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VARIATIONS IN RADON-222 IN SOIL AND GROUND WATER AT THE NEVADA TEST SITE*

Harold Wollenberg[1], Tore Straume[2], Alan Smith[3], and Chi-Yu King[4]

ABSTRACT

To help evaluate the applicability of variations of radon-222 in ground water and soil gas as a possible earthquake predictor, measurements were conducted in conjunction with underground explosions at the Nevada Test Site (NTS). Radon fluctuations in ground water have been observed during a sequence of aftershocks following the Oroville, California earthquake of 1 August 1975. The NTS measurements were designed to show if these fluctuations were in response to ground shaking; if not, they could be attributed to changes in earth strain prior to the aftershocks. Well waters were periodically sampled and soil-gas ^{222}Rn monitored prior to and following seven underground explosions of varying strength and distance from sampling and detector locations. Soil-gas ^{222}Rn contents were measured by the alpha-track method; well water ^{222}Rn by gamma-ray spectrometry. There was no clearly identifiable correlation between well-water radon fluctuations and individual underground tests. One prominent variation in soil-gas radon corresponded to ground shaking from a pair of underground tests in alluvium; otherwise, there was no apparent correlation between radon emanation and other explosions. Markedly lower soil-gas radon contents following the tests were probably caused by consolidation of alluvium in response to ground shaking.

INTRODUCTION

With the observations by Chinese and Russian scientists (Ch'engtu Seismological Detachment, 1975; Shishkevich, 1971) that fluctuations in the radon-222 content of well and spring waters may be used as an earthquake predictor, attention has been focused on this parameter in the United States. Recent reports by King (1975), Teng et al. (1975) and Smith et al. (1975) suggest that variations in soil gas and well-water radon may correlate with seismic activity in California. In the study by Smith et al., radon is measured in well waters in a region undergoing aftershock activity following a magnitude ∿ 6 earthquake near Oroville, California. A question immediately arises in the Oroville study: do the observed radon fluctuations reflect strain buildup prior to discrete aftershocks, or, are the fluctuations just the result of ground shaking from the aftershocks? Similar questions apply to the study by King (1975) of variations in soil-gas radon in a seismically active region of the San Andreas fault zone.

Therefore, the primary purpose of the work reported here was to see if recognizable variations in ground water and soil-gas radon content were associated with discrete episodes of ground shaking. Underground nuclear explosions at the Nevada Test Site (NTS) offered sources for such a study; radon detectors could be arrayed and their emplacement timed to take best advantage of the schedule of explosions (evidence for variations in soil-gas radon to explosions at NTS has been described by Evans et al., 1962). The names, locations and yield ranges of recent underground tests which might have affected the measured radon contents are listed on Table 1. (Unfortunately, the array of soil-gas radon detectors was set for a test which was postponed for several months, but valuable background information was obtained in the meantime.) Specifically, the program at NTS incorporated two sets of measurements: ^{222}Rn in soil gas, and radon in subsurface aquifers. Following a brief description of the location and geologic setting of the study area, each set of measurements will be discussed separately and results evaluated in subsequent sections.

Table 1
Underground nuclear tests which were studied for possible influence on well water and/or soil-gas radon contents.

Shot	Date	Location	Yield Range (kilotons)
Kasseri	28 Oct 75	Pahute Mesa	200 - 1000
Chiberta	20 Dec 75	Yucca Flat	20 - 200
Muenster	3 Jan 76	Pahute Mesa	200 - 1000
Esrom	4 Feb 76	Yucca Flat	20 - 200
Keelson	4 Feb 76	Yucca Flat	20 - 200
Fontina	12 Feb 76	Pahute Mesa	200 - 1000
Strait	17 Mar 76	Yucca Flat	200 - 500

LOCATION AND GEOLOGIC SETTING

The study area was in Yucca Flat, an intermontane basin in the northeast portion of the NTS, approximately 30 miles north of Mercury, Nevada. Figure 1 is a location map of the area, showing appropriate test locations, sampled wells, and soil-gas radon detector sites.

The geologic setting of the NTS is described by Ekren (1968). Detailed descriptions of the Yucca Flat area were provided by Fernald et al.

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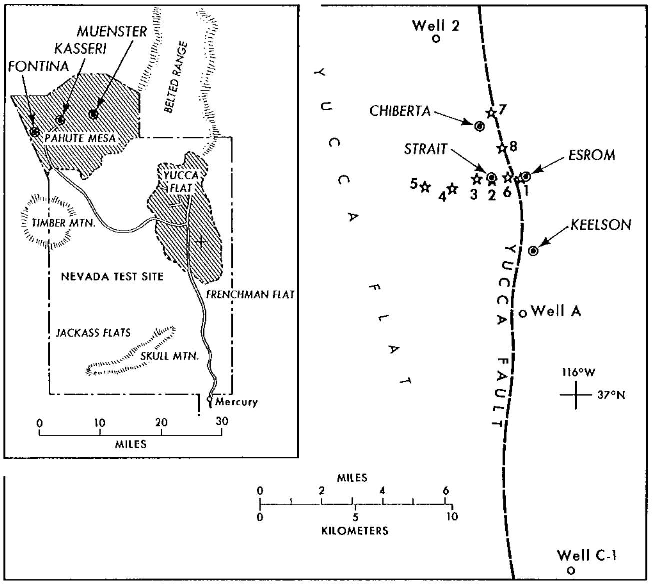

Northern Portion of Nevada, Test Site
Locations of underground tests (◉), wells (o), and radon cups (☆).

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Figure 1 Northern portion of Nevada Test Site, showing locations of underground tests, wells, and radon cups.

Table 2 N.T.S. Well Information

Well	Specific capacity (ℓ per min. per meter draw-down)	Total Depth (m)	Static Water Level (m)	Perforated Interval (m)	Aquifer
2	--	1053	743	831-908	dolomite
A	20.4	575	493	495-575	alluvium
C-1	68.8	525	474	473-508	fractured limestone

(1968) and Hinrichs (1968). The geologic structure of the northeastern portion of Yucca Flat, where the sampled wells and soil-gas radon detectors were located, is dominated by the Yucca Fault, a north-south-trending, nearly vertical normal fault zone along which cumulative dip-slip displacements from natural tectonism are at least 100 feet, with movement down to the east (Dickey, 1968). Underground tests near the Yucca Fault have caused additional fissuring, fracturing, and vertical displacements. Sedimentary material in Yucca Flat consists primarily of poorly sorted alluvium, ranging in grain size from clay to cobbles. Surficial deposits are predominantly alluvial fan sediments, with abundant pebbles and cobbles, derived from bedrock terranes on the sides of the basin. Pre-Tertiary bedrock beneath Yucca Flat consists of late-Paleozoic carbonate rocks, penetrated by two of the three wells sampled in this study. At some locations the carbonates are in thrust- or normal-fault contact with older clastic sedimentary rocks. A sequence of Tertiary volcanic rocks covers the Paleozoic rocks, and is in turn overlain by the Yucca Flat alluvium.

WELL SAMPLES

Three wells were sampled, generally weekly, for radon content. Their locations are shown on Figure 1. The samples were collected at the well-head during periods of flow, or if the well had been shut in, it was flowed substantially before water was collected. Well parameters are listed on Table 2. Water samples, totaling 1.5 liters in three 0.5-liter polyethylene bottles, were collected by NTS personnel, sealed, and transported by air to Livermore, then by car to LBL. The samples were analyzed for their ^{222}Rn content at the LBL low-background gamma-counting facility. The three bottles were placed upright on an 8-in.-(20.3 cm) diameter by 4-in.-(10.2 cm) thick NaI(Tl) detector, and counted for several hundred minutes. Counts were stored by a pulse-height analyzer, which provided a gamma-ray spectrum of each sample. The spectra indicated that essentially all gamma activity came from decay of ^{222}Rn and its daughters. This was confirmed by subsequent counts of some of the samples, disclosing radioactive decay in accordance with the 3.8-day half life of radon. Data are expressed in counts per minute (c/min) in the gamma-spectral interval encompassing 0.13 to 2 MeV, a range which includes most gamma energies associated with the decay of ^{222}Rn. The count rates have been corrected for decay of radon in the sample during the time between collection and counting. A calibration factor of approximately 3 c/min/pico-Curie/liter may be applied.

Well data are illustrated on the time chart, Figure 2. The average radioactivities of waters from Well A and Well 2 are similar, despite their production from contrasting lithologies (alluvium and dolomite, respectively). The radioactivity of water from Well C-1, which produces from limestone, is 1/8 to 1/9 that of waters from Wells A and 2. The low radioactivities of Well C-1 water required inordinately long counting times for statistically significant results; therefore this well was no longer sampled after 7 January 1976. From radiogeologic studies of bedrock terranes elsewhere (Wollenberg and Smith, 1975), it has been shown that "pure" carbonate rocks have appreciably lower radioactivities than have siliceous clastic rocks. Thus, the low radioactivity of water from Well C-1 in limestone, compared to that of water from Well A in alluvium (made up predominantly of siliceous rock debris) is not surprising. However, the rough parity between the radioactivities of waters from Well A, and Well 2 (in dolomite) is difficult to explain, in that one would expect lower radioactivity from the dolomite aquifer; perhaps comparable to that in Well C-1. It is probable that the pathways taken by the water to Well 2 are not confined to the carbonate aquifer; the relatively high radioactivity of this water may reflect its passage through tuffaceous and siliceous clastic rocks.

Examination of the well-water radon time chart (Fig. 2) shows large variations in ^{222}Rn contents but little apparent correlation with tests

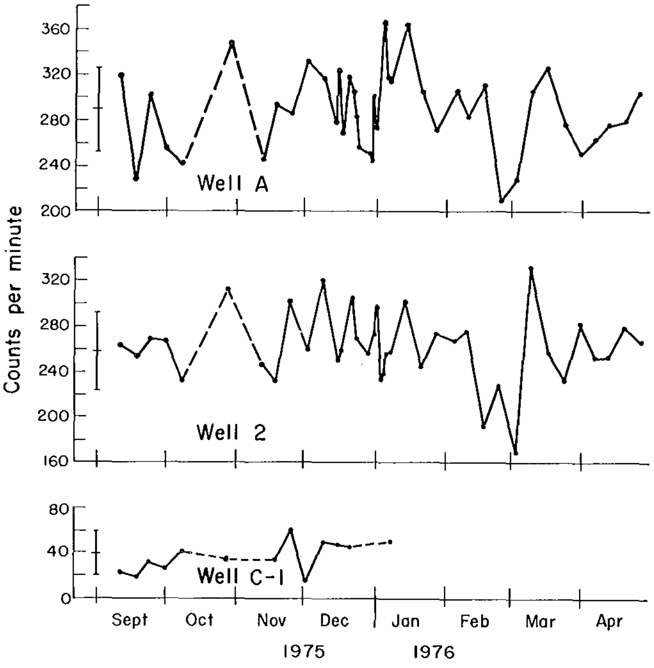

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Figure 2 Variation with time of ^{222}Rn in well water at N.T.S. Data are expressed as counts per minute in the γ-ray energy interval 0.13 to 2 Mev. mean values and standard deviations are illustrated by the error bars.

which closely preceded collection of some of the samples. The time variations in Wells A and 2 are roughly matched, with periods of relatively low radioactivity occurring in October 1975 and late February and mid-March 1976. There is a possible association of high radioactivity and ground shaking in Well A immediately following the Kasseri test of 28 October 1975 and the Muenster test on 3 January 1976, as well as a possible response to Kasseri in Well 2. But similar highs at other times (and, for that matter, the sharp lows in February-March, 1976) do not appear to be associated with underground explosions. It is noteworthy that the possible responses in ground water radon levels were to larger and more distant tests occurring in Pahute Mesa, rather than to smaller explosions located much closer to the wells in Yucca Flat. Daily barometric pressures at Yucca Flat, plotted on Figure 4, show no apparent correlation with well-water radon variations.

SOIL GAS RADON

The development of the alpha-track detector has greatly facilitated the measurement of soil-gas radon. Detectors comprise a rectangular wafer of cellulosic material sensitized for alpha tracks, taped to the bottom of a plastic cup (shown in Figure 3) with median diameter of 6.5 cm. The cup is placed, inverted, on the soil at the bottom of a ∿ 1/2-m-deep hole, and remains there for periods of several days to several weeks; Figure 3 shows a cup installation in Yucca Flat. Radon emanates from the soil into the cup. The alpha particles from its decay attack the plastic detector, which on return to the laboratory, is etched to reveal the resulting damaged areas or alpha "tracks." Tracks are counted manually by microscopic examination of the etched plastic. An advantage of this system over continuous-monitoring systems, besides its simplicity, is that it integrates the rate of track formation over the exposure time, thus smoothing the effects of variations in radon emanations caused by short-term barometric fluctuations or other atmospheric phenomena. (Effects of changes in moisture content and atmospheric pressure on radon flux at N.T.S. were described by Kraner et al, 1964.) This alpha-track detector, utilized extensively in uranium exploration (Gingrich, 1975), was developed and patented by General Electric Company, and patents are now assigned to Terradex Corporation of Walnut Creek, California.

Figure 3 Emplacement of an α-track detector in the ground at N.T.S.

Radon track-etch cup locations in Yucca Flat are shown on Figure 1 and their distances from test locations on Table 3. As mentioned in the introduction, an array of 6 holes, roughly on an east-west line, was designed specifically to measure effects of the Esrom test originally scheduled for September 1975. Indefinite postponement of Esrom and subsequent scheduling of Chiberta, located approximately 3 km north of the Esrom site, caused us to put two more detectors, numbers 7 and 8, in that area. Hole number 2 was subsequently obliterated by activities associated with the construction of a test area.

Table 3
Alpha Track Detector Distances From Test Locations (Km)

Detector Location	Keelson	Esrom	Chiberta
1	4.3	0.2	3.0
2	4.6	1.3	2.5
3	5.3	2.7	2.4
4	5.2	3.8	3.8
5	5.9	4.6	4.2
6	4.4	0.8	2.7
7			0.7
8			1.8

The variation of soil-gas radon contents with time is shown on Figure 4. The range of integration periods varied, to take best advantage of the test schedule, given a limited supply of detectors. Several long periods during times of no test activity were occupied to obtain statistically significant background values. Detectors were changed on the day prior to an announced test (though sometimes the test was postponed) and remained in the ground for approximately one week following the detonation.

All detector holes were in Yucca Flat alluvium; holes 1 through 5 in relatively undisturbed ground; holes 6, 7, and 8 in areas of cracked and fissured ground associated with the Yucca Fault zone.

Alpha track data are expressed as track densities: tracks per day per 100 fields of view under the microscope; the area of 100 fields is 5.75 mm^2. The approximate calibration between track density (normalized to a 30-day exposure) and radon content is 1 track per mm^2 = 9.1 pico Curies per liter (J. Gingrich, private communication). Therefore 1 track per day per 100 fields represents a radon content of $\left(\frac{9.1}{5.75}\right) \times 30 = 47.5$ pico Curies per liter of soil gas.

To evaluate the contribution of radon from depth in the Yucca Flat alluvium, the contributions from the near-surface soil were evaluated. Therefore, samples of soil (800 to 1000 g) from some of the alpha-detector holes were collected and analyzed for their radioelement content by gamma-ray spectrometry. Results are listed on Table 4. Inspection shows that contents of uranium-238, the parent radioelement of radon, are relatively even in holes 1 through 5. The mean values of track densities from the holes have a greater variation than do the uranium contents of near surface soil, suggesting that variations in emanation are associated with sources of radon in deeper alluvium or bedrock.

Table 4 also shows the degree of disequilibrium in the uranium decay series. This was determined by exposing the soil samples to the open air, then counting them immediately after packing in sealed plastic containers. The samples were re-counted 15 to 20 days later.

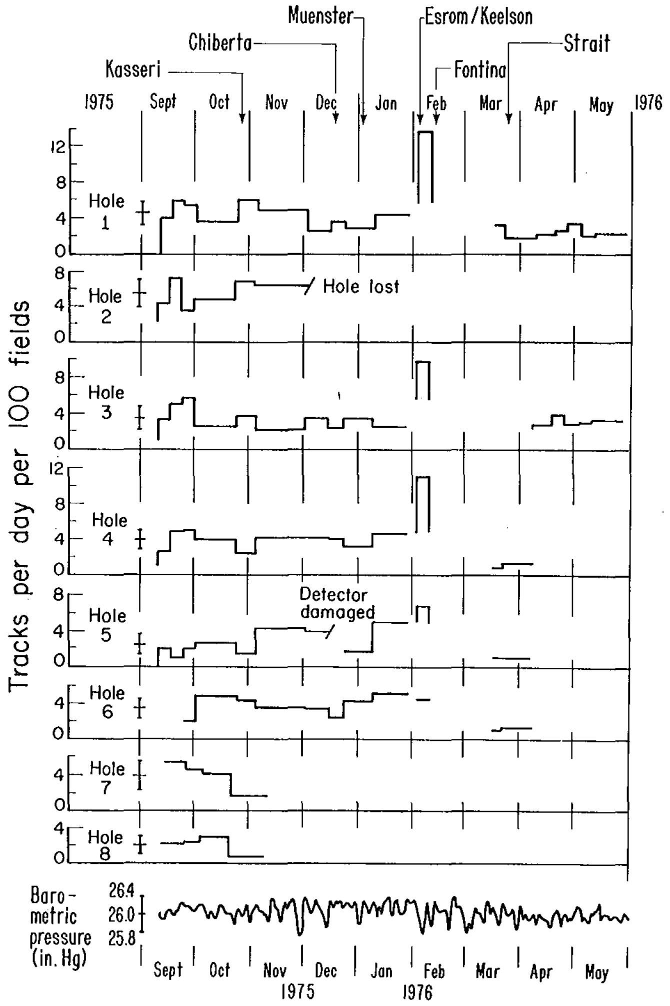

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Figure 4 Variations with time of soil-gas ^{222}Rn. Mean values and standard deviations for pre-Esrom track densities at each location are illustrated by the error bars.

Uranium values are computed for both countings. In the first counting, we observe uranium series γ-rays from only the daughters of ^{222}Rn that are bound in soil particles, having allowed the "soil gas" ^{222}Rn to escape immediately before packing. In the second counting, time has elapsed for re-establishment of equilibrium with ^{222}Rn (3.8 day halflife) in the sealed container; the true uranium content is thus determined. The difference between the apparent uranium values from the two analyses indicates the fraction of ^{222}Rn that can emanate (designated Ueq on the table).

These fractions range from 90 to 93%, indicating that about 7 to 10% of the total ^{222}Rn is available for emanation, and hence for registration by the track detectors.

Table 4

N.T.S. Soils: Radiometric Analyses of soils from radon track holes, showing U, Th, K contents and degree of disequilibrium in the U-series.

Sample Number		Uranium ppm	Thorium ppm	Potassium pct
RN-1	Initial	2.80±0.04	11.8±0.1	2.27±0.01
	Final	3.00±0.03	11.8±0.1	2.26±0.01
	Ueq	0.93		
RN-2	Initial	3.34±0.05	16.5±0.2	3.12±0.01
	Final	3.71±0.04	16.5±0.1	3.12±0.01
	Ueq	0.90		
RN-3	Initial	3.46±0.04	16.2±0.1	3.34±0.01
	Final	3.78±0.05	16.1±0.2	3.36±0.01
	Ueq	0.92		
RN-4	Initial	3.05±0.02	12.7±0.1	2.88±0.01
	Final	3.27±0.03	12.6±0.1	2.89±0.01
	Ueq	0.93		
RN-5	Initial	3.00±0.03	11.3±0.1	2.46±0.01
	Final	3.26±0.03	11.4±0.1	2.47±0.01
	Ueq	0.92		

A similar situation exists in the thorium series with respect to disequilibrium. Gamma-spectrometric analyses of Th are based on γ-rays from daughters of ^{220}Rn. However, the relatively short halflife of ^{220}Rn (55 seconds) prevents this gaseous isotope from diffusing nearly so far from its creation site before decay (and almost immediate binding) as does ^{222}Rn. Thus the thorium series is not likely to be as important a source for the track detectors as is the uranium series. This is substantiated by data on Table 4, where both initial and final thorium values are nearly identical.

Examination of Figure 4 indicates a rather featureless pattern of variation in radon content with time, with one prominent exception: significantly high contents during the one-week period following the Esrom and Keelson tests on 4 February 1976. Prior to that time there was no apparent response to the more distant explosions in Yucca Flat or on Pahute Mesa. The large responses to Esrom and Keelson were in holes 1, 3, 4 and 5; hole 6 showed no apparent response. Hole 6 was in the fractured ground of the Yucca Fault zone, as were holes 7 and 8 which did not respond to the nearby Chiberta test. This suggests that because the Yucca Fault zone has been badly cracked by the long history of nuclear testing at NTS, shaking by recent tests induces little change from long term background in emanation of radon from the broken ground of the fault zone.

After a five week gap during which no data were taken, holes 1 and 3 were monitored over two months following the large response to Esrom/Keelson. As with holes 4 and 5, average radon concentrations were generally lower following the tests, than before the tests. Radon contents in hole 3 showed a slight increase with time over the period February through May. The general decrease in radon emanation following Esrom/Keelson may be due to the consolidation of Yucca Flat alluvium in response to ground shaking and caving, causing a decrease in permeability for radon. This may also account for the apparent lack of response of radon in holes 1, 4, 5 and 6, following the Strait explosion in Yucca Flat on 17 March 1976.

Substantiating evidence is provided by subsidence data from previous tests in Yucca Flat. A zone of at least 3 km radius, with maximum subsidence of 2.5 m (at the edge of the cratered zone) was observed associated with a test (Portmanteau) of yield within the range of Esrom or Keelson. Though the subsidence directly over the detonation point is due mainly to underground caving following the explosion, out from the detonation point a large component of subsidence may be due to consolidation of the alluvium in response to ground shaking.

As with the well samples, there was no apparent correlation of variations in soil-gas radon with barometric changes.

Surface ground motion data indicate appreciable accelerations at sites close-in to the Yucca Flat tests. The data for Keelson indicate accelerations of 15-30 G's within ∿300 m of surface ground zero (directly above the deformation point) and accelerations (>2 G's) as far as ∿2.5 km from surface ground zero. For comparison, accelerations were 1.5-2 G's at a station ∿300 m from the Chiberta surface ground zero, and .05-0.1 at ∿6 km.

CONCLUSIONS

It is concluded that one prominent variation in soil-gas radon content can be attributed to shaking from a pair of underground explosions in Yucca Flat. Except for the test (Esrom/Keelson) for which the detector array was designed, there was no apparent correlation between radon emanation and other explosions in Yucca Flat or Pahute Mesa. The depleted radon contents in holes 1 through 5, following the Esrom/Keelson tests, were probably caused by consolidation of the Yucca Flat alluvium, in response to ground shaking.

Appreciable changes in soil-gas ^{222}Rn in response to underground tests at NTS were observed by Evans et al (1962). Discrete samples of soil gas were taken from tubes inserted one to three meters into the ground. In one test in alluvium, radon decreased within two days following the detonation, then gradually increased to pre-detonation average contents. Responses to two subsequent events were the opposite: ^{222}Rn generally increased by nearly a factor of two within four to five days following each detonation then gradually decreased to pre-detonation levels. The sharp rise of radon in this latter pattern generally matches our observations in holes 1, 3, 4 and 5 (Figure 4), following the Esrom/Keelson events of 4 February 1976.

There is a possible correlation between radon variation in water of Well A and at least one underground explosion on Pahute Mesa; otherwise there are no apparent correlations between well-water radon variations and tests in either Pahute Mesa or Yucca Flat. Therefore, though strongly localized in space and time, soil-gas radon contents appear to have responded to ground shaking at NTS, while it is questionable that there is a similar response in ground-water radon contents.

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