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Colloquium Paper

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Geochemical challenge to earthquake prediction

(groundwater/radon/precursor)

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ABSTRACT The current status of geochemical and groundwater observations for earthquake prediction in Japan is described. The development of the observations is discussed in relation to the progress of the earthquake prediction program in Japan. Three major findings obtained from our recent studies are outlined. (*i*) Long-term radon observation data over 18 years at the SKE (Suikoen) well indicate that the anomalous radon change before the 1978 Izu-Oshima-kinkai earthquake can with high probability be attributed to precursory changes. (*ii*) It is proposed that certain sensitive wells exist which have the potential to detect precursory changes. (*iii*) The appearance and nonappearance of coseismic radon drops at the KSM (Kashima) well reflect changes in the regional stress state of an observation area. In addition, some preliminary results of chemical changes of groundwater prior to the 1995 Kobe (Hyogo-ken nanbu) earthquake are presented.

1. Geochemical Studies and Earthquake Prediction Program in Japan

The earthquake prediction program in Japan started in the early 1960s (Table 1). In 1962 Japanese seismologists compiled a report entitled "Prediction of Earthquakes—Progress to Dates and Plans for Further Development." This report (1), the so-called "Blue Print," set out the principles of the earthquake prediction program in Japan. Two large earthquakes in Niigata and Alaska, with magnitudes of 7.5 and 8.4, acted as a trigger for the project in Japan and the United States.

The Geodesy Council devised the First Earthquake Prediction Plan ("First Plan") covering fiscal years 1965 to 1968. The major aim of the First Plan was establishment of the infrastructure for basic observations by collecting various data, particularly geodetic and seismic. The Matsushiro earthquake swarms lasting 2 years starting from 1965 left an enormous volume of observation data of various kinds. The most peculiar phenomenon associated with the swarms was the gushing of significant amounts of groundwater, which were characterized by an anomalous chemical composition with high concentrations of Ca^{2+}, Cl^-, and CO_2. Combined with geochemical studies including helium measurement of gas discharged from the fault zone, this finding led to a model of the formation of the seismic swarms that attributed them to a diapiric uprise of magma (2).

There was a clear change between the First Plan and the Second Earthquake Prediction Plan ("Second Plan"). The pragmatism of earthquake prediction was introduced in the Second Plan, and an operational organization was established. The Coordinating Committee for Earthquake Prediction was founded in 1969, to comprehensively evaluate available data. To promote earthquake prediction more effectively, the committee designated Areas of Intensified Observation and Areas of Specified Observation in 1970, taking into account such factors as records of historical earthquakes, occurrence of major active faults, and the political and economical situation. Around that time the possibility of impending earthquakes in the Tokai and southern Kanto regions was seriously contemplated.

In 1973, the International Symposium on Earthquake Prediction was held in Tashkent, Uzbekistan, and changes in radon concentration in groundwater prior to a destructive earthquake in 1966 found by Prof. Sultankhodjaev and his group were reported to the participants gathered from many countries. The report was brought back to Japan and inspired geochemical study. Simultaneously, the presentation of the dilatancy–diffusion model proposed by Scholz and others (3) had a major impact on the Japanese seismological community and inspired the building of a geochemical group in the earthquake prediction program.

The Third Plan was oriented toward developing new observation tools, which include adoption of a system for rapid data transmission by telemetry, three seismograms installed at the bottom of 3000-m deep wells in the Tokyo area, cable-type submarine seismographs off the Tokai region, and a series of borehole-type volumetric strainmeter networks consisting of 31 observation sites. The Third Plan was revised twice to cope with anomalous crustal movements in the Tokai region and to encourage introduction of new techniques including geochemical study and groundwater observation. To strengthen the administrative structure, the Headquarters for Promotion of Earthquake Prediction was founded under.the cabinet in 1976. To cope with the impending Tokai earthquake, the Earthquake Assessment Committee for the Tokai Region was established in 1977 and the Large-Scale Earthquake Countermeasures Act was enacted in 1978. Under this law, observed anomalous data are examined by six members of the committee who will advice the Prime Minister to issue a public warning. In response to these circumstances the Laboratory for Earthquake Chemistry was founded at the University of Tokyo.

Under the Fourth and Fifth Plans, the concepts of long-term prediction and short-term prediction were adopted. Through the operation of periodic surveys and observations on a nationwide scale, "locations" and "sizes" of earthquakes are roughly estimated. Based on this, the "time" of an earthquake can be decided by detecting short-term precursors in the selected observation area.

The general concept of the previous Plans was continued for the Sixth Plan, and emphasis was also placed on research on earthquakes occurring inland and in metropolitan areas.

Table 1. Progress of the Earthquake Prediction Program in Japan

Year	Major topics	Remarkable seismic events: Domestic	Remarkable seismic events: Overseas
1962	"Prediction of Earthquake" ("Blue Print")		
1964		Niigata (M7.5)	Alaska (M8.4)
	First Plan (1965–1968): Basic observation networks		
1965		Matsushiro swarms	
1966			Tashkent (M5.5)
1968		Tokachi-oki (M7.9)	
	Second Plan (1969–1973): Practical application and organization		
1969	Coordinating Committee for Earthquake Prediction		
1970	Area of Intensified Observation and Specified Observation		
1973	Tashkent conference and dilatancy model	Nemuro-oki (M7.4)	
	Third Plan (1974–1978): Tokai earthquake, telemetry, and new techniques		
1974	Geochemical observations		
1975	Kawasaki upheaval		Haicheng (M7.3)
1976	Headquarters for Promotion of Earthquake Prediction		Tangshan (M7.8)
1977	Earthquake Assessment Committee		
1978	Large-Scale Earthquake Countermeasure Act Laboratory for Earthquake Chemistry	Izu-Oshima-kinkai (M7.0)	
	Fourth Plan (1979–1983): Long- and short-term prediction and basic studies		
1983		Japan Sea (M7.7)	
	Fifth Plan (1984–1988): Long- and short-term prediction and basic studies		
1984		W Nagano (M6.8)	
1986		Izu-Oshima eruption	
	Sixth Plan (1989–1993): Inland and metropolitan area earthquakes		
1989		Ito-oki eruption	Loma Prieta (M7.1)
1993		Kushiro-oki (M8.1) SW Hokkaido (M7.8)	
	Seventh Plan (1994–1998): Seismogenic potential and GPS real-time monitoring		
1994		E Hokkaido (M8.1) Sanriku (M7.5)	
1995		S Hyogo (M7.2)	

Responsible organizations are as follows: JMA (Japan Meteorological Agency), NIED (National Research Institute for Earth Science and Disaster Prevention), GSI (Geodetic Survey Institute), UNIV (National Universities, National Astronomical Observatory), GSJ (Geological Survey of Japan), HGD (Hydrographic Department), and CRL (Communication Research Laboratory). GPS, Global Positioning System.

This subject was of urgent importance but had built-in difficulties in the observation of environments in large cities. The January 17, 1995, Kobe earthquake was representative of an inland earthquake occurring in a semi-metropolitan area and resulted in a tremendous disaster far beyond our expectations.

Throughout the previous period, seismic activity in and around the Japanese islands had been rather calm. No destructive earthquake had occurred for 50 years (Fig. 1). Most that did occur since the start of the earthquake prediction plan were in rather isolated areas; the exception was the recent Kobe earthquake, which struck the center of a densely populated area. Under these circumstances, the Seventh Plan started in 1994. In addition to the continuation of basic observations, the concept of the assessment of earthquake potential was incorporated with the plan. The target is large earthquakes occurring along plate boundaries and in inland areas. The intention is to enhance the accuracy of long-term prediction. The concept of "earthquake cycles" is well accepted and supported by a persuasive data set. Historical records, trench study of active faults, and geodetic survey data accumulated over 100 years give clear evidence for repetition of large earthquakes in such areas as along the Nankai trough. Another noteworthy aspect of the Seventh Plan is the disposition of GPS (Global Positioning System) observation sites throughout the Islands. Collection of real-time data from about 300 sites will drastically change the concept of crustal deformation observation in the earthquake prediction program in Japan.

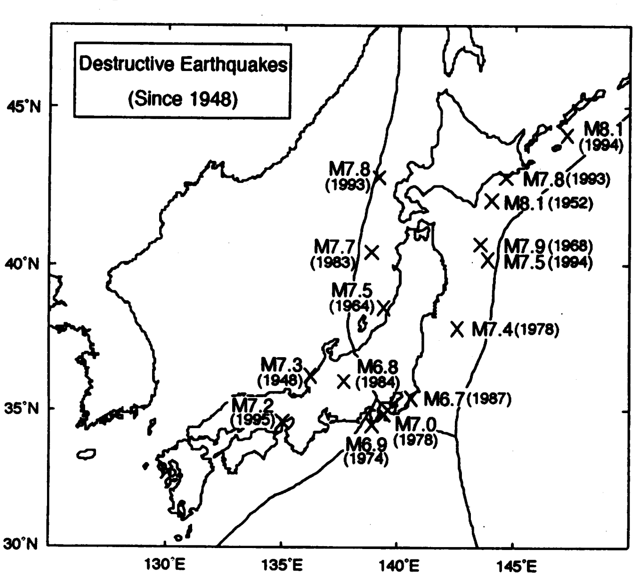

FIG. 1. Locations of destructive earthquakes in and around the Japanese islands since 1948. Most occurred in the sea area.

2. Geochemical Observations

Geochemical observations were formally made a part of the earthquake prediction program in the middle of the Third Plan period, in 1978. The motivation was the finding of precursory radon changes associated with the 1966 Tashkent earthquake and the proposing of a physical base for these changes in the dilatancy–diffusion model. It was also reported that radon observation was useful in the successful prediction of the 1975 Haicheng earthquake in China (4). Japanese seismologists, with Professor Asada as a leading representative, were looking for personnel to manage geochemical observation. Approval of the installation of geochemical facilities required some convincing results.

Such results could be obtained only under minimal conditions including development of continuous monitoring instruments, establishment of fixed observation wells in places relatively unaffected by human activities, establishment of a data transmission system, and maintenance of observations.

The Tokai district and Izu Peninsula were chosen as test sites for geochemical monitoring, and the district was designated as an Area of Intensified Observation in February 1974. Seismic activities in the Izu Peninsula also began to be significant. Additionally, anomalous ground upheaval was observed in Kawasaki, one of the satellite cities of the Tokyo metropolitan area. Through geochemical and hydrological surveys including measurements of chemical composition, radon, tritium, and ^{14}C in groundwater and of water level, the ground upheaval was concluded to be the result of groundwater recovery in a subsided area produced by excess pumping of groundwater (5). A small-scale project carried out by the geochemical group gradually won approval. Studies on gas emission and migration of groundwater in the crust in connection with earthquake occurrence were regarded as quite important. Since then the work of the geochemical group has been firmly established.

2.1. Observation Sites. At present, continuous monitoring data are obtained at 12 observation sites: three in the Tokai region, five in the Izu-Oshima region, one in Kamakura and three in the eastern part of Fukushima Prefecture (Fig. 2). Recently crustal deformation measurement is also incorporated with two new wells at KSM (Kashima) by the installation of multi-component borehole strainmeters.

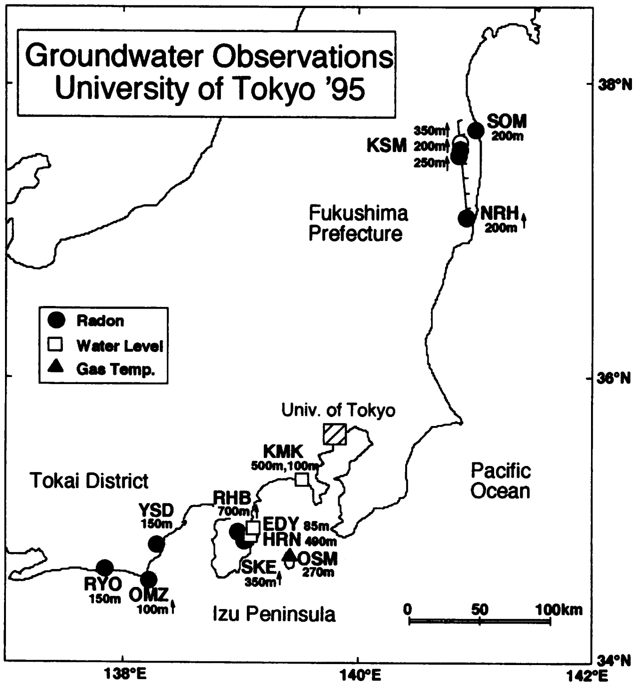

FIG. 2. Distribution of groundwater observation sites operated by University of Tokyo. Arrows indicate artesian wells.

Most of the wells are holes drilled for nonseismogenic study, but some were drilled especially for our purposes. As is described in a later section, some of the wells are known to be extremely sensitive to earthquake occurrences.

2.2. Continuous Monitoring Instruments. The development of continuous monitoring equipment was a matter of primary concern. A system with a ZnS(Ag) scintillation detector (6) has been used with several modifications. The system has the merit of reliable operation for a long period and of requiring little maintenance.

2.3. Long-Term Radon Observation Data. Based on long-term variation patterns, anomalous changes related to earthquakes can be distinguished from background fluctuation. Throughout the observation period, the most significant and meaningful change was that observed in the Izu Peninsula, which was the center of a seismically active region. Fig. 3 shows a long-term record of the radon concentration changes over 18 years at the SKE (Suikoen) site, where the precursory radon change accompanying the 1978 Izu-Oshima-kinkai earthquake (M7.0) was observed (7). Except for one clear change at the time of the 1978 earthquake, no comparative change is observed in the record, which coincides with the absence of other earthquakes of comparative size in the Izu region. As seen in Fig. 3, there are several changes associated with local events including seismic and volcanic activities such as those of 1980, 1984, 1988, 1989, and 1990.

Fig. 4 summarizes the precursory changes of radon and other observations for the 1978 earthquake. It is meaningful that various kinds of anomalous changes, including groundwater, crustal movement, and foreshocks, occurred simultaneously. Particularly, noteworthy is the similarity in changes of these patterns (8, 9). Radon change as an earthquake precursor was evaluated by the IASPEI (International Association of Seismology and Physics of the Earth's Interior) Subcommittee on Earthquake Prediction (10).

3. Criticism of Radon as a Precursor

The argument is sometimes made that the 1978 radon anomaly was only observed at a single station and there was no anomalous change with the succeeding earthquake of M6.7 (June 29, 1980). The lack of a plausible physical explanation is also criticized. A plausible answer to these questions is the proposition that some wells are particularly sensitive and that this sensitivity changes with time, reflecting changes in regional stress in the area.

3.1. Occurrence of Sensitive Wells. One good example of a sensitive well is the EDY (Edoya) well in Izu Peninsula. The water level of the well fluctuates significantly with earthquake occurrence, as seen in Fig. 5. The peculiarity of the well was first recognized at the time of the seismic–volcanic events of 1989. Prior to the major events, the well suddenly gushed considerable amounts of water (11). Similar groundwater changes were often known to be observed before large earthquakes (12). Since then the water level and temperature of the well have been monitored. As seen in the figure, at the time of the Hokkaido-toho-oki earthquake with magnitude of 8.1, the water level rapidly fluctuated over 2 m in height. The epicentral distance was about 1200 km. Needless to say, not all wells will behave like this. The EDY is really a sensitive well.

Another good example is the KSM site in NE Japan. The radon concentration of this well drilled on the Futaba fault decreases after the occurrences of earthquakes nearby (13–15). Fig. 6 shows representative cases observed in 1994, including the Hokkaido-toho-oki earthquake (M8.1). The radon drop was observed for most earthquakes that occurred in the period between 1984 and April 1987.

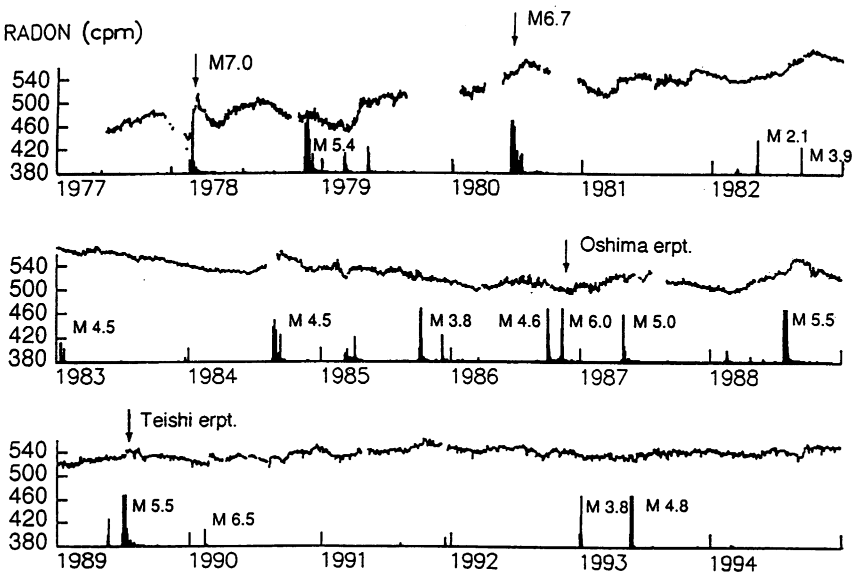

FIG. 3. Long-term variations in the radon concentration observed at the SKE site in Izu Peninsula together with relative seismic activity in and around Izu Peninsula.

3.2. Sensitivity Change Reflecting Changes in Regional Stress. After a series of M6 to M7 earthquakes in the nearby region, the radon drop disappeared. Simultaneously, seismic activity in the northeast Japan had been significantly calm. After a 5-year nonresponsive period, the sensitivity of the well suddenly recovered in May 1992. Once it recovered, the sensitivity became greater with time to reflect earthquakes as small as M4.5. Seismic activity also became significant, and large shocks of M7.8 (January 15, 1993), M7.8 (July 12, 1993), M8.1 (October 4, 1994), and M7.5 (December 28, 1994) occurred successively (Fig. 1). Stress accumulation and release may change the physical properties of rocks in the crust, which will change response in the form of coseismic change of radon (16).

Radon drop disappeared again after an M7.5 earthquake far off Sanriku on December 28, 1994, as summarized in Fig. 7. Since then no drops have been observed for many earthquakes including the largest Sanriku aftershock of M6.9 (January 7, 1995), the Kobe earthquake (M7.2, January 17, 1995), and the Niigata earthquake (M6.0, April 1, 1995).

To conclude, the proposition of sensitive wells and changes in sensitivity with time may be a plausible response to the

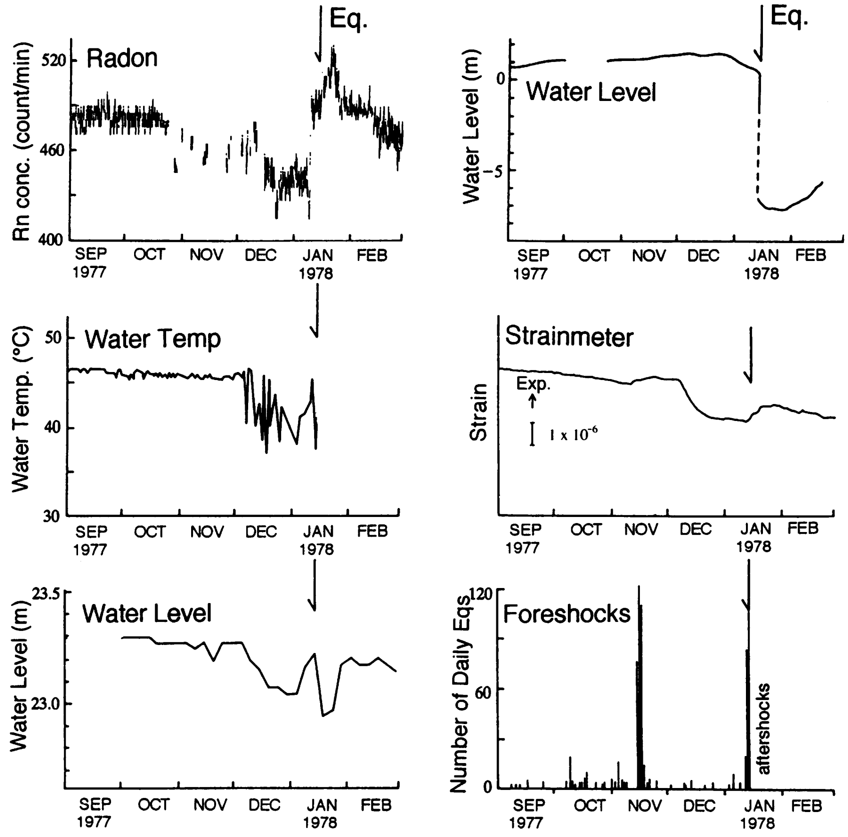

FIG. 4. Precursory changes of the Izu-Oshima-kinkai earthquake (M7.0) on January 14, 1978 (9). Eq., earthquake; Rn, radon.

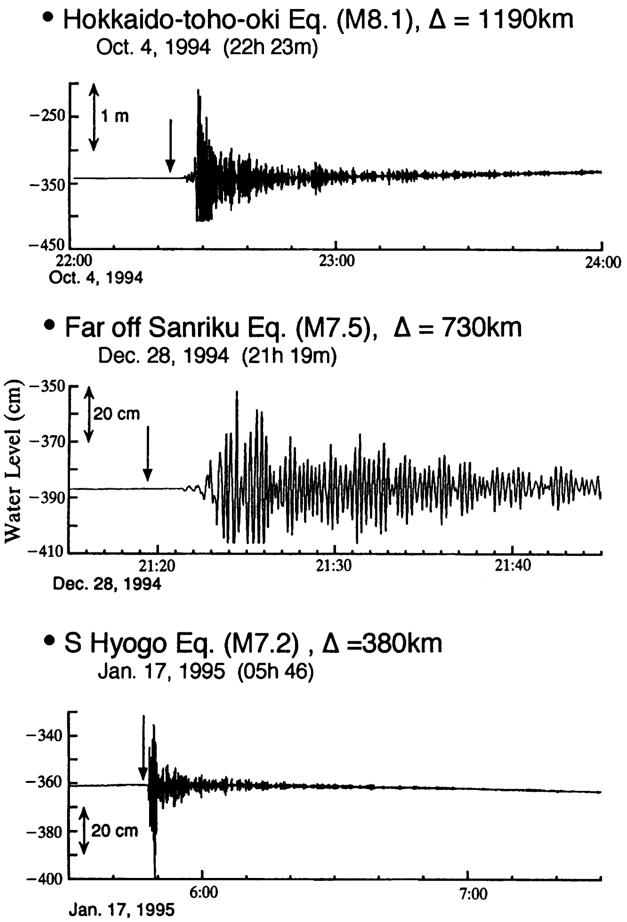

FIG. 5. Water level fluctuations associated with large earthquakes observed at the EDY well in Izu Peninsula. Eq., earthquake.

criticisms. The change in sensitivity detected by radon observations—in other words, the appearance and nonappearance of coseismic signals—will also be recognized in other observations, such as crustal deformation and seismic activity.

4. Precursory Changes and the Kobe Earthquake

Possible precursory changes of chemical components dissolved in groundwater were observed associated with the destructive earthquake (M7.2) of January 17, 1995, in Kobe. One of the most striking features of the Kobe earthquake was various changes in groundwater. Associated with the earthquake, increased groundwater discharge was observed in many parts of the aftershock region. Most was the result of increases in river water flow, in reservoir levels, and in water temperature that occurred after the earthquake. In addition, anomalous increases in issuing groundwater were also reported before the earthquake, despite the fact that this was the lowest precipitation season and that total rainfall in 1994 was extraordinarily small.

Immediately after the earthquake, Tsunogai and I started collecting groundwater samples from Kobe to investigate possible changes in groundwater. 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. Groundwater pumped from wells is sealed in bottles and distributed on the market.

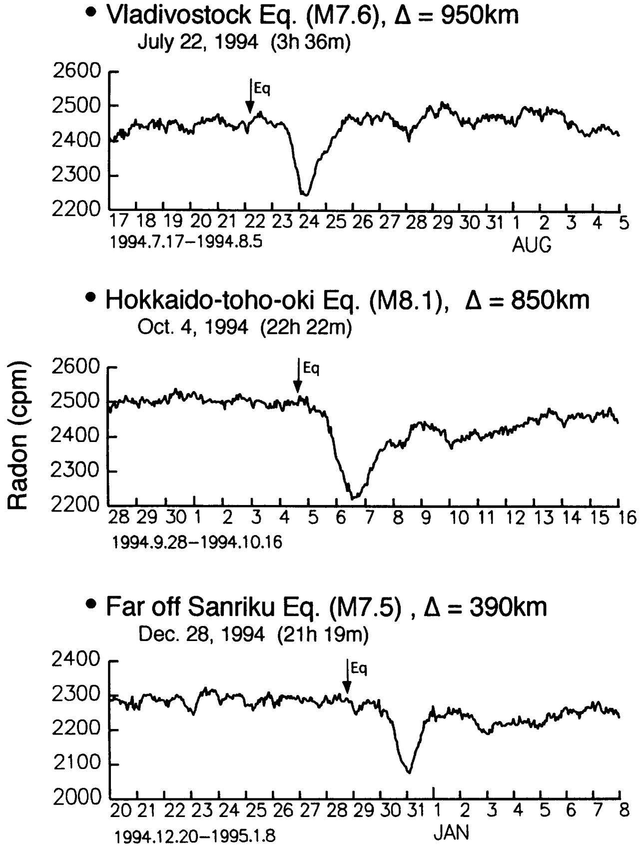

FIG. 6. Coseismic radon drops observed at the KSM site. Eq., earthquake.

We collected a total of 60 bottles with different dates ranging from June 5, 1993, to January 13, 1995. In the first step, dissolved Cl^- ion in samples was measured with an ion chromatograph. During the period from June 1993 to July 1994, the Cl^- concentrations were almost constant. Beginning in August 1994, however, the Cl^- concentration gradually increased with some fluctuations and reached the highest level on 13 January 1995, 4 days before the earthquake. The enhancement of the Cl^- concentration was about 10% higher than the background value. Water sampled after the earthquake showed much higher Cl^- concentration, which is in good accordance with significant increases in the flow rate of issuing groundwater in the area after the earthquake (17).

The observed changes in groundwater chemical composition may reflect the preparation stage of a large earthquake. Chemical changes observed before the earthquake can be attributed to the introduction of deep-seated groundwater enriched in Cl^- to the artesian layer of the wells. High Cl^- is a common feature of deep-source groundwater issuing through a fracture zone near the Rokko mountains. Movement of such groundwater may be caused either by changes in regional

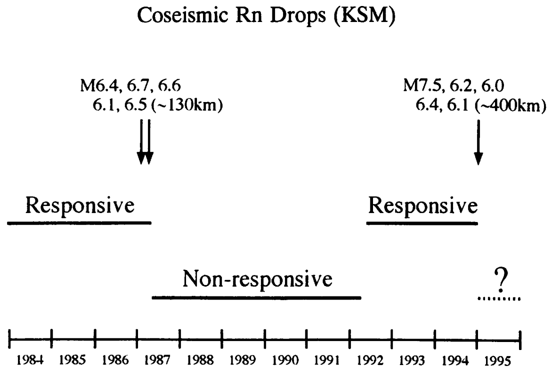

FIG. 7. Appearance and disappearance of coseismic radon drop observed at the KSM site. Rn, radon.

tectonic stress or by permeability change due to micro-crack formation in rocks prior to the destructive earthquake.

The result indicates that groundwater observations can provide useful information on the earthquake formation process and clues to understanding the mechanism of inland earthquakes. The use of commercial bottled water will be a source of information to obtain preseismic data. Detailed descriptions of the study will be published elsewhere. Further study including stable isotope measurements will be helpful in strengthening the findings.

5. Conclusions

Detection of precursory phenomena is of primary importance for earthquake prediction purposes. Coseismic signals, similarly, are useful for clarifying the mechanisms of precursory phenomena. Appearance and nonappearance of coseismic drops in radon content are indicative of stress states in the region.

Our experience enables us to arrive at several conclusions. (*i*) It is clear that movements of fluids in the crust are associated with earthquakes. (*ii*) Earthquake-related changes are not observed at all observation wells but only at a limited number of wells. At sensitive sites, marked changes in groundwater movement that are significantly large and effective even at large distances are observed. (*iii*) Even at sensitive wells, the appearance of signals likely depends on the state of stress accumulation in the region. The sensitivity change is thought to be caused by changes in physical properties of rocks including opening and closure of microcracks.

A possible precursory change in groundwater chemistry at the time of the 1995 Kobe earthquake will substantiate the importance of geochemical and hydrological study.

Fluid movements in the crust play a vital role in earthquake occurrence. Besides its original purpose of predicting earthquakes, monitoring of groundwater movements will also be essential to supplement all kinds of observations on the ground surface and particularly to increase the accuracy of crustal deformation measurement including GPS measurement.

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