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Groundwater Observations at KSM Site in Northeast Japan, a Most Sensitive Site to Earthquake Occurrence

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Abstract: Intensive observations of groundwater, including measurements of the radon concentration, water level, flow rate, and *in situ* temperature of the aquifer, have been carried out at an observation site which has been found to be most sensitive to earthquake occurrence. The KSM site is located in the eastern part of Fukushima Prefecture, Northeast Japan. The observation well is positioned right on the fracture zone of the Futaba fault. In previous studies background fluctuations in the observed radon data were successfully removed using a time-series data analysis based on a Bayesian approach, which enabled us to detect systematic radon changes associated with earthquakes. In the present study we have tried to improve the observation conditions at the site by reducing environmental temperature changes.

Data from intensive groundwater observations at the KSM site are discussed for the period from January 1989 to May 1990; the detection of coseismic radon changes is particularly stressed. During this period the responsiveness of radon changes to earthquake occurrence which had been the characteristic feature of the site seemed to disappear. This may be interpreted as being caused by changes in physical properties of the region where the KSM site is located due to the occurrences of five large earthquakes in succession in the near-by area between February and April 1987.

1. Introduction

After the Miyagi-ken-Oki earthquake ($M=7.4$) in June 1978, the southward migration of large earthquakes off Fukushima Prefecture was seriously hypothesized based on the historical record. After an M 7.7 earthquake occurring off Miyagi Prefecture in 1936, two large earthquakes with magnitudes of 7.1 and 7.7 have taken place off Fukushima Prefecture. In order to develop a groundwater monitoring network on land in the area, a research group (Principal Investigator: T. Asada; Co-Investigators: A. Takagi, H. Shimamura, K. Tsumura, and H. Wakita) was organized in 1978, and three wells were drilled in the eastern part of Fukushima Prefecture under a program funded by the FY1978 Grant-in-Aid for Scientific Research, Ministry of Education, Science and Culture.

We have been carrying out continuous monitoring of the radon concentration of groundwater at these three observation sites since 1980 (Wakita *et al.*, 1986). We have found that the KSM site, one of two observation sites drilled right on the Futaba fault

(Fig. 1), is particularly sensitive to earthquake occurrence: more than ten earthquake-related changes have been detected using a time-series data analysis based on a Bayesian approach during the period 1984-1988 (Wakita *et al.*, 1989). Detailed discussions of the subject, in relation to calculated crustal deformation caused by an earthquake, and of the presence of two less sensitive observation sites were presented by Igarashi and Wakita (1990).

Under the previous observation conditions, due mainly to the slow rate of flow of the groundwater at the KSM well, temperature in the radon detection chamber was significantly disturbed by changes in environmental temperature. Thus, large background fluctuations were observed in the temporal variations of the radon data. Although these background fluctuations were substantially removed by the Bayesian treatment, it was quite difficult to remove them completely (Igarashi and Wakita, 1990). In order to obtain better results for the data analysis, we began to improve environmental conditions at the KSM observatory in April 1989. The outside of the observatory was completely covered with heat insulating materials, and the radon monitoring instrument was replaced by a new and modified one. A low-cost air conditioner was installed in July 1989 to reduce the atmospheric temperature changes. Furthermore, in the hope of clarifying the mechanism that causes the observed radon anomalies, we have installed various instruments to monitor additional hydrological parameters: measurements of water level, flow rate, *in situ* groundwater temperature at the strainer position, and atmospheric pressure. This paper reports preliminary results obtained so far by intensive groundwater monitoring at the KSM site.

2. Intensive Groundwater Monitoring System

The KSM observation site is located in the eastern part of Fukushima Prefecture, Northeast Japan. Northeast Japan is considered to be a typical island arc. The double-planed structure of microearthquake distribution reflects the movement of the Pacific plate relative to the Eurasian plate. Earthquakes occurring in the upper plane are characterized by reverse fault movement of down-dip compression, while those occurring in the lower plane are generally down-dip extension (*e.g.*, Hasegawa *et al.*, 1985). Most of the shallow earthquakes in this region occur beneath the Pacific Ocean between the Japan trench and the coast line.

During the process that leads to an earthquake, various changes in groundwater are expected to take place as a result of the interaction between rocks and groundwater. Although the changes can be attributed to the accumulation of strain within the bedrock, the mechanisms that may cause groundwater anomalies are still uncertain. In order to develop a quantitative framework for interpreting groundwater anomalies, it will be helpful to make a variety of measurements at observation sites sensitive to earthquake occurrence.

Observation Well: The KSM observation well is a 200-meter-deep artesian well drilled right on the Futaba fault, one of the major active faults in Northeast Japan. The

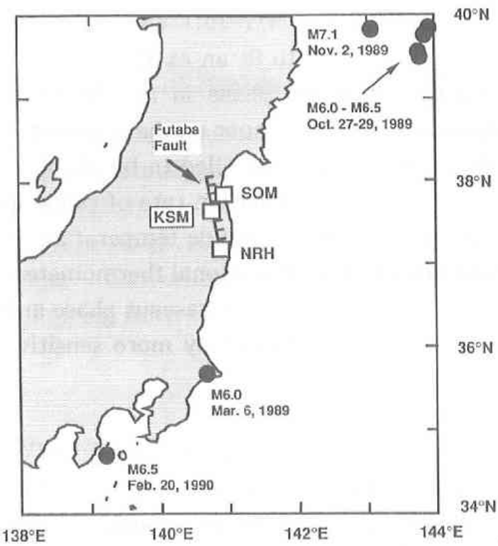

Fig. 1 Location of three observation sites (KSM, SOM, and NRH) for groundwater monitoring in the eastern part of Fukushima Prefecture, Northeast Japan. The epicentral distribution of earthquakes with $M \geq 6.0$ in the area are shown for the period from January 1989 to May 1990.

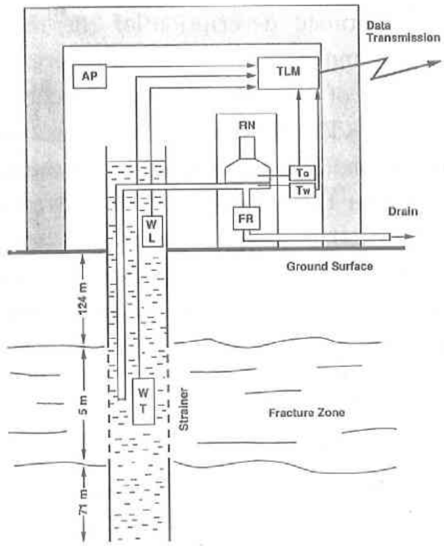

Fig. 2 Schematic diagram of an intensive groundwater observation system at the KSM site. Measurements of radon concentration (RN), water level (WL), flow rate of groundwater (FR), *in-situ* groundwater temperature (WT) at the strainer position (at the depth 126 m), and atmospheric pressure (AP) are being collected. The above data together with monitored temperature data of gaseous (T_G) and water (T_W) phases in the detection chamber are sent to a central observation office through a telemetering unit (TLM).

eastern side of the Futaba fault, the coastal lowland, is covered with Tertiary and Quaternary sediments, while the western side of the fault, the Abukuma high mountain area, is composed of Paleozoic, Mesozoic, and Miocene volcanic materials, including metamorphic rocks of granodiorite (Koike, 1969). Although the upper crustal layer of the KSM site is composed of sandstone and shale, mylonitic granodiorite is found in the layer deeper than 130 m, and the structure of brecciation and pulverization in the rocks clearly reflects the fault movements (Nakamura and Wakita, 1982). An iron casing 10 cm in diameter is installed in the drilled hole. The strainer is positioned at the depth of 124 m–129 m, from which groundwater issues at a flow rate of about 30 cm^3/min. To shorten the response time to possible changes in radon concentration, groundwater at the strainer position is siphoned through a pipe 1.3 cm in diameter to the radon measuring chamber. A schematic diagram of the whole monitoring system is show in Fig. 2.

Radon Measurement: The radon concentration in the groundwater is continuously being measured with a ZnS (Ag) scintillation detector system (Model NW-102, Aloka Co.

Ltd.). Detailed description of the original system (Model NW-101) was made by Noguchi and Wakita (1977). The present model is modified to fit an extremely small flow rate of groundwater by reducing the volume of water phase in the detection chamber. The chamber is heated to avoid deposition of water vapor on the scintillator surface, and the surrounding temperature is thermostatically controlled to be about 5-10℃ higher than that of the groundwater inflow. Since the emanation rate of radon in groundwater is proportional to the surrounding temperature, the inside temperature of the detection chamber has to be monitored. Previously two conventional thermometers with a precision of 0.2℃ monitored temperature changes of the upper gaseous phase and lower water phase in the detection chamber. These were replaced by more sensitive ones, as described below.

Water Temperature Measurement: Two thermometers with a precision of 0.01℃, composed of a thermister sensor and a thermometer (Model D641, Technol Seven Co., Ltd.), were installed in the water and gaseous phases in the detection chamber. One more sensor was placed at the strainer position (the depth of 126 m) of the well to detect possible changes in groundwater movements.

Water Level Measurement: In order to detect the quick response of groundwater movements, a pressure transducer-type water level gauge (Model FBA90WB2-100Y, Fuji Electric Co. Ltd.), which has a nominal resolution of 1 mm of water level change, was installed about 60 cm below the water head of the well.

Flow Rate of Groundwater: The flow rate of the groundwater issuing from the siphon tube is monitored by a electro-magnetic flow meter (Model MAG-OVAL 1000, Oval Co. Ltd.). Although the present instrument is not ideally suited to ordinary observation because of its use near the minimum detection limit, possible large changes in the flow rate can be detected.

Atmospheric Pressure: Since the degassing rate of radon in the aquifer and flow rate of groundwater are affected by changes in atmospheric pressure, a cylindrical resonator-type digital barometer (Model F-451, Nakaasa Instrument Co. Ltd.) is being used.

Data Transmission by Telemetering System: Hourly data are collected at the observation site and then transferred once a day to a central observation office at the University of Tokyo by a telemetering system (JRC Co. Ltd.) over a commercial telephone line.

Data Processing System: A computer (HITAC E-600, Hitachi Ltd.) was replaced by a UNIX workstation (Sun Sparc 370 GX, Sun Microsystems Co. Ltd.). The new system provides much higher performance in speed of calculation, sizes of main memory and internal mass storage, and graphic interface. We have developed the software applied to our continuous monitoring of groundwater in cooperation with Nihon Sun Microsystems K.K. A detailed description of the system will be reported elsewhere.

3. Removal of Background Fluctuations in Radon Concentration

To remove fluctuations due to environmental temperature, we have applied a time-series data analysis based on Bayesian approach developed by Akaike (1980) and Ishiguro *et al.* (1983).

The observed data on the radon concentration y_i are decomposed into three components — temperature response, trend (drift), and irregular (noise) components — in the following form (Igarashi and Wakita, 1990) :

$$y_i = \sum_{k=0}^{K} b_k x_{i-k} + d_i + e_i \tag{1}$$

The temperature-response component is expressed as $\sum_{k=0}^{K} b_k x_{i-k}$, where x_{i-k} is the observed temperature in the chamber and b_k is a response coefficient ; we assume linear responses of radon concentration to the temperature, with time lags from 0 to K hours (the maximum time lag K is also a free parameter to be determined in the statistical model). The trend component d_i is determined under the condition of

$$d_i - 2d_{i-1} + d_{i-2} = \xi_i \tag{2}$$

where ξ_i is a zero-mean Gaussian noise. The irregular component e_i is assumed to be a zero-mean Gaussian white noise. Here, standard deviations of these Gaussian noises ξ_i and e_i remain free parameters to be determined in the model.

According to Akaike (1980), the statistical model expressed as (1) can be determined under the condition (2) using a Bayesian approach. He defined "Akaike's Bayesian Information Criterion (ABIC)" and proved that ABIC is in negative proportion to log-likelihood of the model. The model that minimizes ABIC, therefore, corresponds to the maximum-likelihood model. Thus we can obtain the maximum likelihood estimates of the parameters included in the model. The calculations were performed using the computer program BAYTAP (Bayesian Tidal Analysis Program) developed by Ishiguro *et al.* (1984).

4. Results and Discussion

4.1. Detection of Earthquake-Related Radon Changes

In the previous paper a time-series data analysis was adopted to the radon data for the period from 1984 to 1988. Background fluctuations were substantially removed from the original data, and, consequently, prominent post-seismic decreases lasting for periods ranging from several days to more than one week were seen in the trend for all the nearby earthquakes. Most of the observed abnormal changes were explained as being related to the occurrence of earthquakes (Igarashi and Wakita, 1990). For example, Fig. 3 shows an analytical result removing environmental temperature fluctuation, together with the observed data on radon concentration and temperature in the chamber, in the period when seismic activities off Fukushima Prefecture were very significant, from

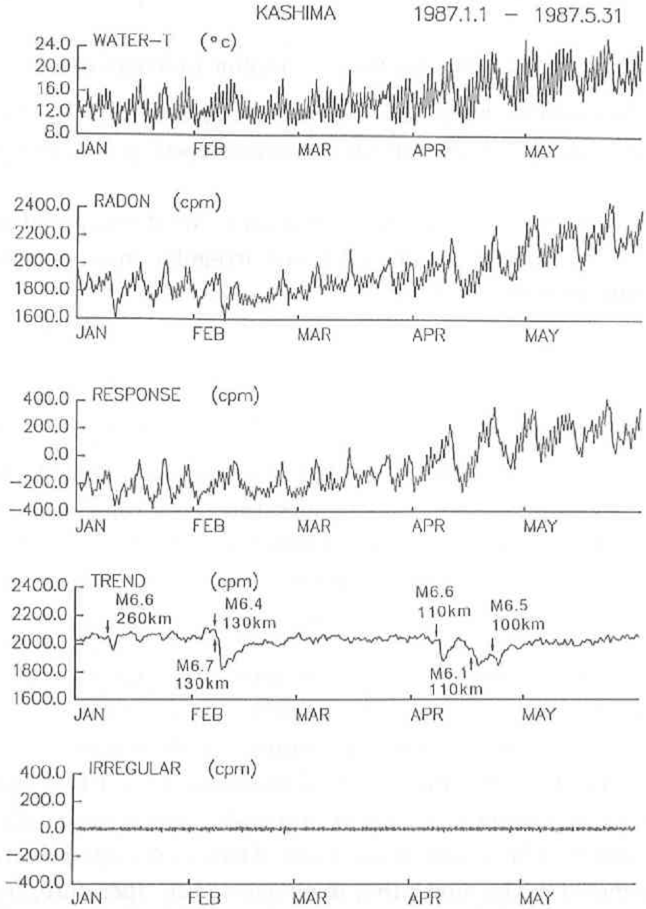

Fig. 3 Observed data on radon concentration and water temperature in the detection chamber obtained at the KSM site, and results of numerical analysis using the computer program BAYTAP (Ishiguro *et al.*, 1984) from January to May 1987. The original radon data are decomposed to trend, temperature-response, and irregular components. Earthquakes with $M \geq 6.0$ are indicated with their magnitude and hypocentral distance.

January to May 1987. At that time five earthquakes with magnitudes greater than 6.0 occurred in the area near the KSM site. The occurrences of those earthquakes are also indicated in the figure, with their magnitudes and hypocentral distances from the KSM site.

During the period between 1984 and 1988, a total of 20 radon anomalies were observed and 30 earthquakes with magnitudes $M \geq 6.0$ and hypocentral distance $D \leq 1{,}000$ km occurred. The 14 anomalies that were observed were attributed to 12 post-seismic and 2 preseismic signals. The other 6 anomalies were interpreted to be related to earthquakes with smaller magnitudes or to changes in the local stress field that did not result in an earthquake (Igarashi and Wakita, 1990).

Most of the background fluctuations remaining in the trend could be attributed to incomplete separation of the temperature response component from the original data. In the numerical analysis, the response coefficients are assumed to be constant. In the actual radon-measuring system, however, the radon concentration may have slightly time-dependent response coefficients, since the emanation rate of radon in the measuring chamber may depend on the time-gradient of the temperature change, the temperature difference between the vapor and liquid phases, and so on. For this reason, it was difficult to separate the temperature-response component more completely from the original data based on the previous observation. Thus, improvement of the environmental conditions was urgently needed.

4.2. *Temporal Variations in the Radon Concentration*

General features of temporal variations in the radon concentration at KSM have been described in previous papers (Wakita *et al.*, 1986 ; Igarashi and Wakita, 1990). Figure 4 shows the observed data on radon concentration and temperature in the detection chamber during the period between January 1989 and May 1990. Plotted are 24-hour moving averages of the raw data taken at one-hour intervals to eliminate diurnal changes. The housing improvements were made in April 1989, and a low-cost air conditioner was installed in July. As seen in Fig. 4, the temperature fluctuations — and, consequently those of radon — were significantly reduced in the period when the air conditioner was properly operated, while these data were disturbed in the period when

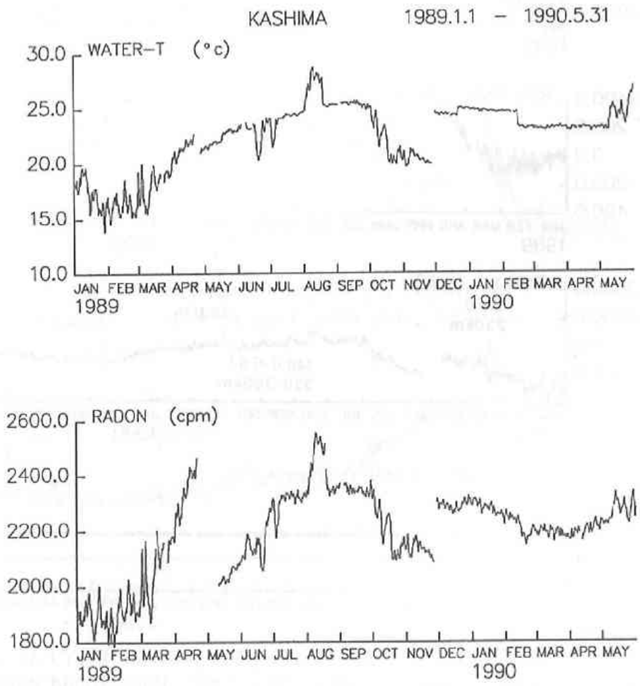

Fig. 4 Observed data on radon concentration and water temperature in the detection chamber obtained at the KSM site (January 1989-May 1990).

the temperature was not controlled. At the end of 1989 we installed a fully automatic air conditioner.

Figure 5 shows the analytical result by BAYTAP for the period from January 1989 to May 1990. The epicentral distribution of earthquakes with magnitudes greater than 6.0 that occurred in the area is shown in Fig. 1. Practically no coseismic changes were observed in the trend component. Even for one large earthquake ($M=7.1$ and $D=300$ km) that occurred on November 2, 1989, no significant drop was observed.

The number of cases without coseismic changes increased in the period after April 1987. This tendency continued in 1989 and 1990, as seen in Fig. 5. We attributed this to a lesser response at the KSM site to earthquake occurrence. The pattern of the 1987

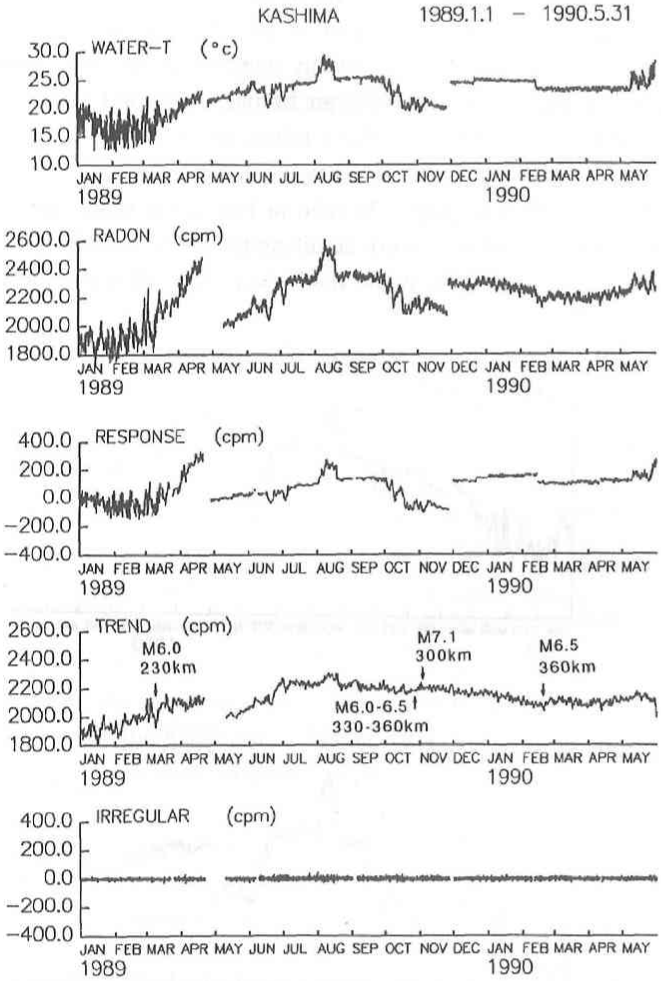

Fig. 5 Results of numerical analysis using the computer program BAYTAP (Ishiguro *et al.*, 1984) in the period from January 1989 to May 1990. Background fluctuations of the observed data were substantially reduced in the periods when room temperature was properly controlled.

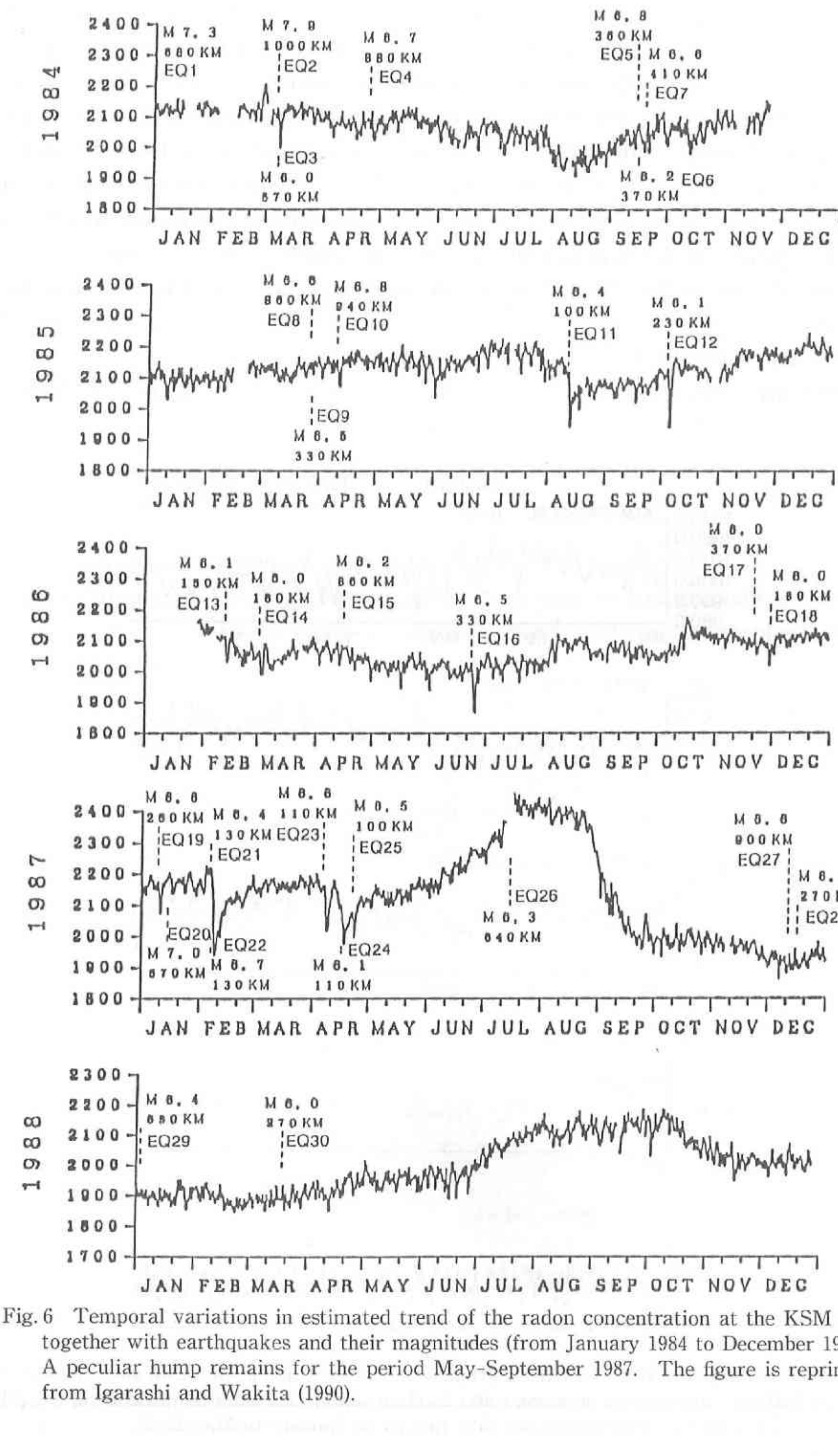

Fig. 6 Temporal variations in estimated trend of the radon concentration at the KSM site together with earthquakes and their magnitudes (from January 1984 to December 1988). A peculiar hump remains for the period May-September 1987. The figure is reprinted from Igarashi and Wakita (1990).

trend is quite different from those of the others. An anomalous hump remains in the trend in the period May-September 1987 (Fig. 6). Throughout the observation period of about ten years, this was the only appearance of this kind of pattern. The appearance of the observed peculiar pattern may reflect changes in physical conditions in the region, although the reasons for this are not fully understood. Changes in tectonic stress near the observation site may have occurred after five large nearby earthquakes in February-April 1987. Some signs of changes in physical properties of the region which may be related to changes in response to tectonic stress are pointed out. A significant decrease in seismic activity in NE Japan is noted to have occurred around that period, judging from the space-time plots of earthquakes ($M \geq 3$ (see Fig. 16(B) in the paper from Tohoku University, 1990).

There are other examples of changes in tectonic response after an earthquake.

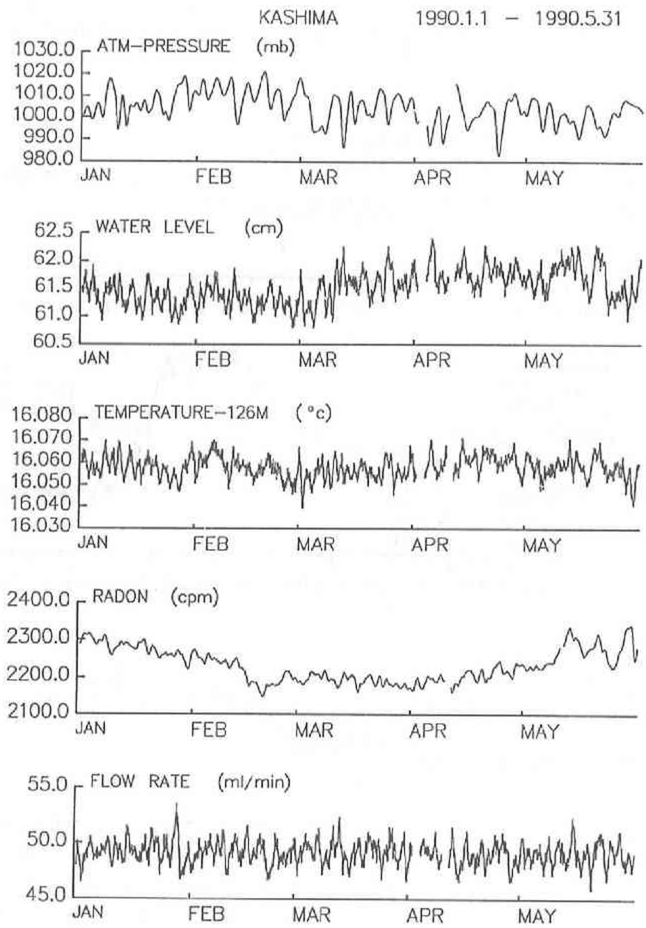

Fig. 7 Preliminary results of intensive groundwater observation at the KSM site. From top to bottom : atmospheric pressure, water level, *in situ* groundwater temperature at a depth of 126 m, radon concentration, and flow rate (from January to May 1990).

Right after the recent M 6.5 earthquake that occurred near Izu-Oshima Island, on February 20, 1990, two meaningful but contradicting observations were reported. One was the changes in tidal amplitude obtained by a borehole-type strainmeter located at Irozaki, Izu Peninsula (JMA, 1990), where the tidal amplitudes increased significantly in association with the earthquake. The other was the tidal amplitudes of a tiltmeter at Habu, Izu-Oshima Is. (National Research Institute for Earth Science and Disaster Prevention, 1990), where decreases by 1/2 in the NS-component and by 1/5 in the EW-component were observed. Changes in earth tidal amplitude and phases imply possible changes in elastic moduli of the region (Beaumont and Berger, 1974 ; Tanaka and Kato, 1974).

Consequently, occurrence of a large earthquake may well change response to tectonic stress in a region, due possibly to changes in physical properties that reflect the dilated or undilated state of the region. Thus, observed changes in the radon concentration pattern and non-response to earthquake occurrence are attributed to changes in the crustal elasticity of the region.

4.3. *Other Hydrological Observations*

Twenty-four-hour moving averages of the flow rate, *in situ* groundwater temperature at the strainer position (at the depth of 126 m), water level, and atmospheric pressure

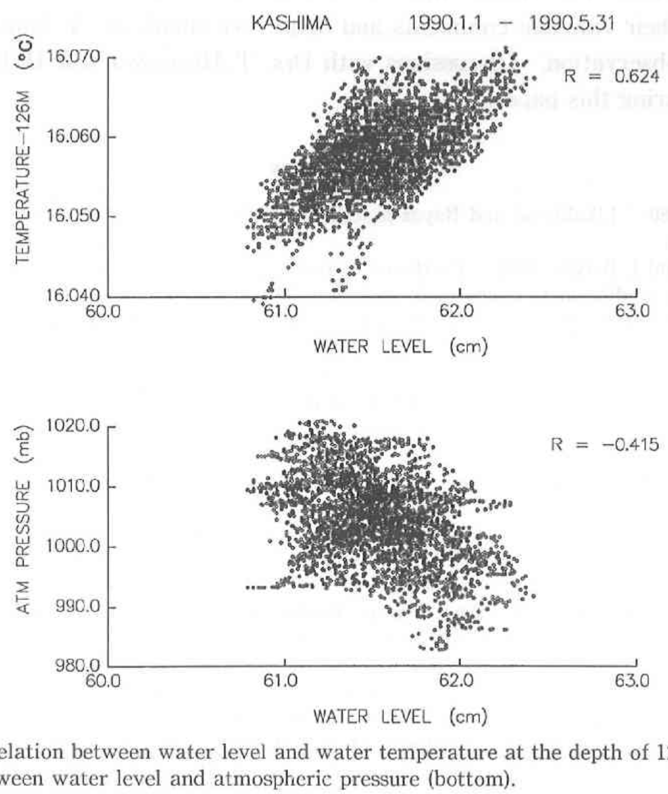

Fig. 8 Correlation between water level and water temperature at the depth of 126 m (upper), and between water level and atmospheric pressure (bottom).

in the period from January to May 1990 are shown in Fig. 7. A positive correlation is observed between *in situ* temperature and water level, with a correlation coefficient of $R=0.624$ (Fig. 8, upper). A negative correlation is observed with atmospheric pressure change (Fig. 8, bottom, $R=-0.415$). Relations between these parameters and flow rate are not obvious, due partially to the low sensitivity of the present instrument. Amplitudes of tidal fluctuations in these hydrological data are negligibly small. According to Bredehoeft (1967), the tidal response should be approximately inversely proportional to porosity in the region. Thus, lack of tidal response at the KSM site may be attributable to high porosity in the aquifer, probably due to brecciation reflecting the fault activity.

5. Conclusions

We have reported recent results for intensive groundwater observations at one of the most sensitive observation sites to earthquake occurrence. Improvement of observation conditions, mainly by reducing the environmental temperature changes, was very effective in obtaining better results for a Bayesian treatment of the original radon data. A recent change of the site to non-response to earthquake occurrence was attributed to changes in physical states in NE Japan, such as changes in crustal elasticity caused by successive occurrence of five large earthquakes near the observation site.

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