Earthquake Potential Seismic Hazard Analysis, Tectonic Geodesy, Fault Systems,

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PROGRESS REPORT

In 2003 we focused on four topics: (1) updating and generalizing our long-term forecast models based on smoothed seismicity and geodetic strain, (2) short term forecasting, (3) strain rate, earthquake rate, and the factors that determine the magnitude distribution, and (4) methods for quantitative testing of earthquake forecasts. In all of this work, we collaborated closely with other SCEC investigators working on the Regional Earthquake Likelihood Models (RELM) project.

(1) Long-term forecast models

Here a forecast is specifying future earthquake rate as a function of location, magnitude, time, and focal mechanism. In previous years we developed long-term (several years) forecasts based on smoothed past seismicity and on geodetic strain rate.

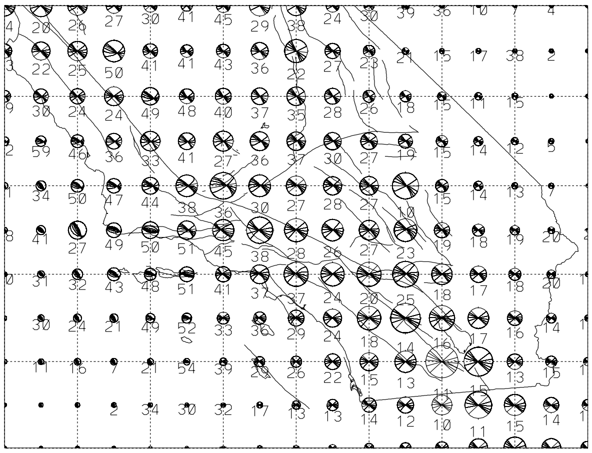

Figure 1. Long-term forecast diagrams of earthquake focal mechanisms in California. The numbers below the diagrams of earthquake focal mechanisms correspond to a standard deviation of a weighted 3-D rotation angle. We first calculate the average seismic moment tensor and then compute the rotation of earthquake focal mechanisms with regard to the average double-couple source. Therefore the average rotation angle shows degrees of tectonic complexity. Points without beachball diagram denote places for which data are inadequate to forecast focal mechanism.

The smoothed seismicity model uses a catalog of earthquakes that we prepared especially for the RELM project. The catalog has several special features, most notably focal mechanisms for all earthquakes over magnitude 4.7, uncertainty estimates for everything, and a representation of all earthquakes over magnitude 6.5 as a sum of rectangular dislocation patches. This year we updated the catalog to include recent earthquakes and published detailed reports of the statistical properties of earthquake recording. These statistical studies were a necessary part of determining the uncertainties; they helped to identify which data sources are most consistent; and they revealed several things that must be borne in mind when using these catalogs. For example, many earthquakes, even fairly large ones, are not reported in some catalogs if they occur soon after large earthquakes. This fact is especially important for studies of short-term earthquake correlations, as discussed below.

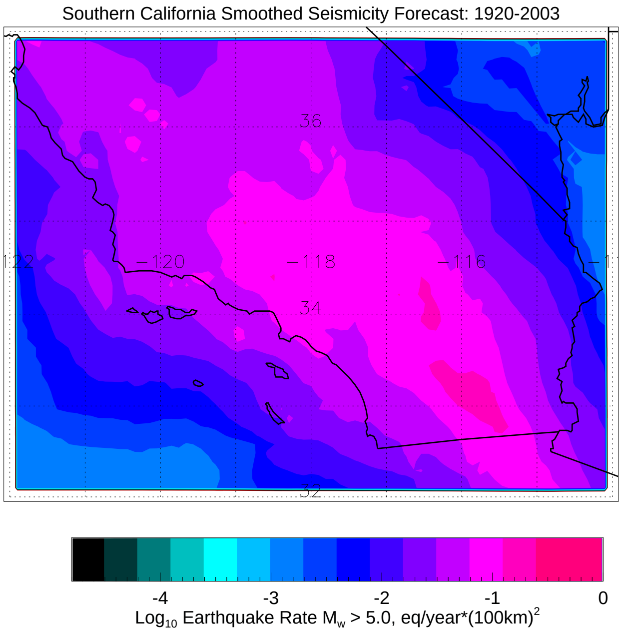

Figure 2. Earthquake potential based on smoothed seismicity. Earthquakes from the RELM catalog since 1920 are used. Earthquake occurrence

is modelled by a time-independent (Poisson) process. Color scale tones show the long-term probability of earthquake occurrence.

We also extended our long-term seismicity forecast to include focal-mechanisms as a predicted quantity (see Figure 1), with a statement of their uncertainty. These focal mechanism forecasts have implications for seismic hazard, because ground shaking depends on faulting style. The focal mechanisms of earthquakes depend on the distribution of fault orientation, so our mechanism studies provide useful data for future models based on stress interactions.

Figure 2 shows the rate density of earthquakes of magnitude 5 forecasted by the smoothed seismicity model. We assume that larger earthquakes will have a rate consistent with a tapered Gutenberg-Richter (GR) magnitude distribution with $b = 0.95$ and corner magnitude 8.3.

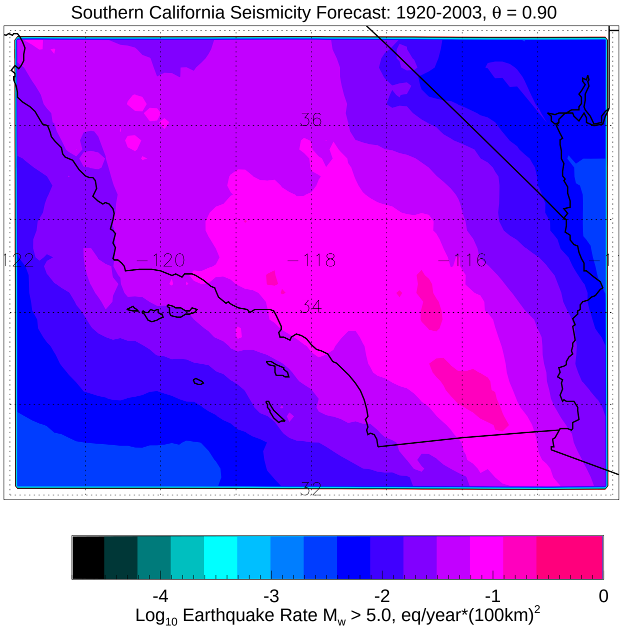

Figure 3. Earthquake potential based on smoothed seismicity. Earthquakes from the RELM catalog since 1920 are used. Earthquake occurrence is modelled by a time-dependent process ($\lambda \propto (\Delta T)^{0.9}$); i.e., recent earthquakes have a stronger influence on the expected rate of occurrence than old events. Color scale tones show the long-term probability of earthquake occurrence.

The smoothing kernel depends linearly on magnitude and inversely on distance. We represent larger past earthquakes as a sum of rectangular dislocation sources, as described above. We give technical details in Jackson and Kagan (1999) and Kagan and Jackson (2000). We made a "pseudo-forecast," using only data before 1993. Earthquakes since 1993 are statistically consistent with the model, but this test is not yet very strong.

To account for temporal and spatial clustering we computed a new model in which the wheighted effect of each previous earthquake is by a power function of its age (Kagan and Jackson, 1991). We found the California catalog is inadequate to optimize the exponent well, so we used a value determined from earthquakes in the western Pacific, adjusted approximately to account for different tectonics and magnitude threshold. Results are shown in Figure 3. In this logarithmic scale the results look similar to Figure 2, but there are important differences. Near the Hector Mine earthquake, for example, the time-dependent model predicts a higher rate.

We also updated our forecast based on geodetic strain rates to include the new SCEC Crustal Motion Model 3.0. We assume the same magnitude distribution is the same as in the smoothed seismicity forecast, except that the a-value is proportional to the maximum horizontal shear strain rate. We use the same distribution of focal mechanisms in both models, independent of the a-values and other parameters.

(2) Short-term forecast models

Jackson worked with Rodolfo Console in Rome on an ETAS model for earthquake clustering. Such models generally assume that each earthquake enhances the rate of future earthquakes; the contribution decays with time according to the generalized Omori law, and increases exponentially with magnitude of the earlier shock. Like Helmstetter (2003), Felzer *et al.* (2002) and others, we found that the exponent (α) is less than or equal to b. This implies that smaller earthquakes dominate the contributions to triggering. The total effects of large earthquakes is limited because their larger individual contributions don't overcome their much lower frequency. Helmstetter and Felzer are both now at UCLA, so we expect to make dramatic progress on short-term models.

Kagan's studies of catalog properties are especially important in this work because clustering models depend on observations of the space-, time-, magnitude- and focal mechanism differences between nearby earthquakes, and the clustering effects are especially strong at short distance and time (Kagan, 2002; Kagan, 2003a,b; Kagan, 2004a,b; Kagan *et al.*, 2003). For this reason the estimated triggering exponent alpha discussed above depends strongly on how well aftershocks are reported immediately after a moderate or large quake, and on how the estimation procedure treats the missing events.

(3) Relationship between tectonic strain rates, earthquake rates, and the magnitude distributions

Bird, Kagan, and Jackson have studied how magnitude distributions vary among different tectonic environments (Bird *et al.*, 2002; Bird and Kagan, 2003; 2004), using a new plate motion model to estimate tectonic strain rates, and either the Harvard CMT catalog or the Pacheco and Sykes (1992) catalog for earthquake rates. We divided plate boundary sections into one of seven tectonic classes, further subdivided according to relative plate velocity, and associated each event with one of the classes. We found that the tapered GR distribution, with a uniform b-value of about 1, is consistent with the earthquakes in all tectonic classes. In subduction zones the corner magnitude (above which the earthquake frequency drops substantially below the simple GR distribution) is about 9.6, and the coupled thickness of the seismogeneric zone is about 18 km. Note that the coupled thickness is the actual thickness times the average coupling coefficient, which cannot be determined independently in our studies. In continental convergent boundaries (like the big-bend of the San Andreas) the corner magnitude is about 8.5, and the coupled thickness is again about 18 km. For continental transform faults the corner magnitude is about 8.0, and the coupled thickness is about 9 km. By contrast the corner magnitude is only about 5.9, and the coupled thickness is less than one km, in oceanic spreading regions. The a-values vary considerably, and when interpreted in terms of the appropriate magnitude distribution they provide a much more stable estimate of the total moment rate than does a moment sum of past earthquakes. These results support the proposition that the magnitude distribution can be inferred reasonably well from the tectonic regime, in which case strain rate is a good estimator of the long-term rate of larger earthquakes.

Bird has over several years constructed a fully annotated and referenced database of fault geometry and fault slip rates for California and western North America. Liu, Jackson, and Kagan (Jackson *et al.*, 2003) used this database and the Wells and Coppersmith (WC) relationship between fault length and maximum magnitude to estimate rates of earthquakes in California. We assumed a Gutenberg-Richter distribution on all faults, truncated at the WC magnitude, and estimated the a-value by matching moment rate on each fault. We then summed the earthquake frequencies as a function of magnitude for all faults, and compared the resulting distribution with the California catalog of Toppozada. The theoretical rate of magnitude 6+ earthquakes for faults alone exceeded the observed rate by a factor of more than three, reminiscent of the "earthquake deficit" problem encountered in the SCEC Phase II report (Jackson *et al.*, 1995). Holt and Jackson (2003) used fault maps (primarily the Jennings maps) made prior to 14 of the California earthquakes listed in the Wells and Coppersmith paper, and 5 of these had rupture zones exceeding prior mapped lengths. These results imply that the fault lengths as shown on comprehensive fault maps do not effectively limit the sizes of earthquakes. There are several ways to resolve the conflict. The predicted and observed earthquakes rates would agree if the coupled thickness were less than 4 km. The WC magnitudes are not upper limits but rather averages; adding 0.8 to the WC magnitudes (accounting for 3 standard deviations) would bring theory and observation to agreement. The earthquake rate in both northern and southern California might have been a factor of three below its long-term average. Or faults may be longer and more numerous than shown on the Jennings map.

(4) Testing earthquake forecasts

Through a series of workshops and personal visits over the last few years, we have developed a consensus on how forecast models would be expressed and tested (Jackson *et al.*, 2001; Kagan *et al.*, 2003; Schorlemmer *et al.*, 2004). The agreements are as follows:

- Forecasts are quantitative (numerical) statements of the expected rate of earthquakes in defined latitude, longitude, magnitude, time and focal mechanism bins.
- We encourage adoption of common bin definitions, so that various forecasts can be compared directly against one another. For this reason we specify two main menu items,which are 5 year forecasts of magnitude 5.0 and above, and daily forecasts of magnitude

4 and above for the next day. Other formats will also be considered, if two or more sufficiently different forecasts use the same format.

- Each model will be tested for self consistency by evaluating the likelihood score for the observed catalog. A model is consistent with the data if the data score is within the 95% confidence limits of the simulated scores.
- Models would be tested against each other in pairs; the test statistic would be the likelihood ratio of data scores for two models, Confidence limits would be established by simulating catalogs from each model, and scoring simulated catalogs using the probabilities from both models (just as for the real data).
- For testing purposes each earthquake will be assigned to a single bin. Its location will be determined by its hypocenter coordinates as reported in the southern California catalog.
- No distinction will be made between foreshocks, mainshocks, and aftershocks.

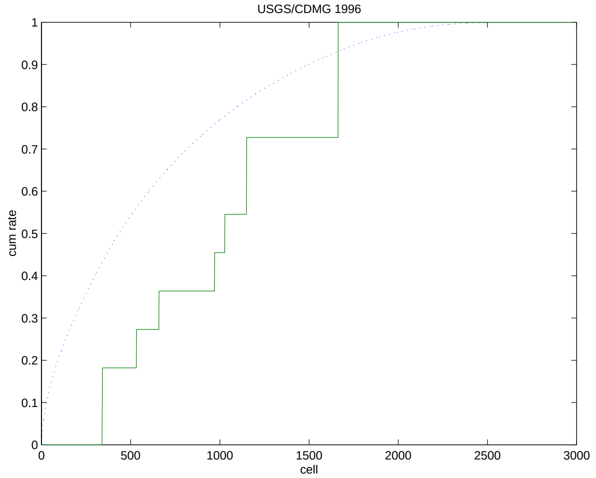

Figure 4. Concentration of theoretical rates (dotted) and earthquake occurrence (solid) for the fault-based USGS/CDMS model.

In collaboration with Schorlemmer and Gerstenberg at ETH Zurich, Jackson has written a paper (Schorlemmer *et al.*, 2004) describing in detail the proposed test procedure, including the main-menu grid definitions. Gerstenberger and Jackson have deconstructed the source model for the 1996 USGS/CDMG probabilistic seismic hazard map and represented it in the form described above. This model is important to test because it is official, and it is based largely on characteristic earthquakes on faults, yet it specifies rates for earthquakes down to magnitude 5 at 0.1 degree resolution.

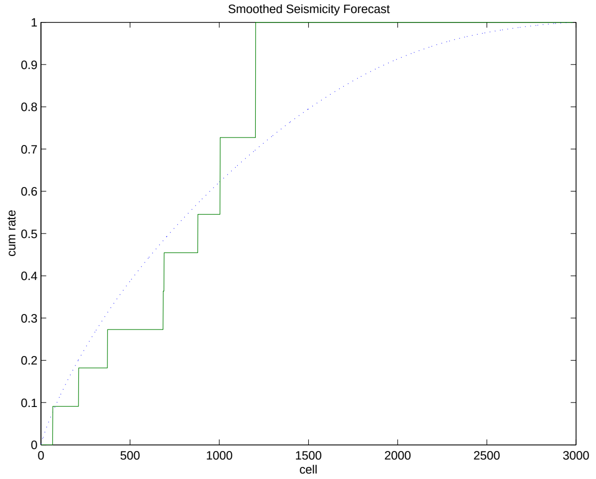

Figure 5. Same as Figure 4 but for smoother seismicity model using pre-1996 data.

Figures 4 and 5 compare the fault-based USGS/CDMG (1996) with a smoothed seismicity model constructed with pre-1996 data. The figures show cumulative rate, and cumulative earthquakes since 1996, as a function of the number of geographic cells included, with the highest rate first. Performance is good if data agree with theory, and if both are concentrated to the left. The USGS/CDMG model (Figure 4) has a higher concentration of its probability (50% in the highest 15% of area) while smoothed seismicity model (Figure 5) is mode diffuse (50% in 23% of area). However, the earthquake data conform better to the smoothed seismicity model (log-likelihood −102) than to the USGS/CDMG model (log-likelihood −106).

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