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Seismic quiescence precursor to the 1983 Nihonkai-Chubu (M 7.7) earthquake, Japan

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Abstract
We analyzed the seismicity of Northern Honshu-Hokkaido region using the declustered earthquake catalog compiled by the Japan Meteorological Agency (JMA), for the period between January 1970 and December 1994. Making use of the ZMAP software tool, we sought to determine whether the quiescence hypothesis is applicable to 16 main shocks ($M \geq 7.0$) of the JMA catalog. We found a highly significant seismic quiescence prior to the May 26, 1983 Nihonkai-Chubu, M_J 7.7, earthquake. The quiescence that preceded the event lasted more than 3.5 years, and was located in the Japan Sea, off Akita and Aomori Prefectures. It was characterized by a standard deviate $Z = 7.4$ ($T_w = 3$ years), within a volume of approximately 200 by 300 by 40 km around the hypocenter. This volume contained 16 earthquakes ($M \geq 3.8$) during the background period which lasted more than 8 years preceding the quiescence, and none during this one. A high concentration of seismic activity exceeding 15 events per year followed the main shock before the rate returned back to the previous value. No quiescence was observed before another strong event of magnitude 7.8 which occurred on July 12, 1993, 200 km north of the former, while three quiescences with the same Z-value were observed in the same region and in the same time period, not followed by any main shocks (false alarms). The probability that the Nihonkai-Chubu earthquake correlated at random with the quiescence period is estimated as approximately 1%, based on the fraction of space-time covered by alarms. The seismicity rate variations observed before and after the 1983 Nihonkai-Chubu earthquake are similar to those observed in the rupture area of the 1980 Irpinia (Italy), M 6.9 earthquake.

Key words *precursory seismic quiescence – ZMAP software tool - Z-test – false alarm*

1. Introduction

The Japan Sea earthquake of May 26, 1983 at 40.68°N, 139.09°E was one of the largest and most destructive events that ever occurred on the Japan Sea side of the Japanese islands (off Akita and Aomori Prefectures), causing a destructive tsunami as well. The Japan Meteorological Agency (JMA) named this earthquake the Nihonkai-Chubu earthquake of 1983 and determined its magnitude, M_J, as 7.7. Apart from the large size of this earthquake, its location is particularly interesting since it occurred on the eastern margin of the Japan Sea where seismicity is much lower and the recurrence time of large earthquakes is longer than that of large earthquakes on the Pacific Coast. This region is a convergence boundary between the Eurasian and the North American plates (Satake, 1986), with a low convergence speed (Kanamori and Astiz, 1985). Many studies have been written on this event because of its tectonic significance and size. Kanamori and Astiz (1985) assumed this was an inter-plate earthquake and gave an estimate of its repeat time between 180

Mailing address: Dr. Maura Murru, Istituto Nazionale di Geofisica, Via di Vigna Murata 605, 00143 Roma, Italy; e-mail: murru@ing750.ingrm.it and 320 years, assuming a completely seismic slip. The source process of the Nihonkai-Chubu earthquake of 1983 was studied by using the long-period waves and tsunamis (*e.g.,* Satake, 1985). The moment tensor solution and first-motion data indicate that the mechanism is dip-slip and the seismic moment is 7.6×10^{27} dyne · cm. The fault size was estimated to be 120 km in length and 40 km in width; the aftershocks distribution suggested that the fault plane was dipping eastward.

Large scale crustal movements before and after the 1983 Japan Sea earthquake were reported by Ishii *et al.* (1986), while episodic aseismic strain signal precursors associated with this event were cited by Linde *et al.* (1988). These phenomena have been claimed to be precursors of the 1983 main shock, as discussed by the IASPEI Sub-commission on Earthquake Prediction (Wyss, 1991).

The Nihonkai-Chubu earthquake provided an opportunity to test the seismic quiescence hypothesis with the methodology of Wiemer and Wyss (1994) and Wiemer (1996) that uses the computer tool called ZMAP. This visualization technique investigates in detail the stability and changes in the seismicity rate as a function of time, space and magnitude band. Moreover, it is able to measure quantitatively the significance of the anomaly, the percent of time-space covered by alarms and the conditions under which a correlation of a quiescence episode with a main shock can be accepted.

Previous case studies have considered the spatio-temporal patterns of seismicity before the occurrence of large earthquakes, including the phenomenon of precursory quiescence, as important tools for understanding seismo-tectonic processes (*e.g.,* Mogi, 1969; Wyss and Habermann, 1988a; Habermann, 1991; Taylor *et al.*, 1991; Ogata, 1992; Wiemer and Wyss, 1994; Wyss *et al.*, 1996a, 1997). These studies usually show a rate decrease of more than 50% in all magnitude bands above the minimum magnitude of homogeneous reporting ($M_{\min}$) useful for analysis.

Precursory seismic quiescence is defined (Wyss and Habermann, 1988b) as a significant decrease (according to some clearly established standard criteria) in mean seismicity rate, as compared with the preceding declustered background rate (*i.e.* the independent component of seismicity), within all or a major part of the source volume. The rate decrease, which can last between one and several years, must precede and lead up to the time of the main shock, or may be separated from it by a relatively short period of increased seismicity rate. The dependence of the duration of the precursory quiescence on the expected main shock magnitude (Wyss and Fu, 1989) and the quiescence dimensions with respect to those of the source volume of the likely main shock are not yet well known. They may also be a function of the tectonic environment (Wyss and Habermann, 1988b; Wyss *et al.*, 1997). Thus it is difficult to know what characteristics of quiescence to expect, and it is uncertain whether quiescence occurs in all tectonic settings. The hypothesis that seismic quiescence precedes some main shocks assumes that in most crustal volumes the independent component background seismicity rate does not change with time over extended periods. Constant rates of background earthquake production, without clusters, have been demonstrated for many crustal volumes (*e.g.,* Wyss *et al.*, 1996a). In this paper we seek to determine whether the quiescence hypothesis is applicable to the main shocks ($M \geq 7.0$) in the data set recorded by JMA since 1970.

2. Data and method of analysis

We performed our analysis using the JMA catalog limited to the area bounded by latitudes 28° to 47.8°N and longitudes 125° to 150°E. It contains 45 960 events ($M \geq 3.0$) for hypocentral depths less than 70 km.

For the quantitative analysis of seismic quiescences it is necessary to use a declustered earthquake catalog. To separate the dependent earthquakes (aftershocks, foreshocks, swarms and doublets) from the independent ones we used Reasenberg's (1985) algorithm. The algorithm removes the clustered events and replaces them with a single event with a magnitude equivalent in energy to that of the total cluster. The declustering process reduced the catalog to 25 530 events.

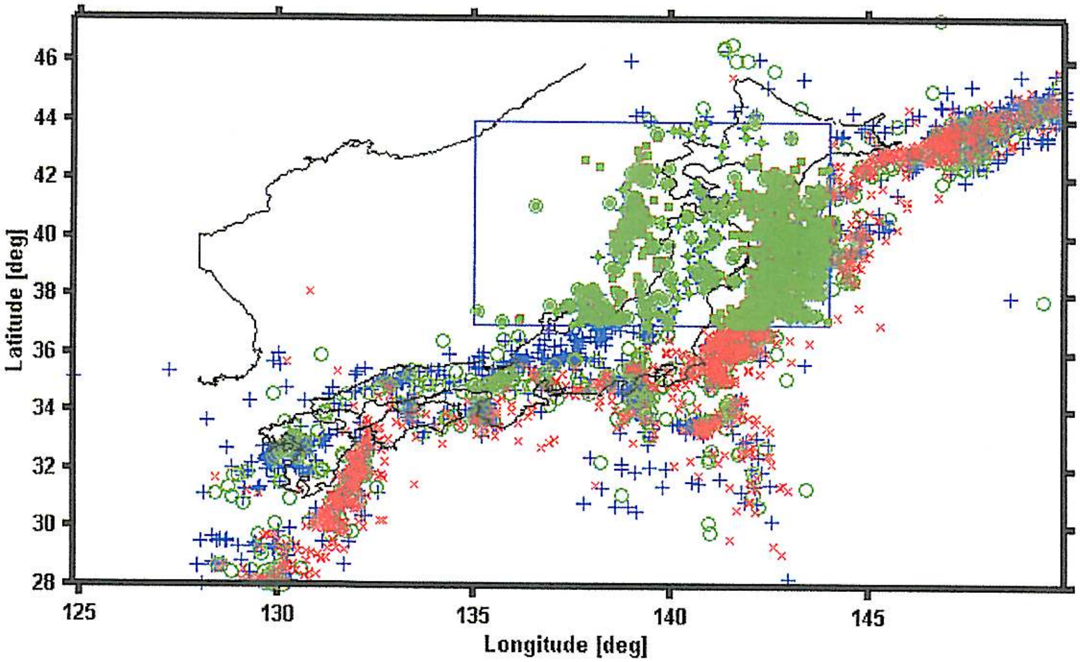


Fig. 1. Epicenter map of the Japan area for the declustered catalog containing 4752 events ($M \geq 3.8$ and depth $H \leq 40$ km) that occurred during the period 1970-1994. Clustered events are replaced by one equivalent earthquake. The rectangle defines the area chosen for the following analysis. Pluses, circles and crosses refer to hypocentral depth ranges down to 12, 24 and 40 km depth, respectively.

Using the computer code «Genas» (Habermann, 1983), to evaluate significant rate changes in background seismicity, the minimum magnitude of homogeneous reporting (M_{min}) was estimated equal to 3.8. Only the events with $M \geq M_{\text{min}}$ and with hypocenters between 0 and 40 km depth were included in the following analysis (fig. 1). In fig. 2, from the declustered catalog, we have reported the cumulative number of events ($M \geq 3.8$, depth $H \leq 40$ km) *versus* time: the constant slope of the curve confirms that the reporting was homogeneous at the magnitude level selected.

We investigated the area to test the quiescence hypothesis for the period preceding the main shocks listed in the declustered catalog with $M \geq 7.0$ (table I). We rejected the main shocks which occurred before 1975 (for lack of a period of previous observation lasting at least four years before the main shocks) and those which occurred in volumes not covered adequately by the catalog, or in volumes where no seismicity existed before the event. To produce a near-continuous image of the rate changes in space and time (ZMAP), we constructed an arbitrarily positioned grid spaced by 0.25°, moving the time by 28-day intervals for a total of 24 years.

For each grid point, a long-term average function, LTA(t), was computed on the nearest 100 events, using the standard deviate Z-test (*e.g.*, Habermann, 1983; Wyss and Burford, 1985) for a statistical evaluation of the confidence level

$$Z = (R_1 - R_2)/(S_1/N_1 + S_2/N_2)^{1/2}$$

where R_1 and R_2 are respectively the long-term mean rate in the data set from the beginning to the end and that of the data within a moving time window, T_w, in the same crustal volume; N_1 and N_2 are the number of samples in the two

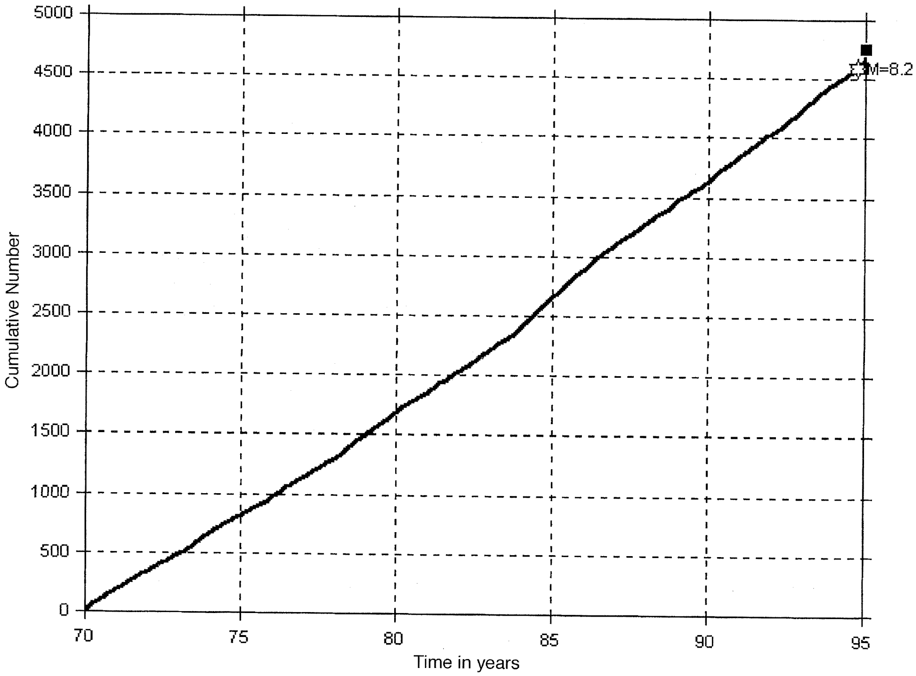


Fig. 2. Cumulative number of events for $M \geq 3.8$ and hypocentral depth $H \leq 40$ km as a function of time for the declustered catalog, in the area defined in fig. 1.

Table I. Independent events for the declustered catalog ($M \geq 7.0$, from January 1975 to July 1993) for the area bounded by latitudes 28° to 47.8°N and longitudes 125° to 150°E.

Year	Month	Day	Long.	Lat.	Depth (km)	M(JMA) equivalent
78	1	14	139.13	34.76	2.4	7.0
78	3	23	149.41	44.26	46.1	7.3
78	6	12	142.35	38.30	34.6	7.4
81	1	19	143.14	38.49	6.4	7.2
82	3	21	142.52	42.08	35.8	7.1
82	7	23	141.60	36.41	40.7	7.1
83	5	26	139.09	40.68	24.5	7.8
87	2	6	141.86	37.04	37.5	7.2
89	11	2	143.56	39.60	5.8	7.3
92	7	18	143.67	39.38	5.4	7.3
93	7	12	139.27	42.29	20.9	7.8

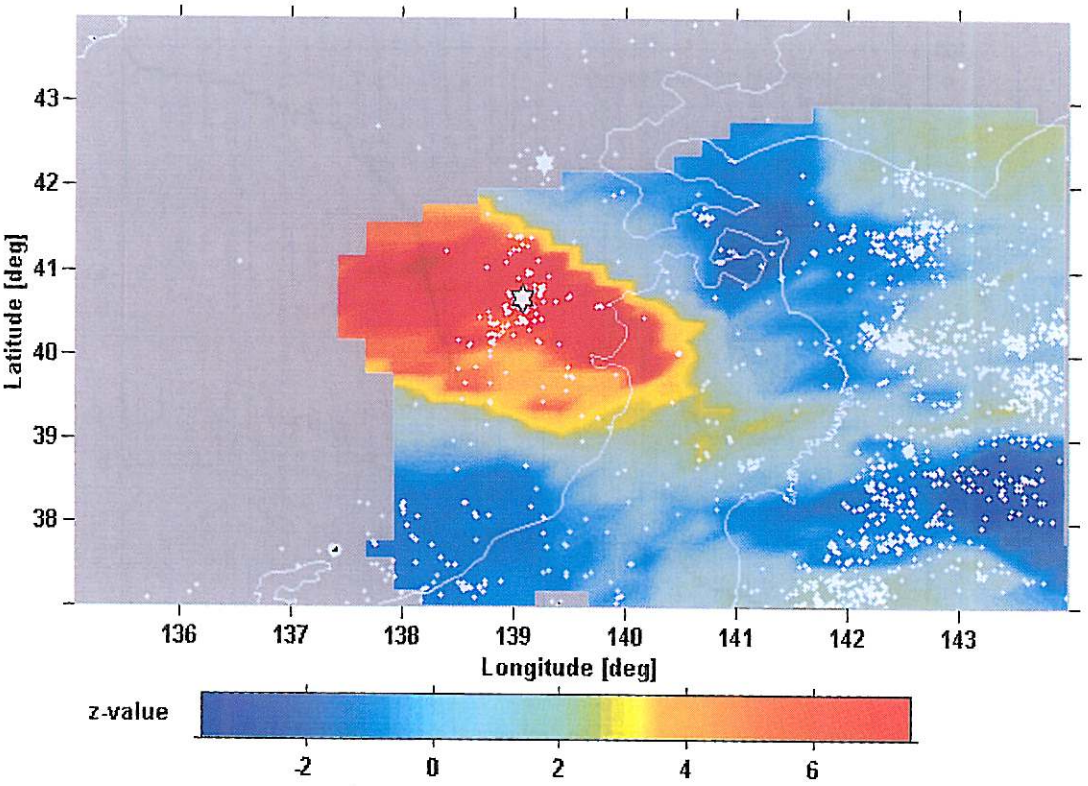


Fig. 3. ZMAP representing seismic quiescence comparing the rate in a 3 year window starting in 1979.0 to the overall average rate (1970.0-1995.0) at every node of a grid with 0.25° spacing. The number of events at each node, $N = 100$, is constant. The minimum magnitude used was 3.8, and the maximum depth 40 km. The star placed on the red area marks the epicenter of the May 1983, M_j7.7, Nihonkai-Chubu earthquake while the other one is relative to the main shock of the July 1993, M_j7.8. Red indicates highly significant seismic quiescence.

time periods, and S_1 and S_2 are the standard deviations of the respective mean rates. We made various Zmaps, keeping the length of the time window at 3.0 years, but considering four different time-window starts: 3.0, 3.5, 4.0, 4.5 years before each main shock. From the observation and analysis of these maps we conclude that the only main shock that can be correlated with an anomalous period using this data set is that of the May 26, 1983 ($M_j = 7.7$). This quiescence is better visible for a start time of 1979 using a window of 3 years ($r_{max} = 180$ km) (fig. 3).

The range of blue to yellow marks the areas of small changes, while the shades of red indicate highly significant seismic quiescence.

The plot of the cumulative number of earthquakes, in a volume containing 100 events ($r \leq 101.8$ km) centered roughly on the May 26, 1983 main shock shows a total absence of events during about 3.5 years before this event (fig. 4). After the main shock, the rate of declustered seismicity increases considerably till about 1988. After this period, the rate returns slowly to the value observed before the anomaly. The plot of the Z-value in the same figure shows a peak ($Z = 7.4$), corresponding to the beginning of the window that covers the period without earthquakes.

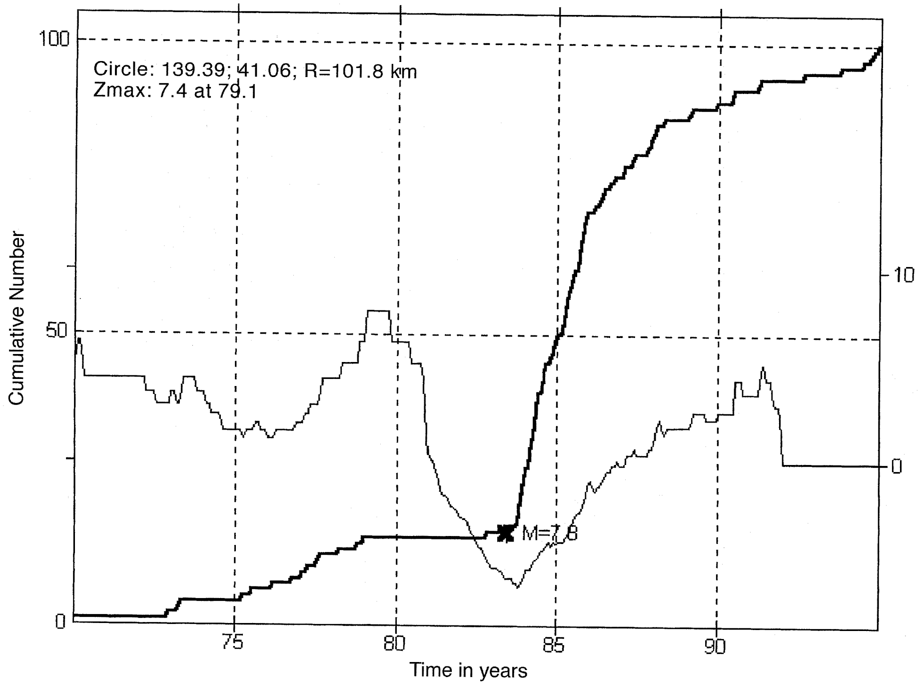


Fig. 4. Cumulative number of earthquakes from the declustered catalog (1970.0-1995.0) as a function of time, in a volume of radius 101.8 km containing 100 events centered approximately on the main shock of 83/05/26. All events reported with a magnitude $M \geq 3.8$ and $H \leq 40$ km are considered, and no magnitude correction is applied to the declustered catalog. The cross marks the time of the main shock. The thin line represents the LTA(t) function showing the Z-values comparing the mean rate within a moving time window of 3 years with the overall mean (1970.0-1994.0).

3. Statistical significance of the precursory seismic quiescence before the Japan Sea earthquake on May 26, 1983

To better test the precursory quiescence hypothesis, we restricted our investigation to the area inside the polygon represented in fig. 1 for the events with $M \geq 3.8$. We made further calculations in order to verify the influence of some parameters on the quiescence evidence. We have analyzed the changes of quiescence significance both in relation to the number of events included in each sample (N = 60, 80, 100, 150 and 200) and in relation to the time window length T_w (3.0, 3.5, 4.0, 4.5 years).

We used a volume with radius $r \leq 101.8$ km containing 100 events centered roughly on this main shock (41.06°N, 139.39°E), the quiescence significance does not change with the number of earthquakes at each node but only with the time window length (T_w). The $Z_{\max}$ value is 7.4 with $T_w = 3$ years and 6.5 with $T_w = 4$ years. The standard deviate Z-test gives the maximum value (7.5) when the time window duration T_w coincides with the real quiescence duration (about 3.5 years).

To make all the alarms visible and to detect false alarms (seismic quiescences not followed by a main shock) present in a data set for a given alarm threshold, we performed the alarm-cube analysis introduced by Wyss *et al.* (1996a). This analysis is of interest to evaluate the usefulness of precursory quiescences for prediction. An alarm is defined as the occurrence of $Z > Z_{\text{alarm}}$

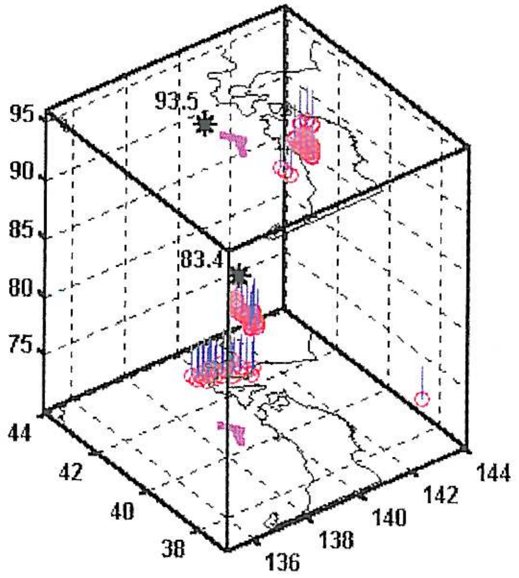


Fig. 5. The positions in time and space of all alarms with $Z > 7.6$ are shown in an alarm cube. Latitude and longitude are plotted as coordinates at the bottom, time in years progresses upward. The map at the bottom outlines the Japan coastlines. The occurrence in space and time of the Nihonkai-Chubu earthquake is marked by the lowest asterisk, and the two fault segments concerning the event are shown in pink color. Circles are beginnings while bars show alarms duration.

for the LTA function in any of the grid points. To minimize the number of false alarms, we selected an alarm level above $Z_{\text{alarm}} = 7.6$. All alarms as a function of location and time are plotted in fig. 5. In this figure, taking into account that the quiescence lasted more than 3.5 years, we show the alarm-cube for the LTA function obtained comparing the mean seismicity rates in 3-years sliding time windows to the long-term mean (1970.0-1995.0). The coordinates at the bottom of the cube are the longitude and the latitude, and the vertical axis is time progressing upward. The beginning of an alarm is marked by a circle, and the duration of it by a straight line. A number of alarms can be counted as a single group according to their vicinity in space and time.

Among the four groups of alarms found in the alarm-cube, only one group is related to the precursor proposed. The number of alarm groups and the percent of time-space covered by alarms are plotted as function of the alarm threshold in fig. 6a,b. We see that only a small percentage, approximately 1%, of space and time is covered by alarms at the $Z = 7.6$ alarm level.

In order to investigate how the statistical significance level of Z depends on the characteristics of the data set (Matthews and Reasenberg, 1987, 1988), we proceeded with the following procedure based on synthetic data:

– 100 samples containing each $N = 100$ events were drawn at random from the data set, regardless of location, but maintaining their origin time, and $T_w = 3$ years. This allowed a statistical analysis on 28 500 Z-values to be performed, obtaining a mean of 0.1269 and a standard deviation of 1.078. Assuming that the Z

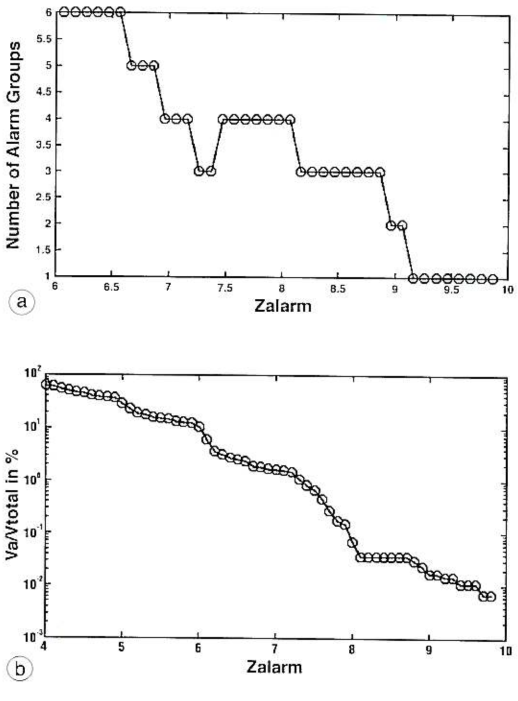
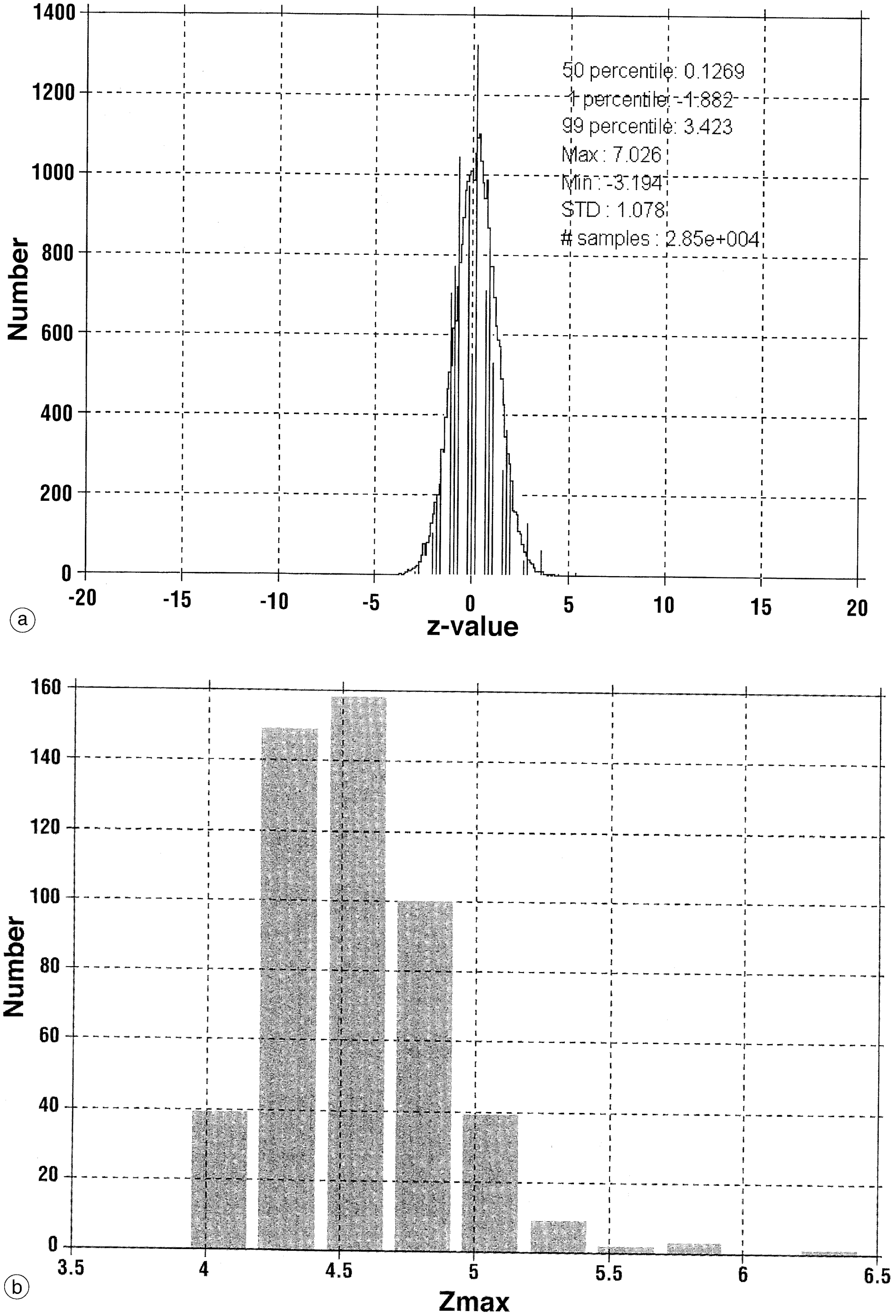


Fig. 6a,b. a) Number of alarm groups and (b) percent of alarms as a function of alarm threshold in the Japan Sea off Akita and Aomori Prefecture for the case of the $N = 100$ grid. Alarms last 3 years, the period of the window used for the LTA functions.


1400
1200
1000
800
600
400
200
0
Number
50 percentile: 0.1269
1 percentile: -1.882
99 percentile: 3.423
Max : 7.026
Min : -3.194
STD : 1.078
samples : 2.85e+004
-20
-15
-10
-5
0
5
10
15
20
z-value
a
160
140
120
100
80
60
40
20
0
Number
3.5
4
4.5
5
5.5
6
6.5
Zmax
b

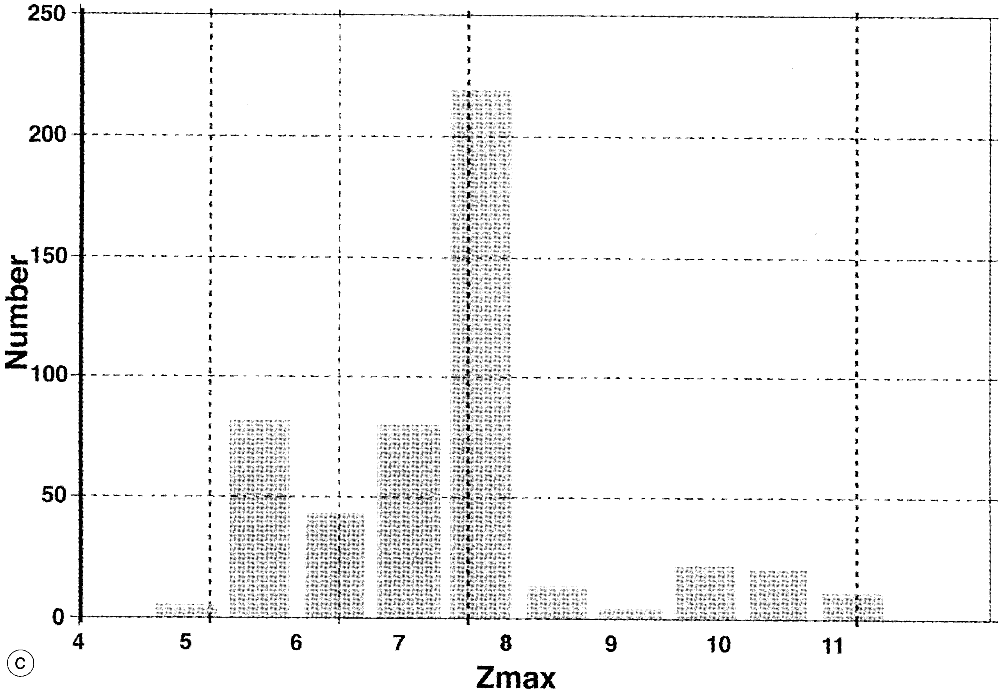


Fig. 7a-c. Valuation of the significance level corresponding to the 7.4 *Z*-value found for the precursory seismic quiescence to the May 26, 1983, earthquake: a) random *Z* statistical distribution, regardless of event location; b) synthetic random *Z*-population, with the mean, the standard deviation and the number of *Z*-values observed; c) estimate of the distribution of Z_{max} in the real data set with samples selected at random, regardless of event location.

statistical distribution is normally distributed (fig. 7a), we generated a synthetic random *Z*-population with the same mean and standard deviation. Repeating this process 500 times we computed that the largest synthetic Z_{max} was from 6.0 to 6.5 (fig. 7b). Thus the $Z = 7.4$ score is clearly anomalous at a significant level above 99% in comparison to a synthetic data set.

– For comparison, we computed *LTA* functions ($T_w = 3$ years) for data sets of $N = 100$ events selected at random in the same way and retained Z_{max} for each. This process was repeated 500 times, and a Z_{max} value was retained for each case, to define the Z_{max} distribution (Wiemer, 1996). Using this second method, however, the Z_{max} obtained is often larger than Z_{max} (7.4). The largest value found by random sampling of the real catalog is 10.7 (fig. 7c).

4. Discussion and conclusions

To verify that the May 26, 1983, earthquake was really preceded by a precursory seismic quiescence we chose an 80-km-wide and 500-km-long cross-section AB (from 39.5°N, 138.5°E to 44.0°N, 139.0°E) as a function of time, containing both the fault plane outlined by the May 26, 1983, aftershock sequence and that one of July 12, 1993 ($M_J = 7.8$) (fig. 8). Over the 3 years before the May 26, 1983, earthquake, the volume of its rupture was practically devoid of earthquakes. After the occurrence of this event there was a renewed activity, as also appears in the cumulative number curve in fig. 4. This shows that the quiescence was not due to excessive declustering and continued up to the main shock.

In conclusion, we propose that the JMA catalog really contains seismicity rate decreases that are strong, some of which are not correlated to a main shock (false alarms). This is the case, for example, of the largest Z-value ($Z_{\mathrm{alarm}} = 9.8$) found in this analysis (fig. 6a). The anomaly, starting in 1991, was located in the area bounded by latitude 40.0° to 42.5°N and longitude 141.5° to 143.0°E (southern coast of Hokkaido).

To confirm that this anomaly was really a false alarm starting at the beginning of 1993 (fig. 5), we considered the data collected by IRIS (the Incorporated Research Institutions for Seismology) from 1995 to 1996: no event with $M \geq 7.0$ has been reported since 1994 in that area. The precursory seismic quiescence prior to the May 26, 1983 event shows a similar behaviour to that of a case studied by Wyss *et al.* (1997) in Southern Italy related to the November 23, 1980, Irpinia earthquake (M_s 6.9). This normal-faulting event that ruptured four fault segments within 40 s was associated with a quiescence period that lasted at least 1.3 years up to the main shock. No $M \geq 3.4$ earthquakes was produced during this time in comparison with the 10 events that occurred during the 4.7 years of background period. In fig. 9 the LTA(t) function shows a peak near $Z = 8$ at the beginning of the window that covers the period without earthquakes.

As noted for the 1983 Nihonkai-Chubu earthquake, also in the Irpinia case the plot of the cumulative number of earthquakes shows a sharp increase after the main shock. After this period of increased activity, the rate seems to return slowly to its previous value. The similarity of this behaviour in two seismic areas so widely apart could be ascribed to the occurrence of aftershocks in a broad sense (or «postshocks»), as pointed out by Papazachos *et al.* (1997), who

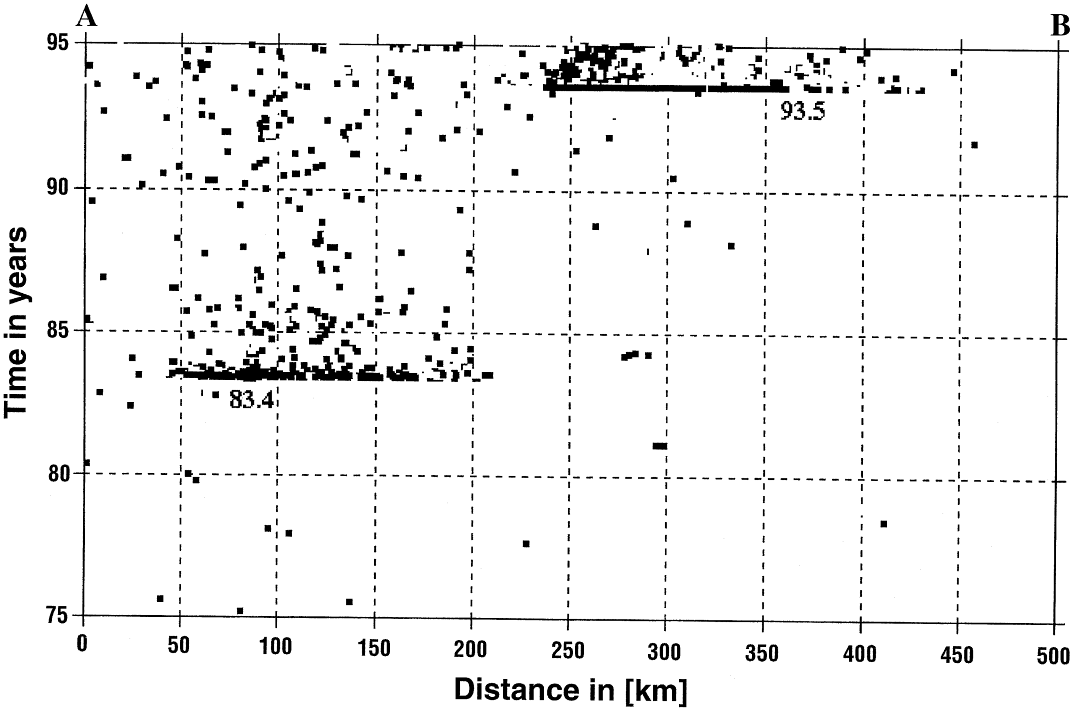


Fig. 8. Time-*versus* distance plot of earthquakes ($M \geq 3.8$) from the complete catalog (including clusters) within an 80-km-wide along the section AB (39.5°N, 138.5°E - 44.0°N, 139.0°E) containing both the 1983 Nihonkai-Chubu aftershocks volume and that one of July 12, 1993 ($M_J = 7.8$).

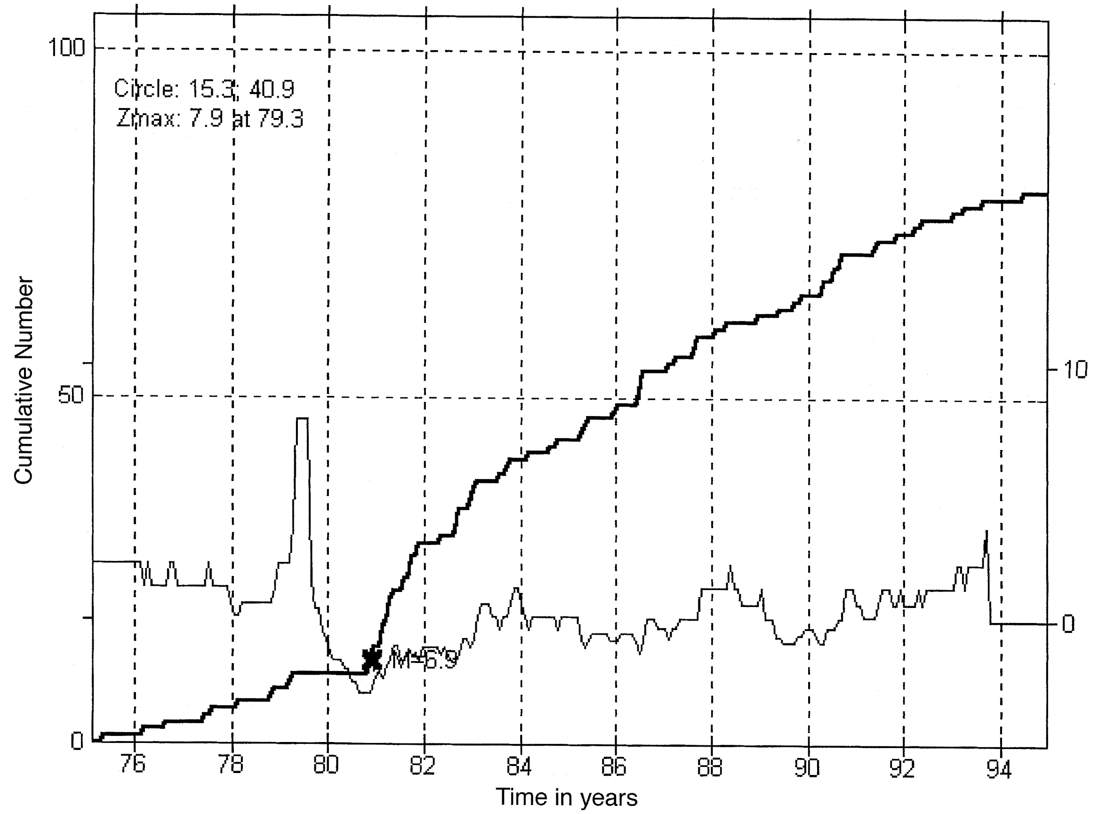


Fig. 9. Cumulative number of earthquakes with $M \geq 3.4$ in a volume circular of 80 events centered at the northern end of the Irpinia rupture volume. The Z-values of the LTA(t) function with a moving time window of 1.3 year are shown as a fine line.

consider it a common feature worldwide. The phenomenon frequently observed in the seismic cicle, including aftershocks, postshocks, quiescence, preshocks and foreshocks, still lacking a deterministic and predictable modelization, demonstrates that seismicity is far from a random process. This deserves further attention for possible forecasting of main shocks.

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