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Tectonophysics 417 (2006) 81–84

TECTONOPHYSICS

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Verification of our previous definition of preferred earthquake nucleation areas in Kanto-Tokai, Japan

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Received 30 August 2004; accepted 17 May 2005
Available online 5 January 2006

Abstract

We have proposed that points of future initiation of rupture may be mapped, based on minima in local recurrence times, which are equivalent to local maxima in the probability for main shocks to occur. These minima are often controlled by anomalously low b-values ($\log N = a - bM$). Of the Kanto-Tokai area, approximately 12% showed anomalously short recurrence times and was proposed as asperities, based on seismicity up to 1999. During the period 1999–2003.5, about 75% of the earthquakes with $M \geq 3.5$ fell into the asperities, earlier defined (for example 19 out of 23 $M \geq 3.8$ events). The probability for this to occur by chance is approximately $2\ 10^{-14}$. This supports our idea that the most likely volumes to produce main shocks may be mapped by minima in local recurrence times.

Keywords: Recurrence time; b-values; earthquake nucleation

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1. Introduction

The probabilistic estimate of the recurrence time of major earthquakes is based on the idea that the frequency-magnitude relationship, observed for small events, can be extrapolated to the magnitude of the expected main shock. It follows that in an area where the seismicity rate is large (large a-value in $\log N = a - bM$), the probability of a main shock is increased. That probability is also enhanced, if the b-value is low. Therefore, the probability for main shocks can vary strongly as a function of space, because both of the parameters a and b vary strongly (e.g., (Wiemer and Wyss, 2002)).

A correlation of minima in recurrence times (maxima in probability) for main shocks with the known asperity under Middle Mountain in the Parkfield segment of the San Andreas fault led to the proposal that asperities may be mapped by minima in local recurrence times (Wiemer and Wyss, 1997). The strong spatial variations of b, found along the San Andreas fault (Wiemer and Wyss, 1997; Wyss et al., 2000), were shown rigorously to be stationary in time (Schorlemmer et al., 2004a).

Applying these ideas to the Kanto-Tokai area, we mapped b-values and local recurrence time (i.e., probability of main shocks), using the NIED earthquake catalog for the period 1980.0 to 1999.0 (Wyss and Matsumura, 2002). As a first step, we mapped the minimum magnitude complete reporting, M_c, in order to define an area within which the catalog is of uniformly

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doi:10.1016/j.tecto.2005.05.050

high quality. Although the offshore areas are of great importance, we did not include them because there the catalog is far less complete than on land. In the study area, defined as the area with $M_c = 1.5$ (dashed line in Fig. 1) we then excluded explosions, which we identified by the ratio of day-to night-time events, because they locally falsify the a and b-values. Then we declustered the catalog (using the algorithm of Reasenberg (1985)) because clusters and aftershock sequences often show anomalous b-values. The resulting data set contained 15,530 events covering the area shown in Fig. 1.

The local recurrence time, TL, we calculated by

$$TL(M) = T\Big/\left(10^{(a-bM)}\right) \tag{1}$$

where a and b are the local parameters from the frequency–magnitude relationship, dT is the duration over which the observations where gathered, and M is the magnitude of the expected main shock. Maps of b and TL were constructed by the gridding technique (Wiemer, 2001). At every node of a tightly spaced grid, we selected the nearest N=const. (usually 100) events to map the b-value. We use a constant number of events to map b with uniform statistical reliability. For mapping TL, the parameters a and b are estimated from the sample within a constant radius (for example R=20 km) from each node. In this case we need to use samples with constant radius because we also calculate the a-value, which would make no sense if we used variable radii. N and R were varied to verify that the results did not depend on its choice.

The areas of anomalously low recurrence times that we identified in our previous work (Wyss and Matsumura, 2002) are shown as pink areas in Fig. 1. They cover approximately 12% of the study area, and we proposed that the larger earthquakes in the Kanto-Tokai area should in future preferably, although not exclusively, occur in these anomalous areas. Here, we verify, whether or not the larger earthquakes that occurred since 1999.0 fell preferably into the areas defined by us earlier.

2. Method and data

Because we used a declustered catalog in our study defining the suspected asperities, we based the current study on the declustered catalog also, and for the same area as defined in out earlier work. The data available at the time of the present study cover the period 1999.0 through 2003.5 with N_{tot}=3787 above the minimum magnitude we accepted for analysis, $M \geq 1.5$.

Although our idea that main shocks are likely to emanate from the low recurrence time areas is mainly valid for the maximum magnitude earthquakes in a region, we assume that intermediate magnitude events also occur preferentially in these anomalies. Therefore,

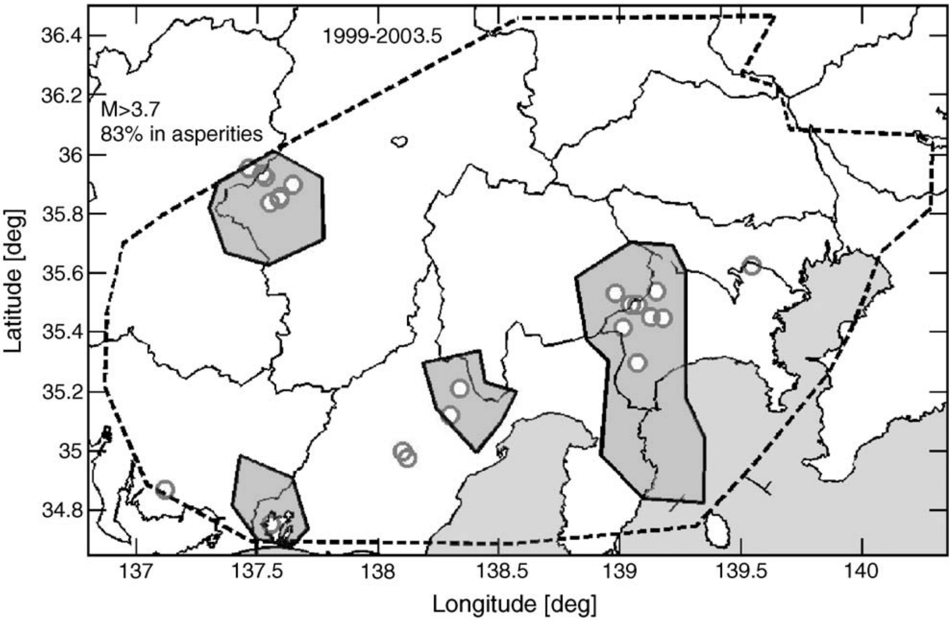

Fig. 1. Epicenters (circles) of the earthquakes with $M > 3.7$ between 1999.0 and 2003.5 in the declustered catalog. The study area selected in our previous work (Wyss and Matsumura, 2002) is outlined by a dashed line, the previously mapped areas of anomalously low recurrence time are outlined by solid lines and colored pink. Of the 23 events, 19 (83%) fall into the anomalous areas.

we take it as support of our hypothesis, if intermediate magnitude events occur mostly in the mapped anomalous areas. To evaluate our hypothesis, we plotted the larger magnitude earthquakes which occurred since 1999.0 to determine what percentage falls into the anomalous areas, and compared that number with the percentage of all earthquakes larger than the minimum magnitude used in both studies (M 1.5) inside the proposed asperities.

3. Results

The largest earthquake during the test period measured M 5.4, and the number of events with $M \geq 3.5$, which we define as 'larger events', was $N_{\text{large}} = 41$. This definition was selected such that we have a sufficient number to make a statistically meaningful statement about whether or not our hypothesis is supported by the data.

The epicenters of earthquakes with $M \geq 3.8$ (Fig. 1) show that indeed most of them fall into the areas of minimum recurrence time. Only four, out of 23 events, fall outside of the target areas. To evaluate the possible dependence of this result on the minimum magnitude selected for 'larger events', we repeated the plot for minimum magnitudes ranging from 3.5 to 4.5 (Fig. 2). For $M \geq 4.5$, there were only 8 events left. Thus we do not discuss results above that cutoff, where we have only weak statistical power to evaluate the hypothesis.

The pattern showing the larger events within the anomalous areas is clearest for cutoffs at 3.7, 3.8 and 3.9, but it is almost equally clear at all magnitude cutoff (Fig. 2). On average, the percentage of larger events within the proposed asperities is 75%. If we plot all events in the catalog, we find that 13% fall into the anomalous areas, which corresponds closely to the 12% of the total area these comprise. However, the single largest earthquake (35.0°N/138.1°E) was not located within an anomalous area mapped by us.

4. Discussions and conclusions

Our result that 75%, on average, of the 'larger events' ($M \geq 3.5$), regardless of the selected cutoff, occurred within the areas we specified in our previous paper (Wyss and Matsumura, 2002) as the most like locations for larger events, can be taken as support of our hypothesis. The probability that an event falls into one of the anomalous areas, A, is $P(A) = 0.12$, and the probability that it falls into the background area is $P(B) = 1 - P(A)$. Taking the case of $M \geq 3.8$, we have $n = 23$ trials, out of which $m = 19$ result in hits (i.e., the event is located in area A, which covers 12% of the total area). Using Bernoulli's formula to calculate the probability, P_{exp}, that by chance the hits in A occur m, or more often, out of n trials

$$P_{\text{exp}} = \sum_{m=19}^{23} \frac{n!}{(n-m)!m!} P(A)^m P(B)^{(n-m)} \tag{2}$$

we find that $P_{\text{exp}} = 2\ 10^{-14}$. In contrast, 13% of all the events contained in the catalog fall into the anomalous

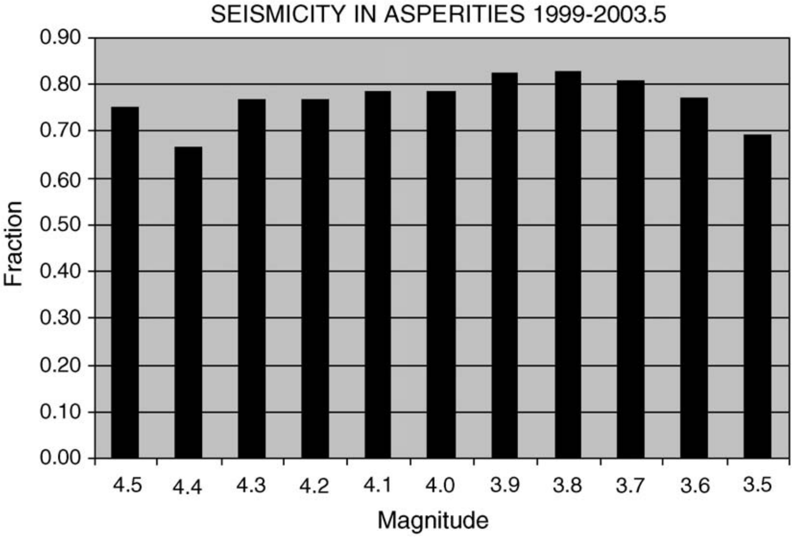

Fig. 2. Percentage of earthquakes that fall into the areas previously mapped (Wyss and Matsumura, 2002) as having anomalously low recurrence times (high probability) for main shocks, as a function of minimum magnitude for the events counted. The anomalous areas covered 12% of the study area, and 13% of the earthquakes in the total catalog fell within these areas.

areas, close to the 12% expected at random. This means that the assumption underlying Eq. (2) that the areas in question should be expected to receive an average number of hits is correct.

If one wanted simply to identify the probable locations of future medium size events ($3.5 \le M \le 4.0$) that happen relatively often, then one could also use a map of the density of these events (equivalent to an a-value with a cutoff at these magnitudes). However, in such an approach the statistics are weak and the b-value is not considered. In our hypothesis, it is important to include the b-value information, and in addition we propose that the probable locations of the larger magnitudes ($M > 4.5$), which happen too infrequently to construct a density map, can be mapped by extrapolation of the frequency–magnitude distribution which yields TL for any magnitude of interest. This is why maps of TL, or maps of the probability, extrapolated to larger magnitudes are important.

The threshold of TL, below which the values are called anomalously low should have been defined rigorously in our original paper. We took approximately $TL = 1000$ years as the limit. However, the gradient of TL near the anomalies is so steep that the results do not depend on the exact choice of the threshold. The total anomalous area changes less than 10% if we use threshold values between 800 and 1200 years. In the present paper, we simply report the results, given the threshold we selected in the first paper.

Due to the density of earthquakes available for mapping local recurrence time, the minimum diameter of anomalous patches that we can map in the study area is about 15 to 20 km. This means that asperities with 10 km diameter, or less, probably exist, but we do not know where they are.

Along the Parkfield segment of the San Andreas fault, (Schorlemmer et al., 2004a) tested rigorously the stationarity of the b-value pattern previously mapped (Wiemer and Wyss, 1997), finding that it remained constant in the most segments of the fault. In addition, (Schorlemmer et al., 2004b) found that using both parameters, a and b, to estimate future seismicity rates at a local scale is superior to the hypothesis that the parameter a alone suffices for this estimate. The Californian dataset did not contain enough ‘larger events’ that one could discerned whether or not the patches with anomalously low recurrence times received anomalously numerous hits.

(Kagan and Jackson, 2000) have advocated a different approach to estimate the local probability for earthquakes. Also extrapolating from the frequency–magnitude distribution to large events, the use they a-value as sole indictor of the seismicity level to be expected. For the b-value, they use the regional average. Recently, rigorous tests comparing our hypothesis with that of Kagan and Jackson showed that clearly the method using local b-values predicts future seismicity better than that using a regional average (Schorlemmer et al., 2004a,b). Given the fact that there exist now several studies which show that future seismicity can be well forecast by mapping local recurrence time (earthquake probability) as finely as possible (diameter 15 km in Kanto-Tokai), we suggest that this method holds promise for identifying the locations of some of the future great earthquake ruptures in Japan.

Acknowledgment

We thank NIEC for the use of the earthquake catalog and S. Wiemer for the use of his program ZMAP. We thank D. Schorlemmer for pointing out inaccuracies in the original text, and M. Krynski for advice with the probability calculation.

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