Search for reliable precursors: A case study of the seismic quiescence of the 2000 western Tottori prefecture earthquake

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[1] How to search for reliable precursors is one of the key problems of the study on earthquake forecast. In this paper a method is presented to judge whether or not a precursor is reliable. Before a potential anomaly can be nominated as a reliable precursor, it should pass or be proved by the following tests or analyses: whether or not it is an artificial anomaly, whether or not it correlates with an investigated event, whether or not it is a random anomaly. As a case study, I have investigated the reliability of seismic quiescence for an $M = 7.3$ earthquake, which occurred in the western region of Tottori prefecture, Japan, on 6 October 2000. The earthquake data (1975–2000) of the Japan Meteorological Agency (JMA) were used in this study. After analyzing the completeness of the catalog and removing aftershocks, a statistical method, which is called the RTL (region-time-length) algorithm and takes into account the information of magnitude, occurrence time and location of earthquakes, was applied to the above preprocessed earthquake data. A clear seismic quiescence anomaly was detected before the 2000 western Tottori prefecture earthquake. Close investigation indicated that the above anomaly is not due to artifacts of the selections of model parameters. After quantifying the anomaly and making statistical analysis over the whole investigated spatiotemporal domain, reasonable correlation between the above anomaly and the main shock in 2000 was recognized. The stochastic test using synthetic randomized catalogs showed the above anomaly is unlikely due to chance. Thus the above seismic quiescence anomaly before the 2000 main shock should be a significant and reliable precursor and the research method revealed in this study can enhance the reliability of precursors.

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1. Introduction

[2] Whether or not an earthquake can be predicted is still controversial [*Geller et al.*, 1997; *Wyss*, 1997; *Sykes et al.*, 1999]. One controversy is differing definitions of earthquake prediction, e.g., *Geller et al.* [1997] implicitly equated earthquake prediction with short-term prediction. Undoubtedly, the problem of earthquake prediction is difficult because the source volume inside the Earth is inaccessible to direct observation and because the most important parameter, the stress level, cannot be measured directly [*Wyss*, 2001]. Because the seismogenic process is very complicated and our understanding of its detailed physics is rather limited at the current stage, earthquake prediction research is still at an empirical stage, i.e., predictions are issued based on some precursory phenomena. Thus how to search for reliable precursors and how to evaluate earthquake prediction hypotheses are becoming more and more important in earthquake prediction research.

[3] *Rhoades and Evison* [1989] presented a methodology to evaluate time-variable earthquake hazard. They showed a general approach covering the whole hazard analysis from data selection to prediction. They focused on the evaluation of earthquake prediction hypotheses, including the probability evaluation of both valid and failed alarms. *Jackson* [1996] conducted similar work of evaluating earthquake prediction hypotheses. The earthquake prediction hypotheses test includes the following three steps: (1) comparing the number of actual earthquakes to the number predicted, (2) comparing the likelihood score of actual earthquakes to the predicted distribution, and (3) comparing the likelihood ratio to that of a null hypothesis.

[4] Besides the above work, scientists are continuing to find valuable precursors for earthquake prediction. Among various precursory phenomena, the analysis of seismicity changes plays an important role in earthquake prediction of intermediate-term because seismicity precursors have been tested for a long period of time and some positive examples have been obtained [e.g., *Wyss and Habermann*, 1988; *Wyss and Martirosyan*, 1998; *Wyss and Matsumura*, 2002; *Kossobokov and Keilis-Borok*, 1990; *Huang and Nagao*, 2002; *Huang et al.*, 2001,

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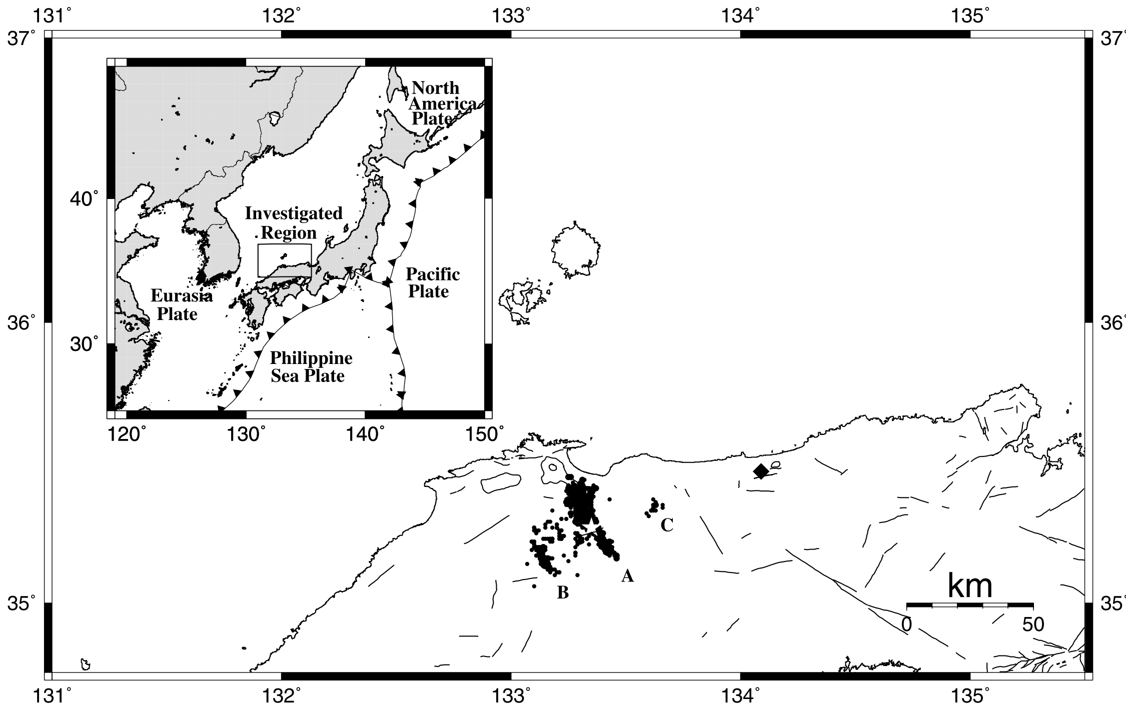

Figure 1. Distribution of the epicenter (star) and the aftershocks (circles) of the $M = 7.3$ western Tottori prefecture earthquake on 6 October 2000 in the investigated region. The epicenter of the 1943 $M = 7.2$ Tottori earthquake is also shown by a black diamond. The bold lines indicate the active faults [*Research Group for Active Faults of Japan*, 1991]. Tectonic setting of the Japan Island is given in the upper left panel.

2002]. The seismicity analysis include the M8 method [e.g., *Kossobokov et al.*, 1997], the Zmap method [e.g., *Wiemer and Wyss*, 1994], the accelerating moment release (AMR) method [e.g., *Jaume and Sykes*, 1999], the Region-Time-Length (RTL) method [e.g., *Sobolev and Tyupkin*, 1997; *Huang et al.*, 2001] (see section 2.1 for details), and so on.

[5] Some recent studies in Russia, Italy, Japan, and Turkey indicate that the RTL algorithm is a useful tool to reveal seismicity precursors for strong earthquakes [*Sobolev and Tyupkin*, 1997, 1999; *Sobolev et al.*, 2002; *Di Giovambattista and Tyupkin*, 1999, 2001; *Huang*, 2004; *Huang and Sobolev*, 2001, 2002; *Huang et al.*, 2001, 2002].

[6] A strong earthquake with $M = 7.3$ struck the western region of Tottori prefecture, Japan, on 6 October 2000 (the main shock is marked by a white star and the aftershocks are marked by black circles in Figure 1). The earthquake data are from the catalog of the Japan Meteorological Agency (JMA). The preliminary results of applying the RTL algorithm to the above earthquake indicated that a seismic quiescence appeared before the main shock [*Huang and Nagao*, 2002].

[7] Although many precursory phenomena have been reported, only a few are being tested quantitatively [e.g., *Kossobokov et al.*, 1997]. Concerning the newly developed RTL algorithm, the previous study showed some positive results of seismicity precursors in various tectonic regions. However, no rigorous quantitative test and evaluation have been done in previous work, including the case of the 2000 western Tottori prefecture earthquake.

[8] Motivated by the work of earthquake prediction hypotheses test, this study presents a research procedure (see section 2.3) which focuses on the detailed evaluation of the reliability of earthquake precursors (including not only stochastic test but also time and space domain correlation analysis) and shows its application in the case study of the Tottori earthquake, which was not involved in the work of *Huang and Nagao* [2002]. It should be mentioned that although the RTL method has been applied to several large earthquakes worldwide and some positive results have been obtained, we also realized there are some problems with this method. Thus this study discusses the possible problems of the RTL method, gives a refinement of the method, and demonstrates that the refined approach, as well as the detailed reliability analysis, can lead to a more convincing study on seismicity changes.

2. Methods

[9] The RTL algorithm takes into account the information of magnitude, occurrence time, and place of earthquakes. Details of the RTL algorithm will be introduced in section 2.1.

[10] Before applying the RTL algorithm, aftershocks are eliminated from the earthquake catalog. There are several kinds of aftershock identification methods, such as hand procedure, window method, and cluster method. Because it

is assumed that aftershock sequences are finite, aftershocks concentrate in space and time but are mixed with background seismicity; thus error-free aftershock identification is not available at the current stage. However, scientists are continuing to look for a more appropriate declustering method with less error, e.g., *Molchan and Dmitrieva* [1992] proposed an improved window method, which is called the local intensity ratio (LIR) method with its validity tested by *Molchan and Dmitrieva* [1992] and *Smirnov* [1998]. *Zhuang et al.* [2002, 2004] presented a method to classify the earthquakes in a given catalog into different clusters stochastically based on a space-time version of the epidemic-type aftershock sequence (ETAS) model [*Ogata*, 1998]. Comparison of the results among various aftershock identification methods would be interesting but is out of the scope of this paper.

[11] In this study the algorithm developed by *Molchan and Dmitrieva* [1992] was adopted to identify aftershocks. The basic assumption is that aftershocks localized in space and time and are mixed with background events. Because larger space-time aftershock windows will lead to false aftershocks, while smaller ones will lose true aftershocks, a trade-off between these two kinds of errors would be a natural basis for rigorous formulation of aftershock identification. The aftershock identification problem can be reduced to finding the rule of minimizing the loss function which depends on the above two kinds of errors.

[12] The principle of the LIR method, which is an improved window method, is based on the modeling of aftershock and background intensities and on their ratio. The determination of main shocks is based on the magnitude ordering: the largest event in the catalog is always considered as a main shock. The window size is determined by fitting an exponential law to the main shock's productivity, the Omori formula [*Omori*, 1900] to the occurrence frequencies of the aftershocks, and a bell-shaped distribution to the aftershock locations. The following a priori parameters are chosen for the first iteration of the above estimation: circular scattering around the main shock, average number of aftershocks for a certain main shock follows an exponential relation, the parameter p in the Omori law is fixed (e.g., $p = p_0 = 1.1$), until there are sufficient preliminary aftershocks (e.g., $n_A > 10$) for the estimation. Once the window size is determined, aftershocks can be identified and all the a priori parameters can be revised after each iteration. Such a separation can be used to get a better estimate of the window size again. Thus aftershocks can be identified by the above iteration steps.

[13] Because earthquakes may not be reported homogeneously due to the inhomogeneous distribution of seismic stations, the completeness of the earthquake catalog is estimated based on the power law of frequency-magnitude [*Smirnov*, 1998].

2.1. RTL Algorithm

[14] In the RTL algorithm, it is assumed that each prior event has some influence on the main event under investigation and its influence weight is varied. The weight of an event is greater when it is larger in magnitude or is closer to the eventual epicenter (x, y, z) or the occurrence time (t) of the earthquake in question. The above idea can be described by the following three functions: epicentral distance, $R(x, y, z, t)$, time, $T(x, y, z, t)$ and rupture length, $L(x, y, z, t)$,

$$\begin{aligned}
R(x,y,z,t) &= \left[\sum_i \exp\left(-\frac{r_i}{r_0}\right) I(r_i \le 2r_0) I(t - t_i \le 2t_0) \cdot I(d_i \le d_0) I(M_i \ge M_{\min})\right] - R_{bk}(x,y,z,t) \\
T(x,y,z,t) &= \left[\sum_i \exp\left(-\frac{t-t_i}{t_0}\right) I(r_i \le 2r_0) I(t - t_i \le 2t_0) \cdot I(d_i \le d_0) I(M_i \ge M_{\min})\right] - T_{bk}(x,y,z,t) \qquad (1) \\
L(x,y,z,t) &= \left[\sum_i \left(\frac{l_i}{r_i}\right) I(r_i \le 2r_0) I(t - t_i \le 2t_0) I(d_i \le d_0) \cdot I(M_i \ge M_{\min})\right] - L_{bk}(x,y,z,t)
\end{aligned}$$

where $I(\Omega)$ is a logical function defined by

$$I(\Omega) = \begin{cases} 1, & \Omega \quad \textit{is} \quad \textit{true} \\ 0, & \textit{otherwise} \end{cases}$$

l_i rupture dimension (a function of magnitude M_i);
t_i occurrence time of the ith earthquake;
r_i distance from the position (x, y, z) to the epicenter of the ith event;
r_0 and t_0 characteristic distance and time span, respectively;
d_i focal depth of the ith event;
d_0 cutoff depth;
$M_{\min}$ cutoff magnitude ensuring the completeness of the earthquake catalog.

$R_{bk}(x, y, z, t)$, $T_{bk}(x, y, z, t)$, and $L_{bk}(x, y, z, t)$ are the trends (background values) of $R(x, y, z, t)$, $T(x, y, z, t)$, and $L(x, y, z, t)$, respectively. In this study, a linear trend model is adopted, which is estimated by the least square method.

[22] $R(x, y, z, t)$, $T(x, y, z, t)$, and $L(x, y, z, t)$ are dimensionless functions, describing the influence weights of location, occurrence time, and magnitude of prior earthquakes on the investigated main event. They can be further normalized by their standard deviations, σ_R, σ_T, and σ_L, respectively, after removing their trends. The RTL parameter is defined as the product of the above three functions and is in units of the standard deviation, $\sigma = \sigma_R\sigma_T\sigma_L$. Thus a decrease of negative RTL parameter means a decrease of seismicity compared to the background level around the study place and time, i.e., seismic quiescence can be quantified using the RTL parameter. A positive RTL represents a higher seismicity compared to the background level.

[23] In this study I calculate RTL at time steps of 10 days. Because the RTL value at time t is calculated based on the earthquakes in the time window $[(t - T_{\max}), t]$, it is not possible to calculate the RTL value for times before $t_{cs} + T_{\max}$, where t_{cs} is the start time of the catalogue in use.

2.2. Q Parameter

[24] In this study I employ a newly developed parameter $Q(x, y, z, t_A, t_B)$ to quantify the seismic quiescence at a

certain position [*Huang et al.*, 2002]. The parameter $Q(x, y, z, t_A, t_B)$ is an average of the RTL values over some time window $[t_A, t_B]$. It can be defined as

$$Q(x, y, z, t_A, t_B) = \frac{1}{m}\sum_{j=1}^{m} RTL\big(x, y, z, t_j\big), \qquad (2)$$

where (x, y, z) is the investigated position; $[t_A, t_B]$ is the investigated time window; t_j is the time in the window $[t_A, t_B]$; $RTL(x, y, z, t_j)$ is the RTL parameter at the position of (x, y, z) and at the time of t_j, which is calculated as the product of the three functions in equation (1) using the earthquakes in a cylindrical volume; m is the number of data points of RTL available in $[t_A, t_B]$. Thus the Q-parameter describes the spatial distribution of seismic quiescence as a function of position. In this study the RTL parameter is calculated for steps of 10 days, so m = integer $[(t_B - t_A)$ days/10 days]; the Q-parameter is calculated at steps of 0.1° for longitude and latitude.

2.3. Research Procedure

[25] The research procedure of searching for reliable precursors (as a case study of the RTL algorithm) includes the following steps.

[26] 1. An appropriate preprocess of data is required before using some algorithm.

[27] 2. Choose an algorithm as the model method of extracting precursors and apply it to the above preprocessed data. In this study, the RTL algorithm is adopted as the model method.

[28] 3. Judge whether or not a clear defined anomaly is "detected" using the applied model method.

[29] 4. If no any anomaly is detected, move to step 9.

[30] 5. If an anomaly is revealed, judge whether the anomaly is an artificial one or not. If yes, move to step 9.

[31] 6. Judge whether or not the above anomaly is an earthquake-related one in time and space domains. For example, after defining an anomaly quantitatively, one can make statistical analysis over the whole investigated spatiotemporal domain to examine the correlation between an anomaly and an earthquake. If not, move to step 9.

[32] 7. Judge whether or not the above anomaly is a random one. The stochastic test (one can find more details in section 4.3) would be an effective tool of identifying a random anomaly. If yes, move to step 9.

[33] 8. Only after the anomaly passed all the tests of steps 5–7, one can conclude that the anomaly is significant and reliable.

[34] 9. No reliable anomaly.

[35] 10. End of the evaluation.

[36] If no anomaly has been revealed by the selected algorithm or an anomaly failed in any of the above tests (steps 5–7), it may lead to the conclusion that no reliable anomaly was obtained using the chosen algorithm.

3. A Case Study

3.1. Western Tottori Prefecture Earthquake of 2000

[37] A strong earthquake with $M = 7.3$ struck the western region of Tottori prefecture, Japan, on 6 October 2000 (Figure 1). This was an inland shallow earthquake with focal depth of 11 km. Although no deaths were reported, nearly 100 people were injured and more than 1500 houses were destroyed.

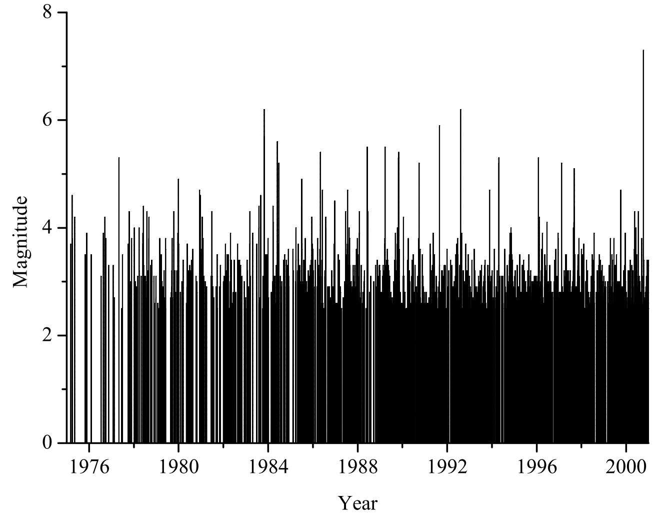

Figure 2. Magnitude-time plot of earthquakes with $M \geq 2.5$ in the investigated region.

[38] The upper left panel in Figure 1 shows the tectonic background of Japan. The Tottori prefecture is in the southwestern region of Japan. In the western Tottori region, northwest-southeast tectonic loading is dominant due to the subduction of both the Pacific plate and the Philippine Sea plate beneath the Eurasian plate. This is the typical stress environment in the southwestern Japan. Thus north-south or east-west trending strike-slip faults are commonly observed (active faults are marked by the bold lines in Figure 1 [see also *Research Group for Active Faults of Japan*, 1991]).

[39] On 10 September 1943, an $M = 7.2$ earthquake (marked by the black diamond in Figure 1) occurred in the western Tottori region, about 80 km to the northeast of the epicenter of the 2000 western Tottori earthquake.

[40] Figure 2 shows the magnitude-time plot of earthquakes with $M \geq 2.5$ in the investigated region. Some earthquake swarms occurred around (about 10 km) the epicenter of the 2000 Tottori event in 1989, 1990, and 1997, including several moderate earthquakes with magnitude $M > 5$. The focal mechanism of these moderate events showed a strike-slip fault type with nodal planes striking northeast and northwest.

[41] The 2000 western Tottori prefecture earthquake has almost the same focal mechanism as those of the above moderate earthquakes. *Zhao et al.* [2004] applied seismic tomography to the arrival time data generated by the 2000 Tottori aftershocks and other local microearthquakes recorded by the dense High-Sensitivity Seismic Network (Hi-net) to determine a high-resolution three-dimensional (3-D) crustal structure in the Tottori earthquake region. Prominent crustal heterogeneities are detected in the Tottori hypocenter, which may have influenced the nucleation and rupture process of the earthquake.

[42] Figure 1 shows the distribution of aftershocks ($M \geq 2$) identified by the algorithm developed by *Molchan and Dmitrieva* [1992]. The main aftershock distribution (indicated by A in Figure 1) was elongated in the northwest-southeast direction, indicating left-lateral faulting on a

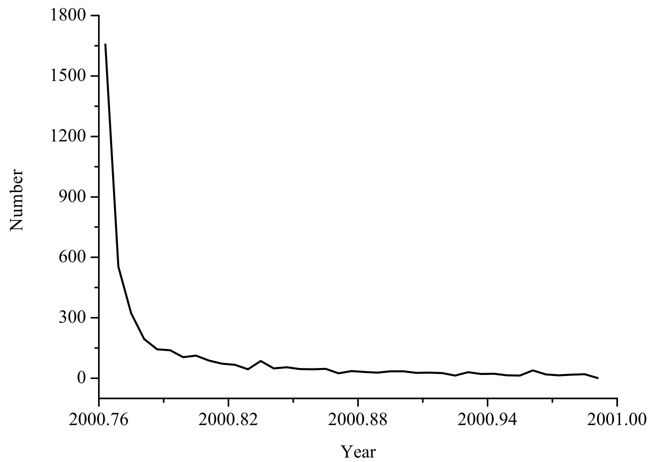

Figure 3. Temporal variation of the aftershocks ($M \geq 2$) of the M = 7.3 western Tottori prefecture earthquake on 6 October 2000.

northwest-southeast striking fault. The earthquake activity in the regions of B and C (Figure 1) are probably triggered seismicity, which started about 2.5 days after the main shock. As discussed by *Enescu and Ito* [2002], it would be appropriate to treat the earthquakes in B and C as aftershocks of the western Tottori earthquake. Figure 3 shows the temporal variation of the aftershocks of the Tottori earthquake. The number of the total aftershocks with $M \geq 2$ is 4388. An exponential decay pattern of aftershocks is recognized, with a decay time of about 84 days.

3.2. Seismic Quiescence of the 2000 Western Tottori Prefecture Earthquake

[43] As mentioned previously, some preprocess (e.g., aftershock elimination and completeness analysis) of earthquake catalogs should be done before applying the model method (step 1 of the research procedure in section 2.3). In this study I eliminated aftershocks from the JMA earthquake catalog on the basis of the algorithm developed by *Molchan and Dmitrieva* [1992] and estimated the completeness of the earthquake catalog based on the power law of frequency-magnitude [*Smirnov*, 1998].

[44] Because the manual operation of data in JMA earthquake catalog has been replaced by a computer operation since 1961, the earthquake catalog (final report of JMA) from January 1961 to December 2000 was chosen in this study. On the basis of the model parameters adopted in this study, I estimated the cutoff magnitude M_{min} in a circular zone with a radius of R_{max} = 100 km at the epicenter of the Tottori earthquake. The M_{min} tends to decrease with time due to the improvement of seismological network and M_{min} = 2.5 is valid since 1975 for the region around the epicenter (Figure 4a). This can be also confirmed by Figure 4b, which shows the magnitude plot of the main shocks in the investigated region during 1975–2000. The spatial distribution of M_{min} also showed that M_{min} = 2.5 is valid for a broad region around the epicenter. Thus a threshold magnitude of M_{min} = 2.5 for the JMA catalog during January 1975 to December 2000 was adopted for investigating the seismicity changes in this study. The investigated region with longitude between 131.00°E and 135.50°E and latitude between 34.75°N and 37.00°N (Figure 1) was chosen for the following reasons: (1) the completeness of the JMA earthquake catalog can be ensured for a threshold magnitude of 2.5, and (2) the 2000 Tottori earthquake is the only large event with $M \geq 6.5$ in this region during January 1975 to December 2000.

[45] In this study, the RTL algorithm was adopted as the model method of investigating the seismicity changes of the 2000 western Tottori prefecture earthquake (step 2 of the research procedure in section 2.3). The estimation of the rupture dimension l_{i} of the western Tottori prefecture earthquake is on the basis of the empirical relation of log l_i (km) = 0.5 M_i − 1.8 [*Kasahara*, 1981]. Because the reports indicated that seismicity quiescence tends to occur around the rupture zone with a duration of the order of 1 year, the rupture dimension of the 2000 Tottori earthquake is several tens kilometers, and the crustal seismicity is dominant in the western Tottori region, taking into account the previous studies of applying the RTL algorithm to the earthquakes in Russia, Japan, and Turkey

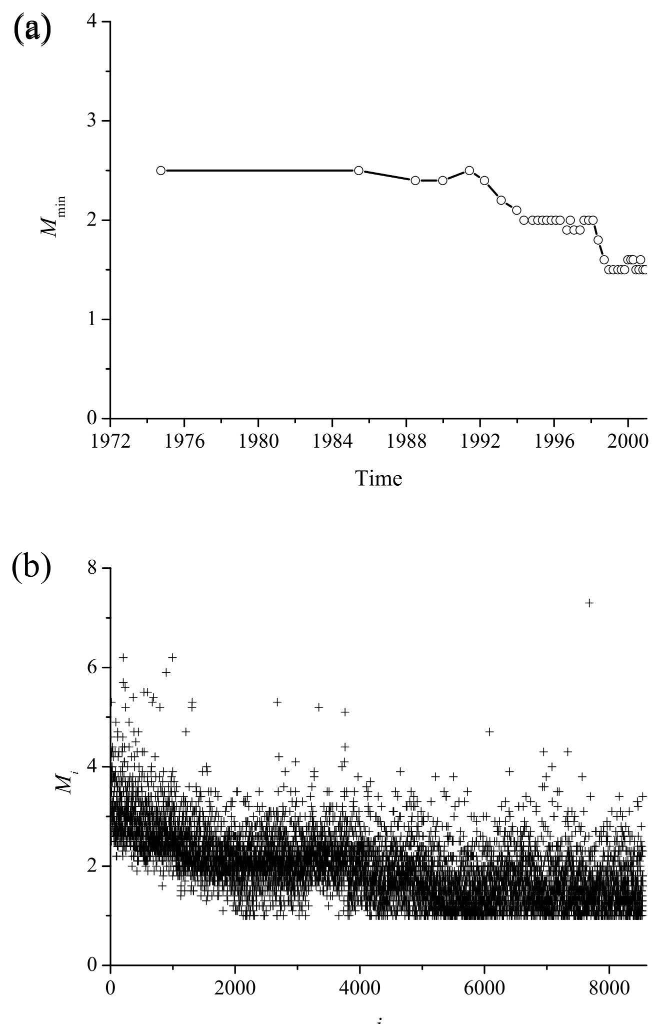

Figure 4. (a) Temporal variation of the cut-off magnitude M_{min} in a circular zone with a radius of R_{max} = 100 km at the epicenter of the Tottori earthquake. (b) Magnitude plot of the main shocks in the investigated region during 1975–2000. Horizontal axis indicates the ith main shock and vertical axis indicates its magnitude.

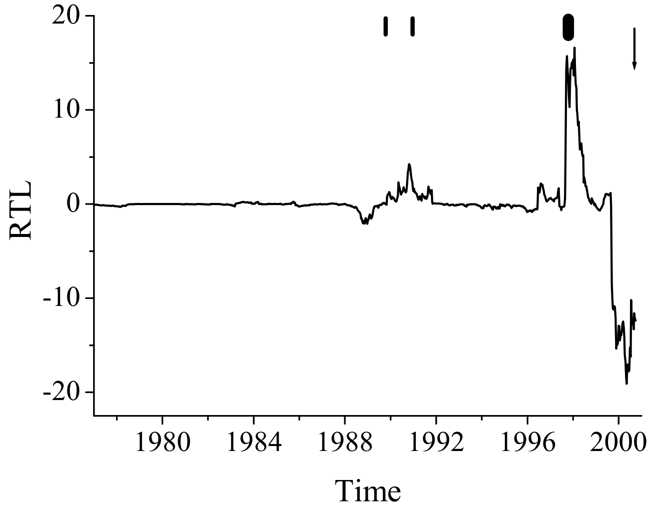

Figure 5. Temporal variation of the RTL parameter at the epicenter of the M = 7.3 western Tottori prefecture earthquake. There is a significant quiescence during 1999–2000. The arrow shows the occurrence time of the main shock in 2000. The bold lines indicate the earthquake swarms in 1989, 1990, and 1997, respectively.

[e.g., *Sobolev and Tyupkin*, 1997; *Huang et al.*, 2001, 2002], I adopted the following model parameters in this study: the characteristic distance r_0 = 50 km, i.e., the threshold distance $R_{max} = 2r_0$ = 100 km; the characteristic time span t_0 = 1 year, i.e., the threshold time span $T_{max} = 2t_0$ = 2 years; the focal depth $d_i \leq d_0$ = 30 km. The possible influence of the selections of the above model parameters will be discussed in section 4.1.

[46] At step 3 of the research procedure in section 2.3, one needs to judge whether or not an anomaly can be detected by the model method. Figure 5 gives the temporal variation of the RTL parameter at the epicenter of the M = 7.3 western Tottori prefecture earthquake. A seismic quiescence started in 1999 and developed until May 2000. Then there is a recovery stage from the quiescence pattern to the background seismicity. The positive RTL anomalies may relate to the earthquake swarms occurred in 1989, 1990, and 1997, which were also marked by the bold lines in Figure 5 (see more details in section 4.4.).

[47] Besides the temporal variation, the spatial distribution is another criterion of quantifying an anomaly of seismic quiescence. In this study the spatial distribution of seismic quiescence was quantified by the Q parameter, which was defined by equation (2). After changing the calculated position at a step of 0.1° respectively along longitude and latitude in the investigated region, one can obtain the spatial distribution of seismicity quiescence. The obtained result is not sensitive to the selection of the calculated grid. In order to emphasize the temporal variation of the seismic quiescence map, the Q parameter in a time window [t_A, t_B] of 0.5 years was adopted in this study. Thus one can obtain the snapshot of the spatial distribution of seismic quiescence. It should be mentioned that the spatial distribution of the Q parameter is not sensitive to the selection of the time window in a reasonable range, e.g., similar results were obtained for a time window of 1 year.

[48] Figure 6 shows the spatial distribution of seismic quiescence quantified by the Q parameter during December 1999 to May 2000, when there was a clear quiescence stage (Figure 5). This seismic quiescence anomaly appeared in a broad area around the epicenter of the 2000 Tottori earthquake. The maximum linear size of this anomalous zone is

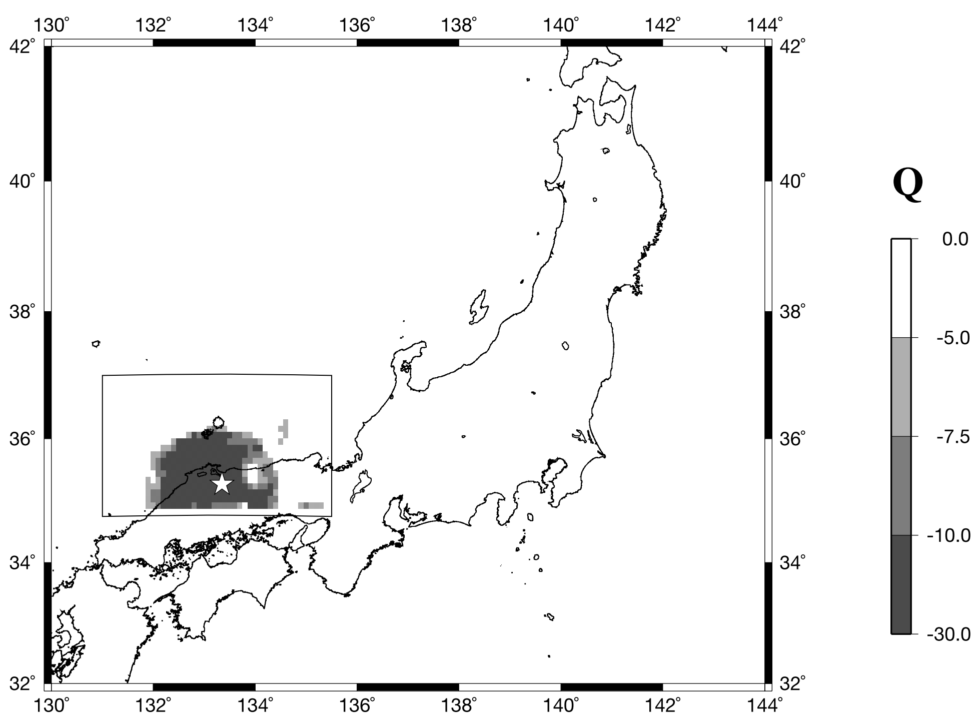

Figure 6. Spatial distribution of seismic quiescence quantified by the Q map during December 1999 to May 2000. The star indicates the epicenter of the M = 7.3 Tottori earthquake.

about 200 km, several times larger than the rupture length of the main shock. Thus there is a seismic quiescence anomaly in both space and time domains.

4. Results and Discussions

4.1. A Precursor or an Artifact

[49] Steps 1–3 of the research procedure in section 2.3 indicated that a seismic quiescence anomaly was detected using the model method in this study (Figures 5–6). According to the research procedure, step 5 should be done next, i.e., it is necessary to judge whether this anomaly is an artificial one or not.

[50] Because there are several model parameters in calculating the RTL parameters, if the RTL parameters are sensitive to the selections of the model parameters, some artificial effects may occur. Thus step 5 should include the evaluation of the possible effects of selections of the model parameters on the RTL parameters.

[51] In order to investigate the possible effects of the cutoff focal depth on the RTL parameters, I calculated the temporal variation of the RTL parameters at the epicenter of the Tottori earthquake after removing the cutoff focal depth and found quite similar variations to the previous result (Figure 5). I obtained almost the same results after replacing the cutoff focal depth by 20 km and 100 km (Figure 7), respectively. A statistical test indicated that significant correlation exists between any two of the above cases at a significance level of 0.05 [*Bendat and Piersol*, 2000].

[52] Besides the cutoff focal depth, it is necessary to investigate the possible influence of other model parameters such as the characteristic distance r_0 and the characteristic time span t_0. I obtained quite similar results in all cases of different r_0 and t_0 (Figure 7). Table 1 gives the result of correlation of RTL values between different model parameters of characteristic distance r_0 and time span t_0. Significant correlation was proved by the statistical test for all above cases at a significance level of 0.05 [*Bendat and Piersol*, 2000].

[53] We introduced the upper cutoff magnitude $M_{\max}$ in one previous study [*Huang and Sobolev*, 2001] because there would be different relations of frequency-magnitude for small and large earthquakes [e.g., *Hamilton and McCloskey*, 1997; *Ikeya and Huang*, 1997]. However, there is a potential danger that artificial changes can be generated either by heterogeneity of earthquake reporting or by introducing two cutoff magnitudes $M_{\min}$ and $M_{\max}$ [*Habermann*, 1987, 1991; *Wyss*, 1991; *Zuniga and Wyss*, 1995]. In order to investigate whether or not our previous results are due to an artificial effect, we excluded the maximum threshold magnitude $M_{\max}$ and proved that such approach does not lead to artificial effect on the results [*Huang and Sobolev*, 2002]. Because the RTL is a combination of the three parameters of earthquakes, the RTL parameter is not sensitive to the selection of earthquake magnitude, as long as the number of events in the investigated region is sufficient for statistical analysis. I made the similar investigation and found that the same conclusion holds for the case of the Tottori earthquake on 6 October 2000. Thus one can conclude that the quiescence anomaly, which appeared at the Tottori earthquake epicenter in early 2000, is unlikely an artifact due to the selection of model parameters.

4.2. Correlation of a Precursor and an Event

[54] Step 6 of the research procedure in section 2.3 is to evaluate the possible correlation between a precursor and an event. This can be done by making statistical analysis of the defined anomalies over the whole investigated spatiotemporal domain. Figure 5 shows that a seismic quiescence anomaly started in 1999 and developed until May 2000. Figure 6 indicates that the seismic quiescence anomaly of the 2000 Tottori earthquake appeared in a broad area (with a maximum linear size of about 200 km) around the epicenter during December 1999 to May 2000. Figures 8a–8e gives the 6-month snapshot of spatial distribution of seismic quiescence from July 1998 to December 2000. There was no anomalous quiescence around the Tottori earthquake epicenter during July 1998 to June 1999 (Figures 8a and 8b). Quiescence anomaly started around the epicenter during July to December 1999 (Figure 8c) and developed during January to June 2000 (Figure 8d). Finally, the above quiescence anomaly around the epicenter tended to disappear during July to December 2000 (Figure 8e). Thus the temporal and spatial evolution of quiescence pattern seems to have a reasonable correlation at least in spatiotemporal domain with the preparation of the Tottori earthquake.

4.3. Stochastic Test of a Precursor

[55] If similar quiescence anomalies occur frequently at locations in space and time where no large earthquakes exist, the temporal and spatial correlation of the quiescence (e.g., Figure 5) with the 2000 Tottori earthquake may not have any significance [*Wyss and Martirosyan*, 1998]. Therefore besides the analyses of artificial effects and spatiotemporal correlation (steps 5–6 of the research procedure in section 2.3), it is necessary to evaluate whether or not the detected anomaly is a random one. As shown in step 7 of the research procedure in section 2.3, the stochastic test would be an effective tool of identifying a random anomaly. Thus step 7 may further enhance the reliability of the anomaly. In order to make quantitative analysis, I define following criteria of an anomaly alarm for the seismic quiescence: (1) minimum RTL parameter $\leq -10\sigma$, and (2) duration time ≥ 0.7 year, where duration time is defined as the interval with RTL parameter $\leq -2\sigma$.

[56] Algorithm S gives the stochastic test in the following steps.

[57] 1. Give a fixed n (e.g., $n = 1000$ in this case study) of the calculated times (i.e., the total number of random catalogs) for stochastic test; set the number of anomalies $m = 0$ and the count number $i = 0$.

[58] 2. Generate a random catalog.

[59] 3. Calculate the temporal variation of the RTL parameters at a certain position (e.g., the epicenter of the investigated earthquake) for the above random catalog. The same model parameters used in the calculations for the real catalog are adopted in calculating the RTL curve for each random catalog.

[60] 4. Evaluate whether an anomaly occurred or not in the above the RTL curve. If no any anomaly occurred, move to step 6.

[61] 5. If an anomaly occurred, $m = m + 1$.

[62] 6. Then $i = i + 1$.

[63] 7. If $i < n$, move to step 2.

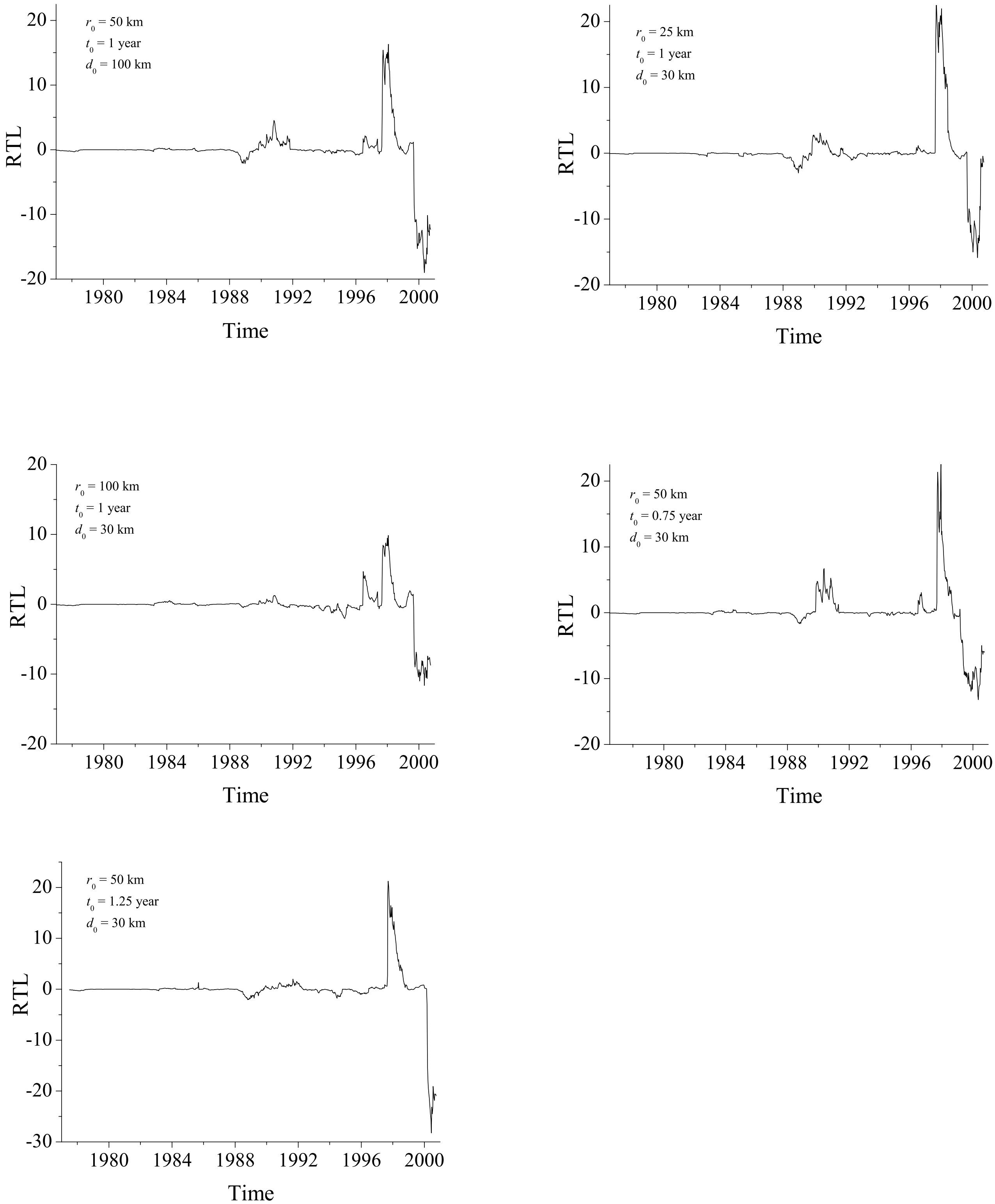

Figure 7. Temporal variation of the RTL parameter at the epicenter of the M = 7.3 Tottori earthquake for different model parameters r_0, t_0, and d_0.

[64] 8. Calculate the probability (P) of an RTL anomaly for the above fixed number (n) of earthquake catalogs by $P = m/n$.

[65] 9. End.

[66] There are several methods of randomizing an earthquake catalog in step S2. For example, (1) randomly permute one or two components of the occurrence time, the epicenter, and the magnitude, with equal probability for each possible permutation; (2) generate the occurrence time by randomizing the time in the study time window with equal probability; (3) generate the epicenter by randomizing the epicenter in the study region with equal probability;

Table 1. Correlation of RTL Values Among Different Model Parameters of Threshold Distance R_{max} and Time Span T_{max} ($R_{max} = 2r_0$ and $T_{max} = 2t_0$)

Case		
A	B	Correlation Coefficient
$d \leq 30$ km, $r_0 = 50$ km, $t_0 = 1$ year, $M \geq 2.5$	$r_0 = 25$ km	0.914
	$r_0 = 100$ km	0.971
	$t_0 = 0.75$ year	0.674
	$t_0 = 1.25$ years	0.692

(4) generate the magnitude according to the power law of frequency-magnitude (e.g., practically, the magnitude is generated in a random way according to the occurrence probability of each magnitude (taking a step of 0.1) calculated from the real earthquake catalog. For simplicity, the total number of earthquakes in a random catalog is assumed to be the same as that in the real catalog in this study). A random catalog can be generated either by each of the above methods or a combination of the above methods. In this study, a combination of the above methods of (2) and (3) is adopted to generate random catalogs.

[67] After applying the above algorithm S to the 2000 western Tottori prefecture earthquake, I obtained the anomaly alarms in the whole investigated space and time. Figure 9 gives all anomaly alarms by circles in space. The black star represents the location of the 2000 Tottori earthquake in space (133.35°E, 35.27°N). The anomaly alarm group has an average location at (133.28 ± 0.68°E, 35.36 ± 0.37°N). Figure 10 shows all anomaly alarms by lines in time domain. The length of a line represents the amplitude of a seismic quiescence anomaly (minimum RTL parameter). The black star represents the occurrence time of the 2000 Tottori earthquake at 2000.76 (6 October 2000). There is an anomaly alarm group with an average start time at 2000.29 ± 0.24 (16 April 2000 ± 88 days) and an average duration of 1.05 ± 0.13 year. This anomaly group has an average minimum RTL parameter of −17.81 with a deviation of 4.19. Figures 9 and 10 indicated that the detected anomaly alarm group is the only alarm group in the whole investigated space and time.

[68] Table 2 summarizes the results of the above stochastic test. Because the quiescence anomaly of the real earthquake catalog had a minimum RTL of −19.10 at the epicenter (133.35°E, 35.27°N) on 8 May 2000 (Figure 5), the probability of generating the detected RTL anomaly by random catalogs is 0.01. Thus the above RTL anomaly is unlikely to be a random anomaly.

[69] It should be mentioned that although different randomization methods in the step 2 of the above algorithm S may affect the *R*, *T*, and *L* functions in equation (1), what concerned in the algorithm S is the appearance probability of the RTL anomalies rather than the *R*, *T*, and *L* functions themselves and the variation details of the RTL curve. In fact, I changed the number of random catalogs (n) in step 1 from 100 to 1000 for the above algorithm S and the statistical analysis did not show any significant different

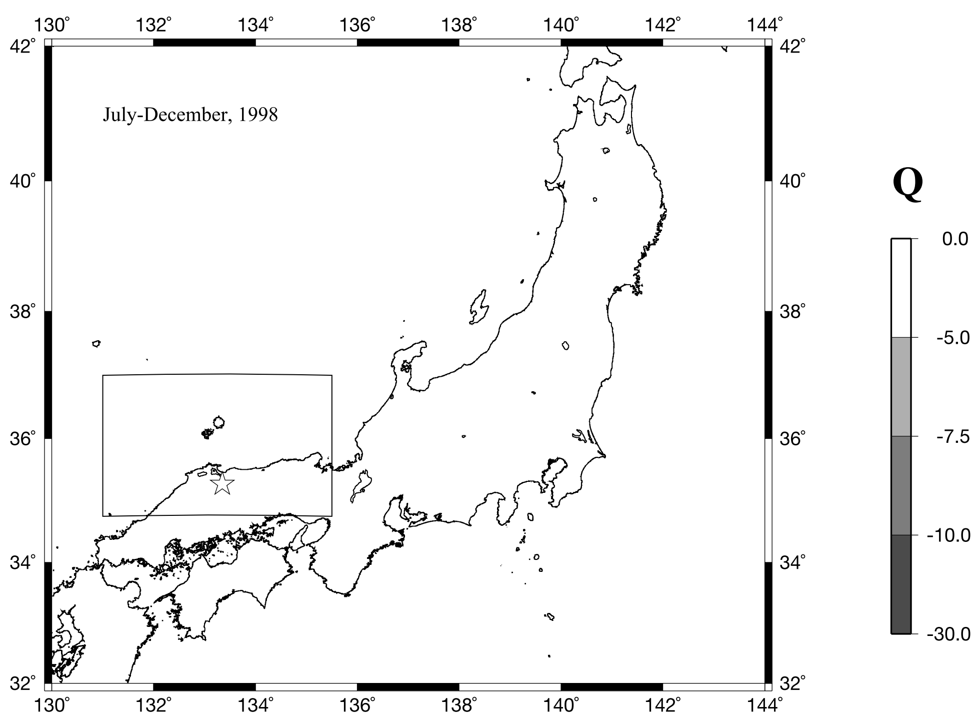

Figure 8a. The 6-month snapshot of spatial distribution of seismic quiescence in the investigated region from July to December 1998.

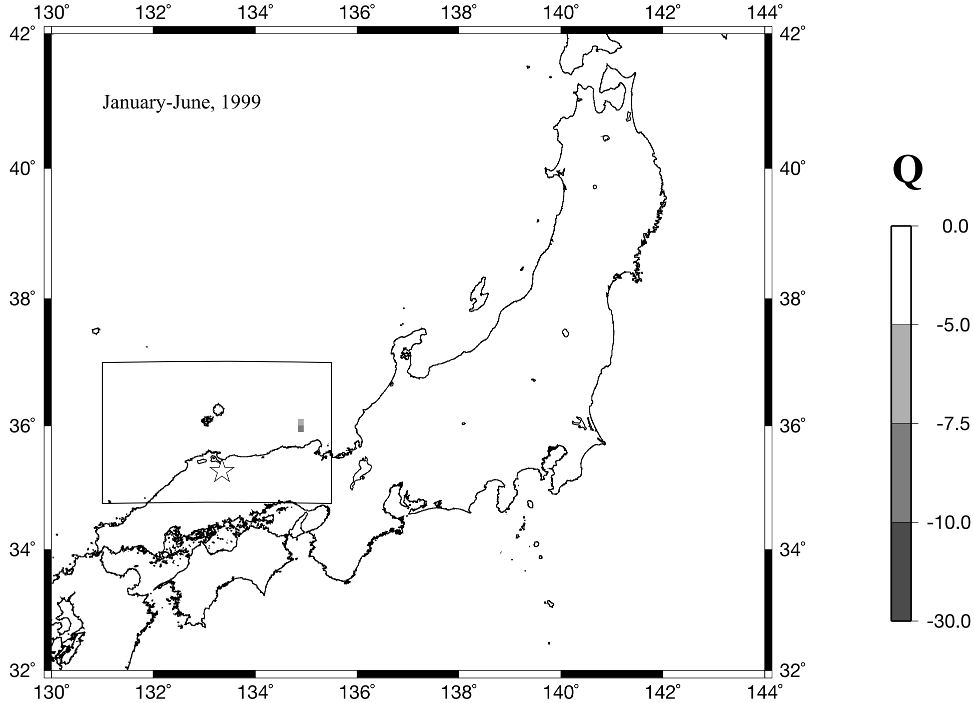

Figure 8b. The 6-month snapshot of spatial distribution of seismic quiescence in the investigated region from January to June 1999.

for the results of stochastic test. The same conclusion also holds for the different randomization of earthquake catalogs in step S2, which is a combination of the above randomization methods of (2), (3), and (4).

[70] Because the RTL anomaly detected before the 2000 western Tottori prefecture earthquake has passed the tests in all steps 5–7 of the research procedure in section 2.3, it would be reasonable to conclude that this anomaly is

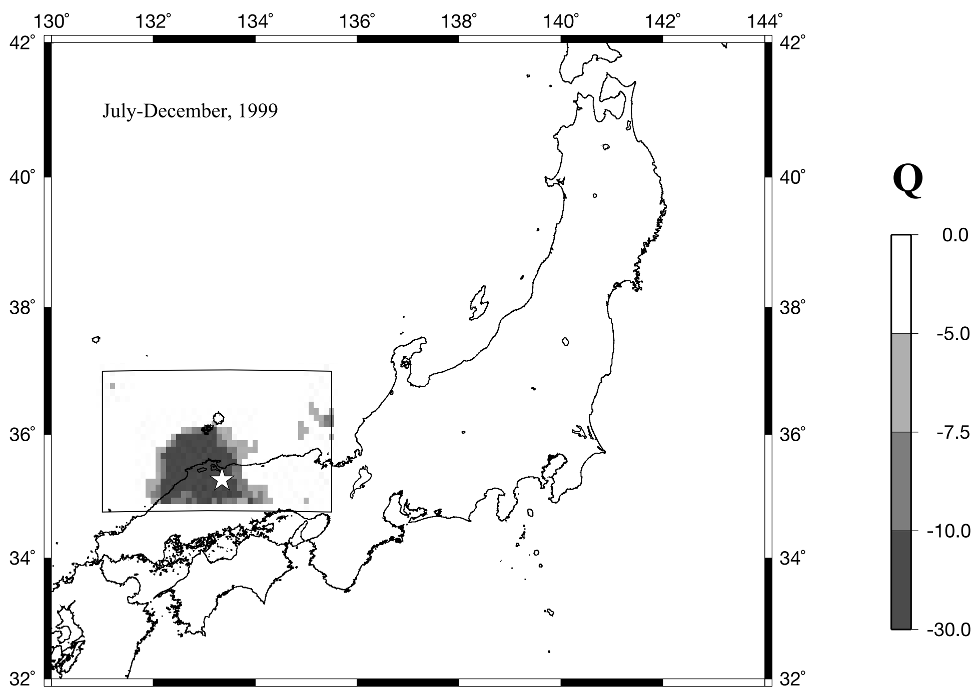

Figure 8c. The 6-month snapshot of spatial distribution of seismic quiescence in the investigated region from July to December 1999.

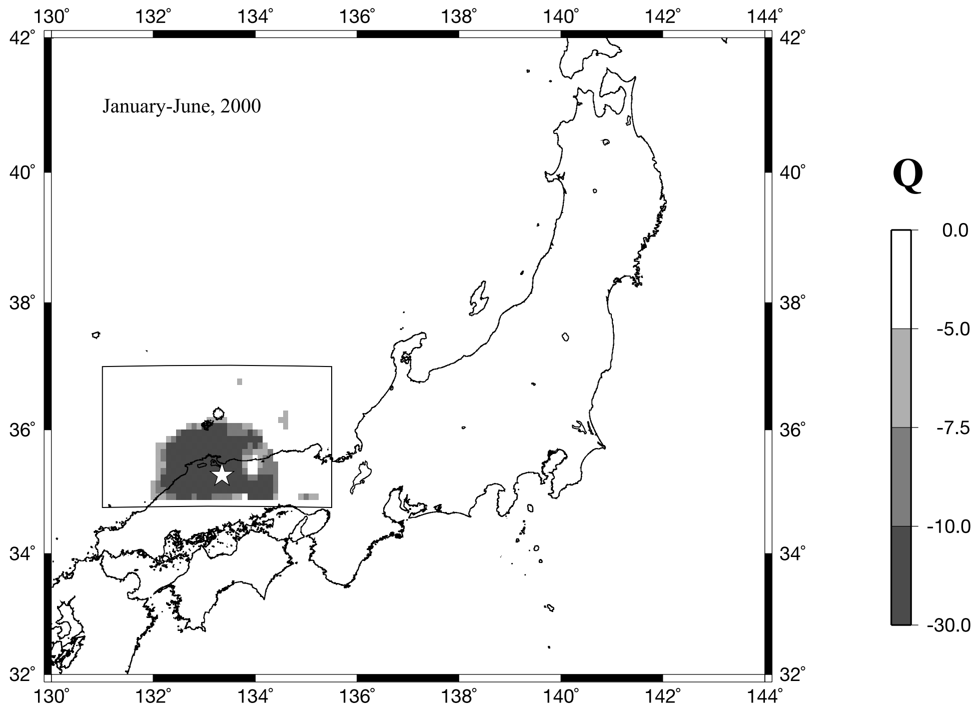

Figure 8d. The 6-month snapshot of spatial distribution of seismic quiescence in the investigated region from January to June 2000.

significant and has correlation in space and time with the 2000 Tottori earthquake.

4.4. Earthquake Swarms in 1989, 1990, and 1997

[71] It should be mentioned that besides the quiescence anomaly during 1999–2000, there are also large positive disturbances in 1990 and around 1998 (Figure 5). In fact, there were earthquake swarms in the region around the epicenter of the western Tottori prefecture earthquake during the following periods: 27 October to 30 November 1989, 21 November to 31 December 1990, and 23 August to 31 December 1997. A series of moderate sized earthquakes occurred in the aftershock zone of the 2000 $M = 7.3$ Tottori earthquake in 1989 and 1990, respectively. Figure 11a

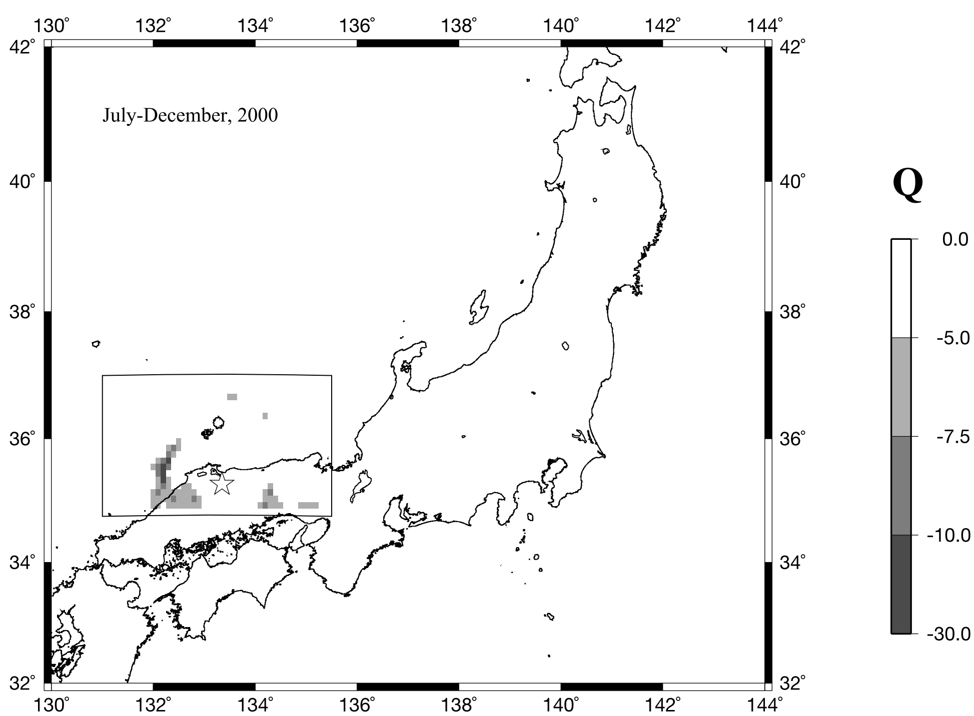

Figure 8e. The 6-month snapshot of spatial distribution of seismic quiescence in the investigated region from July to December 2000.

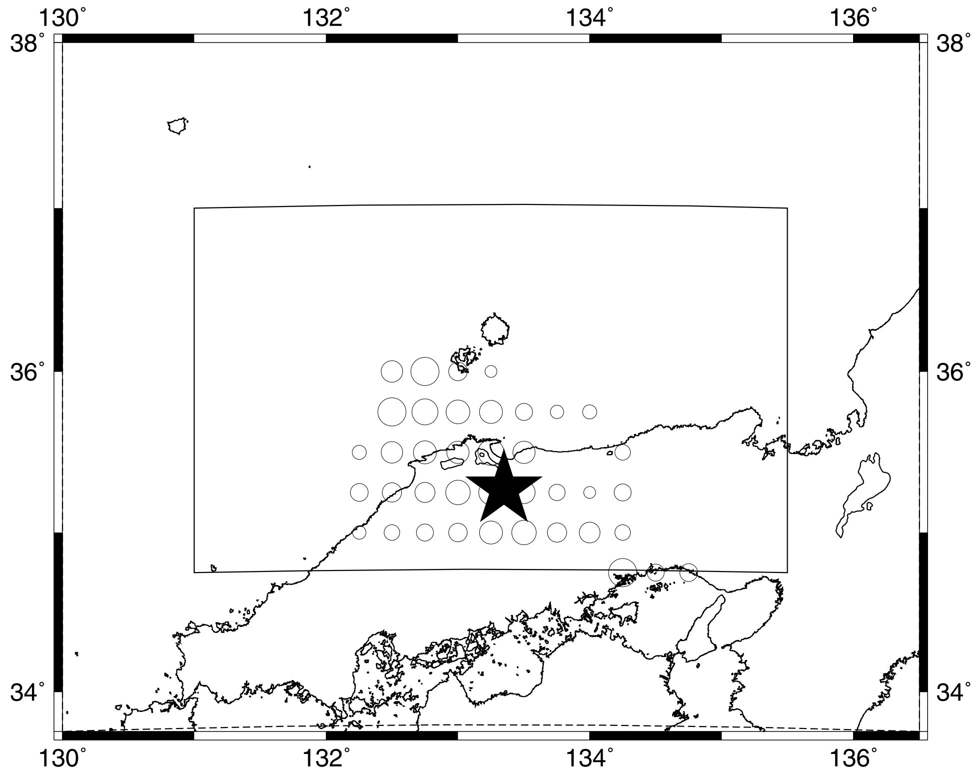

Figure 9. Spatial distribution of anomaly alarms. The star indicates the epicenter of the M = 7.3 Tottori earthquake.

shows the epicenter distribution of the 1989 and 1990 seismic activity. The bold line denotes the Kamakurayama Nanpo Fault (KNF), which is an active fault [*Research Group for Active Faults of Japan*, 1991]. The 1989 sequence (indicated by gray circles) occurred mainly in the south of the KNF and the 1990 activity (indicated by gray triangles) occurred in the north of the KNF (Figure 11a). In 1997, another earthquake swarm (indicated by black circles) started in the south of the fault and moved toward the north (Figure 11b).

[72] *Shibutani et al.* [2002] made detailed investigation of the above three earthquake swarms in 1989, 1990, and 1997. They claimed that these swarms may have some relationship with the 2000 western Tottori earthquake because the three swarms occurred in different parts of the same fault plane as the 2000 event. The main interest of this paper was not to investigate the possible relationship between these swarms and the main shock in 2000; however, it seems that the positive disturbances of RTL parameters revealed here (Figure 5) have some correlation with the swarms in 1989, 1990, and 1997. Similar positive disturbances of RTL parameters were obtained for the Izu earthquake swarm in 2000 [*Huang*, 2006]. Further study on the correlation between the variation of RTL parameters and the earthquake swarm would be interesting but is out of the scope of this paper.

4.5. Possible Problems That Need to Be Refined in the RTL Algorithm

[73] The RTL algorithm has been applied to several large earthquakes worldwide. Some positive results have been obtained, indicating that the RTL algorithm has some advantages in revealing precursory seismicity changes. However, on the basis of our past work and experience, we have also realized that this method has the following possible problems.

[74] Owing to the designation of the RTL method, the RTL values are calculated at the epicenter of the investigated large earthquake. Thus it is difficult to evaluate the

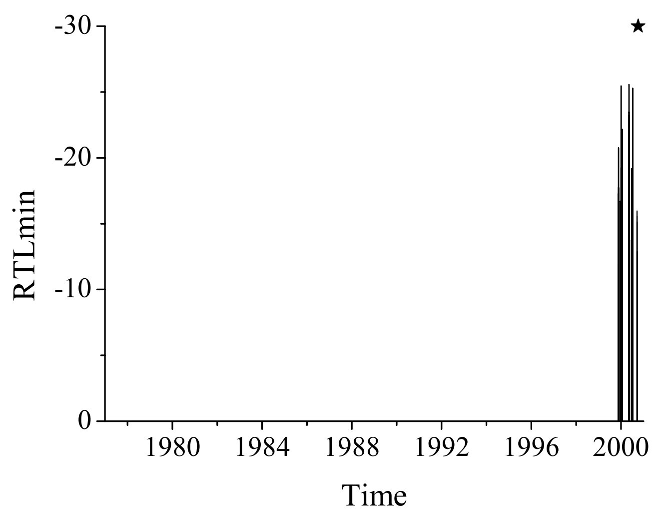

Figure 10. Distribution of anomaly alarms in time domain. The star indicates the occurrence time of the M = 7.3 Tottori earthquake.

Table 2. Results of Stochastic Test[a]

RTL_{min}	t_d	P
−10.0	0.5	0.178
	0.7	0.130
	0.9	0.088
	1.1	0.049
−12.5	0.5	0.090
	0.7	0.068
	0.9	0.048
	1.1	0.025
−15.0	0.5	0.049
	0.7	0.039
	0.9	0.028
	1.1	0.013

[a]The number of random earthquake catalogs is N = 1000. Probability of the anomaly for the western Tottori prefecture earthquake ($RTL_{min} = -19.1$, $t_d = 1.04$ year) is P = 0.010.

seismicity changes after the investigated large earthquake using the RTL algorithm because if the investigated large earthquake is taken in account in the calculation, r_i in equation (1) will be 0 for this event, which leads to a singularity in the calculation. Although we can set r_i to a fixed small value (e.g., 5 km) in case of r_i is 0 in our program to avoid the above explicit singularity, it is hard to guarantee the reliability of the RTL values after the investigated event. On the other hand, because there is usually a sudden change of seismicity background before and after a large earthquake, including the investigated event may lead to some discrepancy in estimating seismicity background. For the above reasons, the RTL method is seldom applied to investigate the seismicity changes after an investigated large earthquake. As an improvement of the RTL method, I developed the Q parameter to describe the seismicity changes in space domain. A comprehensive analysis of Q parameter in space domain and RTL parameter in time domain may give some useful information of seismicity changes just before and after the investigated large event.

[75] How to obtain a more realistic seismicity trend is another complicated problem. A linear trend model is adopted in the RTL method not only for simplicity but also because this method is based on the simple physical model of seismic cycles (linear accumulation of stress in each cycle) and results of rock experiments. If we can understand the complicated physical procedure concerning seismicity trend, of course, we should adopt the trend exactly following the relative physical model. However, unfortunately, so far we do not know much details of the above physical procedure. Thus at least at the current stage, the linear trend is a reasonable choice because of the simple physical model of RTL method. Definitely, searching for a more realistic seismicity trend deserves further study, which is useful not

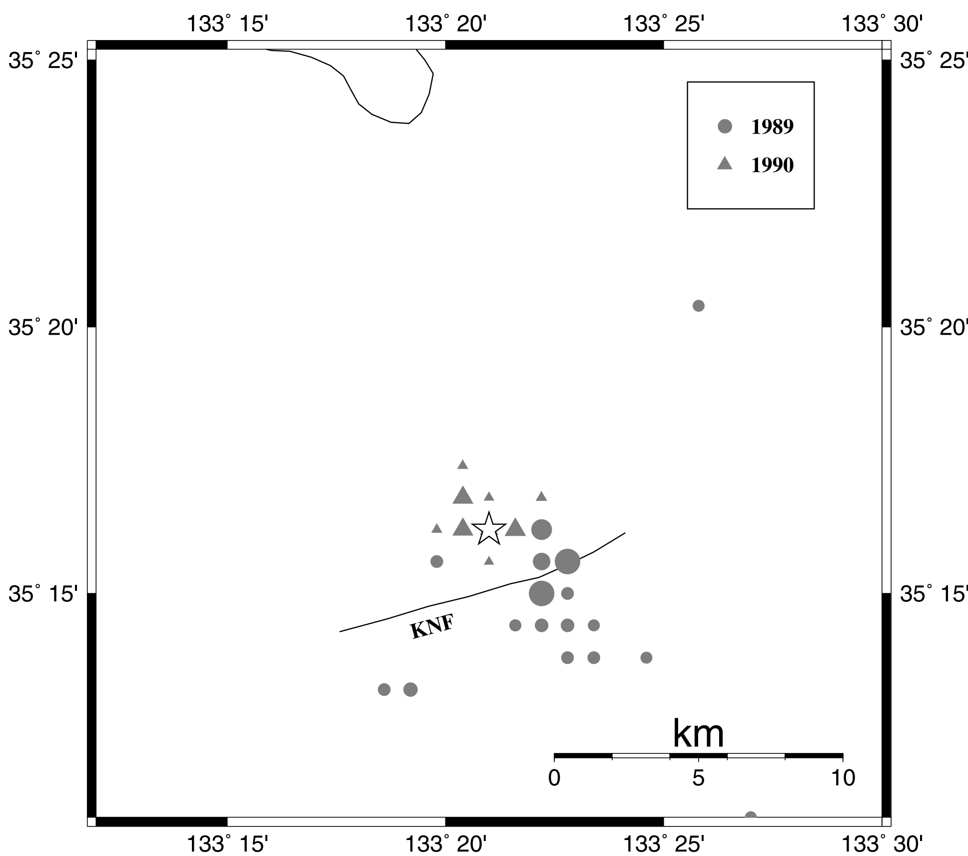

Figure 11a. Seismic activity ($M \geq 2$) in the region around the M = 7.3 western Tottori prefecture earthquake in 1989 (27 October to 30 November, gray circles) and 1990 (21 November to 31 December, gray triangles). The star indicates the epicenter of the western Tottori prefecture earthquake on 6 October 2000.

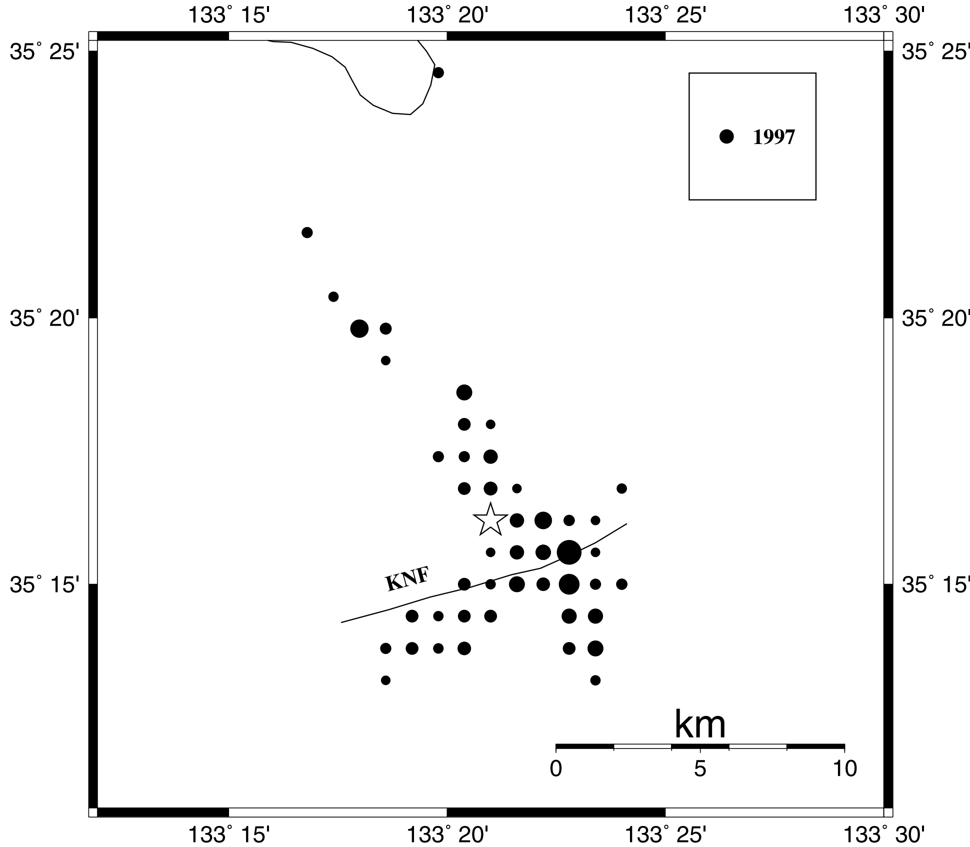

Figure 11b. Similar seismic activity ($M \geq 2$) in 1997 (23 August to 31 December, black circles).

only for the RTL method but also for other method in seismicity study.

5. Summary

[76] This paper presented a research procedure which focuses on the detailed evaluation of the reliability of earthquake precursors, including not only stochastic test but also time and space domain correlation analysis. As an example, this method was applied to evaluate the reliability of seismicity changes associated with the $M = 7.3$ western Tottori prefecture earthquake on 6 October 2000. Close analyses of artificial effects, spatiotemporal correlation, and stochastic test were made. The results indicated that the seismic quiescence anomaly detected before the 2000 western Tottori earthquake was not due to the artificial disturbances of the earthquake data or the selections of model parameters. The above anomaly was not a random anomaly, but a significant one, which correlated with the main shock in spatiotemporal domain. The above example indicated that the method presented here is an effective tool of improving the significance and reliability of earthquake precursors.

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