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Some Recent Studies on Groundwater Radon Content as an Earthquake Precursor

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Some recent studies of groundwater radon content in relation to seismic activities are reviewed. Results from China and Japan are presented, including laboratory experiments and the development of continuous groundwater radon monitoring systems. In addition, groundwater radon monitoring studies conducted at the University of Southern California (USC) since 1974 are presented in some detail. The USC project includes a groundwater radon monitoring network of 14 sampling sites at cold springs, hot springs, deep irrigation wells, and artesian wells that are distributed along a 'locked' stretch of the San Andreas fault from Gorman to San Bernardino in California. Radon contents in weekly samples from these sites are analyzed to the precision of a few percent. No moderate-to-large earthquake has yet occurred in the vicinity, and the results show no clear association of radon anomalies with small ($M \sim 3$) earthquakes to provide better test conditions. In contrast to earlier reports from Russia showing a long-term buildup of radon emission before earthquake occurrence, several recent reports from China and Japan show that groundwater radon anomalies can be short in duration and occur only within a few days before the main shocks. Observations of such effects are made possible with the use of continuous monitoring systems. In general, available data suggest that groundwater radon monitoring could sometimes yield precursor information. However, criteria have yet to be established by which sampling sites and sampling frequencies are selected.

INTRODUCTION

Radon, being an inert and water-soluble gas produced in the naturally occurring uranium decay series, has been used as an in situ stress transducer in earthquake research.

Uranium has a widespread distribution in continental crustal rocks; it amounts to several parts per million (ppm) in concentration on the average. As an intermediate decay product of the ^{238}U radioactive series, radon (^{222}Rn) gas is constantly generated within the rock strata. The release of Rn from natural minerals has long been known and was studied in detail as early as the 1920's [*Spitsyn*, 1926]. At the instant of formation the ^{222}Rn atoms have a recoil energy of about 100 keV. This energy enables them to travel through hundreds of crystalline lattice sites (the mean recoil path in solid matter is a fraction of 1 μm). Often a recoil atom gets lodged in the microcapillary of a mineral structure. It is mostly through these capillaries filled with either an aqueous or an air medium that emanation atoms from a mineral exit.

Radon is fairly soluble in water. Because of its inertness its concentration in groundwater is usually independent of fundamental hydrological characteristics—water composition, mineralization, and the temperature of discharge [*Cherdyntsev*, 1961; *Tanner*, 1964a]. Rather, its fluctuations depend to a large extent on the tectonic disturbance of the host minerals, whereby surface areas of the microfractures and total geometric faces of the minerals are altered. An extensive review on radon migration in the ground is given by *Tanner* [1964*b*, 1978]. According to the dilatancy mechanism for earthquake occurrence [*Scholz et al.*, 1973], when regional stress increases, dilation of rock masses could cause an increase either in the surface area of rocks due to cracking, or in the flow rate of pore fluids as they are forced out of the interstitial space. Both of these processes will enhance the transport of radon from its original enclosures into the groundwater or spring waters.

The analysis of radon emission and earthquake occurrence can be traced back to a study by *Okabe* [1956], who discovered a positive correlation between the daily variation of atmospheric radon content near the ground surface and the local seismicity at Tottori, Japan. Okabe interpreted the association in terms of radon exhalation from soils and rocks following strong ground vibrations.

The long-term radon measurement in the Tashkent artesian basin of Russia first suggested the usefulness of radon variation in groundwater as an earthquake precursor. Ten years before the Tashkent earthquake of 1966 (M = 5.3), Russian scientists at the Semashko Scientific Institute had begun annual measurements of radon content on groundwater samples taken from deep wells in the vicinity (1–1.5 km) of the epicentral region. Despite the lack of data during 1961–1964, the striking association of the radon anomaly with the Tashkent earthquake (Figure 1*a*) led to a more frequent sampling that further confirmed the association during a large aftershock (Figure 1*b*). *Ulomov and Mavashev* [1971] reported that in the Tashkent groundwater basin, (1) the concentration of the radon content increased almost threefold above the background level and (2) the duration of the anomalously high radon content in ground water was proportional to the magnitude of the following earthquake. They further suggested that in one part of the Tashkent groundwater basin where seismicity is high (Figure 2), displacement of rock mass (solid arrows) under increased tectonic stress (open arrows) occurred as fracturing opened up various pathways (dashed lines) for the upward migration of radon. Radon might also be dissolved in pore fluids and migrate into the groundwater-bearing layer. Such an interpretation is quite compatible with the dilatancy-diffusion concept. In another study [*Antsilevich*, 1971] a deep well was drilled to a depth of 2000 m in the Tashkent groundwater basin and radon emission counting was carried out continuously. The results (Figure 3) further showed an association between radon content and small earthquakes. Other chemical elements were also monitored in the Tashkent groundwater basin. A joint analysis of the distributions of radium in rocks and water, plus that of helium in water, showed that the most

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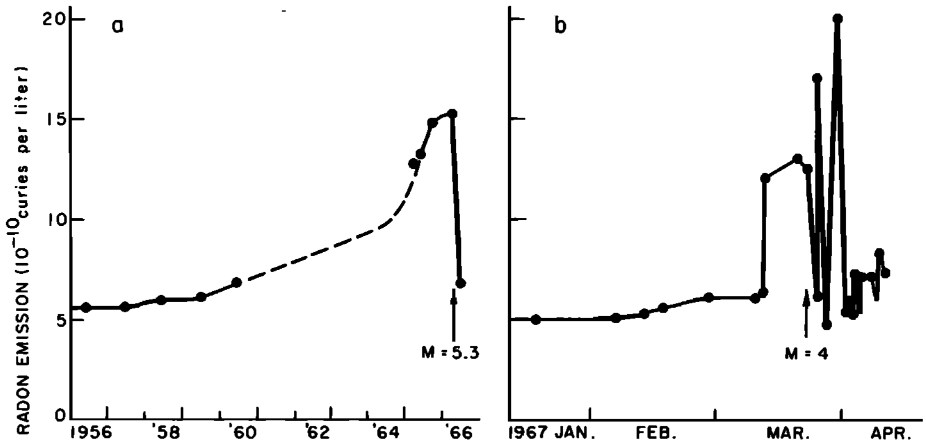

Fig. 1. Groundwater radon content data from a deep well in the epicentral region of (*a*) the 1966 Tashkent earthquake ($M = 5.3$) and (*b*) an aftershock at Tashkent ($M = 4$). After *Ulomov and Mavashev* [1971].

likely sources of these nuclides came from the basement of deeper rocks [*Gorbushina et al.*, 1971].

In China, *Chen et al.* [1973] conducted an extensive study on the geological conditions underlying the presence of groundwater radon for both hot and cold springs in the Peking area. Their findings suggest that crushed zones near faults may provide an important channel for the upward migration of radon from greater depths. A subsequent study by the *Group of Hydro-Chemistry* [1975] of the Hebei Seismological Brigade in China documented two instances of actual earthquake forecasting based primarily on the abnormal variations of groundwater radon content. According to this study, the characteristics of radon anomalies preceding an earthquake may take different forms for different focal mechanisms and ground water conditions. More recently, a number of large earthquakes in China were found to be preceded by spikelike radon anomalies. The Izu Peninsula earthquake in Japan ($M = 7$, January 14, 1978) was also preceded by 5 days of radon content anomaly shown on a continuous monitoring record (H. Wakita, written communication, 1978).

The suggested association between radon anomalies and earthquake occurrence shown by the preceding reports has also been supported by several experimental studies which are discussed in the next section.

The rest of this paper reviews the current status of groundwater radon research in relation to earthquake predic-

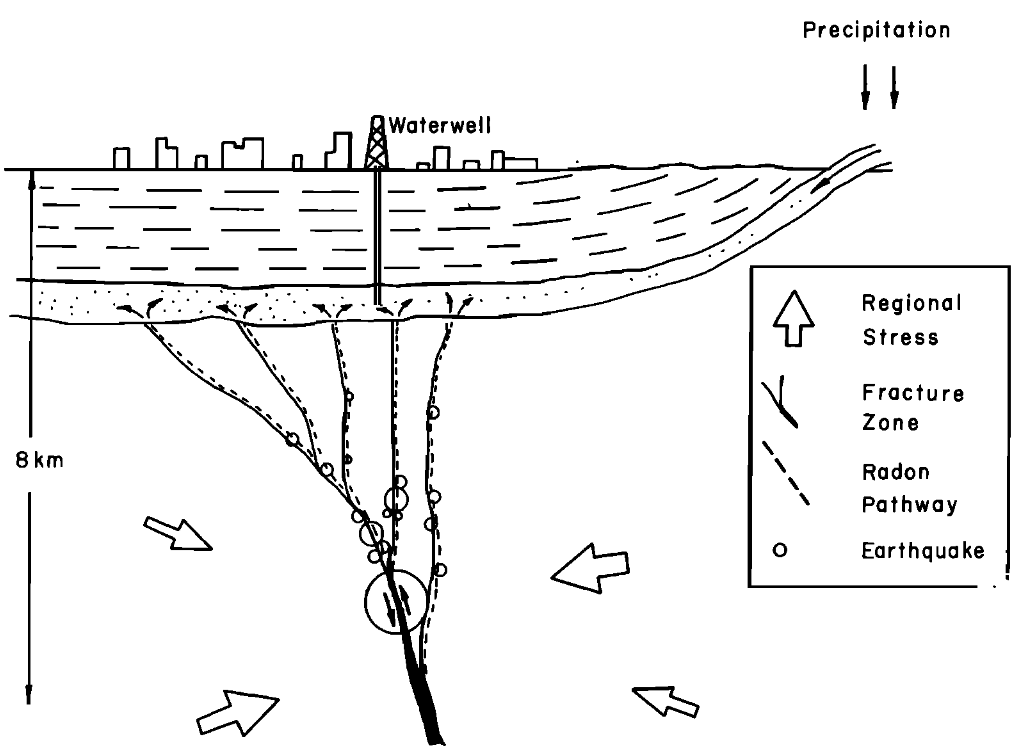

Fig. 2. A schematic cross section of the radon outflux mechanism in the Tashkent groundwater basin. After *Ulomov and Mavashev* [1971].

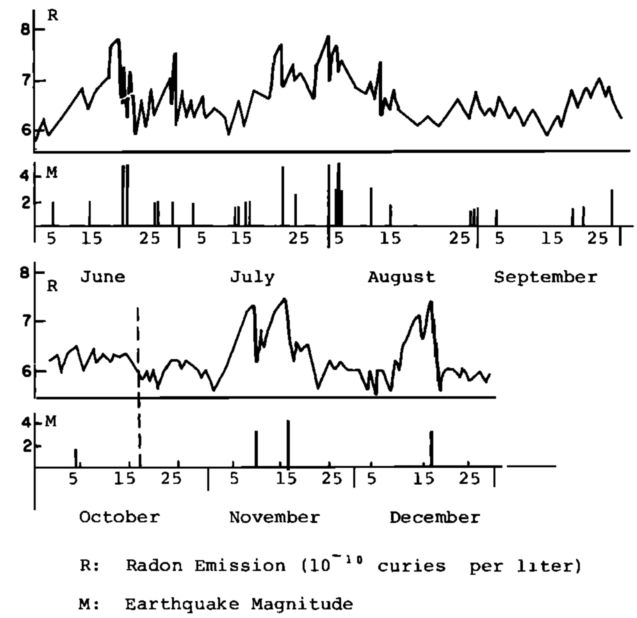

Fig. 3. Correlation of groundwater radon content with small earthquakes in Tashkent. After *Antsilevich* [1971].

tion. No exhaustive survey is attempted. Rather, some representative studies are presented, followed by a brief discussion on possible future approaches.

Controlled Studies on Radon Emission

To establish some causal relationship between variations in stress and radon emission in rocks, a study was conducted by *The Group of Hydro-Chemistry* [1975] in which groundwater radon content was monitored during an explosion. Measurements were made days before the explosion to establish the background radon level and days afterward to record fully the effect of the stress waves on the radon emission. For six different springs and one artesian well, changes in groundwater radon content in response to three different explosions were evident. The changes varied in amplitude from several times to more than 10 times above the ambient variations, with a duration from a few hours to several days (Figure 4). The explosions gave an equivalent magnitude range from 3.1 to 4.4, while the monitoring sites were from 1.2 km to 14 km away from the explosions. This experiment demonstrated that rapid stress variations generated by the passage of seismic waves from small-magnitude sources ($M \sim 3$) nearby indeed may affect the radon content in groundwater.

In another study conducted by *The Group of Hydro-Chemistry* [1977], radon emissions during stress loading and rupture of rocks were investigated in the laboratory. Samples were made of either natural rocks or radium-doped cement cubes. The doped samples were stored for 3 years to allow the radon and the daughter products to reach equilibrium. Small passage channels, either in parallel or in series, were prepared for samples which were subjected to uniaxial stress. A small pump forced the air to flow through the sample channels, carrying the radon to a scintillation counter for monitoring. Figure 5 gives the results for two different samples. The background measurements (obtained without the sample connected) give the ambient level of the scintillation counter and are indicated by B in the figure. The letter I in the figure marks the connection of the sample to the scintillation counter with stress applied subsequently, and the latter R indicates the moment of sample rupture. Figure 6*a* gives the detailed results of a third sample, and Figure 6*b* is an enlarged portion of Figure 6*a* with the strain history of the sample added. The findings indicate that stress loading and rupture of crustal rock are among the mechanisms that can cause an increase in radon emission. Whereas a major increase in radon emission occurs during the sample rupture stage, the increase during the stages of microcracks closure and linear deformation is relatively small.

At the Geophysical Laboratory of the University of Southern California (USC) the association between radon emission and the tidal strain was examined [*Teng and McElrath,* 1977]. A discrete time series of radon values was obtained from water samples taken at 2-hour intervals over a period of 9 days from a hot spring. Using a harmonic analysis followed by a correlation with the spectrum of the theoretical tidal strain, the radon emission data do seem to suggest a diurnal as well as semidiurnal variation (Figure 7), although experimental error related to the two-phase nature (dissolved and gaseous radon) of the hot spring samples precludes a more definite conclusion.

Discrete Groundwater Radon: Experimental Techniques

In earthquake prediction, research investigators from various countries have used similar techniques of radon measurement for discrete groundwater samples. The procedures differ

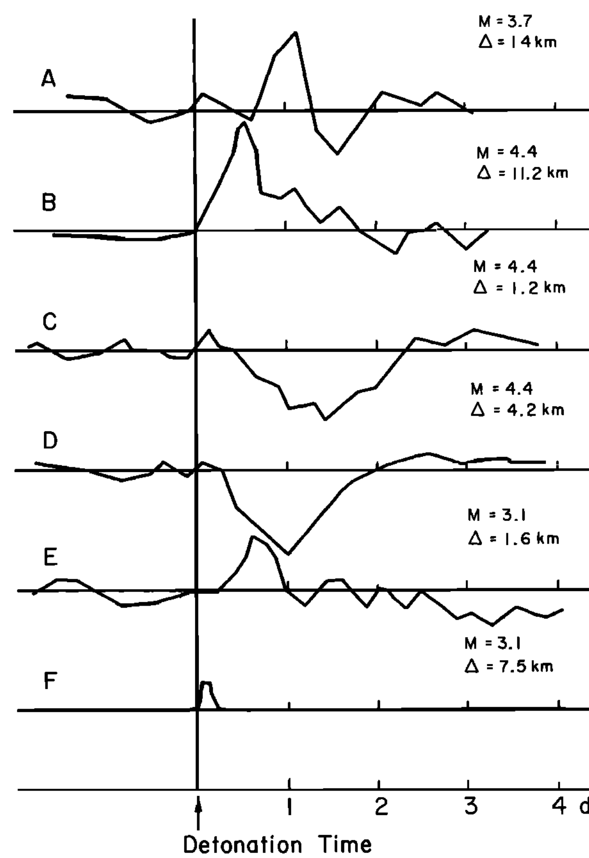

Fig. 4. Responses of groundwater radon content to nearby explosions. After *The Group of Hydro-Chemistry* [1975].

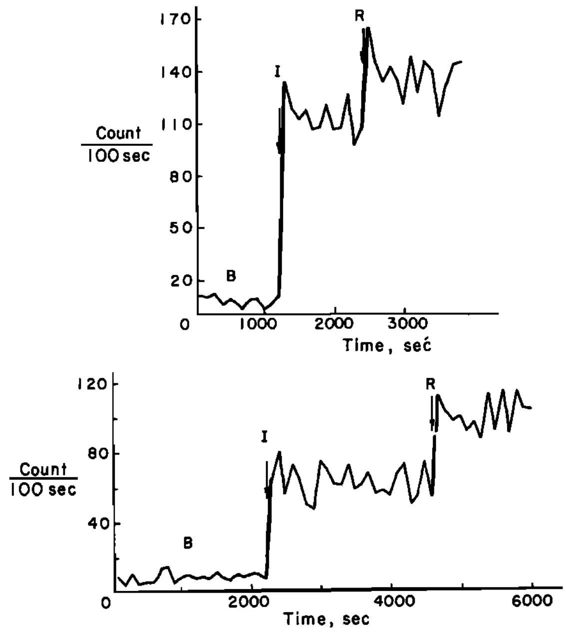

Fig. 5. (*a* and *b*) Results of two sample runs: B, background measurements; I, no stress applied; R, sample rupture. After *The Group of Hydro-Chemistry* [1977].

mainly in the methods used for radon extraction and purification before scintillation counting. Samples are usually taken by specially designed glass or metal extraction vessels fitted with gas dispensers. They are sometimes preevacuated, and water samples are drawn through a tubing into the vessels which are sealed in the field immediately after sampling. Sampling rate ranges from 1–3 times per day in China to once weekly or monthly in the United States and Japan. The Chinese scientists use a simple extraction system: about 100 ml of ground water is collected in a 150-ml evacuated glass vessel; one end of the vessel is connected to a 1-liter detection chamber, which is also evacuated. As bubbling is introduced with a gas dispenser, dissolved radon is driven out of the water and enters the detection chamber through a drying column. In Japan an extraction method making use of the high radon solubility in toluene (about 50 times higher than that in water at room temperature) is described by *Noguchi and Wakita* [1977]. The groundwater sample is transferred into a specially designed separation funnel containing toluene. Upon vigorous shaking, about 80% of the total radon in 300 ml of water is extracted into 30 ml of toluene. After the mixture separates again into two phases the radon is considerably enriched and ready to be introduced into a vial for scintillation counting. The extraction procedures used in the United States are more elaborate and were originally designed for performing radon analysis of seawater to a precision of ±5%. Since the radon content of groundwater is several orders of magnitude higher than that of seawater, liter-sized samples can be measured with high precision even several days after the sampling. The extraction process begins with bubbling helium into the groundwater sample in an otherwise sealed sampling vessel. Helium is then circulated between the extraction vessel and a U trap cooled by liquid N_2 to freeze out the radon. The thawed radon, further purified of CO_2 and H_2O by passing the mixture through a column of ascarite and drierite, is again frozen in a second U trap and finally ready to be transferred to a scintillation counting cell. A typical U.S. counting cell has a volume of about 80 cm^3. It is made airtight through an O ring seal and is coupled to the extraction system with a Swagelok-type double-ended Quick-Connects fitting. The interior wall of the cell is coated with a thin film of ZnS(Ag) powder. The cell holder or counting chamber is made of black anodized aluminum which brings the counting cell in direct contact with a photomultiplier (PM) tube. The cell holder has a felt-covered shutter to insure that the chamber will remain light tight during the insertion and removal of the counting cells. The need to turn down the high-voltage power supply on the PM tube during the change of counting cells is thus avoided, and instrumental stability enhanced. The overall detection efficiency is about 80% as established by analyzing standard 20-l ^{226}Ra solutions. The two alpha daughters of radon (^{218}Po and ^{214}Po) are detected with the same efficiency as their parent. The background noise of the total assembly (i.e., alpha pulses arising from radon content of the counting cells, the extraction system, and the glass extraction vessels) is no more than 0.2 c/m (counts per minute). (1 Ci = 2.22×10^{12} c/m. Groundwater radon concentration data from Russia and China are commonly expressed in terms of 'emans'; 1 eman = 10^{-10} Ci/l or 22.2 c/m l.)

SOME GROUNDWATER RADON RESULTS

The Geophysical Laboratory of USC has been conducting a discrete groundwater radon measurement program since

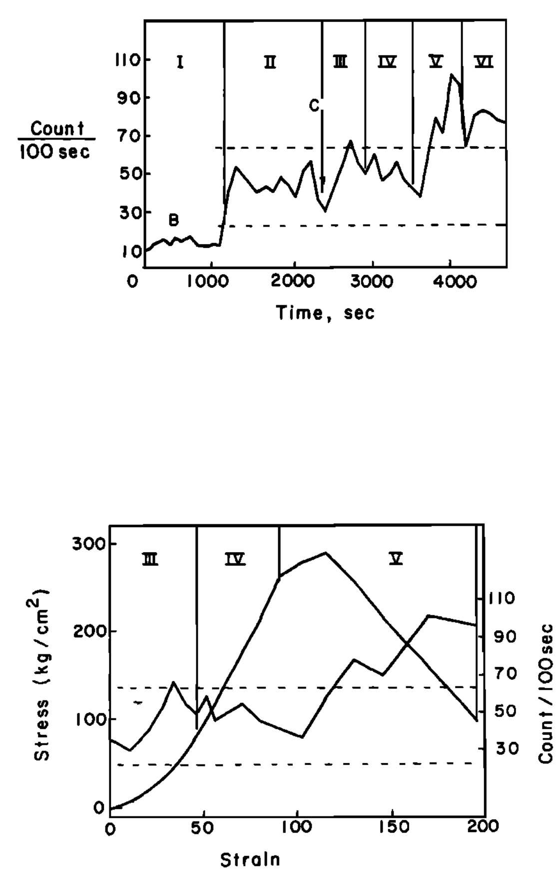

Fig. 6. Detailed result of a third sample run: (*a*) Radon count as a function of time; (*b*) radon count as a function of stress and strain. Stage I, background measurements; stage II, no stress applied; Stage III, stress applied and microcracks closed; stage IV, sample undergoing linear deformation; stage V, sample rupture; stage VI, stress removed. After *The Group of Hydro-Chemistry* [1977].

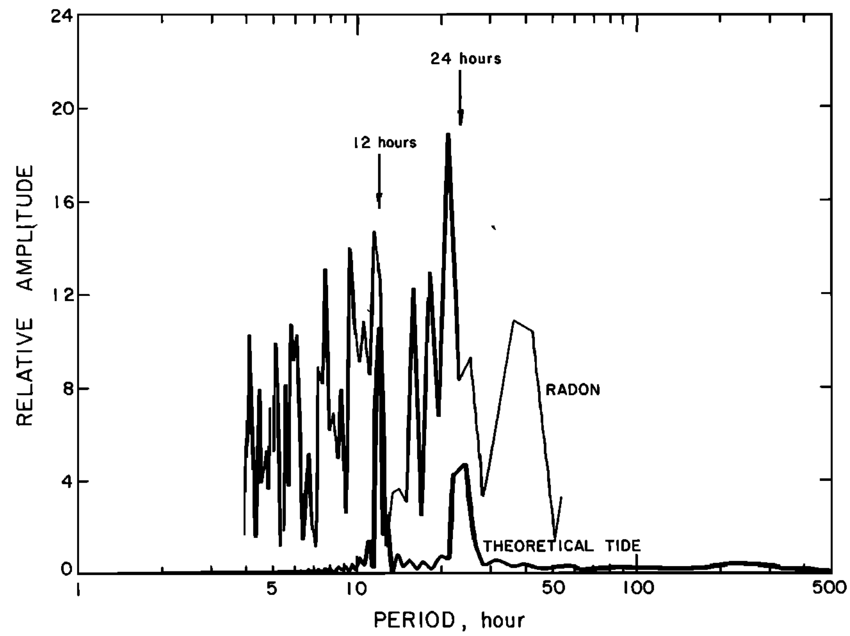

Fig. 7. Correlation of theoretical tidal spectrum with the spectrum of groundwater radon variations.

1974. At the present time the sampling network comprises 14 spring and well sites (Table 1) distributed mainly along a 'locked' segment of the San Andreas fault from Gorman to Cajon in California (Figure 8). A weekly sampling program has been adopted except for one site (BS) located in the Owens Valley inside the Pine Creek Tungsten Mine where only monthly samples are taken. As an example, 4-year weekly groundwater radon measurements at the Switzer Camp site are given in Figure 9. The radon counts from about 200 weekly measurements give an average value of 3426 c/m kg. With a 2.5% measurement error these radon values vary within about ±8% of its mean. Several anomalous high-radon values are noted in September 1975, November 1976, and April 1977. Only the November 1976 high was found to have occurred prior to a known seismic event, a microearthquake swarm in the Pearblossom area some 30 km north of this sampling site. The other two highs did not correspond to noticeable seismic events. Two radon lows are also noticed: one in December 1975 and a less prominent one in February 1978. A careful examination of the circumstances suggests that these

TABLE 1. Groundwater Radon Sampling Sites

Code	Location	Site Type	Sampling Interval	Starting Date
SC	Switzer Camp, west of Mount Wilson	spring	weekly	Oct. 1974
ARP	Arp Well, Altadena	well	weekly	Oct. 1976
AS	Arrowhead Spring, north of San Bernardino	hot spring	weekly	Oct. 1976
BP	Big Pines, near Wrightwood	well	weekly	Oct. 1976
EV	Eternal Valley, Newhall	hot spring	weekly	Oct. 1976
GH	Glen Haven, Pacoima Canyon	well	weekly	Oct. 1976
MS	Mormon Spring, north of San Bernardino	artesian	weekly	Oct. 1976
PD	Palmdale 01, Palmdale	well	biweekly	July 1977
SHS	Seminole Hot Spring, Malibu Canyon	hot spring	weekly	Oct. 1976
TR	Tejon Ranch, north of Gorman	well	weekly	Oct. 1976
BS	Bishop Pine Creek, Union Carbide Tungsten mine, Bishop	spring from deep mine	monthly	July 1977
HK	Haskell Ranch, Banning	deep artesian well	weekly	July 1977
CM	Charles Mason	well	weekly	Oct. 1977
SSP	Soledad Sands Park	well	weekly	Sept. 1977

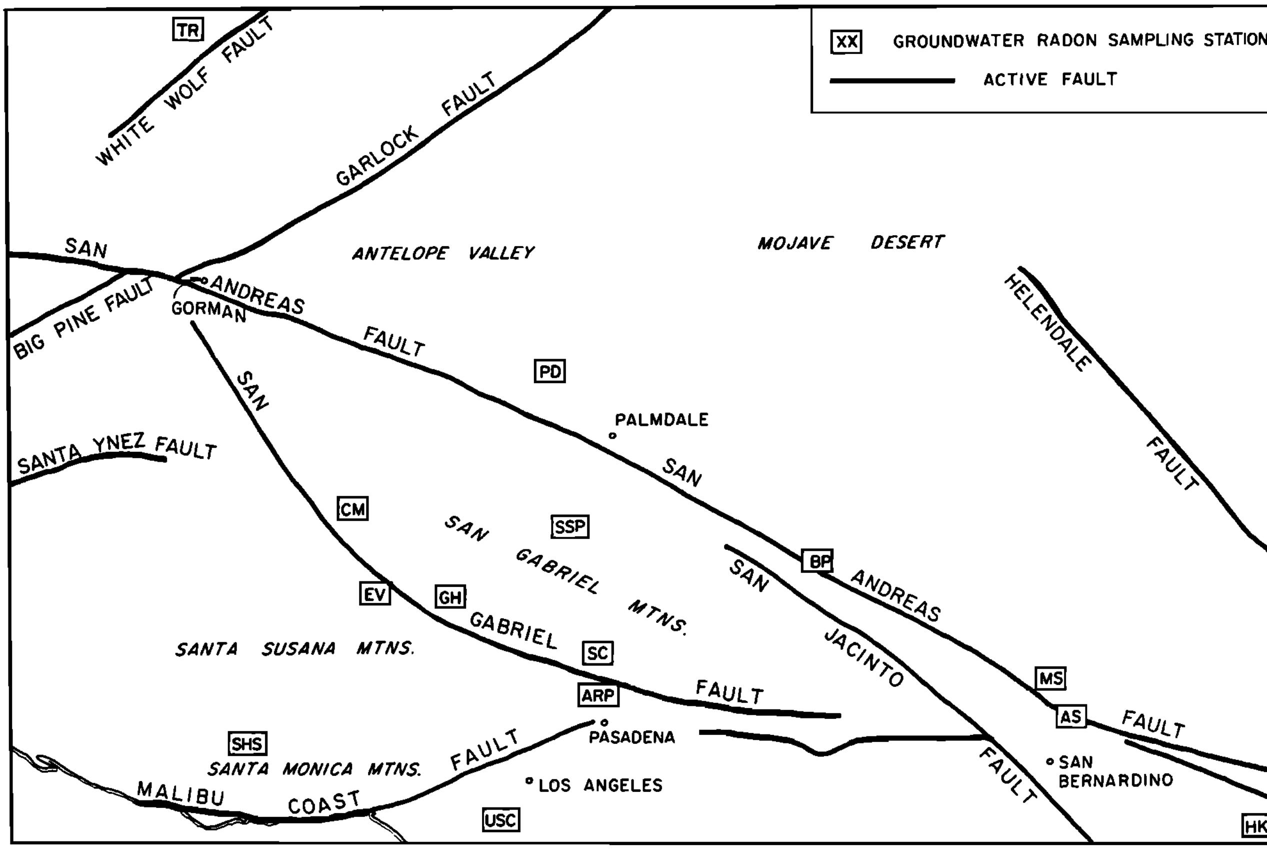

Fig. 8. The USC groundwater radon sampling network.

lows were most likely caused by a leakage of radon gas through the bottle seal during the transport of samples from the field site to the laboratory. During the course of the 4-year period there have been small ($M \sim 3$) events occuring within 50 km to the sampling sites, but we have found no clear correlation between groundwater radon variations and these small-earthquake occurrences. In addition, there is no clear correlation of radon highs from the Switzer Camp with radon data from other sites in our sampling network. No large earthquake has occurred near the sampling sites since monitoring started; therefore the usefulness of this radon monitoring project is indeterminate at the present time.

Even when a large earthquake does occur, it is likely that some sites in this sampling network may prove to be insensitive or unresponsive to the stress buildup. Until such a test event occurs to enable critical evaluation of the data, the most prudent strategy for the time being calls for the continuation of regular radon sampling.

In the meantime, encouraging radon results have been reported from China, where an extensive groundwater radon monitoring program is being pursued. Large earthquakes in China during 1975–1977 have provided a number of test cases for the Chinese scientists to evaluate their radon data, some of which contributed directly to their issuance of earthquake

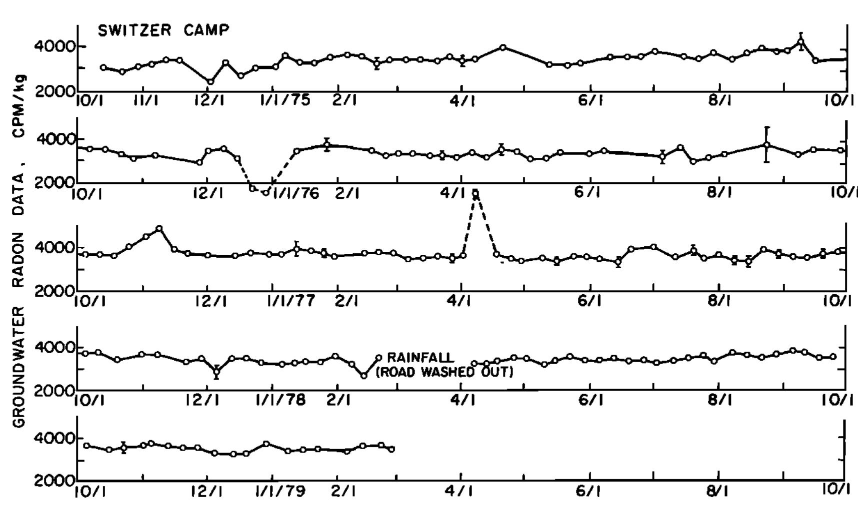

Fig. 9. Groundwater radon data from the Switzer Camp site, California.

TABLE 2. Spikelike Radon Values at the Kutzan Station

Earthquake	Magnitude	Δ, km	On Y-Shaped Fracture Zone	Time of Occurrence	Radon Spikes (Days Before Earthquake)	Percent Above Ambient
April 8, 1972, Sahteh	5.2	70	yes	March 28, 1972	11	55
None	...	...	...	March 29, 1972	...	38
Sept. 27, 1972, Takung	5.8	54	yes	Sept. 16, 1972	11	34
Feb. 6, 1973, Luhuo	7.9	220	yes	Jan. 29, 1973	8	120
Feb. 16, 1973, Luhuo	5.3	220	yes	Feb. 16, 1973	1	36
April 22, 1973, Yiliang	5.2	340	yes	April 9, 1973	13	41
May 8, 1973, Sungpan	5.2	345	yes	April 25, 1973	13	40
June 29, 1973, Mapien	5.8	200	yes	June 21, 1973	8	89
Aug. 11, 1973, Nanping	6.5	420	yes		no radon spike	
Aug. 16, 1976, Sungpan-Pingwu	7.2	320	yes	Aug. 10, 1976	6	70

predictions. The large amount of Chinese data can perhaps be grouped into long-term and short-term anomalies. The long-term anomalies have a radon emission buildup time of from a few months to a few years, similar in nature to the Tashkent data reported in Figure 1*a*. Examples include the Ankochuang and Kuanchuang radon data (Figure 10) before the 1978 Tangshan earthquake ($M = 7.8$), as well as the Lungling, Hsiakuan, Lantsang, and Erhyuan radon data (Figure 11) before the 1976 Lungling earthquake ($M = 7.6$). There was in these data no clear additional anomalous radon signal immediately before these earthquakes. Even if the slow buildups were truly associated with the earthquakes, their usefulness is limited to providing a general indication of a slow regional stress buildup.

The short-term radon anomalies appear to be more useful. The most outstanding examples perhaps come from the Kutzan station in the west of Szechuan province. This station is located at the junction of a major Y-shaped fracture. Groundwater samples are taken from a warm artesian spring. Large earthquakes occur frequently along this fracture zone. Between 1972 and 1976, nine earthquakes with magnitudes ranging from 5.2 to 7.9 occurred on the Y-shaped fracture zone (Table 2). In eight out of the nine cases, spikelike radon anomalies were observed from 6 to 13 days before the earthquakes. Only one spikelike radon anomaly was observed that was not followed by an earthquake. The anomalies range in amplitude from 36% to 120% above the ambient level. Figures 12 and 13 show two of the spikelike anomalies that had a duration of only about 1 day. Their detection requires a minimum sampling rate of a few times per day. The underlying mechanism that produces such a spikelike radon anomalies is not yet understood, nor do we have a stress field model that permits these anomalies to be observed at large epicentral distances. However, the occurrences of the spikelike radon anomalies have not been limited to the Kutzan station. One example is the successfully predicted 1975 Haicheng earthquake ($M = 7.3$), as shown in Figure 14. In this case the rapid increase of groundwater radon content occurred only hours before the earthquake. For the unpredicted Tangshan earthquake of 1976 ($M = 7.8$), Figure 15 shows that spikelike radon anomalies were observed in two stations, but a third station showed practically no information. Spikelike groundwater anomalies were also observed for two of the large aftershocks of the Tangshan earthquake (Figure 16). These records, as well as that from the Langfang station shown in Figure 15, were obtained by automatic groundwater radon monitoring systems to be described in the next section. Not all short-term groundwater radon anomalies are spikelike. Some have substantially longer durations of more than a day (Figure 17). They appear to be most useful for pinpointing the predicted time of occurrence of an earthquake. It should be emphasized, however, that a majority of the radon anomaly groundwater data from China, long-term and short-term types alike, do not have any useful predictive value. This is true also for groundwater radon data obtained elsewhere in the world. This large uncertainty is partly due to a lack of clear understanding of the mechanism by which tectonic stress buildup is manifested in radon anomalies and partly due to the lack of groundwater hydrological information, particularly in connection with the interaction of groundwater-bearing layers with the rock fracture systems.

From Russia, after the group of papers published in the

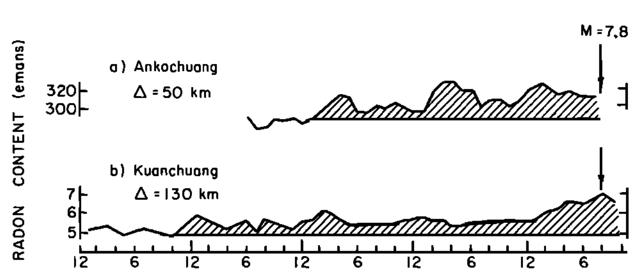

Fig. 10. Groundwater radon data from Ankochuang and Kuanchuang before the 1978 Tangshan earthquake of $M = 7.8$. After *Wakita* [1978]. Crosshatching indicates above average readings.

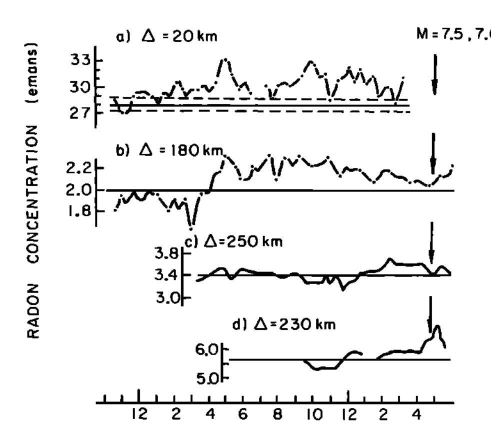

Fig. 11. Groundwater radon data from four locations in Yunan province before the 1976 Lungling earthquake of $M = 7.6$. After *Wakita* [1978]. Horizontal dashed lines indicate one standard deviation. (*a*) Lungling. (*b*) Hsiakuan. (*c*) Lantsang. (*d*) Erhyuan.

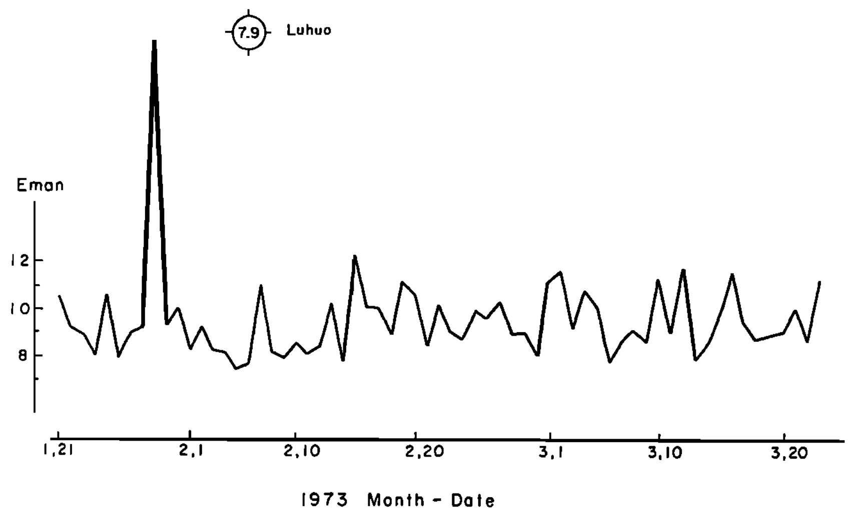

Fig. 12. Spikelike groundwater radon anomaly observed at the Kutzan station 8 days before the $M = 7.9$ Luhuo earthquake of 1973.

early 1970's, no significant report on the earthquake prediction study of groundwater radon anomalies has come to the writer's attention. In Japan a very interesting groundwater radon anomaly (Figure 18) was observed immediately before the 1978 Izu Peninsula earthquake ($M = 7.0$) by a newly installed continuous radon monitoring system (H. Wakita, written communication, 1978). The anomaly started about 5 days before the main shock. It was not spikelike, as typified by the Kutzan data from China, but the duration of the anomaly was as short and would have been easily missed by a monitoring program with a weekly sampling rate. Again, this was only one out of several radon monitoring stations that showed an apparent precursory anomaly for that earthquake in Japan.

Continuous Groundwater Radon Counting Systems

To perform discrete groundwater radon measurement is quite time consuming, both in the field sampling process and in the laboratory analysis. Sampling sites are usually remote, and it often takes 2–5 hours of driving to reach a site. Usually, two to four samples are taken at a given site during one sampling, and each sample takes about 2 hours to go through the radon cold trap and scintillation counting. The time commitment becomes considerable when a network of more than a dozen sampling sites is sampled more than once a week. To take samples several times a day (such as the case in China), it is almost necessary to set up a field laboratory at each sampling site, unless a continuous groundwater radon counting system is used. The need for continuous radon counting is indicated by recent observations (mainly from China) that some of the most interesting anomalies occurred only shortly before the large earthquakes. The anomalies appear to be spikelike with a time duration of as short as 1 day. A monitoring program with a weekly or monthly sampling rate would be inadequate for their detection.

Continuous groundwater radon monitoring systems have been used in Russia, China, and Japan. Little detailed information on the Russian system is available, although the data shown in Figure 3 were reported to have been generated by such a system. A comprehensive discussion of the Japanese system has been given by *Noguchi and Wakita* [1977], and the data shown in Figure 18 were obtained by continuous monitoring during the $M = 7.0$ 1978 Izu Peninsula earthquake. In the United States one such system is installed at a deep (~500 m) artesian well site (Haskell well) south of Redland near the Banning fault, which is a branch of the San Andreas system. As a cooperative project between the University of Tokyo, the U.S. Geological Survey, and USC, this continuous radon counting system has been in operation for about 2 years. The system is functioning properly and needs only monthly maintenance. No anomaly has yet been recorded, however. A sec-

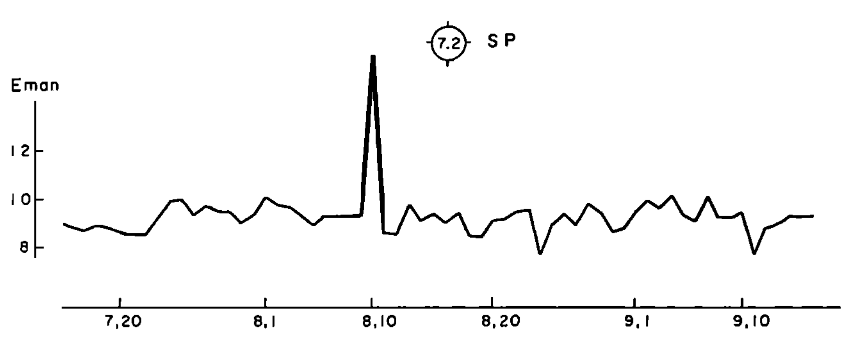

Fig. 13. Spikelike groundwater radon anomaly observed at the Kutzan station 6 days before the $M = 7.2$ Sungpan-Pingnu earthquake of 1976.

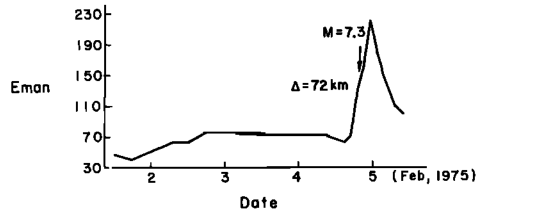

Fig. 14. Spikelike groundwater anomaly before the 1973 Haicheng earthquake of $M = 7.3$, as observed at the Hotang hot spring site of Liaoyang, Liaoning province. After *The Group of Hydro-Chemistry* [1977].

ond system of the same type is operating near Hollister by C. Y. King of the U.S. Geological Survey.

During a recent visit to China the writer was shown the continuous radon counting system now in common use there. A schematic diagram is given in Figure 19. Groundwater is pumped from a sampling well into a waterhead stabilizer tank and is allowed to discharge into a separation chamber through a spray head and a screen so as to increase the release of dissolved radon. A small portion of the water in the stabilizer tank is allowed to discharge through an aspirator, thereby generating a negative pressure in the ZnS cell. This negative pressure serves to draw the radon-air mixture from the separation chamber into the cell. The mixture then passes through an air-cooling column and a flowmeter before entering the ZnS cell. The ZnS cell is directly coupled to a PM tube, with its output feeding into a counter/printer. A radioactive standard is located at the bottom of the cell and provides daily calibration. This spray head design should give better radon flushing efficiency than the Japanese system. The air-cooling column is necessary, especially when the system is operated in a hot spring site, in order to avoid subsequent moisture condensation in the ZnS cell. Heating is not employed in the ZnS cell. Unlike the Japanese system, no thin plastic film is used to protect the Zns surface against moisture condensation, deposition of contaminants, and other possible chemical reactions. In these regards, the Chinese cell design is less sophisticated than that of the Japanese system.

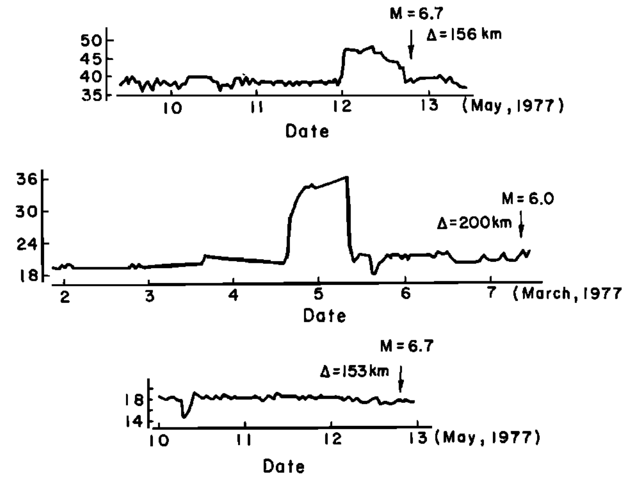

Fig. 16. Groundwater radon anomalies observed at two locations in Peking by automatic groundwater radon monitoring systems. (Top) Peking Shichiao well data before the Lutai event. (Middle) Peking Research well data before the Chien-an event. (Bottom) Peking Research well data before the Lutai event. After *The Group of Hydro-Chemistry* [1977].

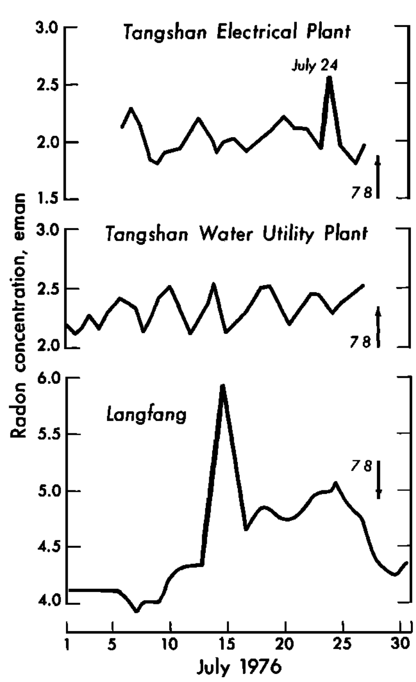

Fig. 15. Groundwater radon anomalies observed at three stations before the 1976 Tangshan earthquake ($M = 7.8$). Top two traces give data from sites in the epicentral region; bottom trace gives data from Langfang station, which is 130 km from the epicenter. After *Wang* [1978].

At the Geophysical Laboratory of USC a prototype continuous radon counting system is being developed. To increase the radon flushing efficiency in the separation chamber, the use of a spray head from above is combined with bubbling air from below. To remove the moisture, a stage of refrigeration was incorporated, followed by a column of drierite. Thus when the radon-air mixture is introduced into the ZnS cell, at least moisture condensation will not be a problem. A column of ascarite is used to remove the CO_2. Preliminary laboratory tests show that a 60% radon flushing efficiency can be achieved with such a system. The output of this system will be temporarily stored in digital memory in the field using a telemetry interface module already in existence. Upon regular (daily) telephone interrogation the stored data will be telemetered back to the laboratory tape file.

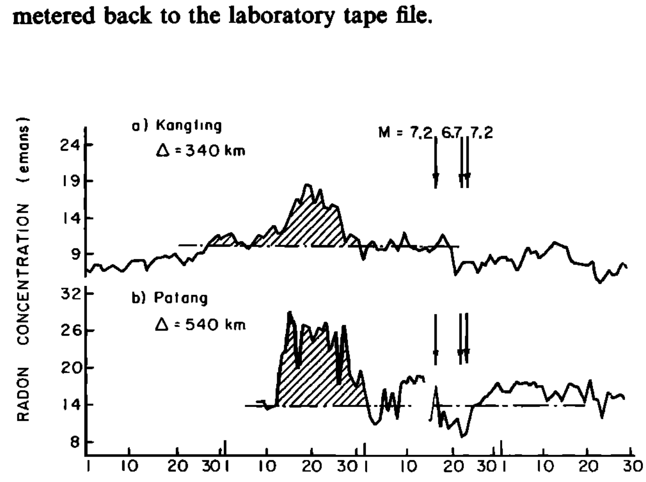

Fig. 17. Groundwater radon anomalies observed before the Sunpan-Pingwu earthquake showing a much longer anomalous duration. After *Wakita* [1978]. Cross-hatching indicates above average readings.

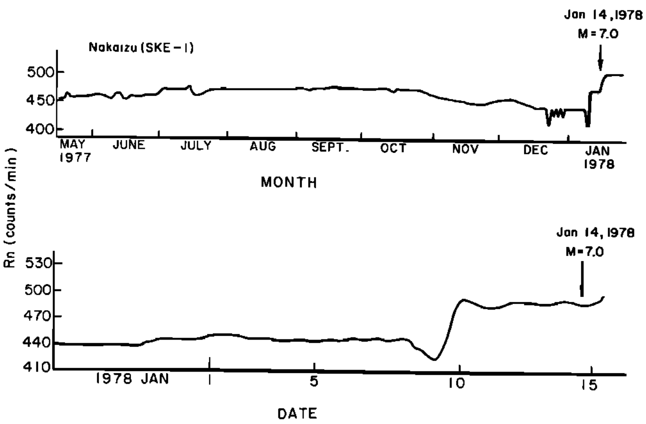

Fig. 18. Groundwater radon anomaly observed before the 1978 Izu Peninsula earthquake ($M = 7.0$). Bottom trace is an enlarged portion of part of the top trace (H. Wakita, written communication, 1978).

CONCLUDING REMARKS

Available evidence suggests an association between regional stress buildup and radon emission from crustal rocks. In the absence of a clear understanding of the mechanism of the stress-induced radon emission and radon transport, the radon precursor problem can be approached empirically. Unexposed (or uncontaminated) groundwater directly issued from deep wells and springs gives the most reliable samples for monitoring the crustal radon emission, although the lack of knowledge of subsurface hydrology makes the selection of useful spring and well sites for radon monitoring rather difficult. By and large the discrete-sample groundwater radon measurement with the liquid N_2 cold trap method gives better accuracy than the continuous radon counting systems. However, in view of the spikelike radon anomalies (high above the ambient values and short in duration) prior to large earthquakes, trading off some measurement accuracy for a much higher sampling frequency seems necessary. The cost of equipment and field installations of the continuous monitoring system will be compensated by decreased manpower spent in field travel and laboratory analysis as part of the discrete sampling procedures.

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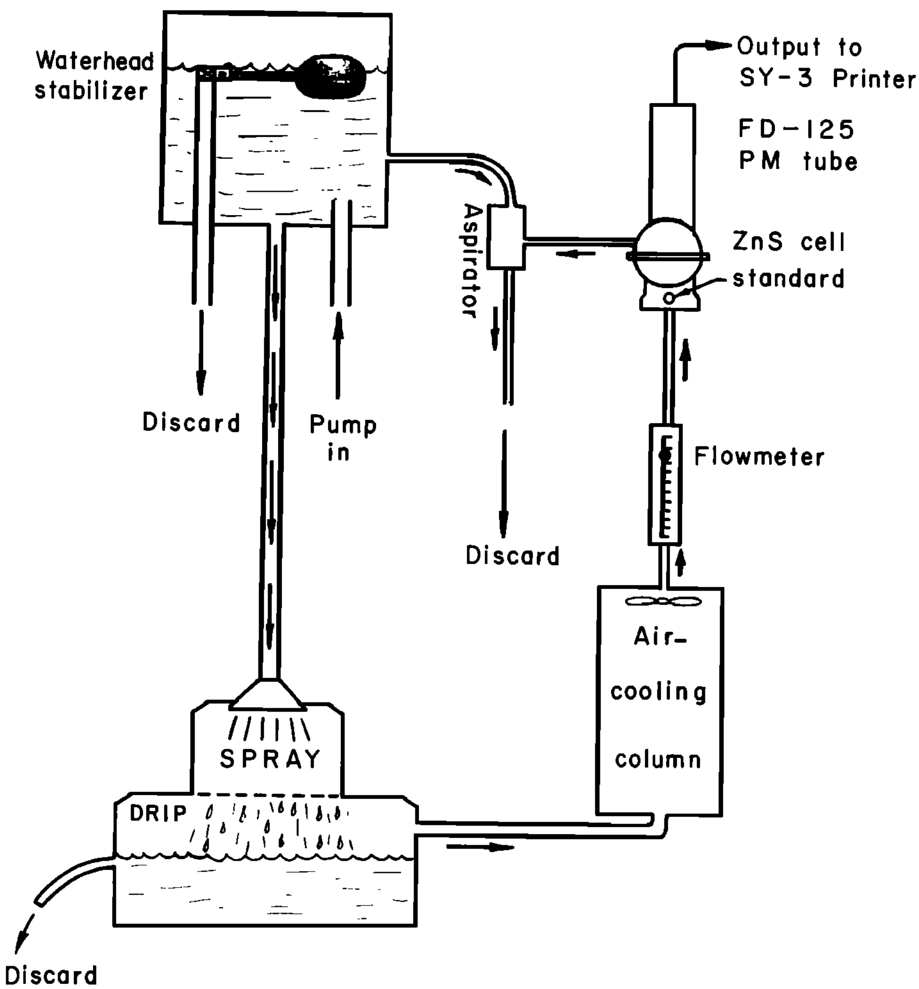

Fig. 19. A schematic diagram of the continuous radon counting system presently being used in China.

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