THE ROLE OF QUANTITATIVE SEISMOLOGY IN REAL-TIME AND DEFERRED TSUNAMI STUDIES

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TSUNAMIS

can be considered a form of ultra-long period seismic wave, and their *warning* could proceed through the calibration of the earth-quake source.

THE CHALLENGE

- Design evalution methods which will correctly retrieve the tsunami potential of an earthquake

  (i.e., the long-period behavior of the source)

  in as little time as possible.

- Note that we want method[s] which will

  WORK in EXCEPTIONAL CASES
  (Giant events and Anomalous [slow] ones).

SO,... How do we measure earthquakes, after all ?

THE FOUNDING FATHERS

EARLY IDEAS

- Describe damage inflicted by earthquake

→ *"INTENSITY Scales"*

Modified Mercalli Intensity Scale, 1931

(" MMI ")

Fr. G. Mercalli at Vesuvius

ca. 1910

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.)

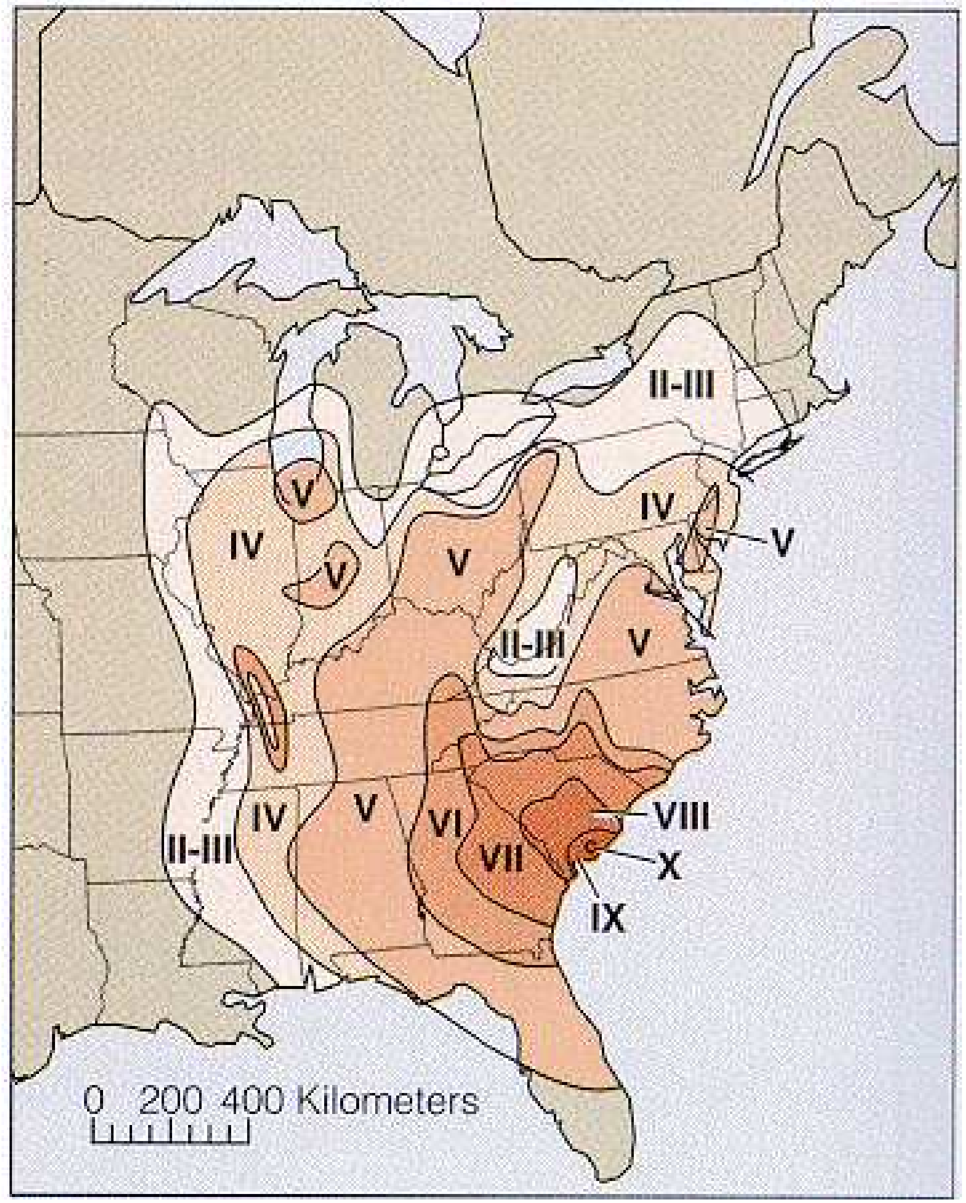
Dynamic connection: Intensity *should express*

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.

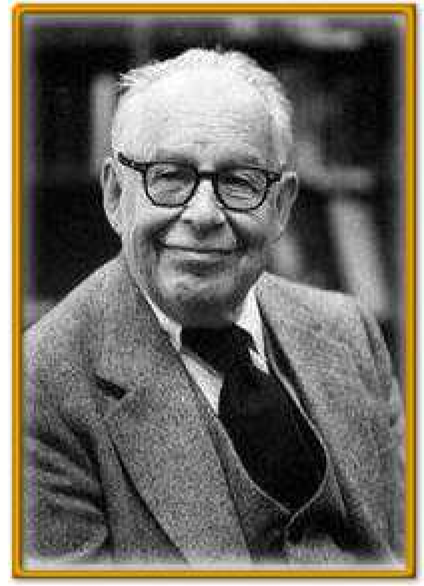
EARTHQUAKE MAGNITUDES

- An essentially empirical concept, intr-oduced by *Richter* [1935], long before any physical understanding of earth-quake sources

→ To this day, measurements have remained largely

ad hoc,

especially at short distances.



Bulletin of the Seismological Society of America

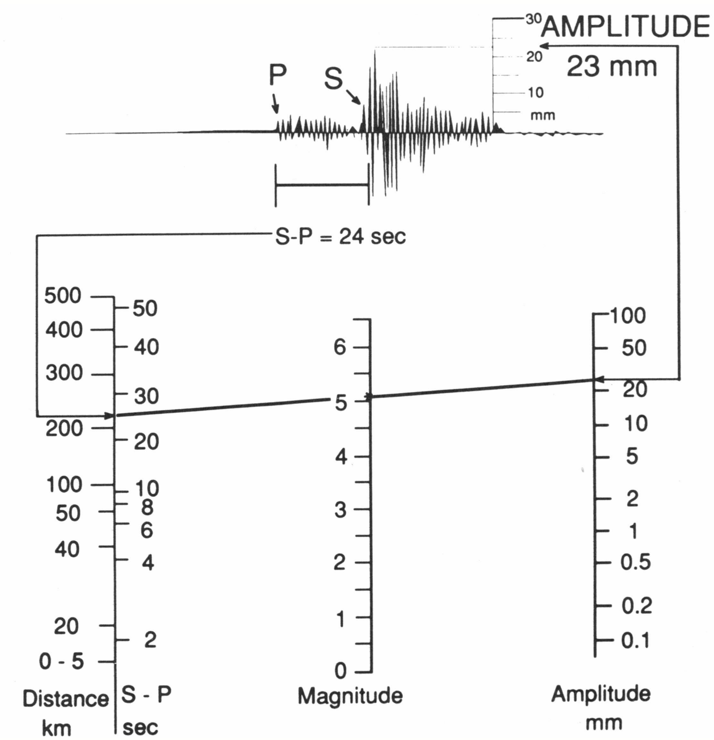
VOL. 25 JANUARY, 1935 No. 1

AN INSTRUMENTAL EARTHQUAKE MAGNITUDE SCALE*

BY CHARLES F. RICHTER

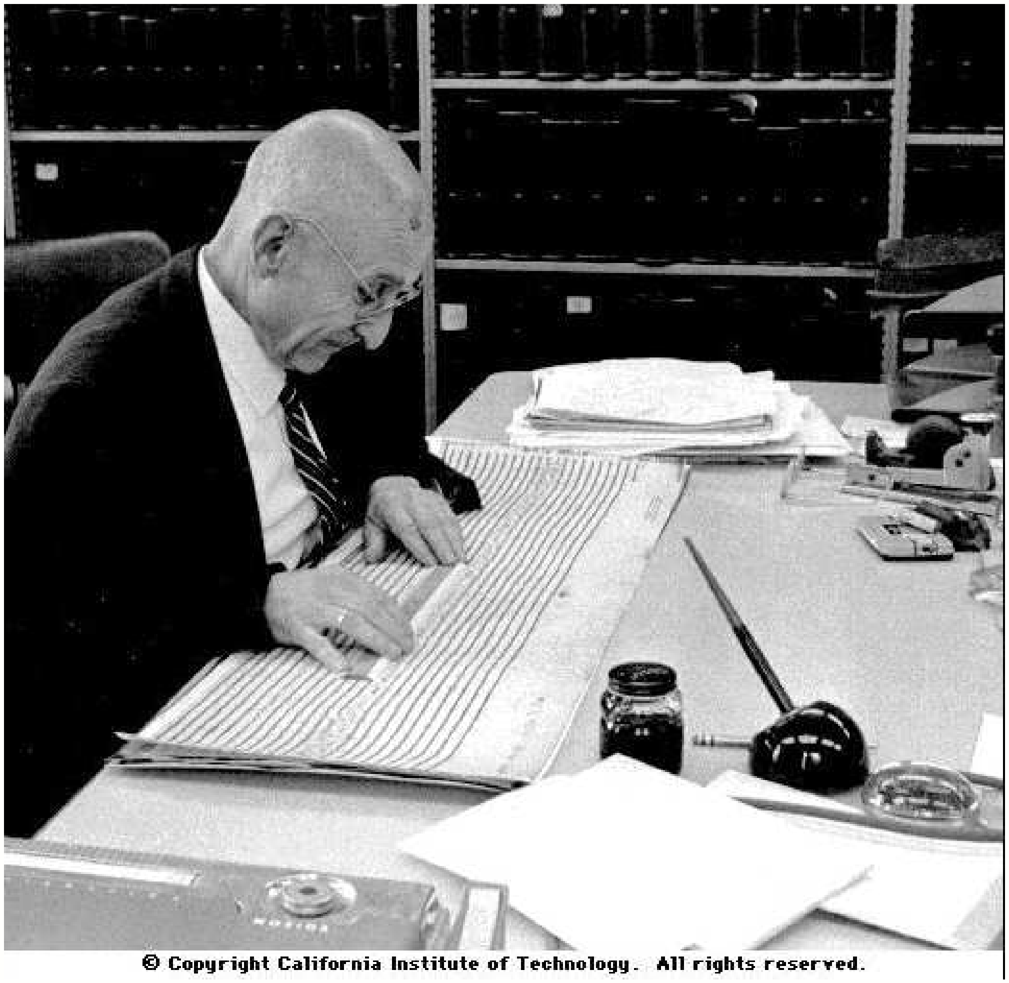
The procedure may be interpreted to give a definition of the magnitude scale number being used, as follows: *The magnitude of any shock is taken as the logarithm of the maximum trace amplitude, expressed in microns, with which the standard short-period torsion seismometer ($T_0 = 0.8$ sec., $V = 2800$,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



B. Gutenberg, 1958

- Apply worldwide
- Try (!!) to justify theoretically

→ Leads to first worldwide quantified catalogue of earthquakes

"Seismicity of the Earth"

Gutenberg and Richter [1944; 1954]

J. VANĚK, A. ZÁTOPEK, V. KÁRNIK, N. V. KONDORSKAYA, YU. V. RIZNICHENKO,
E. F. SAVARENSKY, S. L. SOLOV'EV AND N. V. SHEBALIN

STANDARDIZATION OF MAGNITUDE SCALES*

The authors suggest standard scales for determining magnitude from body and surface waves.

Izv. Akad. Nauk SSSR, Ser. Geofiz., **2,** 153−158, 1962.

"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

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

$Q(\Delta, h)$

h

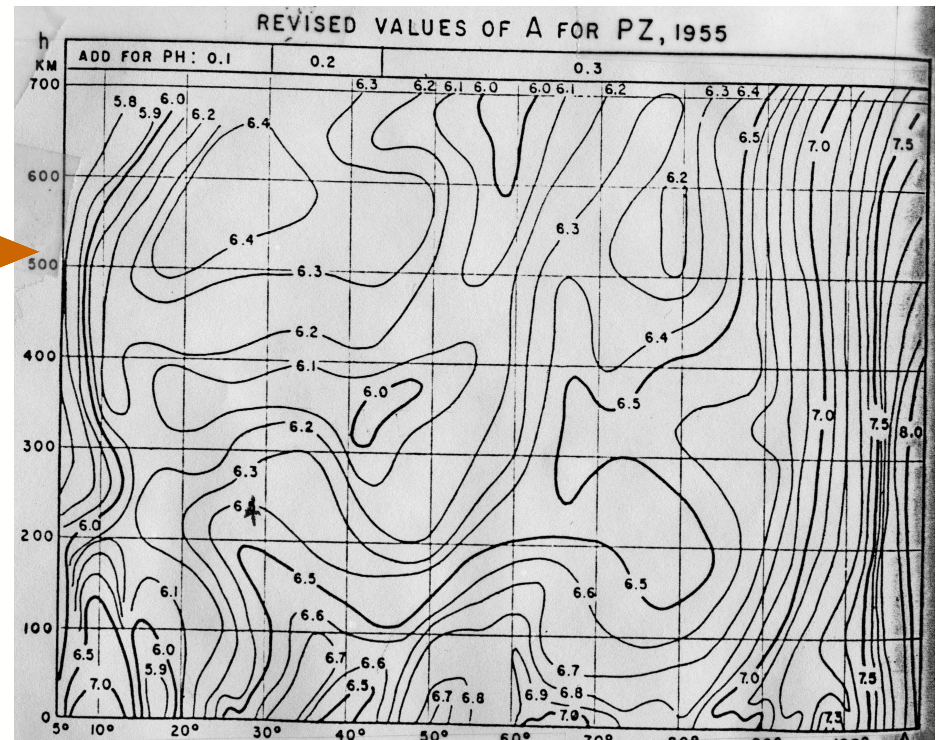


FIGURE VIII-6 *Chart for using amplitude and period of P to find magnitudes.*

Δ

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

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

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

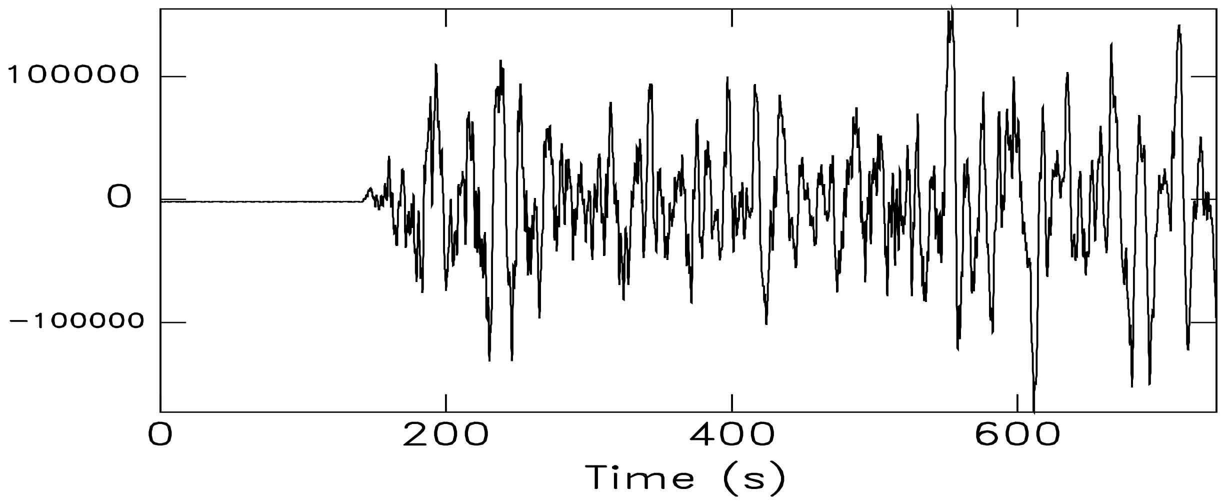
BODY-WAVE MAGNITUDE m_b

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

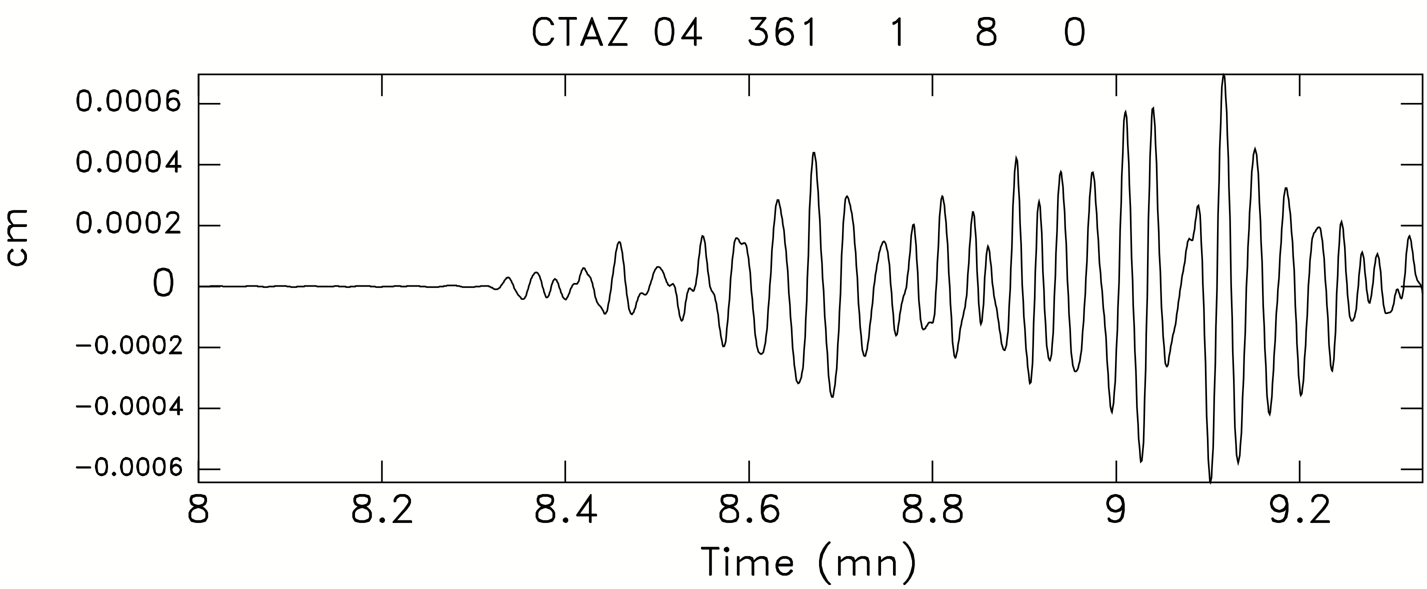
* Should be measured at period close to 1 second

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

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

$$\boldsymbol{m_b = 7.2}$$

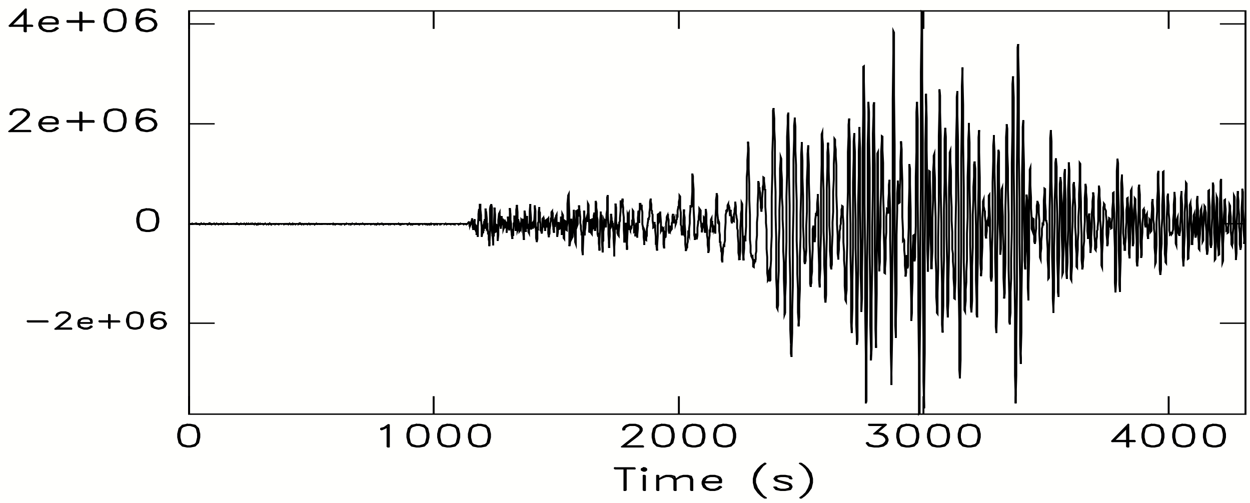
SURFACE-WAVE MAGNITUDE M_s

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

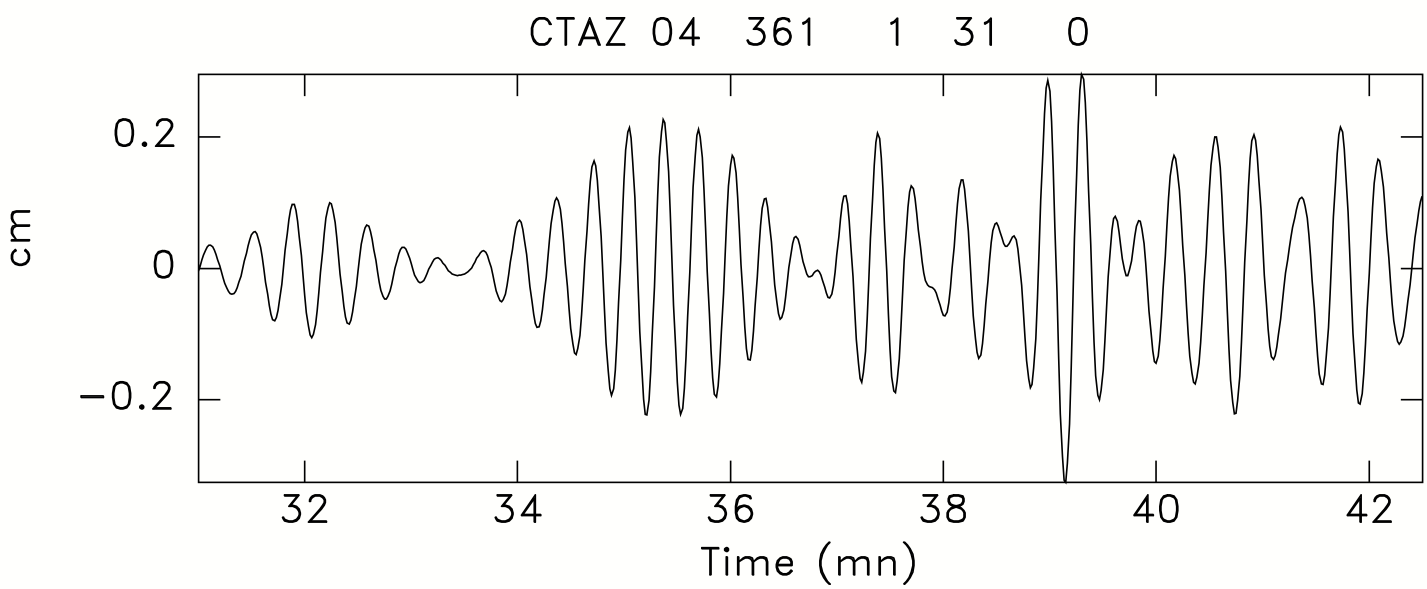
* Should be measured at Period of 20 seconds

SUMATRA–ANDAMAN, 26 DEC 2004

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



- 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

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

$$\boldsymbol{M_s = 8.19}$$

$$m_b \neq M_s$$

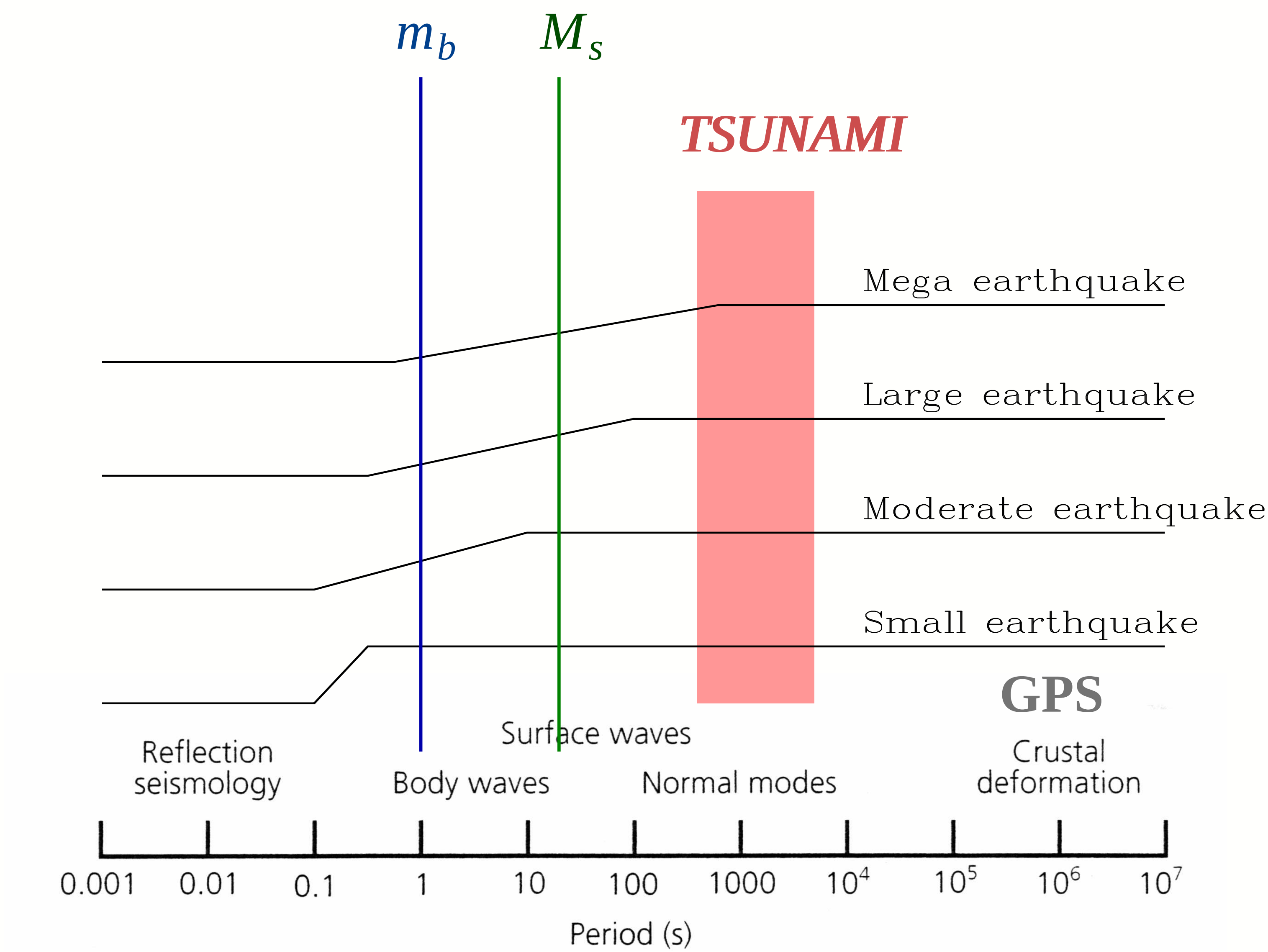
WHY ?

Q.: Which one should we believe ?

A.: **Neither !**

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.

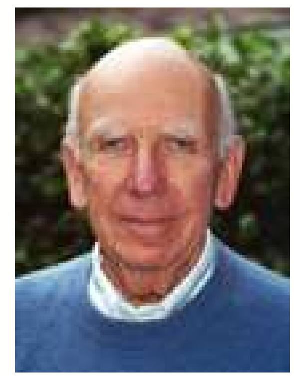


Late 1950s — Early 1960s

BRINGING IN THEORETICAL MECHANICS TO DEVELOP A PHYSICAL FRAMEWORK

Vvedenskaya [1956], later *Burridge and Knopoff* [1964]

introduce the concept of **SEISMIC MOMENT**



ИЗВЕСТИЯ АКАДЕМИИ НАУК СССР,

№ 3 СЕРИЯ ГЕОФИЗИЧЕСКАЯ 1956

А. В. ВВЕДЕНСКАЯ

ОПРЕДЕЛЕНИЕ ПОЛЕЙ СМЕЩЕНИЙ ПРИ ЗЕМЛЕТРЯСЕНИЯХ С ПОМОЩЬЮ ТЕОРИИ ДИСЛОКАЦИЙ

Bulletin of the Seismological Society of America. Vol. 54, No. 6, pp. 1875–1888. December, 1964

BODY FORCE EQUIVALENTS FOR SEISMIC DISLOCATIONS

BY R. BURRIDGE AND L. KNOPOFF

ABSTRACT

An explicit expression is derived for the body force to be applied in the absence of a dislocation, which produces radiation identical to that of the dislocation. This equivalent force depends

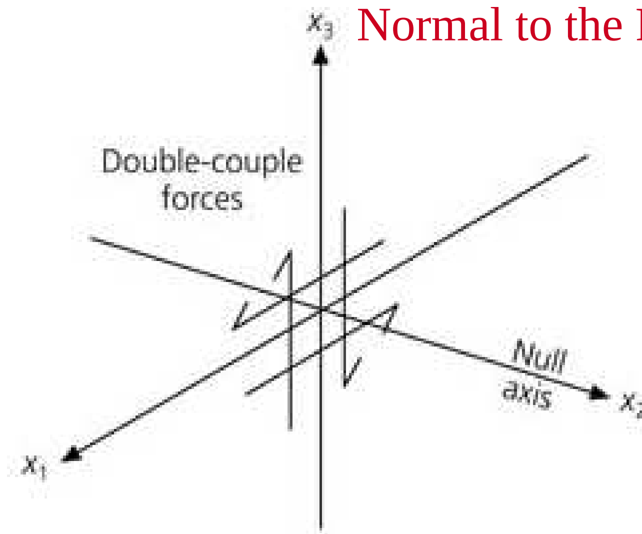
EARTHQUAKE SOURCE GEOMETRY

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

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

[*Stein and Wysession*, 2002]

The scalar is the common **moment** of the 2 couples.
It is called the ***seismic moment*** of the earthquake (M_0)
It represents its source in *true physical units* (**dyn*cm** or **N*m**).

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:

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

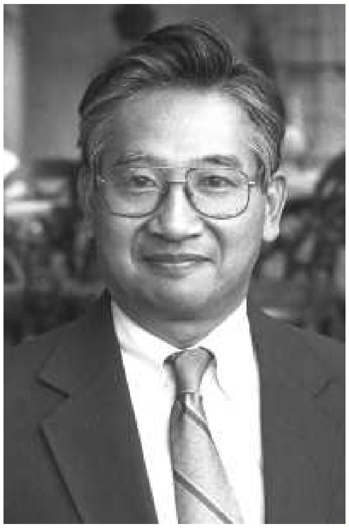
where μ is the rigidity of the medium, Δu the slip between the fault walls at each point of the fault, and the integral is taken over the surface of faulting.

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

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

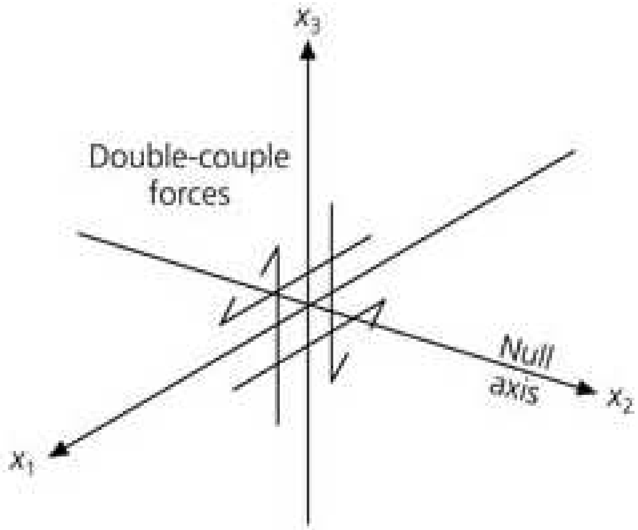
M_0 is measured in dyn*cm (or N*m).

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 Singular Tensor.

Historically, the first measurements of M_0 from seismograms were performed by forward modeling (involving some trial-and-error). **The first M_0 (3×10^{27} dyn*cm) was published for the 1964 Niigata earthquake by** *Aki* [1966].

Around 1970, *Gilbert and Dziewonski* [1970] laid the theoretical ground for the direct *inversion* of the seismic moment from seismograms.

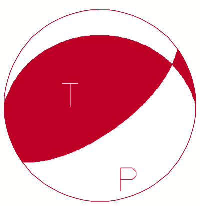
J.F. Gilbert

Example of Global CMT (*ex-Harvard*) Inversion

08 JULY 2007, Aleutian Islands

J.H. Woodhouse

```
CENTROID-MOMENT-TENSOR  SOLUTION
GCMT EVENT:     C200708020321A
DATA: II IU CU IC GE
L.P.BODY WAVES: 64S, 165C, T= 50
MANTLE WAVES:   62S, 138C, T=125
SURFACE WAVES:  64S, 172C, T= 50
TIMESTAMP:      Q-20070802104412
CENTROID LOCATION:
ORIGIN TIME:      03:21:51.2 0.1
LAT:51.11N 0.00;LON:179.66W 0.01
DEP: 32.2  0.2;TRIANG HDUR:  5.6
MOMENT TENSOR: SCALE 10**26 D-CM
RR= 1.010 0.006; TT=-1.050 0.005
PP= 0.031 0.005; RT= 0.740 0.010
RP= 0.716 0.010; TP=-0.403 0.004
PRINCIPAL AXES:
1.(T) VAL=  1.484;PLG=64;AZM=297
2.(N)       0.045;    15;     60
3.(P)      -1.538;    21;    156
BEST DBLE.COUPLE:M0= 1.51*10**26
NP1: STRIKE=271;DIP=27;SLIP= 123
NP2: STRIKE= 54;DIP=67;SLIP=  74
```



Note that intermediate eigenvalue is not exactly zero...

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```

$$M_0 \;=\; 1.5 \times 10^{26} \text{ dyn*cm}$$

A.M. Dziewoński

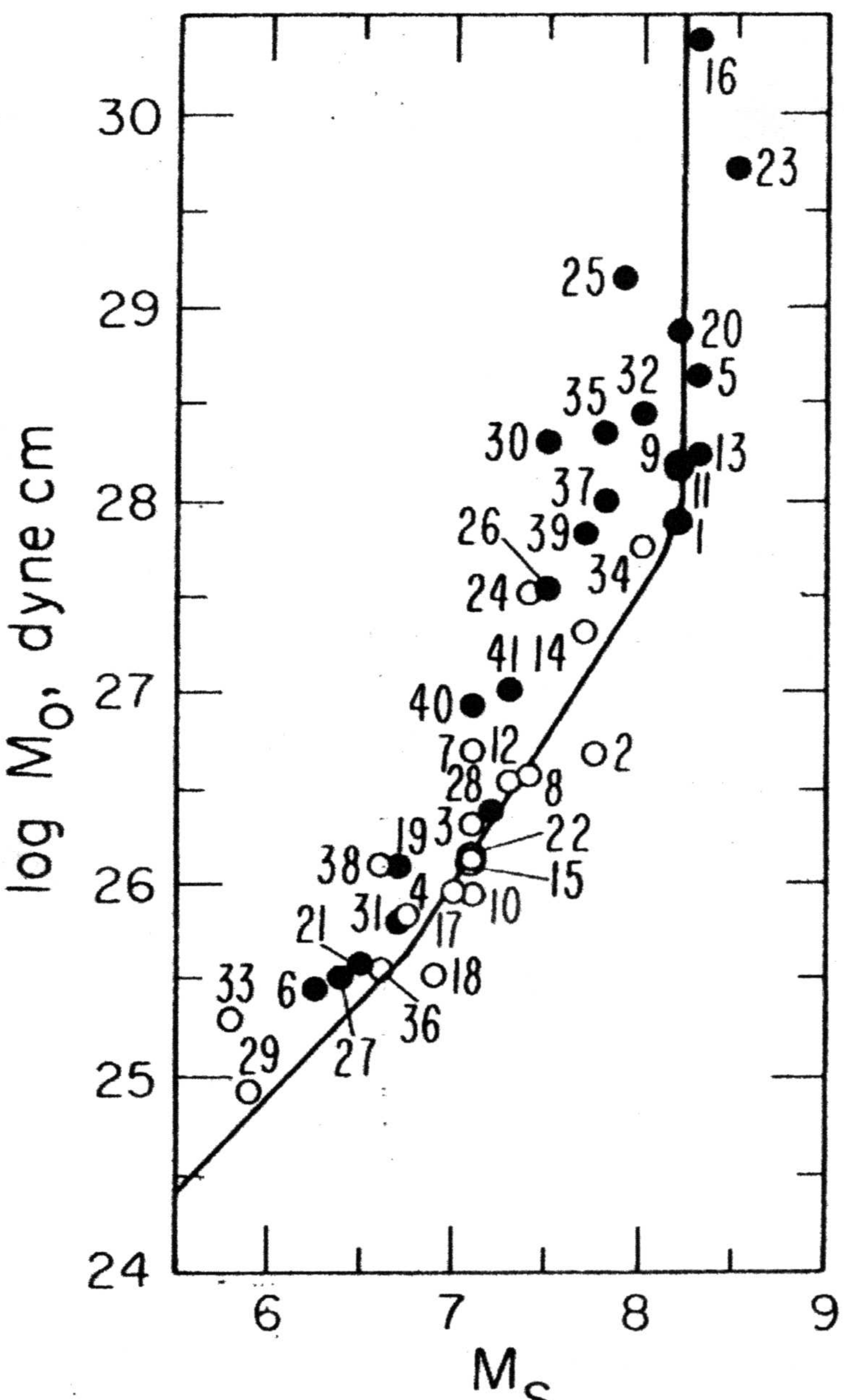
G. Ekström

More than 30,000 CMT solutions have been performed and catalogued under the Global-CMT project.

- Algorithm can *in principle* run automatically.

COMPILATION of SEISMIC MOMENTS ILLUSTRATES SATURATION of m_b and M_S

- *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

CMT AND ITS LIMITATIONS

→ CMT inversions are now performed in quasi-real time

→ But this approach still suffers from limitations:

- Needs a large database (tens of stations)
- Automated algorithm is , *per force*, hard-wired, *i.e.*, universal.
- It will need to be [manually] adapted to recognize anomalous events, either gigantic (*e.g.*, Sumatra) or slow (*"tsunami earthquakes"*; stay tuned).
- There remains the quest for ultra-long periods to properly assess tsunami potential.

HOW TO BEST APPROACH "STATIC" M_0 ?

Need to use the Earth's normal modes, upon which Earth displacement is expressed at lowest frequencies.

High-quality digital data allows routine processing, taking into account splitting due to Earth's rotation and ellipticity using code by *Stein and Geller* [1977], in the framework of *Sailor and Dahlen* [1979].

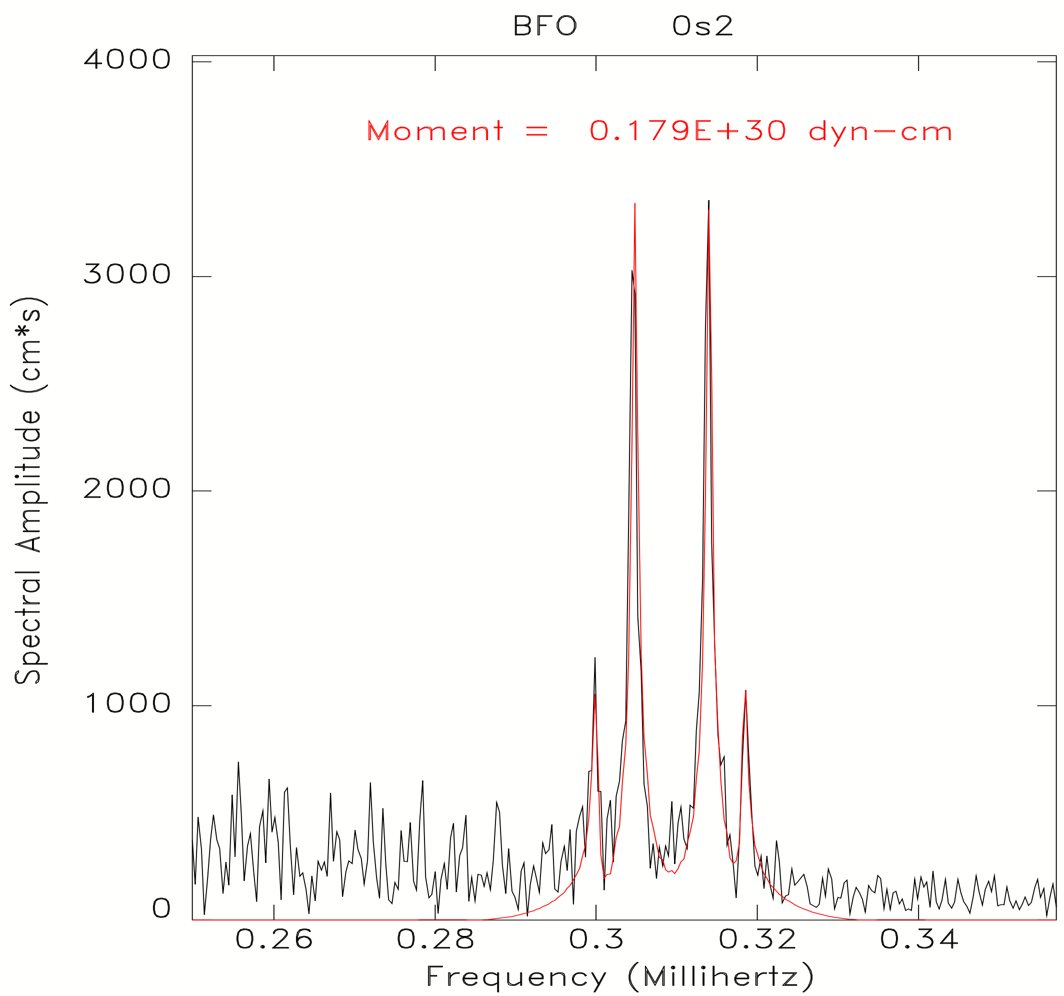
BUT... Correct resolution of spectral line[s] requires time series with duration ($T \cdot Q$), in practice 3 weeks for most modes, 3 months for the "breathing" mode ${}_0S_0$.

CLEARLY OUT OF QUESTION

FOR TSUNAMI WARNING

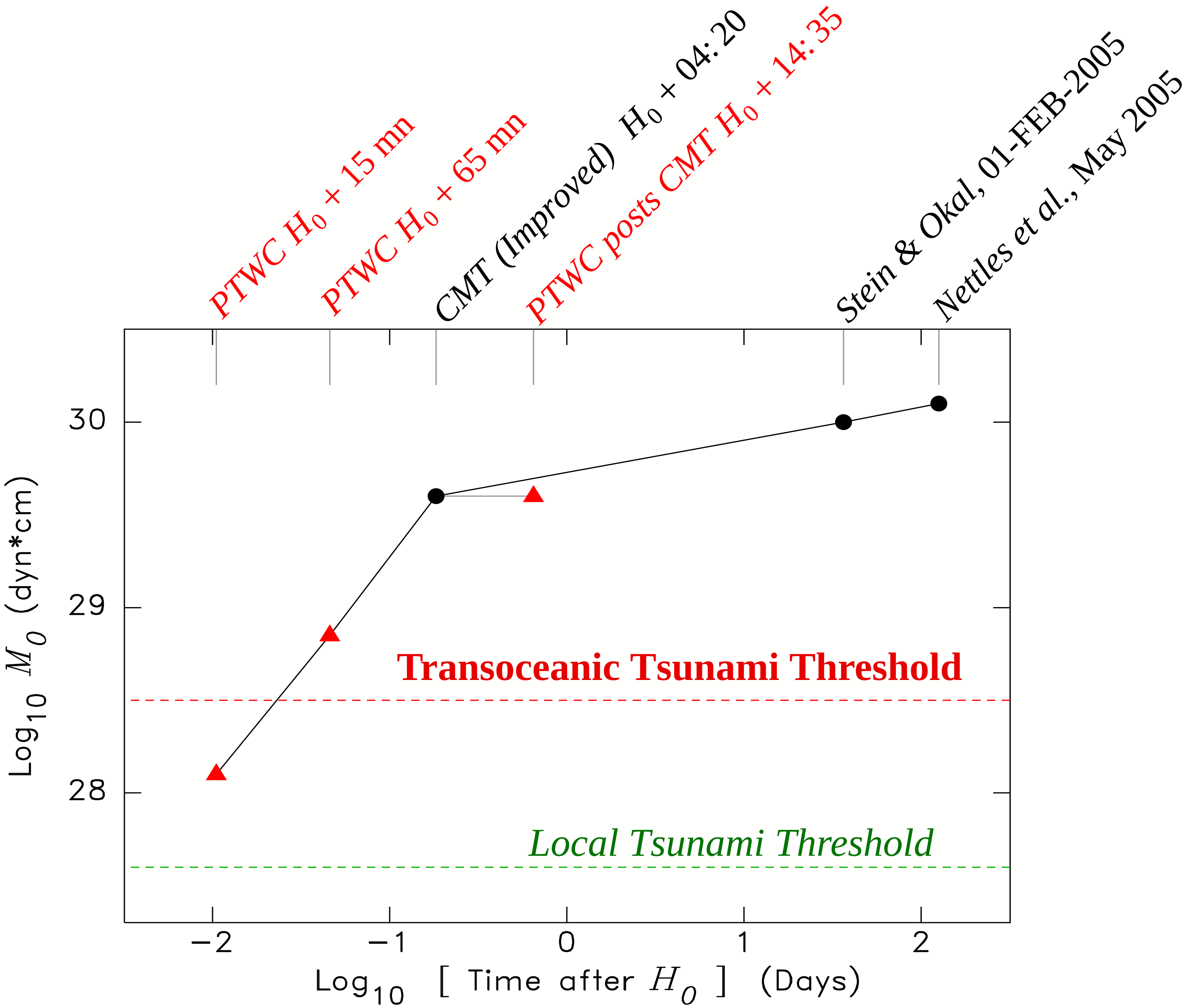
BEST–FITTING M_0 FROM MODES

- At each station, the spectrum of the multiplet is obtained by FFT (black trace).
- A synthetic time series is then computed for the exact same time window, by combining the $2l + 1$ singlets at their own frequencies with the relative amplitudes given by the stick plots. The spectrum of that synthetic is then obtained by FFT (red trace).
- The seismic moment is then derived by scaling the red trace to obtain a best fit with the observed (black) one.



TIMELINE OF MOMENT DETERMINATIONS
SUMATRA 2004

It took up to 2 months to obtain an estimate of the full moment of the event form the study of the free oscillations of the Earth [*Stein and Okal*, 2005].



*But the estimate available at PTWC 1 hour after the event, $M_0 = 8 \times 10^{28}$ dyn*cm, should have been sufficient to trigger a basin-wide warning.*

WHY THEN WAS NO SUCH WARNING ISSUED ?

M_m and TREMORS

M_m [*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)

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*

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

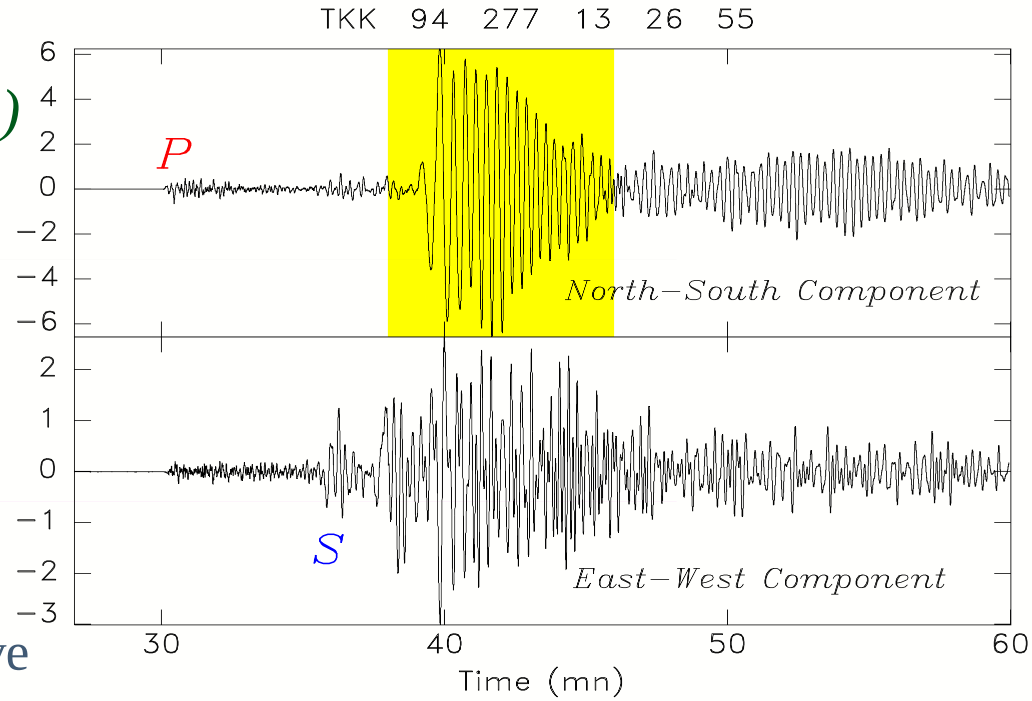
from spectral amplitude $X(\omega)$ of surface (Rayleigh) seismic waves at the longest possible periods (250 to 300 seconds)

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.

TREMORS: EXAMPLE OF APPLICATION

Kurile Is. Earthquake, 04 OCT 1994,
Station: TKK (Chuuk, Micronesia)



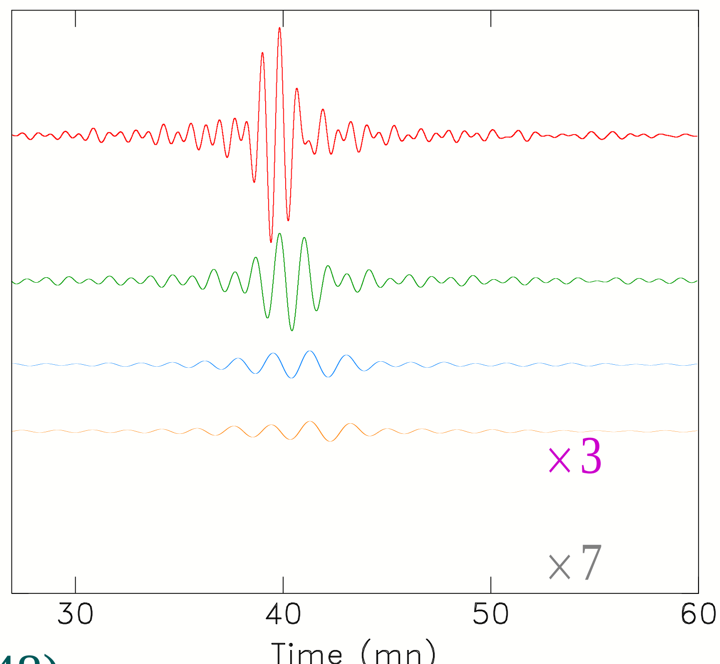
- Detection: Analyse signal level compared to previous minute.
- Location : $S - P$ gives distance (36° or 4000 km).

  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; $M_m = 8.49$

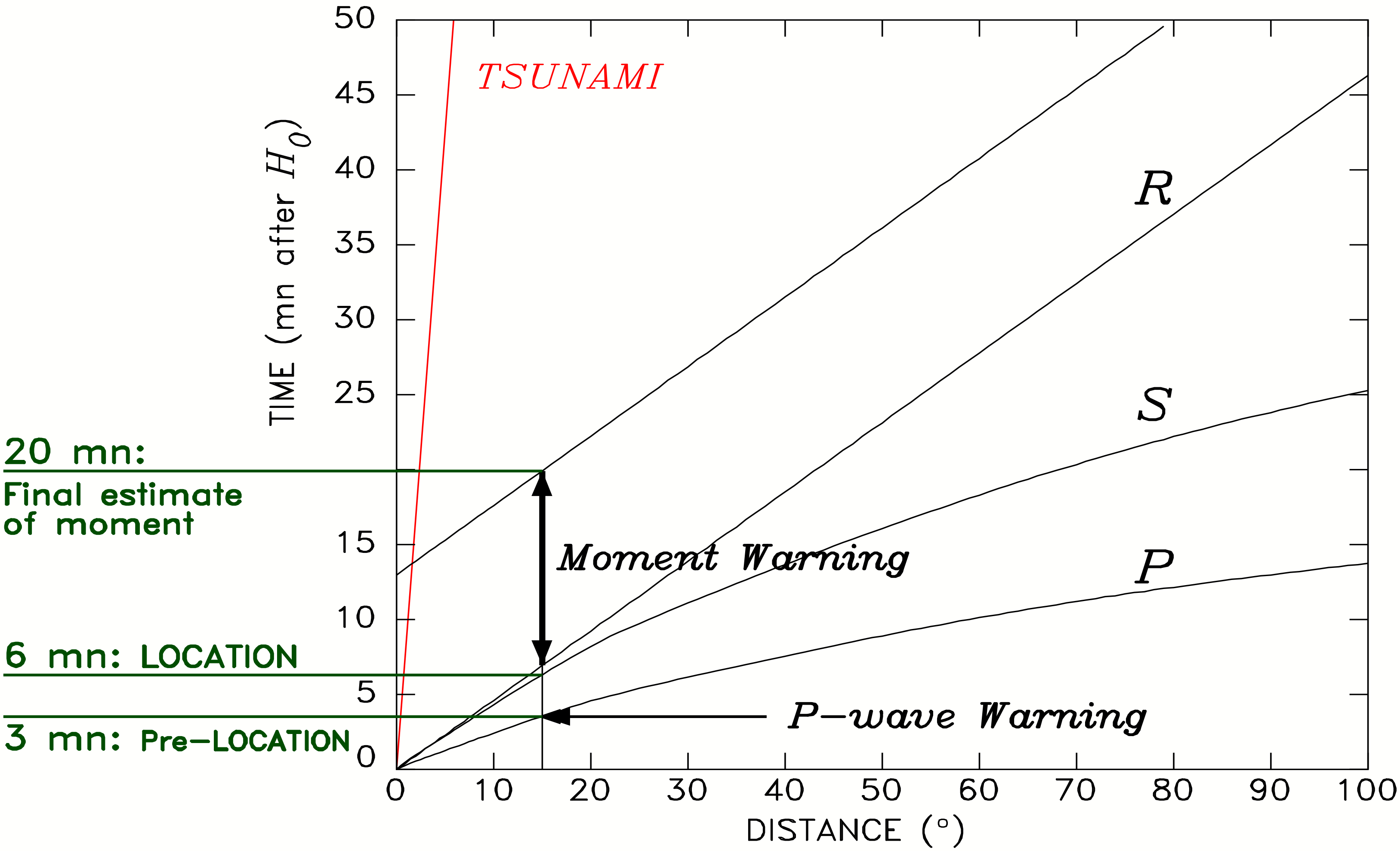
$T = 250$ s; $M_m = 8.40$

Harvard solution (obtained later):

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

TREMORS -- *Operational Aspects*

- 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: APPLICABLE in CHALLENGING CONTEXTS

→ In a series of targetted studies, we have shown that the M_m algorithm can work successfully in challenging contexts, thereby illustrating its reliability and robustness.

M_m CAN WORK at SHORT DISTANCES

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

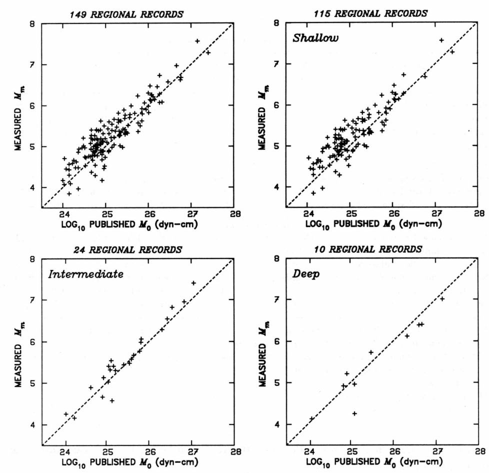


Figure 5

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

$\Delta = 1.5\,°$ (165 km).

M_m WORKS for GIGANTIC EVENTS

Chile, 1960

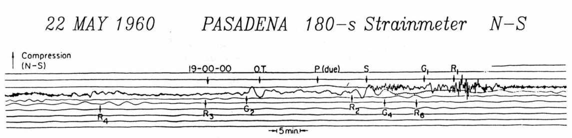
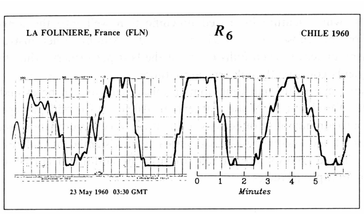
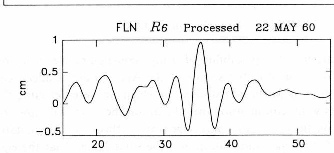


Figure 4

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).





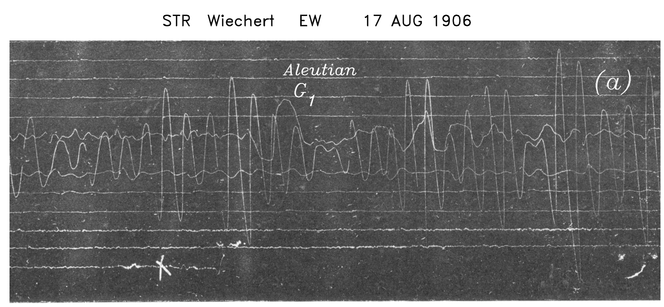
Works even on severely clipped records obtained on instruments with poor dynamic.

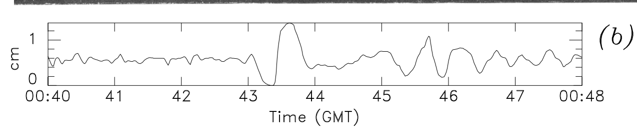
[*Okal and Talandier,* 1991]

M_m CAN WORK for HISTORICAL EVENTS

17 AUGUST 1906 -- Aleutian Islands

Wiechert mechanical seismometer, Strasbourg





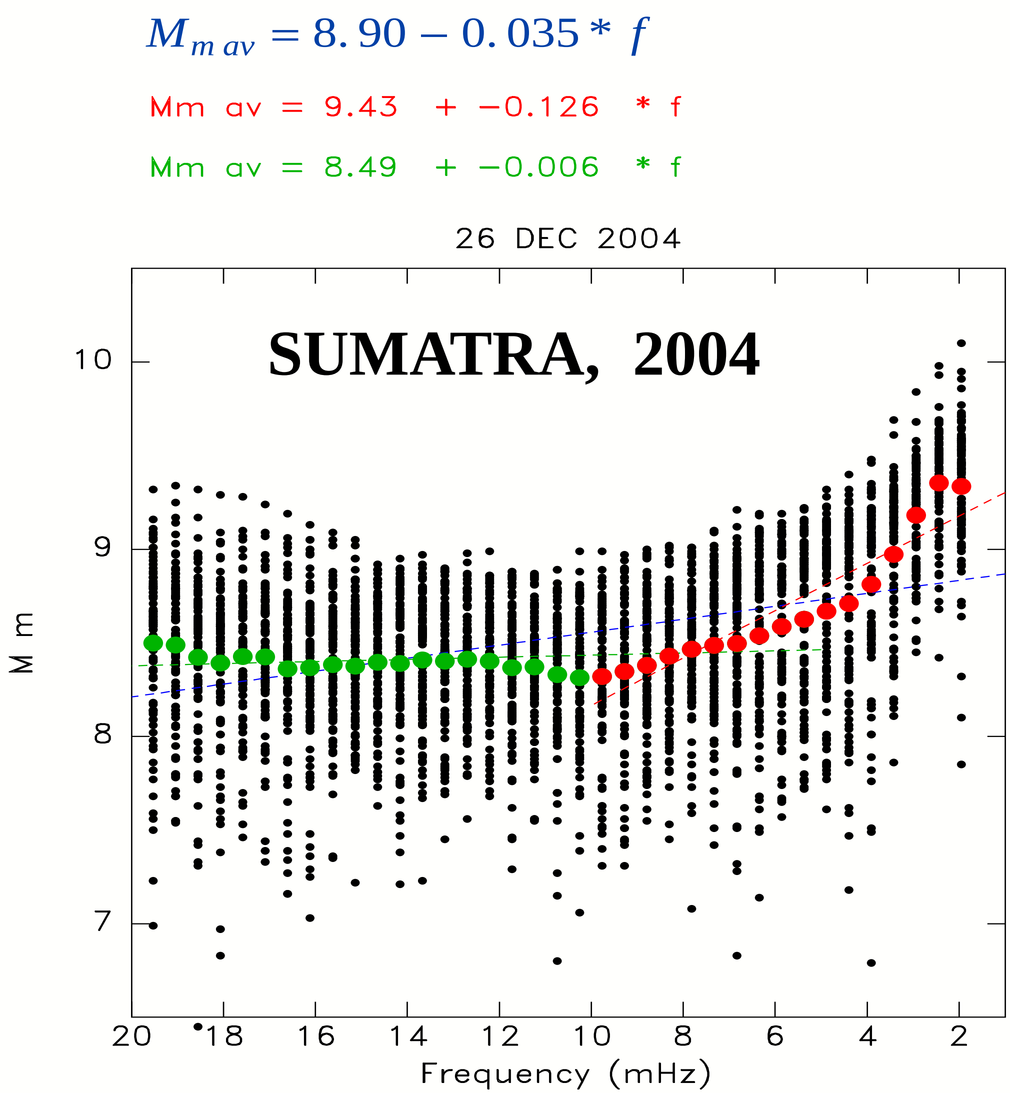
$M_m = 8.58$; $M_0 = 3.8 \times 10^{28}$ dyn*cm

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

M_m: Recent Developments

Introduced by *Okal and Talandier* [1989]   In use at CPPT, PTWC

Performance on very large datasets evaluated by *Weinstein and Okal* [2005].



Recent Improvements

- Boost periods up to 550 seconds
- Regress and compare trends as

$M_m = a_1 * f + b_1$ (all frequencies)

$M_m = a_2 * f + b_2$ (high frequencies 5 − 20 mHz)

$M_m = a_3 * f + b_3$ (low frequencies 2 − 10 mHz)

Devise algorithm to extrapolate static moment ("***b***")

* If earthquake big ($b_1 > 8.2$), **KEEP b_3**

* Else, explore event slowness by comparing a_2 and a_3.
  If earthquake is slow, **KEEP b_3**

  If earthquake is not slow, and is small ($b_1 < 7.3$),
  then **KEEP b_1.**

  Otherwise, **AVERAGE b_1 and b_3.**

This admittedly empirical algorithm gives excellent results

RETRIEVING DIVERSITY IN SEISMIC SOURCES

Not All Earthquakes Are Created Equal...

or

IDENTIFYING THE SCOFFLAWS

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). [*Kanamori*, 1972]

- 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

COULD WE DETECT SUCH EVENTS IN REAL TIME ?

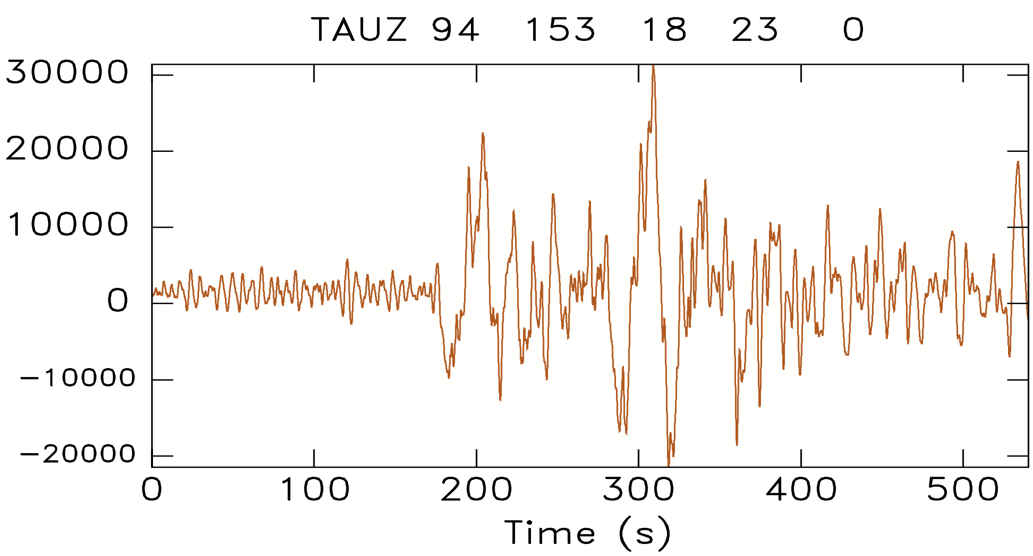
"TSUNAMI EARTHQUAKES"

- *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.

$\longrightarrow$ Use generalized$-P$ wavetrain (P, pP, sP).



1994 Java "Tsunami Earthquake"

Station: TAU (Hobart, Tasmania)

$\longrightarrow$ Compute Energy Flux at station [*Boatwright and Choy*, 1986]

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

$\longrightarrow$ Add representative contribution of S waves.

→ Define *Estimated Energy*, E^E

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

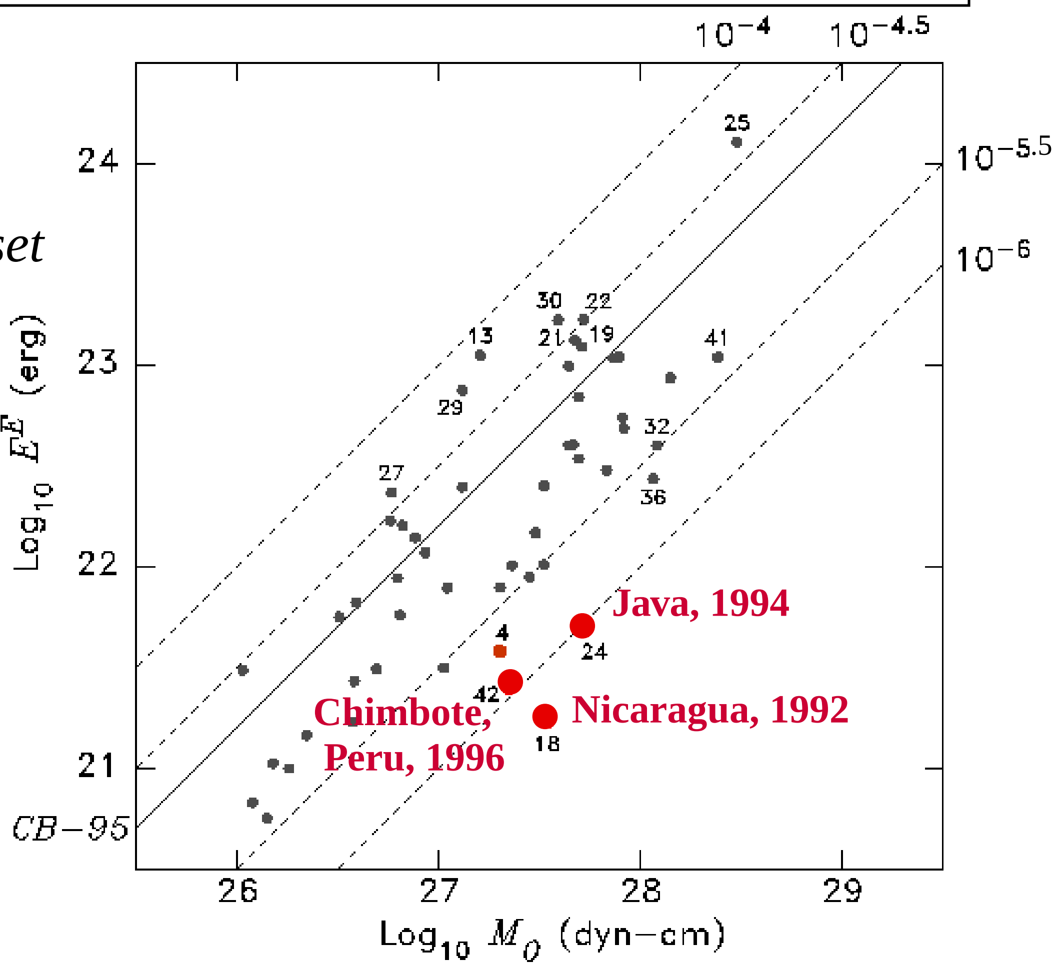
→ Scale to Moment through $\Theta = \log_{10} \frac{E^E}{M_0}$

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

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

Original Dataset

[*Newman and Okal*, 1998]



Now implemented at Papeete and PTWC

SPEEDING UP THE WARNING

Long−Period Waves are Typically [Slow] *Surface Waves*

This delays the process (we must wait for them 30 to 60 mn)

Can the faster Body Waves (mainly P) be used to retrieve the Long-Period Characteristics of the Source ?

BODY-WAVE APPROACH: 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 *far-field P* waves involves

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

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

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

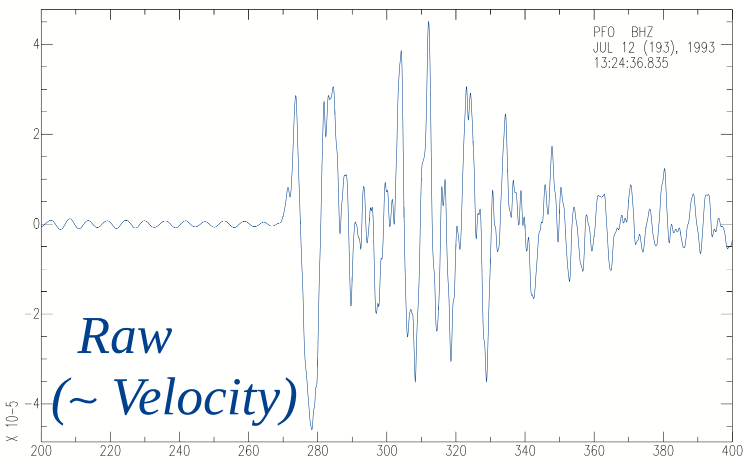
Problems: Instrument records velocity, so **double** integration needed; noisy at long periods; *NOT tested on large earthquakes.*

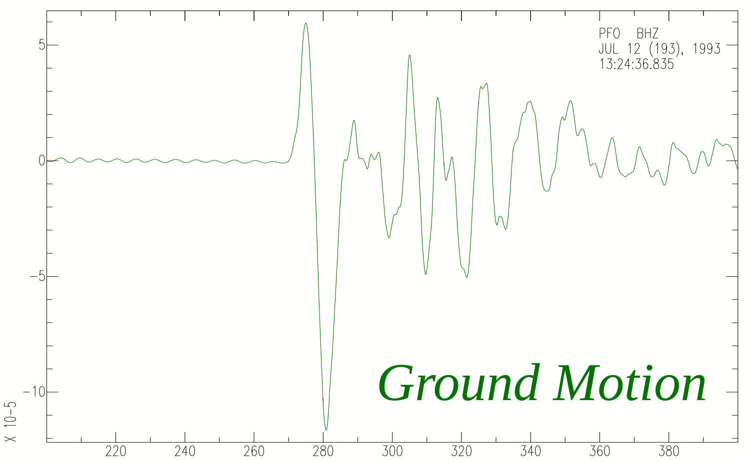
M_{wp} : EXAMPLE of COMPUTATION

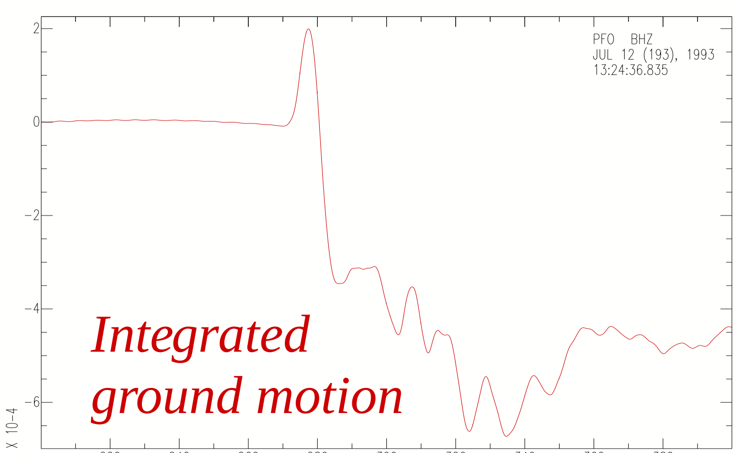
OKUSHIRI, Japan EARTHQUAKE, 12 JULY 1993

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

Station PFO ($\Delta = 77.1°$)

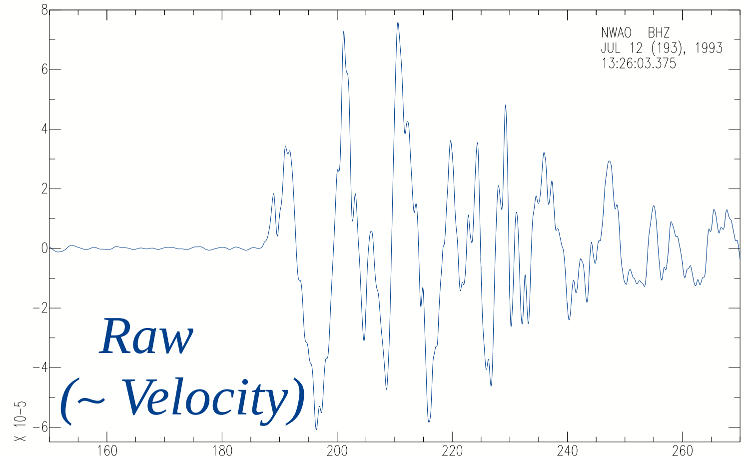


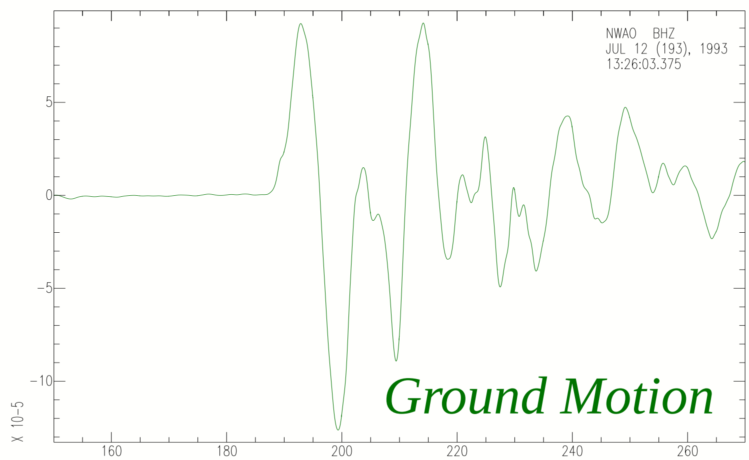


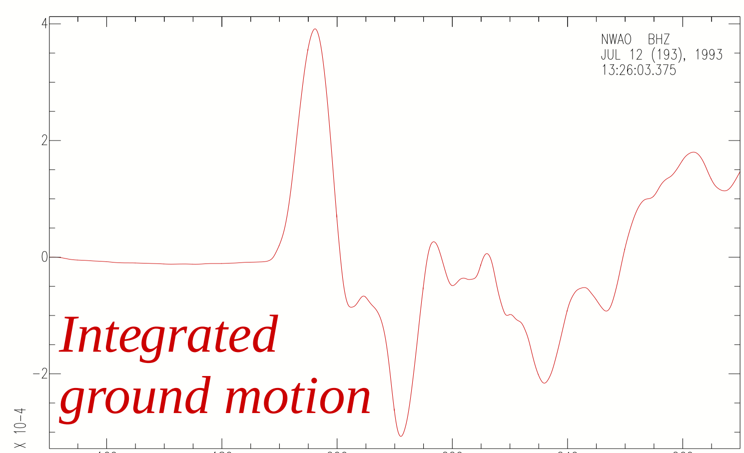


$M_0 = 5.3 \times 10^{27}$ **dyn-cm**

Station NWAO ($\Delta = 78.1°$)







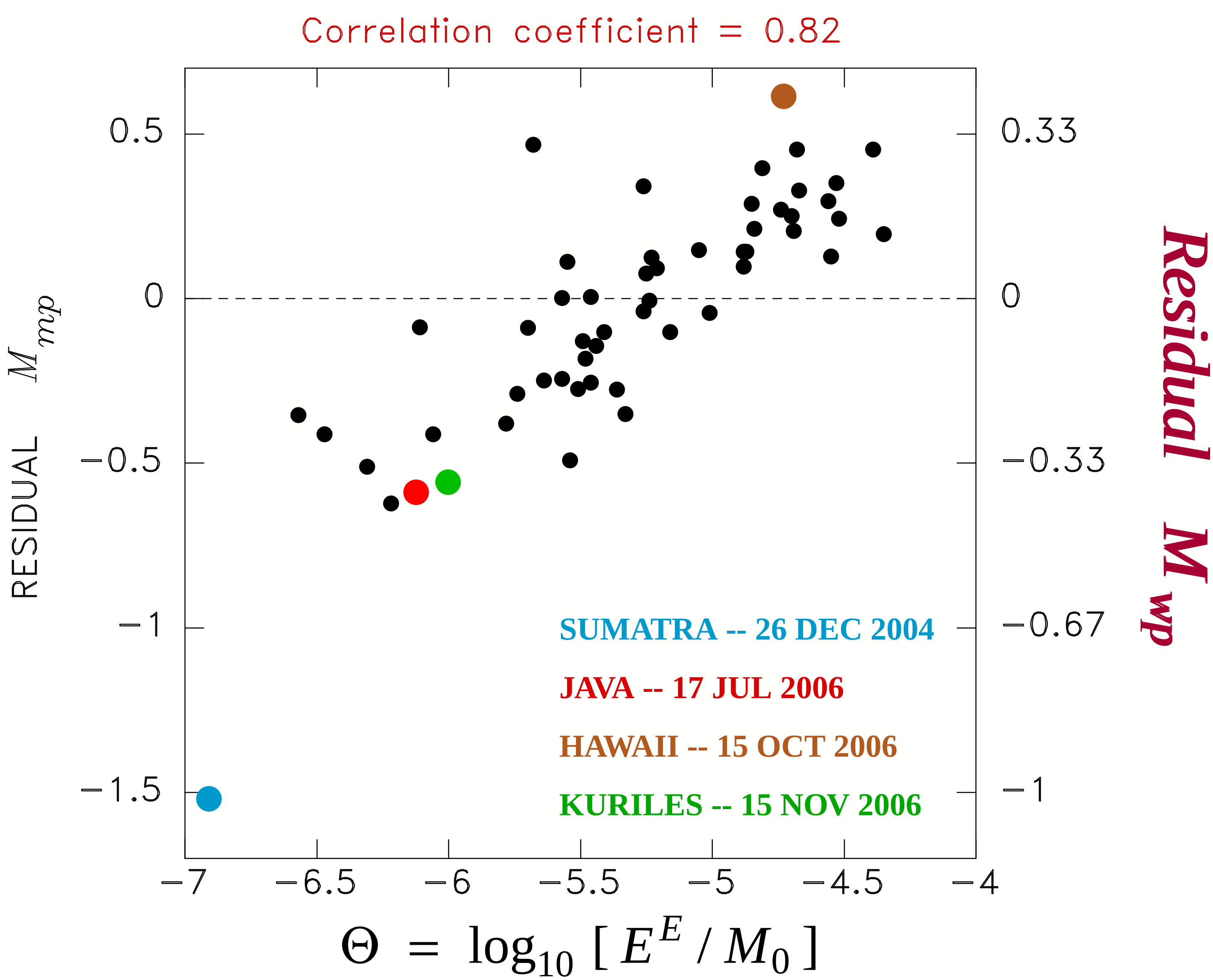
$M_0 = 3.3 \times 10^{27}$ **dyn-cm**

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

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.



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

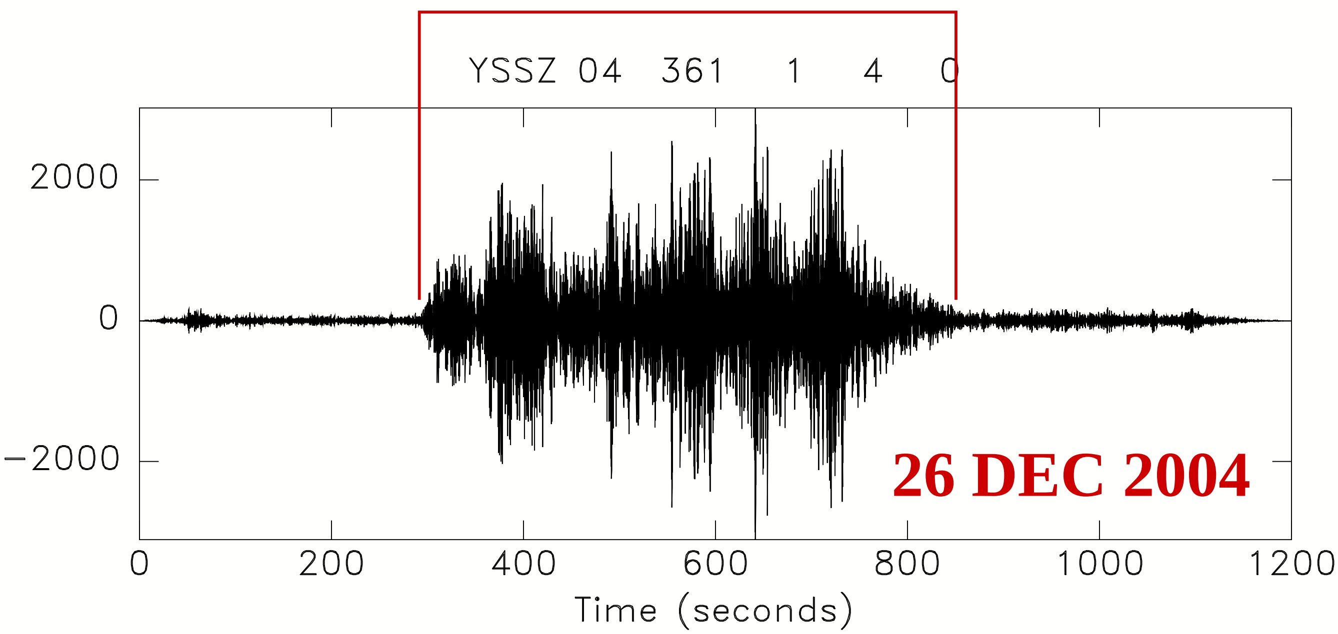
DURATION OF *P* WAVES

A simple [trivial ?], robust measurement

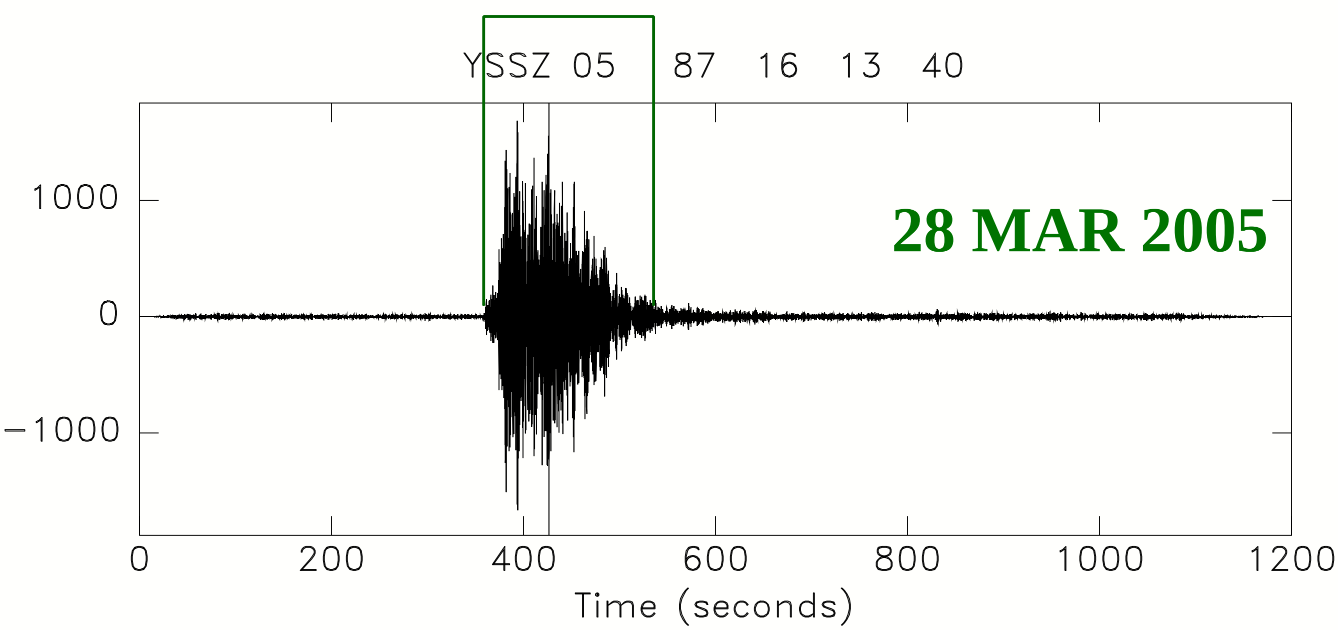
[*Ni et al.*, 2005]

- Duration of source from High-Frequency (2−4 Hz) Teleseismic *P* wavetrain

t = 559 s



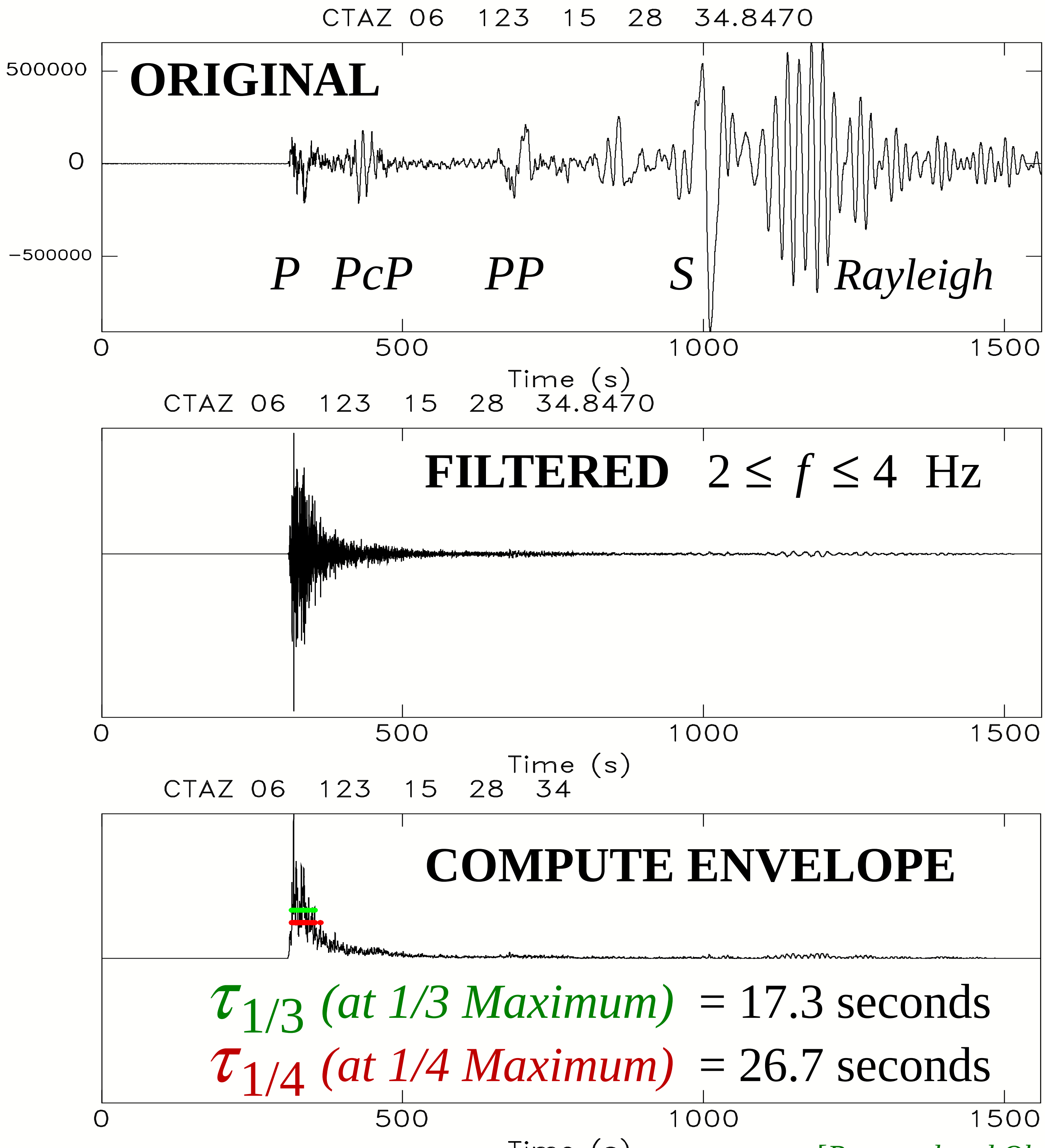
t = 177 **s**



DEVELOP ALGORITHM TO MEASURE HIGH-FREQUENCY P−WAVE DURATION

TONGA, 3 May 2006 — Charter Towers (CTA)

$\Delta = 37°$



[*Reymond and Okal*, 2006]

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

52 earthquakes; 1072 records

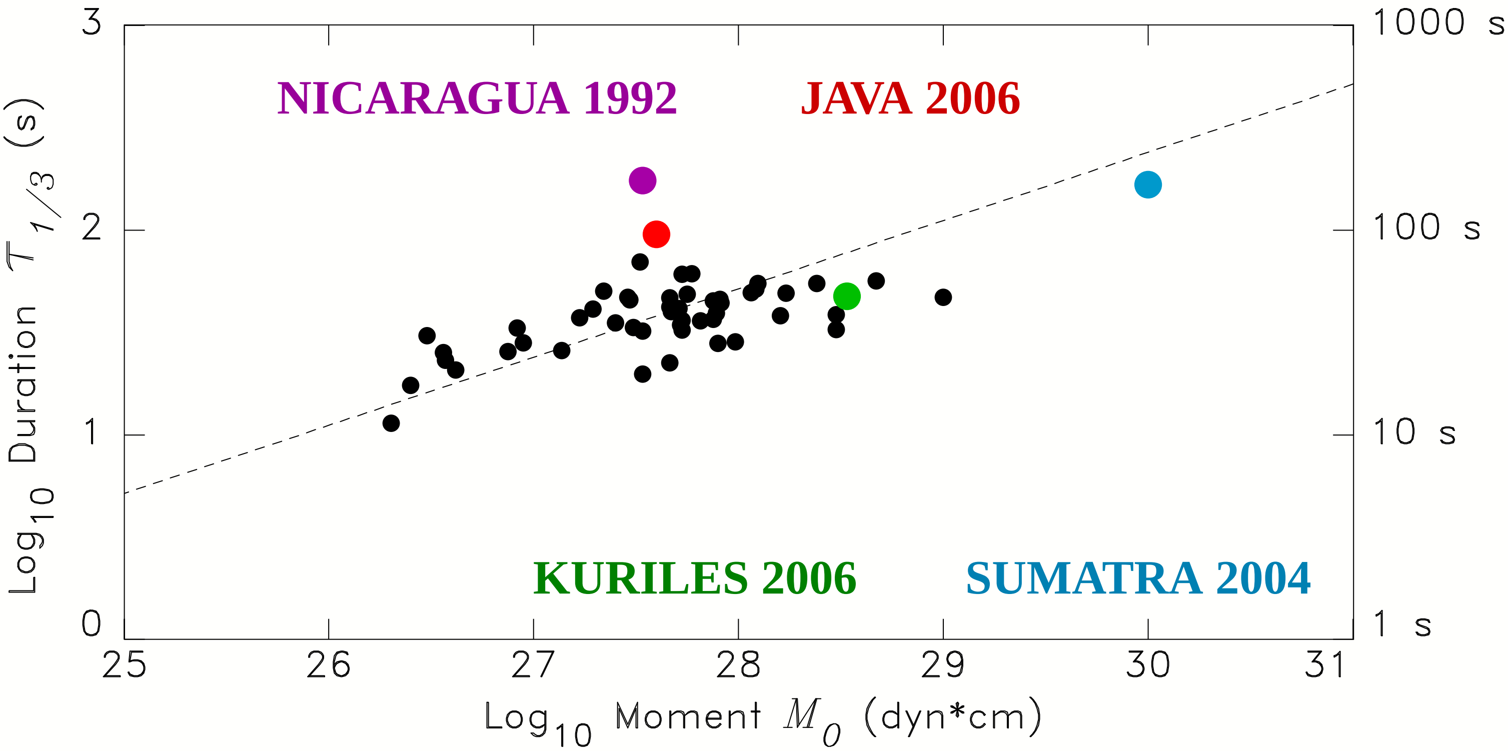
→ **2004 Sumatra event recognized as very long**

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

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

(Java, 2006; Nicaragua, 1992)

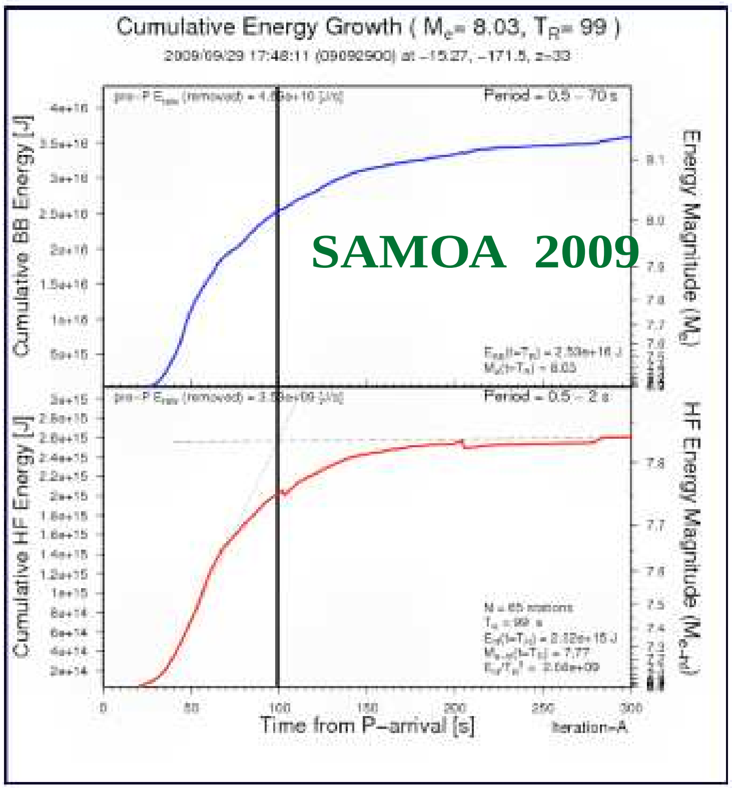
→ By contrast, the 2006 Kuriles earthquake is not found to exhibit slowness.
This confirms its character as weak and late, but not slow.

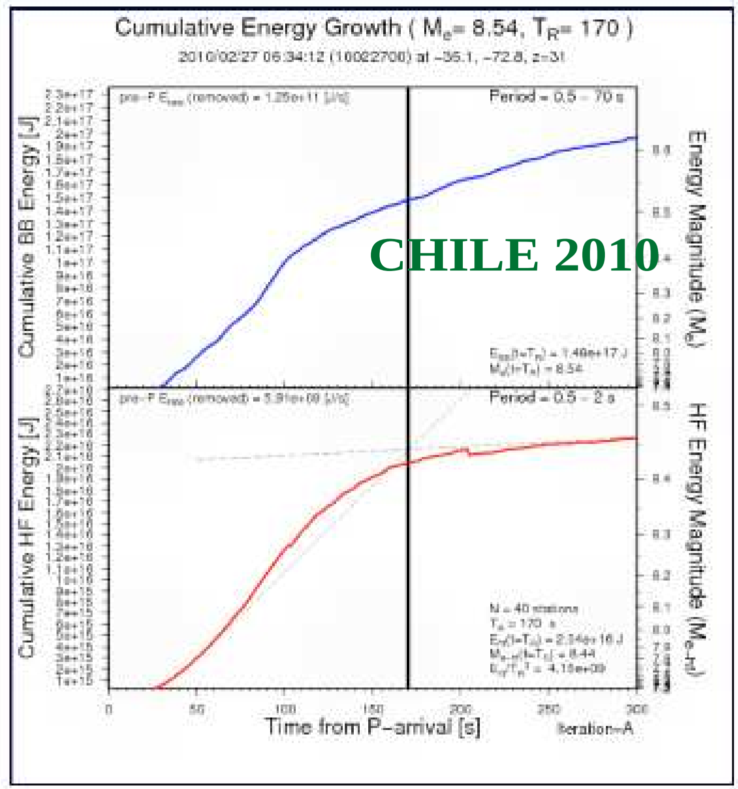


CUMULATIVE ENERGY GROWTH :

An Eye on the Rate of Energy Release

In a recent development, *Newman and Convers* [2009] monitor the rate of build-up of the energy in the *P* waves to define both a high-frequency radiated energy and a *source duration* based on the characteristic corner time of this build-up.





Such methods hold promise for real-time determination of anomalous properties such as exceptional size (Chile, 2010) or source slowness (tsunami earthquakes).

[*A.V. Newman*, pers. comm. 2010, and Research Home Page]

W **Phase**

for "Whistling"

or perhaps *"Wisdom"...*

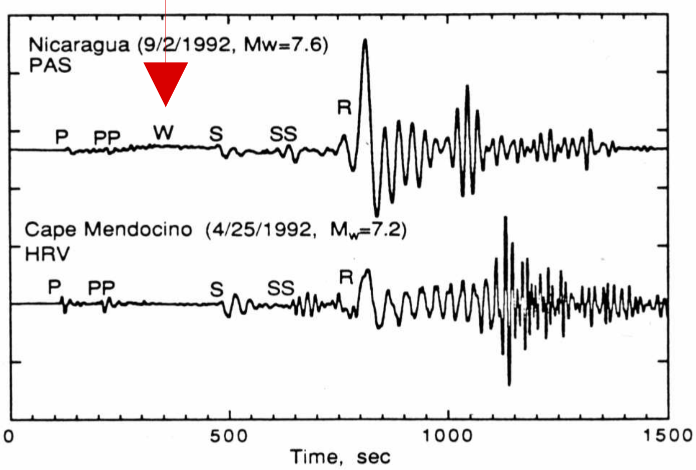
W Phase

The new, definitive, way of quantifying the low-frequency seismic source in quasi-real time.

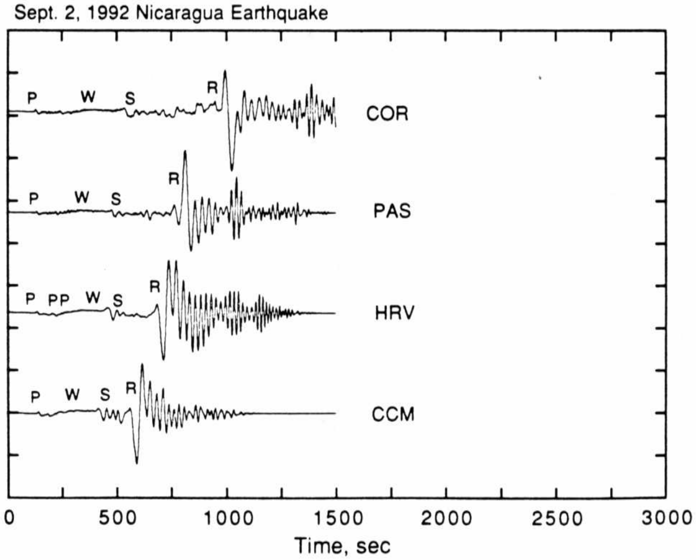
[*Kanamori et al.*, 2008]

EAOkal

Geophysical Research Letters



Sept. 2, 1992 Nicaragua Earthquake



[*Kanamori*, 1993]

AUGUST 20, 1993 Volume 20 Number 16

AMERICAN GEOPHYSICAL UNION

What *IS* the *W* Phase ?

A combination of multiply-reflected body phases sampling the upper mantle at very low frequencies (1 to 5 mHz) and arriving between *P* and *Rayleigh* waves.

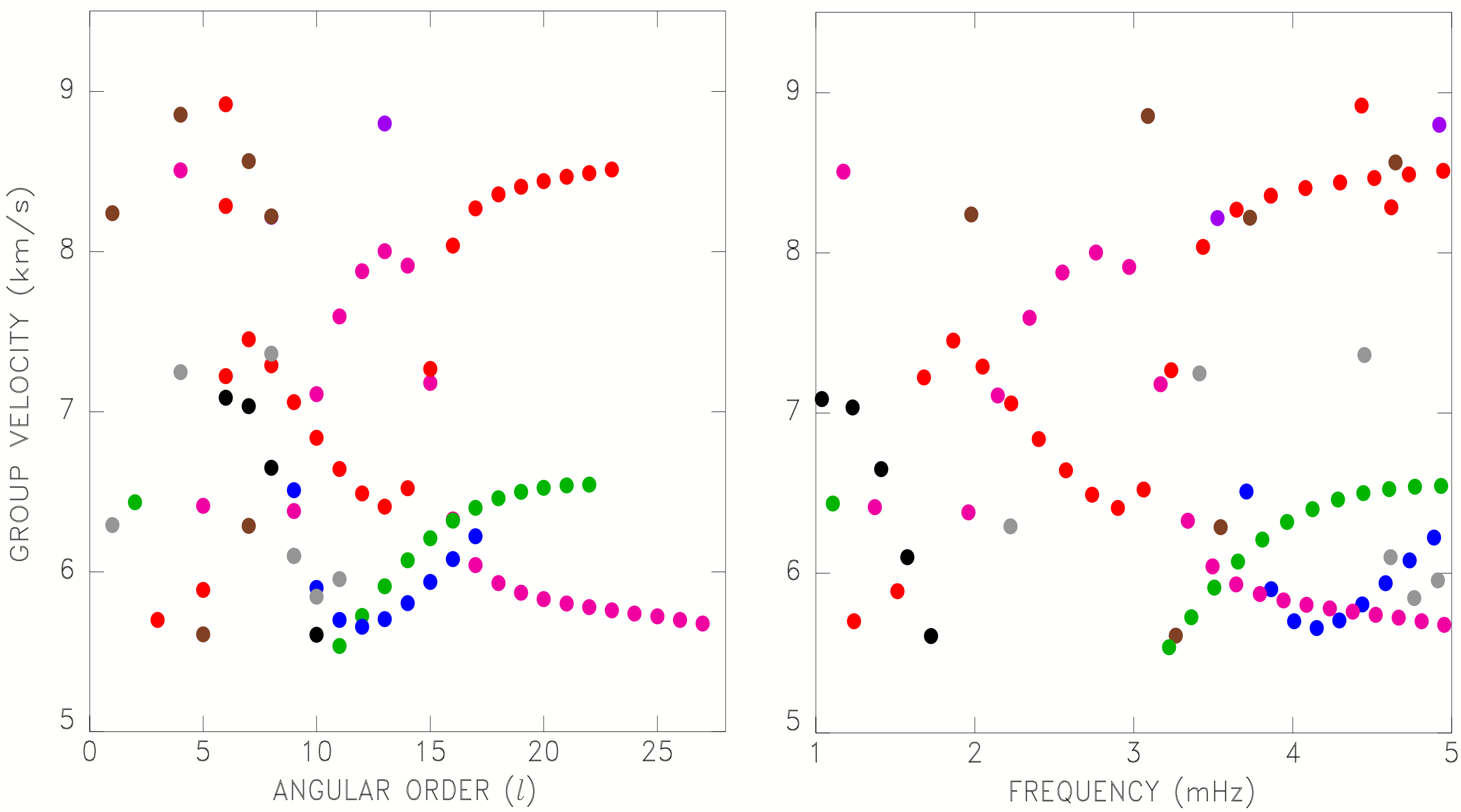
→ The multiply reverberated nature of this amalgam of *PP*, *PPP*, *PPS*, *PSS*, etc. is reminiscent of the "whistling" mode of radio transmission in the atmosphere, hence the name ***W* phase** coined by *Kanamori* [1993].

What *IS* the *W* Phase ? (ctd.)

W PHASE as COMBINATION of SPHEROIDAL MODES

→ *It can also be regarded as a superposition of Rayleigh overtones, i.e., of spheroidal modes of the relevant frequencies, with high group velocities ($5.5 < U < 9$ km/s).*

${}_0S_l$ ${}_1S_l$ ${}_2S_l$ ${}_3S_l$ ${}_4S_l$ ${}_5S_l$ ${}_6S_l$ ${}_7S_l$



As such, the W phase may represent the better of two worlds, being both ***Ultra – Long Period*** *and* ***Fast****.*

EARLY INVESTIGATIONS (1993−94)

Attempt to retrieve long-period behavior of M_0 from
W phase under the *magnitude* concept

1993 FALL MEETING

American Geophysical Union

031B-3 0830h INVITED POSTER

WM_m: An extension of the concept of mantle magnitude to the W phase, with application to real-time assessment of the ultra-long component of the seismic source

Emile A. Okal (Department of Geological Sciences, Northwestern University, Evanston, IL 60208)

Following the recent identification of the so-called *W* phase by Kanamori, and its recognition as a combination of ultra-low-frequency seismic modes, we have investigated the possibility of using this phase for evaluating in real-time the seismic moment release in the period range 200–1000 s, by adapting the formalism of the mantle magnitude, introduced for conventional surface waves by *Talandier and Okal* [1989].

Because it consists of a superposition of many normal mode branches, the *W* phase does not lend itself to a simple expression of its spectral amplitude; in particular, source and propagation effects cannot be separated. By computing normal mode synthetics over a grid of distances and frequencies, and averaging their spectral amplitudes over a large number of shallow depths ($h \leq 80$ km), source-receiver and focal geometries, we have produced a theoretical nomogram of the correction $C(\Delta;\omega)$ to be used in the retrieval of the seismic moment M_0 (or equivalently of a mantle magnitude WM_m) from the spectral amplitude of the ground motion $X(\omega)$:

$$WM_m = \log_{10} M_0 - 20 = \log_{10} X(\omega) + C(\Delta, \omega)$$

This algorithm was then used on a dataset comprising at the time of writing 149 IRIS and GEOSCOPE broadband records from 17 large events of the past decade. Our preliminary results show that the method reliably recovers moment information in the range 200–650 s, with a precision comparable to that of the standard M_m algorithm used on traditional mantle Rayleigh waves. The few data points we have obtained at even longer periods are clearly much less robust. A full study will be presented, including a case-by-case comparison of WM_m and M_m values obtained from the same record, and of the influence of using an average over focal mechanism orientation. In the case of the recent tsunamigenic events of 1992 and 1993, the method reliably reproduces the published values of the long-period seismic moment. In particular, in the case of the Nicaraguan earthquake, we have at present no compelling evidence for a continued increase in M_0 with period beyond that reported in the literature, and obtained in real-time from an M_m measurement at Papeete.

SEISMOLOGICAL
RESEARCH
LETTERS

Volume 65, Number 1, January–March, 1994

SSA 89th Annual Meeting
Pasadena, California • April 5–7, 1994

151.

WM_m: ASSESSING THE POTENTIAL OF THE *W* PHASE FOR REAL-TIME ASSESSMENT OF THE ULTRA-LONG PERIOD BEHAVIOR OF THE SEISMIC SOURCE.

OKAL, E.A., Department of Geological Sciences, Northwestern University, Evanston, IL 60208; SCHINDELE, F. and REYMOND, D., Laboratoire de Géophysique, Commissariat à l'Energie Atomique, Papeete, Tahiti, French Polynesia.

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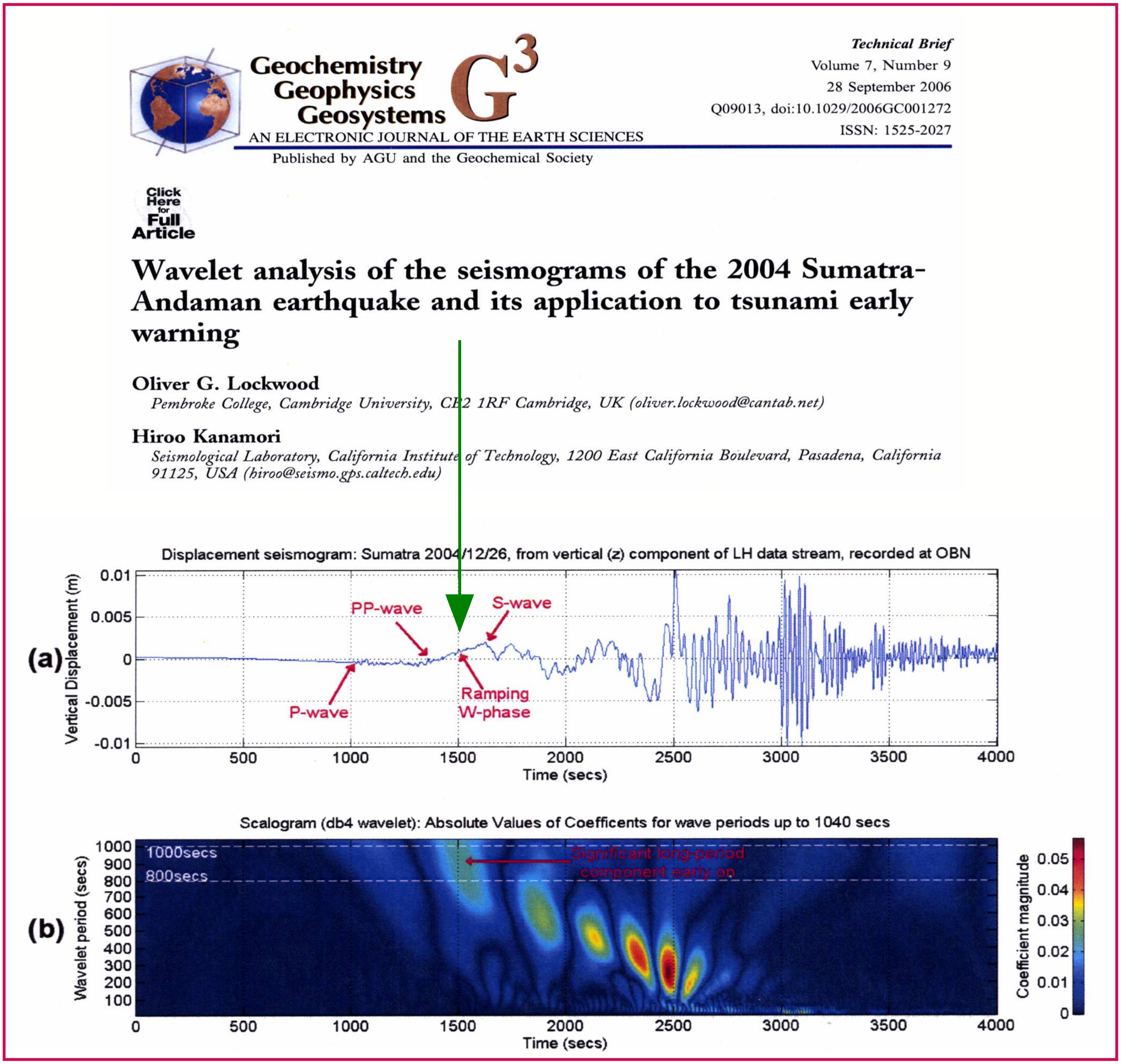
Because it consists of a superposition of many normal mode branches, the *W* phase does not lend itself to a simple expression of its spectral amplitude; in particular, source and propagation effects cannot be separated. Using normal mode synthetics over a grid of distances and frequencies, and averaging their spectral amplitudes over a large number of shallow depths ($h \leq 80$ km), source-receiver and focal geometries, we have produced theoretical nomograms of the correction $C(\Delta;\omega)$ to be used in the retrieval of the seismic moment M_0 (or equivalently of a mantle magnitude WM_m) from the spectral amplitude of the ground motion $X(\omega)$:

$$WM_m = \log_{10} M_0 - 20 = \log_{10} X(\omega) + C(\Delta, \omega),$$

for both the vertical and horizontal components of the spheroidal modes' displacements. This algorithm was used on a dataset comprising at the time of writing about 200 IRIS, GEOSCOPE and Papeete broadband records from the large events of the past decade. Our results show that the method reliably recovers moment information in the range 200–650 s, with a precision comparable to that of the standard M_m algorithm used on traditional mantle Rayleigh waves. The few data points we have obtained at even longer periods are clearly much less robust. An estimate of source duration can be obtained by fitting the variation of the WM_m values with frequency to that expected theoretically for a source ramp function. The only recent event clearly requiring a source longer than 50 s is the 1992 Nicaraguan earthquake.

RECENT DEVELOPMENTS

- In the wake of the 2004 Sumatra event, *Lockwood and Kanamori* [2006] showed that the *W* phase was prominently recorded world-wide and that its spectral amplitude could be quantified.



Geochemistry Geophysics Geosystems G3
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Published by AGU and the Geochemical Society

Technical Brief
Volume 7, Number 9
28 September 2006
Q09013, doi:10.1029/2006GC001272
ISSN: 1525-2027

Click Here for Full Article

Wavelet analysis of the seismograms of the 2004 Sumatra-Andaman earthquake and its application to tsunami early warning

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Hiroo Kanamori
Seismological Laboratory, California Institute of Technology, 1200 East California Boulevard, Pasadena, California 91125, USA (hiroo@seismo.gps.caltech.edu)

→ *Rivera and Kanamori* [2007, 2008] later showed that *W* phase signals could be inverted to obtained the ultra-long period focal mechanism of the event.

FULL *W* PHASE INVERSION

Geophys. J. Int. (2008) **175**, 222–238

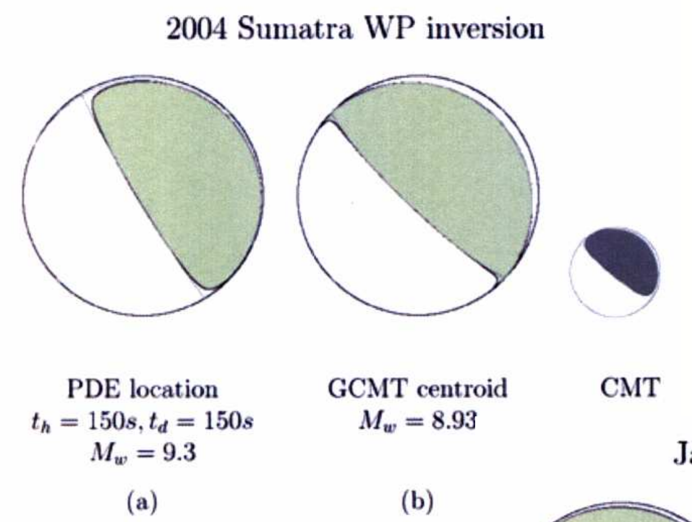
doi: 10.1111/j.1365-246X.2008.03887.x

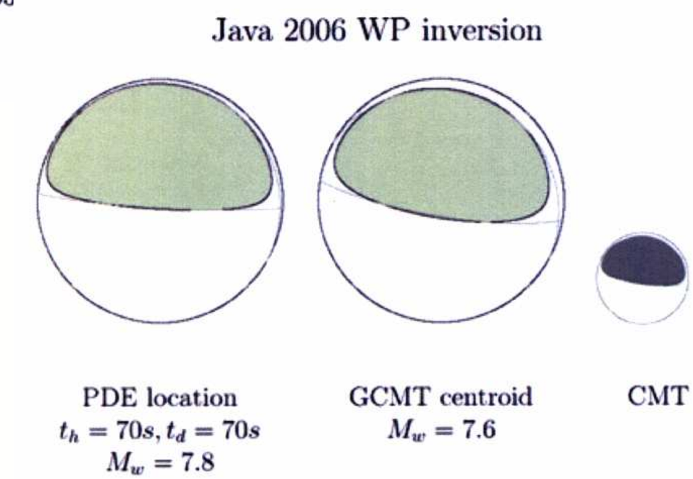
Source inversion of W phase: speeding up seismic tsunami warning

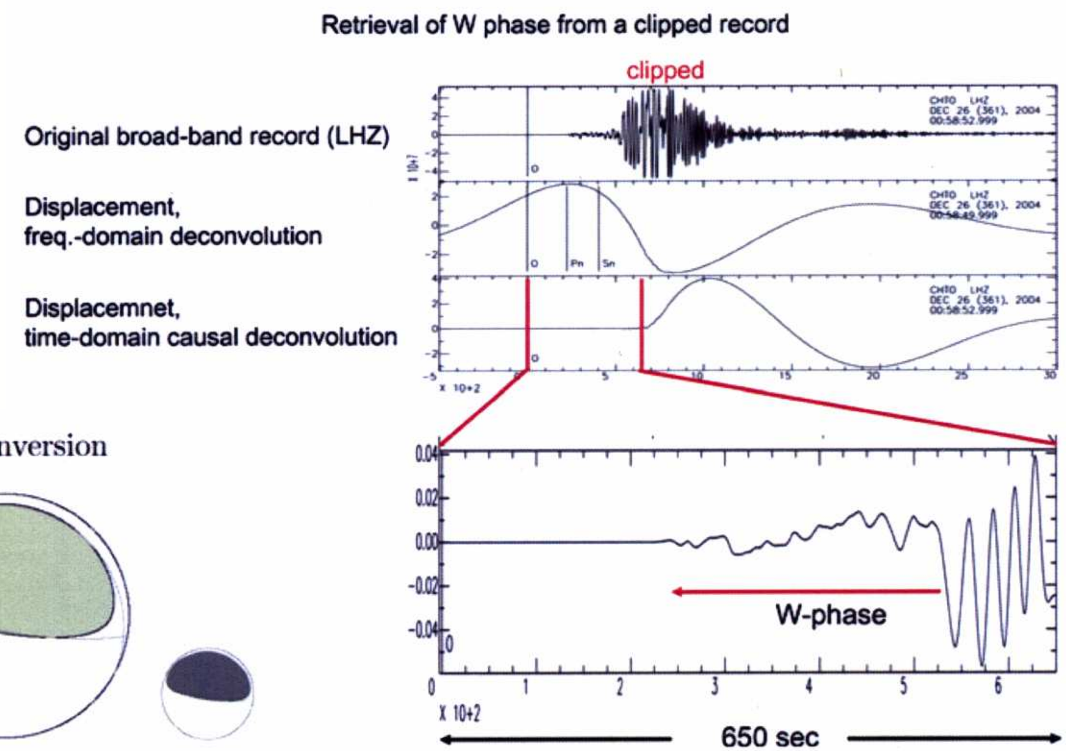
Hiroo Kanamori[1] and Luis Rivera[2]

[1] *Seismological Lab., California Inst. of Technology, Pasadena, CA USA. E-mail: hiroo@gps.caltech.edu*

[2] *Institut de Physique du Globe de Strasbourg, CNRS-ULP, 5 rue René Descartes, Strasbourg Cedex, 67084 France*







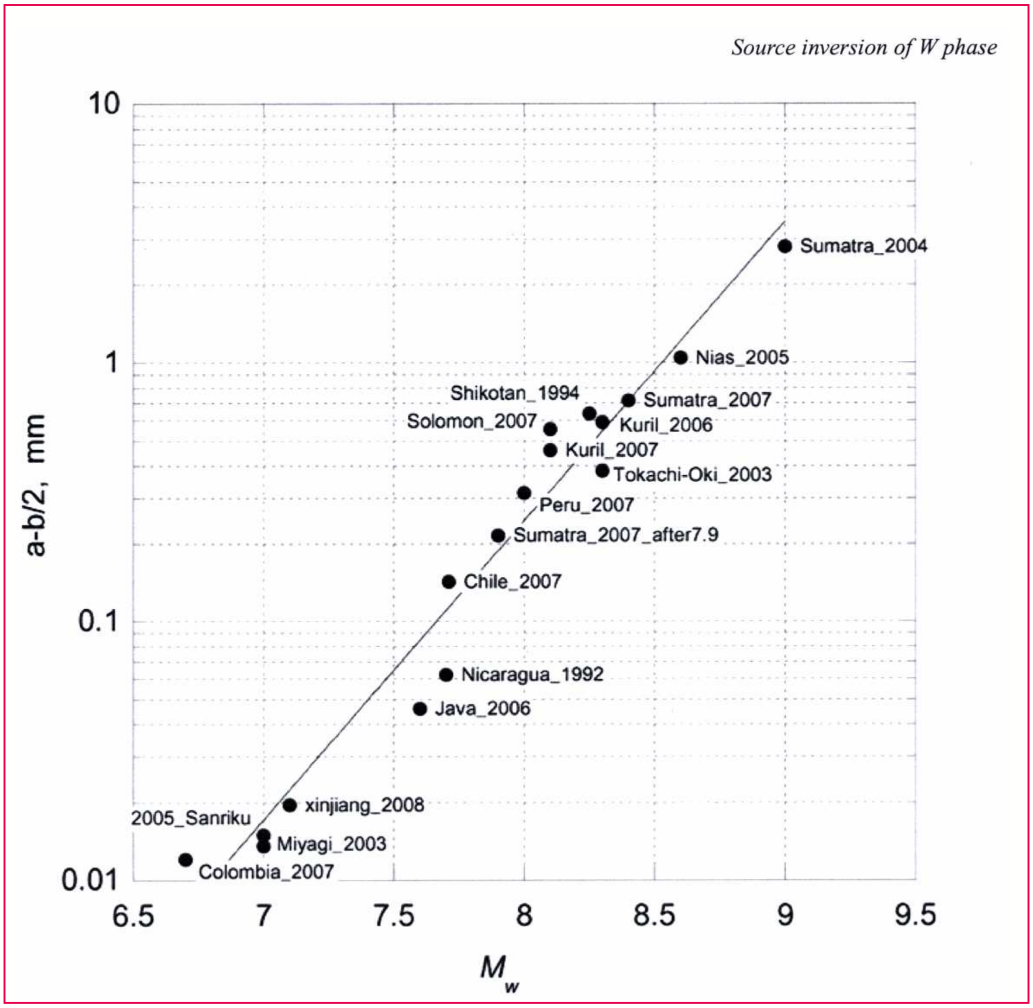
Among fundamental results:

Restores the full seismic moment of gigantic (Sumatra 2004) or slow (Java 2006) events.

BACK TO AN OLD-FASHIONED TIME−DOMAIN MAGNITUDE ?

Kanamori and Rivera [2008] further suggest that the average time-domain amplitude w (in mm) of the W phase could be used to estimate the seismic moment of the event, according to the regression

$$\log_{10} M_0 \;=\; 1.311 \log_{10} w \;+\; 28.89 \qquad (1)$$



Note however

(i) the significant scatter in the data

(ii) that slow "tsunami" earthquakes are significantly underestimated

(iii) that Sumatra is also underestimated

(iv) that the slope, ~ 4/3 in (1), is not easily interpreted

2009: IMPLEMENTED AT NEIC – USGS, Golden

[*G. Hayes*, 2009]

W Phase moments are now routinely computed

and fast becoming the authoritative focal solution.

USGS WPhase Moment Solution

```
10/08/04 12:58:27
ANDREANOF ISLANDS, ALEUTIAN IS.
Epicenter:  51.422 -178.573
MW 6.4

USGS/WPHASE CENTROID MOMENT TENSOR
10/08/04 12:58:27.00
Centroid:   51.422 -178.573
Depth  44         No. of sta: 68
Moment Tensor;   Scale 10**18 Nm
  Mrr= 2.52       Mtt=-2.79
  Mpp= 0.27       Mrt= 3.80
  Mrp= 1.99       Mtp=-0.77
 Principal axes:
  T  Val=  4.95  Plg=60  Azm=322
  N        0.30       7       66
  P       -5.25      28      160

Best Double Couple:Mo=5.1*10**18
 NP1:Strike=272 Dip=17 Slip= 116
 NP2:        64     74        81

              -------
         ----------------
       ------#########------
     ---##################----
   ---#######################---
  --###########################--
  -##########   ###############-#
 -########### T #############----#
 ############   ###########-------
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  ##########--------------------
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     --------------- P -------
       -------------   -----
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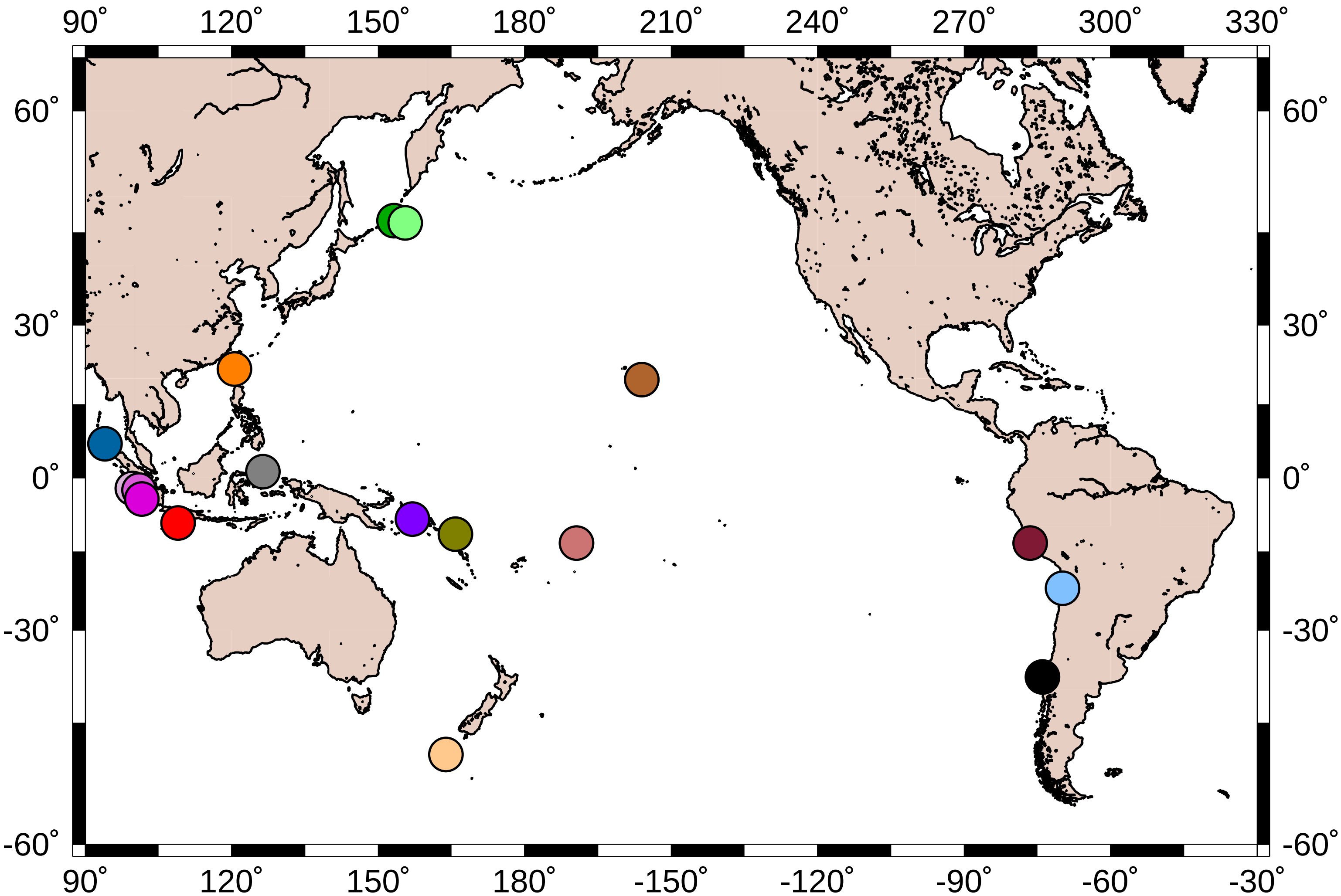
```

How Well do These Various Algorithms Really Work ?

THESE ALGORITHMS WERE APPLIED IN QUASI-REAL TIME

(i.e., following receipt of tsunami bulletins if during working hours)

TO A GROWING DATABASE OF 85 EARTHQUAKES, INCLUDING



JAVA -- 17 JUL 2006

HAWAII -- 15 OCT 2006

KURILES -- 15 NOV 2006

KURILES -- 13 JAN 2007

TAIWAN -- 26 DEC 2006

MOLUCCAS -- 21 JAN 2007

PERU -- 15 AUG 2007

SAMOA -- 29 SEP 2009

SOLOMON Is. -- 01 APR 2007

SANTA CRUZ -- 05 SEP 2007

BENGKULU I -- 12 SEP 2007

BENGKULU II -- 12 SEP 2007

BENGKULU III -- 13 SEP 2007

NEW ZEALAND -- 30 SEP 2007

NO. CHILE -- 14 NOV 2007

CHILE -- 27 FEB 2010

plus SUMATRA -- 26 DEC 2004

REPORT CARD : M_m (Improved)

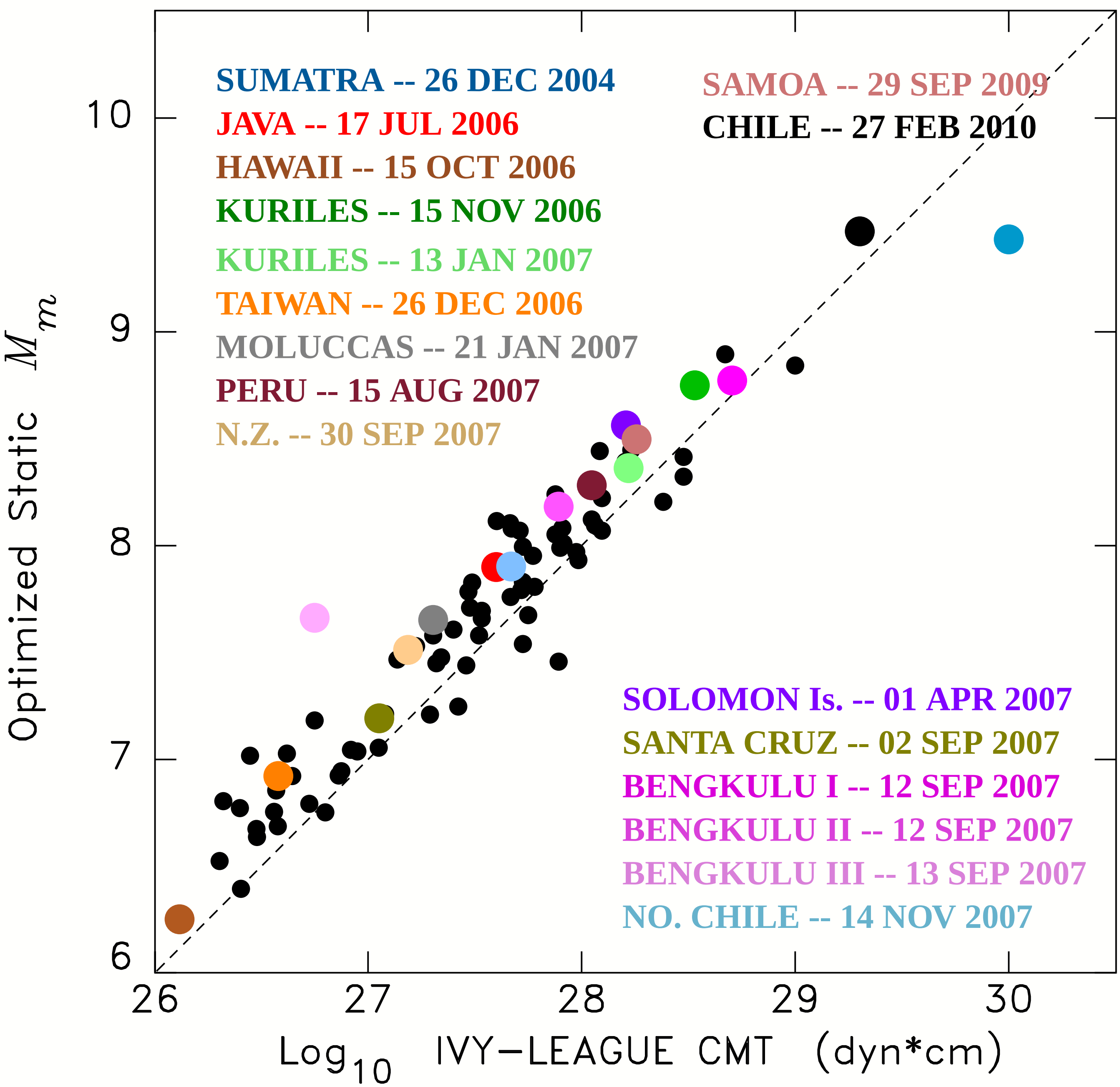
(85 recent events)

A _

→ Improved M_m algorithm gives accurate values for most events, including *"Tsunami Earthquakes"*

- Sumatra 2004 remains somewhat underestimated
  [Expected, given duration of event comparable to lowest usable frequency]

- Only Bengkulu (III) event is grossly over-estimated, due to contamination by previous event at lowermost frequencies.



REPORT CARD : PARAMETER Θ

A _

- Correctly identifies **SLOW "TSUNAMI EARTHQUAKES"**

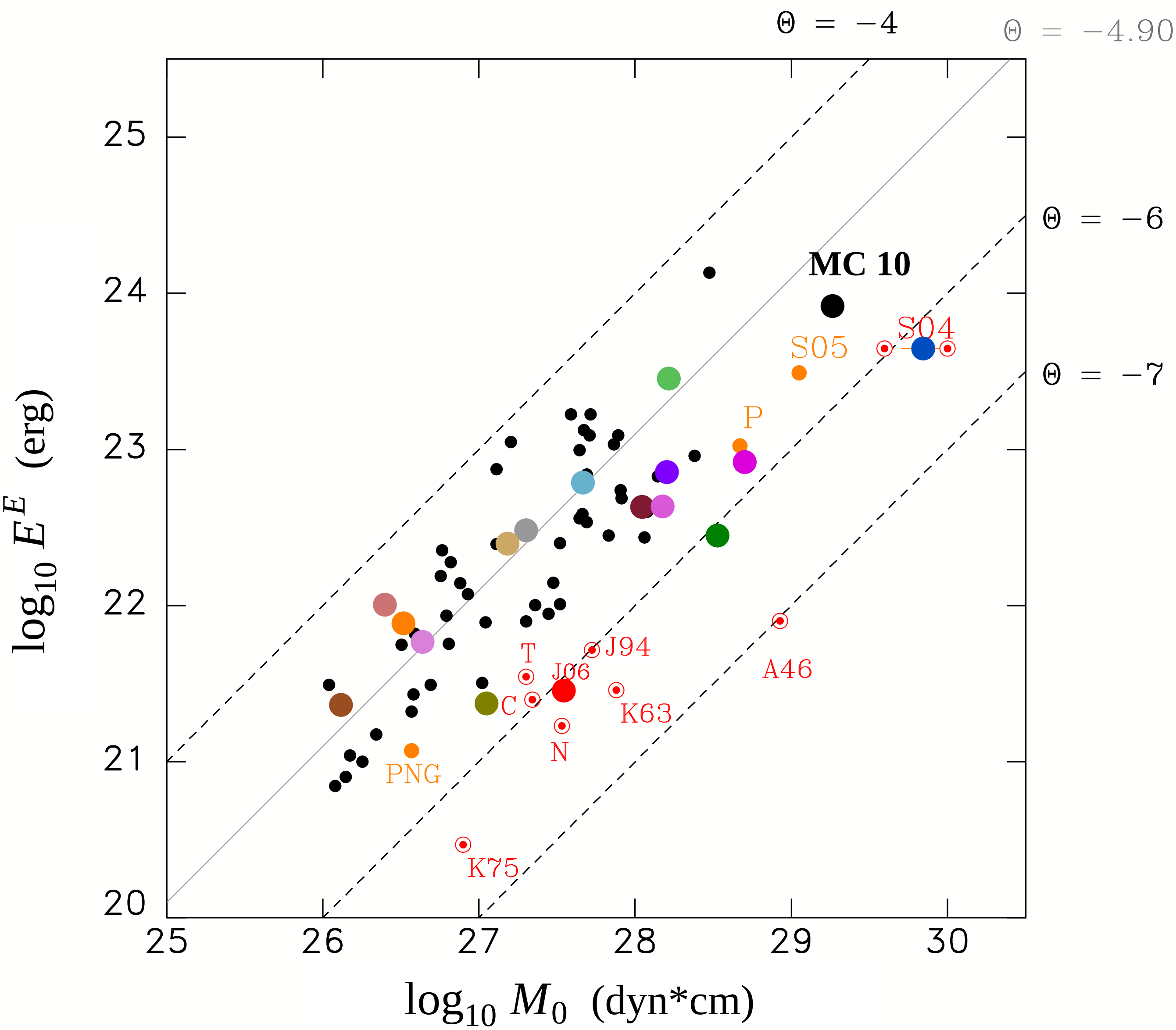
  JAVA 2006 **SUMATRA 2004**

- Correctly identifies **MAULE, Chile 2010** as *Not Slow*

- Identifies "SNAPPY" (Often Intraplate) EVENTS

  KURILES 2007 **TAIWAN 2006** **HAWAII 2006**

- Has trouble distinguishing between Truly Slow and *DELAYED (Late)* Events (**KURILES 2006**).



REPORT CARD : M_{wp}

C _

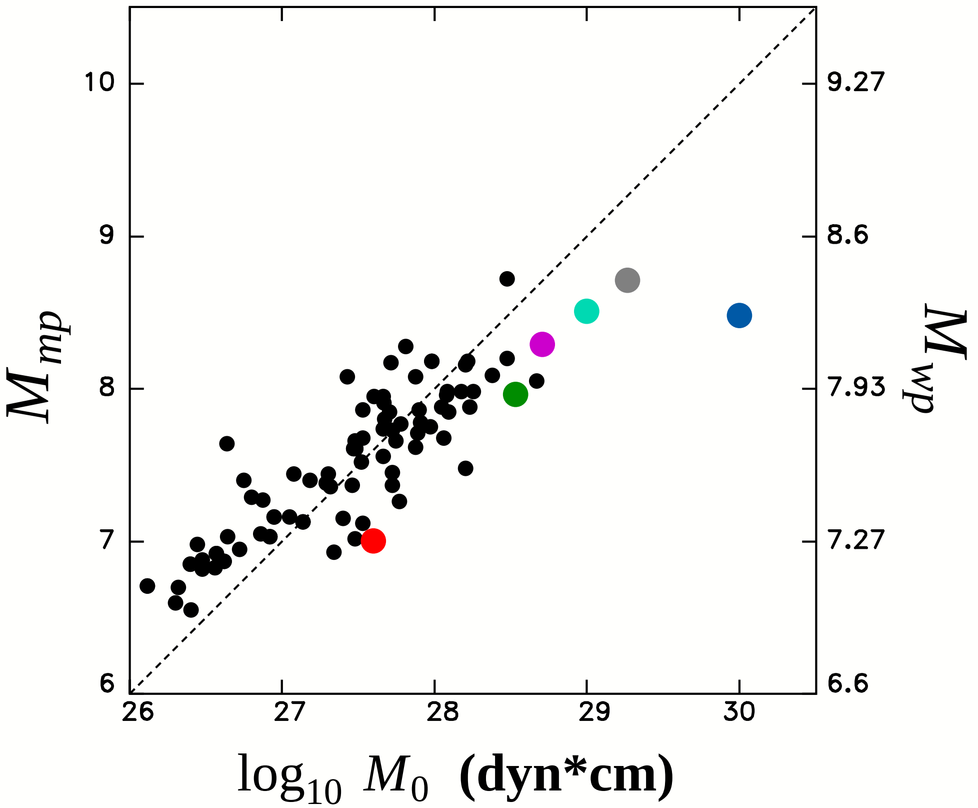
- Problems:

Algorithm fails to recognize truly great earthquakes

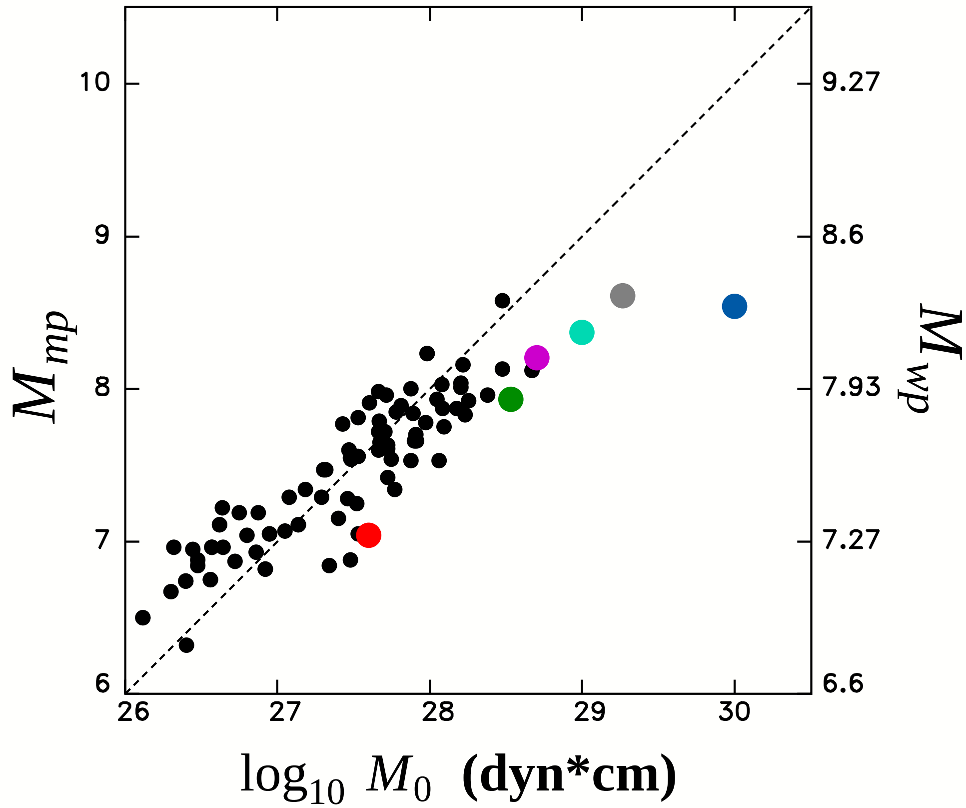
SUMATRA 2004 **NIAS 2005** **BENGKULU (I) 2007** *and now,* **MAULE, 2010**

Also, mis-handles slow or late ones **JAVA 2006** **KURILES 2006**

Time-domain Computation



Fourier-domain Computation



REPORT CARD : $\tau_{1/3}$

B

86 earthquakes

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

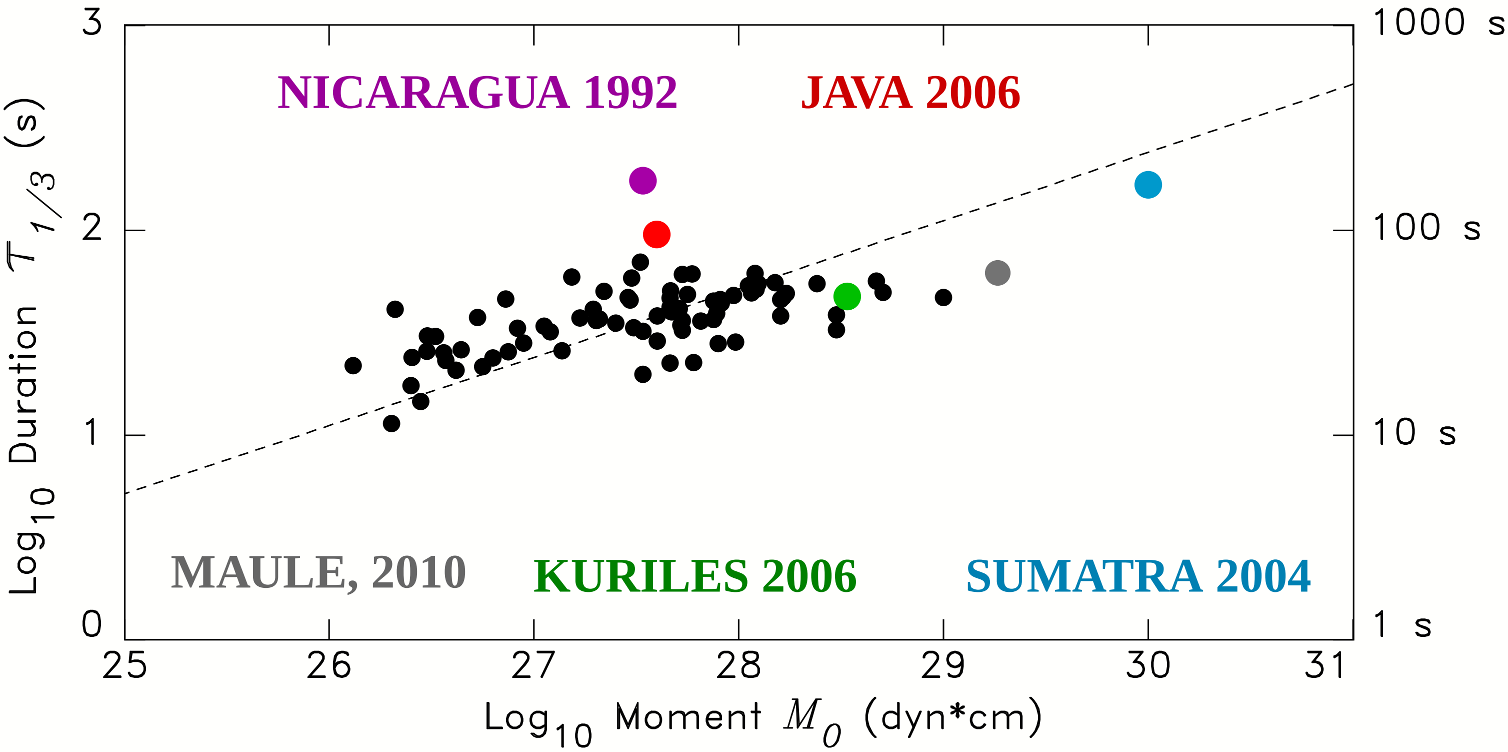
($\tau_{1/3}$ = 167 s; $\tau_{1/4}$ = 291 s)

→ *"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.

→ The 2010 Maule earthquake is also found to have a source slightly shorter than expected for its moment. *Hint:* **Bilateral Rupture ?**



REPORT CARD : $\tau_{1/3}$ (ctd.)

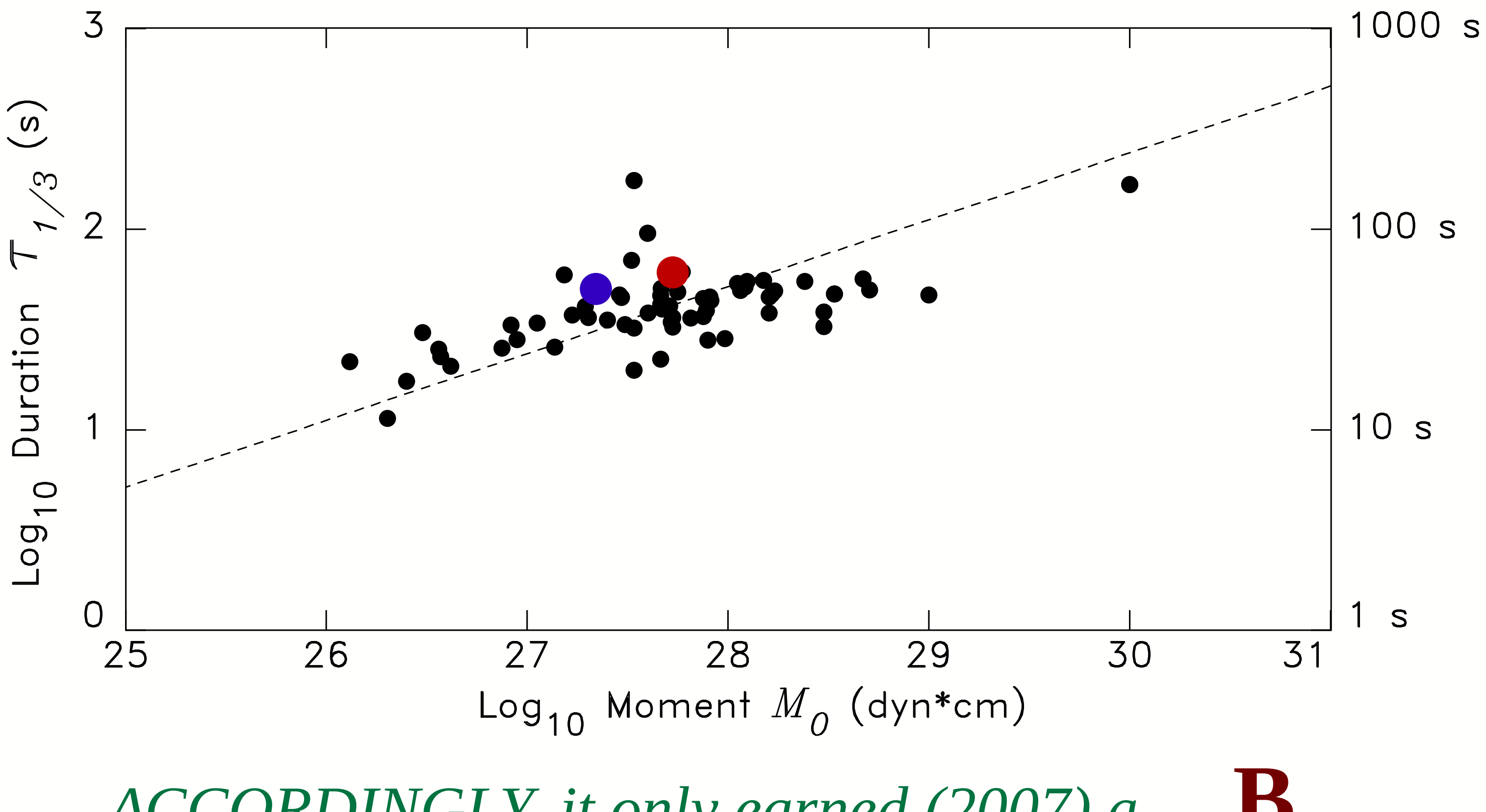
HOWEVER,

The method fails to convincingly identify

all tsunami earthquakes:

It misses

CHIMBOTE, Peru 1996 **JAVA 1994**



ACCORDINGLY, it only earned (2007) a **B**

but pending more research

with INCOMPLETE

$\tau_{1/3}$: EXTRA CREDIT ? Use $\tau_{1/3}$ vs. E^E

A_

Idea:	$\tau_{1/3}$ expected to grow like $M_0^{1/3}$
	Estimated Energy expected to grow like M_0
	Hence $\tau_{1/3}$ / $(E^E)^{1/3}$ should be constant

→ Define *Duration Test*

$$DT = \log_{10} \tau_{1/3} - \frac{1}{3} \log_{10} E^E + 5.86$$

Note: Constant 5.86 predictable theoretically from scaling laws

→ *DT > 0.35* correctly predicts **ALL** Slow Earthquakes

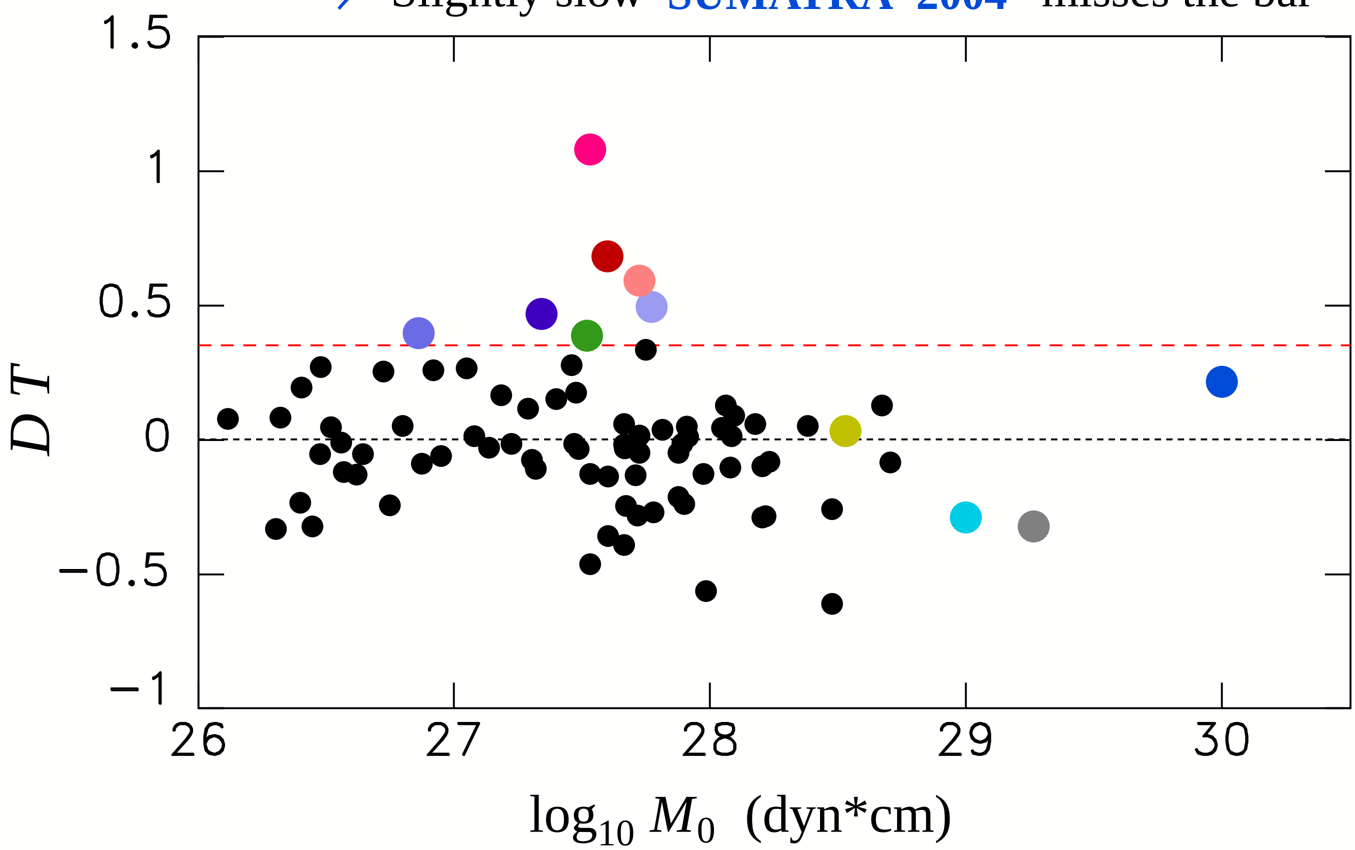
NICARAGUA 1992 **JAVA 1994** **JAVA 2006** **CHIMBOTE, Peru 1996**

but also includes complex strike-slip events **TIBET 2001** **BAJA 2010**

and **[COSTA-RICA 1991]** (??)

→ Succesfully excludes **KURILES 2006** **NIAS 2005** **MAULE 2010**

→ Slightly slow **SUMATRA 2004** misses the bar



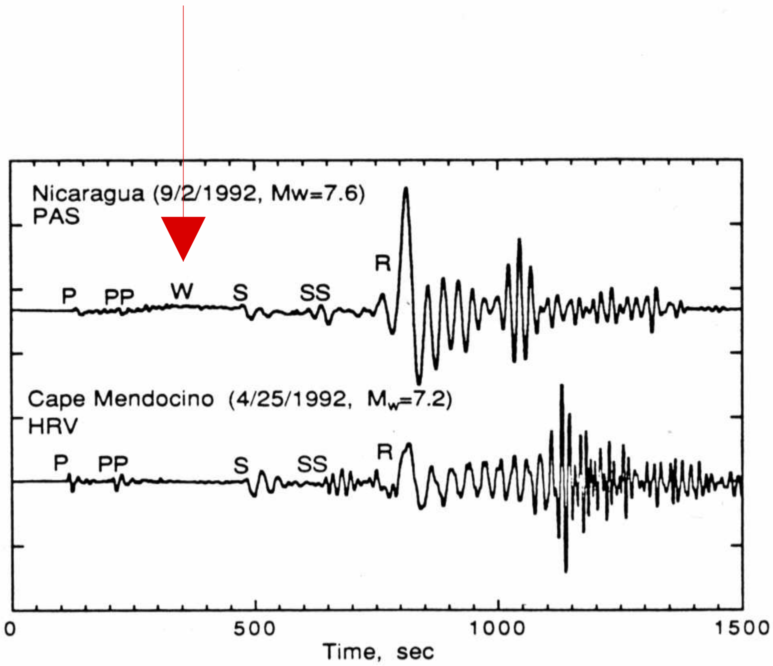
REPORT CARD : ***W* Phase**

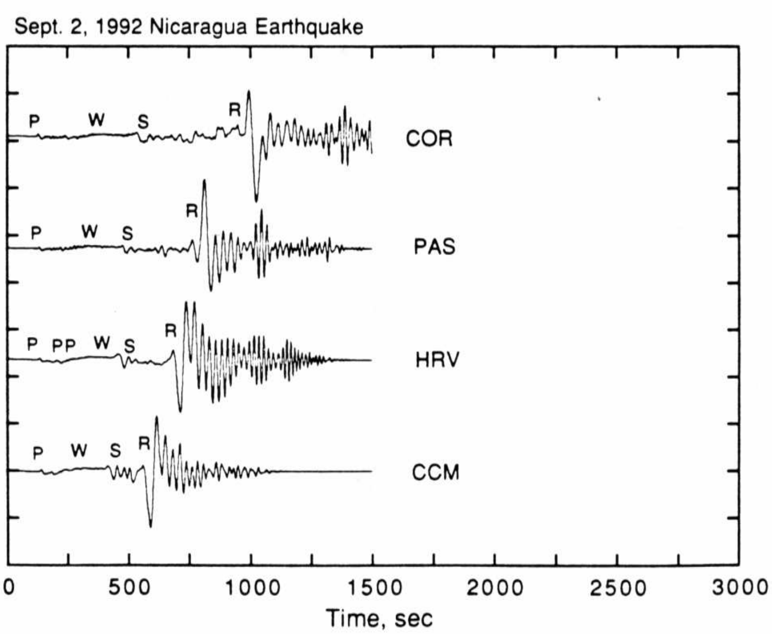
A +

*** *Dean's List* ***

[*Kanamori et al.*, 2008]

Geophysical Research Letters





[*Kanamori*, 1993]

AUGUST 20, 1993 Volume 20 Number 16

AMERICAN GEOPHYSICAL UNION

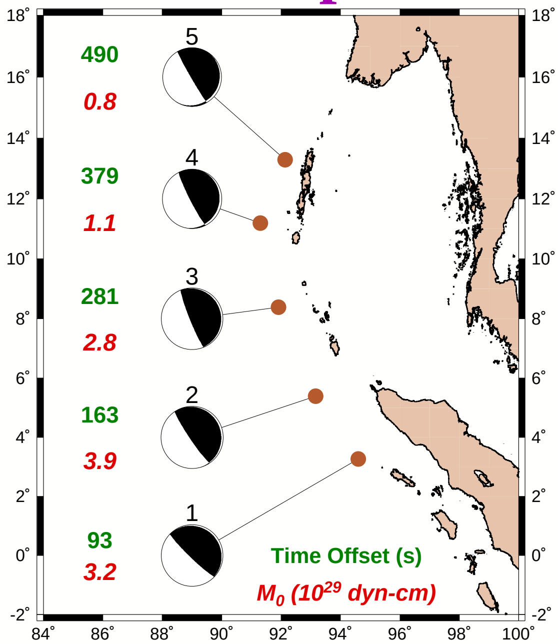
DEFERRED STUDIES

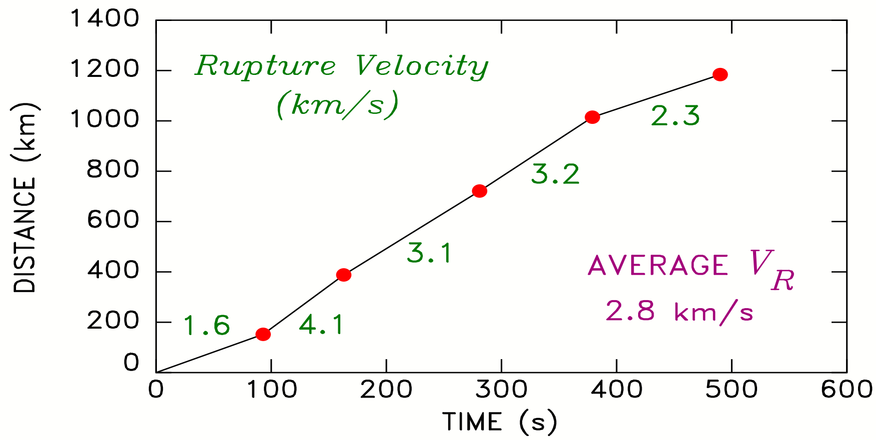
Examples of Detailed Investigations of Earthquake Sources

→ Strictly Non Exhaustive !

DEFERRED ALGORITHMS to EXPLORE SUMATRA SOURCE

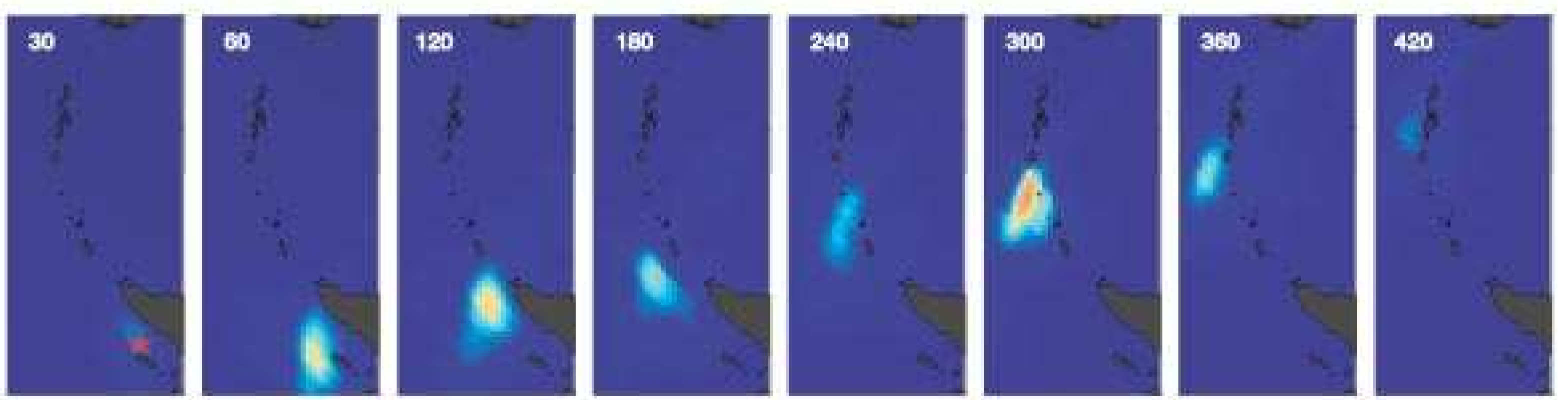
1. Composite CMT inversion [*Tsai et al.*, 2005]

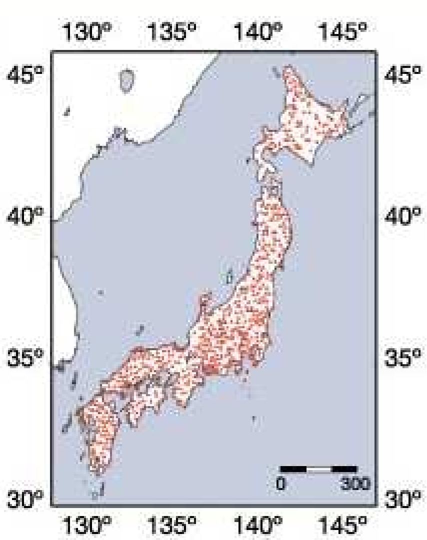




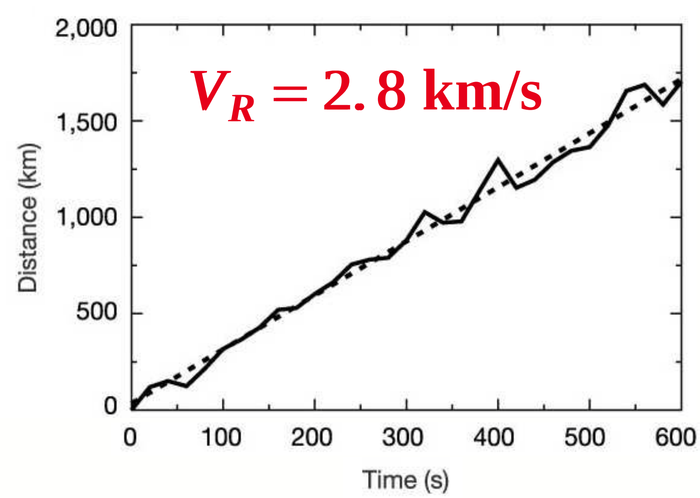
NOTE: **Sumatra 2004 has a slow source**

2. Back-tracking source history from distant seismic array [*Ishii et al.*, 2005]





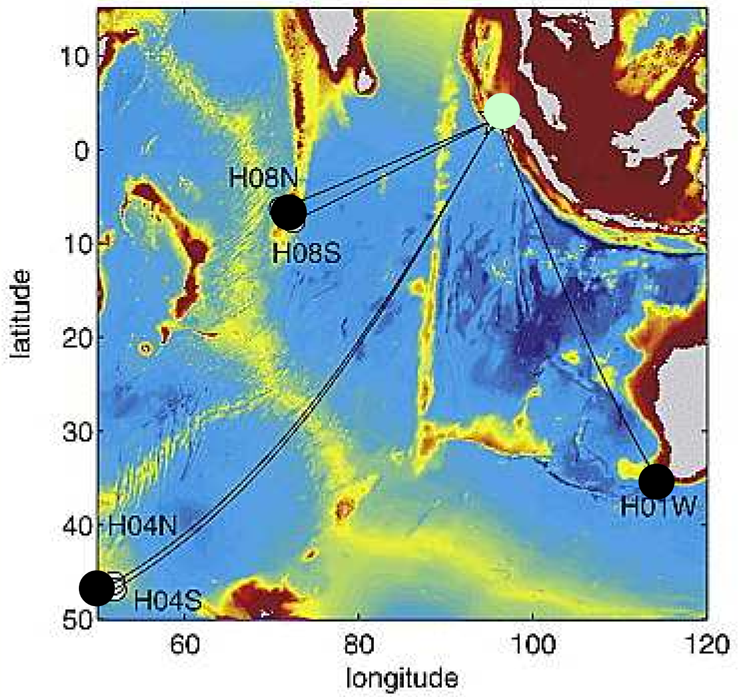
Use
700−station
seismic array



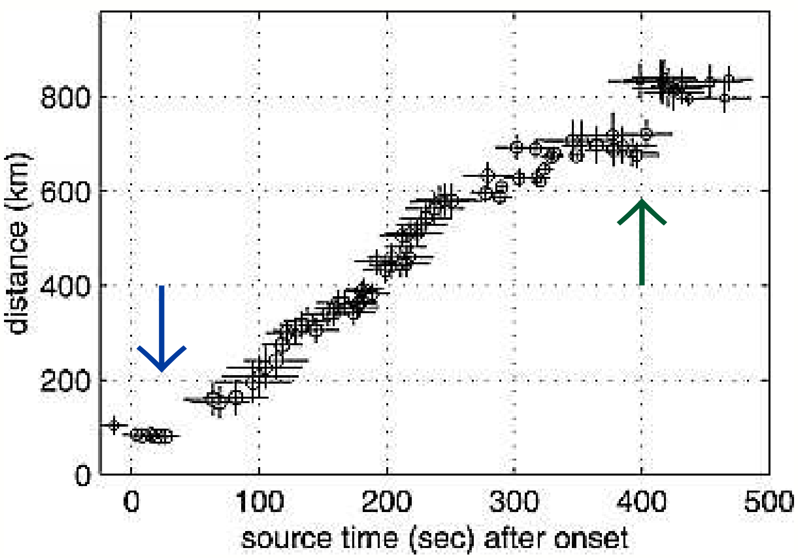
{also *Krüger and Ohrnberger*, 2005; $V_R = 2.7$ km/s}

"HYDROACOUSTIC TOMOGRAPHY"

Use CTBT hydrophone triads to back-track the temporal evolution of $T-$wave energy into individual elements of the rupture.



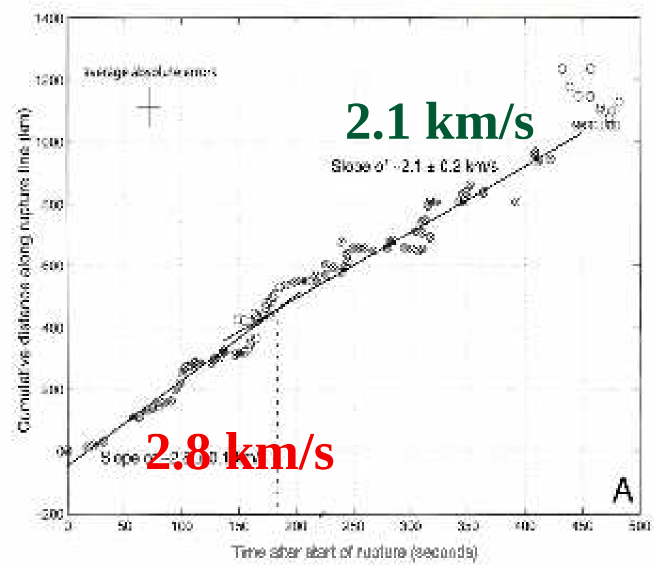
[*deGroot-Hedlin*, 2005]



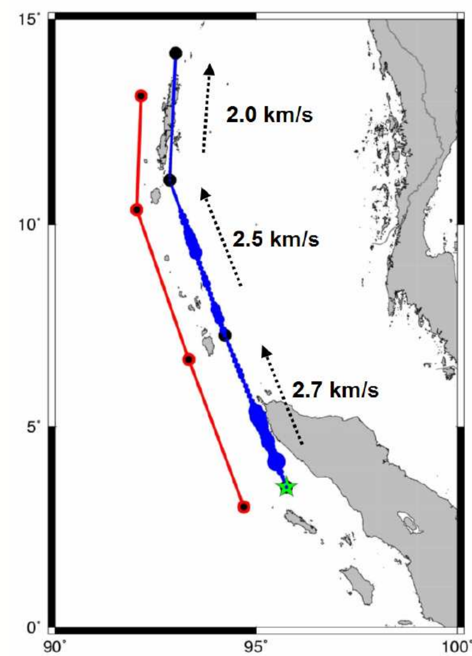
These studies confirm:

- **1000(+)-km rupture**
- **Slow rupture**
- **Slower in the North**

[Perhaps slower initially]



[*Tolstoy and Bohnenstiehl*, 2005]



[*Guilbert et al.*, 2005]

EVEN MORE DEFERRED

Reconstructing Focal Solutions

and Seismic Moments of Historical Earthquakes

IN THE WWSSN ERA

Most critical earthquakes studied by forward modeling [*Kanamori* and collaborators, 197xx].

A few (Alaska, 1964; Colombia, 1970; Peru-Brazil, 1963) inverted [*Gilbert and Dziewonski*, 1973, 1975] under prototype development of future CMT project

HOWEVER, A NUMBER OF CRITICAL $M \approx 7$ EVENTS

REMAIN TO BE FORMALLY STUDIED IN A MODERN FASHION

IN THE PRE−WWSSN INSTRUMENTAL ERA

(1900 −1962)

Formal inversion becomes difficult because of the scarcity of data (and/or its poor azimuthal coverage), and the timing uncertainties affecting the spectral phases.

YET, THERE EXIST SUPERBLY ARCHIVED SEISMOGRAMS

WAITING TO BE ANALYZED

PDFM Method [*Reymond and Okal*, 2000]

<< based on an idea by *Romanowicz and Suárez* [1983] >>

ELSEVIER

Physics of the Earth and Planetary Interiors 121 (2000) 249–271

PHYSICS OF THE EARTH AND PLANETARY INTERIORS

www.elsevier.com/locate/pepi

Preliminary determination of focal mechanisms from the inversion of spectral amplitudes of mantle waves

Dominique Reymond [a], Emile A. Okal [b,*]

[a] *Laboratoire de Géophysique, Commissariat à l'Energie Atomique, Boîte Postale 640, F-98713 Papeete, Tahiti, French Polynesia*
[b] *Department of Geological Sciences, Northwestern University, Evanston, IL 60201, USA*

Received 22 January 2000; accepted 27 May 2000

→ Moment tensor inversion using only **spectral amplitudes**, deleting *phase information*.

- Applicable to depleted datasets (as few as 3 or 4 stations)

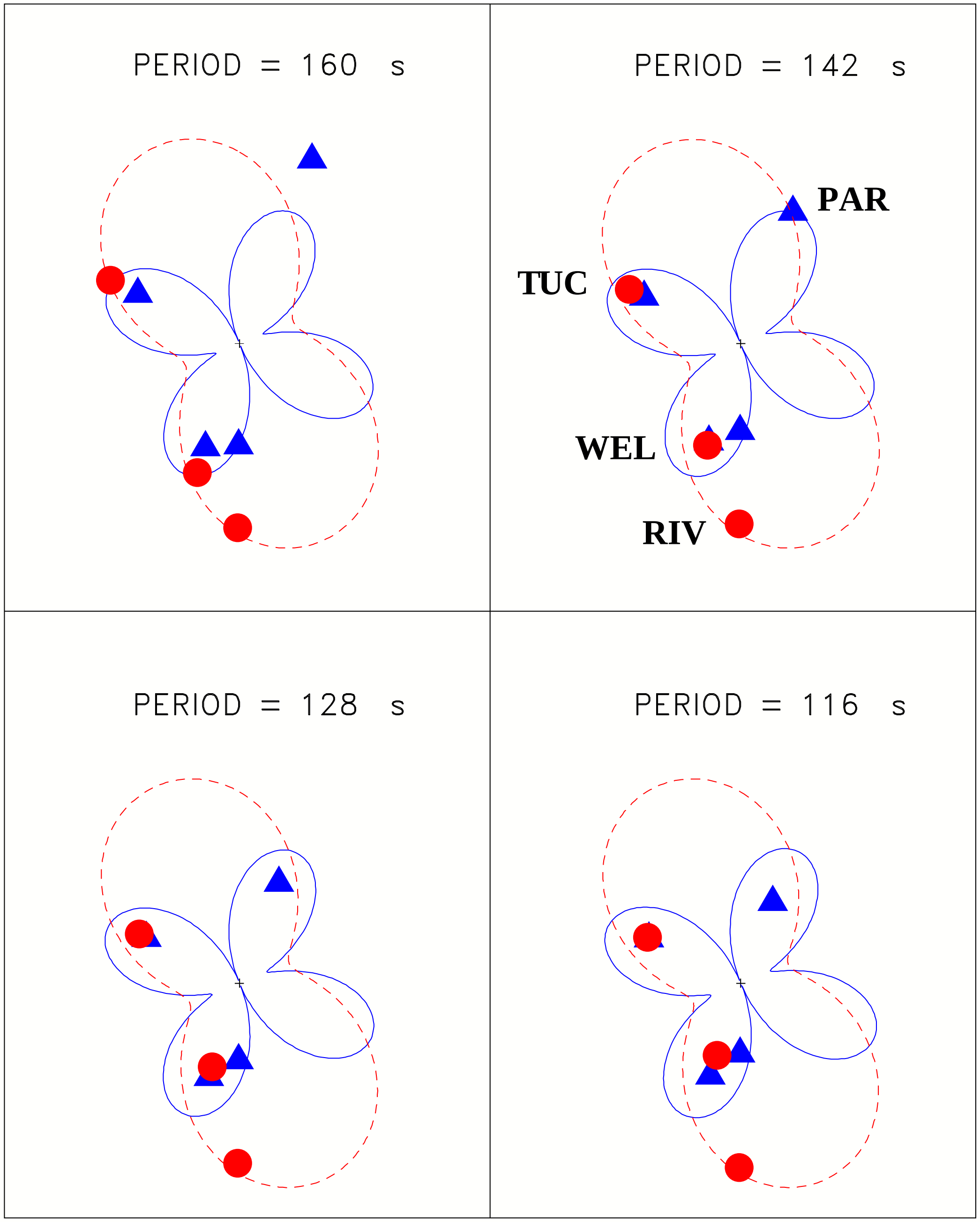
- Particularly adapted to *Historical Events* since exact epicentral location and relative timing at stations become irrelevant [*Okal and Reymond*, 2003].

- *Limitations*

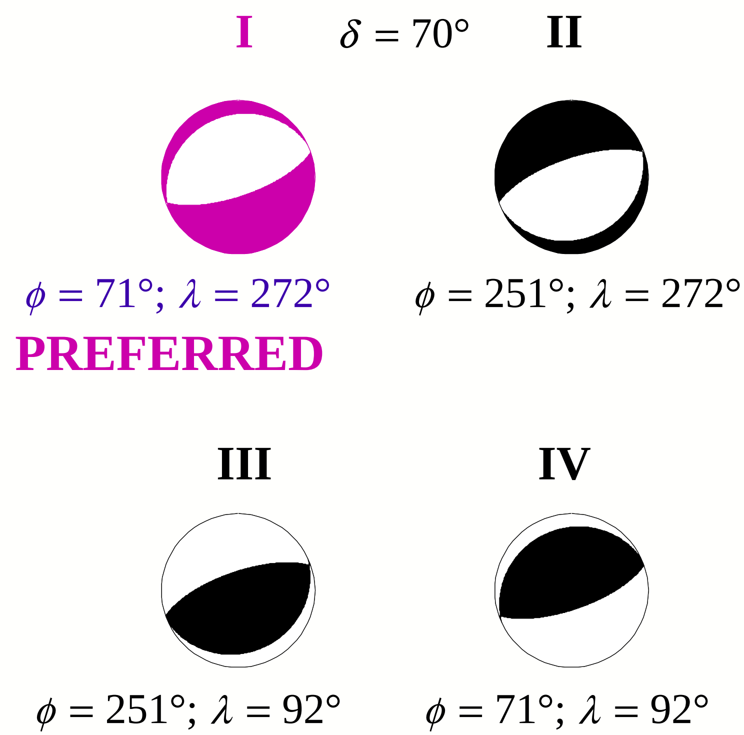
  Double 180° indeterminacy in Strike and Slip angles

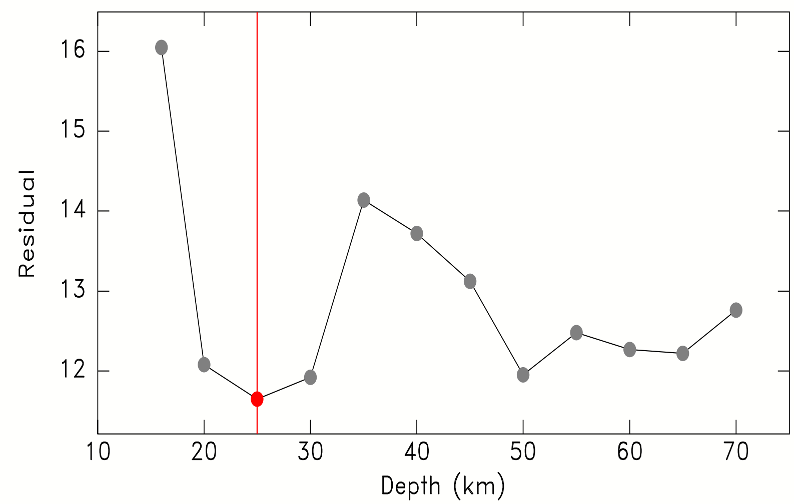
  [Can be resolved with critical body-wave polarities]

So. Sandwich Is. **27 JUNE 1929** $M_0 = 1.7 \times 10^{28}$ dyn-cm



● - - - - - **RAYLEIGH** ▲——— **LOVE**





Best Depth: 25 km

OTHER HISTORICAL EVENTS STUDIED BY THE PDFM METHOD

(as of August, 2010)

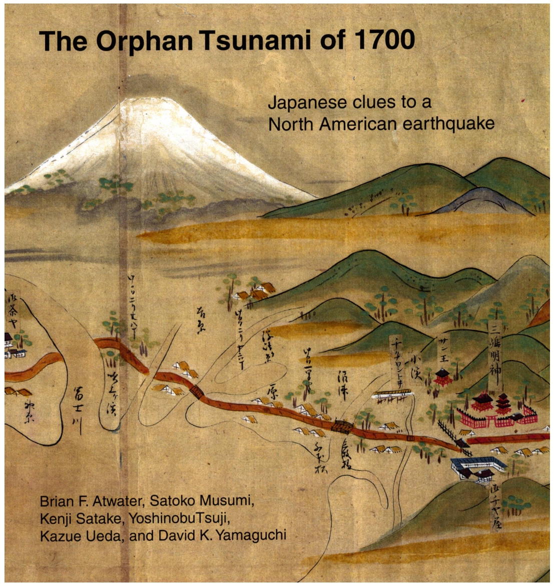
- *Big Twins,* 17 August 1906
- *South Sandwich,* 27 June 1929
- *Sanriku,* 02 March 1933
- *Banda Sea,* 01 February 1938
- *Amorgos, Greece,* 09 July 1956

BEFORE THE INSTRUMENTAL ERA

It is occasionally possible to obtain constraints on earthquake sources from the modeling of historical tsunami reports.

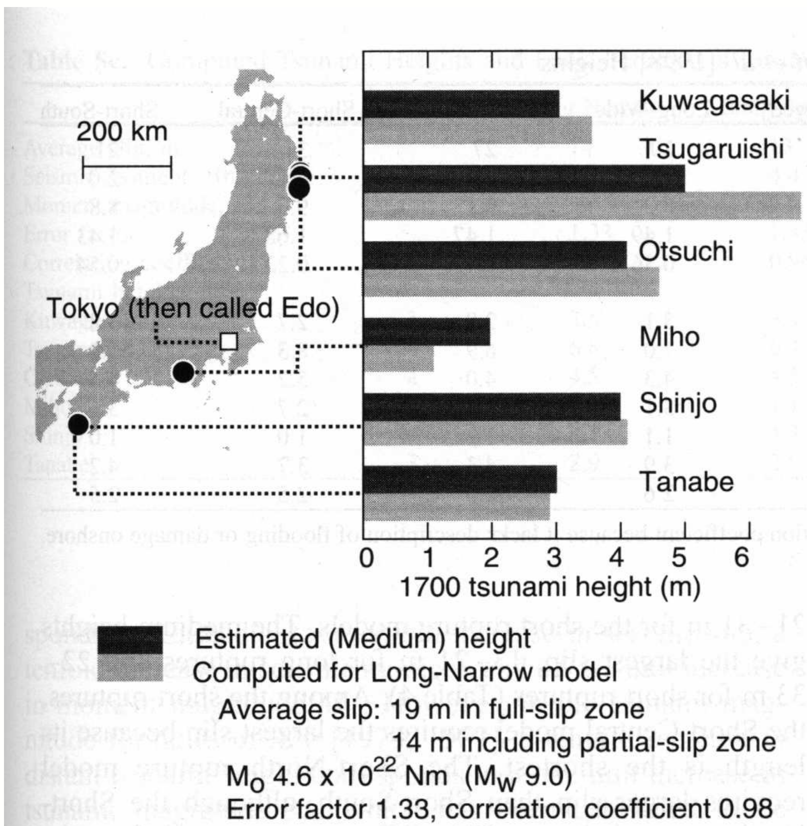
The three examples given provide significant insight into the potential for mega−quakes in the relevant subduction zones.

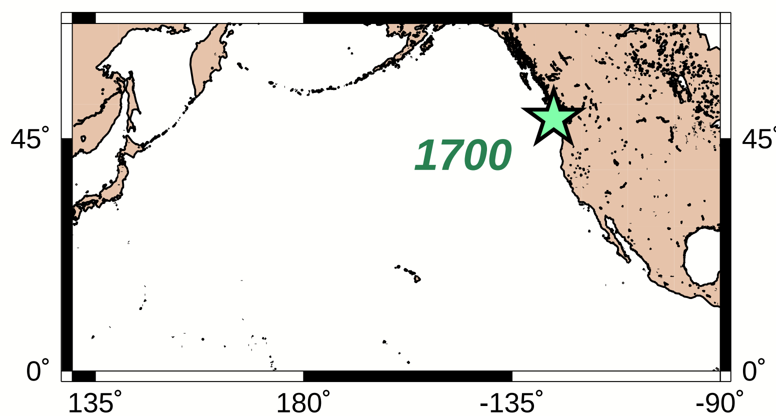
THE CASCADIA EARTHQUAKE of 26 JANUARY 1700



- Reconstructed from tsunami records in Japan.
- Confirmed by analysis of paleotsunami data (dead trees; terraces).
- Prior to *Satake et al.*'s work, Cascadia could have fit the model of a decoupling, permanently creeping, subduction zone.

→ **We now understand that this subduction zone is the site of relatively rare (400 yr ?) but gigantic interplate thrust earthquakes.**





APPLICABLE ELSEWHERE ?

USING TSUNAMI SIMULATIONS to EVALUATE HISTORICAL EVENTS

Example: **1868 South Peru *"Arica"*** Earthquake

Catastrophic destruction by tsunami at **Pisco, Peru**

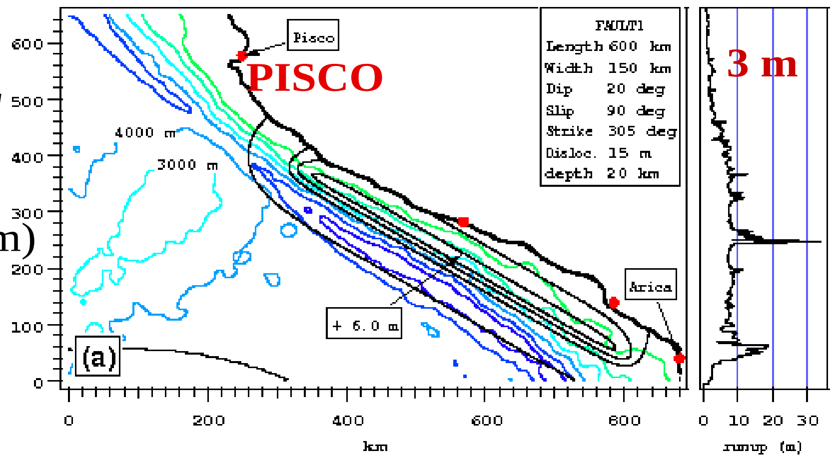
Modeling requires **900 km** fault rupture extending past Nazca Ridge, and thus

$$M_0 \approx 1 \times 10^{30} \text{ dyn-cm}$$

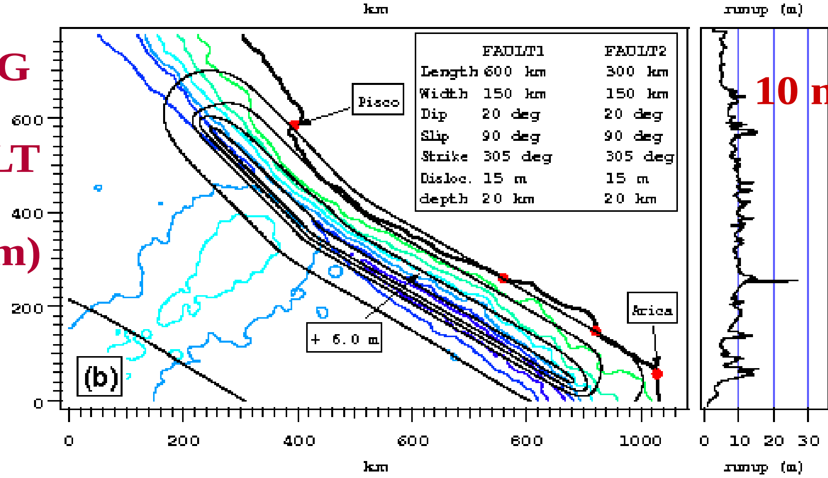
(in the league of Sumatra 2004...)

"Short" Fault

(600 km)



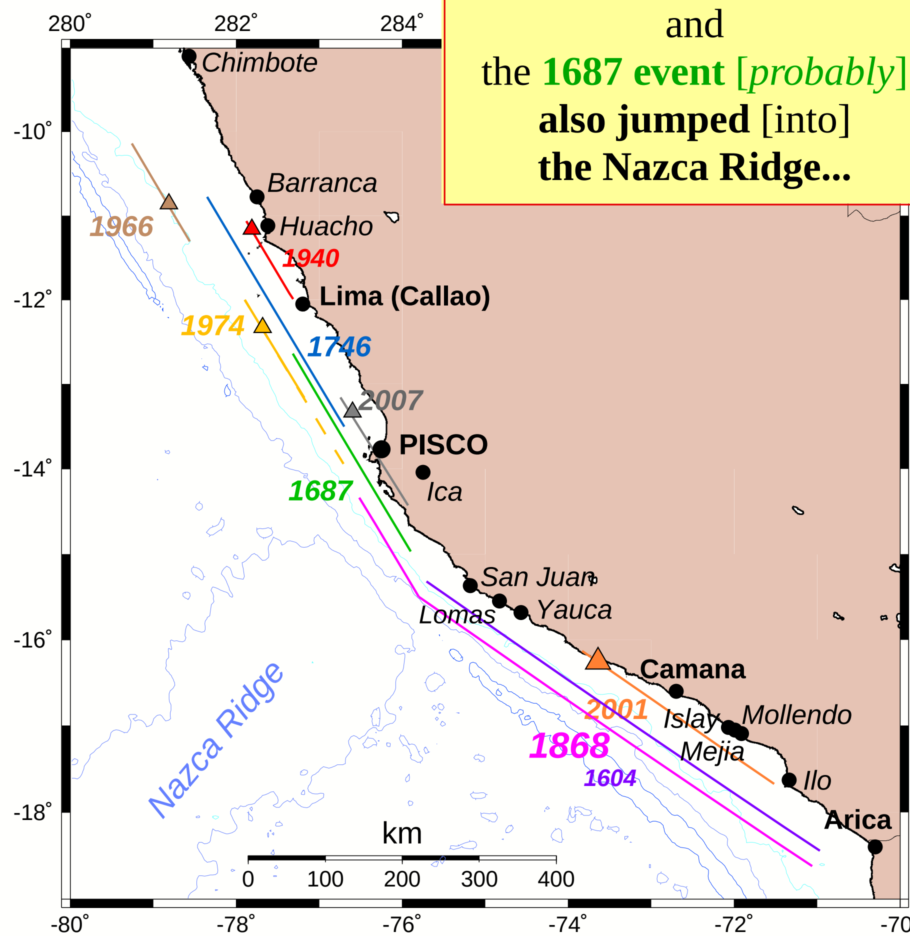
LONG FAULT (900 km)



IMPLICATIONS of 1868 ARICA EVENT

1. Earthquake is *HUGE*
2. Rupture "jumped" the Nazca Ridge
   * What constitutes a "barrier"?
3. Note variability of rupture in Large [Peruvian] earthquakes

NOTE:
The **2007 event** [*partially*]
and
the **1687 event** [*probably*]
also jumped [into]
the Nazca Ridge...



THE TSUNAMI OF 18 NOVEMBER 1865

- *Solov'ev and Go* [1984] mention a strong earthquake in Tonga at 05:40 (presumed local time) felt at sea by several ships, and generating a destructive local tsunami.

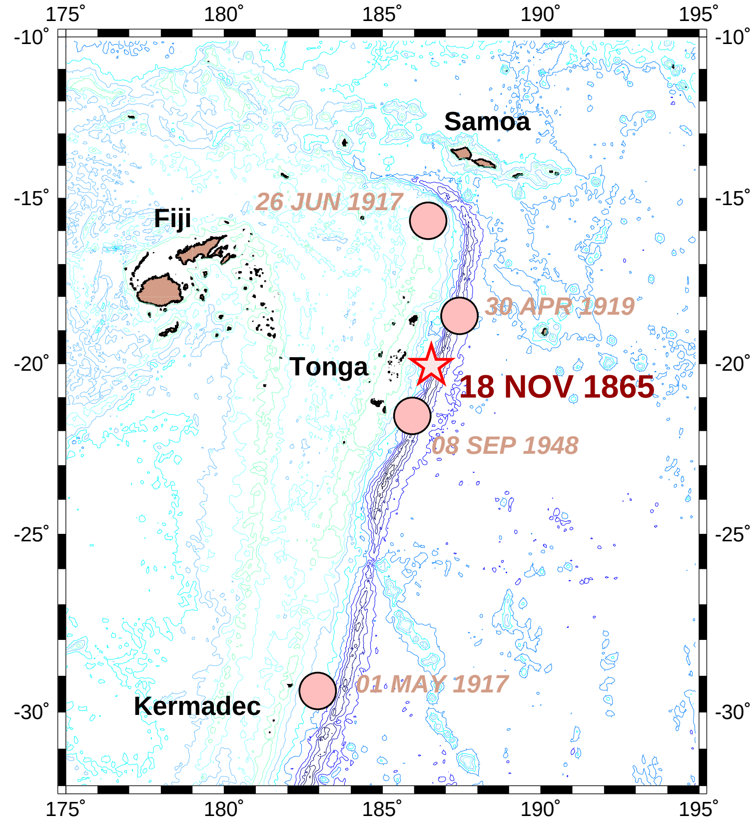
- *Le Messager de Tahiti* reports the following letter from "Avarna, Borotonga" [now Avarua, **Rarotonga**]:

> *"Le 18 Novembre 1865, à* **9 h. 20 m. du matin,** *par un beau temps avec une faible brise du SSE., et à marée presque basse, la mer se retira graduellement d'environ* **4 pieds** *au-dessous du niveau ordinaire des basses eaux, laissant le port presque à sec. Elle s'éleva ensuite lentement jusqu'à* **4 pieds** *environ au-dessus des plus hautes marées. Cependant on ne voyait point de vagues; le mouvement de descente et d'ascension s'opérait, pour ainsi dire avec calme. La mer se retira et monta au même niveau une deuxième et une troisième fois; puis les oscillations allèrent en diminuant pendant l'espace d'une demi-heure, et la mer reprit son niveau habituel et sa tranquillité."*

- In the **Marquesas**, *Lawson* [1869; Bishop Museum] commenting on the great 1868 Chilean tsunami, mentions:

> *"Le tremblement de terre aux Iles Tonga,* **il y a de cela 3 ou 4 ans,** *fut ressenti ici le même jour* **à deux heures de l'après midi** *et se termina vers six heures; mais cette fois-là, la mer monta seulement* **au niveau des plus hautes marées** *environ toutes les 15 à 20 minutes [...]; cela ne fut pas ressenti à Tahiti et dans son voisinage".*

[This reference courtesy of *M. Jean-Louis Candelot* (2000).]



CONCLUSIONS

- The 1865 earthquake probably took place along a segment of the Tonga trench previously described as a seismic gap.

- The reported run-up at Rarotonga is well modeled using a thrust-faulting interplate mechanism with

$$M_0 = 4 \times 10^{28} \text{ dyn} - \text{cm}$$

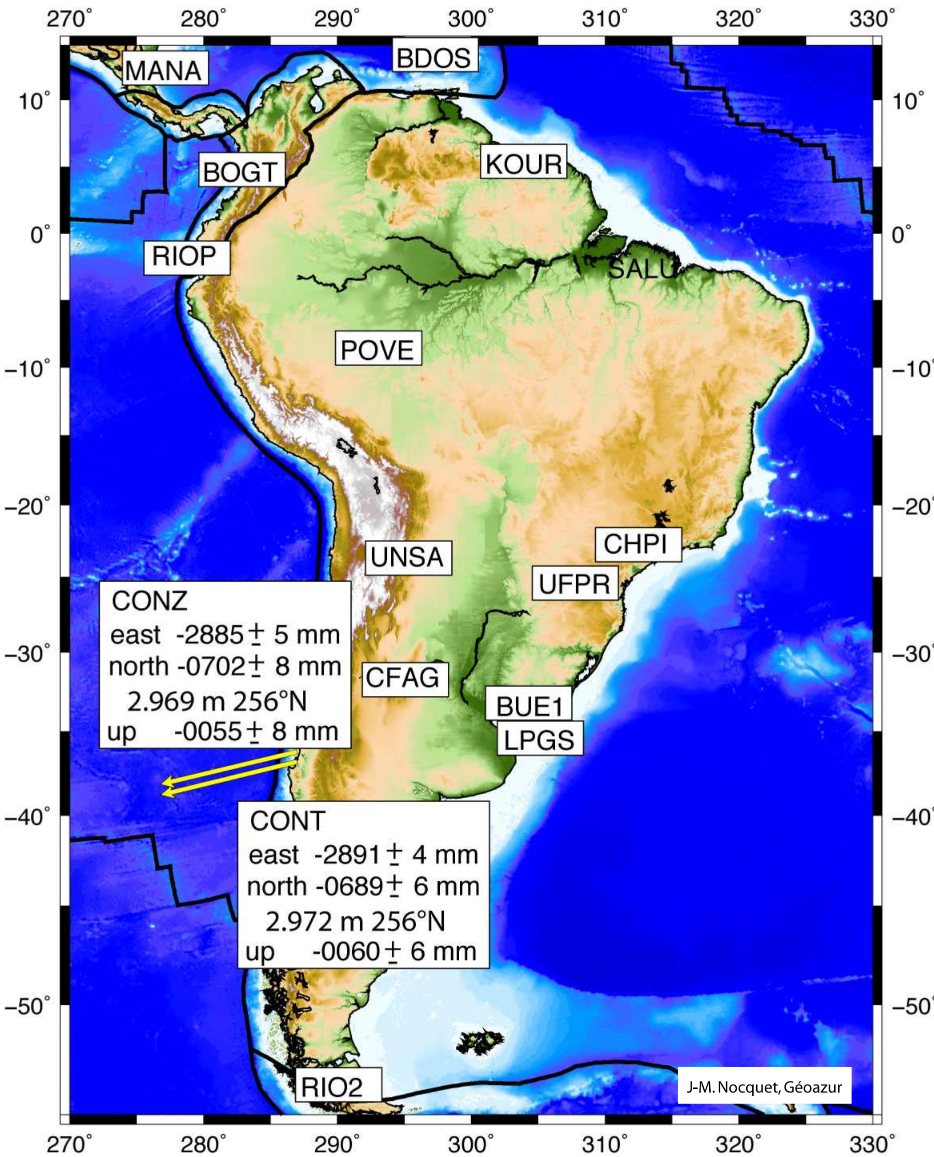
- This is about twice the moment of the largest previously documented shallow earthquake in Tonga.

AS FOR THE FUTURE....

THE COMING OF AGE OF G P S

Continuous GPS allows the recording of the **full static deformation** of the Earth in the epicentral area

2010 Maule, Chile earthquake: **3 m in azimuth N256°E**



[*J.-M. Nocquet; C. Vigny*, **03-MAR-2010**]

→ **Progress in processing should make these data available in real time with exceptional promise for far-field tsunami warning.**

AS FOR THE FUTURE....

The future of Long-Period Seismology may be at UNAVCO...