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# The moment magnitude $M_w$ and the energy magnitude $M_e$ : common roots and differences

by

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## Abstract

Starting from the classical empirical magnitude-energy relationships, in this article the derivation of the modern scales for moment magnitude  $M_w$  and energy magnitude  $M_e$  is outlined and critically discussed. The formulas for  $M_w$  and  $M_e$  calculation are presented in a way that reveals, besides the contributions of the physically defined measurement parameters seismic moment  $M_0$  and radiated seismic energy  $E_S$ , the role of the constants in the classical Gutenberg-Richter magnitude-energy relationship. Further, it is shown that  $M_w$  and  $M_e$  are linked via the parameter  $\Theta = \log(E_S/M_0)$ , and the formula for  $M_e$  can be written as  $M_e = M_w + (\Theta + 4.7)/1.5$ . This relationship directly links  $M_e$  with  $M_w$  via their common scaling to classical magnitudes, and, at the same time, highlights the reason why  $M_w$  and  $M_e$  can significantly differ. In fact,  $\Theta$  is assumed to be constant when calculating  $M_w$ .

However, variations over three to four orders of magnitude in stress drop  $\Delta\sigma$  (as well as related variations in rupture velocity  $V_R$  and seismic wave radiation efficiency  $\eta_R$ ) are responsible for the large variability of actual  $\Theta$  values of earthquakes. As a result, for the same earthquake  $M_e$  may sometimes differ by more than one magnitude unit from  $M_w$ . Such a difference is highly relevant when assessing the actual damage potential associated with a given earthquake, because it expresses rather different static and dynamic source properties. While  $M_w$  is most appropriate for estimating the earthquake size (i.e., the product of rupture area times average displacement) and thus the potential tsunami hazard posed by strong and great earthquakes in marine environs,  $M_e$  is more suitable than  $M_w$  for assessing the potential hazard of damage due to strong ground shaking, i.e., the earthquake strength. Therefore, whenever possible, these two magnitudes should be both independently determined and jointly considered. Usually, only  $M_w$  is taken as a unified magnitude in many seismological applications (ShakeMap, seismic hazard studies, etc.) since procedures to calculate it are well developed and accepted to be stable with small uncertainty. For many reasons, procedures for  $E_S$  and  $M_e$  calculation are affected by a larger uncertainty and are currently not yet available for all global earthquakes. Thus, despite the physical importance of  $E_S$  in characterizing the seismic source, the use of  $M_e$  has been limited so far to the detriment of quicker and more complete rough estimates of both earthquake size and strength and their causal relationships. Further studies are needed to improve  $E_S$  estimations in order to allow  $M_e$  to be extensively used as an important complement to  $M_w$  in common seismological practice and its applications.

## Introduction

The moment magnitude  $M_w$ , as proposed and developed by Kanamori (1977) and Hanks and Kanamori (1979), is often considered as the only physically well defined, non-saturating magnitude scale and estimator of the earthquake size. The methodology of  $M_w$  determination is rather well developed and routinely practised in a standardized way since 1976 as a spin-off of the Harvard procedure of Centroid-Moment-Tensor solutions (Dziewonski et al., 1981). In contrast, the classical magnitude scales for local ( $M_L$ , Richter, 1935) and teleseismic earthquakes ( $m_B$  and  $M_S$ , Gutenberg, 1945a, b, and c; Gutenberg and Richter, 1956a), as well as a host of later introduced complementary or modified versions of them, are measured in

1 different period and bandwidth ranges, often with incompatible procedures that sometimes  
2 even have changed with time (Bormann et al., 2007 and 2009; Bormann and Saul, 2009a).  
3 This is most inappropriate for intermediate and long-term probabilistic seismic hazard  
4 assessment. Therefore, it has become widespread practice to convert traditional local or  
5 teleseismic magnitude values via empirical regression relationships into “equivalent”  $M_w$   
6 values (e.g., Papazachos et al., 1997, Stromeyer et al., 2004; Ristau et al., 2005, Scordilis,  
7 2006). This practice aims at the compilation of homogeneous, with respect to magnitude,  
8 earthquake catalogs suitable for intermediate- and long-term seismic hazard assessment with  
9  $M_w$  as the unified parameter to characterize earthquake size (e.g., Grünthal and Wahlström,  
10 2003, Braunmiller et al., 2005, Grünthal et al., 2009). Although understandable in view of the  
11 often confusing inhomogeneity of different magnitude data sets and lacking standards in  
12 traditional earthquake catalogues, this approach is generally too simple and physically not  
13 justified. Therefore, at least when assessing the hazards associated with actual earthquakes, it  
14 should be replaced by a knowledgeable use of different complementary magnitudes that have  
15 been determined on the basis of modern measurement procedures and standards,.  
16

17  
18 According to numerous authors (e.g., Kanamori, 1977 and 1983; Choy and Boatwright,  
19 1995; Bormann et al., 2002; Kanamori and Brodsky, 2004; Bormann and Saul, 2008 and  
20 2009; Bormann et al., 2009; Yadav et al., 2009; Di Giacomo et al., 2010a and b) a single  
21 magnitude practice overlooks the following considerations:  
22

- 23 a) That the moment magnitude  $M_w$ , derived via the static seismic moment  $M_0$ , is only a  
24 static measure of earthquake “size”, i.e., of the average tectonic effect of an  
25 earthquake.  $M_0$  depends on the difference in strain energy before and after an  
26 earthquake. Thus its value relates to the total non-elastic “work”  $W$  performed in the  
27 source volume but not on the actual time history of the faulting itself.
- 28 b) Accordingly,  $M_w$  and  $M_0$  do not provide direct information about the comparatively  
29 small fraction of released elastic wave energy  $E_S$  and its dominant frequency content.  
30 The latter, however, is largely controlled by the dynamic and kinematic characteristics  
31 of the rupture process and thus is highly relevant for assessing the actual damage  
32 potential associated with seismic energy radiated by an earthquake.
- 33 c) That this inherent limitation of  $M_w$  can only be overcome by a multi-magnitude  
34 approach based on measurements in different hazard-relevant frequency ranges.
- 35 d) For estimating the potential shake-damage of actual earthquakes, local magnitudes  
36 based on high-frequency and/or strong-motion amplitude measurements are  
37 particularly useful for producing shake maps. In reality, most earthquake-prone  
38 countries do not yet avail of the required dense and online operated strong-motion  
39 networks on their own territories. Such countries still have to rely on near real-time  
40 magnitude information provided by regional and global data centres that use modern  
41 broadband records, mostly within the teleseismic distance range.
- 42 e) Broadband records allow for the measurement of both moment magnitude  $M_w$ , based  
43 on long-period displacement data, and energy magnitudes  $M_e$ , based on ground motion  
44 velocity data over a wide range of periods. Both  $M_w$  and  $M_e$  are comparably well  
45 defined in a physical sense. It is their joint consideration which allows a more realistic  
46 quick assessment of the kind and seriousness of seismic hazard associated with an  
47 actual earthquake than  $M_w$  alone.

48 Therefore, we will look in this paper into both the common roots and physical differences  
49 of  $M_w$  and  $M_e$ , how they relate to fundamental classical magnitude standards, and how  
50 these two magnitudes could be used jointly in quick rough assessment of the earthquake’s  
51 damage potential.  
52  
53

## 54 **How was $M_w$ derived?**

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56  
57  
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60

1 Gutenberg and Richter (1956a) published the following standard regression relation  
 2 between medium-period body-wave magnitude  $m_B$ , measured at periods between about 2 and  
 3 20 s (see Abe, 1981) and surface-wave magnitude  $M_S$  measured at periods around 20 s:  
 4

$$5 \quad m_B = 0.63 M_S + 2.5 \quad (1)$$

6 and between  $m_B$  and released seismic energy  $E_S$ :  
 7

$$8 \quad \log E_S = 2.4 m_B - 1.2 \quad (2)$$

9 (if  $E_S$  is given in J = Joule and  $\log = \log_{10}$ ). The semi-empirical relationship (2) is just a rough  
 10 estimate with no error calculation through only 20 data points of different origin in the  
 11 magnitude range  $2 \leq m_B \leq 8.0$  and  $E_S$  has been estimated by the authors on the basis of an  
 12 equation for a wave group from a point source with magnitude-dependent amplitude and  
 13 waveform duration (Gutenberg and Richter, 1956b, and Figure 1 therein).  
 14

15 In the paper “The energy release in great earthquakes”, in which Kanamori (1977)  
 16 intended to estimate via known scalar seismic moments  $M_0$ , the following relationship is  
 17 given between the strain energy drop  $W$  and  $M_0$  for the case of “complete stress drop”  $\Delta\sigma$  in  
 18 the source and with  $\mu$  = average rigidity of the medium in the source area:  
 19

$$20 \quad W = W_0 (=E_S) = (\Delta\sigma/2\mu) M_0. \quad (3)$$

21 However, as explained in more detail in later sections herein on the physical basis of Eq.(3),  
 22 the latter is valid only under the assumptions that during earthquake rupture a) the energy  
 23 required for fracturing is negligible and b) the finally reached stress is equal to the stress due  
 24 to kinematic friction (“complete stress drop”, Orowan, 1960). However, the rupture process  
 25 may deviate from these conditions, as discussed already by Brune (1970; “partial stress drop”)  
 26 or by Savage and Wood (1971, “frictional overshoot”).  
 27

28 Further, Kanamori assumed  $\mu = 3-6 \times 10^{11}$  dyn/cm<sup>2</sup> = 3-6  $\times 10^4$  MPa in the source area  
 29 under average crust-upper mantle conditions, and on the basis of elastostatic  
 30 considerations (as earlier Knopoff, 1958) that also the *stress drop is nearly constant* with  
 31 values between some 20 and 60 bars = 2-6  $\times 10^7$  dyn/cm<sup>2</sup> = 2-6 MPa *for very large*  
 32 *earthquakes*. Users of the moment magnitudes scale in a much wider range down to  
 33 magnitude 3 (Braunmiller et al., 2002), 1 (Abercrombie, 1995) or even -4.4 (Kwiatek et  
 34 al., 2010) seem not to be aware of, or do not question, these underlying assumptions,  
 35 which lead via Eq. (3) to  
 36

$$37 \quad E_S = W_0 \approx M_0/(2 \times 10^4) \quad (4)$$

$$38 \quad \text{or} \quad E_S/M_0 = 5 \times 10^{-5} = \text{constant}. \quad (5)$$

39 Thus, if all these conditions were correct, one could easily calculate  $E_S$  from known  $M_0$  via  
 40 Eq. (5). Kanamori (1977) used this equation to introduce the non-saturating moment-  
 41 magnitude scale  $M_w$ . For practical applications  $M_w$  is a more convenient measure for the  
 42 overall deformation at the source and thus of the “size” of great earthquakes than  
 43

$$44 \quad M_0 = \mu S D \propto u_0 \quad (6)$$

(where  $S$  = rupture surface,  $D$  = displacement averaged over the rupture surface, and  $u_0$  = asymptotic long-period displacement amplitude of the source spectrum), because values of  $M_0$  range over many decades.

In order to scale  $M_0$  to magnitude, an energy-magnitude relationship was required. Yet, Eq. (2) was not suitable for this purpose anymore, since medium-period broadband  $m_B$  was no longer measured at western seismological stations and data centers after the global deployment of the US World-Wide Standard Seismograph System (WWSSN) in the 1960s. Therefore, Kanamori followed the proposal by Richter (1958) to insert Eq. (1) into (2) which yields:

$$\log E_S = 1.5M_S + 4.8. \quad (7)$$

This is the commonly referred to and most widely used ‘‘Gutenberg-Richter’’ energy-magnitude relationship’’.

However, theoretical considerations by Kanamori and Anderson (1975) indicated that  $\log E_S \propto 1.5M_S$  holds for moderate to large earthquakes, that energy estimates from  $M_S$  via Eq. (7) agree in this range fairly well with the static estimates according to Eq. (5) (see also Vassiliou and Kanamori, 1982) but that  $M_S$  tends to saturate for really great earthquakes, as strikingly documented by the great 1960 Chile ( $M_S = 8.3$ ) and 1964 Alaska earthquake ( $M_S = 8.5$ ). Therefore, Kanamori substituted  $M_S$  in the  $\log E_S$ - $M_S$  relationship with the symbol  $M_w$  for the envisaged non-saturating moment (or ‘‘work’’) magnitude. When using the above relationships in international standard units, one arrives via Eq. (5) at

$$\log E_S = \log M_0 - 4.3 = 1.5M_w + 4.8, \quad (8)$$

and when resolving it for  $M_w$ :

$$M_w = (\log M_0 - 4.3 - 4.8)/1.5 = (\log M_0 - 9.1)/1.5. \quad (9)$$

Eq. (9) is identical with the IASPEI (2005) standard formula  $M_w = (2/3) (\log M_0 - 9.1)$ , first proposed by Bormann et al. (2002). This equation avoids occasional differences of 0.1 magnitude units (m.u.) between  $M_w$  values calculated for identical  $M_0$  with a precision of one decimal caused by the too early rounding-off of the constant in the original  $M_w$  formula published by Hanks and Kanamori (1979). When introducing the parameter  $\Theta = \log(E_S/M_0)$  (termed ‘‘slowness parameter’’ by Okal and Talandier, 1989), the Kanamori condition (5) reduces to  $\Theta_K = -4.3 = \text{constant}$  and Eq. (9) reads via Eq. (8):

$$M_w = (\log M_0 + \Theta_K - 4.8)/1.5. \quad (10)$$

This way of writing reveals best both the physics and the classical empirical roots of  $M_w$ :

- 1.5 corresponds to the slope of the  $\log E_S$ - $M_S$  relationship (7) that has been derived via Eqs. (1) and (2);
- 4.8 is the constant in relationship (7) and
- $\Theta_K = -4.3 = \text{constant}$  results from Eq. (3) and the assumptions made by Kanamori (1977) on  $\Delta\sigma$  and  $\mu$ .

Physically, a ‘‘constant-stress-drop’’ scaling of an earthquake source-spectrum would mean that the low-frequency content of the spectrum, which controls  $M_0$ , would also control the high-frequency content, which chiefly contributes to the radiated seismic energy  $E_S$  (see Figure 1 in the last but one section).

This is, in fact, the oversimplified concept of seismic scaling according to Aki (1967), namely that the entire source spectrum could be specified by just one parameter such as seismic moment or a unique magnitude. However, as spelled out earlier, e.g. by Kanamori (1978, 1983), Duda and Kaiser (1989), Bormann et al. (2002), a single magnitude cannot describe essential differences in source characteristics. Beresnev (2009) also emphasises that earthquake dislocation is controlled, even in the simplest case, by at least two independent parameters, namely 1) the final static offset and 2) the speed at which it is reached. The former controls the low-frequency asymptote of the spectrum, whereas rupture speed and stress drop essentially control the position of the source-spectrum's corner frequency  $f_c$  and thus the high-frequency content of the radiated spectrum (compare Figs. 1 and 2). These differences necessitate the development of an energy magnitude which is based on direct calculations of  $E_S$  from the seismic records, thus being free of presuppositions such as constant rigidity, stress drop and/or rupture velocity.

### How was $M_e$ derived?

Choy and Boatwright (1995) scaled the energy magnitude  $M_e$  to  $M_S$  in a similar way as Kanamori (1977) scaled  $M_w$  with the Gutenberg-Richter relationship (7). However, instead of making assumptions about the ratio  $E_S/M_0$ , they calculated  $E_S$  directly by integrating squared broadband velocity amplitudes over the duration of the  $P$ -wave train and corrected the integral for wave propagation and source radiation pattern effects based on suitable Earth and source models. Then they plotted for hundreds of earthquakes  $\log E_S$  over the respective  $M_S$  values between 5.5 and 8.3 and determined from a standard least-square regression the best fitting straight line with the prescribed slope of 1.5 as in Eq. (7). Thus, however, they found instead of the constant 4.8 in relation (7) the constant 4.4 that yielded a better average fit through the data cloud. Nevertheless, Choy and Boatwright decided in their 1995 paper: "For consistency with historical computations as well as with other types of magnitude that have been derived from the Gutenberg-Richter formula, we retain the original constants". Thus they arrived at

$$M_e = (2/3)\log E_S - 3.2 = (\log E_S - 4.8)/1.5 \quad (11)$$

with  $E_S$  in units of Joule. Note: If this mutual scaling of  $M_w$  and  $M_e$  with Eq. (7) would have been kept, and if  $\Theta_{av} = \Theta_K$  would indeed hold on a global average, then the mean difference between  $M_w$  and  $M_e$  would be zero for a representative global event data set. The latter, however, is not the case. Therefore Choy and Boatwright reverted in subsequent papers to the better fitting constant of 4.4 and changed Eq. (11) to

$$M_e = (2/3) \log E_S - 2.9. \quad (12)$$

Until recently, Eq. (12) has been used to calculate the  $M_e$  values published by the US Geological Survey's National Earthquake Information Center (NEIC). Yet this same equation still had the same problem of too early rounding-off the constant (which should be 2.9333... instead of 2.9) as the original  $M_w$  formula published by Hanks and Kanamori (1979). This can be avoided by starting from the best fitting regression to real data in Choy and Boatwright (1995),

$$\log E_S = 1.5M_S + 4.4, \quad (13)$$

replacing  $M_S$  by  $M_e$  and resolving it for  $M_e$ . This yields

$$M_e = (2/3)(\log E_S - 4.4) = (\log E_S - 4.4)/1.5. \quad (14)$$

1 First proposed by Bormann et al. (2002), Eq. (14) is equivalent with the writing of Eq. (9) for  
 2  $M_w$  and now is accepted as standard also at the NEIC/USGS.  
 3  
 4

### 5 **How do the formal definitions for $M_w$ and $M_e$ physically relate to each other?**

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 8 According to the above line of deductions, the energy/moment ratio  $E_S/M_0$  is evidently a  
 9 very useful parameter that characterizes the dynamic properties of an earthquake (Aki, 1966;  
 10 Wyss and Brune, 1968). Kanamori and Brodsky (2004) termed it “scaled energy”, which is in  
 11 fact the seismic energy radiated per unit of moment release. According to (3) it holds  
 12  
 13

$$14 \quad E_S/M_0 = \Delta\sigma/2\mu = \tau_a/\mu \quad (15)$$

15  
 16 with  $\tau_a$  = apparent stress according to Wyss and Brune (1968), which can also be written as  $\tau_a$   
 17 =  $E_S/(D \cdot S)$ . Thus,  $\tau_a$  is equivalent to the seismic energy release per unit area of the ruptured  
 18 surface times slip.  
 19

20 In order to make the physical relationship between  $M_w$  and  $M_e$  according to the above  
 21 stated conditions better tractable, one should write (14) in a form that is comparable with (9)  
 22 and (10) in order to reveal the dependence on rigidity, stress drop and apparent stress,  
 23 respectively. From  $E_S/M_0 = 10^\Theta$  follows  
 24  
 25

$$26 \quad \log E_S = \log M_0 + \Theta. \quad (16)$$

27  
 28 Inserting (16) in (14) yields  
 29  
 30

$$31 \quad M_e = (\log M_0 + \Theta - 4.4)/1.5 \quad (17)$$

32  
 33 and through a few more steps one arrives at  
 34  
 35

$$36 \quad M_e = M_w + (\Theta + 4.7)/1.5 = M_w + [\log(E_S/M_0) + 4.7]/1.5 \quad (18a)$$

$$37 \quad = M_w + [\log(\Delta\sigma/2\mu) + 4.7]/1.5 \quad (18b)$$

$$38 \quad = M_w + [\log(\tau_a/\mu) + 4.7]/1.5. \quad (18c)$$

39  
 40  
 41 Eq. (11) in the paper by Choy and Boatwright (1995) is essentially equivalent with eq. (18c),  
 42 however with other constants, because it was still derived via Eq. (7) instead of (13), and it  
 43 expresses  $E_S$  in terms of  $M_0$  instead of  $M_w$ .  
 44

45 By comparing Eqs. (10) and (17), it becomes very obvious why  $M_w$  and  $M_e$  differ. First,  
 46 there is a constant offset of 0.27 m.u. due to the different constants in the brackets, namely 4.8  
 47 and 4.4. Moreover, there is a variable difference, namely that between  $\Theta_K = -4.3 = \text{constant}$   
 48 and the highly variable real  $\Theta$  of earthquakes, which may range between about -3.2 and -6.9  
 49 (e.g., Choy et al., 2006; Weinstein and Okal, 2005; Lomax and Michelini, 2009a). This  
 50 explains possible differences between  $M_w$  and  $M_e$  by more than a magnitude unit.  
 51  
 52

53 Eq. (18a-c) may be helpful for calculating values of  $\Theta$ , or the dimensionless ratios  $E_S/M_0$ ,  
 54  $\Delta\sigma/2\mu$  or  $\tau_a/\mu$ , respectively, but only when  $M_w$  and  $M_e$  have been reported for a given  
 55 earthquake. From (18a) it is also obvious that  $M_w = M_e$  holds true only for earthquakes with  $\Theta$   
 56 = -4.7. But in no event should these equations be used for converting  $M_w$  into  $M_e$  or vice versa.  
 57 Their purpose is only to show what makes the difference between these two magnitudes,  
 58 under what condition they are equal, how different they may become and what are likely  
 59 physical reasons for their difference.  
 60  
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According to Eq. (18b) there is a trade-off between changes in  $\Delta\sigma$  and  $\mu$ . For  $\mu = \text{constant}$  holds  $E_S \approx \Delta\sigma S D/2$  (Kostrov, 1974), i.e., for a given seismic moment  $M_0$ ,  $E_S$  varies proportional to stress drop  $\Delta\sigma$ .  $M_e = M_w$  corresponds to a stress drop of  $\Delta\sigma \approx 1.2$  to  $2.4$  MPa if Kanamori's (1977) assumption of  $\mu = \text{const.} \approx 3\text{-}6 \times 10^4$  MPa is valid. However, with  $\Theta = \Theta_K = -4.3$ , (18a) yields  $M_e = M_w + 0.27$  and a 2.5 times larger stress drop, as assumed by Kanamori (1977). This is rarely the case and surely not the average condition for earthquakes reported in the USGS SOPAR database (<http://neic.usgs.gov/neis/sopar/>). This indicates that Eq. (5) assumes a larger than empirically measured average ratio  $\Delta\sigma/\mu$  and related  $E_S$ . In fact, average values of  $\Theta$  for different global data sets of earthquakes with  $M_w$  between about 5.5 and 9 vary between -4.7 and -4.9 (Choy and Boatwright, 1995; Choy et al., 2006; Weinstein and Okal, 2005). Accordingly, on average one can expect  $M_e$  to be close to or somewhat smaller than  $M_w$ . If one accepts  $\Theta = -4.9$  as being most representative and, according to Weinstein and Okal, also in good agreement with established scaling laws, than this would correspond to an average global stress drop of only about 0.8 to 1.5 MPa, i.e., a factor 3 to 4 less than assumed by condition (5). This necessitates looking into the theoretical reasons which could explain these discrepancies. Moreover, since according to Eqs. (18a) and (18b)

$$\log(\Delta\sigma/2) = \log\tau_a = \log\mu + \Theta, \quad (19)$$

calculations of stress drop or apparent stress require to know besides  $\Theta$  also the rigidity  $\mu$  in the source volume sufficiently well. Yet uncertainties may be much larger than the factor of 2, which Kanamori (1977) had already accounted for. Especially in the case of slow tsunami earthquakes (Polet and Kanamori, 2000 and 2009) one has to assume much smaller rigidity values than for average crustal-upper mantle conditions. Tsunami earthquakes generate by definition much larger tsunami than expected from their respective  $M_w$ , and  $M_0$  values, most likely due to abnormally low rigidity along the rupture surfaces of shallow earthquakes in some shallow dipping marine subductions zones (Houston, 1999). In such cases – according to Eq. (6) – the product  $S \cdot D$  and thus the generated tsunami has for a given  $M_0$  to be larger in order to compensate for the smaller  $\mu$ . This illustrates the range of uncertainty in estimating  $M_w$  due to average assumptions made in deriving the  $M_w$  formula.

### Why do estimates of $E_S$ via Eqs. (3) to (5) tend to overestimate $\Delta\sigma$ and $E_S$ ?

When introducing the Kanamori (1977) relationship (3) in this paper, we indicated that this relationship is based on simplified assumptions about the rupture process because it does not yet consider the total energy balance of the rupture process, as later done by Kanamori and Brodsky (2004). Using their notations, namely  $E_R$  for radiated seismic energy (instead of the traditional  $E_S$ ),  $E_G$  for the fracture energy and  $E_H$  for the energy dissipated as heat due to kinematic friction on the fault, then the total change in potential energy due to the rupture process can be written as

$$\Delta W = E_R + E_G + E_H. \quad (20)$$

If the initial stress prior to rupturing is  $\sigma_0$  and the final stress reached after rupturing  $\sigma_1$ , which corresponds to a stress drop  $\Delta\sigma = \sigma_0 - \sigma_1$ , then the potential deformation energy at the source is

$$\Delta W = (\sigma_0 + \sigma_1)D \cdot S/2. \quad (21)$$



Further, with  $\sigma_f$  the kinematic friction, the frictional energy is

$$E_H = \sigma_f D S. \quad (22)$$

Kanamori and Brodsky (2004) then introduced the quantity  $\Delta W_0 = \Delta W - E_H$ , which is the difference between total change in potential energy and frictional energy. Inserting this into equation (20) yields  $\Delta W_0 = E_R + E_G$ , being the potential energy available for strain release, termed  $\Delta E_{T0}$  in a later publication by Kanamori (2006).

With the condition by Kanamori (1977 for deriving Eq. (3), i.e.,  $\sigma_1 \approx \sigma_f$ , one can replace in Eq. (22)  $\sigma_f$  by  $\sigma_1$ . When then inserting  $E_H$  in  $\Delta W_0 = \Delta W - E_H$  one arrives with Eqs. (21) and (6) at

$$\Delta W_0 = \Delta \sigma D S/2 = (\Delta \sigma/2\mu) M_0. \quad (23)$$

This is equivalent to Eqs. 3.14 – 3.16 and 4.36 in Kanamori and Brodsky (2004), with the right side being identical with Eq. (3). However,  $E_S = E_R = \Delta W_0$  holds only for  $E_G = 0$ , i.e., when neglecting the fracture energy  $E_G$  in the total energy budget. Generally, however, the radiated energy is less, namely

$$E_R = \Delta W_0 - E_G. \quad (24)$$

Husseini (1977) introduced the term of radiation efficiency

$$\eta_R = E_R/(E_R + E_G). \quad (25)$$

According to Kanamori (2006), Eq. (25) can also be written as

$$\eta_R = (2\mu/\Delta\sigma)(E_R/M_0) = E_R/\Delta E_{T0} = (E_R/\Delta W_0) \quad (26)$$

Then it becomes clear that  $E_S = E_R = (\Delta\sigma/2\mu)M_0$  holds only for  $\eta_R = 1$ , i.e., when all energy available for strain release is converted into seismic wave energy, and no energy  $E_G$  is dissipated during fracturing.

In this context it has to be clarified, however, that *radiation efficiency*  $\eta_R$  according to Eq. (25) should not be mistaken as the better known *seismic efficiency*  $\eta$ , which additionally accounts for the energy loss due to frictional heat  $E_H$ :

$$\eta = E_R/(E_R + E_G + E_H) \quad (27)$$

and, thus, is significantly smaller than  $\eta_R$ .

### Which other parameters besides $\Delta\sigma$ and $\mu$ may strongly influence radiation efficiency?

So far we have only discussed the influence of variations in stress drop, respectively  $\Delta\sigma/\mu$ , on the ratio  $E_S/M_0$  according to the formulas that were used to define  $M_w$  and  $M_e$ . But according to Newman and Okal (1998), even in the case of a kinematically simple rupture model this ratio is controlled by five dimensionless factors, namely the ratios (with different exponent) between 1) S- versus P-wave velocity, 2) rupture length versus rupture duration and Rayleigh-wave speed, 3) rupture velocity  $V_R$  versus shear-wave velocity  $\beta$ , 4) rupture width versus rupture length (i.e., the aspect ratio), and 5) fault slip versus rupture width. Moreover,

one has to be aware that especially in the case of large complex earthquakes, the amount and frequency content of radiated seismic energy is not chiefly controlled by the mean rupture velocity, stress drop and fault displacement over the whole fault, but rather by the respective values related to the braking of asperities, i.e., of major stress or rigidity/friction anomalies along the fault. Yet handling and determining so many parameters with sufficient reliability is usually not possible, and in no event in near real time. Therefore in the following we look only into one of these factors, namely the ratio  $V_R/\beta$ , because there are possibilities of near real-time estimates of  $V_R$  with recently developed procedures (e.g., Krüger and Ohrnberger, 2005). According to Venkataraman and Kanamori (2004a), both theory and empirical data confirm (although the latter only with great scatter) a trend of growing  $\eta_R$  with increasing  $V_R/\beta$ . The ratio may vary between about 0.2 to 0.95, yet being  $> 0.6$  for most of the large earthquakes so far analyzed.

According to Kostrov (1966) and Eshelby (1969) it holds for transverse shear cracks that  $\eta_R \approx (V_R/\beta)^2$ . Inserting this into Eq. (26) and resolving it for the ratio  $E_S/M_0$  yields

$$E_S/M_0 = \eta_R \cdot (\Delta\sigma/2\mu) \approx (V_R/\beta)^2 \cdot (\Delta\sigma/2\mu). \quad (28)$$

Although being model-dependent (and other models are likely to produce other relationships), Eq. (28) illustrates a trade-off between variations in stress drop, rigidity, rupture velocity and shear-wave velocity, which may control the ratio  $E_S/M_0$  and, thus, the relationship between  $M_w$  and  $M_e$ .

### Data that confirm both trend and individual event differences between $M_w$ and $M_e$

The general assumption that  $\eta_R = 1$  is not realistic. Published values of  $\eta_R$  (Venkataraman and Kanamori, 2004a; Kanamori and Brodsky, 2004; Kanamori, 2006) show large scatter due to uncertainties in the determination of  $E_S$ ,  $M_0$  and  $\Delta\sigma$ , as well as the limitations of the slip-weakening model assumed to calculate the partitioning of energy in earthquakes. For most earthquakes  $\eta_R$  ranges between 0.25 and 1, although smaller values - down to about 0.02 - have been determined as well. Strike-slip earthquakes tend to have, on average, the largest radiation efficiencies, yielding typically values  $M_e > M_w$  and the largest values of apparent stress or stress-drop inferred therefrom (e.g., Choy and Boatwright, 1995; Choy et al., 2004). The lowest values of  $\eta_R$  were found for tsunami earthquakes, for which generally holds that  $M_e \ll M_w$  (see below). The great 2004 Sumatra-Andaman earthquake ranged with an average value of  $\eta_R = 0.16$  between tsunami earthquakes and “normal” earthquakes. However, values have been significantly larger in the first rupture segment and dropped down to about 0.05, or even less, in the last two major rupture segments (Kanamori, 2006). Interestingly, the average value  $\eta_R = 0.16$  (as compared to  $\eta_R = 1$  for complete stress drop) would already fully explain the difference between  $M_e(\text{USGS}) = 8.5$  and  $M_w(\text{GCMT}) = 9.0$  for this Sumatra earthquake. In summary:

- The radiation efficiency of earthquakes and thus their ratio  $E_S/M_0$  varies over a wide range and may vary even within a given rupture process;
- The condition  $E_S/M_0 = 5 \times 10^{-5} = \text{const.}$ , on which the definition of the moment magnitude rests, would yield  $E_S$  estimates via  $M_0$  that are on average a factor of 2-3 times too large. Therefore, with procedures for direct energy estimates now being readily available (see next section) this condition should no longer be used for such estimates.
- The range of radiation efficiency variations explains the observed differences between  $M_w$  and  $M_e$ , which may reach more than  $\pm 1$  m.u. for the same event.

Very obvious is the influence of the rupture velocity in the case of tsunami earthquakes, e.g. the 1992  $M_w$  7.6 Nicaragua earthquake with  $M_e = 6.7$  and the more recent 2006  $M_w$  7.7 Java earthquake with  $M_e = 6.8$ . Moment-wise, both earthquakes are comparably large, yet their rupture durations  $T_R$  range between about 100 s and 220 s (Kanamori and Kikuchi, 1993; Hara, 2007b; Lomax and Michelini, 2009a; Bormann and Saul, 2008 and 2009b). According to the relationship  $T_R \approx 0.6M - 2.8$  by Bormann et al. (2009), this is about 2-4 times longer than expected on average for earthquakes of the same moment magnitude.

Other striking examples for differences between  $M_w$  and  $M_e$  are the 2 June 1994  $M_w$  7.8 Java tsunami earthquake where much smaller values were reported for  $M_e$  (6.5-6.8). This strongly contrasts with  $M_e \gg M_w$ , e.g. the 15 October 1997  $M_w$  7.1 Chile earthquake (Choy and Kirby, 2004) and the 12 January 2010  $M_w$  7.1 Haiti earthquake with  $M_e$  values of 7.5 and 7.6, respectively, associated with major devastations due to strong shaking. More examples are given by Di Giacomo et al. (2010a and b).

In the following we look into the different approaches and related uncertainties in calculating  $M_0$  and  $E_S$  values, each of which are the “measured” input parameters for  $M_w$  and  $M_e$  calculations respectively.

### Essential differences in measuring and calculating $M_0$ and $E_S$

The basic procedures for calculating (“measuring”)  $M_0$  and  $E_S$  have been outlined in many publications, e.g., Dziewonski et al. (1981), Boatwright and Choy (1986), Choy and Boatwright (1995), Bormann et al. (2002), Di Giacomo et al. (2010a,b). They will not be repeated here. Most important, however, is to note that the wave amplitudes measured, fitted with synthetics, or integrated when determining  $M_0$  or  $E_S$ , respectively, relate to rather different period and bandwidth ranges. This is illustrated with respect to the classical earthquake magnitudes  $m_b$ ,  $m_B$  and  $M_S$  in Fig. 1. This figure depicts seismic displacement and velocity source spectra scaled to seismic moment and moment rate, respectively, for model earthquakes with  $M_w$  in the range from 4 to 9. The spectral curves (solid lines) have been calculated with an  $\omega^{-2}$  source model (Aki, 1967, 1972). The Fourier transform of the moment rate function can then be expressed as  $\hat{M}(f) = (M_0 f_c^2)/(f^2 + f_c^2)$  (Houston and Kanamori, 1986; Polet and Kanamori, 2000) with the corner frequency  $f_c$  depending on stress drop and seismic moment according to the relationship given by Brune (1970)

$$f_c = c\beta(\Delta\sigma/M_0)^{1/3} \quad (29)$$

where  $\beta$  is the shear-wave velocity near the source (assumed to be 3.75 km/s),  $c = 0.49$  and  $\Delta\sigma = 3$  MPa.

In contrast to the smooth spectral curves in Fig. 1, real spectra calculated from noisy records of limited duration and bandwidth from earthquakes with different source-time functions and fault geometries will show fluctuating spectral amplitudes, sometime more than one corner frequency or a broad range of transition with different slopes from the displacement plateau to the final high-frequency drop-off, typically ranging between about -1 and -3 (e.g., Hartzel and Heaton, 1985; Boatwright and Choy, 1989; Polet and Kanamori, 2000; Baumbach and Bormann, 2002). Therefore, real source spectra may not be well matched by such a smooth “average”  $\omega^{-2}$  source model. Nevertheless, Fig. 1 allows for the discussion of essential differences and required bandwidth ranges for reasonably reliable measurements of  $M_0$  and  $E_S$ .

1 For accurate non-saturating estimates of  $M_0$  and thus of  $M_w$ , the displacement amplitudes  
 2 have to be sampled at frequencies much smaller than the corner frequency  $f_c$ , i.e., on the low-  
 3 frequency asymptote plateau amplitude  $u_0$  of the P- or S-wave source spectrum. Therefore,  $M_0$   
 4 and  $M_w$  are not affected by the variability of the high-frequency roll-off of the spectra.  
 5 Moreover, considering long and very-long periods, the calculation of  $M_0$  is also less affected  
 6 by small scale heterogeneities of the Earth structure along the travel paths and below the  
 7 recording seismic stations. This allows rather precise estimates of  $M_w$  with standard  
 8 deviations  $\leq 0.1$  m.u. (Ekström, 2007; personal communication).  
 9

10 In contrast, good estimates of seismic energy and thus  $M_e$  require the integration of the  
 11 squared velocity amplitudes over a wide frequency range, theoretically from 0 to  $\infty$  Hz (e.g.,  
 12 Haskell, 1964). However, in practice we can use only part of the spectrum, delimited by  $f_{min}$   
 13 and  $f_{max}$ . Different authors (e.g., Di Bona and Rovelli, 1988; Singh and Ordaz, 1994, Ide and  
 14 Beroza, 2001) investigated the effect of the bandwidth limitations on energy estimations. Here  
 15 we report the effect on  $M_e$  estimations when considering the  $\omega^{-2}$  model in Fig. 1 to be roughly  
 16 representative for most shallow earthquakes. In order to assess the possible influence of  
 17 variations in stress drop on such estimates, the same model was applied for  $\Delta\sigma$  varying in  
 18 increments of one order between 0.1 and 100 MPa. The related shift of  $f_c$  for these different  
 19  $\Delta\sigma$  values is shown for an earthquake with  $M_w = 6.5$  in Fig. 2 and in the inset for a wider  
 20 magnitude range between  $M_w$  5.5 and 8.5.  
 21

22 The chosen range of variations in  $\Delta\sigma$  is in agreement with the discussions in the previous  
 23 sections and encompasses most of the published data (e.g., Abercrombie, 1995; Kanamori and  
 24 Brodsky, 2004; Parolai et al., 2007; Venkataraman and Kanamori, 2004a). According to Fig.  
 25 2a, variations in  $\Delta\sigma$  do not influence at all the displacement plateau of the source spectrum  
 26 and thus estimates of  $M_0$  as long as the basic condition of analyzing only frequencies  $f \ll f_c$  is  
 27 observed. Only if this is violated, as sometimes by established routine procedures in the case  
 28 of extreme events, then also  $M_w$  may be underestimated. E.g., for the great 2004 Sumatra  
 29 earthquake, values between 8.2 and 9.0 were reported by different agencies before the final  
 30 value of 9.3 was established by way of special analysis (Stein and Okal, 2005; Tsai et al.,  
 31 2005). In contrast, according to Eqs (18a) and (18b) and in agreement with Fig. 2b, variations  
 32 in stress drop by one order are - for a given seismic moment - expected to change the released  
 33 energy by one order as well and thus the estimates of  $M_e$  by almost 0.7 m.u.. Therefore, the  
 34 determination of  $E_S$  and  $M_e$  requires to integrate the spectrum in a wide frequency range on  
 35 both sides of the corner frequency.  
 36

37 When assuming that the low frequency part of the source spectrum is available, then -  
 38 according to Singh and Ordaz (1994) -  $f_{max}$  should be 6 times  $f_c$  for an  $\omega^{-2}$  model in order to  
 39 assure that 80% of the total  $E_S$  is obtained from the integration of the source spectrum.  $M_e$   
 40 would then be underestimated only by 0.06 m.u.. This is negligible. However, the frequency  
 41 range covered by  $f_{min}$  and  $f_{max}$  may cut off significant amounts of seismic energy contained both  
 42 in the low- and the high-frequency part of the source spectrum, especially, if the bandwidth of  
 43 integration does not cover well frequencies around  $f_c$ . In the latter case  $M_e$  may be  
 44 underestimated up to a few tenths magnitude units.  
 45

46 Current routine procedures operate in the period ranges between 0.2-100 s (procedure  
 47 according to Choy and Boatwright, 1995, applied at the US Geological Survey (USGS)) or 1-  
 48 80 s (automatic near real-time procedure according to Di Giacomo et al., 2010a,b, applied by  
 49 the GFZ German Research Centre for Geosciences). Table 1 summarises the magnitude-  
 50 dependent underestimation of  $M_e$ ,  $-\Delta M_e$ , based on the model used for calculating Fig. 1 but  
 51 assuming variable stress drop between 0.1 and 100 MPa and integration over frequencies  
 52 between 12.4 mHz and 1 Hz only. For catching nearly 100% of the energy radiated by  
 53 earthquakes with magnitudes between  $5.5 \leq M_w \leq 8.5$  and stress drops between  $0.1 \leq \Delta\sigma \leq$   
 54 100 MPa one would need to consider frequencies between 0.001 Hz and 16 Hz. This is,  
 55 however, not realistic for routine  $M_e$  estimations using teleseismic P-wave records.  
 56  
 57  
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 65

Table 1. Estimates of  $-\Delta M_e$ , calculated for earthquakes of different moment magnitude  $M_w$  and stress drop  $\Delta\sigma$  when the integration is performed only in the frequency range between 12.4 mHz and 1 Hz. For the model used see text.

$\Delta\sigma$ (MPa)	$\Delta M_e$ for $M_w = 5.5$	$\Delta M_e$ for $M_w = 6.5$	$\Delta M_e$ for $M_w = 7.5$	$\Delta M_e$ for $M_w = 8.5$
0.1	0.05	0.02	0.05	0.25
1	0.13	0.03	0.02	0.10
10	0.30	0.08	0.02	0.03
100	0.66	0.19	0.05	0.02

According to Table 1, an  $E_S$  procedure operating in the bandwidth range from 1 to 80 s may underestimate  $M_e$  up to  $\sim 0.66$  m.u. for moderate ( $M_w \approx 5.5$ ) earthquakes with very high stress drop and thus  $f_c > f_{max}$ . But for most earthquakes with  $M_w$  between about 6.5 and 8.5 and intermediate  $\Delta\sigma$  between about 1 to 10 MPa the underestimation is expected to be  $< 0.1$  m.u. For great earthquakes ( $M_w > 8$ ) with  $\Delta\sigma < 1$  MPa (possibly  $f_c < f_{min}$ ),  $-\Delta M_e$  may also reach 0.2-0.3 m.u., or even more for extreme events. However, such estimates based on a simple source model, which can not account for source complexities under real conditions, must be used with caution. They can only give a rough orientation of the possible range of  $M_e$  underestimations. Underestimations for extreme events should be somewhat reduced by the more elaborate off-line USGS procedure that uses a slightly larger bandwidth and a residual integral above  $f_c$  (see Boatwright and Choy, 1986).

Besides the integration window, the calculation of  $E_S$  and  $M_e$  is mainly affected by the corrections for propagation effects and source complexities, especially at higher frequencies, which are not considered in  $M_w$  calculations. Correcting for high-frequency attenuation is one of the most challenging tasks. It requires a detailed knowledge of the velocity and attenuation structure along the propagation paths, and also especially below the seismic stations. The usually poor signal to noise ratio at frequencies higher than 1 Hz in the teleseismic range represents another big limitation, especially for moderate and small earthquakes. These combined difficulties and thus - as compared to  $M_0$  and  $M_w$  determinations - related larger possible errors are reasons that  $E_S$  and  $M_e$ , despite their importance in assessing the damage potential of earthquakes, have rarely been used for this purpose so far.

Fig. 3a shows the station distributions for four recent earthquakes with  $M_w$  7.6 and Fig. 3b the corresponding spectral amplitudes for four different periods between 1 and 8 s. The spectral amplitudes should show a smooth decay with distance. On average, this is reasonably well the case for all frequencies and mechanisms. This holds promise that with many good station's records available at different distances, azimuth and site conditions average estimates of  $E_S$  might be correct within a factor of about 2 to 3 (and thus  $M_e$  within about 0.2-0.3 m.u). Fig 3b reveals that, identical  $M_w$  notwithstanding, the observed spectral station amplitudes differ significantly, even when measured at nearby stations. Individual station values may scatter for the same source by a factor of 10 (Fig. 3b) due to source and propagation effects. With regard to propagation path effects, it is hoped that the rapidly increasing number of broadband stations deployed worldwide may soon allow for better accounting of the spectral amplitude attenuation along specific propagation paths and underneath individual station sites.

The influence of corrections on  $E_S$  for specific radiation patterns has been discussed by Boatwright and Choy (1986), and later by Newman and Okal (1998) and Pérez-Campos and Beroza (2001). Opinions differ especially with respect to strike-slip earthquakes, for which

$E_S$ - $M_e$  estimates published by the USGS tend to be systematically larger than other estimates (e.g., Di Giacomo et al., 2010a,b). Generally, corrections for source mechanism are not common for any classical magnitude such as  $m_B$  and  $M_S$ , and special investigations for short-period  $m_b$  (Schweitzer and Kværna, 1999), or  $E_S$ - $M_e$  estimates by other authors (e.g., Newman and Okal, 1998; Di Giacomo et al., 2010a,b) yielded evidence for much smaller or negligible effects within realistically achievable data precision. In this context it is interesting to see that according to Fig. 3b source mechanism-dependent differences in the measured uncorrected spectral amplitudes between the Izmit strike-slip event and the other three thrust events appear to be significant only for the longest period here considered (8 s), but to be absent or much less for shorter periods. This may be due to the larger complexity of source radiation patterns at shorter wavelengths, which are mainly controlled by smaller scale sub-ruptures with orientations that sometimes differ significantly from that of the average overall rupture, as well as due to multi-pathing in the heterogeneous Earth's medium, which is much more pronounced for shorter wavelengths. Further, directivity may affect single station estimates of  $E_S$  by a factor 2-3 (Venkataraman and Kanamori, 2004b) or even more. For most events, such kinds of corrections on a standard routine basis are still difficult and not manageable for near real-time procedures, although they might be considered desirable for more precise research-oriented off-line data processing. In any event, more studies are required to look into the raised pros and cons of such corrections, especially how large they are, not under idealized theoretical model assumptions but rather under real complex rupture and wave propagation conditions.

## Summary Discussion and Conclusions

We argue and demonstrate that the original scaling of moment magnitude  $M_w$  to seismic energy  $E_S$  via the classical Gutenberg-Richter magnitude-energy relationships is essentially arbitrary, as  $M_0$  is only a static measure of earthquake size. Thus,  $M_0$  carries no direct, model-independent information about the amount of seismic energy released, neither in total nor per unit of seismic moment. The ratio  $E_S/M_0$  depends on the kinematics and dynamics of the rupture process, which are chiefly controlled by the rigidity  $\mu$  of the source material, the rupture velocity  $V_R$  and the stress drop  $\Delta\sigma$  in the source volume. Besides several others, these are the main parameters that govern the radiation efficiency and the frequency content of the radiated source spectrum. Therefore, the formulas for calculating  $M_w$  and  $M_e$  have been rewritten in such a way that both their relationships to classic empirical Gutenberg-Richter magnitude-energy formulas and to essential physical source parameters become more obvious at a single glance.

The mutual relationship between  $M_w$  and  $M_e$  is best expressed by the following chain of equations:

$$M_e = M_w + (\Theta + 4.7)/1.5 = M_w + [\log(E_S/M_0) + 4.7]/1.5 = M_w + [\log(\Delta\sigma/2\mu) + 4.7]/1.5 \quad (30)$$

in which 1.5 is the slope of the Gutenberg-Richter relationship between  $\log E_S$  and surface-wave magnitude  $M_S$ . The left-side version of Eq. (30) reveals that  $M_e = M_w$  holds only for  $\Theta = \log(E_S/M_0) = \log(\Delta\sigma/2\mu) = -4.7$  and that for earthquakes according to the Kanamori condition in Eq. (5)  $M_e$  would be 0.27 m.u. larger than  $M_w$ . The versions of Eq. (30) in the middle and on the right side explain why for individual events  $M_e$  and  $M_w$  occasionally differ even more than 1 m.u. The reason is that the  $M_w$  formula has been derived by assuming  $\Theta_K = \log(\Delta\sigma/2\mu) = -4.3 = \text{constant}$  whereas  $M_e = (\log M_0 + \Theta - 4.4)/1.5$  accepts  $\Theta$  in the whole range of its variability between about  $-7 < \Theta < -3$ . This hints to variations in stress-drop, respectively the ratio  $\Delta\sigma/2\mu$ , by more than three orders of magnitude.

1 It is therefore that the difference between  $M_e$  and  $M_w$  be regarded as an important  
2 complementary piece of information in order to gain a more realistic and quick assessment of  
3 rupture peculiarities, and thus of the likely kind and severity of hazard associated with a given  
4 earthquake in its specific environmental context. Although a few examples have been given,  
5 many more carefully validated case studies comparing expected with really incurred effects  
6 are required before final conclusions can be drawn and recommendations be given on how to  
7 best use the difference between  $M_w$  and  $M_e$  in actual disaster management situations or long-  
8 term seismic hazard assessment schemes. In this context one should take into account that  $M_e$   
9 tends on average to be slightly lower than  $M_w$  because  $\Theta$  is in the global mean not -4.7 but  
10 more around -4.9. Therefore, larger  $M_e$  than  $M_w$  may hint already towards slightly larger than  
11 normal shaking damage potential than one would expected on the basis of  $M_w$  alone. and, if  
12  $M_e - M_w \geq 0.5$  m.u., one can for sure already expect much larger than usual devastation for the  
13 given moment magnitude, equal exposure and vulnerability conditions provided.

14 On the other hand, more than 0.6 m.u. smaller  $M_e$  values as compared to  $M_w$ ,  
15 corresponding to  $\Theta \leq -5.7$  hint to a significantly reduced relative potential for causing strong  
16 shaking damage in exposed vulnerable environs. But if such an earthquake occurs at shallow  
17 depth in a marine subduction zone and has an  $M_w > 7.5$  then it is most likely a dangerous  
18 tsunami earthquake (Lomax and Michelini, 2009a). However, being aware that  $M_e$  estimates  
19 are less reliable than those of  $M_w$  and are also possibly biased up to several tenths of  
20 magnitude units for rare but with respect to size stress drop and/or rupture velocity extreme  
21 events, one should be cautious not to overrate small differences in the order of 0.2-0.3 m.u.  
22 only.

23 In no event should the here derived relationships between  $M_w$  and  $M_e$  be misunderstood  
24 and used for converting  $M_w$  into  $M_e$  or vice versa. It is not the average agreement between  
25 these two magnitudes but their sometimes striking difference which carries the important  
26 complementary message as highlighted with the derived formulas in this paper. Accordingly,  
27 with a view to practical applications in the context of timely warning and/or more realistic  
28 near real-time risk assessments, it is recommendable to consider only the energy-moment  
29 ratio, respectively the related  $M_e - M_w$  difference as determined with current routine procedures  
30 despite their inherent shortcomings or still disputed problems both in definition and  
31 measurement practice. Nevertheless, they permit quick rough estimates of the efficiency of an  
32 earthquake to radiate seismic wave energy. This allows, when additionally complemented by  
33 rupture duration estimates as proposed by Lomax et al. (2007), Hara (2007a, b), Bormann and  
34 Saul (2008; 2009b) or Lomax and Michelini (2009a, b), for reasonably good discrimination  
35 between earthquakes with high tsunamigenic potential and those with higher than usual  
36 potential for a given  $M_w$  to cause other types of destruction in the affected areas.

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59 **FIGURE CAPTIONS**  
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1 **Fig. 1. a)** Far-field "source spectra" of ground displacement amplitudes  $A$  for a seismic shear  
2 source model (see text) as a function of frequency  $f$ , scaled to seismic moment  $M_0$  and the  
3 equivalent moment magnitude  $M_w$  and **b)** the same for ground motion velocity amplitudes  $V$ ,  
4 scaled to seismic moment rate and  $M_w$ . Note that the maximum seismic energy  $E_s \sim V^2$  is  
5 radiated around  $f_c$ . The arrows point to the frequencies at which the classical narrow-band  
6 magnitudes  $m_b$  and  $M_S(20)$  are measured. The horizontal bars cover the period range for  
7 measuring the IASPEI (2005) recommended broadband magnitude  $m_B$  for body-waves and  
8  $M_S(BB)$  for Rayleigh surface waves. Copy of Fig. 1 in Bormann et al. (2009, p. 1870), with ©  
9 granted by the Seismological Society of America.  
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14 **Fig. 2. a)** Far-field displacement and **b)** velocity source spectra scaled to seismic moment and  
15 moment rate, respectively, for model earthquake with  $M_w = 6.5$  but different stress-drop  $\Delta\sigma$  in  
16 units of MPa. The inset in Fig. 2b shows the variation of  $f_c$ , obtained according to Eq. (29), in  
17 a wider range of  $M_w$  for  $\Delta\sigma$  varying in increments of one order between 0.1 and 100 MPa.  
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22 **Fig. 3. a)** Global distributions of seismic stations which recorded four  $M_w = 7.6$  earthquakes  
23 (plotted with their GCMT fault plane solutions); **b)** Spectral amplitudes measured at periods  
24 of 1, 2, 4 and 8 s, at stations between  $20^\circ$  and  $98^\circ$  epicentral distance. The color of the  
25 "beach-balls" corresponds with the color of the station symbols and measured spectral  
26 amplitudes; blue inverted triangles: 1999-07-17 Izmit strike-slip earthquake; red triangles:  
27 2001-01-26 India earthquake; black circles: 2002-09-08 Papua New Guinea earthquake;  
28 magenta diamonds: 2005-10-08 Pakistan earthquake. The latter three earthquakes are thrust  
29 events. There is no obvious mechanism-dependent level-trend in the spectral amplitudes.  
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