Critical phenomena of rock fracturing in groundwater level observation before the 2000 eruption of Usu volcano, Japan

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Contents:

Introduction 1: Can we predict an earthquake ?

✓ What is the nature of rock fracturing?

Hypothesis

The rupture is similar to "critical point".

Macroscopic phenomena have their origin in a microscopic organization which can be transferred to large scales.

If true

the mechanism of fracturing would be constrained by critical phenomena, and we can approach to earthquake prediction.

Introduction 2: Examples of critical phenomena

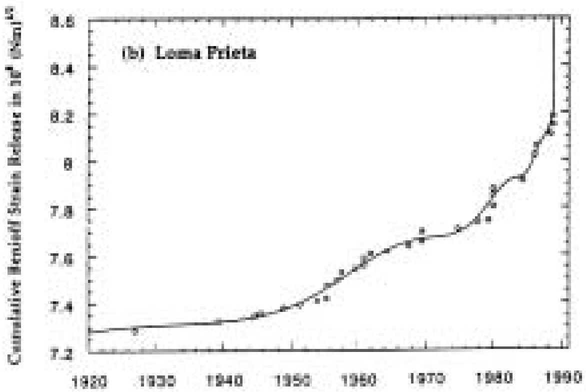
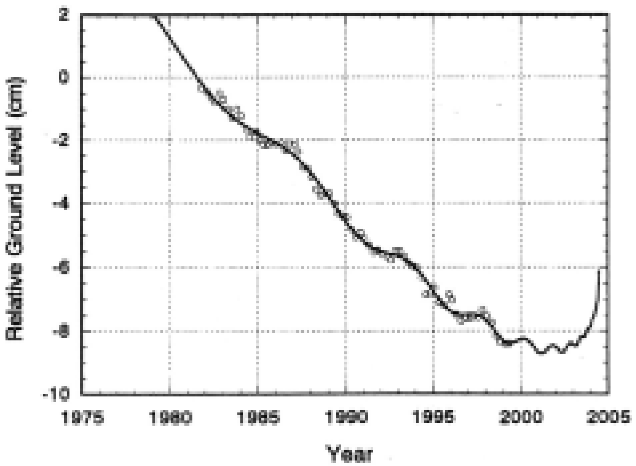


Fig.1
Cumulative Benioff strain release in Loma Prieta Earthquake (San Francisco, USA, 1989)
Sornette & Sammis, 1995



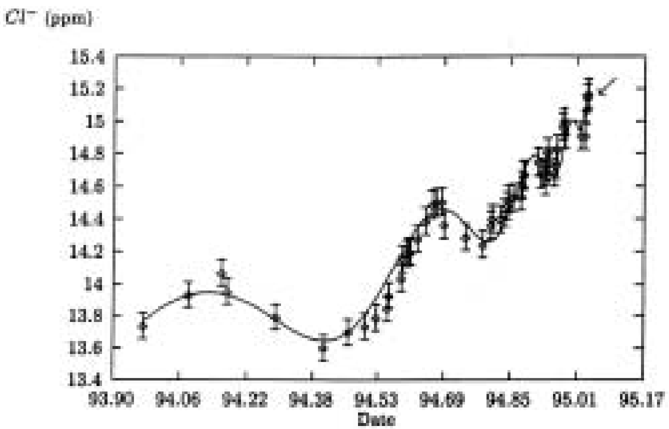


Fig.2
Cl^- concentration in Kobe Earthquake (Kobe, Japan, 1995)
Johansen et al., 1996

Fig.3
Geodetic sign of future earthquake.
Igarashi, 2000

✓ Groundwater level in GSH-1 well indicated log-periodic fluctuation at 3 months before the eruption.

Introduction 3: Hydrological anomalies before the Usu eruption

Usu volcano (42º32’N, 140º50’E) erupted on 31 March 2000 at 13:07 JST (4:07GMT).

» Hydrological anomalies were observed in many wells around the Usu volcano.

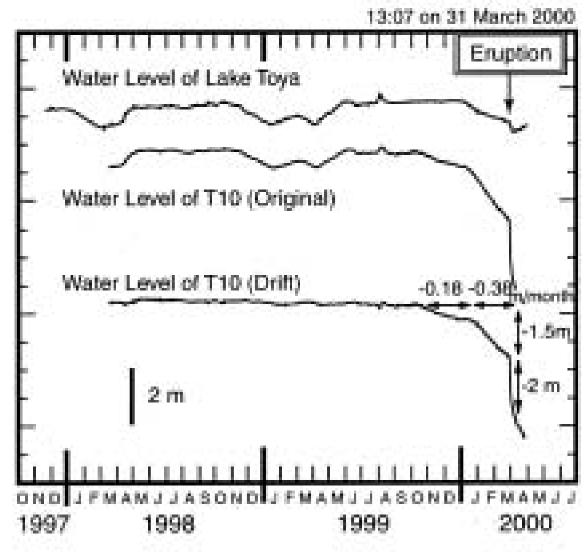


Fig.5 Shibata & Akita, 2001

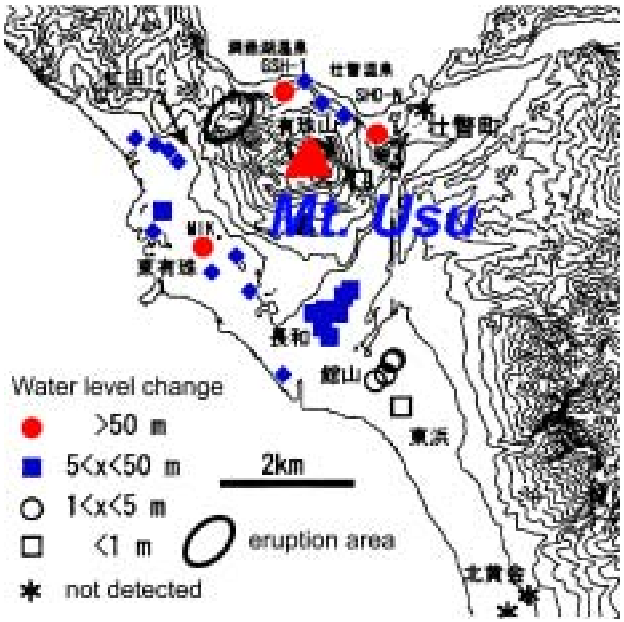


Fig.4 Akita et al., 2000 (modified)

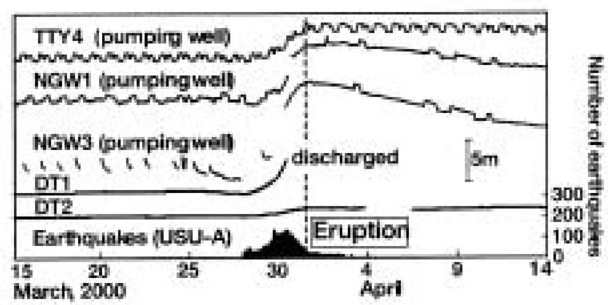


Fig.6 Matsumoto et al., 2002

Introduction 4 : Fluctuation in groundwater level of the GSH-1 well

✓ The water level
 » gradually decreased on 14 December, 1999.

 » dropped by more than 5 m on 28 March, 2000.

 » suddenly increased by more than 100 m on 3 April, 2000, and water spouted from the well like a fountain.

Fig.7 photograph of the GSH-1 well

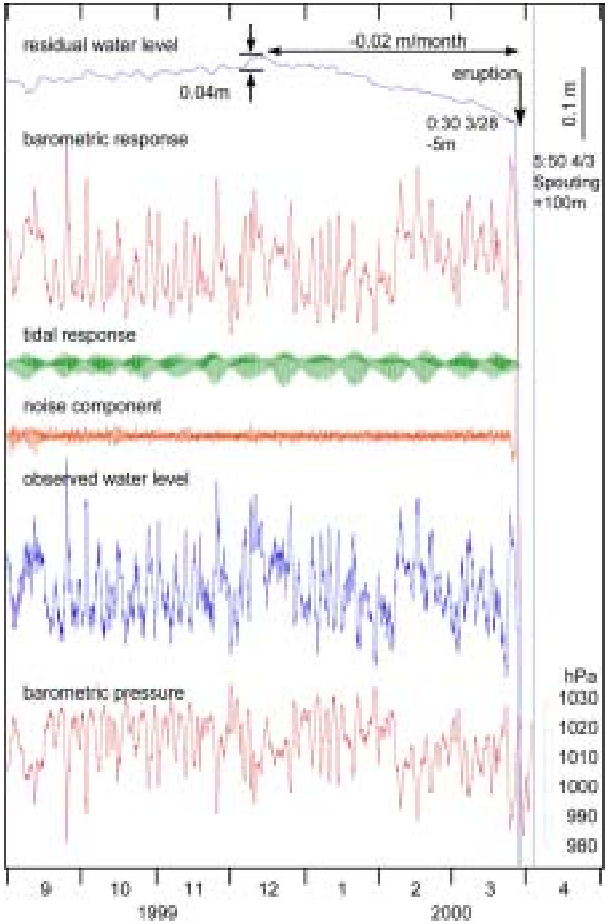


Fig.8 Shibata & Akita, 2001 (modified)

✓ Strain sensitivities are 6.8 and 6.5 mm/10^{-8} strain for M_2 and O_1 tidal constituents (used by a Baytap-G program).

Observation 1: Information of the GSH-1 well

✓ The GSH-1 well
  » is located 2 km north (142 m a.s.l.) from summit of Usu volcano.
  » is 1200 m deep (screen: 930-1200 m).
  » is tapping a confined fractured-rock aquifer in silicified rock.

✓ The water level is ~57 m a.s.l., which is ~85 m below the ground.

✓ The water level is sensitive to the barometric pressure, the tide and the crustal strain.

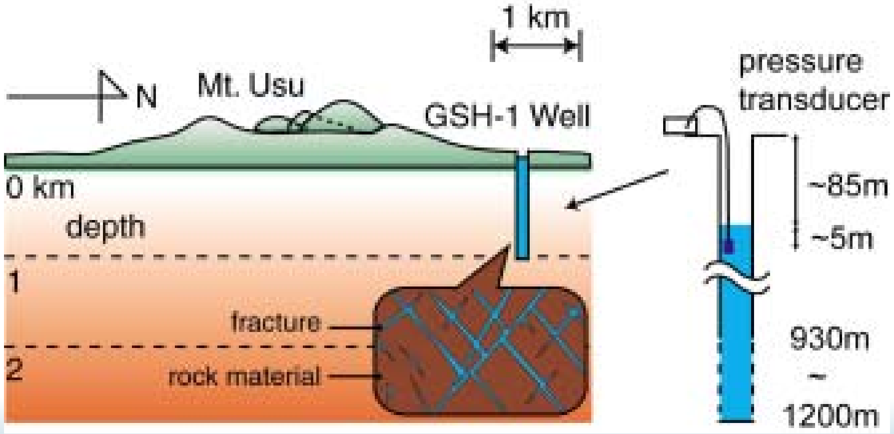


Fig.9 Schematic of the GSH-1 well

Observation 2: Groundwater level before the eruption

✓ There are three specific periods in the entire period.

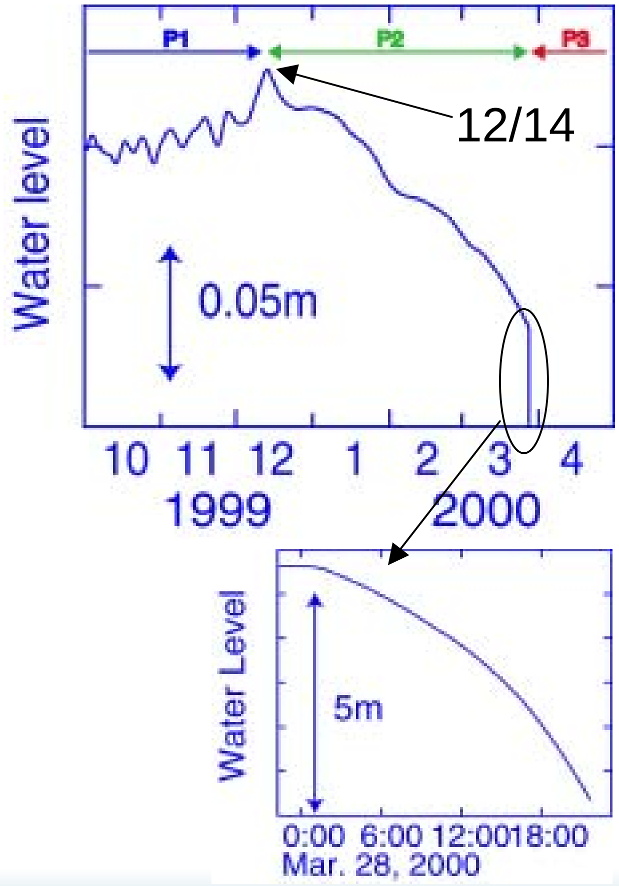


Fig.10 Variation in residual water level

P1 (~ 14 Dec.):
a steady variation.
P2 (14 Dec. ~ 28 Mar.):
an oscillation pattern like self-similarity.
P3 (28 Mar. ~):
an oscillation pattern like self-similarity?

✓ The earthquake started on 27 March about 20:00.

✓ However, the first earthquake, whose epicenter was determined, was 28 March at 0:23.

Fourier power spectrum: Check on self-similarity (fractal)

Important!

- ✓ The concept of fractal is scale invariance (i.e., self-similarity).
- ✓ Spectral analysis is frequency change in observation ($f \rightarrow \lambda f$).
- ✓ Scale invariance is equal to invariance in spectral analysis.

- ✓ If such a transformation ($f \rightarrow \lambda f$) is invariant
  - » the power spectrum, $S(f)$, is proportional to $f^{-\beta}$. »$S(f) \propto f^{-\beta}$
  - » fractal dimension, D, is equal to $(7-\beta)/2$. »$D = (7-\beta)/2$

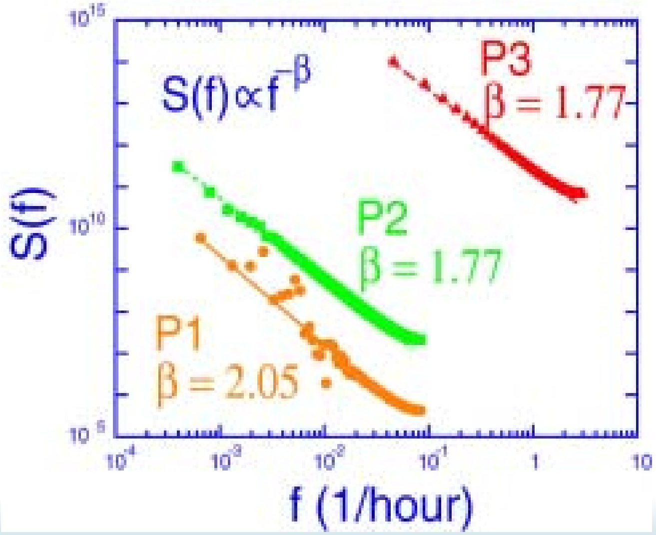


Fig.11 Fourier power spectra

The fluctuations in P2 and P3 are confirmed as fractal (critical) phenomena.

Fractal dimension is 2.62.
Ex.: D=2.25-2.75
experiment of acoustic emission in rock fracturing (*Hirata et al.*)

Log-periodic oscillation

✓ An acceleration of interactive force near a critical point obeys the log-periodic oscillation superposed on the power law.

$$f(t) = A + B\,(t_c - t)^{m}\,\{1 + C\cos[\omega \log(t_c - t) + \psi]\} \quad (1)$$

$f(t)$: water level, t: time, t_c: critical point, m and ω: critical exponents
A, B, C and ψ: constants.

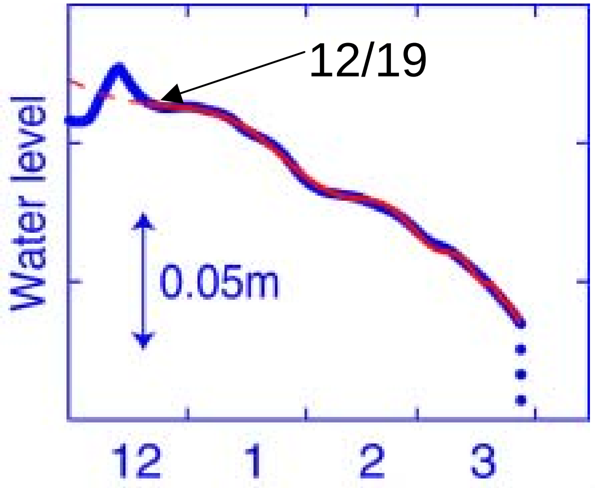


Fig.12 Optimal log-periodic oscillation

Result:
t_c: 0:18±2:11 on 28 Mar.
(first larger earthquake:
0:23 on 28 Mar)
m: 0.694±0.006
ω: 7.96±0.05

Ex. $0.2 \leq m \leq 0.6$, $6 \leq \omega \leq 12$
(*Huang et al.*)

Prediction of the rock fracturing: Initial parameters

✓ The critical point could be estimated from different data period by using Eq. 1.

$$f(t) = A + B\,(t_c - t)^{m}\,\{1 + C\cos[\omega \log(t_c - t) + \psi]\} \quad (1)$$

1. The beginning of data period is fixed to be on 19 December 1999.
2. The target data period is lengthened 5 days from on 18 January 2000.
3. Initial parameters are settled on those listed in Table 1.

Table 1 Initial parameter.

No.	initial parameters t_c	m	w	estimate t_c
1	2000.1.19	0.2	9	2000.3.28
2	2000.1.19	0.4	9	2000.3.28
3	2000.1.19	0.6	9	2000.3.28
4	2000.3.19	0.2	6	2000.8.9
5	2000.3.19	0.2	9	2000.3.28
6	2000.3.19	0.2	12	2000.8.17
7	2000.3.19	0.4	6	2000.7.25
8	2000.3.19	0.4	9	2000.3.28
9	2000.3.19	0.4	12	2000.3.28
10	2000.3.19	0.6	6	2000.3.28
11	2000.3.19	0.6	9	2000.3.28
12	2000.3.19	0.6	12	2000.6.12
13	2000.6.19	0.2	9	2001.5.8
14	2000.6.19	0.4	9	2001.7.3
15	2000.6.19	0.6	9	2000.3.28

» The estimated critical point is settled on 28 March 2000 from 9 sets in 15 sets.

Prediction of the rock fracturing: Estimation of critical point

✓ The best estimation of critical point is determined by minimizing χ^2.

$$\chi^2 = \Sigma\{ [f(t_i) - f_0(t_i)] / \sigma \}^2 \quad (2)$$

$f(t_i)$: value of Eq. 1 *at* $t = t_i$,
$f_0(t_i)$: residual water level,
σ : the standard deviation.

» The critical point is settled on 28 March 2000 at the beginning of March.

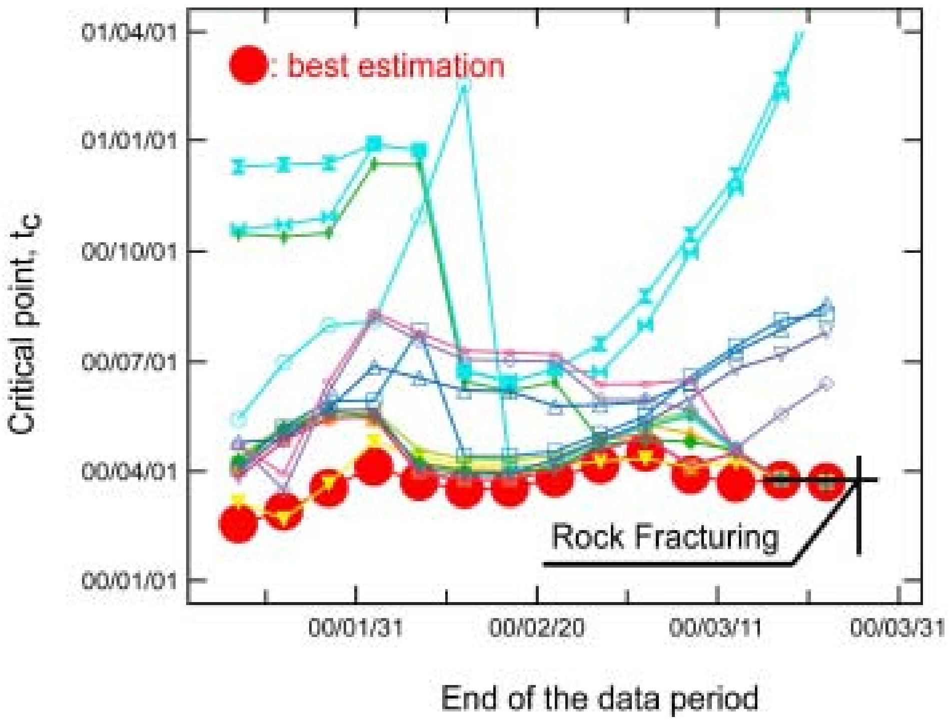


Fig.12 Estimated critical point.

Conclusions

- ✓ Groundwater level indicates critical phenomenon.
- ✓ The critical phenomenon is confirmed by using an analysis of Fourier power spectrum.
- ✓ The fractal dimension is obtained from a Fourier analysis.
- ✓ The rock fracturing would be driven by accumulation and interaction of microcracks in the eruption of Usu.
- ✓ The critical point of rock fracturing can be predicted by a log-periodic equation.

» Concept of fractal would potentially offer earthquake prediction.