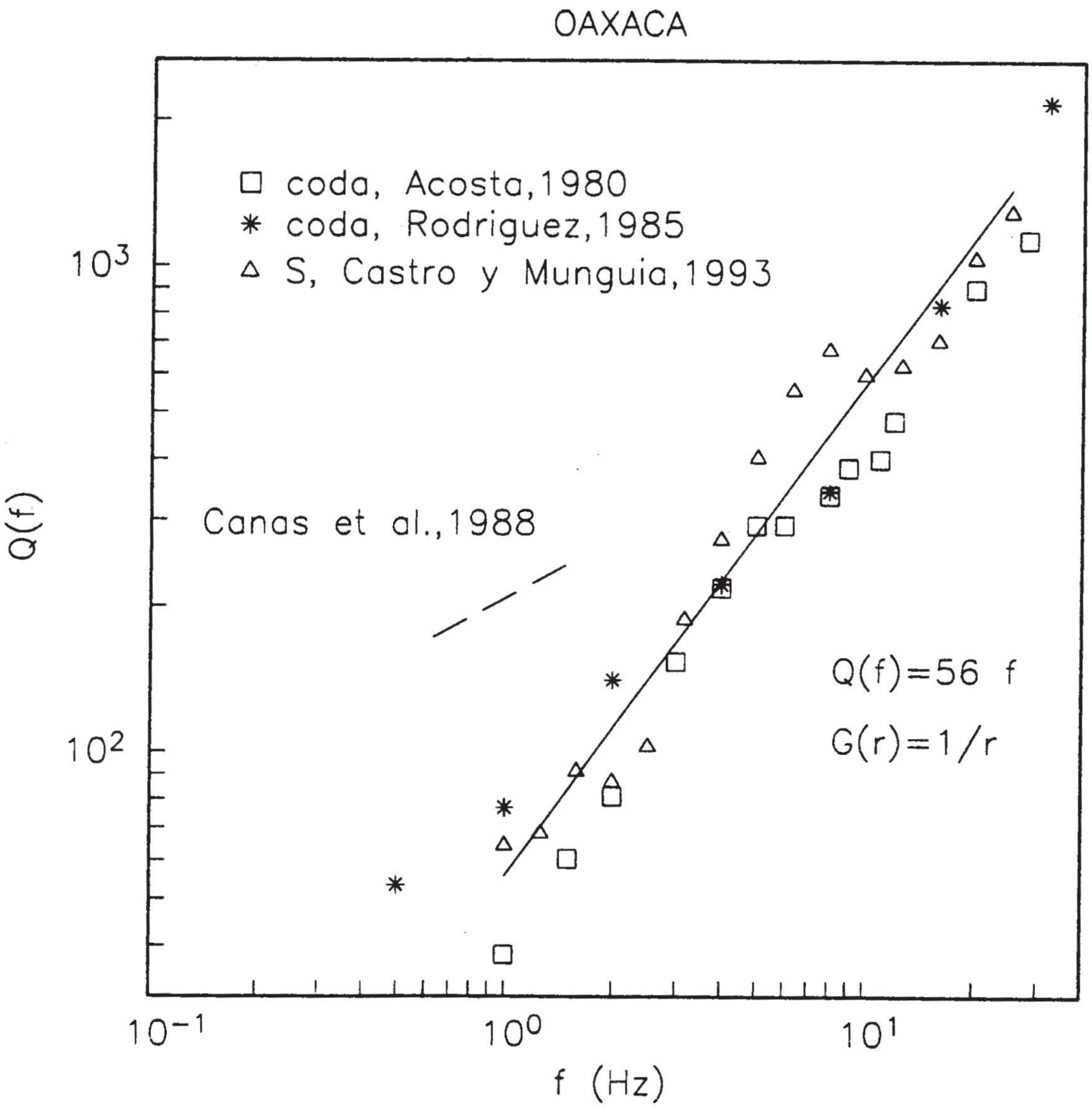

Fig. 1. Estimates of Q for the Oaxaca region. For the estimates of Q_c and Q_s the geometrical spreading function G(r)= 1/r (r being the hypocentral distance) was used to correct the amplitudes. The straight line resulted from a least-square fit of the Q_s estimates reported by Castro and Munguía (1993). The dashed line was obtained by Canas *et al.* (1988) using Lg waves.

frequency relation obtained by Ordaz and Singh (1992) from a different data set. They obtained $Q_s(f) = 273\ f^{0.66}$. This relation is consistent with that obtained by Castro *et al.* (1990).

Figure 3 shows other Q-frequency relations reported for the region of Guerrero. The dashed lines are relations obtained from S waves and the solid lines are coda Q relations. Although these curves cover different frequency bands, they all overlap between 3 Hz and 10 Hz. The wave propagation paths of the data sets used to obtain curves (i) to (v) sampled approximately the same regions (see also Table 2). Functions (i) and (ii) are those displayed in Figure 2. The curve (iii) was obtained by Singh *et al.* (1990) using accelerograms of the September 21, 1985 (Ms=7.6) earthquake recorded by the Guerrero Accelerograph Array. Curves (iv), (v) and (vi) reported by Mahdyiar (1984), Valdés (1993) and Rodríguez *et al.* (1983) respectively were determined using aftershocks of the 1979 Petatlán earthquake (Ms=7.6). Curve (vii) was estimated by Rebollar and Alvarez (1987) using aftershocks of the Ometepec doublet (Ms=6.9 and Ms=7.0) earthquake.

In a more recent attenuation study in Guerrero, Humphrey and Anderson (1992) found that the distance dependence of the spectral decay parameter $\bar{k}(r)$ (Anderson, 1991) is very weak. On the other hand, Rebollar *et al.* (1991) observed that $\bar{k}(r)$ shows a clear dependence on the distance for Oaxaca. Humphrey and Anderson suggested that the weak distance dependence of $\bar{k}(r)$ in Guerrero may be related with the high shear strength of the upper crust.

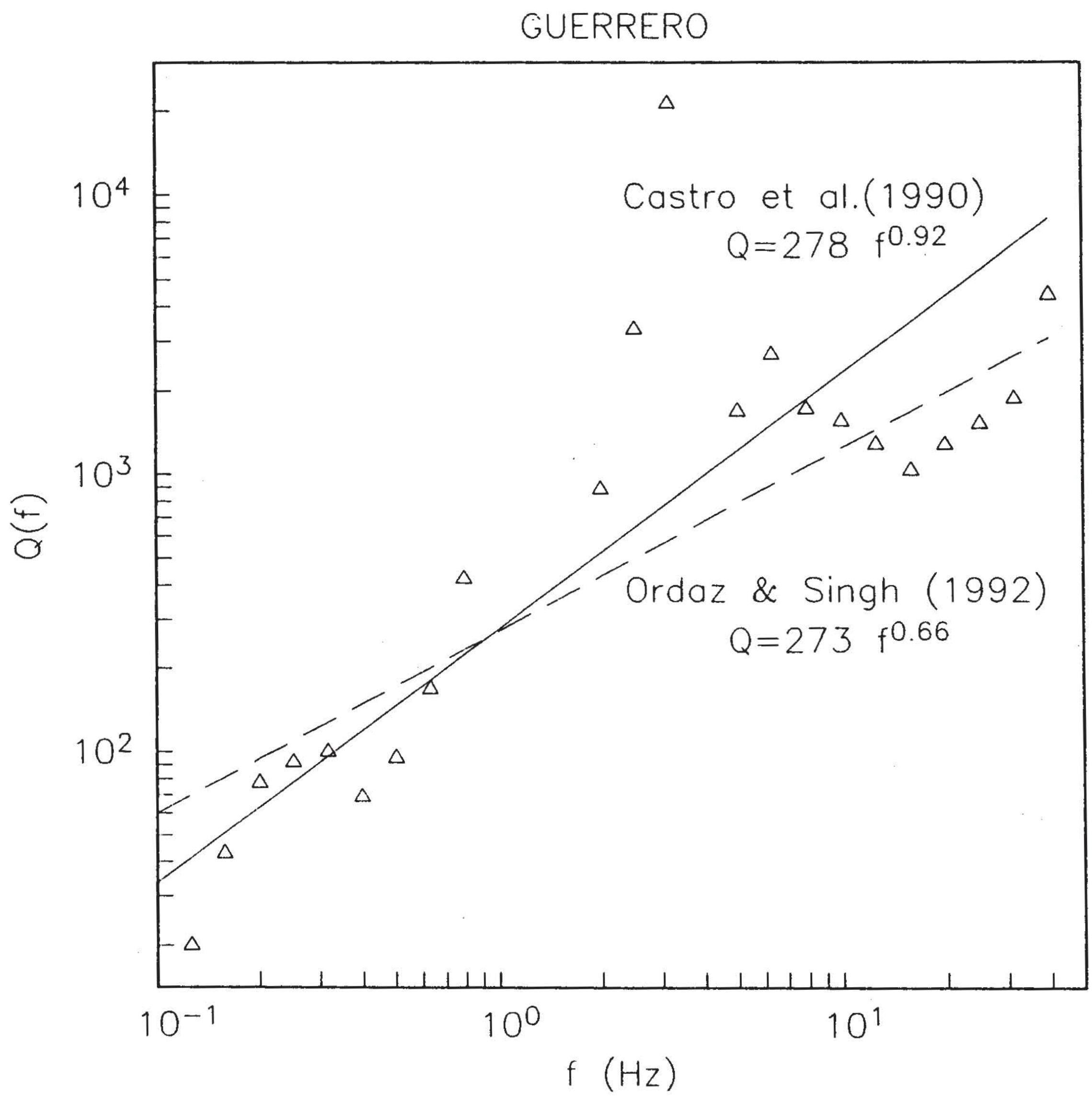

Fig. 2. Q_s values obtained by Castro *et al.* (1990) and the Q_s-frequency relation determined (solid line). The equation $Q_s = 273\ f^{0.66}$ (dashed line) was obtained by Ordaz and Singh (1992) for the same region but using a different data set.

In order to compare the attenuation of S-waves in Oaxaca and Guerrero, we plot in Figure 4 the Q-frequency relations obtained by Castro and Munguía (1993) for Oaxaca and Castro *et al.* (1990) for Guerrero. In both regions Q_s was estimated using spectral amplitudes of direct S-wave arrivals and digital stations located on hard rocks sites. The source and site effects were eliminated using spectral ratios for Oaxaca and a non-parametric model for Guerrero (Castro *et al.*,1990). Q_s in Guerrero increases relative to Oaxaca from a factor of 3.7 at 30 Hz to a factor of 5 at 1 Hz. This high Q ratio between Guerrero and Oaxaca not only reflects a dramatic difference in the attenuation of these neighboring regions, but also may reflect important differences among the physical conditions of the crust. In the next section we describe the main tectonic and geologic features of these regions.

GEOLOGIC AND TECTONIC FRAMEWORK

Ortega-Gutiérrez (1981) has mapped the distribution of crystalline terrains in southern Mexico. According to his map, the Xolapa complex covers most of the Guerrero region along the coast and part of Oaxaca from Zihuatanejo to Puerto Angel. The Xolapa complex consists of crystalline rocks typical of a continental margin. Ortega-Gutierrez (1981) estimated that this complex has a minimum thickness of 10 km. In Oaxaca, igneous and metamorphic rocks with thickness of at least 17 km (Oaxacan complex) are also present mainly in the central part of this region. Thus, in general crystalline rocks are widely distributed in both regions. As result of the convergence among the North American, the Cocos and the Caribbean plates, the southeastern end of the region of Oaxaca is characterized

Table 1

Attenuation studies in the region of Oaxaca

Oaxaca region	Q	Reference
97.5° – 96.0°W	$Q_C = 45f^{0.99}$, $(1.0 < f < 25.0Hz)$	Acosta (1980)
97.5° – 96.0°W	$Q_C = 80\ f^{0.88}$, $(0.5 < f < 30.0Hz)$	Rodríguez (1985)
98.7° – 92.1°W	$Q_{Lg} = 208\ f^{0.4}$, $(0.7 < f < 1.7Hz)$	Canas et al. (1988)
96.5° – 93.0°W	$60 < Q_C < 168$ $(f = 1Hz)$	Chavez et al.(1993)
97.5° – 96.0°W	$Q_S = 56f$, $(1.0 < f < 25.0Hz)$	Castro and Munguía (1993)

by a structurally complex geometry (Delgado-Argote and Carballido-Sánchez, 1990).

Several geophysical differences along the Cocos plate have been reported by Singh and Mortera (1992) (see Figure 5). For instance, they pointed out that the age of the Cocos plate increases from about 5 m.y. in the Michoacán region to about 13 m.y. in Guerrero and to about 20 m.y. near Oaxaca. They also observed that the increase of the plate's age may not be continuous, and perhaps a jump occurs at the intersection of the O'Gorman Fracture Zone, that is between the Guerrero and Oaxaca regions (see Figure 5). On the continental side, on the other hand, the exposed rocks are older in Oaxaca compared to Guerrero (see Figure 6). The Xolapa complex has been dated Paleozoic-Mesozoic (66-570 m.y.) while the Oaxaca complex consists of rocks from the Proterozoic (1500 m.y.)(Ortega-Gutiérrez, 1981).

The age of the crust can be correlated with the seismic attenuation of the structure. Sipkin and Jordan (1980), for example, found that younger oceans tend to have lower Q than older oceans. Jin *et al.* (1985) also found an increase of coda Q with age of the oceanic lithosphere. If the changes in Q with age observed in the oceanic lithosphere are similar for the continental lithosphere, based on the age of the exposed rocks, we would expect higher Q in Oaxaca relative to Guerrero. However, Q is lower in Oaxaca (see Figure 4). Although there is not a clear link between age and Q in the continental crust, it is possible that an older crust is more fractured as a result of greater deformation. If this is the case, the scattering of the traveling waves will be greater in a fractured crust and the apparent Q will tend to be low. However, the amount of deformation also depends on how active the region is. For Oaxaca the crystalline rocks in the central part are older than in Guerrero but the velocity of subduction is smaller (Anderson *et al.* 1989).

The distribution of heat flow along the subduction zone can also give some indication about the origin of the high values of Q observed in Guerrero. In general, regions with high heat flow tend to have low Q (Mikami and Hirahara, 1981). In Figure 5 (modified from Singh and Mortera, 1991) we plot the average value of the heat flow measurements reported by Prol-Ledesma *et al.* (1989) for the oceanic floor and the heat flow values obtained by Ziagos *et al.* (1985) for the continental crust. For the continental side, we plot only the most reliable heat flow determinations, according to Ziagos *et al.*(1985), reported along the coast. For the region of Oaxaca there are no estimates of heat flow available, however the heat flow seems to increase from 13 mWm^{-2} in the western end of Michoacan to 45 mWm^{-2} in Chiapas. In contrast, the heat flow along the trench decreases towards the southeast.

If the heat flow on the continental plate is mainly due to frictional heating, and the mean rate of heat production per unit area is approximately (Turcotte and Schubert, 1982),

$$q = u\tau \tag{1}$$

where u is the mean velocity of the descending plate and τ the mean stress on the fault. Then, using q=39 mWm^{-2}, reported by Ziagos *et al.* (1985) for Guerrero, and u=6.2 cm/yr obtained by Anderson *et al.*(1989) from the moment rate of large earthquakes in the same region, the mean stress on the fault is approximately equal to 198 bars.

Assuming that τ is the same for both regions, then the heat flow in Oaxaca would be 20 mWm^{-2} for the slip rate of 4.4 cm/yr obtained by Anderson *et al.*(1989) for this re-

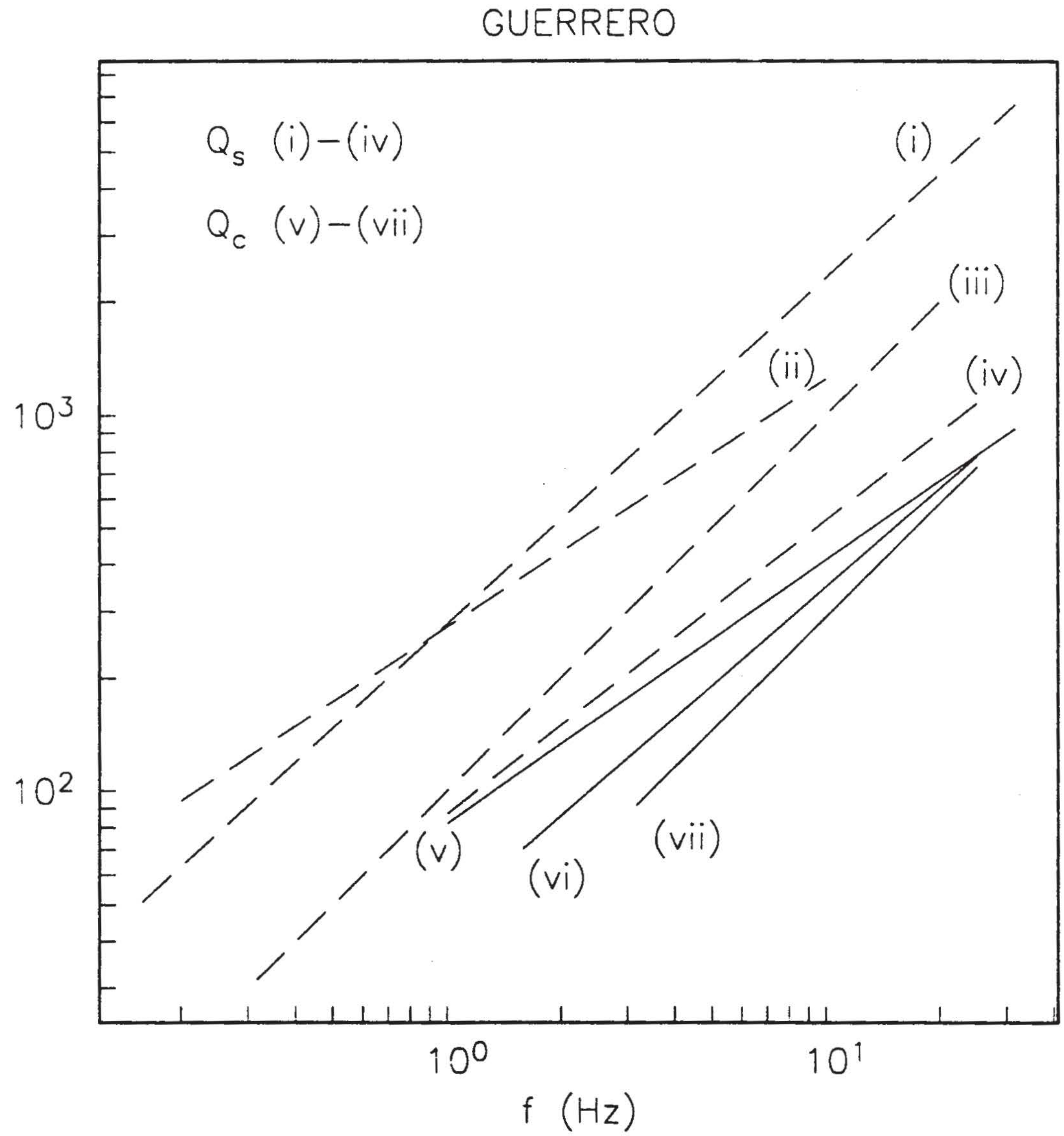

Fig. 3. Q-frequency relations reported for the region of Guerrero (see also Table 1). Dashed lines are relations obtained using S waves by (i) Castro *et al.* (1990), (ii) Ordaz and Singh (1992), (iii) Singh *et al.* (1990) and (iv) Mahdyiar (1984). Solid lines are functions estimated using coda waves by (v) Valdés (1993), (vi) Rodríguez *et al.* (1983) and (vii) Rebollar and Alvarez (1987).

gion, and q=40 mWm^{-2} for the slip rate of 7.5 cm/yr expected from the plate motion between the Cocos and North America plates (Minster and Jordan, 1978,1979). This estimate of q for Oaxaca is very similar to the values of heat flow reported by Ziagos *et al.*(1985) for Guerrero and Chiapas towards the east.

The depth contours of the upper surface of the subducted Cocos plate reported by Singh and Mortera (1991) (Figure 5) show a smooth change in the dip of the subducted plate in the region of Oaxaca, suggesting a greater τ and consequently a greater heat flow than that estimated above. In addition, if the coupling of the subducting interfase in the region of Oaxaca is stronger than in Guerrero, as suggested by Singh and Mortera, then τ may be also greater and then we would expect the heat flow in Oaxaca to be at least of the same order than in Guerrero.

If temperature were the mechanism controlling the attenuation, we would expect Q_s to be similar in both regions, since the expected heat flow values are at least comparable. However, recent estimates of Q_s are considerably higher in Guerrero (see Figure 4).

Q also has been correlated with tectonic activity. In general, low values of Q have been observed (Aki, 1980a, b) in regions with recent tectonic activity compared with those for stable regions. We should note that the values of Q_s reported by Castro and Munguía (1993) for Oaxaca were measured using aftershocks of the 1978 (M=7.8) earthquake, during a period of high tectonic activity, while in Guerrero the estimates of Q_s (Castro *et al.*, 1990; and Ordaz and Singh 1992) were made inside a mature seismic gap (Anderson *et al.*,1989) (see Figure 6). Comparing the values of Q_s estimated for Oaxaca using aftershocks (Fi-

Table 2
Attenuation studies in the Guerrero region

Guerrero region	Q	Reference
101.7°W – 101.0°W	$(vi) Q_C = 47 f^{0.87}$, $(1.5 < f < 24.0 Hz)$	Rodríguez et al. (1983)[1]
102.5°W – 99.9°W	$(iv) Q_S = 87 f^{0.78}$, $(1.0 < f < 25.0 Hz)$	Mahdyiar (1984)[1]
101.7°W – 101.0°W	$Q_C = 175$ at $6HZ$	Novelo-Casanova et al. (1985)[1]
99.°W – 98.0°W	$(vii) Q_C = 29 f$, $(3.0 < f < 24.0 Hz)$	Rebollar and Alvarez (1987)[2]
101.8°W – 99.0°W	$(i) Q_S = 278 f^{0.92}$, $(0.15 < f < 30.0 Hz)$	Castro et al. (1990)[3]
101.0°W – 99.6°W	$(iii) Q_S = 100 f$, $(0.3 < f < 20.0 Hz)$	Singh et al. (1990)[4]
102.7°W – 99.0°W	$(ii) Q_s = 273 f^{0.66}$, $(0.2 < f < 10.0 Hz)$	Ordaz and Singh (1992)[3]
101.4°W – 99.5°W	$20 < Q_C < 70$ at 1 Hz	Flores (1992)[5]
101.3°W – 99.8°W	$(v) Q_C = 82 f^{0.7}$, $(1.0 < f < 32.0 Hz)$	Valdés (1993)[1]

1: Q estimates from aftershocks of the 1979 Petatlán earthquake, 2 :Q estimate from aftershocks of the June 7, 1982 Ometepec earthquake, 3: Q estimates from the Guerrero Accelerograph Array, 4: Q estimate from acceleration records of the September 21, 1985 earthquake, 5: Q estimates from the Guerrero Seismic Network (Suárez *et al.*, 1990).

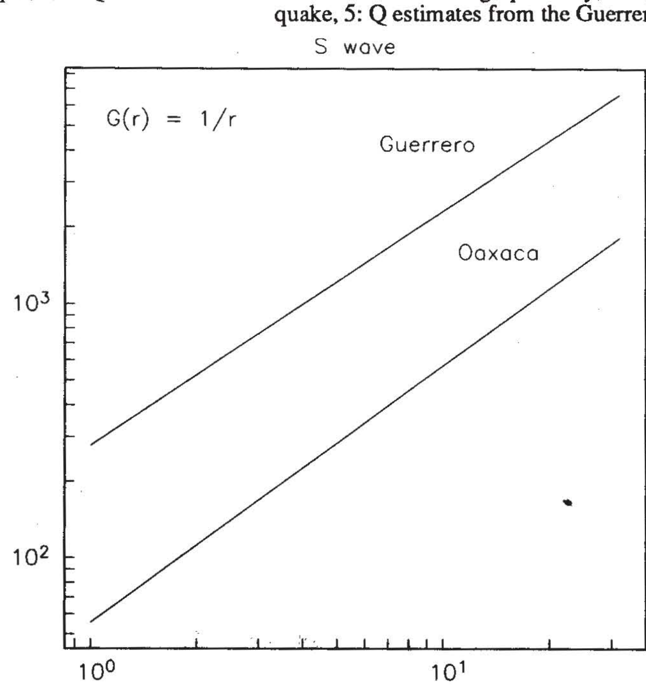

Fig. 4. Comparison of the attenuation of S waves between the regions of Oaxaca and Guerrero, Mexico. A geometrical spreading of 1/r (r being the hypocentral distance) was assumed for both regions. For Oaxaca $Q_s = 56 f^{1.01}$ (Castro and Munguía, 1993) and for Guerrero $Q_s = 278 f^{0.92}$ (Castro *et al.*, 1990).

gure 1) with Q estimates of Guerrero also obtained with aftershocks (see Figure 7), we observed that Q is consistently low for both regions. For instance, Rodríguez *et al.* (1983) found $Q_c=47 f^{0.87}$ analyzing coda waves of the aftershocks of 14 March 1979, Petatlán, Guerrero, Mexico, earthquake (Ms=7.6), located in the northwest edge of the gap. Similar estimates of Q_c were also obtained by Novelo-Casanova *et al.* (1985,1990) for the same region. In the other side of the gap, Rebollar and Alvarez (1987) found $Q_c=29 f^{1.01}$ from aftershocks of the 1982 Ometepec doublet earthquake (Ms=6.9 and Ms=7.0). From Figure 7 we can see that relations (iv) and (v), which sampled the same area, predict similar values of Q, indicating that as in Oaxaca $Q_c=Q_s$. Although relation (vi) was obtained using the same aftershocks than relations (iv) and (v), the distribution of the recording stations used covered a smaller region and consequently the area sampled for the propagating waves differ from that of functions (iv) and (v). This can explain why the relation (vi) in Figure 7 predicts smaller values of Q compared with (iv) and (v).

DISCUSSION AND CONCLUSIONS

It has been recognized from the study of earthquake sequences that the number of aftershocks decays with time. As Nur and Booker (1972) have pointed out, to explain

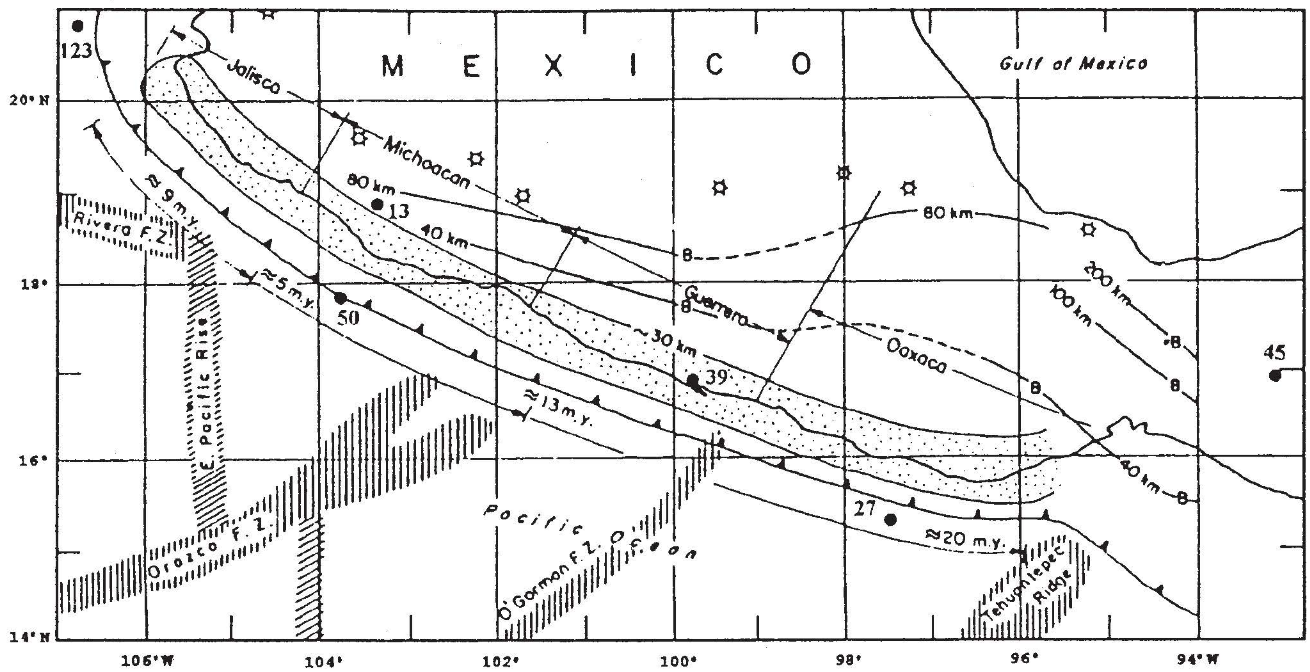

Fig. 5. Main tectonic features (modified from Singh and Mortera, 1991). The solid circles show sites where heat flow has been measured. Points on the ocean floor are the arithmetic average of areas surveyed by Prol-Ledesma *et al.*(1989). Heat flow values in the continental side were taken from Ziagos *et al.* (1985). The estimates of the plate age at the trench, the contours of depth to the top of the subducted Cocos plate and the location of recent active volcanos (stars) were taken from Singh and Mortera (1991).

this time dependence of the aftershock sequences a viscous element is necessary. They show that the flow of pore fluid can provide this viscous element. This model is attractive because it could explain the low values of Q_s obtained in the Oaxaca region after the 1978 event and in Guerrero after the 1979 Petatlán earthquake (Figures 3 and 7), since the presence of fluids may tend to increase the attenuation of the S waves. Laboratory data show that the attenuation of seismic waves in dry rocks is less than in wet rocks (Johnston *et al.*, 1979; Winkler and Nur, 1982). The introduction of fluids in the rocks acts as a crack lubricant, facilitating frictional sliding, and as a result of this Q decreases. The Q_p/Q_s ratio can provide a rough idea of the fluid content of the rocks. In partially saturated rocks, for instance, P waves are more attenuated than S waves whereas in fully saturated rocks the S waves attenuate more (Winkler and Nur, 1982). Intercrack flow is the mechanism that could explain these observations (Mavko and Nur, 1979). Although the presence of fluids, deep in the crust, may be difficult to justify, however, it is interesting to note that even one percent of water saturation can cause a decrease in Q (Born, 1941). Based on a model of pore fluid attenuation, Winkler and Nur (1982) estimated that, averaging over all crack orientations, the compressional attenuation must be approximately 2.5 times greater than shear attenuation for partially saturated rocks. Castro and Munguía (1993) found that in the Oaxaca region, Q_p/Q_s=0.4. This low Q_p/Q_s ratio suggests the plausibility that fluids present in the epicentral area of the 1978 Oaxaca earthquake may be the origin of the high attenuation observed.

Experimental data also show that Q increases with increasing pressure (Johnston *et al.* 1979). It has been observed that changes of porosity with pressure and the closing of cracks cause changes in attenuation. High values of Q have also been correlated with high values of shear resistance. Hough and Anderson (1988), for instance, found that near Anza, California the resistance of crustal rocks to shear faulting and high values of Q were correlated. Likewise, the low attenuation of shear waves observed in the Guerrero gap may be associated with the high accumulation of stresses which tend to close cracks and change the porosity of the rocks. Note in Figure 3 that high values of Q were obtained (curves (i) and (ii)) using "background seismicity" inside the Guerrero gap and low Q values after the occurrence of a main event (see also Figure 7). It is worth noting in Figure 3 that the relation (iii) obtained by Singh *et al.* (1990) using records of a main event (the September 21, 1985 (Ms=7.6) earthquake) predicts intermediate values of Q. Time-space variations of Q have been reported by Novelo-Casanova *et al.* (1985) analyzing foreshocks and aftershocks of the 1979 Petatlán earthquake. They observed values of Qc 23% smaller than those obtained using aftershocks two weeks before the main event. For the region of Oaxaca, the values of Q reported by Canas *et al.* (1988) are higher than those reported for the aftershock region by other authors (see Figure 1). However, the events used by Canas *et al.* (1988) occurred two years after the 1978 Oaxaca earthquake, presumably after the region was restressed.

In conclusion, we suggest that the difference between

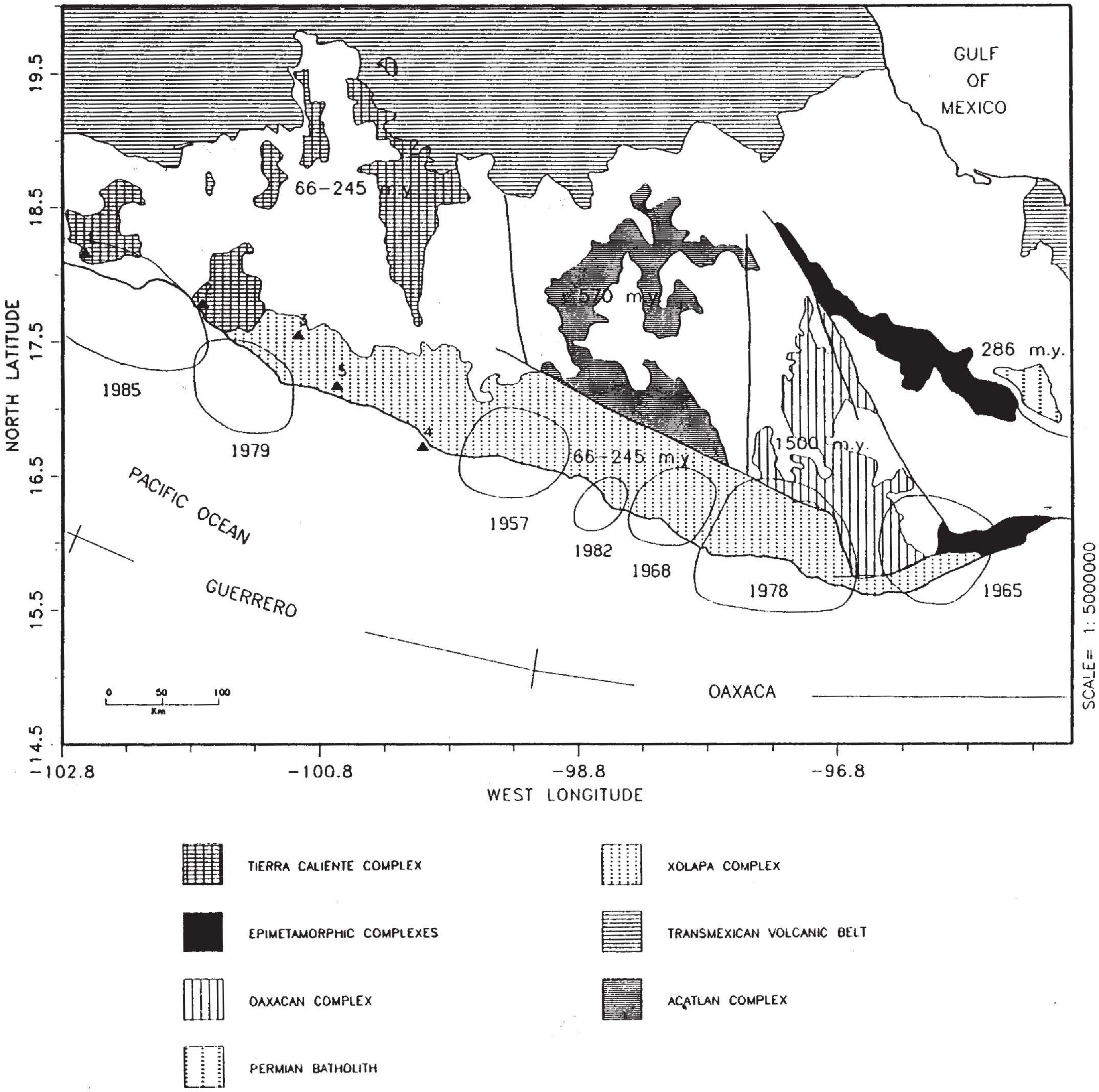

Fig. 6. Geologic map modified from Ortega-Gutiérrez (1981). Rupture zones of major earthquakes along the coast of Mexico are also shown (Kanamori *et al.*,1993). The triangles show the epicenters of the following earthquakes: (1) Sep. 19, 1985 (M_w= 8.1); (2) Sep. 21, 1985 (M_w= 7.6); (3) Feb. 8, 1988 (M_s= 5.8); (4) Apr. 25, 1989 (M_s= 6.9); (5) May 11, 1990 (M_s= 5.5) and May 31, 1990 (M_s= 6.0).

estimates of Q using "background seismicity" and aftershocks (Figure 3 and 4) may be due to the different state of stresses, density of fractures, and perhaps fluid content in the upper crust prevailing when Q was measured.

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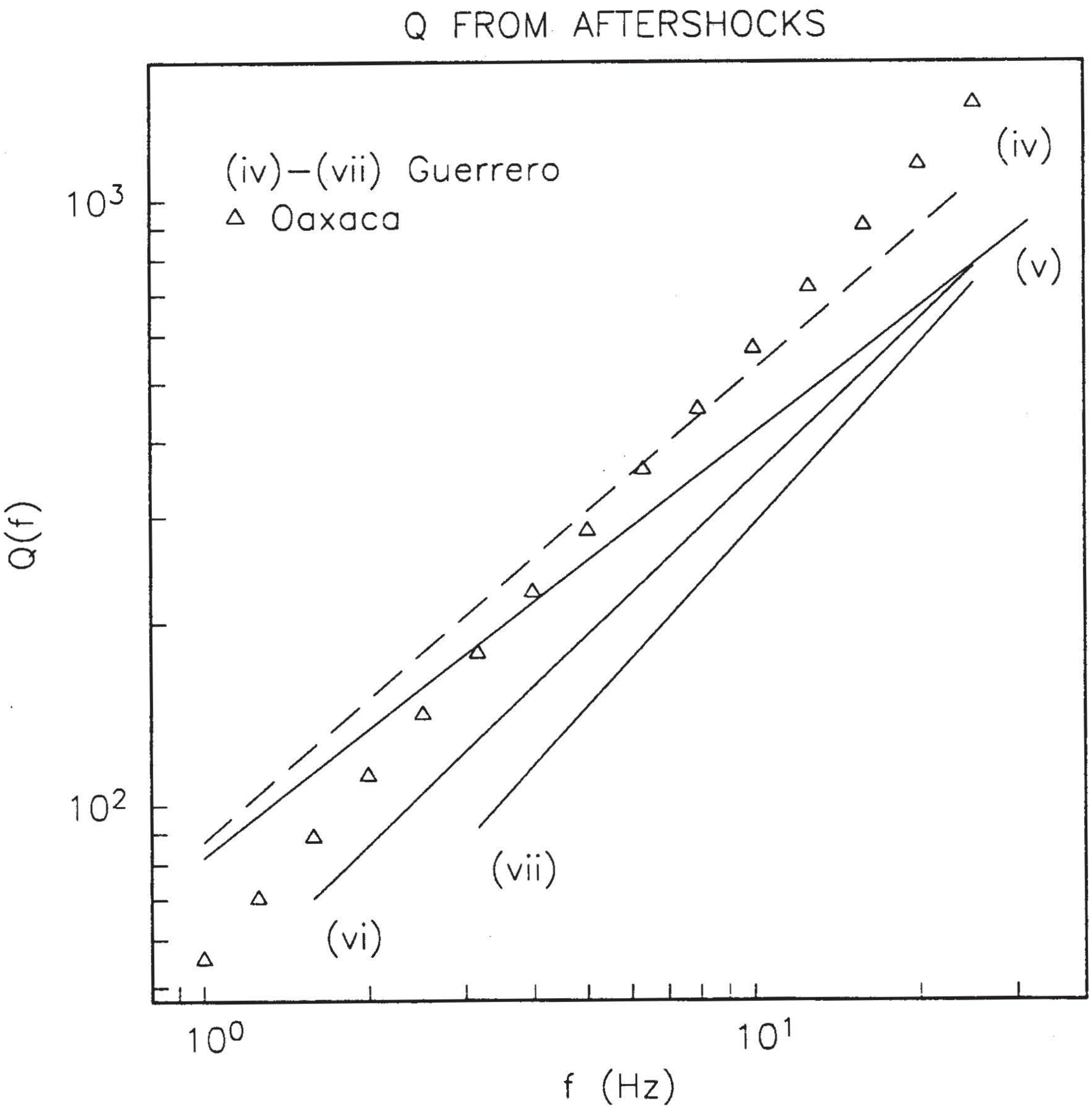

Fig. 7. Q-frequency relations obtained after the occurrence of main events. The triangles represent the function $Q_s = 56$ f obtained for Oaxaca (Castro and Munguía, 1993) using aftershocks of the 1978 earthquake. Curves (4) to (7) are the same as in Figure 3.

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