

A new coda-duration magnitude scale for northern Baja California, Mexico

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RESUMEN

En la región norte de Baja California las duraciones de coda de señales sísmicas registradas en el ambiente sedimentario del Valle Mexicali-Imperial (VMI) son mayores que las registradas en la región granítica de las Sierras Peninsulares de Baja California (SPBC). Además de esta variación regional, la duración de coda también está afectada por la distancia fuente-receptor y las condiciones de la geología local del sitio de registro. Todos los factores que modifican a la duración de coda deben tomarse en cuenta cuando ésta se usa para calcular la magnitud del sismo que la generó. Con base en sismogramas correspondientes a sismos de magnitudes de 1.8 a 5.8, efectuamos un análisis de regresión múltiple a valores de tiempo transcurrido τ desde el origen del sismo hasta el criterio de corte de la duración de la señal sísmica. De este análisis obtuvimos dos relaciones magnitud-duración: $M_D = -(1.56 \pm 0.21) + (2.44 \pm 0.13) \log \tau + (0.0023 \pm 0.0004)\tau + S$, para las SPBC, y $M_D = -(1.27 \pm 0.38) + (2.31 \pm 0.20) \log \tau + (0.0012 \pm 0.0004)\tau + S$, para el VMI. En ambas relaciones S representa las correcciones de estación, las cuales están comprendidas en el intervalo de -0.60 a +0.19. Estas correcciones permiten corregir los valores de magnitud por la influencia del sitio de registro en la duración de coda. Las relaciones M_D - τ propuestas en este estudio, calibradas con una escala de magnitud local definida previamente para la región, permiten obtener valores homogéneos de magnitud.

PALABRAS CLAVE: Magnitud de duración, duración de coda, corrección de estación.

ABSTRACT

In northern Baja California, coda-durations of seismic signals recorded in the sediments of the Mexicali-Imperial Valley (MIV) are longer than those recorded on the granitic Peninsular Ranges of Baja California (PRBC). The source-receiver distance and the local geology conditions also affect coda duration. Using data from earthquakes in the 1.8-to-5.8-magnitude range, we performed a multiple regression analysis to get two new duration magnitude relationships as follows: $M_D = -(1.56 \pm 0.21) + (2.44 \pm 0.13) \log \tau + (0.0023 \pm 0.0004)\tau + S$, for PRBC, and $M_D = -(1.27 \pm 0.38) + (2.31 \pm 0.20) \log \tau + (0.0012 \pm 0.0004)\tau + S$, for MIV, where τ and S are lapse-time values and station corrections, respectively. Station corrections range from -0.60 to +0.19. The new magnitudes are calibrated with a local magnitude scale previously defined for the region.

KEY WORDS: Duration magnitude, coda-duration, station correction.

INTRODUCTION

Amplitude and duration of seismic signals depend upon recording distance, propagation path of the wave through different media, and geology at the recording site. In addition, amplitude varies according to the P- and S-wave radiation patterns. Influence of these factors on seismic signals has been considered for magnitude computation in many seismic regions (e. g., Michaelson, 1990 and Eaton, 1992). In the northern Baja California region (Figure 1a), differences in amplitude, duration and frequency content in the seismograms of earthquakes of similar magnitude have been observed. For instance, seismograms of the granitic Peninsular Ranges of Baja California (PRBC) have a simple appearance as compared with the complex seismograms of the sedimentary environment of the Mexicali-Imperial Valley (MIV) (Nava and Brune, 1983; Castro, 1983; among others). In particular, dif-

ferences observed on amplitude and duration of the seismic signals can lead to underestimation or overestimation of the magnitudes based on these parameters. For the case of seismic amplitude, Vidal and Munguía (1999) found appropriate attenuation functions and station corrections from data of PRBC and MIV earthquakes. Their results were used to determine the local magnitude (M_L) of earthquakes of both areas. With regards to signal duration, however, there were no systematic studies of factors that modify such parameter for these areas.

The main purpose of this paper is to establish a coda-duration magnitude scale for the north Baja California region. This scale would permit the use of clipped seismograms produced by large earthquakes occurring near the stations. By establishing one magnitude relationship for PRBC and other for MIV, the variation of duration due to regional geology is

properly taken into account. Both relationships also consider the effects of the source-to-station distance and the local geology conditions at the recording site. Our proposed relationships were scaled to the local magnitudes reported by Vidal and Munguía (1999).

Regarding station corrections, these must be included in a duration-magnitude scale to improve the accuracy of magnitude estimations (e. g., Bakun, 1984). If they are not, a bias in duration magnitudes might exist when stations are interchanged or are dysfunctional for a period of time (Savage and Anderson, 1995). Since we separated the data by regional geology and took into account the epicenter-to station-paths coverage (Figures 1b, for PRBC and 1c, for MIV), we consider that the resulting station corrections represent the influence of the site on seismic signals. A comparison of the duration station corrections, determined in this study, with the amplitude station corrections reported by Vidal and Munguía (1999) did not show important site effects for seismic stations sited on the PRBC. Nevertheless, contrasting differences among amplitude and duration station corrections were evident at two sites of the MIV area.

SEISMIC SIGNAL DURATIONS IN NORTHERN BAJA CALIFORNIA

Data. The analyzed data consist of 1360 coda-duration values measured on raw vertical-short-period (1-s) seismograms from 349 earthquakes recorded by weak motion stations of the Red Sísmica del Noroeste de México (RESNOM, Figure 1a). Since most of the analyzed seismograms are of the analog type, the duration measurements were done on unfiltered records. However, it is important to mention that records with an evident presence of surface waves were not considered for analysis. This was the case for some records of events with magnitudes larger than 5.0. Thus, even though the number of available seismograms for such larger events is small, records with surface waves and anomalously long durations were rejected.

On the other side, to determine the causes that modify the signal duration, we analyzed the total duration of a seismogram, *i. e.*, the length of time measured from the P-wave onset to the point on the trace at which the coda amplitude has decreased to about twice the level of noise. In the regression analyses that we performed to obtain the magnitude-duration relationships the lapse time was used instead. This time is measured from the origin time of the earthquake to the cut-off criteria on the seismogram.

Regional variation of the signal duration. To highlight the differences in the signal durations recorded for PRBC and MIV earthquakes, we considered epicenter-to station paths comprised entirely within the respective area, with no crossings from one to the other (Figures 1b and 1c). Figure 2 shows plots of the logarithm of duration against the earthquake mag-

nitude (M_{CTT}) reported in the listings of the California Institute of Technology/United States Geological Survey (CIT/USGS). We used this magnitude because it was utilized to calibrate a magnitude-duration relationship proposed by González and García (1986) for the PRBC area. Such relationship, used at RESNOM to estimate coda magnitudes, was based mainly from seismograms of the CBX station and does not include any type of station correction. In all plots of Figure 2 we included two straight lines for comparison purposes. The dashed line represents the empirical relationship of González and García (1986), while the continuous line is our best fit to data of each station. A basic observation from these plots is that stations recording on the sedimentary environment of the MIV area and south of it (MIV epicenter-to-station paths) produce seismograms with long durations (see the upper-left plot). Figure 2 shows that most of the data from MIV stations lie below the dashed line (see plots for individual stations). For PRBC epicenter-to-station paths, the continuous and dashed lines are quite similar. Such observation suggests that the relationship of González and García (1986) is suitable to use with data from other PRBC stations (besides CBX).

At this point, it is important to notice that stations on hard rock normally operate with gains of 44 or 50 dB (most stations), while for stations on sediments or soft rock (two stations), the gains are 32 and 38 dB (Table 1). In spite of the different gains, the stations on MIV (recording MIV earthquakes) produced seismograms with durations that are longer than the durations measured on seismograms of PRBC stations for PRBC earthquakes. So, we consider that the observed differences in the durations might be a combined effect of the propagation medium, the characteristics of the recording site and the distance of recording. With regards to plots of Figure 2, we also note that the scattering observed for both areas is high, so we shall proceed to analyze, besides the recording medium, the other effects on coda-duration.

Distance dependence of the duration. To examine the influence of the recording distance on the signal duration, we prepared plots of these parameters at intervals of 0.5 units of magnitude (Figure 3). Figure 3 reveals, as shown in the previous section, that durations recorded in PRBC tend to be shorter than those recorded in MIV. For both areas, we may note that the average duration values increase for larger magnitude events recorded also at larger distances. For events of comparable magnitudes (in the 0.5 units-of-magnitude intervals), the plotted duration values suggest a slight increase of duration with distance. Except for the 4.6 to 5.5 magnitude bins, which show the larger data dispersion, the average duration for PRBC earthquakes increases only up to around 200 s at almost all distances considered. For other seismic regions and local earthquakes recorded at distances shorter than about 100 km, Aki and Chouet (1975) established that “the total duration of the seismogram is nearly independent of the epicentral distance or azimuth and can be used effec-

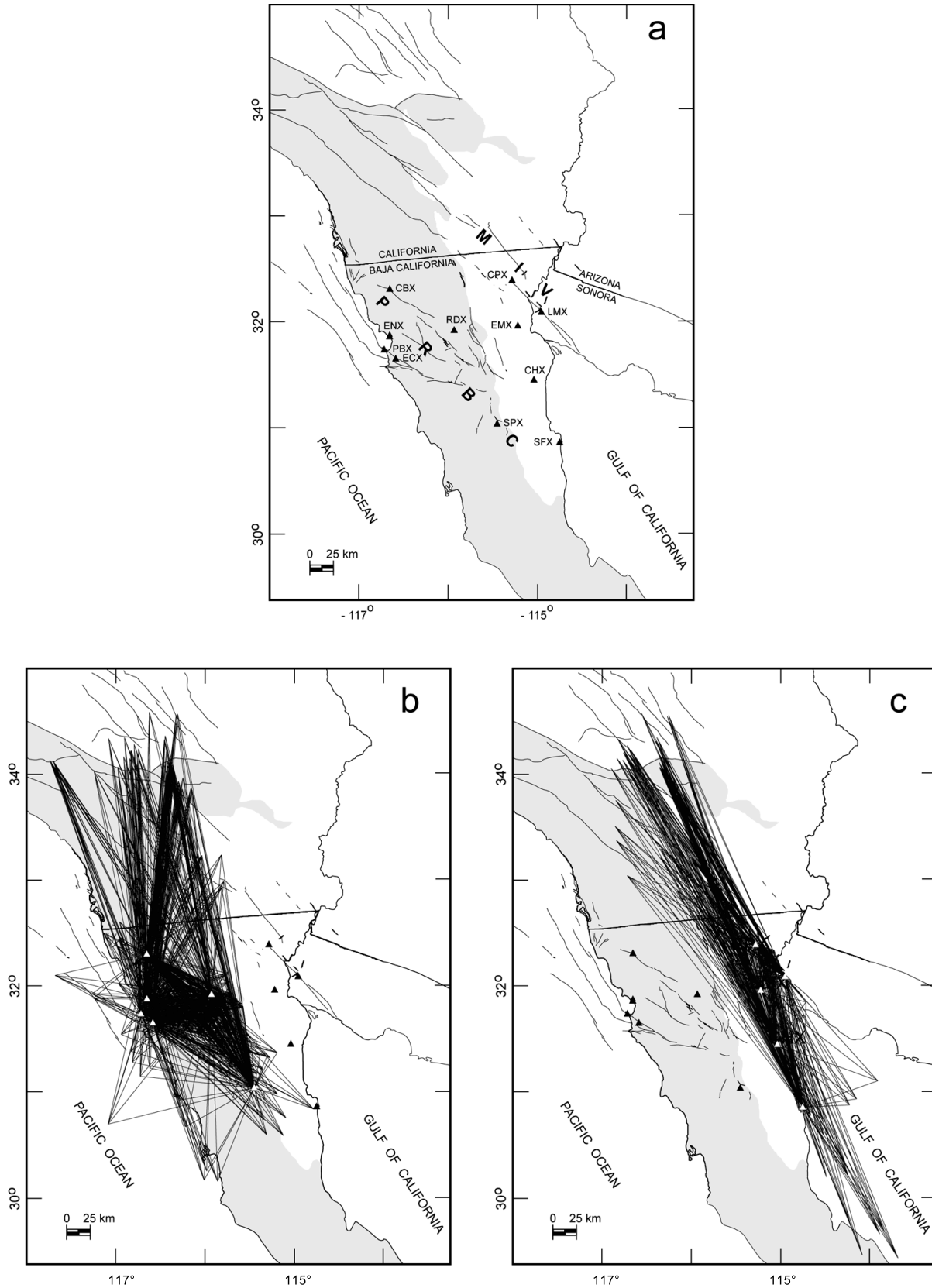


Fig. 1. (a) Map showing the distribution of RESNOM stations (modified from Vidal and Munguía, 1999). The geographical coverage of the epicenter-to-station paths is shown in (b) for the Peninsular Ranges of Baja California-southern California region and (c) for the Mexicali-Imperial (Salton Sea province) and Gulf of California regions.

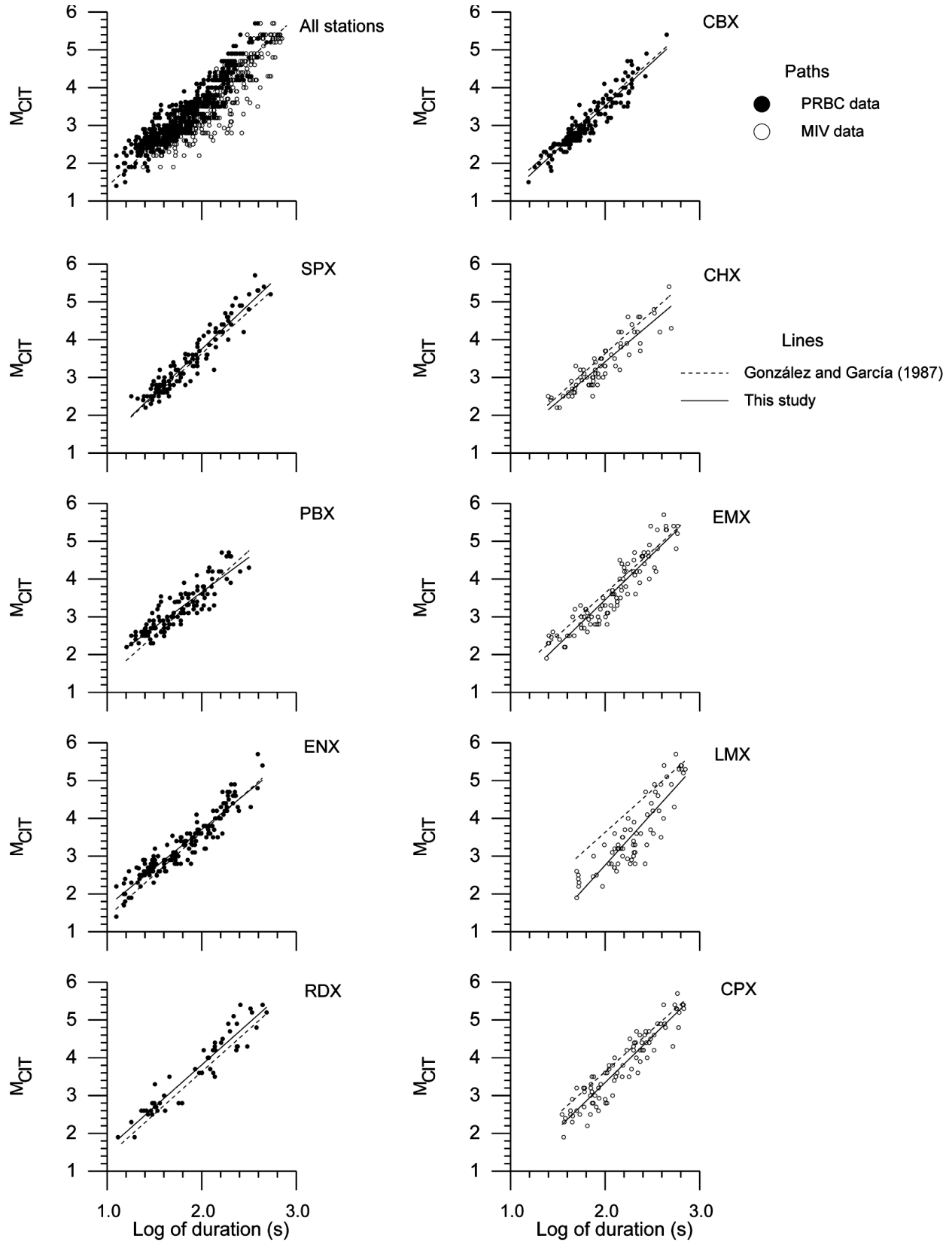


Fig. 2. Local magnitudes reported by CIT/USGS (M_{CIT}) plotted against the logarithm of duration for the studied earthquakes. Dots and circles represent earthquakes with epicenter-to-station paths comprised in the PRBC and MIV areas, respectively. The continuous line represents the best fit to the data. The dashed line represents the magnitude relationship of González and García (1986).

tively as a measure of earthquake magnitude". According to some authors cited by Herrmann (1975), the magnitudes that are estimated from the signal duration are slightly dependent upon distance. In our case, Aki and Chouet statement seems to be valid for PRBC earthquakes recorded at distances of up to 400 km. On the other hand, for MIV earthquakes, we see long durations (though the scatter of the data is large at all distances) most likely due to propagation in a more complex medium. Therefore, it is plausible to say that two magnitude-duration relationships are needed: one for PRBC and the other for MIV. In those relationships the effect of the source-to-station path on the duration of seismic signals must be considered.

Recording site. As aforementioned, site effects play an important role in the duration and amplitude of seismic waves. In magnitude determinations, station corrections take into account these effects. In our case, even though most of the RESNOM stations are located on hard rock, some stations are on sediments (LMX), volcanic rocks (CPX), or at elevated sites (CBX, RDX and SPX) (see Table 1). The LMX and CPX stations deserve special attention because of contrasting differences that were found in their durations and amplitudes. Low amplitudes and long durations characterize the seismograms of LMX, which records on a small quaternary sand promontory called La Mesa de Andrade. In contrast, high amplitudes and slightly long durations are exhibited by seismograms of CPX. This station is located near the crater of the Cerro Prieto volcano (at 180 m high), the only prominent topographic feature in the Mexicali Valley. Figure 4 depicts dif-

ferences in duration and amplitude of seismic signals from 31 earthquakes recorded by CPX and LMX at similar epicentral distances ($40 \leq \Delta \leq 110$ km). Figure 4a shows that the duration values recorded at LMX are longer than those recorded at CPX. In contrast, the amplitudes at CPX are larger than the amplitudes at LMX, as shown by the Figure 4b. These observations clearly indicate how the local geology conditions at each site affect in a different way the amplitudes and durations of the recorded signals.

In what follows, we review the duration magnitude in terms of factors that modify the coda-duration through an analysis of lapse-time values (τ).

REGRESSION PROCESS

In this study, the coda-duration magnitude scale is based on the single scattering model proposed by Aki and Chouet (1975) to explain the amplitude decay of the coda envelope:

$$A_{\tau}(\omega) = A_0(\omega) \tau^{-a} \exp(-\omega\tau/2Q), \quad (1)$$

where $A_{\tau}(\omega)$ is the amplitude of the coda envelope at the particular frequency ω , $A_0(\omega)$ represents the coda source factor, a is a constant that represents the geometrical spreading, Q is the quality factor, and τ is the lapse time, measured from the origin time to the cut-off criteria. For our purpose, we took the logarithm of the above equation and rearranged the

Table 1

Station codes, coordinates, gain settings, and corrections

Station	Name	Latitude (°N)	Longitude (°W)	Elevation (m)	Gain (db)	Station Corrections Duration	Amplitude*	Geology
EMX	El Mayor	31.988	115.242	10	50	- 0.02	+0.26	Granite
LMX	La Mesa	32.109	114.963	25	38	- 0.60	-0.08	Sand
CHX	El Chinero	31.472	115.051	40	44	- 0.08	+0.15	Basalt
SFX	San Felipe	30.881	114.752	55	44	+0.16	+0.01	Weathered granite
CPX	Cerro Prieto	32.418	115.304	180	32	- 0.10	-0.42	Rhyodacite
ENX	Ensenada	31.883	116.663	230	50	+0.07	-0.10	Andesite
PBX	Punta Banda	31.742	116.726	330	44	+0.04	-0.04	Andesite
ECX	Esteban Cantú	31.657	116.598	1040	50	+0.01	-0.09	Andesite
CBX	Cerro Bola	32.313	116.664	1250	50	- 0.26	-0.17	Rhyolite
RDX	Rancho Dawling	31.928	115.942	1680	50	+0.19	+0.18	Granodiorite
SPX	San Pedro Mártir	31.045	115.464	2800	50	- 0.04	+0.22	Granodiorite

* Values reported by Vidal and Munguía (1999)

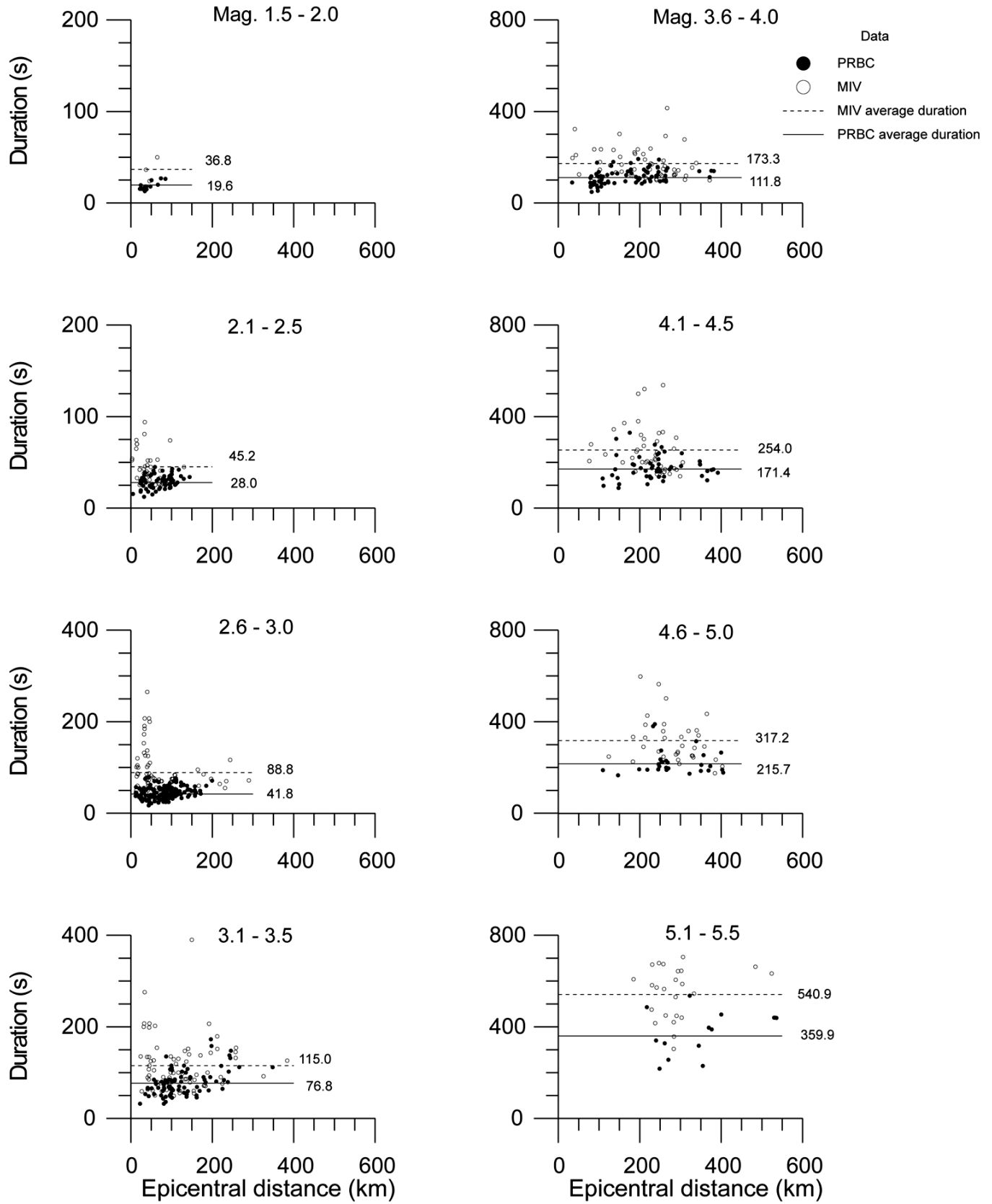


Fig. 3. Duration plotted against epicentral distance. Notice how the duration tends to be longer for epicenter-to-station paths along MIV than along PRBC.

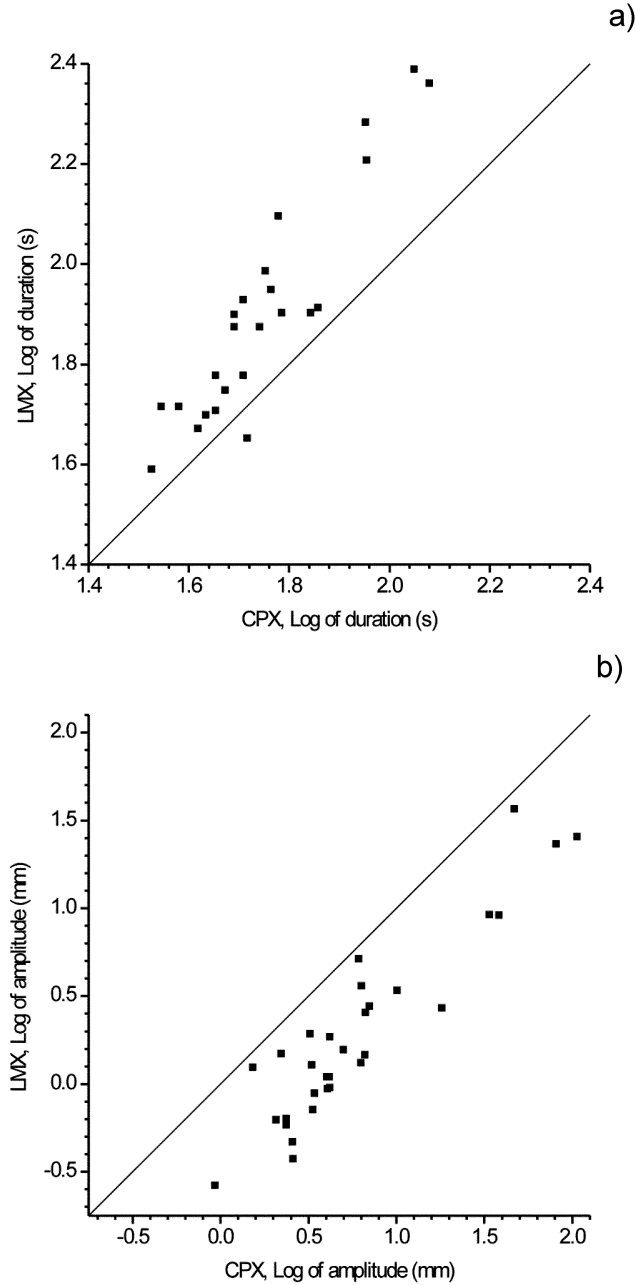


Fig. 4. Comparison of (a) durations and (b) amplitudes measured on seismograms at LMX and CPX stations, for earthquakes ($2.2 \leq M \leq 3.8$) recorded at about the same distances. The amplitude values are the average of the two horizontal zero-to-peak amplitudes measured on synthetic Wood-Anderson seismograms. In both plots, the straight lines represent a slope of 1.

resulting terms to obtain the following expression (see also Michaelson, 1990):

$$\log A_0(\omega) = c_1 + c_2 \log \tau + c_3 \tau, \quad (2)$$

where $c_1 = \log A_\tau(\omega)$, $c_2 = a$, $c_3 = (\omega \log e)/(2Q)$. In equation (2), $A_0(\omega)$ represents the amplitude at the source, so $\log A_0(\omega)$

will be proportional to M . Because $A_\tau(\omega)$ is the cutoff amplitude, it can be considered constant. Then, assuming that $M = \log A_0(\omega) + c$, we can write:

$$M = c_0 + c_2 \log \tau + c_3 \tau, \quad (3)$$

where $c_0 = c_1 - c$. Adding a variable S to include station corrections and using the index notation, equation (3) becomes:

$$M_i = c_0 + c_2 \log \tau_j^i + c_3 \tau_j^i + S_j, \quad (4)$$

In this set of equations, τ_j^i is the lapse-time of the i earthquake recorded at the j station, and S_j is the j station correction accounting for variations of duration due to site effects. The coefficients c_0 , c_2 , c_3 , and S_j were computed from a multiple regression process and calibrated against the local magnitudes (M_L in place of M in equation [3]) reported by Vidal and Munguía (1999). To avoid instability in this process, the sum of corrections for stations on hard rock was forced to be equal to zero. The overdetermined system of equations (3) was solved by a least-squares procedure based on MATLAB software. A relationship obtained from this process represents the coda-duration magnitude that we denote here as M_D .

MAGNITUDE RESULTS

$M_D - \tau$ relationships. We worked with two sets of data, one for MIV and the other for PRBC. Data from earthquakes of one area and recorded in the other one were eliminated from our analysis. As a result of our analysis, we established two relationships:

$$M_D = -(1.56 \pm 0.21) + (2.44 \pm 0.13) \log \tau + (0.0023 \pm 0.0004) \tau + S, \quad \text{for PRBC, and} \quad (5)$$

$$M_D = -(1.27 \pm 0.38) + (2.31 \pm 0.20) \log \tau + (0.0012 \pm 0.0004) \tau + S, \quad \text{for MIV.} \quad (6)$$

In these relationships, it may be seen that C_2 , the geometrical spreading coefficient, has values of 2.44 and 2.31. Although such values are higher than the value $C_2 = 1$ that one would expect for direct body waves, they are in agreement with values reported in studies of coda duration for other regions (e.g., Lee *et al.*, 1972; Bakun, 1984; González and García, 1986; Michaelson, 1990; Eaton, 1992). Although we do not have an explanation for such discrepancy in the geometrical factors, results from array measurements have shown that S-coda waves are not regular plane waves that arrive directly from the epicenter (Aki and Tsujiura, 1959). Moreover, as lapse time increases single or multiple scattered energy would be expected to dominate on the recorded seismogram. Thus, for large lapse times it is reasonable to expect small amounts of direct energy and a smooth spatial distribution of energy density from multiple scattering processes (Sato and

Fehler, 1998). On the other hand, the radiative transfer theory predicts that coda attenuation is dominated by intrinsic absorption. Such theory predicts mean square coda-envelopes decaying according to the -1.5^{th} power of lapse time for uniform distributions of isotropic scatterers and no intrinsic attenuation. Thus, based on theoretical results any coda decay rate larger than $\tau^{-1.5}$ must be due to intrinsic attenuation (see Sato and Fehler, 1998 and references therein). Also, in the single scattering model, it has become usual to fix the geometrical decay parameter to two in order to find the coda attenuation.

Following in this paper is an analysis of results of the regression done on lapse time, and a comparison of predicted M_D against M_L magnitudes for both areas. Figure 5 shows fitted curves to the PRBC (continuous) and MIV (dashed) M_L - τ data, for comparison purposes. The numbers in parenthesis denote the station corrections that are discussed in the next section of this paper. The concavity of the fitted PRBC and MIV curves of Figure 5 is produced by the third term in equations (5) and (6). Sato and Fehler (1998), based on the single scattering model, observed such concavity between magnitude and lapse-time, and Michaelson (1990) found a similar dependence for central California data. For our study region, we note that for magnitudes lower than 3.4 (see arrows in Figure 5) the PRBC and MIV curves are quite similar. Then, at this range of magnitude, any one of these relationships can be used indistinctly to compute the magnitudes for MIV and PRBC earthquakes. For magnitudes larger than 3.4, the concavity of the fit between magnitude and lapse-time becomes greater for PRBC (short durations) than for MIV (long durations).

Next, we compare the coda-duration magnitudes (M_D) estimated from equations (5) and (6) with the local magnitudes (M_L) for PRBC (Figure 6a) and MIV (Figure 6b). This comparison exhibits good fits between the two magnitudes in the range of 1.8 to 5.8. The correlation coefficients of these fits are 0.93 and 0.91 for PRBC and MIV earthquakes, respectively. Plots of magnitude residuals (individual station magnitude M_{Ds} minus the event magnitude M_D) against the logarithm of lapse time for both areas do not exhibit any apparent trend (Figures 6c and 6d). The standard deviation of the residuals, indicated by the dash lines, are 0.13 for PRBC and 0.14 for MIV.

Station magnitude corrections: duration versus amplitude. Figure 7 shows a comparison between the duration station corrections from this study and the amplitude station corrections reported by Vidal and Munguía (1999) (Table 1). The purpose of such comparison is to look for any possible correlation between both types of station corrections. We see that data points from PRBC stations (except for SPX) fall near the line that represents equality between both corrections. The negative corrections found for CBX (sited at 1250 m high)

account for the somewhat high amplitudes and long durations that characterize the seismograms of this station. For the PRBC area, we notice that amplitude and duration station corrections are correlated. On the other hand, for EMX and CHX (south of MIV and on hard rock) the amplitude station corrections are positive (low amplitudes); however the duration station corrections are slightly negative (long durations). For the case of stations LMX (on a promontory of sand) and CPX (close to the crater of the Cerro Prieto volcano), it is hard to establish a correspondence between their corrections. Both stations have negative corrections. The duration station correction at LMX is more negative than it is its amplitude correction. The opposite case occurs for CPX, in which case the amplitude correction is more negative than the duration station correction. Thus, at least for these two stations, large amplitudes on seismograms do not necessarily correspond to long coda durations. The difference in the responses of these sites clearly evidences a strong influence of the topographic and geological characteristics at the site on seismic signals.

Application examples. As it was mentioned at the beginning of this paper, the M_D - τ relationships are useful in computing magnitudes from clipped seismograms of earthquakes recorded at near stations. Figure 8 depicts clipped seismograms of a PRBC earthquake recorded at PRBC stations. This is just an example to illustrate the advantage of using lapse-times in estimating the magnitude of earthquakes in north Baja California. The average magnitude obtained with the correspondent M_D - τ relationship is 4.7, which compares quite well with a value of 4.8 calculated with data from southern California stations (CIT/USGS).

As another validation test, the coda-duration magnitudes for a group of earthquakes that occurred in the PRBC area during 2003 were calculated. For this, the signal durations of the events were taken from monthly RESNOM bulletins, and thus they were measured in an independent way by technicians. It should be noted that these durations were not included in our regression analysis. We should also mention that most of the 2003 earthquakes did not produce saturated records. A comparison of our results and the M_L magnitudes of the earthquakes are shown in the Figure 9. In view of the reasonable agreement between both magnitudes, the proposed M_D - τ relationships will be used in routine procedures of the RESNOM system.

CONCLUSIONS

Two relationships were established to compute coda-duration magnitude (in the 1.8-to-5.8 range of magnitude) for earthquakes in northern Baja California. In these relationships, differences in the regional geology, effects due to source-to-station distance, and the geology characteristics at the recording site are taken into account. Low amplitudes and short coda-durations characterize the seismograms of earthquakes oc-

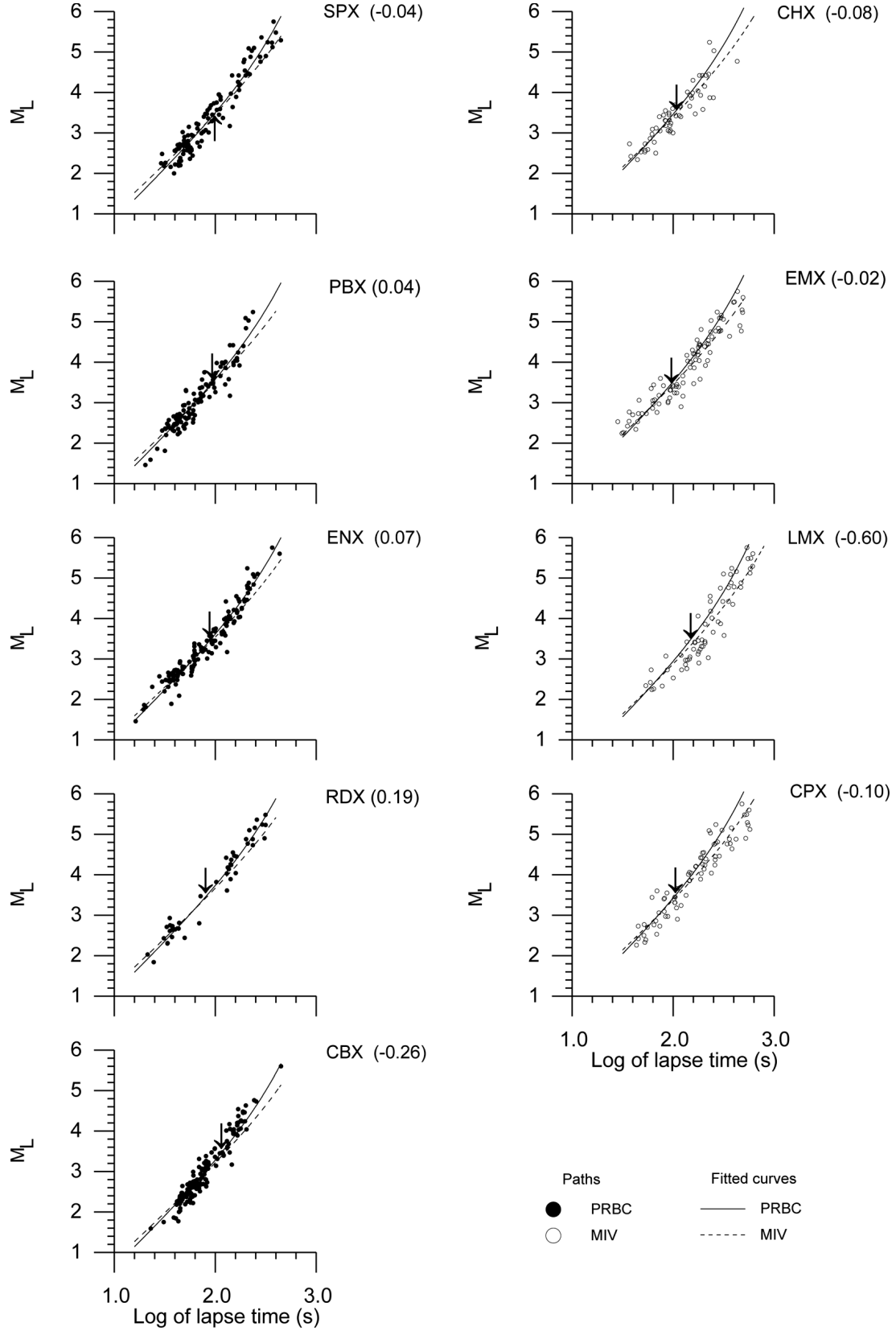


Fig. 5. Local magnitude (from Vidal and Munguía, 1999) plotted against the logarithm of lapse-time for PRBC and MIV epicenter-to-station paths. Continuous and dashed lines represent the best results obtained from the regression analysis. These curves are shown in all plots to highlight differences in the fit for both areas. The numbers in parenthesis denote station corrections.

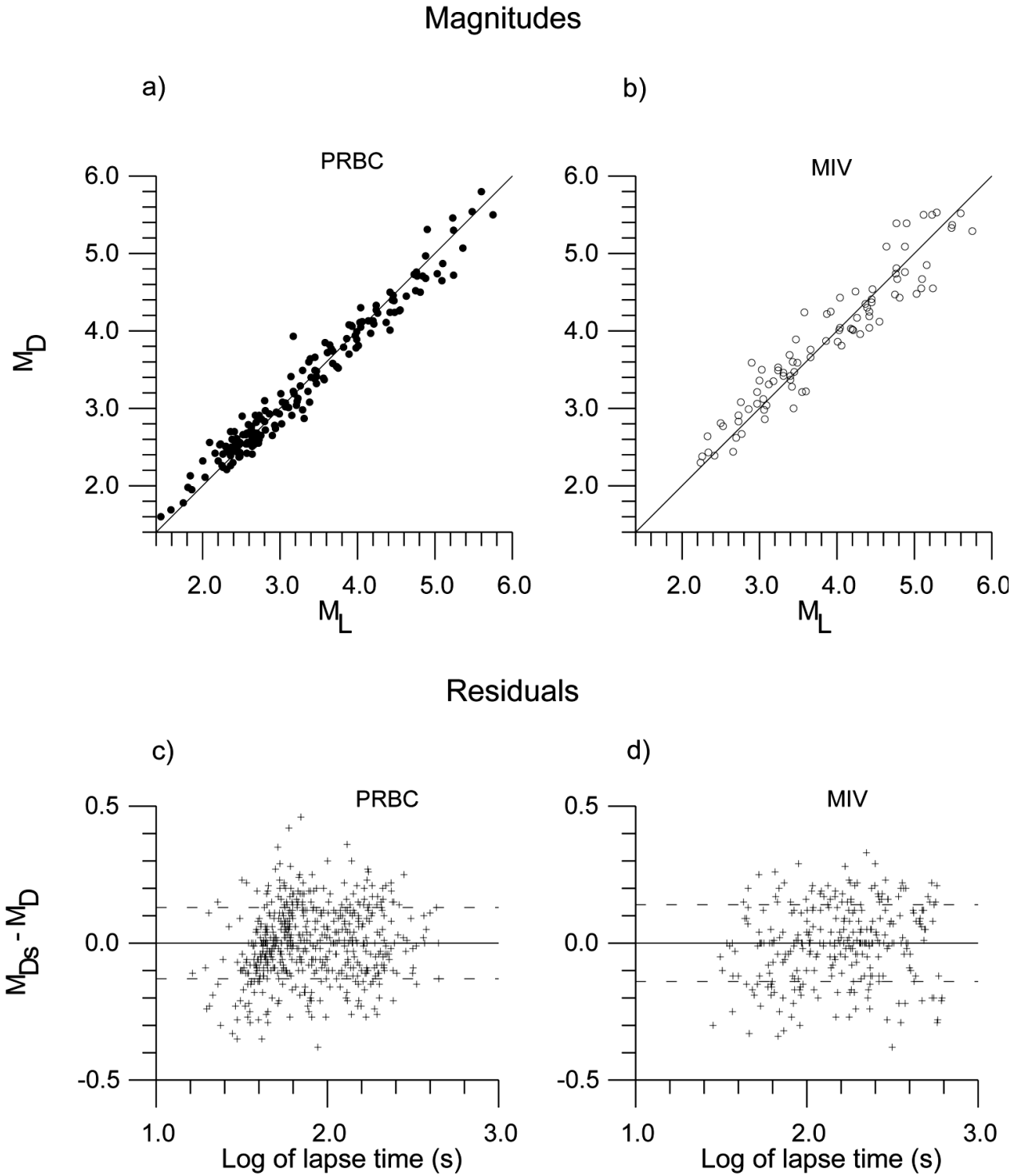


Fig. 6. Plots that show coda-duration magnitude (M_D) compared with local magnitude (M_L) of the earthquakes studied. The straight lines represent slopes of 1. The figure also shows plots of magnitude residuals versus logarithm of lapse time. The residuals are the difference between the magnitude computed from a single station (M_{Ds}) and the event magnitude (M_D), which is the average of the individual station magnitudes. The dashed lines represent standard deviations.

curred and recorded on the granitic PRBC area. For the sedimentary environment of MIV, the coda-durations on seismograms are longer than on seismograms of PRBC stations. For

the MIV area, there is no simple correlation between amplitude and duration. Two opposite cases are evident here. One consists of high amplitudes and slightly long coda-durations

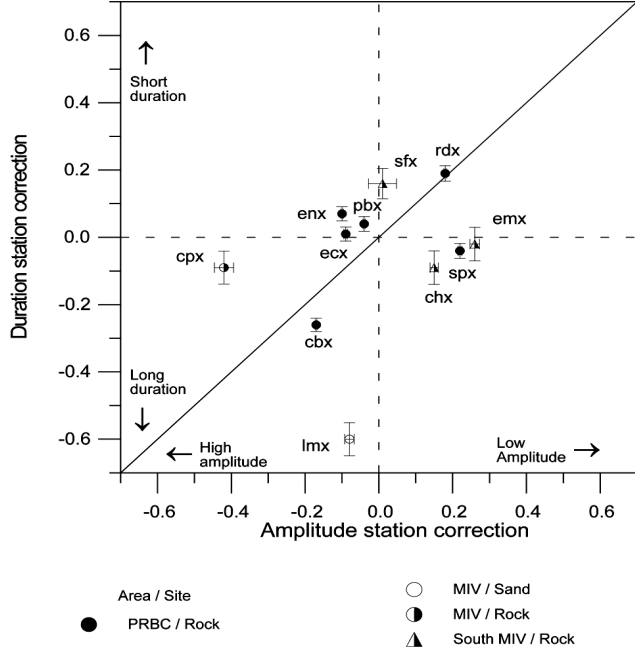


Fig. 7. Plot of amplitude and duration corrections for the RESNOM stations. Notice the contrasting differences in the correction values for LMX and CPX stations both on MIV. See text for explanation.

exhibited by the Cerro Prieto volcano seismograms. The other one refers to low amplitudes and long coda-durations observed on seismograms from La Mesa de Andrade station, which is located on sand. The different ground responses of these two sites clearly evidence a strong influence of the site characteristics on the seismic signals.

The coda-duration magnitude scale of this study supplements the local magnitude scale proposed previously for the region. Both scales produce homogeneous values of magnitude for earthquakes in north Baja California.

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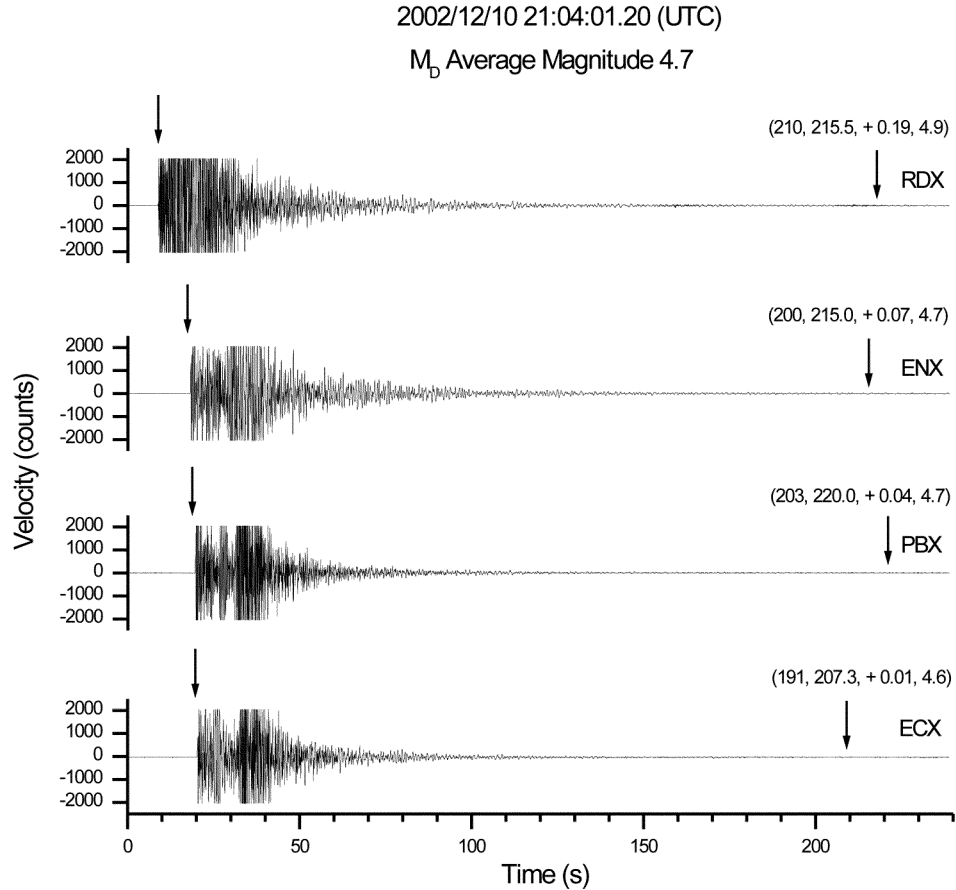


Fig. 8. Vertical-short-period seismograms of a PRBC earthquake (lat. 32.256, long. -115.780) recorded at PRBC stations. Numbers between parentheses are: signal duration (time between the arrows), lapse time, station correction and calculated duration magnitude.

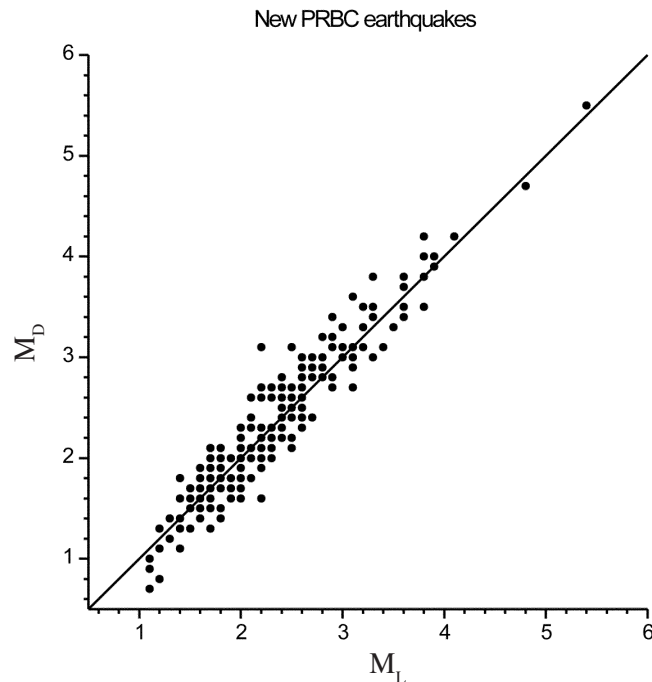


Fig. 9. Plot that shows coda-duration magnitude (M_D) compared with local magnitude (M_L) of PRBC earthquakes recorded during 2003. The straight line represents a slope of 1.

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