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Discrete Scaling in Earthquake Precursory Phenomena: Evidence in the Kobe Earthquake, Japan

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Abstract. — We analyze the ion concentrations of groundwater issuing from deep wells located near the epicenter of the recent earthquake of magnitude 6.9 near Kobe, Japan, on January 17, 1995. These concentrations are well fitted by log-periodic modulations around a leading power law. The exponent (real and imaginary parts) is very close to those already found for the fits of precursory seismic activity for Loma Prieta and the Aleutian Islands. This brings further support for the general hypothesis that *complex* critical exponents are a general phenomenon in irreversible self-organizing systems and particularly in rupture and earthquake phenomena.

Résumé. — Nous analysons les fluctuations de concentrations ioniques de l'eau issue de puits profonds situés à proximité de l'épicentre du récent tremblement de terre de magnitude 6.9 proche de Kobe au Japon, le 17 janvier 1995. Ces fluctuations sont bien reproduites par des modulations log-périodiques autour d'une loi de puissance. Les parties réelle et imaginaire de l'exposant sont très proches de celles trouvées précédemment pour les tremblements de terre de Loma Prieta et des Iles Aléoutiennes. Ces résultats renforcent l'hypothèse que des exposants critiques complexes sont une propriété générale des phénomènes de croissance irréversible, et en particulier des problèmes de rupture et des tremblements de terre.

1. Introduction

Self-similarity is now a widely used concept describing crustal fracture patterns [1,2]. Power law distributions of earthquakes, aftershocks, fault lengths are all signatures of scale invariance. In relation, a picture of earthquakes as “critical points” has been proposed by several authors [3–9]. This picture is suggested from the mounting evidence that large earthquakes

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involves the collective behavior of extended fault networks and many large earthquakes have been preceded by an increasing number of intermediate sized events within a large region surrounding the main shock [10–14]. In the critical point analogy, one views an earthquake as a cooperative phenomenon corresponding to the progressive build-up of stress and damage correlations, culminating in the event. Due to the “critical” behavior of observables near the critical point, characteristic signatures should be observable, such as an acceleration of seismic activity signaling a strengthening in stress and fault correlations. We describe below this first signature for the Kobe earthquake. Another potential signature is the behavior of more global quantities, such as the conductivity and permeability of the crust at various distances from the epicenter. These transport properties are known to exhibit well-defined critical behaviors close to a critical point as they reflect the organization of micro-cracking and damage [15]. Indeed, permeability enhancement [16] as well as changes in groundwater discharge [17] and hydrogeochemistry [18] have been documented after large earthquakes. Our observation reported below complement them in that they occur prior to the earthquake.

A key problem is to characterize how general is this behavior and what constraints does it provide for other precursory phenomena and the modelling of the earthquake physics. In previous works [19,20], evidence has been found that physical quantities before the main shock could be fitted with a power law with log-periodic corrections, suggesting the existence of an underlying discrete scale invariance [21]. Here, we wish to report a similar observation on the fluctuations in ion concentrations of groundwater issuing from wells located near the epicenter of the recent earthquake of magnitude 6.9 near Kobe, Japan, on January 17, 1995 [22]. Using statistical bootstrapping techniques and re-sampling schemes, we qualify the statistical significance of the fit. The parameters are very close to the ones already found for Loma Prieta and Aleutian Islands, confirming the validity of the picture. We comment on the possible use of discrete scaling in precursory phenomena as a predictive tool [19].

2. The Kobe Earthquake

The Kobe earthquake [23] produced a distinct fault rupture with a length of about 9 km appearing along the pre-existing right lateral Nojima fault. Along with the earthquake, increased groundwater discharge was observed in many parts of the aftershock region. Prior to the earthquake, fluctuations in various ions (Cl^- , SO_4^{2-} , Mg^{++} , Sr^{++} , Ba^{++}) concentrations of groundwater issuing from wells located near the epicenter appeared [22]. The granitic Rokko mountains behind Kobe produce high-quality mineral water, which is bottled and sold in Japan. One of the sites used in this study is located about 20 km east of the identified epicenter. Here groundwater is pumped from two 100 m deep wells and sealed in polyethylene terephthalate bottles and sold as mineral water. After the earthquake, bottles with bottling dates ranging from June 3, 1993 were collected and analyzed for various ions. After 1993, the concentration of Cl^- as well as many others rose systematically to a significantly higher level after the earthquake, showing an increase of $\approx 15\%$. This is represented in Figure 1 showing the time evolution of the Cl^- concentration (the other ions behave similarly [22] as has been checked by using the same fitting procedure, see below). On the same curve, we also plot the cumulative Benioff strain over all shallow earthquakes of magnitude larger than 4 from the Japan Meteorological Agency. Both data are compatible with an acceleration up to the main event ⁽¹⁾. We now quantify these observations using the idea of critical points outlined above.

⁽¹⁾ We do not use the same scale for these two data sets since they do not cover the same time interval. We could have reduced the time scale for the seismic precursory activity to the same period of time as for the ions (1993.5–1995) but this would have left over half the points and would have concealed the significant acceleration.

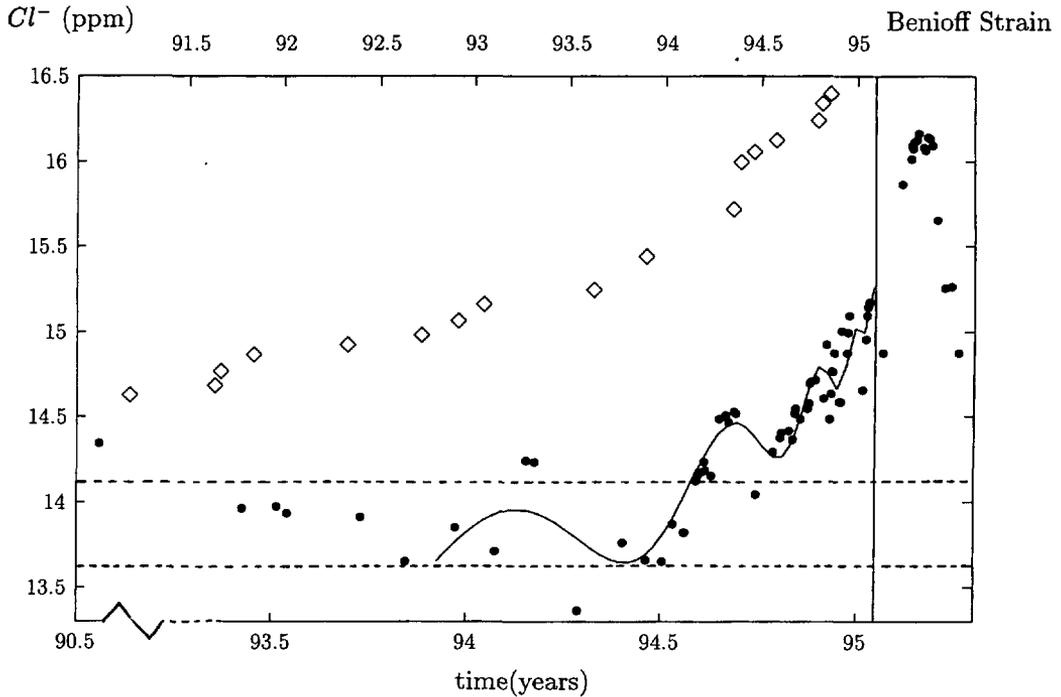


Fig. 1. — Chlorine concentration (black dots and lower and left scales) from around 1993.5 to 1995.3. A single available data point around 1990.5 is also shown. The continuous line shows the fit to equation (1). Cumulative Benioff strain (diamonds and upper and right scales) over all shallow earthquakes in a finite region (roughly 1 degree squared) around the epicenter. The time of the Kobe earthquake is indicated by the vertical line. Notice the large jump in ion concentration at the time of the earthquake (with some delay), in agreement with the term A in equation (1), and the subsequent decay.

3. Statistical Analysis of the Data Using the Critical Point Analogy

A very important consequence of the concept of a critical point is in its ability to provide some universal predictions, even in the absence of a detailed model, by using what amounts essentially to generalized symmetry arguments. For instance, based only on the idea that fault correlations increase drastically near the main event, one predicts, by analogy with standard critical phenomena of solid-state physics [24], that the observed acceleration should be described by a power law. In statistical physics, where the concept of criticality emerged, scale invariance is usually characterized by an invariance of the physics with respect to arbitrary scale transformations. For hierarchical system, however, such as the Ising model on Sierpinsky gaskets, only a *discrete* scale invariance holds [25]. This entails the existence of log-periodic corrections to the free energy close to the critical point [26–28]. In the case of hierarchical models of rupture, the log-periodic structure of equation (1) seems also to be relevant [29].

More surprisingly, we have found evidence of log-periodic corrections to scaling in various Euclidian models of irreversible growth and rupture phenomena [19–21,30], where the discrete scale invariance is **not** built in *a priori*. This suggests that discrete scale invariance can be spontaneously generated by the disorder and the dynamics, in a still not completely understood way [21]. Basically, these periodic structures are the signature that rupture does not occur as

a smooth process but rather as a succession of burst-like events (associated to the formation or fusion of a new largest crack) more and more closely spaced in time until the ultimate macroscopic collapse, thus leading to a hierarchical cascade.

Log-periodic corrections to scaling correspond to the following behaviour of physical quantities

$$c(\tau) = A + B(\tau_c - \tau)^m [1 + C \cos(\omega \log(\tau_c - \tau))], \quad (1)$$

where $\tau = t/\phi$ is non-dimensional time. This equation is the first Fourier component of a general log-periodic correction to a pure power law solution of a renormalization group equation for an observable exhibiting a singular behavior at the time t_c of rupture, *i.e.* which becomes scale-invariant at the critical point [19]. Equation (1) was first proposed to fit experimental measurements of acoustic emissions prior to rupture of heterogeneous composite systems stressed up to failure [20]. It also provides a reasonable fit to the dependence of the released Benioff strain as a function of the time to rupture for various large Californian earthquakes and for the seismic activity of the Aleutian-Island seismic zone [19].

Our purpose here is to investigate whether (1) also provides a good fit for the Kobe earthquake and to assess its statistical significance.

We have fitted equation (1) to the part of the chlorine data showing some structure above the noise level up to the earthquake. In Figure 1, the two dashed horizontal line indicate the 1σ variation range. We started nevertheless the fit at early times where the signal seems to oscillate above and below these lines due to their apparent correlations. In any case, the fitting interval should not be our choice but should be deduced from the data itself. In this goal, we have performed different fits with different time intervals to check its robustness and significance. We find in particular that our results reported below remain the same when we reduce the time interval after august 1994 for which the signal is significantly above the positive 1σ variation range.

The result is shown in Figure 1 with the entire data set. In Figure 2, we show only the part used in the fit under a filtered version. The χ^2 of the data was minimized, where the three linear variables A, B, C were determined analytically *as a function of* the four nonlinear free variables m, t_c, ω and ϕ giving *a priori* a 4-parameter fit. However, we checked that the results are independent of the time unit used (played by ϕ) implying that we face in fact a 3-parameter (m, t_c, ω) fit. Error bars of 1% estimated experimentally were used.

Due to the noisy nature of the data, χ^2 as a function of m, t_c, ω has in general several minima. Hence, a preliminary scan allowed to identify all local minima satisfying $0 < m < 1$, after which the full fit was executed. This Taboo procedure [31] assured that the global minimum indeed was found. In Table I, the values of the physically relevant parameters m, t_c and ω together with the χ^2 for the five minima found are shown. We see that the estimated value of t_c for the global minimum is only two days later than the actual date for the earthquake! Notice that the last three minima have more than double the frequency of the two first and hence correspond simply to noise-fitting. As we shall see later, this will be a useful discriminator. Furthermore, the value for the exponent m is rather low for these minima, whereas the corresponding value for the two first minima is close to the mean-field value of $1/2$ [32]. We have not tried to fit the seismic Benioff strain shown in Figure 1 in view of the sparseness of the data. We just notice the qualitative similarity between the structure of the two different data sets, in agreement with our theoretical picture.

To help the reader appreciate the nature of the log-oscillatory acceleration visually, we have replotted in Figure 3 the data and the fits shown in Figures 1 and 2 using for the abscissa the logarithmic scale $\log_{10}(\tau_c - \tau)$. This representation is such that, according to equation (1), the oscillations should be periodically spaced.

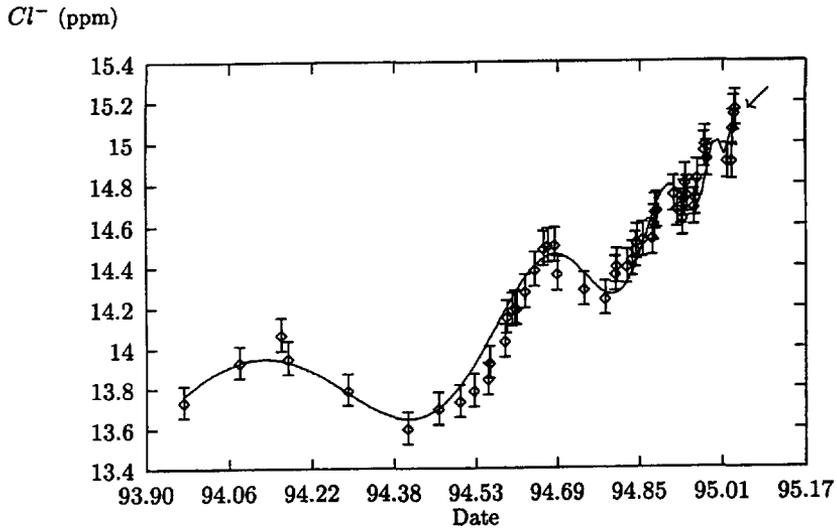


Fig. 2. — Log-periodic fit to the original Cl^- Kobe data. To guide the eye, the data shown has been smoothened, with each point replaced with the average of itself and its two neighbors. The fit has been done on the unfiltered data shown in Figure 1. This has been done in order to make clear how the data contains the information on the accelerating oscillations, which is less obvious in the signal shown in Figure 1. The predicted time t_c is within two days of the earthquake. The $\chi^2 = 1.2$ with error bars of 1%. The time of the earthquake is indicated by the arrow.

Table I. — *The first five minima found in the minimization of the χ^2 of the ion data using equation (1) with their corresponding values for the residual χ^2 , t_c (which has to be compared with the exact value equal to 439, which is the number of days after the first data point), m and ω .*

minimum	χ^2	t_c (days)	m	ω
global	1.2	441	0.45	6.7
2	1.4	452	0.56	6.0
3	1.6	443	0.26	15
4	1.7	437	0.32	15
5	1.7	454	0.17	15

Before we continue qualifying the fit obtained above, we will give an estimate of what should be regarded as a reasonable variation in the values of the three parameters due to noise. This was done by generating data artificially from equation (1) adding Gaussian noise (standard deviation of 1% as for the real data). The parameter values used were those of the global minimum. The artificial data was sampled randomly with a uniform distribution in $\log(t_c - t)$ keeping the number of points and the time interval equal to that of the real data. This sampling

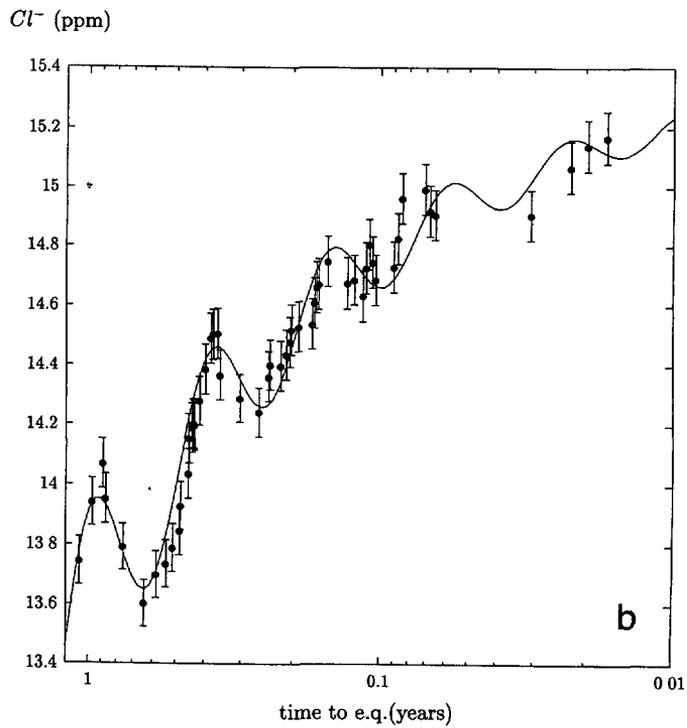
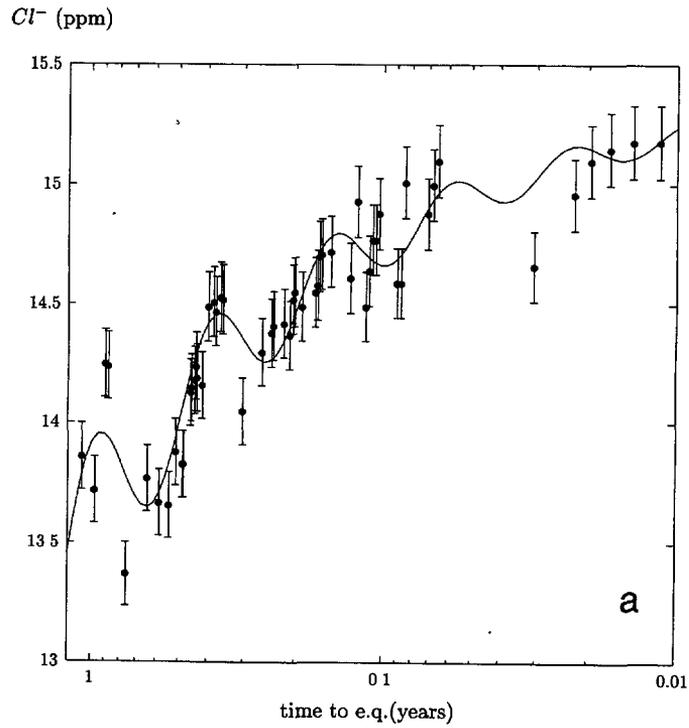


Fig. 3. — a) Same as Figure 1 for the chlorine data but using for the abscissa the logarithmic scale $\log_{10}(\tau_c - \tau)$; b) same as Figure 2 with the logarithmic scale $\log_{10}(\tau_c - \tau)$.

Table II. — *Global minima for five random realizations of equation (1). Gaussian noise with a standard deviation of 1% was added and sampling was uniform in $\log(t_c - t)$ as was the case with the real data.*

#	χ^2	$t_c(\text{days})$	m	ω
1.	0.8	439	0.45	6.5
2.	1.1	439	0.52	6.3
3.	0.7	444	0.51	7.4
4.	0.6	442	0.41	6.9
5.	0.9	443	0.49	6.9

Table III. — (a) *Global minima for five realizations of removing 5 random points.* (b) *Global minima for five realizations of adding Gaussian noise with $\sigma = 1\%$.*

a)	#	χ^2	$t_c(\text{days})$	m	ω
	1.	1.1	436	0.63	6.1
	2.	0.84	435	0.45	6.5
	3.	1.1	442	0.43	6.8
	4.	1.4	451	0.59	5.8
	5.	1.0	435	0.49	6.4

b)	#	χ^2	$t_c(\text{days})$	m	ω
	1.	2.2	438	0.62	6.7
	2.	1.4	437	0.46	6.3
	3.	2.4	452	0.73	5.9
	4.	1.8	455	0.37	6.1
	5.	2.2	451	0.49	5.9

actually corresponds to the time distribution of the real data ⁽²⁾. For five random realizations, we find that the χ^2 fluctuates between 0.6 to 1.1. t_c is between 439 and 444, m is between 0.41 and 0.52 and ω is between 6.3 and 7.4 (see Tab. II). This gives an estimate of the size of fluctuations we should expect.

4. Statistical Significance of the Fit

The robustness of the fit was investigated in several ways. In the spirit of the bootstrap re-sampling scheme [33], points were removed at random. The global minima for five independent random realizations, where 5 (*i.e.* $\simeq 10\%$ of the) points have been removed give values close to the global minimum in Table I, except one which is close to the lowest local minimum: t_c fluctuates between 435 and 442 (except one at 451), m is between 0.43 and 0.63 and ω is between 5.8 and 6.8 (see Tab. III). (Removing additional 5 random points gave practically the same result.) Furthermore, Gaussian noise with a standard deviation of 1% was added to the original data. The fit to five independent random realizations gives results qualitatively identical to the bootstrap re-sampling scheme, but the enhanced noisiness of the data clearly

⁽²⁾ If the removal of water-bottles from the stores is a Poisson process then the probability of finding a water-bottle of a certain age in the store will decay exponentially. This then corresponds to a uniform sampling in log-time.

Table IV. — (a) Global minima for five realizations of the null hypothesis. Full data set. (b) Global minima for five realizations of the null hypothesis. Truncated data set. Note the large value of ω .

#	χ^2	t_c (days)	m	ω
1.	no solution found			
2.	0.6	457	0.87	16
3.	1.1	444	0.95	9.3
4.	0.6	487	0.77	18
5.	no solution found			

#	χ^2	t_c (days)	m	ω
1.	no solution found			
2.	0.7	439	0.44	17
3.	1.1	438	0.86	14
4.	0.4	445	0.24	11
5.	no solution found			

effects the obtained parameter values: t_c fluctuates between 437 and 455, m is between 0.37 and 0.73 and ω is between 5.9 and 6.7 (see Tab. III).

The method of surrogate data involves two ingredients: a null hypothesis for the observations and a discriminating statistic between the null hypothesis and the observations. As a null hypothesis, we have assumed the chloride-content to be constant and noisy until some time-interval before the earthquake. We then assume an exponential increase and fit an exponential to the data. A similar exponential increase of seismic foreshock activity has been proposed in the past [13]. We did not consider a simple power law increase (inverse Omori's law) as a viable null hypothesis, since we did not find any minimum of χ^2 for this case. This is most likely due to the strong log-periodic corrections seen in the data. In other words, this means that the simple power law null hypothesis is automatically rejected by the absence of a minimum of χ^2 .

Using the times of the real data and adding Gaussian noise with standard deviation 1%, we have generated five surrogate data series with the obtained exponential function. We see, in Table IVa, the fits obtained to equation (1) using surrogate data generated for the full time interval. It is clear that the χ^2 is not a good discriminator – the data are too sparse with the error bars given – but m and, especially, ω are. The high values obtained for ω means that we are simply fitting noise. Indeed, a large ω implies fast oscillations which can pass better through random points. Surrogate data were also generated for a truncated time-interval assuming the exponential rise started 169 days before the earthquake. In Table IVb, we see the parameter values obtained. Again the rapid oscillations are simply due to fitting noise and we conclude that the null hypothesis has to be rejected. We must say that it unfortunately could not be done on the basis of a usual statistic, such as the χ^2 , since the data was too sparse. However, we have shown the use of ω as a discriminator turns out to be very selective and provides a convincing classification between genuine information and noise fitting. It is thus clear that a noisy exponential rise in the Cl^- content does not provide a good account for our findings. Combined with the three other tests performed, our investigation supports the claim of log-periodic oscillations in the data. Very similar results are found for the other ions data.

5. Prediction

In extending the rationale above, the possibility of using the data as a predictive tool has been investigated. This was done by simply excluding the last n points, n running between 19 and 0,

Table V. — (a) “Postdiction” for Kobe data. The first entry corresponds to first reasonably close “postdiction” for t_c obtained. $T_c - T_n$ correspond to the number of days between the earthquake and the last data point used. (b) “Postdiction” for 4 random realizations of equation (1). Gaussian noise with $\sigma = 1\%$ was added and sampling was on a two-day interval. $T_c - T_n$ correspond to the number of days between the earthquake and the last data point used. σ_{t_c} is the standard deviation of t_c .

a)

$T_c - T_n$	χ^2	t_c (days)	m	ω
26	1.1	424	0.59	5.7
25	1.1	426	0.52	5.2
11	1.2	429	0.67	5.9
8	1.2	455	0.76	6.1
6	1.4	452	0.71	6.0
4	1.2	441	0.45	6.7

b)

$T_c - T_n$	$\langle t_c \rangle$ (days)	σ_{t_c} (days)	$\langle m \rangle$	$\langle \omega \rangle$
61	447	19	0.42	7.0
51	447	16	0.41	7.0
41	445	13	0.36	7.0
31	445	7	0.37	7.0
21	444	5	0.40	6.9
11	444	6	0.44	6.9

and fitting equation (1) to the truncated data set. In Table Va, we see the obtained parameter values starting from the first reasonable close “postdiction” for t_c obtained.

We also repeated the prediction scheme with 1) the value of the exponent fixed to its mean-field value, $m = 1/2$, and 2) using the filtered version of the data shown in Figure 2. No significant improvement was obtained. The predictivity appears therefore reasonable (the data would predict the earthquake four days ahead of the actual event with an error of +2 days) but not as good as was observed in [19]. However, it must be stressed that the data are sparse and noisy, and moreover that the sampling was quite unsatisfactory.

In order to confirm the role of the sampling, we generated 4 artificial data sets with a 2-day sampling using equation (1) with the parameter values of the global minimum and the errorbars of the true data. In Table Vb, we see that the prediction has been indeed improved considerably. We note without surprise that the spurious “noise-fitting” minima did not appear with the increased sampling.

6. Other Data Sets

An important question concerns the choice of the ion concentration time series among other data sets available before the Kobe earthquake. The phenomenon we aim to document has nothing specific to ions or permeability data since it should derive from the assumed criticality of earthquakes. Its existence would therefore be strengthened if it were to manifest itself in some other time series for the same earthquake. We have thus looked at the few other times series measured before the Kobe earthquake.

One example is the Benioff strain, cumulated over the earthquakes occurred in the region, represented also in Figure 1. The data suggests the existence of an acceleration maybe decorated by jumps, as found for the Loma Prieta and the Aleutian island earthquakes [19], but is too scarce to really allow for a quantitative analysis.

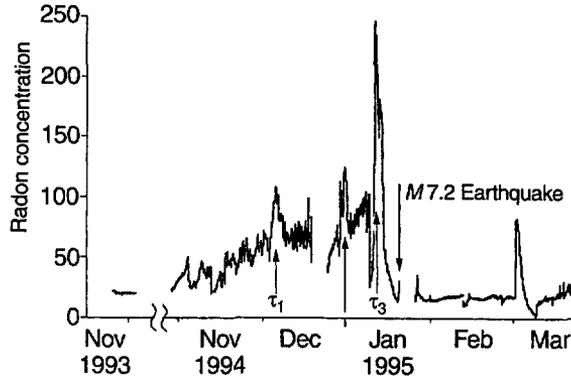


Fig. 4. — Radon concentration data measured in [34] prior to the Kobe earthquake.

In the same issue of *Science* as the one reporting the precursory chemical change we have analysed above [22], a ground water radon anomaly before the Kobe earthquake is also published [34]. We show the dependence, taken from [34], of the measured radon concentration as a function of time in Figure 4. The data is also suggestive of a punctuated acceleration, similar to that observed for the ion concentrations. The data is however too short and too noisy to attempt a full fit with equation (1). However, we can try to check whether the discrete scaling represented by equation (1) is present. In this goal, we notice that equation (1) predicts that maxima of the signals occur at times τ_n such that $\tau_c - \tau_n$ form a convergent geometrical series given by:

$$\tau_c - \tau_n = \frac{1}{\lambda}(\tau_c - \tau_{n-1}), \quad (2)$$

with

$$\lambda = e^{2\pi/\omega}, \quad (3)$$

and τ_c is again the time of the Kobe earthquake. This relation also entails that

$$\tau_{n+1} - \tau_n = \frac{1}{\lambda}(\tau_n - \tau_{n-1}). \quad (4)$$

With $\omega \simeq 7$ determined above, we get $\lambda \simeq 2.5$. In Figure 4, we observe three main peaks before the Kobe earthquake, which are significantly above the background. They are shown by the arrows and we note the three corresponding times as $\tau_1 < \tau_2 < \tau_3$. The ratio $\frac{\tau_3 - \tau_2}{\tau_2 - \tau_1}$ is found close to 1/2.3, in agreement with our prediction (4) obtained from the independent ion data. Furthermore, extending this argument, we can sum the convergent series of the extrapolated geometrical sequence as $\tau_c - \tau_3 = (\tau_4 - \tau_3) + (\tau_5 - \tau_4) + \dots + (\tau_n - \tau_{n-1}) + \dots = (\tau_3 - \tau_2)(\frac{1}{\lambda} + \frac{1}{\lambda^2} + \dots + \frac{1}{\lambda^n} + \dots) = \frac{\tau_3 - \tau_2}{\lambda - 1}$. We thus predict the time of the Kobe earthquake as given by $\frac{\tau_c - \tau_3}{\tau_3 - \tau_2} = \frac{1}{\lambda - 1} \simeq 0.77$, which must be compared with the measured value equal to $\simeq 0.75$. This discrepancy corresponds to the amazingly small offset of less than one day for the prediction done at time τ_3 (8 days in advance). We note that, following our initial proposition [19, 20], the same method described by equation (4) has been used recently to describe the cyclic and self-similar seismic time series preceding an earthquake near the Virgin islands [35]. This procedure could provide a robust and simple alternative method to the fit with equation (1) when data are too small or too noisy.

However, not all measurements of anomalies yield to this quantification. Water temperature and pressure for instance do not seem to be useful probes [36]. In order to provide a meaningful test or measure of the cooperative process that we believe occurs before an impending earthquake, the measured quantity should be a good signature or witness of the cooperativity. In addition, it should not be spoiled too much by noise and/or other competing processes.

7. Concluding Remarks

To summarize, we have performed what is, to our knowledge, the first quantitative analysis of chemical groundwater change in relation to a major earthquake. We find that it correlates with the seismic activity and the anomalous radon concentration.

We attribute the observed increase of ion concentration to a rise of deep-seated groundwater, which is known to have a higher content of Cl^- , SO_4^{2-} , *etc.*, into the artesian layer of the wells. This is due to correlated micro-cracking and fault activation leading to a change of the permeability of the rocks. This follows since there is no principal source of Cl^- and SO_4^{2-} in the shallow strata beneath the Kobe area and high ion content are common features of deep-source groundwater rising through fracture zones near the Rokko mountains.

These micro-cracking and stress correlations that we invoke as the underlying physical mechanisms implies that anomalous creep should have been much stronger closer to the epicenter. To our knowledge, this data is not available but this is a prediction that is worth keeping in mind for future observations.

We have found that log-periodic corrections to scaling provide a reasonably good fit of the data. Of course, despite the careful analysis we have gone through, we are aware that there are presumably other sorts of fits with as many parameters that would work as well. Our attitude is that it is surely irrational to infer the validity of a description based on one fit, but if it works for many fits, it should have some truth in it. Indeed, it is generally quite easy to fit deterministic models to data, if the parameters are numerous enough, but often difficult to obtain consistent parameters values. To validate predicting ability requires that one obtains a good fit in several data sets with the same parameter values. Stated somewhat pointedly: one good fit make a data description; two good fits make a system description. As a test, we observe that the values of m and ω we find are consistent across the two time series which have been analyzed for the Kobe earthquake and are also very close to the ones that have been found for Loma Prieta, the Aleutian Islands [19] and Virgin Island [35] earthquakes. If we were mostly fitting some random fluctuations around the power law, values of ω (*i.e.* λ) would wildly fluctuate from sample to sample (besides the fact that the fit would of course be of lower quality). This work, supplementing [19, 20, 30], suggests a very coherent picture, namely that *complex* critical exponents are a general phenomenon in irreversible self-organizing systems and particularly in rupture and earthquake phenomena. Considering log-periodic corrections to scaling for earthquakes could, as previously indicated in [19], lead to improved earthquake prediction schemes. This is currently being investigated on a broader scale.

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