The Physics of Tsunami Generation: Recent Advances and Persistent Problems

Eric L. Geist
U.S. Geological Survey

http://walrus.wr.usgs.gov/tsunami

Outline

- Introduction
- Problem 1: Fault Slip
  - Scaling of average slip with M_w
  - Distribution of slip
- Problem 2: Tsunami Earthquakes
  - Why, Where?
- Problem 3: Landslide Tsunamis
  - Coupling of slide dynamics with the water column
- Problem 4: Tsunami Probability
  - Computational methods
- Summary

Introduction: Source Physics

- Earthquakes
  - Constitutive Relations
    - Linear elastic

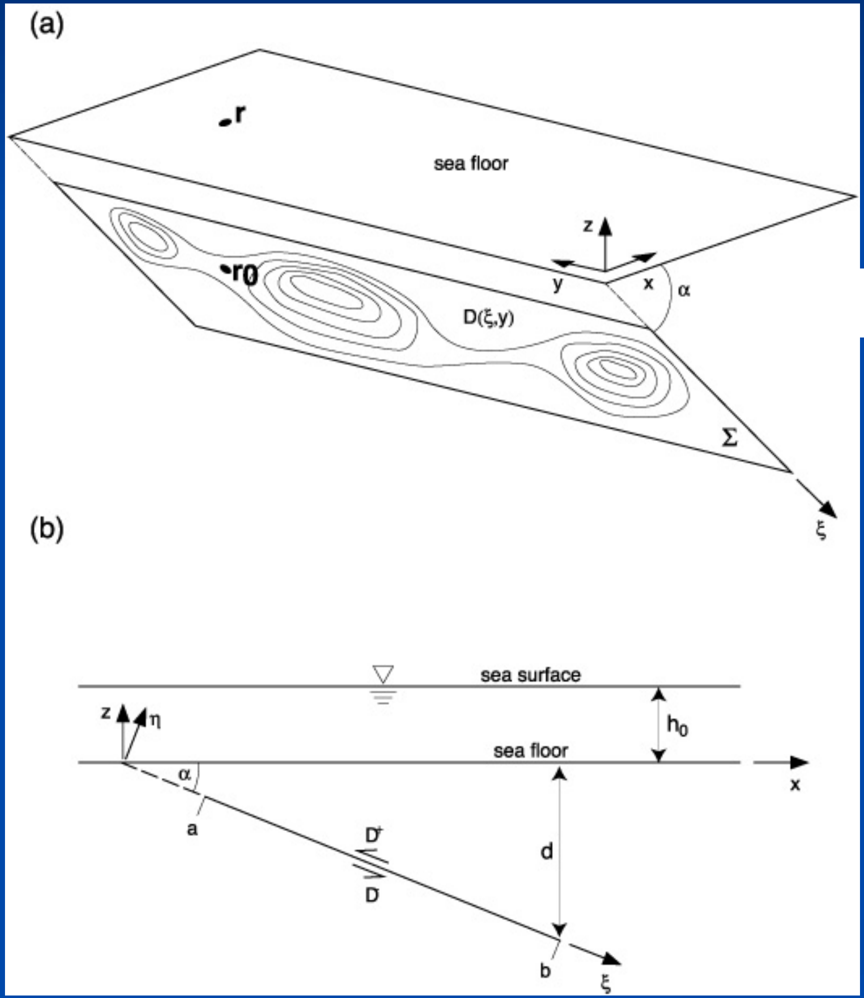
$$\sigma_{ij} = C_{ijpq}\varepsilon_{pq}$$

    - Anelastic (plastic) near fault zone*
  - Equations of Motion

$$\rho\ddot{u}_i = f_i + \sigma_{ij,j}$$

  - Forcing
    - Tectonics
    - Gravity*
- Landslides
  - Constitutive Relations
    - Viscous
    - Bingham Plastic
    - Bi-linear Flow (Newtonian, Bingham)
    - Herschel-Bulkley (non-linear)
    - Other
      - Rigid body
      - Granular
  - Equations of Motion (Cauchy)
  - Forcing
    - Gravity
    - Seismic Loading*

Tsunami Generation: Earthquakes



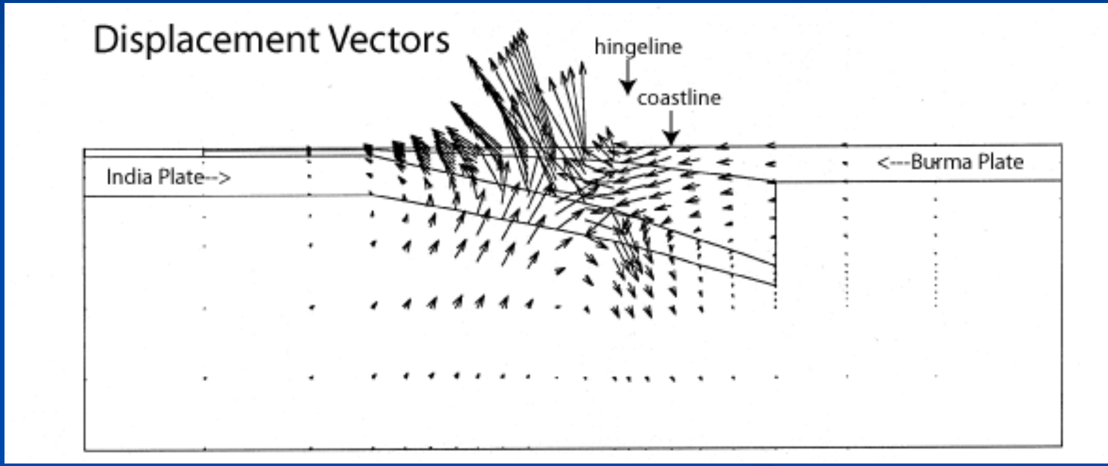
$$u_m(\mathbf{r}) = \iint_{\Sigma} D_i(\mathbf{r}_0)\nu_j(\mathbf{r}_0)U_m^{ij}(\mathbf{r},\mathbf{r}_0)d\Sigma$$

$$U_m^{ij}(\mathbf{r},\mathbf{r}_0) = \lambda(\mathbf{r}_0)\delta_{ij}G_m^{n,n}(\mathbf{r},\mathbf{r}_0) + \mu(\mathbf{r}_0)\left[G_m^{i,j}(\mathbf{r},\mathbf{r}_0) + G_m^{j,i}(\mathbf{r},\mathbf{r}_0)\right]$$

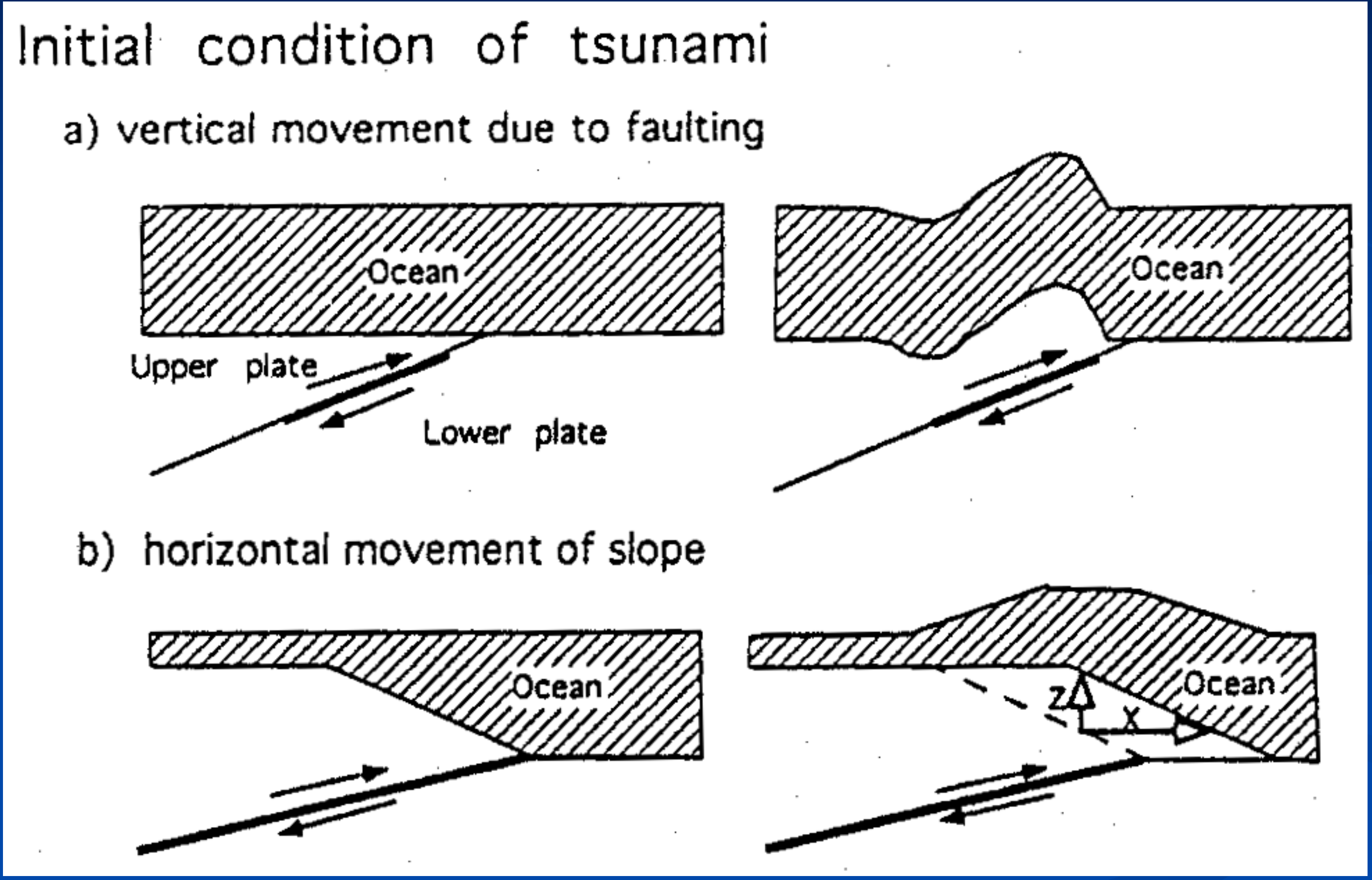
Σ	Rupture area
$D_i(\mathbf{r}_0)$	Slip distribution
$\nu_j(\mathbf{r}_0)$	Surface normal
$G_m^i(\mathbf{r},\mathbf{r}_0)$	Static elastic Green's functions
λ, μ	Lamé constants

Rybicki (1986)

Tsunami Generation: Earthquakes



Effect of Horizontal Displacements

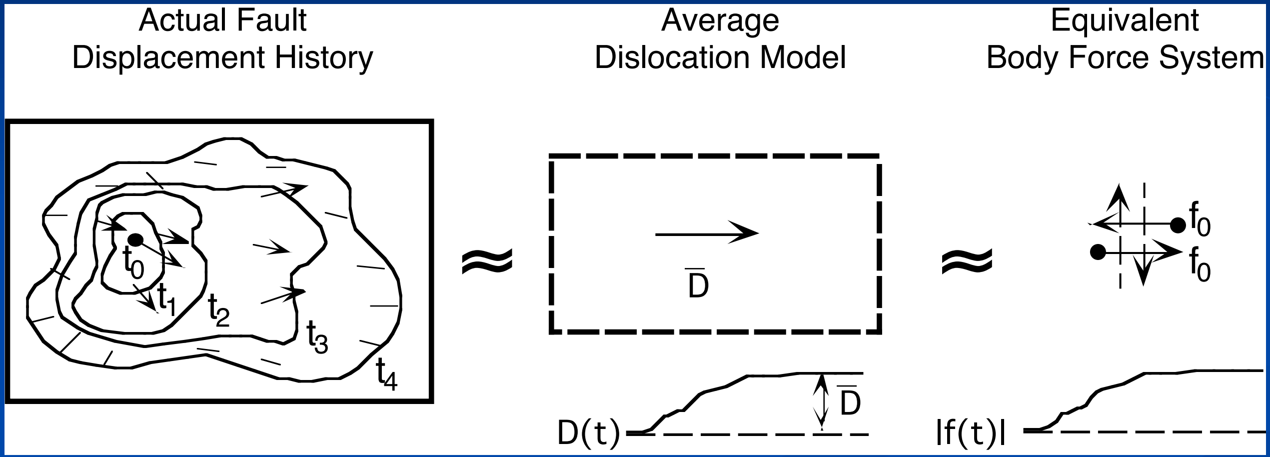


$$u_h = u_x \frac{\partial H}{\partial x} + u_y \frac{\partial H}{\partial y}$$

H: Water Depth (positive downward)

Tanioka & Satake, 1996

Earthquake Rupture: Levels of Approximation



Scalar Seismic Moment

$$M_0 = \mu A \overline{D}$$

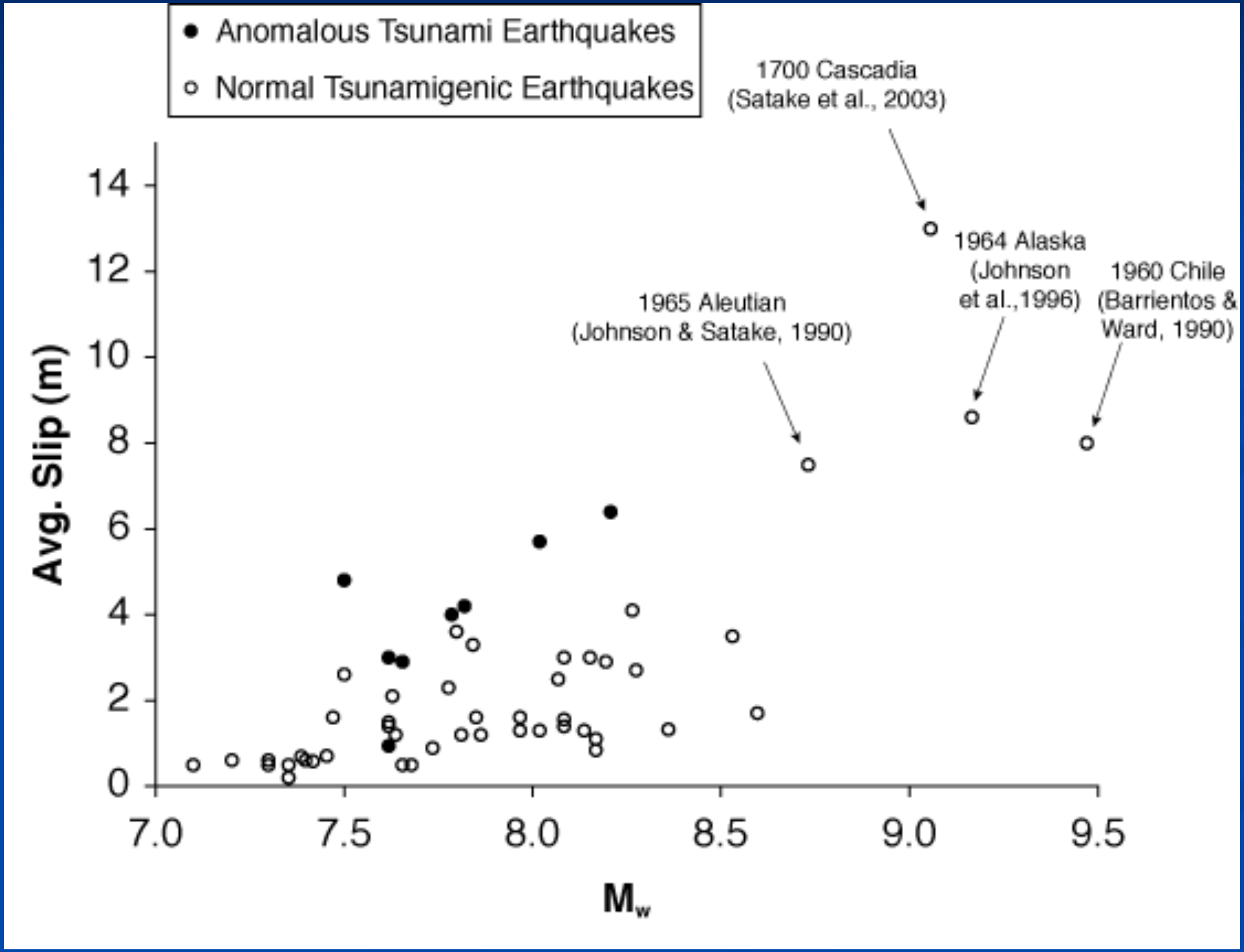
Moment Magnitude

$$M_W = \frac{2}{3} \log M_0 - 10.73$$

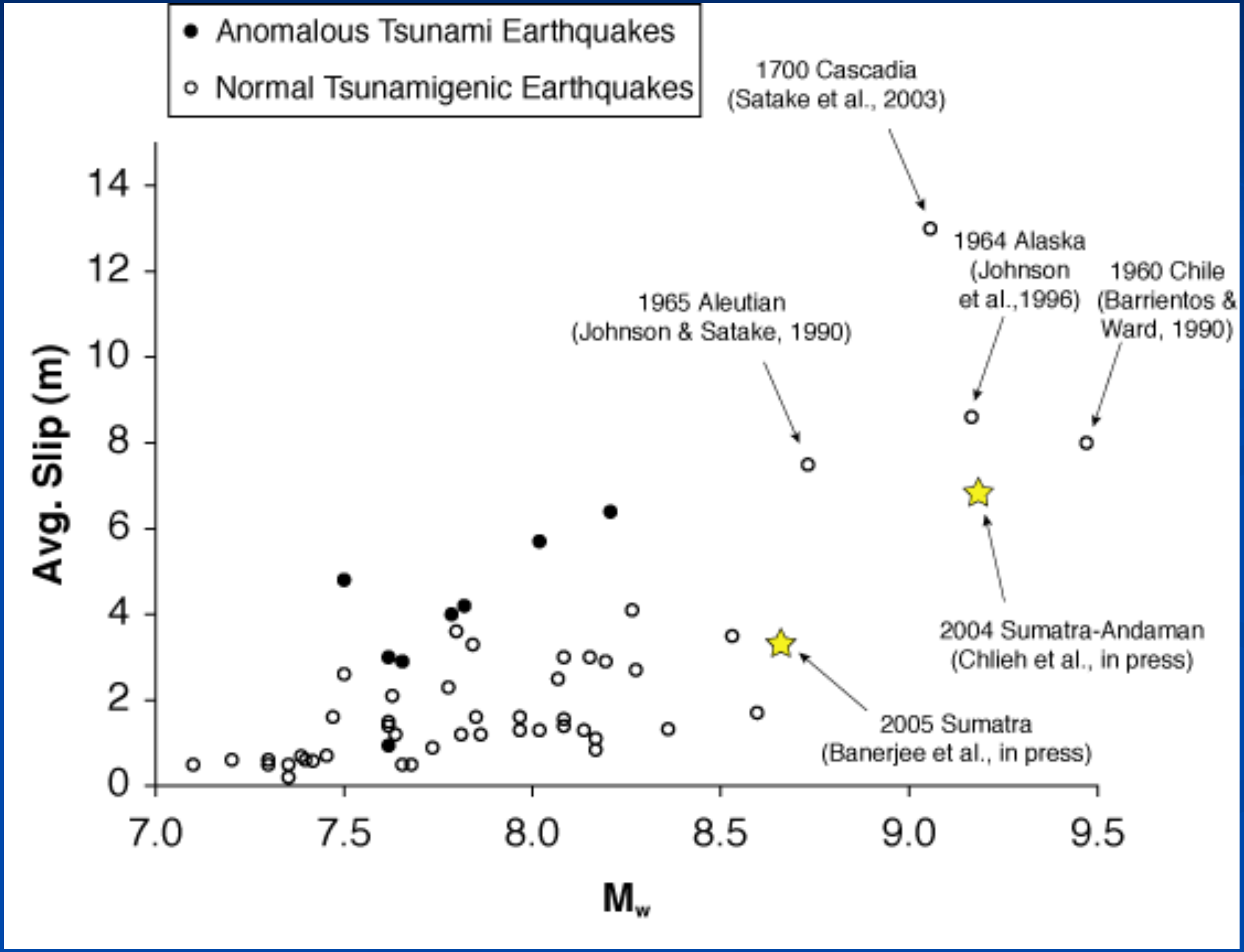
Lay & Wallace (1995)

Problem #1

Scaling of Average Slip



Scaling of Average Slip



Slip Distribution

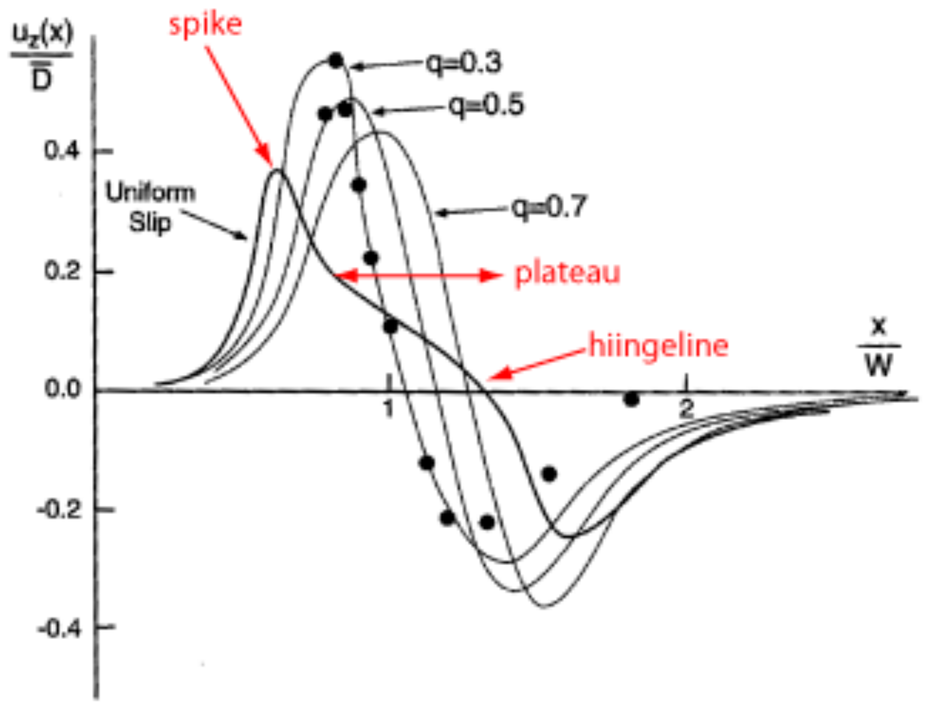
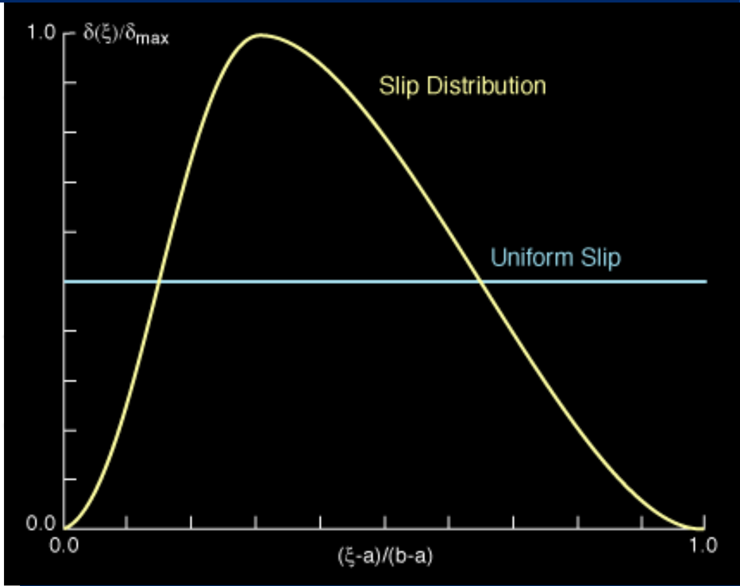
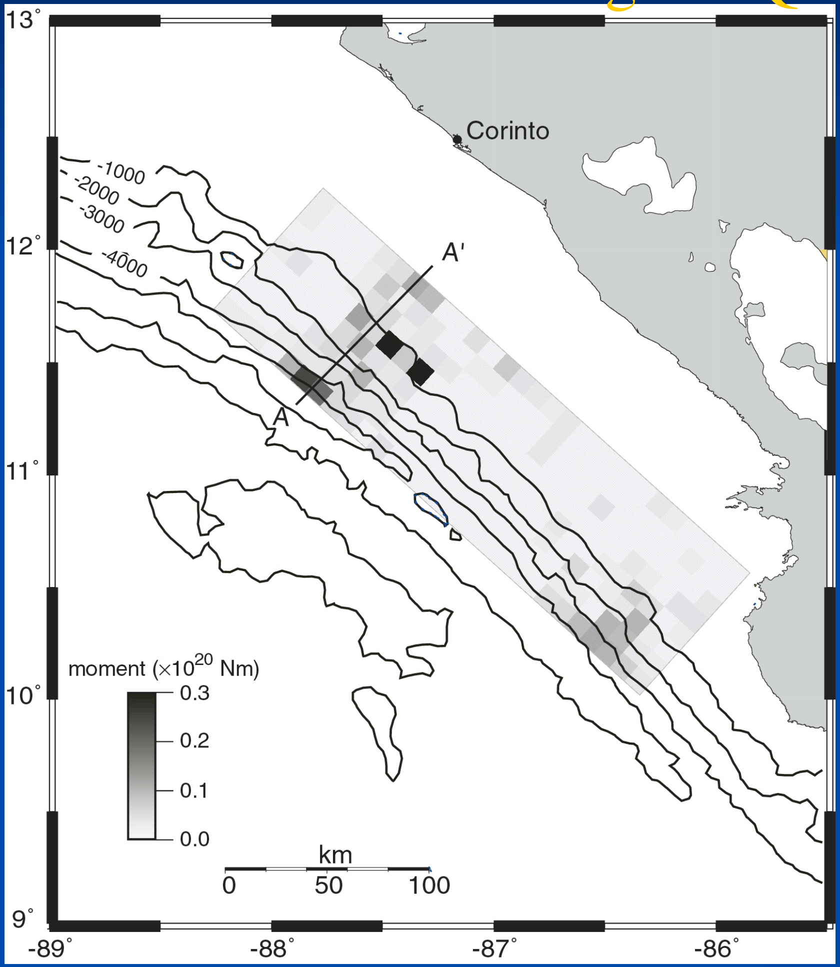


FIG. 21. Comparison of vertical surface displacement (u_z) along a strike-perpendicular profile for different skewness parameters (see Fig. 20). Note that vertical displacement is concentrated toward the center of the rupture zone for each case of variable slip distribution, compared to the vertical surface displacement from uniform slip. Dots represent measured vertical displacement from the 1964 Alaska earthquake. (Freund and Barnett, 1976; reproduced with permission from *Bull. Seism. Soc. Am.*, © 1976 Seismological Society of America)

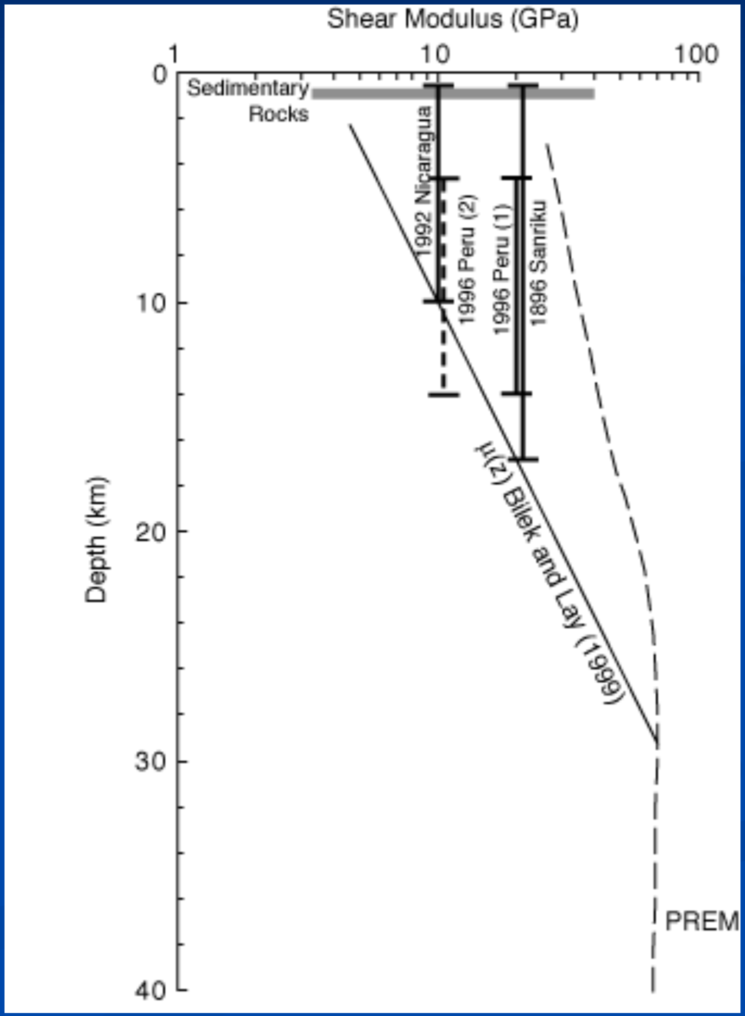


Observed Slip Distributions

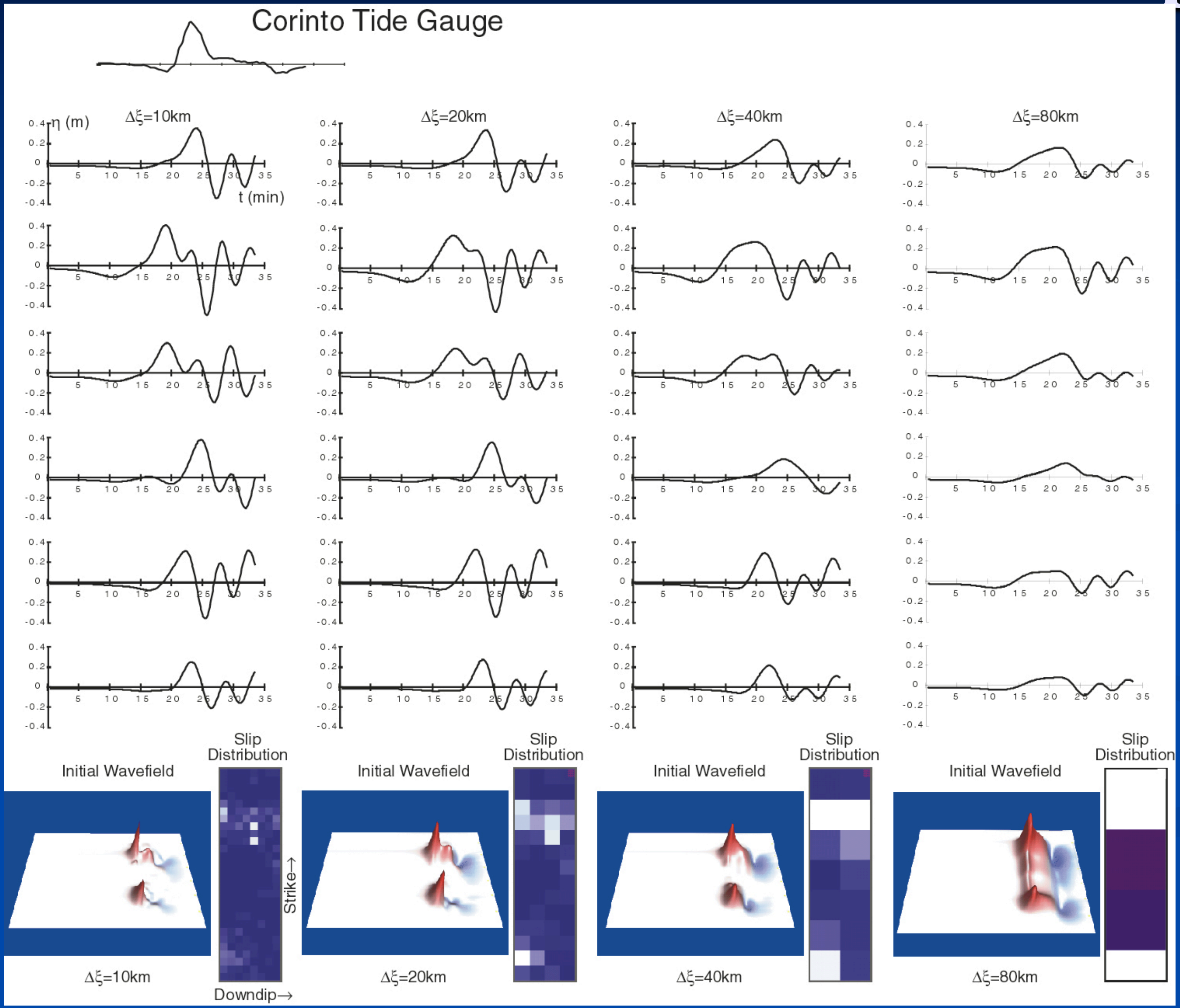
1992 Mw=7.7 Nicaragua EQ



Ihmlé (1996a,b)

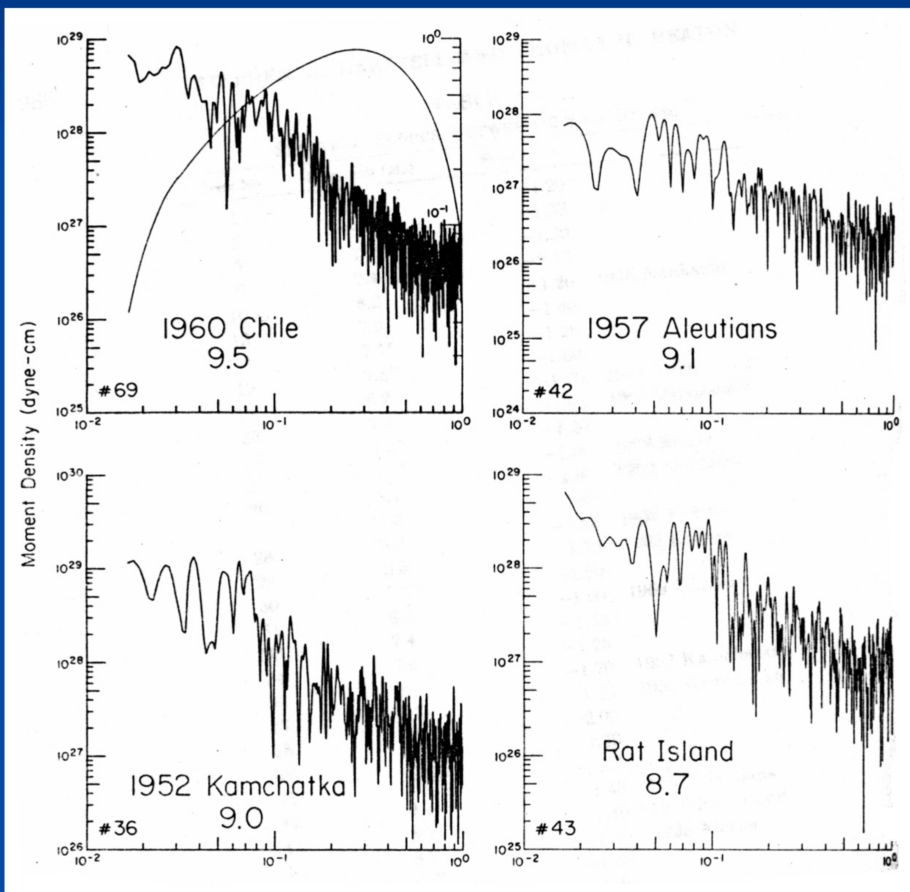


2D Effect of Distributed Slip



Seismic Source Spectra

- Hartzell & Heaton (1985)



- Polet & Kanamori (2000)

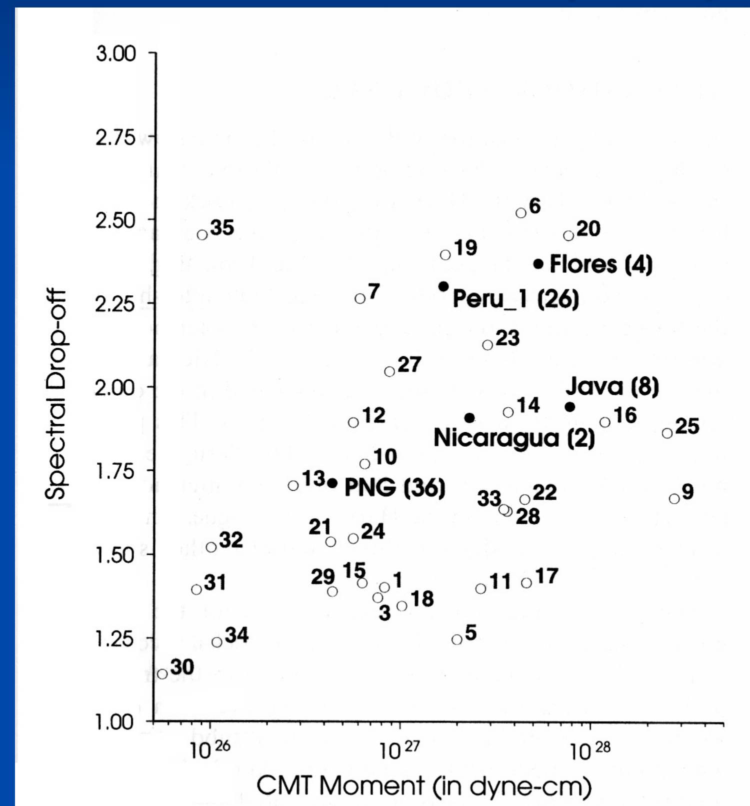
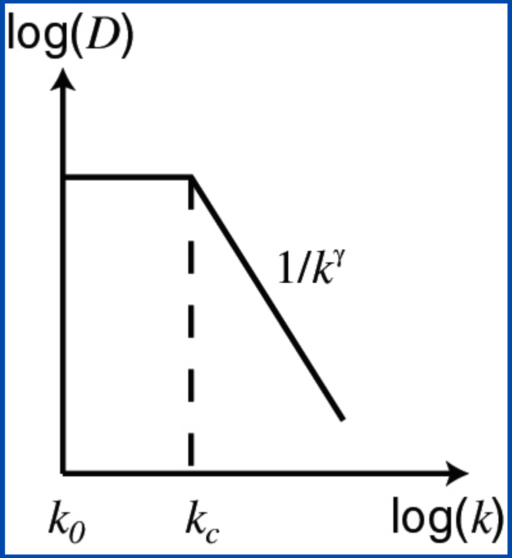


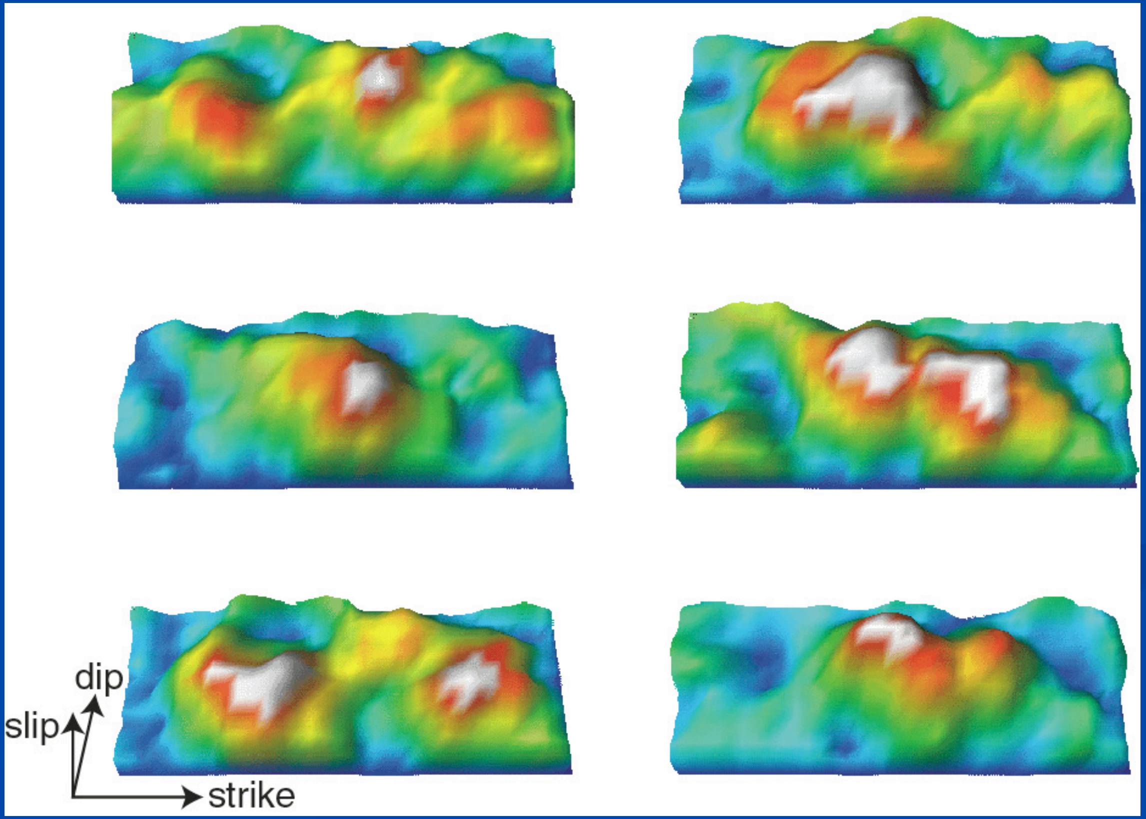
Figure 6. Spectral drop-off values as a function of CMT total moment determined by fitting the measured moment rate values by a function of the form of eq. (3).

Stochastic Source Model

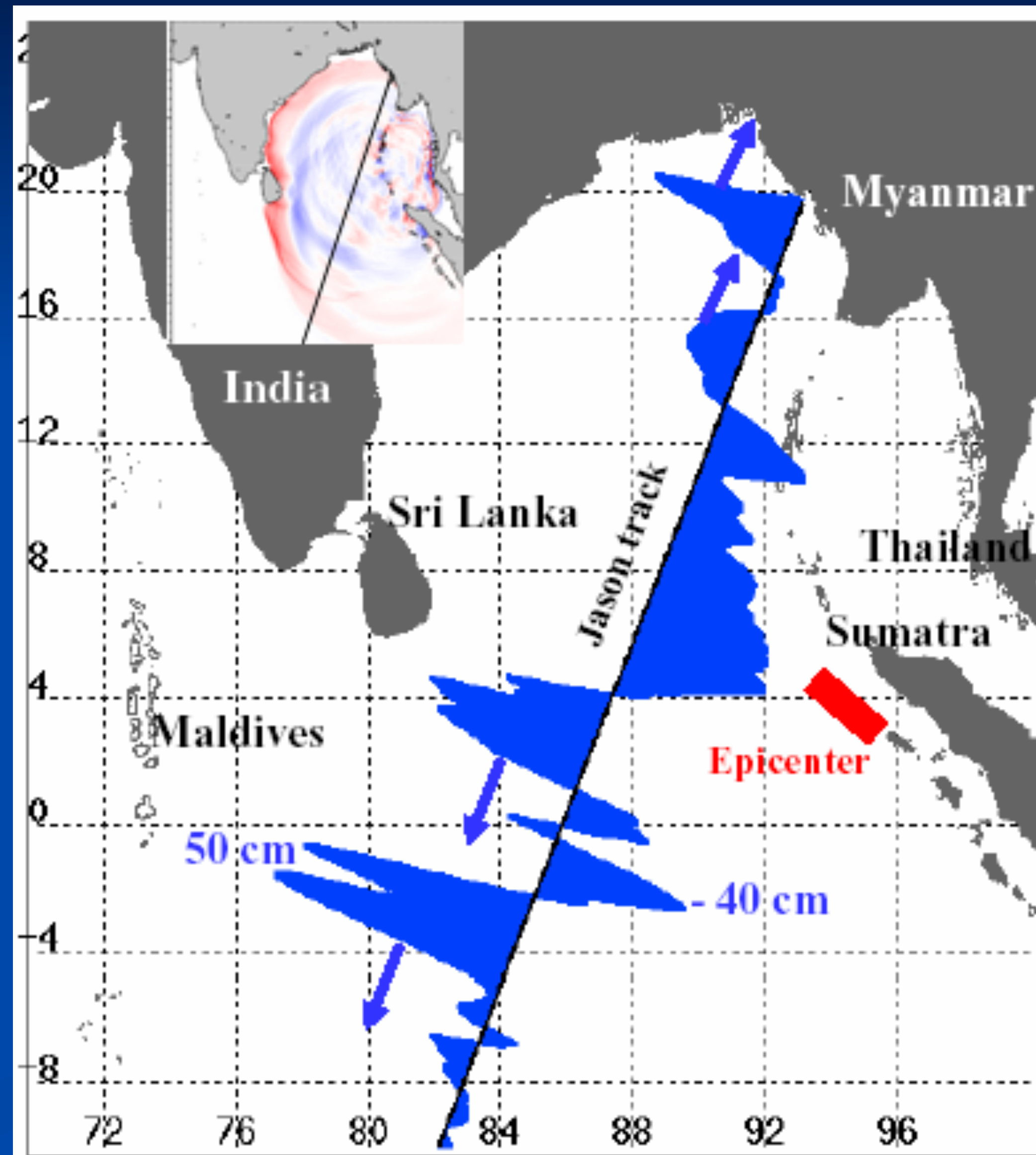
- Self-affine slip spectrum
  (Hanks, 1979; Andrews, 1980; Frankel, 1991; Herrero & Bernard, 1994; Tsai, 1997; Hisada, 2000; 2001; Mai & Beroza, 2000; 2002)
- Strong ground motion applications
  (e.g., Berge et al., 1998; Somerville et al., 1999)

$$D(k) = C\frac{\Delta\sigma}{\mu}\frac{L}{k^{\gamma}} \quad k > k_c$$

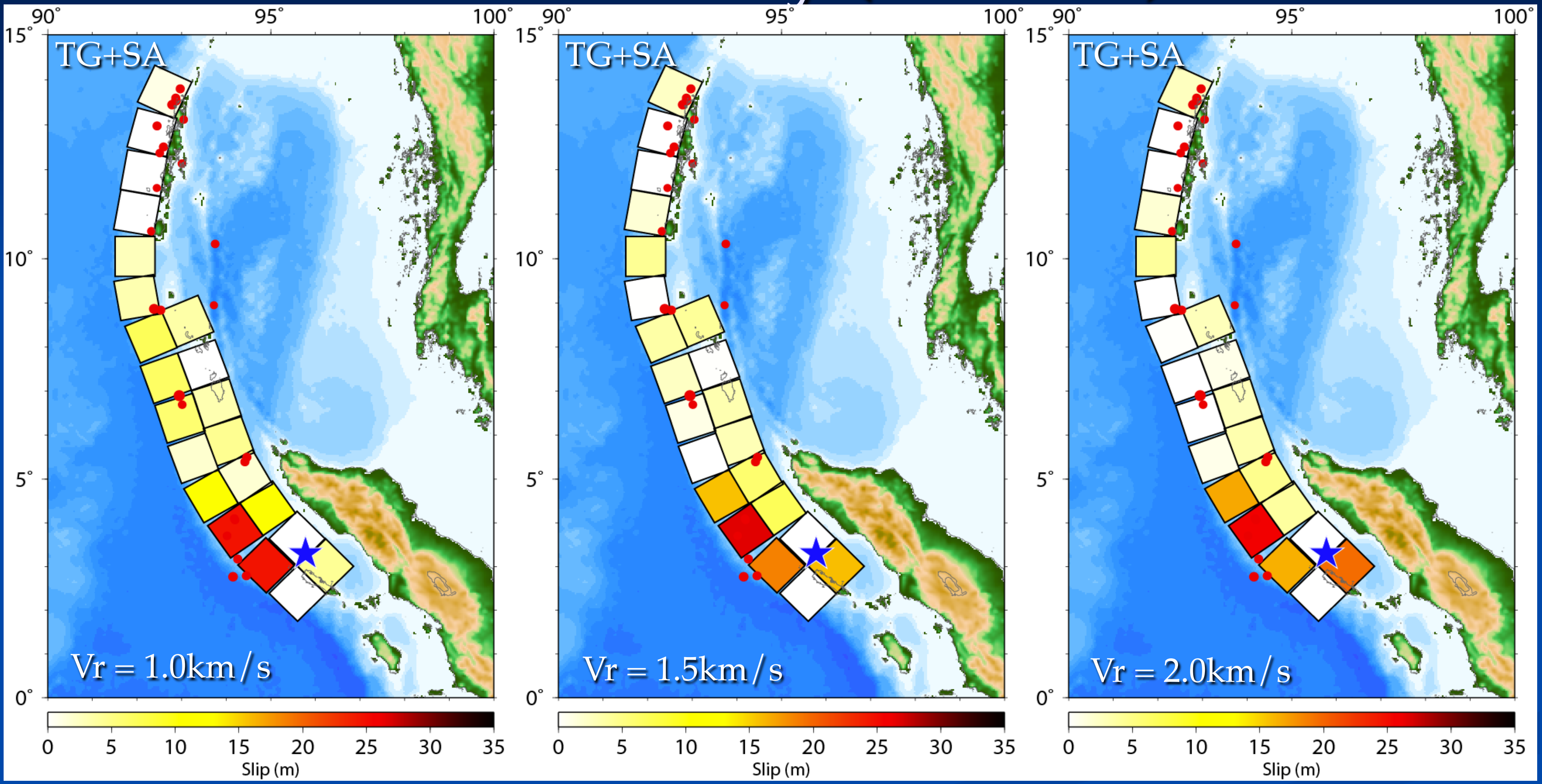




Jason-1 Altimetry: Pass 129, Cycle 109



Joint inversion of tide gauge and satellite altimetry (TG+SA) data



*M*w = 9.1

Fujii and Satake (BSSA, in press)

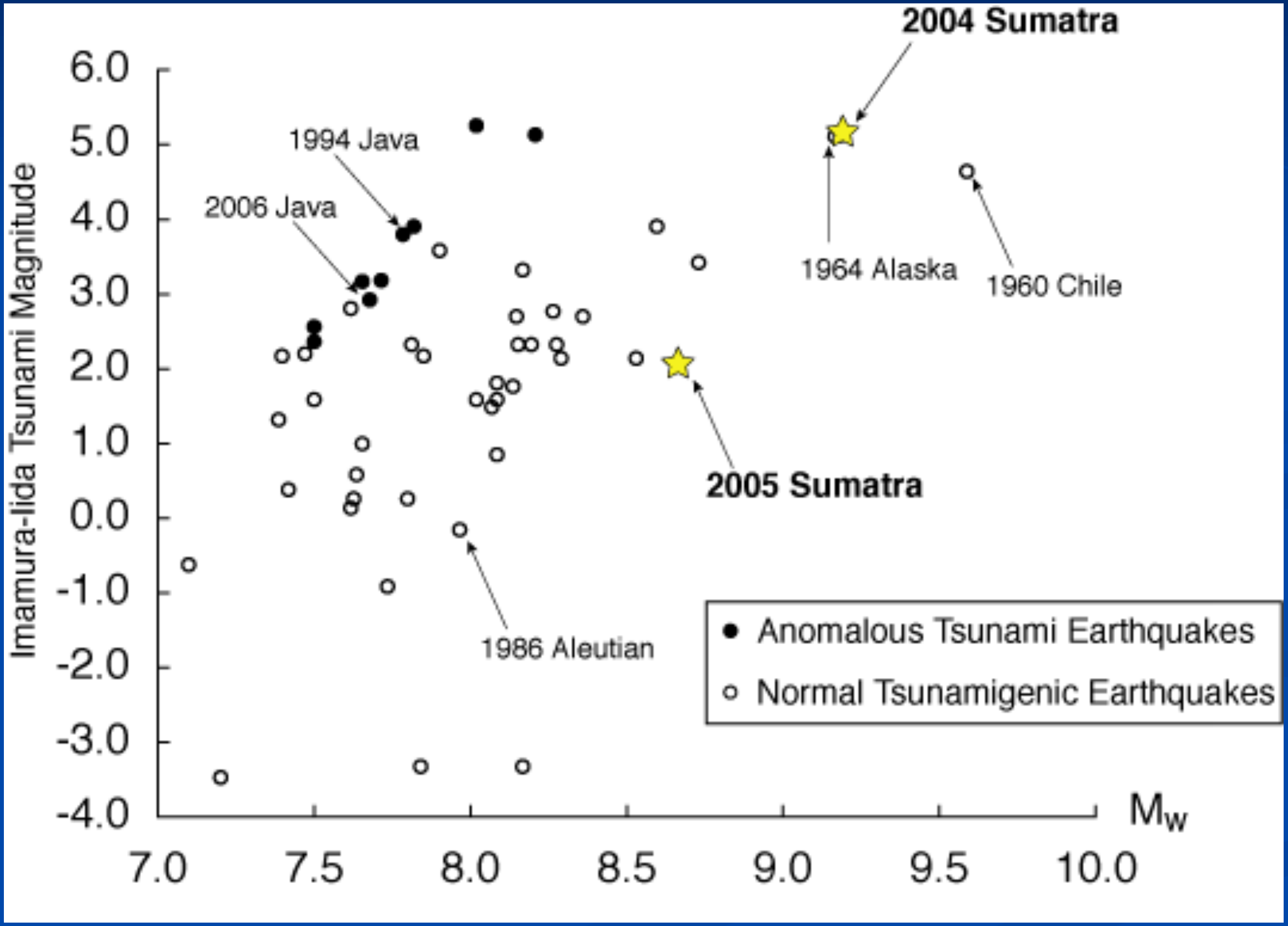
Courtesy Y. Fujii

Problem #2

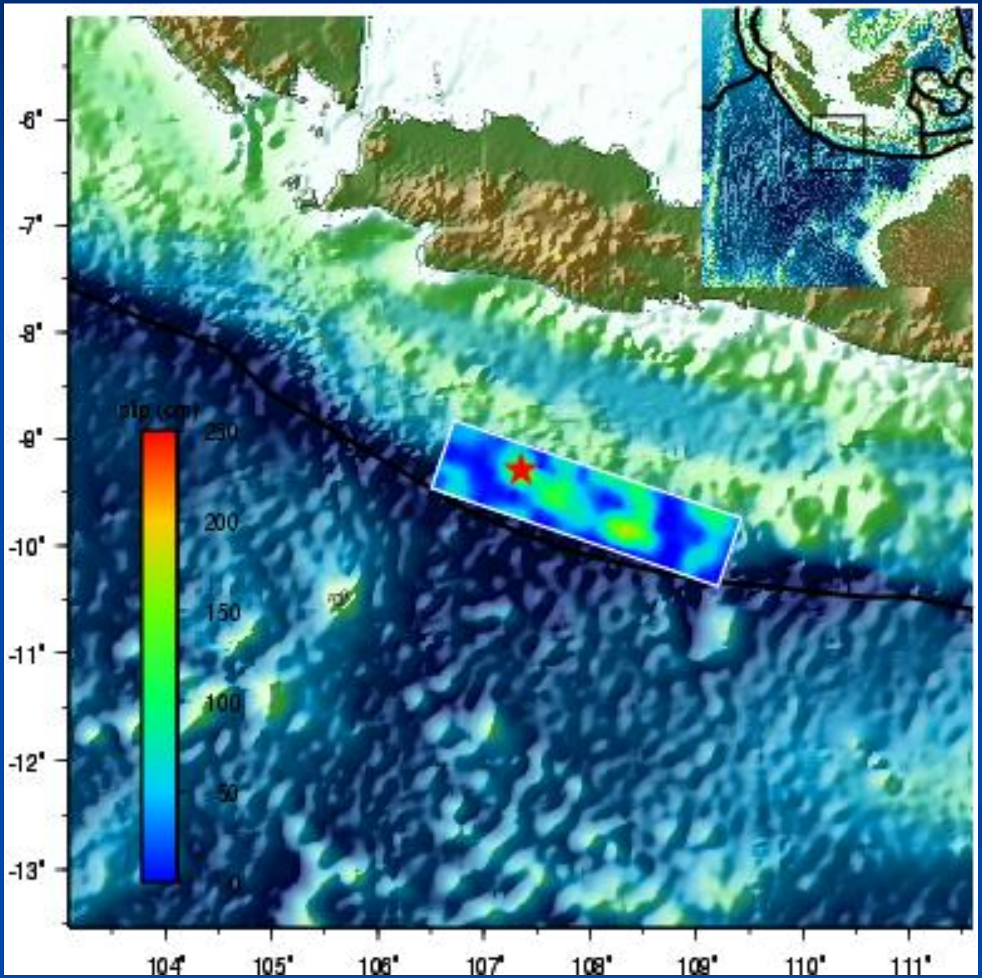
Tsunami Earthquakes

- Originally defined & identified by Kanamori (1972)
- Further elaborated by Kanamori & Kikuchi (1993)
  - Class 1: Non-accreting margins, surface rupture at trench
  - Class 2: Accreting margins, triggered landslides
- Class 1: Characterized by slow rupture velocities
- Increased tsunami excitation from
  - High slip relative to M_w
  - Shallow depth
  - Deep water above source
- Maybe correlated with rough topography of the downgoing plate (Tanioka, et al., 1997; Polet & Kanamori, 2000, Bilek & Lay, 2002)
- Coseismic anelastic deformation ? (Tanioka & Seno, 2001)

Local Tsunami Runup vs. M_w



July 2006 Java Tsunami Earthquake



Chen Ji, UCSB

http://neic.usgs.gov/neis/eq_depot/2006/eq_060717_qgaf/neic_qgaf_ff.html

Abandoning Scaling Relationships

Bilek & Lay (2002)

- Spontaneous rupture modeling (Oglesby et al., 1998; 2000 a,b; 2001; 2002; 2003a, b; 2005)
- Inputs
  - Frictional properties of fault
  - Elastic properties of surrounding rocks
  - Pre-stress distribution
  - Critical slip-weakening distance
- Full elastodynamic modeling
  - Interaction of seismic waves with rupture propagation

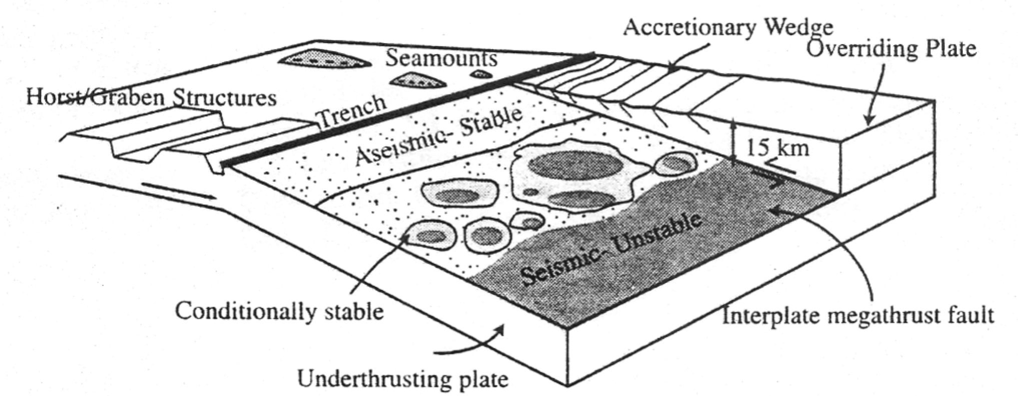


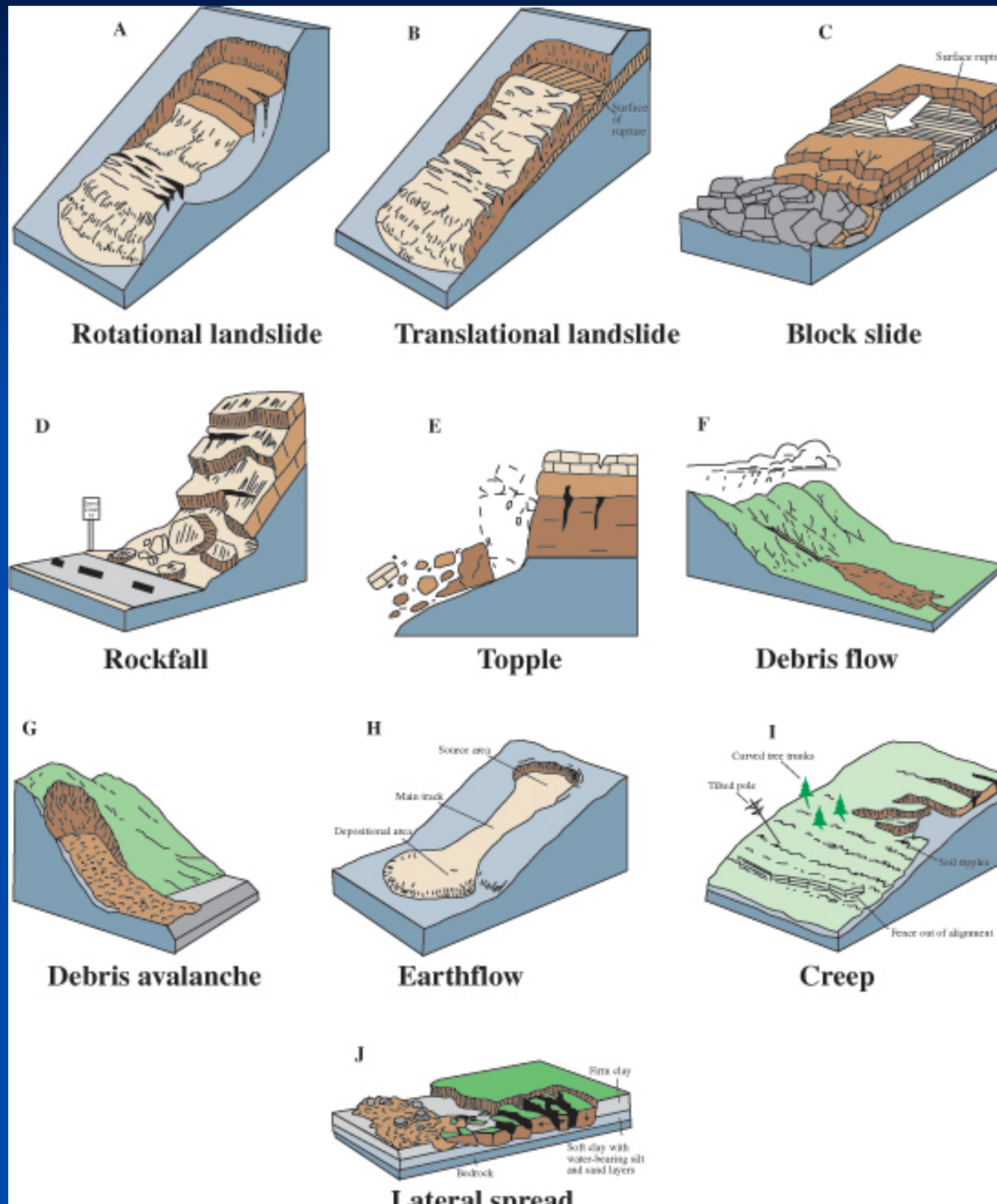
Figure 3. Cartoon illustrating frictional conditions of the subduction thrust fault plane. Individual unstable sliding contact areas (dark gray) can provide the nucleation sites for rupture in the shallow subduction zone environment, which is typically a stable (stippled) or conditionally stable (light gray) frictional region.

Dieterich-Ruina friction law

$$f = f_0 + a\ln\left(V/V_0\right) + b\ln\left(\theta/\theta_0\right)$$

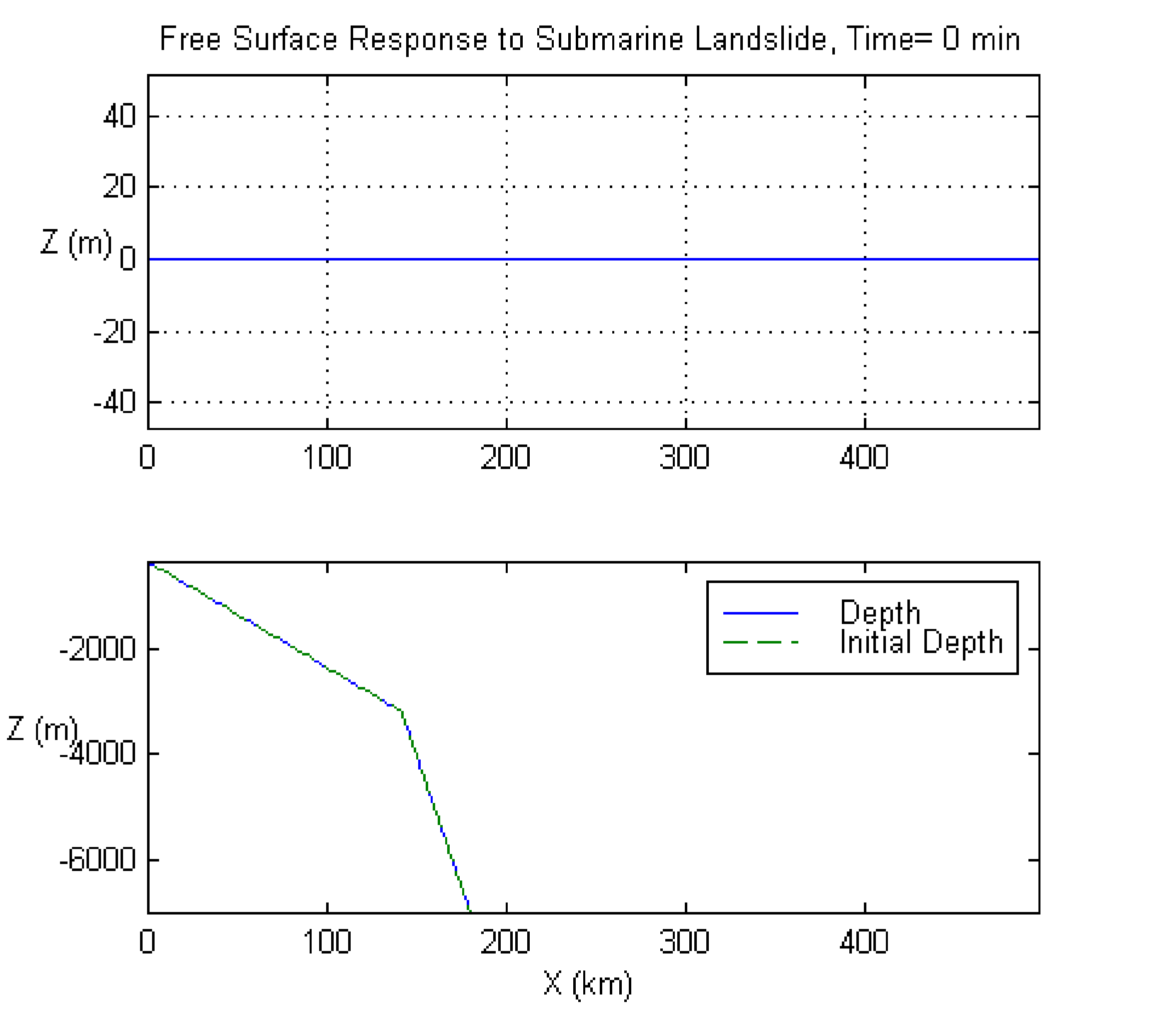
Problem #3

Landslides



Varnes (1978)

Tsunami Generation: Landslides



Patrick Lynett, Texas A&M

Santa Barbara Channel Submarine Landslides

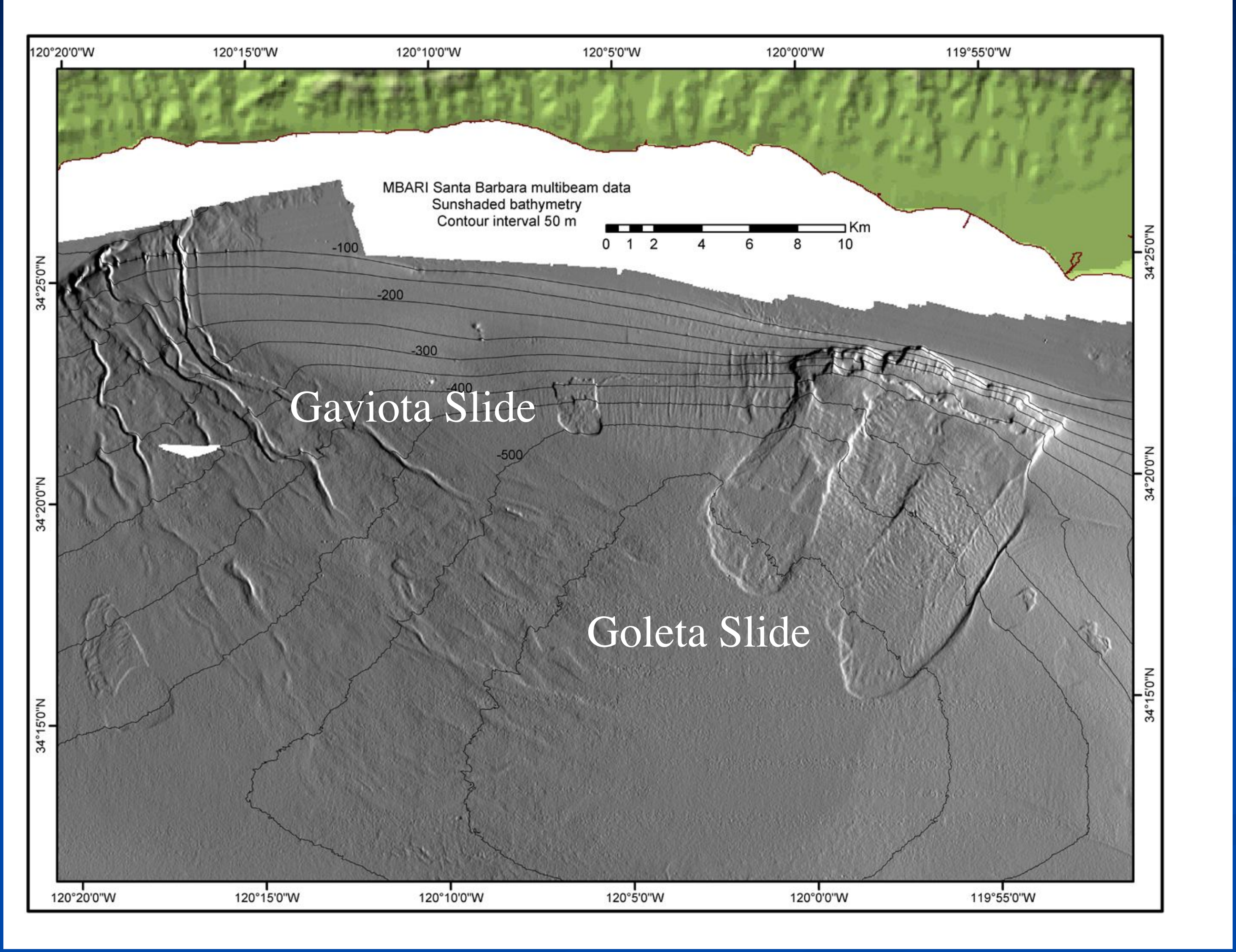
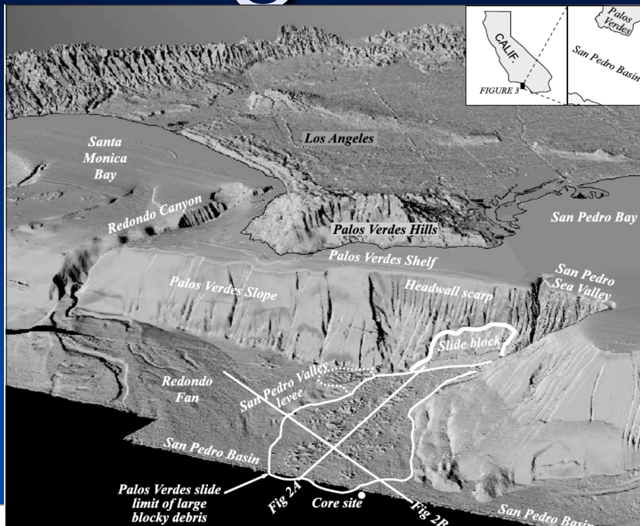
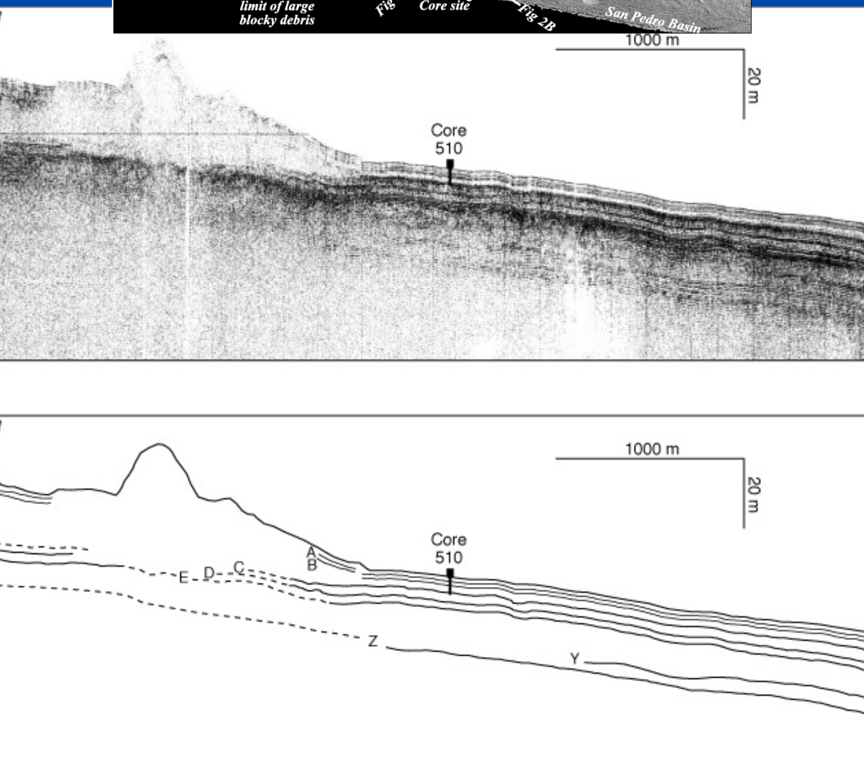


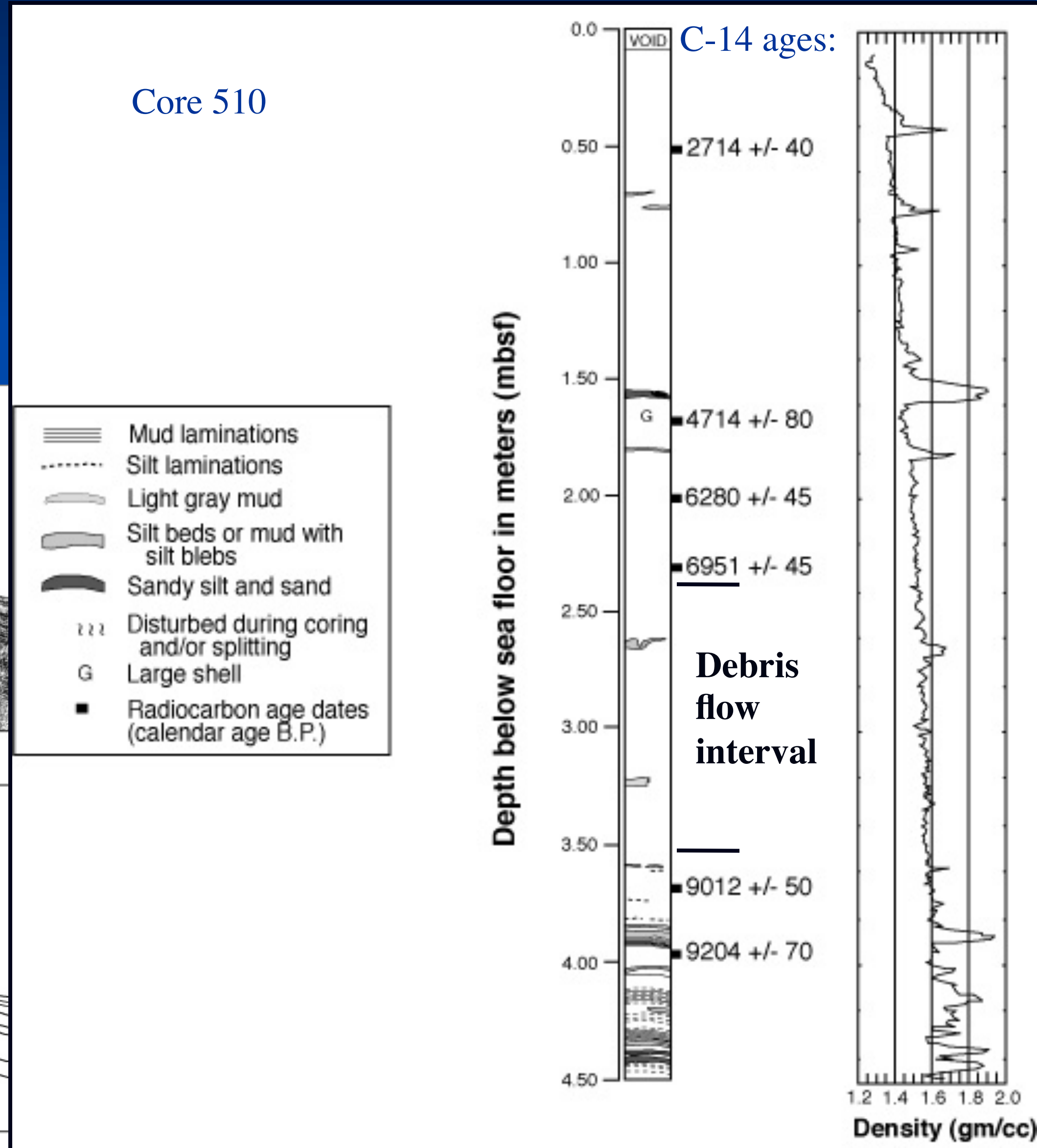
Image courtesy of Monterey Bay Aquarium Research Institute

Dating the Palos Verdes Landslide



Age = 7500 yrs. Normark et al., (2004)



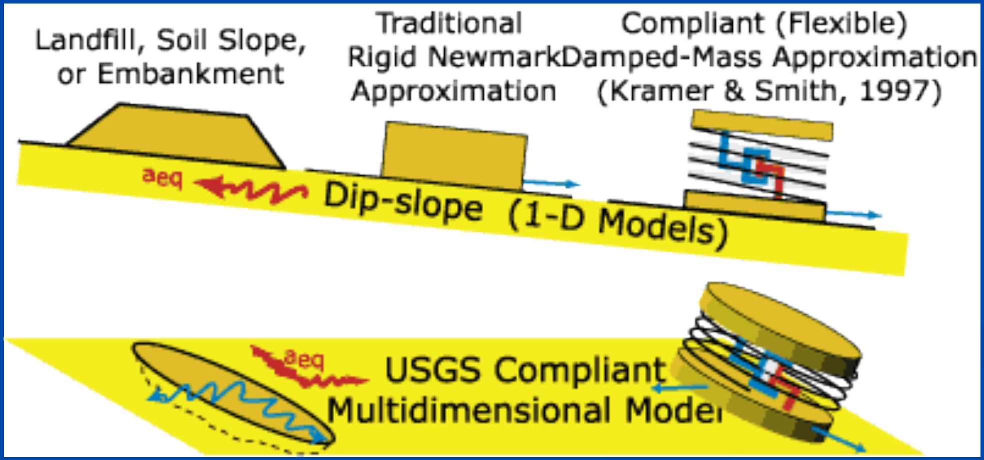


Seismically-Induced Submarine Landslides

- Triggering (Biscontin et al., 2004; Biscontin & Pestana, 2006)
  - Seismic loading -> Excess pore pressure
  - Possibility of later failure from pore pressure redistribution
- Initial (and Inertial) Displacements
  - 2D compliant model (Kayen & Ozaki, 2002)
- Post-Failure Dynamics
  - BING flow dynamics model (Imran et al., 2001)
  - Example: Palos Verdes (Locat et al., 2004)

Seismically Induced Landslides: Dynamic Compliance

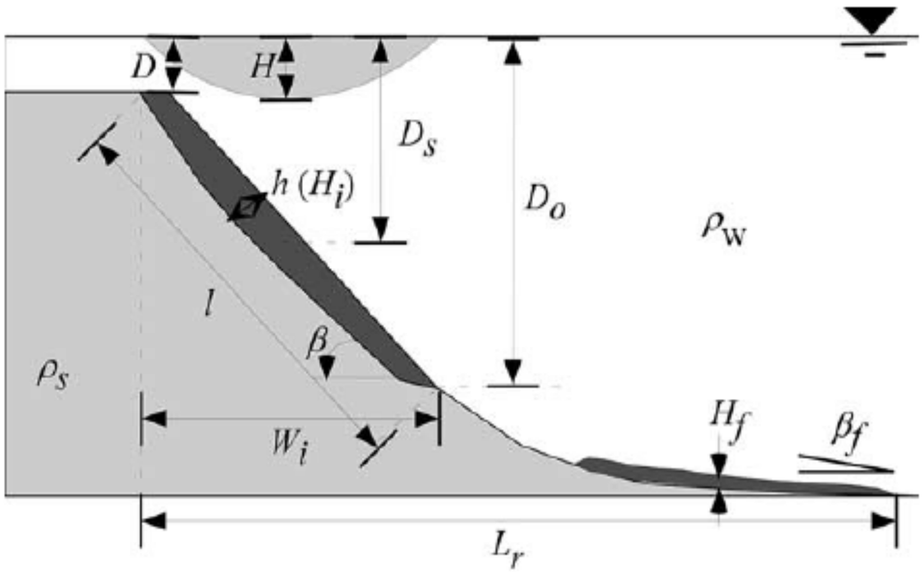
Text from G.K. Gilbert on the1906 event (Lawson, et al., 1908) -"There was also a horizontal shifting of mud over a considerable area", "At various places along the shore...the tidal mud seemed crowded against the firmer ground at the shore, being pushed up into a ridge" "Maximum shifting...was not less than 30 feet."



Courtesy: Rob Kayen (USGS)

Seismically-Induced Landslides: Post-Failure Dynamics

Locat et al. (2004)



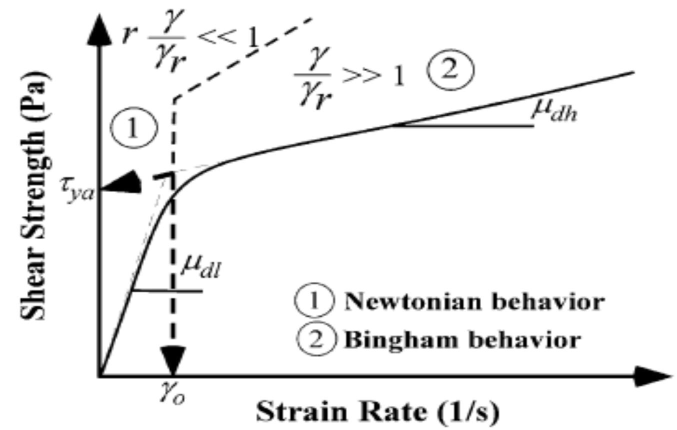
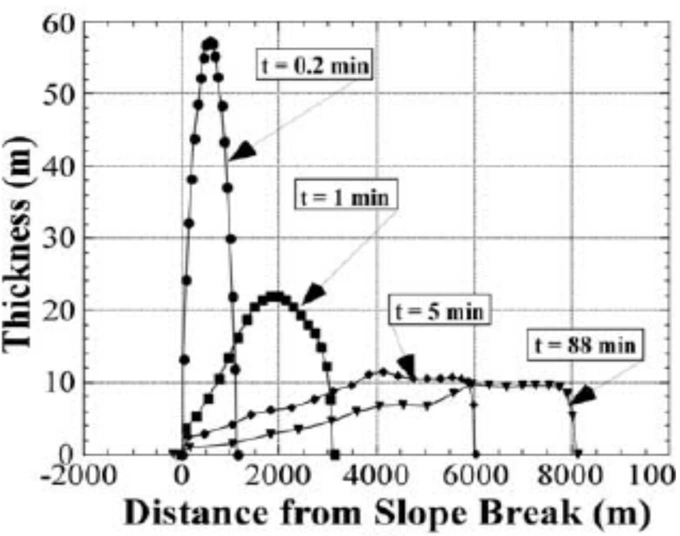
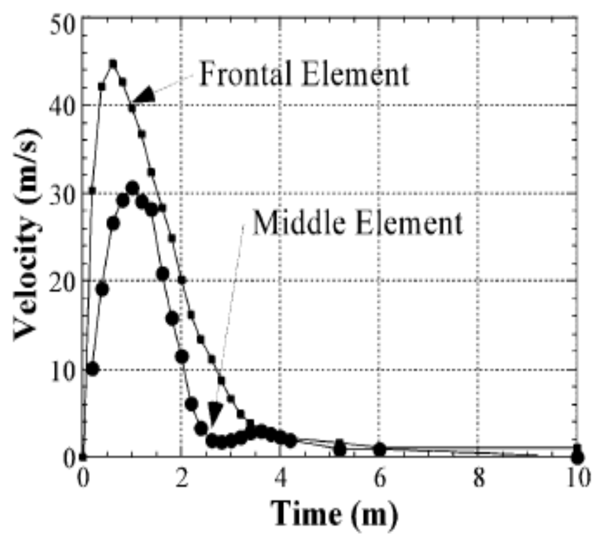
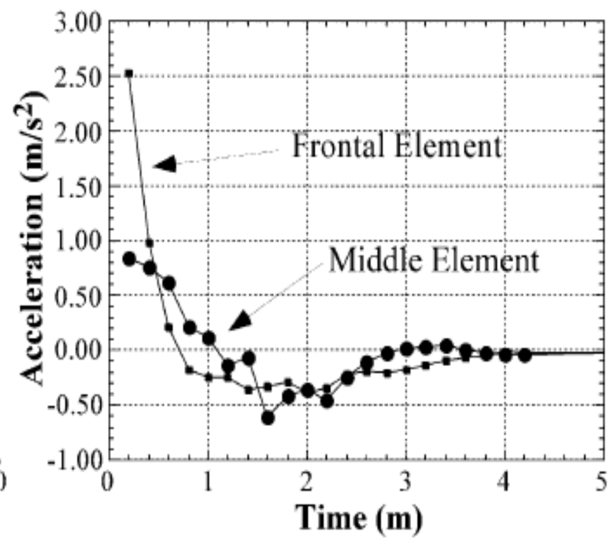


Fig. 4. Bi-linear model of Locat (1997) with the boundary conditions used in the 1D numerical model Bing (Imran et al., 2001), see the text for explanation of symbols.

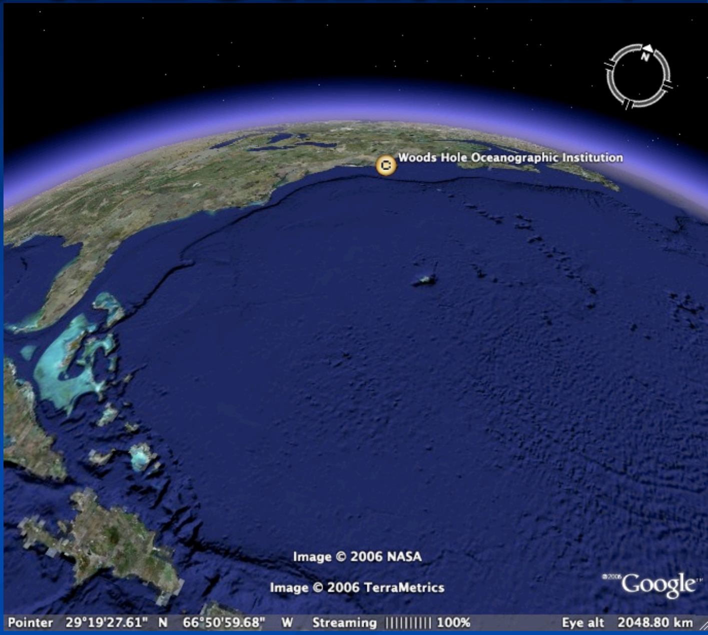






Problem #4

What's the Chance of a Tsunami?

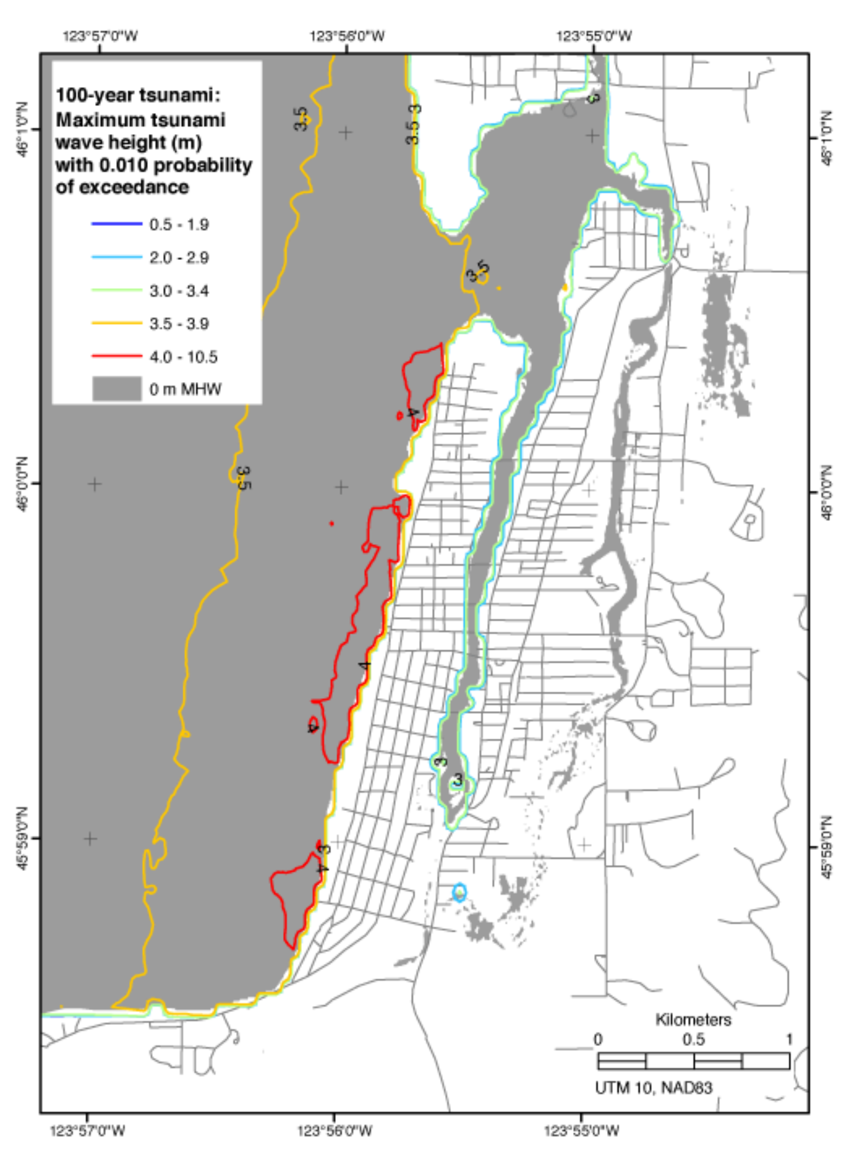


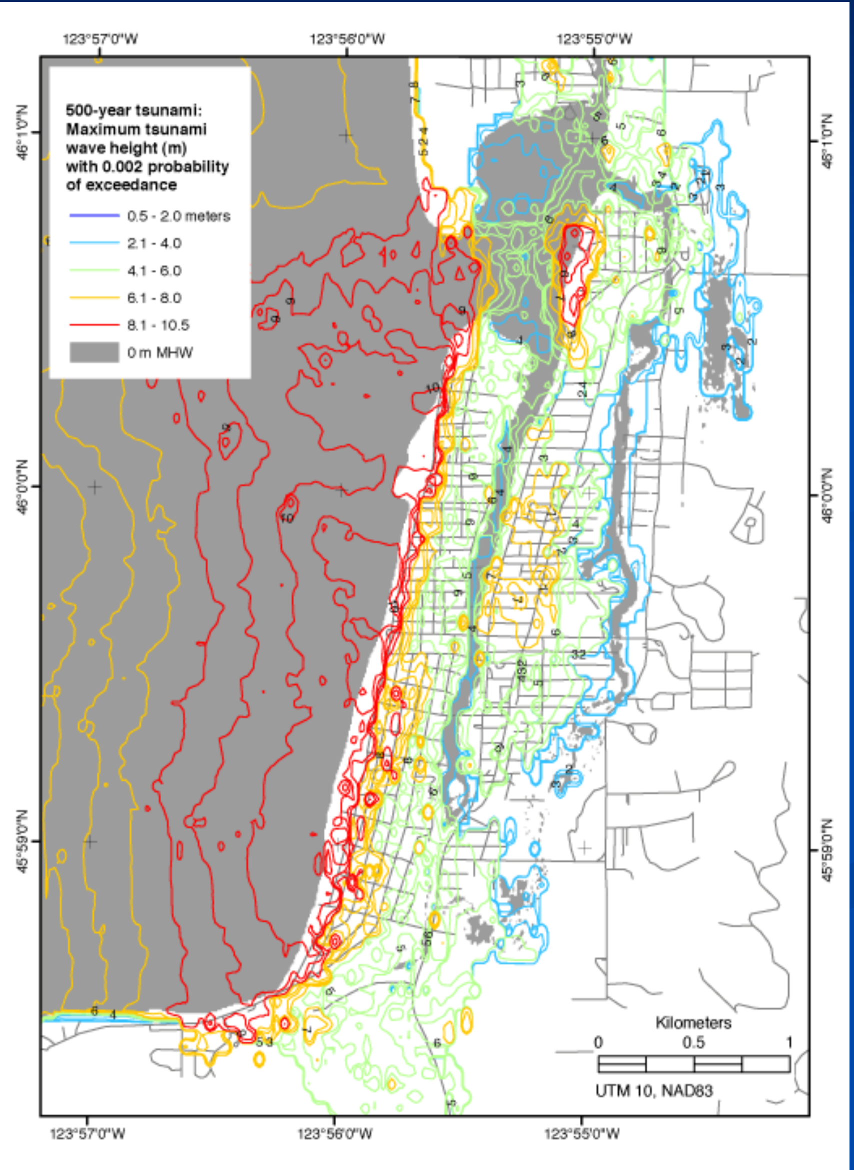
- Necessary Ingredients
  - Statement of the Problem
    - What size?
    - Where?
    - Exposure Time?
    - Starting When?
  - Distribution of Event Sizes
  - Distribution of Inter-Event Times
- Empirical Approach
- Computational Approach
  - Probabilistic Tsunami Hazard Analysis (PTHA)

Computational Probabilistic Tsunami Hazard Analysis (PTHA)

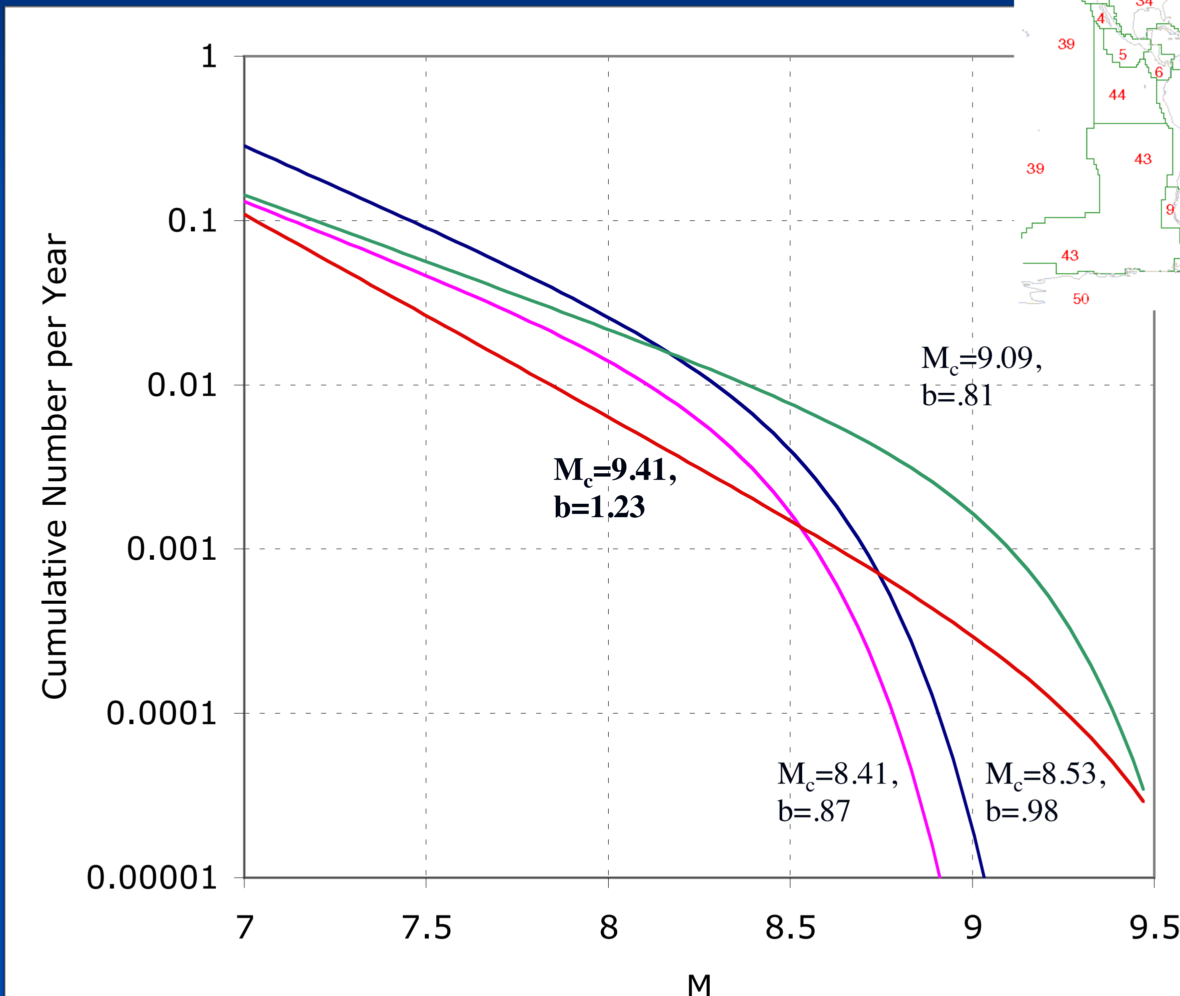
- Based on PSHA
  - Differences:
    - Inclusion of far-field sources
    - Numerical propagation models
- Determine source model (e.g., EQ’ s)
  - Source Parameters
  - Location (Zonation)
  - *Frequency-Magnitude Distribution*
    - *Earthquake Catalog*
    - *Seismic moment balance*
- Propagation-Inundation model
  - Compute for each source
- Calculate Aggregate Probabilities

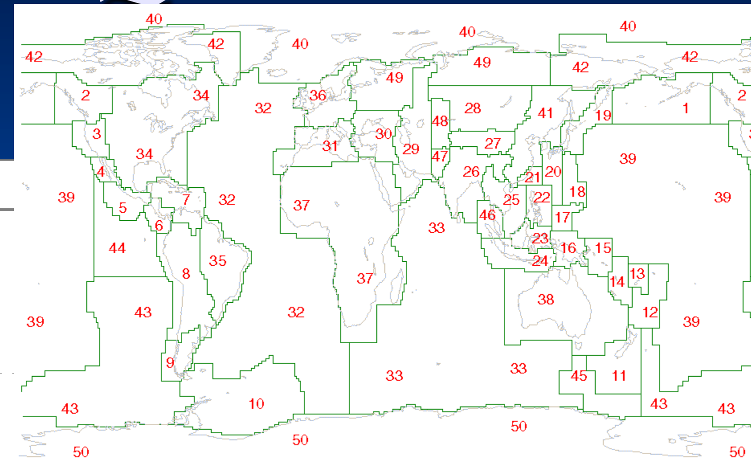
Case Study: Seaside, OR





Distribution of EQ Sizes

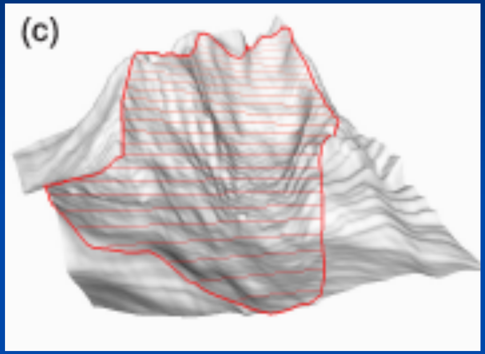


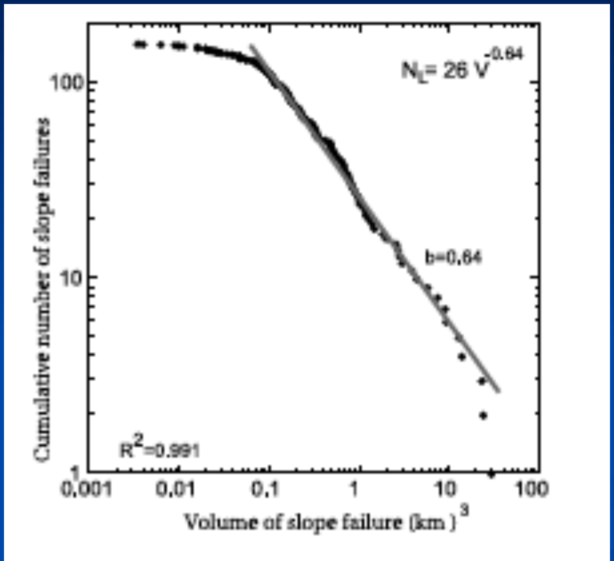


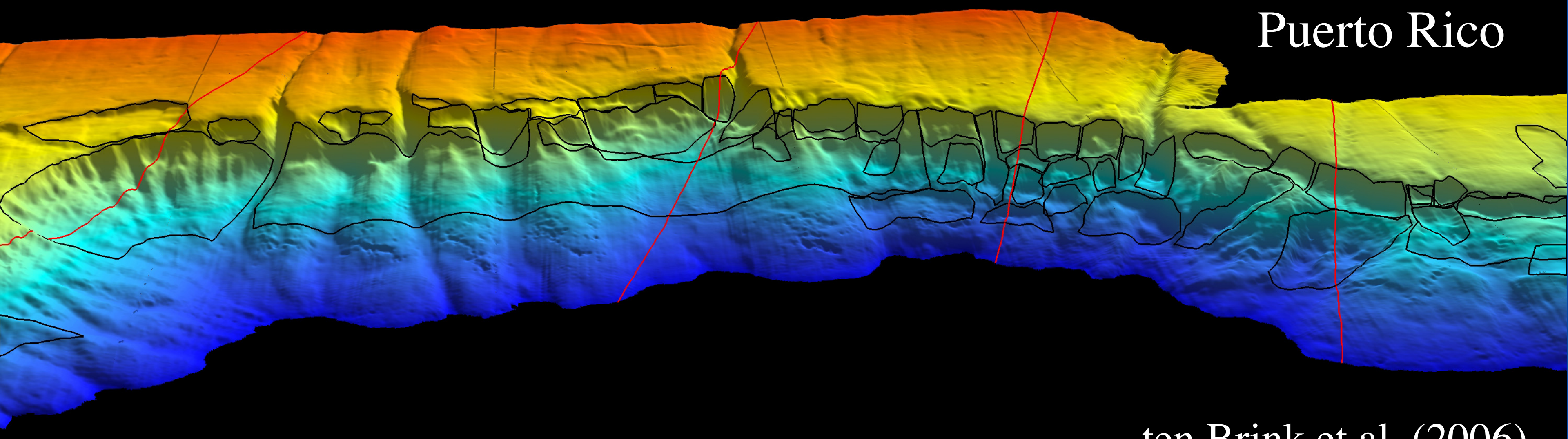
Flinn-Engdahl Regions

Kagan (1997)

Distribution of Landslide Sizes







ten Brink et al. (2006)

Calculating Probabilities

- Cumulative probability that an event will occur during time T

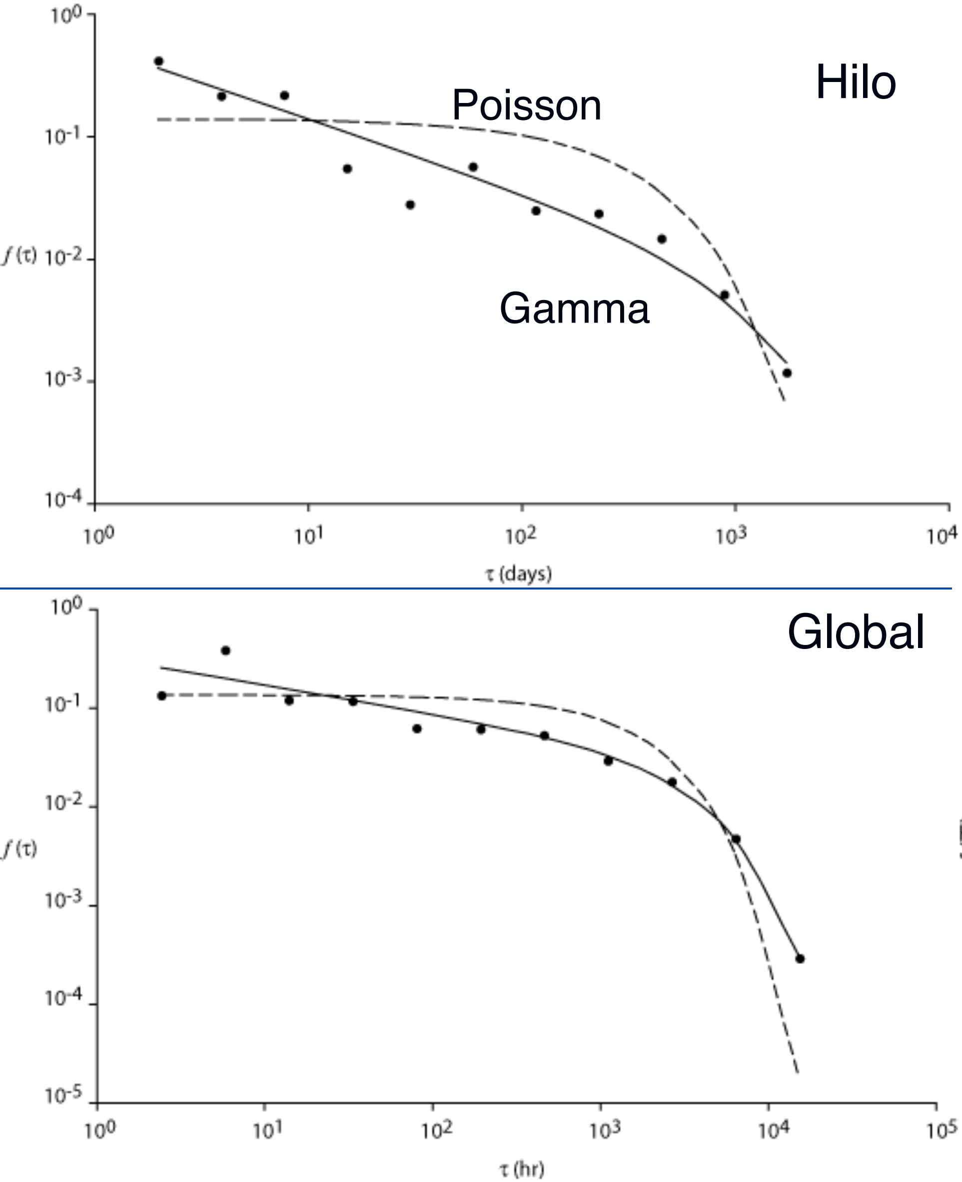
$$P_{pois} = 1 - \exp(-\lambda T)$$

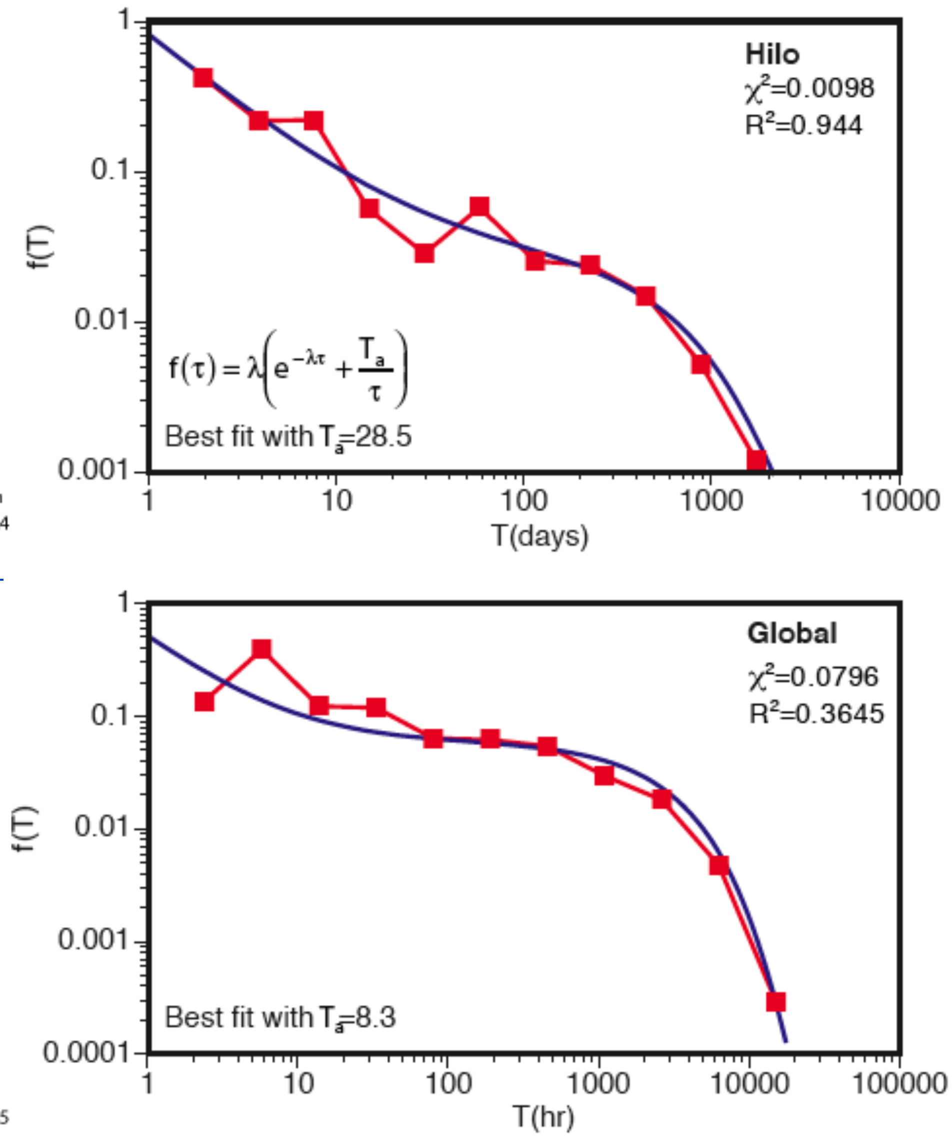
BUT...

Do Inter-Event Times Follow a Poisson Process ?

Non-Poissonian Inter-Event Times

Parsons & Geist (in prep.)





Summary

- Problem 1: Slip
  - Old theory
    - Dislocations
  - Recent Advances
    - Technology: Deep-Sea Tsunami Measurements
    - Results from Sumatra 2004, 2005 Earthquakes: Lower Average Slip Relative to M_w
  - In Progress
    - Large Fluctuations in Slip: Lévy Law Slip Distributions
  - Persistent Problems
    - Scaling Uncertainty

Summary

- Problem 2: Tsunami Earthquakes
  - Recent Advances
    - Broadband Seismology
  - In Progress
    - Spontaneous, Dynamic Rupture Models
  - Persistent Problems
    - Where and Why: Frictional and Pre-Stress Conditions of the Shallow Inter-Plate Thrust

Summary

- Problem 3: Landslide Tsunamis
  - Old theory
    - Rigid Block
  - Recent Advances
    - Technology: Multibeam Bathymetry, Dating
    - Constitutive Description of Landslide Dynamics
  - In Progress
    - Understanding Seismic Triggering
  - Persistent Problems
    - Multiple rheologies
    - Coupling Post-Failure Dynamic Models with Hydrodynamics

Summary

- Problem 4: Tsunami Probability
  - Old theory
    - Seismic-Gap
  - Recent Advances
    - Power-Law Frequency-Size Distribution for Tsunamis
    - Statistics of Subduction Zone Earthquakes
    - Power-Law Frequency-Size Distribution for Submarine Landslides
  - In Progress
    - Non-Poissonian Timing: Temporal Clustering
    - Short-Term Forecasting: Accelerated Moment Release
  - Persistent Problems
    - Time-Dependent Rupture
    - Probabilities of Extreme Events