LESSONS FROM ELEVEN TSUNAMIS
FROM 2004 SUMATRA TO 2011 TOHOKU:
Applications for Haiti and the Caribbean

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• Scientific Lessons?

• Mitigation Lessons?

• Operational Lessons?
The 2004 [and 2005] Sumatra earthquake[s] violated the concept of a maximum expectable subduction earthquake controlled by plate age and convergence rate.

Inspired from Uyeda and Kanamori [1979]
The 2004 [and 2005] Sumatra earthquake[s] violated the concept of a maximum expectable subduction earthquake controlled by plate age and convergence rate.

Modern parameters: > 55 Ma; 5 cm/yr Would predict Maximum 8.0–8.2 not ≥ 9...

[Ruff and Kanamori, 1980]
Over the past 25 years...

→ We have obtained new rates
Tonga (20°S): 185 mm/yr vs. 89
Vanuatu: 103 mm/yr vs. 27

Examples: South Chile 70 mm/yr vs. 111
South Peru: 67 mm/yr vs. 100

We have "discovered" new earthquakes
Examples: Sumatra 2004!
Cascadia, 1700

We have revised the size of historical earthquakes
Example: 1906 Colombia-Ecuador:

\[ M_0 = 6 \times 10^{28} \text{ dyn-cm} \text{ vs. } 2 \times 10^{29} \]

1906

1979

Comparison of the Love waverains \( G_s \) of the 1906 and 1979 Ecuador-Colombia earthquakes, as recorded on the NS component of the Uppsala Wewish. The records are plotted on the same scale, with the abscissa offset so as to align the \( G_s \) waverains, 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.

Japanese clues to a North American earthquake

Embarrassingly so, in subduction zones supposedly "safe" from mega-events!
USING NEW RATES, AGES & MAGNITUDES

MUCH OF THE CORRELATION VANISHES

Correlation: 80% 35%
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

Violators overlooked by RK 1980:
Alaska  Kamchatka  [Aleutians -- 1957 Debatable]

→ That leaves
Tonga (1865)  Ryukyu (1771 ?)  Kuriles  ????
LESSONS for HAITI & CARIBBEAN

Mega-earthquakes DO occur in unsuspected areas!

The Ruff–Kanamori "maximum" earthquakes for East Caribbean or West Caribbean (North of Haiti) MAY BE GROSSLY UNDERESTIMATED

Note incidentally that the 1946 Earthquake violates their model...
Another Suggestion in the Quest for WISDOM?

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

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

LOOKS GOOD! ....

Doesn’t it?
Thick trench sediments lubricate interface & allow rupture to propagate long distances, giving $M_w > 8.5$.

Looks good, but easy to find counterexamples.

**And Then...**

**2011 Tohoku**

$M_w \approx 8.9$

Mediocre Sedimentary Cover...

*Another Suggestion in the Quest for WISDOM?*

[from D. Scholl]

[D. Scholl, pers. comm., 2006, building on a suggestion by L.J. Ruff, 1985]
Thick trench sediments lubricate interface & allow rupture to propagate long distances, giving $M_w > 8.5$

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 $M_w = 8$

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

[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]
SEISMIC SCALING LAWS:

Another Casualty of Tohoku?
SIMPLE IDEAS TOWARDS SCALING LAWS

1. As the source grows, $\mu$, a material property, should remain invariant.

2. The *shape* of the fault zone may remain constant (as long as one does not reach the physical limits of the seismogenic zone — stay tuned). [The rupture can grow in all directions on the fault plane]. Hence $W \sim L$.

3. The rock cracks because it has accumulated too much strain $\varepsilon$. The latter is measured by the ratio $\Delta u / L$, or perhaps $\Delta u / W$. Such ratios should also be invariants, related to the *strength* of the rock, which ruptures at a certain, probably universal, $\varepsilon_{\text{max}}$.

4. Thus, one predicts that the seismic moment $M_0$ should grow as the cube of the linear size of the earthquake:

$$M_0 \sim L^3$$

**VERDICT**: about right (Slope close to $1/3$).

(At least for reasonably sized events).

Remember $M_0 = \mu \cdot S \cdot \Delta u$
So, WHAT DO SEISMIC SCALING LAWS MEAN?

That intensive quantities, such as

- rigidity $\mu$ $(5 \times 10^{11} \text{ dyn/cm}^2)$
- fault shape $W/L$ $(1/2)$
- rupture velocity $V_r$ $(3 \text{ km/s})$
- strain release $\varepsilon$ (or stress drop $\Delta\sigma$) $(3 \times 10^{-5}; 30 \text{ bar})$

are all $\textit{INVARINANTS}$ of the seismic system.

Or, to some extent, that

$\textit{ALL FAULT ZONES (ROCKS ?) ARE CREATED EQUAL}$

In quantitative terms, that

$\textit{ALL PROPERTIES of AN EARTHQUAKE CAN BE DERIVED FROM JUST ONE SCALAR, ITS SIZE}$

$\textit{(or Magnitude; Moment in Physical terms).}$
Tomographic studies of the source of the 2011 event reveal extreme slip ($\Delta u \geq 50$ m) concentrated along a small patch of the fault plane ($W \geq 50$ km), leading to exceptional strains (locally approaching $\varepsilon = 5 \times 10^{-3}$)

**IN CLEAR VIOLATION OF SEISMIC SCALING LAWS**

[Confirmed by seismic, geodetic, and tsunami studies]

**HOW DID THE ROCK ACCUMULATE SUCH STRAIN WITHOUT FAILING?**
Possible Causes for Violations of Scaling Laws

- **Rupturing in SOFTER material?**
  
  *Invoke Splay Faults?*

- **Influence of Landslides?**
  
  *(i.e., Different Boundary Condition)*

**PROBLEM**

→ To significantly affect final solution, such deviations from Paradigm **MUST BE COHERENT over LARGE DISTANCES**

At any rate, Tohoku 2011 reopens the case of several controversial suggestions

*(i.e., Crete, 365 A.D.)*.
LESSONS for HAITI & CARIBBEAN

Noting age similarity between Tohoku Lithosphere and West Caribbean one,

→ Worst-case scenarios of potentially tsunamigenic earthquakes should incorporate events with

Unexpectedly High Slips

relative to their seismic moments
W Phase:

A clear Success Towards

Improved Wisdom
W Phase

W as in... Whisky WISDOM

[Kanamori et al., 2008]

Geophysical Research Letters

[Kanamori, 1993]
The \( W \) phase also represents the superposition of ultra-long period overtones of Rayleigh modes with fast group velocities.

\[ M_0 \]

\[ (10^{29} \text{ dyn} \cdot \text{cm}) \]

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

A BIG STEP IN WISDOM!!
LESSONS for HAITI & CARIBBEAN

W–Phase Algorithm should become the Primary Mode of Seismic Analysis at present and future Tsunami Centers, including in the Caribbean.
• **Scientific Lessons** ?

• **Mitigation Lessons** ?

• **Operational Lessons** ?
POST–SUMATRA: EXPANDING WARNING CENTERS

- **Immediately** (Early 2005)
  PTWC chartered to cover Indian Ocean
  ATWC given responsibility over Caribbean

- Australia establishes Tsunami Warning Center
  Seismology detection at G.A. (Canberra)
  Real-time Simulation at B.M. (Melbourne)

  **Operational, Late 2007** Cost: AUD 70 million

- Indian Ocean
  Nations keep meeting and discussing Regional Center
  Germany installs Warning Center in Indonesia ... *Performance to be critically assessed.*

- Mediterranean and Atlantic Ocean
  Nations keep meeting and discussing Regional Center

  → **2009: France embarks on building a Warning Center for NE Atlantic and Western Mediterranean; Operational 01 JULY 2012.**

  → **2011: Turkey to build Eastern Mediterranean Center**
TSUNAMI WARNING AND EDUCATION ACT

Public Law 109–424
109th Congress

An Act

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,

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
2004-2013: EVOLUTION of the DART SYSTEM

- Funded by PL 109-424

2004: 6 instruments
2008: 39 instruments

Other systems deployed, many of them International
Seismic networks, including OBS
Tethered Pressure Sensors
GPS networks, including Bottom prototypes

Note: Maintenance Issues
→ A test on 23 FEB 2013 reveals 18 (32%) not transmitting, and 2 misfunctioning.
Sophisticated instrumentation such as DART buoys is only as good as it is functional.

Operational Budgets

**must include adequate provisions for their maintenance,**

*both preventive, and remedial.*
• Scientific Lessons

• Mitigation Lessons

• Operational Lessons
POST–SUMATRA TSUNAMIS

What have we learned on the Operational Front?

→ 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 Gold (Excellent) and Green (Very good) through Olive (Good), Yellow (Average), Orange (Mediocre), 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.

$M_0 = 4.6 \times 10^{27}$ dyn*cm  

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].

**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)...

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

**Question:** Does this exclude the danger of a subduction megathrust earthquake in Java?

* What is the role of the 1921 shock (contrary to the T.E.s, strongly felt, but with benign tsunami)?
LESSONS from JAVA 2006 [and Pagai, 2010]

• Recognize Anomalous Events in Real Time

[ and Remember Instrumental [ and other] History ]
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]
• The Unparalleled Value of Education...
PISCO, Peru, 15 AUG 2007,  \( M_0 = 1.1 \times 10^{28} \text{ dyn*cm} \)

- Damaging Earthquake, which destroyed the city of Pisco (514 dead)
- Yet, much smaller than previous events in Central Peru (1687, 1746)
- Significant local tsunami with run-up of 5 m, locally 8–10 m
- Most shore locations successfully evacuated through community-based program using "sergeants" directing residents to shelters built out of harm’s way.

- **EXCEPT...**

  in Lagunilla (Southern coast of Paracas Peninsula), where tsunami ran up to 10 m, penetrating 1 km inland and **killing 3 people.**

**NOTE:**

The 2007 event [partially], the 1868 event and the 1687 event [probably] jumped [into] the Nazca Ridge...

This omission in an otherwise successful program is unexplained and unacceptable.

[Fritz et al., 2008]
LESSONS from PERU 2007

• A good Mitigation Program is only as good as it is COMPLETE
SAMOA, 29 SEP 2009: *A Tale of 2 Islands...*

\[ M_0 = 1.8 \times 10^{28} \text{ dyn*cm} \]

- First tsunami to cause substantial damage and many deaths (34) on U.S. soil (American Samoa) in 45 years.

- Outer Rise Normal Faulting Event with probable predecessor in 1917.

- $200$ million damage (est.)

- **189 total deaths** in Samoa, American Samoa, Tonga.

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**SAMOA, 29 SEP 2009:**

- Population: **179,000**
- Area: Savai’i: **1708 km\(^2\)**  Upolu: **1125 km\(^2\)**  Tutuila: **200 km\(^2\)**

**Tsunami Deaths:**

- Savai’i: 34
- Upolu: 146

Epicenter 250 km to the South
SAMOA, 2009: Survey Results in American Samoa

- Run-up to 17m in Poloa
- North Coast bays significantly affected (run-up to 12 m)
- Pago Pago harbor amplified waves (run-up to 9 m)

"Only" 34 fatalities

Thanks to:

- Signage Program
- Self – Evacuation
- Community–based Evacuation

Population educated and Well prepared
SAMOA, 2009: Survey Results in Samoa (Upolu)

DEVASTATION AT LALOMANU
Run-up reached 11.4 meters, and inundation 250 m

• Run-up to 14.4 m in Lepa

• Two villages eradicated

• North Coast (with Capital, Apia) largely spared

The village was totally eradicated, with 61 fatalities

• Higher Death Toll (146) than on Tutuila
SAMOA 2009: Evacuation on UPOLU

- The population of Upolu was reasonably aware of the tsunami danger, despite the lack of ancestral memory.
- Evacuation drills had been conducted at a number of villages, but not everywhere.
- No signage program on Upolu
- In several areas, evacuation was hampered (with respect to Tutuila) by the need to travel longer distances, due to flatter terrain.
- Congestion trapped several victims in their cars.
- The recent road switch could have instilled in the population the unfortunate perception of vehicles as a panacea to natural hazards.
LESSONS from SAMOA 2009

• The Unparalleled Value of

AWARENESS, PREPARATION, Effective MITIGATION

broadly speaking, all aspects of

EDUCATION
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

- Transoceanic simulations largely correct, showing tsunami lobe between Hawaii and Tahiti, and accurately forecasting deep-water amplitudes (20 to 30 cm).

- Evacuations erred on side of caution, but largely successful. Run-up to 4 m in the Marquesas; no victims; only one boat sunk

- Conflicting reports from Warning Centers

  - Several ocean sensors down; Erratic response in California

Bottom line: **YELLOW**
LESSONS from MAULE (Chile) 2010

• *Official Warnings should be the prerogative of SCIENTIFICALLY TRAINED PERSONNEL not of Incompetent Politicians*

Lesson 2: *We are getting good at simulations and warnings in the far field.*
TOHOKU 11 MAR 2011

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

Baie de Taipivai, NUKU HIVA (Marquesas)

Une population calme

PUNAUAIA, Tahiti

Far field: Green to Olive

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

1933 SANRIKU TSUNAMI HAD REACHED 29 m at YAMADA

YET, 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!
TARO, Japan: A TALE OF TWO SEA–WALLS

A first wall was built after significant damage during the 1933 Showa tsunami.

A second wall was built in the 1970s, following construction sea-wards of the 1933 wall.

The 1930s wall withstood the 2011 tsunami (even though it was overtopped)

BUT THE 1970s WALL WAS TOTALLY DESTROYED

THE OLDER STRUCTURE CLEARLY OUTPERFORMED THE NEWER ONE

which had not been built to even elementary standards (disconnected blocks !)

[Kriebel et al., 2011; Yalçiner et al., 2011; Tsuji et al., 2011]
A Human Success Story ?
As bad as the death toll stands (20,000),

_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]
THE TEPCO DEBACLE

- The report from the second review, in 2010, is available in a TEPCO slide show. It used a number of simulations to infer a maximum wave height of **5.7 m at the site of the plant**.

The following flaws in this report are immediately apparent:

- It fails to quantify (by moment, magnitudes or seismic slip) the sources used;
- The maximum run-up envisioned (6 m) requires source slips \( \leq 3 \text{ m} \), or \( M \leq 7.9 \), underestimating **known seismicity** in Eastern Japan;
- It is against common sense that hazards from local and far-field tsunamis should be found comparable.

**NOTE:**

- It is undefendable that the maximum wave height computed (6 m) should be 5 to 6 times **LESS** than reported on other segments of the Sanriku Coast as recently as in 1933 (29 m) and 1896 (38 m).
THE TEPCO DEBACLE: Post-Mortem

The Simulations are probably NOT COMPUTATIONALLY WRONG

- But their initial conditions fail to represent the worst-case scenario that the construction of a nuclear plant should require.
- The selection of their parameters inexplicably ignored aspects of Japanese seismicity notorious not only in the scientific community, but also within the senior Japanese population (extreme run-up in 1933).
- It is hard to believe that educated "experts" would not have been familiar with this evidence.

Thus, the motivation behind their use of deficient earthquakes as "design sources" is at best obscure, at worst suspect.
LESSONS from TOHOKU 2011

1. We are getting very good at simulations and mitigation in the far field:  
   Only 2 confirmed far–field deaths

2. Unparalleled Value of Education (92% saved...).

3. Make sure Modern Technology is as Resilient as Ancient one (Tora Walls...).

4. Make sure you prepare for the next "war", not just the previous one (6–m walls)

5. Keep common sense when interpreting sophisticated simulations  
   (Worst-case scenario should be, by definition, worse than documented events)

6. Corruption exists even in developed countries
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
**FINAL LESSONS**

**EDUCATION WORKS**

- The Moken people of the Surin Islands
- Little 10-year old English girl in Phuket
- Professor C.H. Chapman in Sri Lanka
- Japanese tourists in high-rise hotels

2004:

→ Post-Sumatra Successes: Nias (SMONG); Solomon (2 ×); Peru; Bengkulu; Maule [partially], Tohoku ("92%"...)

**EDUCATION is NEEDED!**

**DO NOT EXPLORE EXPOSED BEACHES!!**

Coral Reef (normally invisible)


Sumatra Tsunami, Madagascar, 26 Dec. 2004

**RUN TO SAFETY ON HIGHER GROUND!!**