

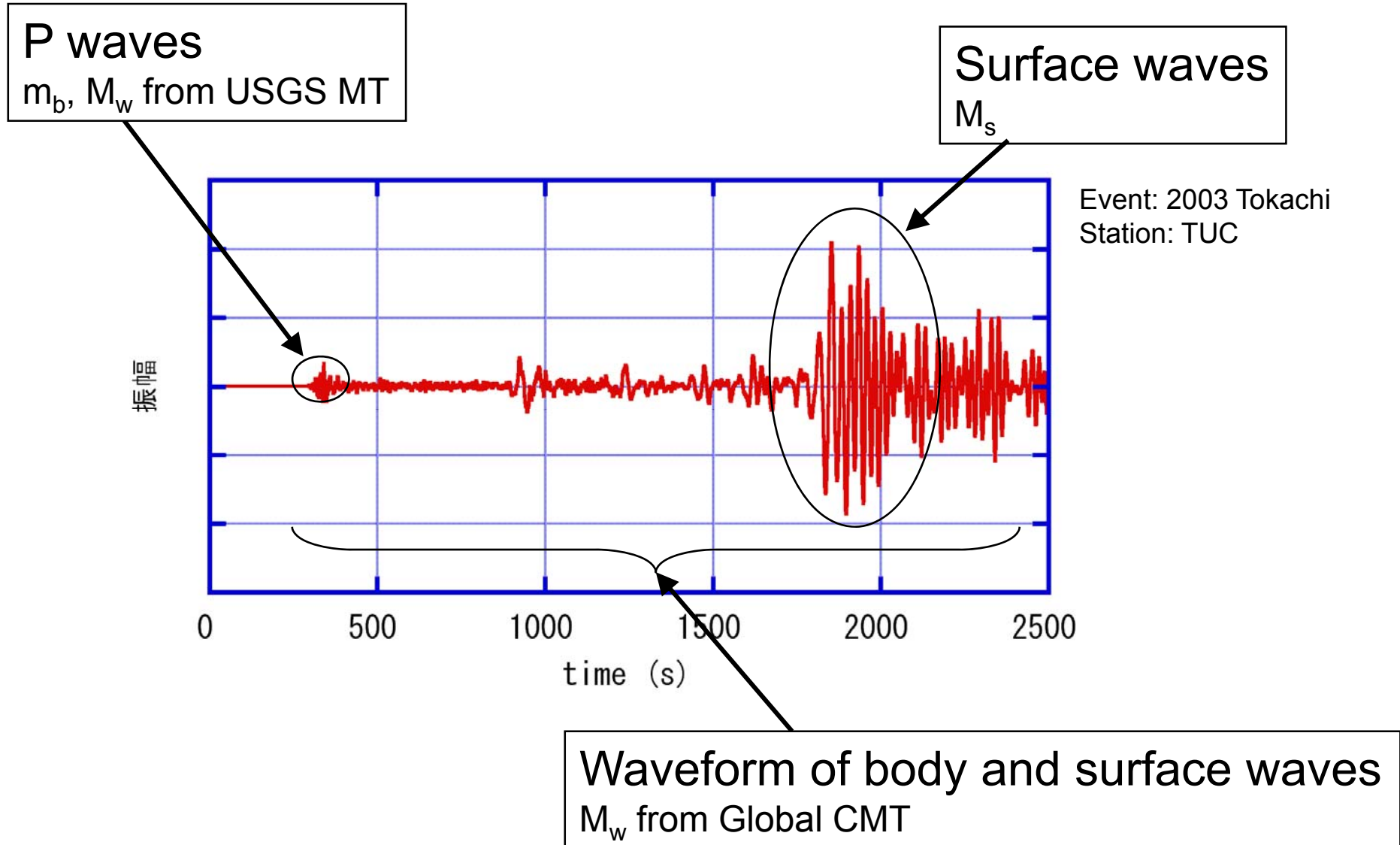
Determination of Broadband Moment Magnitude

Tatsuhiko Hara
(ISEE/BRI)

Various magnitude scales

- Body wave magnitude, m_b
based on amplitudes of P waves ($T \sim 1$ s)
- Surface wave magnitude M_s ,
based on amplitudes of surface waves ($T \sim 20$ s)
- Moment magnitude, M_w
based on moment tensor solutions such as USGS MT solutions and Global CMT solutions

Which part in seismograms is used?



Saturation of magnitudes

Geller, R. J., 1976. Scaling relations for earthquake source parameters and magnitudes, Bull. Seism. Soc. Am., 66, 1512.

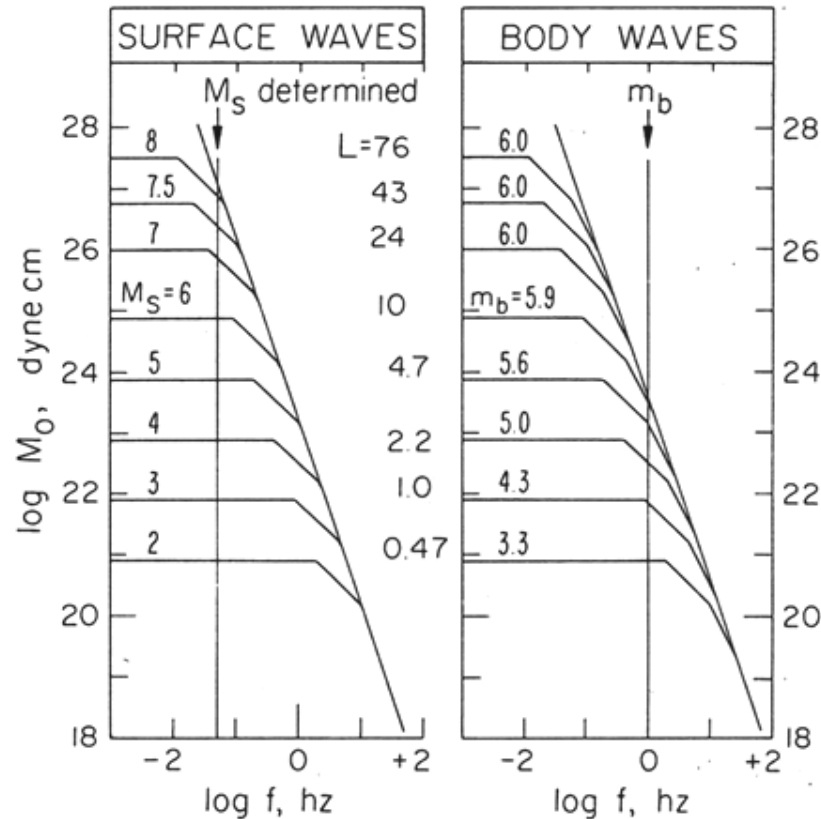


FIG. 4. Source spectra of surface waves (on left) and body waves. Both are identical at frequencies below the ω^{-2} corner frequency. The body waves have a higher width corner frequency than surface waves, which follows from (18), (20), (23) and (24). This difference occurs because teleseismic P waves, which take off essentially straight down, have a much higher apparent velocity (phase velocity) than surface waves. Therefore the separation between rise time and width corner frequencies (the ω^{-2} part of the spectrum) is much greater for body waves than for surface waves.

Typical source times

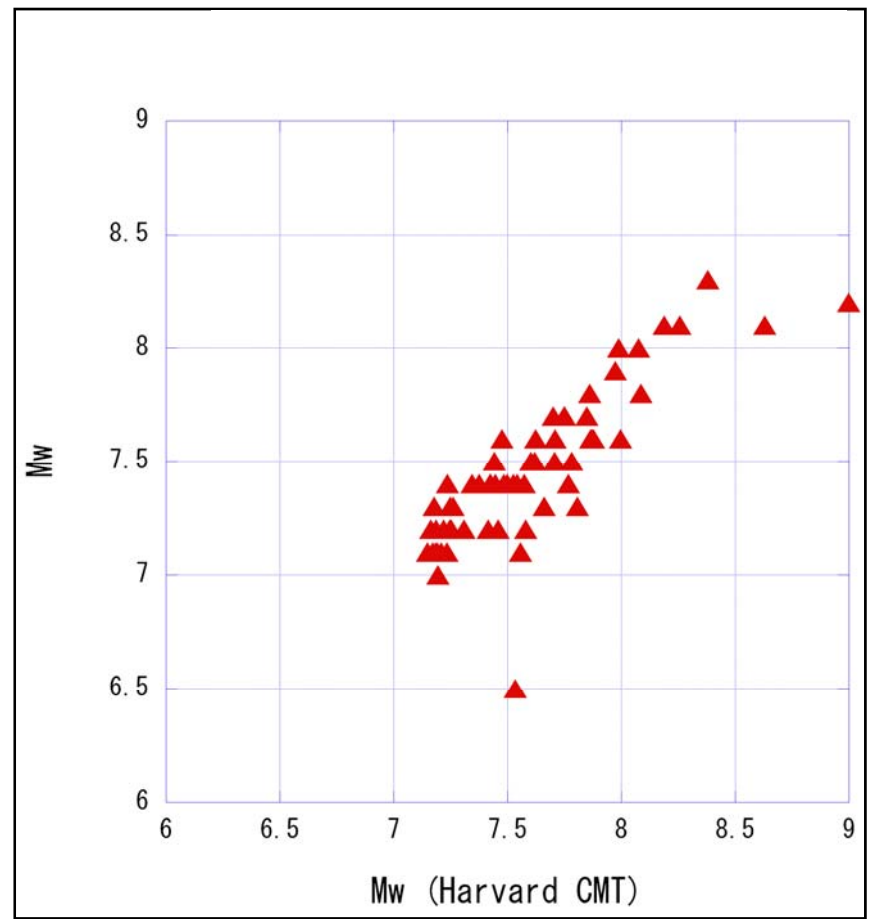
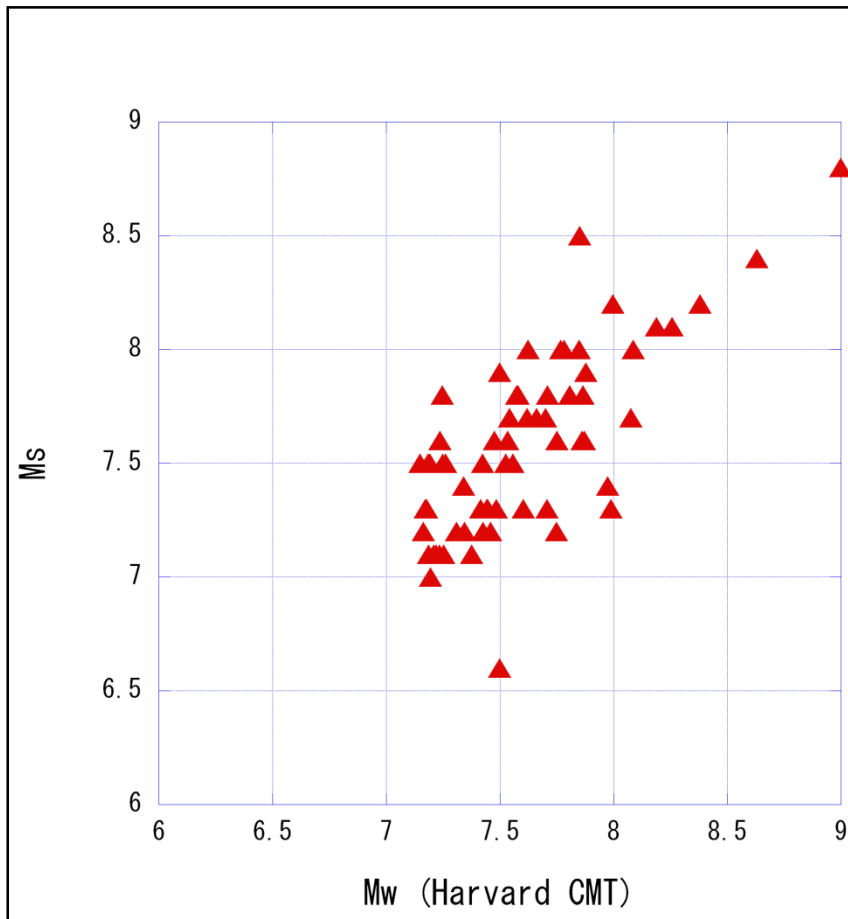
magnitude	Source time (s)
6	4.7
7	14.7
8	46.5
8.5	82.7
9	147.1

Estimates for some recent events

Event	m_b	M_s	M_w (USGS MT)	M_w (Global CMT)
2003/09/25 Tokachi	6.9	8.1	8.1	8.3
2004/12/26 Sumatra	7.0	8.8	8.2	9.0
2005/03/28 Sumtra	7.2	8.4	8.1	8.6
2005/10/08 Pakistan	6.9	7.7	7.3	7.6
2006/07/17 Java	6.1	7.2	7.2	7.7
2006/11/15 Kuril	6.5	7.8	7.9	8.3

Comparison of M_s , M_w (USGS) to M_w (Harvard CMT)

Period: 1994-2005; Depth: 0-50 km; $M \geq 7.2$



Broadband moment magnitude, M_{wp} (1)

- Tsuboi et al. (1995, 1999) developed a technique to determine earthquake magnitudes using broadband seismograms, which they called broadband moment magnitude (M_{wp}).
- This new magnitude scale has been utilized at the Pacific Tsunami Warning Center (PTWC) and the West Coast/Alaska Tsunami Warning Center WC/ATWC).

Broadband moment magnitude, M_{wp} (2)

- A vertical displacement of far-field P wave in a spherically symmetric media, u_z , at receiver x_r is given by

$$u_z(x_r, t) = \frac{F^P \dot{M}_o(t - T_p) R_s(x_r)}{4\pi\rho\alpha^3 R^P(x_r, x_s)} Q(t^*)$$

where

F^P : radiation pattern

M_o : seismic moment

T_p : travel time of P wave

R_s : station function

$R^P(x_r, x_s)$: geometrical spreading factor

$Q(t^*)$: Q filter

Relation between seismic moment and velocity, displacement, and integrated displacement

Velocity	$\propto \ddot{M}(t)$
Displacement	$\propto \dot{M}(t)$
Integrated displacement	$\propto M(t)$

If time dependence of seismic moment release is represented by a Step function, $H(t)$:

Velocity	$\propto \dot{\delta}(t)$
Displacement	$\propto \delta(t)$
Integrated displacement	$\propto H(t)$

Broadband moment magnitude, M_{wp} (3)

- Tsuboi et al. (1995) obtained the following formula

$$M_o = \max \left(\int u_z(x_r, t) dt \right) \frac{4\pi\rho\alpha^3 r}{F^p}$$

under the following assumptions:

$$R_s = 1.5$$

$$R^p = 1.2r$$

$$Q(t^*) = 0.8$$

Broadband moment magnitude, M_{wp} (4)

- They proposed the procedure consisting of the following steps to calculate broadband moment magnitude, M_{wp}

$$M_o' = \left| \max \left(\int u_z(x_r, t) dt \right) \right| 4\pi\rho\alpha^3 r$$

Seismic moment obtained neglecting the effect of radiation pattern

$$M_w' = \frac{1}{1.5} \left(\log M_o' - 9.1 \right)$$

Moment magnitude for M_o'

$$M_{wp} = M_w' + 0.2$$

Correction for radiation pattern

The second formula is from Kanamori (1977). Please note that the above M_w' is different from M_w obtained from moment tensors. The third step is performed to take the effect of radiation pattern into account.

Exercise

- Let us calculate M_{wp} by ourselves. The calculation consists of the following steps:

Tasks	SAC command
Baseline correction	rmean
Remove trend	rtr
Convert to velocity	div ????
Integration (to displacement)	int
Integration	int
Measure peak value	ppk

Improvements in M_{wp} calculation

- Tsuboi et al. (1999)
Using the first and second peaks
- Whitmore et al. (2002)
Magnitude dependent correction
- Hara et al. (2006)
Integration with Level Cross Method

Advantages and disadvantages of M_{wp}

- Advantages
 - Rapid: only first arriving P-waves are used
 - Wide applicability (Δ , magnitude, depth)
- Disadvantages
 - Ambiguity in integration interval
 - Difficulty in treatments of later phases such as PP and S
 - Possible saturation for huge earthquakes

Mantle magnitude, M_m

Okal and Talandier (1989) developed "mantle magnitude" M_m , which is determined by measurements at a variable long periods (51- 273 s):

$$M_m = \log X(\omega) + C_D + C_S - 0.90$$

where

$X(\omega)$: spectral amplitude at angular frequency, ω

C_D : distance correction (geometrical spreading and Q)

C_S : source correction (depends on period)

Comparison of M_m and M_w

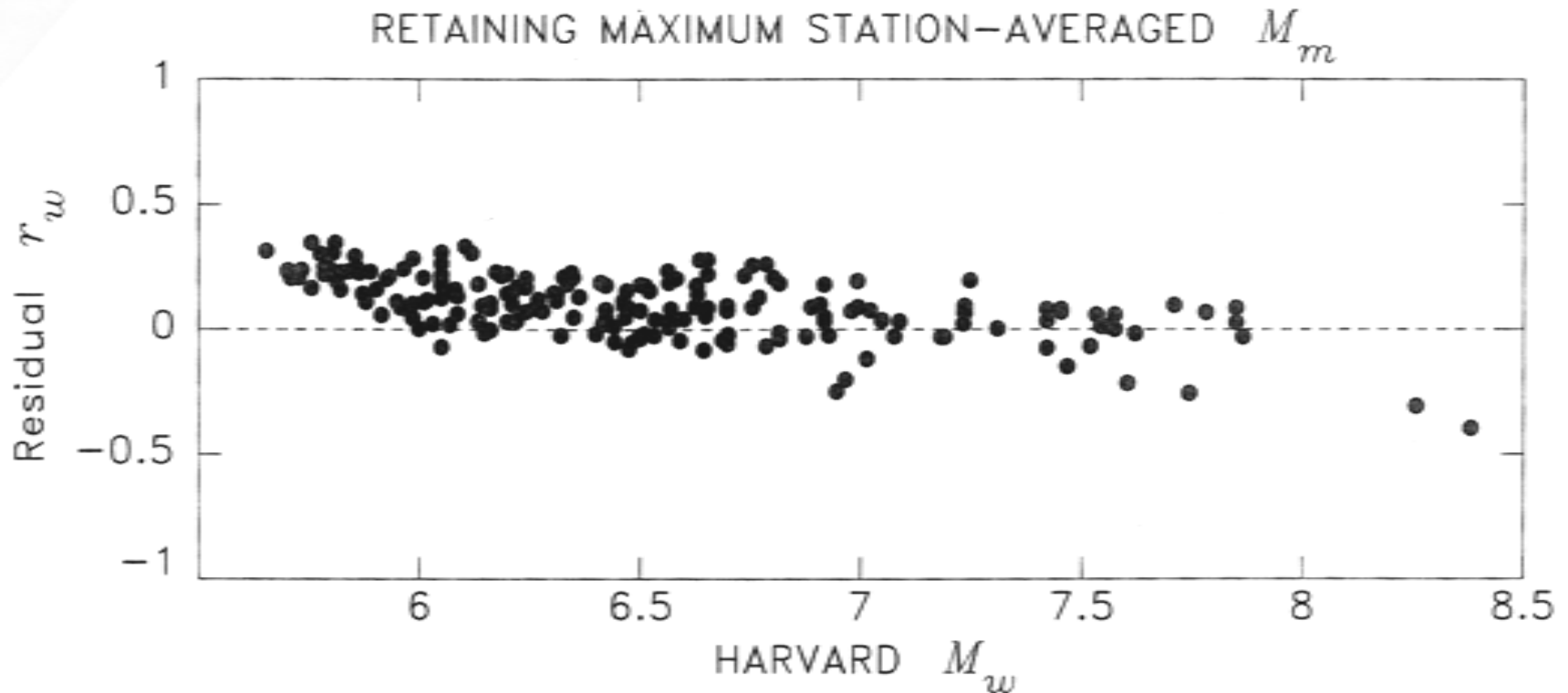


Figure 8. Population of residuals r_w obtained by first averaging M_m values at each period over all contributing stations (with some limitations on non-very-broadband instruments; see text for details), and then retaining the maximum value of the resulting averages over the full period range. Residuals are given against CMT moment values published by Harvard.

Ratio of seismic energy to moment, Θ

Newman and Okal (1998) defined the slowness parameter Θ as

$$\Theta = \log \left(\frac{E^E}{M_o} \right)$$

where

E^E : radiated seismic energy

M_o : seismic moment

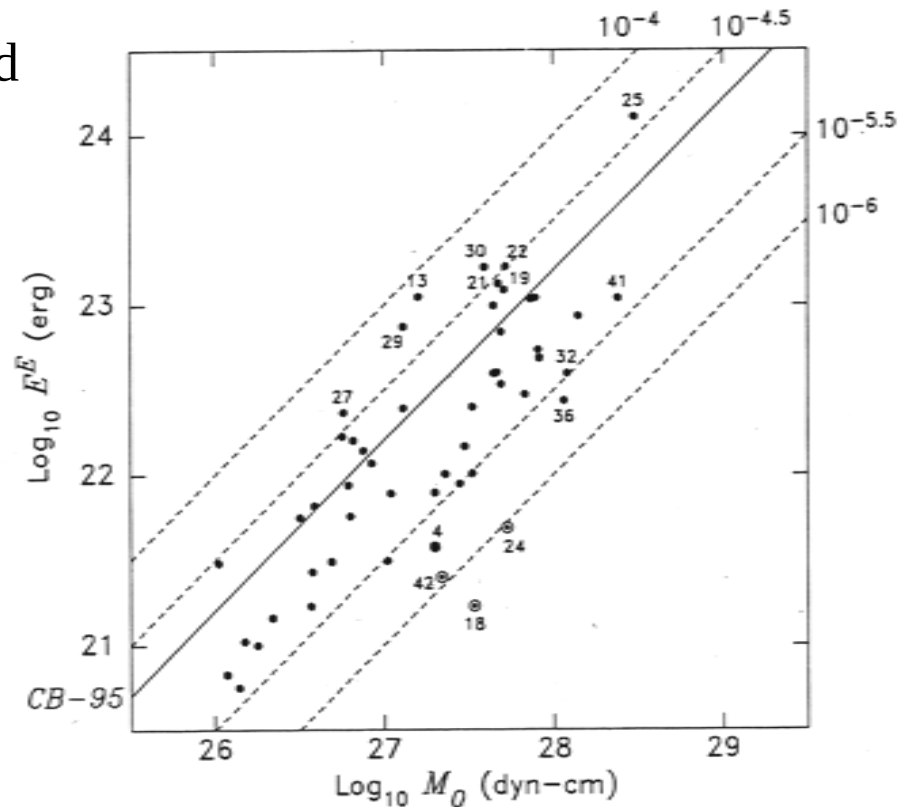


Figure 4. Estimated energy E^E versus seismic moment M_o for the 52 earthquakes in our data set. Diagonal lines correspond to constant values of E^E/M_o . The solid diagonal (labeled CB-95) is for the best fitting value obtained by Choy and Boatwright [1995]. Significant earthquakes described in the text are identified by their numbers, in Table 2. The three recent tsunami earthquakes are shown with circled points. The 1982 Tonga tsunami earthquake (Event 4) is shown with an enlarged solid symbol.

Newman A. V. and E. A. Okal, 1998. Teleseismic estimates of radiated seismic energy: The E/M_0 discriminant for tsunami earthquakes, J. Geophys. Res., 103, 26893.
Copyright 1998 American Geophysical Union.

Tsunami earthquakes

Event	Origin time (UT)	M _w	M _t	M _s
1992 Nicaragua	SEP 02, 00:16:01.6	7.6	8.0 ⁽¹⁾	7.2
1994 Java	JUN 02, 18:17:34.0	7.8	-	7.2
1996 Peru	FEB 21, 12:51:01.3	7.5	7.8 ⁽²⁾	6.6
2006 Java	JUL 17, 08 19 28.7	7.7	-	7.2

The origin times, hypocenters, and M_s are from the USGS bulletins. M_w is from the Harvard CMT catalog. (1) Ide et al., (1993); (2) Abe (1996).

Magnitude estimates of M_{wp} , M_w (M_m), and M_w

Event	M_{wp}	$M_w(M_m)$	M_w
1992 Nicaragua	7.2 ⁽¹⁾	7.55 ⁽²⁾	7.6
1994 Java	7.5 ⁽¹⁾	7.65 ⁽²⁾	7.8
1996 Peru	7.5 ⁽¹⁾	7.45 ⁽²⁾	7.5
2006 Java	7.2	7.4	7.7

(1) Tsuboi (2000). (2) $M_w(M_m)$ was introduced by Weinstein and Okal (2005). We calculated this scale using the averages of the M_m estimates presented by Newman and Okal (1998). M_{wp} and $M_w(M_m)$ for the 2006 Java earthquake are from PTWC. M_w is from the Global CMT catalog.

References

- Abe, K., Tsunami Magnitude of the 21 February 1996 Peru event ; E-mail communication via the tsunami bulletin board, 1996.
- Ekström, G., R. S. Stein, J. P. Eaton, D. Eberhart-Phillips, Seismicity and Geometry of a 110-km-Long Blind Thrust Fault 1. The 1985 Kettleman Hills, California, Earthquake, *J. Geophys. Res.*, **97**, 4843–4864, 1992.
- Geller, R. J., Scaling relations for earthquake source parameters and magnitudes, *Bull. Seism. Soc. Am.*, **66**, 1501-1523, 1976.
- Hara, T., J. L. Cruz-Salcedo, A. Hyder, M. Moihoi, Determination of broadband moment magnitudes for earthquakes in and around Philippines, Pakistan, and Papua New Guinea, 2006 JPGU meeting, S115-005, 2006.
- Ide, S., F. Imamura, Y. Yoshida, K. Abe, Source characteristics of the Nicaraguan tsunami earthquake of September 2, 1992, *Geophys. Res. Lett.*, **20**, 863-866, 1993.
- Kanamori, H., The energy release in Great Earthquakes, *J. Geophys. Res.*, **82**, 2981-2987, 1977.
- Newman A. V. and E. A. Okal, Teleseismic estimates of radiated seismic energy: The E/M0 discriminant for tsunami earthquakes, *J. Geophys. Res.*, **103**, 26885-26898, 1998.
- Okal, E. A. and J. Talandier, Mm: A variable-period mantle magnitude, *J. Geophys. Res.*, **94**, 4169-4193, 1989.
- Tsuboi, S., K. Abe, K. Takano, and Y. Yamanaka, Rapid Determination of Mw from Broadband P Waveforms, *Bull. Seism. Soc. Am.*, **85**, 606-613, 1995
- Tsuboi, S., P. M. Whitmore, and T. J. Sokolowski, Application of Mwp to Deep and Teleseismic Earthquakes, *Bull. Seism. Soc. Am.*, **89**, 1345-1351, 1999.
- Tsuboi, S., Application of Mwp to tsunami earthquake, *Geophys. Res. Lett.*, **27**, 3105-3108, 2000.
- Weinstein S. A. and E. A. Okal, The Mantle Magnitude Mm and the Slowness Parameter Θ : Five Years of Real-Time Use in the Context of Tsunami Warning, *Bull. Seism. Soc. Am.*, **95**, 779-799, 2005.
- Whitmore, P. M., S. Tsuboi, and B. Hirshorn, Magnitude dependent correction for Mwp, *Science of Tsunami Hazards*, **20**, 187-192, 2002.