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Duration Magnitude Scale and Site Residuals for Northern Morocco

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Abstract—The first empirical duration magnitude (M_D) formula is developed and tested for the Northern Morocco Seismic Network (NMSNET). This relationship is obtained by relating the IGN (Instituto Geografico National, Madrid) body-waves mbLg^{IGN} to the duration (τ), and the epicentral distance (Δ), at 25 analogue stations of the NMSNET for 479 earthquakes with $2.5 \leq \text{mb} \leq 5.4$, from March 1992 to February 2001. M_D estimates are significantly more precise while introducing a correction term for each of these stations, $cSta_j$. The magnitude for the i^{th} event $(M_D)_i$ is the mean value of individual $M_{D_{ij}} = -0.14 + 1.63\log_{10}(\tau_{ij}) + 0.031(\Delta_{ij}) + cSta_j$.

The $cSta_j$ corrections reduce considerably the local site effects which influence the recorded durations and cause stations to either overestimate, or underestimate M_D up to 0.5 magnitude units. Average station M_D residuals ($-cSta_j$) are found to be independent of the distance from the epicenter to at least 10 degrees. It seems evident that regional geological features in the immediate behavior of stations have a systematic effect on the corresponding obtained residuals: older well-consolidated Precambrian crystalline rocks produce high negative residuals (shorter durations), younger unconsolidated sediments produce high positive residuals (longer durations), whereas, intermediate M_D site residuals appear to be the result of the effect of various factors, principally age and state of consolidation of the bedrock, combined with the local tectonic.

Key words: Northern Morocco, duration, site residuals, short period, magnitude, tectonics.

Introduction

The frequency distribution of radiated seismic energy changes with earthquake size (AKI, 1967). Local or near-regional large events cause magnitude scales to suffer serious limitations, such as saturation (KANAMORI, 1977; HANKS and KANAMORI, 1979), and discrepancies between scales (GUTENBERG and RICHTER, 1956). In the case when the seismic signal saturates the seismograms, only duration

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can be measured. The usefulness of the coda duration as an estimate of earthquake size has been proved by many authors in the past (LEE and STEWART, 1981). They developed formulas relating the duration of the signal (τ) to the local magnitude for various areas. TSUMURA (1967) established a formula for Japan of the shape: $M_D = -2.53 + 2.85\log(\tau) + 0.0014(\Delta)$, where ($\Delta$) is the epicentral distance in kilometers, with $3 < M < 5$. LEE *et al.*'s (1972) empirical equation for the central California is: $M_D = 0.87 + 2.00\log(\tau) + 0.0035(\Delta)$, where $0.5 < M < 6$. BAKUN (1984), also for central California, proposed a relationship of the form: $M_D = 0.92 + 0.607\log^2(\tau) + \ 0.00268(\Delta)(1.5 < M < 5.3)$. For northern California, HIRSHORN *et al.*'s (1987) formula is of the form: $M_D = -0.72 + 2.95\log(\tau) + 0.001(\Delta)$, with $3 < M < 6$. The preferred equation of MICHAELSON (1990) for central California is without term in distance (Δ), but she included two terms of corrections, one for sensitivity and the other for the station site, respectively α and δ such as : $M'_D = -1.03 + 2.1\log(\tau) + \ 0.0026(\tau) + \alpha + \delta$, with $1.1 < M < 5.6$. EATON (1992) developed for northern California a dependent duration formula for computing magnitudes of the form: $M_D = -0.81 + 2.22\log(\tau) + 0.011(\Delta) + \log(\mathrm{CAL15}/\mathrm{CAL}) + D' + HF(h)$. The majority of these authors developed formulas relating the local magnitude M_L to (τ) and (Δ), where (τ) is the average recorded duration and (Δ) the corresponding average epicentral distance. Following BAKUN (1984), we adopted $m_b\mathrm{Lg}^{IGN}$ magnitude values presented in the IGN Bulletins and considered the individual values of (τ) and (Δ) rather than their averages. The choice of $m_b\mathrm{Lg}^{IGN}$ magnitude to calibrate the Moroccan network for duration-magnitude has been made on the basis of two important reasons. Firstly, the Digital Spanish Seismic Network is the nearest network to the Northern Morocco Seismic Network, and the majority of events occurring in Morocco or neighbouring regions are recorded by both networks. Secondly, the number of these events published in the IGN Bulletins is very important when compared to those published in the ISC (International Seismological Centre) Bulletins. Data from ISC present serious distortions arising from source radiation, distribution of reporting stations, amplitude saturation (KUGE, 1992), and data (concerning Morocco) reported in the NEIC (National Earthquake Information Centre) Bulletins are simply the $m_b\mathrm{Lg}$ (MDD: Madrid) IGN values. Finally, the use of m_b values based on the Lg phase seems suitable for near-regional distances at which these phases (Lg) dominate the records and are followed by a long and slowly decaying coda (SINGH and HERRMANN, 1983; XIE and NUTTLI, 1988). The study of direct Lg recorded at regional distances has recently gained considerable interest for estimating the magnitude-yield relationships (PATTON, 1988).

During the period 1990–1993, duration magnitudes determined by the Geophysics Laboratory (LAG) of the "Centre National de Coordination et Planification de la Recherche Scientifique et Technique" (CNCPRST) of Rabat were obtained using an empirical formula of the form $M_d = a\log_{10}(\tau) - b$. The resulting magnitudes presented serious differences with those published in the

Bulletins of the International Seismological Centre (ISC), the NEIC, or in the IGN Bulletins for the same events. Since March 1994 the LAG adopted duration magnitude formulas for computing magnitudes at individual stations. These individual empirical equations were of the form $M_D = a + b\log_{10}(\tau) + c(\Delta)$, where a, b, and c are constants calculated for each station (MOUAYN, 1994). Stations used in this study are composed of 21 telemetered stations by the LAG, while 4 other non-telemetered stations are run by the Scientific Institute Department of the Physics of the Globe (DPG) of Rabat. These 25 selected stations constitute only a part of the Moroccan Seismic Network. The NMSNET currently covers 95 stations comprising several types of stations: A set of telemetered stations, a set of portable stations, and recently installed broadband seismic stations. For computing the coda-duration magnitude at individual stations, empirical equations have been obtained on the basis of a few durations reported in the 1991–1993 LAG catalogues (less than 15 duration per station). Therefore, the magnitudes calculated suffered severe imprecision. Considering the availability of more numerous and better quality data, establishing a good duration-dependent magnitude formulation was in order.

Data

A set of 479 earthquakes (Fig. 1) was selected as the common events published in the Moroccan LAG and DPG seismological bulletins, and the Spanish IGN seismological bulletins. These events were divided into two subsets: 395 events from January 1993 to December 1998 with a total of 1,934 durations measured from seismograms available at the 25 NMSNET analogue stations (Fig. 1 and Table 1). These data are used to derive the relationship between (τ), (Δ) and M_D and are referred to as the *independent set*. The obtained equation was then applied to an additional 84 events (511 durations) which have known $m_b\mathrm{Lg}^{IGN}$ magnitudes to evaluate how well the new M_D predicted $m_b\mathrm{Lg}^{IGN}$. This second set of earthquakes is referred to as the *test set*, and it is composed of 4 events recorded between March 1992 and December 1992, with magnitude $4.4 \le m_b\mathrm{Lg}^{IGN} \le 5.3$, provided from the yearly seismological bulletin of the I.G.N. The other 80 events were recorded in the period time from January 1999 to February 2001. For both sets, durations were read on the seismograms by using the prescription of REAL and TENG (1973). The duration (τ) is defined as the time in seconds, on a vertical component short-period seismogram, from the P arrivals until the coda falls beneath some absolute amplitude level for the last time. In our case, this level corresponds to the background noise initial signal. Signals abnormally short, abnormally long, or for which the end could not be isolated from the background noise, were not included in this study. Epicentral distances (Δ) in degrees were calculated by using revised Hypo71 (LEE and LAHR, 1975). Origin times, locations, and magnitudes were taken from IGN Bulletins.

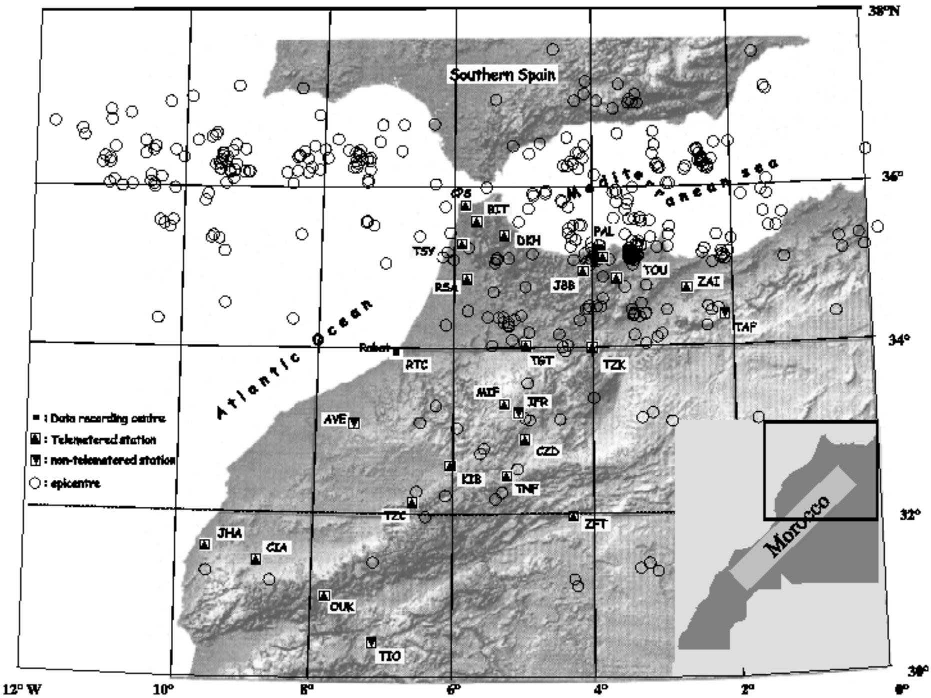

Figure 1
Epicenters and NMSNET station locations used in this study for the entire data set. Background image is a colored shaded topographic relief map of Northern Morocco and Southern Spain.

Data Analysis

Derivation of the M_D Equation

It is now proven that, if the envelope of the coda follows a t^{-q} relationship with increasing time, the duration magnitude, M_D can be computed from a relationship of the form $M_D = q\log_{10}(\tau) + r$ with $q = 1.5$ (HERRMANN, 1975). The observed relationship between magnitude and duration is shown to be a result of the particular shape of the signal coda as a function of time. The correlation between $m_b\text{Lg}^{IGN}$ and the signal duration recorded by the NMSNET stations for the entire data *sets* is illustrated in Figure 2. The best fit between $m_b\text{Lg}^{IGN}$ and the common logarithm of (τ) is represented by a linear function: $m_b\text{Lg}^{IGN} = 1.54\log_{10}(\tau) + 0.12$ where 1.54 is the value of the coefficient q proposed when the envelope of the coda can be well approximated by t^{-q} power law (HERRMANN, 1975). This argues clearly the necessity of adopting a magnitude-$\log_{10}(\tau)$ relationship. The goal here is to quantify $m_b\text{Lg}^{IGN}$, in terms of duration of the coda. The employed technique is a complete linear least-square regression analysis (JOBSON, 1991), with independent

Table 1

Station Corrections $cSta_j$.

No.	Code	Name	Sub-Network/ NT	Location		$cSta_j$	AMSR	Number of data
				Lat. (N)	Long. (W)			
1	TIO	Tiouine	Non-Telemetered	30.550	−7.150	***0.29***	*−0.29*	77
2	OUK	Oukaimden	Chichaoua	31.209	−7.868	***0.24***	*−0.24*	24
3	TZK	Tazeka	Ifrane	34.089	−4.184	***0.17***	*−0.17*	151
4	TAF	Tafouralt	Non-Telemetered	34.480	−2.240	***0.16***	*−0.16*	101
5	MIF	Mishlifen	Ifrane	33.409	−5.229	***0.16***	*−0.16*	48
6	ZAI	Zaio	Zaio	34.803	−2.746	***0.15***	*−0.15*	114
7	ZFT	Ezzeft	Midelt	32.034	−4.352	***0.15***	*−0.15*	29
8	KIB	El Ksiba	Beni Mellal	32.576	−6.039	***0.13***	*−0.13*	81
9	IFR	Ifrane	Non-Telemetered	33.310	−5.070	***0.12***	*−0.12*	125
10	CZD	Col de Zad	Midelt	33.033	−5.043	***0.08***	*−0.08*	127
11	TNF	Tounfite	Midelt	32.530	−5.319	***0.07***	*−0.07*	26
12	TZC	Tazercounte	Beni Mellal	32.148	−6.490	***0.06***	*−0.06*	50
13	PAL	Palemas	Zaio	35.225	−3.942	***−0.04***	*0.04*	109
14	JBB	Jbel Babet	Zaio	35.013	−4.198	***−0.06***	*0.06*	49
15	DKH	Dar Kharkour	Tanger	35.490	−5.360	***−0.08***	*0.08*	51
16	TOU	Touzarine	Zaio	34.962	−3.754	***−0.08***	*0.08*	122
17	CPS	Cap Spartel	Tanger	35.791	−5.910	***−0.11***	*0.11*	87
18	TGT	Taghat	Ifrane	34.070	−5.055	***−0.11***	*0.11*	95
19	RSA	Sarsar	Tanger	34.877	−5.828	***−0.12***	*0.12*	74
20	BIT	Ibn Batouta	Tanger	35.648	−5.729	***−0.13***	*0.13*	63
21	TSY	Tnine Sidi l'Yamani	Tanger	35.373	−5.970	***−0.14***	*0.14*	97
22	JHA	Jbel Lahdid	Chichaoua	31.736	−9.454	***−0.23***	*0.23*	23
23	CIA	Chichaoua	Chichaoua	31.565	−8.759	***−0.25***	*0.25*	58
24	RTC	Rabat Centre	Data Reception Centre	33.990	−6.858	***−0.32***	*0.32*	44
25	AVE	Averoes	Non-Telemetered	33.170	−7.240	***−0.32***	*0.32*	109

NT : Non-Telemetered Station

Number of data : number of duration measurements per station

Magnitude formula used: $Mp_{ij} = -0.14 + 1.63\log_{10}(\tau)_{ij} + 0.031(\Delta)_{ij} + 0.031(\Delta)_{ij} + cSta_j$

$AMSR$ = Average magnitude station residual = $-cSta_j$

variables $\log_{10}(\tau)$ and (Δ). The quantity $m_b\mathrm{Lg}^{IGN}$ is assumed to be the chosen reference magnitude, to which the variables $\log_{10}(\tau)$ and (Δ) are related, with errors ε, as: $m_b\mathrm{Lg}^{IGN} = c_0 + c_1\log_{10}(\tau) + c_2(\Delta) + \varepsilon$, where c_0, c_1 and c_2 are the constants to be determined. We solve for the model the constants, and then use these to calculate M_D. In this case, both the errors due to measurement and the lack of fit of the model are contained in ε. If errors are small and randomly distributed, then the model is considered satisfactory for these work data. We adopt for M_D the model represented by the following equation (1) in which $cSta_j$ is added as station correction, considered also as the *site correction:*

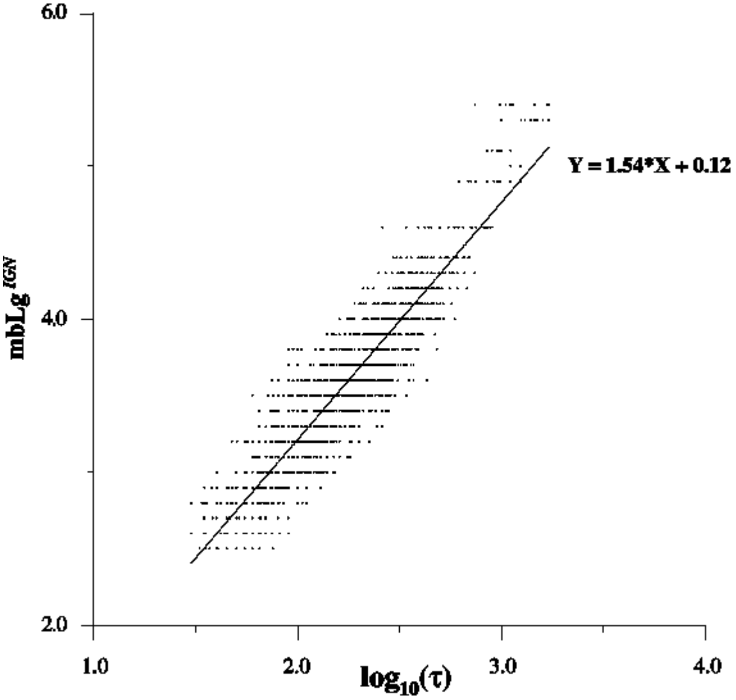

Figure 2
$m_b\mathrm{Lg}^{IGN}$ magnitude per earthquake versus individual observations of $\log_{10}(\tau)$ for the entire data of this study (2,445 durations). The straight line represents the best fit between $m_b\mathrm{Lg}^{IGN}$ and $\log_{10}(\tau)$.

$$M_{D_{ij}} = c_0 + c_1 \log_{10}(\tau_{ij}) + c_2(\Delta_{ij}) + cSta_j \ , \tag{1}$$

where a double subscript *ij* denotes an observation of event *i* at instrument *j*; a subscript *i* denotes a unique event, and a subscript *j* denotes a unique instrument.

Iterative Procedure

To adjust M_D against the data of this paper (*independent set*) we used a two-stage iterative procedure. In the first stage we solve for the constants c_{01}, c_{11}, and c_{21} by regressing initially, τ and Δ against $m_b\mathrm{Lg}^{IGN}$ with the station corrections $cSta_j$ being reset to zero. The quantities c_{01}, c_{11}, and c_{21} are the resultant coefficients of the first iteration of the regression. In the second stage the c_{i1} were substituted into equation (1) and $cSta_{j1}$ estimated. The first station corrections $cSta_{j1}$ are included in the next iteration of the regression, and the process repeated until the variance and standard errors converged to a stable minimum, with station corrections being updated between iterations. The adopted final coefficients c_0, c_1, and c_2 are those obtained from the last iteration of the regression as: $c_{0k} = c_0$, $c_{1k} = c_1$, $c_{2k} = c_2$, and

$cSta_j = \sum cSta_{jk}$, k being the number of iterations. The resultant magnitude estimate formulation is:

$$M_{D_{ij}} = -0.14 + 1.63\log_{10}(\tau_{ij}) + 0.031(\Delta_{ij}) + cSta_j \tag{2}$$

with $c_0 = -0.14$, $c_1 = 1.63$ and $c_2 = 0.031$. The values of $cSta_j$ are listed in Table 1.

The magnitude of the i^{th} event is the mean of individual station estimates $M_{D_{ij}}$, and M_D uncertainty is the standard deviation of the mean. The duration magnitude $M_{D_{ij}}$ estimated by equation (2) is plotted versus $\log_{10}(\tau)$ to illustrate the strong correlation between these parameters (Fig. 3a.). $M_{D_{ij}}$ estimated by equation (2) accounts for 95 percent of the variance pertaining to the regression, predicting $m_b\mathrm{Lg}^{IGN}$ reasonably well (Fig. 3b), while introducing station corrections assumed to be the site corrections, and the opposite of the average station magnitude residuals. This assumption is made on the basis that the sensitivity and the class component (low gain, vertical) had no error leaked into the site corrections, and therefore the instrument corrections were set equal to zero. To ensure that instruments had no direct effect on the durations, we have used in this study only stations with the same instrument response curves (1-Hz natural frequency), and for which attenuation setting does not change during the survey period. It is known that there is no obvious change in the residuals/site corrections when amplification changes at station (BAKUN, 1984). This remains according to the assumption that (τ) does not depend critically on station amplification (LEE *et al.*, 1972).

Testing the Magnitude Equation M_D

One way of investigating whether the newly computed M_D values agree with the $m_b\mathrm{Lg}^{IGN}$ observations was to apply first the new duration-dependent magnitude relationship to the *test set* events. 511 durations for 84 events with epicentral distances ranging between 10 and about 1,000 km (1 to 10°) are used to plot M_D estimated by the model (2) with the appropriate station corrections versus the $m_b\mathrm{Lg}^{IGN}$. Figure 4 is a good illustration of the strong correlation between the two magnitudes scales. M_D estimates are obtained accounting for 91 percent of the data variance (Table 2). The residuals ($M_D - m_b\mathrm{Lg}^{IGN}$) range between -0.16 to 0.4 magnitude units, with 80% of these residuals near zero, proving that the estimated values of magnitude using our formula are mostly equal to those given by the IGN. In the second time the M_D formula is applied to the entire data sets (all events in this study) to determine whether the new computing procedure with the M_D equation is well satisfied (Fig. 5). We effectively found that the best fit between the $m_b\mathrm{Lg}^{IGN}$ and M_D values is a linear function of the form $Y = 0.91X + 0.32$, with a coefficient of determination R-squared of about 0.94. The obtained result confirms the strong evidence that the model used in this study conformed with the data of this paper. Individual residuals ($M_D - m_b\mathrm{Lg}^{IGN}$) calculated for 479 events (2,445 durations) range between – 0.54 magnitude units underestimating $m_b\mathrm{Lg}^{IGN}$ and 0.47 magnitude units

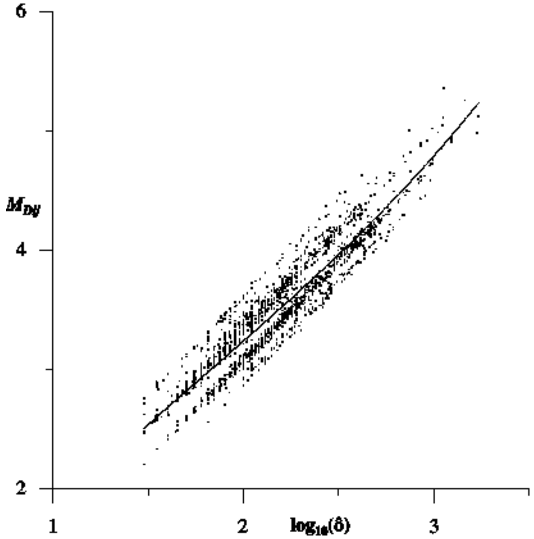

Figure 3a
$M_{D_{ij}}$ estimated and adjusted (independent set) for station corrections. The curved line is the best fit between $M_{D_{ij}}$ (corrected for site effect) and $\log_{10}(\tau)$.

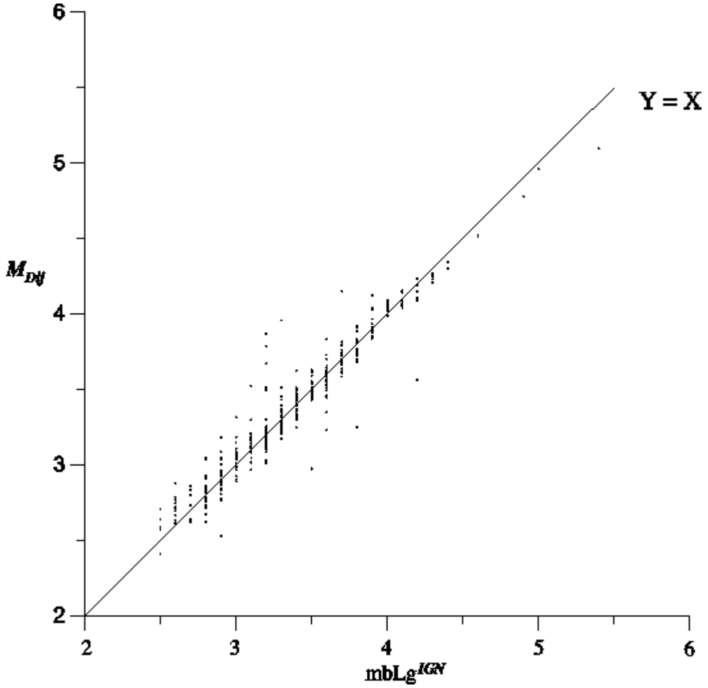

Figure 3b
$M_{D_{ij}}$ estimated versus $m_b\mathrm{Lg}^{IGN}$ for each event of the independent set. The straight line has a slope of 1.

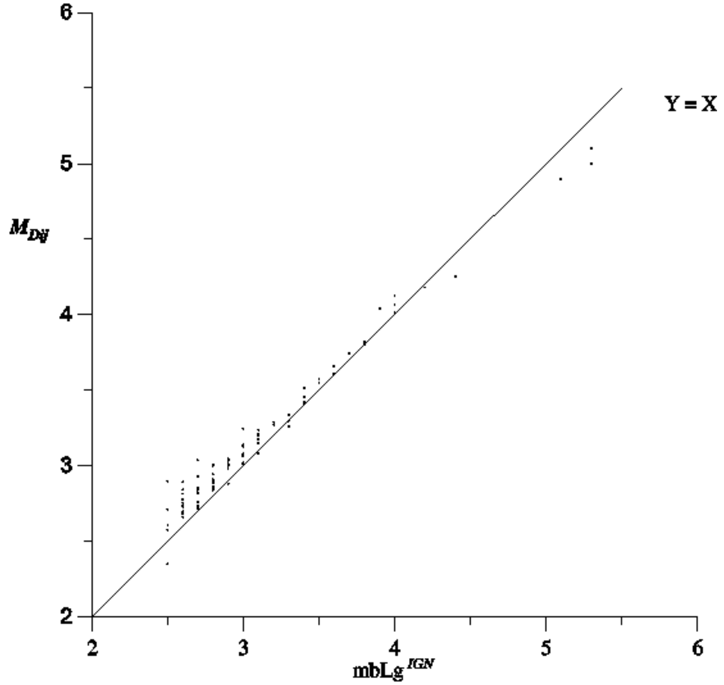

Figure 4

$M_{D_{ij}}$ estimated versus $m_b\mathrm{Lg}^{IGN}$ for each event of the test set. The straight line has a slope of 1.

Table 2

Variance Analysis

	Variables		Standard Error	R^2	*F* Test	Number of degrees of freedom
	$\log_{10}(\tau)$	Δ (km)				
Independent Set						
no $Csta_j$	(+)	(+)	1.08	0.84	5248	1931
with $cSta_j$	(+)	(+)	0.87	0.95	17190	1931
Test set						
with $cSta_j$	(+)	(+)	0.97	0.91	2346	508

(+): variables included in this model
R^2: Correlation coefficient
F Test: *F* test compared to the *F* of the model

overestimating $m_b\mathrm{Lg}^{IGN}$. To check for probable correlation between individual station magnitude residual values and their corresponding M_D estimated magnitudes, durations common logarithm ($\log_{10}(\tau)$), or epicentral distances Δ, we have plotted these residuals (for each event of the entire data) versus M_D, versus $\log_{10}(\tau)$ and

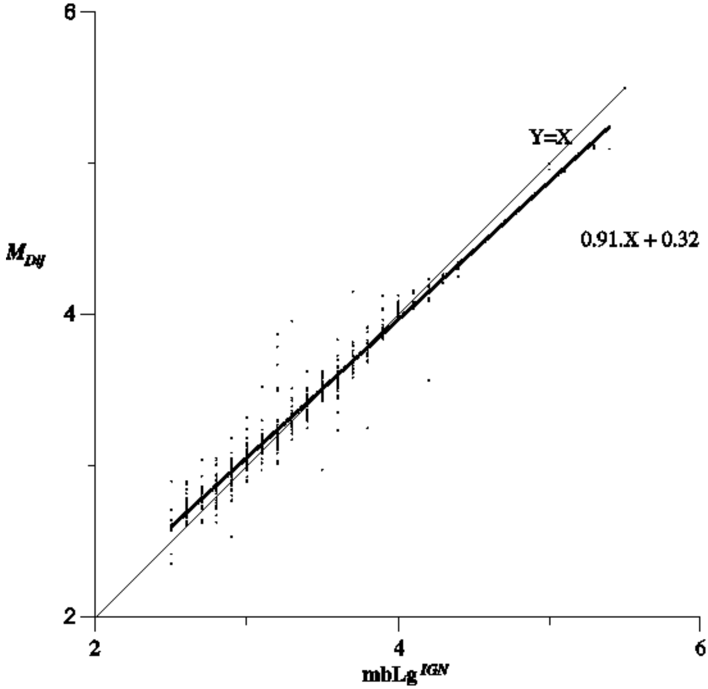

Figure 5
$M_{D_{ij}}$ estimated versus $m_b\mathrm{Lg}^{IGN}$ for the entire data set events. The dashed grey line ($Y = 0.91X + 0.3$) represents the best fit between $M_{D_{ij}}$ corrected for the site effect, and $m_b\mathrm{Lg}^{IGN}$. The straight has a slope of 1.

versus Δ, respectively, (Figs. 6a, b and 6c). It has been found that M_D estimates which are obtained by applying equation (2) show a good agreement for $2.5 \leq m_b\mathrm{Lg}^{IGN} \leq 4.5$ (Fig. 6a.). M_D has a negative bias in the range from 4.5 to 5.4 (Fig. 6a.). This may be due to the insufficiency of data with $m_b\mathrm{Lg}^{IGN} > 4.5$ (Table 3, Fig. 7) but it cannot affect the adequacy of the model, considering the overall character of the data used in this study. This is because the majority of the earthquakes felt in Morocco have magnitudes ranging between 3.5 and 4.5, as underlined in other seismology studies in Morocco (AÏT BRAHIM *et al*, 2002). It is clear and expected that for large events ($M > 4.5$) uncertainties in M_D will be important. For small events ($M \leq 4.5$), however, uncertainties in M_D calculations will be minor. We also found that there is no apparent systematic error in M_D with (τ) (Fig. 6b.), or with Δ (Fig. 6c.), and therefore residuals are uncorrelated as a function of $\log_{10}(\tau)$, or Δ to at least 10°.

Station Corrections (*Site Corrections*)

In this study, station corrections are computed using the model in equation (2) and introduced to reduce the particular effect of local geological heterogeneity at the

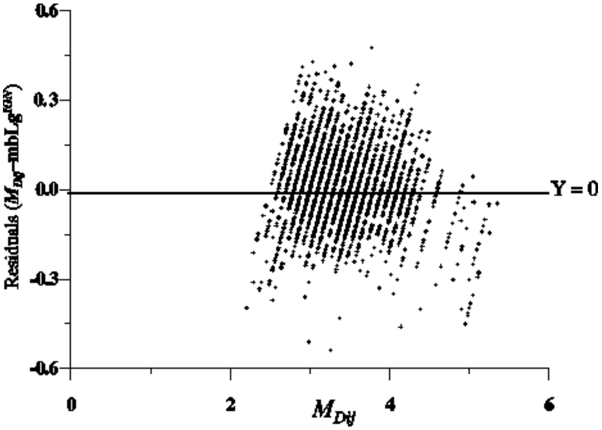

Figure 6a
Residuals $(M_{D_{ij}} - m_b\mathrm{Lg}^{IGN})$ versus $M_{D_{ij}}$ for the entire data sets (2,445 durations).

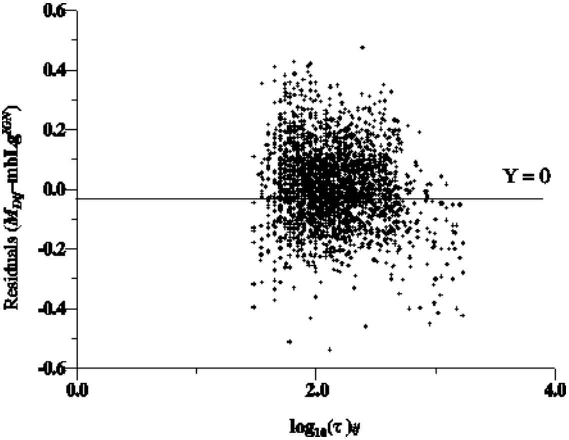

Figure 6b
Residuals $(M_{D_{ij}} - m_b\mathrm{Lg}^{IGN})$ versus $\log_{10}(\tau)_{ij}$ for all the data sets (2,445 durations).

site of the stations, and therefore can be viewed as the resultant errors in the prediction of the coda length assuming a simple description of the physical parameters of a seismic event. The seismic source is in general represented only by a single variable which is the magnitude (or the seismic moment) of an earthquake, and the volume of the medium between the hypocenter and the station is simply represented by the epicentral distance Δ. This single variable Δ cannot explain all the propagation-path effects which influence the durations and result in either overestimating or underestimating the magnitude at a station. It is implicit that station

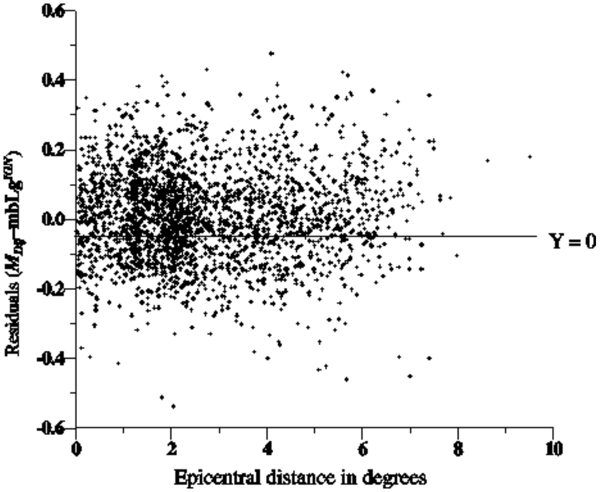

Figure 6c
Residuals ($M_{D_{ij}} - m_b\mathrm{Lg}^{IGN}$) versus Δ_{ij} (in degrees) for the entire data sets (2,445 durations).

Table 3
Distribution by magnitude of Events of this Study

Magnitude	2.5–3	3–3.5	3.5–4	4–4.5	4.5–5	5–5.5
Events	160	181	105	24	5	3

corrections are not resulting from a bad representation of the seismic source properties, since a source can be viewed as a point (as well as it can be considered as a volume) from which the seismic energy is radiated in all directions. This energy is quantified by an intrinsic parameter such as the magnitude (or the seismic moment). Clearly, although durations can be influenced by amplification or attenuation properties in a volume from the hypocenter to the receiver, we can easily consider that only an averaged influence is generated by a backscattering phenomenon in all directions of this volume, especially, backscattering heterogeneity in a volume surrounding the source and receiver (TSUJIURA, 1978; AKI, 1980). The coda-wave energy is observed homogeneously distributed in the crust (AKI, 1969; MAYEDA *et al.*, 1992). This influence may not be evaluated because it may not be isolated—as a known value—from the total correction attributed to each station. Nonetheless it is clear that an implicit error in magnitude estimation due to the path-propagation properties in this volume, and resulting from a particular regions geological properties, can be represented by a characteristic supplementary additive mean value correction for this region, and therefore can be leaked into the station correction for physical attenuation properties of local geology in the immediate vicinity of stations. This is due to the fact that surface geology exerts significant influence on the site

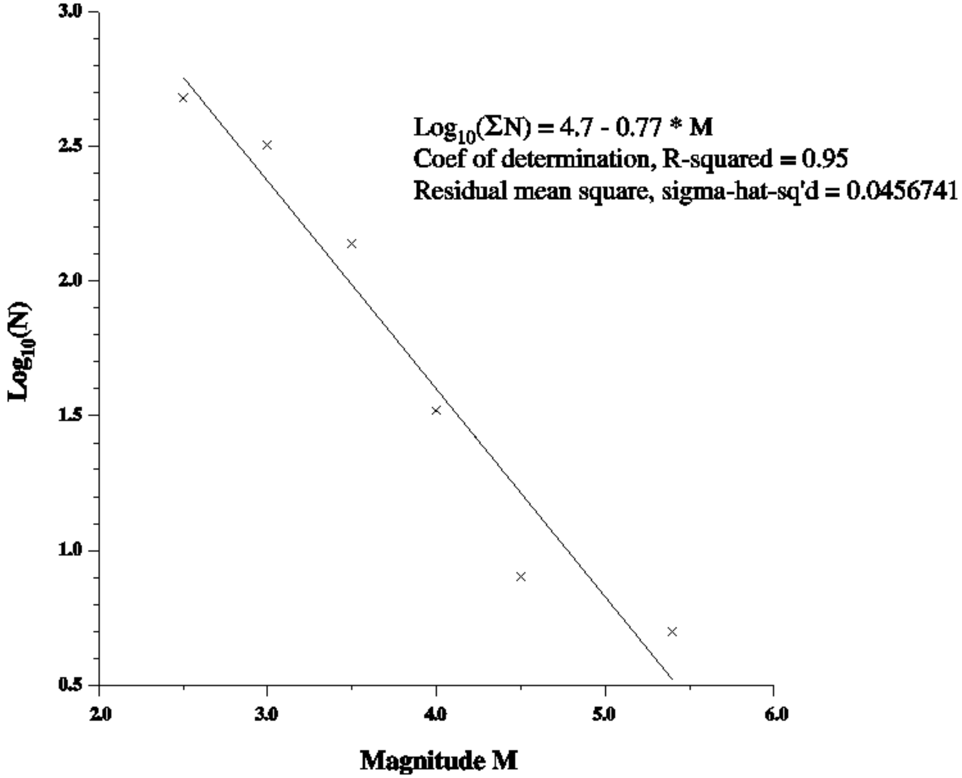

Figure 7
Magnitude-frequency relations for the 479 events used in this study.

amplification (Borcherdt, 1970; Borcherdt and Gibbs, 1976; Rogers *et al.*, 1979; Michaelson, 1990; Su *et al.*, 1992). In this study, site corrections (station corrections) $cSta_j$ are obtained in the range between -0.29 to 0.32 magnitude unit (see Table 2). In an attempt to check for the eventual correlation between these corrections and the geology underlying the stations we prefer the use of the average station magnitude residuals *ASMR* term which are the site residuals (Table 2) rather than using station corrections $cSta_j$ ($AMSR = -cSta_j$).

M_D *Site Residuals and their Dependence on Lithology and Tectonics*

Site residuals *AMSR* ranging between -0.29 and $+0.32$ (Table 2) are plotted at station locations on a simplified schematic structural map with major tectonic features of northern Morocco (Fig. 8). Negative (positive) site residual means that corresponding stations tend to underestimate (overestimate) the M_D magnitude, and consequently have shorter (longer) durations than expected coda duration. The geological properties of the individual sites were read from the 1:10^6 scaled geological

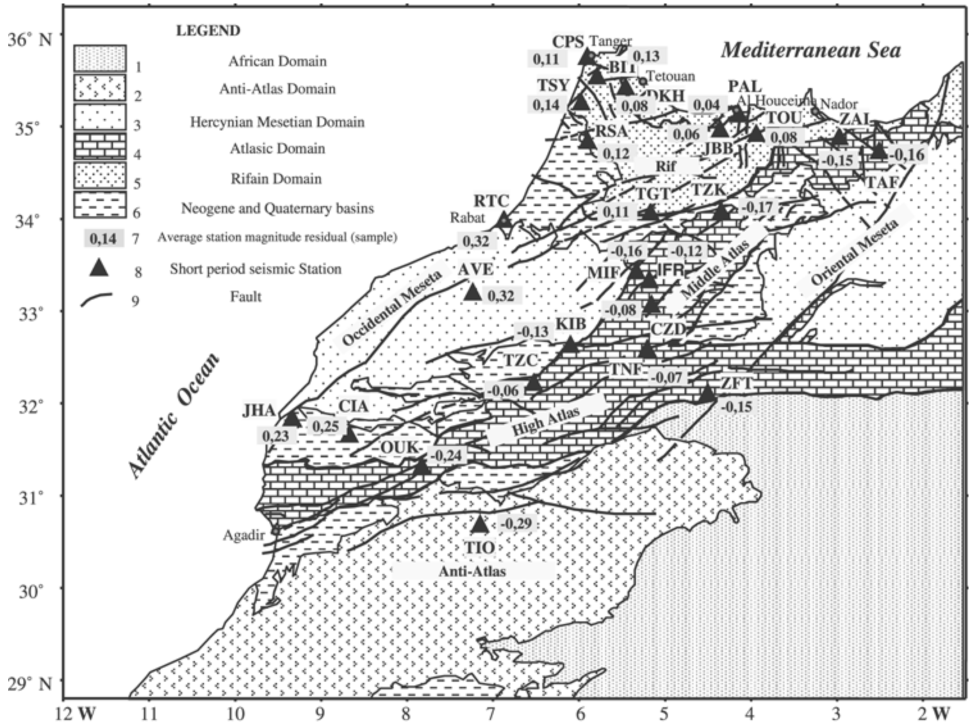

Figure 8
Simplified schematic structural map of northern Morocco.

map of Morocco (editions service géologique du Maroc, 1985), and tectonic map of northern Morocco (AÏT BRAHIM, 1991).

We found that stations AVE, RTC, CIA, and JHA which have the highest positive site residuals (0.23 to 0.32) are installed on a stable competent block corresponding to the occidental Meseta. This domain of the Hercynian chain is composed mainly of Palaeozoic formations deformed during Hercynian orogeny (PIQUÉ, 1979). Since then, this domain is a homogeneous stable and competent block with an isostatically compensated crust (BENSARI, 1987; SEBER *et al.* 1996), and it is characterized by poor seismic activity and a particular amplification of the seismic signals. The amplification effect observed at these stations can be attributed to the low impedance of younger, less consolidated quaternary sediments (BEAUDET, 1961; SU *et al.*, 1992) at station sites, or it can be viewed as a systematic result of the presence of a probable zone which causes the signal to be amplified before being acceded by the Mesetian domain (SEBER *et al.*, 1993). Thickness of sedimentary layers at these sites is not important compared to the thickness of the Palaeozoic substratum. In this case, we note no contradiction with the Kappa effect (ANDERSON and HOUGH, 1984) which predicts the dominance of attenuation due to high absorption for younger sediments since these are not well represented.

The second group of stations with positive residuals ranging between 0.04 and 0.14 is represented by CPS, BIT, TSY, RSA, TGT, DKH, JBB, PAL and TOU. These stations are situated in the Rifain domain. CPS, BIT, TSY, RSA, and TGT are installed along the Rifain external domain with residuals between 0.11 and 0.14. This domain deformed during the middle and upper Miocene tectonic phase (ANDRIEUX, 1971; AÏT BRAHIM, 1991) is characterized by the presence of NW-SE to E-W trending crustal thrust faults. This zone is characterized by an important negative gravity anomaly (−150 m gal) along 300 km (VAN DEN BOSCH, 1974), caused by a tectonic crustal thickening due to the thrusting of the external Rifain domain over the internal domain and the thrusting of this last one over the Mesetian and Atlasic foreland (AÏT BRAHIM *et al.*, 1990). In this area the recent faulting and the absence of younger unconsolidated sediments appear to be the cause of the moderate amplification observed in these sites. Stations JBB, DKH, PAL, and TOU with positive near zero residuals (0.04 to 0.08) are disposed along the thrust front of the Rifain internal domain characterized by the ascension of ultramafic material situated at depth of 23 to 29 km (BELLOT, 1985). This domain comprises napes with a slim continental crust (gneiss and micaschist) and their ultrabasic basement constituting peridotite and Kinzigite over which lay the Palaeozoic and the limestone dorsal (1800 m) at Tetouan (Haouz Chain) and at Al Houceima (Boukkouya chain). In this domain no attenuation or amplification is noted. This is because the majority of events of this study are located in the homogeneous and competent block of the Alboran crust which represents either the source or the receiver areas.

In the Atlasic domain, residuals are negative and range from −0.06 to −0.17 for stations TZC, KIB, ZFT, TNF, CZD, IFR, MIF, TZK, ZAI, and TAF. This domain is affected by the upper Miocene deformation (LAVILLE, 1985; PIQUÉ *et al.*, 1998; MOREL *et al.*, 2000). In this tectonic phase, the competent Precambrian and Palaeozoic substratum were intensively fractured and the Jurassic limestone cover plied and detached at the Triassic argillites level (LAVILLE, 1985; PIQUÉ *et al.* 2000). This intracontinental mountain chain (more than 4 km altitude) with no crustal “root” (WIGGER *et al.*, 1992; GOMEZ *et al.*, 1998) is considered to have a relatively important seismic activity with focal depths up to 150 km (HATZFELD, 1978). This area which absorbs the maximum deformation resulting from the Africa-Europe convergence shows a notable seismic wave decay (low amplification) due, initially, to the dominance of Precambrian and Palaeozoic rigid blocks over which Jurassic limestone formations lay, and secondly, to the absence of younger sediments at station sites. The negative, near zero residuals for TNF, CZD, and TZC (−0.06 to −0.08) may be explained by the location of all these stations on active crustal faults which limit the middle and high Atlas (AÏT BRAHIM, 1991; MOREL *et al.*, 2000).

Lastly, OUK and TIO stations with the highest negative residuals of −0.24 and −0.29 respectively, are located in two different domains; the OUK station in the high Atlas and the TIO station in the anti-Atlas domains, however they are both installed on 2000 M year-old Precambrian crystalline rocks (gneiss, migmatite, granitoid) representing the rigid and stable West African basement (2000 to 4000 M years). This clearly explains the important decay both in duration and amplitude of seismic waves observed in these geological units (old and well-consolidated rocks), and as established by many authors (BOORE and ATKINSON, 1992; EATON, 1992; SU *et al.*, 1992) for different regions of the earth.

Conclusion

The first coda-duration magnitude (M_D) formula is presented and tested for the northern Morocco seismic network (NMSNET). This formula is obtained using 479 earthquakes with $2.5 \leq m_b \leq 5.4$ from March 92 to February 2001. The magnitude for the i^{th} event $(M_D)_i$ is the mean value of individual station estimates: $M_{D_{ij}} = -0.14 + 1.63 \log_{10}(\tau_{ij}) + 0.031(\Delta_{ij}) + cSta_j$ where (τ_{ij}) is the duration of the recorded signal, (Δ_{ij}) the epicentral distance, $cSta_j$ the site correction and subscripts i and j denote an event i recorded at a station j. Instrument gain settings infrequently change during the survey period. Special care was taken to ensure that the corresponding records were not included in this study. Thus no corrections were considered for the sensitivity of the used instruments (low-gain, analogue, short-period vertical component). In this empirical approach we noted the following points: (1) M_D site residuals $(-cSta_j)$ are the results of the local site effects which influence the recorded durations and make stations overestimating or underestimating M_D up to 0.5 magnitude units; (2) M_D site residuals are found to be independent of the distance from the epicenter to at least 10°; (3) particular values of M_D site residuals may be systematically related to geologically underlying stations, such as bedrock lithology, structural domain, and tectonic features. It has been found that higher negative residuals (−0.29 and −0.24) have been obtained for the high and anti-Atlas old Precambrian crystalline rocks (gneiss, migmatite, granitoid,..) which constitute a part of the rigid and stable West African basement. In these units we note an important attenuation (low amplification) of the seismic waves. Intermediate negative residual values (−0.17 to −0.12) have been observed at stations in the middle and high Atlas Palaeozoic deformed rocks, beside a moderate attenuation of the seismic energy. Near zero negative residuals (−0.06 to −0.08) are also obtained for stations located in the areas. These residuals may be explained by the location of the corresponding stations on the active Mesozoic and Quaternary crustal faults limiting the middle and high Atlas belts. Near zero positive residuals (0.04 to 0.08) have been obtained for stations disposed on the thrust front of the Rifain internal domain which is on the Alboran crust.

Intermediate positive residuals (0.11 to 0.14) have been observed at stations located on the thrust front of the external Rifain domain over the Mesetian and Atlasic forelands. The moderate amplification noted here may be caused by the absence of younger sediments and the recent tectonic activity. Concludingly, the higher positive residuals (0.23 to 0.32) correspond to the stations set in the occidental Meseta domain which is a homogeneous block with quaternary younger deposits. In this area we have noted an important amplification of seismic waves mainly due to the low impedance for younger, less consolidated sediments. In general our results have shown that older competent rocks produce higher negative residuals (shorter durations), while younger less consolidated sediments produce higher positive residuals (longer durations). The interpretations given to explain the correlation between geological properties in the immediate vicinity of station sites and intermediate positive or negative residuals, are an unusual result requiring more study, and therefore, may not be fully justified.

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