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RADON IN GROUNDWATER OF THE LONG VALLEY CALDERA, CALIFORNIA

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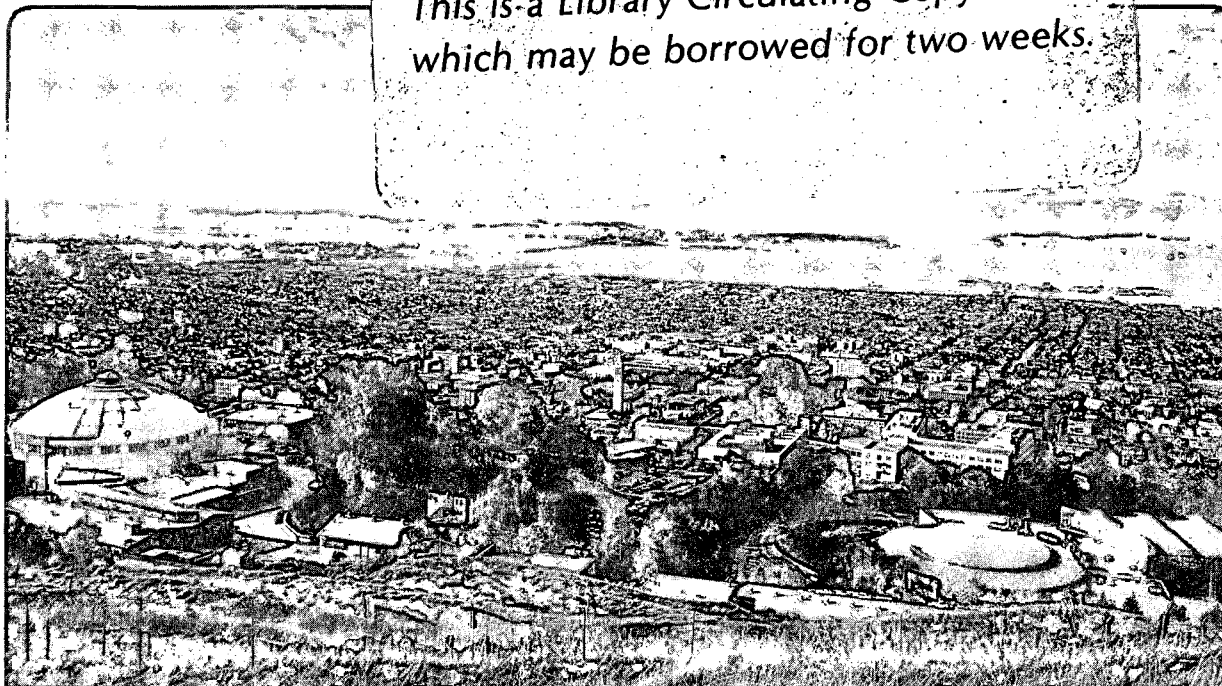
### **RADON IN GROUNDWATER OF THE LONG VALLEY CALDERA, CALIFORNIA**

S. Flexser, H.A. Wollenberg, and A.R. Smith

April 1987

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## RADON IN GROUNDWATER OF THE LONG VALLEY CALDERA, CALIFORNIA

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### Abstract

In the Long Valley caldera, an area of recently (~550 y) active volcanism and current seismic activity,  $^{222}\text{Rn}$  concentrations in hot, warm, and cold spring waters have been measured since 1982. Rn contents of the waters correlate inversely with temperature and specific conductance, with high concentrations (1500 to 2500 pCi/l) occurring in dilute cold springs on the margins of the caldera, and low concentrations (12 to 25 pCi/l) in hot to boiling springs. Rn correlates only slightly with the uranium contents of the wide range of rock types which host the hydrological system feeding the springs.

Anomalous changes in groundwater Rn contents may accompany or precede earthquake or volcanic activity, and a continuous Rn monitoring system was installed in 1983 to monitor short-term variations. A gamma detector is submerged in a natural pond fed by ~11°C spring waters with ~700 pCi/l Rn, and measured gamma activity is due almost entirely to  $^{222}\text{Rn}$  in the water. The gamma record, which is integrated hourly, shows a consistent, pronounced diurnal variation (~30% of mean count rate), and weaker higher frequency variations. This pattern correlates well with small variations (<1°C) in water temperature at the Rn monitoring point, and is strongly influenced by precipitation and by patterns of water flow in the pond. It does not adhere to a tidal pattern.

These environmental effects on the radon record may mask responses to small or distant seismic, volcanic, or crustal deformation events. To date, anomalous changes in water-borne Rn have been observed in connection with at least one earthquake, which occurred close to the monitoring site. This continuing study points out that an understanding of the geological setting, its associated hydrological system, and environmental influences is necessary to properly evaluate concentrations and changes in groundwater radioactivity.

## INTRODUCTION

The Long Valley caldera is an area of active volcanism and ongoing seismic activity. Because of the potential seismic and volcanic hazards--as well as interest in geothermal exploration and production, and intrinsic scientific importance--various geophysical and geochemical parameters have been and continue to be monitored at sites within and adjacent to the caldera. Among these parameters are hydrogen, helium, and radon in soil gas, and chemical constituents of groundwaters. Long Valley is therefore an excellent site for close comparison between variations in groundwater radon and other geochemical and geophysical variations.

Accordingly, since 1982 we have been analyzing radon contents of water from hot, warm, and cold springs. Rocks encompassing the hydrologic systems feeding the springs have been analyzed for their radioelement contents, in an effort to better understand the source term of the  $^{222}\text{Rn}$  in the water. For observation of short-term variations, a continuous monitoring system for measuring water-borne radon at a spring has been in place since 1983. Early results and interpretations of these studies were described by Wollenberg et al. [1]. This report incorporates more recent data, with particular emphasis upon the continuous monitoring system.

## HYDROGEOLOGIC SETTING

The hydrologic system of Long Valley has most recently been described by Sorey et al. [2]. The Long Valley caldera, whose location is shown in Fig. 1, is situated on the eastern front of the Sierra Nevada in eastern California. Volcanism in the Long Valley area has continued intermittently over approximately 3 million years, the most recent activity occurring 500 to 600 years ago. The major event that formed the caldera occurred about 0.7 million years ago, when a very large volume of predominantly rhyolitic material (the Bishop Tuff) erupted, followed by collapse of the roof of the magma chamber. The present configuration of the

caldera is that of a steep-sided bowl demarcated by ring fractures. It is filled predominantly by the Bishop Tuff, but also includes more recent volcanics and fluvial, lake-bed, and glacial deposits. The western part of the caldera is occupied by a resurgent rhyolitic dome which is bounded on the north, south, and west by a moat partly filled with rhyolitic and basaltic volcanic rocks.

Sorey et al. [2] point out that two principal groundwater subsystems, one shallow and at near-ambient temperature and one relatively deep and considerably hotter, make up the hydrologic system of Long Valley. Water in both of these subsystems is derived from meteoric sources, primarily runoff from the Sierra Nevada. The post-caldera volcanic rocks and sediments are relatively permeable, and a stratification of hot and cold aquifers in these rocks is evident from geothermal well logs. By contrast, the underlying Bishop Tuff, predominantly densely welded, is relatively impermeable, and fluid movement in that unit probably is confined to fault zones and fractures.

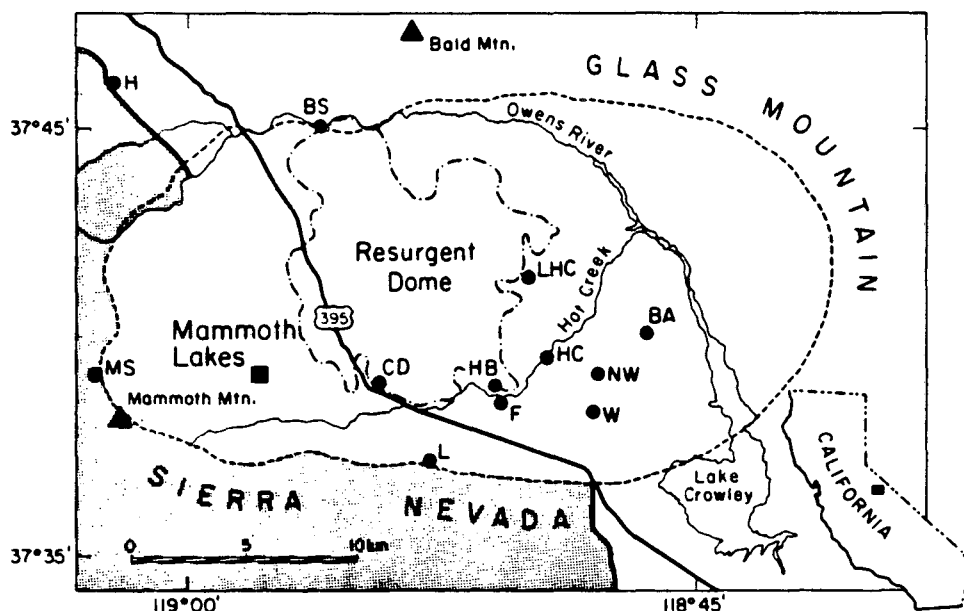


Figure 1. Outline map of the Long Valley caldera (after Sorey et al. [2]), showing locations of the springs sampled. Dashed line: border of caldera; dot-dashed line: outline of resurgent dome. Letter symbols keyed to Table 2.

Chemical geothermometry by Mariner and Willey [3] indicates that water at depth in the geothermal systems at Casa Diablo Hot Springs and Hot Creek gorge attains temperatures well in excess of 200°C. A generalized concept of the hydrothermal system then envisions cold-water recharge from the Sierra Nevada on the west and south sides of the caldera, water moving eastward through caldera fill and becoming heated and at the same time mixing with locally recharged groundwater. The warm and hot water then occasionally 'daylights' at springs whose locations are controlled mainly by faults and fronts of volcanic flows.

#### **RADIOELEMENT CONTENTS OF ROCKS IN THE LONG VALLEY AREA**

The uranium and thorium contents of rocks through which groundwater percolates control the initial abundances of their daughter products in the groundwater. With regard to this we measured radioelement contents of rocks in the Long Valley region by field and laboratory gamma spectrometry. Results of these analyses are listed in Table 1. Low concentrations of uranium and thorium are evident in basalt of the north and south moats and in carbonate rocks that border the caldera in the Sierra Nevada to the south. Metamorphosed volcanic and clastic (sedimentary) rocks bordering the caldera have intermediate radioelement abundances, while the bordering Sierran granitic rocks and rhyolites within the caldera are of relatively high radioactivity. The influence of the rocks' radioelement concentrations on the radon content of the groundwater is discussed in a following section.

The radioelement content of spring deposit material in Long Valley has not yet been fully investigated. Samples have been collected and analyzed from three spring areas: Hot Creek, Casa Diablo, and north of Whitmore. These are predominantly siliceous sinter deposits with low radioelement contents, in keeping with observations of spring deposits in northern Nevada (Wollenberg [6]), where siliceous sinter is of low radioactivity. Further investigation is



required to determine whether some of the Long Valley deposits are of calcium carbonate, shown in the Nevada studies to contain appreciable radium, a near-surface source of springwater radon.

**Table 1. Radioelement Concentrations of Long Valley Rocks**

	U(ppm)	Th(ppm)	K(%)
<b>Caldera fill</b>			
<b>Bishop Tuff<sup>a</sup></b>			
'Early'	6.5	22	4.0
'Late'	2.6	12	4.6
<b>Rhyolite</b>			
Tuffs	4.9	11.2	1.6
Flows and domes	5.6	15.7	4.1
Obsidian, Inyo domes	6.5	20.4	3.8
Rhyolite of moat	5.0	18.8	3.0
Mean:	5.2(±1.4)	16.6(±4.5)	3.5(±1.2)
<b>Basalt</b>			
South moat	0.8	2.0	0.8
North moat	1.3	4.2	1.3
Mean:	1.0	3.1	1.1
<b>Precaldera rocks</b>			
<b>Granodiorite</b>			
Northwest border	6.6	26.1	3.6
South border	4.6	16.3	3.2
Mean:	5.6	21.2	3.4
<b>Paleozoic metamorphics<sup>b</sup></b>			
Carbonates	1.2	1.7	0.3
Clastics	4.4	7.3	1.8
Mean:	2.8	4.9	1.1
<b>Mesozoic metavolcanics</b>			
	2.9	8.9	2.4

<sup>a</sup>Data from Hildreth [4].

<sup>b</sup>Data for Paleozoic carbonate and clastic rocks from Wollenberg and Smith [5].

## DISCRETE RADON MEASUREMENTS OF WATERS

Water samples were collected from several springs in the Long Valley region to provide a baseline of radon and water-chemistry data, for comparison with future resamplings, and to choose sites for long-term continuous monitoring of radon concentrations.

The location of the water sources sampled is shown in Fig. 1. The sources include many of those sampled and analyzed over the past decade by members of the U.S. Geological Survey (Mariner and Willey [3]). Sampling was done at orifices where boiling occurs as well as at those of intermediate and cold temperature. Temperature, pH, specific conductance, and radioactivity were measured at the time of sampling. Samples for laboratory gamma-counting for  $^{222}\text{Rn}$  were obtained by filling two 500 ml thick-walled Nalgene bottles, which were then capped and taped tightly. Samples were also collected for analyses of major and trace elements by the filtering of water into two polyethylene bottles at each site, one acidified to preserve the dissolved silica contents in solution. Unfiltered samples were also taken in small glass bottles for oxygen and hydrogen isotope analyses (only the radon data are reported and discussed here).

At the laboratory the total gamma radioactivity of the two 500 ml samples was measured with a NaI(Tl) detector in a low-background counting facility; the total gamma radioactivity of the water was observed to be due entirely to the presence of radon and its daughter products in the water. Following a procedure described by Smith et al. [7], the initial counting rates were corrected for the 3.8-day half-life decay of  $^{222}\text{Rn}$  and for a slight leakage of radon through the walls of the bottles. The corrected counting rates were then converted to radon concentrations (in picocuries per liter) with the calibration constant of  $1 \text{ count/min} = 0.84 \text{ pCi l}^{-1}$ .

Field-measurement data and results of laboratory gamma spectrometric measurements of the waters'  $^{222}\text{Rn}$  concentrations are listed in Table 2. An examination of the table indicates a wide range of radon concentrations, generally corresponding inversely to the temperature and specific conductances measured at the springs. These are illustrated in Fig. 2. The highest radon concentrations are in cold springs on the western and southern margins of Long Valley (Hartley, Laurel, and Minaret Summit), while the waters sampled at several of the hottest springs (Casa Diablo, Hot Creek, and Hot Bubbling Pool) are very low in radon content. Springs of intermediate temperature in Long Valley proper--Big Alkali Lake, Whitmore, and north of Whitmore--have easily measured radon concentrations, as do the cool springs at the Fish Hatchery and Big Spring.

The rough inverse correlation between radon concentration and surface temperature of the springwater is attributed to the diminished solubility of radon with increasing temperature (Wilhelm et al. [9]). A similar inverse correlation between radon and specific conductance can be attributed to the strong correlation between the temperature and the specific conductance of water. There is a poorer correlation between  $^{222}\text{Rn}$  concentrations and expected temperatures of unmixed thermal water, calculated by Fournier et al. [8] with chemical geothermometers. The very low contents of  $^{222}\text{Rn}$  observed in the water of the hottest springs, Casa Diablo and Hot Creek, and of Hot Bubbling Pool, are attributed to flushing of radon from near-surface water due to boiling or bubbling of exsolving gas.

Table 2. Radon Concentrations and Other Parameters of Springwater

Name	Rock type <sup>a</sup>	(pCi l <sup>-1</sup> )	No. of analyses	Spec. conductance (μmho-cm <sup>2</sup> )	pH	Temp. (°C)	Na-K-Ca geothermometer <sup>b</sup> (°C)	
BA	Big Alkali Lake	al	225	1	1700-1750	6.4	59	200
BS	Big Spring	b	601 ± 67 <sup>c</sup>	4	175-180	6.6	10	83
CD	Casa Diablo	r	23	1	1400-1425	7.7	94	238
F	Fish Hatchery	b						
	'CD' pool		789±170 <sup>c</sup>	4	210-220	6.7	14	50
	'H-2 & 3' pool		667±39 <sup>c</sup>	9	130-160	6.7	11	
H	Hartley Spring	g	2490	1	40-60	6.6	2	
HB	Hot Bubbling Pool	r	43	1	1800-1850	7.6	63	189
HC	Hot Creek Gorge	r	16	2	1700-1750	8.2	90	192
L	Laurel Spring	g	2467±214 <sup>c</sup>	45	90-110	8.6	11	11
LHC	Little Hot Creek	r,l	319	2	4700	7.4	80	172
MS	Minaret Summit	m	1430	1	210-220	6.7	3	
NW	North of Whitmore	r,l	200	1	1400-1450	7.5	53	
W	Whitmore	r,al	395	1	625-650	7.1	31	

<sup>a</sup>Rock types encompassing spring systems: al = alluvium, b = basalt, g = granitic rock, l = lake-bed deposits, m = metavolcanic rocks, r = rhyolite.

<sup>b</sup>From Fournier et al. [8].

<sup>c</sup>Values are means ± standard deviation.

As shown in Fig. 2, there is only a slight apparent correlation between <sup>222</sup>Rn concentrations in water and uranium in the rocks from which the springs flow. The highest concentrations are associated with the dilute cold springs at Hartley, Laurel, and Minaret in the granitic and metamorphic rocks, while the concentrations of the cool springs flowing from the basalt of relatively low radioactivity at the Fish Hatchery and Big Spring are significantly lower. The concentrations of the basalt springs, however, are higher than those of intermediate-temperature and hot springs, whose systems primarily flow through the more radioactive rhyolites, lake deposits, and alluvium. Thus, at Long Valley the <sup>222</sup>Rn concentrations of springs are most strongly determined by the temperature of the shallow portions of the hydrothermal system

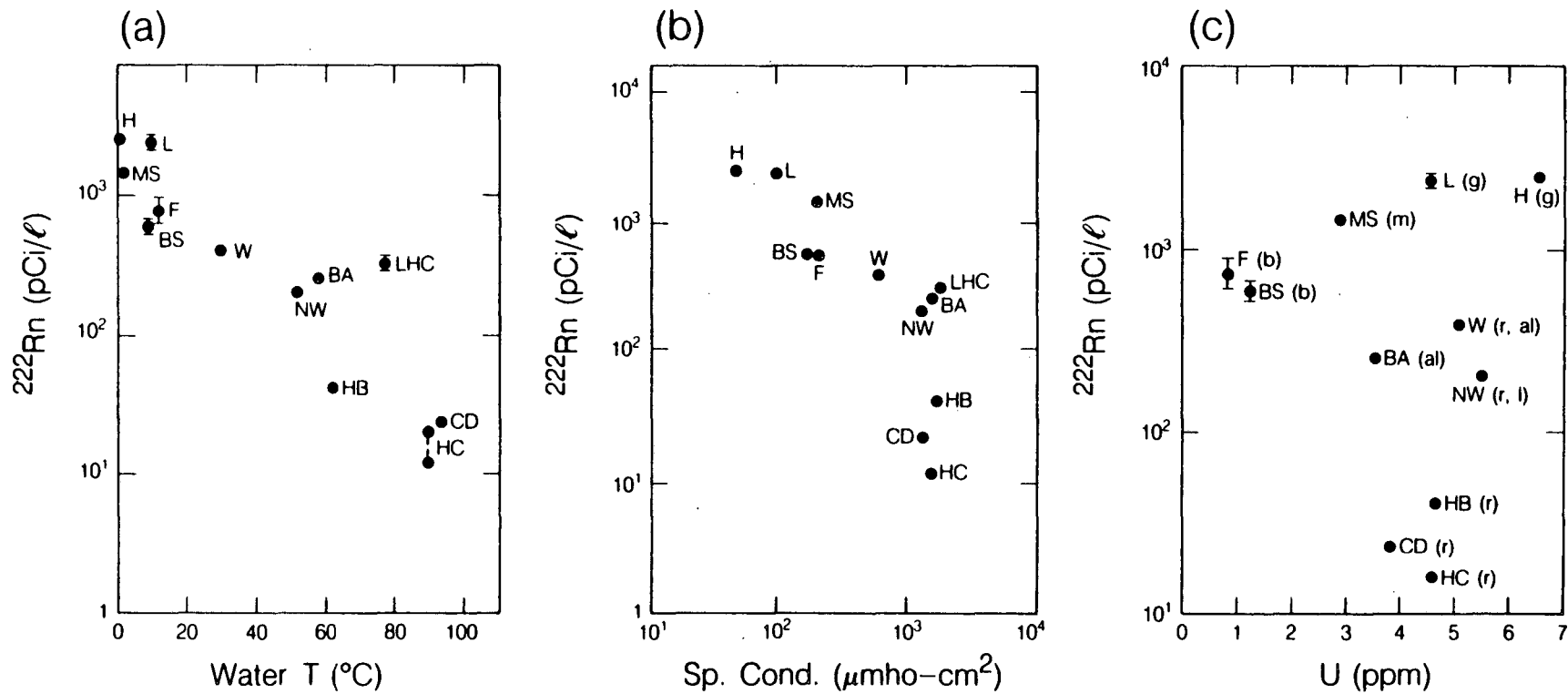


Figure 2. Variation of radon with temperature (A) and specific conductance (B) of springwaters, and with uranium concentrations of rocks that encompass the spring systems (C). Letter symbols keyed to Table 2.

and, where present, by boiling or bubbling of gases from solution. They are determined to a much lesser degree by the radioelement contents of the rock through which the water is percolating.

Repeated sampling has been conducted at one of the most radioactive springs, Laurel, flowing from granite on the south border of the caldera. A time record of the  $^{222}\text{Rn}$  concentration of this spring is shown in Fig. 3. Sharp variations over relatively short periods are evident at several points. These exceed the range of standard deviation (10%) but cannot be ascribed to significant seismic or crustal deformation events, partly because of the wide and variable spacing between sampling. Samples were also collected at other springs in the caldera, though less frequently than at Laurel Spring.

## CONTINUOUS MONITORING

### Instrumentation and Setting

In order to observe short-to-intermediate-term groundwater radon fluctuations, a continuously monitoring gamma detection system was installed in August, 1983, at Fish Hatchery spring "H-2,3" (table 2). This site was chosen on the basis of discrete sampling of the springwaters, the availability of a source of power and shelter for instrumentation, and because a pond is situated at the outflow of the spring. The monitoring system is similar to that described by Smith et al. [7, 10]. A Na(Tl) gamma detector is submerged in a pool so that it is surrounded on all sides by at least 1 m of water. The data are acquired by a gain-stabilized gamma spectrometer, whose output is organized into several broad gamma-energy windows. The integrals in these windows are recorded hourly as the radon data. The one-hour integration time is appropriate to the several-hour residence time for water in the pond, and to the 35-40 min half-life for ingrowth of the gamma-emitting daughters of  $^{222}\text{Rn}$ . The gamma-ray spectrum from this location, shown in fig. 4, demonstrates that variations in radioactivity

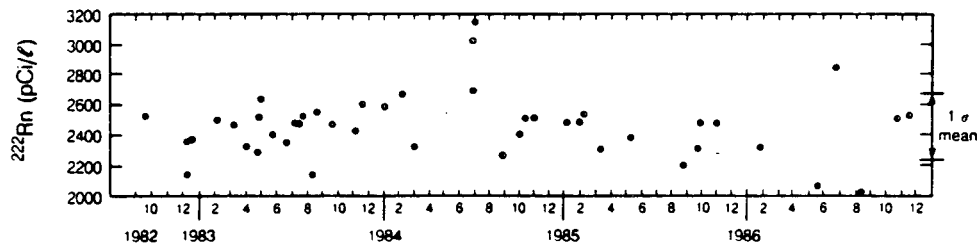


Figure 3. Variation with time of radon concentration in water of Laurel Spring.

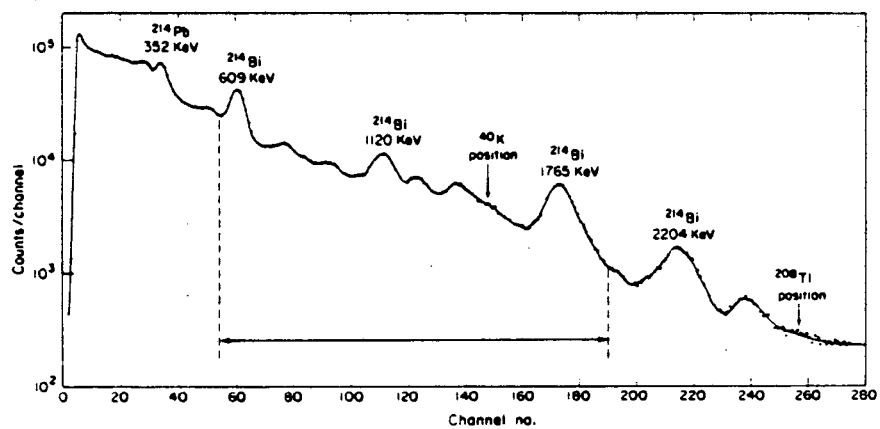


Figure 4. Gamma-ray spectrum measured by a NaI(Tl) detector suspended in water of the Fish Hatchery spring. Arrows: interval measured for radon content.

measured in this manner are due almost entirely to variations in the radon content of the water. As shown in the figure, the recorded interval in the gamma-ray spectrum contains contributions primarily from the  $^{214}\text{Bi}$  daughter of  $^{222}\text{Rn}$ . The absence of appreciable peaks from  $^{40}\text{K}$  and  $^{208}\text{Tl}$  in this spectrum attests to the effectiveness of the water surrounding the detector in shielding it from radioactivity of the rock, soil, and concrete dam that line the pond.

The spring system that feeds the Fish Hatchery springs has been described by Sorey [11] and by Farrar et al. [12]. The recharge for the system is in the southwestern part of the caldera, and the water flows eastward, with a small component of northward flow, primarily through fractured basalt. Some of the water may also flow through the Quaternary glacial debris that underlies the basalt. From the chemistry of the springwater Sorey [11] estimated that a small amount (1% to 3%) of geothermal water mixes with the eastward-flowing water. An estimate of the effective range of radon carried by the springwater may be obtained by means of the model of Stoker and Kruger [13]. Using measured emanation values for the basalt, rock porosities between 5% and 15%, and considering radial and linear flow models, radon is being contributed to the springs from a maximum of between 0.3 and 1.0 km.

The pond in which the gamma-detector is located is shown in fig. 5A. It is fed by a line of springs along the southern margin of the pond, at the base of a basalt flow. The temperature of the spring averages about  $11^{\circ}\text{C}$ , and although constant over the short term it shows a yearly cyclic variation of about  $0.5^{\circ}\text{C}$ . The average flow rate is about 140 l/sec, also varying seasonally, from high flows in early summer to low flows in late fall and winter. Outflow from the pond is through a small concrete dam to Hatchery fish ponds below, and residence time of water in the pond is on the order of 2-3 hours. In order to discourage the growth of algae and interference with flow to the fish ponds, Hatchery personnel stretched a tarp over the surface of the pond in March, 1984. The gamma detector was removed before the tarp was emplaced, then re-inserted through a hole to its original position about 6 ft out from the dam, 10 ft to the side of the outflow, and about 6 ft deep. The position of the detector beneath the tarp is



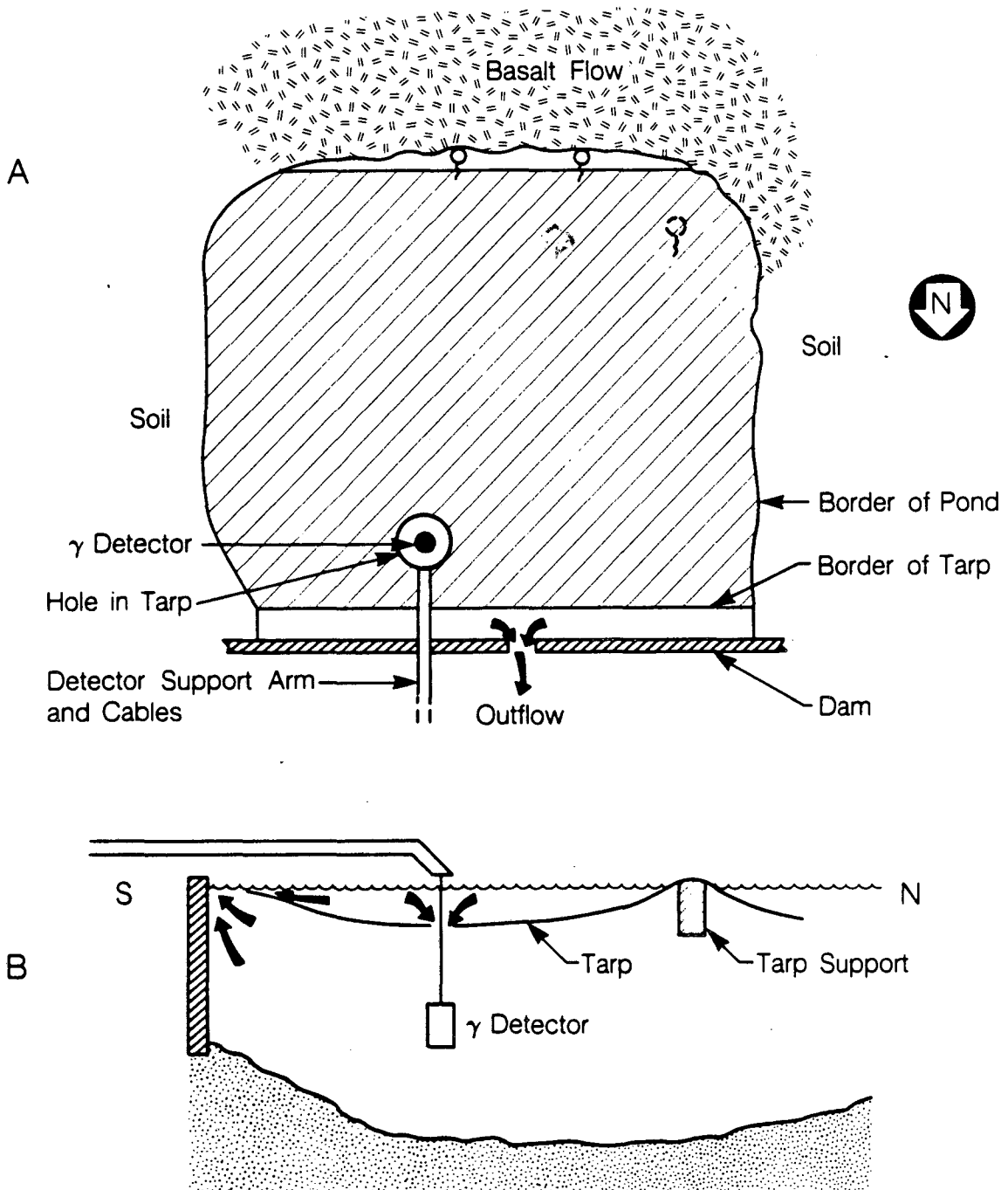


Figure 5. (A): Plan view of the main features of the Fish Hatchery pond, including springs along southern margin, tarp covering surface, and position of gamma detector. Not to scale. (B): North-south cross-section through detector showing gaps in tarp at dam and above detector. Heavy arrows: flow of water toward outflow (out of plane of section), and of cold water below tarp. Not to scale.

shown in fig. 5B.

### Character of the Radon Record

Although the original intent in installing the continuous system was to monitor changes in groundwater radon concentration associated with seismic or volcanic activity, it soon became apparent that environmental factors were strongly affecting radon concentration and could mask such effects. In order to gain a better understanding of the environmental effects on radon concentration, we have examined continuous records of water temperature and specific conductance measured just above the gamma detector, and discharge measured somewhat downstream from the pond. These have been monitored since February, 1985, using a power source independent of that of the radon system, by Chris Farrar of the U.S. Geological Survey. In addition, records of precipitation, maximum and minimum air temperatures, and barometric pressure were provided by the U.S. Forest Service and Mammoth Lakes Airport for several locations within the caldera.

Comparison of these data with radon concentration shows pronounced correlations between radon, water temperature, and precipitation. Specific conductance shows a lesser, but distinct correlation with radon, but this may be due largely to the dependence of conductance upon temperature. Changes in barometric pressure often correlate with disruptions in the radon pattern, but barometric effects usually cannot be separated from those of associated precipitation. Continuous barometric records have not been available, so that effects from short-term changes would probably not be detected.

Shown in fig. 6 are portions of the radon record along with precipitation and water temperature. The radon cycle typically shows a daily variation of 25% to 35% about a mean of about  $6 \times 10^4$  counts/hr, with a nighttime peak. It varies seasonally, with a higher amplitude, strongly diurnal pattern typical of cold weather (fig. 6A, F), and a lower amplitude, more

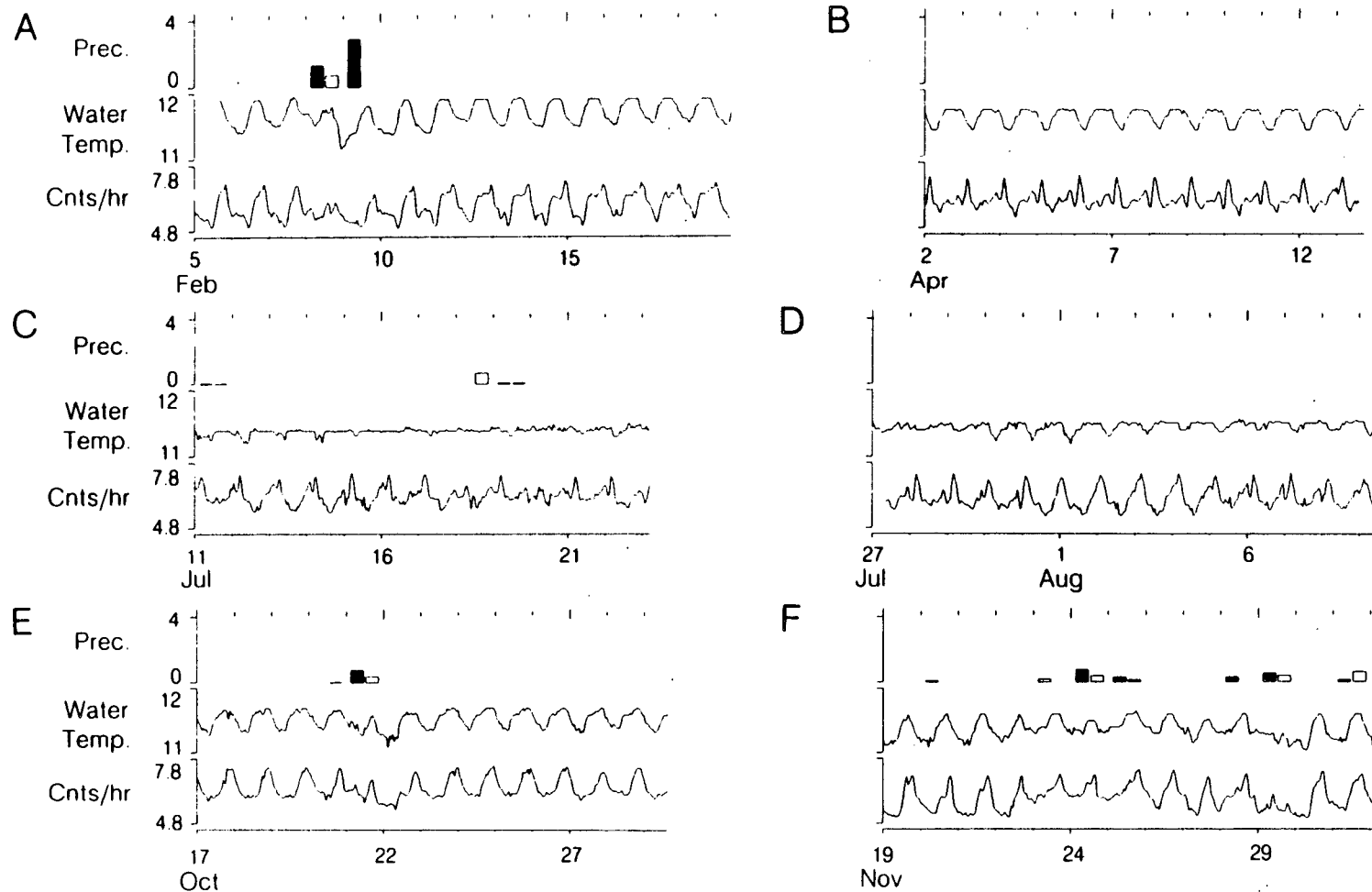


Figure 6. Segments of 1985 radon record at the Fish Hatchery spring, along with corresponding records of water temperature at the gamma detector, and daily precipitation totals. Radon expressed in  $(\text{gamma counts/hr}) \times 10^4$ , temperature in  $^{\circ}\text{C}$ , precipitation in inches. Solid bar: precipitation at Mammoth Lakes, elev. 7800 ft; open bar: precipitation at Little Hot Creek, elev. 6960 ft (see fig. 1 for locations). Elevation of Hatchery is 7200 ft.

irregular pattern, with later peak positions, seen in warmer weather (fig. 6C, D). The record of water temperature at the detector usually has a well-defined daily cycle similar to radon, with a daily variation of  $0.5^{\circ}\text{C}$  or less. (Differences between mean temperatures in the different segments of the record shown in fig. 6 are due mainly to instrument drift, which is corrected periodically. This drift appears to be steady and not to exceed  $\sim 1^{\circ}\text{C}/\text{month}$ .) The temperature pattern has broader peaks than radon, often truncated at the top; but it has the same tendency for peaks to decrease in amplitude and to shift toward later hours in warm weather. Both radon and water temperature show a clear response to precipitation. Larger amounts of precipitation may suppress the daily radon and water temperature peaks, and most precipitation events appear as perturbations in the radon and temperature patterns that often parallel one another closely (e.g., fig. 6A, E, F).

Frequency distributions obtained by Fast Fourier transforms are shown in fig. 7 for four of the six segments of the radon and water temperature records in fig. 6. For the radon record (fig. 7A), the strong 24-hour component typical of cold weather is seen in the February and October plots, and the increased amplitude of the 12-hour and shorter period components often observed in warmer weather is seen in the April plot. The water temperature record generally has a similar frequency distribution to that of radon, with a somewhat stronger 24-hour component. But during periods in summer when minimum air temperatures remain near or above the temperature of incoming springwater ( $\sim 11^{\circ}\text{C}$ ), the water temperature record can be nearly constant (fig. 6C, D), with periodic components sharply attenuated (fig. 7, July). Both water temperature and radon also show little or no response to precipitation during these periods. (It should be noted that some distortion may be introduced in the frequency distributions by the presence of angular features or other shape characteristics in these time series. The Fourier transform program attempts to fit these features, such as truncated peaks in the temperature pattern, with higher frequency harmonics of the 24-hour peak.)

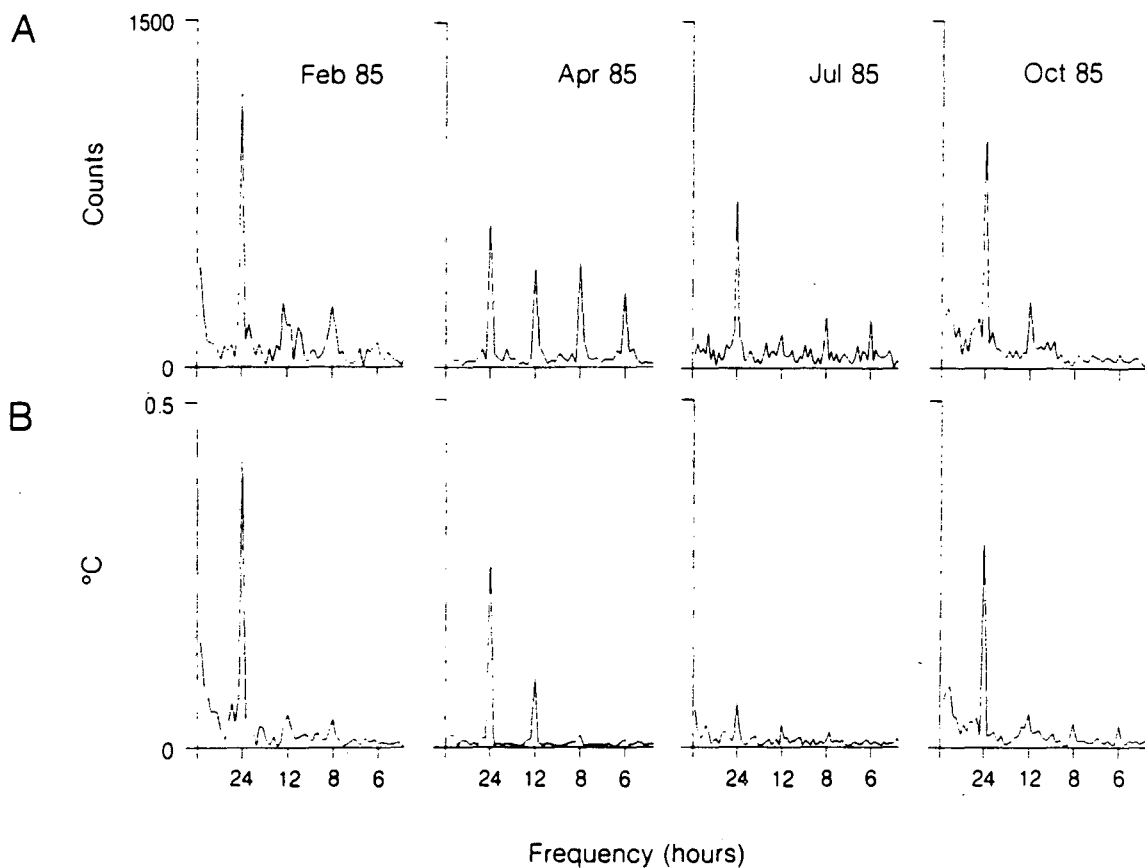


Figure 7. Frequency distributions of radon (A) and water temperature (B) records covering time periods shown in fig. 6A, B, C, E.

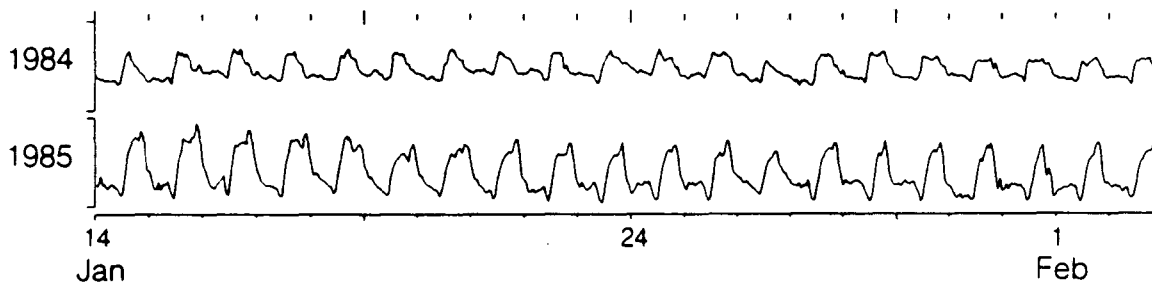


Figure 8. Portions of winter 1984 and 1985 radon records, showing effect of pond cover on amplitude of 1985 pattern. Limits on radon axes are as in Fig. 6.

### Factors Influencing Radon Concentration

The nature of the close association of radon concentration and water temperature suggests that dilution by cold radon-depleted surface water is a major influence on radon concentration measured at the detector. The main route of descent for surface water is probably through the hole in the tarp above the gamma detector, although some water probably also descends along the border of the tarp on the northern margin of the pond (fig. 5). The hole above the detector (which we plan to plug in the near future) is near the bottom of a sagging section of tarp, and although in effect an annulus only 2 to 3 inches wide, it may serve as a funnel for cold surface water or precipitation to descend from a much larger area (fig. 5B). This is suggested by the magnitude of the precipitation effect on radon and water temperature, which is much larger, given the flow rate of the spring, than the average dilution of pond water by precipitation. It is also consistent with the lower amplitude and more irregular radon pattern observed before the cover was put on the pond in 1984. This can be seen in fig. 8, which compares portions of the 1985 and the pre-cover 1984 radon patterns. The amplitude of the 1984 pattern is roughly half that of the 1985 pattern, but it is similar in phase and frequency distribution. These similarities suggest that descending surface water was probably also an influence on radon concentration prior to covering of the pond, but was less pronounced than in the present configuration.

As previously noted, the correlation between radon and water temperature observed during most of the year is much reduced during warm periods in summer. Although water temperature may be nearly constant at these times, the cyclic character of the radon record persists, only somewhat reduced in amplitude and regularity (fig. 6C, D). This indicates that factors other than descending surface water are affecting radon concentration in the pond. These factors could be related to the configuration of the pond--such as water circulation patterns, or oscillation in the level of a cool, radon-depleted, relatively stable bottom layer of water--or to other environmental effects such as day/night barometric changes. Alternatively, the observed

radon pattern could be related to factors operating on groundwater feeding the springs, such as earth tidal variations.

Earth tides represent a plausible mechanism for affecting radon concentration at the Fish Hatchery because of their strong diurnal and semi-diurnal periodicities. An earth tidal mechanism was originally proposed to explain the observed radon variation, based on early results of the continuous monitoring system (Wollenberg et al. [1]). In fig. 9, three segments of the radon record are shown along with corresponding plots of theoretical earth tides. (The theoretical tides have been checked against recording gravimeter measurements at several different times, and they follow the measured gravity variations closely, with a phase difference of 1.5 hours.) Although the earth tide and radon records appear similar over selected intervals (e.g., portions of fig. 9C), in general there are difficulties in correlating earth tide and radon. The radon pattern is typically unaffected by short-term amplitude changes in the tidal record (e.g., fig. 9C), as well as by short-term changes in tidal periodicity (compare the first and second halves of fig. 9A, and Oct 24-26 with Nov 2-4 in 9B). (These discrepancies cannot be attributed to precipitation which, with the exception of Oct 20-21, was absent or minor during the time periods shown in fig. 9.) Moreover, the frequency distribution of the tidal pattern usually differs significantly from that of radon. Fig. 10 shows typical frequency distributions of the tidal record. Intervals of two weeks or longer show 24-hour and 12-hour components that are roughly equal in amplitude (long intervals show splitting of these peaks and slight offsets from 12 and 24 hours, as in fig. 10C), while either of the components may be dominant over shorter periods. This contrasts with the dominance of the 24-hour component usually observed in the radon pattern (compare fig. 10A, B with fig. 7A, Oct).

Another measure of the correspondence between radon and earth tide may be obtained by cross-correlation of their time series. Fig. 11 shows results of cross-correlations between radon and earth tide and between radon and water temperature for four time periods which include records shown in figs. 6 and 9. (These time periods were chosen to avoid

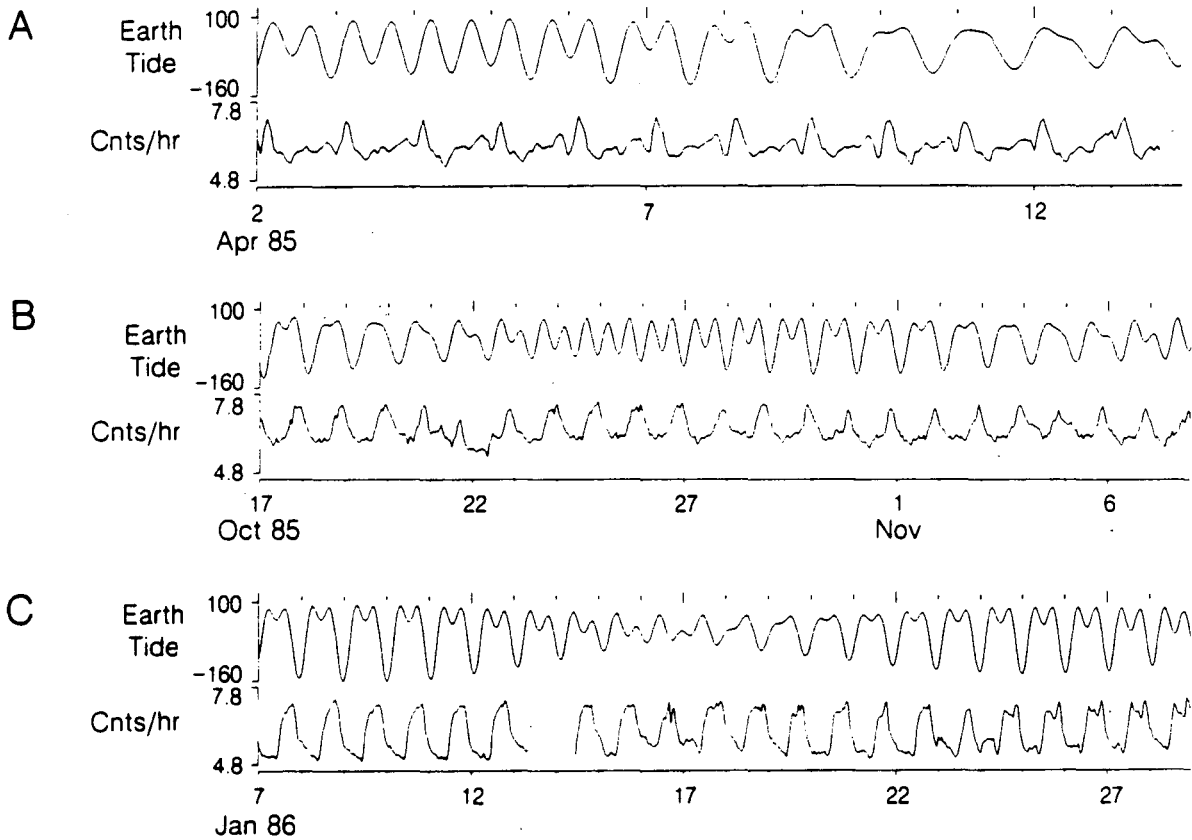


Figure 9. Segments of 1985 and 1986 radon records, with plots of theoretical earth tides for same time periods. (A) and (B) correspond to fig. 6B and E, respectively. Earth tide expressed in  $\mu\text{gal}$ , radon as in Fig. 6.

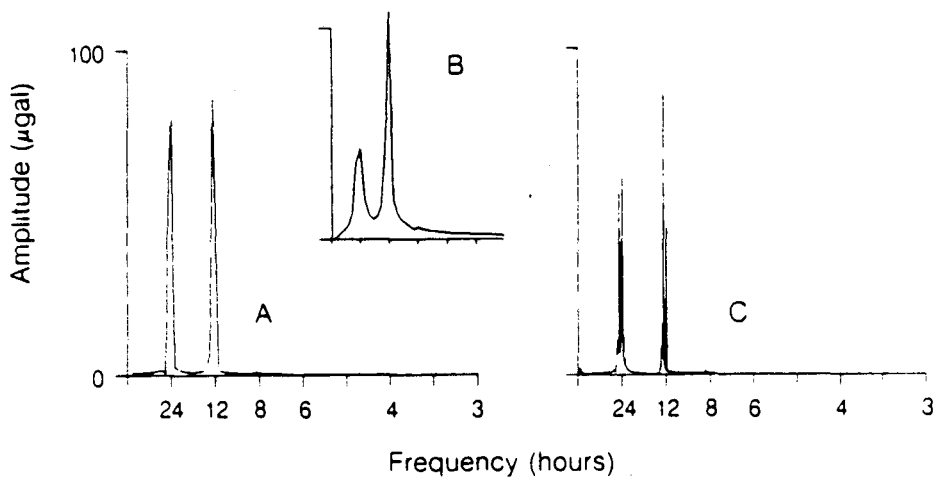


Figure 10. Typical frequency distributions of earth tide patterns. (A) and (B) correspond to portions of the tidal pattern shown in Fig. 9B: (A) Oct 23-Nov 7; (B) Oct 23-29. (C) corresponds to tidal pattern for first half of 1985. (Narrow peaks in (C) are due to longer time period.)



precipitation-caused perturbations of the radon or water temperature patterns.) Cross-correlations have been evaluated for relative shifts between time series of 0 to 24 hours, and the correlation coefficients corresponding to the best fits are noted in the figure. (For example, the 4-hour shift that gives the best fit, .69, between radon and water temperature in (A) represents a 4-hour lag of radon behind temperature.) The correlation of earth tide and radon is substantially poorer than that of water temperature and radon in three of the four plots in fig. 11, and the difference in the fourth case (B) is due more to the irregular and low-amplitude temperature record (fig. 6C, D) than to a strong correlation between tide and radon. Earth tide-radon correlation coefficients are low for all four plots in fig. 11, and correlation over longer intervals than the 33-37 days used in the figure causes these coefficients to decline further. An indication of how poor the correlation is between earth tide and radon is the fact that, in the time periods shown in fig. 11, earth tide correlates better (in two cases), or only slightly worse, with water temperature than with radon. As any relation between earth tide and water temperature in the pond seems improbable (short-term variations in the temperature of springwater entering the pond have not been observed during several years of monitoring), a relation between radon and earth tide seems improbable as well. (In the initial portion of the continuous radon record (fig. 12), stronger 12-hour and weaker 24-hour components were observed than for subsequent portions of the record. Although this suggested a tidal effect on radon concentration (Wollenberg et al. [1]), this now seems unlikely as cross-correlation shows no better fit for that earlier period than for the periods shown in fig. 11.)

These considerations indicate that the radon record is probably unrelated to earth tidal effects, and that other factors not yet understood are causing the cyclic variation of the radon record.

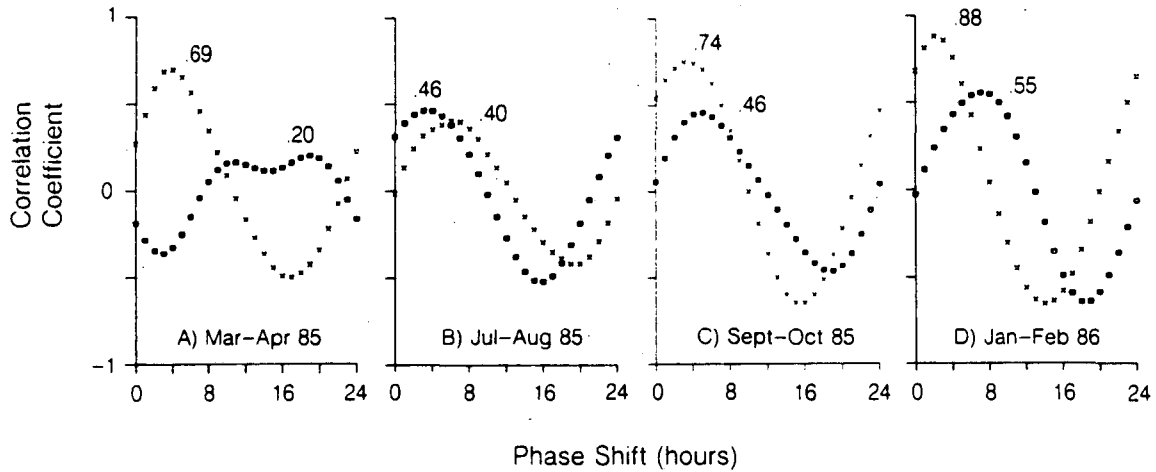


Figure 11. Cross-correlations between water temperature and radon patterns (crosses), and between earth tide and radon patterns (solid symbols), plotted against backward shifts of the radon pattern with respect to temperature and tide. Intervals plotted cover time intervals shown in figs. 6 and 9: (A), (C), and (D) correspond to fig. 9A, B, and C, respectively, and (B) spans the summer periods of fig. 6C-D. Time periods are 33 days for (A), (C), and (E), and 37 days for (B). Starting dates are: (A) Mar 11, (B) Jul 8, (C) Sep 17, (D) Jan 7.

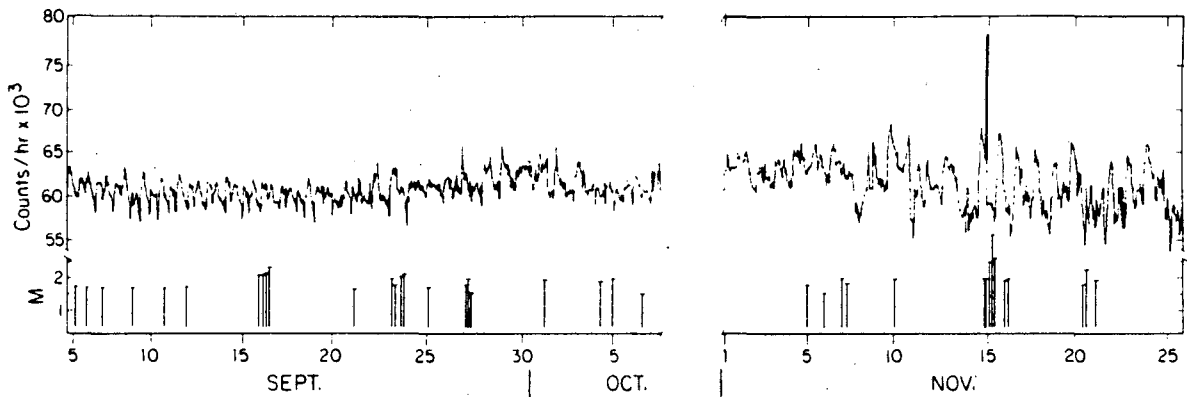


Figure 12. Initial portion of continuous radon record at the Fish Hatchery spring, September-November, 1983. Earthquakes of magnitude >1.5 in the caldera shown by vertical lines below radon record. Earthquake data provided by R. Cockerham (private communications, 1984).

### Association of Radon and Seismic Events

Groundwater radon anomalies associated with seismic activity have been documented by a number of workers in different parts of the world (a summary of many of these anomalies is given by King [14]), and radon anomalies associated with volcanic activity have also been reported, although far less frequently (Gasparini and Mantovani [15]). Accordingly, one goal in installing the continuous monitoring system was to observe changes in radon concentration associated with seismic (or possibly volcanic) activity. To date, there has been one significant perturbation in the radon record that appears to correlate clearly with earthquake data. This occurred on November 14, 1983, soon after the inception of the monitoring program. The radon record for that time period is shown in fig. 12, along with the occurrence of caldera earthquakes of magnitude greater than 1.5. A distinct spike is observed in radon concentration that is approximately coincident with several small earthquakes which just precede a moderate earthquake of magnitude 3.4 (epicenter approximately 5 km southwest of the Hatchery springs).

The initial portion of the continuous radon record, beginning in September, 1983, is also shown in fig. 12. As noted above, the character of this early record is significantly different from subsequent portions, and this is probably due to the lack of a cover on the pond, in combination with warm weather in the initial part of the record. The fact that we have not observed clear associations between radon variations and seismic events subsequent to the 1983 event may be that such variations would be masked by the effect of radon-depleted surface water (and other as-yet-unknown causes of the radon pattern) on measured radon concentration, an effect that has been enhanced by the presence of the cover on the pond. But we have also been hampered by the sparseness of the seismic record, with only one other event of magnitude equal to or greater than that of the November, 1983 earthquake occurring within the caldera during operation of the monitoring system.

## CONCLUSIONS

The principal conclusions of the investigation to date are as follows:

1. The range of radon concentrations of springs in the Long Valley caldera covers several orders of magnitude. The concentrations are controlled primarily by water temperature and near-surface exsolution of gases, and to a lesser degree by the radioelement concentrations of the rocks that encompass the hydrologic systems. The cold springs on or near the western, northern, and southern margins of the caldera, which may represent water that is recharging the caldera's hydrothermal system, have high radon concentrations relative to those of the cool, warm, and hot waters of the caldera.
2. Radon in groundwater is readily monitored by an in-situ gamma-radiometric system. The radioactivity of the water is due almost entirely to its  $^{222}\text{Rn}$  content.
3. Radon concentration of springwater monitored in the Hatchery pond exhibits strong diurnal and generally weaker sub-diurnal variations. It is strongly influenced by precipitation and by descent of radon-depleted surface water to the vicinity of the gamma detector. Other factors responsible for the cyclic radon variation pattern are not yet understood, but may be related to stratification or circulation patterns in the pond, or to barometric pressure changes. The radon pattern does not appear to be influenced by earth tides.
4. In the present configuration of the monitoring system, radon variations associated with small or distant seismic or volcanic events probably stand little chance of being detected. We will need to understand better the nature of the "normal" variations in the radon record, and to filter or eliminate the main influences on the cyclic radon pattern, in order to recognize correlations between radon anomalies and seismic or other geophysical events.

Operation of the present system continues, and we plan several modifications in the near future. One is the completion of the covering over all portions of the pond, in order to close off all routes to descending surface water. We also plan to improve the monitoring system to reduce the frequency of breaks in the radon record, and possibly to introduce continuous monitoring of meteorological parameters, especially barometric pressure. These measures could aid greatly in deciphering causes of the radon variation that are not yet understood, in observing longer term periodicities and trends in the record, and in detecting influences which may at present be masked or distorted. Deployment and concurrent operation of several systems at springs and, with some modification, wells in the caldera would permit us to observe better the relationship between radon and seismic or volcanic activity.

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