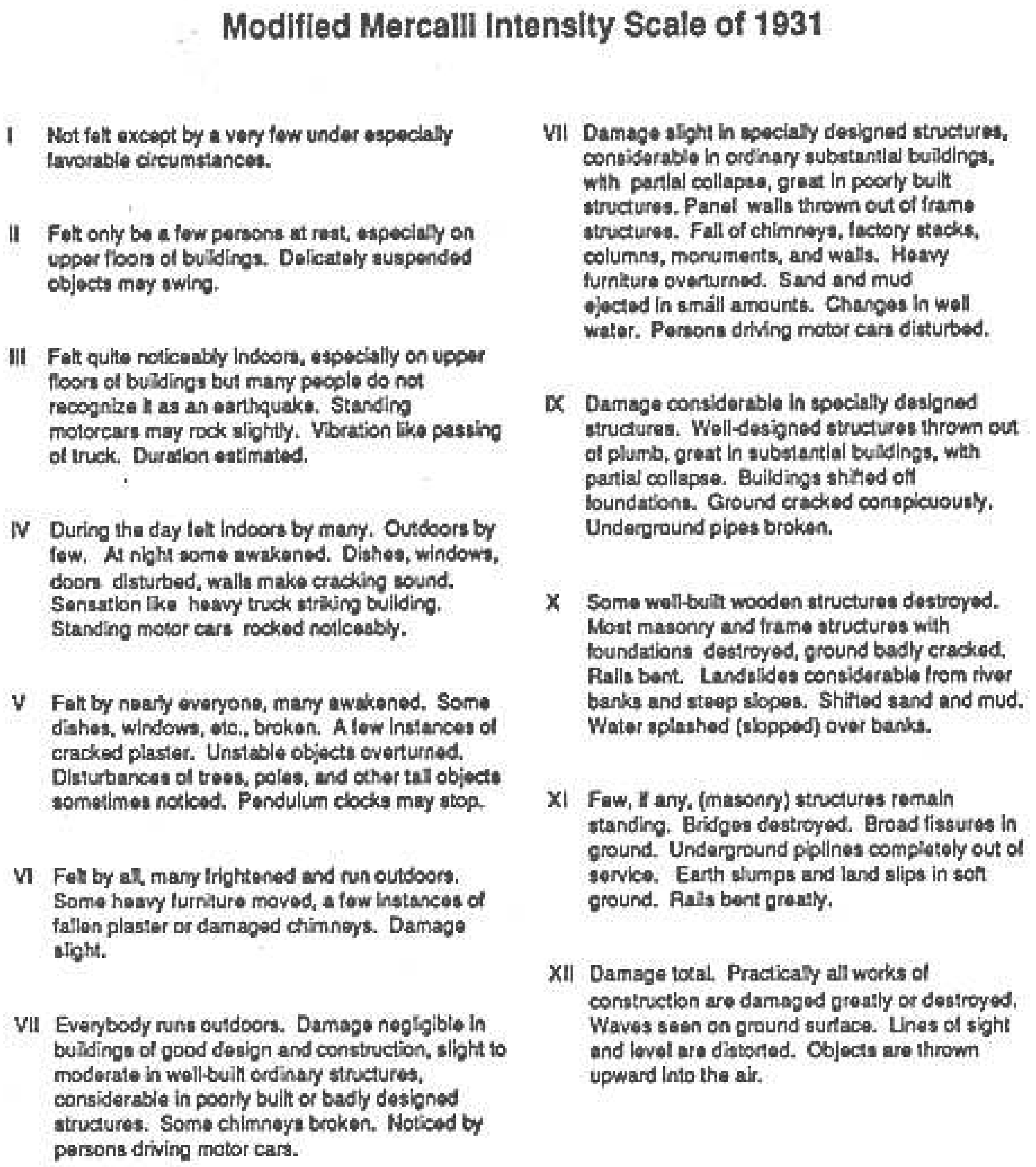
LECTURE 4

MEASURING
EARTHQUAKE SIZE

EARLY IDEAS

- Describe damage inflicted by earthquake

→ *"INTENSITY Scales"*



Modified Mercalli Intensity Scale of 1931

I Not felt except by a very few under especially favorable circumstances.

II Felt only be a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III Felt quite noticeably indoors, especially on upper floors of buildings but many people do not recognize it as an earthquake. Standing motorcars may rock slightly. Vibration like passing of truck. Duration estimated.

IV During the day felt indoors by many. Outdoors by few. At night some awakened. Dishes, windows, doors disturbed, walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V Felt by nearly everyone, many awakened. Some dishes, windows, etc., broken. A few instances of cracked plaster. Unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.

VI Felt by all, many frightened and run outdoors. Some heavy furniture moved, a few instances of fallen plaster or damaged chimneys. Damage slight.

VII Everybody runs outdoors. Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary structures, considerable in poorly built or badly designed structures. Some chimneys broken. Noticed by persons driving motor cars.

VII Damage slight in specially designed structures, considerable in ordinary substantial buildings, with partial collapse, great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, and walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motor cars disturbed.

IX Damage considerable in specially designed structures. Well-designed structures thrown out of plumb, great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X Some well-built wooden structures destroyed. Most masonry and frame structures with foundations destroyed, ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.

XI Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground piplines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII Damage total. Practically all works of construction are damaged greatly or destroyed. Waves seen on ground surface. Lines of sight and level are distorted. Objects are thrown upward into the air.

Always written with roman numerals (IV, VII, XI, etc.)

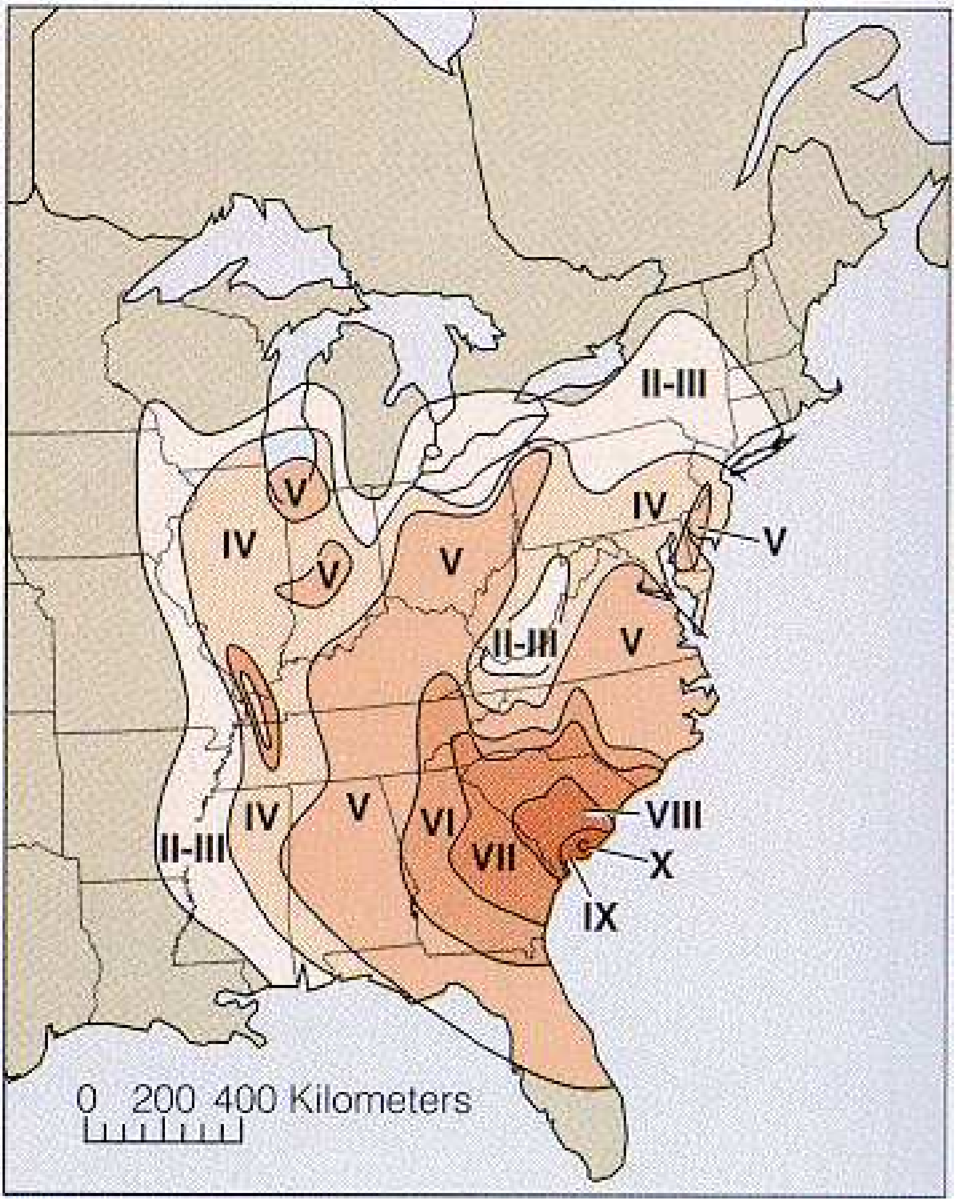
Dynamic connection: Intensity *should express*

ground acceleration

BUT...

Shortcomings of Intensity Scales

- Not directly related to earthquake source
- Damage obviously distance-dependent
- Needs population to report damage
- Affected by site response



Example of Intensity maps for
1886 Charleston, USA, earthquake.

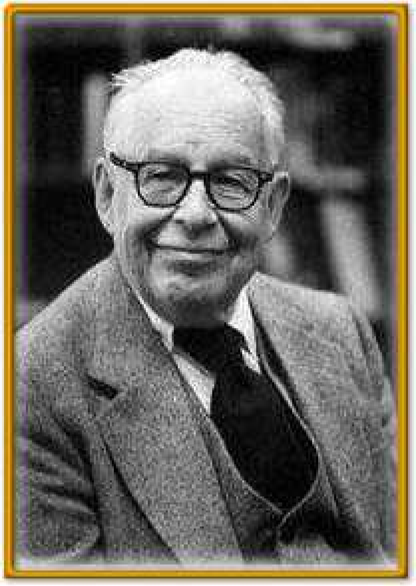
EARTHQUAKE MAGNITUDES

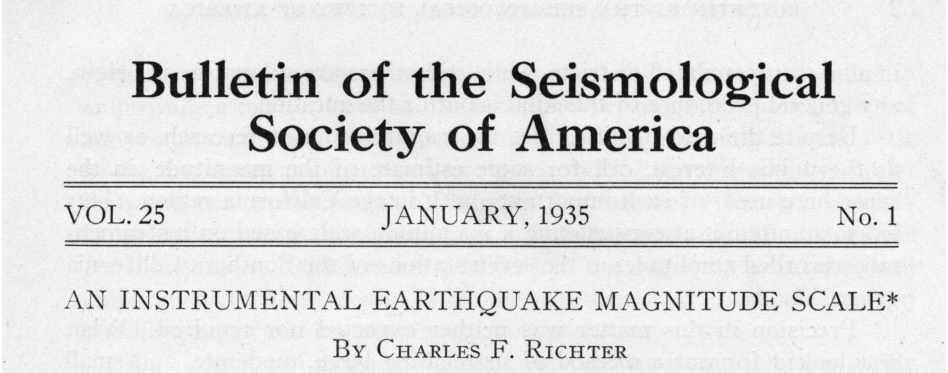
- An essentially empirical concept, introduced by *Richter* [1935], long before any physical understanding of earthquake sources

→ To this day, measurements have remained largely

ad hoc,

especially at short distances.



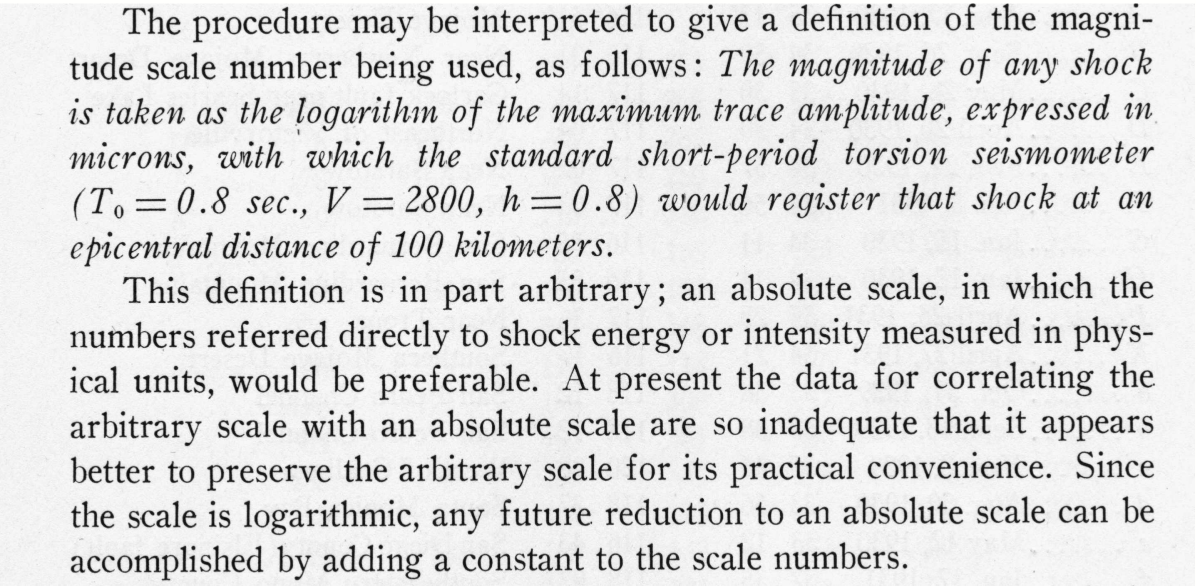


Bulletin of the Seismological Society of America

VOL. 25 JANUARY, 1935 No. 1

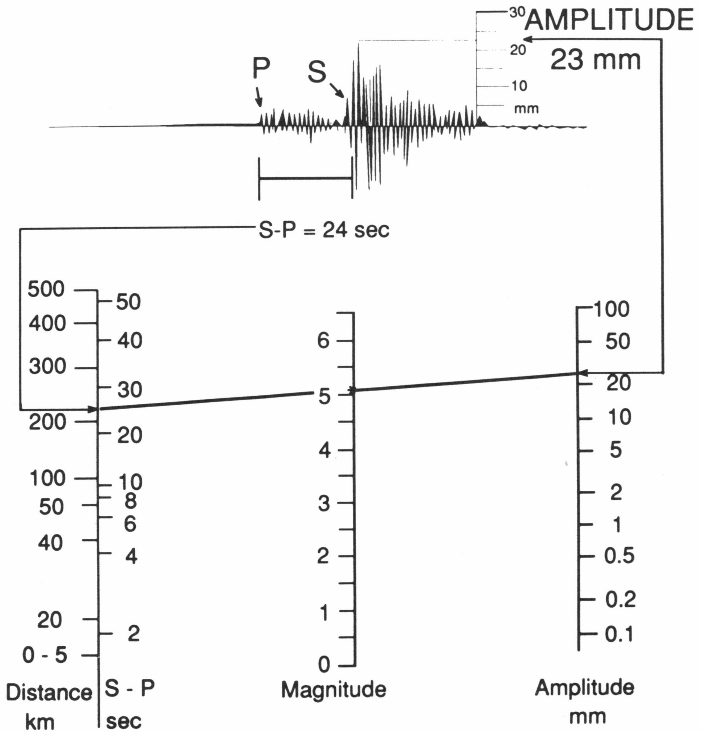
AN INSTRUMENTAL EARTHQUAKE MAGNITUDE SCALE*

BY CHARLES F. RICHTER



The procedure may be interpreted to give a definition of the magnitude scale number being used, as follows: *The magnitude of any shock is taken as the logarithm of the maximum trace amplitude, expressed in microns, with which the standard short-period torsion seismometer* ($T_0 = 0.8$ *sec.,* $V = 2800$, $h = 0.8$) *would register that shock at an epicentral distance of 100 kilometers.*

This definition is in part arbitrary; an absolute scale, in which the numbers referred directly to shock energy or intensity measured in physical units, would be preferable. At present the data for correlating the arbitrary scale with an absolute scale are so inadequate that it appears better to preserve the arbitrary scale for its practical convenience. Since the scale is logarithmic, any future reduction to an absolute scale can be accomplished by adding a constant to the scale numbers.



[*Bolt*, 1987]

PROGRESS in the 1940s

- Apply worldwide

- Try (!!) to justify theoretically

→ Leads to first worldwide quantified catalogue of earthquakes

"Seismicity of the Earth"

Gutenberg and Richter [1944; 1954]

B. Gutenberg, 1958

"MODERN" MAGNITUDES

Standardized at Prague meeting of the IUGG (1961)

- Use Body (P) Waves to define short period magnitude, m_b around a period of 1 second

$$m_b = \log_{10}\frac{A}{T} + Q(\Delta; h)$$

$Q(\Delta, h)$

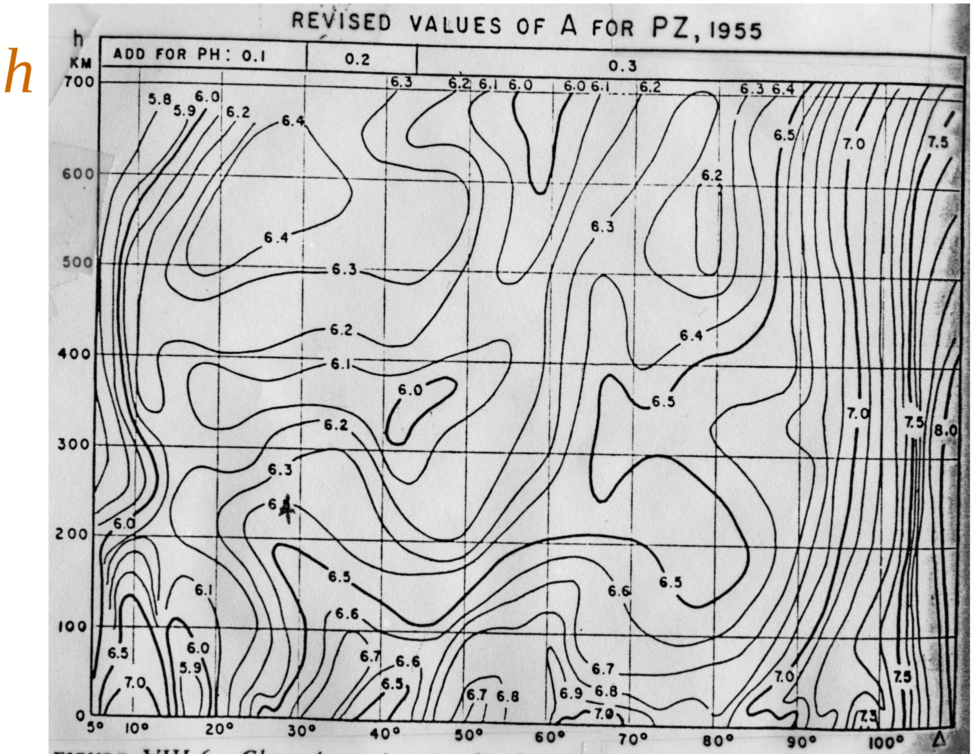


FIGURE VIII-6 *Chart for using amplitude and period of* P *to find magnitudes.*

Δ

- Use Surface (*Rayleigh*) wave to define "Long"-period magnitude, M_s, at T = 20 seconds

$$M_s = \log_{10}\frac{A}{T} + 1.66\log_{10}\Delta + 3.3$$

Still largely empirical; Constants not justified [*Okal*, 1989]

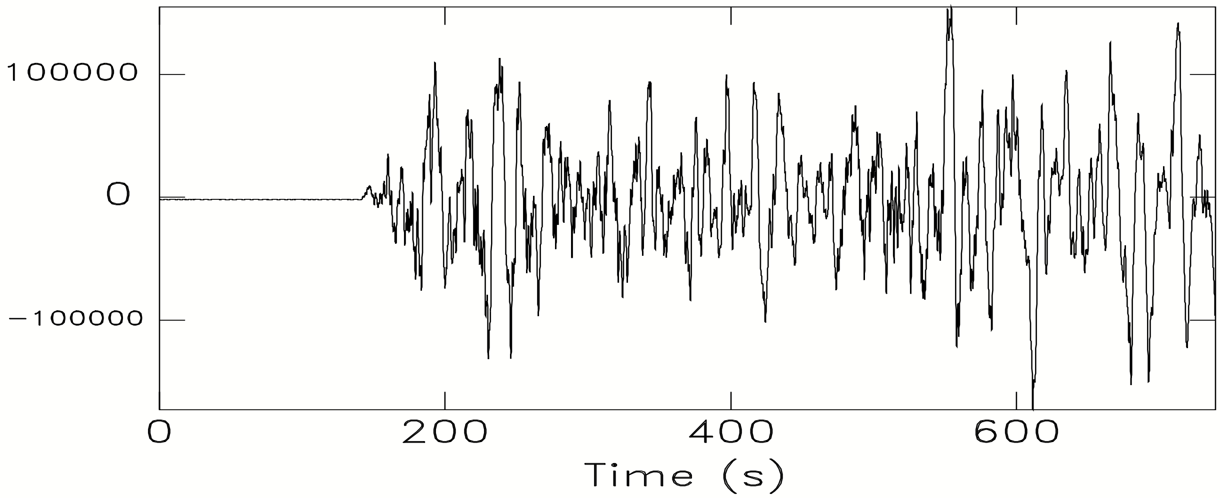
BODY-WAVE MAGNITUDE m_b

From first-arriving wave trains ("P" Waves)

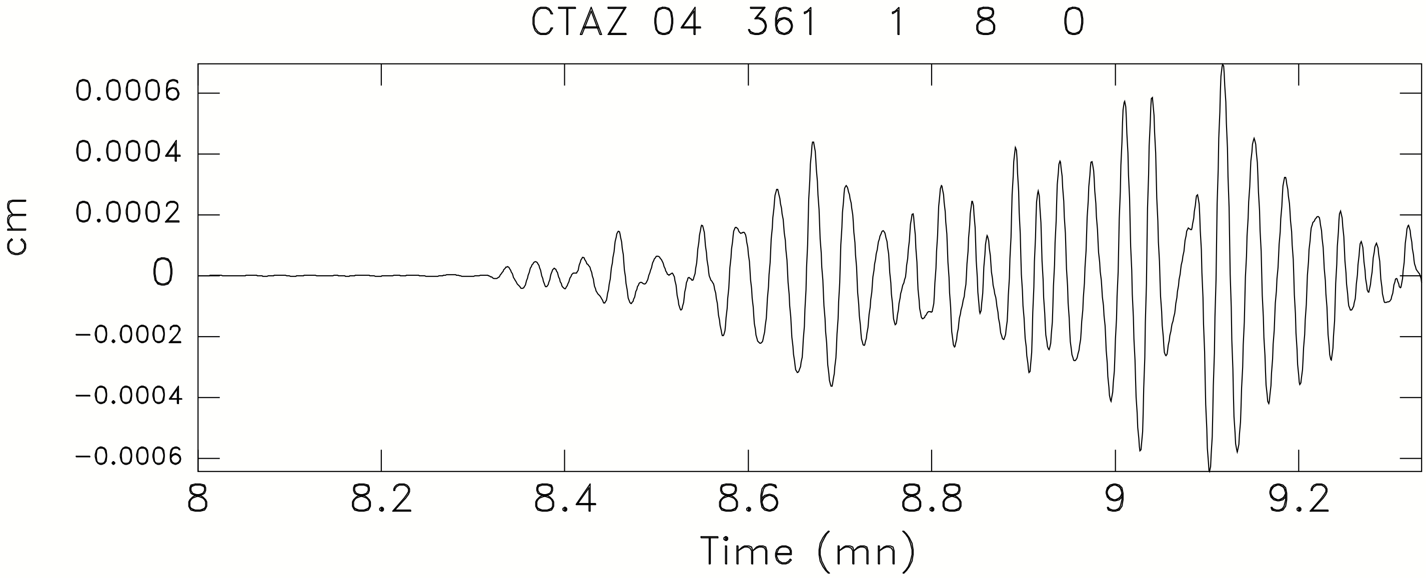
* Should be measured at period close to 1 second

SUMATRA−ANDAMAN, 26 DEC 2004

Station CTA (Charter Towers, Queensland, Australia); $\Delta = 55°$



- Remove instrument response
- Band-pass filter between 0.3 and 3 seconds
- Select window of 80 seconds duration around *P* wave



- Apply Body-wave Magnitude formula

$$m_b = \log_{10} \frac{A}{T} + Q(\Delta; h) \qquad (A \text{ in } microns)$$

$$\boldsymbol{m_b = 7.2}$$

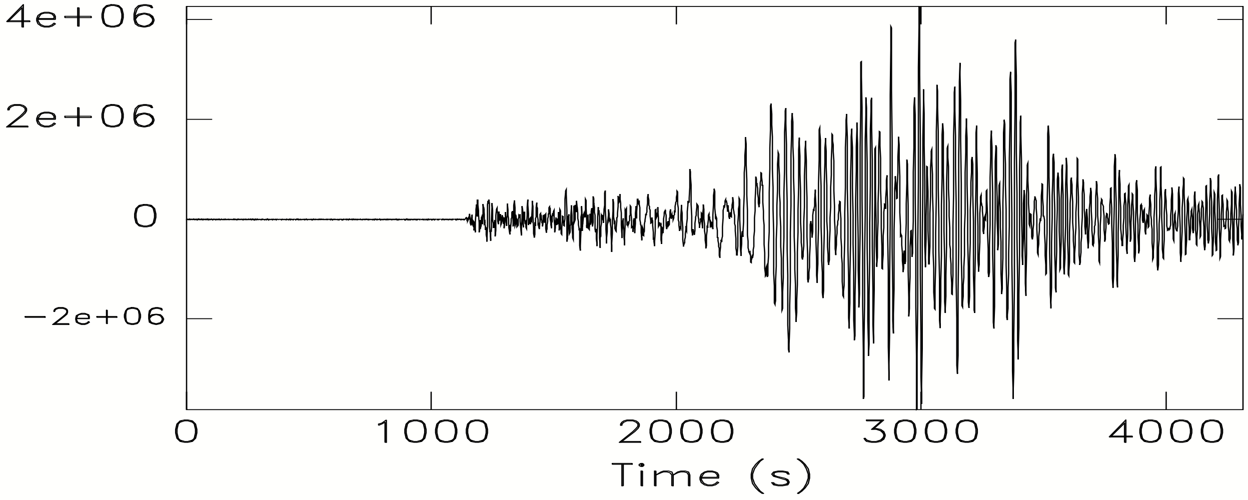
SURFACE-WAVE MAGNITUDE M_s

From later Surface-wave train (" *Rayleigh* " Waves)

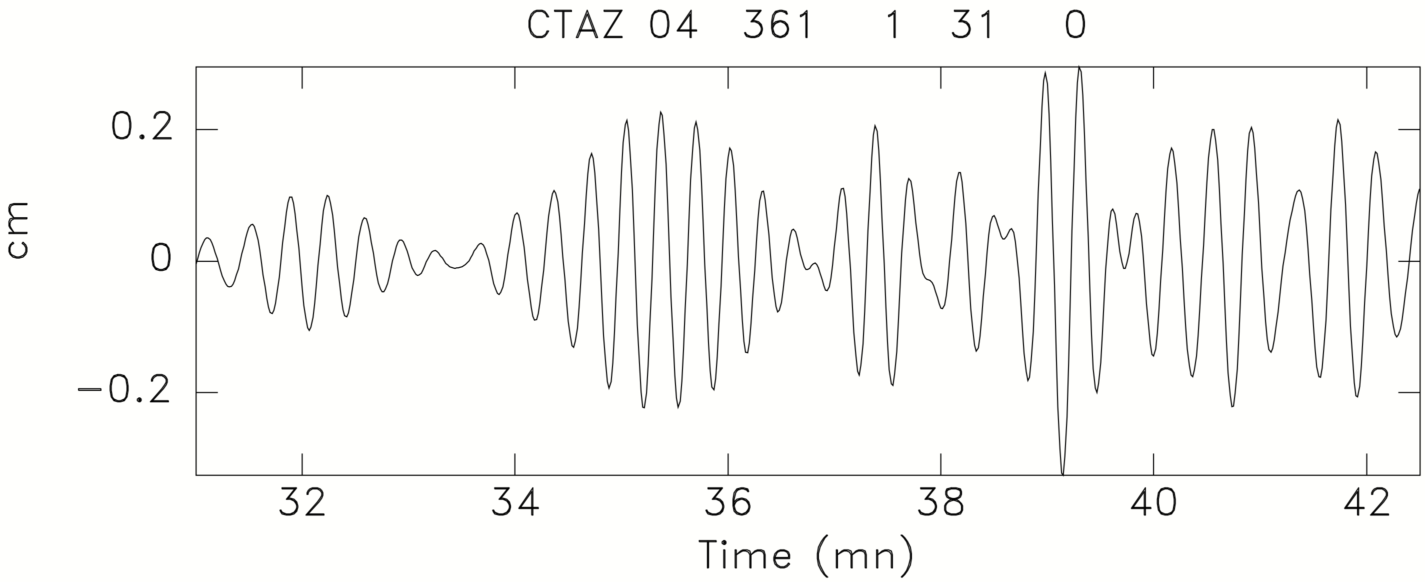
* Should be measured at Period of 20 seconds

SUMATRA−ANDAMAN, 26 DEC 2004

Station CTA (Charter Towers, Queensland, Australia); Δ = 55°



- Remove instrument response
- Band-pass filter between 15 and 25 seconds
- Select window of 11 minutes duration around Rayleigh wave



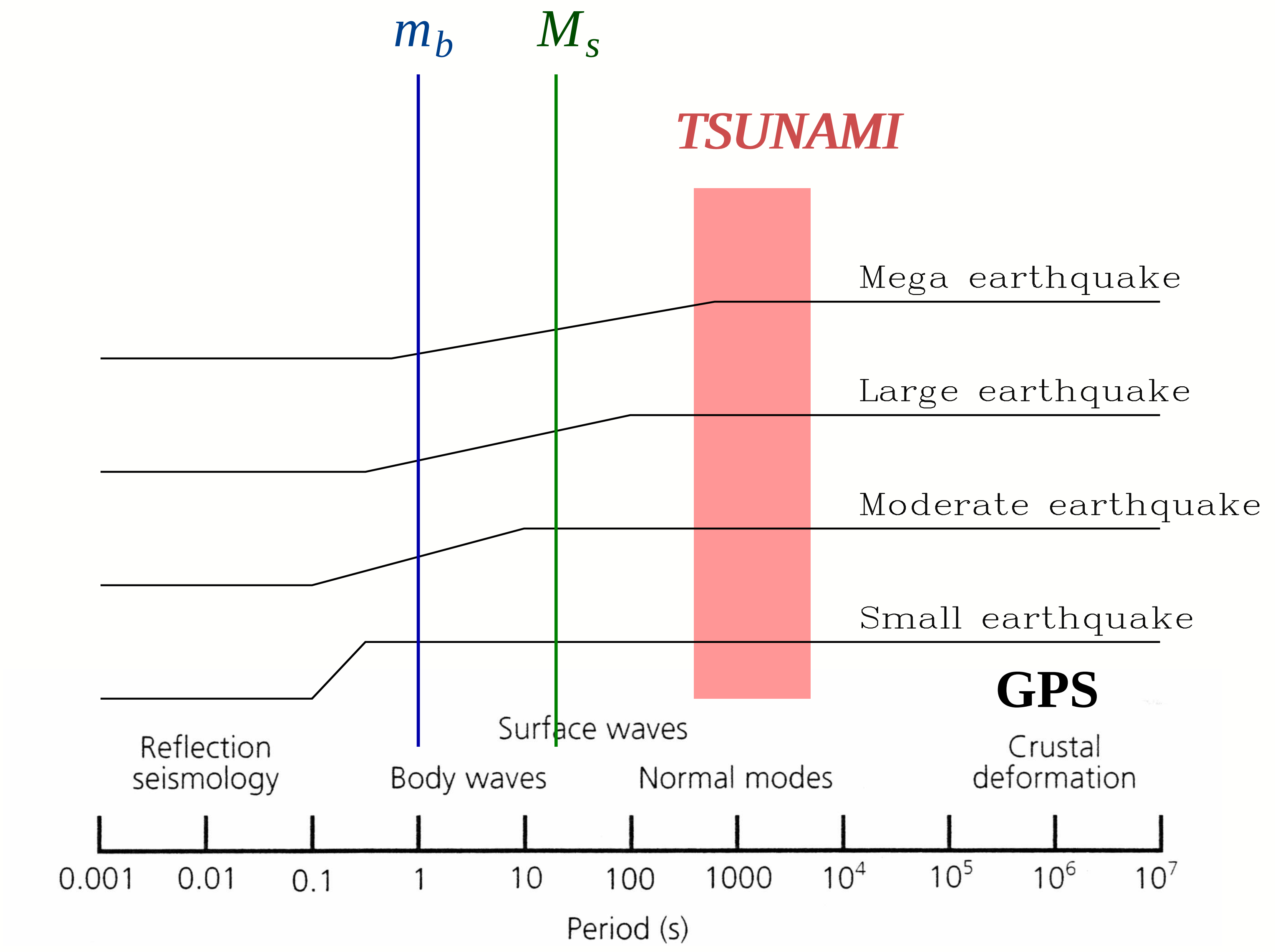
- Apply Surface-wave Magnitude formula

$$M_s = \log_{10}\frac{A}{T} + 1.66\log_{10}\Delta + 3.3 \qquad (A \text{ in } \mathit{microns})$$

$$\boldsymbol{M_s = 8.19}$$

EARTHQUAKES TAKE TIME TO OCCUR

- The larger the earthquake, the longer the source *("Scaling Law").*
- Measuring large earthquakes at small periods simply misses their true size.
- In the case of Sumatra, full size available only from normal modes.

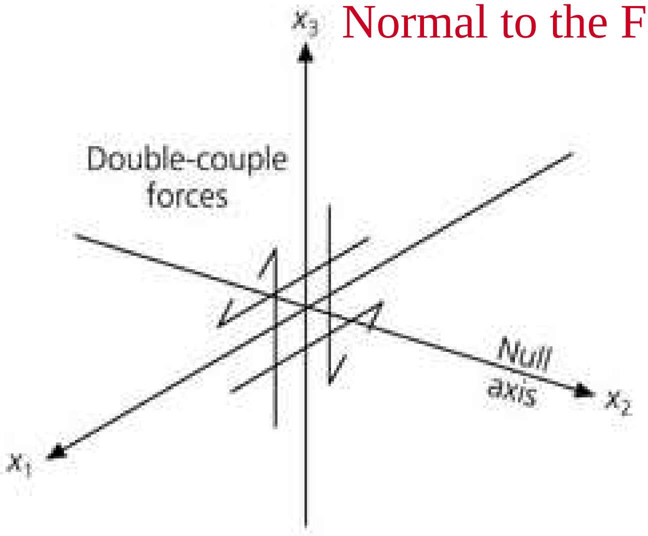


EARTHQUAKE SOURCE GEOMETRY

From Single Force to Double-Couple

The physical representation of an earthquake source is a system of forces known as a *Double-Couple*, the direction of the forces in each couple being the direction of slip on the fault and the direction of the normal to the fault plane.

Single Force



Normal to the Fault

Direction of Slip

Double Couple

[*Stein and Wysession*, 2002]

Mathematically, the system of forces is described by a *Second-Order Symmetric Deviatoric TENSOR* (3 angles and a scalar).

SEISMIC MOMENT

The double-couple representing a seismic source is quantified through its **moment,** which represents the common torque of the opposing couples.

It is a real physical quantity, called the seismic moment and its expression is:

$$M_0 = \int_{\Sigma} \mu \, \Delta u \, dS$$

where μ is the rigidity of the medium, Δu the slip between the fault walls at each point of the fault, and the integral is taken over the surface of faulting.

In particular, for a rectangular fault of length L and width W,

$$M_0 = \mu \cdot L \, W \cdot \Delta u$$

M_0 is measured in dyn*cm (or N*m).

Note that *Kanamori* [1977] has introduced a so-called "moment magnitude" M_w given by

$$M_w = \frac{2}{3}\left(\log_{10} M_0 - 16.1\right)$$

The retrieval of the seismic moment M_0 from seismological data is a relatively complex procedure.

While the equations relating the double-couple to the observable seismic waveforms are indeed linear, they involve not only the scalar moment M_0, but rather the various elements of the double-couple, which make up the components of a

Second-Order Symmetric Deviatoric Tensor.

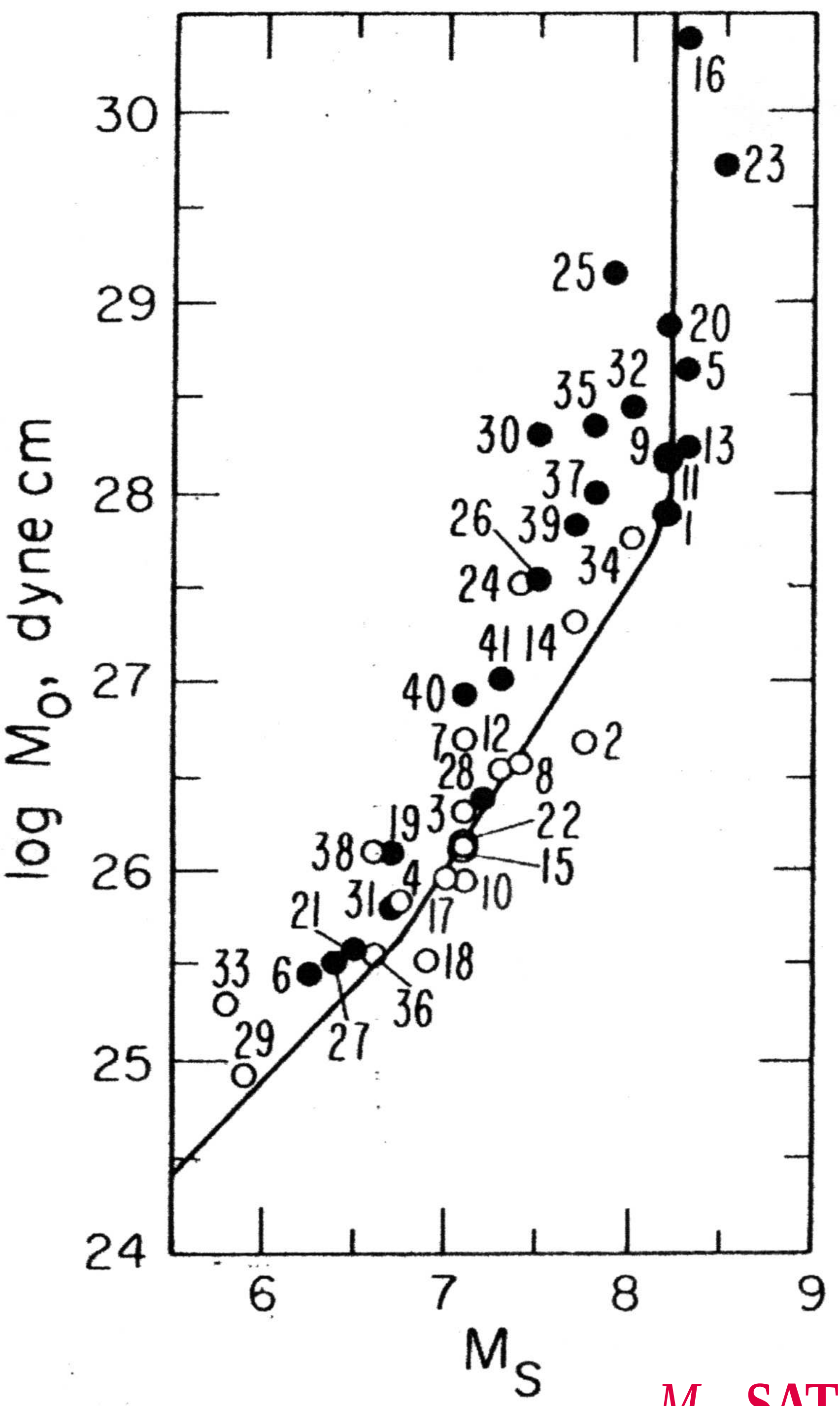
The inversion of these components is a difficult problem in theoretical seismology, which requires, at the minimum, a very large dataset.

This is why it may be interesting to develop and apply methodologies which explore the low-frequency part of the seismic spectrum, while at the same time keeping the concept of a single number, namely the philosophy of a

magnitude scale.

TSUNAMI WARNING: THE CHALLENGE

- Upon detection of a teleseismic earthquake, assess in real-time its tsunami potential.
- *HINT:* Tsunami being low frequency is generated by longest periods in seismic source ("static moment M_0").
- *PROBLEM:* Most popular measure of seismic source size, surface wave magnitude M_s, saturates for large earthquakes.



FAR-FIELD TSUNAMI DANGER

EXTREME

PROBABLE

LOW

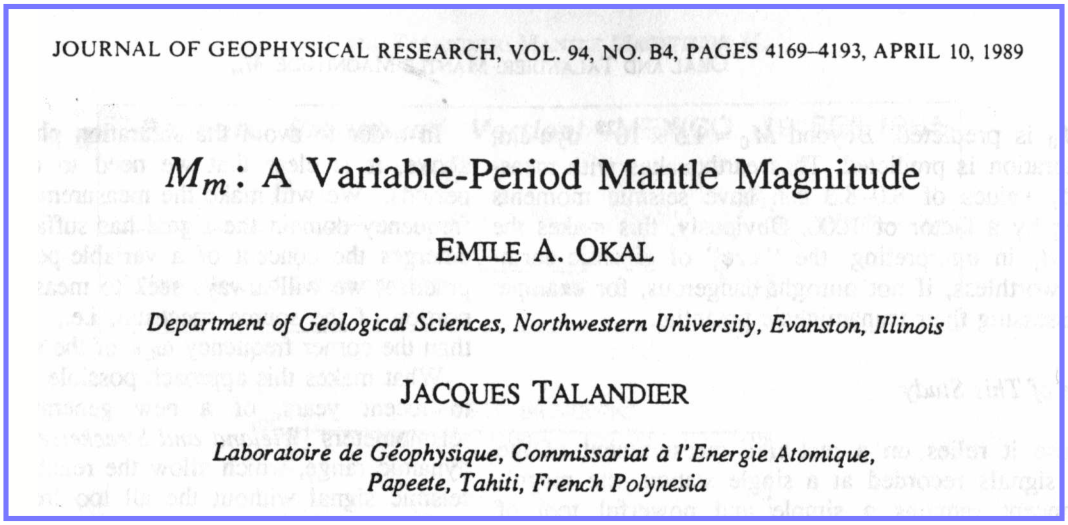
NIL

[*Geller*, 1976]

M_S SATURATES AROUND 8.2

M_m and TREMORS

[*Okal and Talandier*, 1989]



JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 94, NO. B4, PAGES 4169–4193, APRIL 10, 1989

M_m: A Variable-Period Mantle Magnitude

EMILE A. OKAL

Department of Geological Sciences, Northwestern University, Evanston, Illinois

JACQUES TALANDIER

Laboratoire de Géophysique, Commissariat à l'Energie Atomique,
Papeete, Tahiti, French Polynesia

- Design *NEW* Magnitude Scale, M_m ,
  using mantle Rayleigh waves,
  with ***variable*** period

- Directly related to seismic moment M_0

- All constants justified theoretically

- Incorporate into Detection Algorithms to

  AUTOMATE PROCESS

* Implemented,
Papeete, Tahiti (1991),
PTWC (1999)

ORIGIN of MANTLE MAGNITUDE M_m

- Now possible to make measurement in Fourier space (frequency domain)
- Spectral amplitude of Rayleigh wave controlled by *Source*, *Propagation*:

$$X(\omega) = a\sqrt{\frac{\pi}{2}} \cdot \frac{e^{-\frac{\omega a \Delta}{2UQ}}}{\sqrt{\sin\Delta}} \cdot \frac{1}{U} \left| s_R\, l^{-1/2} K_0 - i\, q_R\, l^{1/2} K_1 - p_R\, l^{3/2} K_2 \right| \cdot M_0$$

→ The K_i depend only on frequency and source depth;

→ Trigonometric factors s_R, q_R, p_R depend only on the geometry of focal mechanism and source-receiver layout.

Conversely, one can extract M_0 from

$$M_m = \log_{10} M_0 - 20 = \log_{10} X(\omega) + C_D + C_S + C_0$$

where

- $$C_D = \frac{1}{2}\log_{10}\sin\Delta + \log_{10} e \cdot \frac{a\omega\Delta}{2UQ}$$ (distance correction)
- C_S is a *Source correction* which, at each frequency, can be built theoretically by averaging the source terms over many geometries and source depths.
- C_0 is a locking constant, predicted theoretically (depends only on π and Earth radius a).

TREMORS

Single-Station Algorithm for Automated Detection and Evaluation of Far-Field Tsunami Risk

Jacques Talandier, Emile A. Okal, Dominique Reymond, 1991

- Automatic detection of distant earthquake
- Automatic Location of Epicenter
- Automatic computation of the event's *Mantle Magnitude*

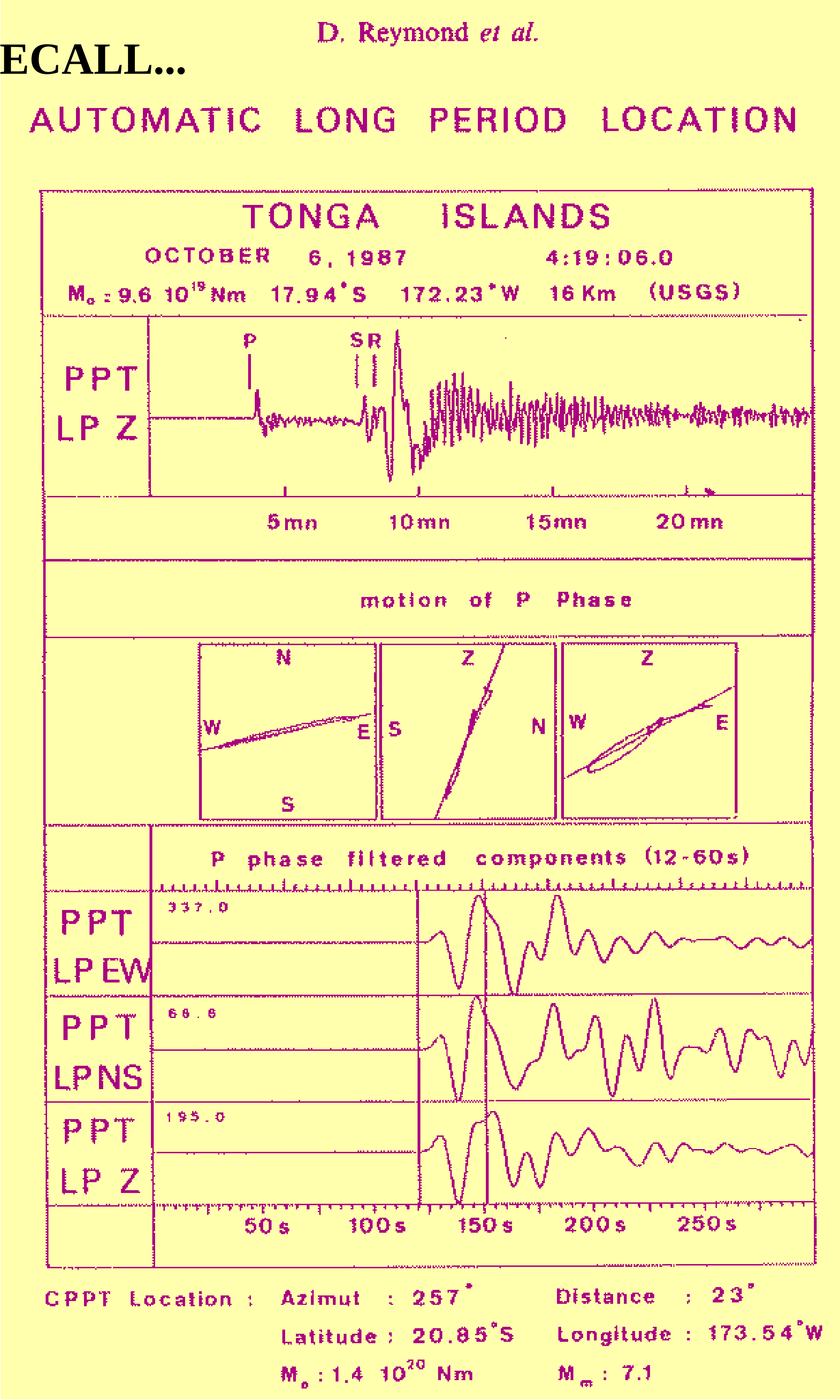
$$M_m = \log_{10} X(\omega) + C_D + C_S - 0.90$$

from spectral amplitude $X(\omega)$ of surface (Rayleigh) seismic waves at the longest possible periods (250 to 300 seconds)

AVOIDS MAGNITUDE SATURATION

- Allows quasi-real time estimation of tsunami risk
- Operational at Laboratoire de Géophysique, Tahiti since 1991.
- Also in use at Pacific Tsunami Warning Center, Ewa Beach; Chile.

RECALL...



D. Reymond *et al.*

AUTOMATIC LONG PERIOD LOCATION

TONGA ISLANDS

OCTOBER 6, 1987 4:19:06.0

M_o : 9.6 10^{19} Nm 17.94°S 172.23°W 16 Km (USGS)

CPPT Location : Azimut : 257° Distance : 23°

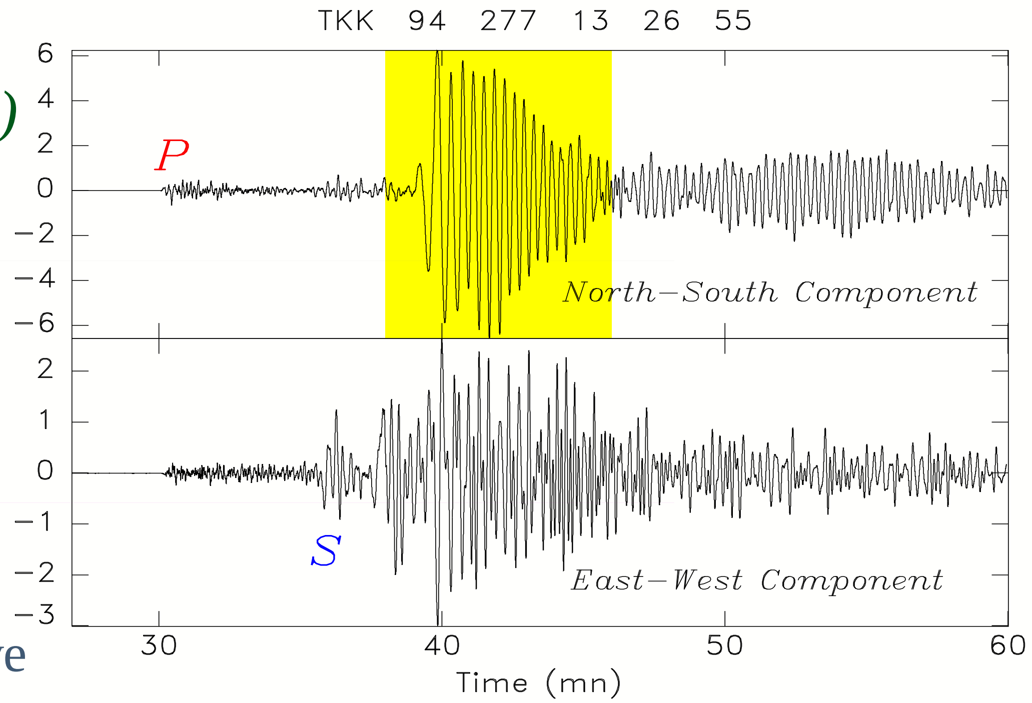
Latitude : 20.85°S Longitude : 173.54°W

M_o : 1.4 10^{20} Nm M_m : 7.1

TREMORS: EXAMPLE OF APPLICATION

Kurile Is. Earthquake, 04 OCT 1994,

Station: TKK (Chuuk, Micronesia)



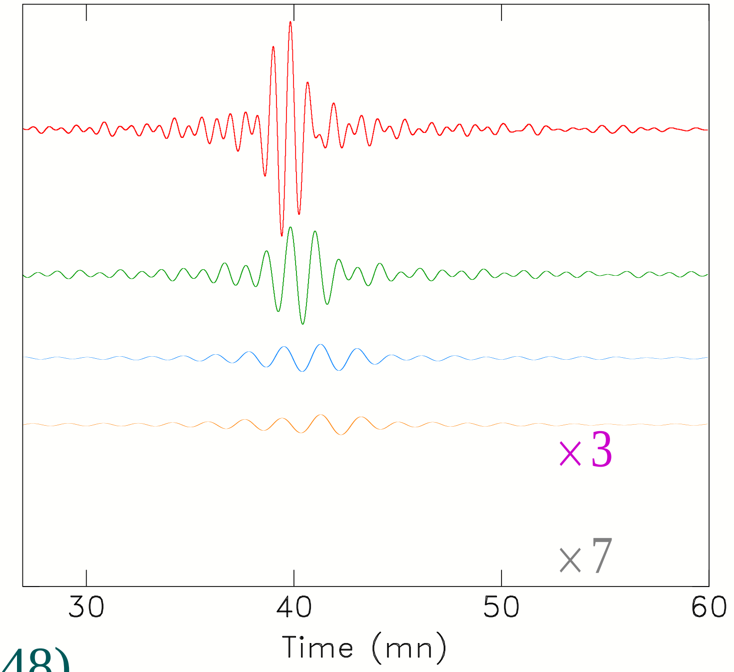
- Detection: Analyse signal level compared to previous minute.
- Location : $S - P$ gives distance (36° or 4000 km).

  Geometry of P wave gives azimuth.
- Estimate seismic moment

→ Fourier-transform Rayleigh wave (highlighted)

→ At each period, compute spectral amplitude, correct for excitation and distance; obtain M_m

→ Conclusion: Average $M_m = 8.60$ ($M_0 = 4 \times 10^{28}$ dyn-cm).



$T = 55$ s; $M_m = 8.78$

$T = 80$ s; $M_m = 8.71$

$T = 120$ s; $M_m = 8.60$

$T = 150$ s; $M_m = 8.55$

$T = 200$ s; $M_m = 8.49$

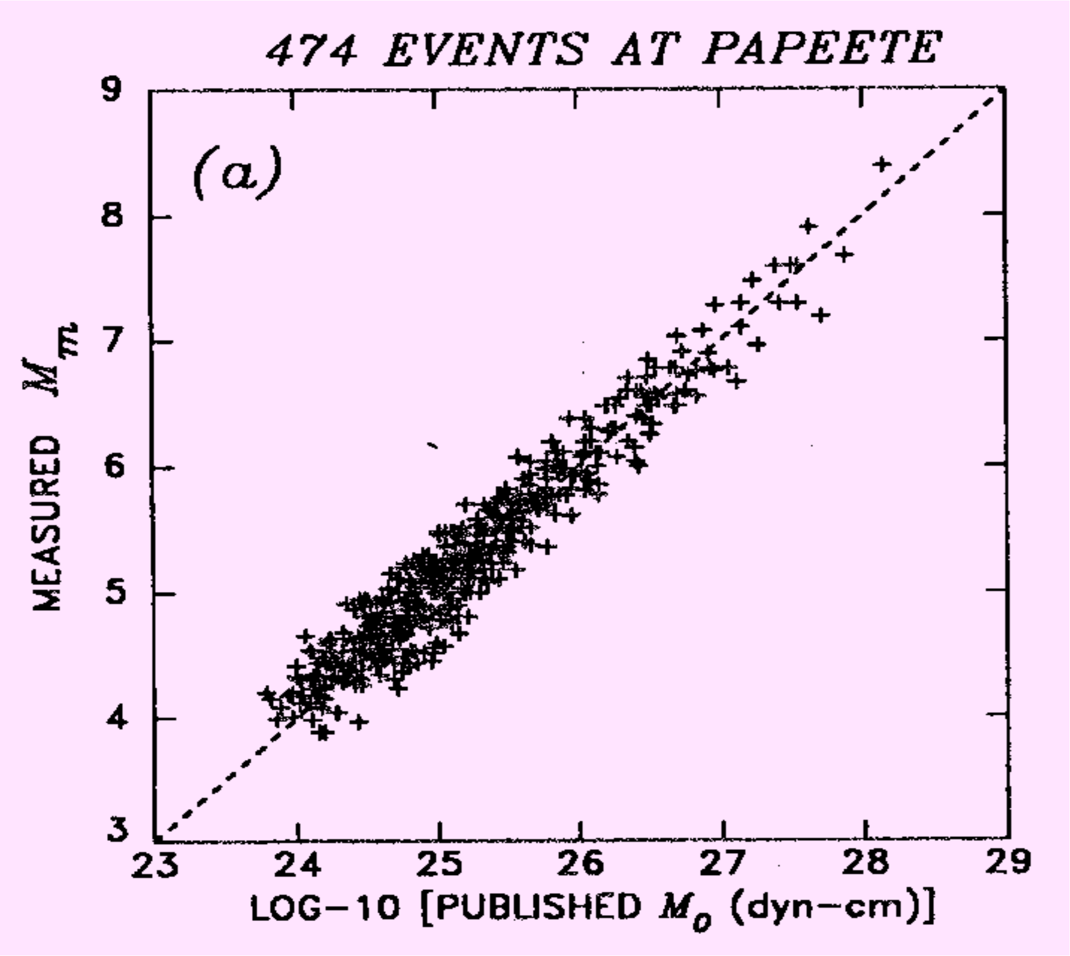
$T = 250$ s; $M_m = 8.40$

Harvard solution (obtained later):

$M_0 = 3 \times 10^{28}$ dyn-cm ($M_m = 8.48$)

TREMORS -- *Operational Aspects*

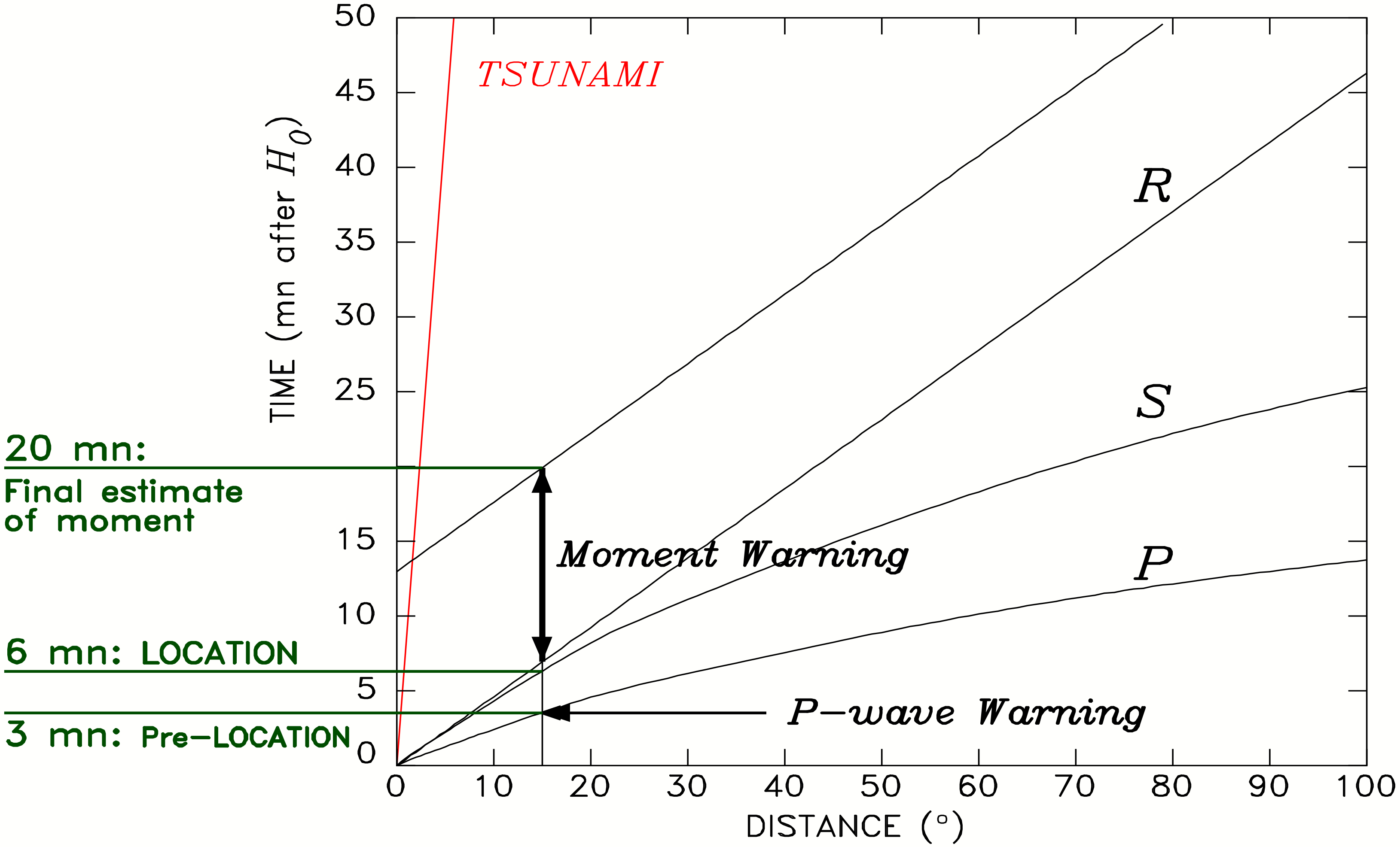
- Performance against subsequently published values of M_0



CONFIRMED: AVOIDS SATURATION

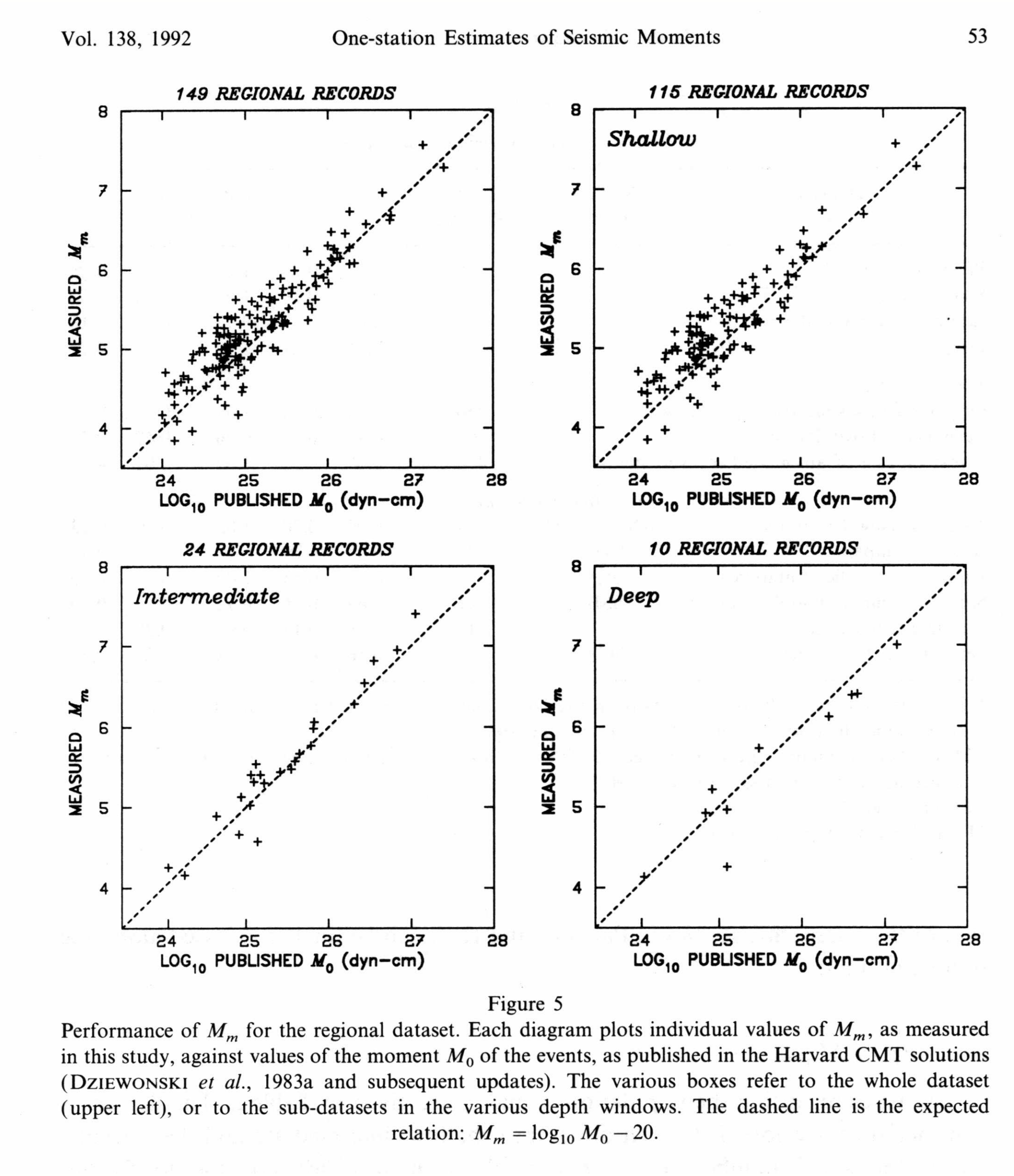
TREMORS -- *Operational Aspects*

- Response Time of TREMORS algorithm



A TREMORS station at an epicentral distance of 15° can issue a useful warning for a shore located 400 km from the event.

M_m CAN WORK at SHORT DISTANCES



Vol. 138, 1992 One-station Estimates of Seismic Moments 53

Figure 5

Performance of M_m for the regional dataset. Each diagram plots individual values of M_m, as measured in this study, against values of the moment M_0 of the events, as published in the Harvard CMT solutions (Dziewonski *et al.*, 1983a and subsequent updates). The various boxes refer to the whole dataset (upper left), or to the sub-datasets in the various depth windows. The dashed line is the expected relation: $M_m = \log_{10} M_0 - 20$.

Tested by *Okal and Talandier* [1992] down to

$\Delta = 1.5^\circ$ (165 km).

M_m WORKS for GIGANTIC EVENTS

Chile, 1960

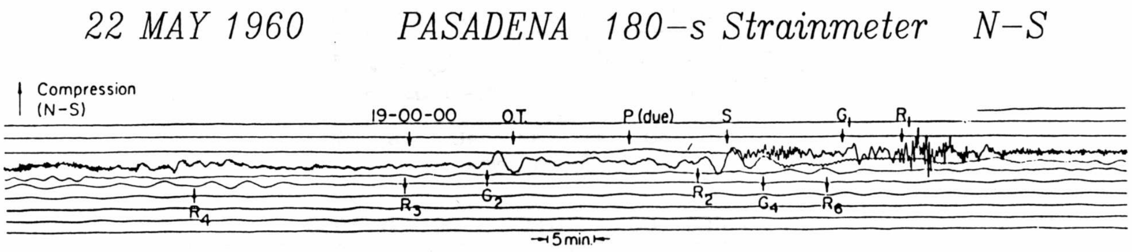
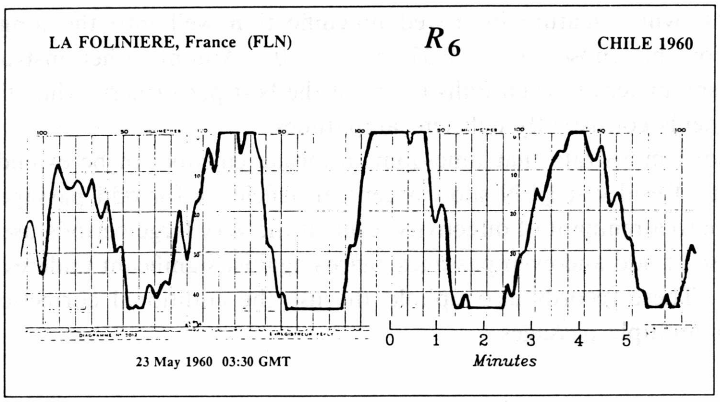
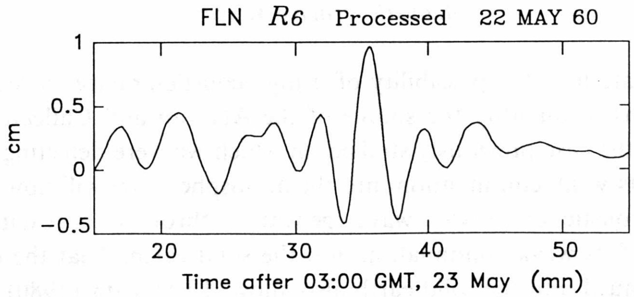


Figure 4
Pasadena record of the 1960 Chilean earthquake on the low-gain, 180-s strainmeter. The wavetrains G_2, R_2, G_4 and R_4 were used in this study. After KANAMORI and CIPAR (1974).





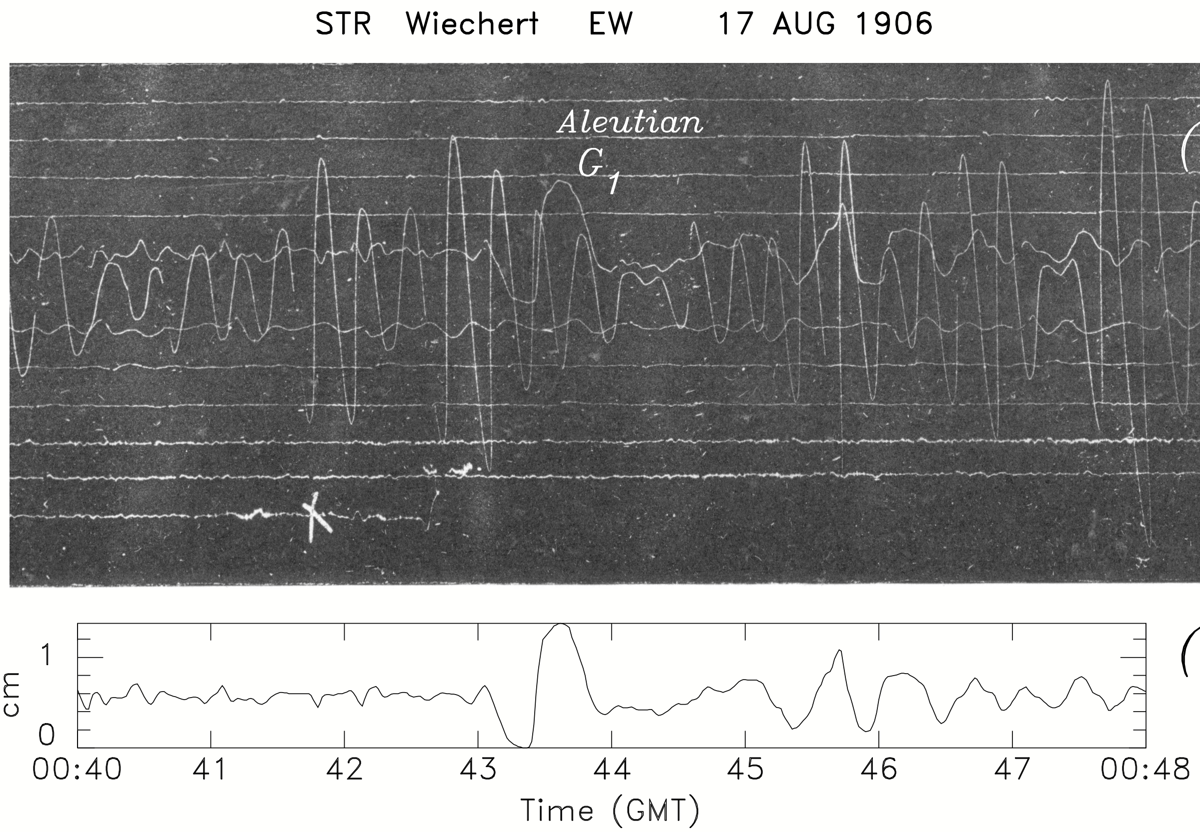
Works even on severely clipped records obtained on instruments with poor dynamic.

[*Okal and Talandier,* 1991]

M_m CAN WORK for HISTORICAL EVENTS

17 AUGUST 1906 -- Aleutian Islands

Wiechert mechanical seismometer, Strasbourg



$$M_m = 8.58; \quad M_0 = 3.8 \times 10^{28} \text{ dyn*cm}$$

Important for reassessment of old events, based on very sparse datasets.

THE INFAMOUS "TSUNAMI EARTHQUAKES"

- A particular class of earthquakes defying seismic source scaling laws.

  Their tsunamis are much larger than expected from their seismic magnitudes (even M_m).

- Example: Nicaragua, 02 September 1992.

THE EARTHQUAKE WAS NOT FELT AT SOME BEACH COMMUNITIES,

WHICH WERE DESTROYED BY THE WAVE 40 MINUTES LATER

170 killed, all by the tsunami, none by the earthquake

El Popoyo, Nicaragua

El Transito, Nicaragua

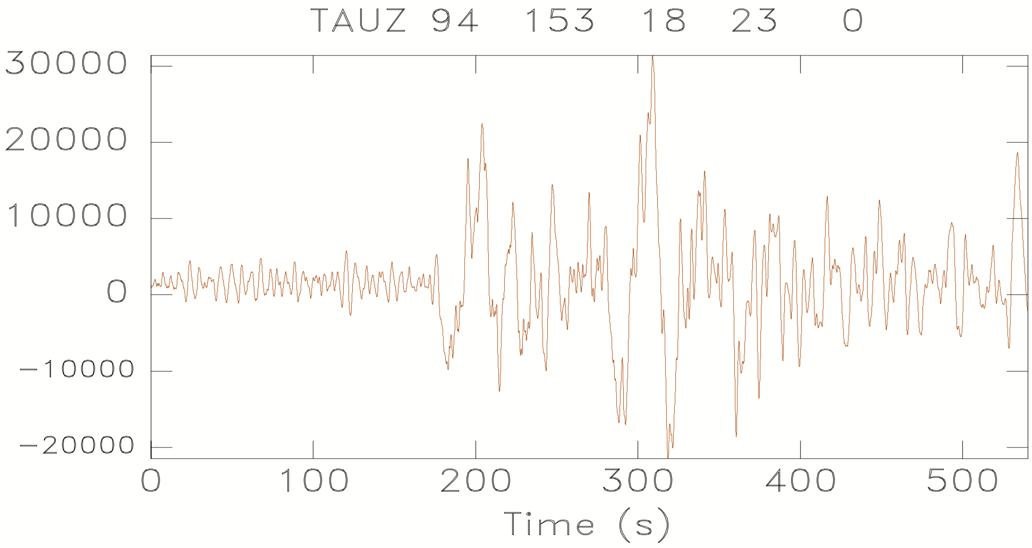
"TSUNAMI EARTHQUAKES"

- *The Cause:* Earthquake has exceedingly slow rupture process releasing very little energy into high frequencies felt by humans and contributing to damage [*Tanioka,* 1997; *Polet and Kanamori,* 2000].

- *The Challenge:* Can we recognize them from their seismic waves in [quasi-]real time?

- *The Solution:* The Θ parameter [*Newman and Okal*, 1998] compares the "size" of the earthquake in two different frequency bands.

→ Use generalized−P wavetrain (P, pP, sP).



1994 Java
"Tsunami Earthquake"

Station: TAU
(Hobart, Tasmania)

→ Compute Energy Flux at station [*Boatwright and Choy*, 1986]

→ *IGNORE Focal mechanism and exact depth* to effect source and distance corrections (keep the "quick and dirty *"magnitude"* philosophy).

→ Add representative contribution of S waves.

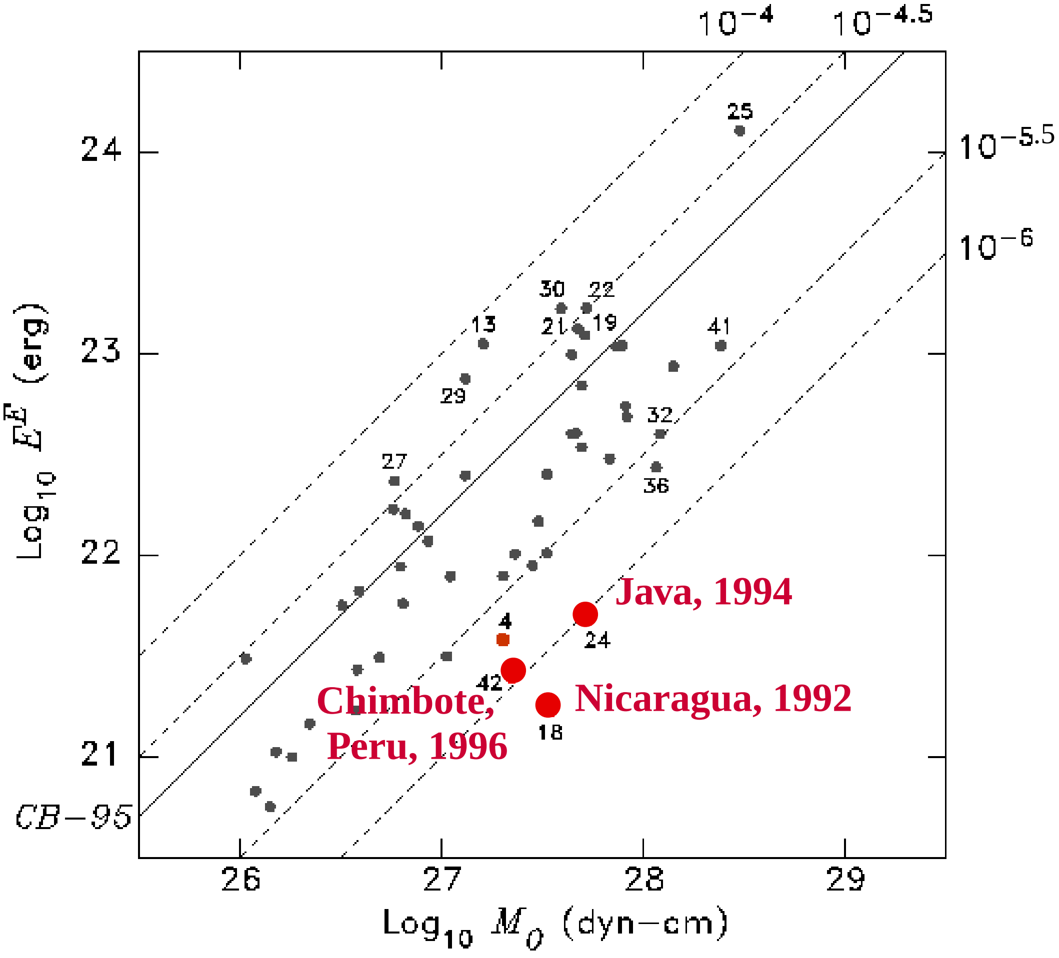
→ Define *Estimated Energy*, E^E

$$E^E = (1+q)\,\frac{16}{5}\,\frac{[a/g(15;\Delta)]^2}{(F^{est})^2}\,\rho\,\alpha \int_{\omega_{\min}}^{\omega_{\max}} \omega^2\,|\,u(\omega)\,|^2\, e^{\omega\, t^*(\omega)}\cdot d\omega$$

→ Scale to Moment through $\Theta = \log_{10} \dfrac{E^E}{M_0}$

→ Scaling laws predict $\Theta = -4.92$.

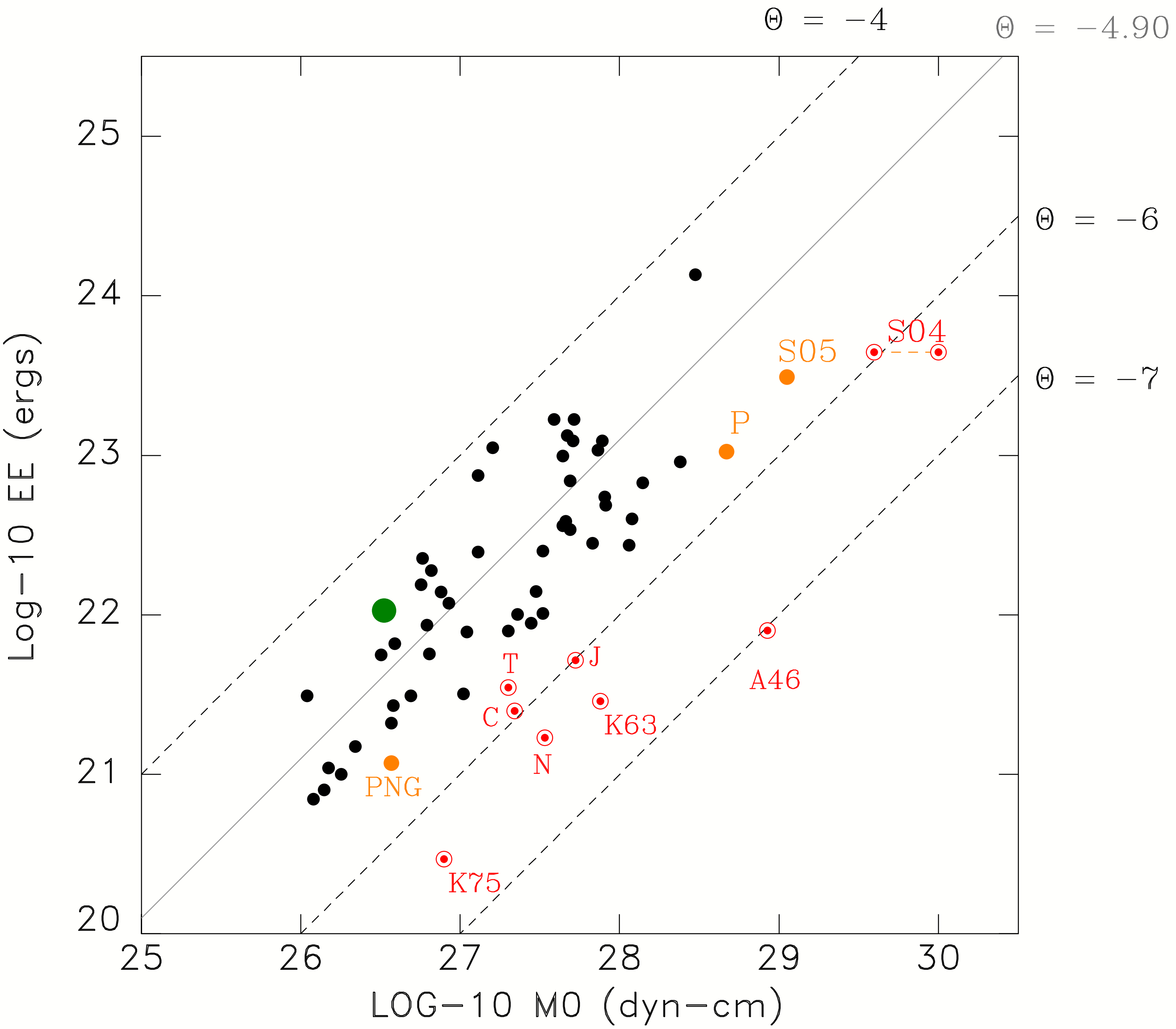
- **Tsunami earthquakes characterized by** *Deficient Θ (as much as 1.5 units).*



Now being implemented at Papeete and PTWC

EXAMPLE of COMPUTATION of PARAMETER Θ

JAPAN 14 NOV 2005 -- 21:38



RED Events are SLOW ($\Theta \leq -5.8$)

Note that this event had a trend towards being FAST

(Outer ridge event *NOT at SUBDUCTION INTERFACE*)

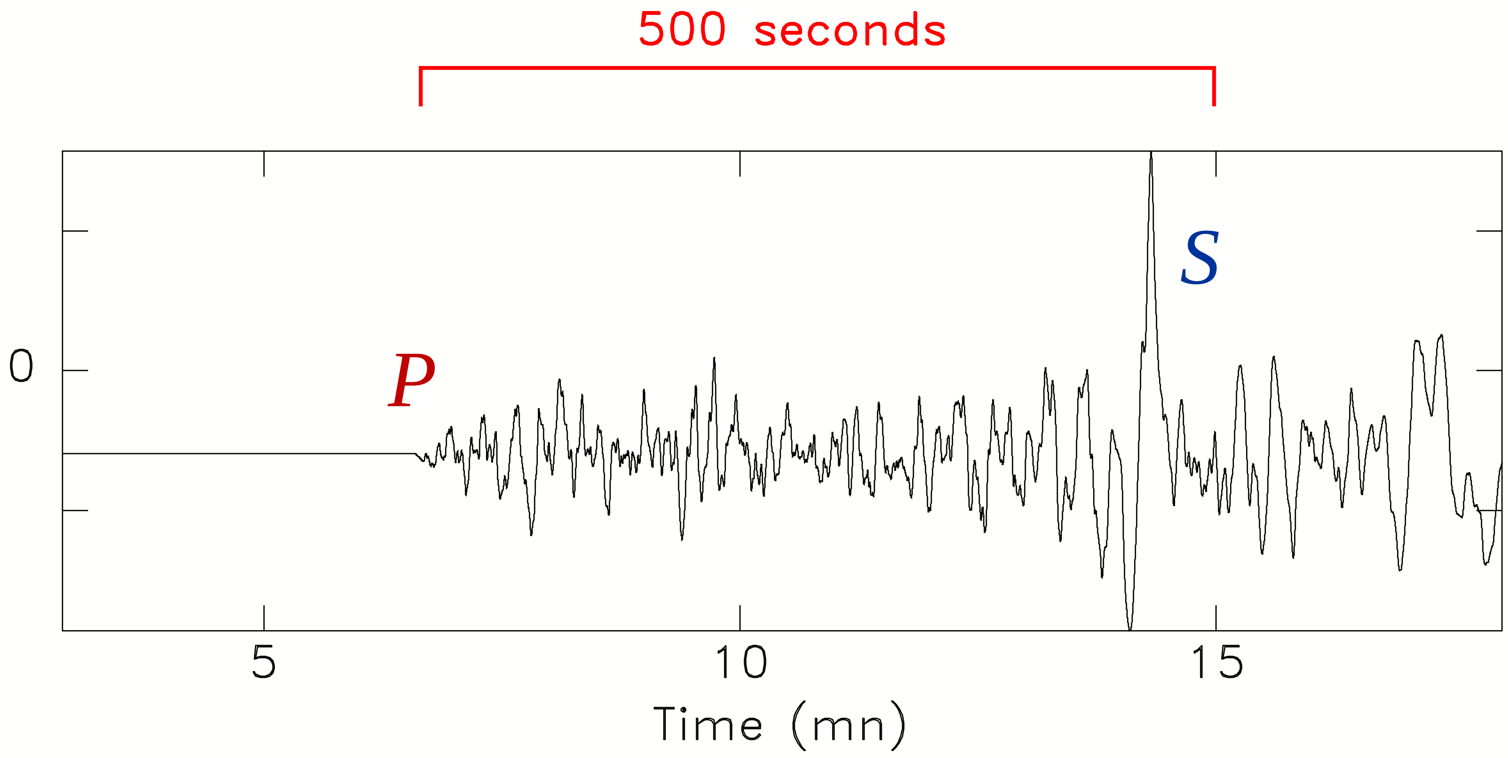
PROBLEM with Θ for VERY LARGE EVENTS

- The duration of the source (and hence of the *P*-wave train may be so long that the *P* wave interferes with subsequent phases (*PP*, even *S*)

Example: Sumatra-Andaman Event, 26 DEC 2004

Station MSEY (Mahé, Seychelles; Δ = 41°**).**

Duration of Source: 500 to 600 seconds (8 to 10 minutes)



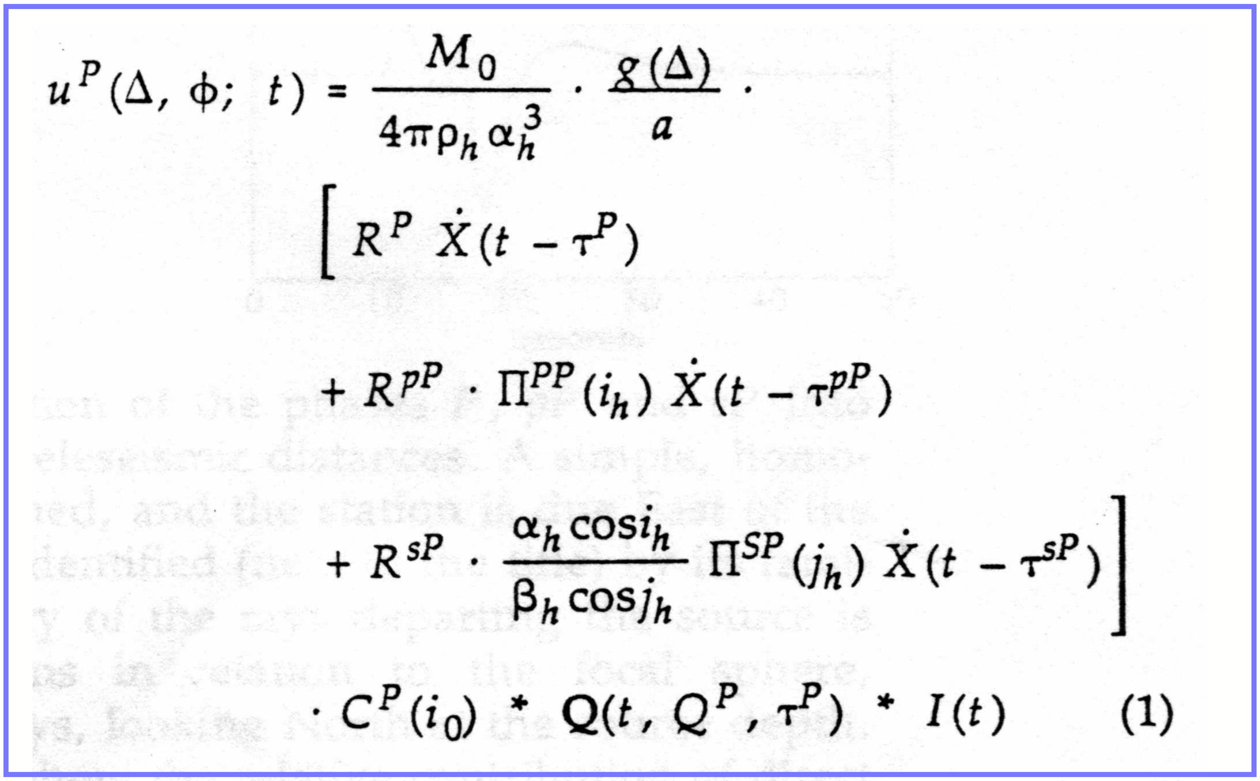
OTHER APROACHES

- M_{wP} [*Tsuboi*, 1996]

  Idea: Try to recover the full moment information from the *P* waves which arrive faster than the Rayleigh waves.

- Note that formula for *P* waves involves

TIME DERIVATIVE of MOMENT FUNCTION, $\dot{X}$



$$u^P(\Delta, \phi;\ t) = \frac{M_0}{4\pi\rho_h\alpha_h^3} \cdot \frac{g(\Delta)}{a} \cdot \Big[R^P\, \dot{X}(t-\tau^P) + R^{pP} \cdot \Pi^{PP}(i_h)\, \dot{X}(t-\tau^{pP}) + R^{sP} \cdot \frac{\alpha_h \cos i_h}{\beta_h \cos j_h}\, \Pi^{SP}(j_h)\, \dot{X}(t-\tau^{sP}) \Big] \cdot C^P(i_0) * Q(t, Q^P, \tau^P) * I(t) \qquad (1)$$

Idea is to compute *TIME INTEGRAL* of *P* wave deformation to recover X, and hence static moment M_0.

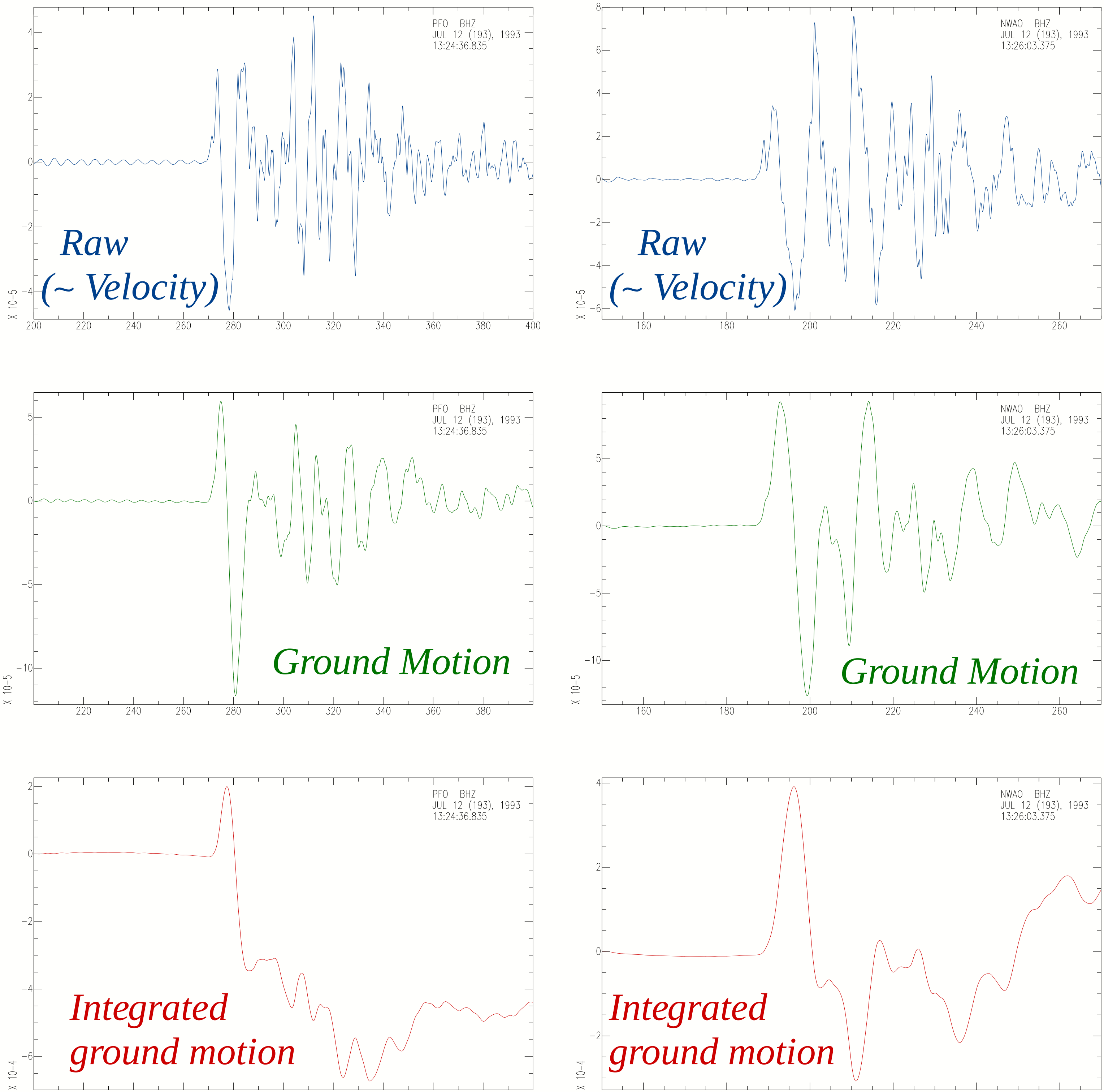
Problems: Instrument records velocity, so **double** integration needed; noisy at long periods; *NOT tested on large earthquakes.*

M_{wp} : EXAMPLE of COMPUTATION

OKUSHIRI, Japan EARTHQUAKE, 12 JULY 1993

Harvard CMT: $M_0 = 4.7 \times 10^{27}$ **dyn-cm**

Station PFO ($\Delta = 77.1°$) **Station NWAO** ($\Delta = 78.1°$)



$M_0 = 5.3 \times 10^{27}$ **dyn-cm** $M_0 = 3.3 \times 10^{27}$ **dyn-cm**

[*J. Hebden*, Northwestern Univ., 2006]

M_{wp}

[*Tsuboi*, 1997]

Other Problems:

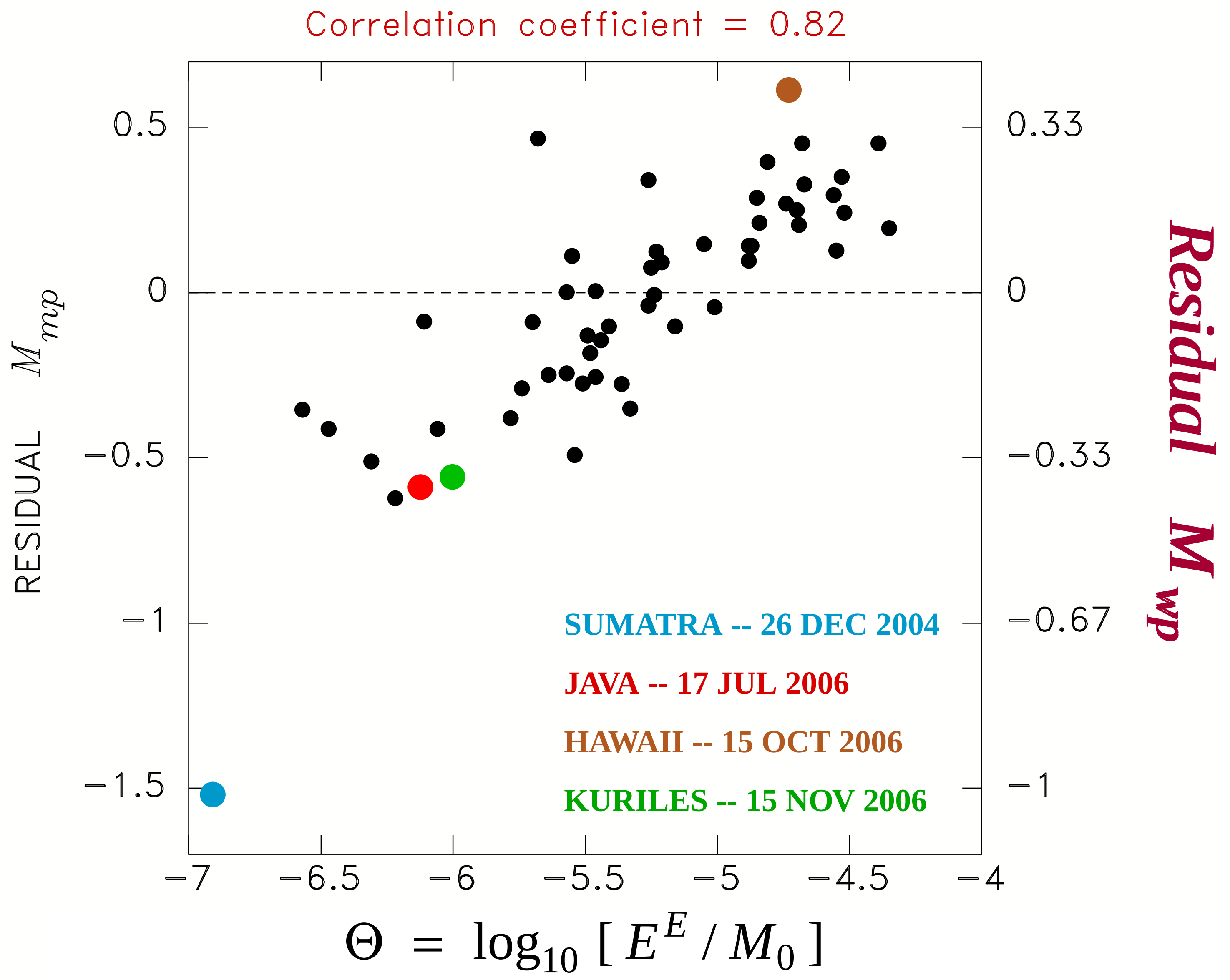
- Theory valid only in **far-field**

  Yet, applied undiscriminately in both near- and far-fields
- Length of window / Frequency band never satisfactorily resolved
- Influence of depth phases / triplications not sorted out
- Operational details of algorithm unresolved
- Performance on large dataset, including tsunami earthquakes, not assessed
- Empirical patches for big events (change α_h ??) unsatisfactory
- In time domain algorithm, instrument response not flat at long periods

M_{wp} **Recent developments**

- Compilation of M_{wp} for a dataset of 55 recent events shows a **systematic correlation** between slowness (expressed through Θ) and the *residual of* M_{wp} with respect to published moment.

→ This indicates that the standard M_{wp} algorithm suffers from the *same inadaptation to exceptional events* (slow or gigantic) as other methodologies.



Σm_b: A new, promising development

[*Bormann and Wylegalla*, 2005]

- Idea: Make standard measurements of m_b but keep adding their contributions throughout the P wavetrain, as long as enough energy is present.

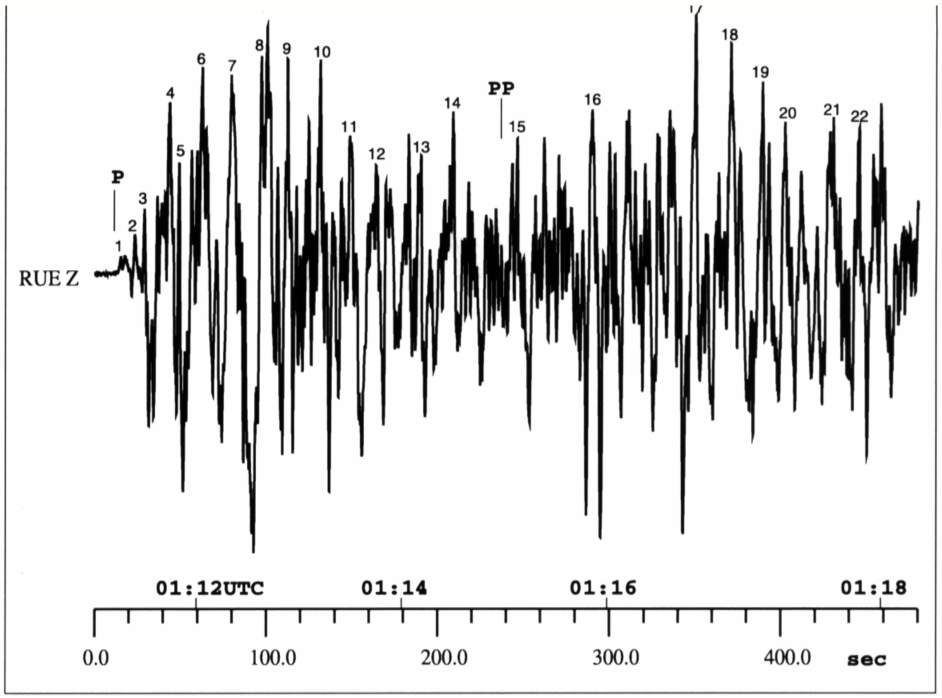


Fig. 1. Vertical component velocity-proportional broadband record at the Berlin seismic station RUE (D = 82.5°) of the P-wave group generated by the Sumatra earthquake of 26 December 2004. The times of the P and PP first arrivals have been marked. Numbered are the analyzed amplitudes originating from sub-events of the long progressing multiple rupture process.

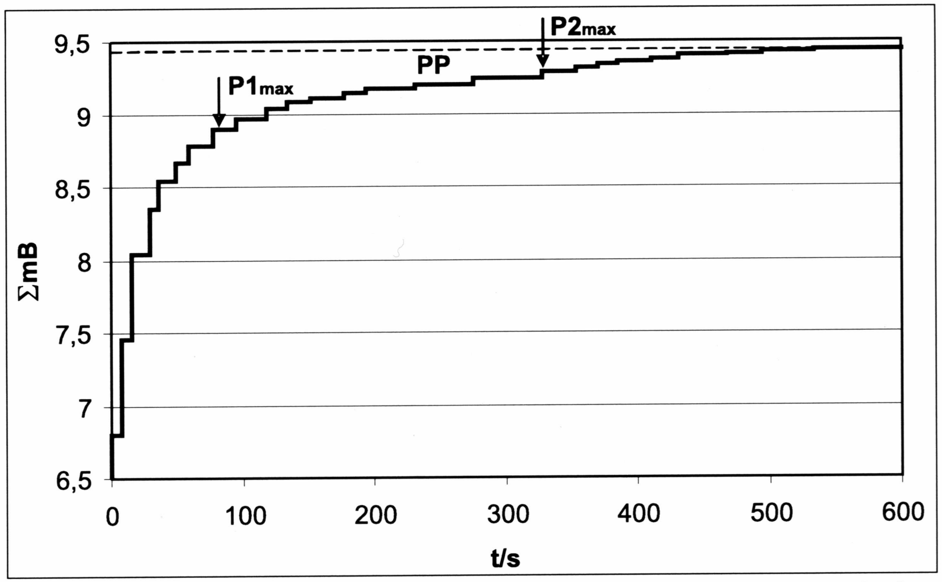


Fig. 2. Cumulative broadband body wave magnitude Σm_B as a function of time t in seconds after the first onset for the whole P-wave group of the Sumatra earthquake of 26 December 2004.

- Seems to work fine, even for large earthquakes
- Drawbacks: Operational aspects of algorithm still largely *ad hoc*.

  Lacks theoretical justification.

  Same problems as Θ, M_{wp} (duration of window).

- Sumatra, 28 March 2005: $M_w = 8.6$, $M_e = 8.5, \Sigma m_B = 8.6$
- Hokkaido, 25 September 2003: $M_w = 8.3$, $\Sigma m_B = 8.4$
- Alaska, 3 November 2002: $M_w = 7.9$, $M_s = 8.5, \Sigma m_B = 8.4$
- Peru, 23 June 2001: $M_w = 8.4, \Sigma m_B = 8.4$.

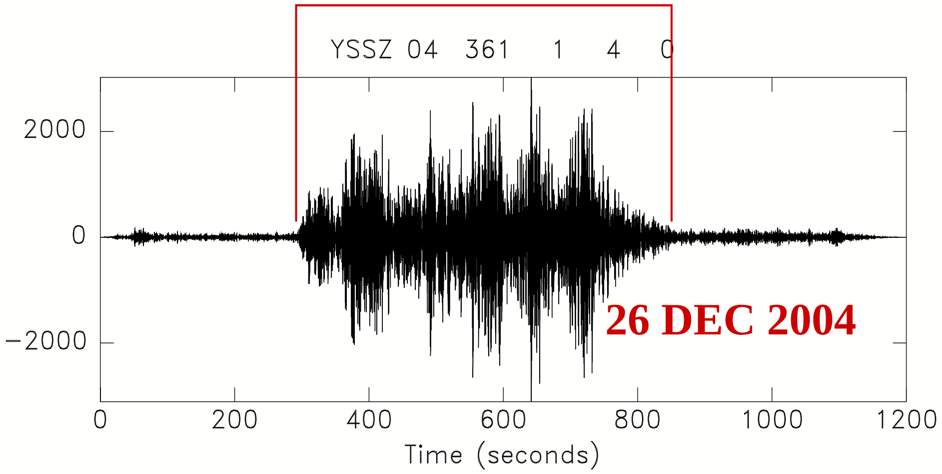
A simple [trivial ?], robust measurement

[*Ni et al.*, 2005]

- Duration of source from High-Frequency (2−4 Hz)

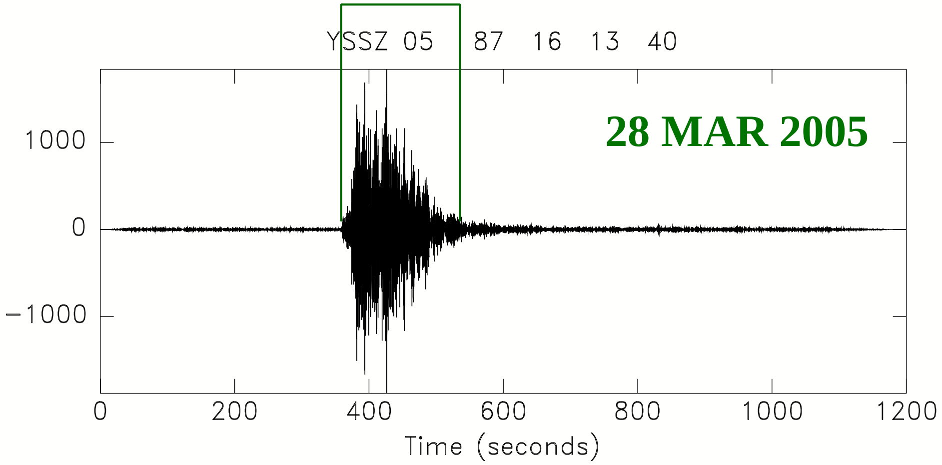
  Teleseismic *P* wavetrain

$t = 559$ s



26 DEC 2004

$t = 177$ s

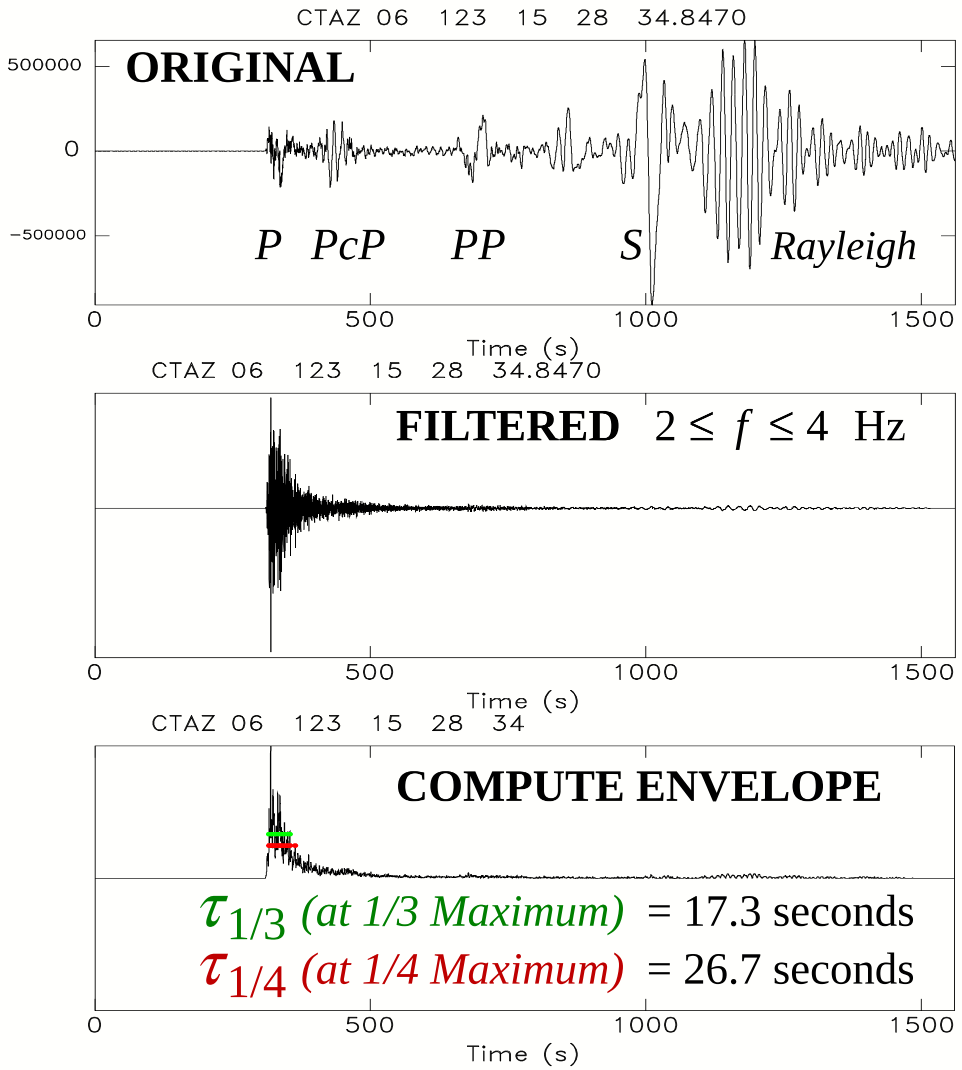


28 MAR 2005

DEVELOP ALGORITHM TO MEASURE HIGH-FREQUENCY P−WAVE DURATION

TONGA, 3 May 2006 — Charter Towers (CTA)

$\Delta = 37°$



$\tau_{1/3}$ *(at 1/3 Maximum)* = 17.3 seconds

$\tau_{1/4}$ *(at 1/4 Maximum)* = 26.7 seconds

[*Reymond and Okal*, 2006]

PRELIMINARY DATASET ($\tau_{1/3}$)

52 earthquakes; 1072 records

→ **2004 Sumatra event recognized as very long**

($\tau_{1/3}$ = 167 s; $\tau_{1/4}$ = 291 s)

→ *"Tsunami Earthquakes"* **also identified**

(**Java, 2006**; **Nicaragua, 1992**)

→ By contrast, the 2006 Kuriles earthquake is not found to exhibit slowness.
This confirms its character as weak and late, but not slow.