LECTURE 5

EARTHQUAKE

SCALING LAWS

EARTHQUAKE SOURCE PARAMETERS

- We seek to understand the properties of very large earthquakes. However, they are very rare.

- Thus, we look at patterns in the *growth* of earthquakes

- We examine the various parameters describing the earthquake source.

- Recall

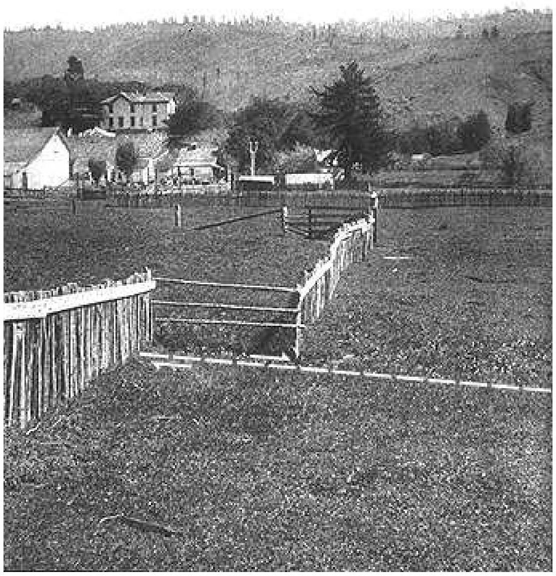
$$M_0 = \mu \cdot S \cdot \Delta u = \mu \cdot L \cdot W \cdot \Delta u$$

→ Can we measure these terms independently?

* *FAULT SLIP* Δu

Imperial Valley, 1979

$M \approx 6$; $\Delta u = 25$ **cm**



San Andreas, 1906

$M \approx 8$; $\Delta u = 2.6$ **m**

EARTHQUAKE SOURCE PARAMETERS

* *FAULT LENGTH L*

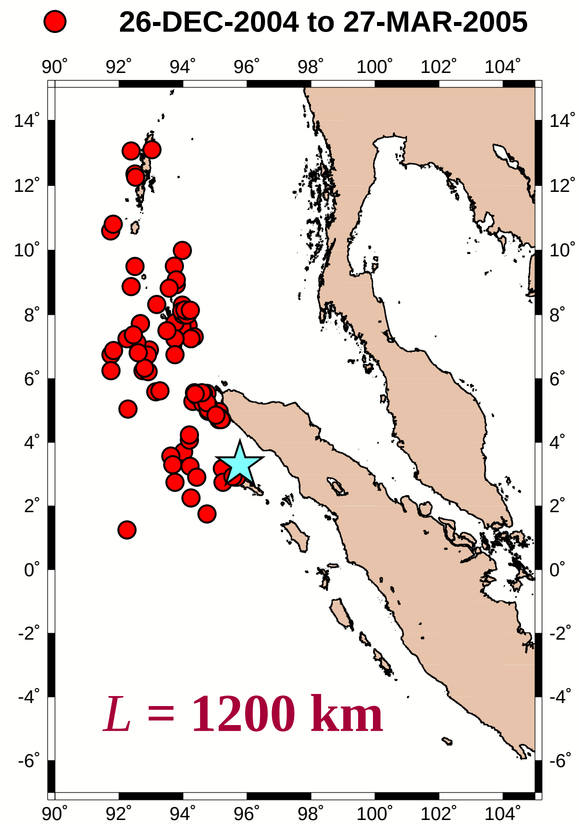
- It is some times possible to follow an earthquake rupture on the field, and to gain an estimate of its length *L*.

Borah Peak, Idaho; 1983

Landers, Calif.; 1992

- *Aftershocks* are universally used as espressing the extent of the rupture zone of a major earthquake.

This approach also yields an estimate of the transverse dimension (width *W*).



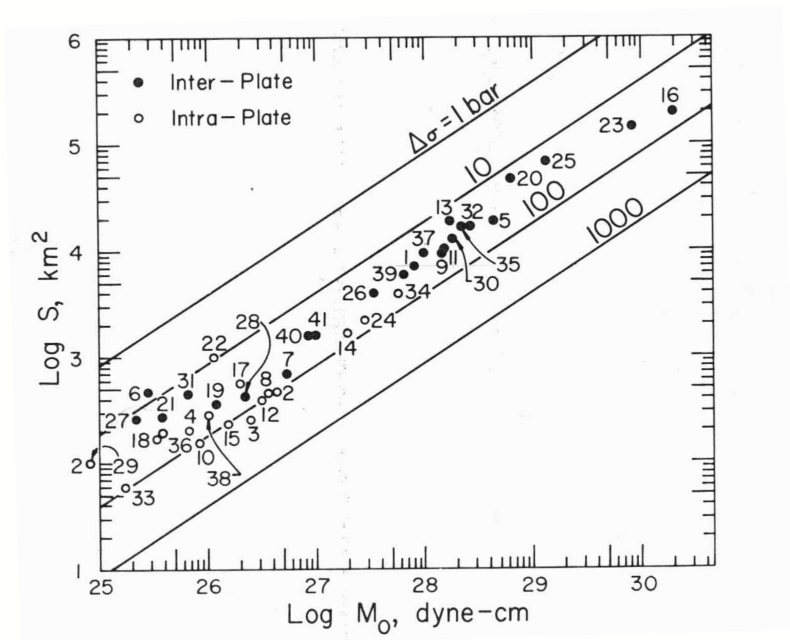
Principal Aftershocks of the 2004 Sumatra earthquake

GROWTH of PARAMETERS with EARTHQUAKE SIZE

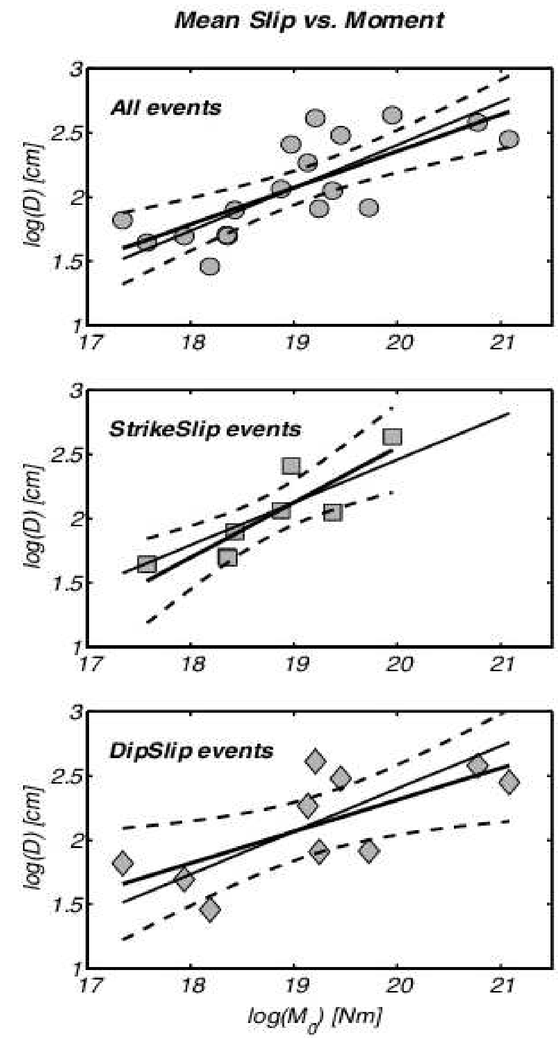
- Empirical evidence verifies that parameters such Δu, L, S, perhaps W, grow with the size of the earthquake, expressed by its seismic moment.

$\Delta u\ [D]$ *vs.* M_0

S *vs.* M_0



[*Kanamori and Anderson*, 1975]



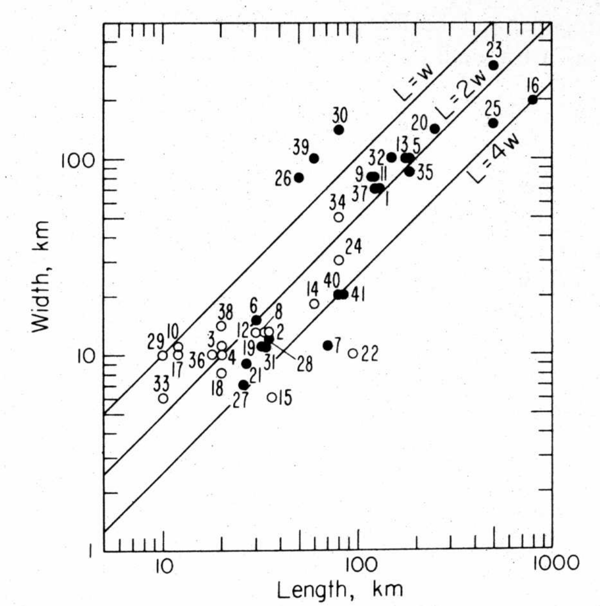
[*G. Beroza*, www.stanford.edu]

SIMPLE IDEAS TOWARDS SCALING LAWS

1. As the source grows, μ, 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* ε. 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, $\varepsilon_{\max}$.



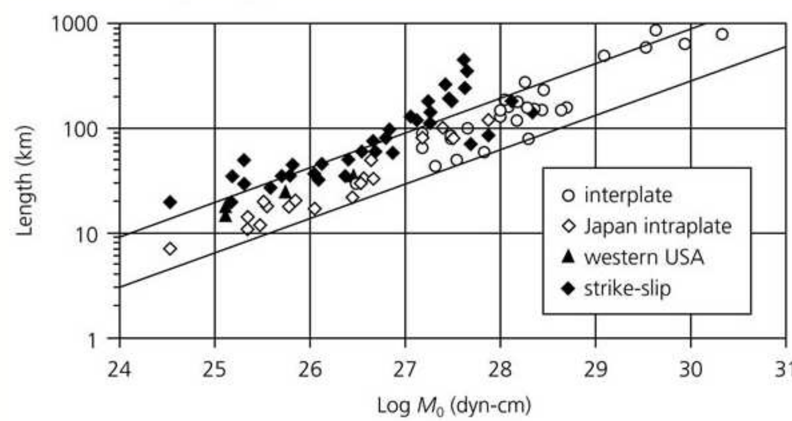
[*Geller*, 1976]

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).



[*Stein and Wysession*, 2002]

SCALING LAWS and $b-$ [β–]VALUES

Frequency−Size Distributions

- It is known that there are more small earthquakes than large ones.

  Why ? and can it be quantified ?

→ *Gutenberg and Richter* [1954] proposed $\log_{10} N = a - b \cdot M$, with $b \approx 1$.

- *JUSTIFICATION:* [*Rundle*, 1989] Rupture is a scale-invariant process, or "All elements of a fault have the same probability of being released by an earthquake of any size".

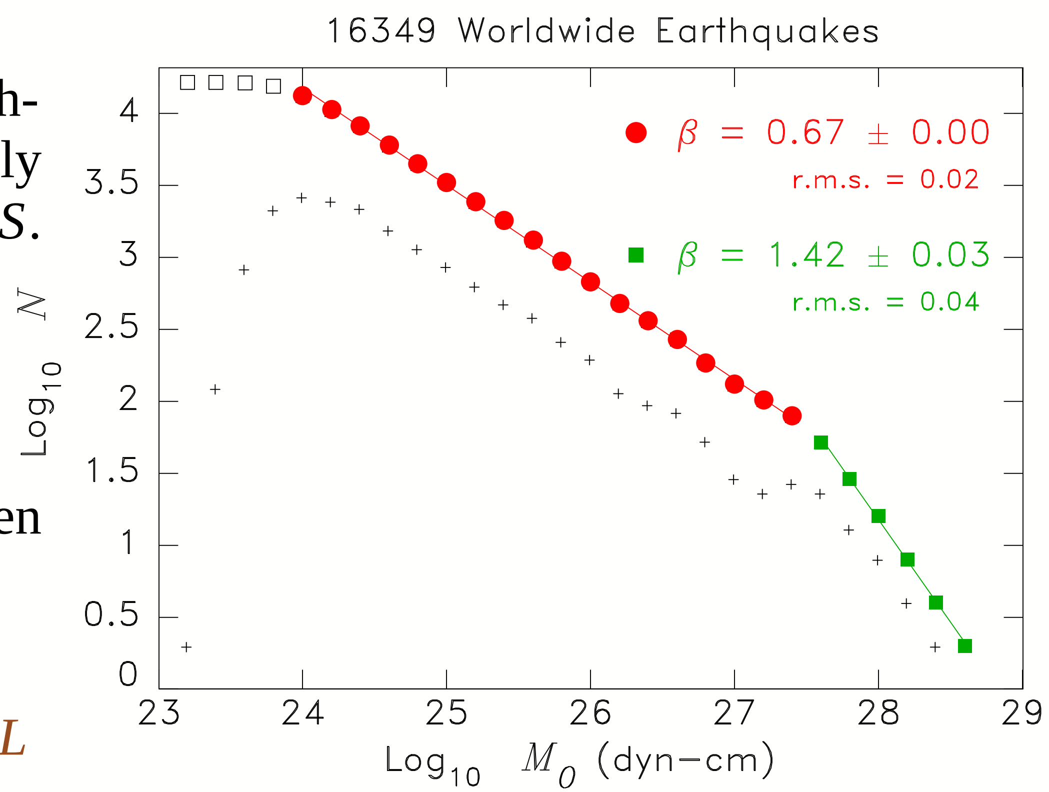
This suggests that the number of earthquakes of any given size N, is inversely proportional to the area of rupture, S. Hence $N \sim 1/S$, or as $M_0 \sim S^{3/2}$,

$$\log_{10} N = a - \beta \cdot \log_{10} M_0 \qquad \beta = \frac{2}{3}$$

[and if one uses a slope of 3/2 between M_0 and a magnitude M, then $b = 1$.]

UPHELD SPECTACULARLY WELL

[at least for "not too large" earthquakes]



[*Okal and Sweet*, 2007]

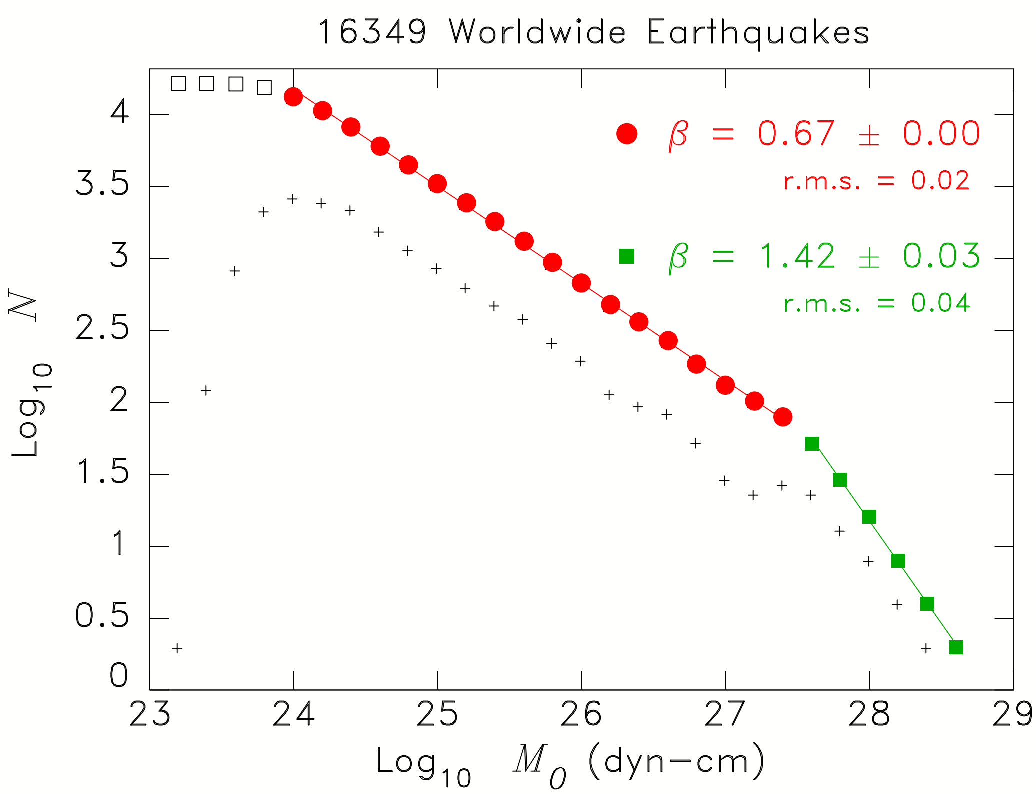
BREAKDOWN of SCALING LAWS

at Large Moments

- The seismogenic zone is limited in space, principally the parameter W, due to the *increasing temperature at depth* in the Earth; the material ceases being *brittle*.

- Δu may also stop growing with earthquake size, to keep the strain $\varepsilon = \Delta U / W$ invariant.

- Then one predicts $M_0 \sim L$, and $\beta = 1$.



$\rightarrow$ Rather *WELL VERIFIED*, but *CONTROVERSIAL* (the population of large events is small and may be heterogeneous).

SOURCE FINITENESS and GROWTH

→ To understand the properties of waves (seismic or tsunami) from great earthquakes, we must remember that

A GREAT EARTHQUAKE IS

EXTENDED IN TIME and SPACE

(it needs Room and it needs Time)

- *RISE TIME* τ is the time necessary for walls of the fault to move with respect to each other.
- *RUPTURE TIME (or DURATION)* T_R is the time it takes for the cracking to propagate from one end of the fault to the other.

→ **SIMPLE IDEAS:**

- If the motion of the particles along the fault is at a constant velocity, then

$$\tau \sim \Delta u \sim M_0^{1/3} \qquad = \quad \text{a few seconds}$$

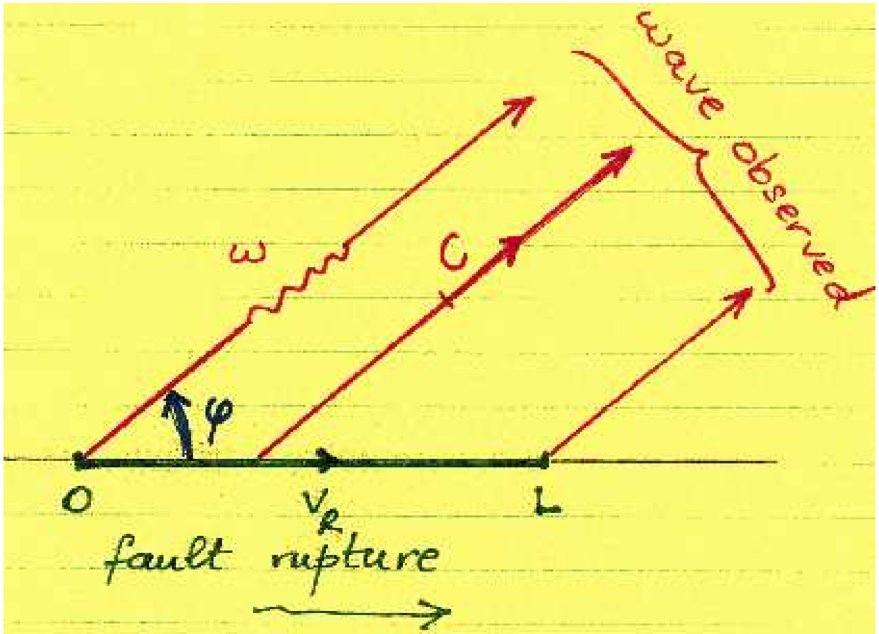
- If the propagation of the rupture along the fault is at a constant velocity, then

$$T_R \sim L \sim M_0^{1/3} \qquad = \quad \text{tens of seconds}$$

($\geq$ 500 seconds for Sumatra, 2004).

FAR FIELD: THE BASICS of DIRECTIVITY

[*Ben Menahem*, 1962]



If a source propagating a length L at velocity V_R in the direction x generates a wave traveling at phase velocity C observed at an angle ϕ from x, then the amplitude of the wave is affected by a *DIRECTIVITY* function D

$$D = \frac{\sin Y}{Y} \quad \text{with} \quad Y = \frac{\omega L}{2C} \cdot \left[\frac{C}{V_R} - \cos\phi \right]$$

This formula simply expresses that the various elements of the source always interact destructively at high enough frequencies, *except when the wave propagation compensates exactly the offset of source time*

($\sin Y / Y$ maximum requires $Y = 0$.)

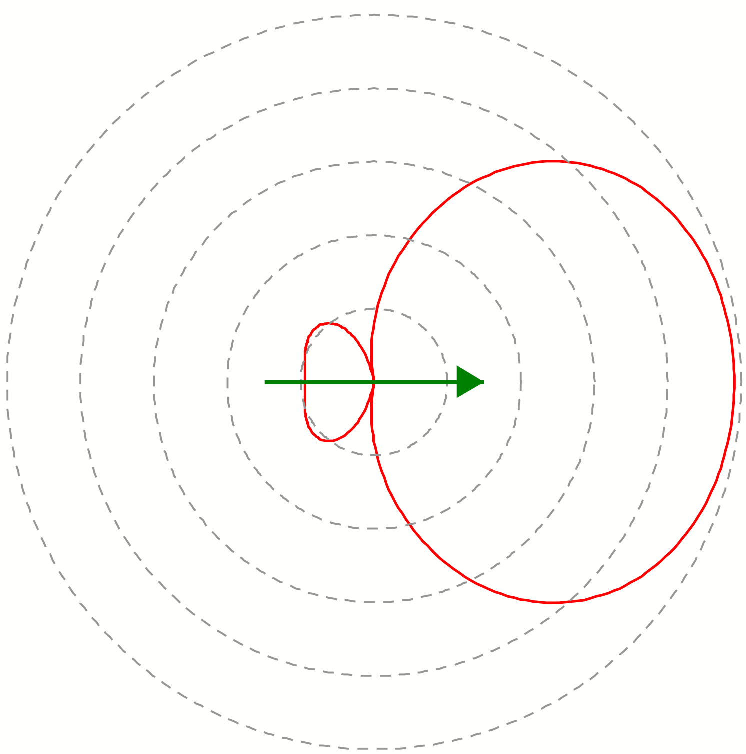
$$D = \frac{\sin Y}{Y} \quad \text{with} \quad Y = \frac{\omega\, L}{2\,C} \cdot \left[\frac{C}{V_R} - \cos\phi \right]$$

Then several scenarios can take place

- *Seismic surface wave generated by a seismic dislocation*

Then, V_R is close to C (3.5 to 4 km/s), and the maximum of directivity is *in the direction of propagation*.

120 s; 300 km; VR =3.5 km/s; C = 4 km/s



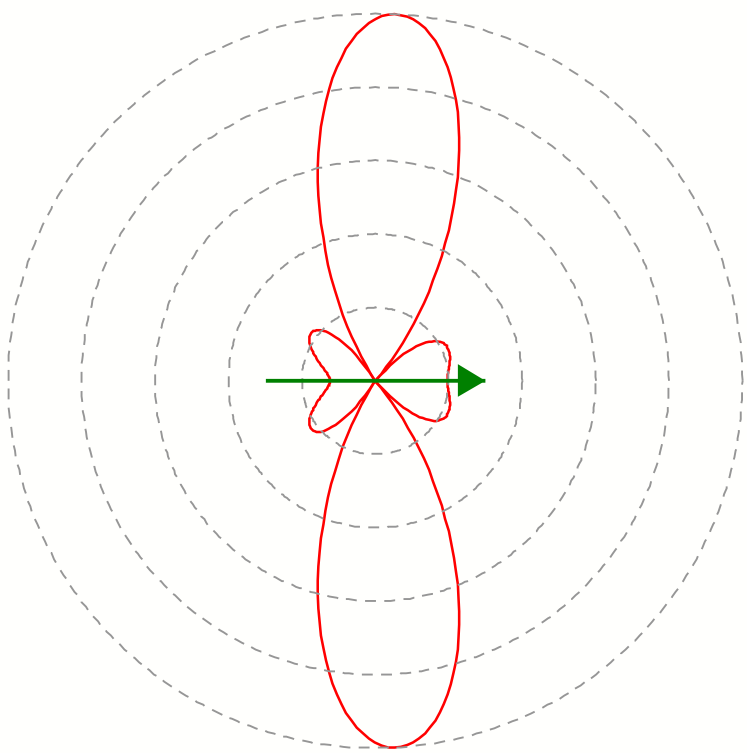
(A classic result in Seismological Source theory)

$$D = \frac{\sin Y}{Y} \quad \text{with} \quad Y = \frac{\omega L}{2C} \cdot \left[\frac{C}{V_R} - \cos\phi \right]$$

• *Tsunami generated by a seismic dislocation*

Then, V_R is always much greater than C, and the maximum of directivity is *at right angles to the fault strike.*

900 s; 300 km; VR =3.5 km/s; C = 0.2 km/s



[*Ben-Menahem and Rosenman*, 1972]

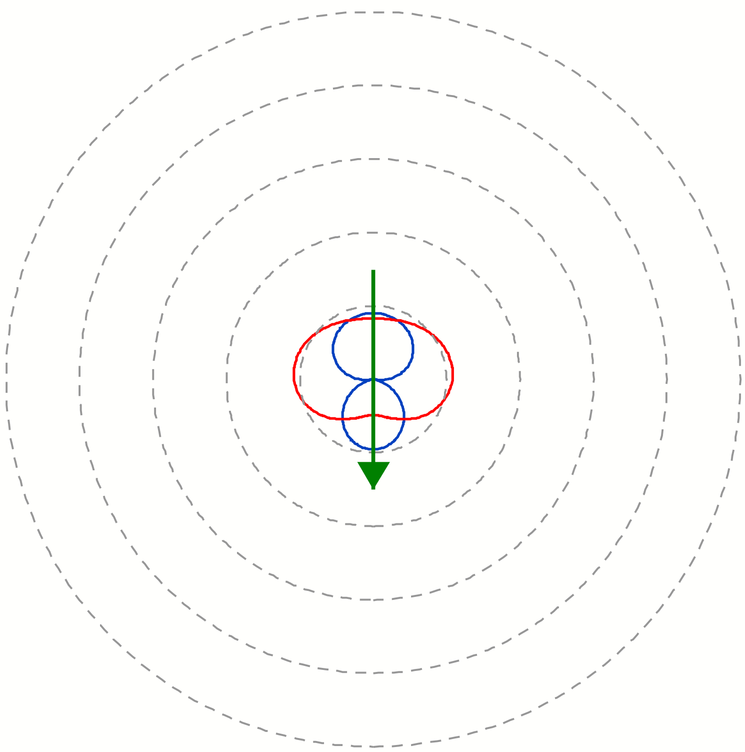
The tsunami is so slow that the source appears instantaneous, and the interference is constructive only in a direction where distance is stationary along the fault line.

$$D = \frac{\sin Y}{Y} \quad \text{with} \quad Y = \frac{\omega L}{2C} \cdot \left[\frac{C}{V_R} - \cos\phi \right]$$

- *Tsunami generated by a landslide*

Then, V_R is always much *SMALLER* than C, and the interference is always destructive (for long enough sources).

600 s; 25 km; VR =0.04 km/s; C = 0.2 km/s
900 s; 50 km; VR =0.04 km/s; C = 0.2 km/s



The rupture is so slow (with respect to the wave) that there are no directions in which it can be compensated by the variations of phase due to propagation.

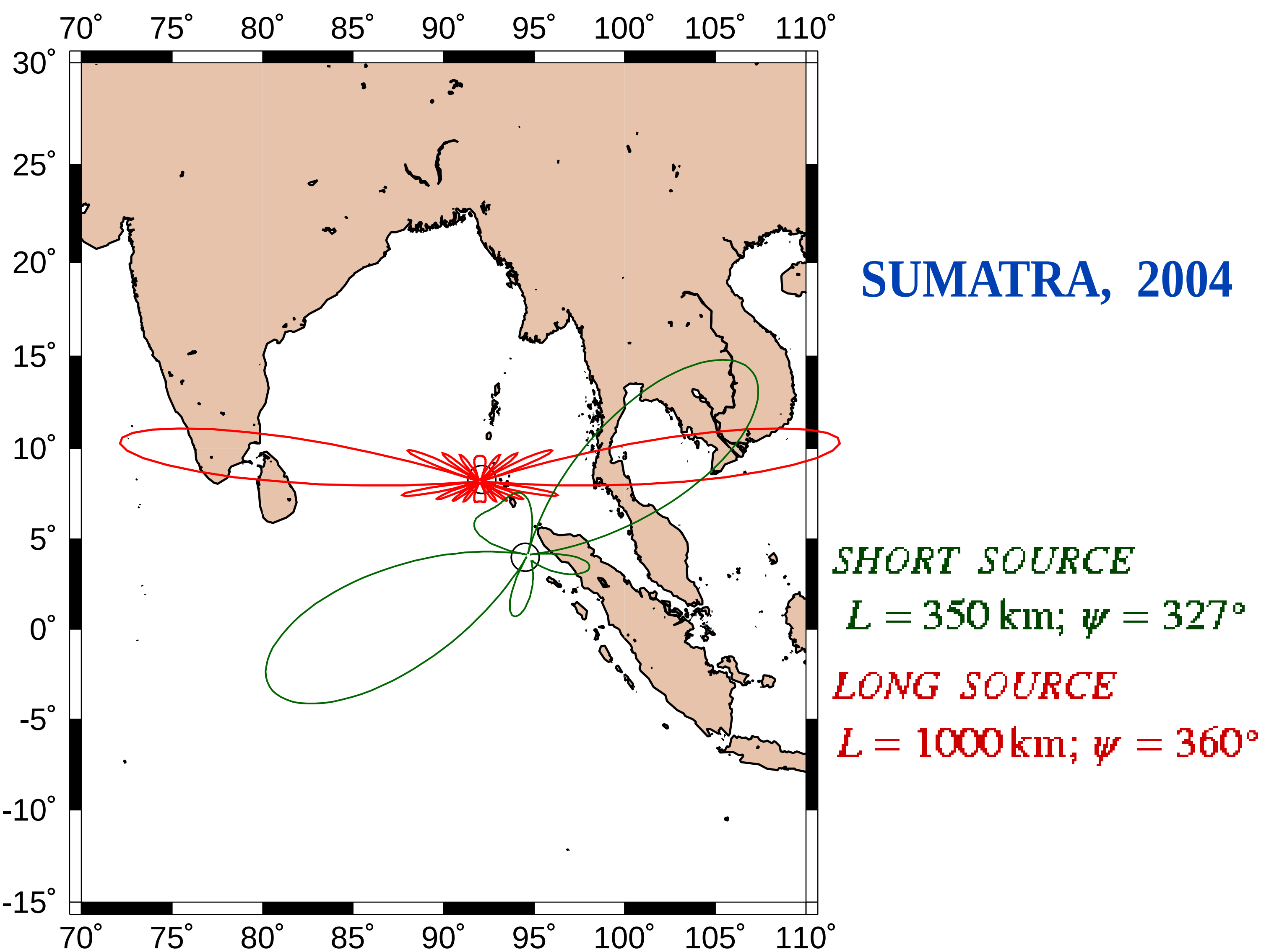
LANDSLIDES CANNOT GENERATE FAR-FIELD DIRECTIVITY

Note in particular

- Even *slow* earthquake rupture velocities **(1 km/s)** are hypersonic with respect tsunami propagation.

- Even the *fastest recognized* submarine landslide velocities **(50 m/s)** are considerably slower than tsunami velocities.

→ Directivity lobes for tsunami become **narrower** as Earthquake size increases [*Okal and Talandier,* 1991].



FROM FINITENESS to SATURATION

- In general, any seismic wave (body or surface) of (angular) frequency ω will have a spectral amplitude directly proportional to the seismic moment, or

$$X(\omega) \sim M_0 \sim L^3$$

→ Effect of directivity:

$$D = \frac{\sin Y}{Y} \quad \text{with} \quad Y = \frac{\omega L}{2c} \cdot \left[\frac{C}{V_R} - \cos\phi \right]$$

For small events (small L), $Y \to 0$ and $D \to 1$.

For big events (large L), $Y \to 0$ and $D \sim \frac{1}{L}$.

We anticipate $X(\omega) \sim L^2$.

→ But, there should also be a similar effect along the width W of the fault. Hence an additional factor $D_W \sim 1/W$ for large events.

→ And the source has a rise time τ, which also grows with earthquake size, leading to yet another function $D_\tau = \frac{\sin Y_\tau}{Y_\tau} \sim \frac{1}{\tau}$.

In the end, the spectral amplitude of a wave is expected to grow like

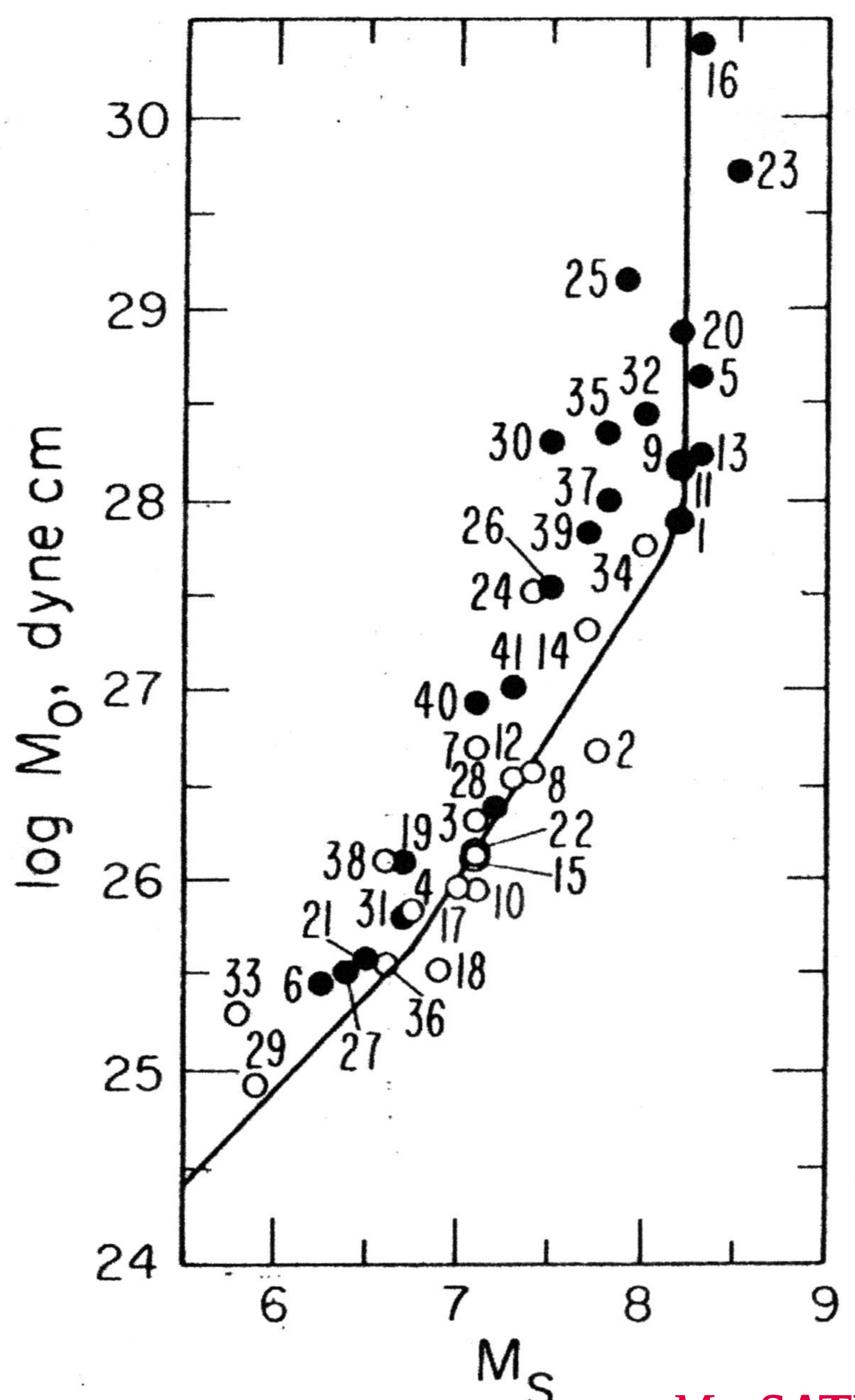
$$X(\omega) \sim \frac{M_0}{L \cdot W \cdot \tau} \sim \frac{L^3}{L^3} = \text{constant}$$

WE PREDICT TOTAL SATURATION !!

SATURATION Of M_s

Any magnitude scale measured using a constant period *T* (20 s for M_s) will saturate for large enough earthquakes, namely when the *duration* of the source becomes longer than *T*.

• In REMARKABLE agreement with OBSERVATIONS.



FAR-FIELD TSUNAMI DANGER

EXTREME

PROBABLE

LOW

NIL

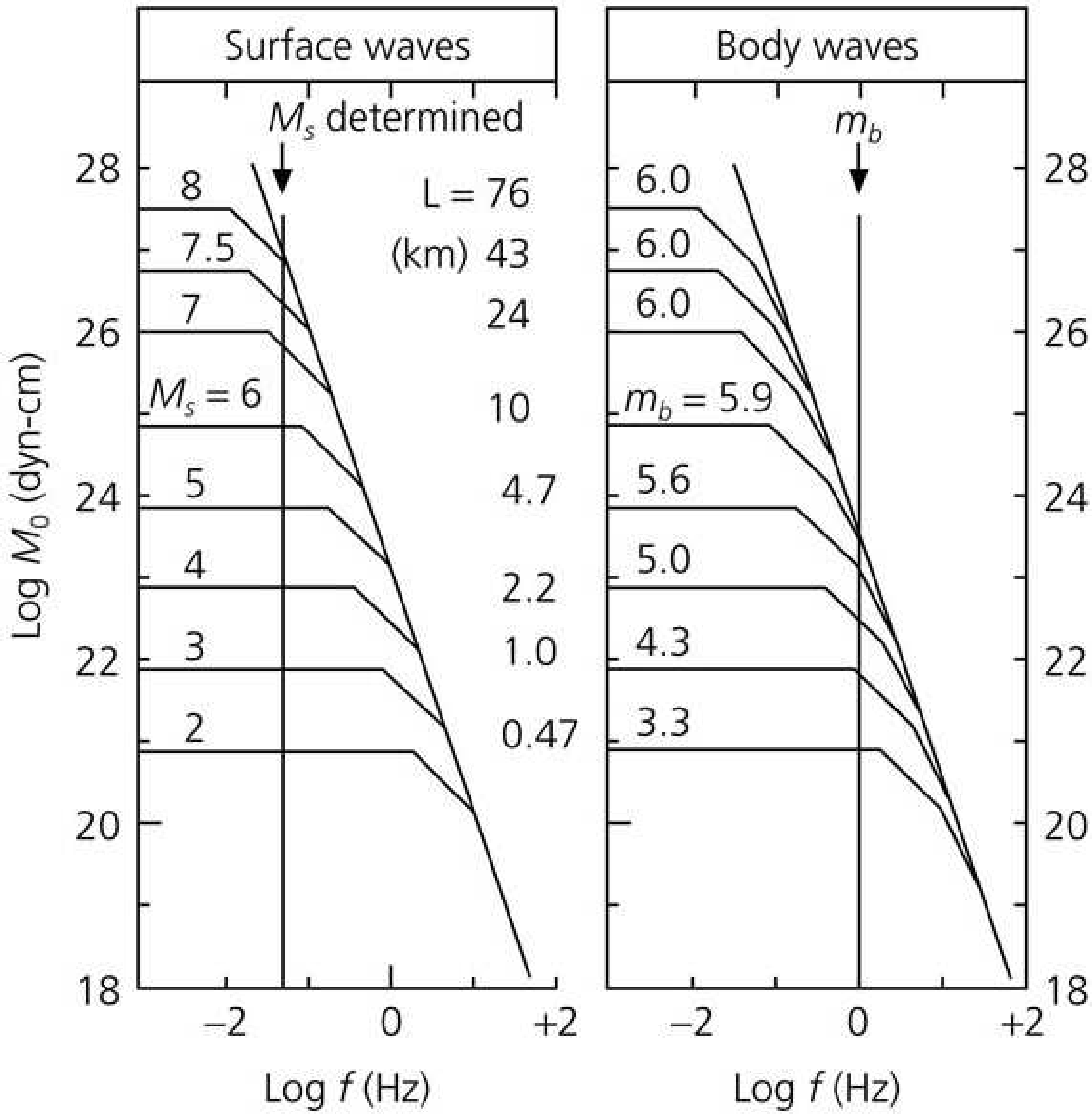
INVALIDATES USE of M_s for TSUNAMI WARNING

[*Geller,* 1976]

M_s SATURATES AROUND 8.2

ALL CONVENTIONAL MAGNITUDES SATURATE

It is only a question of the period T which they use.



- m_b , measured at 1 s, would saturate event earlier (at $m_b = 6$ if properly measured at exactly $T = 1$ s).

SCALING TSUNAMIS in the NEAR FIELD

Okal and Synolakis [2004]

- **SIMPLE IDEAS:** Consider a seismic source

→ Everything else being equal, the maximum value of run-up on a beach should grow like the slip, Δu.

→ Everything else being equal, the lateral extent of run-up on the beach should grow like the size of the fault, L.

→ The ratio of the two, which is the *aspect ratio* of the distribution of run-up along the beach, should behave like $\Delta u / L$, which being the strain released, ε, should be invariant under seismic scaling laws.

- Thus we predict that all earthquakes should feature the *same distribution of run-up along a beach in the near field.*

→ TEST this theoretically.

→ COMPARE with data from tsunami surveys.

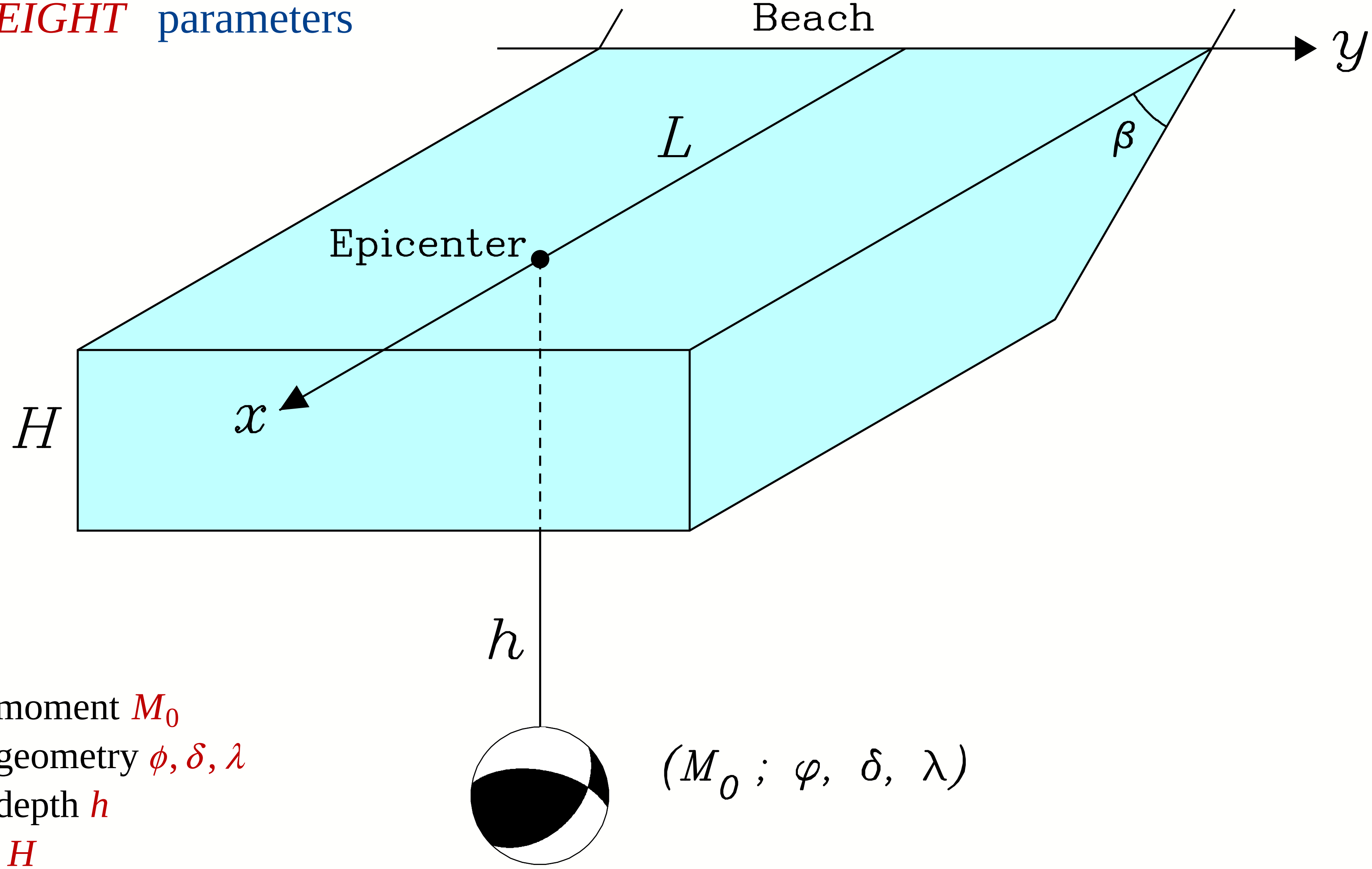
- If this invariant is violated, it means the source does not scale like an earthquake.

  It probably is not one !

  [LANDSLIDE ?]

GENERIC DISLOCATION in the NEAR FIELD

Involves *EIGHT* parameters



Earthquake moment M_0

Earthquake geometry ϕ, δ, λ

Earthquake depth h

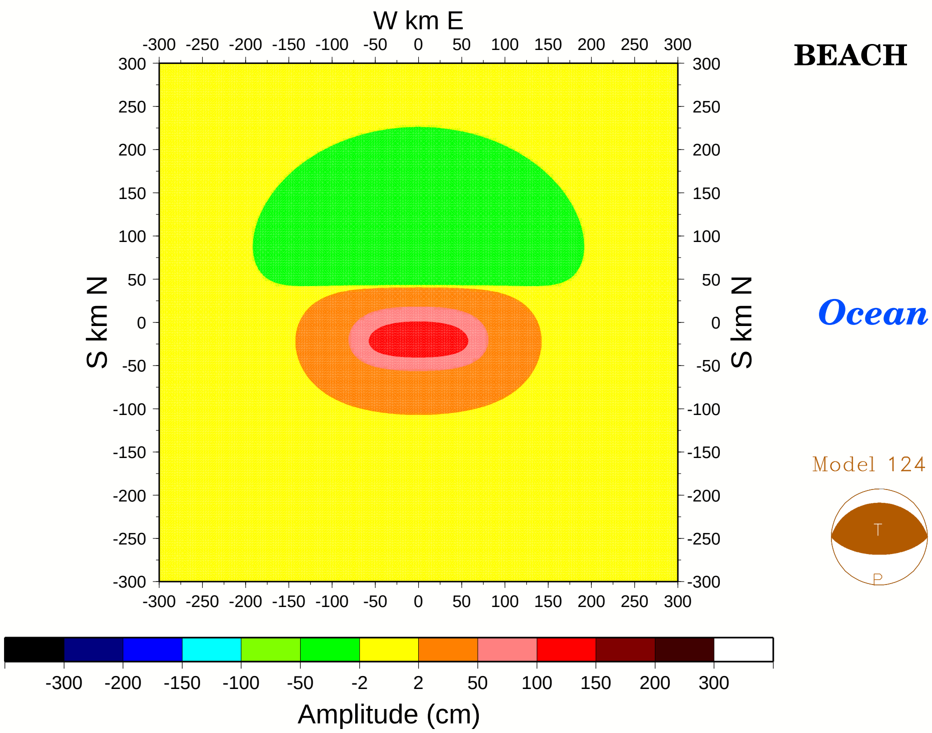
Water depth H

Epicentral distance to shore L

Beach slope β

NEAR-FIELD: *The Earthquake Dislocation*

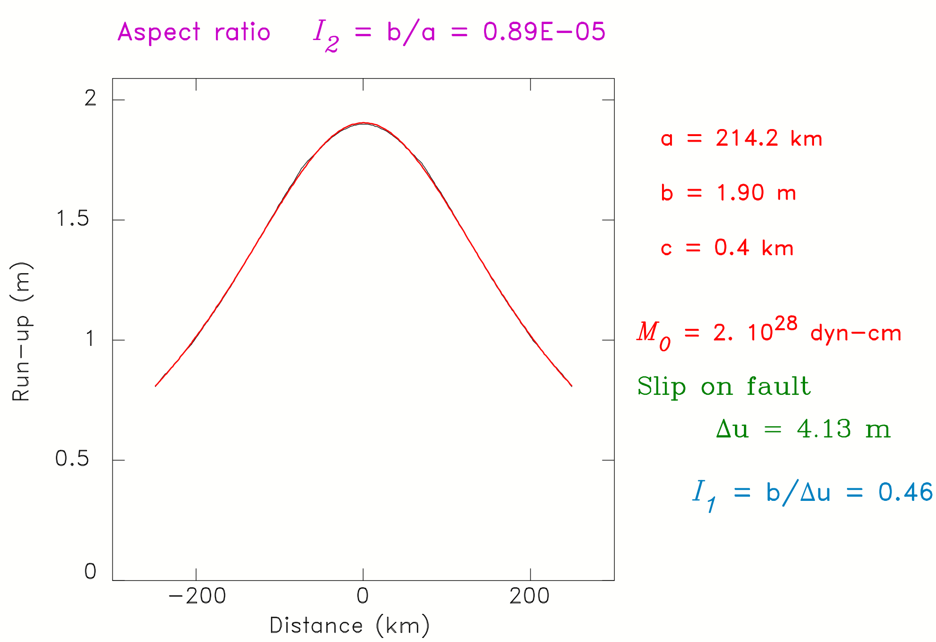
- Compute Ocean-Bottom Deformation due to Dislocation



- Simulate Tsunami Propagation to Beach and Run-up

- Fit Bell Curve

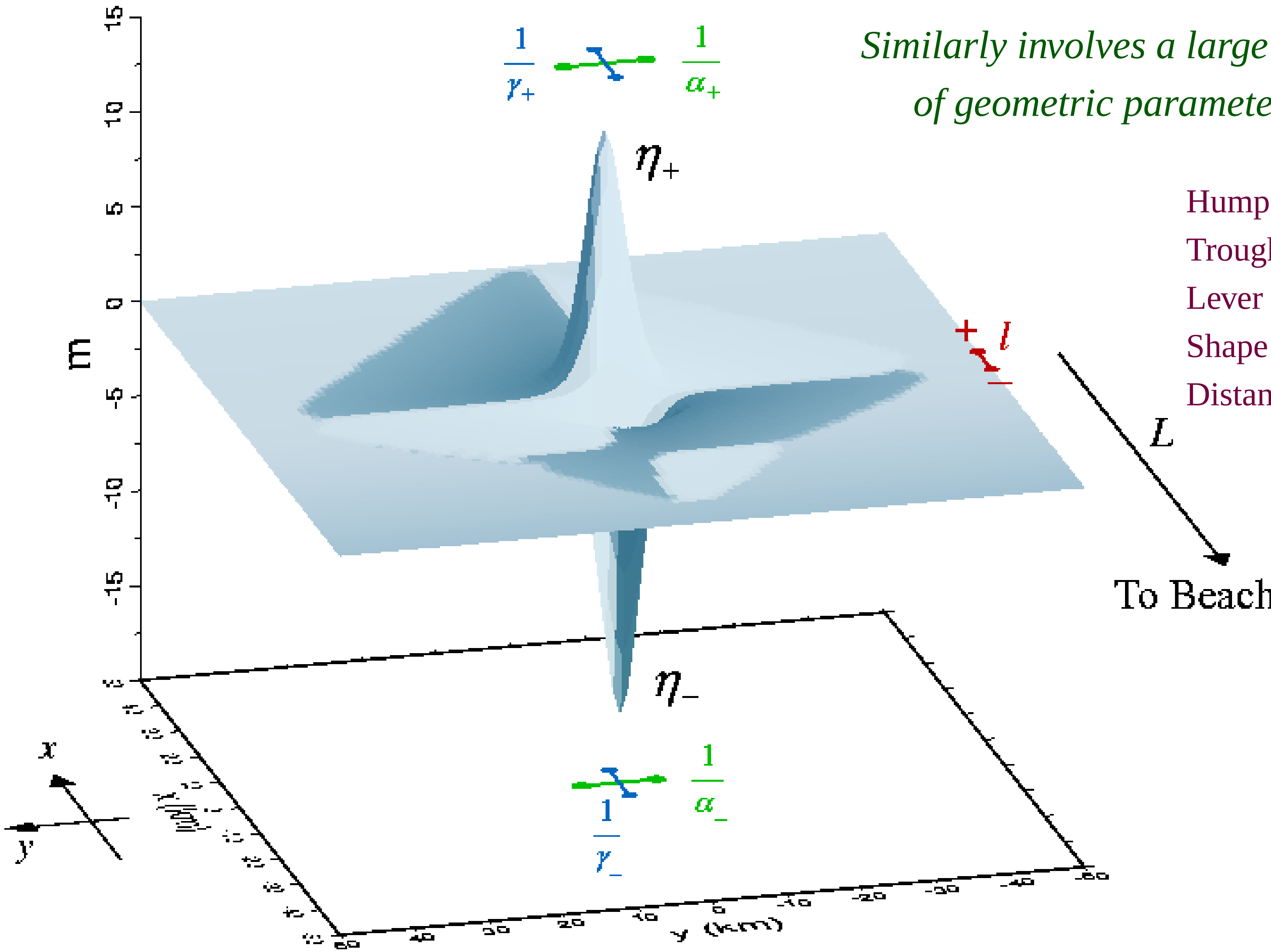
$$\zeta = \frac{b}{\left(\frac{x-c}{a}\right)^2 + 1}$$



- Retain aspect ratio $I = b/a$

- Vary source parameters: I no greater than 2.3×10^{-5}.

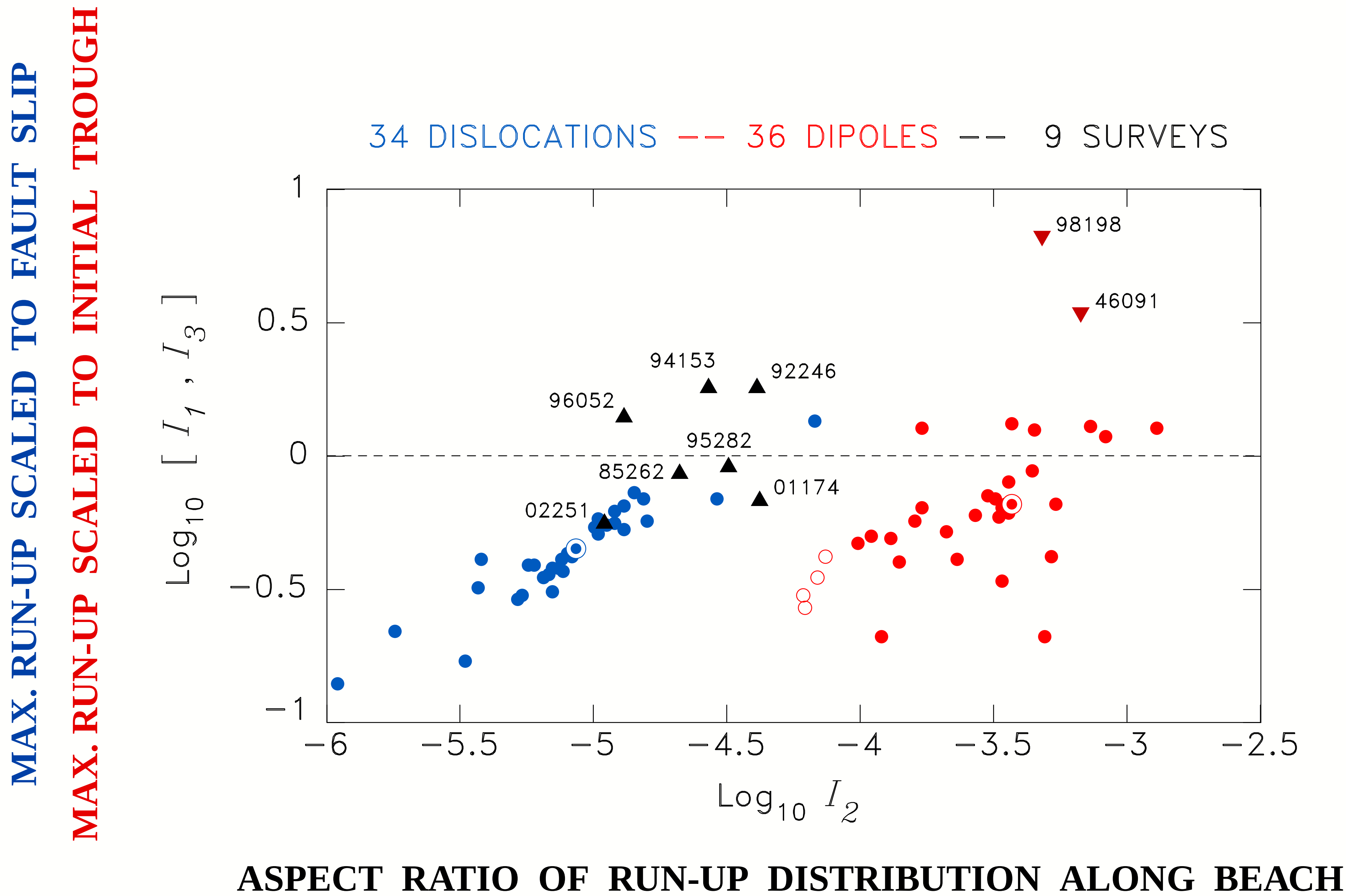
THE DIPOLAR SOURCE (Landslide)



Similarly involves a large number of geometric parameters

- Hump
- Trough
- Lever
- Shape of poles
- Distance to Beach...

[*Okal and Synolakis*, 2004]



[*Okal and Synolakis*, 2004]

PAPUA NEW GUINEA: A TALE of TWO EARTHQUAKES

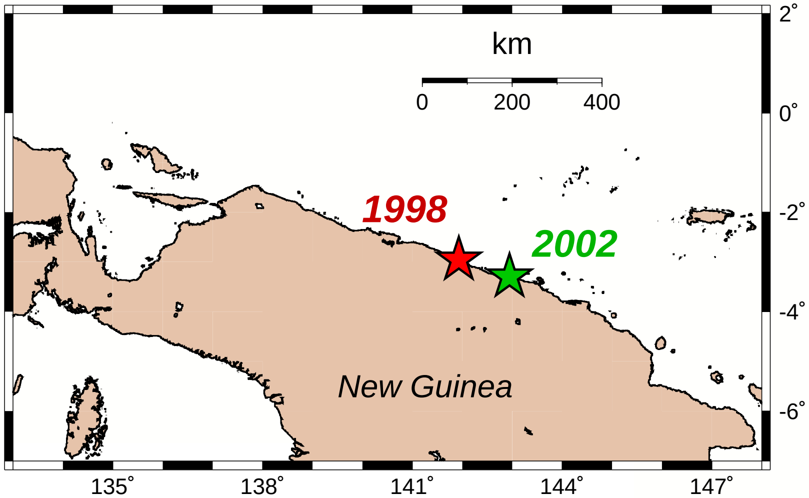
- 08 SEP 2002: Regular Earthquake, A.R. = 2.6×10^{-5}

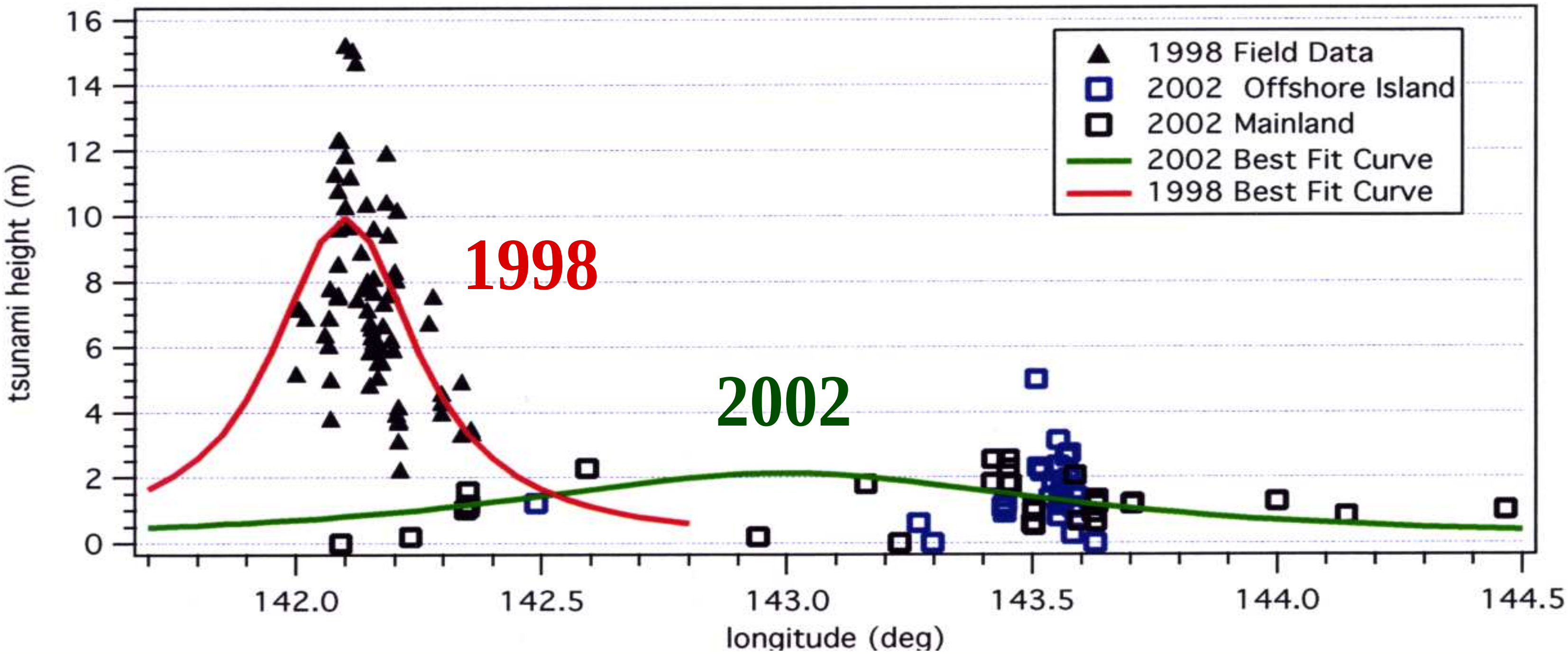
  No tsunami deaths.

- 17 JUL 1998: Landslide Tsunami,

  A.R. = 4.8×10^{-4}

  2200 Tsunami Deaths





VIOLATORS of SEISMIC LAWS

Apart from non-earthquakes [landslides, volcanic eruptions, etc.], seismic events will violate scaling laws if *invariants are not followed.*

- Anomalous material properties (μ; *weak* sediments)
- Anomalous shapes of fault zones (W/L; *ribbon like; shallow strike-slip events)*
- Anomalous rupture velocities (V_R; slow or irregular, jagged ruptures).

→ It is important to detect such events because

(i) we may not catch the true size of the source by using conventional methods;

(ii) their tsunami potential may be enhanced.

- In general, all *"Tsunami Earthquakes"* are violators of scaling laws.

THE INFAMOUS "TSUNAMI EARTHQUAKES"

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

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

- Example: Nicaragua, 02 September 1992.

THE EARTHQUAKE WAS NOT FELT AT SOME BEACH COMMUNITIES,

WHICH WERE DESTROYED BY THE WAVE 40 MINUTES LATER

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

El Popoyo, Nicaragua

El Transito, Nicaragua

"TSUNAMI EARTHQUAKES"

- *The Events:*

1896 Sanriku, Japan

1946 Aleutian

1923 (13 April) [*probably*] Aftershock of large Kamchatka earthquake

1932 (22 June) [*Probably*] Aftershock of Jalisco, Mexico earthquake

1963 (20 Oct.) Aftershock of great Kuriles earthquake

1975 Kuriles (following regular 1973 Nemuro-Oki event)

1982 Tonga

1992 Nicaragua

1994 Java **2006 Java** (cc. of 1994)

1996 Chimbote, Peru

2004 Sumatra (*?; features some slowness)*

"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].

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

Candidates: Kuriles, 1963, 1975; Sanriku, 1896

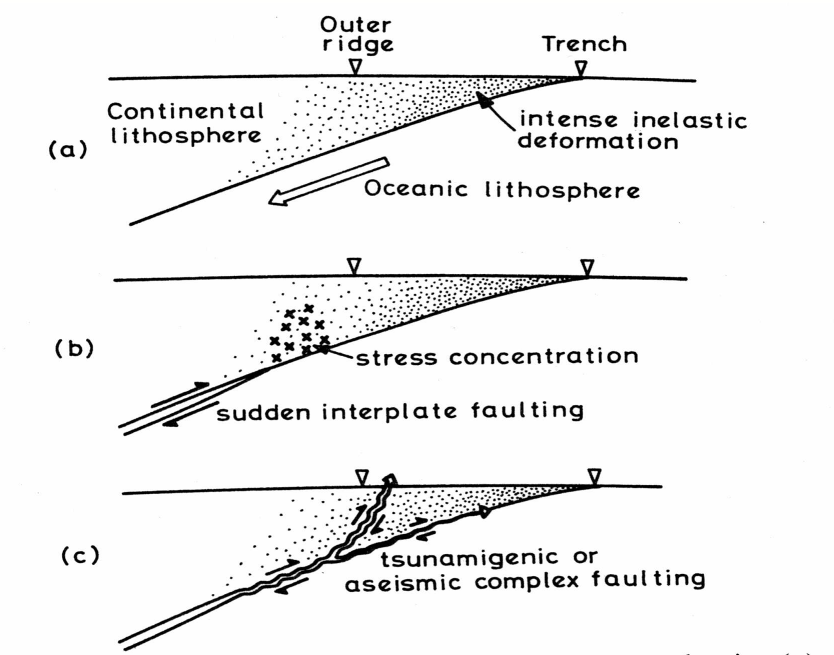


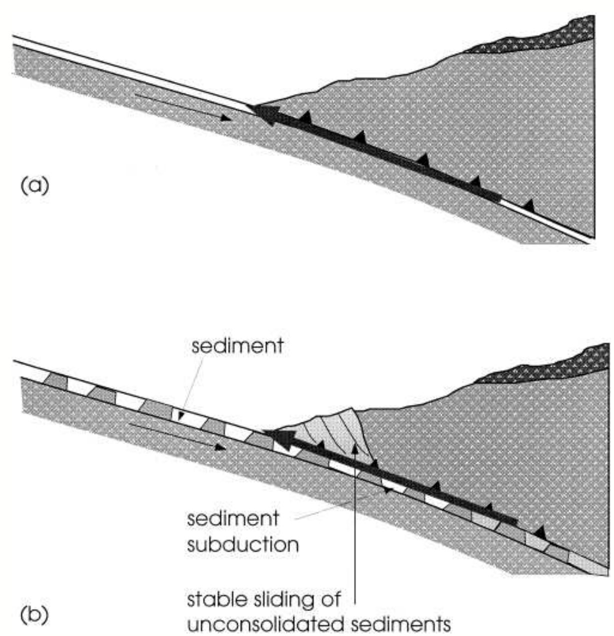
Fig. 19. A model for a great earthquake sequence showing (*a*) interseismic stage, (*b*) coseismic stage, and (*c*) postseismic stage. See the text for details.

[*Fukao*, 1979]

- *The Origin:* Generally interperted as involving rupture in anomalous situations, which could involve

→ 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"

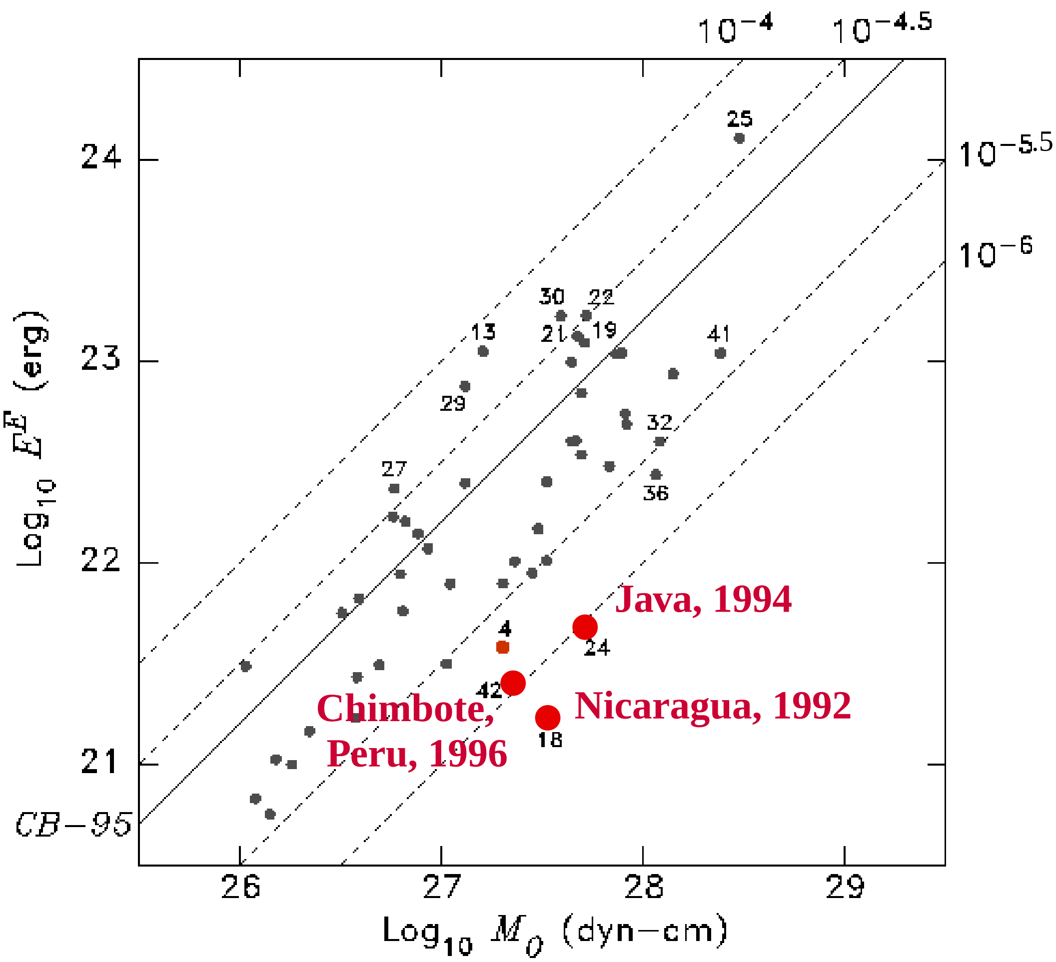
→ Define *Estimated Energy*, E^E

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

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

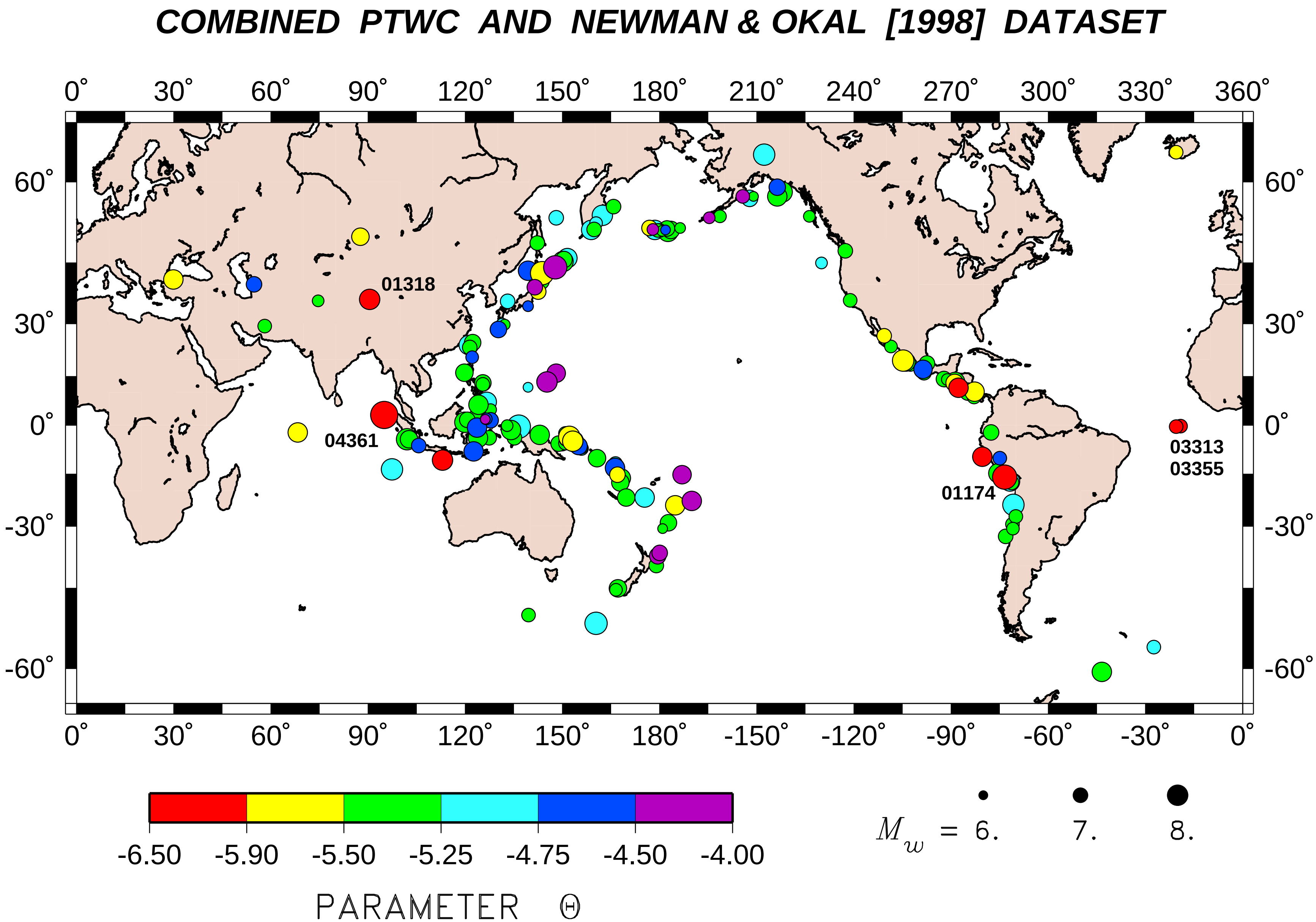
→ Scaling laws predict $\Theta = -4.92$.

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



Now being implemented at Papeete and PTWC

COMPUTATION of Θ OPERATIONAL at PTWC since 2001



OTHER PROXIES for "TSUNAMI EARTHQUAKES"

- Use hydroacoustic T phases propagating in water column at high frequencies ($f \geq 3$ Hz) to explore relative properties of earthquake source in different frequency windows and detect any anomalous behavior.

- Define *T−PHASE ENERGY FLUX (TPEF)* using algorithm similar to E^E and scale to moment M_0 to obtain new slowness parameter γ.

- Define Amplitude-Duration discriminant D to characterize slowness of events.

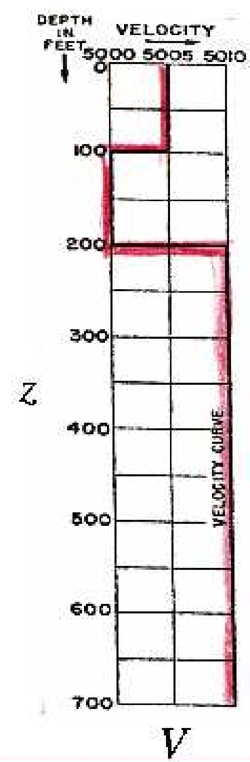
- Examine correlation between Θ, γ and D.

[*Talandier and Okal*, 2003] [*Okal et al.*, 2003]

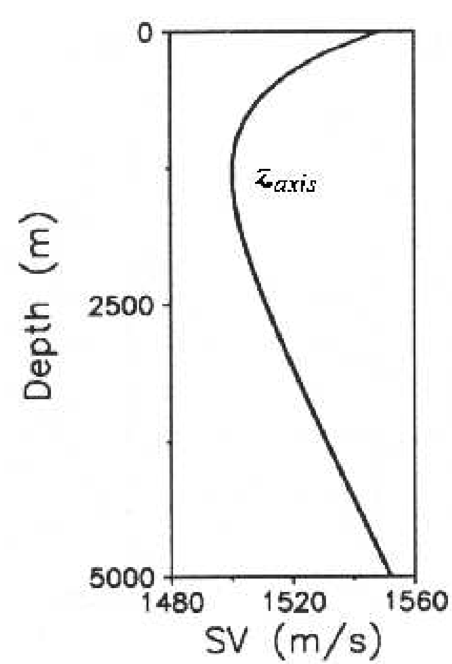
THE SOFAR CHANNEL

- Variations in pressure, temperature and salinity of seawater with depth create a *channel of minimum velocity* around $z = 1000$ m.
- This acts as a *WAVEGUIDE* allowing exceptionally efficient propagation of acoustic energy in the ocean basins ($f \geq 3$ Hz).

[*Pekeris*, 1948]



[*Munk*, 1972]



T PHASE ENERGY FLUX ($TPEF$) and PARAMETERS Γ (γ)

[*Okal et al.*, 2003]

- We seek to combine the amplitude and duration information to retrieve a measure of source size.

- Recall the definition of *Seismic Energy radiated into Body Waves* [*Boatwright and Choy*, 1986; *Newman and Okal*, 1998]: integrate energy flux at receiver; correct for distance.

- **Define** $TPEF = \rho\,\alpha \int_W [\dot{u}(t)]^2 \cdot dt$,

  which is more readily computed in the Fourier domain as

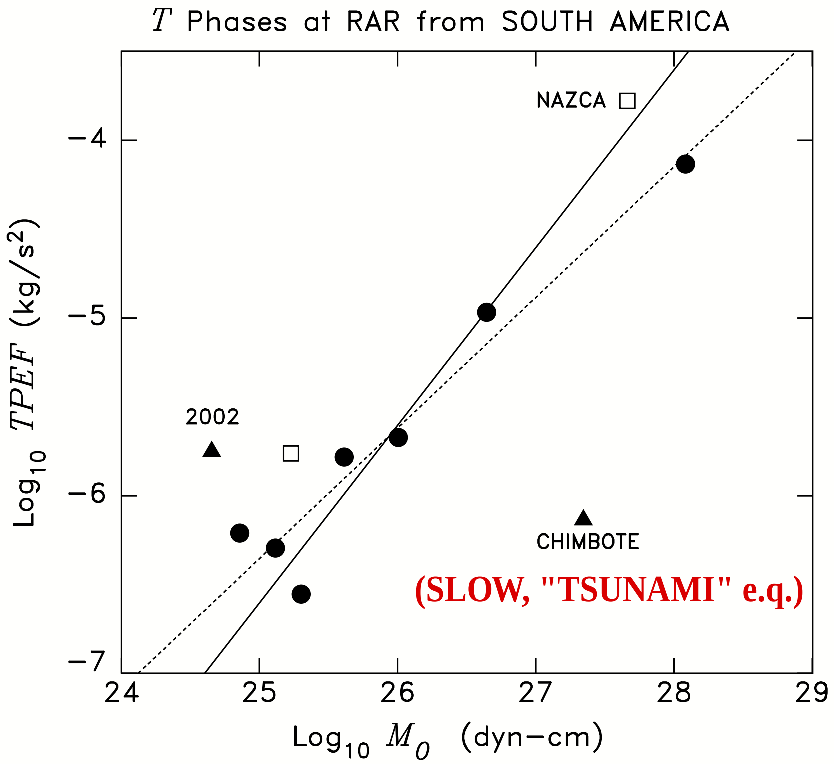
$$TPEF \approx \frac{\rho\,\alpha}{\pi} \int_{\omega_{\min}}^{\omega_{\max}} \omega^2 \,|U(\omega)|^2 \cdot d\omega$$

- To eliminate receiver effects, *use ONLY TO COMPARE RECORDS AT SAME RECEIVING STATION*

- **Then TPEF scales with *MOMENT*. Define**

$$\Gamma = \frac{TPEF}{M_0} \quad \text{and} \quad \gamma = \log_{10}\Gamma + 30$$

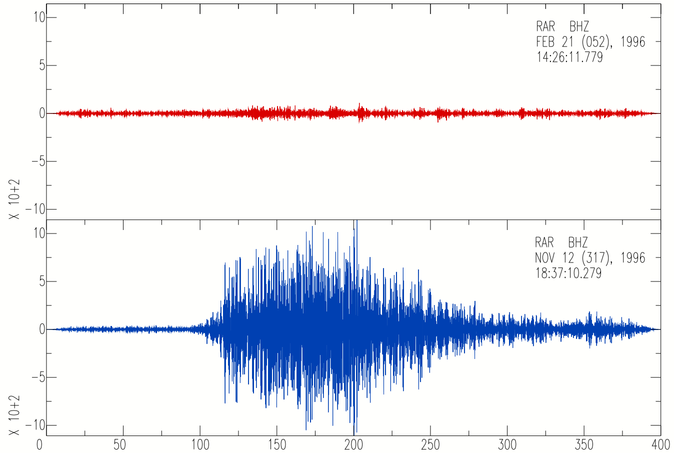
Γ is invariant for constant source−receiver geometries.

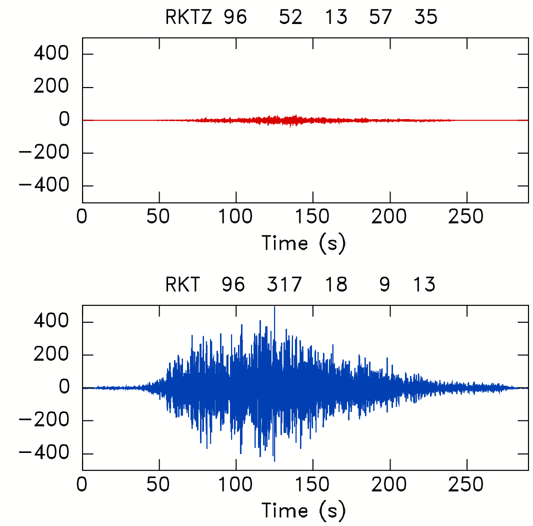


TPEF (Γ ; *γ*) IDENTIFYING SLOW ("*TSUNAMI*") EARTHQUAKES

Contrast *CHIMBOTE*, *Peru* (21 *FEB* 1996) and *NAZCA*, *Peru* (12 *NOV* 1996)

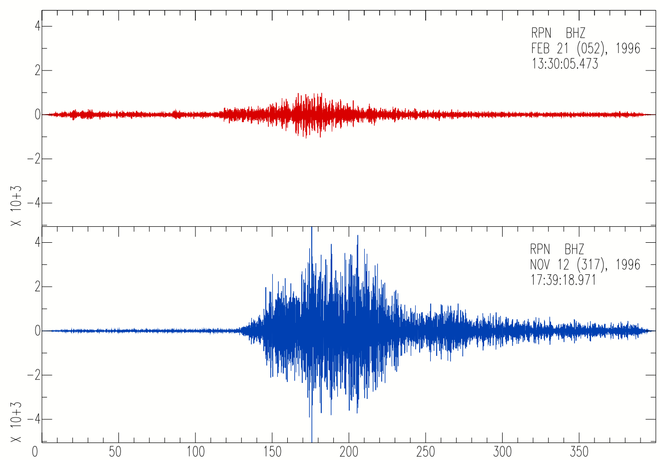
RAR

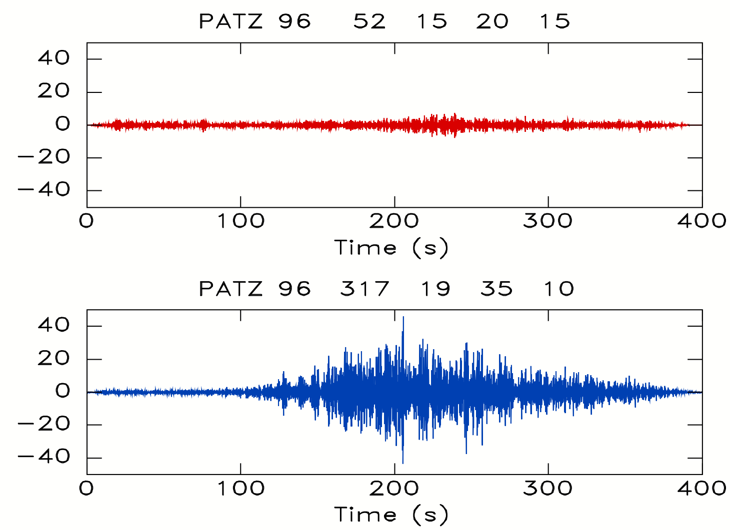




RKT

RPN





PATS

[*Okal et al.*, 2003]

$$\gamma_C - \gamma_N = -1.14 \text{ to } -2.29 \text{ log. units}$$

T WAVES as a PROXY to SOURCE SLOWNESS

- Use *T* phases at RAR from a series of regular, fast, and slow earthquakes in Peru and Chile.

- **Compare the three parameters**

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

    Energy-to-moment ratio, characterizing slowness of the source.
    [*Newman and Okal*, 1998]

  * $\gamma = \log_{10} \dfrac{TPEF}{M_0} + 30$:

    T –phase efficiency of the source

  * *D*: amplitude-duration discriminant.

A remarkable correlation exists between all 3.