A Discussion of Elastic Rebound, Earthquake Recurrence and Characteristic Earthquakes

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One hundred years have passed since H.F. Reid proposed the elastic rebound model for earthquakes, in which fault slip during an earthquake releases stored elastic strain energy. Today, we apply our underlying knowledge of plate tectonics and the concepts of interseismic strain accumulation, coseismic strain release and postseismic adjustments to forecast future earthquakes and fault system behavior.

A central question that has emerged is the relationship between one faulting event and the next; i.e. how is the strain released in one event related to the amount of strain accumulated during the interseismic period and/or the strain released in the preceding event?

Periodic? Randon? Clustered? Time-Predictable? Slip-Predictable? Characterisitc? None of the Above?

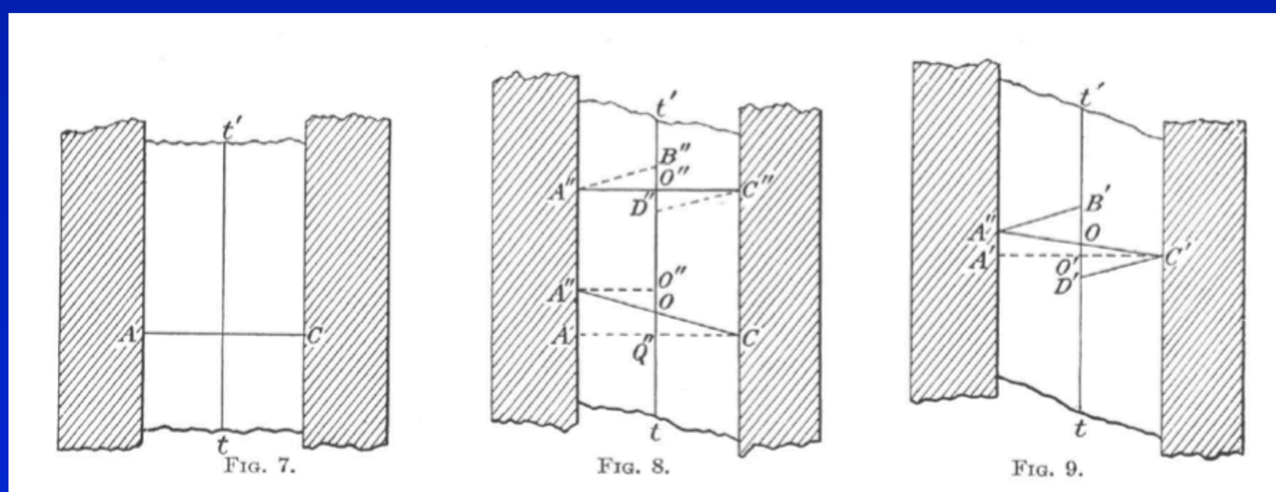
A Discussion of Elastic Rebound, Earthquake Recurrence and Characteristic Earthquakes

Overview

- Part I. Implications of Seismological and Geodetic Data (Bill)
- Part II. Discussion (Ray and Audience)
- Part III. Implications of Geological and Paleoseismic Data (Ray)
- Part IV. Discussion (Bill and Audience)

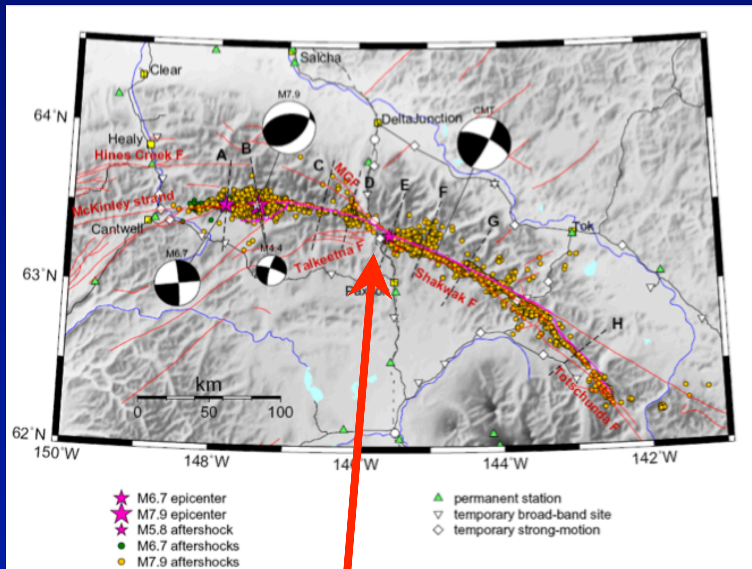
Outline of This Talk

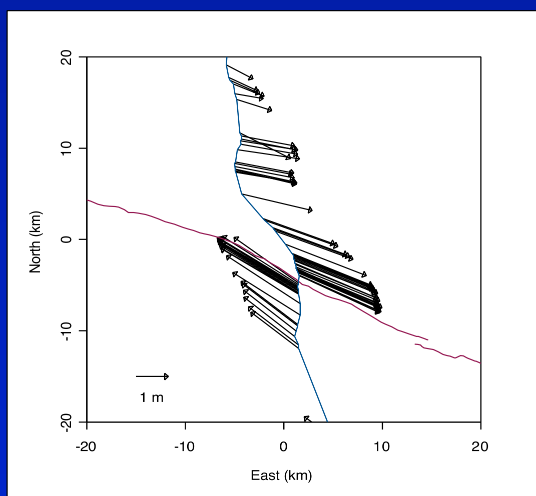
- Elastic Rebound
- Reid Cycle and Crustal Rheology
- Repeating Earthquakes (10 m – 1,000 km)
- Recurrence Models
- Reality Check
- Summary



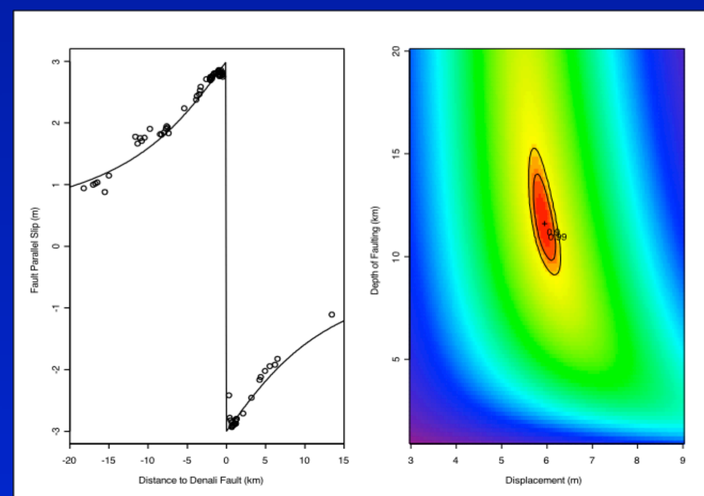
H. F. Reid (1910)

Elastic Rebound in the 2002 Mw 7.9 Denali Fault, Alaska Earthquake



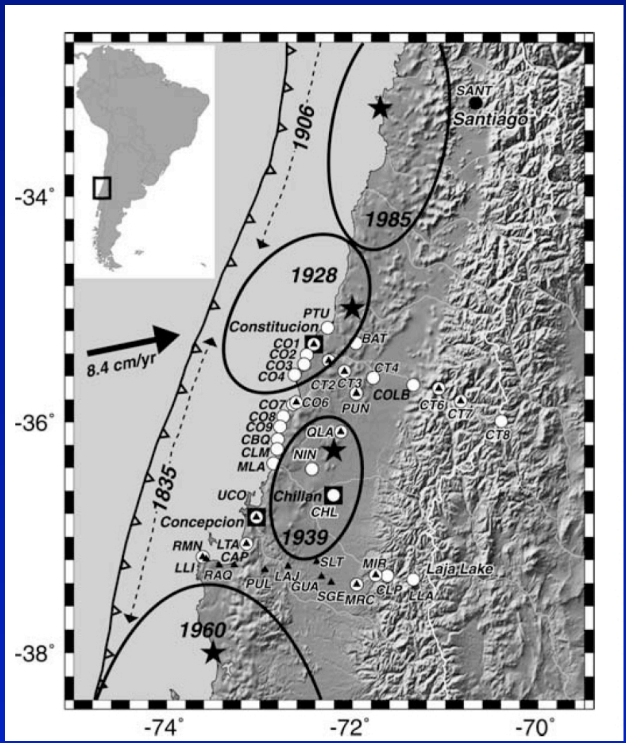


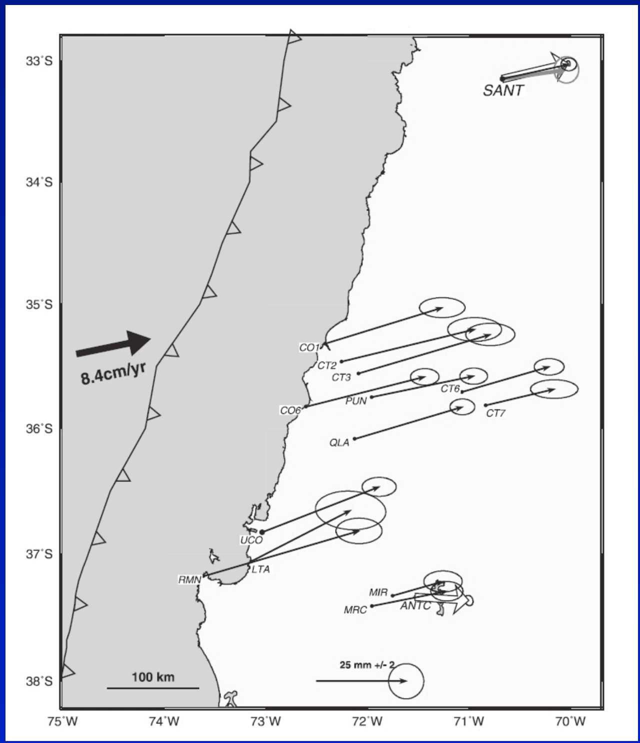
Displacements along the Richardson Highway



Uniform dislocation: 5.95 m slip from 0 to 11.6 km

Interseismic Strain Accumulation in the Concepcion Seismic Gap, Chile

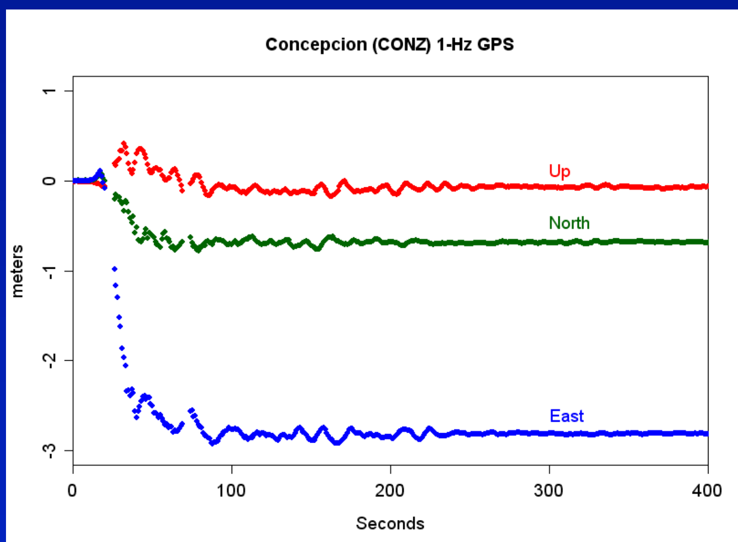




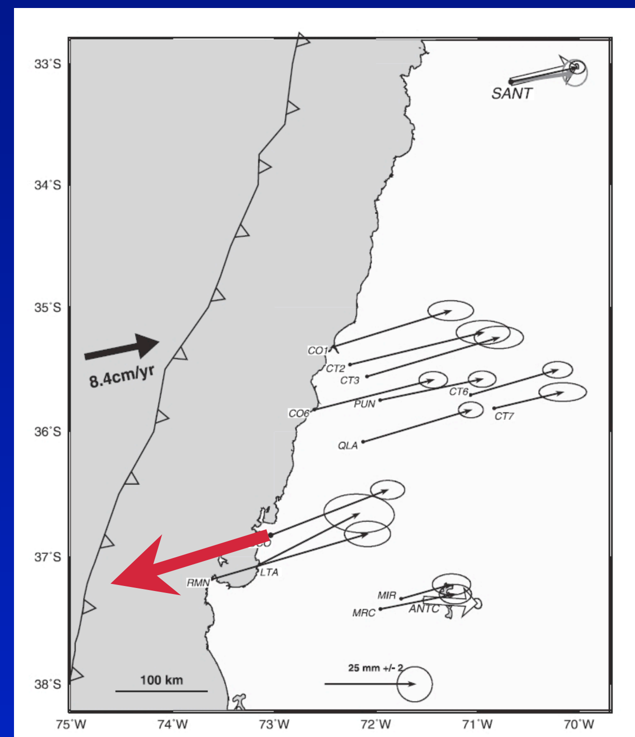
Ruegg, et al., GRL 2002

Interseismic Strain Accumulation in the Concepcion Seismic Gap, Chile

Elastic Rebound in the M 8.8 Maule, Chile earthquake at Concepcion was equal to about 100 years of strain accumulation

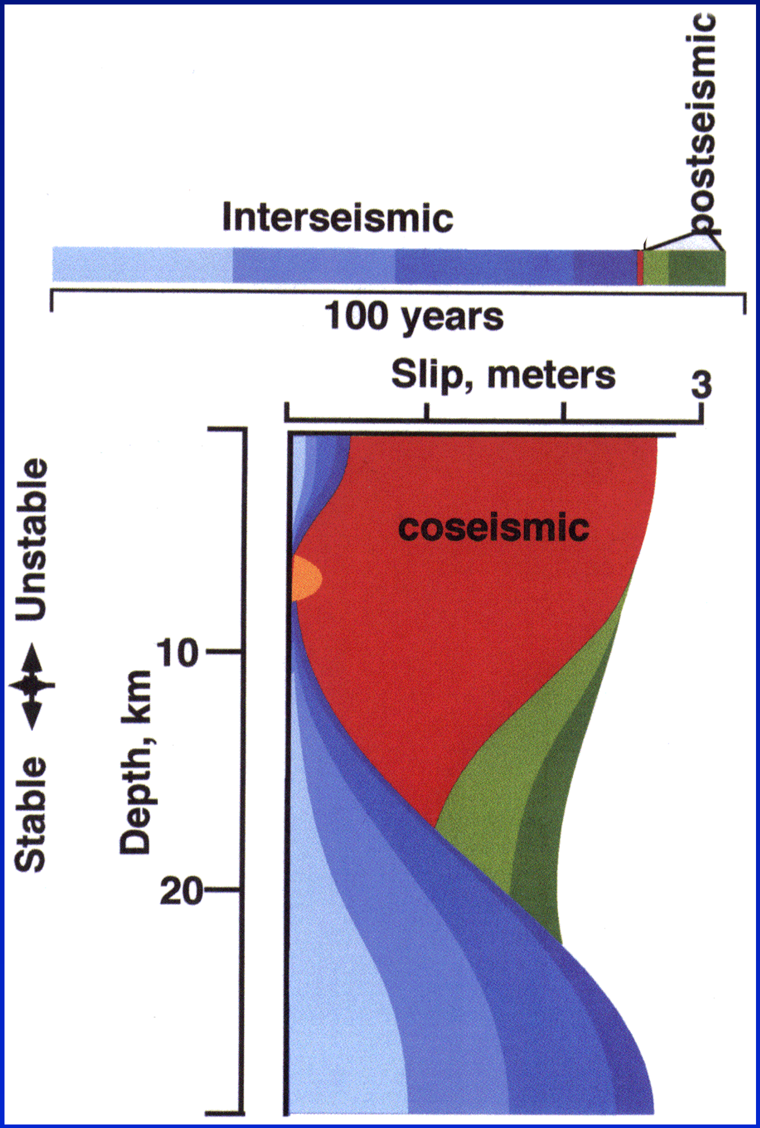


1 Hz GPS courtesy of Kristine Larson

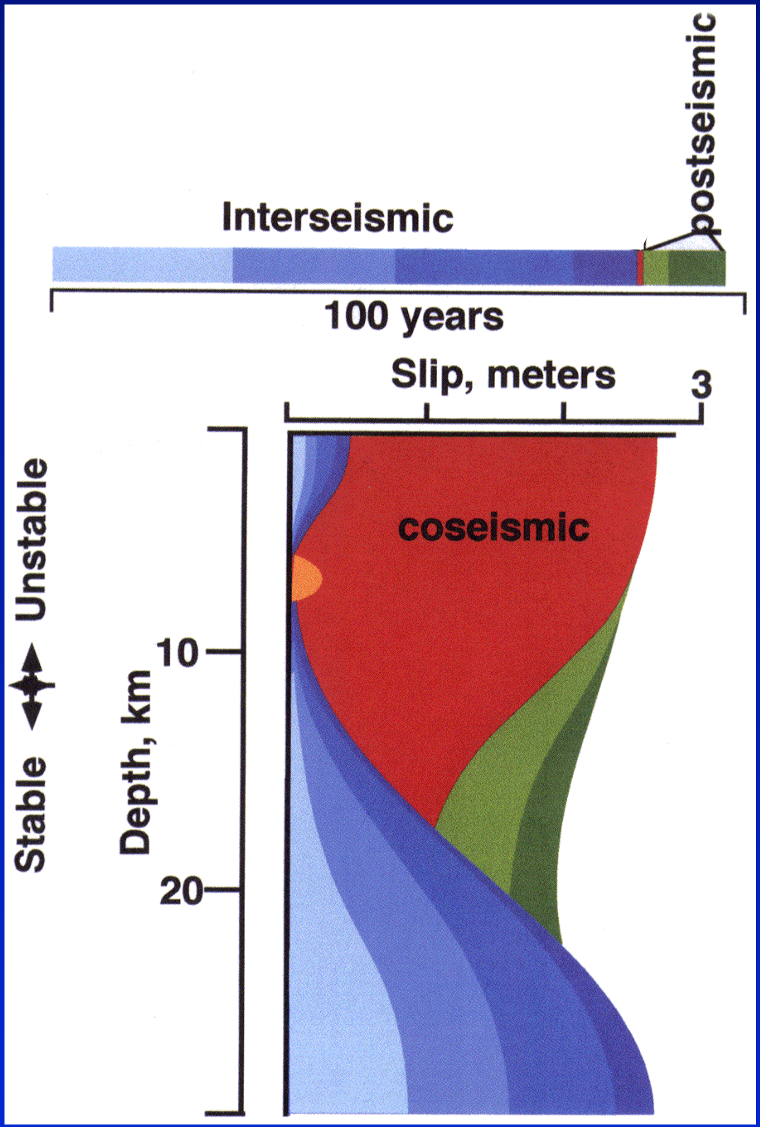


Ruegg, et al., GRL 2002

Reid Cycle and Rheology



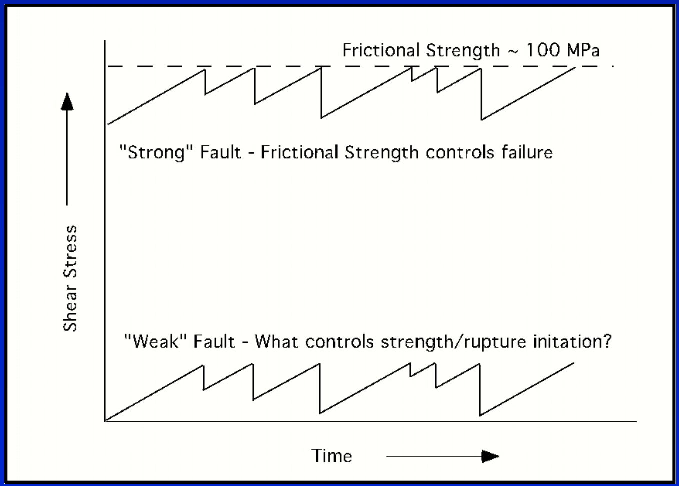
Reid Cycle and Rheology



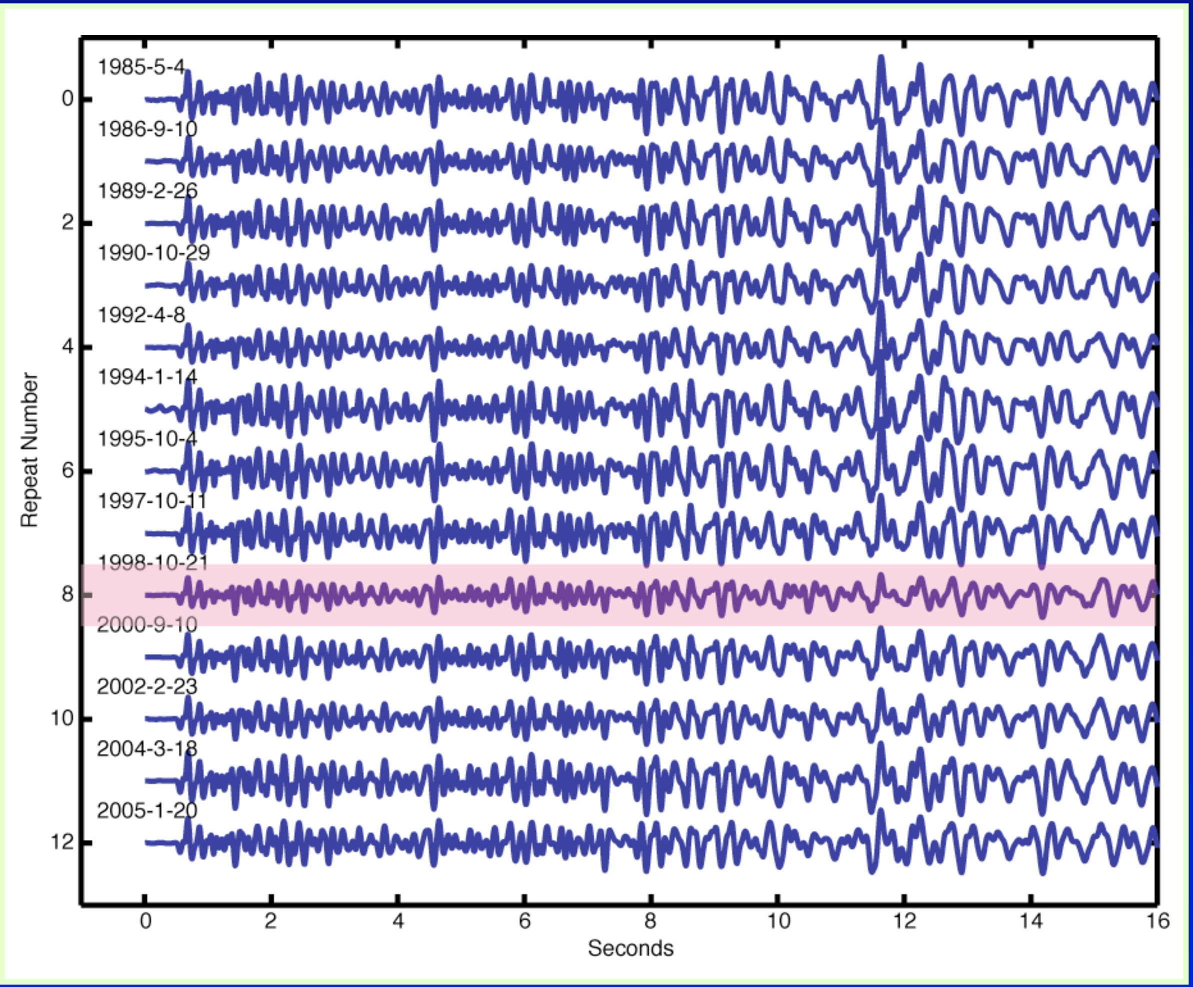
Negligible stress in the upper ~km

High stress in the nucleation zone (?)

High or low stress along rupture?

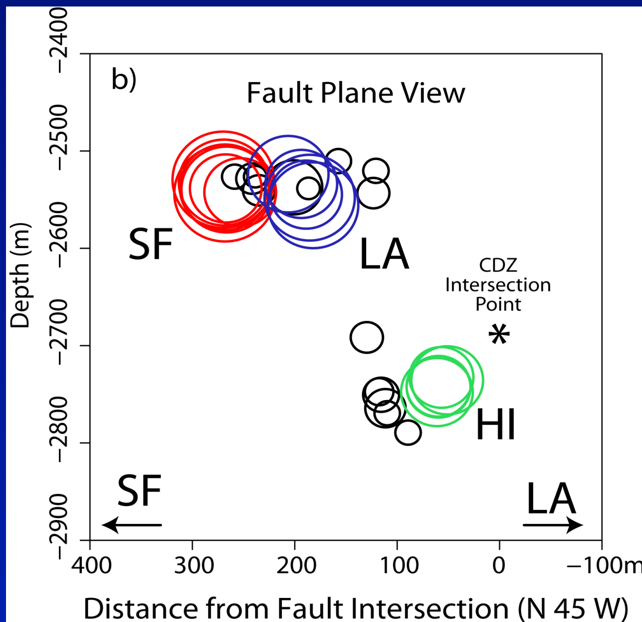


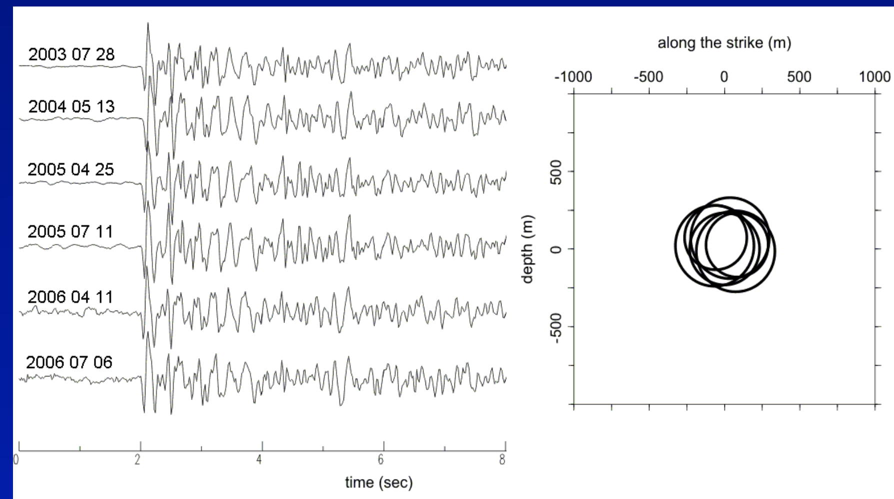
Repeating Earthquakes Provide a Window into the Physics



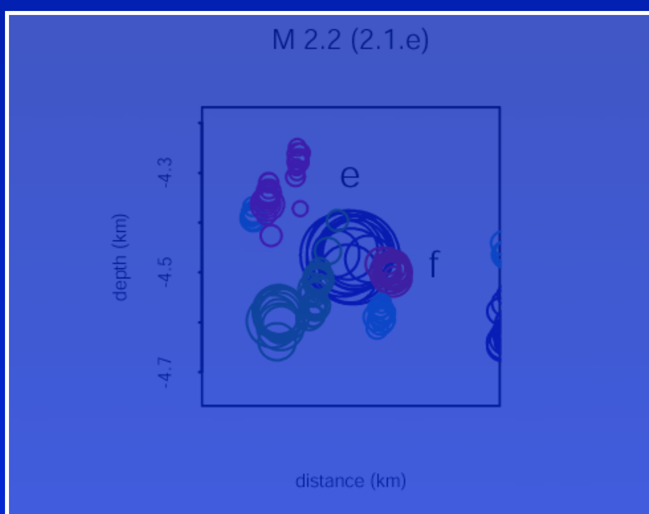
SAFOD target earthquakes

Repeating earthquake on the N. Anatolian Fault, Turkey





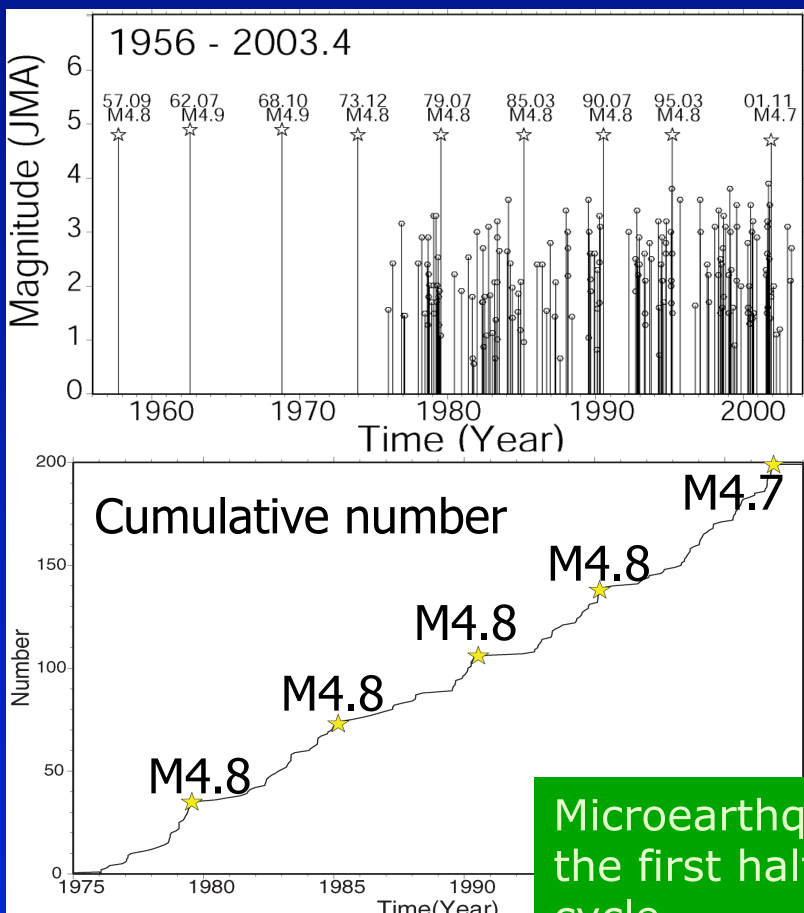
Bulut, et al., SSA 2010

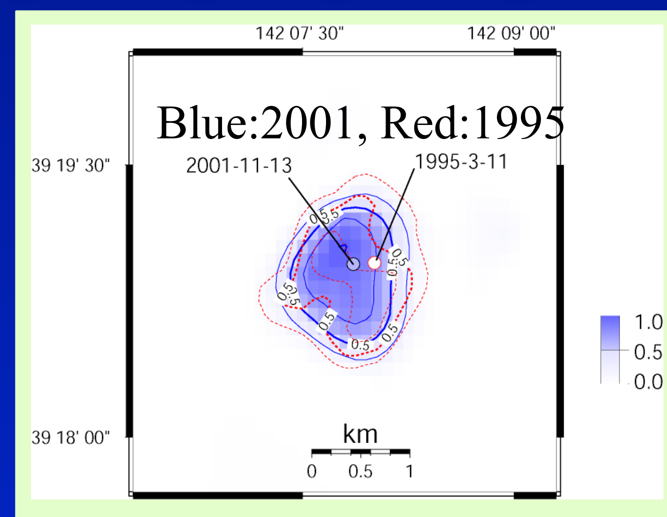


Cluster of multiple earthquakes in a “streak” along the central creeping San Andreas Fault

M4.8 'characteristic earthquake' sequence off Kamaishi, northern Honshu, Japan

Matsuzawa et al. (2002); Okada et al. (2003); Uchida et al. (2007)



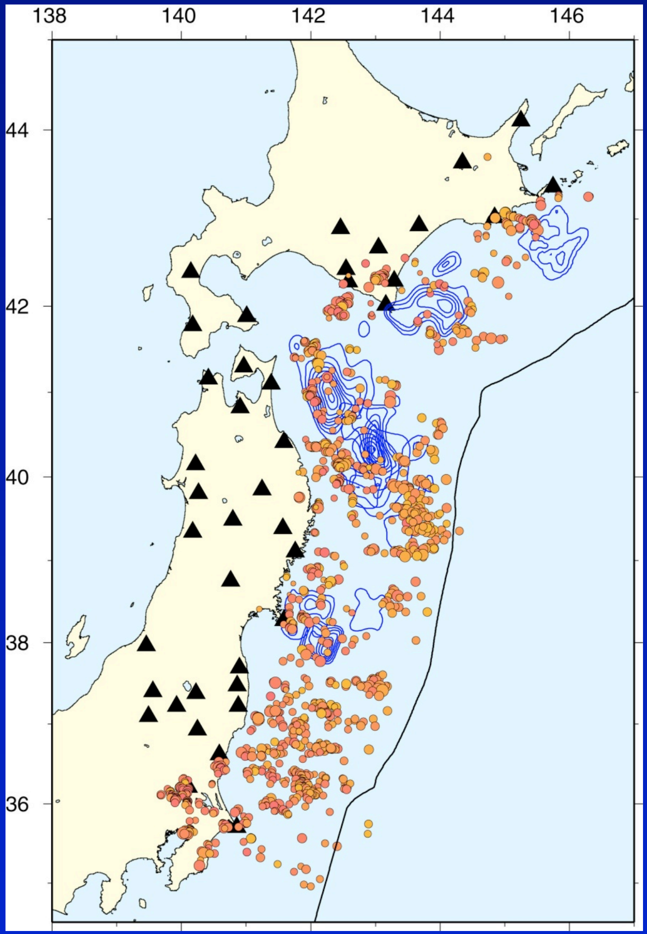


Slip areas for M4.8 earthquakes

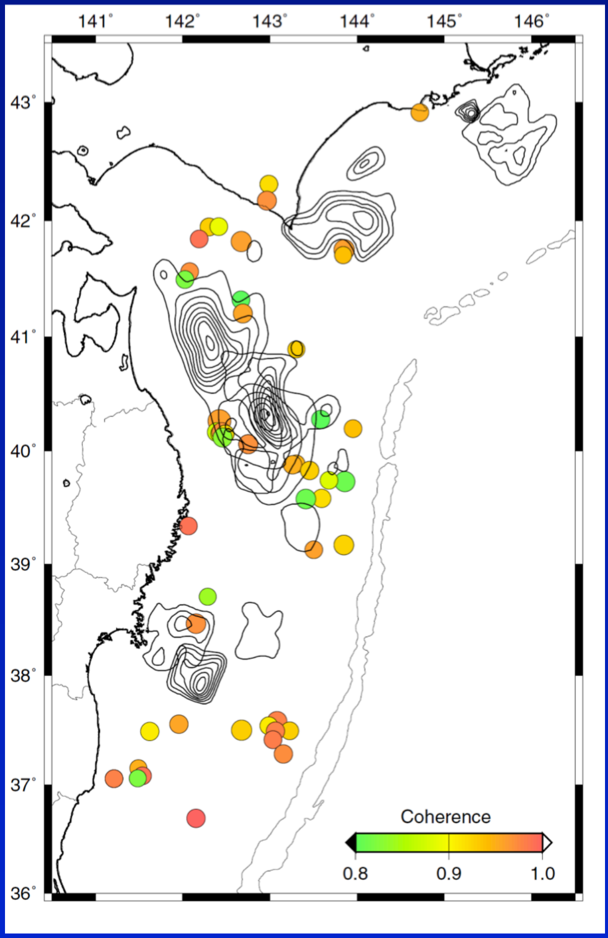
Microearthquake is low in the first half of the seismic cycle.

Distribution of Repeating Earthquake Sequences on the Pacific Subduction Zone 1984 – 2009

(Naoki Uchida, in prep.)



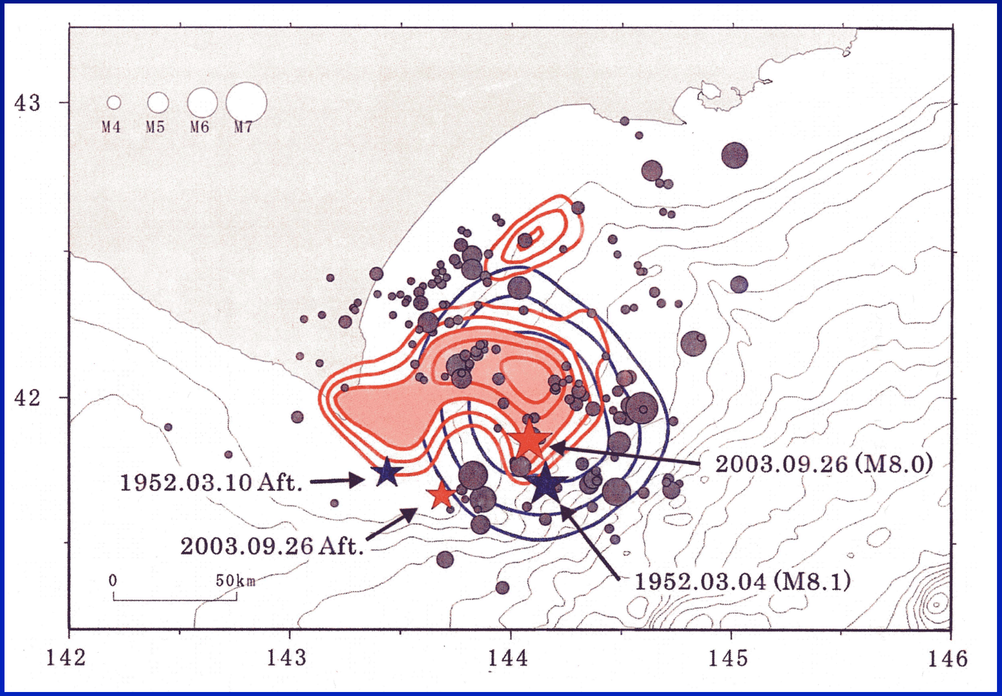
M 2.5 – 4.9



M 4.5 – 6.2

Contours: Asperities for M>=7 earthquakes (Yamanaka and Kikuchi 2003, 2004)

Slip distributions of the Tokachi-Oki event 2003 vs 1952



Black contour: 1952 event

Red contour: 2003 event

(Yamanaka and Kikuchi, 2003)

Cascadia

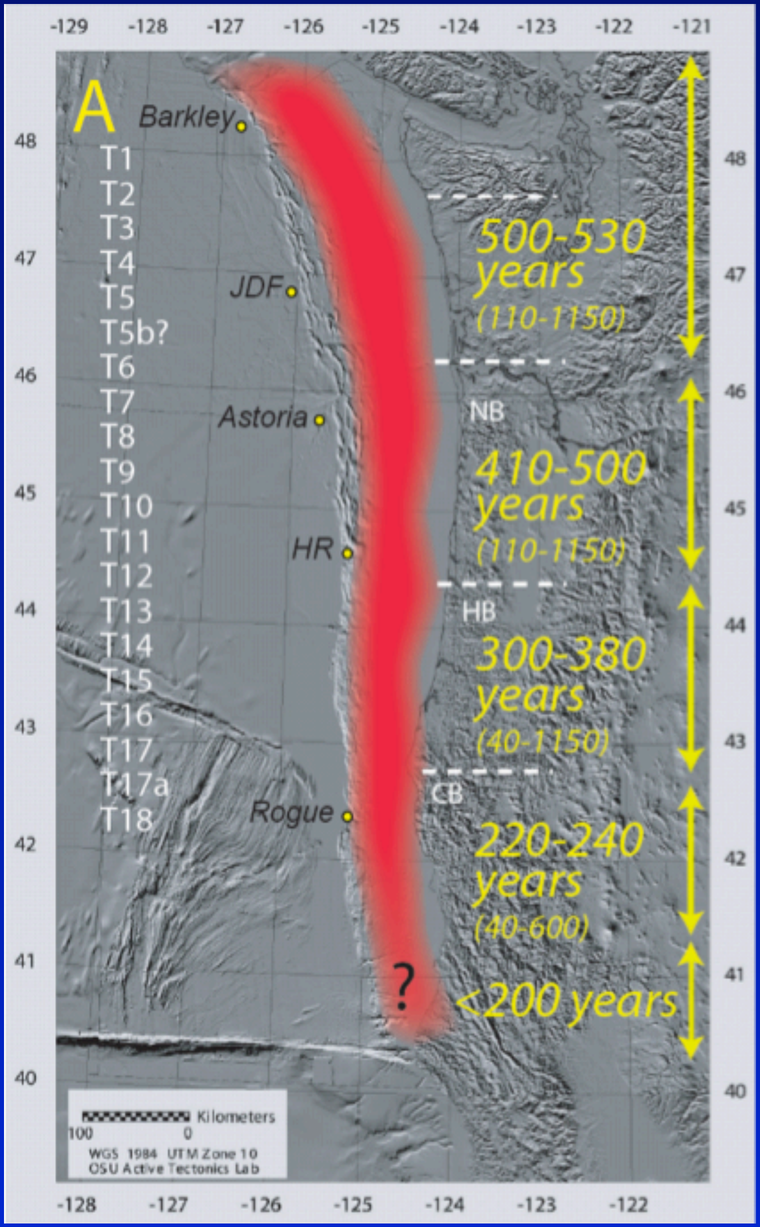
Atwater, B.F., 1987, Evidence for great Holocene earthquakes along the outer coast of Washington State: Science, v. 236, p. 942-944.

Adams, J., 1990, Paleoseismicity of the Cascadia subduction zone: evidence from turbidites off the Oregon-Washington margin: Tectonics, v. 9, p 569-583.

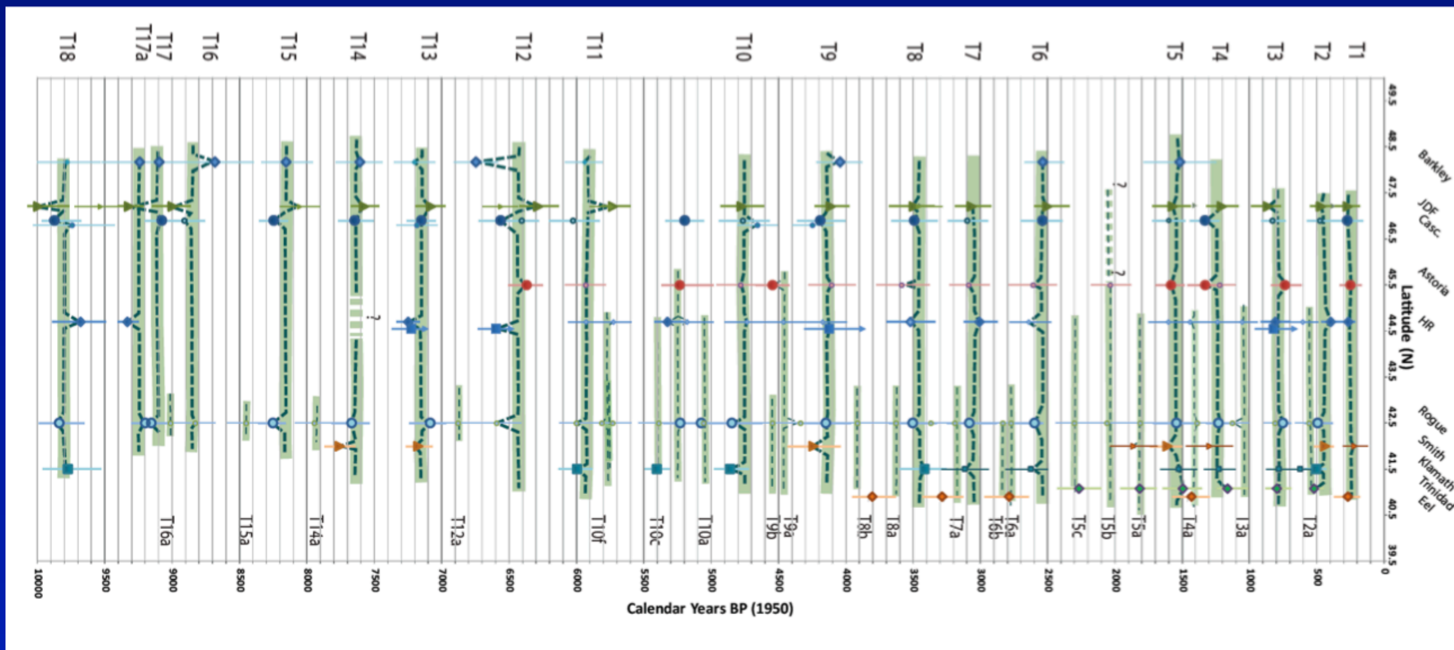
Satake, K., Shimazaki, K., Tsuji, Y., and Ueda, K., 1996, Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami records of January, 1700: Nature, v. 379, p. 246-249.

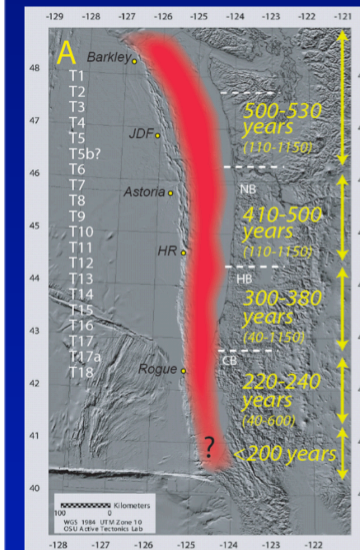
Atwater, B.F., and Hemphill-Haley, E., 1997, Recurrence intervals for great earthquakes of the past 3500 years at northeastern Willapa Bay, Washington: U.S. Geological Survey Professional Paper 1576, 108 p.

Chris Goldfinger, C. Hans Nelson, Joel E. Johnson, Ann E. Morey, Julia Gutiérrez-Pastor, Eugene Karabanov, Andrew T. Eriksson, Eulàlia Gràcia, Gita Dunhill, Jason Patton, Randy Enkin, Audrey Dallimore, Tracy Vallier, and the Shipboard Scientific Parties, in press, Turbidite Event History: Methods and Implications for Holocene Paleoseismicity of the Cascadia Subduction Zone, U. S. Geological Survey Professional Paper.



Goldfinger, et al., in press





- Wall-to-Wall Ruptures
- Clusters of Great Earthquakes
- Partial Rupture in South
- Southern End is Late in Recurrence Cycle

Goldfinger, et al., in press

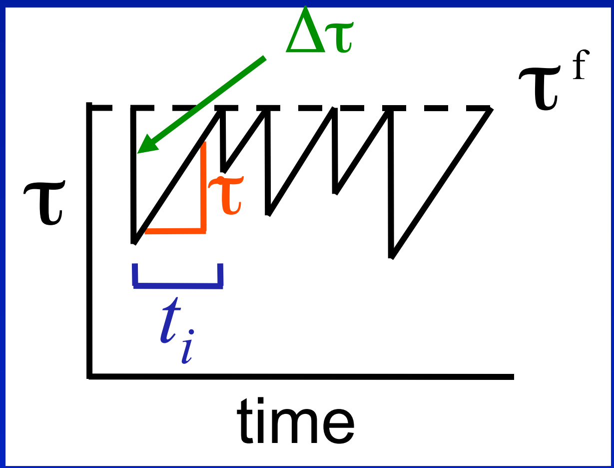
Conceptual Models

- Time predictable model (Shimazaki & Nakata, 1980)
  - Size of last earthquake and loading rate sets time of next
- Slip predictable model (ditto)
  - Time of next earthquake and loading rate set size of next
- Characteristic earthquake model (Schwartz & Coppersmith, 1984)
  - Every earthquake is “the same”
- Renewal models (Cornell & Winterstein, 1988)
  - Independent Identically Distributed intervals (IID)

Time and Slip Predictable Models

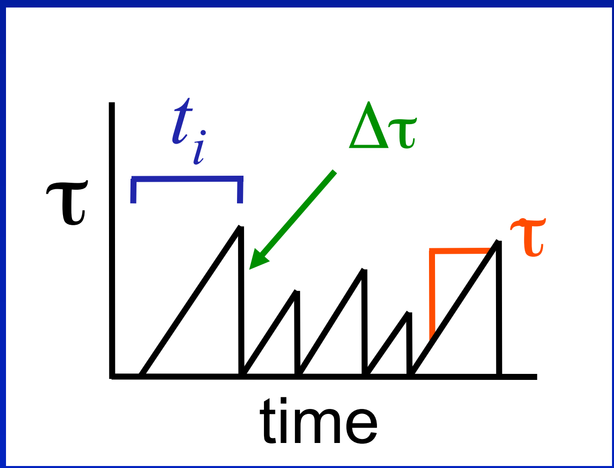
Constant Stressing Rate Assumed

Time predictable



Constant Failure Stress

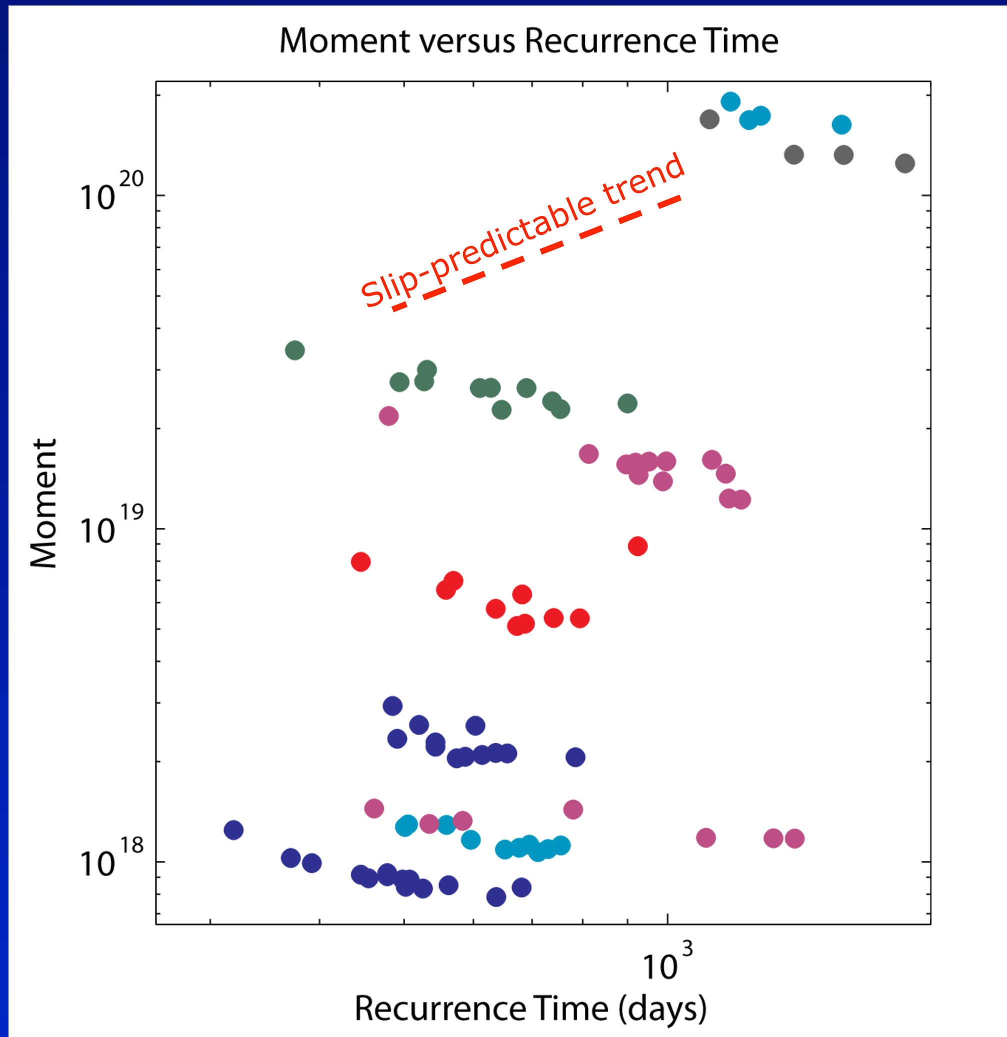
Slip predictable



Constant Residual Stress

t_i = interevent time M_o = moment $\dot{M}_d$ = moment deficit rate

Parkfield Repeaters are Anti-Slip-Predictable



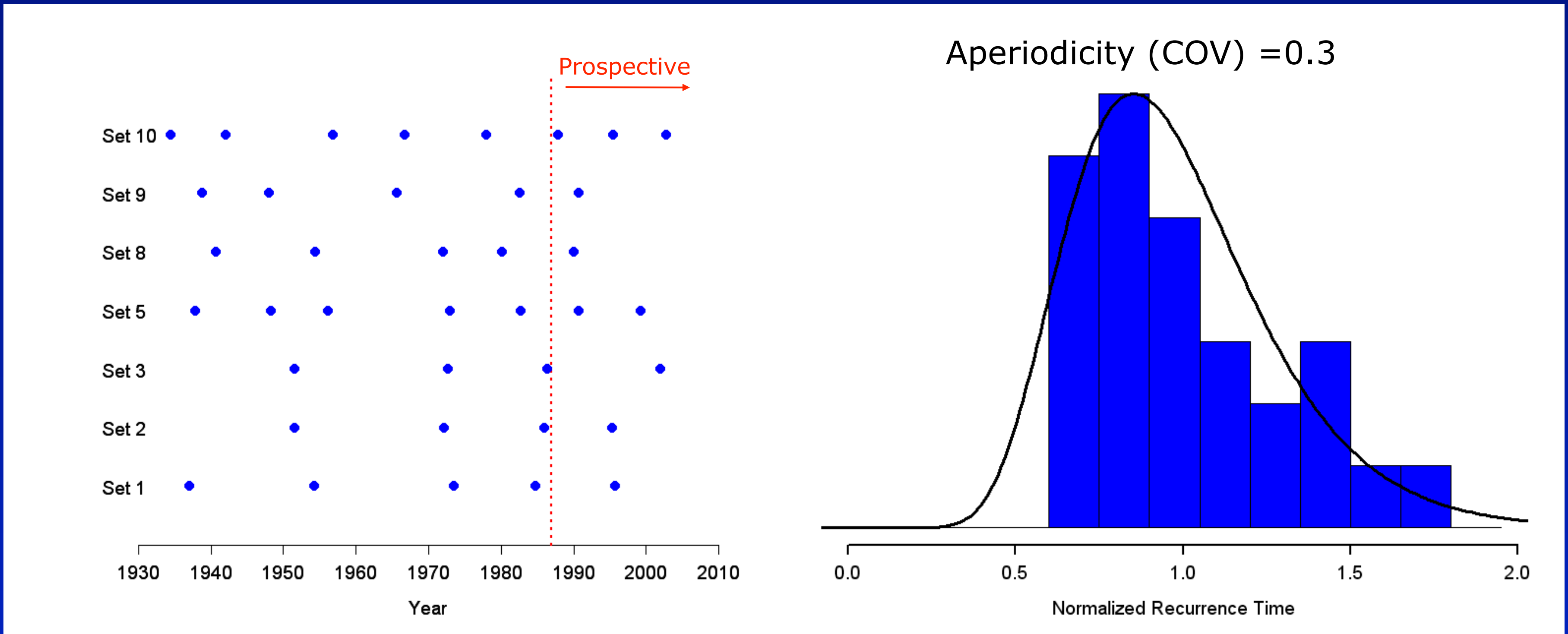
"Parkfield Repeating Earthquakes are Neither Time- nor Slip-Predictable"
Justin Rubinstein, Friday 2:45 PM Salon A

Point Process Renewal Models
(Independent Identically Distributed intervals)

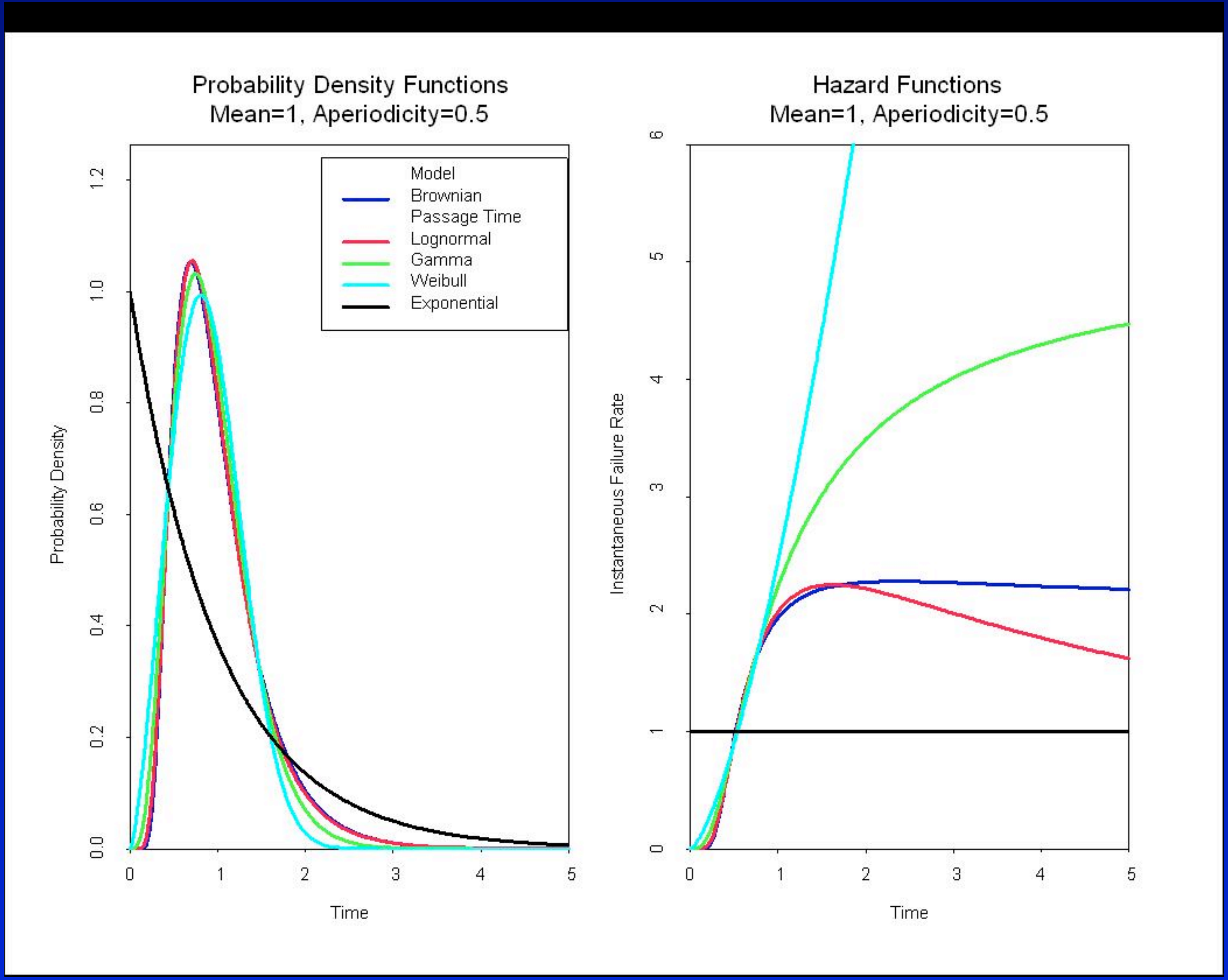
There are many probability models to chose from in the literature

- Exponential (for a Poisson process)
- Double Exponential (Utsu, 1972)
- Gaussian (Rikitake, 1974)
- Weibull (Hagiwara, 1974)
- Gamma (Utsu, 1984)
- Lognormal (Nishenko & Buland, 1987)
- Brownian Passage Time (Kagan & Knopoff, 1987)
- Empirical Model (Reasenberg et al., 2002)
- Many more (e.g. Birnbaum-Sanders)

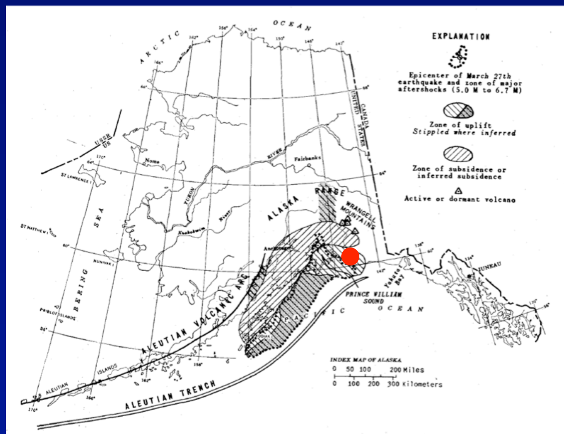
Stone Canyon Repeating Earthquakes
M 4 – 5
(Central San Andreas Fault)

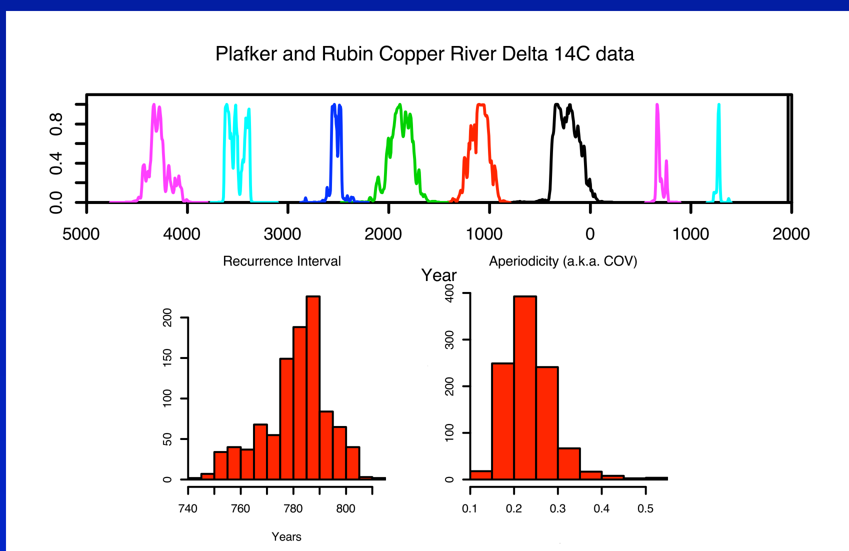


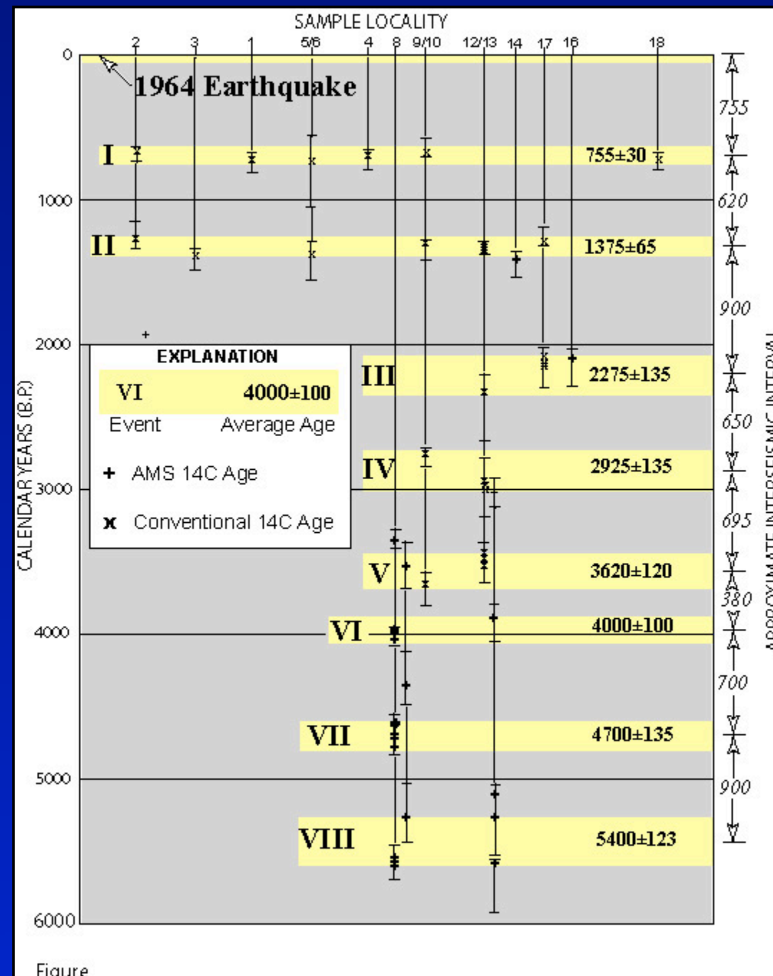
How distinct are these models?



Great Alaskan Earthquake Recurrence Intervals from the Copper River Delta







Plafker & Rubin (1994) Paleoseismic evidence for "yo-yo" tectonics above the eastern Aleutian subduction zone; coseismic uplift alternating with even larger interseismic submergence.

Influence of Loading Rate Variations on Recurrence Interval

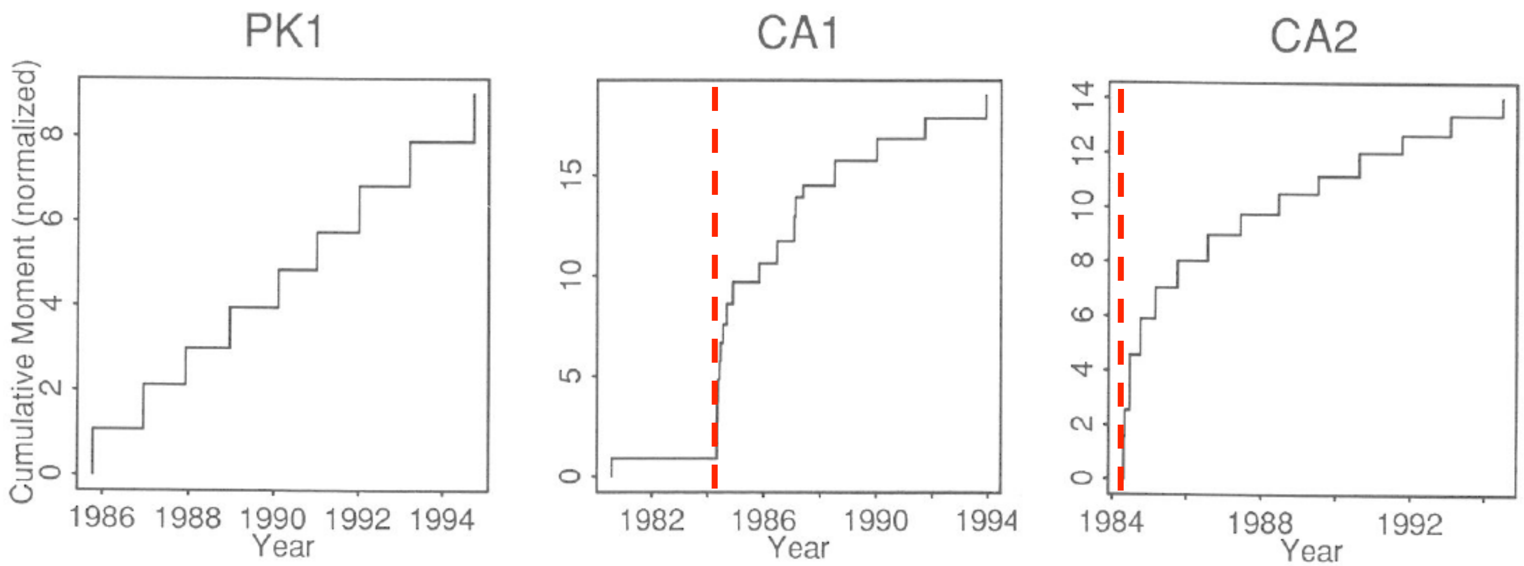
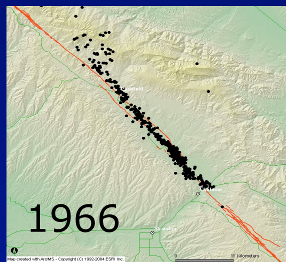
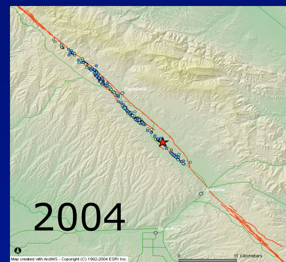


Fig. 3. Cumulative seismic moment versus time for repeating earthquake sources. Left: Multiplet PK1, located to the northwest of the 1966 Parkfield earthquake. Center: Multiplet CA1, located on the Calaveras fault at the southern end of the 1984 Morgan Hill earthquake aftershock zone. Right: Multiplet CA2, located on the Calaveras fault 4 km southeast of CA1 and further from the Morgan Hill earthquake.

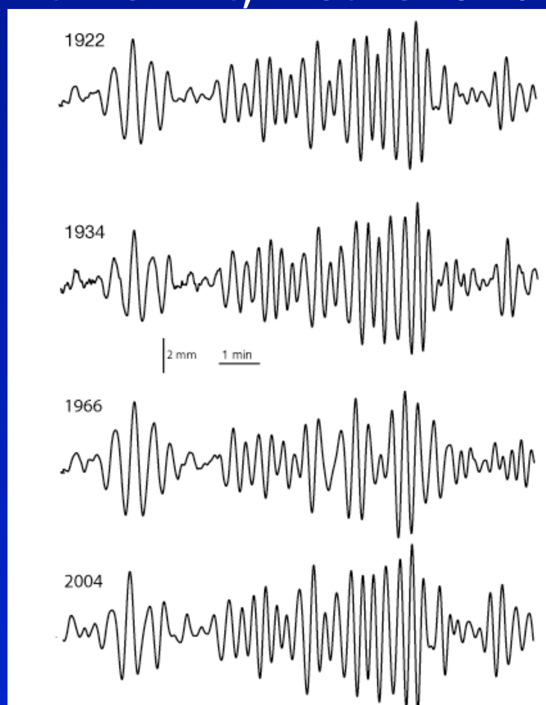
Ellsworth (1995)





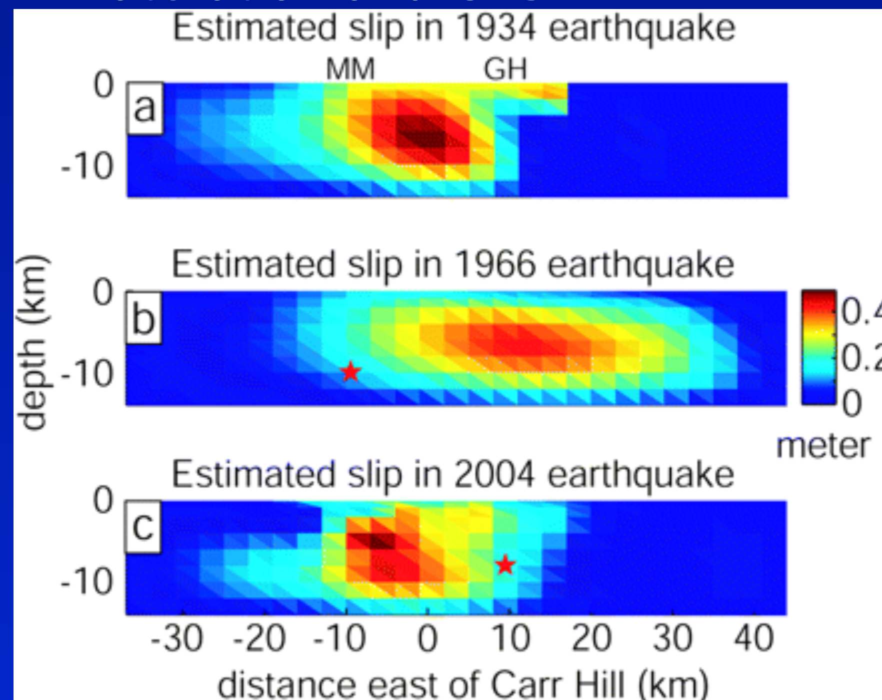
Parkfield Earthquakes:
How similar they are depends on where you stand and how closely you look.

Teleseismic Waveforms At De Bilt, Netherlands



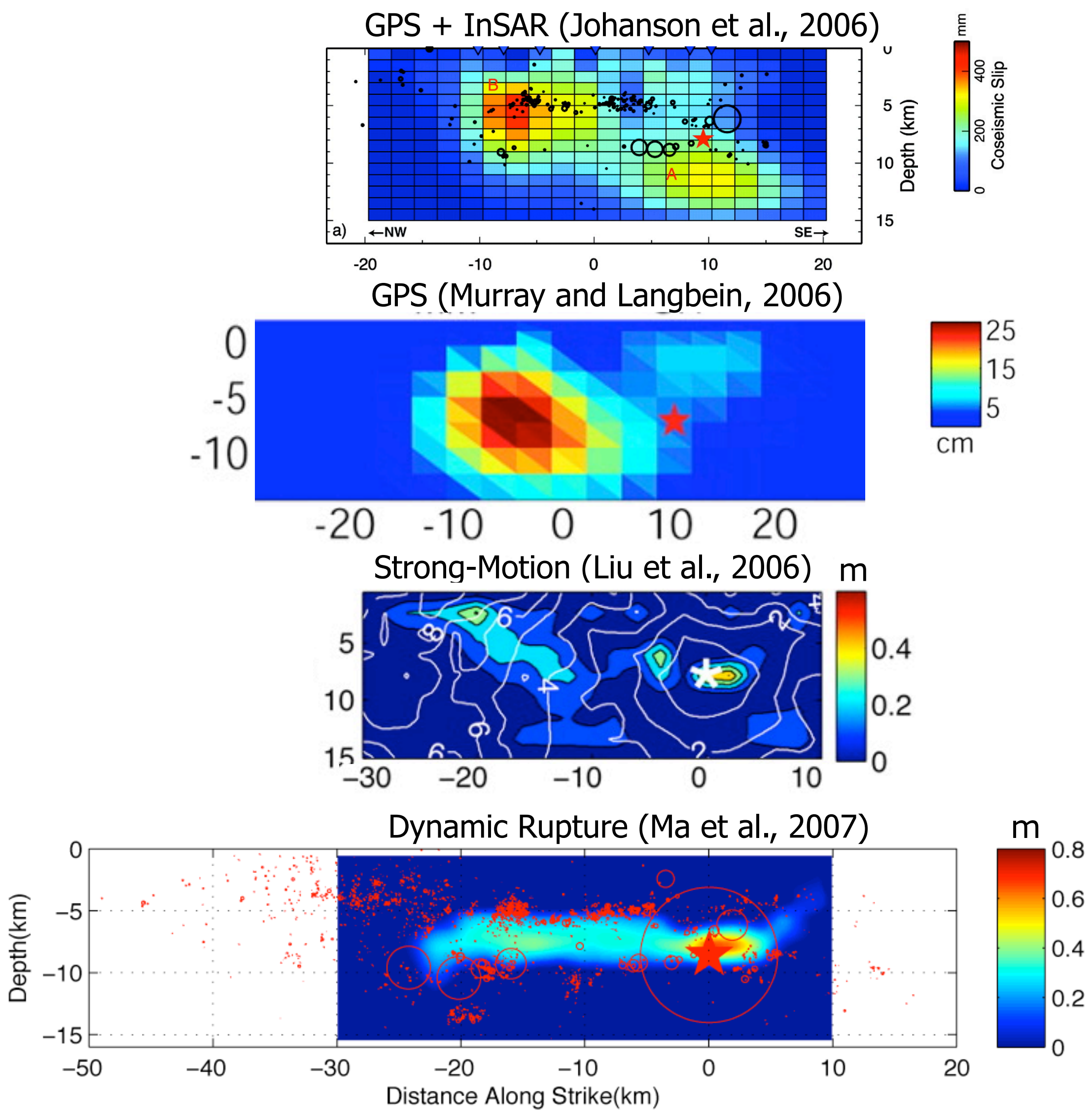
Dost and Haak (2006)

Slip Inversion using Triangulation, Trilateration and GPS



Murray and Langbein (2006)

Comparison of Models for 2004 Parkfield Earthquake



SUMMARY

- Reid’s Elastic Rebound hypothesis provides a sound framework for understanding fault behavior over multiple earthquake cycles.
- Repeating earthquakes are found in a wide range of tectonic environments with magnitudes from <0 to >9.
- Repeating earthquakes with regular time intervals between events are most common when isolated from perturbing influences.
- Neither the time-predictable, slip-predictable nor exponential models provide a satisfactory explanation of recurrence behavior for these earthquakes.
- Residual stresses, post-seismic transients, and stress transfer likely play a major role when fault behavior is highly variable in space and time.
- Fault geometry and rheology must also play a major role in determining when recurrence is simple or complex.