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Original paper

Attenuation of Coda Waves in the Central Region of the Gulf of California, México

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Resumen

Se analizan las ondas de coda de eventos registrados por la red sísmica de NARS que cuenta con instrumentos instalados a lo largo de ambas márgenes del Golfo de California, México, para estimar atenuación Q_c. Se utilizó modelo de dispersión simple de Sato (1977) para ventanas tiempo de 20 a 25 segundos comenzando en dos veces el tiempo de viaje de la onda S. Se analizaron eventos registrados entre 2003 y 2007 ocurridos en la región central del Golfo de California. Las distancias fuente-receptor analizadas son entre 40 y 500 km. Suponiendo una relación de dependencia de Q_c de la frecuencia de la forma $Q_C(f) = Q_O f^a$, los valores promedio encontrados fueron de Q_O = 83±3 y una dependencia de la frecuencia a de 1.06±0.03 en el rango de frecuencias de 1 a 7 Hz. El valor Q_O y la alta dependencia de la frecuencia están de acuerdo con los valores reportados para otras regiones caracterizadas por una alta actividad tectónica. Con base en la distribución de estaciones respecto a las fuentes, se definieron dos subregiones (norte y sur). Se calcularon los valores de Q_C y se correlacionaron con la tectónica y morfología de cada zona. Se observa una mayor atenuación en la región sur que puede ser atribuida a que esa zona esté más fracturada dado que los eventos sísmicos mayores ocurren de la zona centro del Golfo de California hacia el sur. Por otro lado, la corteza de la zona sur es de menor espesor que la zona norte.

Palabras clave: Atenuación de coda, atenuación-frecuencia, Golfo de California, Mexico.

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Abstract

Coda waves were analyzed from events recorded by NARS seismic network deployed along both margins of the Gulf of California, Mexico, to estimate coda attenuation Qc. Sato's (1977) single scattering model was used for a coda window of 20 to 25 s beginning at twice the S-wave travel time. Events recorded from 2003 to 2007 located in the central region of the Gulf of California were analyzed.
Source-to-receiver distances are between 40 and 500 km. Assuming a power law of the form $Q_c(f) = Q_o f^a$, Q_c values were averaged and a value of Q_o = 83±3 and a frequency-dependence ɑ value of 1.06±0.03 in the frequency range from 1 to 7 Hz was obtained. Q_o value and the high frequency dependency agree with the values of other regions characterized by a high tectonic activity.
Based on source-station distribution two subregions (north and south) were defined. Q_c values were calculated and correlated with tectonics and morphology of each area. The observed higher attenuation in the south region can be attributed to the fact that south region is more fractured since the greater earthquakes occur in central to south Gulf of California and the oceanic crust is reported to be thinner in the southern region.

Key words: Coda attenuation, attenuation-frequency, Gulf of California, Mexico.

Introduction

The Gulf of California, Mexico, is a complex tectonic zone where the peninsula of Baja California is separating from the continent. This active zone has generated moderate earthquakes which have affected cities on both sides of the gulf. In 2012, an M6.0 earthquake affected the city of Los Mochis, where damages in the regional hospital were reported. Last earthquake occurred on September, 2015 (M_W6.7).

Social and economic effects resulting from earthquakes can be reduced through seismic risk analysis. The elaboration of good quality hazard maps is required. To do this, studies of source characteristics and wave propagation are essential. Attenuation is an important factor to such studies.

Attenuation of seismic waves has been widely studied in different regions around the world since Aki and Chouet (1975) and Sato (1977) introduced their theories on coda waves attenuation (Q). Different tectonic regions around the world (e.g., volcanic, active, stable) have been characterized by their Q^{-1} values (Pulli, 1984; Jin *et al*., 1985; Wiggins-Grandison and Havskov, 2004, among others). In Mexico there are attenuation studies mostly for the south and southeastern for the subduction zones of the Rivera and Cocos plates (Castro and Munguía, 1993; Ordaz and Singh 1992; Domínguez *et al*., 2003, among others) and for the northwestern zone of Mexico for the Gulf of California region (Domínguez *et al*., 1997; Castro *et al*., 2008).

In the present study, Sato's formulation (Sato, 1977) was used to estimate Q_c at the central zone of the Gulf of California.

Data from 6 stations of the NARS-Baja network (Network of Autonomously Recording Seismographs of Baja California) installed by Utrecht University, CALTECH and CICESE (Centro de Investigación Científica y Educación Superior de Ensenada Baja California, México) during 2002 were used. This region was chosen due to its implication in terms of civil protection for the cities on both sides of the Gulf. The correlation of the results with the morphology and tectonics of the region is also presented.

Tectonic Setting and Seismicity

The Gulf of California forms an oblique-divergent boundary between the Pacific and North America plates. Relative motion between the peninsula of Baja California and North America plate in the southern gulf is about 46 mm/yr (Plattner *et al*., 2007). It consists of a system of linked transform faults and short spreading centers forming basins (Lonsdale, 1989). Deformation accommodates in oblique faults to the north and transform faults to the south (Fenby and Gastil, 1991; Nagy and Stock, 2000). Northern basins are shallower than those to the center and southern basins (Curray *et al*., 1982; Lonsdale, 1989; Persaud *et al*., 2003).

In the north zone of the Gulf, an incipient spreading center begins in the Wagner basin (Persaud *et al*., 2003) developed from Cerro Prieto and Wagner transform faults, and ending in the south with the East Pacific Rise which corresponds to the northern limit of the Rivera plate.

Lonsdale (1989) suggested the presence of a transitional crust at the Guaymas basin in the middle sector of the Gulf of California. In this location, there is a high rate of sedimentation,

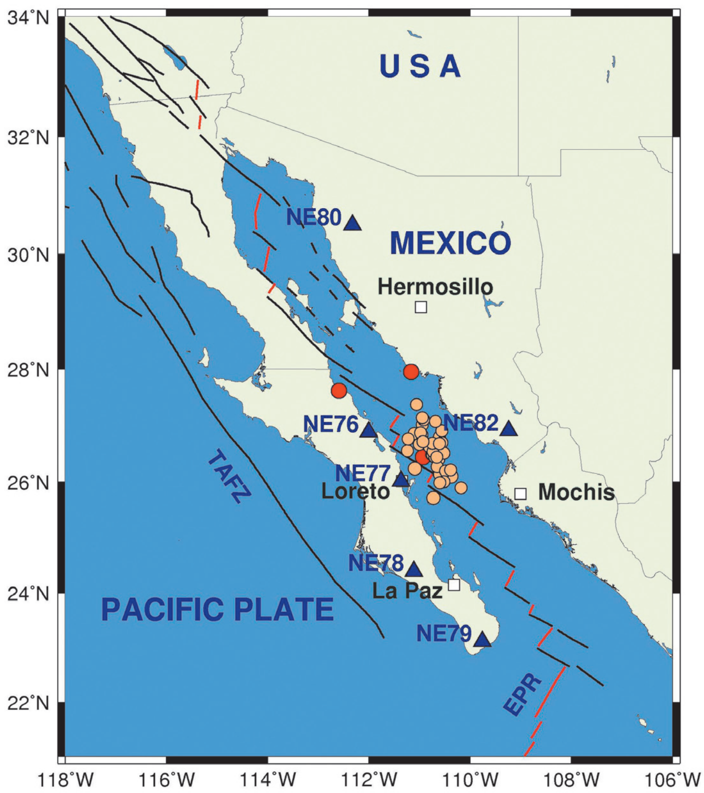

Figure 1. Tectonic setting and location of used seismic stations (triangles) and analyzed earthquakes (circles). White squares indicate main cities in the area. Red circles indicate events with Mw >5. TAFZ (Tosco-Abreajos fault zone), EPR (East Pacific Rise).

which promoted the development of a basin containing sills and altered sediments.

Most of the seismicity is distributed in the NW–SE direction along the axis of the Gulf of California, following a linear trend that, from north to south, steps southward near the main basins (Wagner, Delfin, Guaymas, Carmen, Farallon, Pescadero, and Alarcon) and spreading centers. Seismicity in the northern zone has low magnitude (Castro *et al*., 2007) but increases to the south reaching magnitudes of M>6 such as the 2010 and 2015 earthquakes that occurred near (south) parallel 25° N, or the 1992 earthquake (M7.0), which is the greater earthquake ever recorded in this zone (Pacheco and Sykes, 1992).

Only good quality data (high signal/noise ratio) was used from five years recording which included 4 moderate events (M>5) and their aftershocks (Figure 1).

Method

Sato's (1977) formulation was used to estimate Q_C through measurements of the amplitude decay of coda waves with time. The model assumes a source embedded in an infinite medium populated by a random distribution of scatterers in an infinite volume and cross-sectional area σ. The density of energy in terms of root mean square (*rms*) amplitude, scattered by the inhomogeneities on the surface of an ellipsoid whose foci are the source, and the receiver can be expressed as

$$A(r,t \setminus \omega) = \frac{1}{\omega}\left[\frac{\Omega(\omega)\Delta f}{2\pi\sigma L}\right]^{1/2} \frac{\left[K(\alpha)\right]^{1/2}}{r} e^{-\omega t/2Q}, \quad (1)$$

where A is the *rms* amplitude of the coda wave, $\Omega(\omega)$ is the total energy radiated by the source within a frequency band, r is the distance between the source and the receiver, $K(\alpha) = \frac{1}{\alpha} ln[(\alpha+1)/(\alpha-1)]$ and $\alpha = t/t_s$, t is the elapsed time of the coda wave, t_s is the elapsed time of the S wave, both measured from the earthquake origin time. $L = 1/N\sigma$ is the mean free path.

Usually (1) is expressed as the linear function

$$\frac{\ln\left[A(r,t \setminus \omega)\right]}{\left[K(\alpha)\right]} = \ln C - (\pi f / Q)t \quad (2)$$

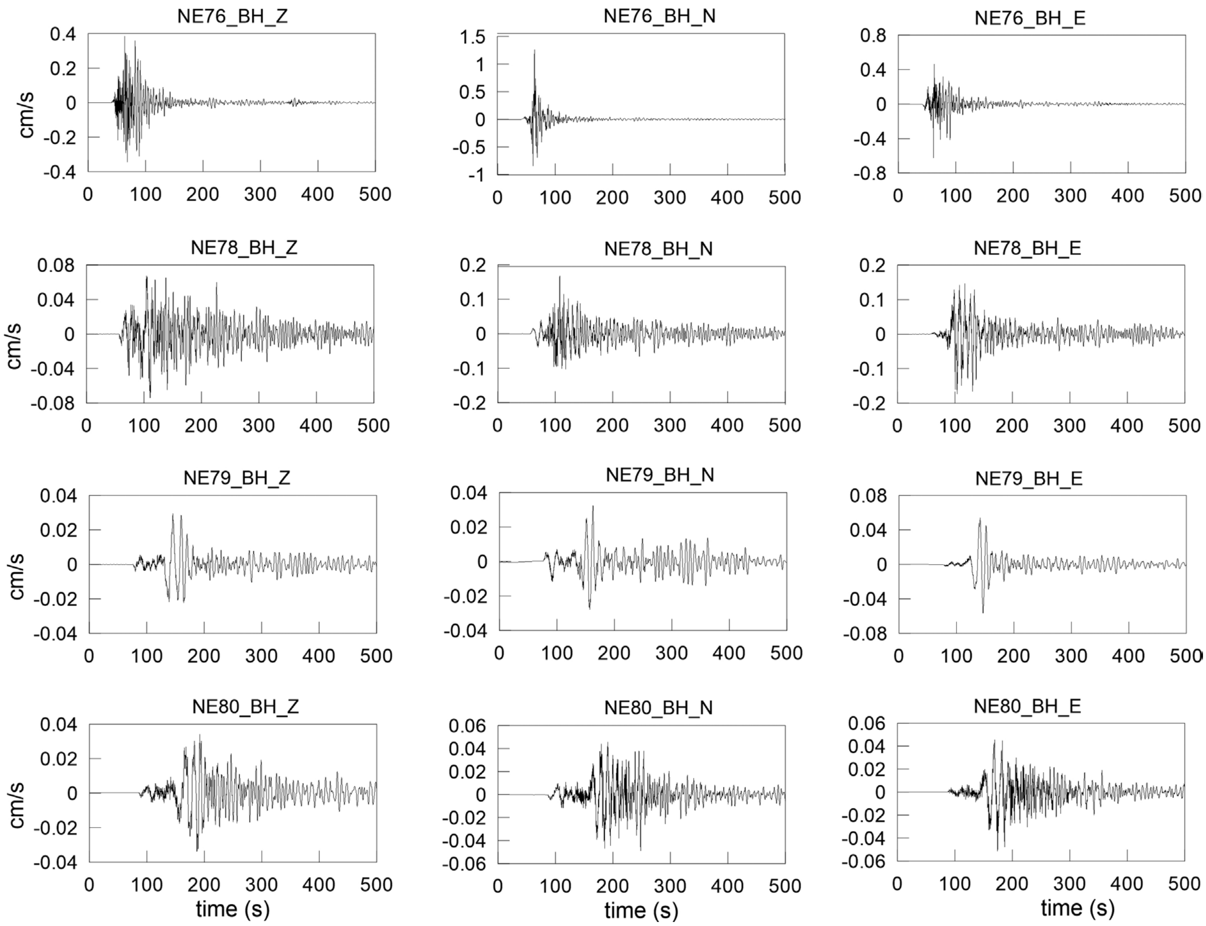

Figure 2. Example of an event used for Q_c calculation. Records correspond to the 2003/03/12 earthquake (M_w6.3).

Table 1: Velocity model.

Vp (km/s)	Vs (km/s)	Density (kg/m^3)	Thickness (km)
4.0	2.6	1800	4.0
5.7	3.3	2500	4.0
6.7	3.8	3000	16.0
7.8	4.0	3400	400.0

where the quality factor Q can be obtained from the slope of the linear fit of the logarithm of the observed amplitude (root mean square amplitude) of the coda wave vs t for the frequency f.

Data

Records from the three components of six stations of NARS were used (Trampert *et al*., 2003). Each station consists of a 3-channel, broad band STS-2 sensor (velocity) connected to a 24 bit resolution recorder. 20 samples per second are recorded. For this reason the analysis was restricted to frequencies below 10 Hz.

Records from 2003 to 2007 were available. From this database only events recorded by at least four stations, presenting no saturation, showing high signal/noise ratio (>5) and no overlapping with other events (case of aftershocks) were selected to ensure good quality data. An example of a record is shown in Figure 2.

Processing began with locating events. Hypocenter (Lienert *et al*., 1986; Lienert and Havskov, 1995) which is included in SEISAN code (Ottemöller *et al.,* 2013) was used. The one-dimensional velocity model used by Rebollar *et al*. (2001) shown in table 1, was also used. From all the located events, we selected only those which were in the area of interest, between parallels and N. 50 events filled these criteria and those mentioned above, and were

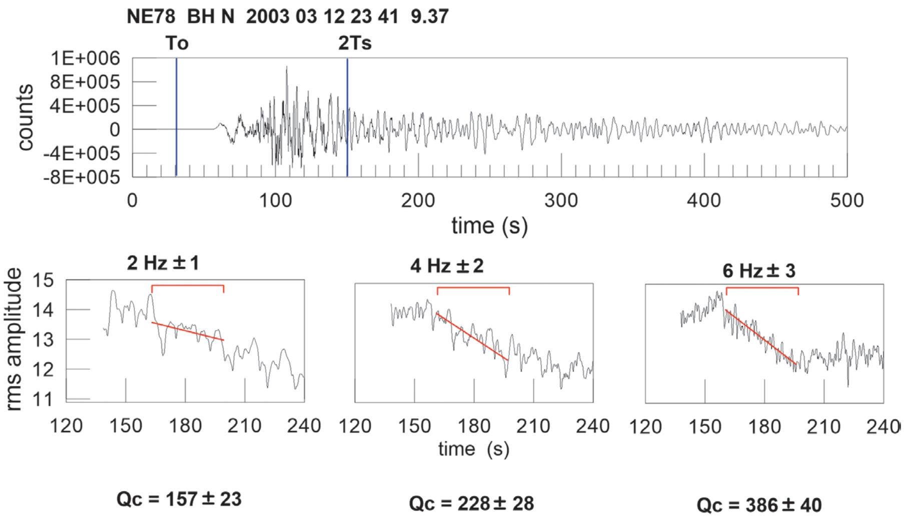

Figure 3. Coda Q_C estimation procedure. The unfiltered seismogram is shown at the top. *rms* amplitudes *vs* lapse time for the time window indicated at the different frequency bands are shown below.

used for Q_C estimation. These events included four events with M>5 and their aftershocks.

Each record was bandpass-filtered for seven frequencies between 1 and 7 Hz with an eight-pole Butterworth filter and bandwidths of two-thirds of the center frequency

rms amplitudes were determined for sliding windows of 2 seconds width and 1 second advance. Assuming that noise is not correlated with signal, the seismogram can be considered as a linear superposition of noise and signal. Corrected amplitudes (A_C) were calculated using

$$A_c = (A_T^2 - A_N^2) \tag{3}$$

where A_N is the maximum amplitude (*rms*) of the noise and A_T is the actual amplitude (*rms*) of the seismic record. For each band, *rms* amplitudes of a representative window of noise before the P arrival and corrected *rms* amplitudes were calculated according to (3).

A_C versus t was plotted and fitted a straight line by a least squares method to calculate the slope from which was obtained. The lower bound of the time window started always after twice the S-wave travel time. The upper bound was usually given by the change of the trend of $A(t)$. The time windows selected in this way were between 20 and 65 s in all cases. Figure 3 shows an example of this procedure. The unfiltered seismogram is shown at the top, below it, the *rms* amplitudes from the bandpass filtered windows, and the fitted line for the selected time window. Q_C estimated values for each frequency are also shown.

Results

Q_C average was obtained at each station for central frequencies 1 to 7 Hz. Figure 4(up) shows the values for the six stations and a comparison of the Q_C values estimated for the different stations, from December, 1997, to May, 1998, (down). Vertical bars indicate standard deviation in Q_C estimation (±1s).

Some observations can be drawn from this figure. Within the bounds of the variation, it can be seen that Q_C values at each frequency are similar between stations and the general trend is the same for all of them. Assuming a power law of the form $Q_C(f) = Q_O f^a$, we averaged Q_C values and obtained a value of Q_O = 82±3 and a frequency-dependence α value of 1.05±0.03 in the frequency range from 1 to 7 Hz.

Lapse time used to evaluate Q_C and epicentral distance are related to the size of the sampled region. For a source in a homogeneous half-space with random scatters, scattered energy arriving at time t in the coda comes from scatterers lying on an ellipsoidal shell, which surface projection is defined by

$$\frac{x^2}{(vt/2)^2} + \frac{y^2}{(vt/2)^2 - (r/2)^2} = 1 \tag{4}$$

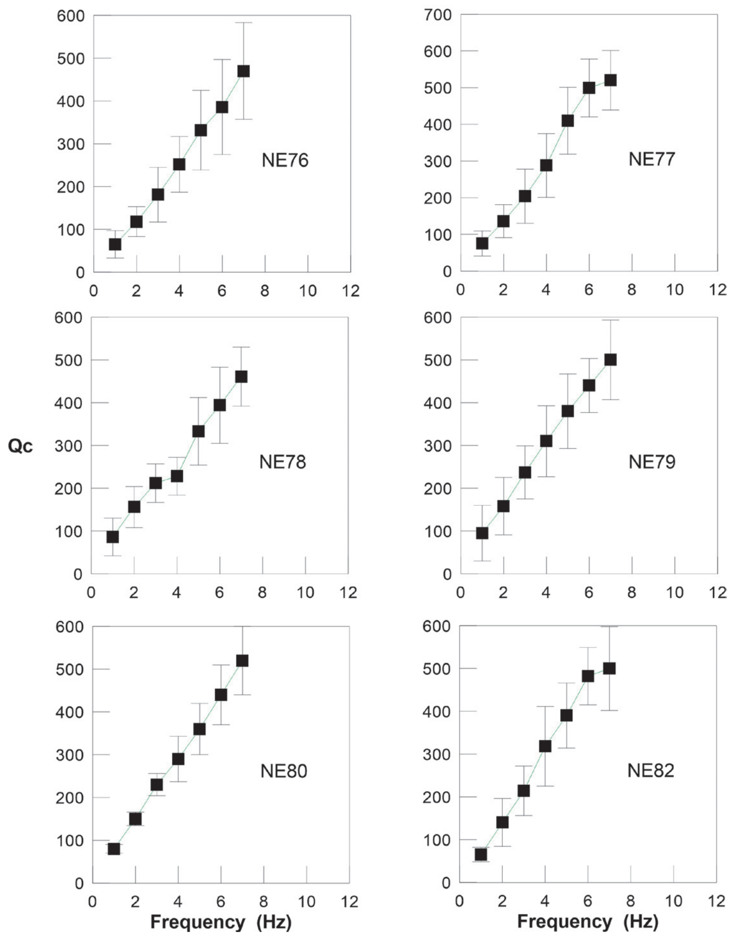

Figure 4. Coda Q_c values obtained for different stations. Vertical bars indicate standard deviation in Q_c estimation.

Figure 5. North and South subregions of Gulf of California for attenuation analysis.

where r is the source-station distance, v is the wave velocity (averaged S-wave velocity of the model of Table 2), and x and y are the surface coordinates (Pulli, 1984).

Ellipses for each source-station pair were plotted and an envelope was drawn. Two subregions could be defined; the first one with stations to the south of the epicenters (NE78 and NE79) and the second one with the other stations including the most northern station (NE80, Figure 5) since the region between NE80 and the cloud of epicenters to have similar characteristics were considered. Attenuation-frequency dependency function for the north subregion was of $(85\pm3)f^{1.03\pm0.03}$ and of $(75\pm3)f^{1.07\pm0.03}$ for the south subregion. Q for the closest stations to the epicenters cloud (NE76, NE77 and NE82, distances between 40 a 200 km) were also estimated in order to see if there was a significant difference for this smaller region,obtaining $(83\pm3)f^{1.16\pm0.03}$. A higher value of the frequency-dependence α which could be expected as this zone correspond to events occurrence, and can be considered as the most heterogeneous zone.

Discussion and Conclusions

In this study an estimation of averaged value of parameter coda attenuation($Q_C(f)$) was obtained for the center and south of the Gulf of California, Mexico.

The obtained relation, shows that attenuation is highly dependent on frequency which is in agreement with the high tectonic activity of the Gulf.

A slightly higher attenuation in the south subregion was observed. Oceanic crust is reported to be thinner in this region (López-Pineda, 2007). Lonsdale (1989) suggested the presence of a transitional crust at the Guaymas basin in the middle sector of the Gulf of California. In this location, there is a high rate of sedimentation, which promoted the development of a basin containing sills and altered sediments. The greater earthquakes occur in central to south Gulf of California (M>6). We can thus infer that the southern region is more fractured than the northern one, explaining the observed difference in attenuation.

For a small zone of 1.5x1.5 degrees located inland (northeastern Sonora state) within the north subregion (region of the 1887, Mw 7.5 earthquake rupture zone which included the Otates, Teras and Pitáycachi faults), Castro *et al*. (2008) found an S-wave attenuation-frequency dependent function $Q_S = 83.8 f^{0.9}$. Very similar values to those obtained in the present study. They suggested scattering to be an important mechanism controlling the decay of spectral amplitudes. The higher frequency dependence in the present case could be

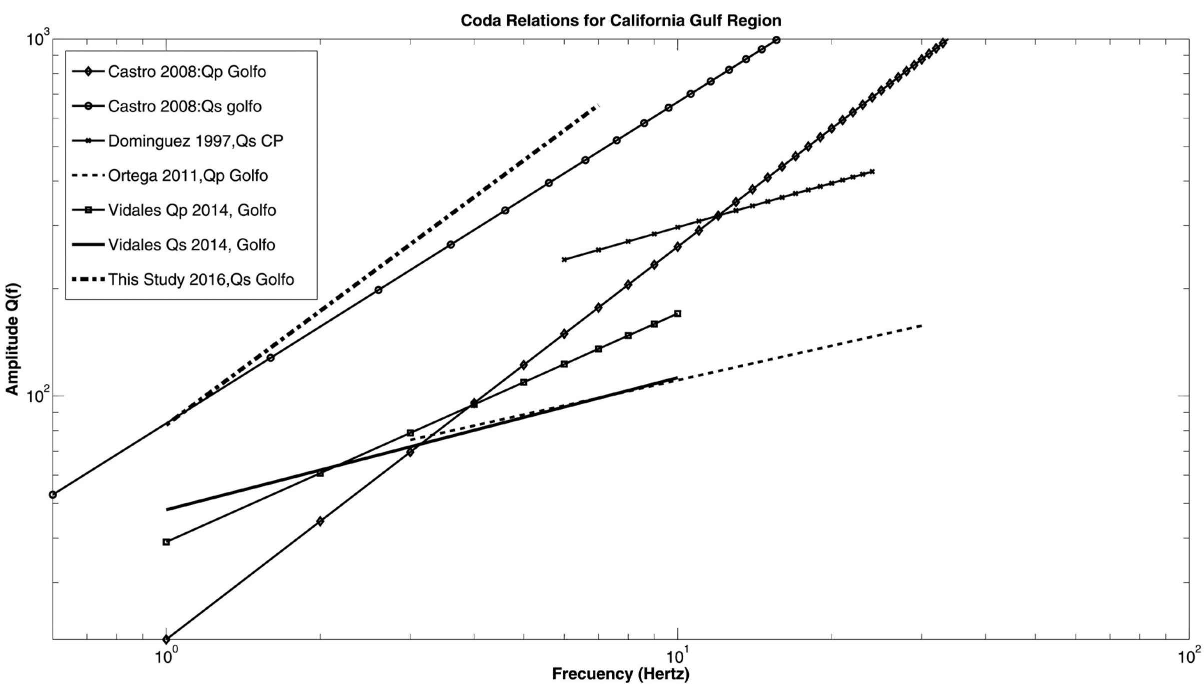

Figure 6. Comparison of Q values found in the California and the Gulf of California regions

reflecting the paths that approach the boundary between the North America and Pacific plates where higher heterogeneity is to be expected, the thickness of the crust is thinner, and new ocean floor is being created.

To the north from the Gulf of California, some attenuation studies have been performed: Reyes *et al*. (1982) obtained Q_C = 250, independent of frequency between 5 and 12 Hz using aftershocks of the 1980 Victoria earthquake, using spectral ratios. Another study of attenuation was made at Imperial fault region by Singh *et al*. (1982); they used a spectral approach to estimate attenuation of SH waves and obtained a linear functional relation of $Q_S = 20 f^{1.0}$ in the frequency range from 3 to 25 Hz. Dominguez *et al*. (1997), found $Q_C = 111.5 f^{0.41}$ between 6 and 24 Hz for a small area (less than 10 km) around the Cerro Prieto Geothermal field. More recently, Vidales *et al*. (2014) studied attenuation of the same region of this study but restricting their source-station paths up to 220 km. They found $Q_S = 176 f^{0.6}$ for distances up to 120 km and $Q_S = 48 f^{0.37}$ for 120-220 km. Similar values to those obtained by Ortega and Quintanar (2011) for the southern zone of the Gulf of California ($Q_p = 56 f^{0.3}$) which are very different from that obtained by Castro *et al*. (2008) of $Q_p = 20.8 f^{1.1}$ for the Sonora Region. Although they are different regions (Sonora is part of the basin and range province), no such differences were to be expected, specially the differences in frequency dependence (Figure 6).

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