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Magnitudes for local earthquakes calculated with the El Salvador seismic network

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RESUMEN

La red sismográfica de El Salvador está compuesta principalmente por 19 estaciones telemétricas de período corto instaladas entre 1983 y 1992. La red tiene una central digitalizadora instalada en 1992 de tal manera que a partir de este año, todos los datos son digitalmente procesados. Los nuevos datos digitales de El Salvador y de otros países de América Central han sido utilizados para probar y calibrar diferentes escalas de magnitud basadas en coda y amplitud. Debido a la pequeña dimensión de la red de El Salvador, ninguna función de atenuación significantemente diferente de la relación original de Richter (1935) pudo ser determinada. La escala de magnitud de ondas de coda calibrada con Ml es la siguiente:

$$Mc = 2.5*\log(coda) + 0.0016*dist - 1.7$$

donde *coda* es la longitud de la coda en segundos y *dist* es la distancia hipocentral en km. Para esta escala, algunos datos de otros países de América Central han sido utilizados con el objeto de conseguir un mejor rango de distancia y magnitud de lo que se puede obtener utilizando únicamente los datos de El Salvador. Magnitudes de momento sísmico Mw fueron calculadas basándose en el espectro de la onda P, y comparadas con Ml y con Mb de PDE. El promedio de Ml, Mw y de Mb fue de 4.9, 5.2 y 5.0 con datos en el rango de magnitudes 3.4-6.4, 4.1-6.2 y 3.6-6.0 respectivamente. La diferencia sistemática entre Ml y Mw calculada con el mismo conjunto de datos posiblemente indica que las funciones de atenuación utilizadas son inadecuadas, que hay problemas instrumentales o que hay alguna diferencia sistemática en la manera en que Ml y Mw son determinadas. A pesar de las incertidumbres, la buena consistencia de las magnitudes obtenidas con relación a las obtenidas externamente significa que podemos determinar magnitudes en el rango de 4 a 6 utilizando la red digital de El Salvador, ya sea a base de duración de la coda y/o amplitudes de ondas P o S.

PALABRAS CLAVE: América Central, magnitud, El Salvador.

ABSTRACT

The seismic network in El Salvador consists of mainly 19 telemetered short-period stations installed between 1983 and 1992. The network has a central digitizing unit installed in 1992; all data is digitally processed. The new digital data from El Salvador and other Central American countries has been used to test and calibrate different magnitude scales based on coda duration and amplitude. Due to the small dimension of the network in El Salvador, no attenuation function significantly different from the original Richter relation could be determined. The coda wave magnitude scale calibrated with Ml is:

$$Mc = 2.5 * \log(coda) + 0.0016 * dist - 1.7$$

where *coda* is the coda duration in secs and *dist* is the hypocentral distance in km. Some data from other Central American countries have been used in order to get a better distance and magnitude range than provided by the El Salvador data. Using the same data set, moment magnitudes Mw were calculated based on P-wave spectra and compared to Ml and Mb from PDE. Average Ml, Mw and Mb were 4.9, 5.2 and 5.0 with data in the magnitude ranges 3.4-6.4, 4.1-6.2 and 3.6-6.0 respectively. The systematic difference between Ml and Mw for the same data set might indicate that the attenuation functions used are inadequate, that there are instrumental problems or that there is some systematic difference in the way Ml and Mw are determined. Despite the uncertainties, internally consistent magnitudes in reasonable agreement with externally determined magnitudes in the range 4 to 6 can now be determined using the El Salvador digital network based on both coda duration and P or S-wave amplitudes.

KEY WORDS: Central America, magnitude, El Salvador.

INTRODUCTION

The seismicity in El Salvador, as in the other Central American countries, is mainly caused by the Cocos plate subducting under the North American plate (e.g. Isacks and Molnar, 1971), which generates earthquakes up to magnitude 8.0. However, more destructive are the shallow inland events from the volcanic zone. Here the magnitudes do not exceed 6.0, but the associated seismic hazard is higher in the densely populated centers along the volcanic zone.

Seismic stations have been in operation in El Salvador since 1896, and the telemetered network since 1984. In 1992, the central recording became digital. The network is geographically centered around the capital of San Salvador, partly to monitor the nearby volcanoes and partly because of logistical problems caused by the civil war.

In 1988, a cooperative project in disaster prevention between all Central American countries was begun and coordinated through CEPREDENAC (Centro de Prevención de Desastres Naturales en América Central) in Guatemala. The most important component in the program was seismology. In 1992 the cooperation was increased to include processing of the data. Digital data is now available for all Central American countries, collected in a uniform format in Guatemala (Vega *et al.*, 1994), and calibration curves are available for most stations (Escobar, 1993).

With the availability of digital data, it becomes possible to start improving the magnitude scales for El Salvador. The purpose of this paper is to present some preliminary results for these studies.

THE SEISMIC NETWORK IN EL SALVADOR

In 1983, the first part of the telemetered seismic network (10 stations) was installed in El Salvador. Following the large San Salvador earthquake of 1986 (Harlow *et al.*, 1993), the telemetered network was expanded to 20 stations under the global program of reconstruction. The additional stations are situated near San Salvador and have the purpose of monitoring both the seismic and volcanic activity. At the present, the network has 24 stations of which 19 are telemetered to San Salvador. One station is located at the central recording site and 4 are autonomous analog stations (Figure 1 and Table 1). In addition, 55 analog accelerographs are in operation (Ciudad Real *et al.*, 1992).

The data is transmitted from the field stations using conventional FM radio equipment. At the central recording site at Centro de Investigaciones Geotécnicas (CIG), San Salvador, the signals are demodulated and recorded on a Kinemetrics DATASEIS digital data acquisition system. All channels are also recorded on paper. The timing is by GOES satellite clocks. An FBA23 accelerometer is installed at the central recording site thus providing unclipped signal for all larger events on the DATASEIS system. From this system, the data is transferred to a local personal computer using a removable disk, and from the PC to a SUN computer via ethernet for further processing.

DATA PROCESSING

All events on the DATASEIS system are manually transferred to the SUN once per day. Here all detections are manually checked and real events are system transferred to the data base for further processing, while non-seismic events are deleted. The data is processed (phase picking, location, hard copy, etc.) using the SEISAN analysis software (Havskov and Utheim, 1992, Havskov and Lindholm, 1992). The hypocentral location program used is the modified HYPOCENTER program (Lienert, 1988, 1991), which uses the crustal phases Pg, Pn, Sg, Sn, Lg in addition to P and S, as well as azimuth information obtained from the 3 component stations.

All data from the network (waveforms and readings) are sent to the Central American Seismic Database (at INSIVUMEH) in Guatemala, where all Central American data are processed together, The complete data set is returned to each Central American country after processing has been completed.

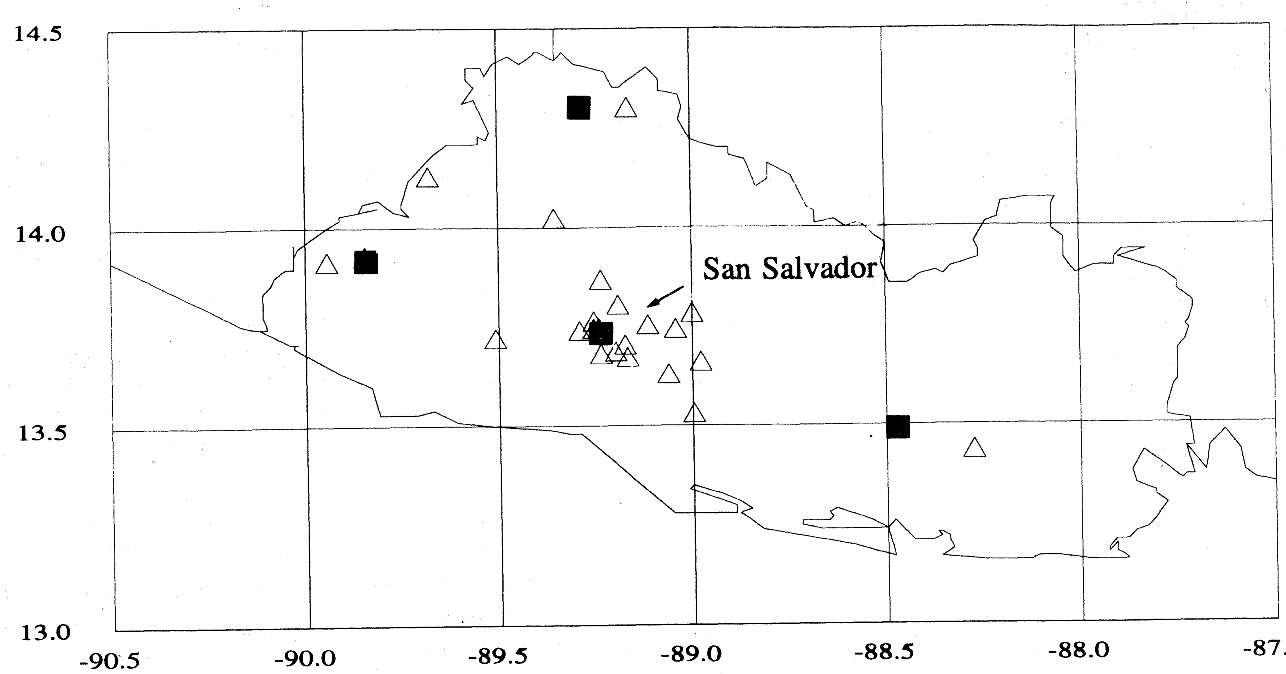

Fig. 1. Seismic stations in El Salvador. The telemetered stations are marked with a triangle and the autonomous stations with a square. Note the concentration of stations around San Salvador where also the SSS station is located.

Table 1

Current (July 1, 1994) seismic stations in El Salvador. All telemetered stations have single component vertical short period seismometers. CIG, the central station has a 3 component accelerometer and a short period vertical seismometer. The 4 autonomous stations marked with a * at the bottom of the table are recording in analog form. Station SSS is a WWSSN station, SMS is using a Wiechert 3 component seismograph, AHS and LPS are horizontal component mechanically registering seismographs made in El Salvador. Latitude N and longitude E is given in degrees and minutes. Stat Corr means station correction when determining Ml. Stations which do not have a station correction noted, were not used for Ml or Mw determination.

Name	Code	Latitude	Longitude	Height(m)	Stat Corr
Cusmapa	CUS	13 54.55	89 56.65	677	-0.1
Yupe	YPE	14 07.30	89 40.83	1581	0.3
La Fuente	LFU	13 44.92	89 06.83	732	0.3
Quezalapa	QZA	13 31.43	88 59.82	250	
San Jacinto	SJA	13 40.00	89 10.00	1100	
Tecomasuche	TME	14 01.02	89 21.33	516	
Volcán San Salvador	VSS	13 44.50	89 14.50	1250	
Volcán San Miguel	VSM	13 25.68	88 16.45	2129	
Centro de Investigaciones Geotécnicas, San Salvador	CIG	13 41.88	89 10.40	616	
San Jacinto	SJA1	13 40.00	89 10.00	1100	-0.3
Sta. Adelaida	ADE5	13 40.50	89 14.20	1200	
Las Granadillas	GRD5	13 45.50	89 15.30	1520	-0.1
El Boquerón	BOQ6	13 44.10	89 17.50	1830	-0.2
El Picacho	PIC4	13 44.36	89 15.30	1960	-0.3
Ojo d'Agua	OJO4	13 51.80	89 14.20	645	0.4
El Faro	LFR1	13 37.40	89 03.70	1000	0.0
Las Brisas	LBR3	13 44.30	89 02.60	770	-0.3
Huehuecho	HUE2	13 46.70	89 00.00	910	0.3
Nejapa Angel	ANG3	13 48.00	89 11.50	850	0.0
La Ceiba	LCB2	13 39.30	88 58.70	710	-0.1
*San Salvador	SSS	13 40.87	89 11.88	665	
*La Palma	LPS	14 17.53	89 09.72	1000	
*Ahuachapán	AHS	13 55.30	89 50.75	810	
*Santiago de María	SMS	13 29.17	88 28.23	950	

Seismic stations in Central America are almost exclusively of the short period 1 Hz type. Filters and gains are very similar. The station response is flat in velocity from 1 Hz to 10 Hz (Escobar *et al.*, 1993). There are 3 three-component LP stations participating in the data exchange (Guatemala, Nicaragua and Panama), however, coda durations are not routinely read on these stations. From an instrumental point of view, coda durations should be similar on all instruments.

MAGNITUDE

Generally coda wave magnitudes are used in Central America. Until recently, the Lee *et al* (1972) scale has been widely used:

$$Mc = 2.0*\log(coda) + 0.0035*dist - 0.87 \qquad (1)$$

A preliminary Central American coda-wave magnitude scale has been developed by calibrating the coda durations with PDE-Mb magnitudes (Marroquin and Ariola, 1992, Vega *et al*, 1994):

$$Mc = 2.4*\log(coda) + 0.00046*dist - 0.72 \qquad (2)$$

Richter local magnitudes Ml can also be calculated using a synthetic Wood-Anderson trace produced with the SEISAN system. Because of delays in obtaining the final calibration values for all stations this is not yet routinely done, and a proper attenuation relation had not been estimated. However, the modified Richter attenuation relation given by Hutton and Boore (1987) for California seems to give reasonable values (Vega *et al.*, 1994). The only difference for Central America is that hypocentral distances are used instead of epicentral distances in order to get magnitudes for deep events.

One of the problems with this coda magnitude scale is that only large events were available for calibration and no Ml magnitudes were used. It has become apparent that the scale overestimates the magnitudes of smaller events.

The data for this study were selected from 99 well-recorded events in El Salvador mainly in 1993. The events have been selected on the basis of being recorded on as many stations as possible with unclipped records. This severely limits the amount of data. Most of the earthquakes recorded over the whole network originated in the coastal subduction zone and had similar distances to all stations. The network saturates at magnitudes around 4, and the signal-to-noise ratio at magnitude around 2.5 become too low. The data set used is shown in Figure 2. For all events, peak amplitudes were read on simulated Wood-Anderson traces for as many stations as possible (at least 3). The internal consistency of the magnitudes calculated with each station was used to reject stations with obviously incorrect calibration. In addition, some stations were out of operation. Of the 21 stations, only 13 were used for amplitude measurements (Table 1).

The selected events are mostly in the distance ranges from 50 to 200km and magnitudes Ml in the range 2.4 to 4.2. The data set consists of mostly shallow events: 88 % have depths less than 400 km and only 4 events are deeper than 70 km. Considering the depth distribution and the small epicentral area covered, no attempt was made to subdivide the data set according to depth or epicenter.

First an attempt was made to improve on the Hutton and Boore attenuation relation. Assuming that the attenuation can be written in the form

$$- \log(A) = a*\mathrm{Log}(R) + b*R \qquad (3)$$

where A is peak amplitude, R is hypocentral distance in km and a and b are constants describing geometrical spreading and anelastic attenuation, the whole data base can be inverted to calculate the constants a and b following the procedure used by Alsaker *et al.* (1991).

This resulted in the values a=0.4 and b=0.005 which are physically unrealistic. This is attributed to the small range of distances available for each event due to the small size of the network. Fixing the geometrical spreading term to Hutton and Boore's value of 1.11 yields an attenuation term of 0.0025±0.0008 against the original Hutton and Boore term of 0.0019. It is not surprising that the small El Salvador seismic network does not enable us to improve on the standard attenuation relation. However, considering the small distances and assuming that the local magnitude relation is tied to the Richter relation at 100 km epicentral distance, it will not make much difference whether we use a local attenuation relationship or the original Richter attenuation curve. Considering the comparison of Ml with Mb by Vega *et al* (1994), and the Ml values from this study (see below), it seems that the Hutton and Boore attenuation relation will give reasonable Ml estimates for El Salvador. It will therefore be used in the following. Table 1 shows the station corrections for El Salvador stations calculated from the 99 test data and the Hutton and Boore attenuation relation.

Ml was now calculated for the 99 events. The average Ml values were 1.1 units lower than the average Mc values calculated from (2). Assuming the Ml values to be correct, a new Mc relation was developed. Using the whole data set, a least-squares inversion was done, assuming the form

$$Ml = a*\log(coda) + b*dist + c \qquad (4)$$

which results in the following relation

$$Ml = 1.1*\log(coda) + 0.004*dist + 0.4 \qquad (5)$$

Relation (5) seems unreasonable compared to most coda-magnitude scales. It appears that the distance resolution was not adequate with El Salvador network alone. Additionally, the upper part of the magnitude scale was poorly defined as there were no large-magnitude events in the data set. More data from Central America were therefore included. The data set collected by Vega (1993) with all Mb > 5 events for 1992 was used, plus a set of events from 1993 and 94 (Villagrán, 1994). Using these three data sets, the following magnitude scale was obtained:

$$Mc = 2.5*\log(coda) + 0.0016*dist - 1.8 \qquad (6)$$

The distance correction term (0.0016) is smaller than the term in the Lee scale (1) but larger than in the scale (2) by Marroquin and Arriola (1992). Marroquin and Arriola did not determine the distance term but used the same value as in Mexico (Havskov and Macías, 1983), which had been based on a comparison with Mb. The distance term obtained here falls between the value obtained from smaller distances (W. Lee) and larger distances (Havskov and Macías). This seems reasonable considering that our data set consists of a mixture of local and regional data.

Figure 3 shows the data for Ml against log(coda) + (0.0016/2.5) * dist. The El Salvador data gives higher log(coda) or lower Ml values than the other data. A reexamination of some of the original records revealed significant difference in the practice of reading coda durations. The records from El Salvador yielded longer coda durations than similar data from other countries. This does not imply that coda duration measurements are wrong for El Salvador, but rather that the local routine is different though consistent. This is an inherent problem in using coda duration for magnitudes. In El Salvador the end of the coda is read where the signal could not be distinguished any longer, while in the other countries the end of the coda is read when the amplitude is still above noise level. As no clear and consistent procedures exist, it seems that the only solution is to automate coda length determinations.

The new scale includes data from other countries, but it will mostly reflect data from El Salvador at the lower end of the magnitude scale since these data are dominant. Thus the new coda magnitude scale should give much more accurate Mc values for the El Salvador network than the earlier scale, while continuity with the old scale with respect to

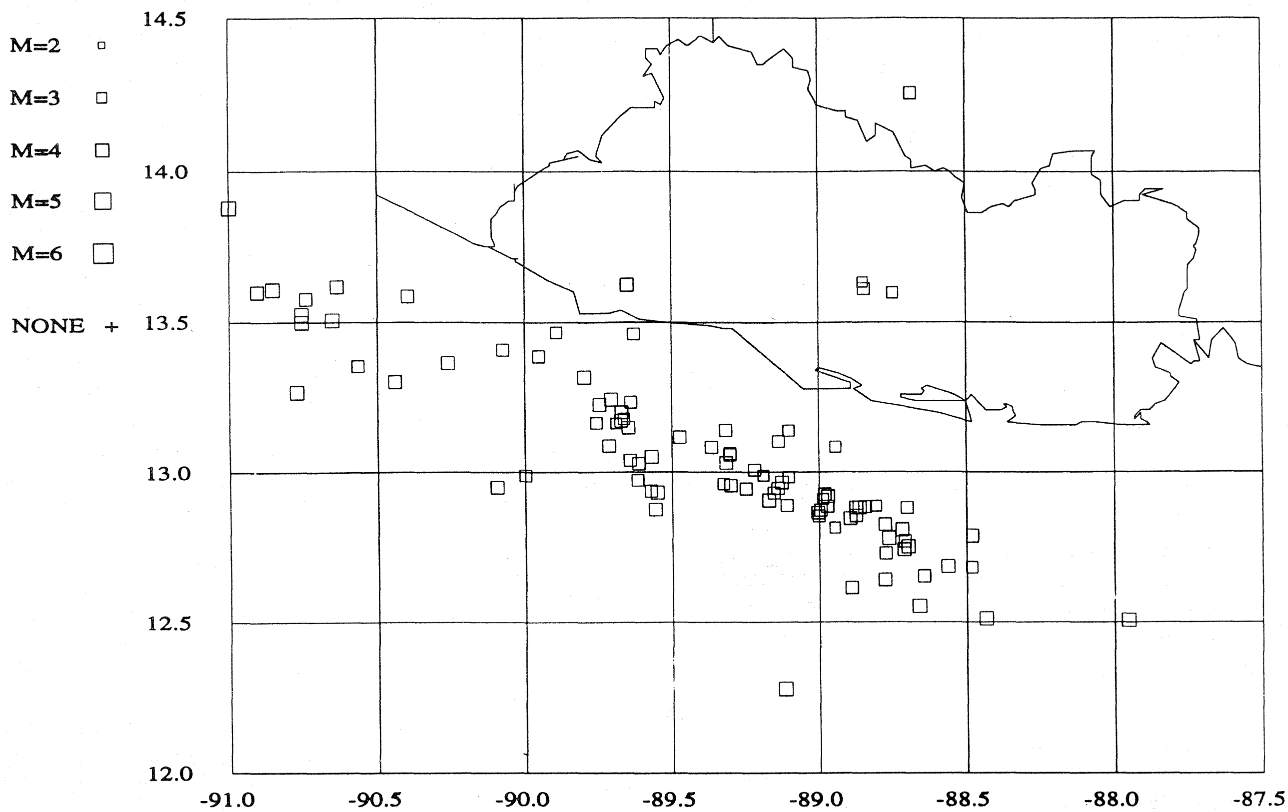

Fig. 2. Epicenter of events from the El Salvador network used in this study. Magnitudes are proportional to symbol size.

large events is preserved. A typical event of 100 s. coda duration and a distance of 100 will yield a magnitude of 3.4 with the new scale while the old scale yielded 4.2, and the familiar scale by Lee *et al.* (1972) yields 3.5.

Moment magnitudes were calculated by using the P-wave spectra as in the SEISAN system (Havskov and Lindholm, 1994). The spectra were corrected for spherical spreading and attenuation using Q= 70*f**0.98 (Martínez, 1994). The P-wave velocity was assumed to be 6.0 km/sec and the density 3.0 g/cm**3. Moment magnitude was calculated using Mw = 2/3 * moment - 10.7 (Hanks and Kanamori, 1979), with the moment in dynes-cm. When P-wave amplitudes can be used for magnitude determination, amplitude-dependent magnitudes can be determined for events where the S-waves but not the P-waves are clipped. The relation between Ml and Mw for the data is seen in Figure 4. There is a good linear relationship between the two data sets: Mw = 0.97 Ml + 0.38. On average, Mw is higher by 0.3 than Ml. These observations are valid for all three data sets shown in Figure 4. A linear relationship is not surprising, considering that both Ml and Mw are measured from the same records. Thus calibration or scaling problems would equally affect both magnitudes. On the other hand, Ml is measured from S-waves and Mw from P-waves so some differences would be expected. On Figure 4, Mb (reported by PDE) is plotted versus Ml for events having both values; it appears that the Mb values are in quite good agreement with the Mw and Ml magnitudes, indicating that the absolute values of Ml and Mw are in reasonable agreement with independently determined Mb magnitudes. The average Ml, Mb and Mw values were 4.9, 5.0 and 5.2 respectively. As observed in Vega *et al.* (1993), Mb is very close to Ml as also here. The close correspondence of Mb, Ml and Mw suggests that the seismic stations used in this study are reasonably well calibrated.

DISCUSSION

Obviously these magnitude scales can only be considered preliminary; however, the Mc scale obtained in this study should be more accurate than (2). We have shown that amplitudes can be used for magnitude determination, and that coda wave magnitudes, although simple to use and calibrate, will depend on the users and to some extent on instrumental characteristics and local noise levels. Considering the uniformity of instrumentation in Central America the differences observed must be due to different reading practices, some operators reading the point where the signal disappears in the noise while others consider when the signal is twice the background noise. A possible way to overcome this problem is by automating the coda duration measurements, which has the potential of producing very stable coda-magnitude estimates. Coda durations for El

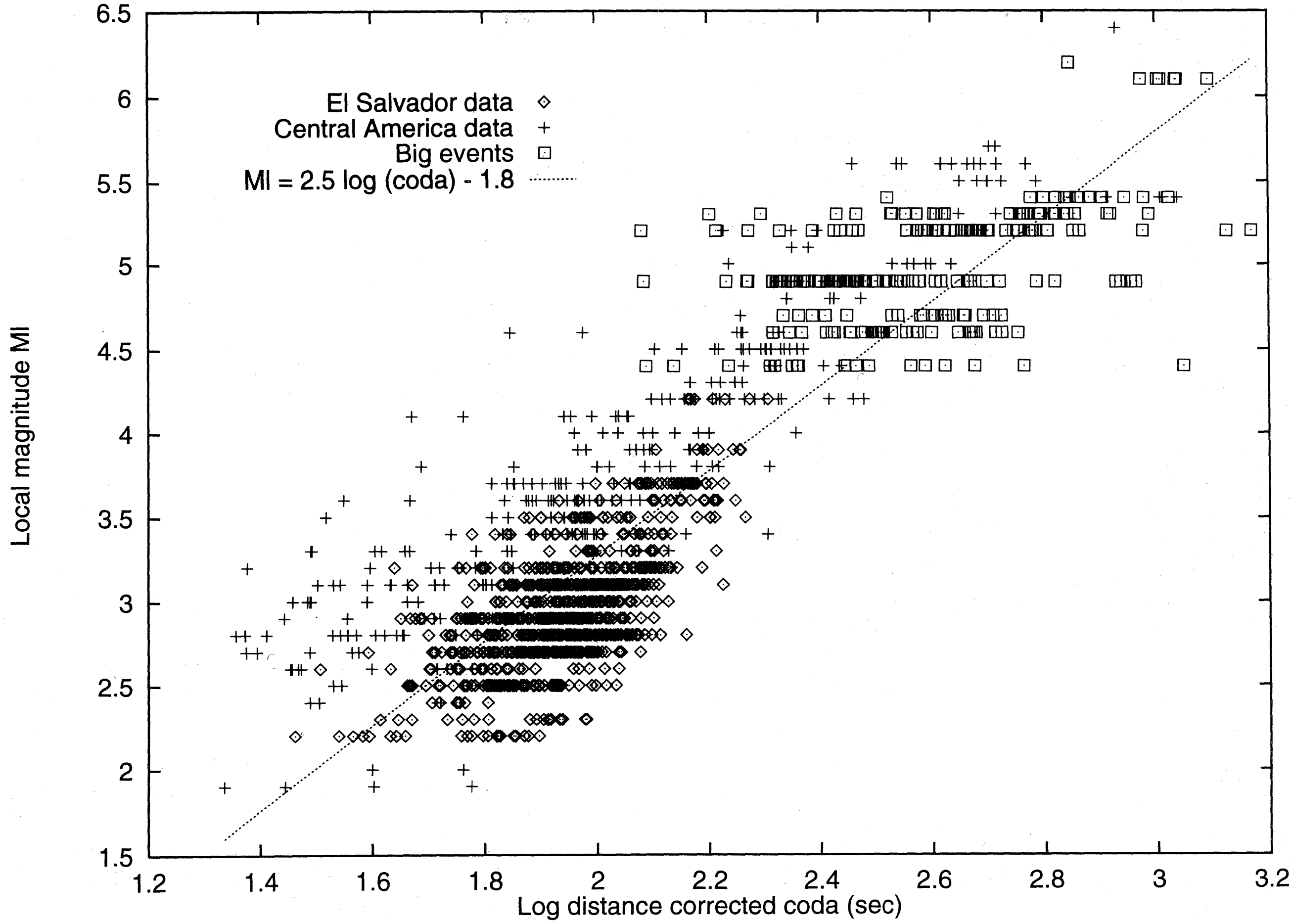

Fig. 3. Local magnitude Ml as a function of log(coda) + 0.00062 * distance. Each point represent one station reading. The different data sets used are indicated with different symbols. El Salvador data means the data seen on Figure 2, Central America data is from Villagrán (1994) and Big events from Vega (1993). The El Salvador data is concentrated in the range log(coda) 1.7 to 2.2.

Salvador seem very consistent. Clearly, amplitudes will give more consistent magnitudes when using data from different networks. However, the instruments must be well calibrated and attenuation relationships known. The Ml and Mw relations have not been adjusted for the region except for the anelastic attenuation part in the Mw determination. On the other hand, distances are quite short in El Salvador so for local events (less than 200km), the lack of an accurately known local attenuation function may not affect the magnitudes very much. Mw and Ml give different values for the same event with Mw giving on average 0.3 units higher than Ml and 0.2 units higher then Mb. Ml and Mw are supposed to be very similar in the magnitude range Ml = 3 - 7 (Hanks and Kanamori, 1979). The observed differences between Ml and Mw might be due to errors in the procedures in determining Ml and Mw or to incorrect attenuation functions; however, since both are close to Mb it is difficult to say which is more correct. More work on a regional scale must be done with all of these problems.

Using the above methods of magnitude determination, it is now possible to determine magnitude from amplitude (P or S), or coda duration consistent with each other within ± 0.2 units of magnitude for earthquakes in El Salvador and perhaps also in other countries in Central America.

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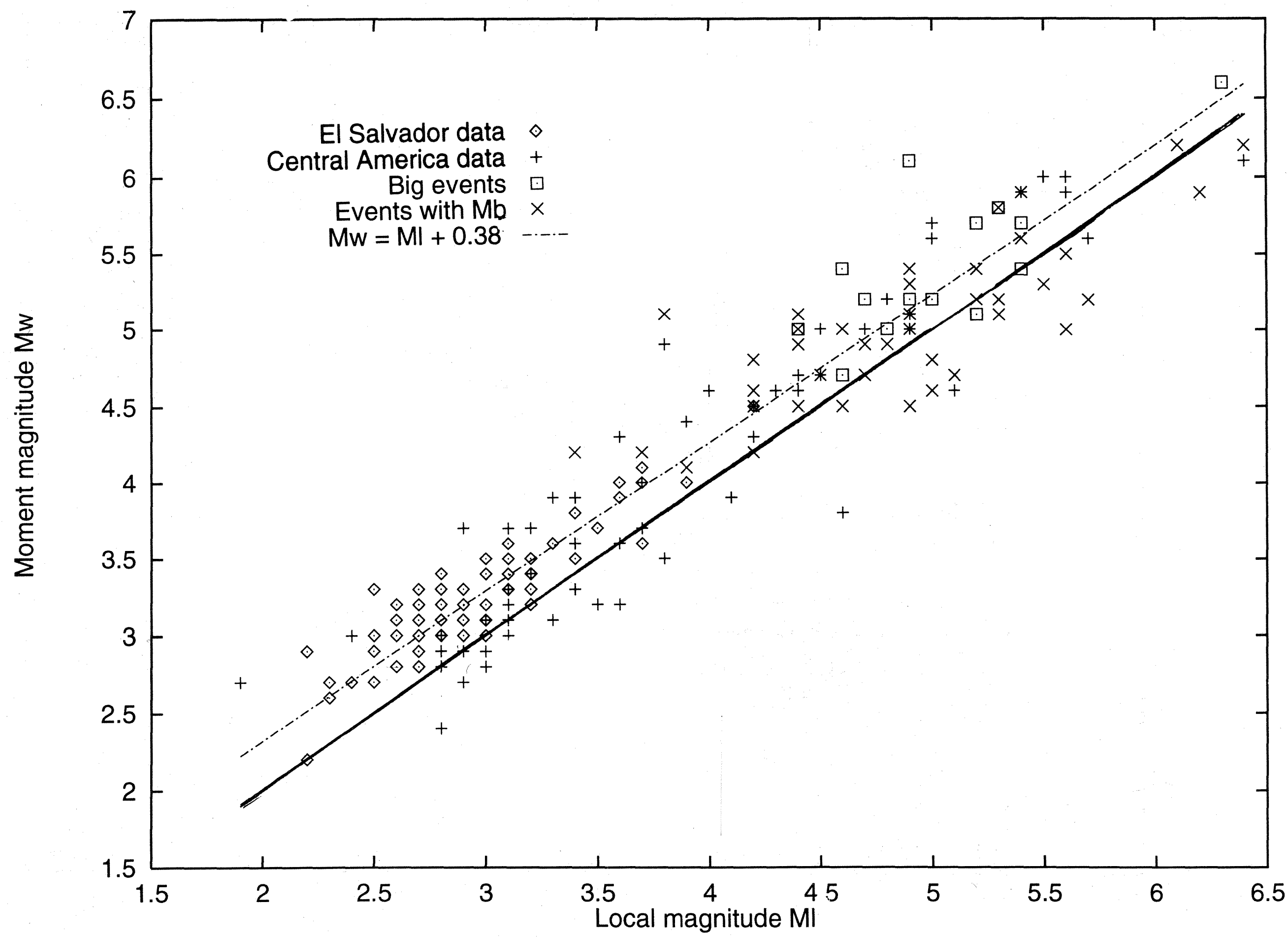

Fig. 4. Moment magnitude Mw as a function of Ml. Contributions from the different data sets are indicated as in Figure 3. In addition, events with both Ml and Mb from PDE are plotted as with Mb as a function of Ml. The figure shows the least squares relation between Mw and Ml and the line Ml=Mw (solid line).

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