**SOUTHERN CALIFORNIA EARTHQUAKE CENTER**

**Title of Project:** Research toward the Master Model
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**Institution:** University of California, Santa Cruz

## Annual Report, 1998:

SCEC funded research under this project in 1998 saw the completion and publication of three studies, and the initiation and submission of one other. I abstract these below:

**Ward, S. N., 1998a. On the Consistency of Earthquake Moment Rates, Geological Fault Data, and Space Geodetic Strain: The United States,** *Geophysical Journal Int.,* **134, 172-186.**

New and dense space geodetic data can now map strain rates over continental-wide areas with a useful degree of precision. Stable strain indicators open the door for space geodesy to join with geology and seismology in formulating improved estimates of global earthquake recurrence. In this paper, 174 GPS/VLBI velocities map United States' strain rates of <0.03 to >30.0 x$10^{-8}$/y with regional uncertainties of 5 to 50% (Figure 1). Kostrov's formula translates these strain values into regional geodetic moment rates. Two other moment rates, $\dot{\overline{M}}_{seismic}$ and $\dot{\overline{M}}_{geologic}$, extracted from historical earthquake and geological fault catalogs, contrast the geodetic rate. Because $\dot{\overline{M}}_{geologic}$, $\dot{\overline{M}}_{seismic}$ and $\dot{\overline{M}}_{geodetic}$ derive from different views of the earthquake engine, each illuminates different features. In California, ratios of $\dot{\overline{M}}_{geodetic}$ to $\dot{\overline{M}}_{geologic}$ are 0.93 to 1.0. The consistency points to the completeness of the region's geological fault data and to the reliability of geodetic measurements there. In the Basin and Range, Northwest and Central United States, both $\dot{\overline{M}}_{geodetic}$ and $\dot{\overline{M}}_{seismic}$ greatly exceed $\dot{\overline{M}}_{geologic}$. Of possible causes, high incidences of understated and unrecognized faults most likely drive the inconsistency. The ratio of $\dot{\overline{M}}_{seismic}$ to $\dot{\overline{M}}_{geodetic}$ is everywhere less than one. The ratio runs systematically from 70-80% in the fastest straining regions to 2% in the slowest. Although aseismic deformation may contribute to this shortfall, I argue that the existing seismic catalogs fail to reflect the long term

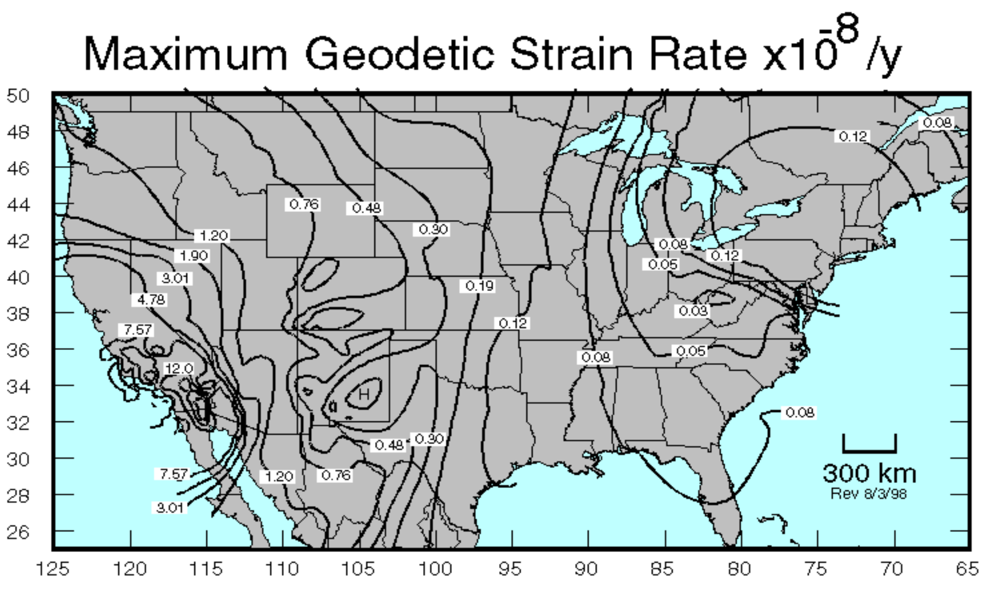


**Figure 1.** Maximum geodetic strain rates in units of $10^{-8}$/y as determined from space geodetic data. Strain rates in the United States vary by over a factor of 1000 from <0.03 x$10^{-8}$/y in the Central/Southeast to >30.0x$10^{-8}$/y in southern California.

situation. Impelled by the systematic variation of seismic to geodetic moment rates and by the uniform strain drop observed in all earthquakes regardless of magnitude, I propose that the completeness of any seismic catalog hinges on the product of observation duration and regional strain rate. Slowly straining regions require a proportionally longer period of observation. Characterized by this product, gamma distributions model statistical properties of catalog completeness as proxied by the ratio of observed seismic moment to geodetic moment. I find that adequate levels of completeness should exist in median catalogs of 200 to 300 year duration in regions straining $10^{-7}$/y (comparable to southern California). Similar levels of completeness will take more than 20,000 years of earthquake data in regions straining $10^{-9}$/y (comparable to southeastern United States). Predictions from this completeness statistic closely mimic the observed $\dot{\bar{M}}_{\text{seismic}}$ to $\dot{\bar{M}}_{\text{geodetic}}$ ratios and allow quantitative responses to previously unanswerable questions such as: “What is the likelihood that the seismic moment extracted from a earthquake catalog of X years falls within Y% of the true long term rate?” The combination of historical seismicity, fault geology and space geodesy offers a powerful tripartite attack on earthquake hazard. Few obstacles block similar analyses in any region of the world.

**Ward, S. N., 1998b. On the consistency of earthquake moment release and space geodetic strain rates: Europe**, *Geophys. Jour. Int., 135,* **1011-1018**.

In this article, approximately 100 VLBI/SLR/GPS velocities map European strain rates from $<0.09\times10^{-8}$/y to $>9.0\times10^{-8}$/y with regional uncertainties of 20 to 40%. Kostrov’s formula translates these strain rate values into regional geodetic moment rates $\dot{\bar{M}}_{\text{geodetic}}$. Two other moment rates $\dot{\bar{M}}_{\text{seismic}}$, extracted from a 100-year historical catalog and $\dot{\bar{M}}_{\text{plate}}$, taken from plate-tectonic models, contrast the geodetic rates. In Mediterranean Europe, the ratios of $\dot{\bar{M}}_{\text{seismic}}$ to $\dot{\bar{M}}_{\text{geodetic}}$ stand between 0.50 and 0.71. In Turkey the ratio falls to 0.22. Although aseismic deformation may contribute to the earthquake deficit ($\dot{\bar{M}}_{\text{seismic}}$ values less than $\dot{\bar{M}}_{\text{geodetic}}$), the evidence is not compelling because the magnitudes of the observed shortfalls coincide with the random variations expected in a 100-year catalog. If the lack of aseismic deformation inferred from the 100-year catalog holds true for longer periods, then much of Europe’s strain budget would have to be accommodated by more frequent or larger earthquakes than have been experienced this century to raise the ratios of $\dot{\bar{M}}_{\text{seismic}}$ to $\dot{\bar{M}}_{\text{geodetic}}$ to unity. Improved geological fault data bases, longer historical earthquake catalogs, and densification of the continent’s space geodetic network will clarify the roles of aseismic deformation versus statistical quiescence.

**Ward, S. N., 1998c. A deficit vanished,** *Nature, 394,* **829-830.**

**News and Views:** The southern California earthquake deficit — “Now you see it, now you don’t”, according to an article in the Bulletin of the Seismological Society of America[1] by Stein and Hanks. Not done with smoke and mirrors, the vanishing act enlisted a careful revision of our understanding of twentieth-century historical seismicity, and it helped to spirit away a thorny issue that arose in 1995. This was the year that the Working Group on California Earthquake Probabilities[2] (WGCEP/95) published the report “Seismic Hazards in Southern California: Probable Earthquakes 1994–2024”.

The WGCEP/95 document was remarkable because it struck a new path into earthquake hazard analysis. Previously, geologists and seismologists had independently staked-out their own areas of earthquake rate estimation, the heart of hazard calculation. Geologists reckoned the recurrence interval and magnitude of earthquakes by locating active faults, mapping their length and total offset, and resolving their age. Seismologists concentrated on historical catalogues. Earthquake patterns of the past, they presumed, reflect where and how often earthquakes should strike in the future, and how large they will be. Early geological and seismological studies tended to be piecemeal with few cross-checks. Publication of WGCEP/95 brought order to the field by combining diverse information into a quantitative and consistent multidisciplinary assessment. Space geodesy catalysed the leap forward by providing accurate measures of the pattern and pace of tectonic strain that eventually manifests itself as earthquakes.

Of all the advances in WGCEP/95, one finding seemed to take on a life of its own — the preferred seismicity model predicted twice the number of magnitude 6 to 7 earthquakes than had actually been observed since 1850 (red area, Fig. 2). The shortfall put experts in a pickle. If the earthquake deficit was genuine, then they had to tell California that it faces a far rougher ride than it had experienced in the recent past. If the deficit was an artefact, then one or both of the curves in Fig. 2 was wrong, and those experts had to discover why if they expected to maintain credibility. To address the issue, Stein and Hanks[1] revisited the WGCEP/95 earthquake catalogue. In parallel, Field, Jackson and Dolan[3,4] dissected the WGCEP/95 seismicity model.

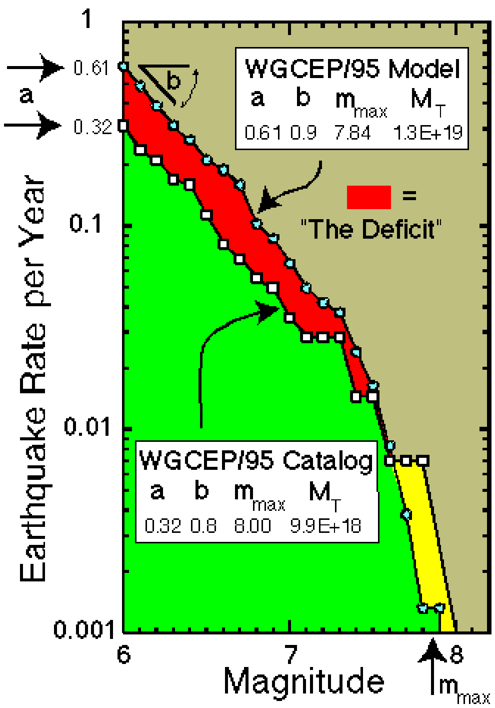


**Figure 2** Annual rates of earthquakes greater than magnitude *m*, for southern California. The lower curve follows the observed rates of earthquakes since 1850 as catalogued by WGCEP/95. The upper curve follows the predictions from the preferred WGCEP/95 seismicity model. The red no-man's-land between the curves is southern California's earthquake deficit, now closed by Stein and Hanks[1], and Field *et al.*[3,4]. Seismic moment $M_T$ has units of Nm/yr$^{-}$.

Stein and Hanks[1] conclude that the factor of two mismatch between the rate of observed earthquakes and the rate predicted by the WGCEP/95 seismicity model is not real. The blame splits equally between undercounts of historical earthquakes and overstatements springing from assumptions in the WGCEP/95 model. That is, the lower curve in Fig. 2 should be raised part way, and the upper curve dropped. Stein and Hanks's review of post-1903 earthquakes gives a = 0.49 yr$^{-1}$ and b = 1.0 compared to a = 0.32 yr$^{-1}$ and b = 0.8 from WGCEP/95's post-1850 catalogue. They argue that many magnitude 6 to 7 earthquakes were not reported before 1903, which is why they chose the later date as a starting point.

Field et al.[3,4] further identified and removed several elements that inflated $M_T$ in the seismicity model used in WGCEP/95. These included a mistranslation of magnitude into moment and the assumption of non-Poissonian earthquake recurrence. The most recent seismicity models that draw upon the new analyses[1,3,4] show no difference between predicted and observed earthquake rates, or between the total moment expended by earthquakes and that inferred from geodesy and geology.

A deficit vanished? One might dismiss this 'news' as much ado about nothing, or conclude that earthquake hazard assessments have yet to evolve beyond magic. In my view, however, these developments demonstrate the new and critical self-evaluation mechanisms available in the current class of multidisciplinary hazard models. In particular, scientists can now recognize where a statistically significant inconsistency exists, quantitatively assess the effects of the various parameters on the inconsistency, and decide whether it is real or artificial. They can then act in response or revise the model, exactly as in the exercises carried out by Stein and Hanks, and Field et al.

In truth, of course, unsettled aspects of earthquake recurrence abound even in California, host to the world's most complete earthquake laboratory. Earthquakes will always be difficult to predict due to their elusive and hidden nature. Against these odds, we can make progress only by arming ourselves with the widest range of geophysical weapons.

**Ward, S. N., 1998d. San Francisco Bay Area Earthquake Simulations: A step toward a Standard Physical Earthquake Model,** *Bull. Seism. Soc. Am.*, **submitted.**

Earthquakes in California's San Francisco Bay Area are likely to be more strongly affected by elastic stress interaction than earthquakes in any other place in the world because of the region's closely spaced, sub-parallel distribution of faults. I believe therefore, that meaningful quantification of earthquake probability and hazard in the Bay Area can be made only with the guidance provided by physically-based and region-wide earthquake models that account for this interaction. This paper represents a first step in developing a *Standard Physical Earthquake Model* for the San Francisco Bay Area through realistic, 3000-year simulations of earthquakes on all of the area's major faults (Figure 3). These simulations demonstrate that a *Standard Physical Earthquake Model* is entirely feasible, they illustrate its application, and they blueprint its construction. A *Standard Physical Earthquake Model* provides the mechanism to integrate fully the diverse disciplines within the earthquake research community. As a platform for data utilization and verification, a physical earthquake model can employ directly any earthquake property that is measurable in the field or in the laboratory to tune and test its seismicity products. As a platform for probability forecasts, a physical earthquake model can supply rational estimates of every imaginable earthquake statistic while simultaneously satisfying all slip and earthquake rate constraints (Figure 4). As a platform for hazard analysis, a physical earthquake model can compute earthquake shaking intensity from first principles by convolving a full suite of rupture scenarios with site-specific dislocation Green's functions (Figure 5). Physical earthquake models have advanced greatly in the last decade. Simulations of earthquake generation and recurrence are now sufficiently credible that such calculations must begin to take substantial roles in scientific studies of earthquake probability and hazard.

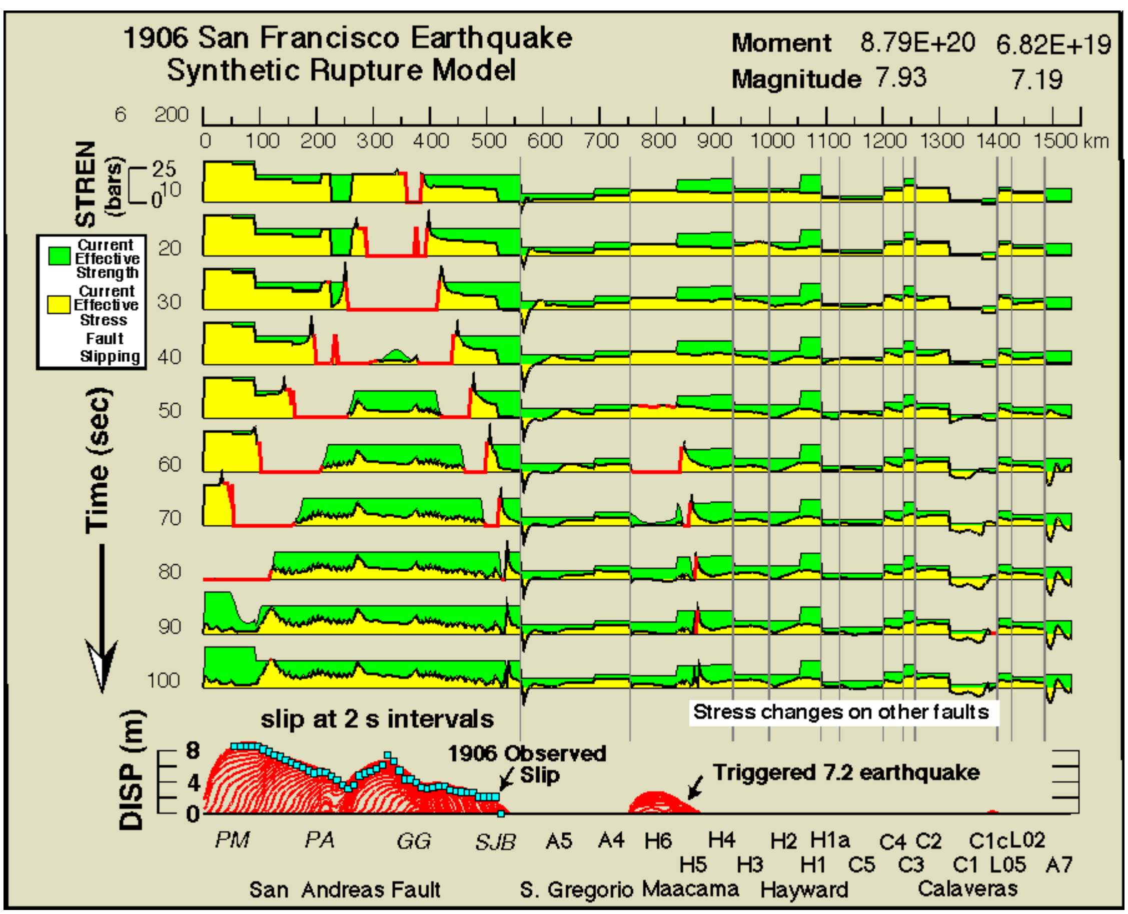


**Figure 3.** Calculated stress effects of the 1906 San Francisco earthquake. To the left appears the developing 1906 rupture. To the right are the time-dependent induced changes in effective stress on all of the other faults of the system. Vertical lines separate individual faults. During rupture, columb stresses can rise then fall, or vice-versa. Intra-rupture stresses may not resemble the final static condition. In this case, a M7.2 earthquake on the North Maacama Fault was triggered some 50 seconds after nucleation of the main event.

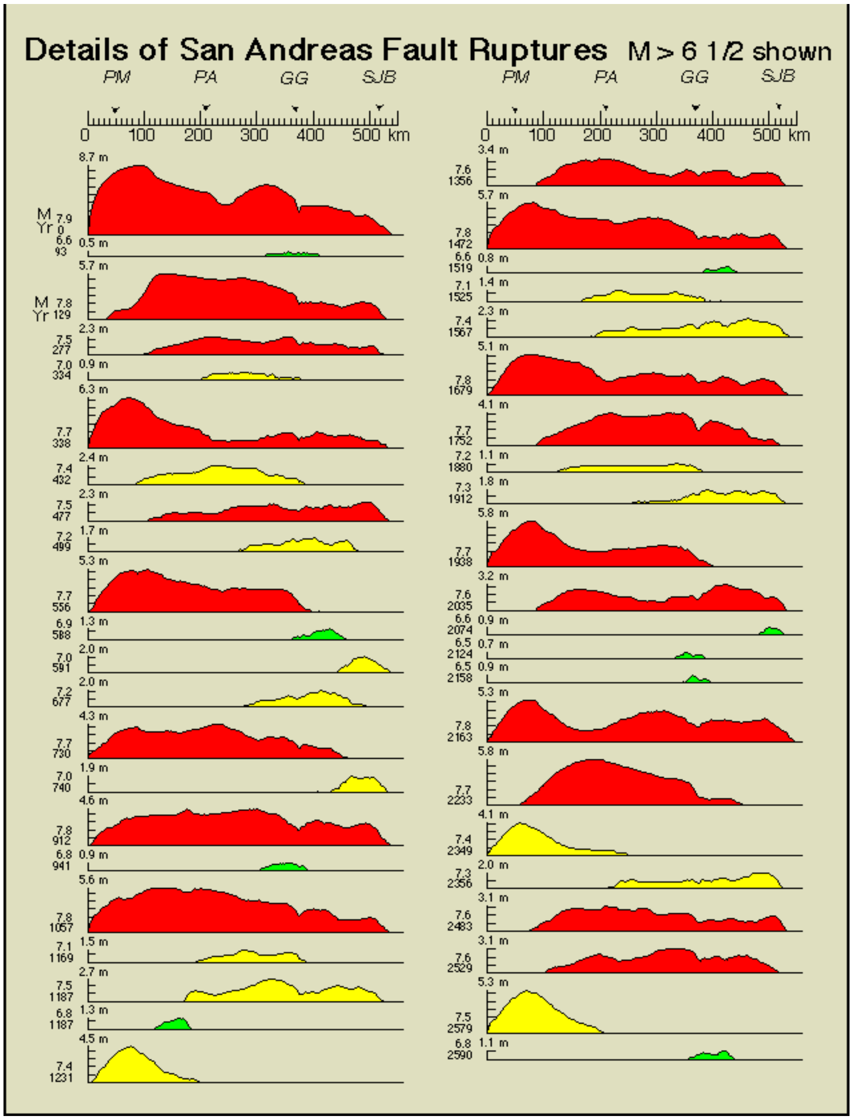


**Figure 4** Details of the final slip distributions of all M>6.5 quakes on the San Andreas Fault for the first 2600 years of the 3000 year simulation. Magnitude and year of occurrence are listed to the left of each trace. Red, yellow and green events are M>7.5, 7<M<7.5 and 6.5<M<7 respectively. Rupture encyclopedias like this can be compared directly with site-specific paleoseismic studies that quantify slip-per-event and variation in slip-per-event.

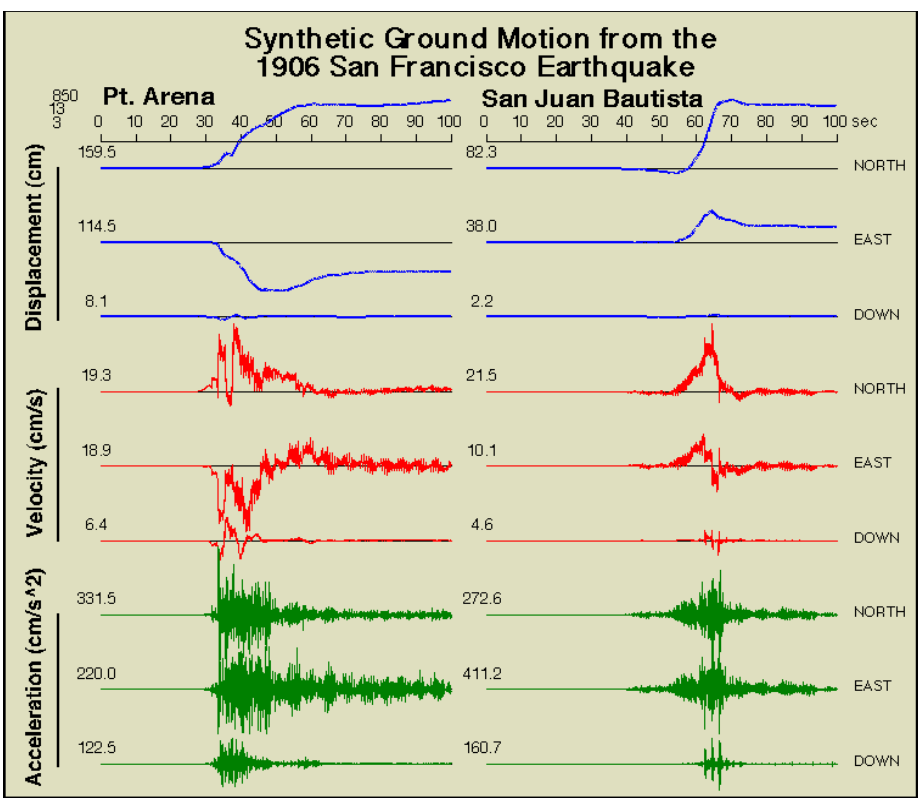


**Figure 5.** Ground motions from the 1906 San Francisco earthquake simulation of Figure 3. Displacements, velocities and accelerations are shown at Point Arena (5 km from the fault) and at San Juan Bautista (1 km from the fault). Velocities and accelerations at these sites are roughly twice as large of those at South Pier due to rupture directivity.