2004 Annual Report

Southern California Earthquake Center-sponsored research project:

"Kinematic Model of Fault Slip and Anelastic Strain Rates and Long-Term Seismicity"

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Proposal category:	Integration and Theory
Disciplinary Committee(s):	Seismology
Focus Group(s):	Seismic Hazard Analysis
Special Project(s):	(none)

I. Overview:

We refined and applied two useful tools for forecasting long-term-average (Poissonian) seismicity maps at any desired magnitude: (1) A kinematic finite-element program which uses geologic, geodetic, stress-direction, and plate-rotation data to solve for long-term-average fault slip rates and anelastic strain rates; (2) A global calibration of plate-boundary seismicity which permits fault slip rates and/or anelastic strain rates to be converted to long-term seismicity. We applied these to the SCEC region, using a fine FE grid, CGS2002 fault data, CMMv3 geodesy, and the World Stress Map. However, it was first necessary to model to broader region of the Gorda-California-Nevada orogen in order to obtain velocity boundary conditions for the SCEC region. After optimization of a few tuning parameters, we were able to match all data sets with a common model of the SCEC domain. Results include estimates of off-fault (but probably seismic) anelastic deformation rates in the lithosphere, and also a long-term-average seismicity forecast map which integrates to 174% of the 1933-2003 historical seismicity rate based on the TriNet catalog (m>5). The reason for this discrepancy is under investigation.

II. Background information: Pre-2004 development of a kinematic F-E model:

In the last 6 years, we have developed kinematic finite-element program *NeoKinema*, which simulates neotectonics by fitting all available data with a conceptually simple (but algebraically complex) weighted least-squares algorithm:

Input Data

- ☑ Traces of active (and potentially-active) faults, with assigned dips;
- ☑ Geologic slip rates with uncertainties, if available (or zero rate, with large uncertainty);
- ☑ Geodetic velocities (horizontal components only) with covariance matrix, if available; (Coseismic velocities are edited out, leaving typical interseismic velocities.)
- ☑ Horizontal principal stress directions, from EQ mechanisms & in-situ data;
- ☑ Velocity boundary conditions from a global plate model.

Methods

- ♦ 2-D spherical-shell grid of spherical-triangle continuum finite elements;
- ♦ Velocity boundary conditions applied to edges (within rigid portions of plates);
- ♦ Solve for horizontal components of long-term-average velocity at nodes;
- ♦ Weighted least-squares criterion, with 2 major tuning parameters controlling weights;
- ♦ Unfaulted elements are quasi-rigid (within a tolerance determined by bootstrap);
- ♦ Strain-rates of unfaulted elements have principal axes approximately aligned with interpolated stress directions (achieved by iteration);
- ♦ Known fault slip rates contribute to the target strain rates of faulted elements;
- ♦ Uncertainties in fault slip rate contribute anisotropic compliance to faulted elements;
- ♦ Geodetic velocities are corrected (by iteration) for transient fault locking to determine estimated long-term-average velocities;
- ♦ Geodetic reference frame may be fixed or free-floating.

Output

- ➢ Long-term-average velocity field (interpolated from nodal values);
- ➢ Long-term-average anelastic/permanent strain rates;
- ➢ Preferred long-term-average slip rates of faults;
- ➢ Interpolated principal stress directions.

No rheologic parameters need to be assumed, and no lengthy trial-and-error process is needed to fit the input data. In fact, there are only 2 important adjustable parameters: (1) relative weight of trace-based geologic data (relative to point-based geodetic data); & (2) relative weight of area-based continuum constraints. We adjust these so as to achieve good fits to all data sets.

With NEHRP and SCEC support, we have nearly completed a *NeoKinema* model of the western United States, and a more detailed model of the SCEC subregion (see figures below). This work is unpublished but has been presented at AGU (2002 AGU NG62A-0931) and at SCEC annual meetings (2003, 2004). We have also applied the method to Eurasia (2003 AGU T42B-0294).

III. Background Information: Pre-2004 global calibration of coupling and frequency/magnitude parameters:

Predicting long-term-average seismicity requires knowledge of the thickness of the seismically-coupled lithosphere, spectral slope β, and corner magnitude, for each type of plate boundary (continental transform fault, continental rift, continental convergent boundary, ...). As a basis for a global calibration, I compiled the updated global plate model *PB2002*, with 52 plates and 13 non-rigid orogens [*Bird*, 2003, $\underline{G}^3$, **4**(3), 1027, doi:10.1029/2001GC000252]. (Non-subscribers can find the **.pdf**, data files, and graphics at: **http://element.ess.ucla.edu**.) Yan Kagan and I then classified all shallow earthquakes 1977-2002 from the Harvard CMT catalog by plate boundary type, and used them to determine absolute seismicity rates ("*a* values") and spectral slopes *(β)* of tapered Gutenberg-Richter frequency/moment distributions. To increase subcatalog sizes during the determination of corner magnitudes, we also classified all shallow earthquakes 1900-1975 (m>7.1) from *Pacheco & Sykes* [1992, BSSA **82**, 1306]. Corner magnitudes were determined (with confidence limits) by maximum-likelihood methods. Comparing the integrals (over moment) of the frequency/moment distributions for each plate boundary type with the line integrals (along plate boundaries) of relative plate velocity, we determined the coupled lithosphere thicknesses for each plate boundary type.

Results will soon be published in the December 2004 BSSA, and can also be seen on-line at: **http://element.ess.ucla.edu**

IV. Activities and Results in 2004:

1. The *NeoKinema* v.2 algorithm was documented in a 28-page technical appendix, including all equations, and a discussion of basic validation tests. This is available as a **.pdf** file on request. It is our intention to submit it as an electronic supplement to the first peer-reviewed paper that appears with *NeoKinema* results.

2. We initially tried to model the SCEC domain (32.5-36°N, 121-115°W) directly, with unknown boundary velocities (along the northern boundary) left unconstrained. This approach failed, because it lead to unphysical strain-rate concentrations at the domain corners, and a strain-rate shadow along the middle of the northern boundary. (A similar effect would be seen in dynamic FE modeling with velocity boundary conditions around 3 sides, and a traction-free boundary on the north. There is a good analogy between dynamic and kinematic FE models for unfaulted continuum regions, because the *NeoKinema* constraint of minimized continuum deformation gives velocities equivalent to those obtained from the dynamic response of a uniform viscous sheet in plane stress.)

3. To determine velocity boundary conditions for the SCEC region, we next modeled the larger Gorda-California-Nevada orogen [*Bird*, 2003, *ibid*] which extends out to rigid

plates on all sides (**Figure 1**). This modeling used our own compilation of fault slip rates, and our own merged GPS velocity set based on the SCEC Community Motion Model v.3. Rigid-plate velocity boundary conditions were from Euler poles of the PB2002 global model of *Bird* [2003, *ibid*], which is locally equivalent to NUVEL-1A of *DeMets et al.* [1994, GRL, **21**(20), 2191-2194].

4. We conducted a suite of 82 *NeoKinema* simulations to find the optimal combination of tuning parameters.
5. We then interpolated velocities from the best orogen model to the edges of the SCEC domain.
6. We repeated parameter testing with 59 local models on a finer grid, using the CGS2002 fault data set and the CMMv3 geodetic solution. This showed that our current definition of tuning parameters does not give results that are independent of the FE grid resolution. This problem will be corrected with new definitions in *NeoKinema* v.2.
7. We discovered that many uncertainties (σ's) in the CGS2002 data set are unreasonably small. For example, in the absence of piercing points, many "minor" faults were assigned a low slip rate, with a σ which is 25% or 50% of the estimated rate. Assuming that the weight on geologic data is set high enough to get a good fit to San Andreas fault rates, such small sigmas on minor faults "lock" their slip rates in *NeoKinema* solutions. This is unfortunate because these are precisely the faults for which we most need an independent estimate (based on geodesy and regional kinematic consistency).
8. We wrote program *Long_Term_Seismicity* to use the global calibration (III above) to convert the *NeoKinema* fault slip rates and anelastic strain rates to long-term-average seismicity rates. To fix the coupled lithosphere thickness, β, and corner magnitude, each strike-slip fault (or continuum region with a vertical intermediate strain-rate axis) is modeled as a local example of a Continental Transform Fault (CTF) plate boundary, while each thrust fault is modeled as a CCB boundary, and each normal fault is modeled as a CRB boundary, *etc.*.
9. *Long_Term_Seismicity* produces maps of long-term (Poissonian) seismicity above a given threshold (*e.g.*, $m>5$ in **Figure 2**) with high spatial resolution. The match with the 70-year TriNet catalog looks good. However, the area integral of the model rate is 256 events/70 years, whereas the catalog rate is only 147 events/70 years. This discrepancy is too large to be due to sampling variance. We will test our codes in the near future for errors or systematic bias. However, our preliminary interpretation is that California seismicity has actually been below its long-term average during the last 70 years, which occurred in the aftermath of the great earthquakes of 1857 (southern San Andreas faults), 1872 (Owens Valley), and 1906 (northern San Andreas fault).

V. Contribution to Research Objectives of SCEC:

The seismicity maps (and derived shaking maps) contributed to VII.B.5 Seismic Hazard Analysis/ Regional Earthquake Likelihood Models and /Contribute to SCEC's System-Level Earthquake Rupture Forecast Model. Our method did not use assigned fault segmentation, characteristic earthquakes, a committee of experts, or a logic tree. Thus it represents an independent approach that tests how firmly our hazard projections are founded on (common) data.

The project also contributed to VII.A.1 Seismology/Data Products: by estimating long-term-average seismicity *independent of the local seismic catalog*, so we can see the existing catalog in a new light, *as a record of a set of positive and negative seismicity anomalies*. This approach gave a warning that California seismicity may have been abnormally low in the instrumental catalog period of the last 70-100 years.

Our maps of off-fault anelastic strain rates also contributed to VII.B.1 Structural Representation/ Community Fault Model by highlighting "hot zones" in which additional active faults or important shear bands may lie. They also challenged the common assumption that background off-fault anelastic strain rate is not a significant contributor to tectonic strain and seismic hazard (VII.B.2 Fault Systems/Fault System Behavior).

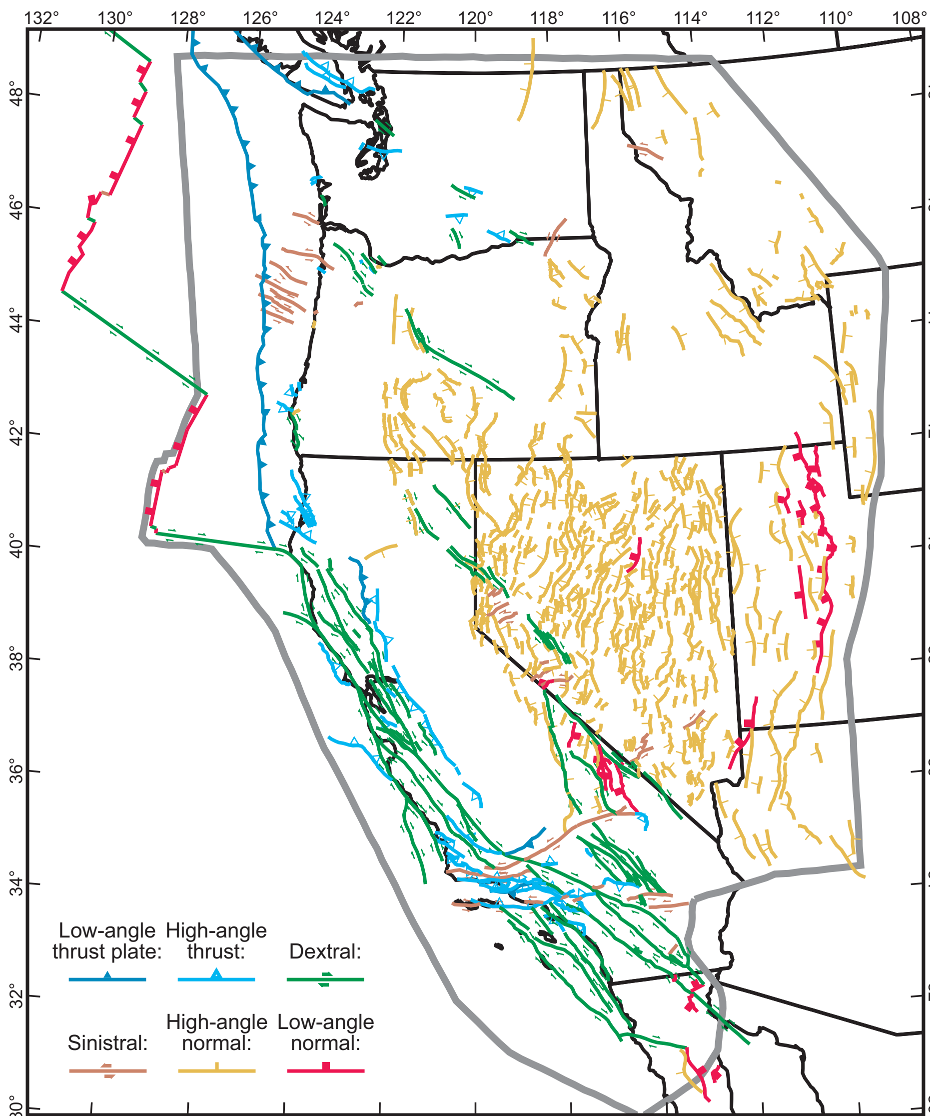

Figure 1. Domain of the Gorda-California-Nevada orogen model (heavy outline) and traces of active (or suspected active) faults included in our geologic slip-rate data set.

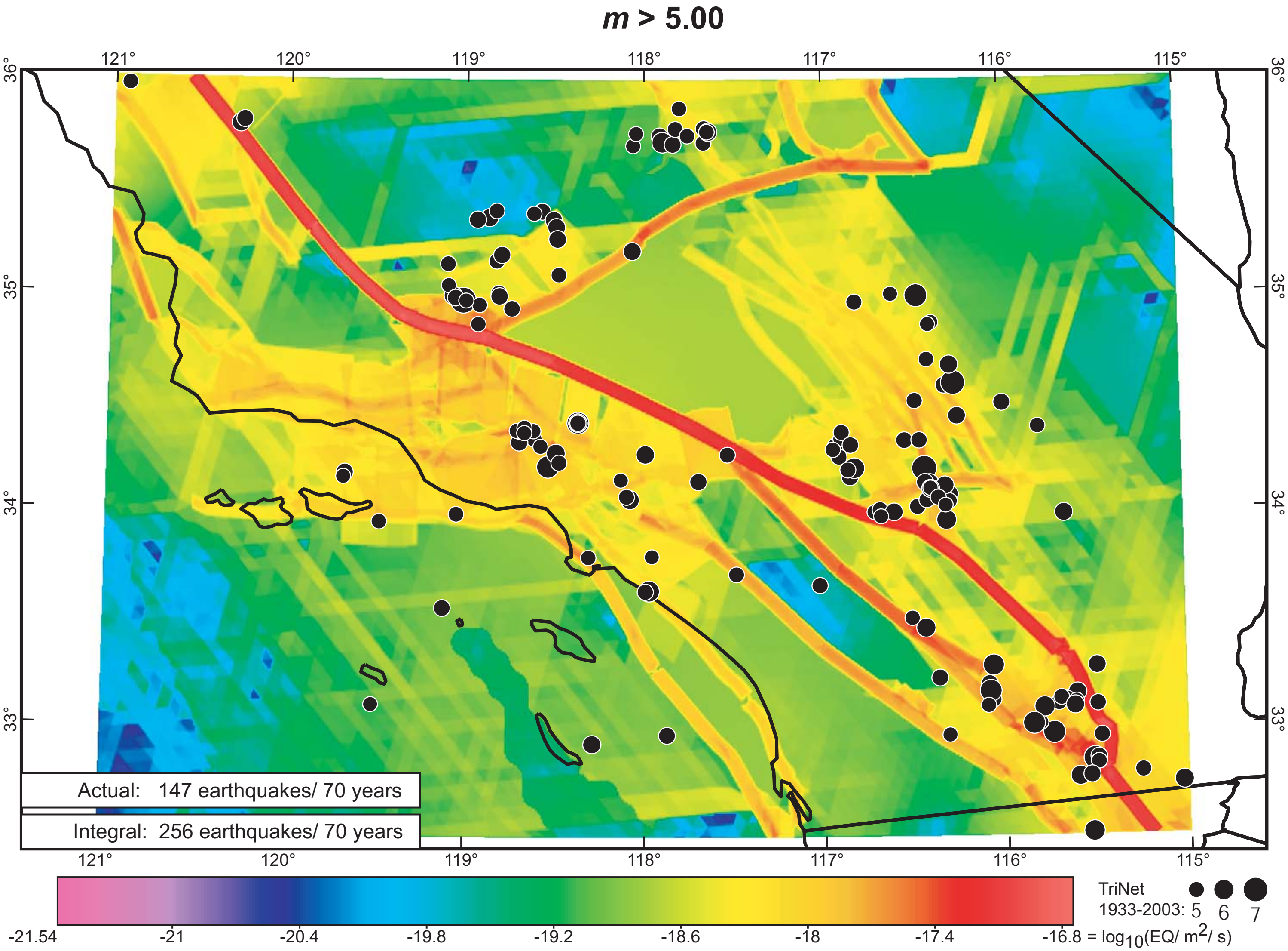

Figure 2. Forecast long-term-average (Poissonian) seismicity (for *m*>5) based on the best *NeoKinema* model of the SCEC region (using CGS2002 fault data, CMMv3 geodesy, and the World Stress Map), and the program *Long_Term_Seismicity* which converts slip- and strain-rates to seismicity based on a global calibration. Note that the model predicts 256 events/70 years, whereas the TriNet catalog shows only 147 events/70 years.