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Evidence of precursor phenomena in the Kobe earthquake obtained from atmospheric radon concentration

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Abstract

Atmospheric ^{222}Rn concentrations were determined over a 10a period, which included the date of the Kobe, Japan earthquake, on January 17th 1995. It was found that the seismically related ^{222}Rn anomaly was higher than the 99% confidence limits for the residual value of atmospheric ^{222}Rn which had been observed 2 months before. The residual ^{222}Rn concentration, in which residual values of the daily minimum are the difference between each normal ^{222}Rn concentration (calculated from January 1984 to December 1993) and the daily minimum ^{222}Rn concentration (January 1994 to January 1995), was calculated by applying the exponential smoothing method to the residual values for each day. It was found that the fluctuations of the residual values can be fitted very well to a log-periodic oscillation model. The real residual values stopped increasing at 1994.999 (December 31st 1994), which corresponds with the critical point (t_c) of best fit model. This anomalous ^{222}Rn variation can be seen as the result of local stresses, not primary stresses which directly lead to the Kobe earthquake. On the other hand, when the critical exponent (z) and the radial frequency (ω) of the model were simultaneously fixed $0.2 \leqslant z \leqslant 0.6$ and $6 \leqslant \omega \leqslant 12$, t_c (critical point) was between January 13th 1995 and January 27th 1995. The Kobe earthquake occurrence date (January 17th 1995) is within this range. Therefore this anomalous ^{222}Rn variation can also be seen as the result of primary stresses which possibly led to the Kobe earthquake. There is a distinct possibility that similar statistical oscillations will be detected in other measurements such as microseismicity, tectonic strain, fluctuation in the ground level, or changes in groundwater elevations and composition.

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1. Introduction

The Kobe earthquake (magnitude 6.9 Mw, depth 14 km) occurred beneath the sea between Kobe and Awaji Island in Japan on January 17th 1995 (Fig. 1). Movement on a right lateral strike-slip fault about 40 km in length was presumed to be the cause. Several clear geochemical anomalies include a ^{222}Rn anomaly in the ground water (Igarashi et al., 1995), chemical anomalies in the ground water (Tsunogai and Wakita, 1995), and a ^{222}Rn

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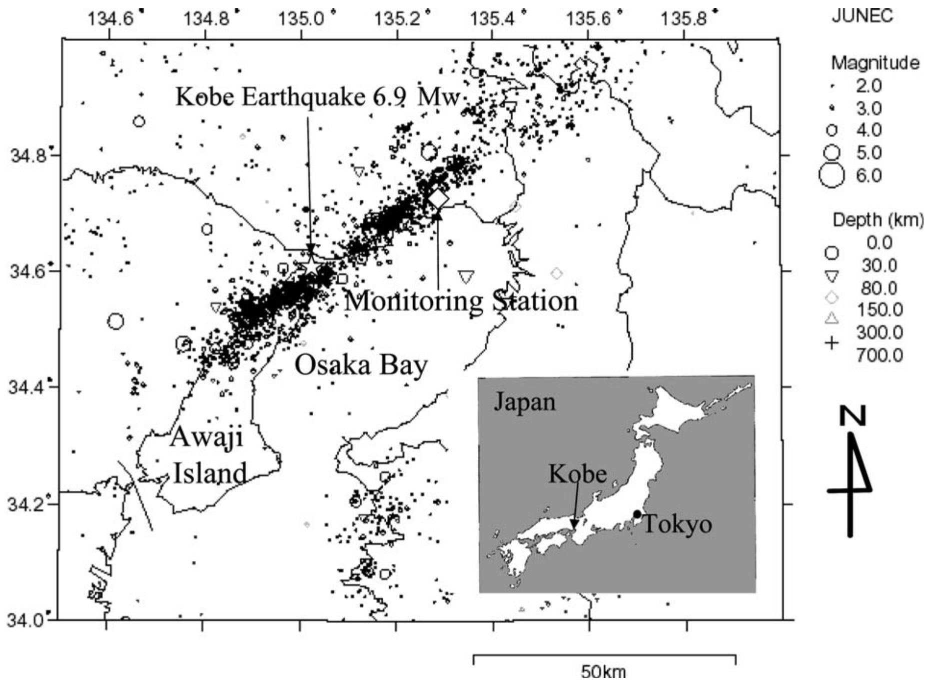

Fig. 1. Location of the ^{222}Rn monitoring station, epicenter of the Kobe earthquake and the aftershock region. This figure is taken from Citation of Japan University Network Earthquake Catalog Hypocenters File.

anomaly in near ground atmosphere (Yasuoka and Shinogi, 1997) before the earthquake.

The log-periodic oscillation model was applied to the chemical anomalies in the ground water (Johansen et al., 1996, 2000). The authors propose that the ^{222}Rn anomaly in the near ground atmosphere is consistent with the model presented in these papers. Atmospheric ^{222}Rn concentrations were observed over a 10a period, which coincided with the Kobe earthquake. It was reported that the seismically related ^{222}Rn anomaly was higher than the 99% confidence limit for the residual value of atmospheric ^{222}Rn which had been observed for the previous 2 months (Yasuoka and Shinogi, 1997).

2. Material and methods

2.1. Monitoring station

The monitoring station used, located at Kobe Pharmaceutical University, was near a major active fault at the foot of Rokko Mountain; it was within the aftershock region, and about 20 km away from the epicenter (Fig. 1). Rokko Mountain is composed primarily of granite that tends to contain more ^{226}Ra than other common rock types. ^{222}Rn gas is the first decay product from the α-decay of ^{226}Ra.

2.2. Atmospheric ^{222}Rn data

The measurements of atmospheric ^{222}Rn concentration were made continuously and automatically by the use of a flow-type ionization chamber with a volume of 1.8 L. Filtered air, 5 m above the ground was pumped into the chamber. The hourly mean was measured continuously from January 1984 to February 1996. For the purpose of this paper, the daily minimum was used to represent the regional ^{222}Rn value, because the ^{222}Rn concentration was decreased by atmospheric convection and diffusion from the earth source (Ikebe et al., 1983; Jacobi and Andre, 1963).

The daily minimum of the ^{222}Rn concentration was calculated by using the hourly data observed between January 1984 and February 1996. A small period with no monitoring occurred between January 1989 and December 1989, due to a mechanical failure. The normal values were calculated from the daily minimum ^{222}Rn concentrations from January 1984 to December 1993, in order to obtain the seasonal ^{222}Rn variation. For example, the averages of ^{222}Rn concentration for January 1st were calculated using the 9 daily minimums observed on each January 1st from 1984 to 1993 (with the exception of 1989, see above). It was assumed that the influence of the meteorological variables would be very low after the exponential smoothing method was applied to the 9a of data (Gardner, 1985). The smoothed normal values were then calculated by applying the exponential smoothing method to the normal values for each day. The residual value of the daily minimum is the difference between each smoothed normal ^{222}Rn concentration and the individual measured daily minimum ^{222}Rn concentration. Under normal conditions, residual values can be positive or negative and will balance out to an average deviation of zero. The smoothed residual ^{222}Rn concentration was then calculated by applying the exponential smoothing method to the residual values for each day.

3. Results

3.1. Log-periodic oscillation model

Ben-Zion and Lyakhovsky (2002) reported that subsequent observational analyses of accelerated seismic release, or cumulative Benioff strain fits a power-law time-to-failure equation;

$$f(t) \approx A + B(t_c - t)^z \tag{1}$$

where t_c is the critical point, t is time, A and B are constant, and z is the critical exponent. The critical exponent z in cumulative Benioff strain is usually about 0.3 (Ben-Zion and Lyakhovsky, 2002). A is the value of $f(t)$ when $t = t_c$, in other words, A is the final Benioff strain up to and including the largest event. Sornette and Sammis (1995) proposed that if the regional fault network is a discrete hierarchy, then the critical exponent z in Eq. (1) is complex, following a log-periodic oscillation model:

$$f(t) \approx A + B(t_c - t)^z[1 + C\cos(\omega \log(t_c - t) + \psi)]$$
$$\omega = \frac{2\pi}{\log \lambda} \tag{2}$$

where $f(t)$ is an arbitrary function which reflects interactive forces (Benioff strain), ω is the radial frequency, ψ is the phase, and C is constant (Igarashi, 2000; Huang et al., 1998). The authors found that the fluctuations of the residual values of atmospheric ^{222}Rn can be fitted very well into Eqs. (1) and (2).

3.2. Fitting the ^{222}Rn concentration with a power law and a log-periodic oscillation model

The smoothed residual values of the daily minimum of ^{222}Rn concentration demonstrated an upward trend between 1994.667 (September 1st 1994) and 1994.999 (December 31st 1994) (Fig. 2).

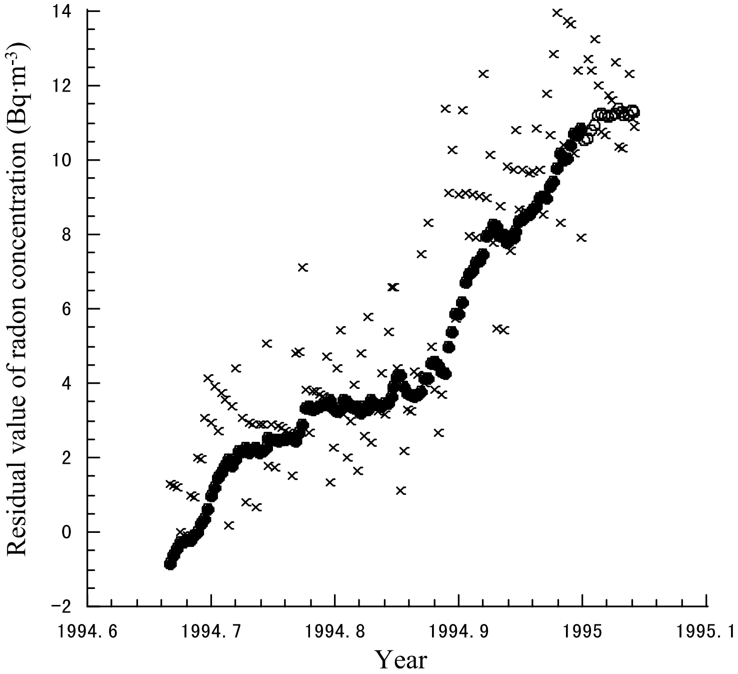

Fig. 2. Fluctuations of the residual value of the ^{222}Rn concentration (crosses), the smoothed residual ^{222}Rn concentration (analytical data: closed circles, non-analytical data: open circles).

The data, taken from January 1st 1995 until the actual Kobe earthquake, was not used, because the ^{222}Rn residual stopped increasing at 1994.999 (December 31st 1994). It is commonly thought that the strain along the main fault before the largest earthquake should cause a decrease in stress levels found in the surrounding area (Mjachkin et al., 1975).

Figs. 3–6 show fit with the Eqs. (1) and (2) respectively. The unknown parameters of these equations were determined by non-linear, least-square methods, so that χ^2, or the variance of residuals, were minimal. The z, ω, t_c and χ^2 parameters were calculated using the three following methods. The first method was either smoothed curve or the absolute best-fitting analysis of Eqs. (1) and (2) (Figs. 3 and 4). The second method, in which upward trends were shown (Figs. 5 and 6), was the best-fitting analysis of Eqs. (1) and (2) with fixed $t_c = 1995.045$ (January 17th 1995) on the Kobe earthquake occurrence date. The third method was the best-fitting analysis of Eq. (1) with $z = 0.3$. The results for the z, ω, t_c and χ^2 parameters are summarized in Table 1.

After applying the absolute best-fitting analysis of Eq. (1), $t_c = 1995.084 \pm 0.353$ and $z = 0.0356 \pm 1.1288$, the value of z is smaller than 0.3, which is the usual critical exponent value in cumulative Benioff strain (Ben-Zion and Lyakhovsky, 2002). Therefore the margin of error (1.1288) was too large. It is impossible to apply the absolute best-fitting analysis of Eq. (1).

Regarding the best-fitting analyses of fixed $t_c = 1995.045$, z was 0.25 ± 0.07. And when a fixed $z = 0.3$ was calculated, $t_c = 1995.037 \pm 0.022$. The Kobe earthquake occurrence date, 1995.045 (January 17th 1995), was within the margin of error using $z = 0.3$ in Eq. (1). This atmospheric ^{222}Rn data can be applied to Eq. (1) using $z = 0.3$. χ^2 of absolute best fitting was 46.0. χ^2 of a fixed $z = 0.3$ and $t_c = 1995.045$ were 46.2 and 46.1, respectively. The differences of χ^2s were very small (less than 0.4%).

The results, for the absolute best-fitting analysis of Eq. (2) were, $z = 0.78 \pm 0.04$, $\omega = 4.6 \pm 0.1 (\lambda = 3.9)$, and $t_c = 1994.999 \pm 0.004$. The results of the best-fitting analyses of fixed $t_c = 1995.045$ were, $z = 0.47 \pm 0.05$, and $\omega = 6.51 \pm 0.11$ ($\lambda = 2.6$). This atmospheric ^{222}Rn data can be applied in Eq. (2). Figs. 7 and 8 show the distribution of χ^2, z and ω for Eq. (2), when t_c fluctuated between 1994.999 (December 31st 1994) and 1995.084 (January 31st 1995). The vertical dotted line and the solid line in Figs. 6 and 7 mark the values of $t_c = 1994.999$, the

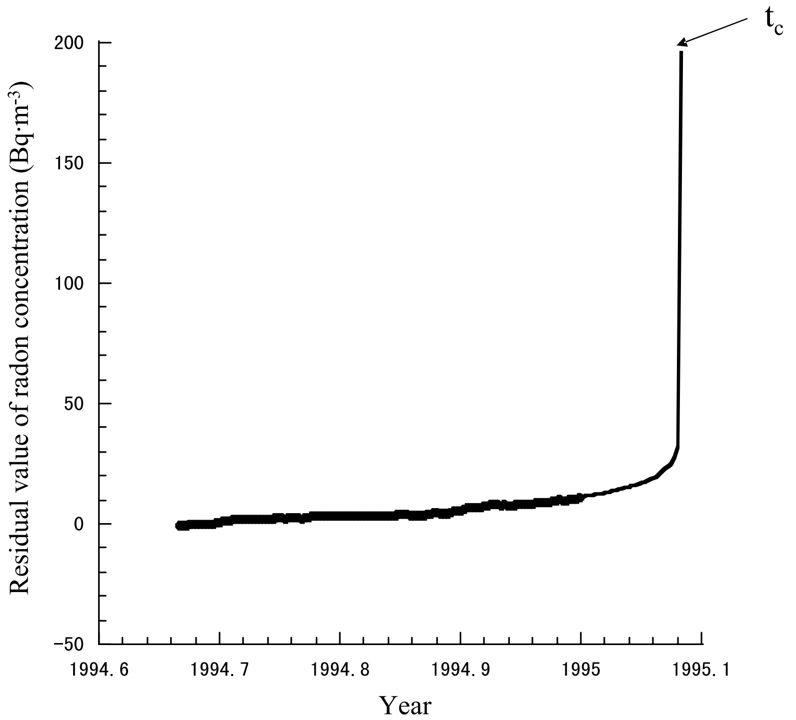

Fig. 3. Fluctuations of the analytical smoothed residual ^{222}Rn concentration (closed circles) and the power-law curve (Eq. (1) smoothed curve). An arrow indicates the critical point.

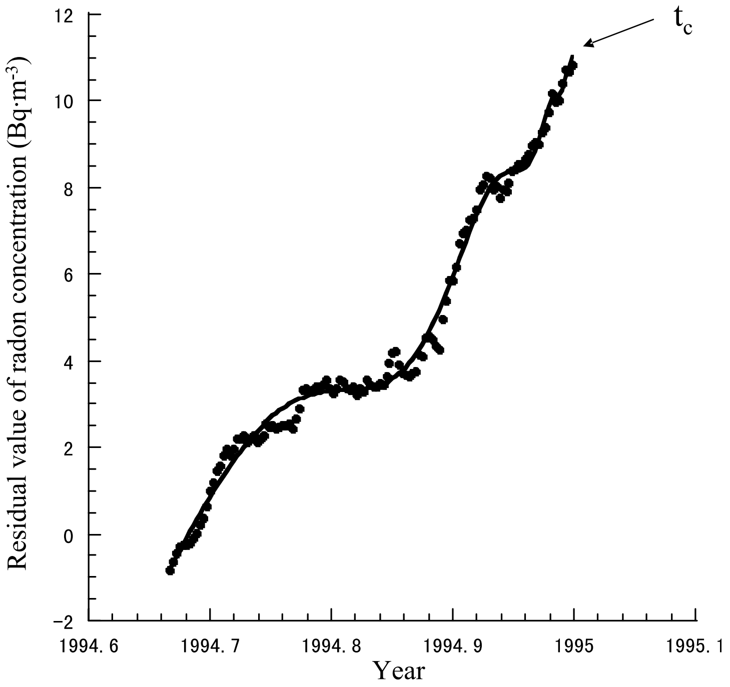

Fig. 4. Fluctuations of the analytical smoothed residual ^{222}Rn concentration (closed circles) and the log-periodic oscillation curve (Eq. (2) smoothed curve). An arrow indicates the critical point.

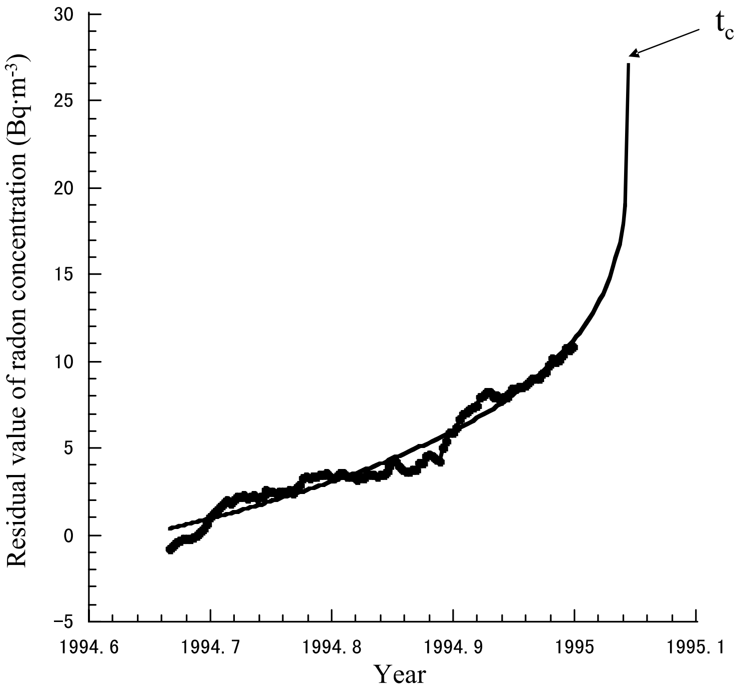

Fig. 5. Fluctuations of the analytical smoothed residual ^{222}Rn concentration (closed circles) and the power-law curve (Eq. (1) fixed $t_c = 1995.045$). An arrow indicates the critical point.

optimal value, and $t_c = 1995.045$, the earthquake date. Table 1 shows reference lists, which are the best fitting values of z, ω and t_c for Eqs. (1) and (2) using Benioff strain and Cl^- concentration in ground water (Sornette and Sammis, 1995; Johansen et al., 2000). Compared with the reference

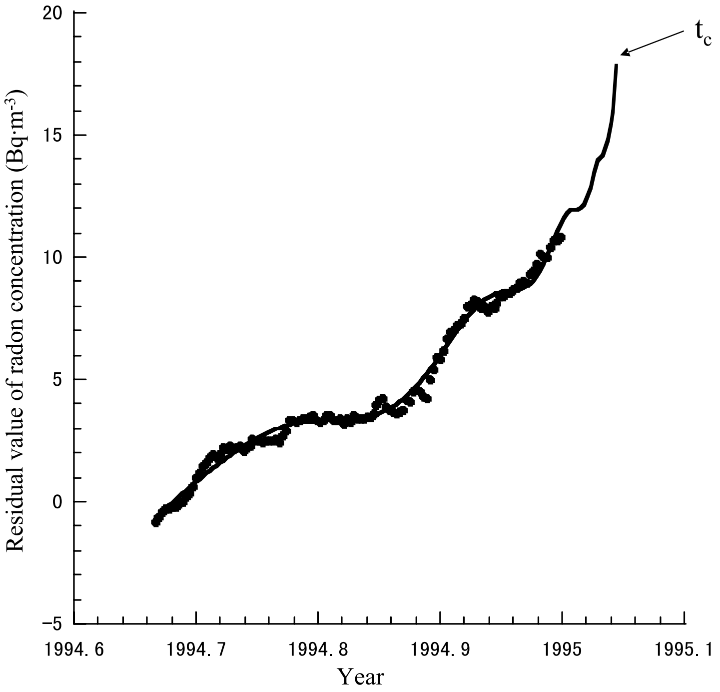

Fig. 6. Fluctuations of the analytical smoothed residual ^{222}Rn concentration (closed circles) and the log-periodic oscillation curve (Eq. (2) fixed $t_c = 1995.045$). An arrow indicates the critical point.

Table 1
Summary of the results and the references obtained by fitting the ^{222}Rn data and some observational studies of accelerated seismic release to the power law (Eq. (1)) and the log-periodic oscillation model (Eq. (2))

Reference	Radon data			Sornette and Sammis (1995)	Johansen et al. (2000)
Earthquake	Kobe Earthquake January 17th 1995 (1995.045)			Loma Prieta October 18th 1989 (1989.8)	Kobe Earthquake January 17th 1995 (1995.045)
Precursor data	Atmospheric radon			Benioff strain	Cl^- in ground water
Type of analysis	Smoothed curve	$t_c = 1995.045$	$z = 0.3$	Smoothed curve	Smoothed curve
Equation / Parameters	Power fit: Eq. (1)				
z	0.0356 ± 1.1288[a]	0.25 ± 0.07	Fixed at 0.3	0.35 ± 0.23	–
t_c	1995.084 ± 0.353[a]	Fixed at 1995.045	1995.037 ± 0.022	1990.3 ± 4.1	–
χ^2	46.0[a]	46.1	46.2	–	–
Equation / Parameters	Log-periodic corrected fit: Eq. (2)				
z	0.78 ± 0.04	0.47 ± 0.05	–	0.34 ± 0.08	0.58
ω	4.6 ± 0.1	6.51 ± 0.11	–	5.5	7.0
t_c	1994.999 ± 0.004	Fixed at 1995.045	–	1989.9 ± 0.8	1995.06
χ^2	8.9	11.4	–	–	–

[a] Donates figures that are impossible to analyze by Eq. (1), using the absolute best fitting.

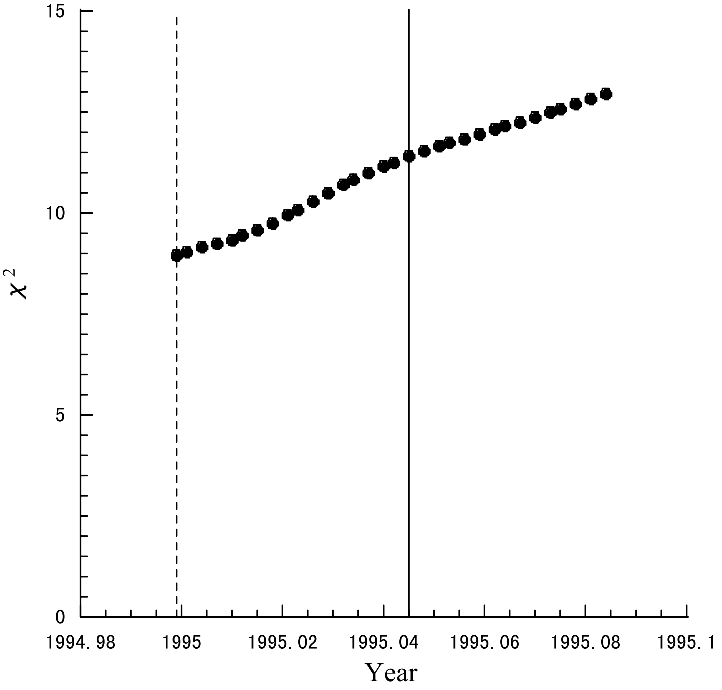

Fig. 7. Trend data of χ^2 (the variance of residuals: closed circles) of Eq. (2), when t_c fluctuated between 1994.999 (December 31st 1994) and 1995.084 (January 31st 1995). The vertical dotted line and solid line mark the values of $t_c = 1994.999$, or the optimal value, and $t_c = 1995.045$,or the earthquake date.

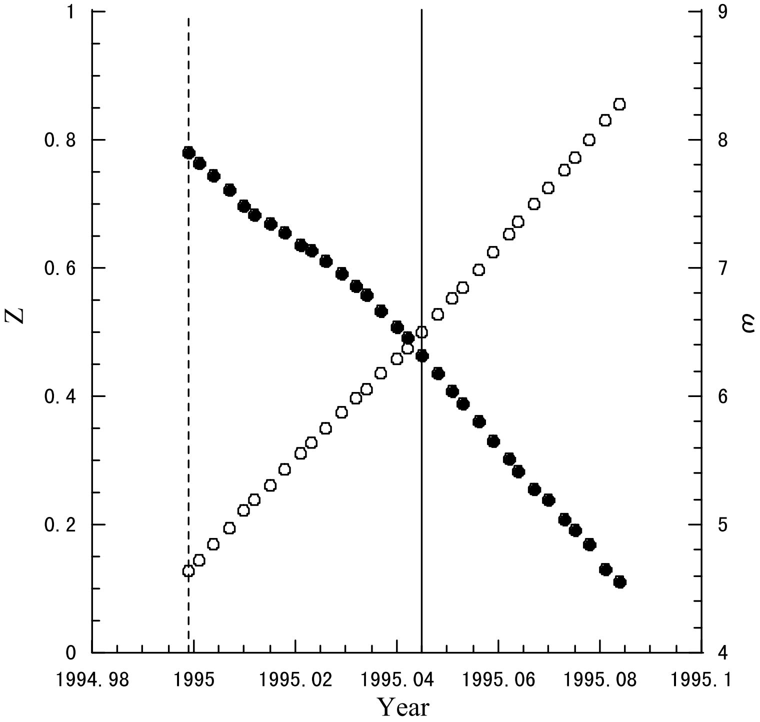

Fig. 8. Trend data of z (the critical exponent: closed circles) and ω (the radial frequency: open circles) of Eq. (2), when t_c fluctuated between 1994.999 (December 31st 1994) and 1995.084 (January 31st 1995). The vertical dotted line and solid line mark the values of $t_c = 1994.999$, or the optimal value, and $t_c = 1995.045$,or the earthquake date.

Table 2
Statistical parameters of the linear, power law, and log-periodic oscillation models

Function	Method of analysis	χ^2	Number of free parameter	Number of data points	AIC[a]
Linear	Smoothed curve	83	3	122	891
Power low	Smoothed curve	46	5	122	823
Log-periodic oscillation	Smoothed curve	9	8	122	630
Log-periodic oscillation	Fixed $t_c = 1995.045$	11	8	122	655

[a] AIC (Akaike Information Criterion) provides a criterion for selecting the best statistical model among different models; As AIC decreases, the model can be regarded as better.

parameters, the parameter of fixed $t_c = 1994.045$ was closer to the parameters of the absolute best-fitting analysis. Furthermore, regarding Benioff strain, Huang et al. (1998) found ranges of $0.2 \leqslant z \leqslant 0.6$ and $6 \leqslant \omega \leqslant 12$, and Sornette (1998) suggested the preferred scaling ratio was $\lambda \approx 2.0$.

3.3. Akaike information criterion

The following Eq. (3) demonstrates the statistical significance for the log-periodic oscillation model. To select the best statistical model, when there can be some different models for explaining given data variations, Akaike proposed AIC (Akaike Information Criterion) as:

$$\begin{aligned}\mathrm{AIC}(k) &= -2(\text{Maximum Log} - \text{Likelihood}) + 2k \\ &= n \log 2\pi + n \log \chi^2 + n + 2k \qquad (3)\end{aligned}$$

where k is the number of free parameters (the number of unknown coefficients +1), n is the number of data points, and χ^2 is the variance of the residuals (Akaike, 1973). The best model for a given data set can be selected by minimizing AIC from a statistical point of view (Igarashi, 2000). In Table 2 the statistical parameters of 3 models, which were linear ($f(t) = A + Bt$), power law (Eq. (1)) and log-periodic oscillation model (Eq. (2)), are compared with each other. The log-periodic oscillation model (Eq. (2)) has the smallest variance of residual values and the smallest AIC. Both the smoothed curve, and the fixed $t_c = 1994.045$ log-periodic oscillation models produced the best fitting results.

4. Discussion

A seismically related ^{222}Rn anomaly in the atmosphere was observed for about 2 months before the Kobe earthquake within the aftershock region. Quantitative analysis of atmospheric ^{222}Rn change was performed; and the AIC indicates the best fit was the log-periodic oscillation model, or Eq. (2).

4.1. Interpretation of local stress

Using the absolute best-fitting analysis of Eq. (2), t_c was determined to be 1994.999 ± 0.004 (December 31st 1994). The real data, which was the smoothed residual values of the daily minimum of ^{222}Rn concentration, stopped increasing at 1994.999 (December 31st 1994). Therefore it can be said with confidence that the peak of measured data corresponded with the critical point (t_c).

This anomalous ^{222}Rn variation can be seen as local stress, not the main stresses which directly led to the Kobe earthquake. Igarashi et al. (1995) also reported that the ^{222}Rn concentration in ground-water started to increase from the beginning of the observation in October 1994. These authors reported a sudden increase on January 7th 1995. Furthermore, Igarashi et al. (1995) indicated the high ^{222}Rn concentration suddenly ended on January 10th 1995, just before the Kobe earthquake. It is a contention of this paper that the critical point of the anomalous ^{222}Rn variation can be interpreted as the critical point of the local stresses. This is a reasonable conclusion based on the accurate results obtained by the log-periodic oscillation model (Eq. (2)). Furthermore there is evidence that the local stresses stopped increasing just before the Kobe earthquake.

4.2. Interpretation of the main stress

Benioff strain can be seen as the main stress which directly leads to an earthquake. The critical exponent z of Eq. (1) is usually about 0.3 (Ben-Zion and Lyakhovsky, 2002); Huang et al. (1998) found ranges of $0.2 \leqslant z \leqslant 0.6$ and $6 \leqslant \omega \leqslant 12$ in Eq. (2). These values are supported by some observational evidence which applies to the atmospheric ^{222}Rn concentration.

When z of Eq. (1) was fixed at 0.3, then $t_c = 1995.037 \pm 0.022$ (Table 1). The Kobe earthquake occurrence date (1994.045) was well within the margin of error. When z and ω of Eq. (2) were fixed at $0.2 \leqslant z \leqslant 0.6$ and $6 \leqslant \omega \leqslant 12$ (Fig. 7), t_c was between 1995.034 (January 13th) and 1995 .073 (January 27th). The Kobe earthquake occurrence date (1994.045) is once again within this range. This anomalous ^{222}Rn variation can be interpreted as linked to the main stresses which directly led to the Kobe earthquake.

It is a second contention of this paper that the power-low (Eq. (1)), and the log-periodic oscillation model (Eq. (2)), applied to not only Benioff strain, but also to atmospheric ^{222}Rn change.

5. Conclusions

This research presents a reliable way to predict an accurate range of days when an earthquake could occur near a monitoring station. There is agreement between the statistical data on the seismic related ^{222}Rn anomaly and the resulting best-fit Eq. (2), the anomalous ^{222}Rn can be seen as a local stress. There may be similar statistical oscillations that can be detected in other measurements such as microseismicity, tectonic strain, fluctuation in the ground level, or changes in groundwater elevation and composition.

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