SUBDUCTION ZONE TSUNAMIS

Principal Challenges

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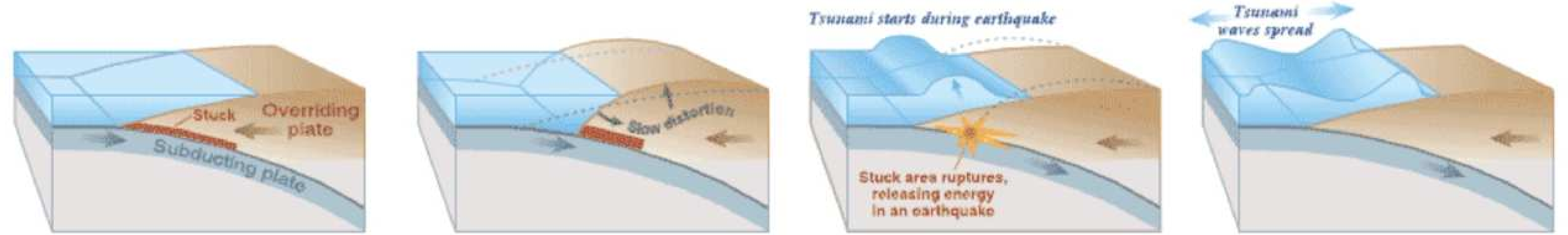
SUBDUCTION ZONE TSUNAMIS

The Basic Story

Tsunami Generation



Vertical Slice Through a Subduction Zone

One of the many tectonic plates that make up Earth's outer shell descends, or "subducts," under an adjacent plate. This kind of boundary between plates is called a "subduction zone." When the plates move suddenly in an area where they are usually stuck, an earthquake happens.

Between Earthquakes

Stuck to the subducting plate, the overriding plate gets squeezed. Its leading edge is dragged down, while an area behind bulges upward. This movement goes on for decades or centuries, slowly building up stress.

During an Earthquake

An earthquake along a subduction zone happens when the leading edge of the overriding plate breaks free and springs seaward, raising the sea floor and the water above it. This uplift starts a tsunami. Meanwhile, the bulge behind the leading edge collapses, thinning the plate and lowering coastal areas.

Minutes Later

Part of the tsunami races toward nearby land, growing taller as it comes in to shore. Another part heads across the ocean toward distant shores.

Source: U.S. Geological Survey Circular 1187

SUBDUCTION ZONE EARTHQUAKES

Principal Challenges

- **Some S.Z. deficient in Mega-Thrust Events ?**
- **The Infamous "Tsunami Earthquakes"**
- **Irregular Fragmentation of Rupture**
- **Other Events**

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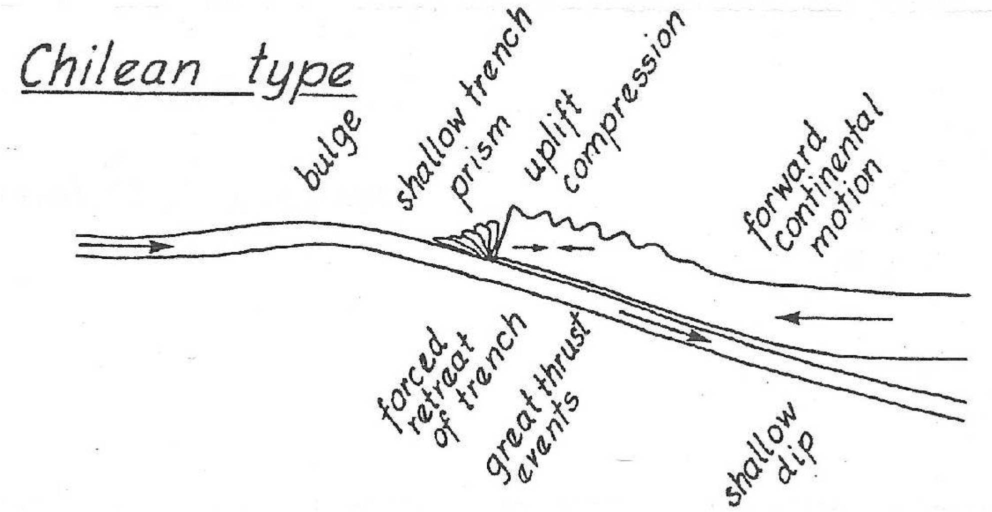
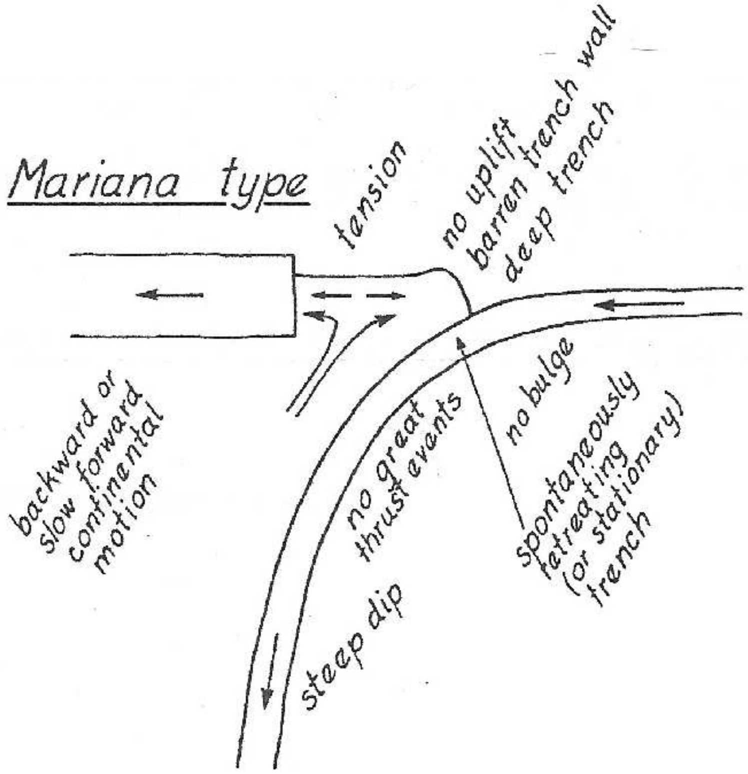
NOT ALL SUBDUCTION ZONES ARE CREATED EQUAL...



Strong coupling

MEGA-THRUST EARTHQUAKES $M_w \approx 9$



Weak coupling

NO MEGA-THRUST EARTHQUAKES $M_w \leq 7.5$

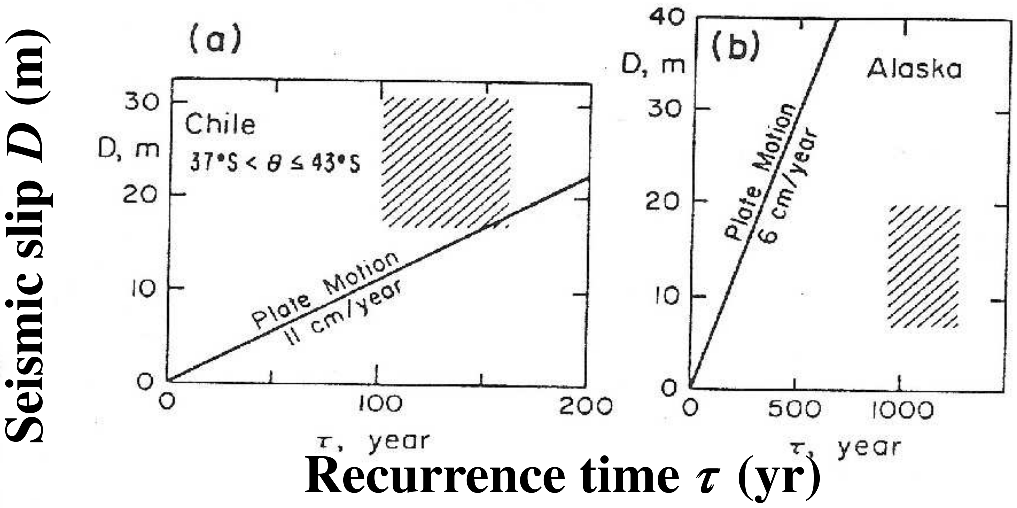
[*Uyeda and Kanamori*, 1979]

- In a parallel study, *Kanamori* [1977] suggested that the level of coupling could control the

  seismic efficiency

  of the subduction zone, *i.e.*, the fraction of tectonic convergence expressed through large earthquakes.

Strong coupling **Weaker coupling**

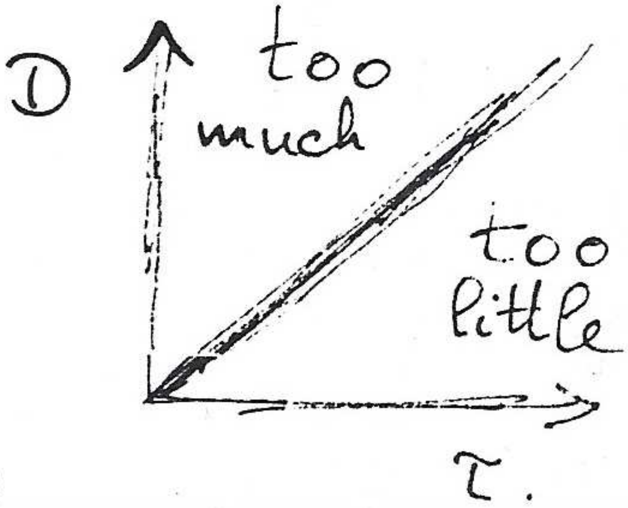


Seismic slip, repeat time of major earthquakes and the rate of plate motion for Chile and Alaska. Hatching indicates the range of seismic slip and the repeat time.

→ *Note that this efficiency should not, in principle, be greater than 100%*

NOTE that Kanamori's generous error bars just about reconcile his data with the Chilean's plate motion rate... which we now know was

overestimated!



BEFORE 2004 ....

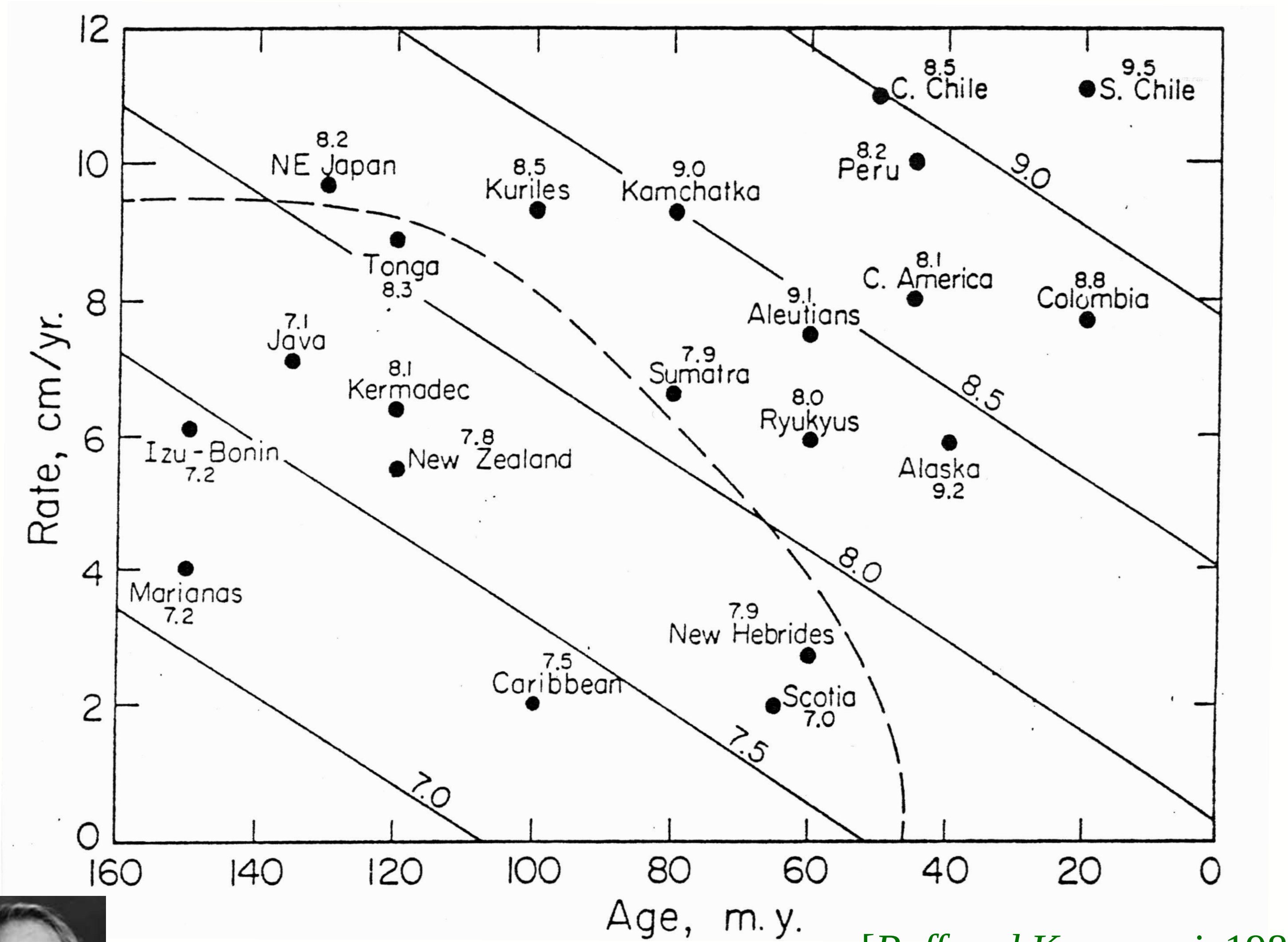
We lived happily under

the concept of a

maximum expectable

subduction earthquake controlled by

***plate age* and *convergence rate*.**



[*Ruff and Kanamori*, 1980]

Inspired from *Uyeda and Kanamori* [1979]

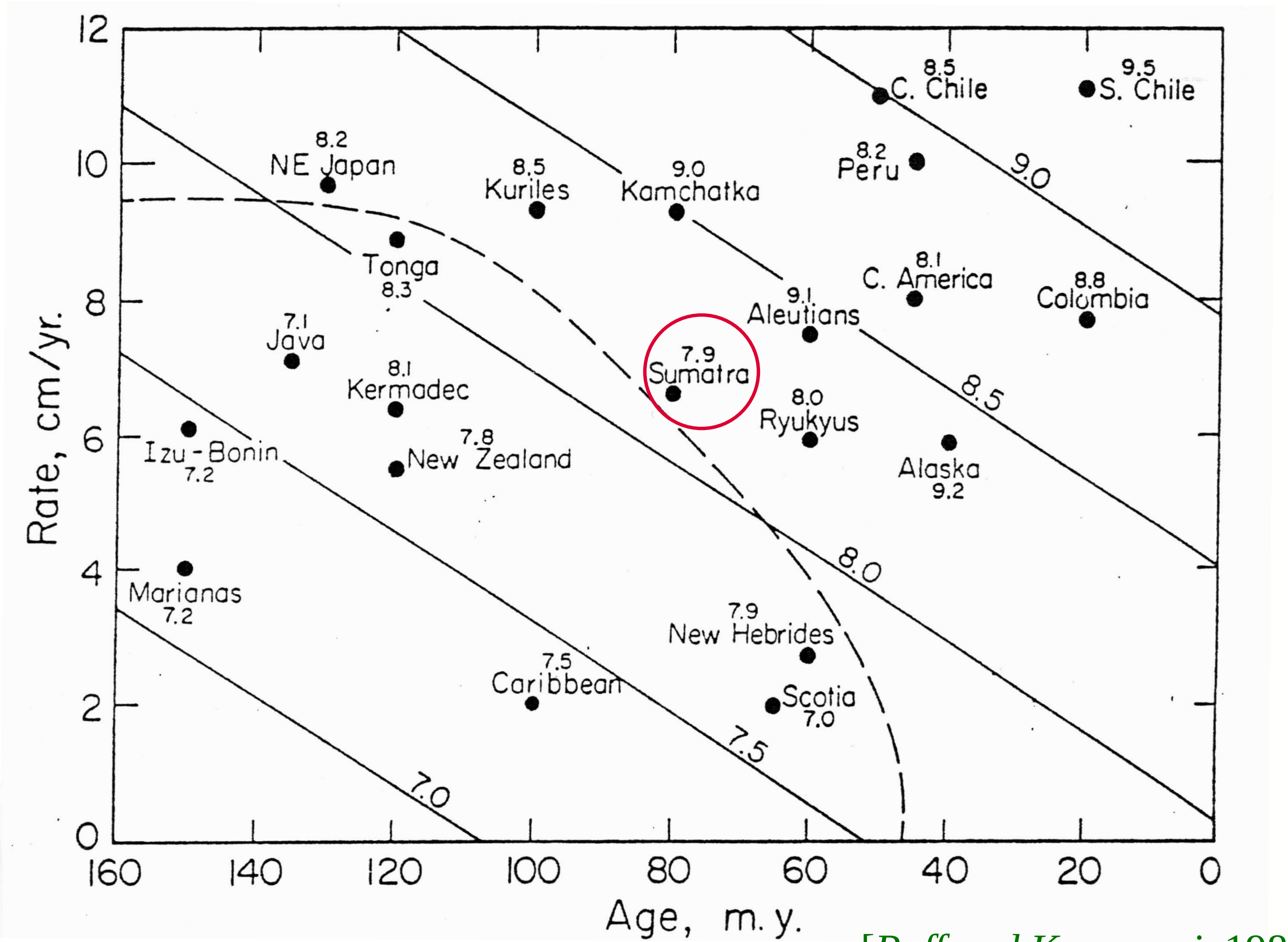
2004 : THE EARTHQUAKE OCCURRED WHERE A MEGA−EVENT *WAS NOT EXPECTED*

The 2004 [and 2005] **Sumatra earthquake[s] violated the concept of a**

maximum expectable

subduction earthquake controlled by

***plate age* and *convergence rate*.**



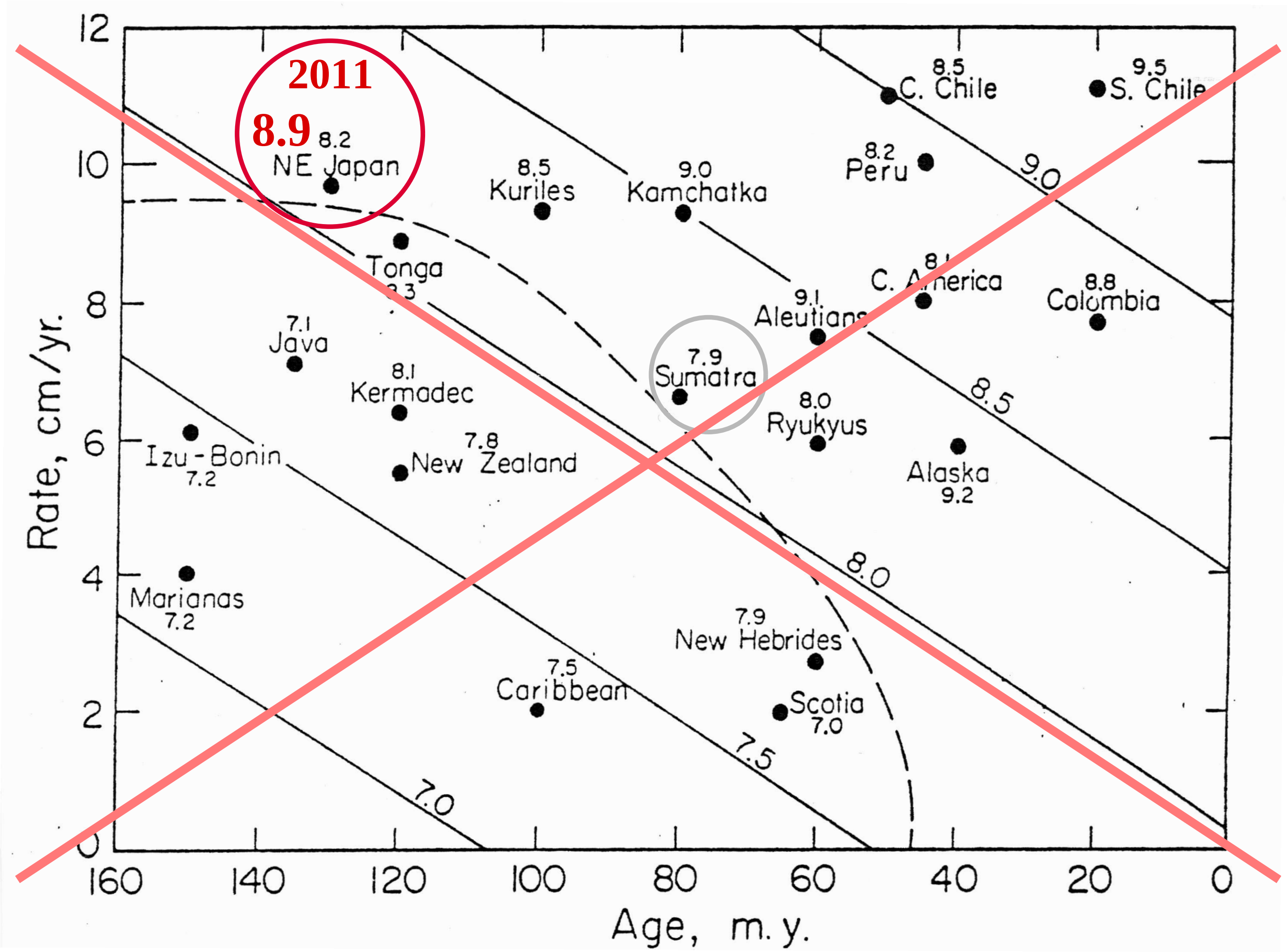
[*Ruff and Kanamori*, 1980]

Modern parameters: **> 55 Ma; 5 cm/yr**

Would predict Maximum **8.0−8.2 not ≥ 9...**

2011 TOHOKU EVENT CONFIRMS HARSH LESSON:

Mega-earthquakes DO occur in unsuspected areas !



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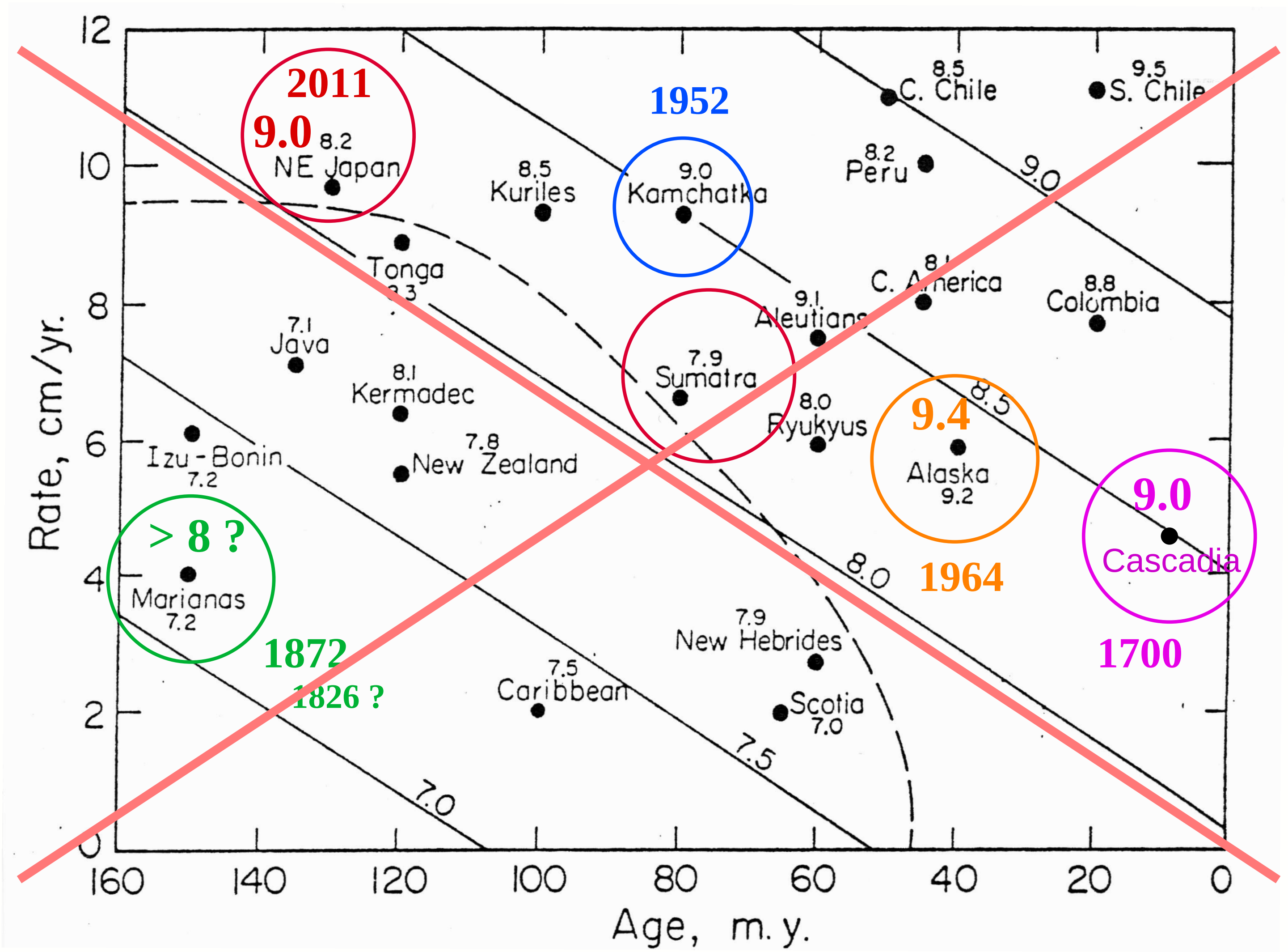


NOTE IN PARTICULAR

THE POOR PERFORMANCE OF THE

8.0 to 8.5 BAND:

Proven new violators: **Sumatra 2004** **Tohoku 2011**

Violators overlooked by RK 1980:

Alaska **Kamchatka** [Aleutians -- 1957 Debatable]

→ That leaves

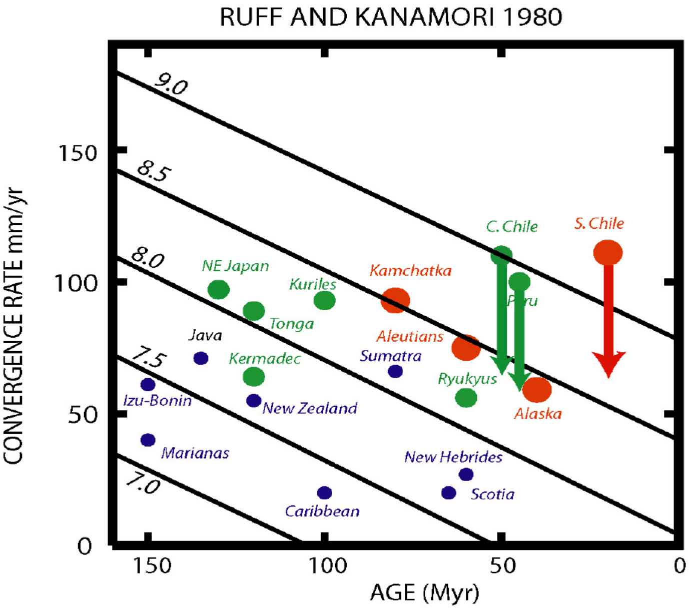
Tonga (1865) Ryukyu (1771 ?) Kuriles ????

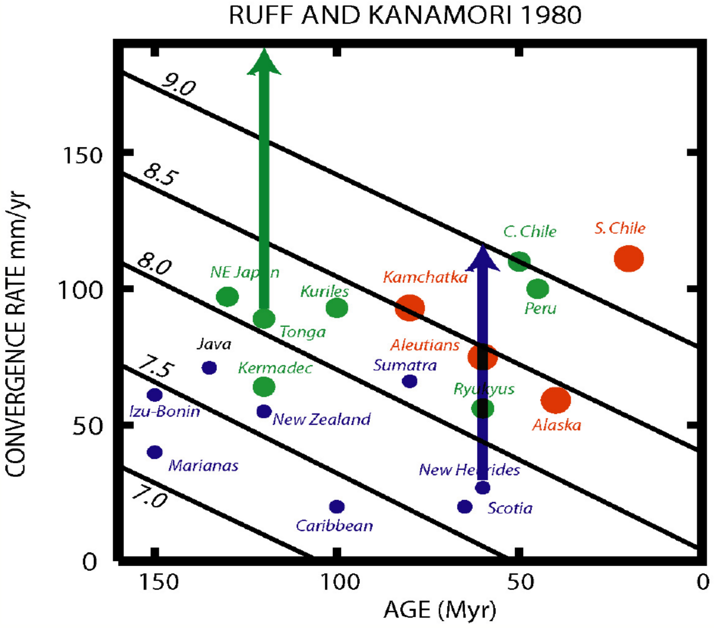
UPDATING THE RUFF-KANAMORI DIAGRAM ?

Over the past 25 years... → **We have obtained new rates**

Examples: South Chile **70** mm/yr *vs.* 111 Tonga (20°S): **185** mm/yr *vs.* 89

South Peru: **67** mm/yr *vs.* 100 Vanuatu: **103** mm/yr *vs.* 27





Over the past 25 years... → **We have *"discovered" new earthquakes***

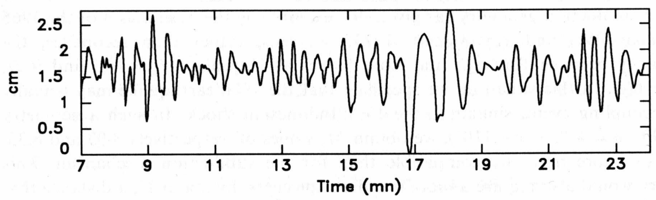
→ **We have revised the size**
of historical earthquakes

Examples: **Sumatra 2004 !**
Cascadia, 1700

Example: 1906 Colombia-Ecuador:

$M_0 = 6 \times 10^{28}$ dyn-cm *vs.* 2×10^{29}

1906



1979

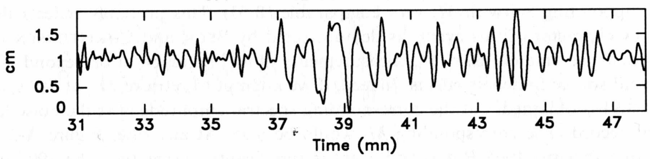


Figure A-1
Comparison of the Love wavetrains G_1 of the 1906 and 1979 Ecuador-Colombia earthquakes, as recorded on the NS component of the Uppsala Wiechert. The records are plotted on the same scale, with the abcissæ offset so as to align the G_1 wavetrains, thus allowing a direct comparison of their relative sizes. Note that while the 1906 earthquake is undoubtedly the larger of the two, it cannot have a moment 10 times larger than the 1979 event.

The Orphan Tsunami of 1700

Japanese clues to a
North American earthquake

[Okal, 1992]

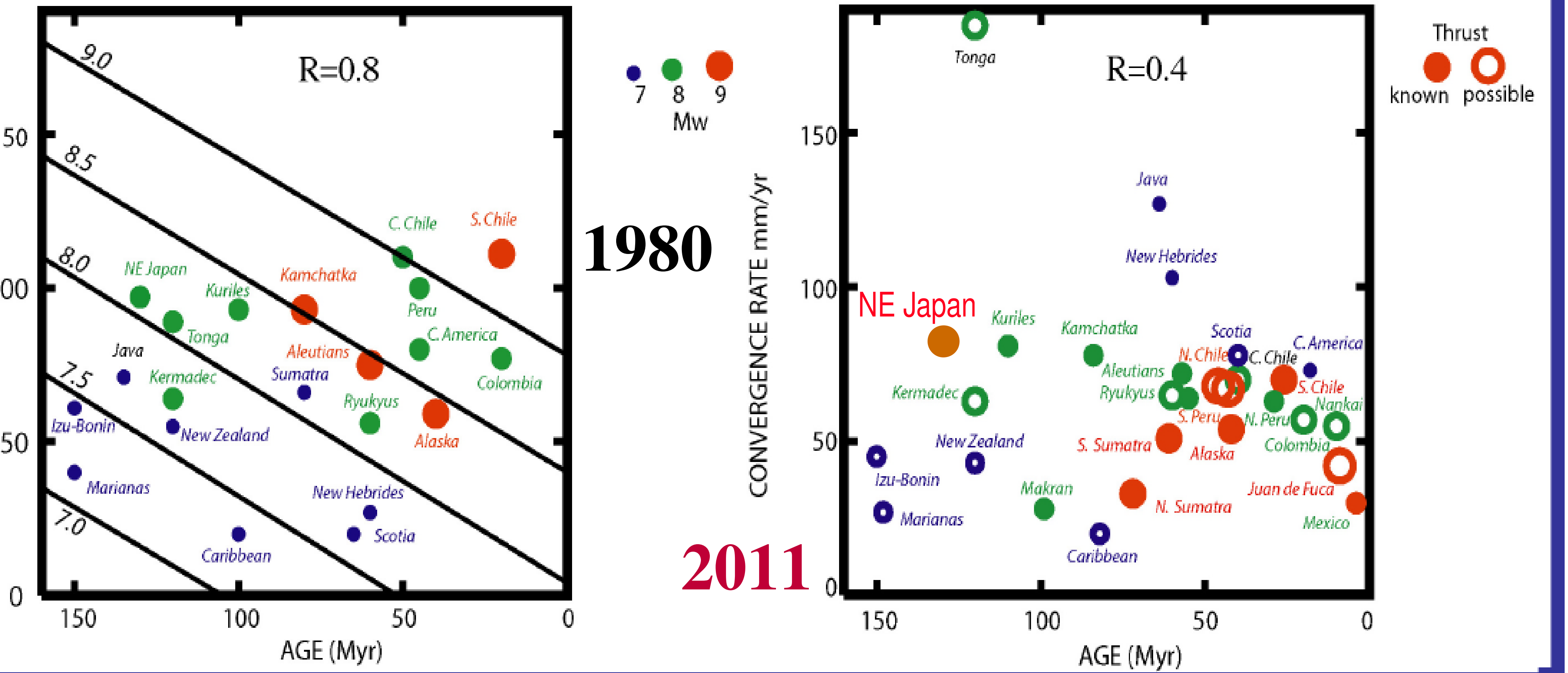
Brian F. Atwater, Satoko Musumi,
Kenji Satake, Yoshinobu Tsuji,
Kazue Ueda, and David K. Yamaguchi

embarrassingly so, in subduction zones supposedly "safe" from mega-events !

USING NEW RATES, AGES & MAGNITUDES

MUCH OF THE CORRELATION VANISHES

RUFF AND KANAMORI 1980



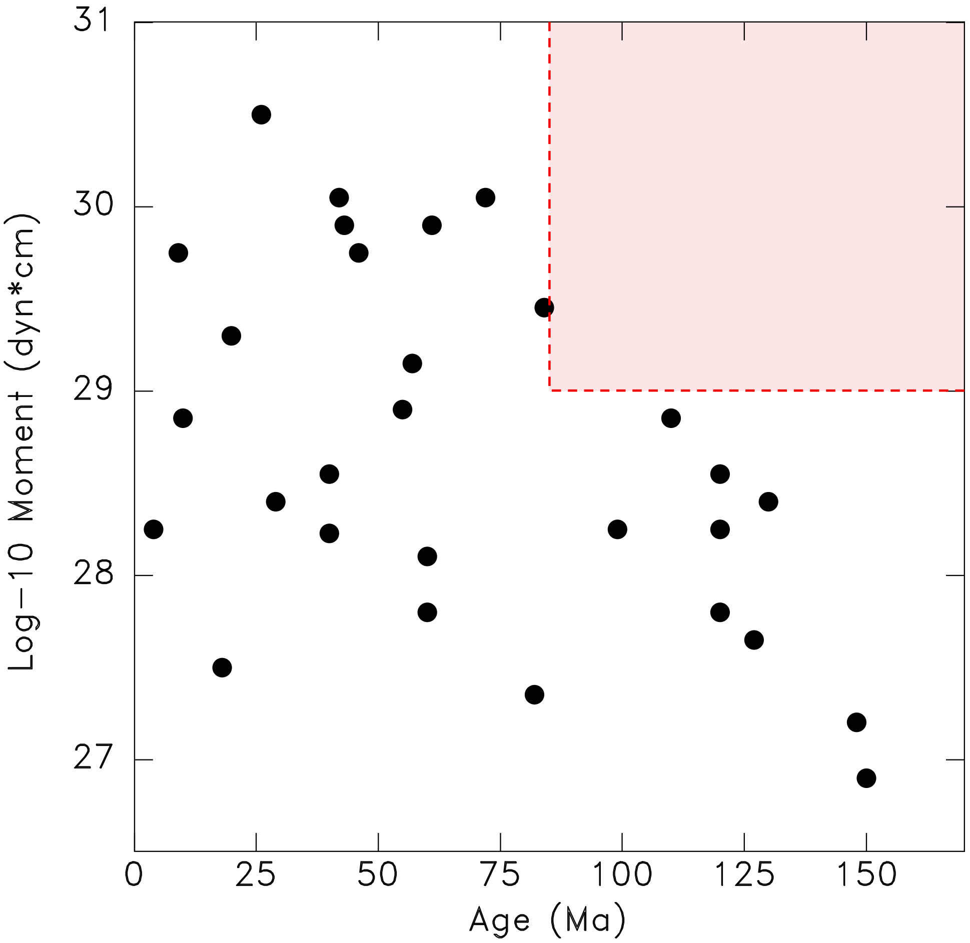
Correlation: 80% **32%**

THE QUEST FOR A BETTER

An idea in gestation, ca. 2010....

MEGA EVENTS (*M_0* > 10^{29} dyn*cm)

ARE LIMITED TO AGES LESS THAN 85 Ma



→ *This suggests a kind of "wilting" age for the oceanic lithosphere, which after 85 Ma, cannot* [pro−]*create Mega-Earthquakes.*

~~εμμηνοπαυση~~

λιθοπαυση ?

- It is remarkable that this age (85 Ma) is also that beyond which the simple half-space thermal model no longer applies.

- *AND THEN.....* **2011 TOHOKU !**

MEGA EVENTS ($M_0 > 10^{29}$ dyn*cm)
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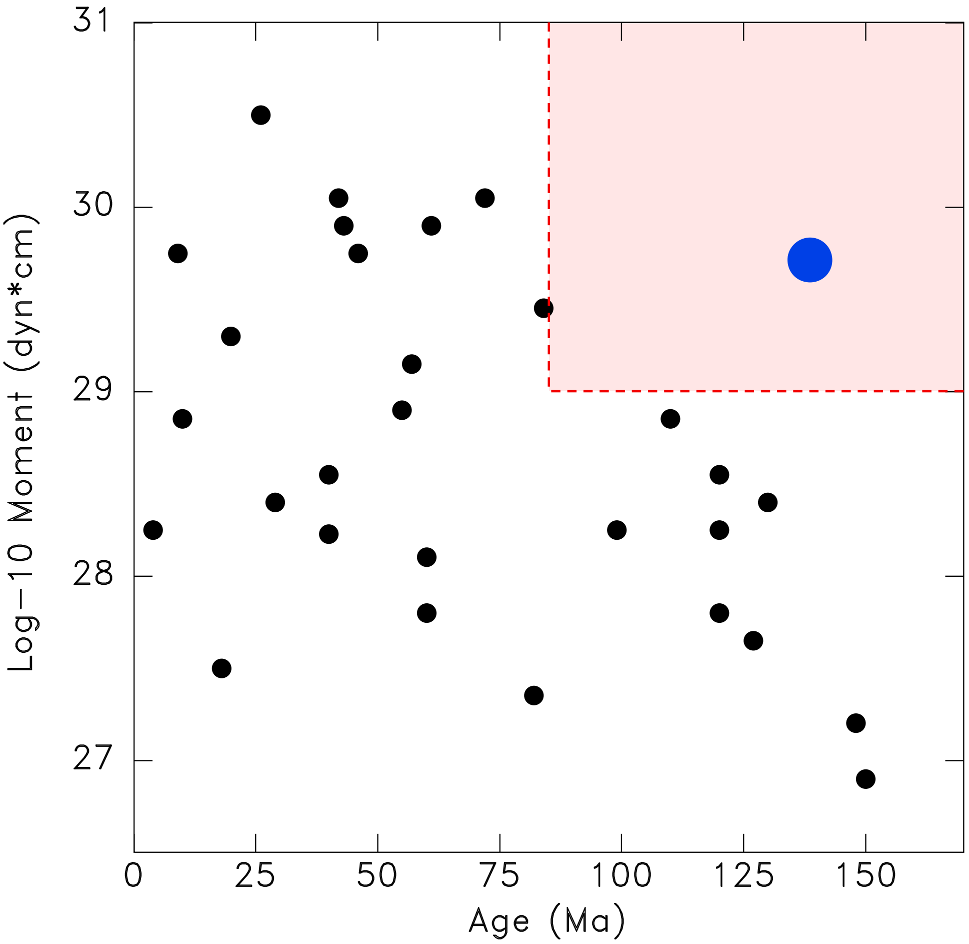

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$\lambda\,\iota\,\theta\,o\,\pi\,\alpha\,\upsilon\,\sigma\,\eta$?

- It is remarkable that this age (85 Ma) is also that beyond which the simple half-space thermal model no longer applies.

AND THEN..... **2011 TOHOKU**

Nixes one more Potential Paradigm...

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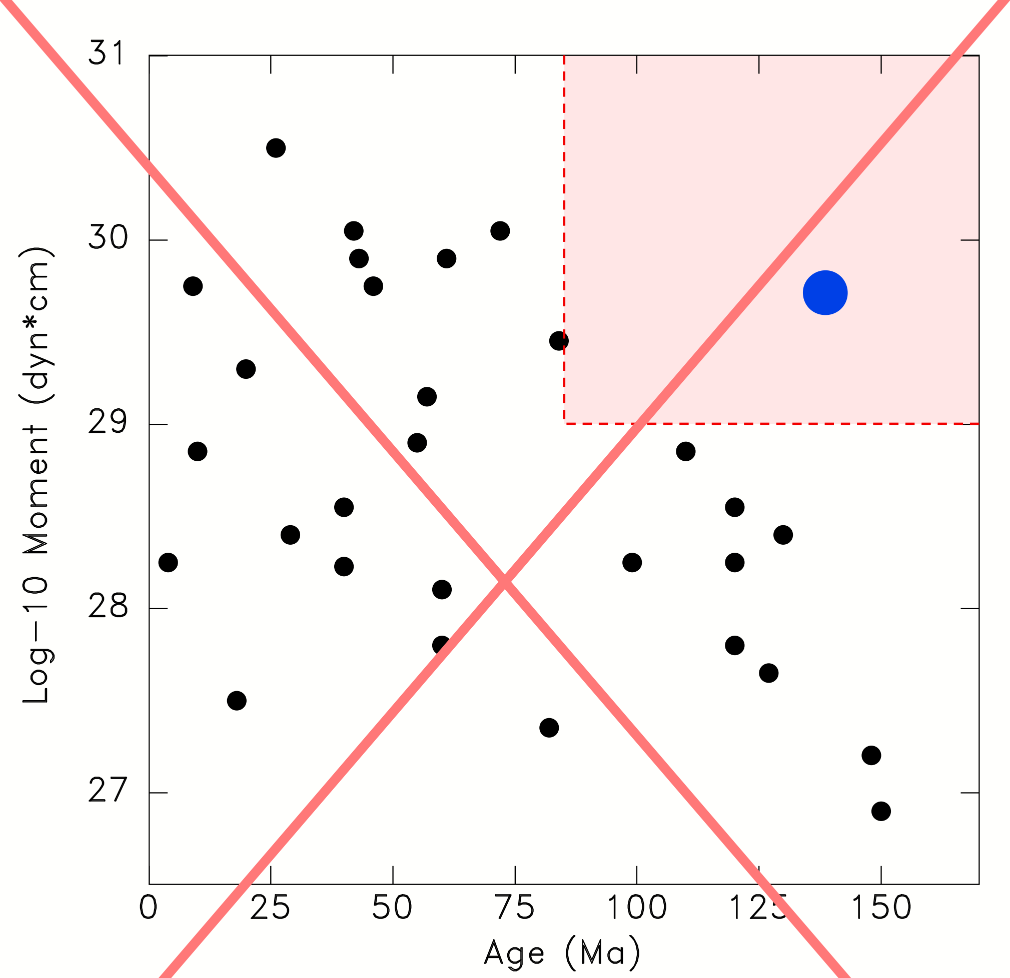

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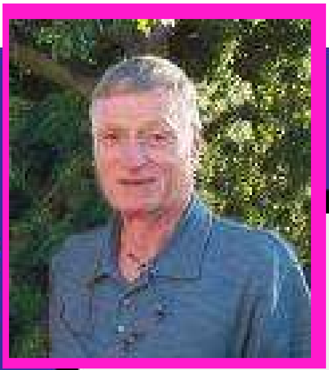
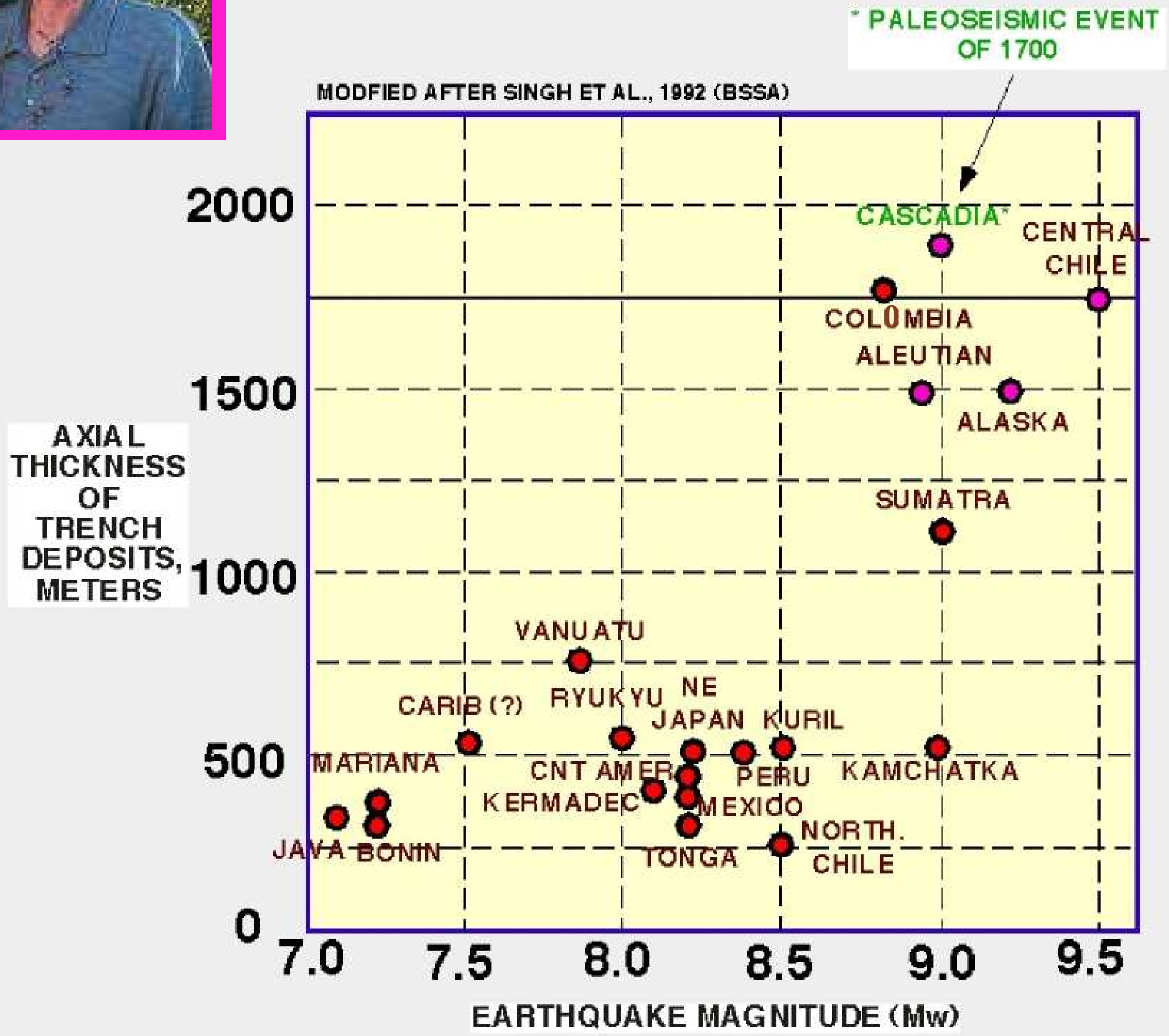
Another Suggestion [from D. Scholl] *in the Quest for WISDOM ?*



Thick trench sediments lubricate interface & allow rupture to propagate long distances, giving $M_w > 8.5$

LOOKS GOOD ! ....

Doesn't it ?



[*D. Scholl*, pers. comm., 2006, building on a suggestion by *L.J. Ruff*, 1985]

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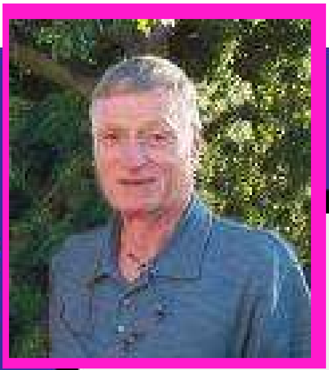

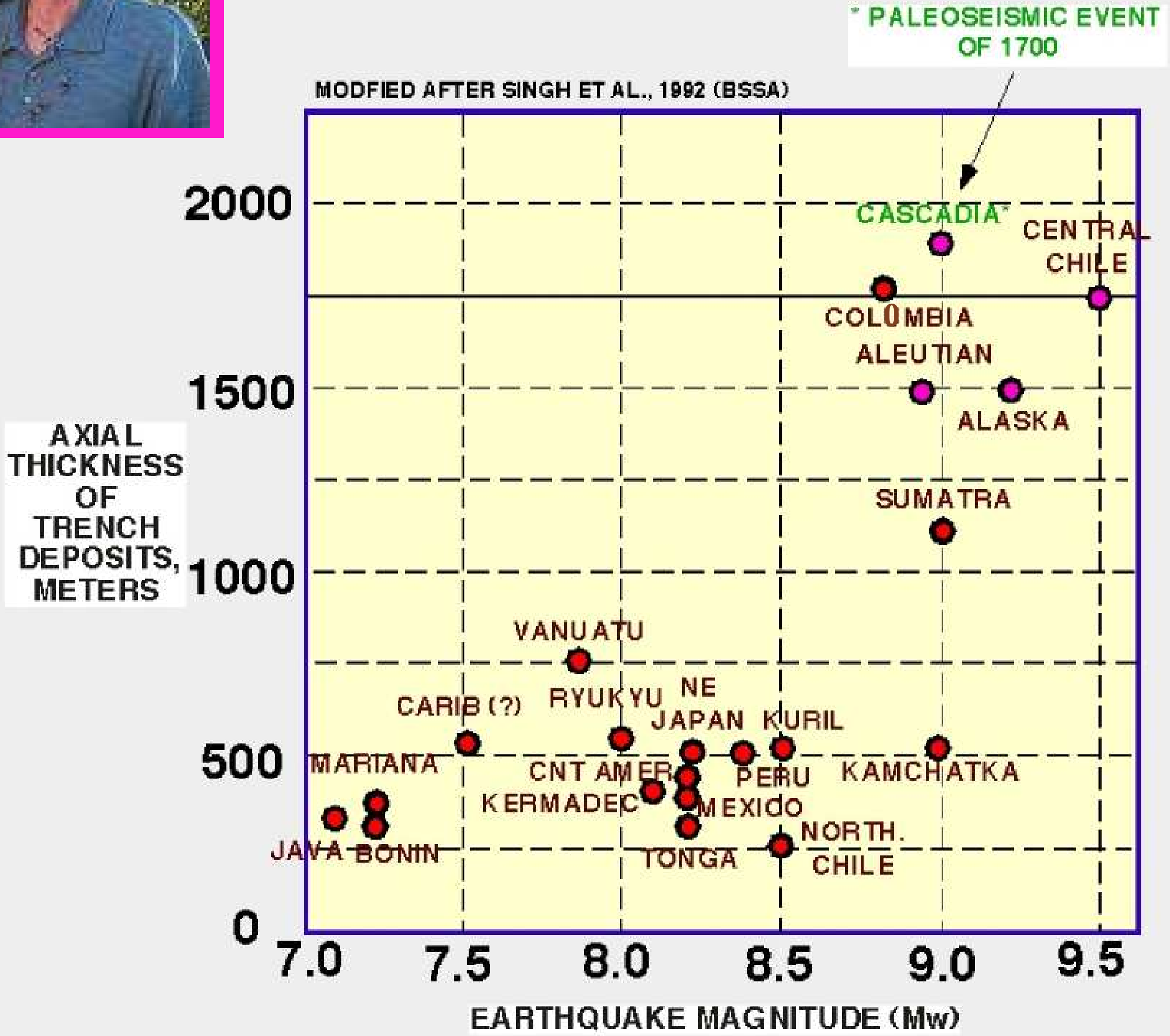

MODFIED AFTER SINGH ET AL., 1992 (BSSA)

LOOKS GOOD ! ….
Doesn't it ?

Except perhaps
KAMCHATKA !!

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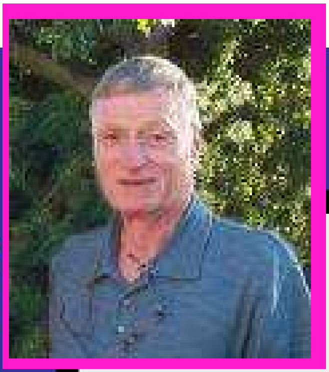

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Looks good, but easy to find counterexamples

South Peru: 1868

$M_w \approx 9.2$

no sediments...

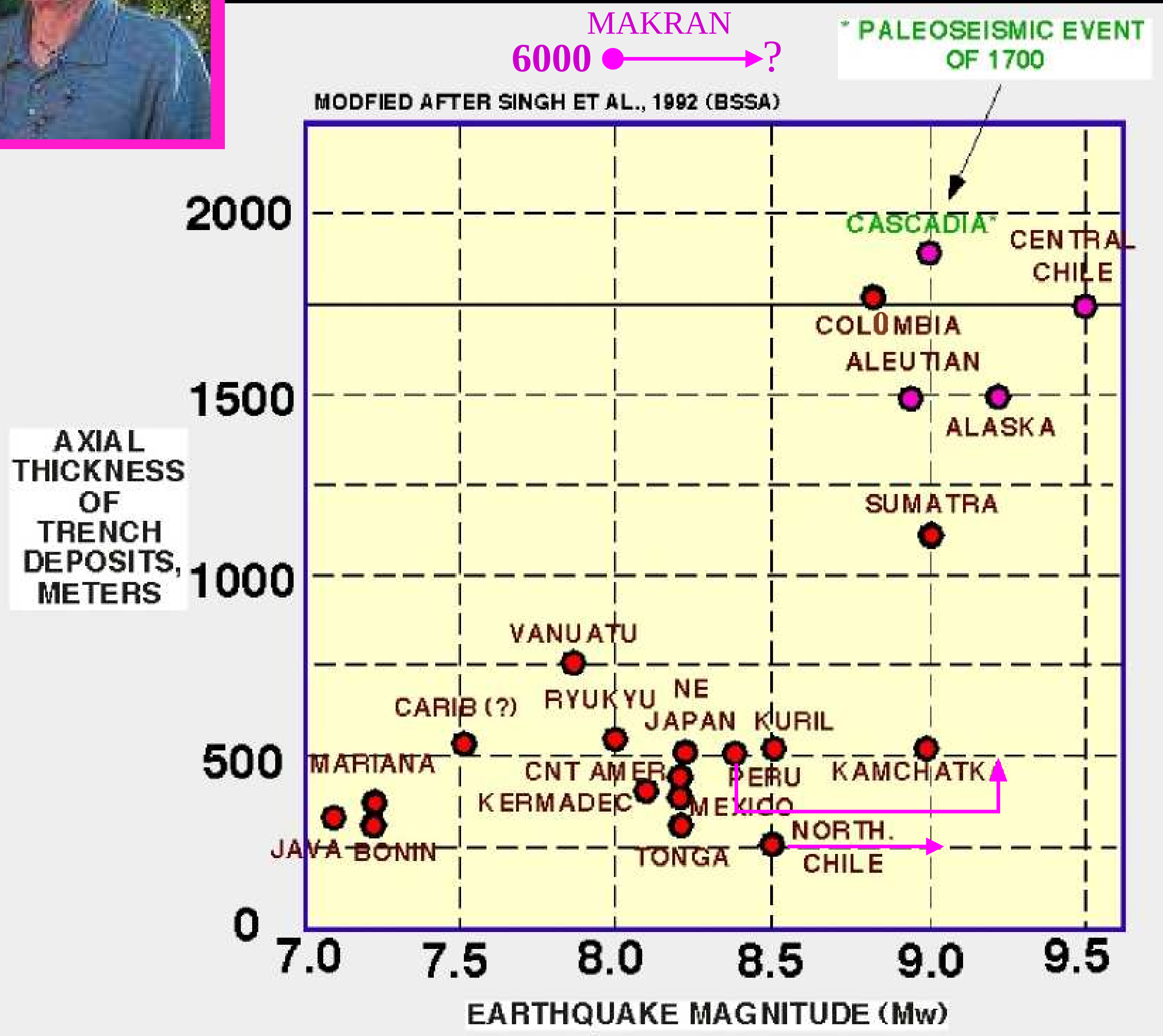
No. Chile *Based on 1922*

BUT 1877 ?

Makran

6000 m of sediments

Max **KNOWN** $M_w = 8$



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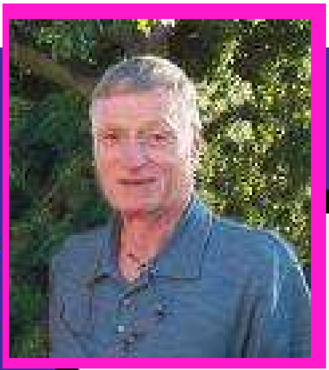
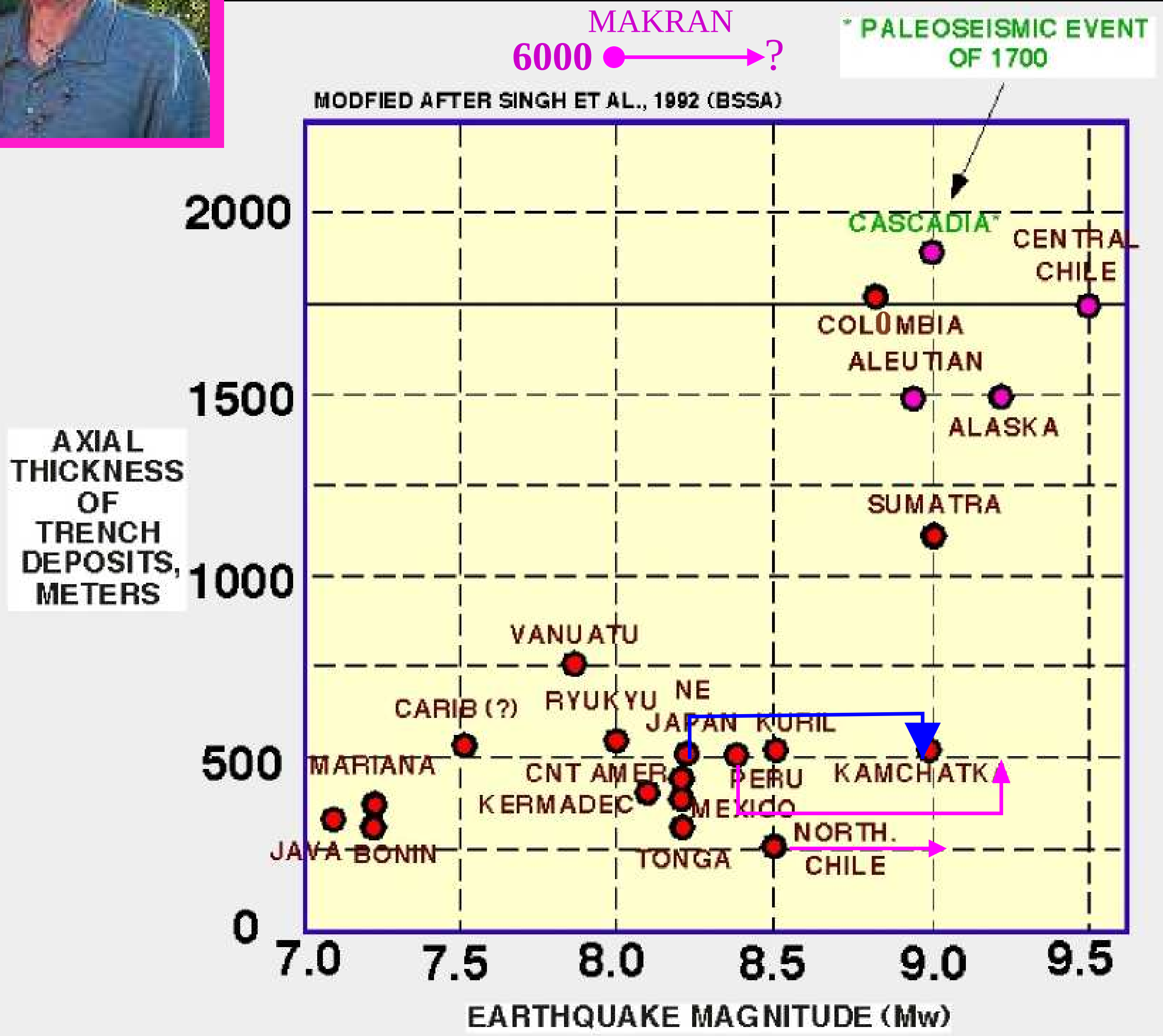


And Then...

2011 Tohoku

$M_w \approx 8.9$

Mediocre Sedimentary Cover...



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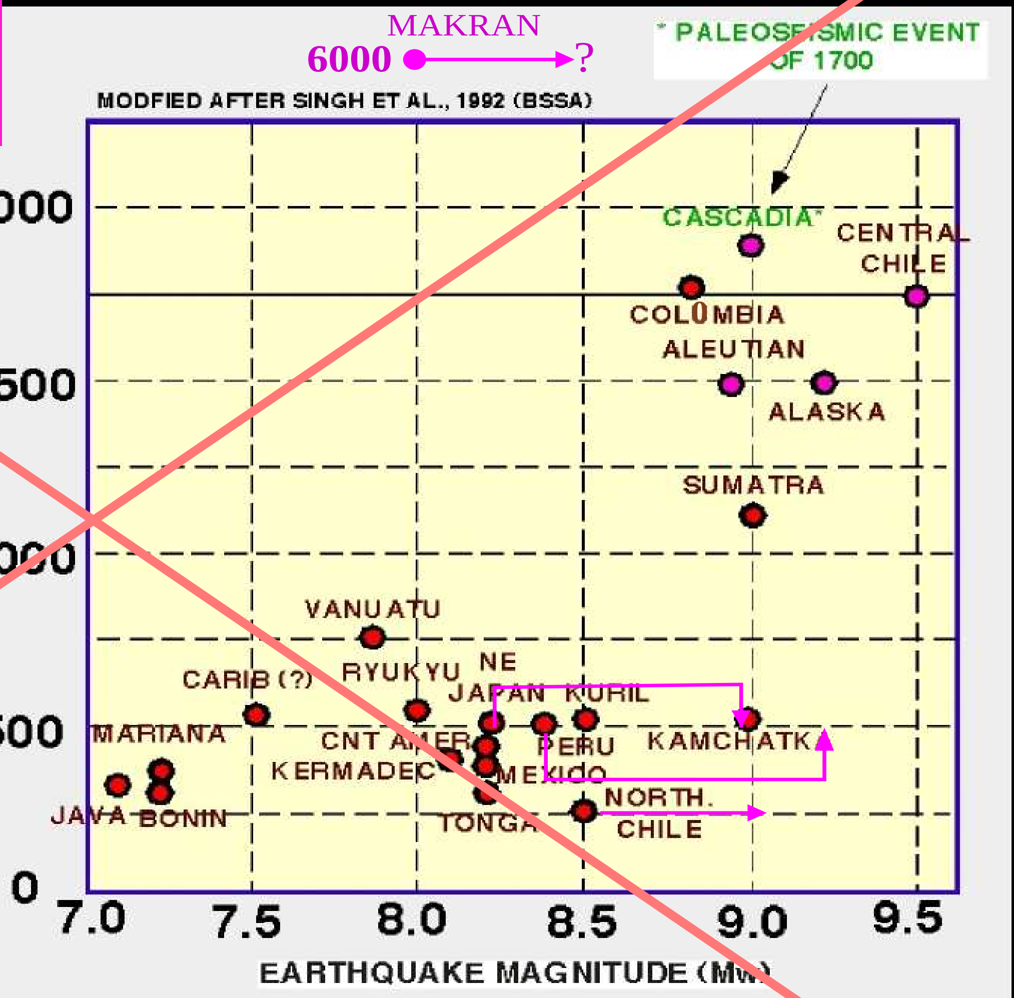


[*D. Scholl*, pers. comm., 2006, building on a suggestion by *L.J. Ruff*, 1985]

⟶ *AFTER SENDAI, D. SCHOLL* [pers. comm., 2011] *ACKNOWLEDGES FAILURE OF MODEL*

OTHER IDEAS

?

So, have we become...

Humbler : CERTAINLY

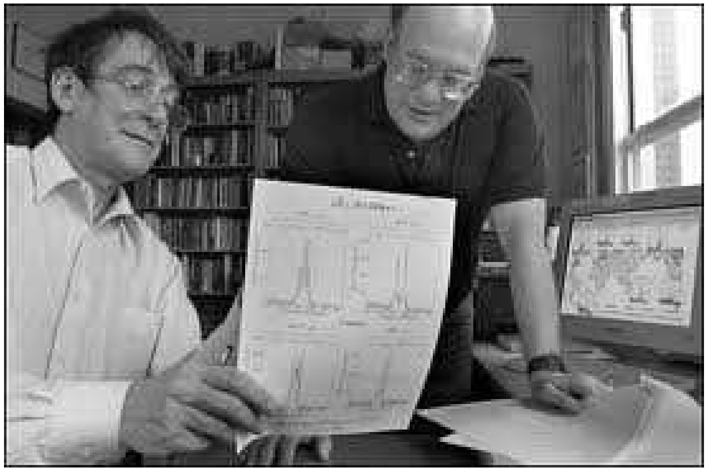
Wiser : ? ? ?

We still have not devised the better

IN THE MEAN TIME, WE SHOULD CONSIDER

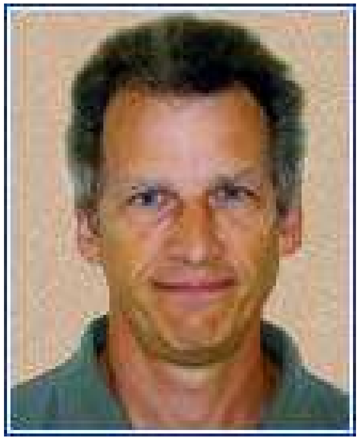
ALL LONG SUBDUCTION ZONES

AS POTENTIALLY MEGA−GENIC



[*Stein and Okal*, 2007;

McCaffrey, 2007]



SUBDUCTION ZONE EARTHQUAKES

Principal Challenges

- **Some S.Z. deficient in Mega-Thrust Events ?**
- **The Infamous "Tsunami Earthquakes"**
- **Irregular Fragmentation of Rupture**
- **Other Events**

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

Documented Tsunami Earthquakes, as of 2022

Year	Region	Θ	
	Charter Events [*Kanamori,* 1972]		
1896	Sanriku		
1946	Aleutian	-7.0	
	Primary Events		
1907	Sumatra		**INDONESIA**
1947	Hikuranga I	-5.94	
1947	Hikuranga II	-6.51	
1960	Northern Peru	-6.13	
1979	Colombia	-6.22	
1982	Tonga	-5.76	
1992	Nicaragua	-6.47	
1994	Java	-6.57	**INDONESIA**
1996	Chimbote, Peru	-6.06	
2004	Sumatra	-6.40	**INDONESIA**
2006	Java	-6.01	**INDONESIA**
2012	El Salvador	-6.42	
2013	Santa Cruz	-6.30	
2021	South Sandwich	-6.39	
	Aftershocks		
1923	Kamchatka		
1932	Mazatlan, Mexico	-6.18	
1934	Santa Cruz	-6.10	
1963	Kuriles	-6.42	
1965	Vanuatu	-5.88	
1975	Kuriles	-6.43	
2000	New Britain	-6.11	
2010	Mentawai, Sumatra	-6.22	**INDONESIA**

"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 Origin:* Generally interpreted as involving rupture in anomalous situations, which could involve:

→ Rupture in weak sedimentary material on splay fault through accretionary prism.

Candidates: Kuriles, 1963, 1975; Sanriku, 1896. *NOTE: OFTEN, AFTERSHOCKS !*

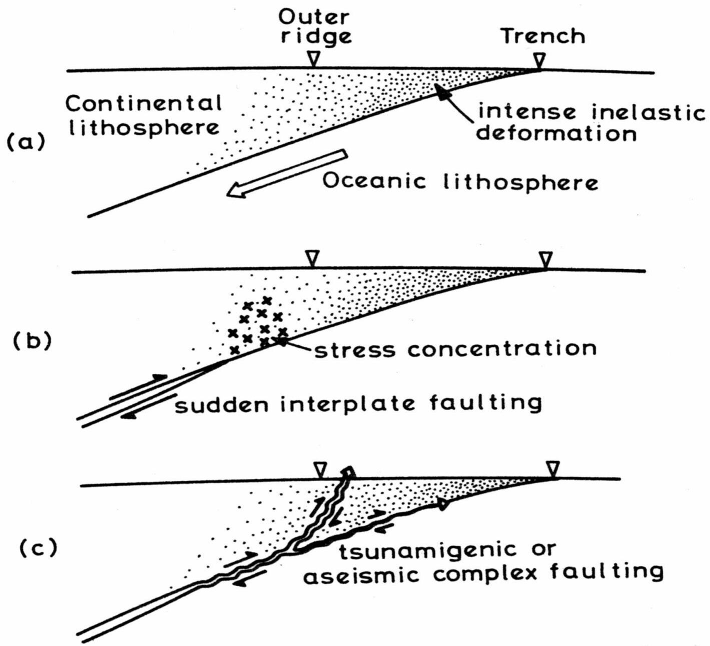
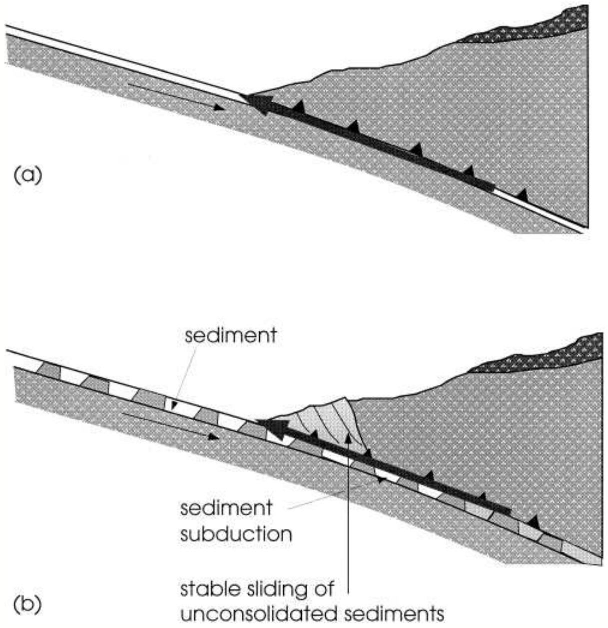


Fig. 19. A model for a great earthquake sequence showing (*a*) interseismic stage, (*b*) coseismic stage, and (*c*) postseismic stage. See the text for details.

[*Fukao,* 1979]

→ Rupture in jagged mode along corrugated interface poorly coupled due to sediment starvation [*Tanioka et al.,* 1997].

Candidates: Nicaragua, 1992; Chimbote, Peru, 1996



[*Polet and Kanamori,* 2000]

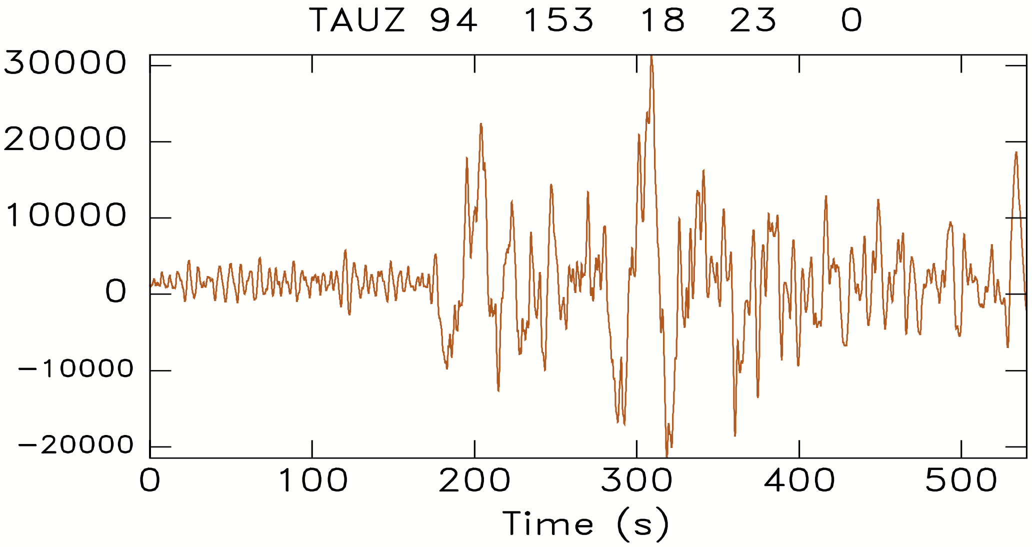
"TSUNAMI EARTHQUAKES"

- *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.

"TSUNAMI EARTHQUAKES"

$\longrightarrow$ Define *Estimated Energy,* E^E

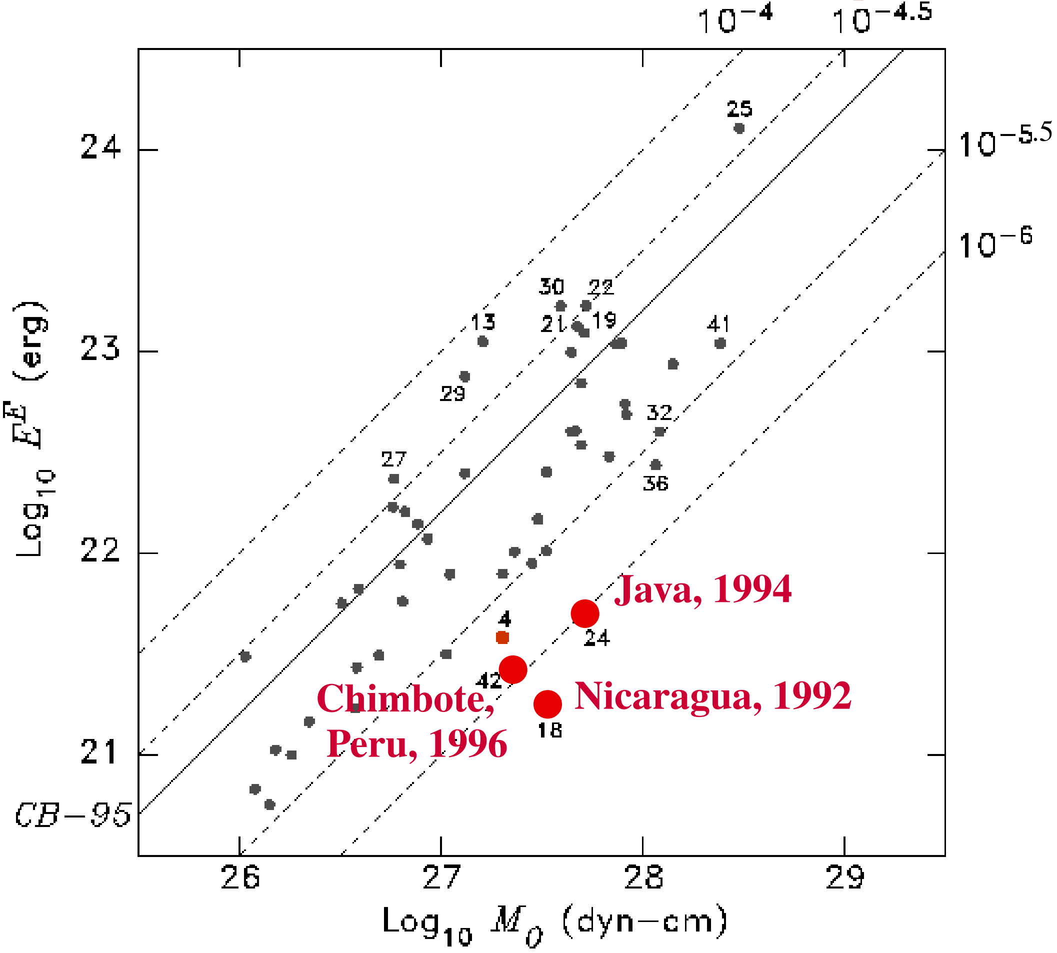
$$E^E = (1+q)\,\frac{16}{5}\,\frac{[a/g(15;\Delta)]^2}{(F^{est})^2}\,\rho\,\alpha \int_{\omega_{\min}}^{\omega_{\max}} \omega^2\,|\,u(\omega)\,|^2\, e^{\omega\, t^*(\omega)} \cdot d\omega$$

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

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

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

[*Newman and Okal,* 1998], based on *Four* tsunami earthquakes

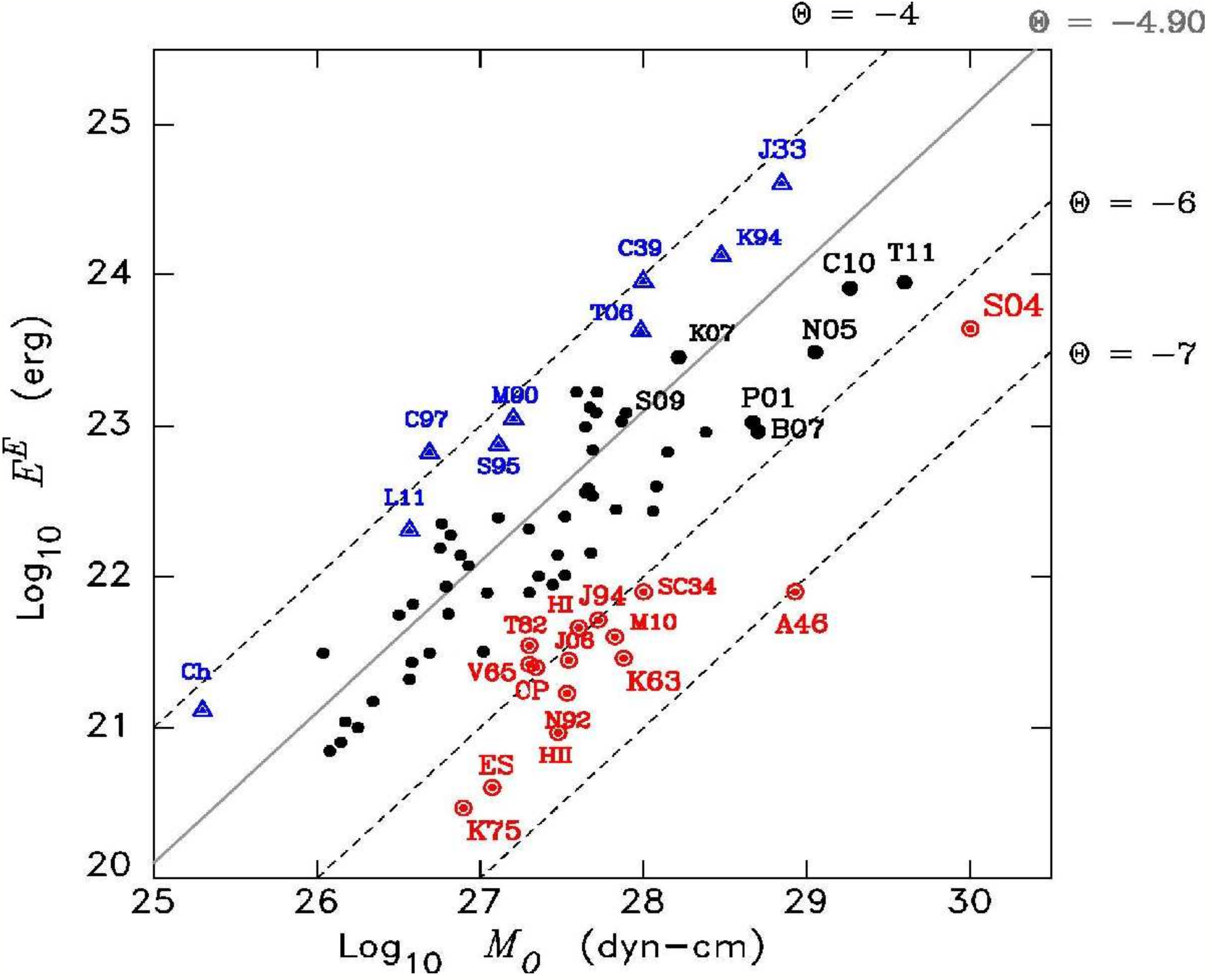


Now implemented at Papeete and PTWC

"TSUNAMI EARTHQUAKES"

Updated Dataset (2022)

→ The Θ algorithm has been successfully applied to more than 1000 earthquakes, of which **21** have been identified as *"tsunami earthquakes"*, including *SEVEN historical events* with only analog data.

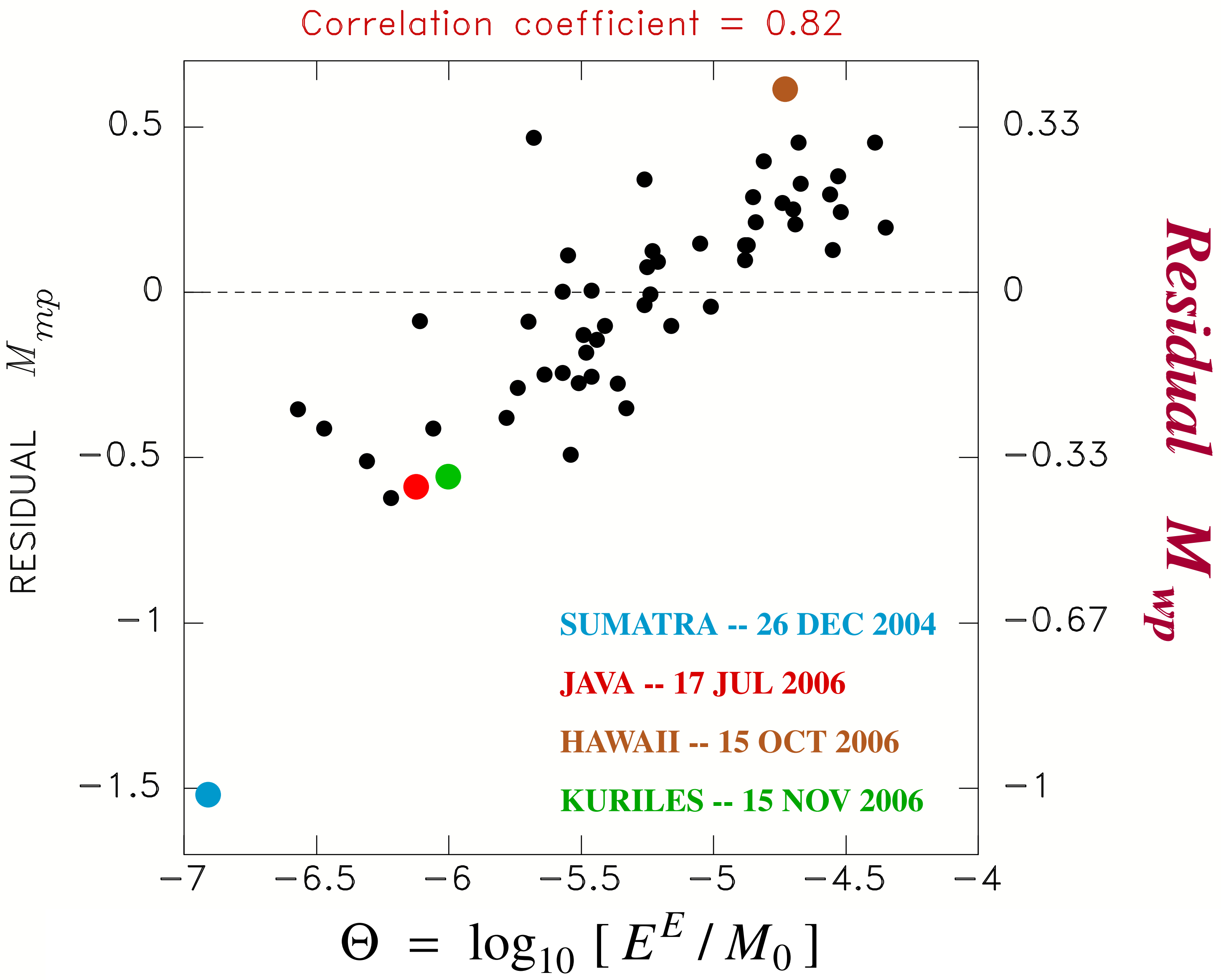


- Incidentally, events with anomalously high values of Θ correspond to *"snappy"* earthquakes whose source spectrum is **blue-shifted**, leading to extreme accelerations and enhanced damage (*e.g.*, Christchurch, 2011).

Θ and 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 classical methodologies.

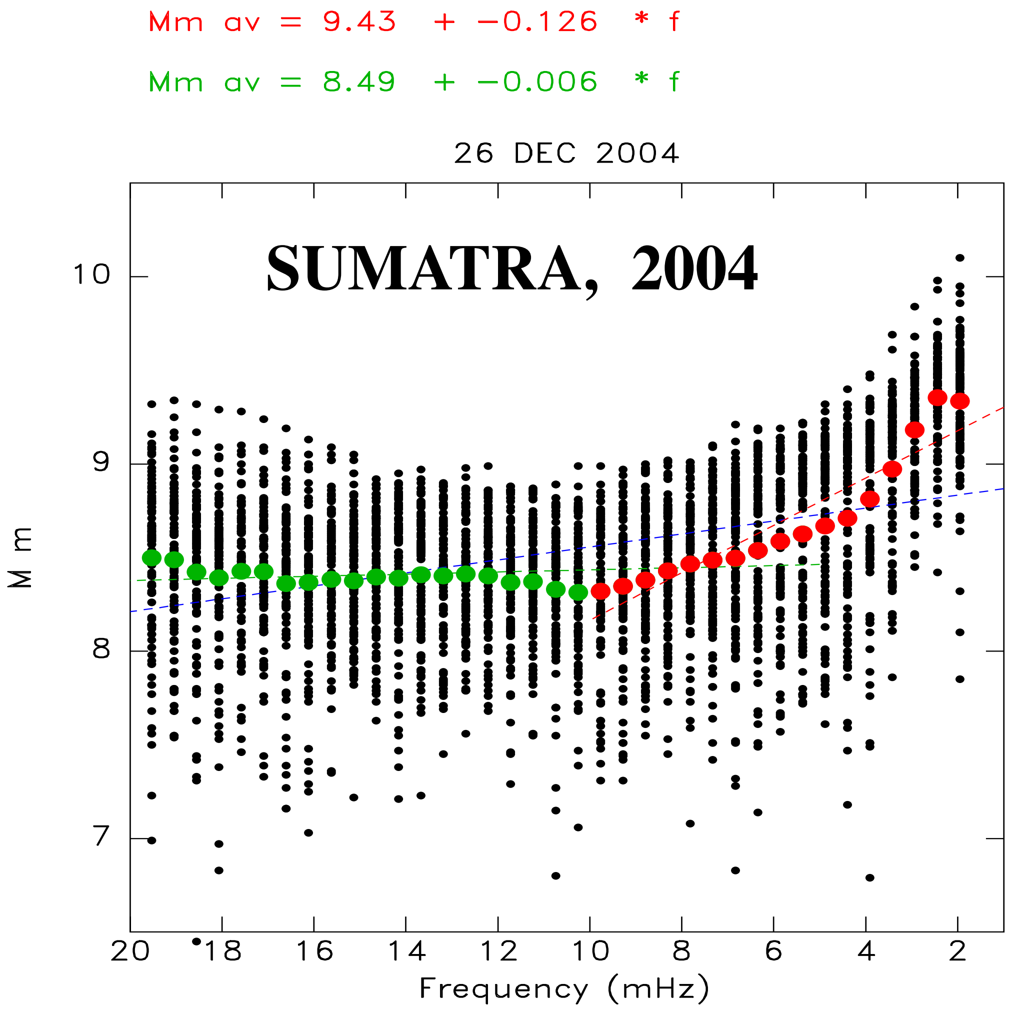


M_m: Recent Developments

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

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

$M_{m\ av} = 8.90 - 0.035 * f$



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.**

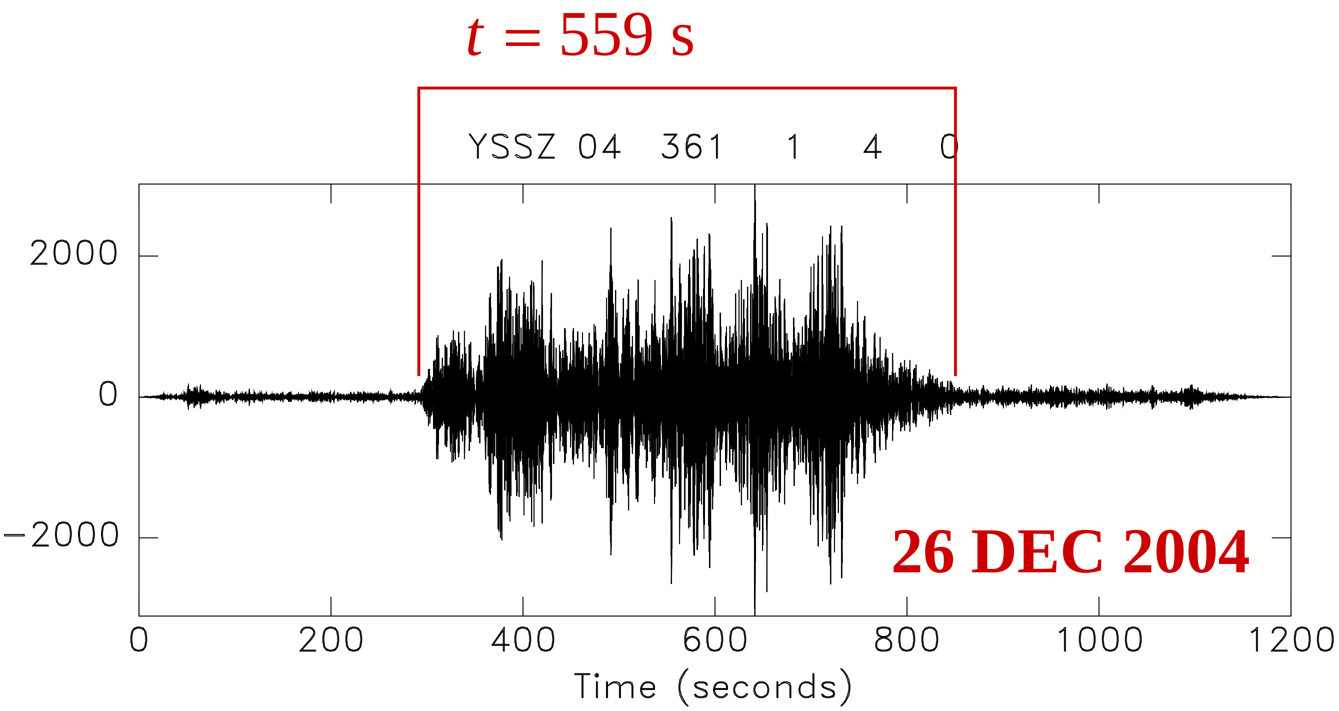
This admittedly empirical algorithm gives excellent results

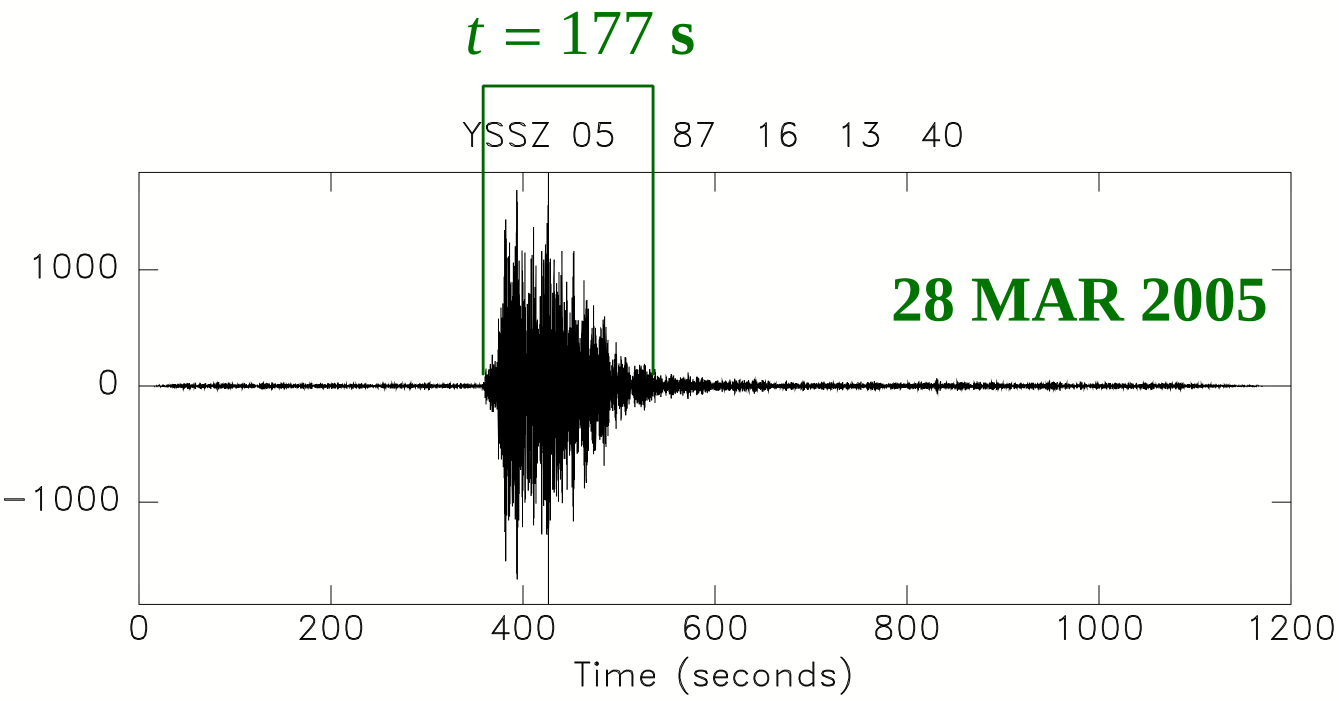
2005: DURATION OF *P* WAVES

A simple [trivial ?], robust measurement

[*Ni et al.*, 2005]

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

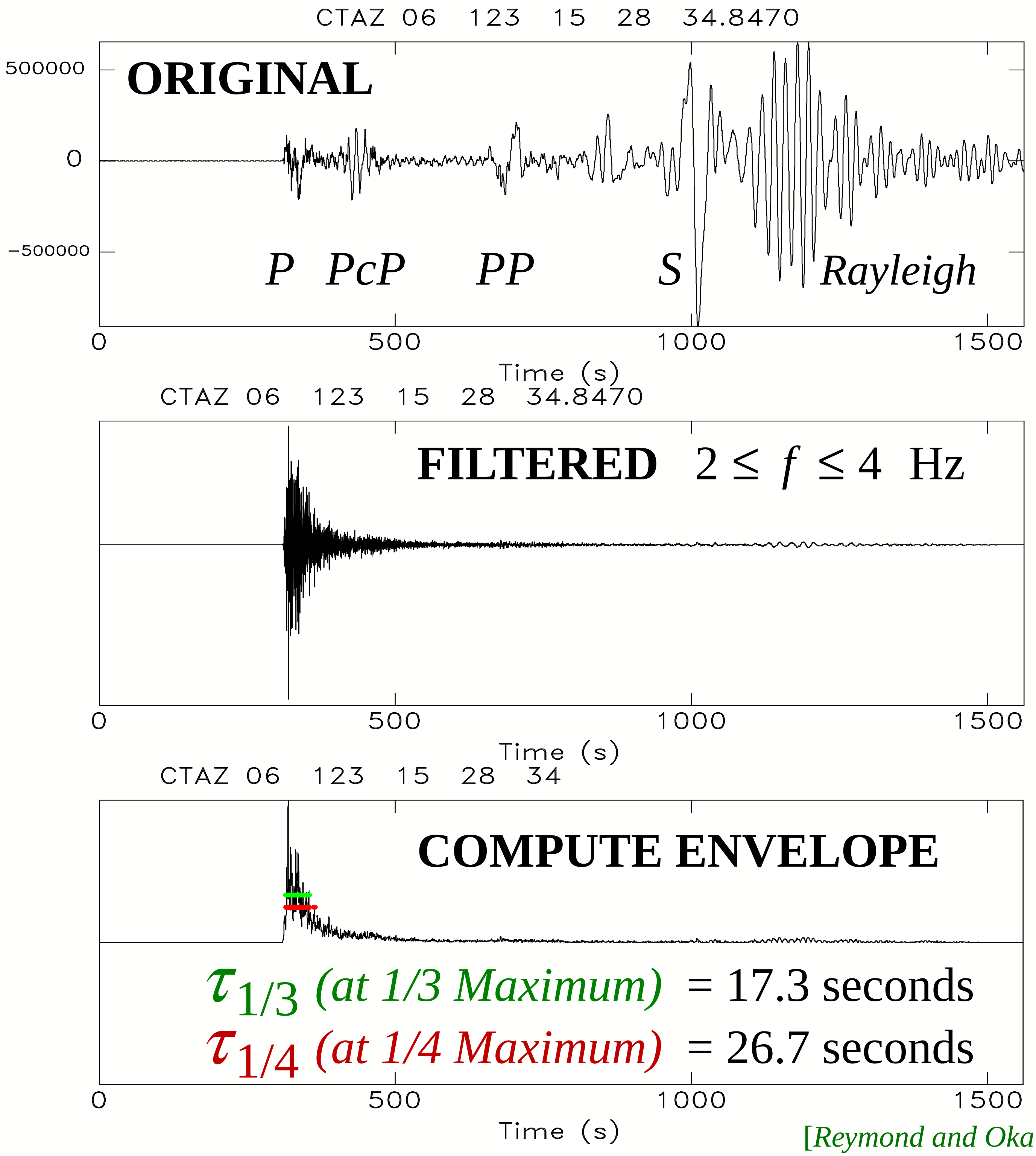




DEVELOP ALGORITHM TO MEASURE HIGH-FREQUENCY P−WAVE DURATION

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 ($\tau_{1/3}$)

54 earthquakes; more than 1000 records

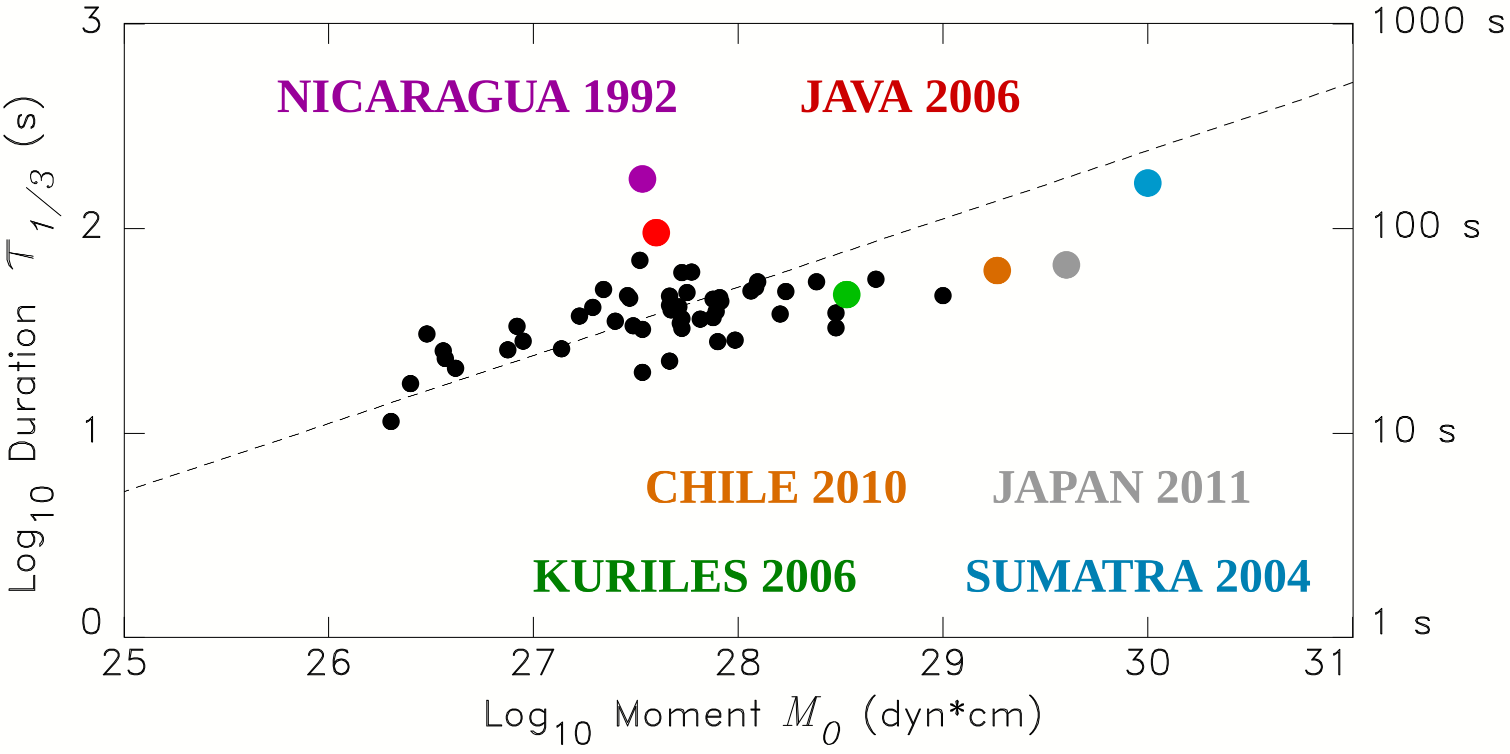
→ **2004 Sumatra event recognized as very long**

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

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

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

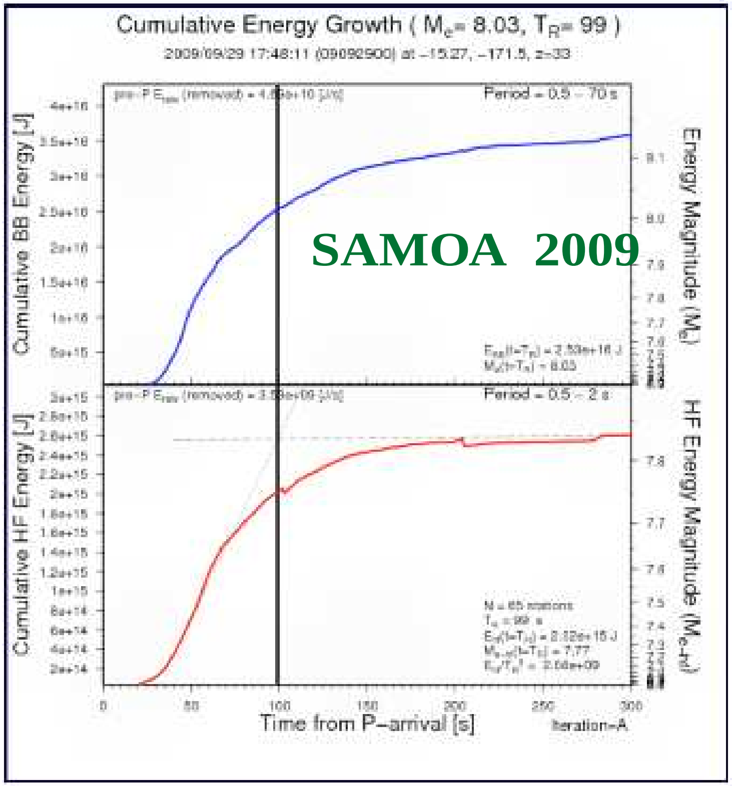
→ By contrast, the 2006 Kuriles earthquake is not found to exhibit slowness.
This confirms its character as weak and late, but not slow.



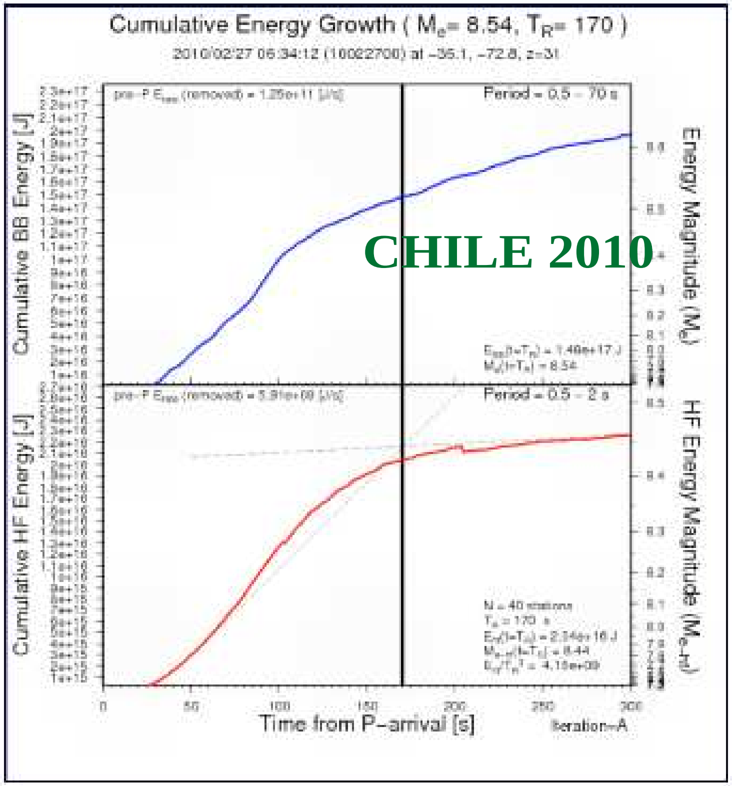
CUMULATIVE ENERGY GROWTH :

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.



SAMOA 2009



CHILE 2010

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]**

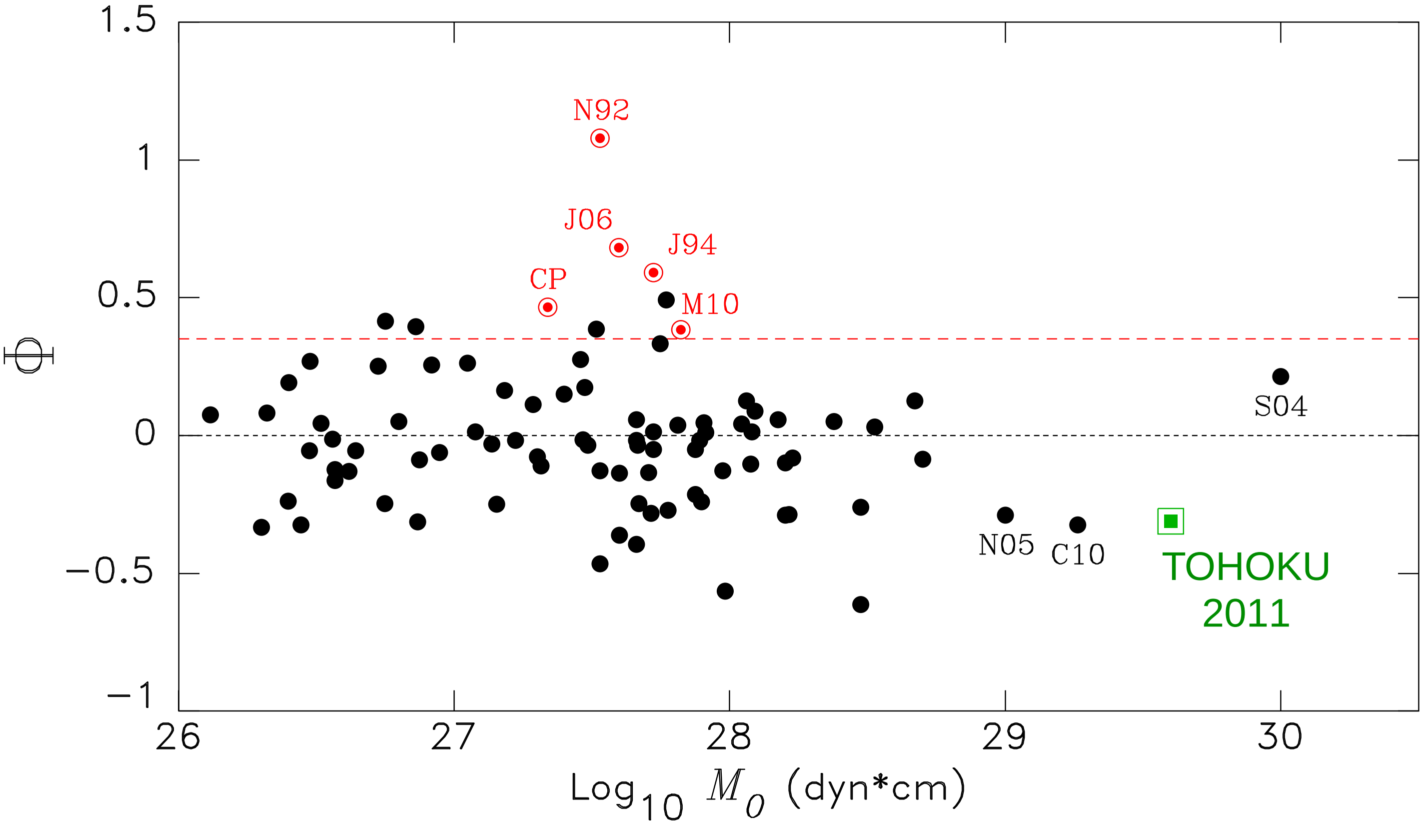
Duration vs. Energy: The Parameter Φ

We compare directly Duration and Energy, two quantities available immediately from P waves alone, through the parameter:

$$\Phi \;=\; \log\;\tau_{1/3} - \frac{1}{3}\,\log_{10} E^E + 5.86$$

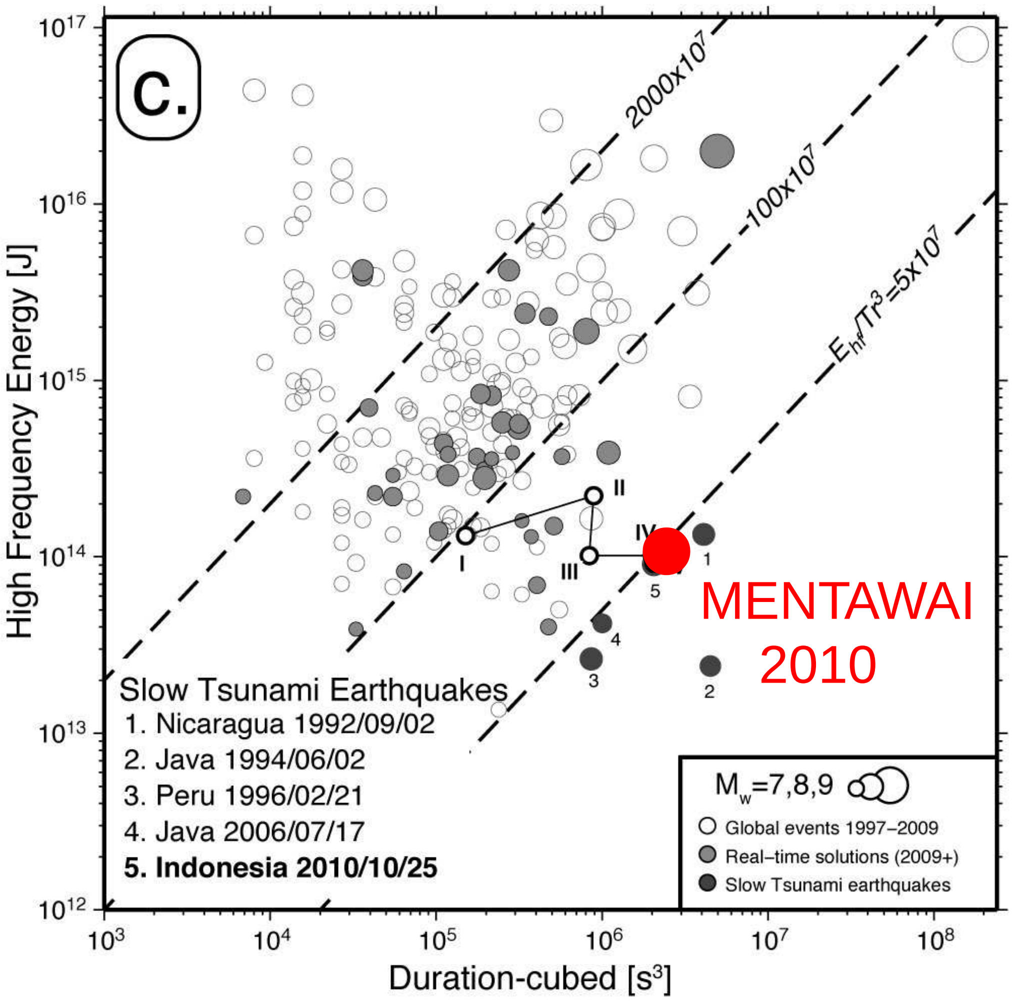
$\Phi > 0.35$ indicates anomalous slowness in the source.

→ The 2011 Tohoku earthquake has a regular $\mathbf{\Phi = -0.31}$, comparable to those of large subduction events (Chile, 2010; Nias, 2005).



ENERGY *vs.* DURATION

→ Note that *Newman et al.* [2011] haved developed a very similar method, comparing directly the logarithms of **Duration cubed** and **Estimated Energy**



and implemented this algorithm in real time.

- They were able to determine the slow character of the 2010 Mentawai event, **only 17 minutes after origin time**.

Hydroacoustic *T* phases *also lend themselves to the characterization of Tsunami Earthquakes.*

→ The latter feature very weak *T* phase amplitudes, but enhanced duration for similar propagation geometries.

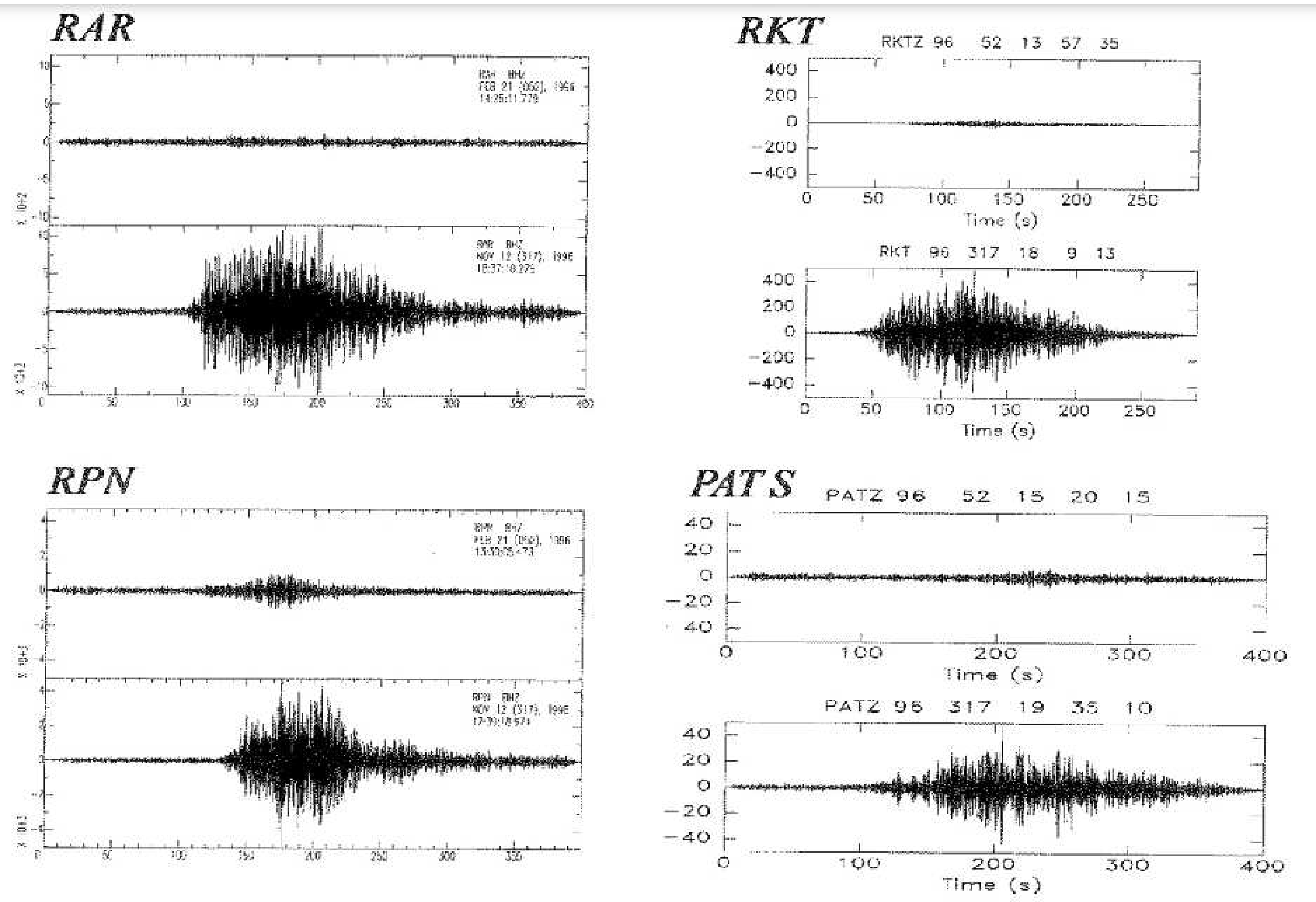


Figure 3. Comparison of T phases recorded at four teleseismic stations from the 1996 Chimbote and Nazca earthquakes. For each station, the two records are plotted on the same scale, after applying a high-pass filter ($f \geq 2$ Hz). The top trace is from the Chimbote tsunami earthquake (21 February), the bottom one from the regular Nazca event (12 November). Windows are 400 s long, except at Rikitea (290 s).

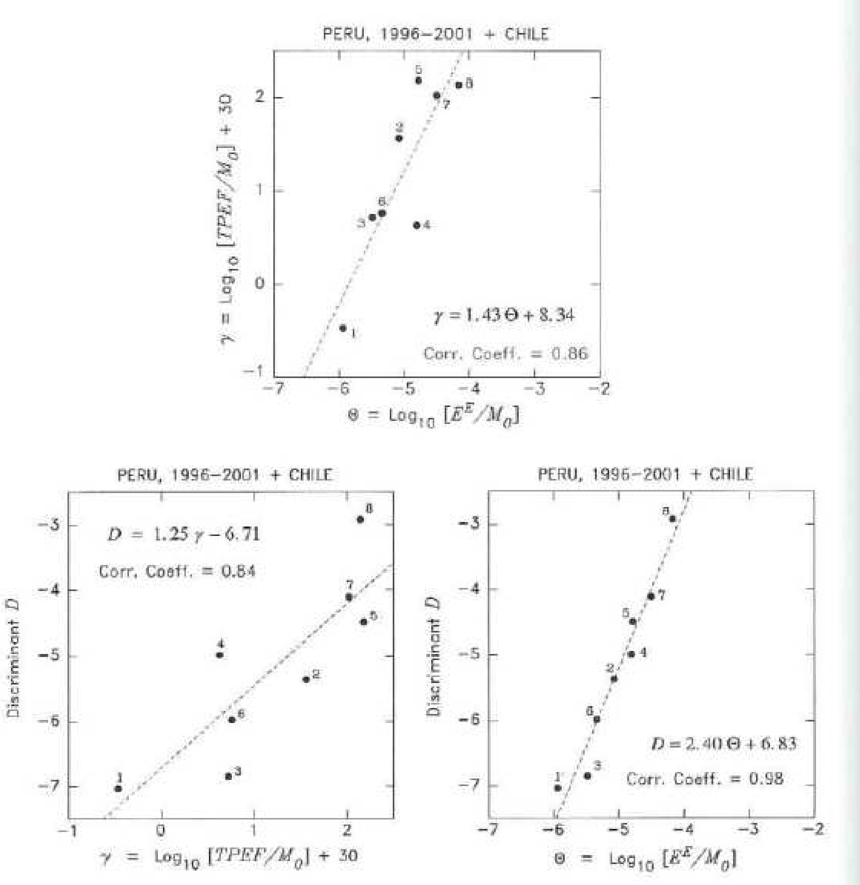
→ *COMPARE T* phases from two 1996 Peruvian events of similar moment at several Pacific stations:

* **Chimbote Tsunami Earthquake** (21 FEB 1996) -- *Top frames*

* Nazca Regular event (12 NOV 1996) --*Bottom frames*

[*Okal et al.*, 2003]

The energy of the *T* phase can be compted via a "*T*–Phase Energy Flux", similar in concept to the radiated energy introduced for body waves by *Choy and Boatwright* [1986].



Number	Date	Event	Remarks
1	1966:052	Chimbote, Peru	Tsunami Earthquake
2	1996:317	Nazca, Peru	
3	2001:174	Peru, Main shock	
4	2001:177	Peru, First Large Aftershock	
5	2001:186	Peru, Triggered Normal Faulting	Snappy
6	2001:188	Peru, Largest Aftershock	
7	1997:288	Ovalle, Chile	Snappy (Okal and Kirby, 2002)
8	1998:210	Chile (Outboard, Intraplate)	Snappy

→ **The ratio of TPEF to the seismic moment M_0** (parameter Γ) correlates remarkably well with the energy-to-moment parameter Θ and with the amplitude-duration parameter *D* introduced for *T* waves by *Talandier and Okal* [2001].

→ *As such, Γ can be used a discriminant to identify tsunami earthquakes.*

[*Okal*, 2007]

"TSUNAMI EARTHQUAKES: THE REGIONAL CHALLENGE"

More than 20 "tsunami earthquakes" have been documented since 1896.

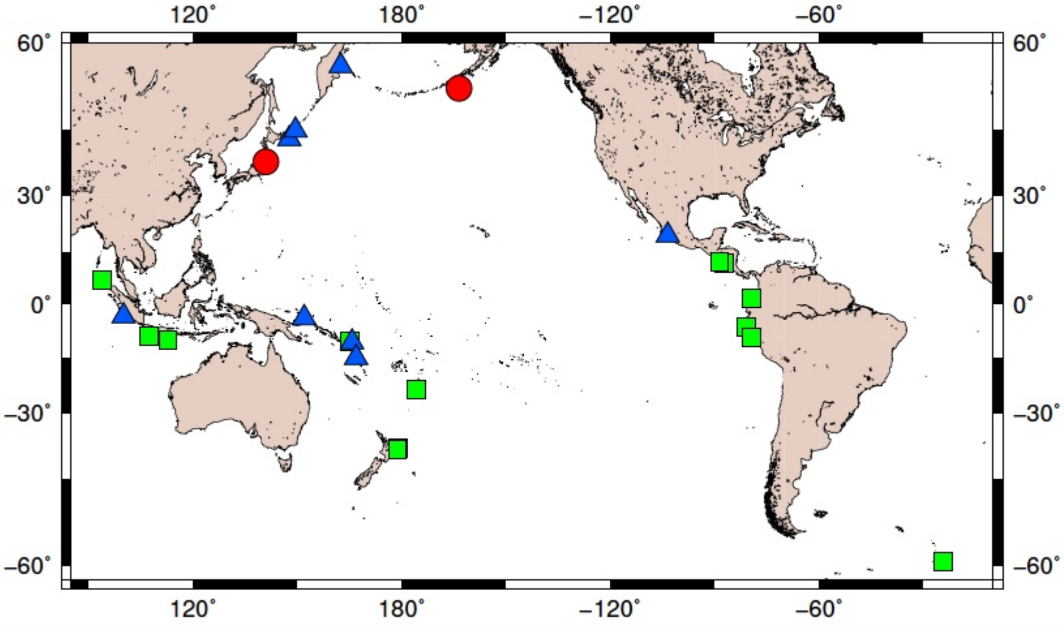
A significant challenge is

Whether they can occur at ANY subduction zone or are restricted to particular geological settings.

The documentation of more such events with time suggests the former,

either as primary events,

or as aftershocks of larger, regular earthquakes



Documented Tsunami Earthquakes, as of 2022

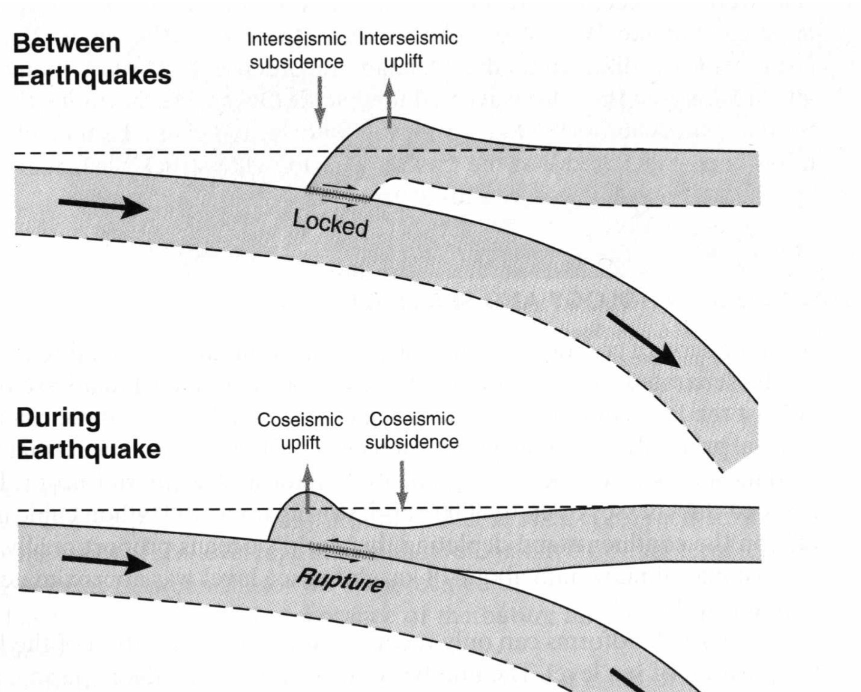
Year	Region	Θ
	Charter Events [*Kanamori*, 1972]	
1896	Sanriku	
1946	Aleutian	-7.0
	Primary Events	
1947	Hikuranga I	-5.94
1947	Hikuranga II	-6.51
1960	Northern Peru	-6.13
1979	Colombia	-6.22
1982	Tonga	-5.76
1992	Nicaragua	-6.47
1994	Java	-6.57
1996	Chimbote, Peru	-6.06
2004	Sumatra	-6.40
2006	Java	-6.01
2012	El Salvador	-6.42
2013	Santa Cruz	-6.30
2021	South Sandwich	-6.39
	Aftershocks	
1923	Kamchatka	
1932	Mazatlan, Mexico	-6.18
1934	Santa Cruz	-6.10
1963	Kuriles	-6.42
1965	Vanuatu	-5.88
1975	Kuriles	-6.43
2000	New Britain	-6.11
2010	Mentawai, Sumatra	-6.22

SUBDUCTION ZONE EARTHQUAKES

Principal Challenges

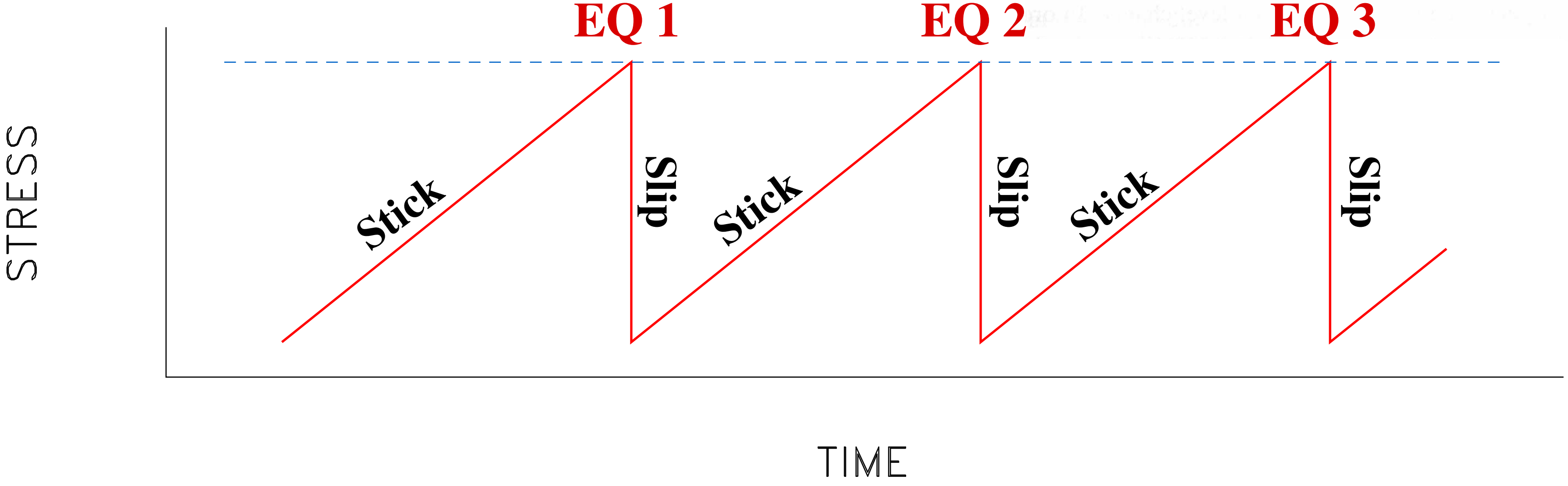
- **Some S.Z. deficient in Mega-Thrust Events ?**
- **The Infamous "Tsunami Earthquakes"**
- **Irregular Fragmentation of Rupture**
- **Other Events**

THE SEISMIC CYCLE CONCEPT



Along a plate boundary, tectonic forces are continuously **loading** the fault at a constant stress rate.

When the stress reaches the *STRENGTH of the MATERIAL,* the rock fails (*the earthquake occurs*), and the cycle is restarted.



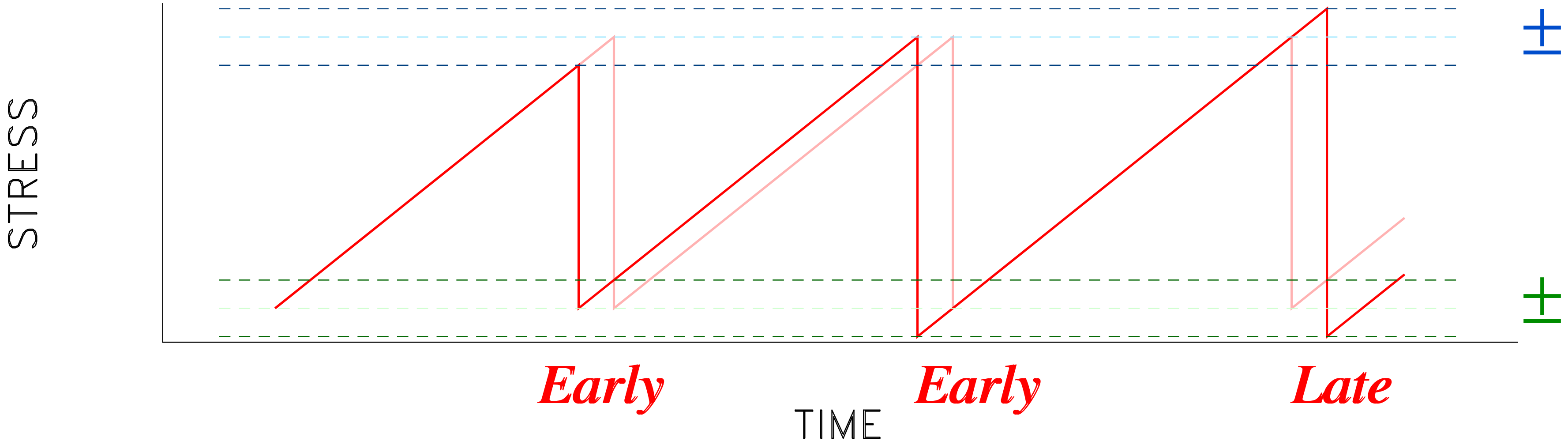
This very simple model suggests a process of *Stick-and-Slip* which predicts a

PERIODICITY of the EARTHQUAKE CYCLE

DIFFICULTIES with EARTHQUAKE CYCLE CONCEPT

- The typical Earthquake Cycle *MAY BE* on the order to 1 to 10 *CENTURIES* and Seismology is a very young Science (!)

→ Fluctuations about these "periods" are so large (typ. 100 years) **as to render prediction impossible** on a time scale relevant to Society.



- There is great diversity in the regime of coupling and stress release at various plate boundaries.

  Not all of them are efficiently locked. Some are creeping.

FAULT FRAGMENTATION is IRREGULAR: ANDO [1975]

Large earthquakes in Nankai province (SW Japan) may rupture through

one or **more** of **up to 4**

segments of the plate boundary.

Apparently, the pattern is random and cannot be predicted.

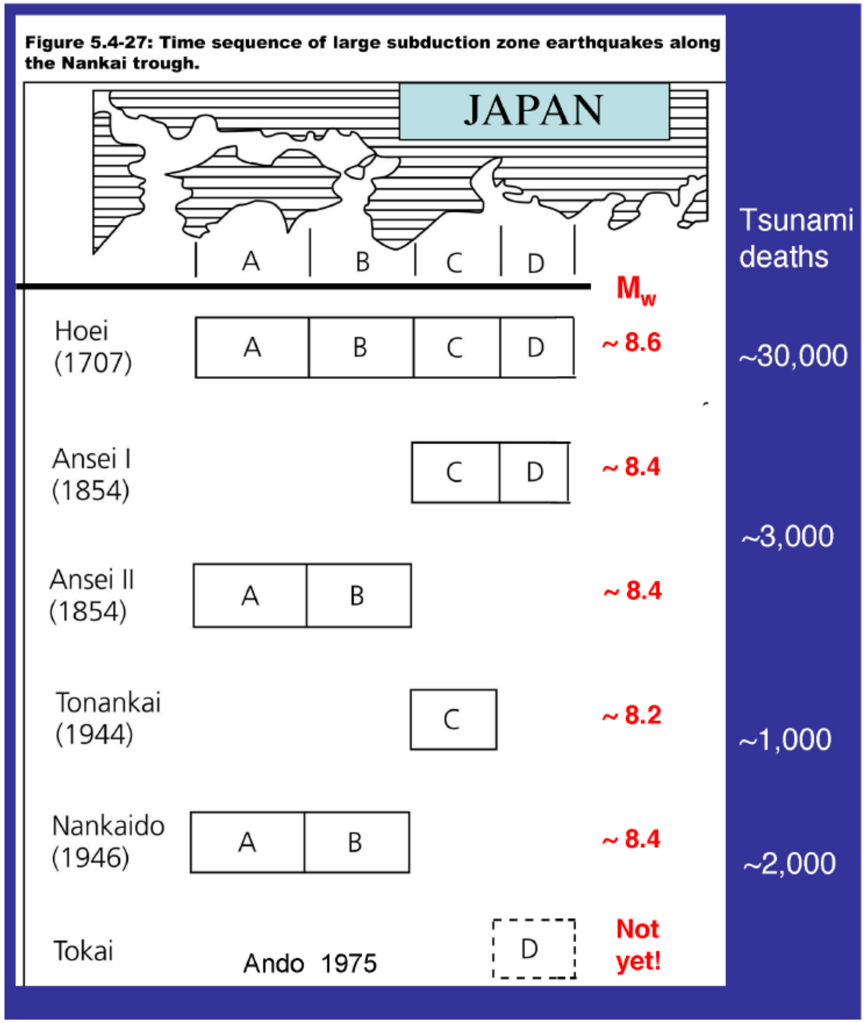


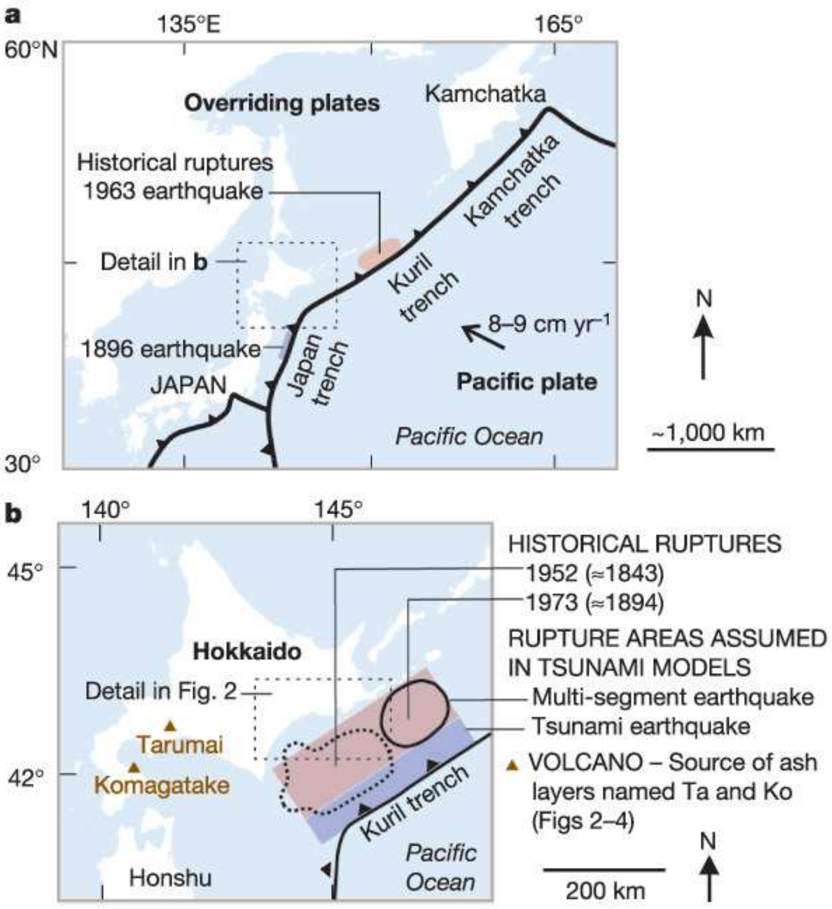
Figure 5.4-27: Time sequence of large subduction zone earthquakes along the Nankai trough.

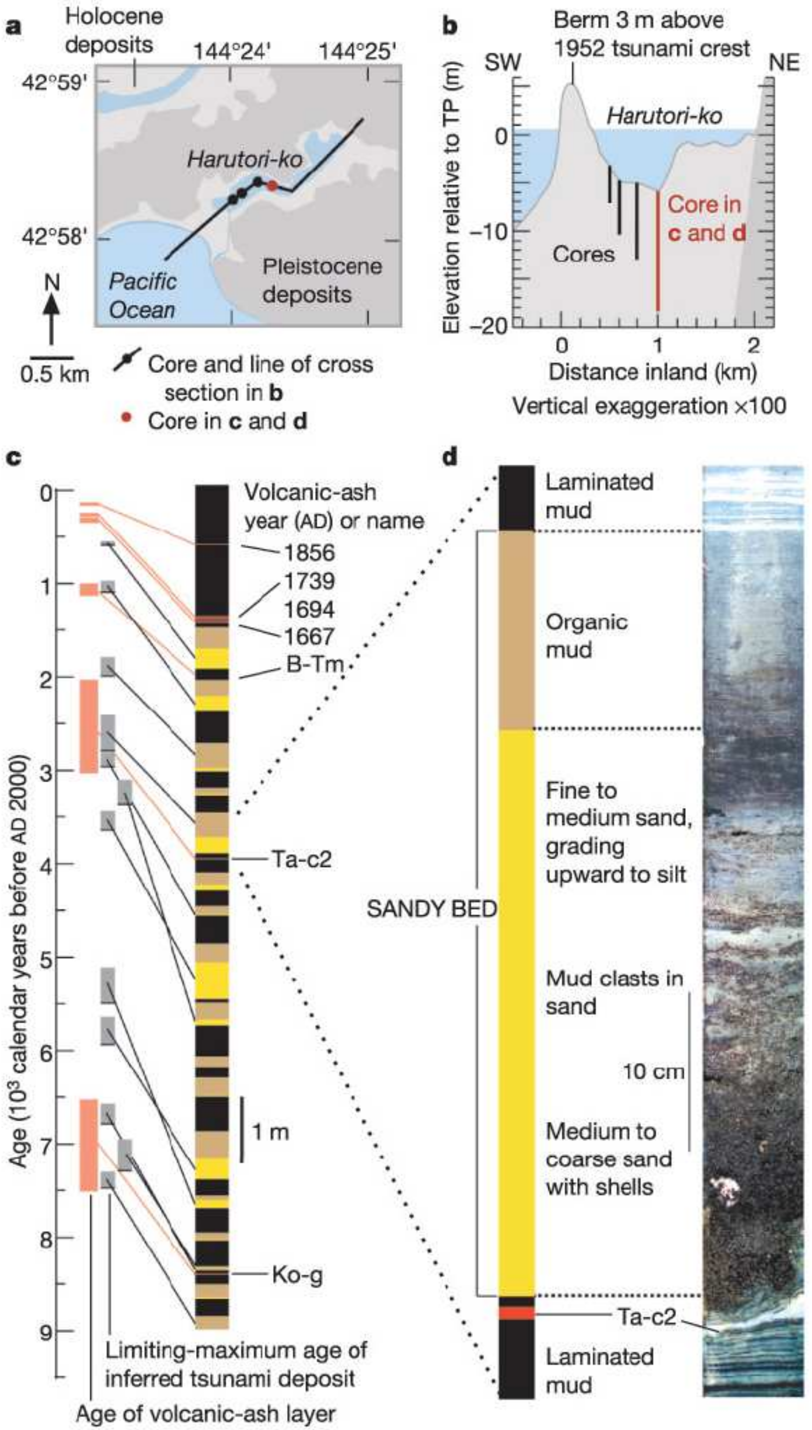
DIVERSITY of SIZE and RUPTURE

Evidence from other subduction zones

NORTH JAPAN KURILES

Deposits from Paleo-Tsunamis
suggest $M \approx 9$ events





[*Nanayama et al.*, 2003]

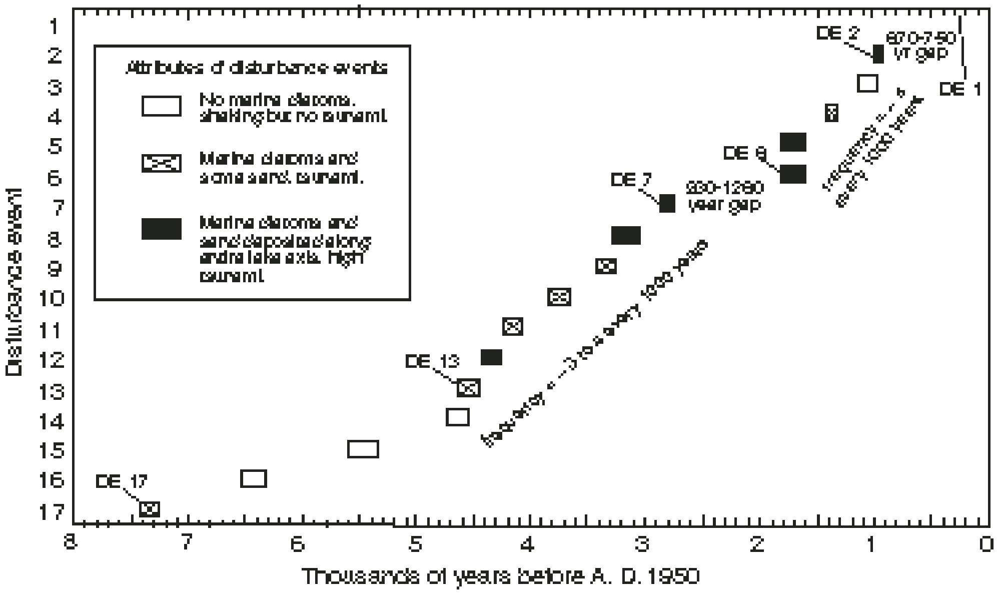
DIVERSITY of SIZE and RUPTURE

Evidence from other subduction zones

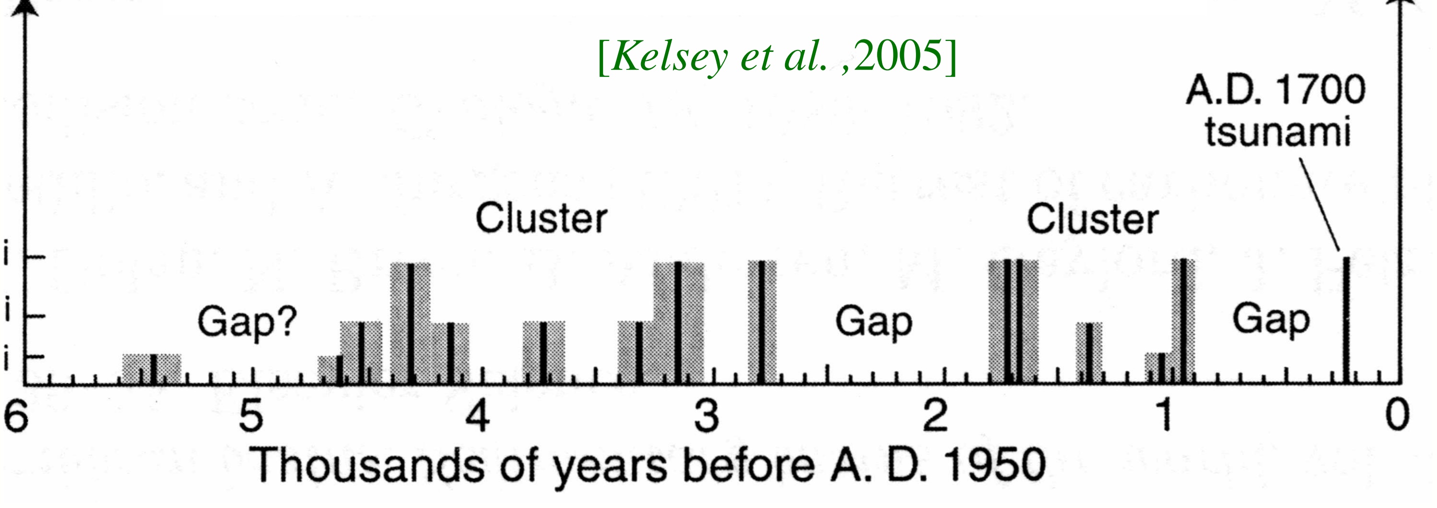
CASCADIA, NW USA

→ Sedimentary work on lake beds helps distinguish between

- Events with shaking but no tsunami
- Events with and shaking and [small] tsunami
- Events with shaking and **large** tsunami (*e.g.*, 1700)



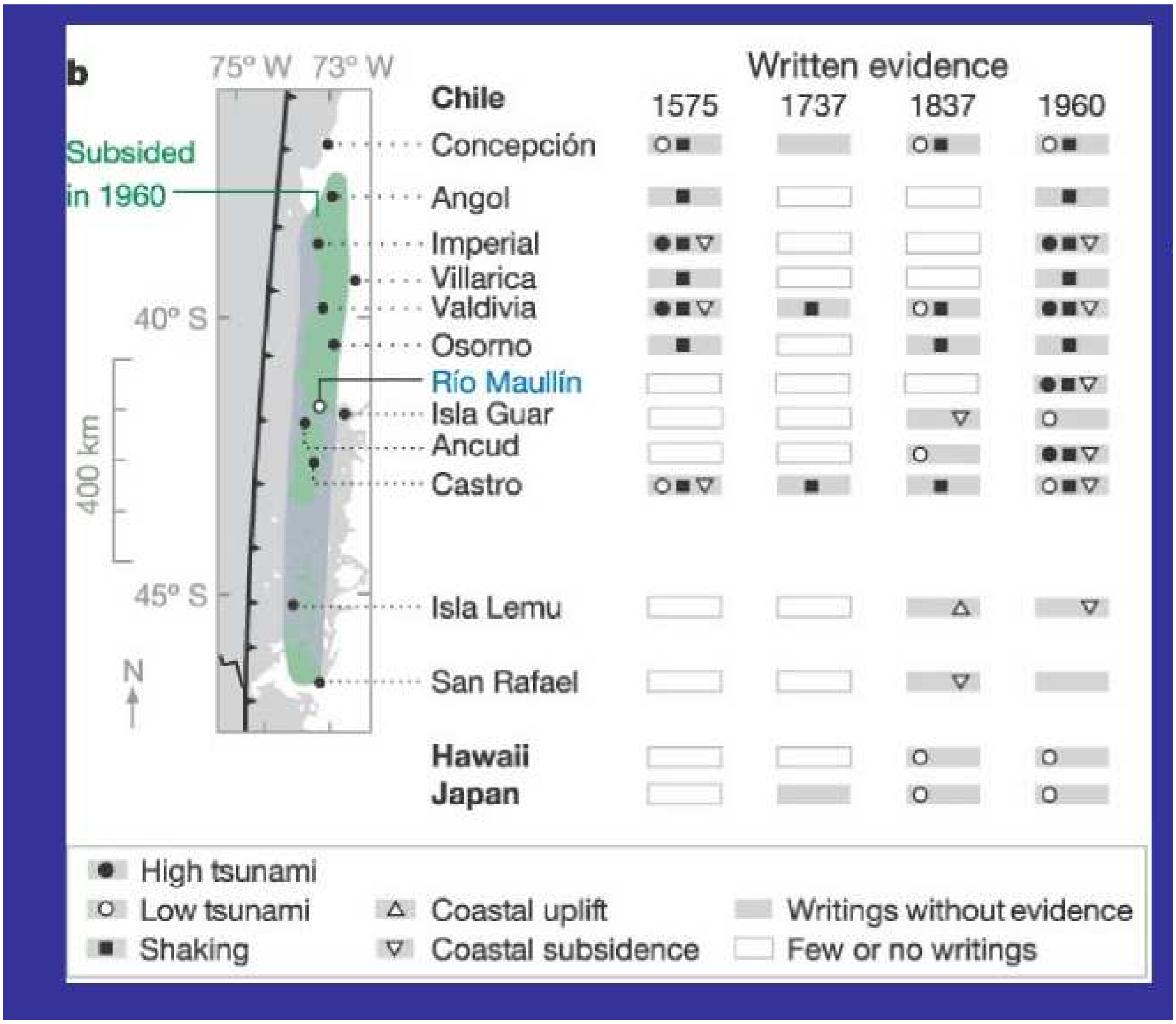
[*Kelsey et al.* ,2005]



THE CASE OF SOUTHERN CHILE

- Similar properties are found in Southern Chile, as evidenced by paleo-seismic work.

[*Cisternas et al.*, 2005]

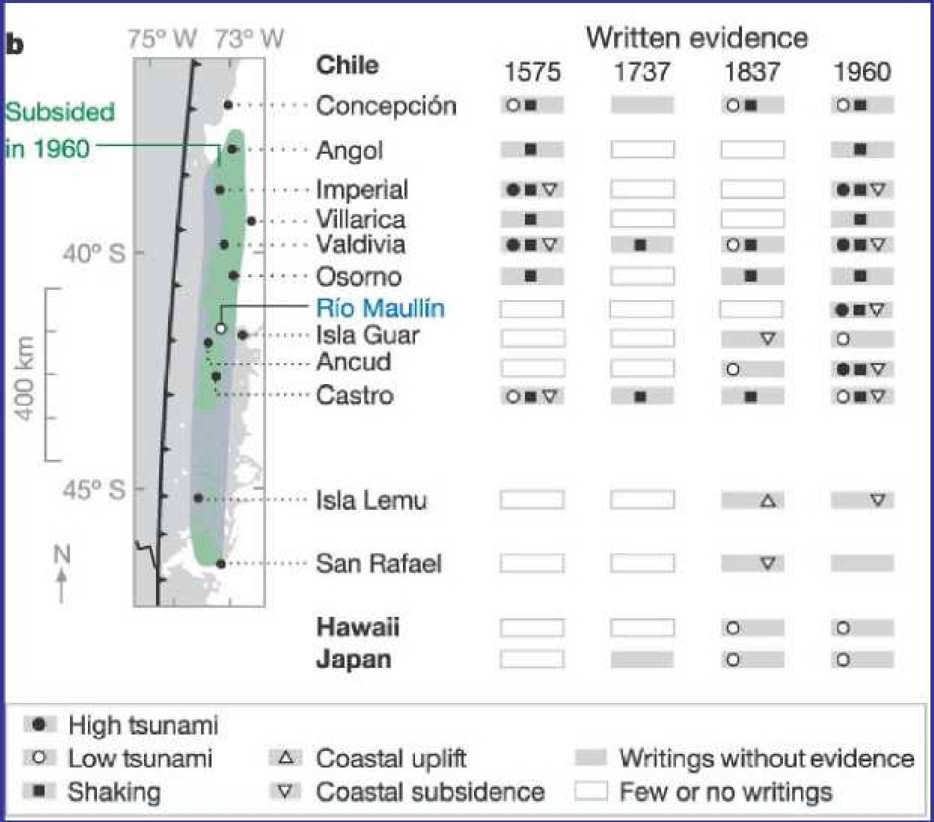


	Written evidence			
Chile	1575	1737	1837	1960
Concepción	○■	▨	○■	○■
Angol	■	□	□	■
Imperial	●■▽	□	□	●■▽
Villarica	■	□	□	■
Valdivia	●■▽	■	○■	●■▽
Osorno	■	□	■	■
Río Maullín	□	□	□	●■▽
Isla Guar	□	□	▽	○
Ancud	□	□	○	●■▽
Castro	○■▽	■	■	○■▽
Isla Lemu	□	□	△	▽
San Rafael	□	□	▽	▨
Hawaii	□	□	○	○
Japan	□	▨	○	○

● High tsunami
○ Low tsunami
■ Shaking
△ Coastal uplift
▽ Coastal subsidence
▨ Writings without evidence
□ Few or no writings

Remember Kanamori's [1977] *nearly inconsistent slip rate? for South Chile ?*

Seismic slip rate, estimated from slip in great 1960 earthquake and historical records indicating major earthquakes ~ every 130 years in past 400 years, exceeds the plate convergence rate



Written evidence

Chile	1575	1737	1837	1960
Concepción	○■	▒	○■	○■
Angol	■	☐	☐	■
Imperial	●■▽	☐	☐	●■▽
Villarica	■	☐	☐	■
Valdivia	●■▽	■	○■	●■▽
Osorno	■	☐	■	■
Río Maullín	☐	☐	☐	●■▽
Isla Guar	☐	☐	▽	○
Ancud	☐	☐	○	●■▽
Castro	○■▽	■	■	○■▽
Isla Lemu	☐	☐	△	▽
San Rafael	☐	☐	▽	▒
Hawaii	☐	☐	○	○
Japan	☐	▒	○	○

● High tsunami
○ Low tsunami
■ Shaking
△ Coastal uplift
▽ Coastal subsidence
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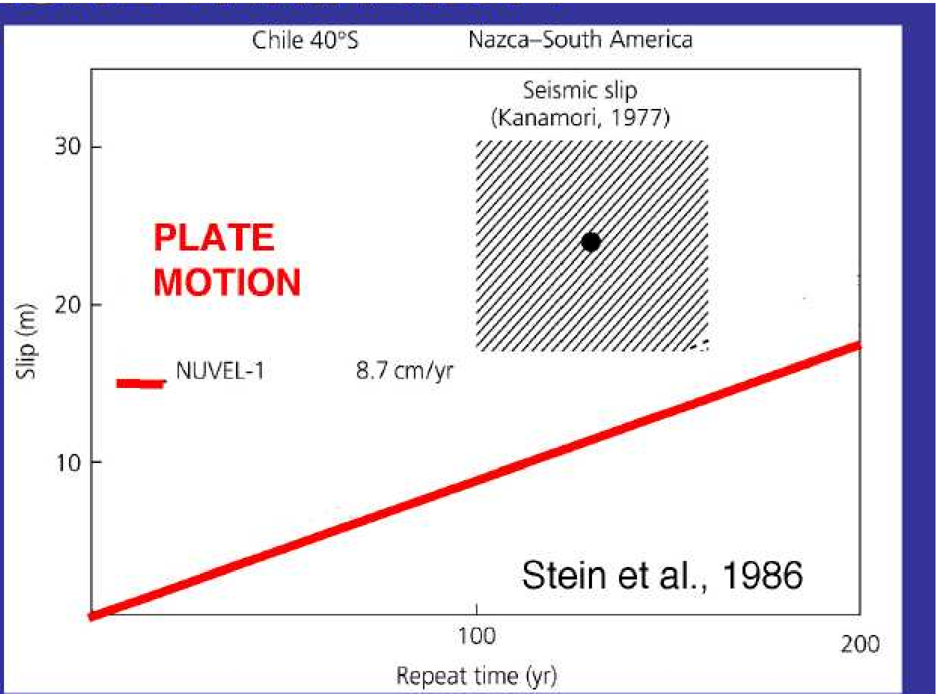


Stein et al., 1986

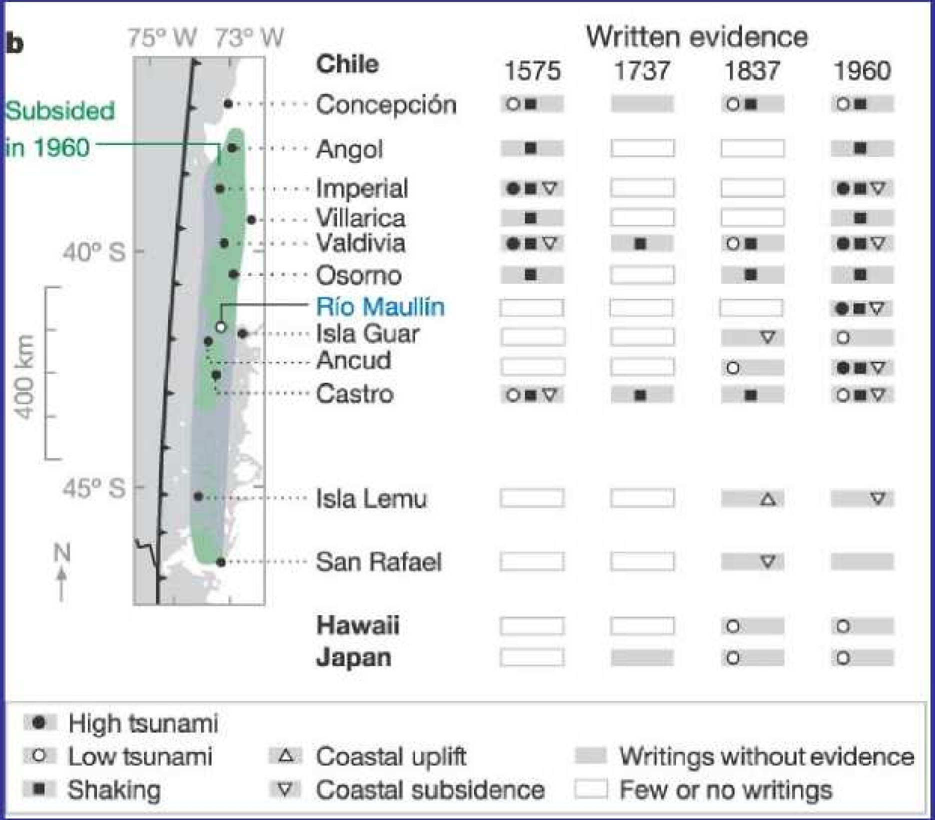
[Some] Earlier Earthquakes
were significantly
smaller than the 1960 event

EARTHQUAKE REPEAT
is CAPRICIOUS

Cisternas et al., 2005

Remember Kanamori's [1977] *nearly inconsistent slip rate? for South Chile ?*

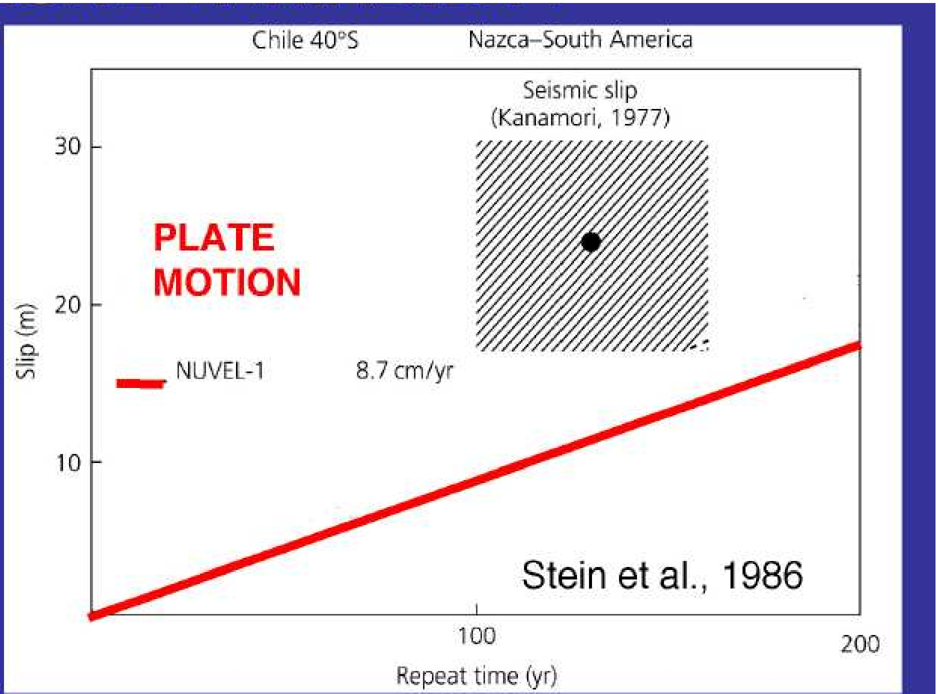
Seismic slip rate, estimated from slip in great 1960 earthquake and historical records indicating major earthquakes ~ every 130 years in past 400 years, exceeds the plate convergence rate



Chile	1575	1737	1837	1960
Concepción	○■	▨	○■	○■
Angol	■	☐	☐	■
Imperial	●■▽	☐	☐	●■▽
Villarica	■	☐	☐	■
Valdivia	●■▽	■	○■	●■▽
Osorno	■	☐	■	■
Río Maullín	☐	☐	☐	●■▽
Isla Guar	☐	☐	▽	○
Ancud	☐	☐	○	●■▽
Castro	○■▽	■	■	○■▽
Isla Lemu	☐	☐	△	▽
San Rafael	☐	☐	▽	▨
Hawaii	☐	☐	○	○
Japan	☐	▨	○	○

Written evidence

● High tsunami
○ Low tsunami
■ Shaking
△ Coastal uplift
▽ Coastal subsidence
▨ Writings without evidence
☐ Few or no writings



Stein et al., 1986

ANDO'S CONCEPT & CISTERNAS' DATA

SAVE the DAY !!

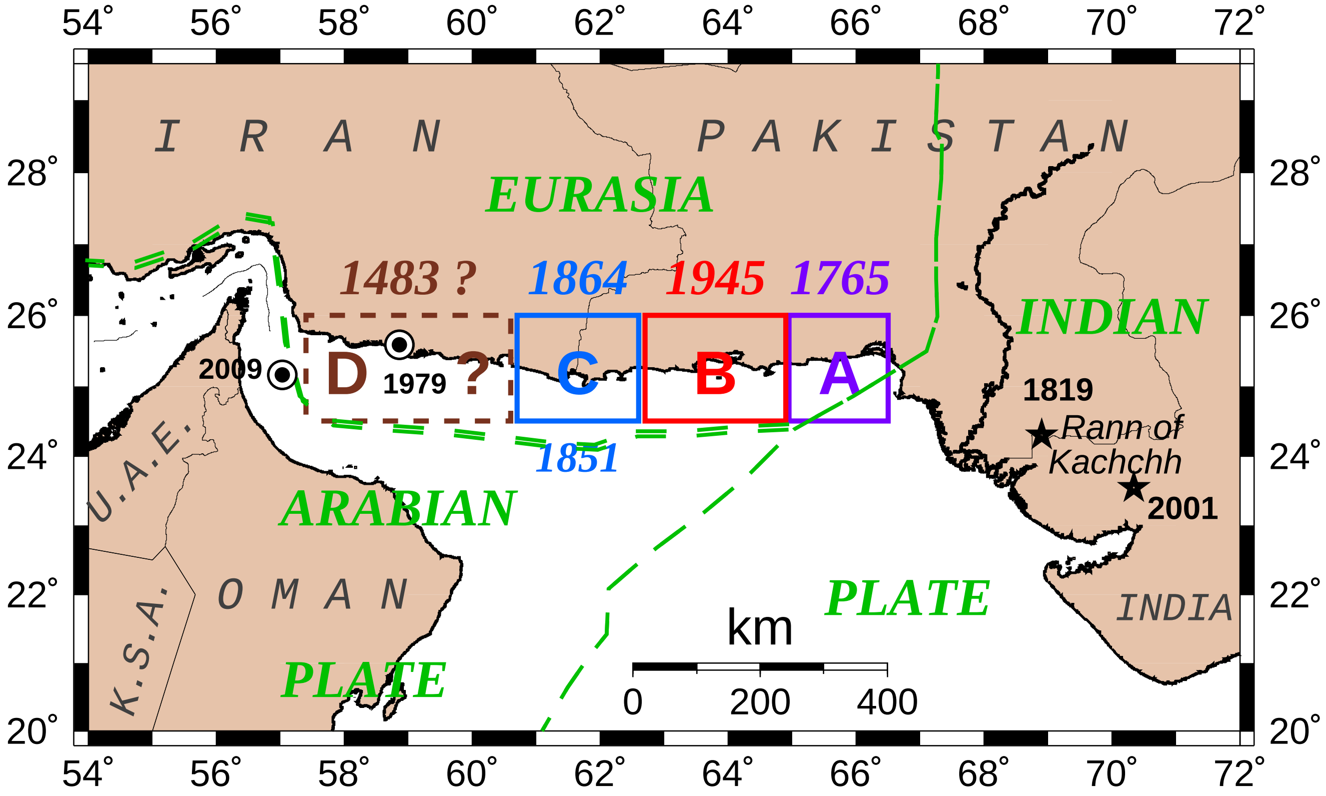
EARTHQUAKE REPEAT is CAPRICIOUS

Cisternas et al., 2005

FAULT FRAGMENTATION

The case of the Makran

- **1945 ("B") : Well documented major earthquake with devastating tsunami**



- **1765 ("A") and 1864 ("C") : Probable major events**

  [*Ambraseys and Melville*, 1982]

- **1483 ("D") ? Controversial, unconfirmed, event**

→ *QUESTION: Is the convergence in the Western Makran taken up seismicially, and if so, could the entire region rupture in a single, catastrophic earthquake* **(A–B–C–D)***?* [*Okal and Synolakis*, 2008]

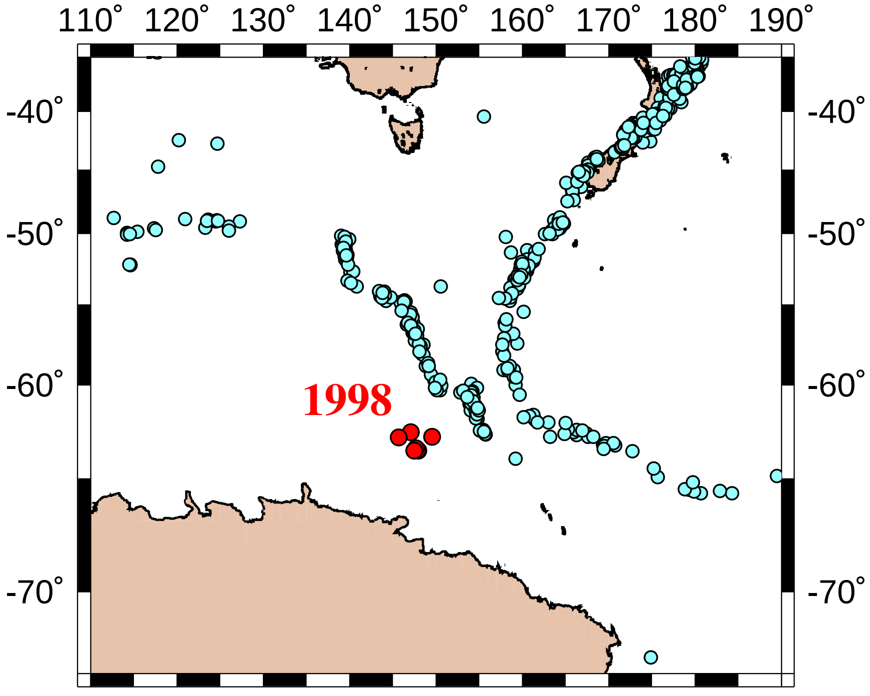
SUBDUCTION ZONE EARTHQUAKES

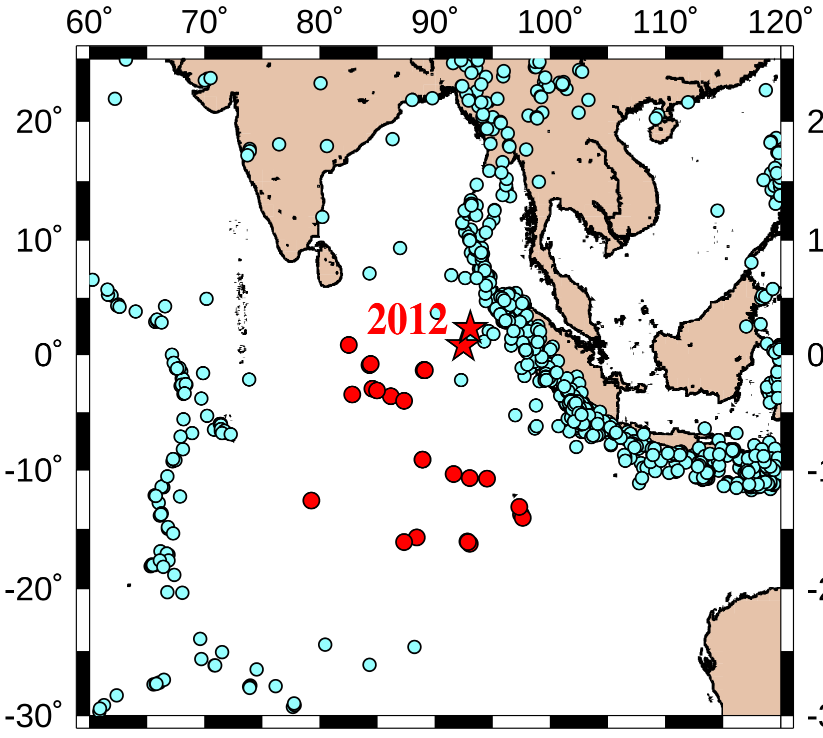
Principal Challenges

- **Some S.Z. deficient in Mega-Thrust Events ?**
- **The Infamous "Tsunami Earthquakes"**
- **Irregular Fragmentation of Rupture**
- **Other Events**

THE CASE of INTRAPLATE EARTHQUAKES

- Most very large earthquakes capable of generating tsunamis occur at plate boundaries.
- However, intraplate activity, or activity related to diffuse plate boundaries can lead to major earthquakes (with magnitudes greater than 8).
- Examples include the 1998 Balleny Island event near the Australian-Antarctic-Pacific triple junction, and historical events near the Indian-Australian diffuse boundary in the Indian Ocean.

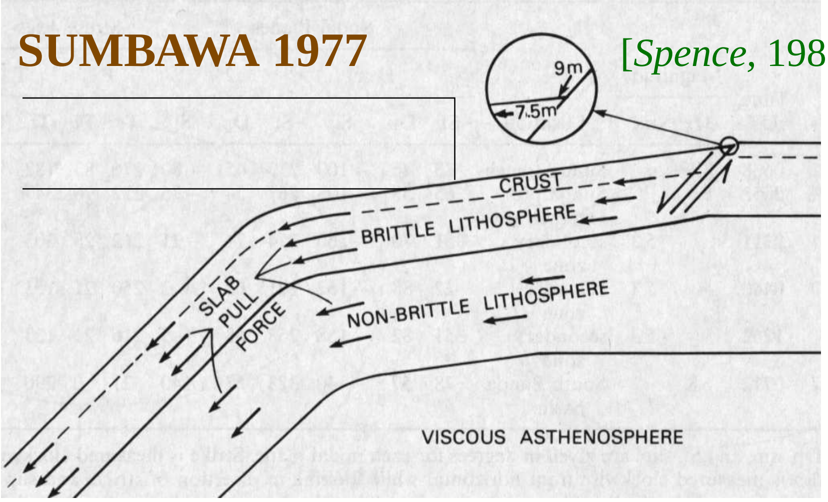




OTHER INTRAPLATE EARTHQUAKES

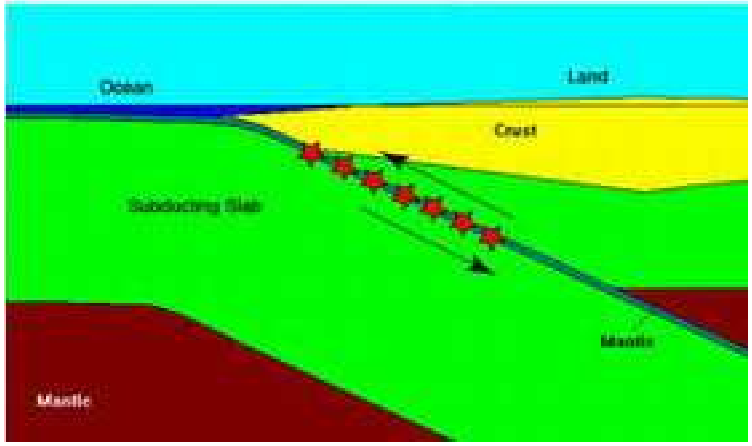
Large earthquakes (reaching magnitude 8) can also occur *in the vicinity of plate boundaries*, but without expressing relative motion of the two plates.

Some events can take place *outwards of the trench*, as a result of the buckling of the plate during the interseismic cycle (*e.g.*, 1933 Sanriku, Japan; 1977 Subawa, Indonesia).


SUMBAWA 1977

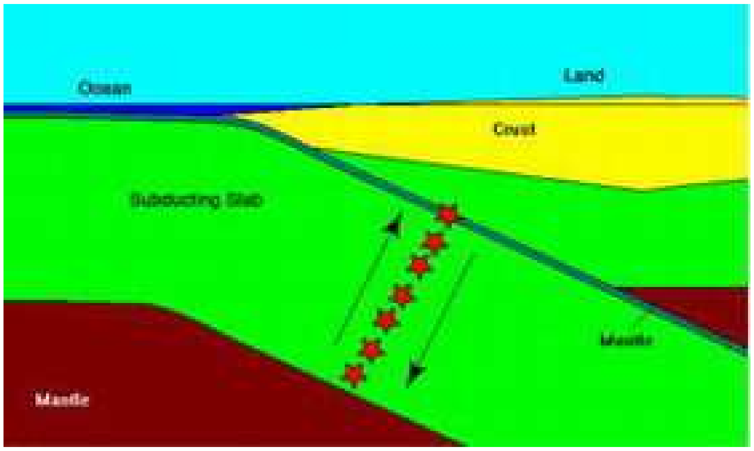
[*Spence*, 1986]

Some events can represent a break in the downgoing slab, under the forces controling its subduction (*e.g.*, Tonga, 1977 and 2006).



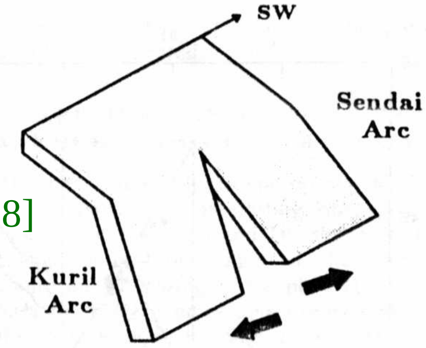
Regular (Inter-Plate) Earthquake

[*D.A. Wiens*, 2006]



Intraplate Earthquake (Tonga 2006)

Some events can represent a tear between two sections of the slab descending at different geometries (*e.g.*, the 1994 Kuriles earthquake).



[*Lundgren et al.*, 1988]

All above examples generated significant tsunamis.

OUTER RISE NORMAL FAULTING EVENTS CAN BE LETHAL !

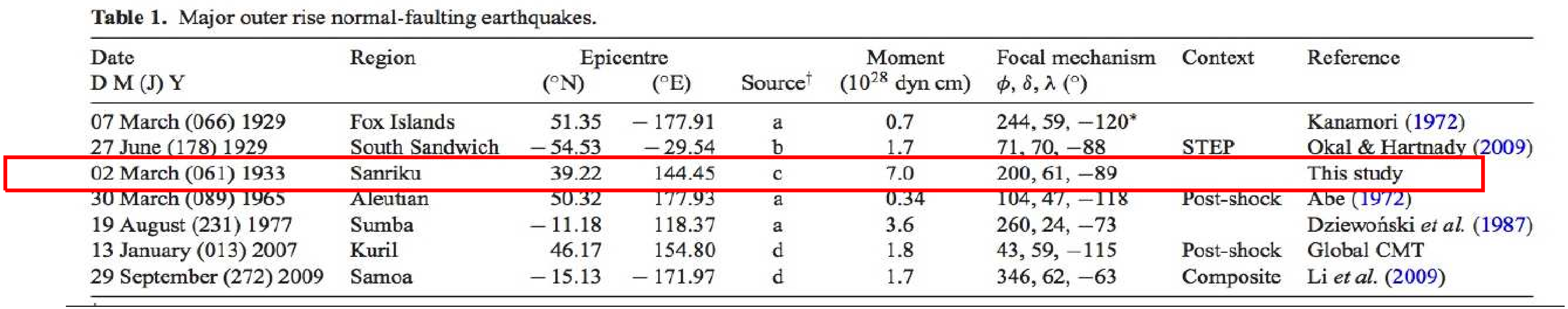
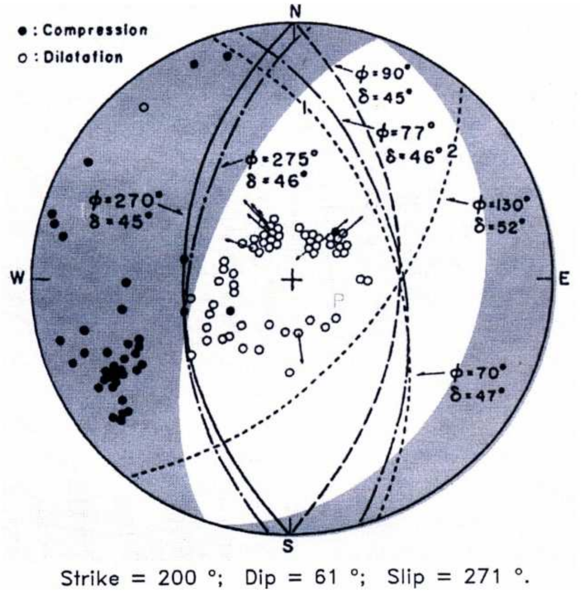


Table 1. Major outer rise normal-faulting earthquakes.

Date D M (J) Y	Region	Epicentre (°N)	 (°E)	Source†	Moment (10^{28} dyn cm)	Focal mechanism ϕ, δ, λ (°)	Context	Reference
07 March (066) 1929	Fox Islands	51.35	−177.91	a	0.7	244, 59, −120*		Kanamori (1972)
27 June (178) 1929	South Sandwich	−54.53	−29.54	b	1.7	71, 70, −88	STEP	Okal & Hartnady (2009)
02 March (061) 1933	Sanriku	39.22	144.45	c	7.0	200, 61, −89		This study
30 March (089) 1965	Aleutian	50.32	177.93	a	0.34	104, 47, −118	Post-shock	Abe (1972)
19 August (231) 1977	Sumba	−11.18	118.37	a	3.6	260, 24, −73		Dziewoński *et al.* (1987)
13 January (013) 2007	Kuril	46.17	154.80	d	1.8	43, 59, −115	Post-shock	Global CMT
29 September (272) 2009	Samoa	−15.13	−171.97	d	1.7	346, 62, −63	Composite	Li *et al.* (2009)

Example: **SHOWA SANRIKU, 02 MAR 1933**

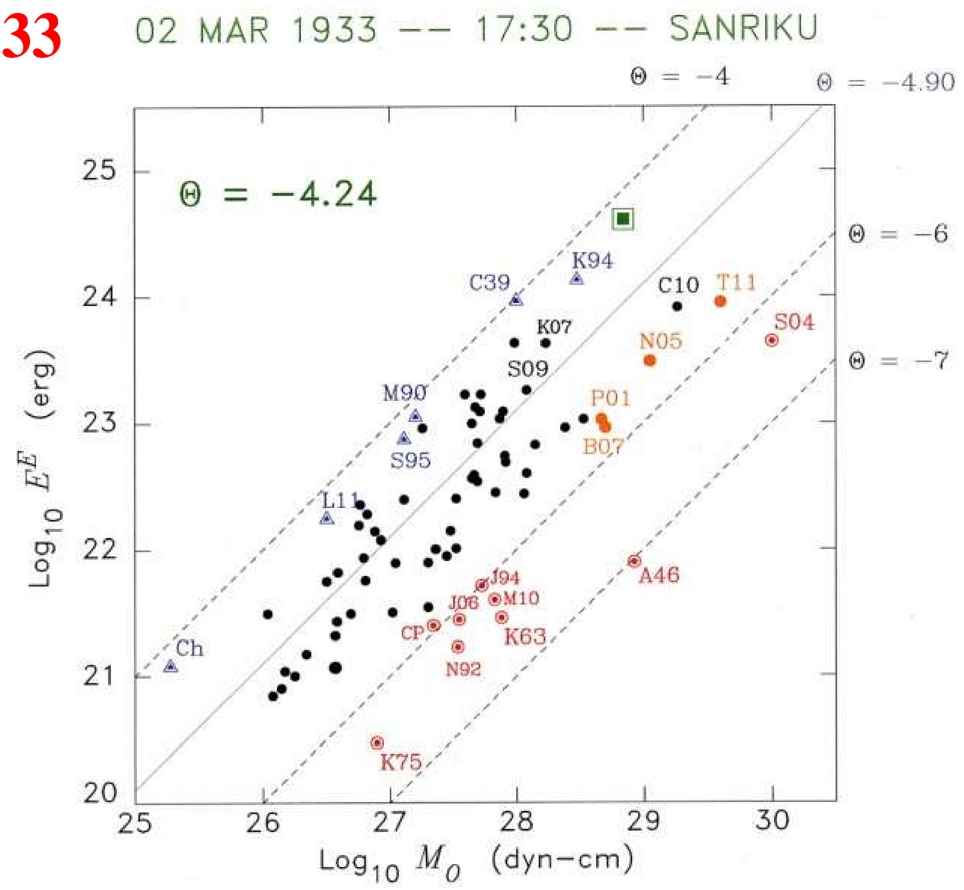
Despite **"Snappy"** character,



3000 killed in Japan

Significant damage in Hawaii

[*Okal et al.*, 2016]

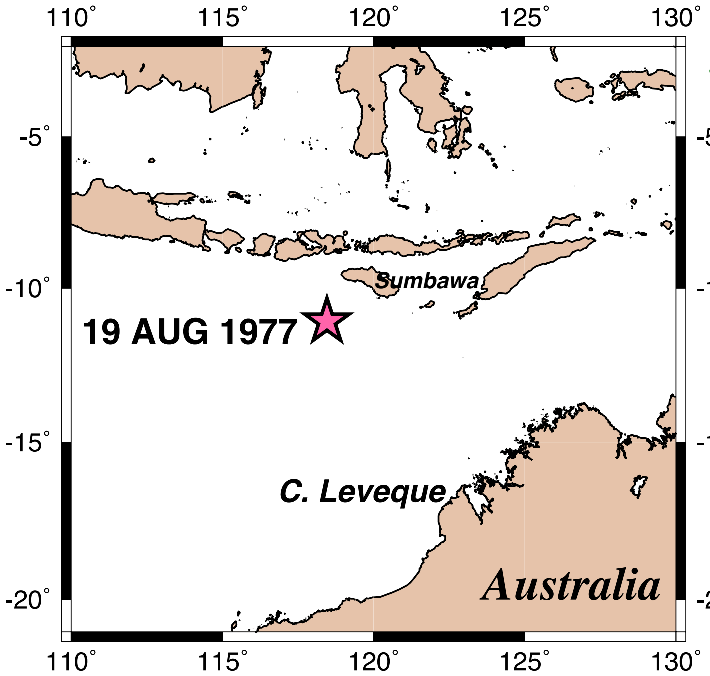


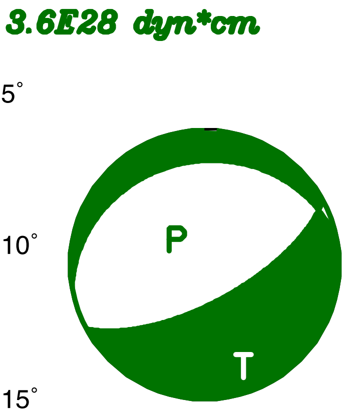
SUMBAWA, Indonesia — 19 AUGUST 1977

- This was a normal faulting earthquake occurring seaward (South) of the trench in the buckling Australian plate.
- The tsunami was damaging locally, with several hundred fatalities and waves reported to reach 15 m on Sumbawa, as well as on the sparsely populated Northwestern coast of Australia, reaching 6 m at Cape Leveque (220 km North of Broome).

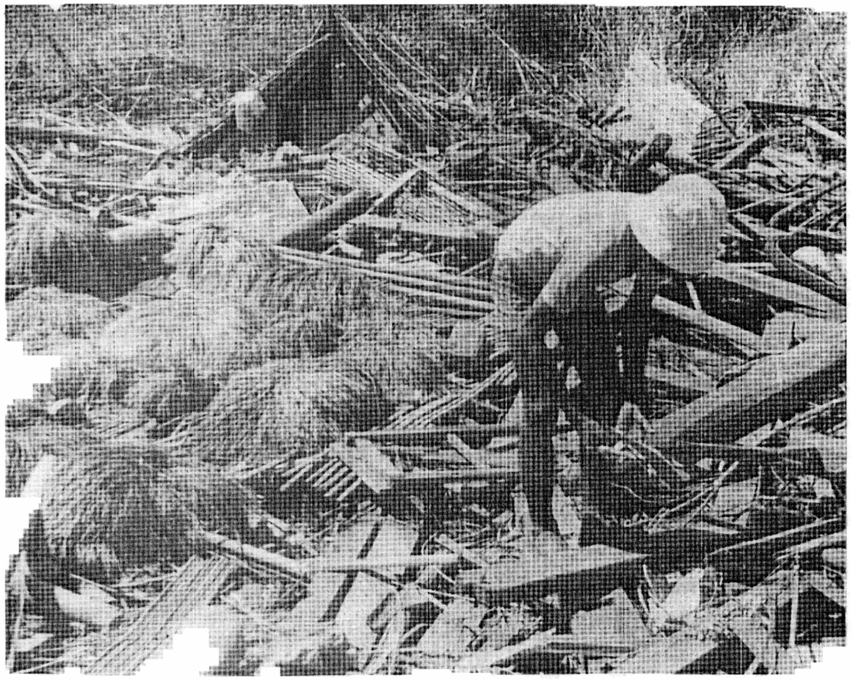
above - Coastal area of Sumbawa Island, near Lunyuk, devastated by August 19, tsunami wave.

below - Lunyuk Village, Sumbawa Island, destroyed by the August 19 tsunami. (Associated Press, Jakarta, Indonesia)





[*ITIC*, 1977]



OUTER RISE NORMAL FAULTING EVENTS CAN BE LETHAL !

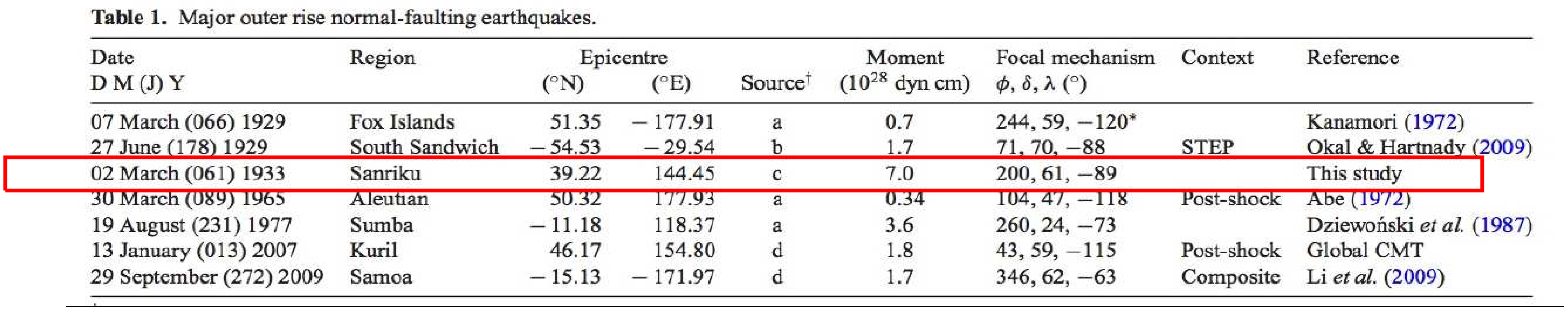


Table 1. Major outer rise normal-faulting earthquakes.

Date D M (J) Y	Region	Epicentre (°N)	 (°E)	Source†	Moment (10^{28} dyn cm)	Focal mechanism ϕ, δ, λ (°)	Context	Reference
07 March (066) 1929	Fox Islands	51.35	− 177.91	a	0.7	244, 59, −120*		Kanamori (1972)
27 June (178) 1929	South Sandwich	− 54.53	− 29.54	b	1.7	71, 70, −88	STEP	Okal & Hartnady (2009)
02 March (061) 1933	Sanriku	39.22	144.45	c	7.0	200, 61, −89		This study
30 March (089) 1965	Aleutian	50.32	177.93	a	0.34	104, 47, −118	Post-shock	Abe (1972)
19 August (231) 1977	Sumba	− 11.18	118.37	a	3.6	260, 24, −73		Dziewoński *et al.* (1987)
13 January (013) 2007	Kuril	46.17	154.80	d	1.8	43, 59, −115	Post-shock	Global CMT
29 September (272) 2009	Samoa	− 15.13	− 171.97	d	1.7	346, 62, −63	Composite	Li *et al.* (2009)

AND WE KNOW ESSENTIALLY

NOTHING

ABOUT THEIR RECURRENCE RATES…