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AUTOMATED RADON MONITORING AT A HARD-ROCK SITE IN THE SOUTHERN CALIFORNIA TRANSVERSE RANGES

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Abstract. Data are presented from 20 months of near-real-time (three samples per day) radon monitoring at a hard-rock site in the Transverse Ranges of southern California. An annual cycle is evident in the data which is attributed to thermoelastic strains in the vicinity of the borehole site. Between April 1, 1977, and October 31, 1978, there were 11 earthquakes with magnitudes ≥2.0 within 25 km of the monitoring site. Three of these events appeared to be preceded by precursory signals, four were preceded by 'possible' precursory signals, and four were not preceded by any apparent precursors. Before the 4.6 M Malibu earthquake of January 1, 1979, a possible precursory signal sequence of 40-45 days' duration was observed.

Introduction

There have been many reports suggesting that measurements of radon concentrations in groundwater and/or in soil gas may provide useful premonitory signals before seismic events [Birchard, 1977; Birchard and Libby, 1976, 1978; Haicheng Earthquake Study Delegation, 1977; King, 1976, 1977, 1978a, b; Kisslinger, 1974; Li et al., 1975; Moore et al., 1977; Sadovksy et al., 1972; Shapiro et al., 1979; Smith et al., 1975]. To some extent these field observations support the qualitative predictions of the dilatancy-diffusion model [Scholz et al., 1973], which suggest that anomalous changes in subsurface radon concentrations may be expected prior to large earthquakes. At the same time, there are many unanswered questions about the usefulness of radon monitoring in earthquake prediction programs. These include questions concerning the types of monitors to be employed, the types of sites to be employed, the nature of the premonitory signals that may be expected from larger events, the nature of interfering signals from nonseismic sources, and the possibility of removing such interferences from the data. Several groups currently monitor radon in California using a wide variety of techniques. At the California Institute of Technology an automated radon-thoron monitor for field use that provides near-real-time data [Melvin et al., 1978; Shapiro et al., 1979] has been developed and is being deployed at several sites in the Transverse Ranges of southern California. One of these monitors, the first prototype unit, has been operating continuously since April 1976. This paper reports the data and field experience obtained with this prototype monitor.

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Instrumentation and Siting

The radon-thoron monitor that we have developed uses aerosol filtration to concentrate samples of radon and thoron daughters. A microcomputer controls all electromechanical operations of the instrument; collects background, radon, and thoron data; and monitors the status of key electrical and mechanical components. The monitor can be used to measure radon levels in wet or dry static boreholes, in water from pumped wells, or in the air of tunnels or mine shafts. A complete description of the instrument has been given previously [Melvin et al., 1978; Shapiro et al., 1979].

The prototype radon-thoron monitor was installed over a static borehole at the Kresge Seismological Laboratory in Pasadena, California (34°08.9'N, 118°10.3'W). This location is close to the Verdugo, Raymond Hill, and Sierra Madre fault zones, which are part of a system of faults that extend across the edge of the Los Angeles basin along the southern side of the Santa Monica mountains. The borehole is 24.1 m deep. It is cased through the soft overburden with a 7.6-cm-diameter plastic pipe which is 9 m long. The lower part of the borehole is in hard rock (mostly granite) and is not cased. The monitor vault is connected directly to the casing and is sealed from the ambient atmosphere. The Kresge site is in a small canyon with moderately steep sides.

At the time the borehole was drilled, drought conditions had prevailed in southern California for 2 years. Nevertheless, the borehole filled with water to within 5.5 m of the surface immediately after it was drilled and bailed. From the local topography it appears that a perched water table exists in the vicinity of the borehole and that water continuously flows through the seams and joints in the rock toward lower elevations in the nearby Arroyo Seco basin.

The monitor strips radon and thoron from the water in the borehole by bubbling the exhaust from its air pump through the water. The pump is operated for 5 min at a time, 3 times per day. Approximately 0.5 m^3 of air is moved in each pump cycle. This provides samples of radon and thoron daughters every 8 hours whose β activity subsequently is counted with a Geiger tube.

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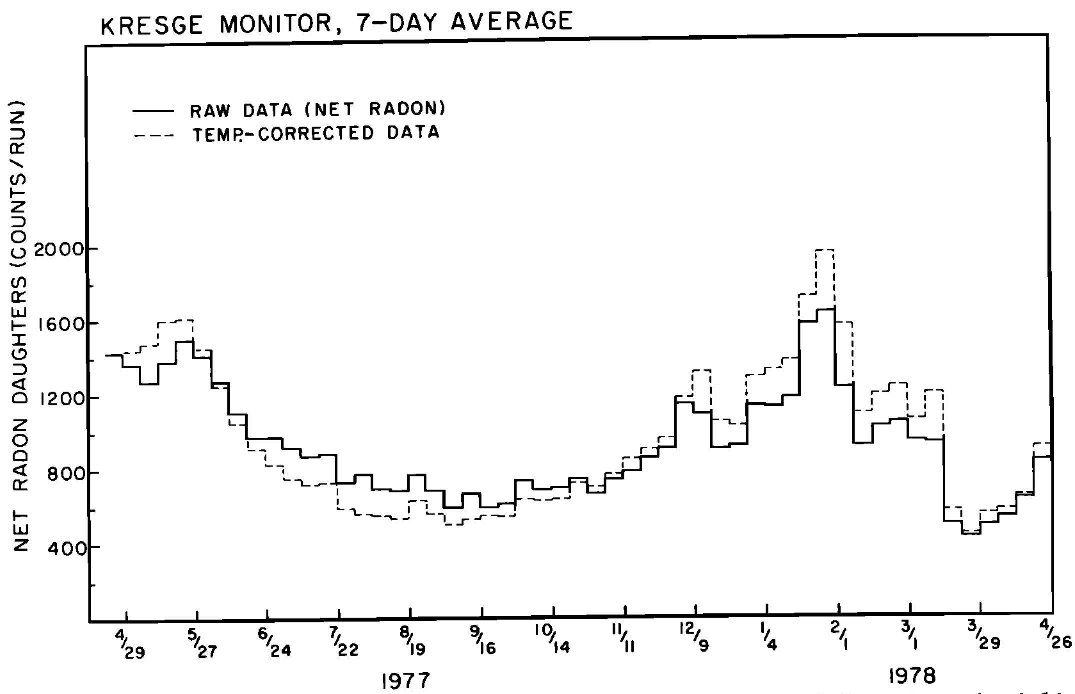

Fig. 1. Seven-day averages of raw data and temperature-corrected data from the California Institute of Technology radon-thoron monitor at Kresge Laboratory, Pasadena, during the first 12 months of operation.

Operating Experience

Initially, strong diurnal variations in the data from the borehole operation of the monitor were noted. These were found to correlate with the external ambient air temperature, with morning values of radon being low and afternoon values being high. This effect was believed to be the result of condensation in the instrument vault at low temperatures, which removed radon daughters from the instrument vault air space. Insulation of the instrument vault and the installation of a small, thermostatically controlled heater eliminated almost all of the diurnal variations in the data. During the first month of operation the remaining short-term, temperature-related variations in the data were found to be nearly a linear function of temperature. A correction formula for removing these variations was developed. These temperature corrections are described in more detail by Melvin et al. [1978], who present typical raw data, short-term temperature dependences, and temperature-corrected 24- and 72-hour running averages of the raw data.

The short-term temperature corrections have little effect on data obtained over a 20-month period. Seven-day averages of the raw data and the temperature-corrected data for the first 12 months are shown in Figure 1. By the time the first 9 months of data were obtained, the suggestion of an annual cycle was evident. To test this hypothesis, the first 9 months of data were fitted with a curve of the form

$$R(t) = R_{ave}[1 + A \cos(\frac{2\pi}{52} t - \theta)] \qquad (1)$$

where t is time (in weeks), taking $t = 0$ to represent the week of maximum average ambient air temperature (during the first year of operation), and θ is a phase delay representing the amount of time required for the radon levels to respond to the input temperature wave. Good fits to the first 9 months of data were obtained with $A = -0.4$ and $\theta = 20^\circ$, indicating both strong and rapid coupling of the radon levels to the surface temperature variation. The mechanism for the coupling between subsurface radon levels and surficial temperature is believed to be through thermoelastic strains in the rock in the vicinity of the borehole.

In Figure 2 the curve based on the first 9 months of data is compared to the full 20-month span of data. Considering the simplicity of the assumed annual temperature cycle, the fit is remarkably good. Major departures from the curve occur only during weeks 39-41 and weeks 47-51. The first period was during the very heavy rains of the 1977-1978 winter, while the second major departure is believed to be an artifact in the data caused by an instrumentation problem (a pressure leak in the air pump exhaust hose fitting that was later corrected).

While the existence of an annual cycle might at first sight seem to preclude the usefulness of the data for prediction, this need not be the case. If the cycle is reasonably regular, in the absence of major seismic activity, then corrections can be made to the data to eliminate this temperature effect. Furthermore, precursory signals of duration shorter than 6 months are easily separated from the more slowly varying annual cycle.

With the accumulation of 20 months of data from the Kresge monitor, it has been possible to begin a detailed examination of the record for possible precursory signals prior to the small

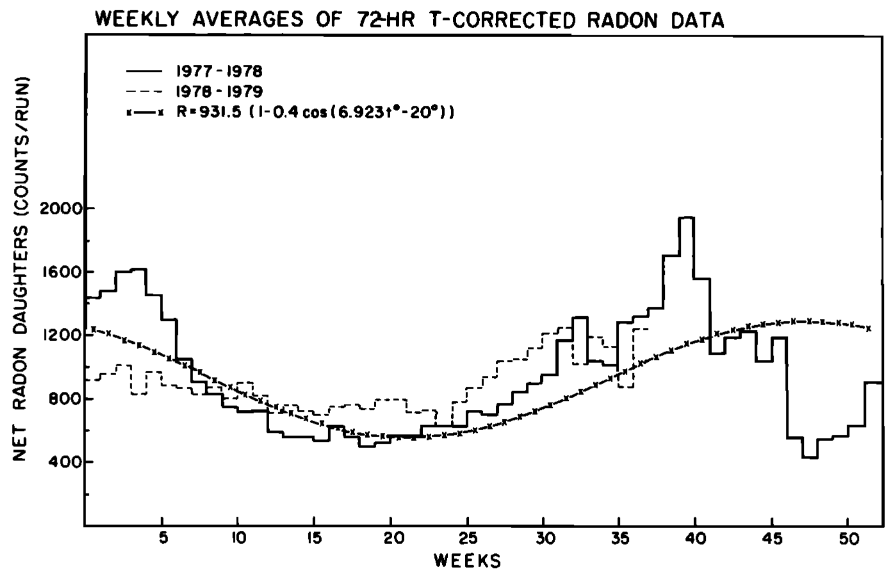

Fig. 2. Annual temperature cycle in the Kresge data. The smooth curve $R = 931.5 \times [1 - 0.4\cos(6.923^\circ t - 20^\circ)]$ with t in weeks is a fit based on the first 9 months of data. This is compared with 7-day-averaged temperature-corrected data for a 20-month period.

earthquakes that have occurred in the vicinity of the monitor during this period. At this point an objective set of criteria for what constitutes an 'anomaly' has not yet been developed; therefore the searching of the record has been done on a somewhat subjective basis by visual inspection of graphs of the data. In general, the data are considered anomalous if there is a departure from the regular trend of the data that clearly exceeds the random noise in the data. Since the possibility always exists that short-term departures from the long-term trends in the data may be caused by nonseismic phenomena such as rainfall-induced changes in the local hydrological conditions, or extreme weather conditions, these effects also are considered for the explanation of any anomalous signal.

During the period from the beginning of monitoring to the end of October 1978 there were 11 earthquakes with magnitude 2.0 or greater with epicenters within 25 km of the monitor. Most of these were not strong enough to be felt at the monitor site. Information on magnitude, distance, depth, and direction from the monitoring site for these earthquakes is given in Table 1. Of the 11 events listed in the table, three appeared to be preceded by precursory signals that could not be attributed to other causes, four were preceded by possible precursory signals for which other causes such as rainfall could not be excluded, and four events appeared to give no precursory signal. Seven events occurred to the south or southwest of the monitor (essentially perpendicular to the fault system near which the monitor is located). Of these seven events, one produced a well-defined anomaly, two were preceded by possible anomalies, and four failed to produce any anomaly. There was one event southeast of the monitor which produced a well-defined anomaly. Three events

TABLE 1. Earthquakes With $M \geq 2.0$ Within 25 km of PAS (34°08.9'N, 118°10.3'W) During the Period From April 1, 1977, to October 31, 1978

Date	Magnitude	Epicentral Distance, km	Direction	Depth, km	Hypocentral Distance, km
June 14, 1977	2.8	19.5	SW	5.0	20.1
June 20, 1977	2.5	19.4	S	10.2	21.9
June 27, 1977	2.7	19.9	S	11.7	23.1
Sept. 24, 1977	2.9	20.8	SE	15.1	25.7
Oct. 6, 1977	3.3	14.5	S	13.9	20.1
Dec. 3, 1977	2.2	23.3	W	7.0	24.3
Dec. 20, 1977	2.8	12.2	S	5.9	13.6
Jan. 25, 1978	2.8	24.5	NW	5.0	25.0
May 11, 1978	2.8	22.9	SW	5.0	23.4
June 3, 1978	2.3	25.1	NW	5.0	25.6
Sept. 27, 1978	2.2	23.7	SW	2.1	24.3

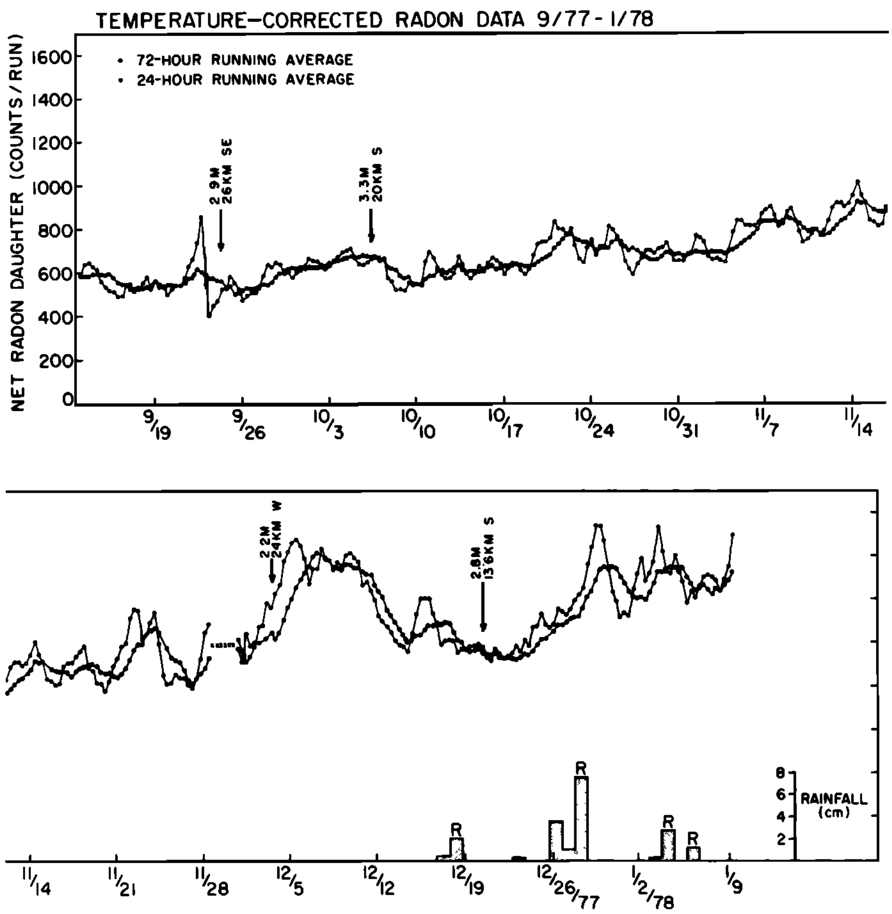

Fig. 3. The 72- and 24-hour running averages of temperature-corrected radon data from Kresge for the period September 13, 1977, to January 9, 1978. This period includes four small earthquakes with epicenters within 25 km of the monitor. Duration and magnitude of rainfall are indicated by blocks marked 'R.' Hypocentral distances and earthquake magnitudes are indicated. Interruptions in the data are indicated by crosses.

occurred to the west or northwest of the monitor. One of these produced a well-defined anomaly prior to the event, and two produced possible anomalies.

Because all the events listed in Table 1 are quite small, the duration of precursory signals would be expected to be a few days or less [Rikitake, 1976]. Most such events are unlikely to produce anomalies that would be seen in weekly or monthly records; however, our near real-time record with three daily sampling periods is well suited to the investigation of these smaller-magnitude events as well as large events. In addition to the weekly averaged data (as shown in Figures 1 and 2), 72- and 24-hour running averages are maintained to facilitate identification of short duration anomalies.

Figure 3 shows the record obtained between mid-September 1977 and January 1978. Both 72- and 24-hour running averages of the temperature corrected data are shown, and the record covers the period when four of the earthquakes listed in Table 1 occurred. This record illustrates examples of 'definitive' and 'possible' anomalies, as well as a case where no anomaly is apparent. Before the 2.9 M event of September 25, 1977, a short sharp spike of about 1-day duration is seen in the 24-hour running average. The magnitude of the spike is about 44% above the base line for that time of year, and the spike occurred during a period when there was no significant rainfall and when the record was relatively free of noise. The record remained quiet throughout October 1977, although a 3.3 M event took place 20 km south of the monitor early in October. About mid-November the record became somewhat nosier, although there was no significant precipitation until December 17, 1977. A 2.2 M event took place on December 3, 1977, about 24 km west of the instrument. One week before this event a 'bump' in the record occurred; however, the generally rising data trend at this time of year and the 'noise' during the weeks before places this 'anomaly' in the possible category.

The earthquake that occurred on December 20, 1977, had a magnitude of 2.8 and was located about 13.6 km south of the monitor. This earthquake was felt in the vicinity and was the closest event to the monitor of those listed in Table 1. This earthquake produced the most well defined anomaly during the 20-month monitoring period. The radon level rose to about 40% above the trend line of the data and remained high for

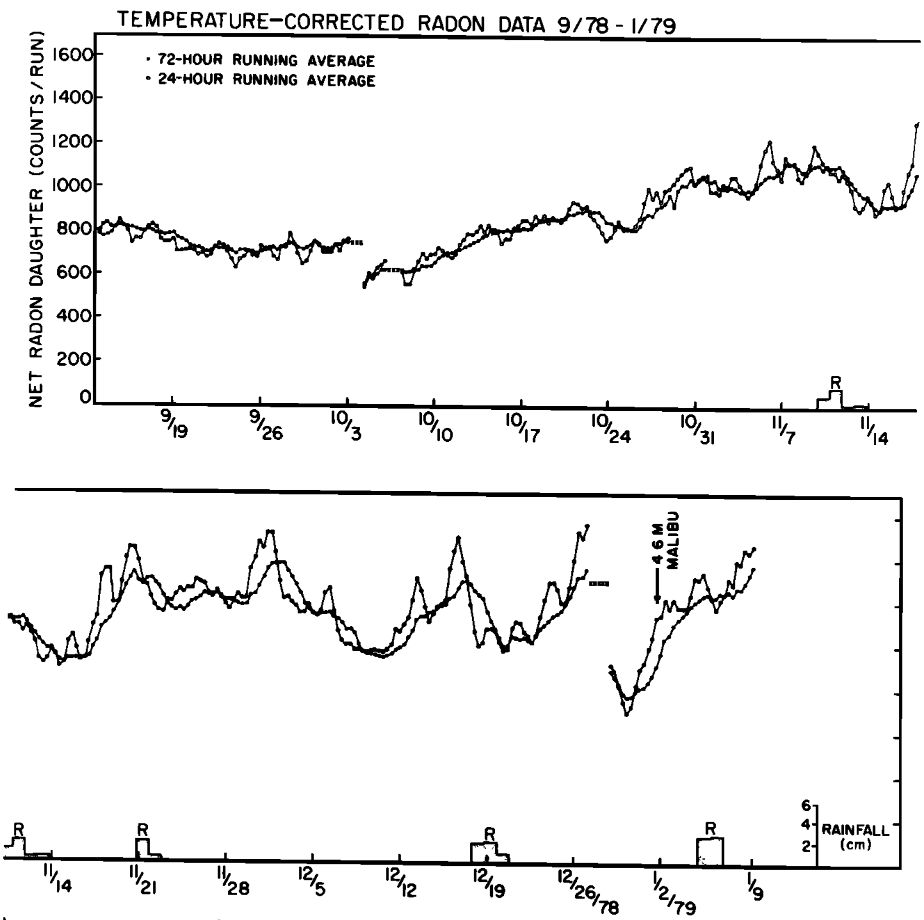

Fig. 4. The 72- and 24-hour running averages of temperature-corrected radon data from Kresge for the period from September 13, 1978, to January 9, 1979. This period includes the 4.6 M Malibu earthquake.

about 9 days, terminating about 6 days before the event. The anomaly was pronounced in the 24- and 72-hour running averages and in the weekly averages.

The largest-magnitude event to be felt in the vicinity of the monitor was a 4.6 M earthquake just south of Malibu (about 54 km west of the monitor) that took place on January 1, 1979. The record before this earthquake is shown in Figure 4, which covers a time period comparable to that in Figure 3. For more than a month before the event the record is characterized by a series of spikes that are most pronounced in the 24-hour running average. While there had been some rain during this period, it was not heavy or prolonged. Considerably more rainfall had occurred the previous year before comparable noise in the record was seen. Unfortunately, the instrument vault had to be opened to change the filter paper strip a few days before the January 1, 1979, event. This resulted in the break in data shown by the crosses. When the instrument vault is opened for maintenance, there usually is a drop in the data for a day or two until equilibrium is reestablished. However, the sharp drop immediately prior to the January 1, 1979, earthquake is much larger than the drops produced by previous openings of the vault. For example, during the week of October 3, 1978, the vault was opened twice, causing a 14% drop in the data for a few days (see Figure 4), while the drop in the 24-hour average just before the January 1, 1979, earthquake was 59%, and the drop in the 72-hour average was 43%.

Discussion

Annual cycle. The annual cycle in the data from the Kresge site, which is evident in Figures 1 and 2, is of considerable interest since its explanation may shed some light on the mechanisms responsible for changes in the radon concentrations in groundwater. Among the possible explanations which may be considered are the following: (1) instrumental effects, (2) hydrological effects, and (3) thermoelastic effects. The possibility that the observed annual cycle is a result of instrumental drift is very unlikely. First, any change in the sensitivity of the counting electronics would be reflected in a change in the level of the background count taken before each data run. Examination of the background counts, however, shows no discernible annual cycle or other variation. Second, the known short-term temperature dependences of the instrument which were discussed previously are in the opposite direction from the observed annual cycle. In addition, the vault temperature has been stabilized to the point where these short-term variations are much smaller than the observed annual variation. We also rule out hydrological factors, since the annual cycle seems relatively independent of the rainfall patterns and water level in the borehole. For example, during the first year of data collection, drought conditions prevailed up to week 35 (Figure 2), yet the data had already risen substantially from its summer minimum. During the second year of operation, winter rains began several weeks earlier, yet the general shape of the annual cycle is similar to the previous year. The most likely explanation for the annual cycle, in our view, is the effect of thermoelastic strains on the rock within the surface thermal boundary layer. Harrison and Herbst [1977] have considered an annual surficial temperature variation of the form $T = T_0 \cos \omega t$ which penetrates to a depth y as a damped progressive wave of the form $T = T_0 e^{-ky} \cos(\omega t - ky)$ (where k is given by $(\omega/2\kappa)^{1/2}$, κ is the thermal diffusivity, $\omega = 2\pi/52$ weeks, and t is time in weeks). They have found that this thermal wave results in vertical expansion on flat surfaces as well as additional tilt components on rolling or sloping terrain in response to the surface temperature variation.

The calculations of the tilts and strains induced by the thermal wave are highly dependent upon the nature of the topography. However, the results of Harrison and Herbst for substantially more gentle terrain than that found at the monitor site indicate that horizontal strain components of greater than 5×10^{-6} could exist at the depths from which we monitor radon.

The drop in radon levels observed during the summer months could result either from additional compression closing cracks and pores or from expansion causing temporary undersaturation of the pore volume. In the former case the reduction in emanating surface results in fewer radon atoms traversing the saturated pores, while in the latter case, undersaturated pore spaces result in more radon recoils completely traversing the pores rather than stopping in the pore fluid. Because of the complicated terrain in the vicinity of the borehole, additional information is needed in order to decide between these possibilities. In particular, a continuous record of the water level in the borehole would be helpful. The instrumentation to accomplish this is being added to the borehole at present. The crude information that is available about the water level has been obtained by direct measurements when the instrument vault has been opened for service. This indicates that the water level has always been quite high — never less than 5.5 m below the surface. This suggests that the rock in the vicinity of the borehole is fully saturated and that the decrease in radon levels during the summer months largely results from compression at the bottom of the canyon caused by thermoelastic compressive strains on the rock on the sides of the canyon. Until more definitive information becomes available, these ideas remain hypotheses.

Precursors. The data shown in Figures 3 and 4 provide encouraging evidence that at least some earthquakes are preceded by recognizable radon precursors. However, many crucial questions remain to be answered. Among these are the following: (1) What are the mechanism(s) responsible for the anomalies? (2) What relationships exist between the magnitude and duration of radon anomalies and the magnitude and location of the event? (3) Is there a threshold for magnitude and/or distance before an anomaly is evident? (4) What nonseismic effects produce similar radon anomalies?

Since the distance between the monitor and the closest earthquake for which a precursor was noted was about 14 km, it is unlikely that any direct transport of radon from the source region to the monitor locale is responsible for the observed anomalies. It would seem that a more indirect mechanism related to stress changes extending into or near the monitor location is needed. This could be either a change in the stress field in the immediate vicinity of the monitor that causes a marked change in pore volume and/or saturation or a change in the stress field that extends sufficiently close to the monitor region so that the flow of subsurface fluids and gases changes markedly enough to alter radon concentrations in the borehole.

Rikitake [1976] has proposed the following empirical relationship between the duration of a wide variety of precursory phenomena and the magnitude of the event that follows: $\log_{10} T = 0.76M - 1.83$. For magnitude 3 events, precursors of a few days' duration would be expected. Our results are generally consistent with Rikitake's formula, especially considering the spread in the data used by Rikitake. The repeated burstlike nature of the record before the Malibu earthquake makes it somewhat difficult to assign a duration to that particular anomaly. However, if one takes November 17, 1978, as its beginning, then the duration of 40-45 days would be quite consistent with a magnitude 4.6 event.

The data accumulated to date are inconclusive regarding any possible relationships between the magnitude of the anomaly and the magnitude of the event. Most of the anomalies noted so far have been deviations from the long-term data trend line of about 40%, which is well outside the noise in the data during a large part of the year at this site. However, there have been no moderate- or high-magnitude events close enough to determine if larger excursions can be expected for larger events.

Since at least four of the events with magnitudes between 2.0 and 3.3 listed in Table 1 produced no anomalous signals, it would appear that there is a magnitude-distance threshold, although no quantitative relationship is evident. This threshold may, in any event, be structure dependent. For this particular site, sensitivity appears to be lower in directions prependicular to the fault system than in directions parallel to the fault system, but since the statistics are still very limited, this conclusion is tentative.

It does appear that very heavy rainfall such as that which occurred during the winter of 1977-1978 can produce sudden rises in the radon level which could be mistaken for an earthquake precursor. More normal precipitation levels have been experienced at the sampling site during the 1978-1979 winter, but the occurrence of the Malibu earthquake makes the interpretation of the data difficult. Additional base line data must be accumulated to firmly establish the extent to which normal rainfalls produce fluctuations in the radon record.

It also is possible that large changes in barometric pressure could affect the radon signal. Since the time scale for changes in barometric pressure is a few days, any response of the radon signal to these changes might be mistaken for a precursor to a small earthquake ($M \leq 3.0$). At the monitor location, short-term variations in atmospheric pressure typically have been small — usually less than 1%, and no clear correlation was found to exist between the radon signal and barometric pressure at this level. The largest pressure changes recorded during the 23-month period of operation of the prototype monitor have been of the order of 3%. Even at this level there appears to be no well-defined response of the radon signal, although in one case an increase in barometric pressure of this magnitude that took place between December 5 and 12, 1978, may have been associated with a small decrease in the radon level. In general, it appears that the procedure that has been adopted for casing the borehole through the overburden substantially decouples the radon signal from changes in barometric pressure.

Summary and Conclusions

More than 20 months of near-real-time monitoring at a hard-rock borehole site in the Transverse Ranges has provided encouraging evidence that some earthquakes are preceded by discernible radon anomalies. Much additional work with a network of monitors is needed to firmly establish the sensitivity and reliability of such a monitoring system for earthquake prediction and to establish quantitatively the extent of interfering nonseismic phenomena.

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