20 YEARS since SUMATRA :

Advances in Tsunami Science and Mitigation

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Intergovernmental Oceanographic Commission EC-57

UNESCO

Paris, 25-28 Juin 2024

Roger Revelle's Connection to Tsunamis

Roger Revelle (standing, center, the tallest guy !) is seen in 1950 on Bikini Atoll while conducting research on the oceanographic effects of early nuclear tests in the lagoon. In particular, he was interested in whether they could generate tsunamis.

Kneeling, center: H.W. Menard

The 1955 deepwater test WIGWAM did generate a local tsunami which rocked a few USN ships observing at a somewhat insufficient distance. R. Revelle used the dispersion of radionuclides from the test to investigate the stratification of oceanic currents in the Pacific.

Banda Aceh, SUMATRA 2004

JAVA, 2006

Niautoputapu, Tonga

In this context, and given

24 significant tsunamis since 2004

What have we learned ?

ARE WE GETTING ANY WISER ?

Which challenges remain ?

IN 20 YEARS

Have we Become Wiser ?

- **Scientific Wisdom ?**
- **Mitigation Wisdom ?**
- **Operational Wisdom ?**
- **Societal Wisdom ?**

BEFORE 2004 ....

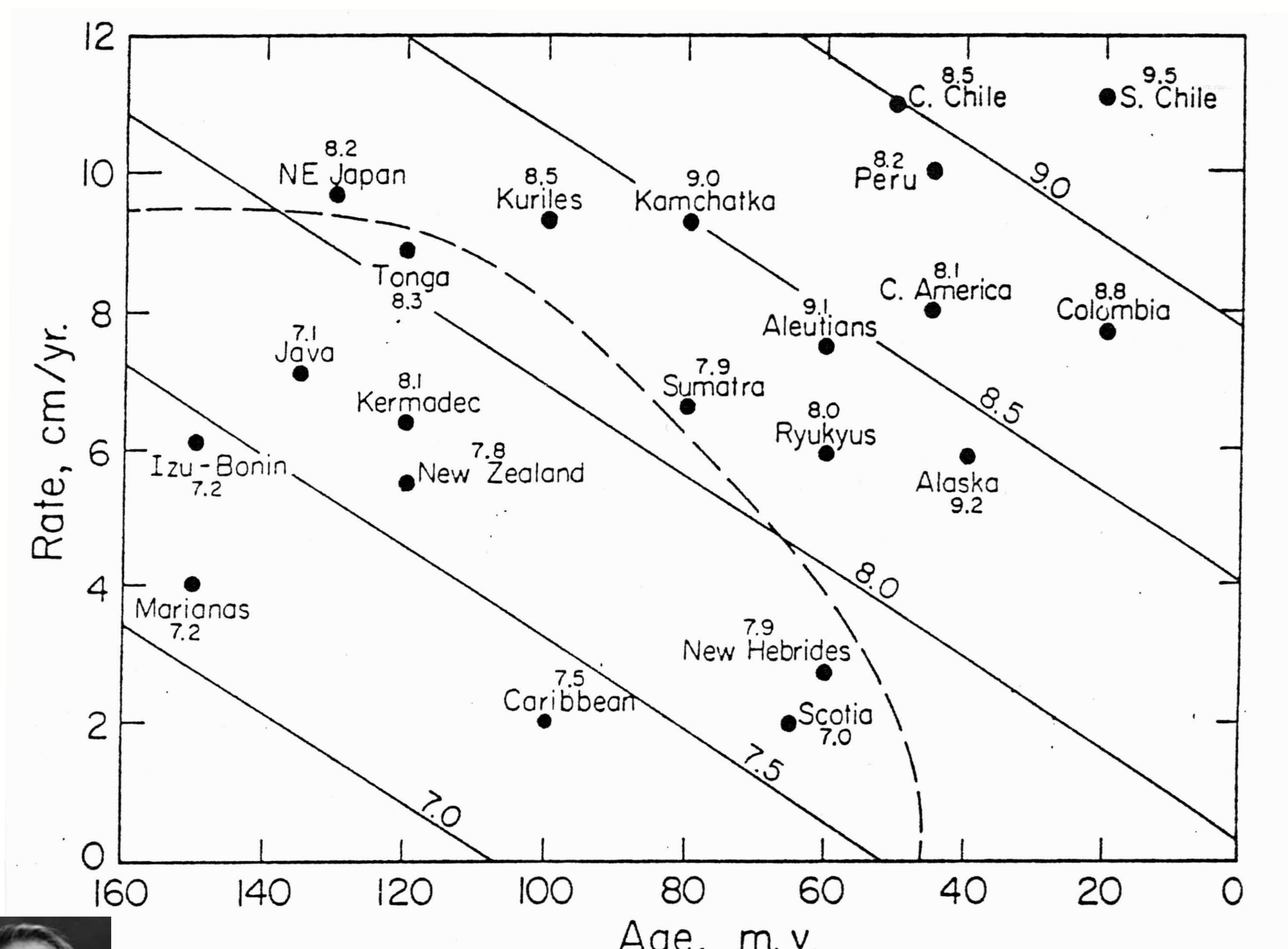
We lived happily under

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]

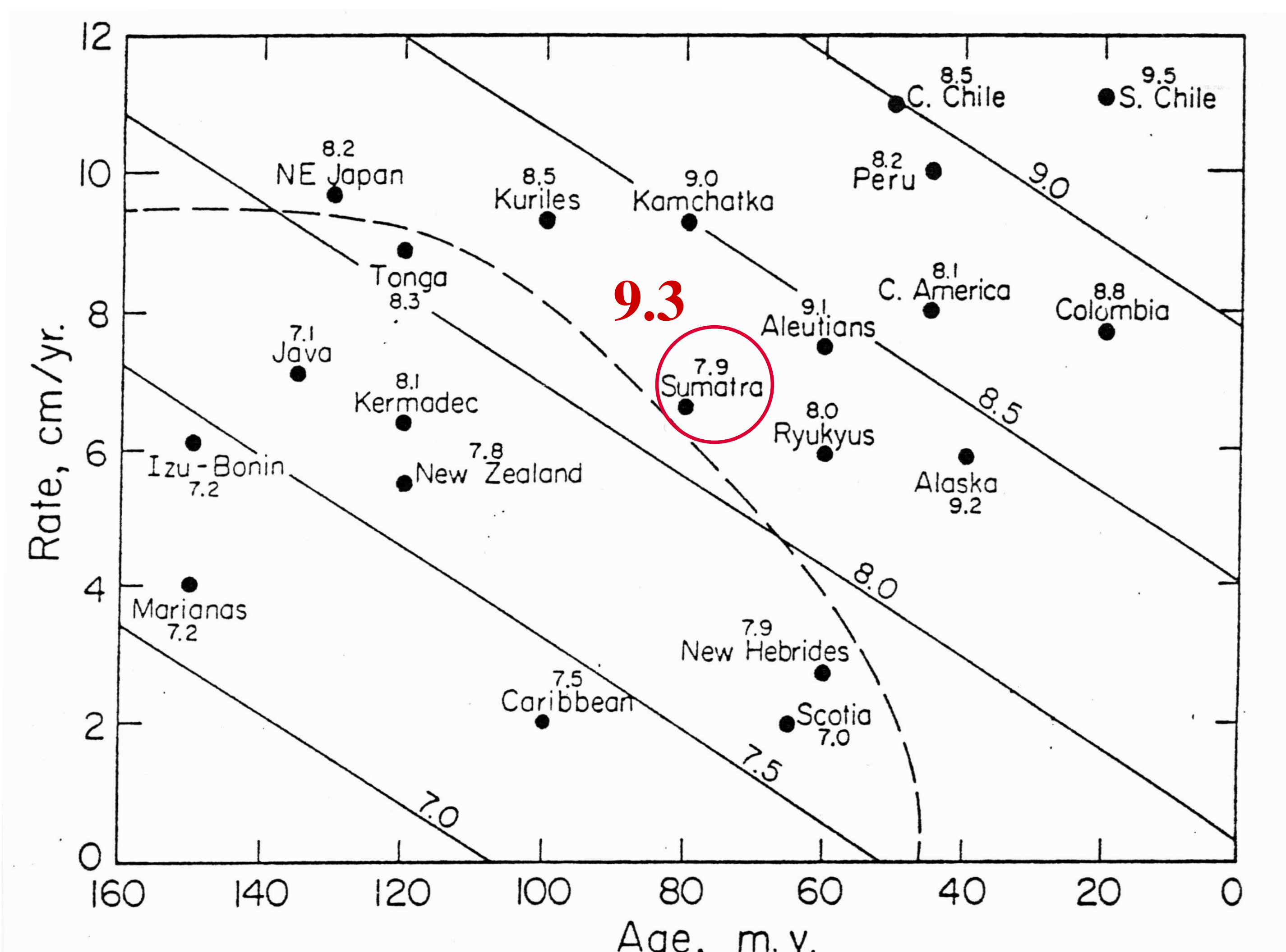
2004 : THE EARTHQUAKE OCCURRED WHERE A MEGA–EVENT *WAS NOT EXPECTED*

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

maximum expectable

subduction earthquake controlled by

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



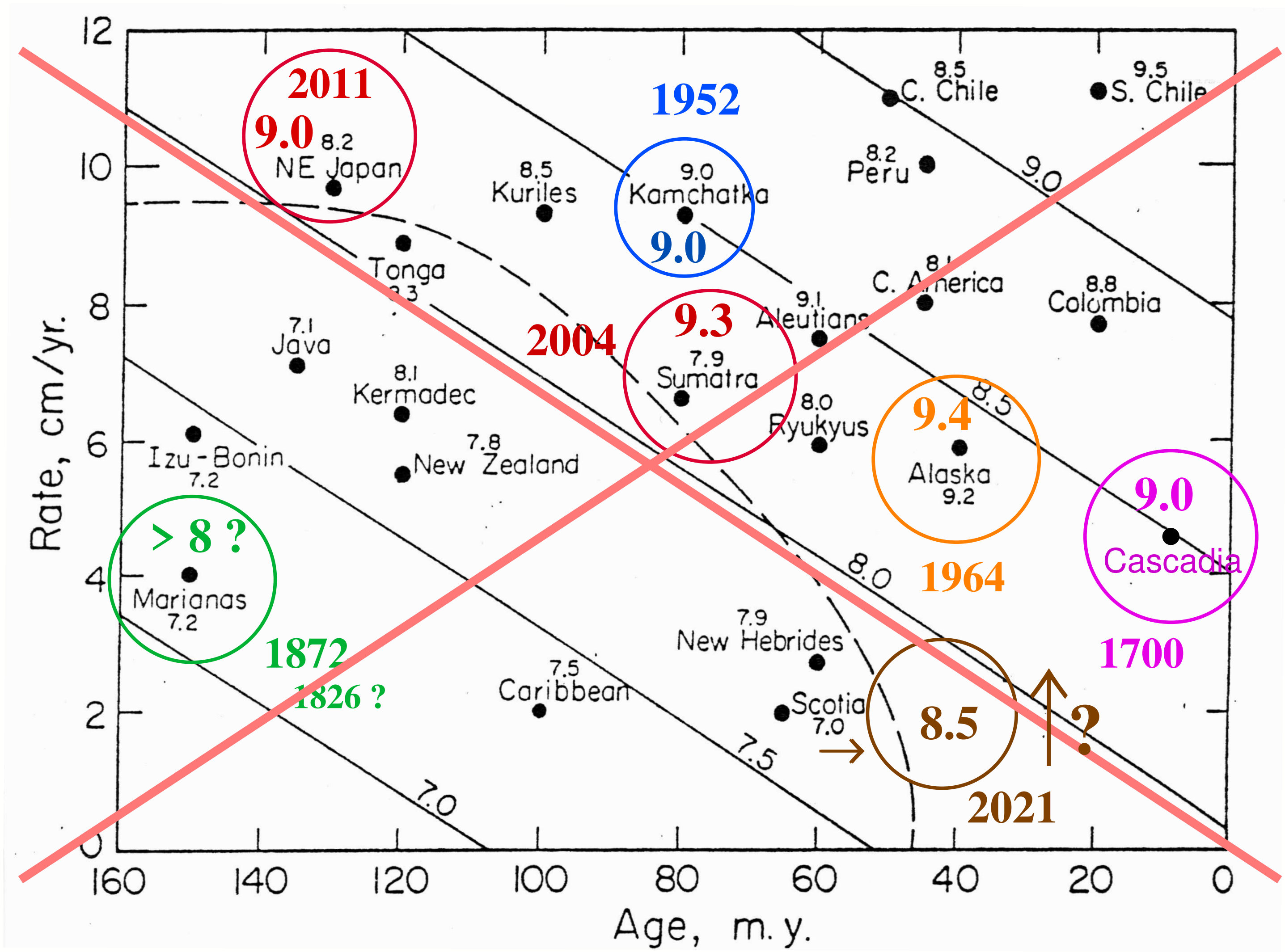
[*Ruff and Kanamori,* 1980]

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 !



NOTE IN PARTICULAR

THE POOR PERFORMANCE OF THE

8.0 to 8.5 BAND:

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

Scotia 2021 ?

Violators overlooked by RK 1980:

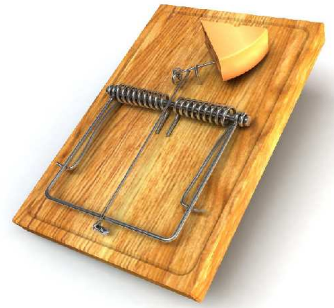
Alaska **Kamchatka** [Aleutians -- 1957 Debatable]

→ That leaves

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

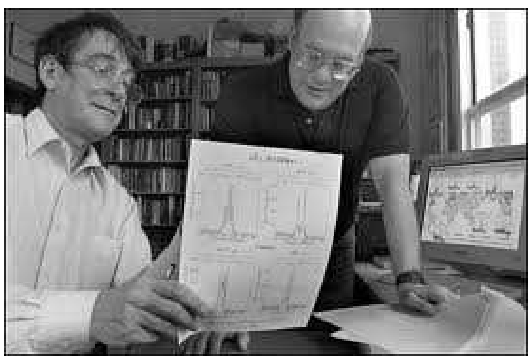
So, have we become...

Humbler ? CERTAINLY !



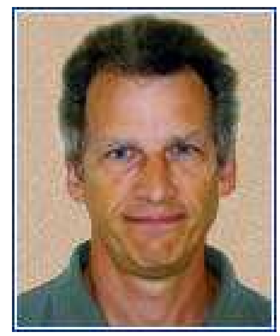
We still have not devised the better

IN THE MEAN TIME, WE SHOULD CONSIDER
ALL LONG SUBDUCTION ZONES
AS POTENTIALLY MEGA−GENIC



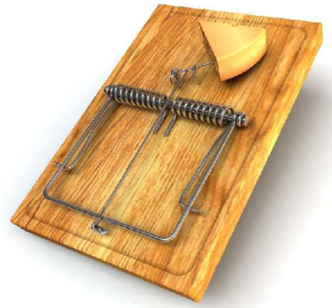
[*Stein and Okal*, 2007;

McCaffrey, 2007]



So, have we become...

Humbler ? CERTAINLY !



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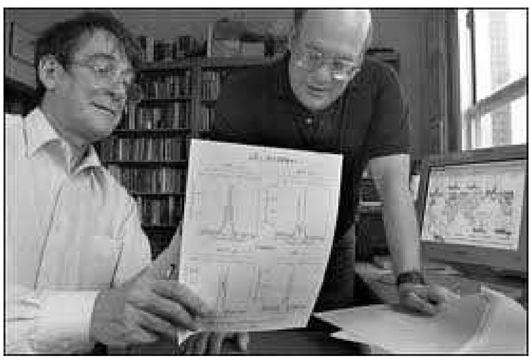

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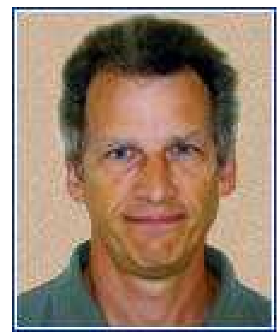
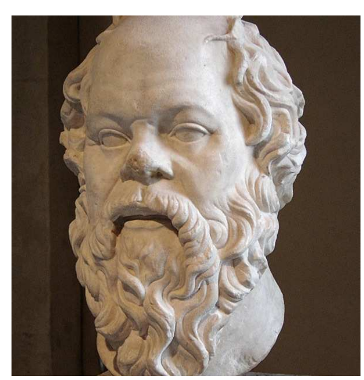


Have we become WISER ? PERHAPS !

" εν οιδα οτι ουδεν οιδα "

[I know one thing; that I know nothing]



Σωκρατης

→ **Stay Tuned !**

W Phase:

A clear Success Towards

Improved Wisdom

W Phase

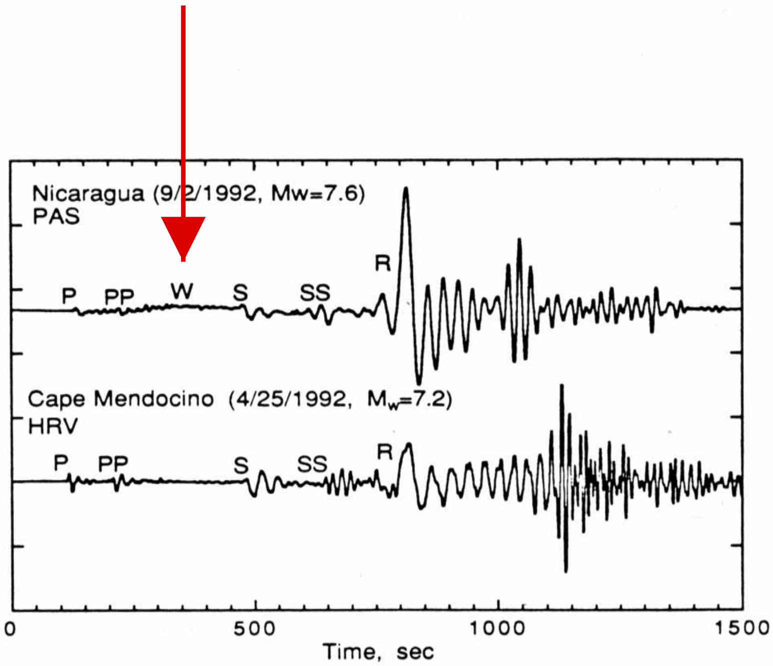
W *as in...* ~~*Whisky*~~ ***WISDOM***

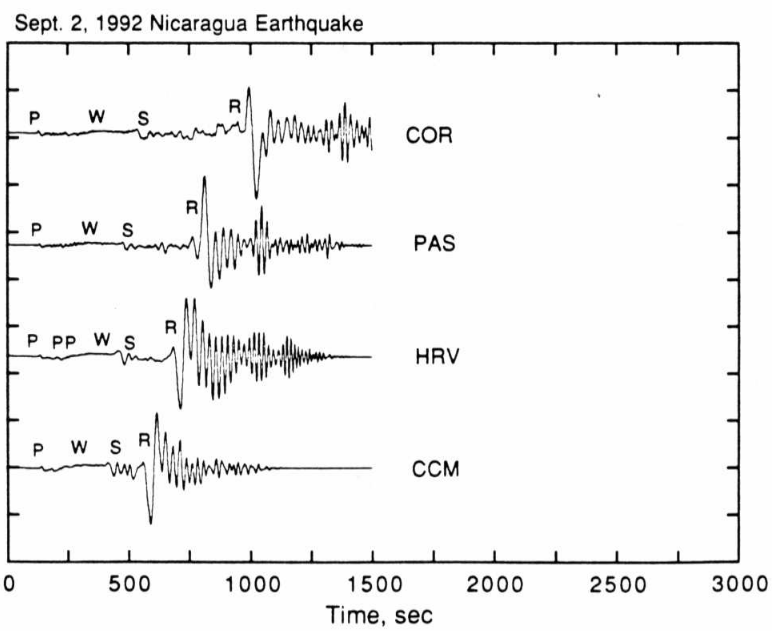
A +

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

Geophysical
Research
Letters

[*Kanamori et al.*, 2008]





[*Kanamori*, 1993]

AUGUST 20, 1993 Volume 20 Number 16

AMERICAN GEOPHYSICAL UNION

Receiver

What is the W Phase?

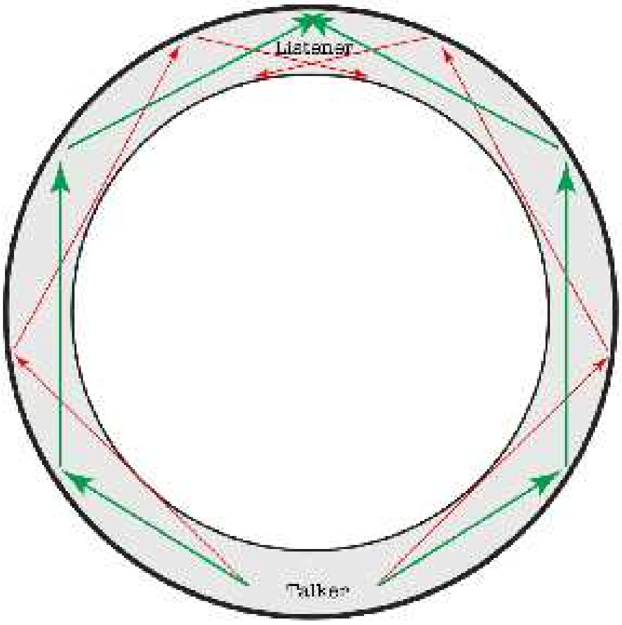
Complex interference of body waves at very long periods.

Arrives between the P- and surface-waves ==> fast.

Travels in the upper mantle ==> stable (unaffected by shallow heterogeneity).

Analogous to a whispering gallery effect - hence 'W' phase.

Can be synthesized by the superposition of normal modes.

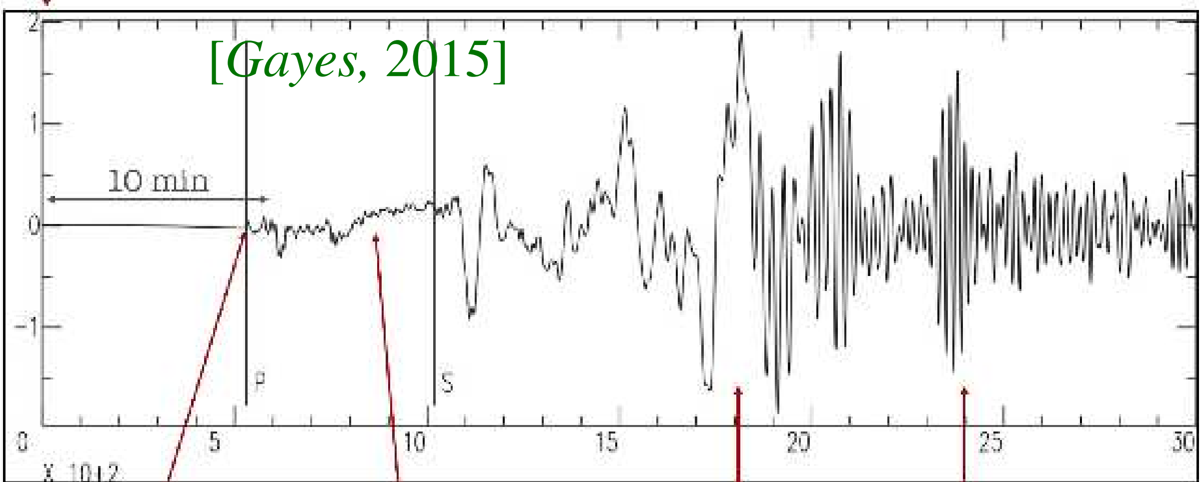


Source

***BOTH*: Very Long Period and *FAST* !**

Earthquake Origin Time

IDEAL for TSUNAMI WARNING



P wave, 10 sec

W phase (~1000 sec)

LP (200 sec) surface wave

20 sec surface wave

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*

The *W* phase also represents the superposition of ultra-long period overtones of Rayleigh modes with fast group velocities.

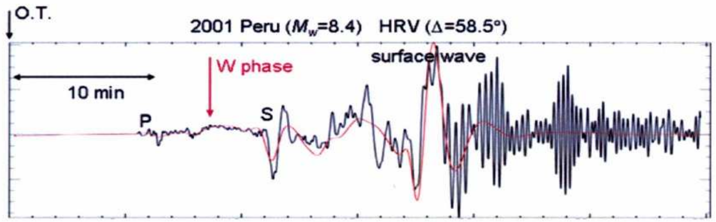


Figure 1. W phase from the 2001 Peruvian earthquake (M_w = 8.4) recorded at HRV, and the synthetic W phase computed by mode summation using the GCMT solution.

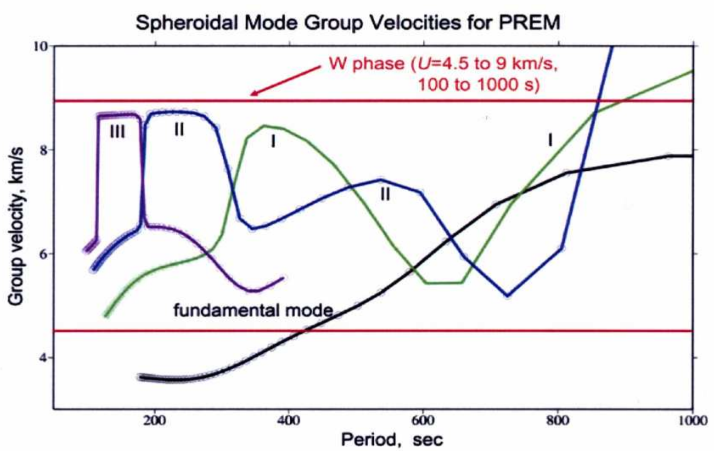
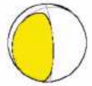


Figure 2. Group velocity dispersion curves of spheroidal modes computed for PREM. Dispersion curves for the fundamental mode (black), the first overtone (green), the second overtone (blue) and the third overtone (magenta) are shown. The horizontal red lines bound the group velocity of W phase.

→ *IT ALLOWS FAST, LOW-FREQUENCY CMT INVERSIONS IN REAL TIME.*

Time Line after 2011 Tohoku Event

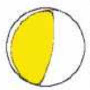
M_0 (10^{29} dyn*cm)

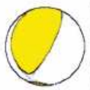
T+ 00:20 
20min after O.T: USGS Internal W phase solution (6 channels)
Mw=9.0
Centroid loc.: Lat= 36.82N; Lon= 142.87E; Dep= 24.4 km
Time delay = Half duration = 68.7 sec
Best Double Couple: M0=3.941E+29 dyn.cm
NP1: Strike=222.7 ; Dip=16.8 ; Slip=134.6
NP2: Strike=356.8 ; Dip=78.1 ; Slip=78.0
3.9

T+ 00:22 
22min after O.T: PTWC Automatic W phase solution (29 channels)
Mw=8.8
Centroid loc.: Lat= 39.00N; Lon= 142.80E; Dep= 83.5 km
Time delay = Half duration = 56.0 sec
Best Double Couple: M0=1.934E+29 dyn.cm
NP1: Strike=165.4 ; Dip=10.3 ; Slip=55.3
NP2: Strike=20.5; Dip=81.6 ; Slip=95.9
1.9

T+00:30 
30min after O.T.: PTWC Automatic W phase solution (74 channels)
Mw=8.8
Centroid loc.: Lat= 38.30N; Lon= 143.50E; Dep= 83.5 km
Time delay = Half duration = 68.0 sec
Best Double Couple: M0=1.775E+29 dyn.cm
NP1: Strike=194.3 ; Dip=22.8 ; Slip=81.3
NP2: Strike=23.7 ; Dip=67.5 ; Slip=93.6
1.8

T+00:40 
40min after O.T.: PTWC Manual W phase solution (105 channels)
Mw=9.0
Centroid loc.: Lat= 38.40N; Lon= 142.90E; Dep= 24.4 km
Time delay = Half duration = 69.0 sec
Best Double Couple: M0=4.325E+29 dyn.cm
NP1: Strike=190.6 ; Dip=11.1 ; Slip=76.7
NP2: Strike=24.2 ; Dip=79.1 ; Slip=92.6
4.3

T+00:48 
48min after O.T: USGS Internal W phase solution (74 channels)
Mw=8.9
Centroid loc.: Lat= 37.82N; Lon= 142.87E; Dep= 24.4 km
Time delay = Half duration = 72.2 sec
Best Double Couple: M0=3.225E+29 dyn.cm
NP1: Strike=204.4 ; Dip=14.8 ; Slip=104.3
NP2: Strike=9.7 ; Dip=75.7 ; Slip=86.3
3.2

T+01:00 
1hour after O.T.: USGS Published W phase solution (89 channels)
Mw=8.9
Centroid loc.: Lat= 38.32N; Lon= 141.77E; Dep= 24.4 km
Time delay = Half duration = 48.0 sec
Best Double Couple: M0=2.836E+29 dyn.cm
NP1: Strike=162.0 ; Dip=16.9 ; Slip=45.1
NP2: Strike=28.2 ; Dip=78.1 ; Slip=102.1
2.8

T+01:30 
1hour 30min after O.T.: IPGS W phase solution (146 channels)
Mw=9.0
Centroid loc.: Lat= 38.12N; Lon= 142.97E; Dep= 24.4 km
Time delay = Half duration = 72.0 sec
Best Double Couple: M0=3.507E+29 dyn.cm
NP1: Strike=196.3 ; Dip=14.4 ; Slip=85.1
NP2: Strike=21.4 ; Dip=75.7 ; Slip=91.3
3.5

A BIG STEP IN WISDOM !!

OTHER SCIENTIFIC MILESTONES since 2004

- **Tsunamis recorded by seismometers** — Observed [*Yuan et al.*, 2005]; Quantified [*Okal,* 2007]

- **Tsunamis interact with atmosphere and ionosphere** — Observed and quuantified [*Occhipinti et al*., 2006] as predicted [*Peltier and Hines,* 1976]

- **Tsunami shadows** — Confirmed as predicted [*Godin et al*., 2009]

- **Tsunamis trigger deep infrasound signals** — Observed [*Le Pichon et al.,* 2005]

- **Tsunamis affect Earth's magnetic field** — Observed [*Manoj et al*., 2011]

- **Tsunamis affect Earth's gravity field** — Detected from GRACE orbits; modeled [*Ghobadi-Far et al*., 2020]

- **High-frequency components set harbors in delayed resonance** — Observed [*Okal et al*., 2006]; Quantified [*Pančošková et al*., 2007]

- Scientific Wisdom ?
- Mitigation Wisdom ?
- Operational Wisdom ?
- Societal Wisdom ?

INTERNATIONAL: *Over the past 20 years, many Tsunami Warning Centers have been built*

France

Australia

Indonesia

etc.

Oman

Only time will tell How Well They Perform in real time

SIGNAGE

An Efficient, Low-Cost Step in Mitigation

Canada

Indonesia

Chile

Japan

Israel

American Samoa

Haiti

Korea

Thailand

USA

2006

TSUNAMI WARNING AND EDUCATION ACT

Public Law 109–424
109th Congress

An Act

Dec. 20, 2006
[H.R. 1674]

To authorize and strengthen the tsunami detection, forecast, warning, and mitigation program of the National Oceanic and Atmospheric Administration, to be carried out by the National Weather Service, and for other purposes.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

Tsunami Warning and Education Act. 33 USC 3201 note.

SECTION 1. SHORT TITLE.

This Act may be cited as the "Tsunami Warning and Education Act".

SEC. 8. AUTHORIZATION OF APPROPRIATIONS.

There are authorized to be appropriated to the Administrator to carry out this Act—

(1) $25,000,000 for fiscal year 2008, of which—

(A) not less than 27 percent of the amount appropriated shall be for the tsunami hazard mitigation program under section 5; and

(B) not less than 8 percent of the amount appropriated shall be for the tsunami research program under section 6;

(2) $26,000,000 for fiscal year 2009, of which—

(A) not less than 27 percent of the amount appropriated shall be for the tsunami hazard mitigation program under section 5; and

(B) not less than 8 percent of the amount appropriated shall be for the tsunami research program under section 6;

(3) $27,000,000 for fiscal year 2010, of which—

(A) not less than 27 percent of the amount appropriated shall be for the tsunami hazard mitigation program under section 5; and

(B) not less than 8 percent of the amount appropriated shall be for the tsunami research program under section 6;

(4) $28,000,000 for fiscal year 2011, of which—

(A) not less than 27 percent of the amount appropriated shall be for the tsunami hazard mitigation program under section 5; and

(B) not less than 8 percent of the amount appropriated shall be for the tsunami research program under section 6; and

(5) $29,000,000 for fiscal year 2012, of which—

(A) not less than 27 percent of the amount appropriated shall be for the tsunami hazard mitigation program under section 5; and

(B) not less than 8 percent of the amount appropriated shall be for the tsunami research program under section 6.

Approved December 20, 2006.

Total Appropriation: $135 million over 5 years

2004-2023: EVOLUTION of the DART SYSTEM

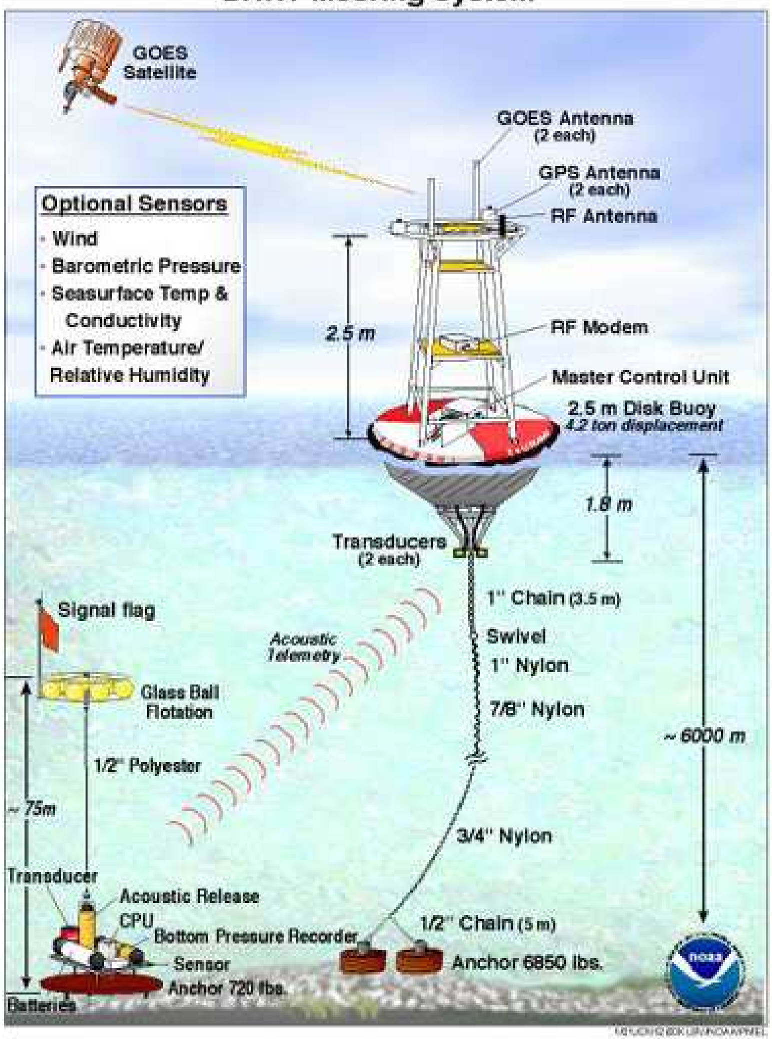
E.N. Bernard

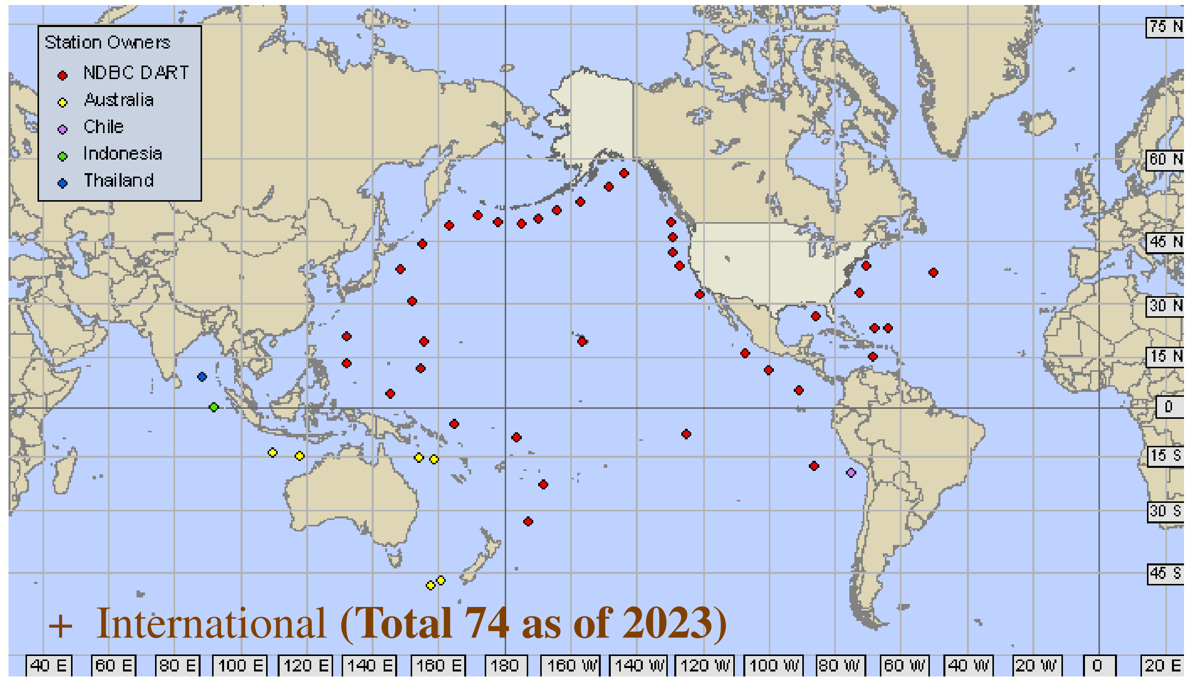
- Funded by PL 109-424

U.S. Dept. of Commerce Gold Medal, 2005

2004: 6 instruments **2008: 39 instruments**

DART Mooring System





\+ International **(Total 74 as of 2023)**

Note: Maintenance Issues

→ A test on 17 MAR 2024 reveals **21 (28%)** *not transmitting, or misfunctioning.*

- Other systems deployed, many of them International

Seismic networks, including OBS

Tethered Pressure Sensors

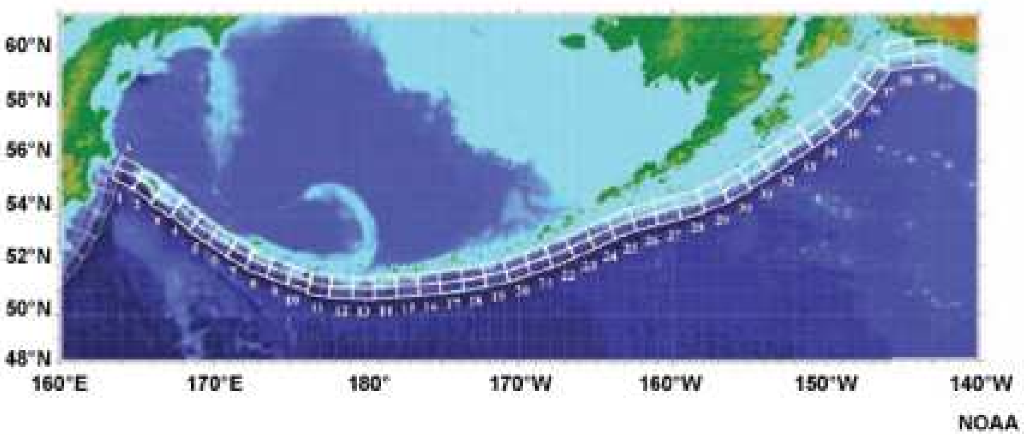
GPS networks, including Bottom prototypes

SIFT: *A DART-based Real-Time Forecast Algorithm*

[*V.V. Titov et al.*, 2002+]

A. *Ahead of time*
(Very long, number-crunching process)

1. Have relevant subduction zone partitioned into segments

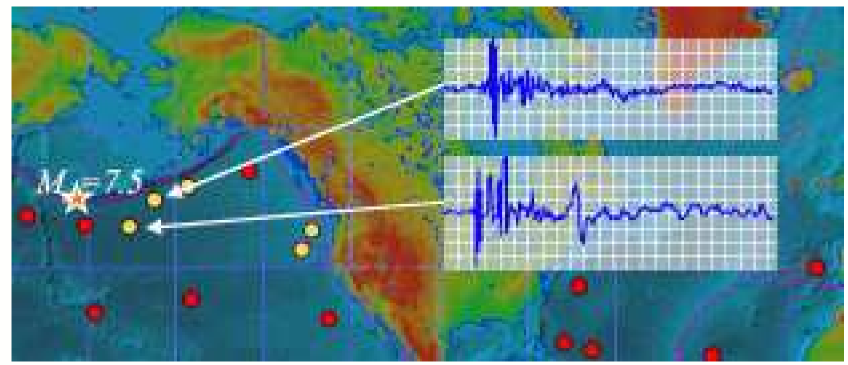


2. For each segment and unit moment **pre-compute** forecast time series, either at DART buoy, or at individual coastal tide gauges (including run-up).

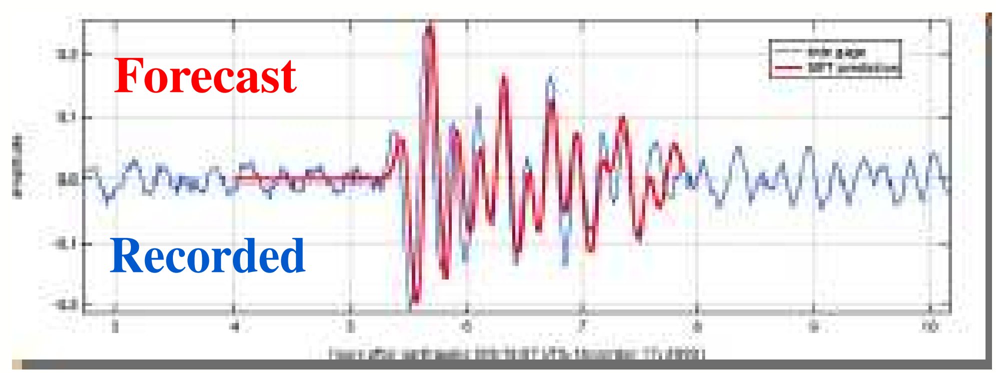
   Store as permanent database *(DB)*.

B. *Upon significant trigger of DART buoy.*
(Very fast, all simulations stored in DB)

3. *Use time series recorded at DART buoy[s] to* **invert** tsunami source, expanded on source segments (1.).



4. Linearly combine simulations (*DB*) as weighted by (3.) to forecast tsunami amplitudes at strategic coastal locations.



SIFT: *A DART-based Real-Time Forecast Algorithm*

[*V.V. Titov et al.*, 2002+]

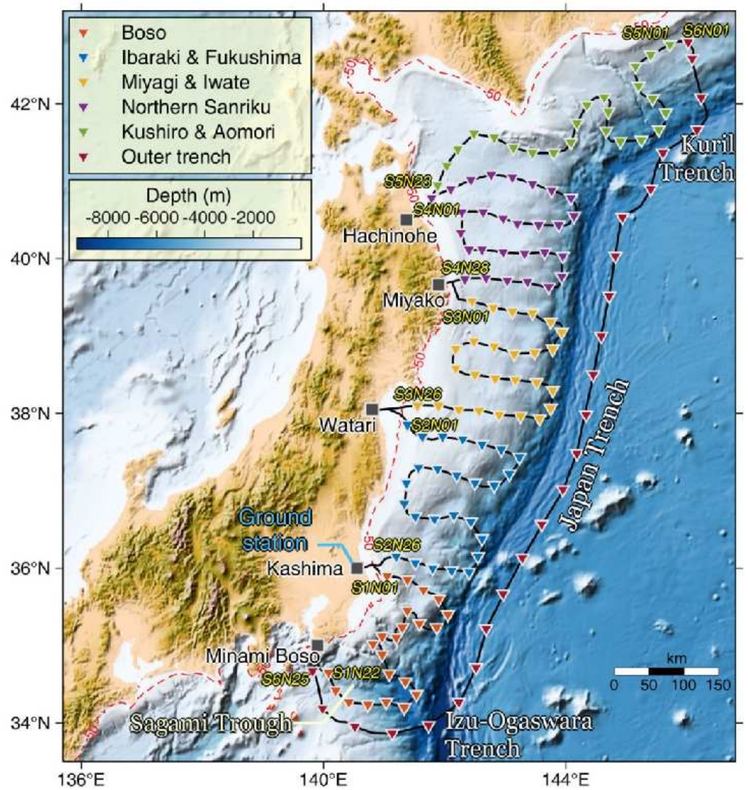
THIS ALGORITHM REPEATEDLY TESTED AND VALIDATED USING DATABASES OF DART RECORDINGS

NOW IN ROUTINE USE AT PTWC and NTWC

DIRECT DETECTION OF TSUNAMIS ON THE HIGH SEAS

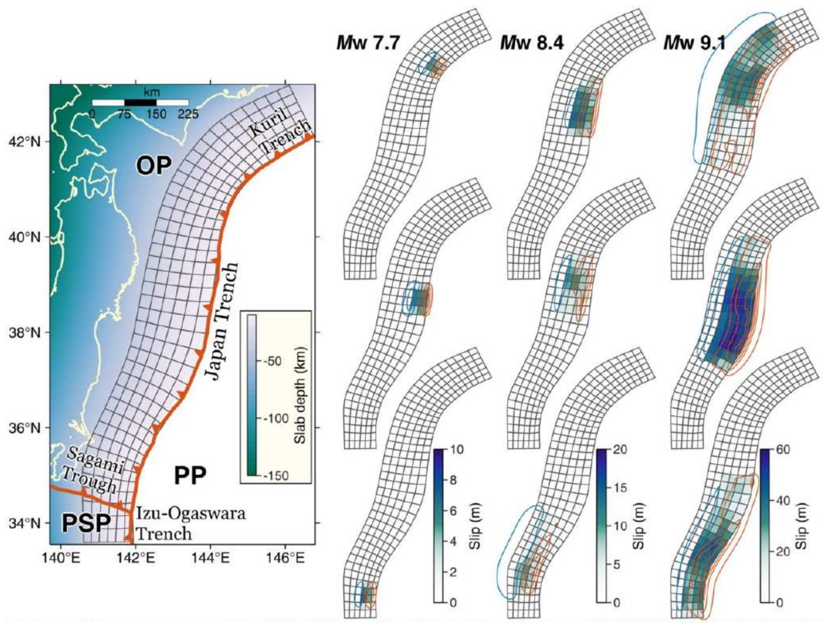
TOWARDS NEW SENSORS

Motivated in part by the complexity and high costs for maintenance of DART-type equipment, efforts are made to adapt the concept to hard-wired **tethered sensors**



- *In the Near Field,* a remarkable example is the ***S – Network*** consisting of **150 seafloor observatories** each equipped with seismometers and pressure sensors, and linked by **5800 km of cable** off the coast of Honshu [*Mizutani et al.,* 2020; *Mulla and Satake,* 2021].

- S–net data can then be used in a way very similar to the SIFT concept developed by *Titov et al.* [2002 +].



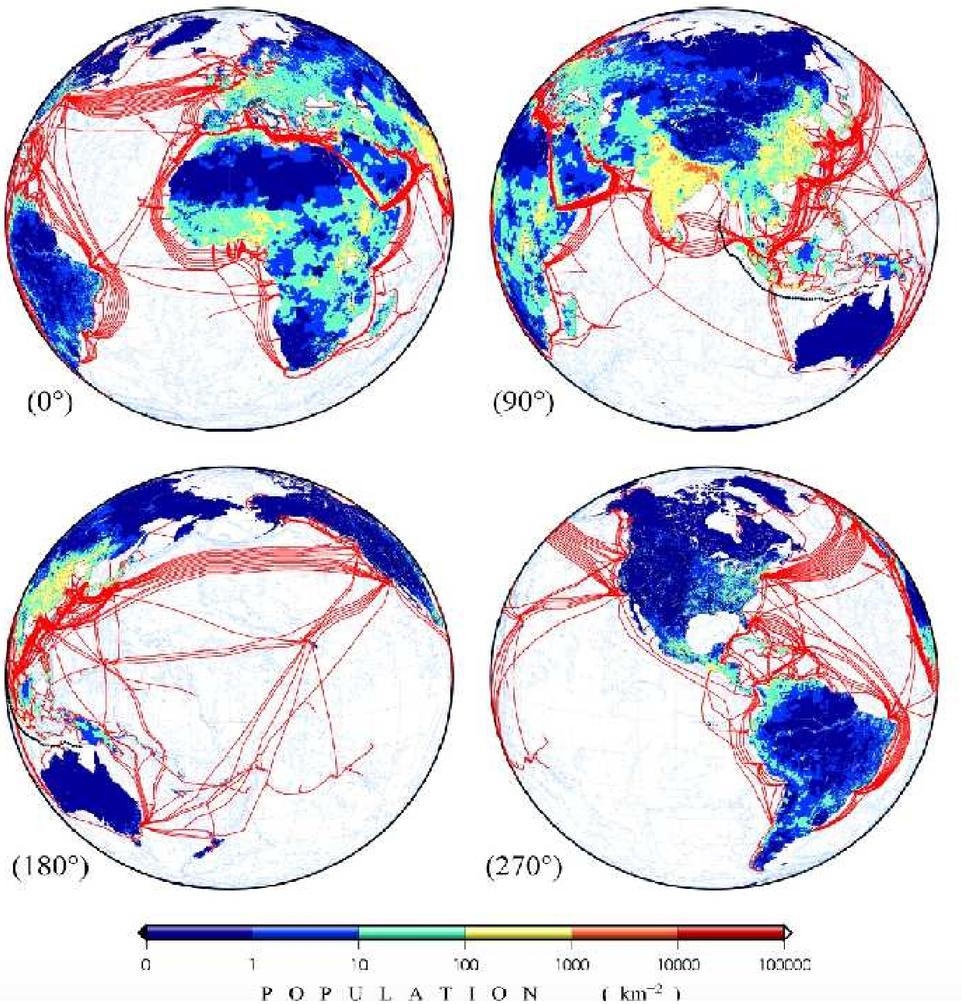
DIRECT DETECTION OF TSUNAMIS ON THE HIGH SEAS

TOWARDS NEW SENSORS

- *Salaree et al.* [2022] have recently proposed to instrument **existing** underwater **fiber-optics telecommunication cables** to detect tsunamis on the high seas.

→ *The exceptional density of such cables could greatly enhance tsunami detection at only a minor incremental cost.*

→ This approach would improve tsunami warning in **both the near and far fields**



→ *The project is reminiscent of the "H_2O" seafloor seismic station operated on a retired [metallic] telecommunications cable linking Hawaii and the US West Coast, in the 2000s.*

The last ~~*mile*~~ **km**: **EVACUATION**

Tohoku, Japan
2011

→ Involves **INDIVIDUALS** who must be properly

EDUCATED

including in informal ways

TSUNAMI DRILLS

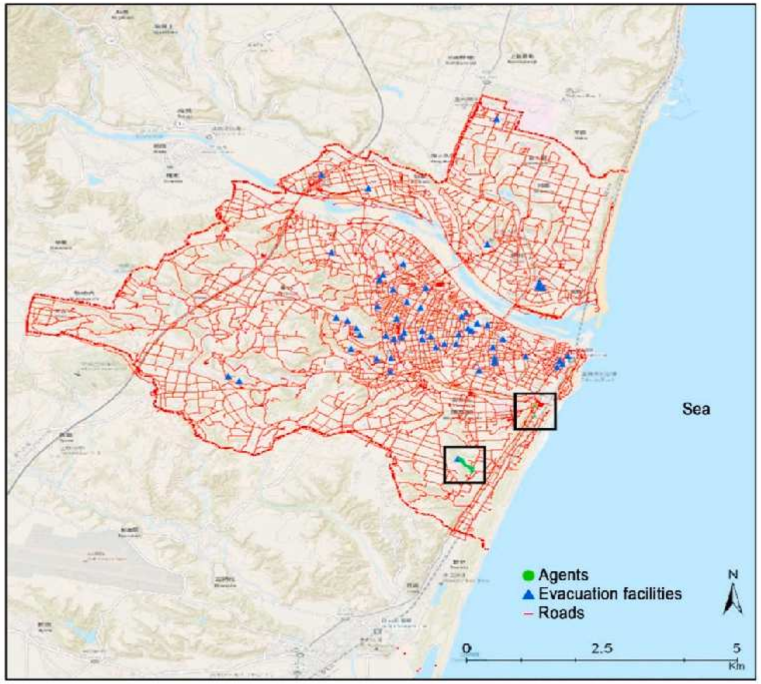
Have been implemented on a generally yearly basis in many countries to **maintain risk awareness** in the populations at risk

Japan *(on Disaster Day, 01 Sept.)*

Fiji

E.A. Okal *Lori Dengler*

RECENT ADVANCES in EVACUATION STRATEGIES

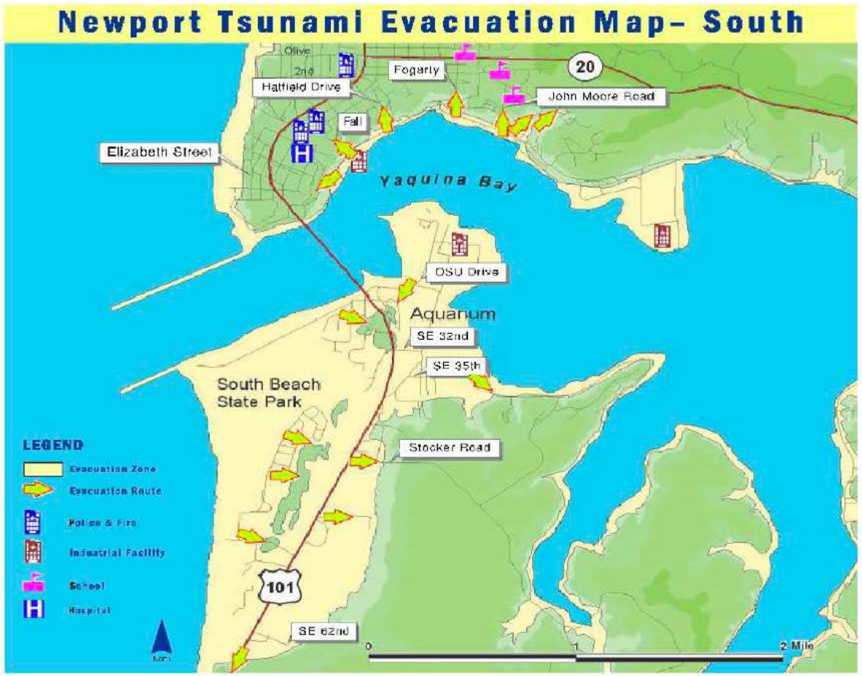


Evacuation Simulations

[*Yamada and Yamasaki,* 2021]

Vertical Evacuation Tower

Inundation Maps



Height: 20 m
Capacity: 5000

TSUNAMI READY

This program recognizes and certifies communities which have developed and maintain a number of standard procedures towards the efficient mitigation of tsunamis,

- **Inundation maps for realistic scenarios**
- **Education of populations at risk, notably schoolchildren**
- **Development of real-time infrastructure (Sirens, etc.)**
- **Development of tsunami-resilient permanent infrastructure (including, *e.g.*, vertical evacuation)**
- **Updating of building codes to restrict construction in areas featuring tsunami risk**
- **Regular live drills**

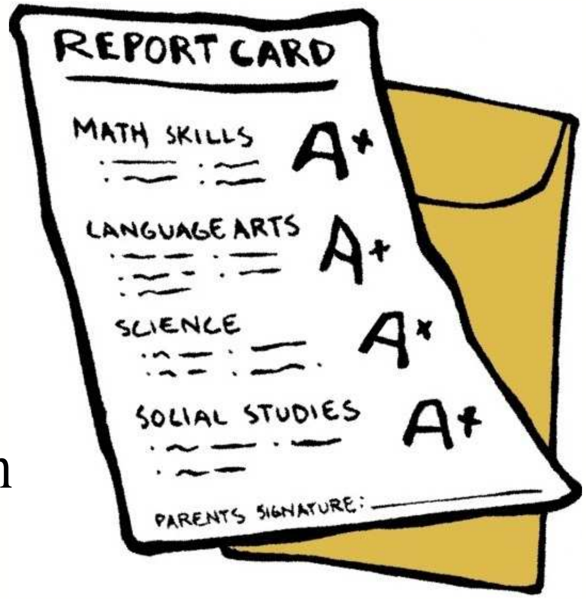
→ **As of March 2024, there are more than 200 TsunamiReady communities in 16 US states and territories and tens more in foreign countries.**

- Scientific Wisdom ?
- Mitigation Wisdom ?
- **Operational Wisdom ?**
- Societal Wisdom ?

POST–SUMATRA TSUNAMIS, 2004–2021

Building a [subjective] WISDOM INDEX

→ We now examine significant tsunamis since 2004, from the standpoint of the performance of the warning centers, and of the response of the populations at risk.



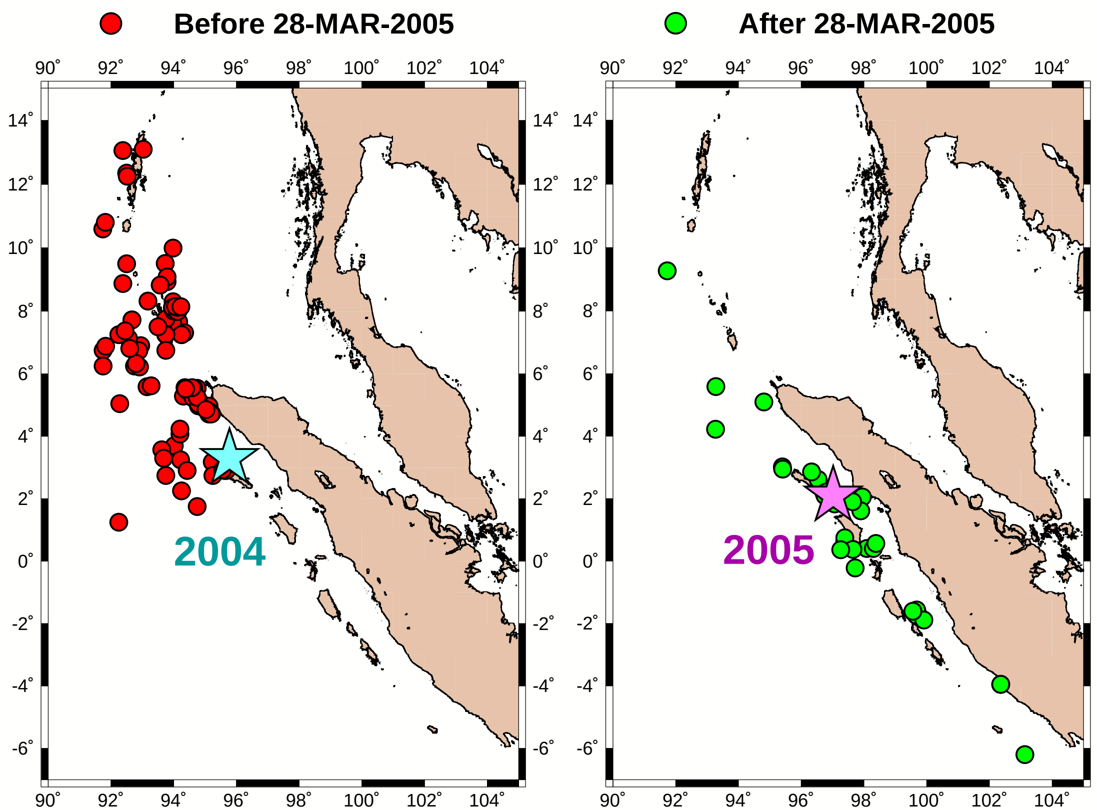
• In this context, we assign to each event a **color–coded** report card, from *Green* (Excellent) and *Blue* (Very good) through *Yellow* (Average), to *Red* (Bad) and *Black* (Disastrous).

→ The report card is not directly a function of the death toll in the tsunami, but rather, reflects on the various components of its mitigation.

EXAMPLE: NIAS (Sumatra), 28 MAR 2005, $M_0 = 1.0 \times 10^{29}$ dyn*cm

Would be Largest Event since 1965 Rat Island, but for 2004 Sumatra earthquake...

28-MAR-2005 (SUMATRA-II) EARTHQUAKE PREDICTED ON THE BASIS of STRESS TRANSFER by McCLOSKEY *et al*. [*Nature*, 17 MAR 2005].



In the far field, general warning issued throughout Indian Ocean Basin, followed by [night-time] evacuation.

At least 10 people killed in Sri Lanka and 6 in Madagascar during evacution

YET, NO DETECTABLE FAR-FIELD TSUNAMI... WHY ?

- Local tsunami with significant damage and **run-up to 8 m**

Only **8 local fatalities**

Residents were

** Educated through ancestral tradition (SMONG)*

** Sensitized to tsunami by 2004 Sumatra event*

** [Temporarily] relocated to higher ground following Sumatra disaster*

"TSUNAMI EARTHQUAKE", JAVA, 17–JUL–2006:

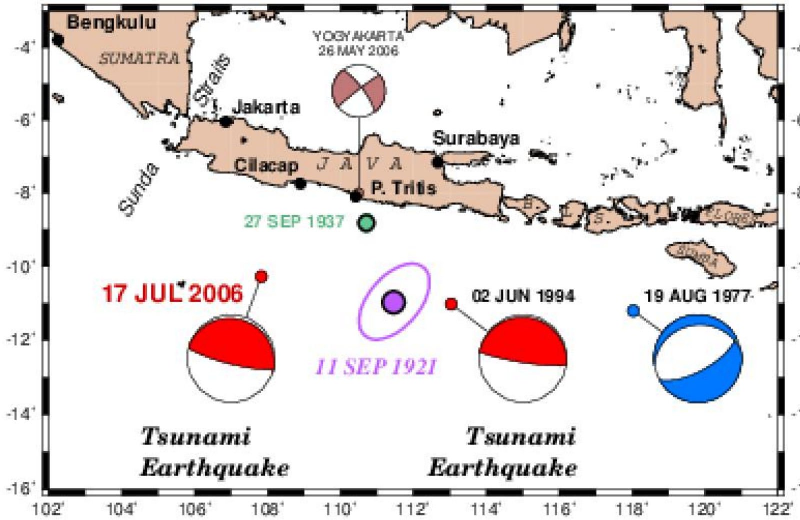
A Flagrant RED CARD !

$M_0 = 4.6 \times 10^{27}$ dyn*cm *Slow event,* $\Theta = -6.13$

Typical "Tsunami Earthquake"; — 700 killed by tsunami

Carbon copy of 1994 event, 600 km to the East

T.E. : Event whose tsunami is stronger than suggested by its seismic magnitudes [*Kanamori*, 1972].



This event suggests that *"tsunami earthquakes"* could feature a regional character.

Question: **Does this exclude the danger of a subduction mega-thrust earthquake in Java ?**

* **What is the role of the 1921 shock (contrary to the T.E.s, strongly felt, but with benign tsunami)?**

Warning and Arrival Timeline (GMT)

08:19 H_0

08:20 *BMG (Indonesia):* Notes **"non-typical earthquake"**

08:36 *PTWC :* Watch for Indonesia and Australia

" EVALUATION A DESTRUCTIVE WIDESPREAD TSUNAMI THREAT DOES NOT EXIST BASED ON HISTORICAL EARTHQUAKE AND TSUNAMI DATA. "

08:40 *Tsunami arrives at Pangandaran,* **Second wave reaches 5 m**

08:46 *JMA :* Tsunami watch for all Sunda Islands

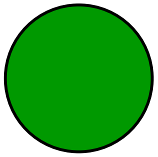
08:49 – 09:14 : *Tsunami reaches all Southern coast of Java*
Run-up to 21 m; **700 casualties**

VERDICT:

Despite Recognition of anomalous character by BMG and history of "Tsunami Earthquake" in the region in 1994, **no Warning issued !**

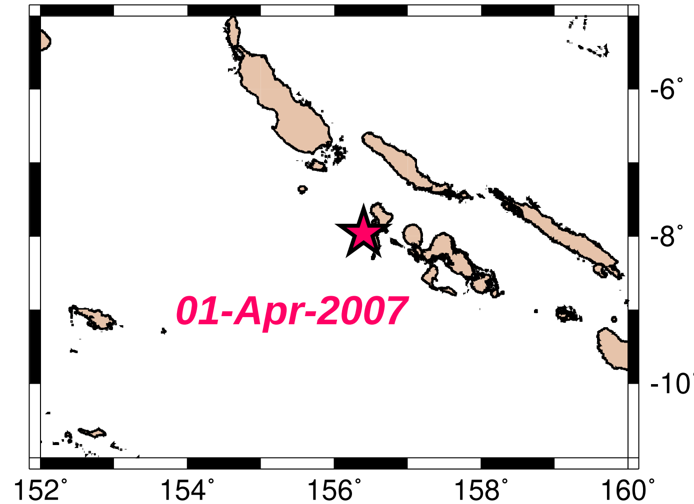
No data available from New Networks (Seismic and GPS)...

SOLOMON Is., 01-APR-2007



[The Miracle ?]

$M_0 = 1.6 \times 10^{28}$ dyn*cm



[Fritz & Kalligeris, 2007]

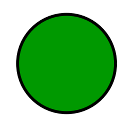
Local Tsunami, resulting in significant damage on several islands

More than 6000 houses destroyed; **Only 52 dead or missing**

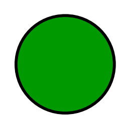
The community apparently had the reflex of *Self-Evacuation*

(probably conditioned by the memory of strong waves during a volcano-seismic swarm in the 1950s ?)

NOTE SIMILAR RESULTS on 03-JAN-2010



And Again, VERY SIMILAR RESULTS on 06 FEB 2013
(Santa Cruz Islands, part of Solomon Is.) [courtesy H.F. Fritz]



MAULE, Chile, 27 FEB 2010

- More than 200 victims killed by tsunami

Majority of population along Chilean coast self-evacuated, but
Many trapped camping on island in Rio Maule

Highest Government Officials
Discounted Tsunami Threat

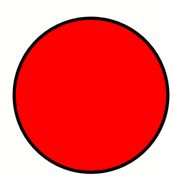
- **Juan Fernandez Islands — at least 16 killed**
Run-up to 15 m.
Propagation time ~ 1 hour
No warning whatsoever

Almirante Edmundo González Robles,

Chief-of-Staff, Chilean Navy
Advisor to President Michelle Bachelet

"El epicentro está en tierra, luego no debiera hacer tsunami "
["The epicenter is on land, hence there should not be a tsunami"]
27 FEB 2010, 08:15 GMT

TOHOKU 2011

Average: Green + Black = Red = 

TOHOKU 11 MAR 2011 *The Far Field*

→ Far field a reasonable success

Evacuations successful and by and large orderly (Polynesia, Chile...).

One death-by-stupidity in Crescent City

One death-by-negligence in Indonesia

Une population calme

HAUTEURS DE PUNAAUIA. Le ballet des voitures a commencé avant le
les voitures commençaient à s'installer soit à courte distance au-dessus c
pour qui voulait voir au loin pour mieux scruter le lagon. Habituée aux év
Ne croyant pas au risque d'une vague déferlant sur les terres, beaucoup

Dès l'aurore, la voie surplombant la route des Plaines était déjà occupée par une interminable file de v

Far field: Green

Baie de Taipivai, NUKU HIVA (Marquesas)

[*Video: Mr. Vohi, Taipivai; Courtesy O. Hyvernaud*]

TOHOKU 11 MAR 2011

Near Field

→ Structural Mitigation a Disaster

Mitigation had been designed (including nuclear plants!)
for 6–m wave.

OVER-RUN of the 6–m WALL at MIYAKO [*The New York Times*]

YET,

1933 SANRIKU TSUNAMI HAD REACHED 29 m at YAMADA

1896 SANRIKU TSUNAMI HAD REACHED > 20 m ON SAME COASTLINES

1611 SANRIKU TSUNAMI HAD REACHED 25 m at YAMADA

869 JOGAN SANRIKU TSUNAMI PENETRATED ~5 km INLAND

At best NEGLIGENT, at worst **CRIMINAL engineering!**

VOLCANIC COLLAPSE, **ANAK KRAKATAU 22 DEC 2018**

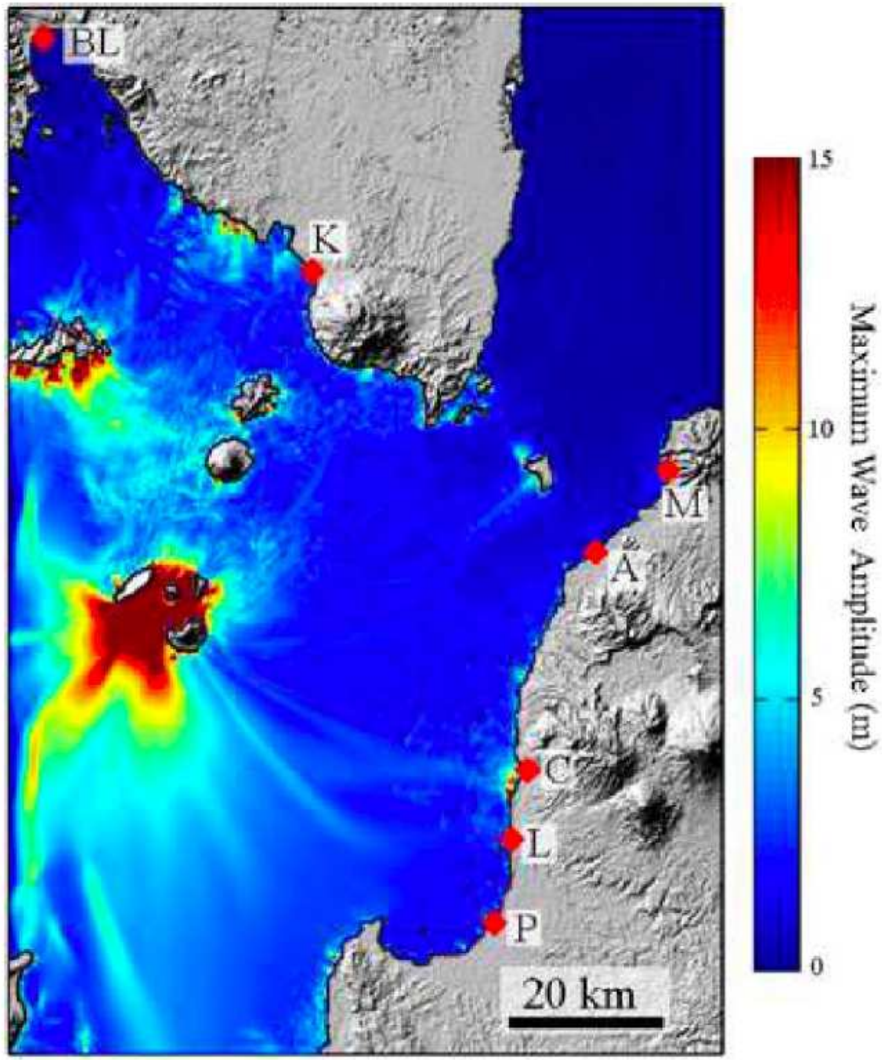
→ Locally catastrophic tsunami **(400 deaths)** due to underwater landslide during collapse of subaerial volcano.

West Java
23 December 2018

E.A. Okal on Anak Krakatau September 2016

This part of the island no longer exists

REMARKABLY, THIS SCENARIO WAS QUANTITATIVELY



PREDICTED [*Giachetti et al.*, 2012] **!**

KRAKATAU 22 DEC 2018

→ We seem to be reasonably capable of building realistic models for the geometry of potentially tsunamigenic volcanic collapses, and of predicting their amplitudes on coastlines at regional distances.

→ In the wake of the Krakatau tragedy, and of course *in hindsight*, it may not be a smart idea to organize a rock concert in a closed building on the beach with your back at the sea, when the horizon is glowing with a volcanic eruption 40 km away...

Anak Krakatau photographed from the Java coast
by Oysten L. Andersen

two hours before the flank collapse

SOUTH SANDWICH ISLANDS — 12 AUG 2021

First known mega-thrust in Scotia Arc; *Extremely Isolated Location*

Violates Ruff and Kanamori’s model, but convergence rate poorly known

No Known Human Casualties -- Either Earthquake or Tsunami

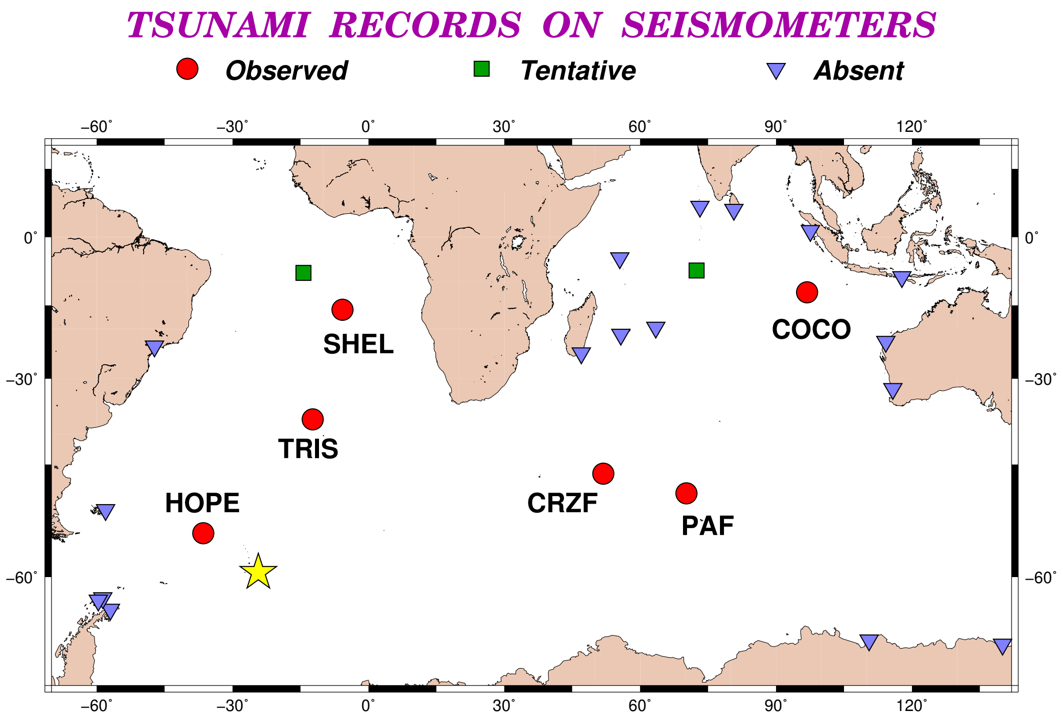
Near-Field Tsunami unsurveyed (COVID Pandemic)

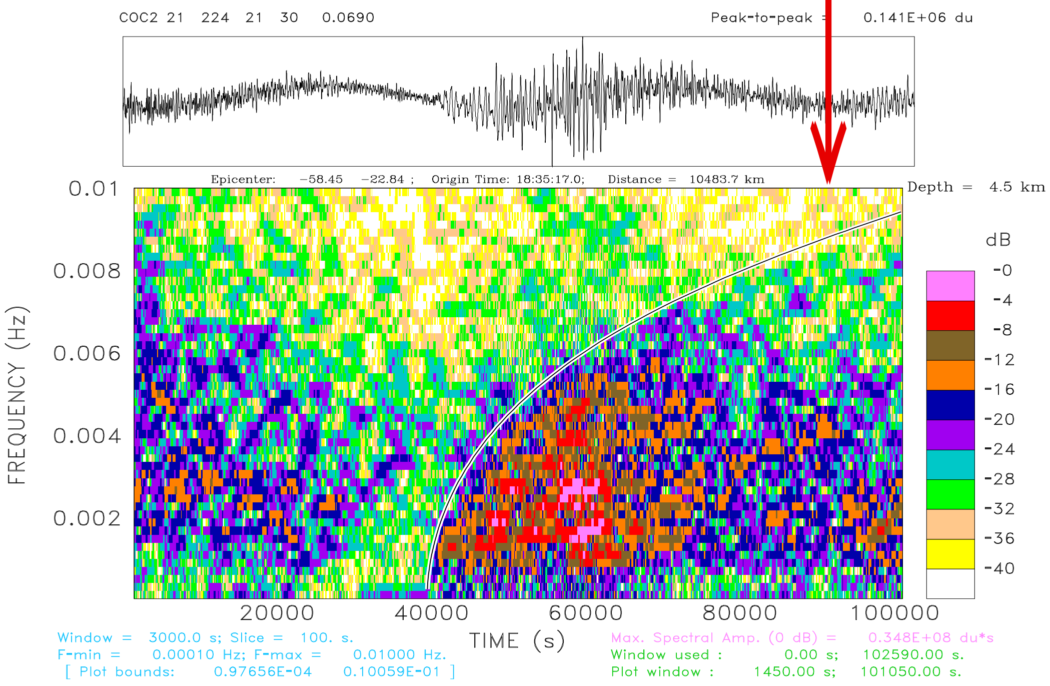
Far-Field Tsunami decimetric (Maximum 0.64 m at Mossel Bay)

Seismic records of Tsunami in Far field very irregular

BUT…. Many stations missing (Interrupted maitenance during COVID)

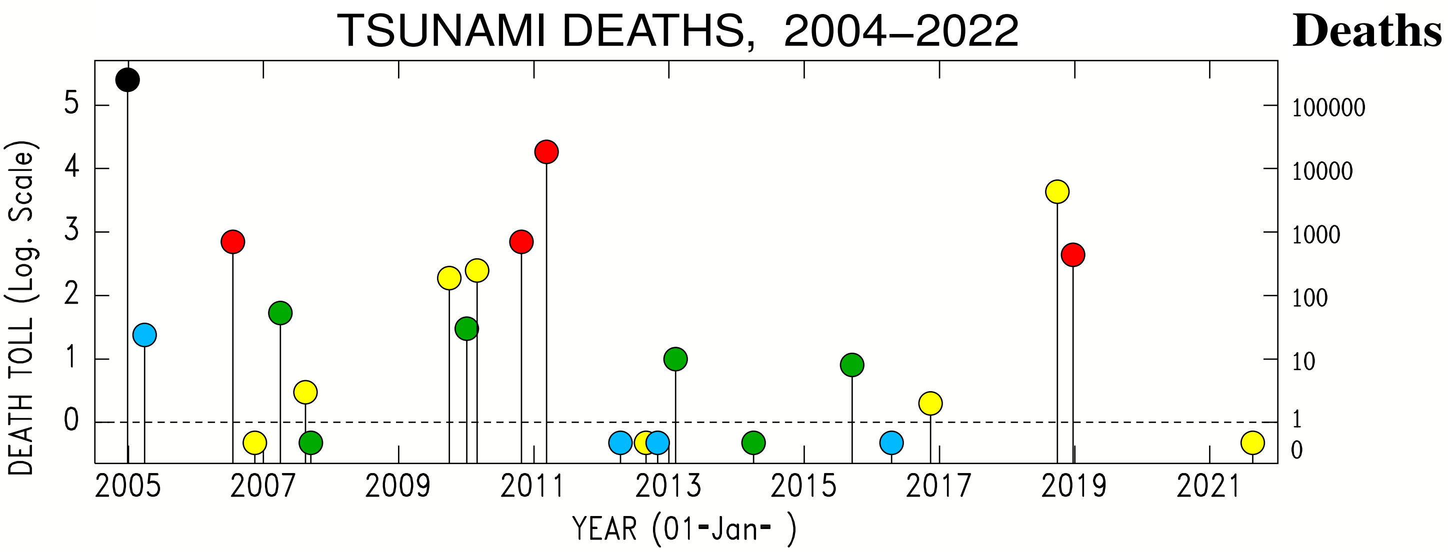
Seismic Record COCO

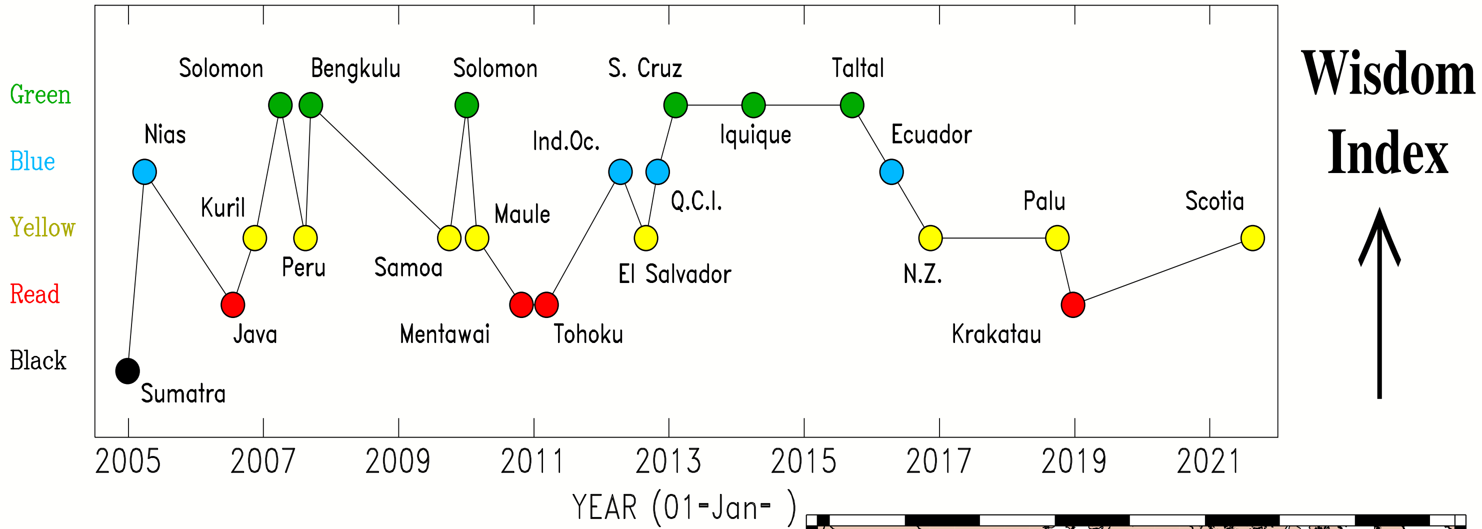




EVENT WOULD WARRANT A MUCH MORE DETAILED STUDY

CONCLUSION: *Post–TOHOKU: Any WISER ?*

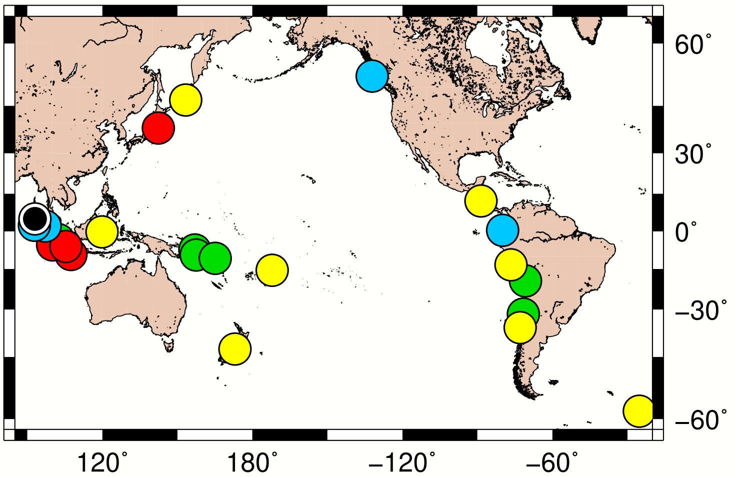




- *A "Mixed Bag"*, with **no evident trends**
  - *Indonesia: A Special Case*

    One country, diverse results

→ *Brace yourself for Padang, 20xx ...*



→ **Note consistently good results in Solomon Is...** *EDUCATION !*

ROBUST RESULTS

- Far field generally well managed
- *"Tsunami Earthquakes"* remain major challenge in near field
- **Value of education once again stressed**
- Frequent cacophony between Scientists and Decision-makers

- **Scientific Wisdom ?**
- **Mitigation Wisdom ?**
- **Operational Wisdom ?**
- **Societal Wisdom ?**

TWO REVEALING STATISTICS

1. TOHOKU — 11 MAR 2011

A Human Success Story ?

As bad as the death toll stands (19,000),

IT HAS BEEN ESTIMATED THAT, OF THE POPULATION PRESENT in the FLOODED AREA,

AS MANY AS **92 %** **SURVIVED**

This constitutes a remarkable tribute to the awareness and preparedness, in a word to the education, of the people of Japan.

[*L. Dengler,* pers. comm., 2011; *H. Fritz,* pers. comm., 2011]

TWO REVEALING STATISTICS

2. IN THE FAR FIELD, *and since Sumatra,*

We have suffered

***ONLY* FIVE (5) Tsunami Casualties**

- **Tohoku 2011**

  One death in Crescent City, California
  One death near Jayapura, Papua, Indonesia

  Both in defiance of evacuation orders

- **Queen Charlotte 2012**

  One person killed by drunk driver during evacuation in Hawaii

  Does this constitute a tsunami casualty ?

- **Tonga Explosion 2022**

  Two persons killed in Peru
  Apparently in defiance of evacuation order

ANOTHER, OMINOUS CONCLUSION

→ *Careful scientific post-mortem of Fukushima disaster reveals negligent design, engineering and management of nuclear plant, suggestive of incompetence, and/or even corruption.*

Fukushima nuclear disaster was preventable: Study

Published September 22, 2015 | By admin

SOURCE: TNN

The Fukushima nuclear disaster of 2011 could have been prevented, a new review has found. It said that "arrogance and ignorance," design flaws, regulatory failures and improper hazard analyses doomed the costal nuclear power plant even before the tsunami hit.

[*C.E. Synolakis and U. Kânoğlu,* 2015]

A FEW REMAINING CHALLENGES

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

SUCH EVENTS ARE
PARTICULARLY TREACHEROUS
AS THEY NEGATE THE CONCEPT OF

"The Warning is the Shaking"

WHICH HAS BEEN AN OTHERWISE
SUCCESSFUL MEANS OF REAL-TIME
TSUNAMI MITIGATION IN THE NEAR FIELD

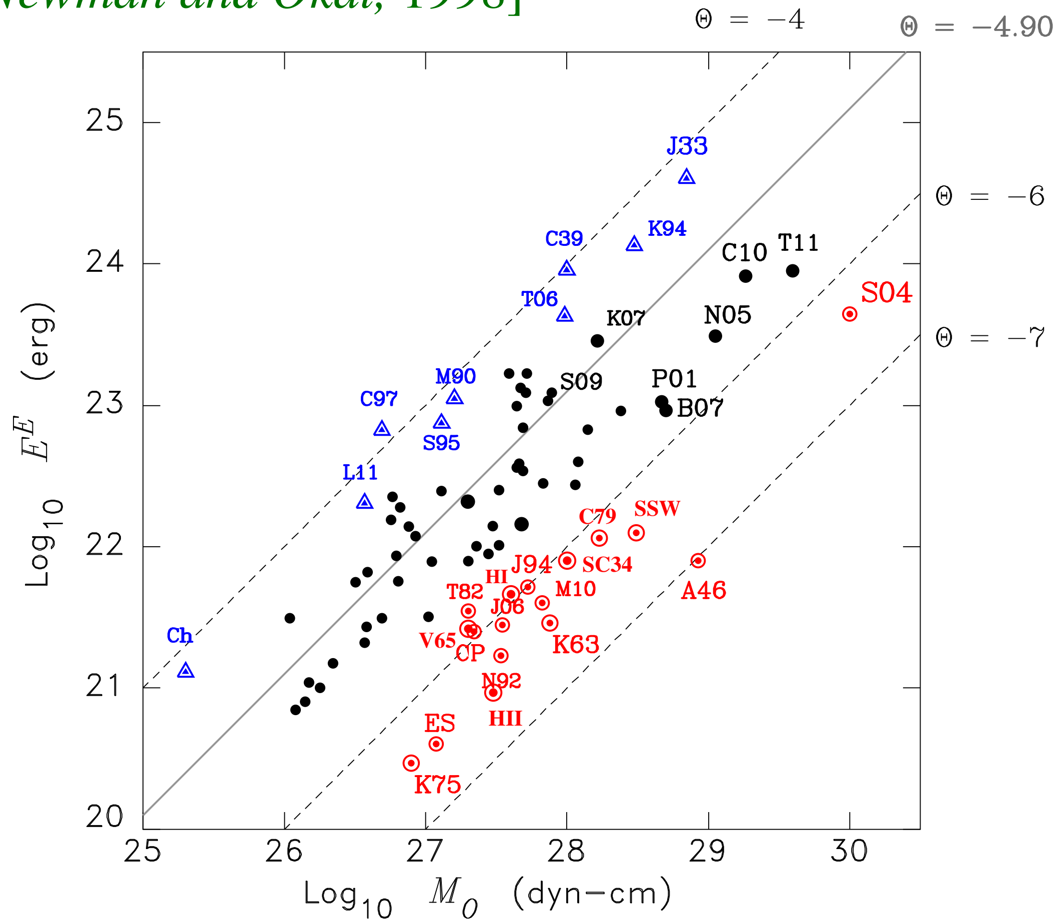
24 Documented Tsunami Earthquakes as of 2023

Year	Region	Θ
	Charter Events [Kanamori, 1972]	
1896	Sanriku	
1946	Aleutian	–7.0
	Primary Events	
1907	North Sumatra	
1947	Hikurangi I	–5.94
1947	Hikurangi 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	–6.10
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

ENERGY–to–MOMENT RATIOS

$$\Theta = \log_{10} E / M_0$$

[*Newman and Okal,* 1998]



RED: *SLOW Source, Deficient in Energy*

[BLUE: *FAST, Snappy Source*]

ALL TSUNAMI EARTHQUAKES HAVE DEFICIENT Θ (≤ – 5.8)

ACCELERATE THE WARNING

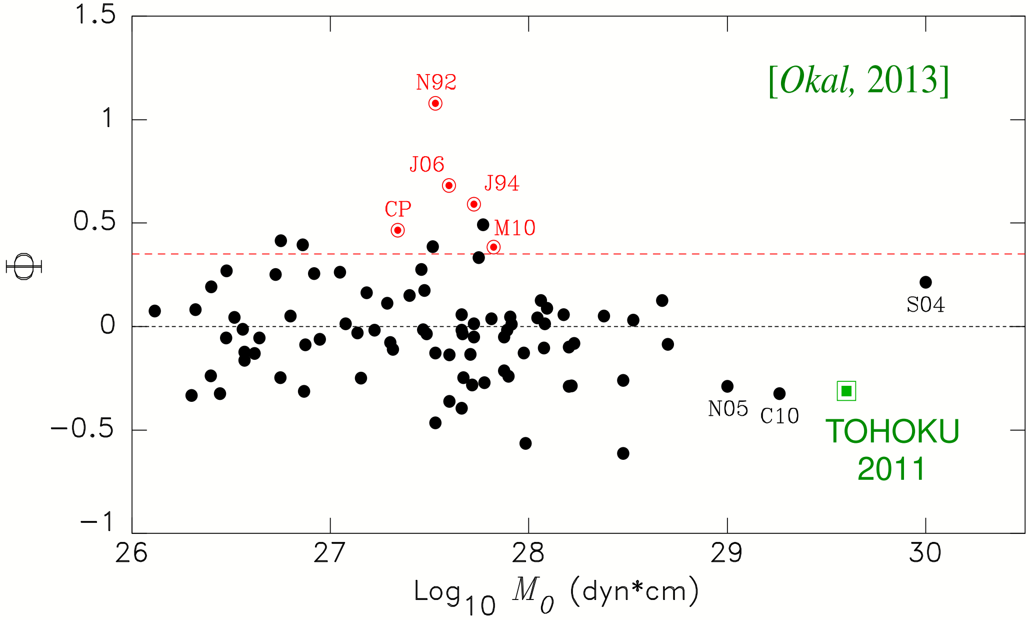
A SLOW EARTHQUAKE SHOULD HAVE :

- *AN INCREASED DURATION* $(\tau_{1/3})$
- *A DECREASED ENERGY* (E^E)

both measurable from *P* waves

→ **Hence, FORM THE DISCRIMINANT:**

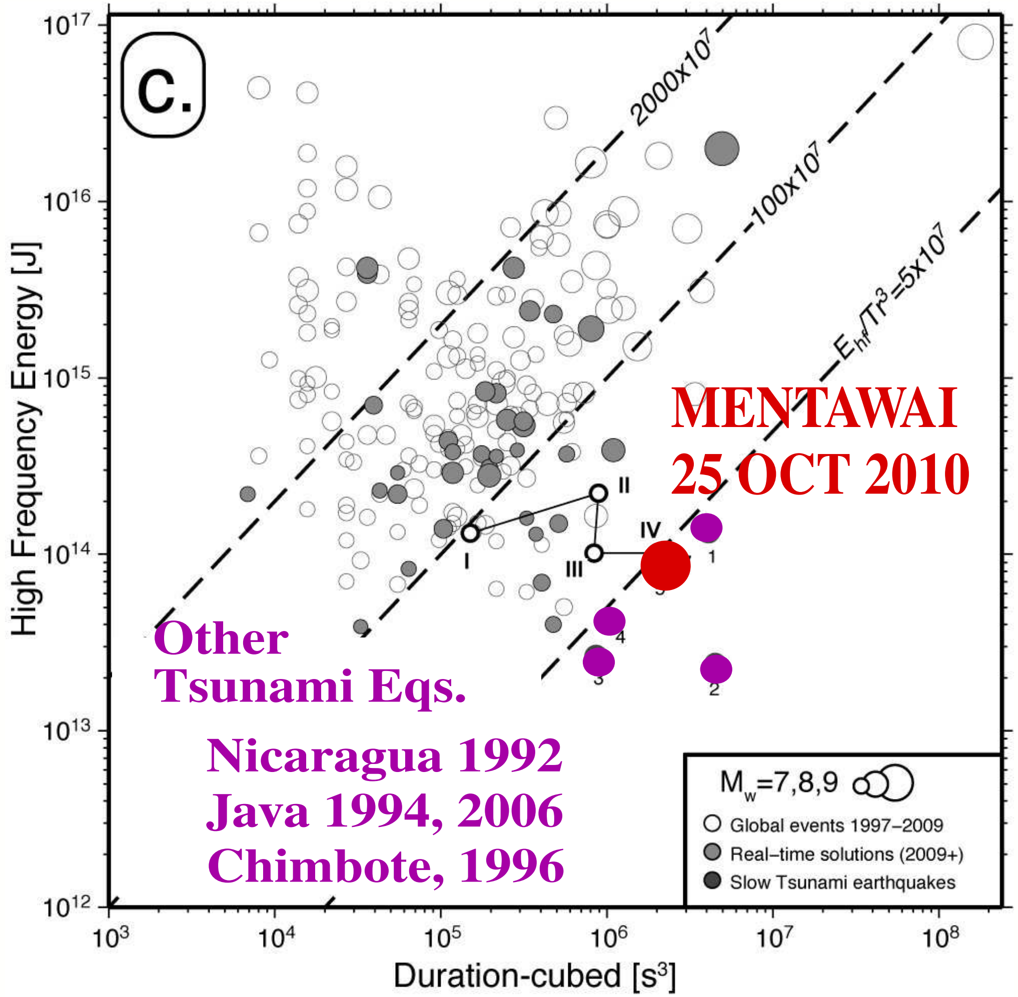
$$\Phi = \log \tau_{1/3} - \frac{1}{3} \log_{10} E^E + 5.86$$



ALL TSUNAMI EARTHQUAKES HAVE $\Phi > 0.38$

NEWMAN's RATIO E_h / T_r^3

A very similar approach was developed by Newman et al. [2011], who incorporated it into a real-time algorithm testing the ratio E_h / T_r^3 of high-frequency energy to rupture time cubed.



MENTAWAI E.Q. IDENTIFIED AS TSUNAMI EARTHQUAKE by AVN 17 min after Origin Time

Challenges...

LANDSLIDE TSUNAMIS

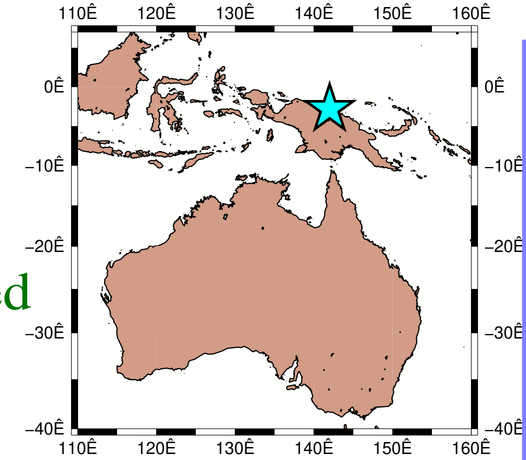
Landslides suggested as tsunami sources as early as *Gutenberg* [1939]

***Wake – up Call*: PAPUA NEW GUINEA (PNG)**

17 JULY 1998

2200 dead

- Ten villages eradicated



YET, The Earthquake was relatively small

$(M_m = 6.8)$

More Events

CLASSIC: **1929 Grand Banks**

1958 Lituya Bay (run-up 525 m!)

RECENT:

* **Taan Bay, Alaska, 2015.** *Run-up:* **193 m**

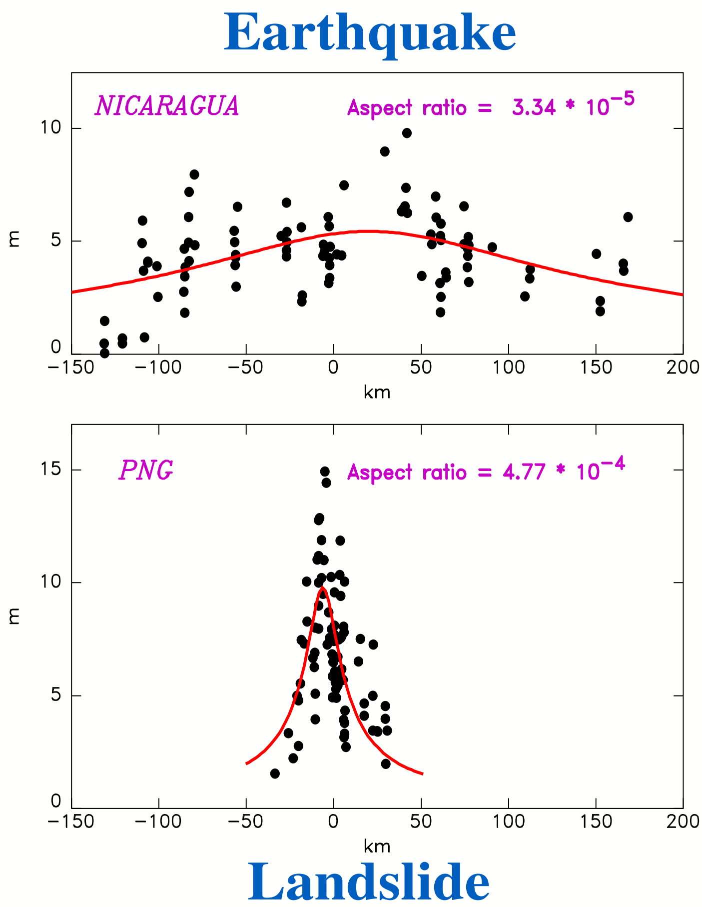
* **Karrat Fjord, Greenland, 2017. 4 dead**

c [*Paris et al.*, 2019]

LANDSLIDE TSUNAMIS

SOBERING FACTS

* **Small sources with large displacements** result in *NEAR FIELD RUN-UP Concentrated in short segment of coast*



* Small sources mean *SHORTER WAVELENGTHS*

* Slower Rupture Velocities create Destructive Interference at Sources

BOTH combine to

DISPERSE TSUNAMI IN THE FAR FIELD

[*Okal and Synolakis,* 2003]

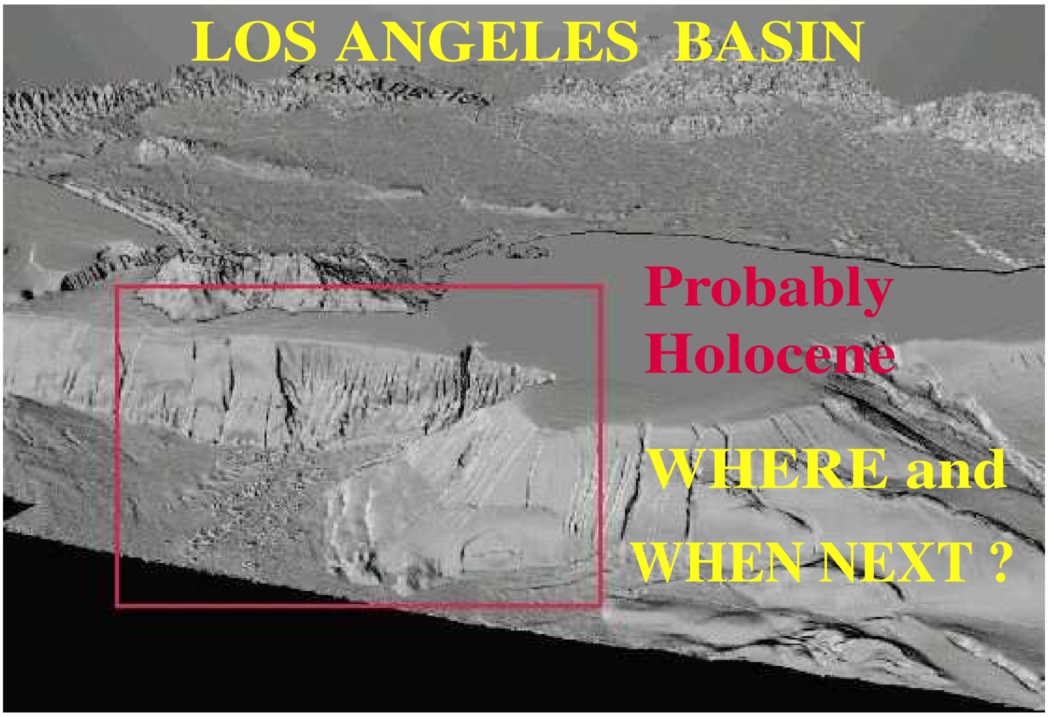
FOR AERIAL LANDSLIDES FALLING INTO THE SEA, We should be reasonably well equipped to monitor areas at risk with modern technology (GPS, LIDAR, etc.)

LANDSLIDE TSUNAMIS

OMINOUS FACTS

* **Landslides can be triggered by** *SMALL EARTHQUAKES*, even **UNFELT** ones
* **Landslides can be triggered at great distances (Rukwa, 1910: ≥ 900 km)**

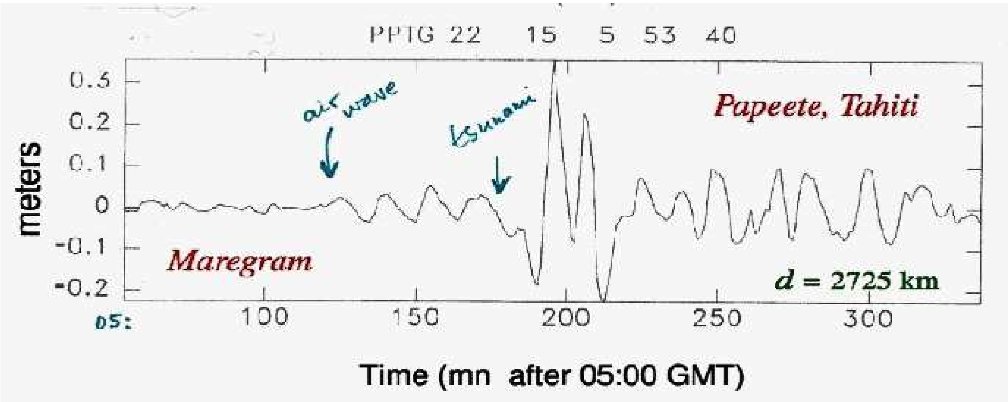
FOR UNDERWATER LANDSLIDES, WE PRESENTLY HAVE NO MEANS of MONITORING PREMONITORY SEAFLOOR CREEP OR DEFORMATION



The development of such technology should be a scientific priority of further tsunami mitigation in the next decades

A FEW QUICK FACTS ABOUT TONGA 2022

The volcanic explosion in Tonga was the first of a comparable size since Krakatau in 1883. It generated two kinds of waves



- *A genuine tsunami travelling only in oceanic basins at the classical velocity $\sqrt{gH}$, generated as a combination of the landslide involved during the collapse of the island, and of the excitation of the atmospheric continuation of the tsunami eigenfunction into the atmosphere, by the ensuing atmospheric explosion.*

  This genuine tsunami reached about 15 m in the Tongan Islands, and stopped at far-field continental shores, where it reached ~1 m in Peru (2 far-field casualties).

- *An atmospheric ("Lamb") air wave propagating **in the atmosphere** at a velocity of ~313 m/s, **both over land and sea**.*

  This wave is **primarily elastic** and does **NOT** constitute a "tsunami" of the atmosphere.
  It went around the Earth several times.

→ *When passing over a water basin, it is prolonged in the liquid layer, but the oscillations of the sea surface again* **DO NOT** constitute a genuine tsunami, of which they **do not** share the structure.

The amplitude of these oscillations was at most **decimetric** and decreases **strongly with decreasing water depth**.

The amplitude *reported* by DART sensors is ***WRONG*** because the pressure response of the water column, *strongly dependent on water depth* ***NEVER*** takes the hydrostatic value 1 cm/mbar.

→ **THIS SYSTEM DOES NOT CONSTITUTE A "METEOTSUNAMI" BECAUSE IT DERIVES ITS ENERGY FROM THE EARTH's INTERNAL ENGINE, NOT FROM THE WEATHER SYSTEM.**

La Science est l'Asymptote de la Vérité

Ou, peut-être...

à l'envers !

Victor Hugo