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The 1999 Chi-Chi, Taiwan, earthquake as a typical example of seismic activation and quiescence

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[1] The Pattern Informatics algorithm, which has recently shown promising performance for earthquake forecasting in Southern California, has been used to detect the locations where precursory seismic activity occurred preceding the 1999 Chi-Chi, Taiwan, earthquake. Using the Pattern Informatics method as presented in this paper, the epicenter of the Chi-Chi main shock was found to exhibit signatures of anomalous activity related to the seismic activation and quiescence in the Taiwan region over a time span of about 6 years before the main shock. A strategy of making intermediate-term earthquake hazard assessment by means of Pattern Informatics is therefore proposed on the basis of retrospective analysis of the Chi-Chi earthquake.

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1. Introduction: Seismic Activation and Quiescence Before the Chi-Chi Earthquake

[2] Two primary changes in seismic activity prior to a major earthquake are widely observed, seismic quiescence and activation [*Wyss and Habermann*, 1988; *Jaume and Sykes*, 1999] These and other well-known precursory seismicity patterns were described by, e.g., *Kossobokov and Carlson* [1995]. While the literature presents individual case studies of seismic quiescence or activation, a few systematic tests for such precursory phenomena also exist [*Bowman et al.*, 1998; *Zoller et al.*, 2002]. Most research on seismic activation emphasizes the increasing activity of moderate-sized earthquakes [*Sykes and Jaume*, 1990]. On the other hand, it is not clear which earthquake magnitudes participate in quiescence [*Wiemer and Wyss*, 1994; *Huang et al.*, 2001; *Zoller et al.*, 2002]. Results seem to indicate seismic quiescence is marked by low activity for all magnitudes of earthquakes, while activation occurs for moderate-sized earthquakes only.

[3] The Chi-Chi earthquake (Figure 1) with $Ms = 7.6$ struck central Taiwan on 21 September 1999 (or at UTC 17:47 20 September), and was the largest island earthquake in Taiwan in the 20th century. *Chen* [2003] investigated with a local catalogue the accelerating activity of moderate earthquakes before the Chi-Chi earthquake. With a global USGS NEIC catalogue, Kossobokov also demonstrated similar activation before the Chi-Chi event (V. G. Kossobokov, personal communication, 2005) and suggested a wider area of about 5 $\sim$ 10 times the rupture area involved into the activation process. Activation of earthquakes with magnitudes larger than 5 began at the end of 1993, and was terminated 6 years later by the main shock [*Chen*, 2003, Figure 3]. Examination of the frequency-magnitude statistics in the years prior to the earthquake indicates that three distinct stages can be identified. The first stage represents a typical Gutenberg-Richter scaling relation. In the second stage, seismic activation of moderate earthquakes ($M \geq 5$) occurs, while in the third stage, the observations indicate a hybrid of seismic quiescence for small events ($M < 5$) and continued activation for moderate events. In the context of the self-organizing spinodal model of earthquake fault systems [*Rundle et al.*, 2000], the time evolution of the frequency-magnitude distributions of earthquakes in Taiwan before the Chi-Chi main shock represents a definite example of seismic activation, demonstrating the systematically temporal change in seismicity.

[4] While seismic quiescence and activation are well documented, there is a lack of an accepted theoretical approach that describes the preparation process and precursory phases of a major, catastrophic earthquake [*Hainzl et al.*, 2000; *Rundle et al.*, 2000; *Turcotte et al.*, 2003]. This deficiency makes most techniques for earthquake prediction either functionally ambiguous or theoretically unsound. Algorithms have been developed [e.g., *Wyss and Martirosyan*, 1998; *Huang et al.*, 2001; *Keilis-Borok*, 2002] that attempt to identify anomalies in seismic activity indicating signatures of future earthquakes. One such algorithm, "Pattern Informatics (PI)", has been proposed recently [*Rundle et al.*, 2002; *Tiampo et al.*, 2002; *Rundle et al.*, 2003] to identify both anomalous activation and quiescence. In the research presented here, we find that patterns of activation and quiescence exhibited by small earthquakes may be associated with the future occurrence of large earthquakes.

[5] To develop a satisfactory theory of earthquake prediction/forecasting, we would like to improve our understanding of earthquake physics. Specifically, the issue addressed in this paper is how to identify the time and the place that seismic quiescence and activation may occur. This issue will be demonstrated here by our

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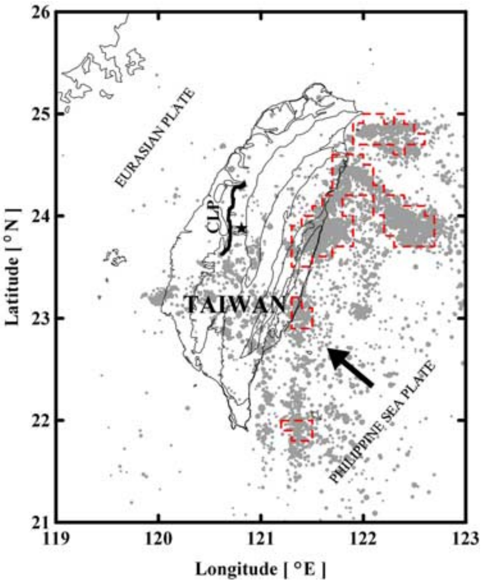

Figure 1. Map showing the epicenters of earthquakes used in this study (dots) and the Chi-Chi main shock (star). CLP = the Chelungpu fault. Thick arrow shows the direction of relative motion between the Eurasian Plate and the Philippine Sea Plate. The highlighted area denotes the top 5% active area of historic coarse-graining intensity of earthquake.

retrospective analysis of the 1999 Chi-Chi, Taiwan, earthquake.

2. PI Method: A Method to Locate Precursory Activation and Quiescence

[6] Here we have slightly modified the PI method for earthquake forecasting as described by *Rundle et al.* [2002], *Tiampo et al.* [2002], and *Rundle et al.* [2003]. A physical interpretation of the PI method in terms of stress accumulation and release, and its relation to rotations of a state vector in a Hilbert space, is given in those references.

[7] The steps in the modified method are: a) The seismically active region is binned into boxes or pixels of size $.1^\circ \times .1^\circ$ and all events having $M \geq 3.4$ are used. b) Only the top, say, 30% most active boxes are considered. c) Seismicity is spatially averaged over each box and its 8-box Moore neighborhood, divided into time steps of 1 day, and the resulting time series is assigned to the central box. d) Each time series is normalized in time by subtracting the temporal mean and dividing by the temporal standard deviation. e) Each time series is then normalized in space for each value of time by subtracting the spatial mean and dividing by the spatial standard deviation. f) If the time at which the data record used begins is t_0, two intensity maps $I_1(x, t_b, t_1)$, $I_2(x, t_b, t_2)$ are computed by averaging all the time series from an initial time, t_b to t_1 where $t_0 < t_b$; and then from t_b to t_2. Here t_0 = January 1, 1987. Also, t_1 = November 1, 1993 and t_2 = June 30, 1999 (3 months prior to Chi-Chi main shock) define the change interval from t_1 to t_2. Recall the temporal changes of the Gutenberg-Richter relation in Taiwan [*Chen*, 2003, Figure 3] indicate that major change in seismicity before the Chi-Chi event began in November 1993 and lasted through the main shock occurrence. g) The intensity change $\Delta I(x, t_b, t_1, t_2) = I_2(x, t_b, t_2) - I_1(x, t_b, t_1)$ is computed at each location and the absolute value is taken $|\Delta I(x, t_b, t_1, t_2)|$. h) The average of $\langle|\Delta I(x, t_b, t_1, t_2)|\rangle$ over all values of $t_0 \leq t_b \leq t_{max}$ is then computed. In view of the fact that a time scale $\tau = t_2 - t_1$ has been implicitly chosen, the time t_{max} is chosen to be $t_{max} = t_1 - \tau$. This choice also gives the averaging time periods in the intervals t_b to t_1 and t_b to t_2 more equal weight, thereby excluding the possibility of large fluctuations (main shocks) occurring just prior to t_1 that may receive too much weight if t_b were integrated from t_0 to t_1. i) Finally, the mean squared change in probability $\Delta P(x, t_1, t_2) = \{\langle|\Delta I(x, t_1, t_2)|\rangle\}^2$ is computed. j) Note that steps b), c), f) and g) have been modified from the original algorithm. This modification produces increased stability in the original method by eliminating "noise" that is associated with sites having very low seismicity, and/or location errors of small events.

[8] The original algorithm, published on Feb 19, 2002, has shown considerable success in locating 16 of the 18 significant large earthquakes that have occurred since Jan 1, 2000 (J. R. Holliday et al., Earthquake forecasting and its verification, submitted to *Nonlinear Processes in Geophysics*, 2005) (15 of these have occurred since Feb 22, 2002). Since the growing precursory phenomena of seismic quiescence and activation induce the probability changes [*Rundle et al.*, 2002; *Tiampo et al.*, 2002; *Rundle et al.*, 2003], we emphasize that the PI method is not only an earthquake forecasting method, but also a method for locating the spatial patterns of sites where significant precursory activity relative to the background seismicity are occurring.

3. PI Result: The Anomaly Preceding the Chi-Chi Earthquake

[9] The temporal changes in the Gutenberg-Richter relation in Taiwan indicate that the precursory activation and quiescence of the Chi-Chi main shock began in November of 1993 [*Chen*, 2003]. Using the PI method, we address the second relevant issue of seismic activation and quiescence: Where did the anomalous activity occur? For data, we used an earthquake catalogue maintained by the Central Weather Bureau (CWB) of Taiwan. This catalog contains data for earthquakes that occurred in and around Taiwan beginning in 1973 over a large range of magnitudes and depths. The selected events for our PI analysis are those with depth shallower than 20 km and magnitude $M \geq 3.4$, the level at which the earthquake catalog data can be considered complete.

[10] Shown in Figure 2 is the coarse-grained PI map for Taiwan. The mapped region was divided into a grid of 2,000 boxes, each with a linear dimension of 0.1°. As described in Section 2, the change interval was from t_1 = November of 1993 to t_2 = June of 1999 (almost 6 years). The color-coded hotspots highlight several anomalous locations where the largest changes in seismicity occurred during the change interval. It is clear from this map that the epicentral area of the Chi-Chi main shock was located in a connected cluster of hotspots with high probability change. It should be noticed that the spatial scale of hotspots on the PI map is different from the regional activation size of *Chen* [2003]. While the overall seismicity in the Taiwan region exhibited

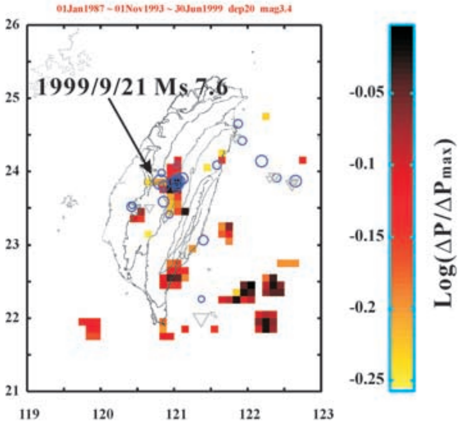

Figure 2. Taiwan PI map over the change interval from t_1 = November 1993 to t_2 = June 1999. Circles represent earthquakes with $M \geq 6$ that occurred after t_2 and inverted triangles represent earthquakes with $M \geq 6$ that occurred between t_1 and t_2. Colored pixels (hotspots) represent areas with large seismicity change caused by both the seismic activation and quiescence, indicating high probability for future large events.

precursory patterns of activity prior to the Chi-Chi earthquake [*Chen*, 2003], the hotspot area depicted in Figure 2 is only a few tens of kilometer in linear size. The difference can be attributed to the fact that the hotspots on the PI map represent only the locations with the largest changes in seismicity, and do not include other correlated regions where the fluctuation amplitudes (changes) are smaller. One important question related to the concept of the critical earthquake is thus raised: Could one infer the change in correlation length using the PI method? While we cannot for the moment answer this question, the anomalous seismic activity around the epicenter of the Chi-Chi main shock is certainly a striking feature of the map and a promising direction for future work.

4. Discussion: How Much Better is PI Than Seismic Intensity as a Forecasting Tool?

[11] The idea of precursory activation discussed above led us to define forecast map based on the historic intensity of small earthquakes $M \geq 3.4$ for Taiwan, the level of catalog completeness. This map, which can be contoured to produce a Relative Intensity (RI) map, can be used as a null hypothesis for evaluating the forecast skill of the PI method. Physically, the RI map is based on the simple hypothesis that large earthquakes will tend to occur where the greatest number of earthquakes has occurred in the past. The RI map is simply a count of the earthquake numbers that occurred in a set of spatial grid points, divided by the intensity value of the box with the greatest intensity.

[12] We have compared the forecasting "performance" (Figure 3) of our PI map against the RI map using both the Success/Error (S/E) diagram [*Molchan*, 1997] and the Relative Operating Characteristic (ROC) diagram [*Swets*, 1973; *Jolliffe and Stephenson*, 2003]. To discuss performance measures for $M \geq 6$ events occurring after t_2, we define a = the number of hotspots with an earthquake "hit" on the hotspot or within its 8 Moore neighbors; b = the number of hotspots with no earthquake hit either on the hotspot or within its neighborhood; c = number of white boxes (non-hotspot boxes) where a large earthquake occurred; d = number of white boxes where no large earthquake occurred; e = the number of predicted target events hit on a hotspot or within its 8 Moore neighbors; f = the total number of target events; and $n = a + b + c + d$.

[13] In an S/E diagram, we define $S = e/f$ and $E = (a + b)/n$. For the ROC diagram, we define $H = a/(a + c)$ and $F = b/(b + d)$. Recall that the line H = F indicates the expectation for a random forecast with no skill. For both diagrams, a larger area between the S/E or ROC curve and the line H = F indicates higher skill of the forecast algorithm. It is easily shown that, for a perfect forecast, this area → 0.5, whereas for a forecast with no skill, this area → 0. Based on both the S/E and ROC diagrams in Figure 3, it can be seen that the forecast performance of our PI map is significantly better (i.e., more skillful) than the RI, historic earthquake intensity map. Furthermore, for 19 degrees of freedom and a confidence level of 95%, the Kolmogorov-Smirnov statistic [*Davis*, 2002] of about 0.79 indicates that the scorecard statistics for PI and for RI are really different.

5. Concluding Remarks: A Suggested Strategy for Earthquake Forecast

[14] The phenomenon of precursory seismic activation and quiescence before the Chi-Chi earthquake has been explored using both temporal patterns [*Chen*, 2003] and now spatial patterns as well. Using correlation-coefficient calculations [*Chen*, 2003], the precursory activity was confirmed to begin in November 1993 and last through the main shock occurrence. Using the Pattern Informatics method presented above, the location of the main shock epicenter was shown to have exhibited signatures of anomalous activity. We therefore conclude that the 1999 Chi-Chi, Taiwan, earthquake might be a typical example of seismic activation and quiescence.

[15] For the goal of hazard prevention we might also formulate a strategy of earthquake forecasting emerging

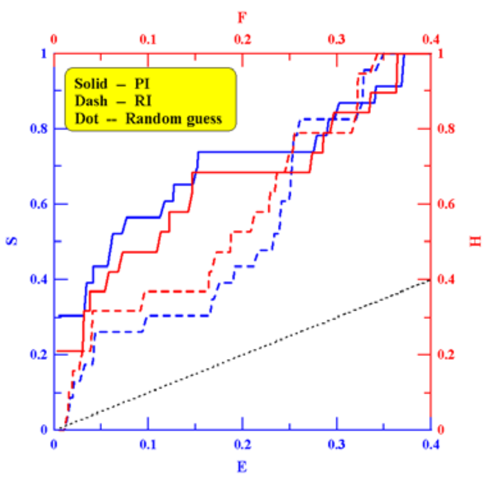

Figure 3. Success/Error (blue) and ROC (red) diagrams for earthquake forecasts using both PI (solid) and RI (dashed) maps. For details, please refer to the text.

from the previous paper by one of the authors (CCC) and the present paper. That is, by inspecting temporal variations in the frequency-magnitude distributions of earthquakes and the hotspot locations with intense seismicity changes in the PI map, it is possible to shed light on the relevant preparation processes of the forthcoming catastrophic earthquake. Such a strategy might be useful in short- to intermediate-term earthquake forecasts.

[16] With these techniques, the detection of precursory seismic activity preceding a major earthquake remains a subtle but exciting new possibility in earthquake physics. It may represent a new and promising method to realize the goal of practical earthquake prediction [*Wyss*, 1997; *Wyss and Booth*, 1997], based as it is on the standpoint of seismic precursory phenomena [*Keilis-Borok*, 2002]. While we are still a long way from achieving this goal, the study of precursory seismic activity using both extensive new data sets and new theoretical approaches [*Hainzl et al.*, 2000; *Rundle et al.*, 2000; *Turcotte et al.*, 2003] will speed us towards our objective. Retrospective analyses of the type presented here should help us towards this end.

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