2018 Annual Report #17134
Testing Fault-based Forecasts
Principal Investigator: David D. Jackson
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Abstract

The goals of this project have been to examine the implications of the hiatus of paleoseismic events in California since 1918, to study methods to associate and test objective descriptions of finite ruptures on faults, and to test the agreement of past forecasts by the Working Group on California Earthquake Probability (WGCEP) with subsequent earthquakes.

The paleoseismic hiatus in California is statistically inconsistent with the rate of events estimated from paleoseismic data, almost all of which were estimated before seismic networks began operating in the early 20th century. Hypotheses for the discrepancy were extreme luck, an unknown (and counter-intuitive) physical mechanism for coordinating rupture statewide, and over-estimation of earthquake rate by including non-earthquake events before seismic networks could verify true seismic events. Each of these hypotheses has quite different implications for use of paleoseismic data in earthquake forecasts. We've discovered that a similar hiatus occurred in New Zealand. Explaining the joint observations for California and New Zealand pretty much rules out the first two hypotheses, implicating over-estimation.

We've tested both the 1988 and 1995 WGCEP forecasts retrospectively and prospectively using modifications of the CSEP N-test and S-test. The 1988 forecast is for large earthquakes on the major faults, assuming quasi-periodic characteristics on prescribed fault segments. Since 1988 only the Parkfield earthquake of 2004 matches the prescribed segment description, and the forecast fails the N-test at 95% confidence. If the segment boundaries are retrospectively adjusted to match the rupture of the 1989 Loma Prieta Earthquake, the N-test is barely met at 95%. The forecast is consistent with the S-test of earthquake location. The 1995 WGCEP associates each earthquake with one of 65 seismotectonic zones, and includes both a time dependent and time independent forecast. Both significantly over-predict the number of expected events after 1995, and the time-dependent forecast significantly over-predicts the number from 1932 till now.

Intellectual Merit

Our project explores the extent to which prior earthquake forecasts, based on common assumptions, agree with earthquake occurrence before and after the forecasts. Thus is contributes to the understanding of earthquake processes, a major goal of the Earthquake Forecasting and Prediction project in SCEC. We also developed methods for associating finite ruptures on faults with prescribed descriptions of such events, a necessary step in evaluation forecasts of such events, and we tested some of these ideas on forecasts of the Working Group on California Earthquake Probabilities (WGCEP). Association and testing of finite ruptures have been major goals of the Collaboratory for Study of Earthquake Predictability (CSEP).

Broader Impacts.

Our research affects seismic hazard estimation, which has implications for public safety, risk management, and public policy. We've presented our results to students and faculty at universities, including UCLA, UCR, ETH Zurich, Victoria Univerity Wellington, and at the 2017 SCEC Annual meeting, showing how Physics, Geology, Geodesy, and Statistics can be combined to solve real world problems. We've discussed our analysis with students and faculty in Statistics, showing them applications and encouraging their participation in seismological research.

Technical Report

Paleoseismic Tests

We continued analysis of paleoseismic dates and rates in California and New Zealand. The 32 paleo sites used in the UCERF3 report and 29 sites in New Zealand showed no events in the last century except for one secondary displacement in New Zealand. Statistical aspects of the hiatus in both locations were reported this year at StatSei10, (10th Statistical Seismology conference in New Zealand), the SSA meeting in Denver, and a European Probabilistic Seismic Hazard meeting at Lenzberg, Switzerland. Numerical results for California were presented in last year's report, so we'll focus here on results for New Zealand as shown in Table 1.

Site	Fault	type	youngest age	indep rate/yr	
2	Rotoitipakau	N	23	0	secondary, Edgecumbe
13	Hope_(Hope_Segment)	SS	122	0.0077	
11	Southern_Wairarapa	SS/R	155	0.0008	
1	Eastern_Awatere	SS	162	0.0011	
12	Alpine_(central)	SS	184	0.0067	
17	Ohariu	SS	205	0.0008	
23	Matata	N	270	0.0013	
20	Wellington_(Hutt_Valley)	SS	270	0.0005	
12.5	Southern_Alpine_(Hokuri_	SS	293	0	
22	Ihaia	N	410	0.0005	
6	Paeroa	N	460	0.0004	
5	Whirinaki	N	560	0	
15	Lachlan	R	610	0.0008	
10	Eastern_Porter's_Pass	SS	610	0.0006	
16	Ngakuru	N	690	0	
14	Kiri	N	990	0.0011	
24	Oaonui	N	990	0.0001	
4	Rangipo	N	1010	0.0005	
9	Mangatete	N	1010	0	
18	Snowdon	N	1010	0	
25	Rotohauhau	N	1010	0	
27	Whakatane_(north)	SS/N	1460	0.0004	
8	Cloudy	SS?	1800	0.0003	
21	Eastern_Clarence	SS	1820	0.0006	
3	Wairau	SS	2000	0.0004	
26	Waimana_(north)	SS/N	2310	0.0003	
7	Pihama	N	3060	0.0001	
19	Vernon	SS	3200	0	
	Total rate/yr			0.0253	

Table 1. Paleoseismic event data for New Zealand, compiled by Nicol et al., with rate calculations provided by us from data in the Nicol et al. paper.

The probability for hiatus since 1918 in California, given past event rates, is less than 1.4 percent. For New Zealand, the comparable probability is about 4 percent. The probability of both occurring at random in the last century is less than 0.1 percent. We searched for reasons why sites throughout California or New Zealand might be internally dependent, with no satisfactory answers. Inter-dependence between California and New Zealand paleo events is even more difficult to explain. For California sites we listed three possible alternatives: extreme luck, unknown physical interactions over large distances, or overestimation of event rates caused by lack of seismological confirmation before seismic networks were installed in the early 20'th century. With New Zealand data included in the puzzle, the solution appears more and more to be overestimation of rates before seismic networks.

Testing of the 1988 and 1995 Forecast Models of the Working Group on California Earthquake Probabilities (WGCEP)

We set up criteria for prospective fault-rupture forecasts, and showed examples using retrospective tests on earthquakes. We used only instrumentally recorded events after

1932. A central problem for finite ruptures is "association": finding objective measures to describe earthquake ruptures in order to assign a probability to each future event. The Working Group on California Earthquake Probabilities has published long-term earthquake rate forecasts for California since 1988. We focused first on prospective and retrospective testing of the 1988 and 1995 versions, because those contain information by which probabilities can be associated with any future earthquake over magnitude 6.0. The 1988 WGCEP forecast was based on the characteristic earthquake assumption and was specifically time dependent. For testing purposes we constructed a time-independent model assuming Poisson recurrence with the same rates on the same segments adopted by WGCEP. The 1995 forecast, for Southern California only, attributed earthquakes to 65 "seismotectonic" zones that covered the entire study area.

We participated in bi-weekly phone conference with other CSEP members, and a common theme is broadening CSEP testing beyond epicenter rates to finite surface rupture. For them the association problem is challenging, because finite ruptures have more dimensions than hypocenters do, they need some quantitative descriptions, and there is no authoritative compilation as there is for epicenters.

We began with retrospective tests of published forecasts like the 1995 WGCEP report (Jackson et al., 1995) which provides fault-centered polygons which can capture finite ruptures on or near known major faults. "Near" is important, because large earthquakes may get off the tracks. WGCEP forecasts generally cover 30-year time intervals. Revisions come more frequently than that but the fundamental ideas and assumptions in the forecasts are older than 30 years. Both retrospective and prospective tests are still important for several reasons. Testing "outdated" models can still reveal important information about what worked well or didn't, and formulating the tests can be very helpful in understanding what the forecast model is really about. Is it meant to illustrate the impact of certain assumptions like Coulomb stress triggering or on-fault magnitude distribution, or rather to provide a robust source model for hazard estimates? Is the target large structures like bridges, infrastructure, or private homes? Each suggests different test measures. Ideally forecasts and test plans should be developed together. Our purpose is to expand the menu of testing options by testing past forecasts. Figure 1 below shows the geometry of 65 "seismotectonic" zones used in the 1995 WGCEP report and the locations of magnitude 6+ earthquakes since 1932. The N-test, whether the total number of events is consistent with the forecast, is simplest. The forecasted annual rates of earthquakes in the 1995 report are shown in the third column of Table 2. The fourth column, lamda, is the expected rate for 86 year intervals (the interval between 1932 and 2018), N is the observed number in the last 86 years, and Prob(0-N) is the probability that the observed number or fewer would occur, based on a Poisson model. The Poisson model is appropriate for the "TI" or Time Independent alternative model. The "TD" or Time Dependent model, described as "preferred" in the 1995 model) assumes lognormal recurrence. The 2010 El Mayor-Cucupah event was not counted because its epicenter was outside the study area. Including it would not change the results. Even retrospectively, both 1995 models over-estimated the rates of

magnitude 6+ and 7+ earthquakes. The discrepancy at 6+ for the Time Dependent model is highly significant and, well, dramatic. The basic assumptions of the TD model are still used in modified form in UCERF3 and other forecasts, so further examination is appropriate.
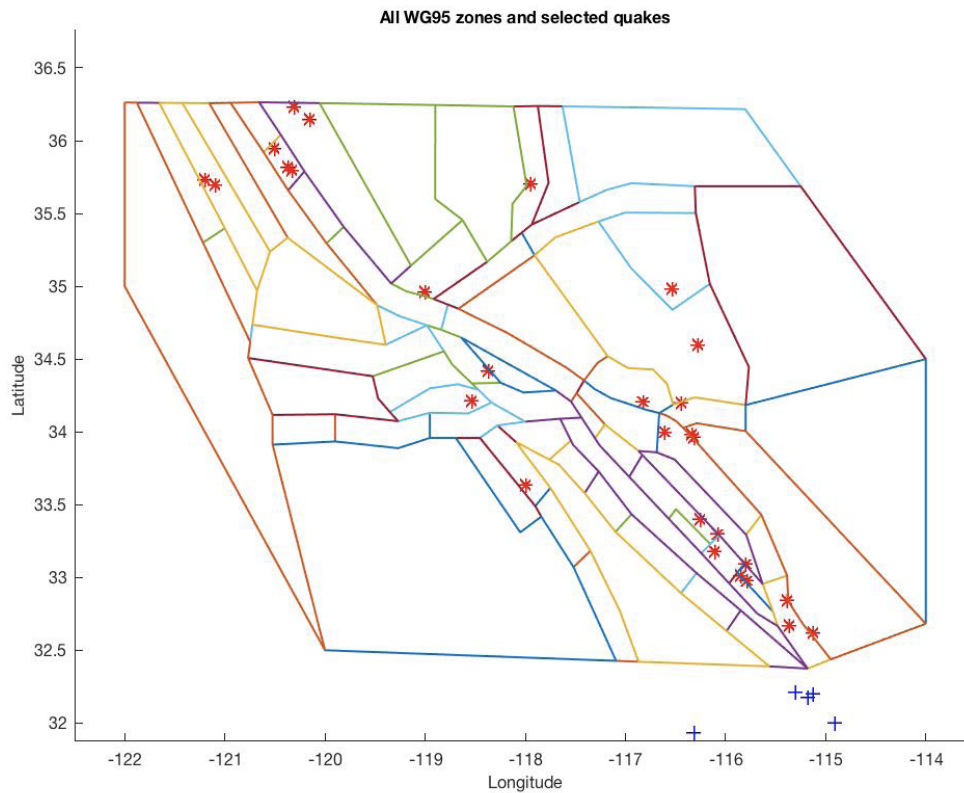

Figure 1. Earthquakes after 1932 occurring within the 65 "seismo-tectonic" zones used in the 1995 WGCEP report. There are 28 events over magnitude 6, but only three (Hector Mine 1999, San Simeon 2003, and Parkfield 2004) occurred from 1995 to 2018. The 1995 WGCEP time-dependent model forecast over 13 such events, and the time independent model forecast over 9 such events.

Model	Mag	Total rate	lamda	Events, N	Prob (0 - N)
TD Total	6+	0.605	52.05	28	0.000
TI Total	6+	0.406	34.92	28	0.137
TD Total	7+	0.067	5.76	3	0.174
Ti Total	7+	0.064	5.50	3	0.201

Table 2. Retrospective performance of the Time Dependent and Time Independent versions of the 1995 WGCEP forecast on earthquakes since 1932. Last column is cumulative Poisson probability of N given expected number lamda. Red highlight indicates statistically significant discrepancy.

Twenty four years have elapsed since the "30 year" 1995 report was finalized, but we have done an early prospective test with just a few adjustments. In this case we "rolled the clock back" to calculate the Time Dependent probabilities for a 23 year interval. A map of the earthquakes since 1995 is shown in Figure 2, and results in Table 3. Only three m6+ and one m7+ events have occurred since 1995. The 1995 report contained specific descriptions of "characteristic" earthquakes, included magnitudes and possible combinations of involved fault segments. No such events occurred after 1995. Again, both the TD and TI forecasts over-predicted the earthquake rate, significantly so for those in red font in Table 3. The TI and TD models both pass the magnitude distribution tests (M-test) and conditional locations tests (S-test). Clearly the 1995 forecasts , especially the preferred model, over-estimated the future earthquake rate significantly. The 1995 report acknowledged that the estimated rates exceeded the historic rate of 0.35/a, but the assumption was made that an earthquake deficit would have to be repaid. The lesson: instrumentally determined earthquake data after 1932 do not support the time-dependent model for southern California. A second lesson visible in Figure 1 is that the earthquakes occurred near but not precisely on previously mapped faults. Future forecasts could use aftershocks to measure finite fault extent in prospective tests, but associating earthquakes by zone is more robust.

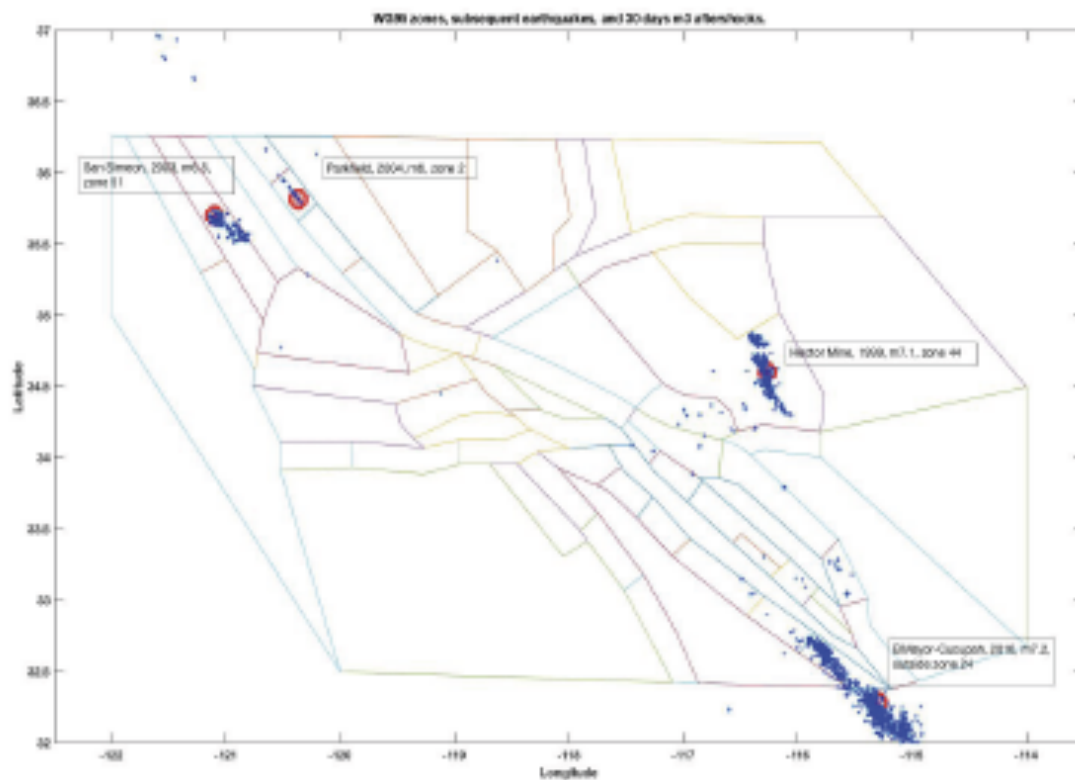| Model	Mag	Total rate	lamda	Events, N	Prob (0 - N)
TD Total	6+	0.605	13.62	3	**0.001**
TI Total	6+	0.406	9.12	3	**0.019**
TD Total	7+	0.067	1.51	1	0.555
TI Total	7+	0.064	1.44	1	0.578
TD Char	Char	0.149	3.36	0	**0.035**
TI Char	Char	0.065	1.45	0	0.234

Table 3. Early prospective N-test of 1995 WGCEP forecast.

Figure2. Map of seismo-tectonic zone used in the 1995 WGCEP forecast, and m=3+ aftershocks within 30 days of the four subsequent m=6+ earthquakes. Probabilities were assigned to each of the zones in 1995. Aftershock zones are adequate to assign each m=6+ event to a zone, but not necessarily to an individual fault.

Publications

Jackson, D.D. 2018. Testing the Classic 1988 Forecast. *Seismological Research Letters* doi: https://doi.org/10.1785/0220180039

Weiser D, Porto N, Jackson D.D. 2018, Fault Dimensions and Maximum Magnitude. *Proceedings of the 11 th National Conference in Earthquake Engineering, Earthquake Engineering Research Institute*, Los Angeles, CA. 2018

Presentations

Jackson, D.D., 2018. Testing Fault-Based Rupture Models. Presentation at Seismological Society of America, Miami FL, 5/16/2018.

Jackson, D.D. , 2018. The Collaboratory for the Study of Earthquake Predictability: Achievements and Priorities. Presentation at Seismological Society of America, Miami FL, 5/17/2018

Jackson, D.D., 2017. Large earthquake rates from geologic, geodetic, and seismological perspectives, Presentation and Annual Meeting of the American Geophysical Union, New Orleans, LA

Jackson, D.D. , 2017. Mind the Gap, Keynote Presentation at 10th International Workshop on Statistical Seismology, 21 February 2017, Wellington, New Zealand. doi: 10.21420/G23S33

Jackson, D.D. , D. Weiser, and N. Porto, 2017. Resistance to Rupture, Keynote Presentation at PSHA Workshop "Future directions for probabilistic seismic hazard assessment at a local, national, and transnational scale", Lensburg, Switzerland, Sep 5 – 7, 2017