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MAGNITUDE SCALES IN CENTRAL GREECE

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Abstract

The Gulf of Corinth is one of the most active tectonic rifts around the world. Data used in the present study are obtained by the four digital stations of the Cornet Network which was installed in 1995 around the Eastern Gulf of Corinth. A velocity model was calculated, while the majority of local events were located within the Gulf of Corinth. Main scope of the study is the determination of a reliable earthquake magnitude. Concerning the duration magnitude M_D, a multiple linear regression technique was developed for the determination of the constants α, β and γ with very satisfactory values of errors. The coefficient of determination (goodness of fit) R^2 was found equal to 0.99. Following, the moment magnitude Mw, which is considered to be the most reliable magnitude scale, was determined. Spectral analysis was applied for the calculation of the seismic moment M_0 and a seismic catalogue was created. After the determination of the moment magnitude Mw and of the duration magnitude M_D for the same dataset, a relationship between them was obtained, according to which Mw is systematically larger than M_D. Relationships between these magnitudes, the local magnitude M_L and the body wave magnitude m_b were also obtained.

Key words: *Velocity Model, Duration Magnitude, Spectral Analysis, Moment Magnitude.*

Περίληψη

Ο Κορινθιακός κόλπος είναι μία ασύμμετρη τεκτονική τάφρος που οριοθετείται από ενεργά κανονικά ρήγματα και αποτελεί μία από τις περιοχές με τις μεγαλύτερες συγκεντρώσεις σεισμικών εστιών στον Ελληνικό χώρο. Η έλλειψη μόνιμων σεισμολογικών σταθμών στην περιοχή του Ανατολικού Κορινθιακού κόλπου οδήγησε στην εγκατάσταση του τηλεμετρικού δικτύου Cornet που έλαβε χώρα κατά το έτος 1995 και αποτελεί το μόνιμο δίκτυο του Τομέα Γεωφυσικής - Γεωθερμίας του Τμήματος Γεωλογίας και Γεωπεριβάλλοντος του Πανεπιστημίου Αθηνών. Καθορίστηκε ένα μοντέλο μέσων ταχυτήτων, αποτελούμενο από έξι σεισμικά στρώματα, στην περιοχή του Ανατολικού Κορινθιακού κόλπου, προκειμένου να επιτευχθεί ο καλύτερος δυνατός προσδιορισμός των υποκέντρων και των εστιακών παραμέτρων. Ο προσδιορισμός ενός αξιόπιστου σεισμικού μεγέθους αποτέλεσε τον κύριο στόχο της παρούσας εργασίας. Αναπτύχθηκε λογισμικό για τον υπολογισμό των σταθερών α, β και γ για τον υπολογισμό του μεγέθους διάρκειας M_D. Ακολούθως, προσδιορίστηκε το μέγεθος σεισμικής ροπής M_W, το οποίο θεωρείται το πλέον αξιόπιστο. Ο προσδιορισμός της σεισμικής ροπής M_0 επετεύχθη μέσω φασματικής ανάλυσης. Μετά τον ανεξάρτητο προσδιορισμό του μεγέθους σεισμικής

ροπής M_W και του μεγέθους διάρκειας M_D, υπολογίστηκε προσεγγιστική σχέση μεταξύ τους, καθώς και σχέσεις που τα συνδέουν με το τοπικό μέγεθος M_L, με το χωρικό μέγεθος m_b και με το λογάριθμο της σεισμικής ενέργειας.

Λέξεις κλειδιά: *Μοντέλο Ταχύτητας, Μέγεθος Διάρκειας, Φασματική Ανάλυση, Μέγεθος Σεισμικής Ροπής.*

1. Introduction

The Gulf of Corinth is an asymmetric tectonic graben, whose creation is due to the activity of faults with a mean E-W direction (Makropoulos and Burton 1981), mainly along the southern coast. The high level of seismicity (Makropoulos and Burton 1984, Ambraseys and Jackson 1990), the quaternary local faulting (Sebrier 1977) and the 10 to 15 mm/year overall N-S extension rate (Fig. 1), obtained by geodetic studies (Billiris *et al.* 1991, Briole *et al.* 1994, 2000), imply that the Gulf of Corinth is a key place in Europe for the studies of various physical processes related to the origin of earthquakes. Seismological and tectonic studies (Jackson *et al.* 1982, Armijo *et al.* 1996) indicate that the morphology of the Gulf of Corinth is mainly due to repeated earthquakes that have occurred on 40° to 60° north-dipping normal faults. The Gulf is characterized by the long term subsidence of the northern coast and the upward displacement of the main footwalls. Furthermore, it is one of the most active tectonic regions of the Eastern Mediterranean.

Several large historical earthquakes have destroyed cities in the Gulf, but only few of them have provided information about the faults that produced them. The most well-known historical event is the Helike earthquake of 373 B.C. (Papazachos and Papazachou 1997) that destroyed and submerged Helike in the waters of a coastal lagoon. It is worth noticing that in 2001, archaeologists discovered the first traces of the long-lost site of Helike in an alluvial plain on the southwest shores of the Gulf of Corinth. Recent large events are characterized by normal faulting with an approximately E-W direction, while their focal depths are about 10 km.

In the framework of the present study the seismic activity of the Gulf of Corinth, as well as a velocity model, are presented. Nevertheless, the main scope is the determination of a reliable earthquake magnitude. The duration magnitude M_D, using data recorded by the Cornet Network, is rapidly calculated and consequently it is the magnitude scale which is available in near real time after the occurrence of an earthquake. Nevertheless, the most important task of the present study is to calculate the moment magnitude M_W, using spectral analysis, which is the most reliable magnitude scale. Finally, relationships between the magnitude scales are obtained.

Figure 1 - Seismicity and active normal faults of the Gulf of Corinth and surrounding area. The arrows present the extension of the Gulf of Corinth. Focal mechanisms of large events are also presented

2. Data Analysis

2.1. The Cornet Network

The Seismological Laboratory of the Geophysics – Geothermics Department of the University of Athens installed since 1995 the Cornet permanent telemetric network (Fig. 2) around the Eastern Gulf of Corinth (Papadimitriou *et al.* 1996, Kaviris 2003). This was the first digital permanent network installed in Greece. The area was chosen due to its continuous seismic activity, which is characterized by normal faulting with an approximately E-W direction, and the absence of permanent seismological stations. On the other hand, several temporary seismological networks were installed in the broader area of the Gulf of Corinth since 1990. Some of them were installed to record background seismicity (EPOC Final Scientific Report 1995, Rigo *et al.* 1996, Tiberi *et al.* 2000, Papadimitriou *et al.* 2001), while others to record the aftershock sequences of large events, as the 1992 Galaxidi (Kemezentzidou *et al.* 1993) and the 1995 Aigion (Bernard *et al.* 1997) earthquakes.

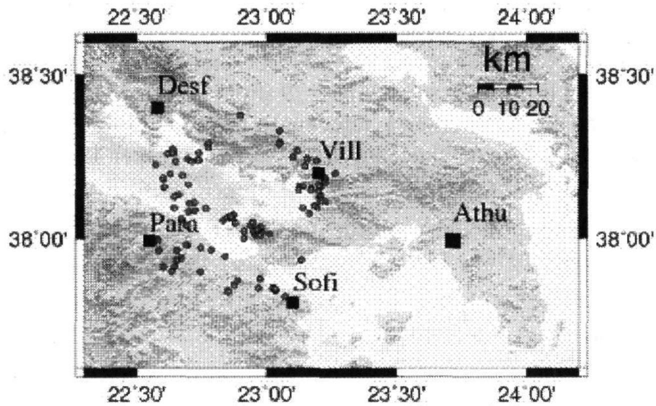

Figure 2 - The permanent digital Cornet Telemetric Network and epicenters of the events used for the calculation of the velocity model

Table 1 – Stations of the Cornet Network

Station Name	Location	Longitude (°E)	Latitude (°N)	Altitude (m)	Events ≥
Athu	Athens	23.785	37.962	307	70
Desf	Desfina	22.594	38.425	983	5000
Para	Paradisi	22.640	37.947	782	1600
Sofi	Sofiko	23.064	37.805	719	1200
Vill	Villia	23.247	38.184	1384	800

The network initially consisted of 5 stations, but due to hardware limitations only 4 stations operated. At the beginning 3 seismometers of 1Hz were installed at each station. Following, these seismometers were replaced with 3D 5 sec Lennartz seismometers. The station coordinates of the Cornet network, as well as the number of events recorded by each station for the time period October 1995 – December 1997, are presented in Table 1. The network is also equipped with a Lennartz 5800 PCM central system. The recorded signals are transmitted directly or through repeaters to the central station, located in the premises of the Faculty of Geology and Geoenvironment of the University of Athens, via antennas at predefined frequencies. The main goal of installation of the network was the recording of all local events and the accurate determination of their source parameters. Furthermore, analysis of local earthquakes recorded by the Cornet network and located in the Gulf of Corinth has revealed the existence of shear-wave splitting, consistent to the extensive dilatancy anisotropy (EDA) model (Papadimitriou *et al.* 1999, Kaviris 2003).

All data used in the present study are recordings of the digital stations of the Cornet network for the time period October 1995 – December 1997. The velocity model was determined using 103 events, whereas for the calculation of both the duration magnitude and the moment magnitude the same dataset that comprises of 101 events with $M_D \leq 4.5$ was used.

2.2. Velocity Model

The velocity model that was initially used for the location of the events recorded by the Cornet network was the one obtained by Rigo *et al.* (1996). The calculation of a reliable velocity model is necessary for the best possible determination of hypocenters and of source parameters. The first step was the Vp/Vs ratio determination, using the Chatelain (1978) method that takes into account all events. The events used for that purpose were the ones located around the Eastern Gulf of Corinth (37°-47'N, 38°-27'N, 22°-33'E και 23°-16'E). The Vp/Vs ratio was calculated using difference of P and S arrival times and is equal to 1.79 (Fig. 3) both when all the above-mentioned events were used and when selection criteria, relevant to location errors, were applied. The Vp/Vs ratio obtained by other studies in neighboring areas varies between 1.77 and 1.83 (King *et al.* 1985, Melis *et al.* 1989, Hatzfeld *et al.* 1990, Amorese 1993, Rigo *et al.* 1996).

In the present study the velocity model was calculated using the RMS minimization method for each seismic layer (Crosson 1976). The events used for that purpose fulfilled the following criteria: a.) Area: 37°-47΄N, 38°-27΄N and 22°-33΄E, 23°-16΄E, b.) Number of Phases ≥ 6 and c.) RMS<0.3 sec, ERH<5 km, ERZ<5km.

The 103 events that matched these criteria are presented in figure 2. The obtained dataset formed a representative sample both in vertical and horizontal distribution. Furthermore, both systematic and random errors are reduced. The obtained velocity model consists of six (6) layers, the first of which extends until a depth of 1.3 km (Table 2).

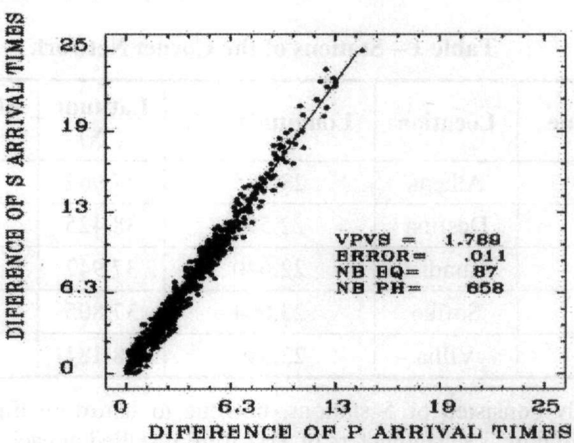

Figure 3 - Vp/Vs Ratio Estimation

Following, the model was verified by using a larger dataset. It was also compared with the one determined by Rigo *et al.* (1996) for the Western Gulf of Corinth and gave better results.

The obtained velocity model and the HYPO71 program (Lee and Lahr, 1975) were used to locate the microseismic activity which was recorded in a very detailed way by the Cornet network (Fig.

4). Concentration of seismic sources was observed within the Gulf of Corinth, along a line with a NW-SE direction. An important number of epicenters was located very close to the Cornet stations. The seismicity can be related to the main normal active faults of the area. Focal depths of the majority of the located events vary from 5 to 15 km.

Table 2 – Velocity Model

Velocity Vp (km/sec)	Depth (km)
4,5	0,0
5,5	1,3
5,7	4,2
6,1	7,0
6,3	11,5
6,5	16,5
7,0	30,0

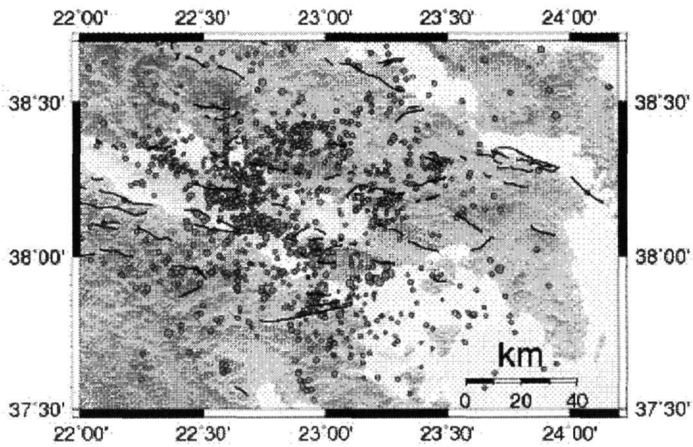

Figure 4 - Epicenters located by the Cornet network for the period 1995-1997. Faults of the area are also presented

2.3. Determination of Duration Magnitude M_D

One of the most commonly used magnitude scales for rapid magnitude determination by local networks is the duration magnitude M_D (Tsumura 1967, Lee *et al.* 1972, Tsujiura 1978, Suteau and Whitcomb 1979, Bakun 1984). The duration magnitude is calculated using the formula (Hermann 1975):

$$M_D = \alpha + \beta \cdot \log D + \gamma \cdot \Delta$$

where D is the total signal duration in seconds (until the signal to noise ratio is equal to 1), Δ is the epicentral distance in kilometres and α, β, γ constants.

In order to obtain a reliable duration magnitude the constants α, β, γ were determined. The selected dataset consisted of 101 earthquakes for which the Local Magnitude (M_L), calculated by the Geodynamic Institute of the National Observatory of Athens, and the body wave magnitude m_b, calculated by the ISC, were both available. The epicentral distances of these events varied between 10 and 200 km.

Following, software was developed for the determination of the constants α, β and γ using linear multiple regression. The whole mathematical procedure is described in detail by Kaviris (2003). The values of the constants α, β, γ, standard deviation s and coefficient of determination (goodness of fit) R^2 were calculated for each station and are presented in Table 3. In many cases worldwide, the values of α, β, γ are not the same for all the stations of a network and corrections are calculated for each station (Mouayn *et al.* 2004). Nevertheless, for the Cornet Network the values of the constants α and γ were identical for all the stations and the constant β varied only between 2.34 and 2.36. For these reasons no station correction is needed and the constants α, β, γ were following calculated for the whole Cornet Network (Table 3).

Table 3 – Values of the constants α, β, γ, standard deviation s and coefficient of determination (goodness of fit) R^2 for each station and for the whole Cornet Network

Station Name	α	β	γ	s (Richter)	R^2	Observations
Desf	-1.1	2.34	0.0012	0.029	0.988	92
Para	-1.1	2.36	0.0012	0.027	0.991	98
Sofi	-1.1	2.34	0.0012	0.028	0.991	89
Vill	-1.1	2.35	0.0012	0.025	0.992	73
CORNET	**-1.1**	**2.35**	**0.0012**	**0.027**	**0.991**	**352**

Whence the obtained formula is:

$$M_D = -1.1 + 2.35 \log D + 0.0012\ \Delta$$

The obtained values of the constants α, β and γ were compared with the ones calculated by other studies in Greece (Table 4). The value of the constant γ coincides with the one given both by Kiratzi (1984) and by Tselentis (1997). The values of the constant α vary between -1 (Tselentis 1997) and -1.28 (Kiratzi 1984), while the value -1.1 obtained by the present study lies between them. The obtained value of the constant β is slightly larger compared to the one obtained by the other two studies. Concerning the errors, the standard deviation s for the Cornet Network is approximately 7.5 times smaller than the one given by Kiratzi (1984) and 4.5 to 6 times smaller than the one given by Papanastassiou (1989). The coefficient of determination (goodness of fit) R^2 was found equal to 0.991 (99.1 %), almost equal to 1 (100 %) These very satisfactory values of errors of determination of the constants α, β and γ, guarantee that the Duration Magnitude M_D calculated by the Cornet Network is reliable.

Following, using the least-squares method, relations between the duration magnitude M_D, calculated by the Cornet Network, the Local Magnitude (M_L), calculated by the Geodynamic Institute of the National Observatory of Athens, and the body wave magnitude m_b, calculated by the ISC, were obtained. These relations are:

Table 4 –Values of the constants α, β, γ, standard deviation s and coefficient of determination (goodness of fit) R^2 in Greece

Author	α	β	γ	s (Richter)	R^2	Observations
Kiratzi (1984)	-1.28	2.31	0.0012	0.20	0.83	958
Papanastassiou (1989)	-0.4226 to 0.8506	1.301 to 1.911	0.0006 to 0.0030	0.126 to 0.165	0.943 to 0.970	118 to 630
Tselentis (1997)	-1	2.31	0.0012	-	-	-
Present Study	**-1.1**	**2.35**	**0.0012**	**0.027**	**0.991**	**352**

$m_b = 1.03\ M_D - 0.03$ for $3.0 \le M_D \le 4.5$, $R^2=0.81$

$M_L = 1.06\ M_D - 0.31$ for $3.0 \le M_D \le 4.5$, $R^2=0.66$

2.4. Determination of Moment Magnitude M_W

The next goal was the determination of the moment magnitude M_W. This is considered to be the most reliable magnitude scale, since it is not saturated and does not depend on the frequency window.

The calculation of the seismic moment M_0 was performed using spectral analysis (Aki, 1967), through the equation (Thatcher and Hanks 1973):

$M_0 = 4\pi\rho\beta^3\Omega_0 R/0.85$

The Moment Magnitude M_W is calculated as (Hanks and Kanamori 1979):

$$M_W = \frac{2}{3}\log M_0 - 10.73$$

It is the first time in Greece that a seismic catalogue is created, where the moment magnitude M_W is directly calculated by processing digital data in near real time.

The response spectra of the Desf (component E-W) and the Sofi (component N-S) stations for the same earthquake (1-6-96) are presented in figures 5a and 5b, respectively. After the determination of the spectral amplitude Ω_0, the value of the seismic moment M_0 was found equal to $M_0 = 4 \cdot 10^{22}$ dyn•cm, resulting a moment magnitude M_W=4.2. Furthermore, the corner frequency is f_o=3 Hz.

After the independent calculation of both the Moment Magnitude M_W and the Duration Magnitude M_D a relationship between them was obtained (figure 6a), using linear regression:

$M_W = 0.99\ M_D + 0.61$ for $3.0 \le M_D \le 4.5$, R^2=0.63

This equation is similar with the one obtained by Papazachos *et al.* (1997) for Greece:

$M_W = 0.97\ M_L + 0.58$, where $M_L = M_D$

The relation obtained in the framework of the present study can be replaced by the:

$M_W = M_D + 0.6$

which is more practical and gives the same results.

Using linear regression, relations between the moment magnitude Mw and the local magnitude M_L (Geodynamic Institute of the National Observatory of Athens), the body wave magnitude m_b given by the ISC (Fig. 6b) and the seismic energy E were obtained:

$M_W = 0.63\ M_L + 2.04$ for $2.8 \le M_L \le 4.9$, R^2=0.44

$M_W = 0.77\ m_b + 1.37$ for $3.2 \le m_b \le 4.8$, R^2=0.52

$\log E = 1.61\ M_W + 7.97$ for $3.3 \le M_W \le 5.3$, R^2=0.52

3. Conclusions

The Gulf of Corinth is an asymmetrical active tectonic rift, characterized by normal faulting in an almost E-W direction. The Gulf has suffered destructive earthquakes since the antiquity and is an area of high tectonic, geodetic and seismological interest. The permanent Cornet network is installed since 1995 around the Eastern Gulf of Corinth.

For the best possible determination of hypocenters and of source parameters, a velocity model that consists of six seismic layers was calculated. The microseismic activity was recorded in a very detailed way. Concentration of seismic sources was observed within the Gulf of Corinth, along a line with a NW-SE direction. An important number of epicenters was located very close to the Cornet stations. The seismicity could be related to the normal active faults of the region.

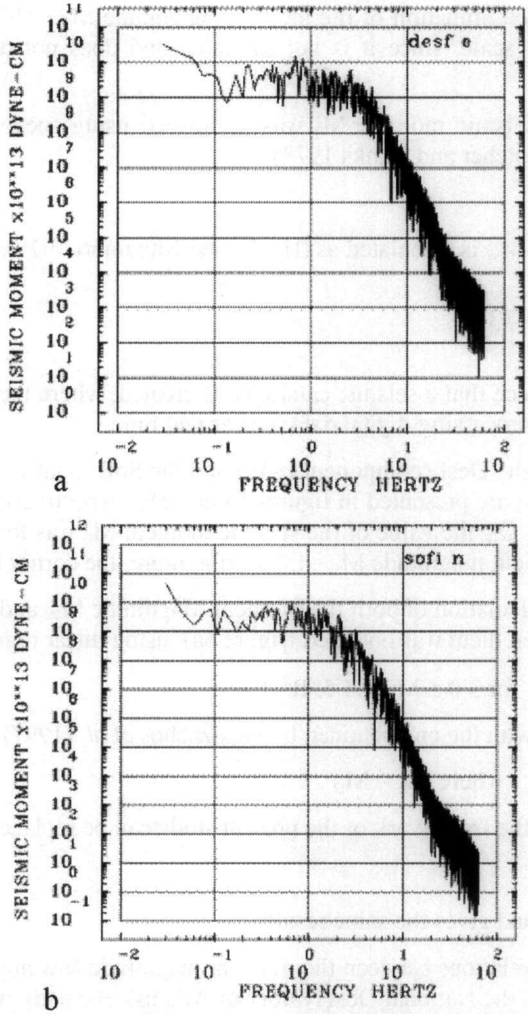

Figure 5 - Spectral analysis of the 1 June 2006 event for the calculation of the spectral amplitude Ω_0 and the value of the seismic moment for the stations *(a)* Desf and *(b)* Sofi

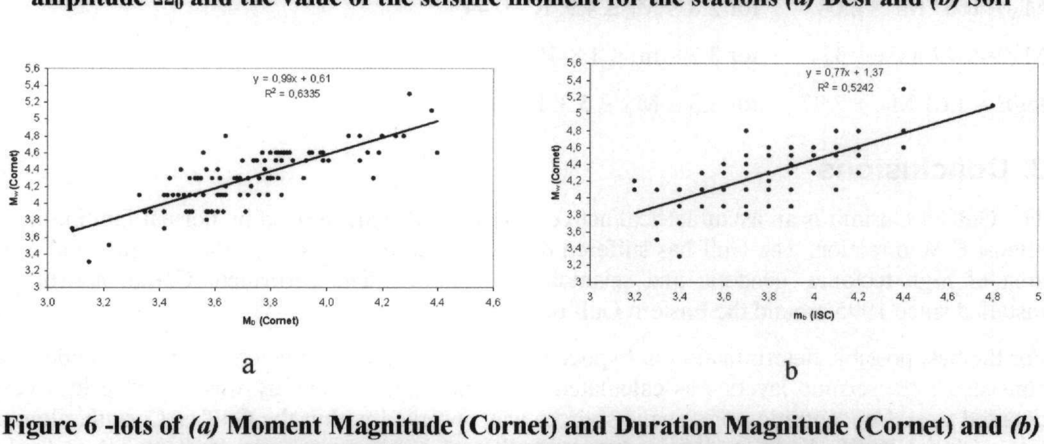

Figure 6 -lots of *(a)* Moment Magnitude (Cornet) and Duration Magnitude (Cornet) and *(b)* Moment Magnitude (Cornet) and Body Wave Magnitude m_b (ISC)

A reliable duration magnitude M_D was obtained using linear multiple regression. For that purpose the constants α, β and γ were calculated with small errors. Following, relations were obtained between the duration magnitude M_D, calculated by the Cornet Network, the Local Magnitude M_L, calculated by the Geodynamic Institute of the National Observatory of Athens, and the body wave magnitude m_b, calculated by the ISC.

The moment magnitude M_W was calculated using spectral analysis. This is considered to be the most reliable magnitude scale and a catalogue was created. The obtained relation between the two magnitude scales calculated by the Cornet Network reveals that the moment magnitude Mw is systematically 0.6 larger than the duration magnitude M_D.

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