Quantitative mapping of precursory seismic quiescence before the 1989, *M* 7.1 off-Sanriku earthquake, Japan

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Abstract
The first main shock of the off-Sanriku earthquake sequence (02/11/89, M7.1; 18/07/92, M 6.9; 28/12/94, M 7.5) was preceded by a precursory seismic quiescence lasting 2.5 ± 1 year and up to this main shock. The detailed properties of this quiescence were mapped as a function of time and space by a gridding technique using the ZMAP computer code, and the statistical significance was estimated by generating a synthetic catalog based on the microearthquake catalog of Tohoku University, which was the data set used. The statistically most significant expression of this precursory quiescence has a probability of 0.1% to have occurred at random and was located in the eastern part of the 1989 aftershock area, at a point to which the 1994 aftershocks extended also. If we define the dimensions of the quiescence anomaly by a vertical cylinder with the depth of the entire seismogenic layer, centered at the point of most significant quiescence and showing a rate decrease of 75%, then we find its radius is 25 ± 9 km. If we allow other shapes, such as the simplified aftershock volume of 1989, or other simple geometric figures, to define the rate decrease we find dimensions of 80 by 80 km. The characteristics of the quiescence anomaly do not depend strongly on the choice of free parameters within the following ranges: 100 ≤ number of events ≤ 400, $2.0 \leq M_{min} \leq 3.0$, 1 ≤ time window ≤ 3 years. With our method, a thorough analysis of the period before the 1994 main shock is not possible because of the interference of the extended aftershock sequence of 1989. Nevertheless, we identified a quiescence of nearly zero earthquakes located near the center of the 1994 aftershock area that lasted for one year up to that main shock. However, this quiescence period ranked only 46th in significance, behind other quiescences of equal duration and similar dimensions distributed in time and space through the data set. Because of the ubiquitous existence of periods of near zero activity during short periods like one year, we find that quiescences shorter than about 1.5 years cannot be defined with high statistical significance in most earthquake catalogs. In the last two years of the data (1995.3-1997.3) we see no extensive quiescence of high significance off the east coast of Honshu between 36.5° and 42°N in the currently available data.

Key words *seismic quiescence – earthquake prediction – Sanriku Japan*

1. Introduction

It is important to test the validity of the hypothesis that before some large earthquakes on the megathrust off the eastern shore of Japan microearthquake activity is reduced significantly within and near the future rupture area, because little information is known about this phenomenon to date. Seismic quiescence has not been mapped in detail and quantitatively before a large rupture along the plate boundaries east of Honshu. The questions that need to be answered are: Does quiescence occur before most large megathrust earthquakes off Honshu? How long a quiescence may be expected? Is there a relationship between precursor time and

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magnitude? What is the spatial relationship of quiescence anomalies and aftershock volumes? How can quiescence best be mapped using microearthquake data? What are the percentages of false alarms and missed events?

Off Hokkaido, there are two examples of precursory seismic quiescence measured based on microearthquake catalogs. Precursory seismic quiescence was mapped for the 1982, *M* 7.1 Urakawa-oki (Taylor *et al.*, 1991) and the 1994, *M* 8.3, Kurile Island (Katsumata and Kasahara, 1996; Takanami *et al.*, 1996) thrust earthquakes. The pattern of seismic quiescence before a strike-slip earthquake in the upper plate off Izu (M = 6.5, 1990) was also mapped in detail (Wyss *et al.*, 1996). In addition, the source volumes of subduction zone earthquakes world-wide have shown quiescence precursors (Habermann, 1983; Kisslinger, 1988; Ogata, 1992; Ohtake *et al.*, 1977, 1981).

Ogata (1992) argues that nine very large to great earthquakes that occurred off the eastern shores of Japan between 1923 and 1972 have been preceded by seismic quiescence measured by $M > 5$ earthquakes in volumes of about 6° to 12°on a side. Some of these quiescences appear only after the dependent earthquakes are modeled by Omori's law, and the spatial relationship between the quiescences and the main shocks was not investigated. Although it is important to document and understand quiescence of moderate magnitude earthquakes in very large volumes, this information is of limited use for predicting the locations of future earthquakes. If we can demonstrate that microearthquakes in the immediate vicinity of the future source areas of large earthquakes show significant quiescence before main shocks, we would be a step closer to estimating the locations of future large earthquakes.

The reason for the lack of detailed case histories for precursory seismic quiescence in this economically important segment of the circum-Pacific seismic belt is that few large earthquakes have occurred there since the beginning of high quality earthquake catalogs. Extensive reporting of events with $M < 3$ is necessary for the detailed mapping of seismic quiescence. Seismograph networks in most of Japan were strongly improved in the 1970s, and then again during the 1980s, reducing in steps the magnitude of completeness, M_c, as well as the minimum magnitude of homogeneous reporting, M_{homo}. Since we define seismic quiescence as a decrease of the mean rate of earthquakes in a volume, compared to the background rate in this same volume, we must base our analysis on a catalog with homogeneous reporting as a function of time. Also, we must maximize the number of events available for study to achieve a high statistical significance. Therefore, we have to find the onset time for the data set that leads, together with the M_{min} that it dictates, to the largest homogeneous data set. In the case of the area off northern Honshu, the optimal starting time is January 1, 1981 (1981.0), as explained below. Therefore, the earliest main shocks for which we can test the hypothesis are those that occurred in the late 1980s or later, because nearly a decade of high quality information on seismicity rate is needed before a target event, in order to define the background seismicity.

The only target earthquakes for testing the hypothesis, located within the area covered by the Tohoku University seismograph network, in conjunction with neighboring networks, are those of the relatively recent sequence of large earthquakes in the area off Sanriku: 2 November 1989 (*M* 7.1), 18 July 1992 (*M* 6.9) and 28 December 1994 (*M* 7.5) (Hasegawa and Matsuzawa, 1995; Tanioka *et al.*, 1996; Nakayama

Table I. List of earthquakes with $M > 6.5$ in the Sanriku area.

Date	Lat.	Long.	M
27 05 1928	39°57	143°15	7.0
03 03 1933	39°14	143°31	8.1
13 10 1935	39°58	143°42	6.9
21 03 1960	39°50	143°26	7.2
23 03 1960	39°25	143°43	6.7
16 05 1968	40°42	143°36	8.1
12 06 1968	39°25	143°08	7.2
02 11 1989	39°51.3	143°03.4	7.1
18 07 1992	39°22.8	143°39.3	6.9
28 12 1994	40°26.3	143°44.9	7.5

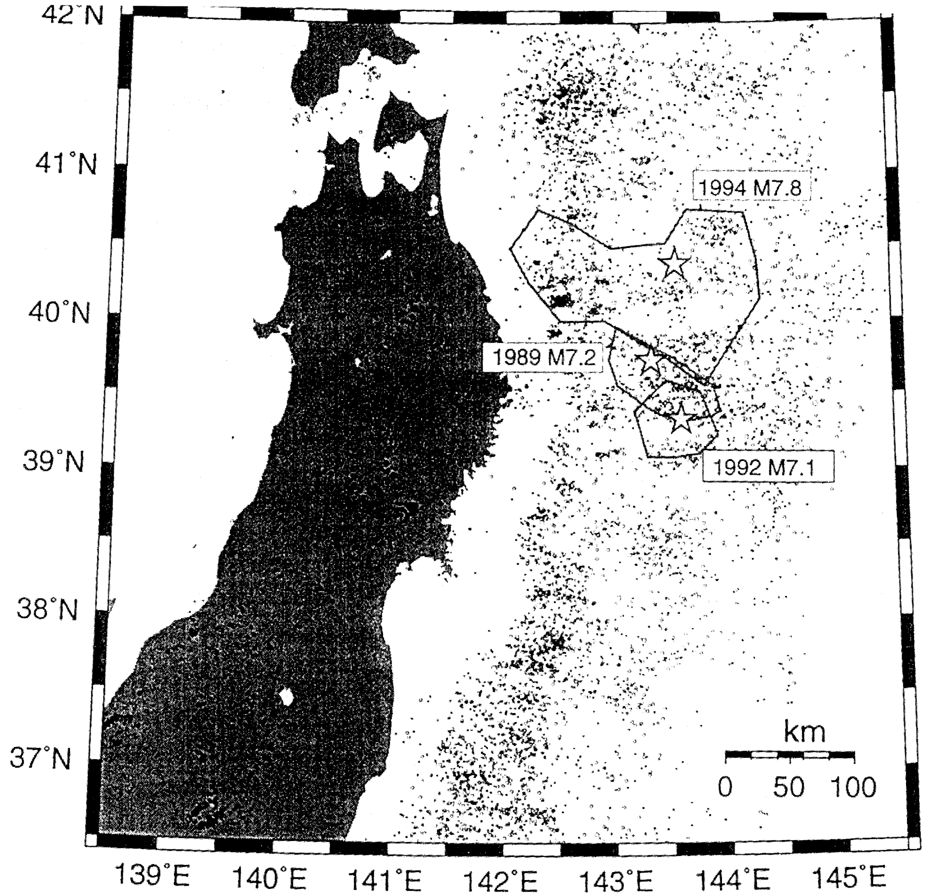

Fig. 1. Epicenter map of the 8677 earthquakes with $M \geq 2.8$ and depths < 60 km during the period 1981.0-1997.3 in the declustered earthquake catalog for the off-northern Honshu area investigated. The aftershock areas of the 1989 and 1994 Sanriku main shocks are outlined. Epicenters of earthquakes with $M > 6.8$ are marked by stars.

and Takeo, 1997; Nakahara *et al.*, 1998 (table I, fig. 1). The larger two of these had approximately abutting source areas, overlapping slightly, with dimensions of 80 by 30 km (1989) and 150 by 50 km (1994).

It would be desirable to study these three earthquakes separately because we need numerous case histories to define the properties of precursory quiescence. However, this is not possible because the first of these ruptures (1989), and its afterslip on the megathrust (Miura *et al.*, 1994), disturbed the seismicity production in an extended area and over several years. That means that the later two earthquakes occurred within the extended aftershock sequence of the first one. If one is willing to assume that in such a case the «normal background rate» can be modeled correctly by the Omori law, as was done in cases of regular aftershock sequences (Matsu'ura, 1986; Ogata, 1992), then one might be able to argue that the presence of quiescence even after the 1989 event can be estimated. However, we are not certain that this approach would be fruitful in this case. Therefore, we conclude that the only large earthquake in northern Honshu for which we can test the precursory quiescence hypothesis is the first event in this sequence, the M 7.1, November 1989 off-Sanriku earthquake.

The Tohoku University earthquake catalog covers three tectonic provinces: 1) The off-shore plate boundary or megathrust; 2) the shallow intraplate crustal seismicity on land and 3) the intermediate and deep seismicity within the descending Pacific plate. Category (1) is characterized by a high seismicity rate covering most of the megathrust about evenly, whereas the shallow seismicity on land (2) is sparse and unevenly distributed in disconnected patches of activity (Hasegawa *et al.*, 1985, 1994). The intermediate depth seismic zone is very active down to depths of about 160 km and is divided into an upper and lower zone (Hasegawa *et al.*, 1978; Unimo and Hasegawa, 1975). The target earthquake occurred along the megathrust, so our search for a possible quiescence precursor concentrated on the off shore area. However, we also investigated the possibility that the seismic provinces (2) and (3) may have been affected.

The hypothesis we test is the one formulated by Wyss and Habermann (1988) to which we add the constraint that the duration of the quiescence should be within the bounds $1.5 \leq t_Q \leq 7.5$ years. These bounds are proposed because we know of no quiescence durations outside them for $M \approx 7.1$ earthquakes. The quiescence hypothesis, as formulated by (Wyss and Habermann, 1988), postulates that the quiet volume overlaps the main shock source volume. The rate decrease takes place in all magnitude bands, and the null hypothesis is that earthquakes in a given crustal volume occur at a constant rate.

The parameter investigated in this study is the rate of earthquake production, not the energy released. With this parameter, we investigate the probability for an asperity to rupture per unit time in the crustal volume selected. We assume that the background seismicity rate is constant. Each asperity that breaks can end as a small earthquake, or grow into a lager one, with a probability according to the observed magnitude-frequency relation. The balance between the constant input rate of stress and the constant production of earthquakes is disrupted if a change in process occurs. In a volume where loading is suddenly increased by a nearby major earthquake, or a creep episode, an aftershock sequence follows. In volumes where the stress level is decreased by these same processes, seismic quiescence will result for a period until the previously suffered stress drop is recovered by the loading process. In this framework of thinking, quiescence is as obvious a consequence of events that redistribute the stress substantially, as aftershock sequences. Alternatively, quiescence may be brought about by a sudden increase in strength of the faults in the crust, which occurs if the pore pressure of underground fluids drops. Laboratory experiments show that both, strain softening (Dieterich, 1978; Stuart, 1979) and dilatancy (Scholz *et al.*, 1973), could occur before major ruptures in the earth and bring about the changes of process leading to precursory quiescence.

2. Data

We used the earthquake catalog of Tohoku University. Since our target earthquake is located off shore (39°51.3′/143° 03.4′, fig. 1), and since the recording history and coverage on land is different from off shore, we limited the area to be studied to off shore (fig. 1). The farther off the coast, the more uncertain becomes the hypocentral depth. Most of the depths listed in the catalog for earthquakes 100 to 200 km off shore scatter in the top 60 km. It is generally believed that this scatter is not real, but that most of these events occur along the shallow dipping megathrust (Umino *et al.*, 1995; Hino *et al.*, 1996; Zhao *et al.*, 1997). Therefore, we must include all earthquakes in the top 60 km if we want to study the shallow seismicity, and we are unable to map quiescence in cross sections as a function of depth.

Since we wish to work with a homogeneous data set with $M \geq M_{\mathrm{homo}}$, and since M_{homo} is usually tied to M_c, we mapped M_c as a function of space and time. We also searched the catalog for significant artificial reporting rate changes by the magnitude signature method (Habermann, 1991). The two most significant changes in re-

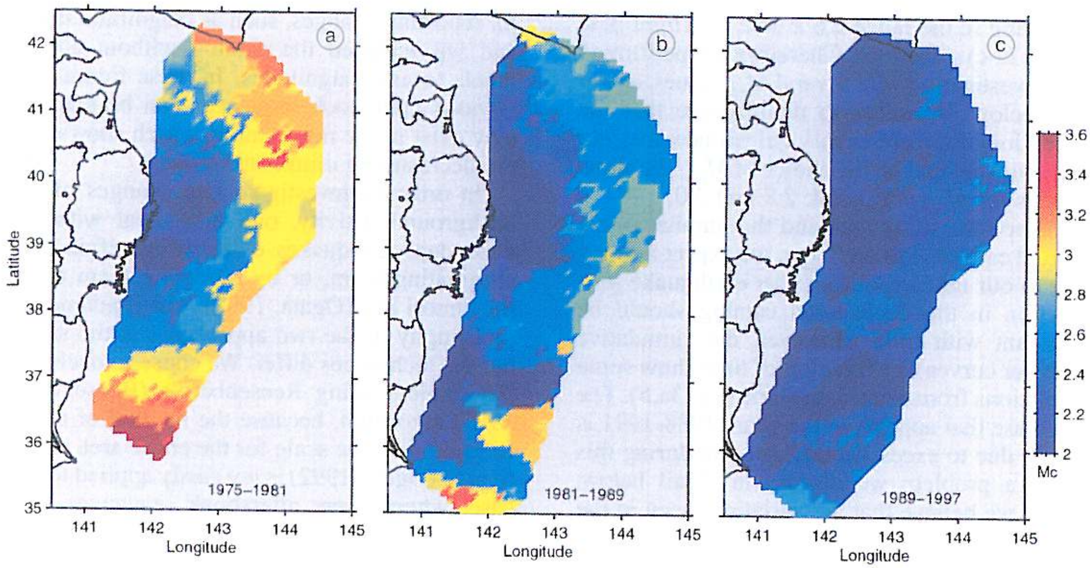

Fig. 2a-c. Maps of magnitude of completeness of reporting off northern Honshu, based on the Tohoku University earthquake catalog for three periods (a) 1975.0-1981.0, (b) 1981.0-1989.0 and (c) 1989.0-1997.3. Mc is estimated as the point of largest derivative of the number *versus* magnitude distribution of the 400 nearest earthquakes at each node of a grid with about 1600 nodes and spacing of 0.1°. Polygons show the approximate aftershock areas of the 1989 and 1994 Sanriku main shocks.

porting we found for the off shore area occurred in 1981 and 1989. Maps of M_c, made by ZMAP (Wiemer, 1996), for the three periods before, between and after these dates show that strong improvements were achieved, except in the core area nearest to the center of the network, where the reporting was of high quality since 1975 (fig. 2a-c). The maps of M_c are based on finding the point of highest derivative in the cumulative Frequency-Magnitude Distributions (FMD) of the nearest $N = 400$ earthquakes to each of about 1600 grid points, spaced 0.1° apart. Quality checks of the algorithm's performance were carried out by inspection of the FMD at randomly selected points, and in locations where we had some doubts about the reliability of the results shown on the maps. We found that our subjective judgment of the choice of M_c agreed with that of the algorithm in most cases, but in some areas (*e.g.*, 36° to 38°N) the M_c was underestimated because the FMD turned off a straight line in a very subtle way only.

In the most recent segment of the data (post 1989.0), we found $M_c < 2.5$ almost everywhere (fig. 2c). Before 1981.0, about half of the area mapped showed $M_c \approx 3$, including in most of the aftershock volume of the target earthquake (fig. 2a). Including these pre-1981 data in our study, would have meant that we would have had to raise the minimum magnitude for the analysis to about $M = 3$. Thus we excluded the data before 1981. In the remaining data set, the area south of 36.5°N during the period before 1989 stands out as one with reporting inferior to the rest of time and space (fig. 2b). Therefore, we limited the area of study to latitudes between 36.5° and 42° N. Within this area we can accept the catalog as complete at the $M_c = 2.8$ level, based on the M_c maps (figs. 2b,c). This conclusion is also born out by the FMD for the area selected for study (fig. 3c).

We may not necessarily have to restrict our analysis to data with $M \geq M_c$ because by far the largest portion of the study area shows complete reporting in the range $2.6 \geq M \geq 2.4$ (light blue in fig. 2a-c) since 1981. Therefore, we performed our investigation with several M_{min} values, above and below $M_c = 2.8$, to demonstrate that the detection of the precursory quiescence does not critically depend on the choice of M_{min}. We show results for $M_{min} = 2.0$, 2.4, 2.8 and 3.0.

Since the study area and the number of reported earthquakes are large, we expect according to our null hypothesis that earthquake production in the declustered catalog should be constant with time. However, the cumulative number curves as a function of time show some deviations from a constant slope (fig. 3a,b). The decrease that appears in the years 1988-1991 is partly due to excessive declustering during this time, a problem we discuss in detail below. Thus, we believe that the variations seen in the cumulative number curves do not indicate major reporting changes, such as magnitude shifts, and we accepted the catalog without adjustments to any magnitudes. In these figures, no obvious aftershock sequences can be seen, as they exist in the raw catalog, which shows that the declustering eliminated these.

In order to investigate rate changes of the background activity, one must deal with the dependent earthquakes, either by identifying and eliminating them, or by modeling them using the Omori law (Ogata, 1992). The fundamental philosophy of the two approaches is the same, but the techniques differ. We chose to decluster the catalog, using Reasenberg's (Reasenberg, 1985) algorithm, because the method of transforming the time scale for the entire area investigated (Ogata, 1992) is not easily applied to our case, where many aftershock sequences with numerous events in small areas are embedded in

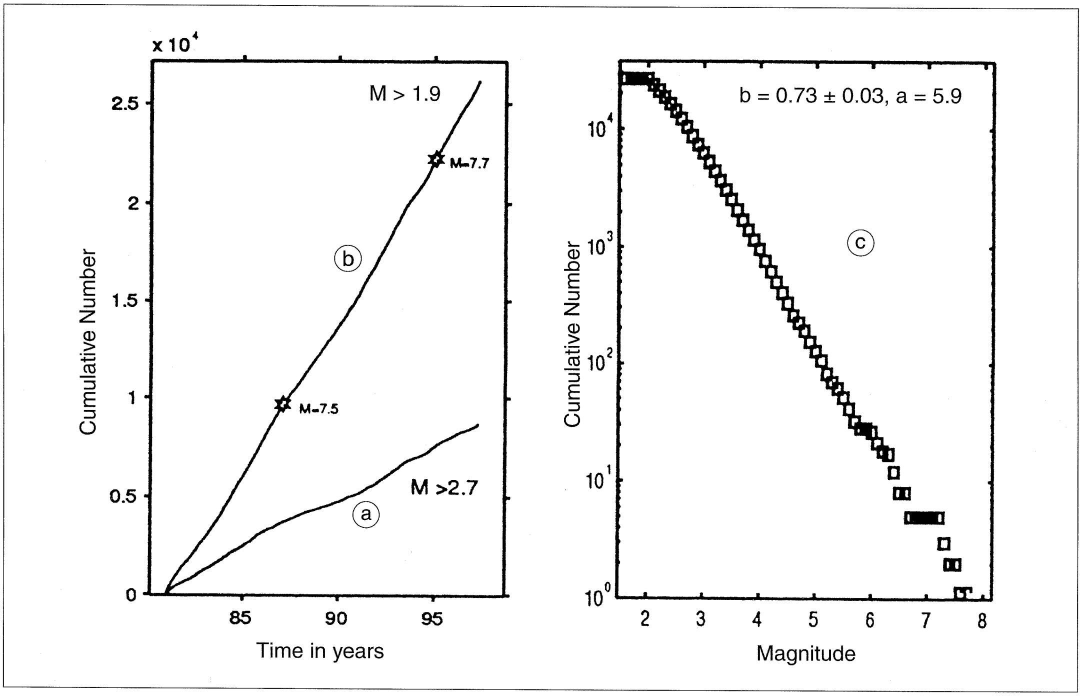

Fig. 3a-c. Cumulative numbers of earthquakes as a function of time (a) with $M \geq 2.8$ and (b) $M \geq 2.0$ reported for the off-northern Honshu area of fig. 1. c) Frequency-magnitude distribution for earthquakes with $M \geq 2.8$ in the study area (fig. 1) for 1981.0-1997.3 .

a much larger study area. Since a transformation of the time scale due to each moderate earthquake is not applicable to the entire study area it would have to be estimated separately for every local point investigated. The declustering method is thus easier to apply, its consequences are more easily recognized, and quality control is possible.

Similar to our previous experience with declustering in Japan (Wyss *et al.*, 1996), we found that the declustering parameters applicable for California (Reasenberg, 1985) left visible clusters in the catalog. Therefore, we used again the parameters found for Utah (Arabasz and Hill, 1996). With these parameters, the obvious clusters disappeared, but in some areas all earthquakes were removed for extended periods, as it is unavoidable when intense earthquake activity occurs (Eneva *et al.*, 1995).

3. Method

The gridding technique to map quiescence is explained elsewhere (Wiemer and Wyss, 1994). We summarize it briefly. Changes in the seismicity rate are evaluated as a function of time at every node of a grid with 0.1° spacing. At each node, the data analyzed are the nearest N events (here $N = 100$, 150, 200, 250, 300, 400 in separate analyses), and a window (T_w = 1, 1.5, 2, 2.5, 3 years) is moved through the time series, stepping forward by one sampling interval (two months). For each window position, we calculate the standard deviate Z, generating the function LTA(t) (Wiemer and Wyss, 1994), which measures the significance of the difference between the mean seismicity rate within the window, R_2, and the background rate, R_1, here defined as the mean rate outside the window, but in the same volume. The Z-value is defined as

$$Z = (R_1 - R_2)/(S_1/n_1 + S_2/n_2)^{1/2}, \qquad (3.1)$$

where S and n are the variances and numbers of samples, within and outside the window. The resulting three dimensional (lat., long., time) matrix of Z-values constitutes the basis of our quantitative analysis of quiescence.

The radii of the crustal volumes sampled are variable and inversely related to the local seismicity rate because we keep N constant to satisfy assumptions for statistical evaluations. Along the coast, where the seismicity rate is highest, the radii are at their lowest of about $r = 5$ km, farthest from the coast they tend to be $r = 50$ km.

The Z-maps show the local relative strength of rate changes at the time of the window position selected. In movies we can view Z-maps for all possible window positions in time, and a summary of all values of Z above a selected alarm level is given in alarm-cube representations of the results (Wiemer, 1996; Wyss *et al.*, 1996, 1997). Thus, we can find all false alarms that may be present in a data set. To verify the reliability of a mapped rate change, we show the cumulative numbers of earthquakes as a function of time for volumes of interest.

For judging the significance of Z-values calculated for the data set at hand, we generate synthetic Z-value matrices based on random selection of samples from the earthquake catalog of the area studied, excluding the sub-areas with known rate anomalies (see below). N events are extracted from the catalog at random, regardless of location, but retaining the origin time, and an LTA function for a given window length (*e.g.*, $T_w = 3$ years) is calculated. Repeating this process 1200 times, results in a matrix equal in size to the one obtained with the grid size used in this paper. Such synthetic matrices are calculated 1000 times and the maximum Z-value, Z_{max}, is retained each time. The significance of a Z-value obtained in the analysis of the real data is judged in comparison to this synthetic Z_{max} distribution (Wiemer, 1996; Wyss *et al.*, 1996).

The free parameters in the analysis are N and T_w. We chose N such that average sampling radii were about 15 km. This means that the diameter of the sampling cylinders, with height equal to a nominal 60 km, was typically 30 km or less. The true height of the seismogenic crust was probably more like 30 km, because of the hypocentral depth uncertainties. Thus, the sampled volumes had approximately equal dimensions laterally and in depth in major parts of the study area. LTA functions were calculated for window lengths between 1 and 3.5 years, to demonstrate that the

Table II. Parameters of the seismic quiescence before the off-Sanriku 1989, M 7.1 earthquake as a function of M_{min}, N and T.

M_{min}	N	T (yr)	Z_{max}	P (%)	Lat. (deg)	Long. (deg)	ts (date)	r (km)	dR (%)	dV (%)	N_{tot}
3.0	100	3	7.9	5	39.56	143.85	87.0	22	93	0.015	6258
2.8	200	2	9.3	2.5	39.85	142.90	88.1	34	78	0.014	8677
2.4	150	3	9.2	0.1	39.55	143.76	87.0	16	91	0.010	16127
2.0	400	2	9.4	0.1	39.75	142.80	88.1	22	69	0.016	25979

significance of the anomalies does not critically depend on the choice of T_w within this range.

By declustering, one may artificially introduced quiescence, a total absence of earthquakes, for some time and at some distance of main shocks (Eneva *et al.*, 1995). Therefore, we must make sure that a quiescence anomaly we propose as a precursor was not generated by declustering. We do that by verifying that the quiescence can be identified by inspection in the original data set. In this point our approach differs from that of Ogata (1992).

The total catalog for the study area contains about 60 000 earthquakes with $M \geq 2.0$. The numbers remaining after declustering in each data set with different M_{min} are given in table II.

4. Results

We investigated the possibility of seismicity rate changes in the three tectonic provinces, off-shore east of Tohoku along the plate boundary, subcrustal activity within the descending slab and the shallow intraplate seismicity on land. For all three areas we first examined the reporting homogeneity as a function of time using the GENAS (Habermann, 1983) and magnitude signature method (Habermann, 1991; Zuniga and Wyss, 1995). We found the most consistent reporting in the off-shore area and attribute this to the fact that no new seismograph stations have been installed there, and thus reporting since 1981 was fairly homogeneous. Within the descending slab we found that the reporting rate of earthquakes with $M > 2$ was reduced in all of Tohoku (most at the center of the network) during the years 1988 to 1991, while the reporting rate of $M < 2$ events was increased by just the amount to keep the total rate ($M > 0$) constant. We interpreted this temporary change as due to an artificial magnitude shift (Habermann, 1991; Wyss, 1991; Zuniga and Wyss, 1995) in 1988 that was corrected in 1991. Recognizing this one strongest change in reporting, we performed the analysis without corrections of the catalog because the other changes we noticed were not strong enough to introduce serious problems.

The analysis of the deep earthquakes was restricted to the depth range $60 < H < 160$ km. Below the 160 km depth contour, which coincides with the western coast of Japan, the M_c increases dramatically and above 60 km depth the relationship between intra- and interplate earthquakes becomes unclear. We found no statistically significant seismicity rate decrease within the descending slab in the 1980s or early 1990s. The results are not shown here to reduce the number of figures, but the Z-maps we constructed were of relatively uniformly blue to green color showing no quiescence anomalies.

The analysis of the shallow seismicity on land was not very worthwhile because there the rate is low and the seismicity is patchy. Nevertheless we included these data in some of the Z-maps of the off-shore data on which we concentrated the analysis. After constructing Z-maps and alarm cubes for off- and on-shore areas (Wiemer, 1996; Wyss *et al.*, 1997) for several magnitude cutoffs (M_{min} = 3.0, 2.8, 2.4, 2.0) and time windows (T_w = 1, 1.5, 2, 2.5, 3, 3.5 years) and inspecting the cumulative number *versus* time plots, we came to the conclusion that there existed a clear quiescence that conforms to the hypothesis and to the association rules. Below we present the evidence that brought us to this conclusion.

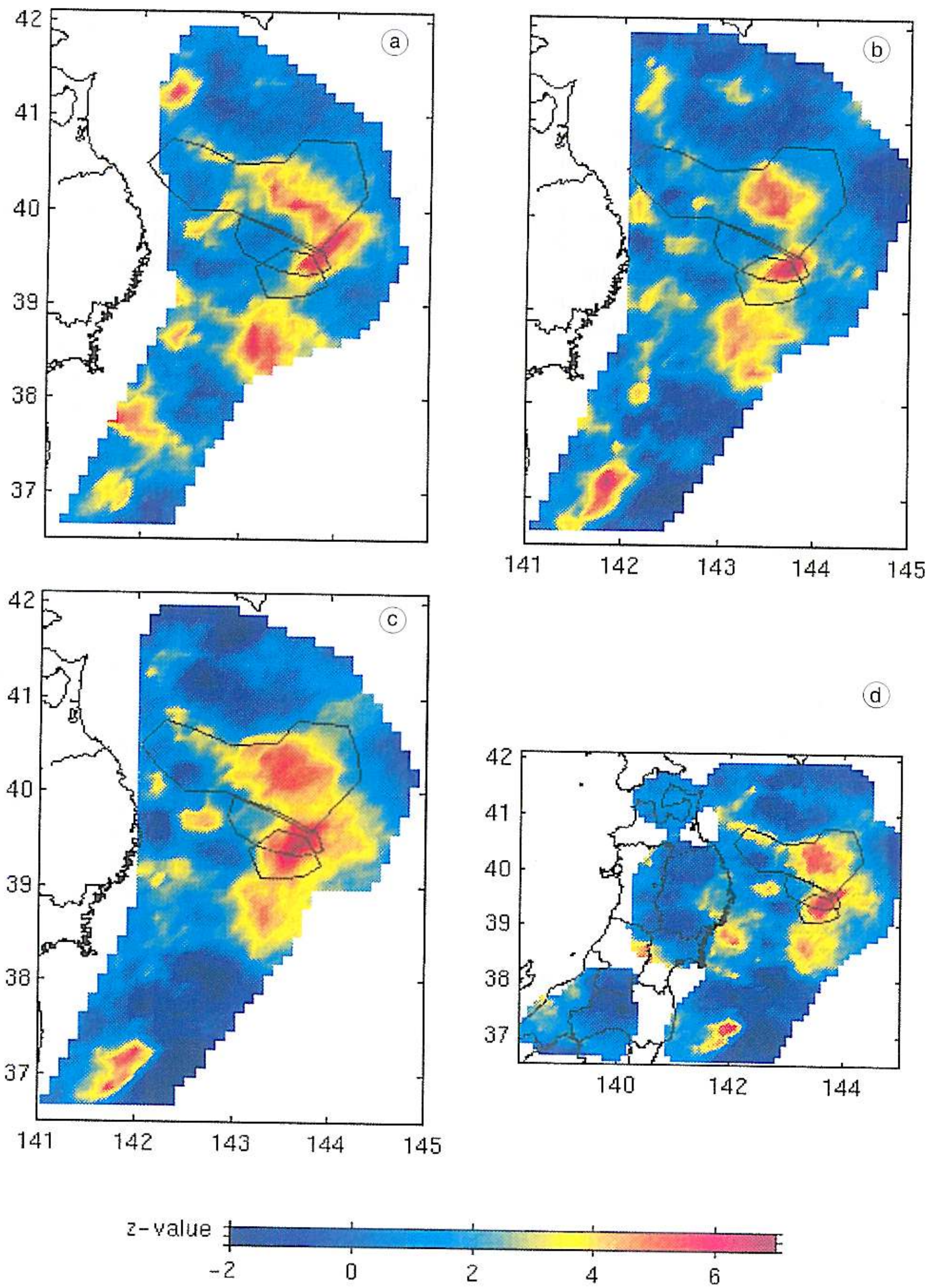

Fig. 4a-d. Z-maps showing the precursory seismic quiescence before the Sanriku earthquakes (a) for $M \geq 3$ earthquakes in a 3 year window; b) for $M \geq 2.8$ earthquakes in a 2 year window; c) for $M \geq 2.4$ earthquakes in a 3 year window and d) for $M \geq 2$ earthquakes in a 3 year window before 1989.9, the time of the M 7.1 Sanriku earthquake. Values of $Z > 8$ tend to have less than a 5% probability to occur at random.

4.1. *Location and spatial extent of the 1989 quiescence anomaly*

Maps of Z-values for four values of M_{min} are shown in fig. 4a-d. For two of the maps T_w is 2 years, and for the other two it is 3 years. The two maps that include an analysis of the seismicity of the land area are based on data from the top 30 km on land, but data down to 60 km farther than 50 km off shore, because the latter hypocentral depths are poorly constrained and all these events probably occur at shallow depths (Umino *et al.*, 1995; Hino *et al.*, 1996; Zhao *et al.*, 1997).

All of the maps show high Z-values of about $Z = 8$ in the aftershock area of the off-Sanriku earthquake of 1989 and south of it. The aftershock area of the 1994 off-Sanriku earthquake also shows high values, but of somewhat lesser intensity. The color scale for all maps is the same, but the significance of these values vary between the maps because the data sets with different M_{min}, containing different total numbers of earthquakes, have different probabilities to show a quiescence pattern by chance. The maximum Z-values (Z_{max}) that are found for each map in association with the 1989 aftershock area, and the corresponding probabilities, P, that this Z_{max} was attained by chance, are listed in table II.

If we examine the precursory seismicity rate in a short window like $T_w = 2$ years (fig. 4b-d), the area that appears quiet is large. If we map longer quiescence $T_w = 3$ years (fig. 4a-c), the anomalously quiet area is more concentrated in the center of the eastern aftershock area of the 1989 main shock, at a location to which some of the aftershocks of the 1994 event reached.

Results for shorter and longer windows are not shown for the following reasons. For longer windows the significance is degraded at most nodes because only very restricted volumes show durations of 3.5 years of quiescence (*e.g.*, fig. 5a-f). For shorter windows than 2 years some volumes show quiescences that are striking to the eye (*e.g.*, fig. 5c), but their statistical significance is usually low, because the data set contains many short periods with locally low activity. With the alarm cube method we identify all of these periods of low seismicity rate. Shorter periods of quiescence can only be defined with high statistical significance if the number of events is large (fig. 5c). In general, we find that periods of zero earthquakes during one year occur frequently in volumes with radii of about 10 to 20 km in a data set like the one analyzed here. It is therefore not possible to establish with high statistical confidence that a quiescence that appears to be correlated with an earthquake did not occur by chance.

The spatial extent of the anomaly is estimated as follows. For each of the parameter choices used for the four maps in fig. 4a-d (*i.e.* the four cases listed in table II), we increased the radius of a sampling cylinder placed at the point of maximum quiescence as found by the grids, until the rate decrease was degraded to 75%. This choice of defining the limit of the anomaly is arbitrary (Wyss *et al.*, 1996). It corresponds approximately to an anomaly that is clearly acceptable by naïve examination, as the case of fig. 5f. For the data set with $M_{min} = 2.0$ we could not define the dimension of the anomaly in this standard way because the maximum decrease was less than 75%, although the probability that it occurred by chance is low (table II). The radii found ranged from 16 to 34 km (table II). On average we thus estimate 25 ± 9 km (table III), where the limits are chosen to include the extreme values given in table II.

Table III. Average characteristic of the precursory quiescence before the *M* 7.1, 1989, off-Sanriku earthquake.

Radius (km)	Duration (yr)	Starting time (date)	Probability (%)	Decrease (%)
25 ± 9	2.5 ± 1	1987.3 ± 1	2.5 ± 2.49	80 ± 10

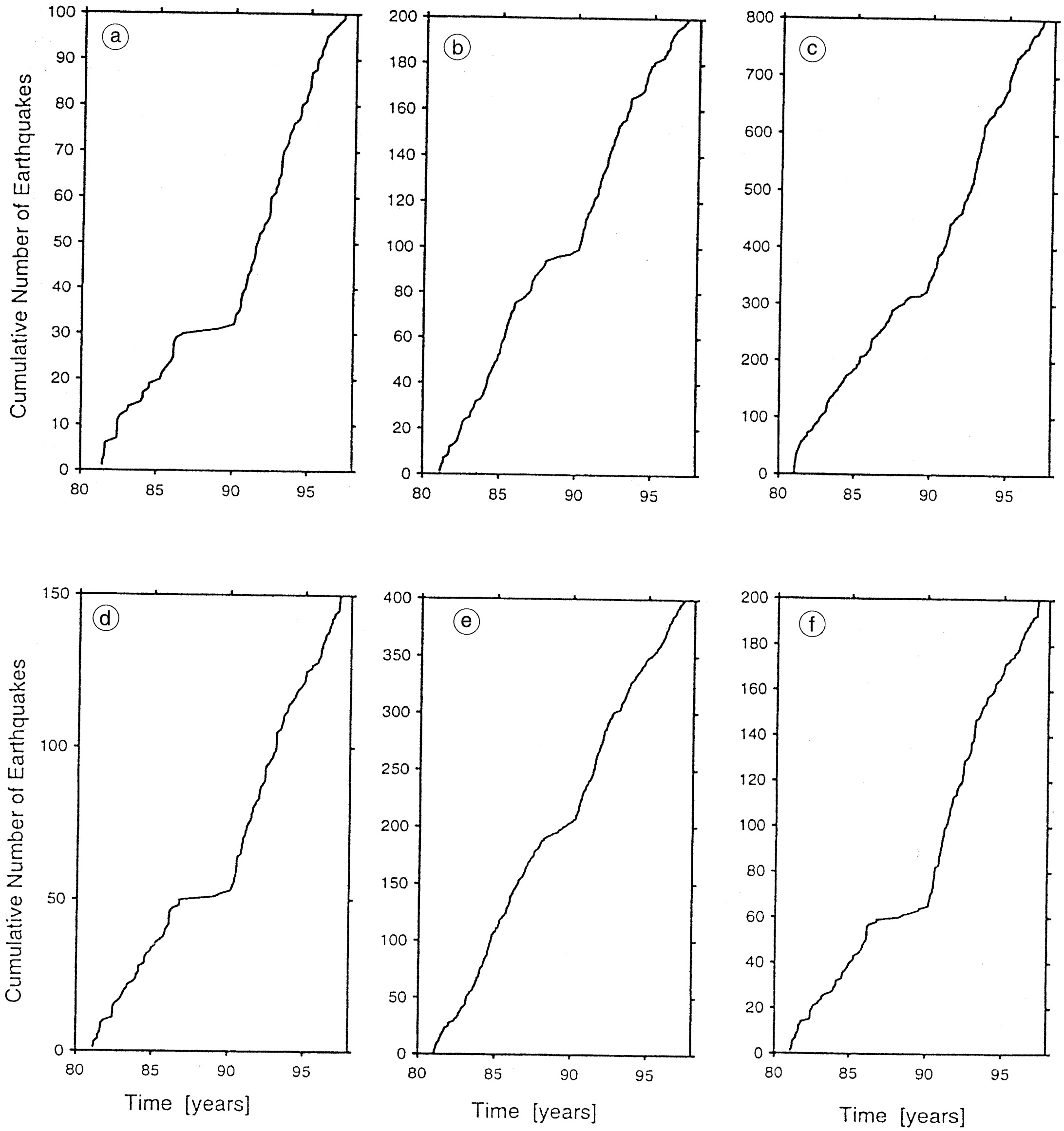

Fig. 5a-f. Cumulative numbers of earthquakes as a function of time (1981.0-1997.3) for cylindrical volumes in which Z-map detected a highly significant seismic quiescence before the 1989 M 7.1 Sanriku main shock. This selection demonstrates that the precursory seismic quiescence is found using a range of volume sizes ($r < 35$ km), window lengths ($3.5 \geq T_w$) and magnitude band ($M \geq 2$). a) $N = 100$, $M \geq 3$; b) $N = 200$, $M \geq 2.8$; c) $N = 800$, $M \geq 2$; d) $N = 1990$, $M \geq 2$, simplified aftershock area; e) $N = 400$, $M \geq 2$; f) original catalog including clusters for the same volume as fig. (d), $M \geq 2.4$.

4.2. *Timing and duration of the 1989 quiescence anomaly*

The cumulative number plots (fig. 5a-f) show that the quiescence we mapped occurs during the time before and up to the off-Sanriku *M* 7.1 earthquake that occurred at 1989.84. In all the cumulative number curves of the declustered catalog (fig. 5a through 5f) the seismicity rate before and after the quiescence period is remarkably stable.

The duration of the quiescence, t_Q, is measured from the strongest point of rate change (peak of the statistical function LTA) to the main shock origin time. However, the change of rate occurs so abruptly that it can be estimated accurately by eye. One can see that t_Q varies from a maximum of 3.5 years, when small numbers involving small volumes are considered (fig. 5a,d), to 1.5 years, when larger volumes are examined (fig. 5b,c). Thus, we estimate the duration $t_Q = 2.5 \pm 1$ years (table III), to include the range of observed values (table II).

4.3. *Verification of the natural origin of the 1989 quiescence anomaly*

The fact that the precursory quiescence discussed so far was not generated by declustering is demonstrated by the cumulative number curve (fig. 5f) of the complete catalog (including clusters) for the same volume as that used for fig. 5d, one of the volumes showing the anomaly clearly. The 3.5 years before the off-Sanriku earthquake (which occurred at 1989.84) are al-

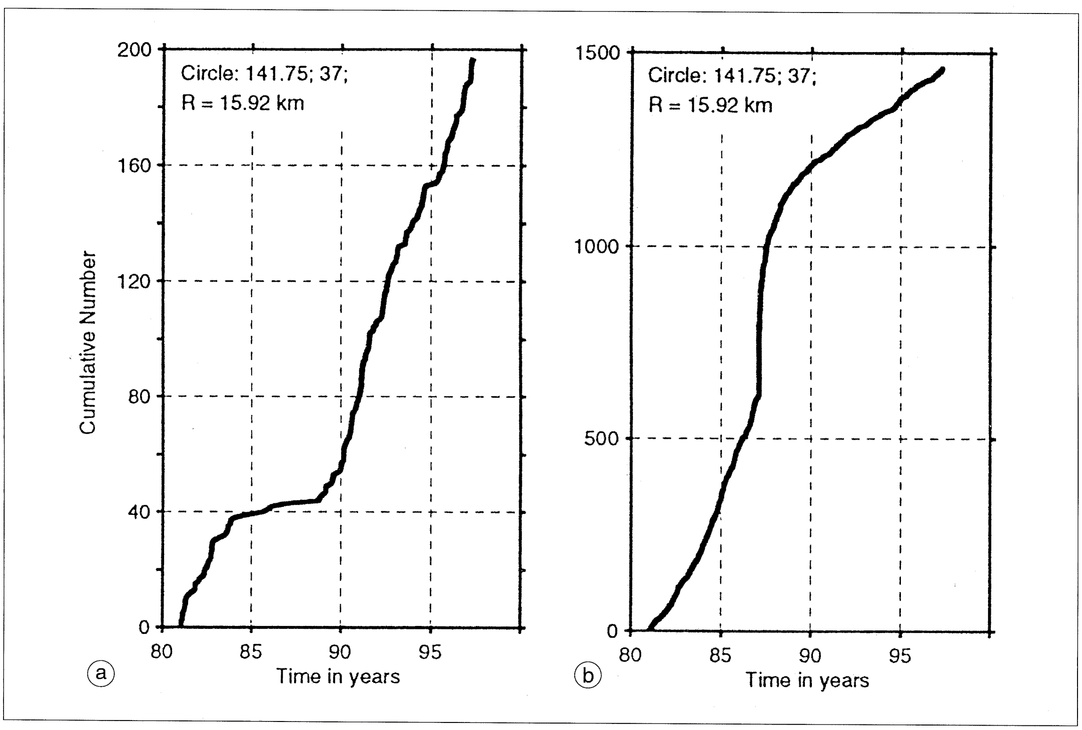

Fig. 6a,b. Cumulative numbers of earthquakes as a function of time (1981.0-1997.3) in the (a) declustered catalog compared to that in the (b) complete catalog for a volume of quiescence artificially generated by the declustering process.

most devoid of earthquakes in the declustered as well as the clustered catalog.

However, if an aftershock sequence has very numerous events in close proximity, all events are removed by the declustering process. This has happened in the southern part of the study area, where the enhanced activity before and after a main shock of M = 6.7 was removed almost completely (fig. 6a,b). This means that the declustering introduced an erroneous alarm into the data. This will not be called a false alarm. We define a false alarm as one in which a natural quiescence achieves a significance level equal to or larger than the proposed precursory alarm. An erroneous alarm is one demonstrably introduced artificially by a part of the data analysis, and will not be considered in the evaluation of the performance of the proposed precursor.

4.4. *Estimate of the significance of the 1989 quiescence anomaly*

The probability that a quiescence with the observed Z-value is generated by chance in a data set with the characteristics at hand was estimated by the distribution of Z_{max} values in random selections of data as described in the paragraph on method. We did not use the catalog of the entire study area for generating the synthetic catalogs, but we excluded two areas: 1) the aftershock areas of the 1989 and 1994 off-Sanriku earthquakes, and 2) the area containing the erroneous alarm. The reason for this exclusion is that the erroneous data should not be included in estimating the normal background behaviour, and nor should the anomaly we seek to define.

The percent of Z_{max} values in the LTA calculations on the synthetic data set that exceeded the Z_{max} values observed in each of the four analyses of the data are given in table II as the probability of chance occurrence P. As a characteristic value, we used $P = 2.5 \pm 2.49\%$ the median with errors that encompass the smallest and largest values of P (table III).

In addition to the comparison of the observed Z_{max} of the 1989 off-Sanriku quiescence anomaly with the synthetic distribution of Z_{max}, it is of interest to compare it with the observed distribution. The numbers of alarms as a function of the alarm level show the ranking of the quiescences actually present in the data (fig. 7a-d). In this figure the numbers of alarm groups are plotted, where an alarm group is defined as a cluster of adjacent nodes reporting a Z-value larger than the alarm level at the same time.

The two erroneous alarms due to declustering (occurring in separate volumes but in the same general area of the south-west) are the statistically strongest cases in the data sets with M_{min} = 2.0 and 3.0. In the sets with M_{min} = 2.4 and 2.8 the proposed precursor is strongest (fig. 7a-d). Once the erroneous alarms are disregarded, as they must be since they are clearly recognized errors, the proposed precursor is the strongest alarm in all data sets. This uniqueness of significance strongly supports the idea that the quiescence is a precursor, not a chance occurrence.

The percentage of the time-space volume occupied by alarms, dV, at the level of the proposed precursor is estimated by the alarm cube method (Wiemer, 1996; Wyss *et al.*, 1996, 1997; Wyss and Wiemer, 1997). For brevity, figures are not shown, but the values for dV are given in table II. Even though the erroneous alarms are included in this count, the values are minuscule, all below 0.02%.

4.5. *Quiescence before the 1994 off-Sanriku earthquake*

As we argued in the introduction, we believe we cannot reliably define possible precursory quiescence before the large earthquakes that followed the 1989 off-Sanriku earthquake in its close vicinity. Nevertheless, we notice that a near complete absence of seismicity was recorded in a volume using N = 200 (resulting in r = 26 km) surrounding a node within the aftershock zone of the 1994 main shock during the year before it (fig. 8a,b). The radius of this cylinder can be increased to 31 km (N = 290), without adding additional earthquakes during the one year period before the main shock. For a naïve evaluation, that is by eye, the anomaly is impressive, it occurs before and up to the 1994

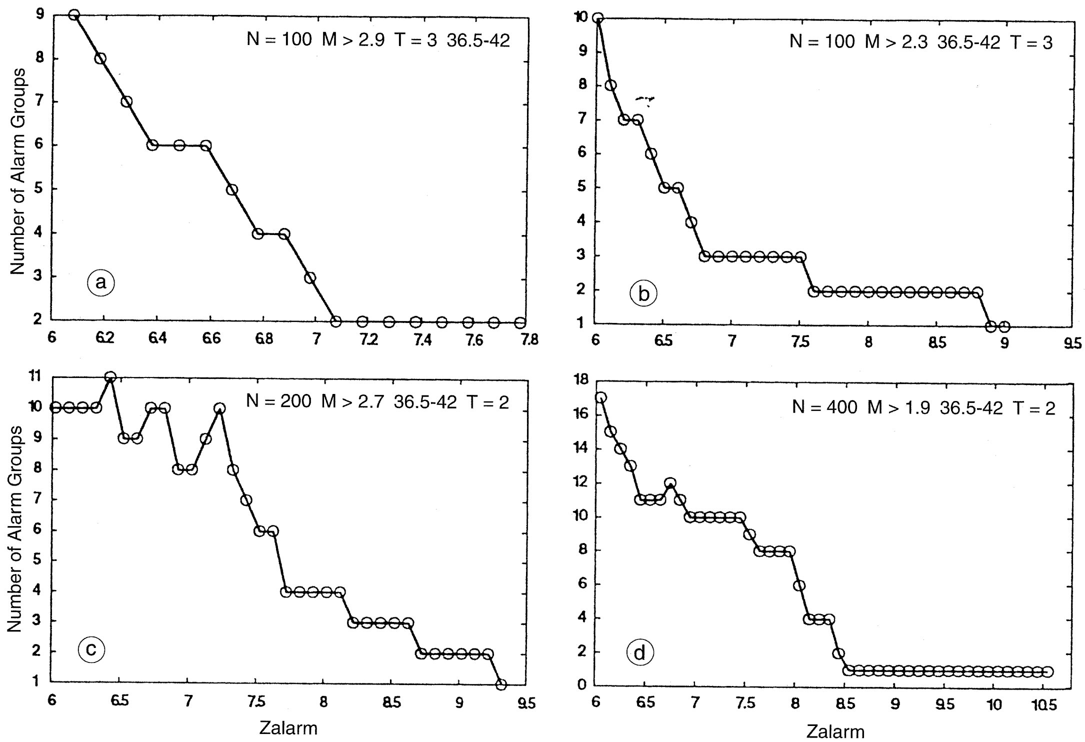

Fig. 7a-d. Numbers of alarm groups as a function of alarm level expressed by a Z-value for the different choices of volume size (r), time window (T_w) and magnitude band used in fig. 4a-d.

event, and its location is within the source volume. Based on this, one may wish to propose the quiescence seen in fig. 8a,b as a precursor to the 1994 M 7.5 main shock. However, there are 46 other instances in the data set, found by the alarm-cube method, for which Z_{max} surpasses that of the 1994 anomaly. Greater uniformity (lower S in eq. (3.1)) in these other data sets is the reason why they can eclipse in significance the anomaly in fig. 8a,b that appears so strong to the eye.

5. Discussion and conclusions

The true extent, in space and time, of a quiescence anomaly is what we would like to measure. However complicated the extent may be, we restrict ourselves to mapping techniques by crude and geometrically inadequate shapes, in order to satisfy requirements for statistical tests. It is most likely that precursory quiescence anomalies have complicated shapes in space that mirror to some extent the complexity of the main shock rupture. For example, the shape of the anomaly could be long but narrow, like the rupture plane, and it could vary in strength of expression, as the amount of slip in the main shock varies. In addition, the critical level of stress, at which quiescence starts may be reached at different times in various parts of the anomalous volume. The obvious strategy to map such a complex phenomenon in space and time would be to modify the sampling shape, in space and time, until the quiescence signal is maximized. However, if we construct an infinitely complex

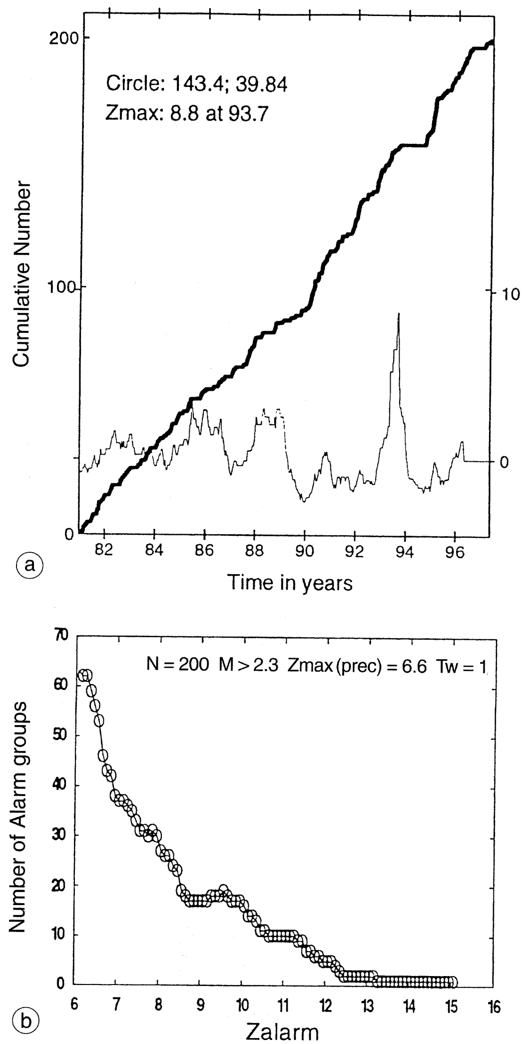

Fig. 8a,b. a) Cumulative numbers of earthquakes as a function of time (1981.0-1997.3) in a volume within the aftershock area of the 1994, M 7.5, off-Sanriku earthquake; b) numbers of alarm groups as a function of the alarm level for T_w = 1 year and M_{min} = 2.4.

shape of the sample boundaries in space and time, we have no means of estimating the probability that we find the observed pattern just by chance. Therefore, we must stick to the application of simple geometric shapes in our effort to define the extent of quiescence anomalies. As a result, we obtain a somewhat fuzzy, possibly distorted picture of the anomaly.

Suppose an anomaly is statistically highly significant, but its shape is long and thin, and we insist on investigating it in spherical volumes, then we may not even notice it because all spheres large enough to include the minimum number of events required for a meaningful analysis have radii larger than the width of the anomaly and reach out into the surrounding space, which is characterized by normal background rate. To deal with this dilemma, we use a double approach: For establishing the existence of the anomaly we need a statistical evaluation of its significance, and hence we strictly stick to the simple sampling shape of a cylinder with the center placed at a random point which is part of a grid without special position, and a time window with length measured in even years and half years. On the other hand, for estimating the true extent of the anomaly we use samples with simple geometric shapes, as those of a rectangle or an aftershock zone.

5.1. *Establishing the existence of a precursory quiescence before the 1989 off-Sanriku earthquake*

We searched for all existing deviations from the average seismicity rate in time and space by the gridding technique, placed them in a matrix and ranked them by their significance, using the Z-value. The filters through which we viewed the seismicity are the free parameters N and T_w, and to some extent also M_{min}. These were varied over a range of values, so we could evaluate how the appearance of anomalies changes with filters. In the shallow earthquake catalog off northern Honshu, three quiescence anomalies competed for first place in significance. These are the three first anomalies that are recognized in fig. 7a-d, when lowering the alarm level starting from infinitely high values. Two of these top alarms were located between 37° and 38°N and turned out to be erroneous alarms, created by the declustering process. The cumulative number curve for one of these erroneous alarms shows how the high seismicity rate in the original catalog is reduced to nearly no activity in the declustered data (fig. 6a,b). This regrettable phenomenon occurs often in declustering (Eneva *et al.*, 1995). These two erroneous alarms may not be the only ones generated by declustering, but others were not investigated because they did not compete in rank with the proposed precursor.

The alarm that remained at the top of the significance scale (fig. 7a-d), after removing from consideration the erroneous alarms, started in 1987.3 ± 1 year and lasted for 2.5 ± 1 years (fig. 5a-f). This means it occurred before and lasted up to the 1989 off-Sanriku *M* 7.1 earthquake. Mapping the 1987-1989 quiescence, we found that its strongest expression was located in the eastern and southern-most part of the aftershock area, depending on the filter used to view it (fig. 4a-d).

Thus we conclude that the most significant quiescence anomaly in the Tohoku earthquake catalog for the eastern off-shore area during the years 1985-1997.3 occurred before and up to the 1989 off-Sanriku main shock, and it overlapped in space with the aftershock volume. This means that the quiescence fulfills the association rules and qualifies formally as a precursory seismic quiescence.

5.2. *Estimating the statistical significance of the precursory quiescence before the 1989 off-Sanriku earthquake*

The *Z*-value itself is useful to classify the relative significance of episodes of low activity within each data set studied. For a fixed set of parameters, the quiescence with the largest *Z*-value is the most significant, and other significant anomalies can be identified by the alarm-cube technique (Wiemer, 1996; Wyss *et al.*, 1997) and ranked, according to the plots of alarm number *versus* alarm level (fig. 7a-d). In this relative ranking the precursory quiescence to the 1989 off-Sanriku earthquake is in first place. The fact that this anomaly is unique in the 16 year catalog available suggests strongly that it is significant at a high level. However, to compare the anomaly's ranking with other case histories and to evaluate the probability of its chance occurrence, we generated numerous synthetic catalogs, as described above, and calculated the distribution of Z_{max}-values that occurred in these simulation of the experiment. Synthetic distributions were calculated for the cases of each N, T_w and M_{min} combination used. From the number of synthetic Z_{max}-values that occurred in 1% or 5% of the cases only, we could then estimate the probability with which the observed Z_{max}-values were to be expected by chance (table II). These probabilities were very low in all combinations of the free parameters, on average $P = 2.5 \pm 2.49\%$ (table III). We thus conclude that the precursory quiescence before the 1989 off-Sanriku earthquake was unlikely to have occurred by chance, and even more unlikely to have been correlated by chance with the only large earthquake available in the data for testing the quiescence hypothesis.

5.3. *The quiescence episode before the 1994 (M 7.5) off-Sanriku earthquake*

In the circumstances of disturbed, but declustered, seismic activity after the 1989 *M* 7.1 off-Sanriku earthquake it is difficult to make a quantitative measurement of possible precursory quiescence. We identified a period of one year with near complete absence of earthquakes in a volume with radius up to 31 km in the aftershock zone of the 1994 rupture. Although this quiescence is quite clearly seen by inspection of the cumulative number curve (fig. 8a), and although it correlates perfectly in time and space with the 1994 main shock, we cannot claim it as a precursor with confidence. The fact that it ranks only 46th in significance, topped by alarms that were not followed by main shocks (fig. 8b), shows that one cannot make a case that this quiescence was not correlated by chance.

The 1994 quiescence ranks relatively low, although the activity had dropped to almost zero. It is disappointing that a nearly 100% drop in seismicity cannot be identified as a precursor with high confidence. The reasons for the relatively low ranking are that the period of one year is too short and the earthquake production rate was not as uniform as in some other volumes. One-year periods with nearly no seismicity are not uncommon in all the regional and local earthquake catalogs we have studied. The significance of a rate decrease in cases of a drop to zero activity depends on the standard deviation of the background rate (eq. (3.1)). In this data set the top ranked one year quiescence ($Z = 15$) shows an extraordinarily steady production of earthquakes over the entire catalog period. The 1994 quiescence in the source volume of the M 7.5 off-Sanriku earthquake of that year was not lacking in the amount of quiescence, but in the relatively low degree of uniformity (large S in eq. (3.1)) of background seismicity, and that may in part have been due to the occurrence of the neighboring 1989 main shock.

The relatively low ranking of the 1994 quiescence does not mean that it was not a precursor, it only means that we cannot claim it as a precursor with high confidence. Thus we conclude that there existed a quiescence of 90% rate decrease before the 1994 off-Sanriku main shock that conformed to the association rules. Because it did not rank statistically high enough to be claimed as a precursor with high confidence due to its short duration of one year, we will treat it as a possible, but not confirmed precursory quiescence.

5.4. *Comparison of the off-Sanriku precursory quiescences with other mapped quiescences*

The quiescences mapped quantitatively in detail in this study, based on a regional catalog with magnitudes down to $M = 2$, cannot be compared with the results of Ogata (1992), because these were based on $M > 5$ events in very much larger volumes than the study area considered here. Our results are most comparable to those of Katsumata and Kasahara (1996) who used the same quantitative method we used. The M 8.1 earthquake they studied was preceded by a longer lasting quiescence of 6 years (table IV). The results of Taylor *et al.* (1991) and Takanami *et al.* (1996) are hard to interpret. Although they claim quiescences (table IV) and map them, they give no information on how they estimated the duration, and they did not assess the significance of their claimed rate changes. They only indicate the percent of rate change, which could be meaningless if it is based on small numbers of events (a drop of 70% from 10 to 3 events, for example).

The results of Wyss *et al.* (1996) are most readily compared to our results here because they were derived by the same method, and all parameters of their quiescence are defined (table IV). However, the Izu-Oshima earthquake was a strike-slip event in the upper plate, thus different scaling laws may exist than in interplate thrust events as the off-Sanriku cases.

If we use the largest quiescence durations and the largest dimensions for the cases estimated quantitatively in all aspects (Izu-Oshima M 6.5, off-Sanriku M 7.1, Hokkaido M 8.1), then one could argue that the precursor time as well as the anomaly dimensions scale with the size of the main shock (table IV). However, since we have only three data points we do not put enough stock in this result to calculate a regression line.

Table IV. Characteristics of quantitatively mapped precursory quiescences off Japan.

Date	Name	Location	M	t_Q (yr)	Size (km)	P (%)	References
21 03 1982	Urakawa-oki	42.17/142.59	7.1	2			Taylor *et al.* (1991)
02 11 1989	Sanriku-oki	39.86/143.06	7.1	3.5	50 to 100	0.1	This study
20 02 1990	Izu-Oshima	34.71/139.3	6.5	2.5	10 to 30	1	Wyss *et al.* (1996)
04 10 1994	Hokkaido-Toho	43.37/146.79	8.1	3			Takanami *et al.* (1996)
same	same	same	8.1	6.5			Katsumata and Kasahara (1996)

We conclude that some large main shocks in Japan are preceded by precursory seismic quiescence within and near their source volume, and that the modern regional earthquake catalogs allow the detailed quantitative mapping of this phenomenon.

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REFERENCES

ARABASZ, W.J. and S.J. HILL (1996): Applying Reasenberg's cluster-analysis algorithm to regional earthquake catalogs outside California, *Seism. Res. Lett.*, **67**, 30.

DIETERICH, J.H. (1978): Preseismic fault slip and earthquake prediction, *J. Geophys. Res.*, **83**, 3940-3948.

ENEVA, M., R.E. HABERMANN and M.W. HAMBURGER (1995): Artificial and natural changes in the rates of seismic activity: a case study of the Garm region, Tajikistan (CIS), *Geophys. J. Int.*, **116**, 157-172.

HABERMANN, R.E. (1983): Teleseismic detection in the Aleutian Island arc, *J. Geophys. Res.*, **88**, 5056-5064.

HABERMANN, R.E. (1991): Seismicity rate variations and systematic changes in magnitudes in teleseismic catalogs, *Tectonophysics*, **193**, 277-289.

HASEGAWA, A. and T. MATSUZAWA (1995): Seismological characteristics of the 1994 Far-Off-Sanriku earthquake, *J. Jpn. Geotech. Soc.*, **43**, 3-8.

HASEGAWA, A., N. UMINO and A. TAKAGI (1978): Double-planned deep seismic zone and upper-mantle structure in the Northeastern Japan arc, *Geophys. J. R. Astron. Soc.*, **54**, 281-296.

HASEGAWA, A., N. UMINO and A. TAKAGI (1985): Seismicity in the Northeastern Japan arc and seismicity patterns before large earthquakes, *Earthquake Pred. Res.*, **3**, 607-625.

HASEGAWA, A., S. HORIUCHI and N. UMINO (1994): Seismic structure of the Northeastern Japan convergent margin: a synthesis, *J. Geophys. Res.*, **99**, 22295-22311.

HINO, R., T. KANAZAWA and A. HASEGAWA (1996): Interplate seismic activity near the Northern Japan trench deduced from ocean bottom and land-based seismic observations, *Phys. Earth Planet. Inter.*, **93**, 105-121.

KATSUMATA, K. and M. KASAHARA (1996): Synchronized changes in seismicity and crustal deformation rate prior to the Hokkaido Toho-oki earthquake (M_w = 8.3) on October 4, 1994, in *Proceedings of Japan Earth and Planetary Science Joint Meeting*, p. 433.

KISSLINGER, C. (1988): An experiment in earthquake prediction and the 7 May 1986 Andreanof Islands earthquake, *Bull. Seismol. Soc. Am.*, **78**, 218-229.

MATSU'URA, R.S. (1986): Precursory quiescence and recovery of aftershock activity before some large aftershocks, *Bull. Earthquake Res. Inst., Univ. Tokyo*, **61**, 1-65.

MIURA, S., K. TACHIBANA, T. SATO, K. HASHIMOTO, M. MISHINA, N. KATO and T. HIRASAWA (1994): Postseismic slip events following interplate thrust earthquakes occurring in subduction zone, in *Proceedings of the Eighth International Symposium on Recent Crustal Movements*, Kobe, pp. 83.

NAKAHARA, H., T. NISHIMURA, H. SATO and M. OHTAKE (1998): Seismogram envelop inversion for the spatial distribution of high-frequency energy radiation from the earthquake fault: application to the 1994 far east off-Sanriku earthquake, Japan, *J. Geophys. Res.*, **103**, 855-868.

NAKAYAMA, W. and M. TAKEO (1997): Slip history of the 1994 Sanriku-Haruka-Oki, Japan, earthquake deduced from strong-motion data, *Bull. Seismol. Soc. Am.*, **87**, 918-931.

OGATA, Y. (1992): Detection of precursory relative quiescence before great earthquakes through a statistical model, *J. Geophys. Res.*, **97**, 19845-19871.

OHTAKE, M., T. MATUMOTO and G.V. LATHAM (1977): Seismicity gap near Oaxaca, Southern Mexico, as a probable precursor to a large earthquake, *Pageoph*, **115**, 375-385.

OHTAKE, M., T. MATUMOTO and G.V. LATHAM (1981): Evaluation of the forecast of the 1978 Oaxaca, Southern Mexico earthquake based on a precursory Seismic quiescence, in *Earthquake Prediction, Maurice Ewing Series, Am. Geophys. Union*, **4**, 53-62.

OMORI, F. (1900): Investigation of aftershocks, *Report of Imperial Earthquake Investigation Committee*, **30**, 4-29.

REASENBERG, P.A. (1985): Second-order moment of Central California Seismicity, *J. Geophys. Res.*, **90**, 5479-5495.

SCHOLZ, C.H., L.R. SYKES and Y.P. AGGARWAL (1973): Earthquake prediction: a physical basis, *Science*, **181**, 803-810.

STUART, W.D. (1979): Strain softening prior to two-dimensional strike slip earthquakes, *J. Geophys. Res.*, **84**, 1063-1070.

TAKANAMI, T., S.I. SACKS, J.A. SNOKE, Y. MOTOYA and M. ICHIYANAGI (1996): Seismic quiescence before the Hokkaido-Toho-Oki earthquake of October 4, 1994, *J. Phys. Earth*, **44**, 193-203.

TANIOKA, Y., L. RUFF and K. SATAKE (1996): The Sanriku-oki, Japan earthquake of December 28, 1994 (M_w 7.7): rupture of a different asperity from a previous earthquake, *Geophys. Res. Lett.*, **23**, 1465-1468.

TAYLOR, D.W.A., J.A. SNOKE, I.S. SACKS and T. TAKANAMI (1991): Seismic quiescence before the Urakawa-Oki earthquake, *Bull. Seismol. Soc. Am.*, **81**, 1255-1271.

UNIMO, N. and A. HASEGAWA (1975): On the two-layered structure of the deep seismic plane in the Northeastern Japan arc, *J. Seismol. Soc. Japan*, **28**, 125-139.

UMINO, H., A. HASEGAWA and T. MATSUZAWA (1995): *sP* depth phase at small epicentral distances and estimated subducting plate boundary, *Geophys. J. Int.*, **120**, 356-366.

WIEMER, S. (1996): Analysis of seismicity: New techniques and case studies, *Dissertation Thesis*, University of Alaska, Fairbanks, Alaska.

WIEMER, S. and M. WYSS (1994): Seismic quiescence before the Landers (M = 7.5) and Big Bear (M = 6.5) 1992 earthquakes, *Bull. Seismol. Soc. Am.*, **84**, 900-916.

WYSS, M. (1991): Reporting history of the Central Aleutians seismograph network and the quiescence preceding the 1986 Andreanof Island earthquake, *Bull. Seismol. Soc. Am.*, **81**, 1231-1254.

WYSS, M. and R.E. HABERMANN (1988): Precursory seismic quiescence, *Pageoph*, **126**, 319-332.

WYSS, M. and S. WIEMER (1997): Two current seismic quiescences within 40 km of Tokyo, *Geophys. J. Int.*, **128**, 459-473.

WYSS, M., K. SHIMAZAKI and T. URABE (1996): Quantitative mapping of a precursory quiescence to the Izu-Oshima 1990 (M 6.5) earthquake, Japan, *Geophys. J. Int.*, **127**, 735-743.

ZHAO, D., T. MATSUZAWA and A. HASEGAWA (1997): Morphology of the subducting slab boundary and its relationship to the interplate seismic coupling, *Phys. Earth Planet. Inter.*, **102**, 89-104.

ZUNIGA, R. and M. WYSS (1995): Inadvertent changes in magnitude reported in earthquake catalogs: influence on b-value estimates, *Bull. Seismol. Soc. Am.*, **85**, 1858-1866.