Ground-Water Radon Anomaly Before the Kobe Earthquake in Japan

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Radon concentration in ground water increased for several months before the 1995 southern Hyogo Prefecture (Kobe) earthquake on 17 January 1995. From late October 1994, the beginning of the observation, to the end of December 1994, radon concentration increased about fourfold. On 8 January, 9 days before the earthquake, the radon concentration reached a peak of more than 10 times that at the beginning of the observation, before starting to decrease. These radon changes are likely to be precursory phenomena of the disastrous earthquake.

Motivated by the report of precursory changes in ground-water radon associated with the 1966 Tashkent earthquake (*1*) and some radon observations in China (*2*), a group of scientists developed an automated continuous monitoring system for ground-water radon in Japan (*3*). For some 20 years, an extensive network of ground-water radon monitoring has been operated mainly by the University of Tokyo and the Geological Survey of Japan for the purpose of earthquake prediction in eastern Japan. A number of anomalous changes associated with earthquakes have been reported (*4*), which support the idea that ground-water radon is, if it is observed at suitable sites, a sensitive tracer for crustal strain changes associated with earthquake occurrences.

The ground-water radon concentration is expected to reflect not only chemical but also structural properties of rocks in an aquifer. The radon concentration in ground water is basically proportional to the U concentration in adjacent rocks in an aquifer. Radon-222 is a radioactive nuclide with a half-life about 3.8 days that is chemically inert and highly soluble in water. Its behavior in geological environments is simple and can be understood on the basis of physical processes such as dissolution, adsorption, diffusion, and fluid advection, as well as radioactive decay. Because of the short recoil length of radon (about 3×10^{-8} m), only a small portion of radon atoms produced in the rocks is released to the surrounding ground water; except for those atoms produced at the surface of rock grains, radon cannot escape from rock grains. Therefore, the radon concentration in ground water is largely dependent on, and roughly inversely proportional to, the effective grain size of rocks in an aquifer (*5*). Formation of microcracks will reduce the effective grain size of rocks and thereby enhance radon concentration in the ground water.

To accumulate data on ground-water radon concentration, we began studying the southern part of Nishinomiya city, Hyogo prefecture, because the ground-water systems in this region are well studied (*6*). The ground water in this region has long been known as a most suitable water for brewing sake. To preserve the quality of the water, intensive examinations of the ground-water systems have been made; over 60 wells have been bored to determine the arrangement and distribution of permeability, and measurements of chemical composition and water level have been carried out for about 40 years (*6*).

The radon monitoring system used in this study was originally developed in 1989 for monitoring background α-particle levels in "KAMIOKANDE," the underground cosmic ray observatory in central Japan (*7*). Because the system has a semiconductor α-particle detector (PIN photodiode) with high energy resolution, it can discriminate α particles emitted by daughter nuclei of radon from other α particles and γ rays with higher and lower energies, which enables noise-free radon monitoring (*8*). The monitoring system has been operating in the underground laboratory without trouble since 1989. Thus, the radon monitoring system is sufficiently applicable to earthquake prediction studies, which require both reliability and stability during long-term observations.

We carried out an initial observation at a well located in the southern part of Nishinomiya city (Fig. 1) for 7 days from 26 November to 2 December 1993 (*9*), and then started a long-term observation on 27 October 1994. The observation well is 17 m deep and is located about 30 km northeast of the hypocenter of the magnitude (M) 7.2 earthquake that occurred at 5:46 a.m. 17 January 1995 (Japanese standard time). On the basis of the distribution of the aftershocks, the faulting generated by the earthquake probably extended close to the observation well. The radon detection chamber fell down as a result of strong vibrations caused by the earthquake, and therefore we could not obtain data for several days after the earthquake. However, we confirmed that the radon monitoring system had been operating correctly until the earthquake.

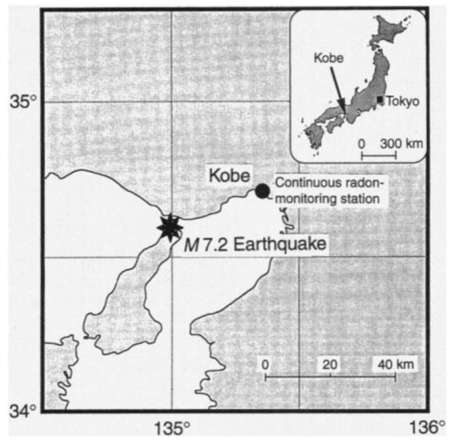

Fig. 1. Map of the continuous radon monitoring station and the epicenter of the Kobe earthquake (from Japan Meteorological Agency).

The radon concentration at the end of 1993 was stable at 20 becquerels (Bq) per liter (Fig. 2). The radon concentration started to increase gradually from the beginning of the observation in October 1994, and by the end of November 1994, it reached about 60 Bq/liter, which was about three times that in the same period one year before. Furthermore, a sudden increase was seen on 7 January. The high radon concentration then suddenly decreased on 10 January, 7 days before the earthquake. After the earthquake, we repaired the radon monitoring system and started the observation again on 22 January, by which time the radon concentration had already returned to the pre–October 1994 level.

It is impossible to attribute these radon changes to environmental conditions such

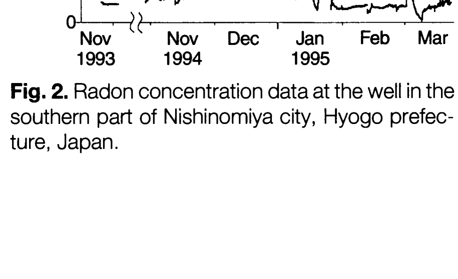

Fig. 2. Radon concentration data at the well in the southern part of Nishinomiya city, Hyogo prefecture, Japan.

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as temperature, atmospheric pressure, or rainfall. The temperature of the ground water is very stable and its variation was less than 0.2°C during the observation period. The response of radon concentration to atmospheric pressure is also negligible (*9*). There was no heavy rainfall from the summer of 1994 to the spring of 1995 (*10*).

A fault has been recognized in the subsurface about 500 m west of the observation well. The fault was identified in layers deeper than about 8 m from the surface. It is not certain whether this fault ruptured during the earthquake. However, the anomalous increase in radon concentration near the fault may suggest that there was some strain around this fault. Because it is difficult to explain such a large radon increase by mixing of ground water, it may reflect formation of microcracks in the aquifer system. The sudden radon decrease 1 week before the earthquake may be attributable to some sealing of microcracks. Convergence of strain along the forthcoming earthquake fault might have caused strain release at places off the fault line before its rupture.

Since the earthquake, the radon concentration has been rather stable at a low level. However, some irregular variations have been observed, which we interpret as an indication that the strain release by the main shock was not complete and that some accumulation and release of strain have still continued in the region.

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8. The radon monitoring system consists of a radon detection chamber, a 256-channel high-speed analog-to-digital converter (AD), and a personal computer. Ground water is continuously introduced into a detection chamber with a flow rate of about 1 liter/min. Radon dissolved in ground water is degassed to the gas phase in the chamber. A container of electrostatic collector is mounted just above the interface between the gas and liquid phases in the chamber. The container is equipped with an α-particle detector of a PIN photodiode (Hamamatsu Photonics K. K.) with a surface area of 1 cm^2. Because a static voltage of −120 V is applied between the PIN photodiode and the bottom of the container, positive ions in the gas phase are collected on the surface of the PIN photodiode. The α particles emitted mainly by the decays of ^{214}Po and ^{218}Po (daughters of ^{222}Rn) are detected as electric currents through the PIN photodiode. The electric currents are amplified and then digitized with the AD converter, which is controlled by a Z80 microcomputer system. The data of the α-particle counting are transmitted to a personal computer once per hour and stored in a floppy disk.
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10. Since 21 October 1994, we have monitored radon concentration at a shallower well, 4 m deep, drilled about 1 m from the 17-m-deep well. The shallower well taps the shallowest major aquifer in the region, whose radon concentration is expected to be influenced more easily by rainfall, but there was no notable radon change related to rainfall during the observation period. Above all, the shallower well did not show radon increase before the Kobe earthquake. The anomalous radon increase was detected only at the 17-m-deep well, which taps the second-shallowest major aquifer.

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Precursory Chemical Changes in Ground Water: Kobe Earthquake, Japan

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Chloride (Cl^-) and sulfate (SO_4^{2-}) ion concentrations of ground water issuing from two wells located near the epicenter of the Kobe earthquake in Japan fluctuated before the disastrous magnitude 7.2 event on 17 January 1995. The samples measured were pumped ground water packed in bottles and distributed in the domestic market as drinking water from 1993 to April 1995. Analytical results demonstrate that Cl^- and SO_4^{2-} concentrations increased steadily from August 1994 to just before the earthquake. Water sampled after the earthquake showed much higher Cl^- and SO_4^{2-} concentrations. The precursory changes in chemical composition may reflect the preparation stage of a large earthquake.

A destructive magnitude (M) 7.2 earthquake (*1*) occurred at 05:46 on 17 January 1995 (Japanese standard time) in the Kansai district near Kobe, Japan (Fig. 1). The focal mechanism of the earthquake was a quadrant type with the maximum compression axis in an east-west direction. A distinct 9-km rupture appeared along the preexisting right lateral Nojima fault, which strikes northeast in Awaji Island. Maximum displacement was about 1.7 m horizontally and about 1.3 m vertically (*2*). The distribution of the aftershock area coincided well with the earthquake fault region (*3*).

A striking feature of the earthquake was the variation in ground-water flow. After the earthquake, increased ground-water discharge was observed in many parts of the aftershock region. Increases were seen in river flow, reservoir levels, and water temperature. In addition, Kyoto University reported an unusual increase in the discharge rate of ground water in a tunnel of the Rokko-Takao Station for crustal movement observation that began more than 2 months before the main shock (*3*). The rate increased by about 7% from early November 1994 and suddenly by 1000% after the earthquake, even though this period is typically a season of low precipitation and the total rainfall in 1994 was low. Here we report geochemical evidence of precursory ground-water changes observed near the epicentral region, recorded in commercial bottled drinking water.

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Many chemical and hydrological changes are reported to have occurred before past large earthquakes. One of the best examples is a sudden hot-spring eruption observed several months before the 1923 Great Kanto earthquake (M 7.9) in the epicentral region (*4*). Geochemical monitoring of ground water may provide useful information for earthquake prediction.

Shortly after the Kobe earthquake, we started collecting ground-water samples from Kobe in order to investigate possible changes in ground water. We collected commercial bottled water with as many different bottling dates as possible. The granitic Rokko mountains rising behind Kobe City are known to produce high-quality mineral water mainly used in the brewing of Sake and as drinking water. One of the water sources is at the ROK site, located about 20 km east of the epicenter (Fig. 1). Ground water pumped from two 100-m-deep wells is passed through a microfilter (0.2 μm), sealed in polyethylene terephthalate bottles, and distributed on the market. The chemical composition of the ground water is bicarbonate [~70 parts per million (ppm)], chloride (~14 ppm), sulfate (~14 ppm), nitrate (~10 ppm), calcium (~24 ppm), and sodium (~15 ppm). This bottled water has the merit of providing samples with known dates.

We collected a total of 72 water bottles, including 59 bottles with different dates