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Spatial Variations of Local Magnitude in Earthquakes Recorded in Northeastern Spain

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Abstract — Since 1984, a seismic surveillance of the Baix Ebre Region (NE of the Iberian Peninsula) and the La Cerdanya Valley (Eastern Pyrenees) has been performed by the Institut d'Estudis Catalans and the Universitat de Barcelona, by means of four digital stations. An investigation of the apparent magnitude has been carried out to explain the observed anomalous differences between the amplitude of the recorded events and their associated magnitude, as given by the different agencies. Calculating the local magnitude with independent attenuation parameters and comparing the obtained results using the different stations, we obtain differences up to 1.0. These differences are interpreted in terms of very local effects and point out the uselessness of some stations to assign magnitudes of local events. Results emphasize that the effectiveness of the trigger algorithms in digital stations rarely depends on the apparent (local) magnitude. As expected, the magnitude sensitivity is related to the values of the station correction terms, meaning that extra information is required for an optimum surveillance of a local area. A 2-D analysis of the distribution of the differences between the computed and reported magnitude shows no significant azimuthal dependence. This indicates that the obtention of a local magnitude scale with an appropriate station correction term related to epicentral distance, results in an important factor to provide magnitude to local events. The obtained results corroborate previous works done at the same area and emphasis is placed on further analysis directed to obtain a better characterization of the local site influence.

Key words: Seismicity, local magnitude, site effects, lateval variations

1. Introduction

Since the 1980's the *Institut d'Estudis Catalans* (IEC) and the *Universitat de Barcelona* (UB) operate a set of seismic stations in Catalonia, Northeastern Iberian Peninsula (Vila, 2002). During the last 20 years, several updates have been conducted to provide the stations with the maximum capabilities regarding quality

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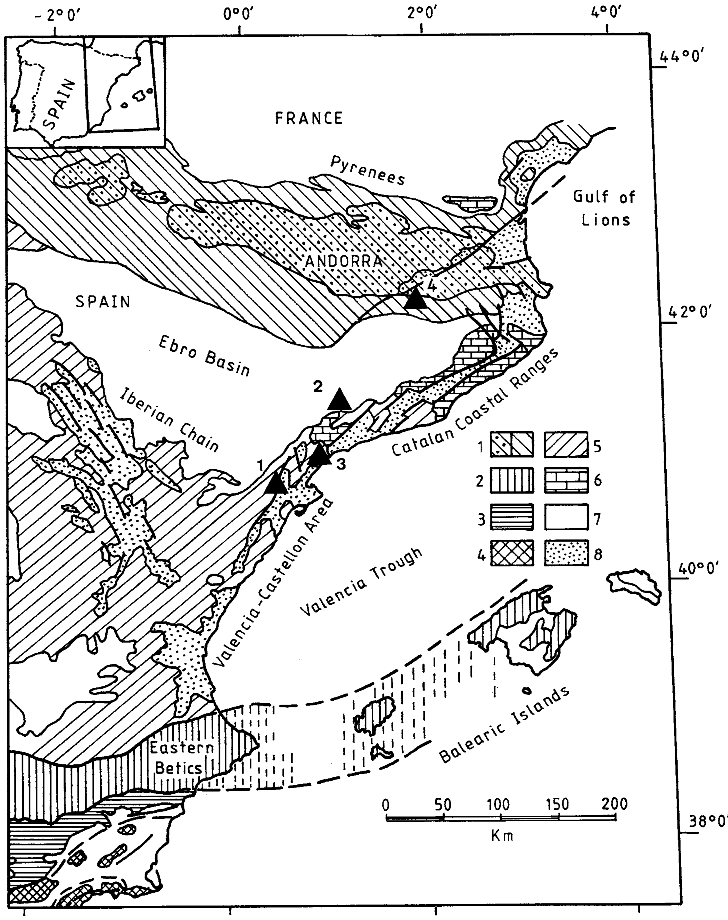

Figure 1

Overall view of the main geological units of the northeastern part of Spain (adapted from VILA *et al.*, 1996). 1 = Pyrenees; 2 = Prebetic zone; 3 = Sub-betic zone; 4 = Betic zone; 5 = Mesozoic Iberian Chain; 6 = Paleozoic coastal ranges; 7 = Tertiary basins; 8 = Neogene basins. Triangles show the seismic stations EBR[1], POBL[2], VAN2[3] and CADI[4].

and state-of-health control. The work of the IEC and the UB group has been focused on two areas: the *Baix Ebre* region in Southern Catalonia (stations 1, 2 and 3 in Fig. 1) and the Pyrenees (station 4 in Fig. 1).

The monitoring of the *Baix Ebre* region (Southern Ebro Basin), is mainly directed to surveillance by means of stations POBL (3) and VAN2 (2) (operating since 1984 as permanent stations), whereas EBR (1) more occasionally. Different types of instruments have operated in POBL and VAN2 stations. The first instrumentation consisted of one component short-period sensor (Kinemetrics Ranger SS-1) connected to a Kinemetrics PDR-1 datalogger (SUSAGNA, 1990). The stations were updated to three components in 1990, and in 1994 the acquisition systems were updated to 16-bit digital (IDS3602A Terra Technology). This configuration has been in operation until January 2000, when a third generation of instruments (NMX Orion; 24 bit) was installed. Since November 2000, POBL has been configured as a broadband station, equipped with a Streckeisen STS-2 sensor.

The second area corresponds to the La Cerdanya Valley (Eastern Pyrenees) where studies began in 1985 by means of a 2-year temporarily local network of 5 short-period vertical component seismic stations. Details of results of the network operation can be found in CORREIG and MITCHELL (1989) and CORREIG *et al.* (1990). In 1990, a permanent digital three-component station (CADI) was installed and in 1995 this station was updated to broadband (NMX RD316 digitizer + Guralp CMG-3T sensor). For further details about this station see VILA (1998) and VILA and MACIA (2002).

The period of time considered for this study spans from March, 1994 to January, 2000. This interval corresponds to the operation of the second generation of instruments in POBL and VAN2. Both stations worked under a trigger algorithm directed to local seismicity. The sampling rate was of 250 sps and the instrument transfer function of the entire system presents two corner frequencies: 1 Hz, provided by the natural period of the sensors, and a 5th-order Butterworth anti-alias filter at 50 Hz. From April 1994 to September 1997, a third station with the same characteristics operated in the *Observatori de l'Ebre*, EBR, located 79 km from POBL and 32 km from VAN2. The fourth station CADI, equipped with a broadband system, records in a continuous mode at 80 sps and with trigger algorithms defined to identify very local events in the Pyrenees.

The two regions under study have different geological characteristics. The Ebre basin is a Foreland Alpine basin filled with deposits from the Pyrenean Alpine Chain in the north and from the Iberian Chain and the Catalan Coastal Ranges in the southwest and southeast, respectively. The La Cerdanya Valley, where the CADI station is located, is an intramountain basin that originated at the intersection of the southern end of La Têt fault with an E-W strike-slip fault system. The formation and further evolution of the La Cerdanya basin is related to the rifting episode that occurred in Western Europe during the upper Paleogene and Neogene. La Cerdanya basin, together with other neighboring basins, is located along a 120-km-long fault extending from Perpignan toward the southwest (see Fig. 1). For more detailed geological information about the two areas see MUÑOZ *et al.* (1992), ARANDON *et al.*, (1981) and the references therein.

One of the topics studied using data from all stations was directed to local determination of attenuation and local site response. Results of previous works clearly showed severe discrepancies of attenuation and structural parameters when analyzing records of common events (VILA *et al.,* 1996; SERRA, 1997). In southern Catalonia, the analysis of the efficiency of the event trigger algorithm clearly showed differences between the POBL and VAN2 stations in spite of the fact that both

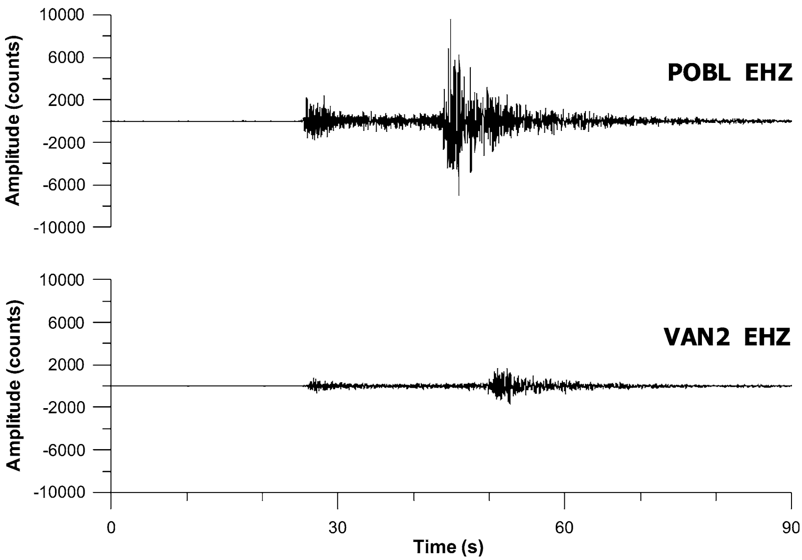

Figure 2
Example of waveforms of the event 3 January 2000, 18:29' (m_b[IGN] = 3.4: M_L[LDG] = 3.5), as recorded in POBL (Δ = 160 km) and VAN2 (Δ = 190 km).

stations are separated by only 52 km. Many times the VAN2 seismograph was not triggered when, according to the magnitude and epicentral distance of the earthquake, a clear activation was expected. During the period under study, while POBL detected 1164 events in 1751 days, VAN2 detected 450 events in 1993 days of operation. In addition, when an event is recorded in both stations, for similar distances, the amplitude in POBL is around three times larger than the record in VAN2 (see Fig. 2 as an example). This evidence has been supported a variety of seismic instruments that have been in operation at all sites. The capabilities of the currently installed seismographs allow us to define multiple trigger algorithms in diverse frequency bands. Results from 2000 to 2003 show that the efficiency of the trigger algorithms does not vary when compared with previous instruments (VILA and CORREIG, *Institut d'Estudis Catalans,* unpublished data). This indicates that differences in detectability cannot be directly related to different levels of seismic noise between both stations.

Because of the purpose of surveillance of the stations in Southern Catalonia, one of the objectives is to provide values of magnitude according to the observations and as close to the real value as possible. It is worth while to state that the evidence mentioned in the former paragraph has been observed in three different types of seismic instruments simultaneously installed in POBL and VAN2. Until November 2000 both stations were equipped with the same type of instruments and with differences between their responses less than 2%. This means that none of the discrepancies are due to instrumental effects.

CADI station plays a different role in the set of stations operated by the IEC. The continuation of the studies in La Cerdanya Valley that began in 1985 were also directed to arrange a station in which diverse systems could be tested. There are two main reasons for the inclusion of CADI to analyze the lateral variations of magnitude. First, in spite of the very different geological and tectonic characteristics, the station acts as a complement in the northern part of Catalonia, and second, CADI is, technically, completely different and more suitable to be used as a reference.

In this study we present the results of the analysis of lateral variations of local magnitude, M_L, computed using local events recorded in CADI, POBL and VAN2, and examples of EBR. The structure of this work is as follows: The first part compares the computed local magnitude M_L with the magnitudes reported by the agencies that consider the area of radius < 600 km of the stations as local. These agencies are the Spanish agency *Instituto Geográfico Nacional* (IGN) and the French agency *Laboratoire de Détéction et Geophysique* (LDG). Information pertaining to earthquakes which occurred during the period of time considered in the present study can be found in IGN (2000) and in LDG (2000). It is of value to mention the novelty of the data used in the present study. The set of data analyzed in the current work is not considered by any of the agencies to report the focal parameters of the earthquakes. As a second part, a 2-D map of the differences of magnitude (computed and reported) is constituted for each station vs. each agency. This gives us an image of apparent magnitude and could indicate the possibility of privileged directions. The third part is devoted to the comparison of the computed M_L for common events and to the obtaining of a magnitude expression for the stations. According to the results of the previous sections, a set of specific magnitude expressions, adjusted to the IGN and LDG agencies, are presented with the aim of establishing an independent means of quantifing local records of each station. Lastly, a discussion and conclusions of the present work and a comparison with previous studies are presented.

2. Data Selection and Processing

The earthquakes considered in this study have been selected according to the trigger algorithm activations of the four stations. Only those events detected and reported by the IGN and/or the LDG agencies have been analyzed. The events recorded by the stations in Southern Catalonia consist of waveform segments with a length defined by means of the trigger algorithm, whereas CADI operates in a continuous mode. The total amount of selected data results in a total of 963 seismic traces with epicentral distances reaching 700 km.

Data processing comprised the computation of the Wood Anderson simulation of the selected events. After obtaining the values of maximum amplitude (A) of the simulated horizontal component by means of the composition of the amplitudes of the N-S and E-W records, the local magnitude is obtained using the classical expression $M_L = \log A - \log A_0$, where A_0 is a function of the epicentral distance that accounts for the attenuation of the region. The A_0 values used are those reported by RICHTER (1958). Although the A_0 coefficients depend on the region under study and the values used are specifically for California, previous works have emphasized its utility in NE Spain (BATLLÓ 1990; CORREIG *et al.,* 1990). However, this does not mean that it could be the most appropriate for a specific station. The obtained M_L could reflect some particularities of the observation point. For this reason, the magnitude computed by means of the above expression can differ from the true magnitude and hence forth it will be named *apparent magnitude*.

M_L has been obtained for all traces available in the four stations. Because the present work is focused on comparing the computed apparent magnitude vs. the magnitudes provided by the agencies, the values of M_L are obtained from the diverse focal information provided by each agency (see maps on the right side of Fig. 3).

3. Magnitude Analysis

Figure 3 (left) displays the comparison of the magnitude given by the agencies LDG and IGN with the computed apparent magnitude M_L as well as the fit between both values. In order to avoid the influences of the scatter of the experimental data on the regression analysis, the fits have been carried out by using minimum squares linear orthogonal regression (CRAMER, 1951; chap. 21). The use of orthogonal regression (also called "major axis solution"), provides a solution that can be inverted (BÅTH, 1981).

To perform the fits, we have considered events with epicentral distances ranging from 30 km to 600 km and apparent magnitudes ranging from $2.0 < M_L < 5.0$. Because of the reduced number of events with magnitude higher than 5, we have excluded these events in order to avoid singularities. The lower limit 2.0 is chosen as a criteria to ensure the completeness of the catalog for the region and period of study. The value of 30 km as a lower limit for the epicentral distances has been chosen because apparent magnitudes for lower epicentral distances are strongly influenced by local effects. The 600 km upper limit for epicentral distances has been considered to preserve the range of validity of the classical expression of the Wood Anderson simulation.

Table 1 presents the values of the obtained fits. The positive independent terms (φ) indicate an apparent magnitude lower than those provided by the agencies. These discrepancies are considerably more evident in VAN2 and CADI stations. Another

▶

Figure 3

Left: Comparison between the computed apparent magnitudes M_L and the magnitudes given by the agencies LDG (crosses) and IGN (open circles) for all four stations considered in this study. Straight lines are the resulting fits that correspond to the values of Table 1. *Right*: Maps of the epicentral locations of the events used for the fits (same symbols).

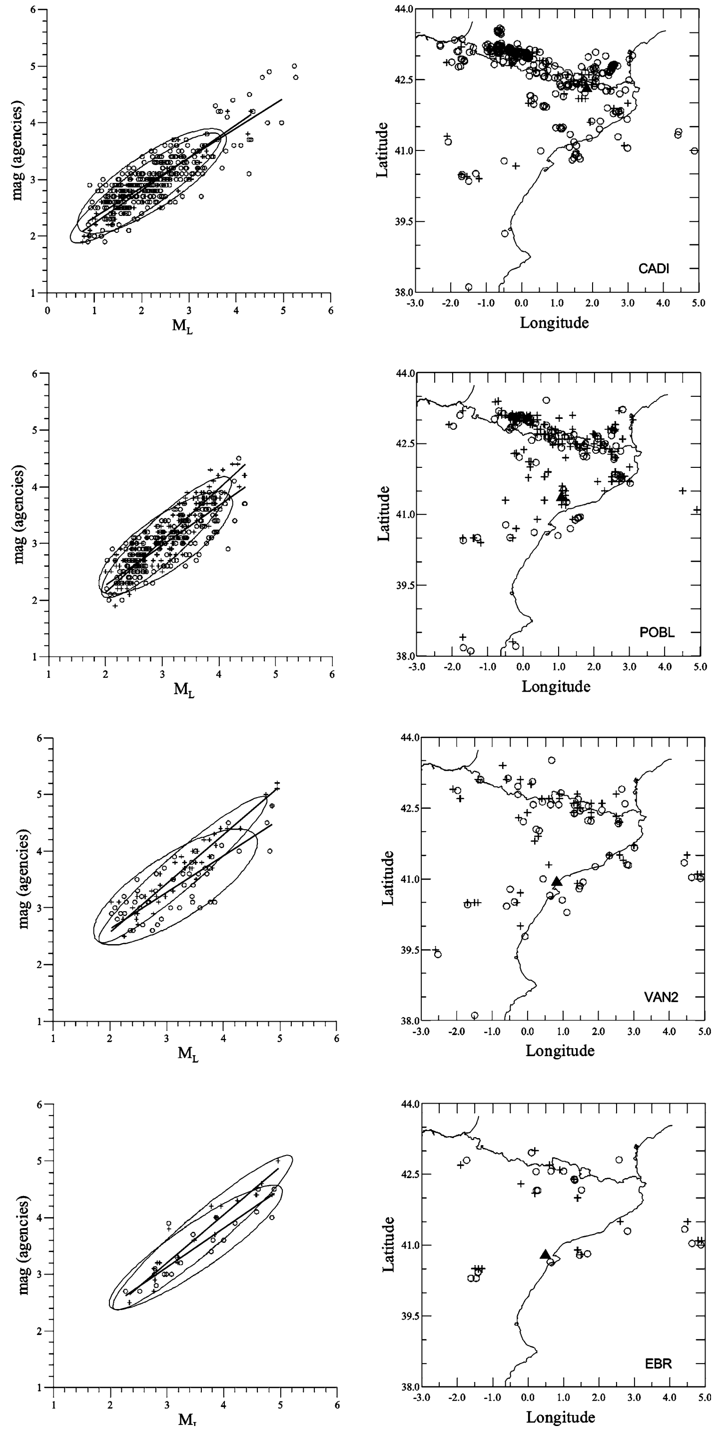
mag (agencies)
M_L
Latitude
Longitude
CADI
POBL
VAN2
EBR

Table 1

Coefficients and correlation factor ρ of the orthogonal fits $M_{\text{agency}} = \alpha M_L + \varphi$

	IGN Agency			LDG Agency		
Seismic station	φ	α	ρ	φ	α	ρ
CADI	1.81	0.53	0.80	1.64	0.58	0.90
EBR	1.05	0.69	0.90	0.64	0.85	0.95
POBL	0.84	0.71	0.79	0.29	0.92	0.90
VAN2	1.34	0.64	0.77	0.83	0.87	0.95

important remark is that the linear coefficients (α) are significantly lower than 1. For all four stations, the obtained values of φ when comparing with LDG agency are systematically lower than those obtained when comparing with IGN. On the contrary, the coefficient α is always higher when comparing with LDG. The intersection of both fits occurs in the lower limits of the magnitudes considered to perform the fit (at around 2). According to the fits, the largest differences correspond to CADI whereas the minor discrepancies are with respect to POBL. Particularly, we could say that the best fit corresponds to the comparison POBL station vs. LGD agency.

It is of value to mention that the differences between the values of the coefficients obtained for POBL and VAN2 stations are the same for both agencies. This means that a similar behavior, except for the *"base level"* is shown in both stations. Figure 4

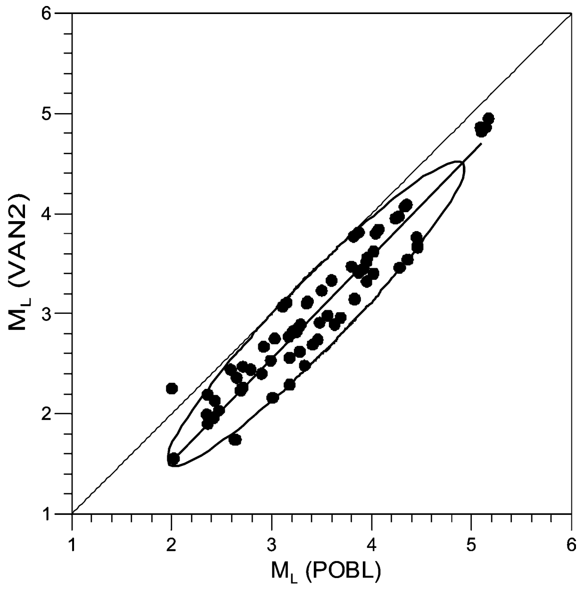

Figure 4
Comparison of the computed apparent magnitude M_L for events recorded boh in POBL and VAN2 stations, along with the fit and its corresponding confidence ellipse.

displays the comparison of the local magnitude M_L for events recorded both in POBL and VAN2 stations. The parameters of the fit are

$$M_{L(\mathrm{VAN2})} = -0.54 + 1.03\ M_{L(\mathrm{POBL})}, \qquad \rho = 0.96. \tag{1}$$

According to these values, the average difference between the amplitude of an event recorded by both stations is a factor of 3.4, in good agreement with the observations that reflect a significant reduction of the amplitude of the events recorded in VAN2 compared to POBL (see Fig. 2). The loss of energy that this reduction implies on the seismic waves also explains the differences regarding the detectability of both stations, that has a value of 2.95. This evidence, jointly with the short distance between POBL and VAN2 (52 km), clearly defines and quantifies a differential local effect.

4. Lateral Variations of Apparent Local Magnitude

To study the lateral variations of local magnitude M_L, a 2-D pattern has been constructed by means of a grid from the irregularly spaced data of residuals between the apparent magnitudes M_L and the magnitudes provided by the agencies. Due to the different nature of the 2-D plots, no clip has been applied to experimental data in this section, thus considering the full range of magnitudes and epicentral distances. The gridding method used is the "*krigging*." To remove noise or variability between grid nodes, a 2×2 Matrix Smoothing method has been applied. Because of the small data set recorded at EBR station, this station has not been considered in the analysis of lateral variations.

The obtained 2-D plots (Fig. 5) display a rather circular pattern of "anomalous" magnitude with maximum negative discrepancies centered at the stations. A close look at the scale also indicates the major differences between the station correction terms (φ) presented in Table 1 and, in particular, the differences between POBL and VAN2 shown in Fig. 4. No clear azimuthal variations nor privileged directions are observed. In the case of the CADI station, a different behavior seems to be pointed out when considering events with radial or transverse paths with respect to the Pyrenean axis. However, this could be due to the geographical location of the station (border between Spain and France), being in the limit where the accuracy of the national agencies is conditioned by the azimuthal coverage.

The lack of clear azimuthal dependence reveals another factor that influences the discrepancies between the apparent magnitude and reported magnitude. The major discrepancies between both values arise for events located close to the observation points, whereas the differences highly decrease (and tend to zero) for epicentral distances exceeding 250 km (see Fig. 6). This evidences a factor dependent on the epicentral distance to correct the observations in order to report a value of the "*real*" magnitude using the records from the studied observation points.

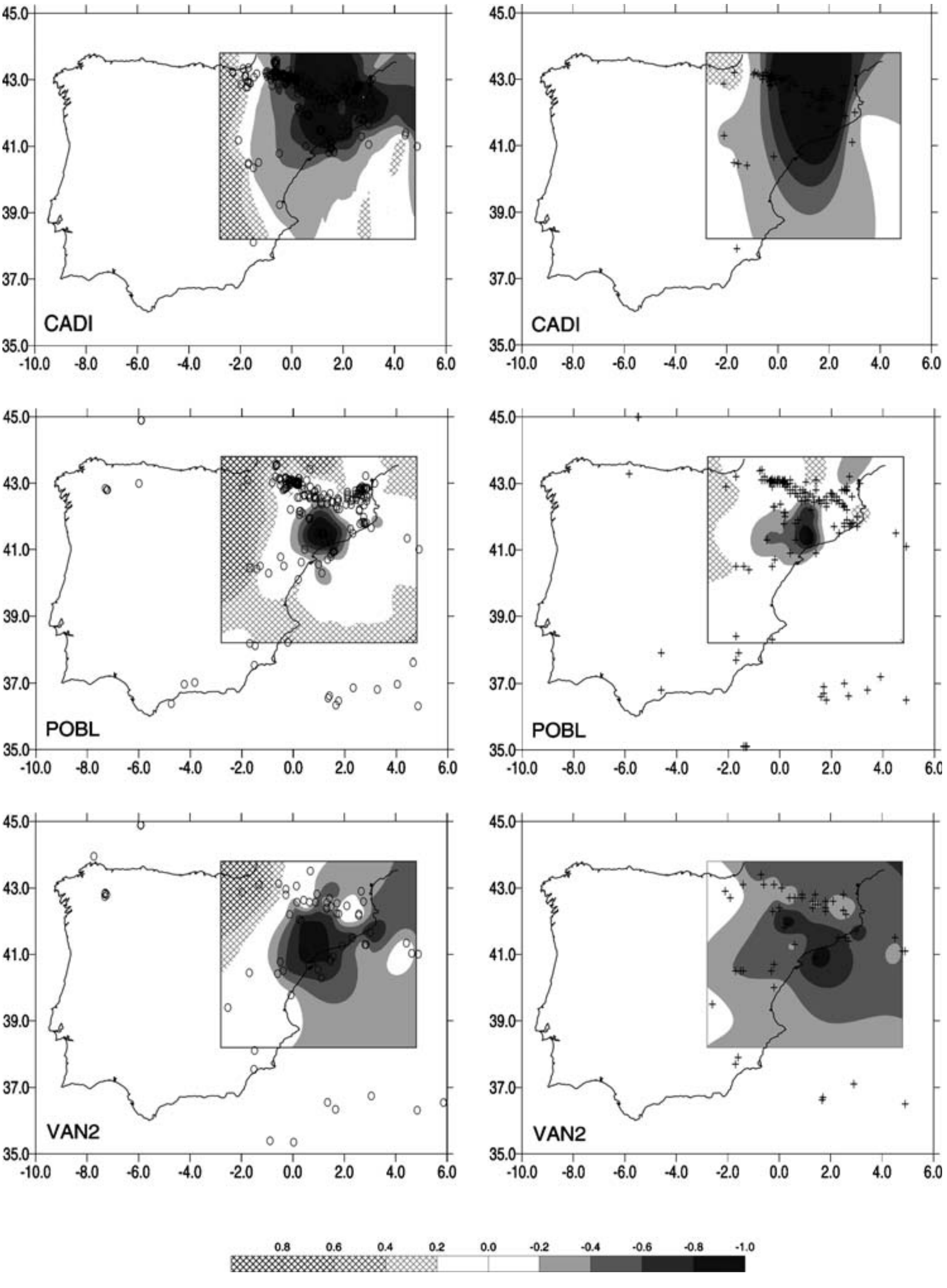

Figure 5
2-D plots of residuals between the computed apparent magnitudes and the values provided by the agency LDG (right plots) and IGN (left plots).

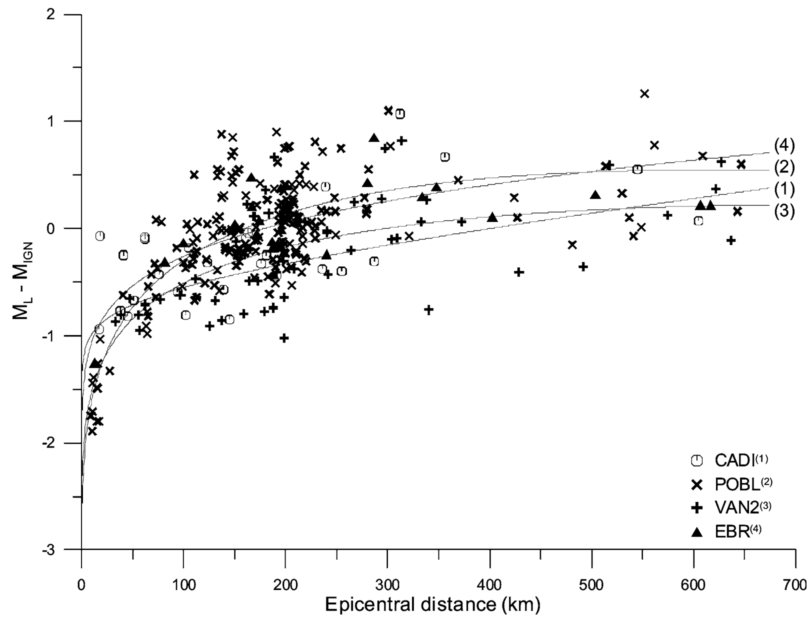

Figure 6
Plot of the differences between the computed M_L and the magnitude provided by the IGN agency vs. the epicentral distance and its corresponding fit, $f(\Delta)$.

5. Magnitude Expression Calculations and Test

The results of the fits presented in section 3 allow the obtainment of values of "real magnitude" for seismic events from data recorded in a given station, however there are some factors that make it not appropriate for all events. First, in order to avoid singularities, the obtained fits are limited to a rang of distances. Second, there is a linear factor (α) significantly different from 1 that means a non-negligible dependence with the reported magnitude. This implies that the computation of the apparent magnitude plus a station correction term is not enough to quantify the differences.

Looking at Figure 6, it can be seen that a reasonable hypothesis to avoid the discrepancies could be a term dependent upon the epicentral distance. The absence of clear privileged directions shown in Fig. 5 makes this hypothesis more suitable. Thus, removing the residual effect by fitting the observations of Fig. 6, a magnitude expression based only on local records can be obtained.

Figure 6 indicates two clearly different behaviors at short epicentral distances (high slope) and distant epicentral distances (low slope tending to zero). These behaviors could be modeled by means of linear fits for specific ranges of epicentral distance, which provides diverse values for different segments. However, it is not clear which and how many different intervals should be considered. One plausible function to report both conducts is the combination of linear and power-law functions in the form

$$f(\Delta) = a + b\Delta + \Delta^c. \tag{2}$$

Assuming a given agency to which establish the comparison, the difference of apparent (M_L) and reported (M_{agency}) magnitude can be expressed as

$$M_L - M_{\text{agency}} = f(\Delta), \tag{3}$$

and going back to the classical Wood-Anderson magnitude expression that has been used to compute M_L, an expression for the corrected local magnitude M_L' of an event can be obtained by means of

$$M_L' = \log A - \log \tilde{A}_0, \tag{4}$$

where

$$\log \tilde{A}_0 = \log A_0 - f(\Delta) \tag{5}$$

would be specifically defined for each site.

The application of this methodology to the recorded data provides the values of the parameters presented in Table 2.

In order to illustrate the usefulness of the obtained expressions (4), two tests have been performed. First, the application of the corrections to the data presented in the previous sections; second, its application to a new set of data corresponding to the list of triggered events during year 2001. Figure 7 (top) displays the original and corrected local magnitudes pertaining to events recorded in POBL stations from 1994 to 2000, using the LDG agency as a reference. Figure 7 (bottom) displays the application of the correction to data recorded in CADI during 2001. As it can be seen, not only is a significant improvement shown in the case of using the same set of data but also for the case of completely new events.

Table 2

Coefficients and R-squared of the fit $M_L - M_{\text{agency}} = a + b\Delta + \Delta^c$

	IGN Agency				LDG Agency			
Seismic station	a	b	c	$\sqrt{R}$	a	b	c	$\sqrt{R}$
CADI	−2.2632	0.0010	0.1038	0.44	−2.2632	0.0010	0.0542	0.60
EBR	−2.5782	0.0000	0.1826	0.48	−2.1883	−0.0007	0.1531	0.12
POBL	−3.3981	−0.0023	0.2614	0.59	−2.9261	−0.0024	0.2318	0.61
VAN2	−3.1682	−0.0013	0.2227	0.39	−2.5650	0.0000	0.1437	0.28

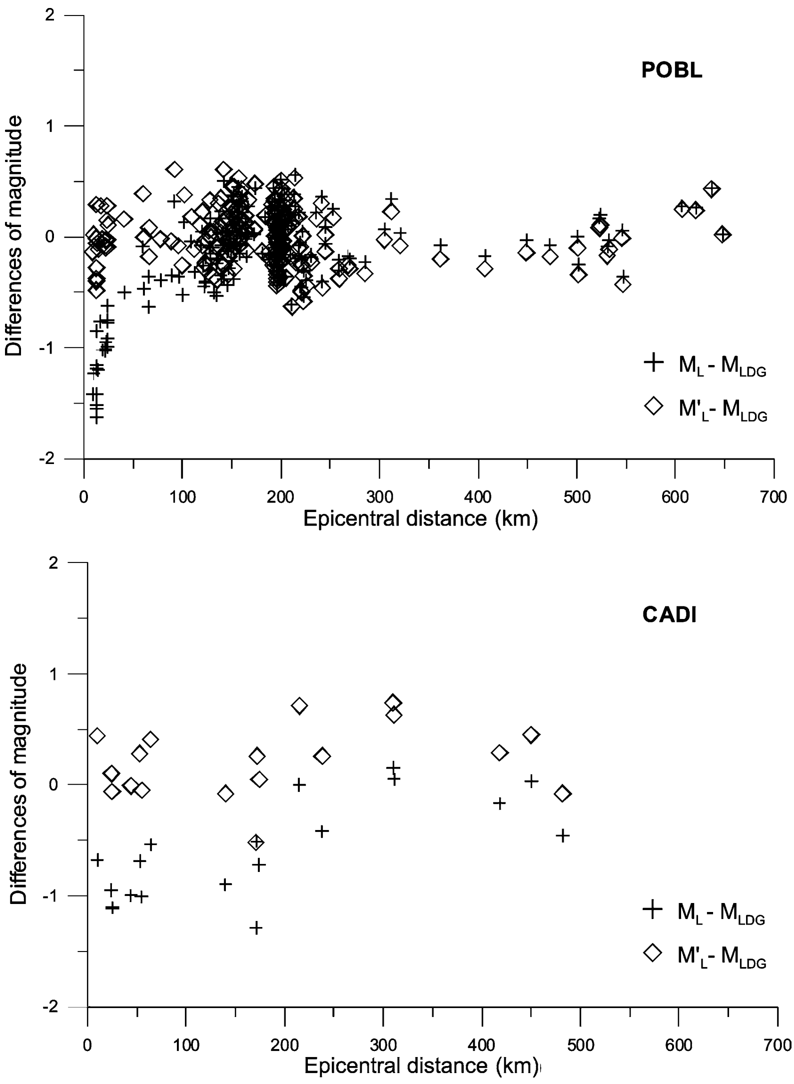

Figure 7
Improvement of the difference between computed and reported (LDG agency) magnitudes after considering the correction term (1). *Top*: Application to data recorded in POBL. *Bottom*: Application to an independent set of data recorded in CADI during 2001.

6. Discussion and Conclusions

The obtention of an expression to provide the real magnitude, using the observations for a given site, is an important tool for studying and qualifying local responses. However, there are several factors with determinant influence to the final values that should be taken into account. It is well known that magnitude values present discrepancies depending on the site of measurement, and differences around widely 0.2 are commonly accepted and widely reported. Effects of attenuation and scattering of seismic waves along the raypath, and local effects, clearly affect the shape of the recordings. However, in cases where the purpose of the stations is directed to seismic surveillance, it is necessary to provide values of magnitude according to the observations, and as close as the real value of the measured seismic event.

Because each observation point records data according to its own characteristics, we must differentiate what we are dealing with: the real magnitude of a seismic event or the observed (*apparent*) magnitude. Through the examples of seismic records obtained in the Northeastern Iberian Peninsula since 1984, clear differences of behavior have been pointed out. The substantial differences in apparent magnitude observed in stations placed several kilometers apart explain why algorithms do not trigger, when according to the distances, a declaration of an event should have occurred. Conformable to what the station sees, apparent magnitudes can differ by more than 1 with respect to those reported by the agencies and, for very short epicentral distances, differences of two units are reported. For stations whose main task is seismic surveillance as is the case of POBL and VAN2, the correction factors are very important to provide credibility both to the reported values and to justify whether or not the algorithms have been triggered.

As exposed in the present paper, a simple linear fit between the computed and reported magnitudes gives an independent term, indicating that the reported magnitudes depend on the observation point. However, it is useful to mention that the slopes are significantly different to 1. A value of the slope close to 1 would indicate that the differences between the apparent magnitudes for each station are mainly due to local effect. To provide magnitudes, agencies use averaged values of structural parameters for major areas and the reported values cannot take into account individual singularities for a given site. Slope values not closest to 1 (dependence with the provided magnitude) indicate that it exists as a different effect not exclusively related to a site effect. This dependence was already pointed out, for the area under study, in VILA *et al.* (1996) when an independent magnitude expression was investigated for events recorded in EBR by means of its WWSSN-SP analog system. It is note worthy to remark that the linear term reported in that work is 1.47 in good agreement with the one obtained in the current work, that is 1.45 ($1/\alpha$ in Table 1).

There are significant differences between the independent terms of the fits for different stations. These differences are an indication of an offset of proper station and can be explained as due to local effects (i.e., an area of high absorption). It is useful to point out that, as demonstrated in VILA *et al.*, (1996), the application of the methodology shown in this paper in the area under study, computes the magnitude through Lg waves. The significant differences between the computed and reported magnitudes, obtained for epicentral distances lower than 250 km, indicate a high attenuation for CADI and VAN2 stations, and POBL is the station that presents lower discrepancies. The relative magnitude station correction term $\varphi_{\mathrm{VAN2}} - \varphi_{\mathrm{POBL}}$ is of 0.54, which means a greater absorption of energy at VAN2 with respect to POBL, in agreement with the 18 years of observations carried out in the area. The short distance between the stations suggests a very local attenuation source. In the case of CADI, this also corroborates the low values of coda-Q (at around 20–30) obtained by CORREIG *et al.* (1990). In spite of the small amount of digital data obtained at EBR station, it is important to note the consistence of the results of the present work with respect to those reported in VILA *et al.* (1996).

The mentioned evidence points out two important results. First, the differences between the computed and reported magnitudes depend on the observation point and, second, the dependency of these differences with respect to the epicentral distance indicates a local/regional attenuation effect. The lack of clear azimuthal variations of M_L, not detected in the present work, suggests a second correction step based on the epicentral distance. This correction accounts for the differences of the real attenuation with respect to the values used to compute the local magnitude only with observations in isolated seismic stations.

In conclusion we can say that a local magnitude expression for stations CADI, EBR, POBL, and VAN2 has been developed to account for the magnitude as reported by the IGN and the LDG agencies. The formulas have been developed in two steps. First, a linear orthogonal fit, comparing the reported and computed values and, second, a correction of the residuals by means of a conjunction of a linear and power fit as a function of the epicentral distance. The obtained results corroborate the previous works done at the same area. In particular the results explain the very different level of detectability of VAN2 with respect to POBL and an emphasis on further analysis directed to obtain a better characterization on the local site influence is given.

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