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# Spatial radon anomalies on active faults in California

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**Abstract**—Radon emanation has been observed to be anomalously high along active faults in many parts of the world. We tested this relationship by conducting and repeating soil–air radon surveys with a portable radon meter across several faults in California. The results confirm the existence of fault-associated radon anomalies, which show characteristic features that may be related to fault structures but vary in time due to other environmental changes, such as rainfall. Across two creeping faults in San Juan Bautista and Hollister, the radon anomalies showed prominent double peaks straddling the fault–gouge zone during dry summers, but the peak-to-background ratios diminished after significant rain fall during winter. Across a locked segment of the San Andreas fault near Olema, the anomaly has a single peak located several meters southwest of the slip zone associated with the 1906 San Francisco earthquake. Across two fault segments that ruptured during the magnitude 7.5 Landers earthquake in 1992, anomalously high radon concentration was found in the fractures three weeks after the earthquake. We attribute the fault-related anomalies to a slow vertical gas flow in or near the fault zones. Radon generated locally in subsurface soil has a concentration profile that increases three orders of magnitude from the surface to a depth of several meters; thus an upward flow that brings up deeper and radon-richer soil air to the detection level can cause a significantly higher concentration reading. This explanation is consistent with concentrations of carbon dioxide and oxygen, measured in soil–air samples collected during one of the surveys. Copyright © 1996 Published by Elsevier Science Ltd

## INTRODUCTION

Anomalously high radon concentration has been measured along many active faults (e.g. Tanner, 1980). Israel and Bjornsson (1967), for example, reported high concentrations of radon and thoron in soil air at 1-m depth along transects perpendicular to the strikes of several faults near Aachen, Germany. They attributed the radon anomalies that were accompanied by thoron anomalies to enrichment of parent nuclides in the corresponding fault zones, and the other radon anomalies to upward migration of radon. However, active faults are also found to be commonly associated with anomalously high concentrations of other terrestrially generated gases, such as helium, hydrogen, mercury vapor, and carbon dioxide. Irwin and Barnes (1980), for example, showed that the worldwide distribution of springs in which the groundwater $HCO_3^{-1}$ contents exceeded 1000 ppm generally coincided with major seismic belts. Yanitskiy *et al.* (1975) surveyed helium concentrations in ground water at depths of 30–50 m in north Kazakhstan, and found the concentrations to be anomalously high along active faults, especially at intersections of faults. Wakita *et al.* (1980) found anomalously high amounts of hydrogen (up to more than 3% by volume) in soil gas at depths of 0.5–1.0 m along the Yamazaki fault in Japan; these values are as much as 5 orders of magnitude higher than values measured on either side of the fault. During the last decade, the Chinese State Seismological Bureau organized a national effort in which scientists from more than ten institutions conducted various gas surveys across many faults in China. They found anomalous gas concentrations not only along many major faults but also above some buried faults (Wang *et al.*, 1991). Other recent studies include Sugisaki *et al.* (1983) and Duddridge *et al.* (1991).

To account for the anomalously high values of radon and other gases requires a mechanism of generation and migration of the terrestrial gases as a whole. One such mechanism was proposed by King (1978, 1986, 1990), who suggested that active faults are significant "leaks" in the crust for the earth's ongoing outgassing process; an outward flow of soil air in or near a fault can bring up deeper air which contains more such gases to the detection level. Independently, Dikun *et al.* (1975) invoked the same mechanism to explain some fault-related helium anomalies they had observed in the former Soviet Union.

In California, where the San Andreas fault system separates the Pacific and North American plates, concentrations of radon and other gases (such as hydrogen and carbon dioxide) were monitored in soil air at many sites during the decade of 1975–1985 in search of temporal anomalies for earthquake prediction (see reviews by King, 1986, 1990). No radon or other gas survey has been conducted systematically, however, across the faults to search for spatial anomalies. In order to investigate whether active faults in California show any such anomalies, we began in July 1992 to conduct radon surveys across several kinds of fault segments (creeping, locked, and freshly broken). Some preliminary data were presented by King *et al.* (1994). Here we give a more detailed report on the results obtained so far, and consider several possible explanations, including outgassing, for our observations.

## SURVEY INSTRUMENT

Two portable radonmeters (model FD-3017) manufactured by Shanghai Electronic Instrument Co. were used for the surveys. (The first one was used until early October 1993 when it was returned to China and exchanged for the second one.) This type of instrument has been used extensively in China in recent years with accurate and repeatable results (Wang *et al.*, 1991). The measurement procedure is as follows. A gas-sampling probe is pushed or hammered into the ground. It is connected to and used with a pump to suck out a 1.5 L sample of soil air from a depth of about 32 cm through a dehumidifying chamber. The upper part of the probe is larger than the sampling section and is thus kept tightly fitted in the soil to prevent atmospheric air from being sucked into the pump along the probe–soil interface. A metal plate, which has been placed in the pump, is then charged with a negative high voltage of 2.8 kV for 2 min to collect the positively charged $^{218}$Po particles produced by the decaying radon (the only gaseous nuclide in the uranium decay chain) in the sample. The plate is then promptly transferred (within 15 s) to a battery-powered counting chamber where the alpha particles generated by the collected $^{218}$Po, which has a short half-life of 3.05 min, are counted for two min. The particle count is used as a measure of the radon concentration. Each count corresponds to 0.15 and 0.164 Bq $L^{-1}$ for the first and second instruments, respectively. The counting error is within 10% when the instruments are used in the temperature range of $-10$ to 40°C. Each measurement takes only 5–10 min, and each survey consisting of 20–40 measurements takes 4–8 h. The rapidity in obtaining results enables the surveyors to recognize the possible need for additional data points while in the field. Also, this technique has very little background noise (less than 0.07 count), because, unlike other techniques, it measures alpha particles generated mainly by $^{218}$Po. The lack of background noise is evident when the radon-poor atmospheric air is measured, resulting in zero count, and in the survey data in Landers shown in Figs 8 and 9. However, this technique only measures soil–air at discrete sampling points in space and time; it does not provide a continuous record or an areal coverage of the ever-changing radon concentrations in soil air.

## THE SURVEYS

During a survey, radon was measured normally at points of equal spacings along a line, unless an obstacle is encountered or an adjustment is needed: denser measurement where radon concentration showed large spatial variation and vice versa. The survey locations are shown in Fig. 1. Two of the surveys were conducted across well defined creeping fault segments. The first of them was on a flat alluvial valley in San Juan Bautista, along a line parallel to and about 10 m south of the long entrance driveway to the main house of the Nyland ranch (36°57.3'N, 121°32.7'W). Here the driveway and its two side fences have been offset right-laterally by the San Andreas fault at an average rate of 8 mm/yr, according to data recorded here by a 12 m-long creepmeter (SJN) operated by the U.S. Geological Survey during 1968–1977 (Schulz and Burford, 1979). The second survey line crossed the Calaveras fault in Hollister and is located at Dunne park and adjacent blocks between sixth and seventh streets (36°51.1'N, 121°24.2'W). The eastern side of the fault is about 0.5 m higher than the western side. The survey line was a few meters north of the edge of the adjacent sidewalk of Seventh street, which has been offset right-laterally by fault creep at an average rate of 8 mm/yr, as shown by data recorded during 1970–1977 by a 12 m-long USGS creepmeter (HLS) deployed nearby.

We measured the spatial variation of radon across a locked segment of the San Andreas fault at the Earthquake Trail in Point Reyes National Seashore near Olema (38°02.7'N, 122°47.9'W). The survey line followed and extended from the southern fence of the fenced-in display area. An old fence nearby was offset almost 5 m by fault movement associated with the 1906 San Francisco earthquake, but no significant earthquake has occurred here since. The fault trace cuts through the southwestern 30° slope of a small hill about 30-m high. The west side of the fault is underlain by the Salinian block which consists largely of granitic rocks and contains more uranium (the progenitor of radon), whereas the eastern side is underlain by mainly Franciscan rocks, consisting largely of graywacke, shale, mafic volcanic rocks, chert and limestone, with less uranium (Irwin, 1990).

Measurements were also carried out along two lines crossing a freshly broken segment of the Johnson Valley fault in the flat Mojave desert. This segment ruptured in the magnitude 7.5 Landers earthquake, which occurred on 28 June 1992 (Staff, 1992; Hart *et al.*, 1993). The surveys were conducted three weeks after the earthquake alongside two parallel roads

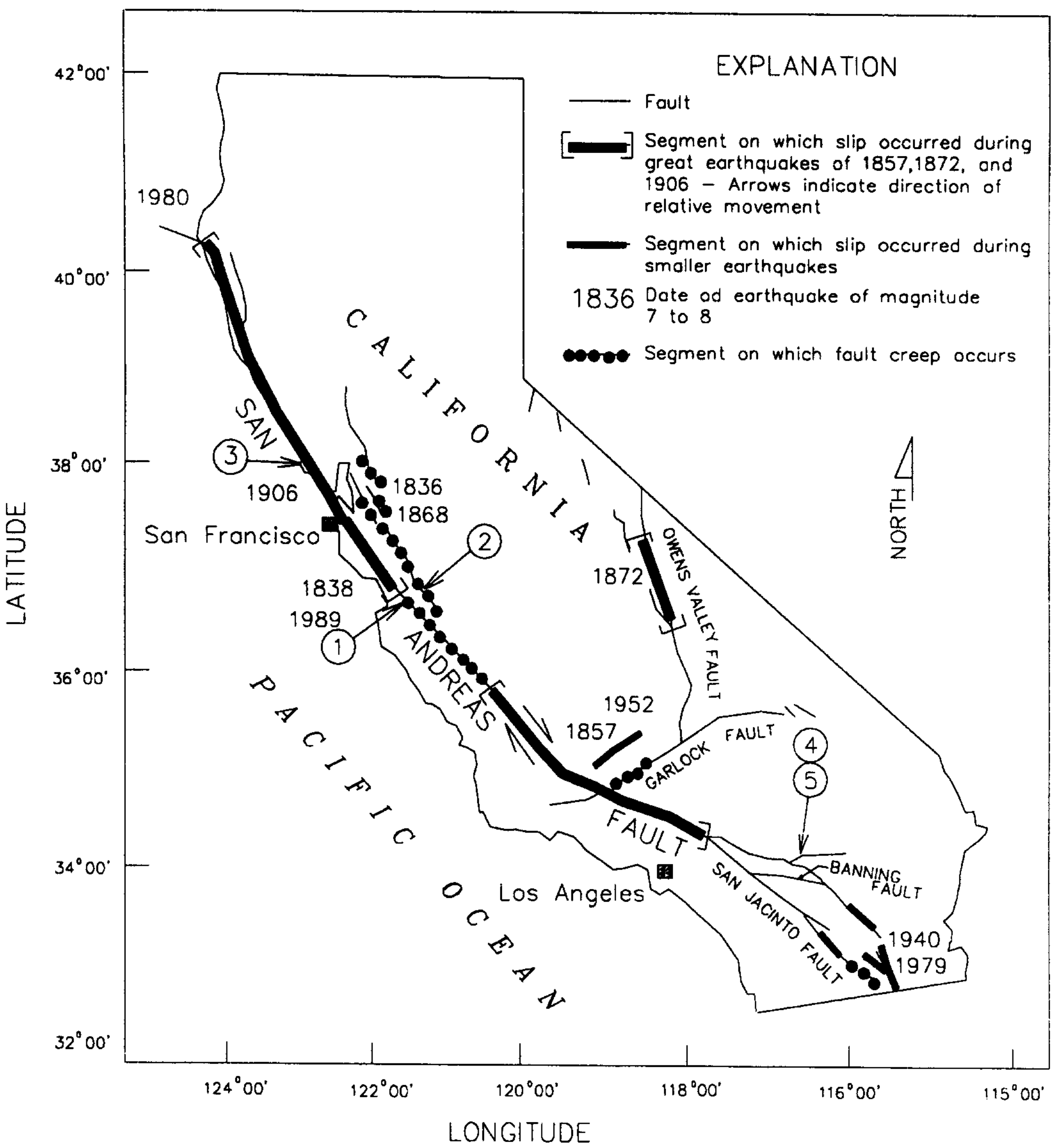


Fig. 1. Map of San Andreas and other large faults in California showing location of radon-survey sites: (1) Nyland Ranch in San Juan Bautista; (2) Seventh Street in Hollister; (3) Earthquake Trail in Point Reyes National Seashore; (4) and (5) Landers. (Map modified from (Wallace, 1990).)

(Encantado Road and Reche Road), which are about 1.7 km apart and had both been offset nearly 3 m during the earthquake. At Encantado Road, the survey was conducted and repeated along a line about 2 m south of the adjacent road edge and 0.3 m north of a fence, which had also been offset by the ruptures. At Reche Road, a survey was made along a line about 45 m south of the center of the road and another in and along the ruptures themselves that cross the road.

At shown in Table 1, the first set of surveys was conducted on sunny days in summer 1992. Repeated surveys were conducted in summer, autumn, and winter of 1993–1994, on sunny or cloudy days sufficiently long after rainfall so that the ground surface was relatively dry. The barometric-pressure changes were small during every survey, ranging, for example, from 754.4 to 755.8 mm Hg on 30 September 1993 in Hollister (Fig. 3b) and from 762.0 to 764.5 mm Hg on 20 January 1994 at Nyland (Fig. 2b).

## RESULTS

*Creeping segments*

Figure 2a shows the result obtained on 16 July 1992 along a 350-m survey line across the creeping segment of the San Andreas fault at Nyland Ranch in San Juan Bautista. The radon concentrations showed two major fault-straddling peaks that are 5 times higher than the background values and separated from each

Table 1. Locations and dates of radon surveys

| Location | Date |
|---|---|
| Nyland Ranch, San Juan Bautista | 16 July 1992 |
| | 20 January 1994 |
| Seventh Street, Hollister | 17 July 1992 |
| | 30 September and 1 October 1993 |
| | 30 and 31 December 1993 |
| College Street, Hollister | 5 February 1994 |
| Earthquake Trail, Point Reyes | 28 July and 8 August 1992 |
| | 19 March 1994 |
| Encantado Road, Landers | 21 July 1992 |
| | 23 July 1992 |
| Reche Road, Landers | 22 July 1992 |
| Along fault Breaks at Reche Rd. | 24 July 1992 |

other by about 40 m. A secondary peak nearly three times higher than background was also observed about 60 m to the west of the fault. No anomalous concentrations, however, were measured on the fault itself, in contrast to the single-peak feature commonly reported in the literature. The background radon value on the west side was significantly higher than the east side. This feature may be due to increasing depth to bedrock from the west to the east or may be caused by different rock compositions, for the San Andreas fault here separates the relatively uranium-rich Salinian block on the west side from the Franciscan assemblage on the east side (Irwin, 1990).

A partial repeat survey was carried out at Nyland in a rainy season, on 20 January 1994. As shown in Fig. 2b, the peak values were found to be reduced by a factor of two to a level which is insignificantly higher than the few background values measured at the six points relatively far away from the fault on both sides (where the radon values were found to be low in the previous survey). The background values were slightly higher than in the previous survey. In this survey, the gas-sampling time (the time interval required for the pressure in the pump to recover from partial vacuum created by the pumping action to that of the soil air) was also recorded as a measure of the gas permeability of the soil at the point of measurement. The sampling times were very short (mostly $<3$ sec), indicating high permeability at this site, and they do not show obvious correlation with the measured radon concentrations, except at one point in the fault–gouge zone, where the longest sampling time and lowest radon concentration was recorded.

Along a line about 410-m long across a creeping segment of the Calaveras fault in Dunne park alongside Seventh Street in Hollister, a similar twin-peak feature was observed on 18 July 1992 (Fig. 3a). In the figure the peak values are 7 to 11 times higher than the background values. They are broader, separated by about 90 m, and have some fine structures. The background values on both sides are the same, as may be expected from the geological homogeneity of the site (both sides are in rocks of the Great Valley sequence).

Another survey was conducted here on 30 September and 1 October 1993. It revealed a similar feature, except that the eastern peak rose somewhat (Fig. 3b). During the second survey we also took soil–air samples from some of the measurement points to the laboratory and analyzed other gas concentrations with a gas chromatograph. The limited data set obtained here show relatively high $CO_2$ and low $O_2$ values for the high radon-value points (see Figs 4a and b, respectively). Similar correlations were observed later at three other sites (not shown here). The $N_2$ concentrations, which might have been perturbed by fertilizing activities in the park, varied very little from the atmospheric level. We also recorded barometric pressure during this survey. As mentioned above, the barometric pressure varied very little.

On 30 and 31 December 1993, we conducted yet another survey at the same location. This time we made three measurements at each point in order to check measurement reproducibility, which was found to be good (Fig. 5). However, while the peak values remained essentially the same, the lower values showed significant increases. During this survey we also measured sampling times, which are generally much longer than those measured at Nyland Ranch, indicating a much lower gas permeability here. The three sites showing the longest sampling times had very high radon concentration also, but this apparent correlation is not shared by similar data recorded elsewhere and may be just fortuitous.

A control survey was conducted nearby on 5 February 1994 alongside the College Street, which is parallel to and about 270 m to the west of the Calaveras fault. The survey line begins at the western extension of the above-mentioned cross-fault line and ends about 100 m to the north. As shown in Fig. 6, the radon measurements are quite reproducible, and the concentration values obtained here are at or below the background level previously observed in the cross-fault survey (Fig. 5).

### *Locked segment*

Figure 7a shows the result obtained on 28 July and 8 August 1992 along a 144-m survey line across the

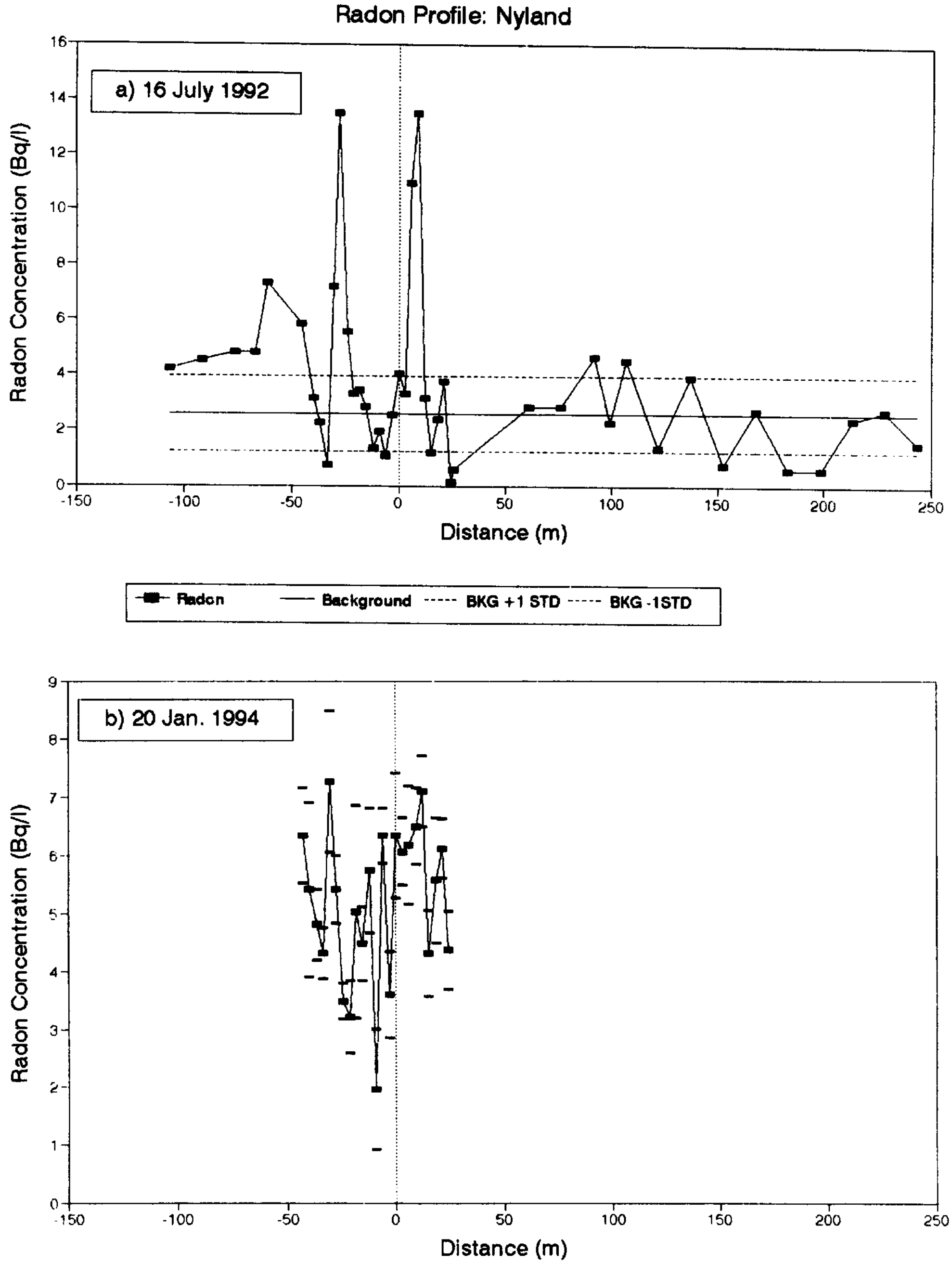


Fig. 2. (a) Soil–air radon concentration vs. distance along a survey line crossing the creeping San Andreas fault at Nyland Ranch in San Juan Bautista, observed on 16 July 1992. Northeast is plotted to the right of the figure. The fault is located at the origin; the 3 horizontal lines indicate average background value (the arithmetic mean for sites outside the peaks) and one standard deviation above and below the average. The same is true in subsequent data plots, unless noted otherwise. (b) Observed on 20 January 1994. This time three measurements were made at each point, and the plotted data represent the average values, and ± one standard deviation. The background values were not measured this time.

currently locked segment of the San Andreas fault at Earthquake Trail in Point Reyes National Seashore. As commonly reported in the literature, the radon concentration shows a single peak about six times above the background values. The peak was not recorded on the fault trace itself but about 10 m to the west. The width of the anomaly is about 30 m; it has a slight depression on the fault trace, possibly because of the existence of gouge material there as discussed below.

A partial repeat survey conducted here on 19 March 1994 showed a similar radon profile (Fig. 7b). This time, the peak and background values were mostly a little higher than before.

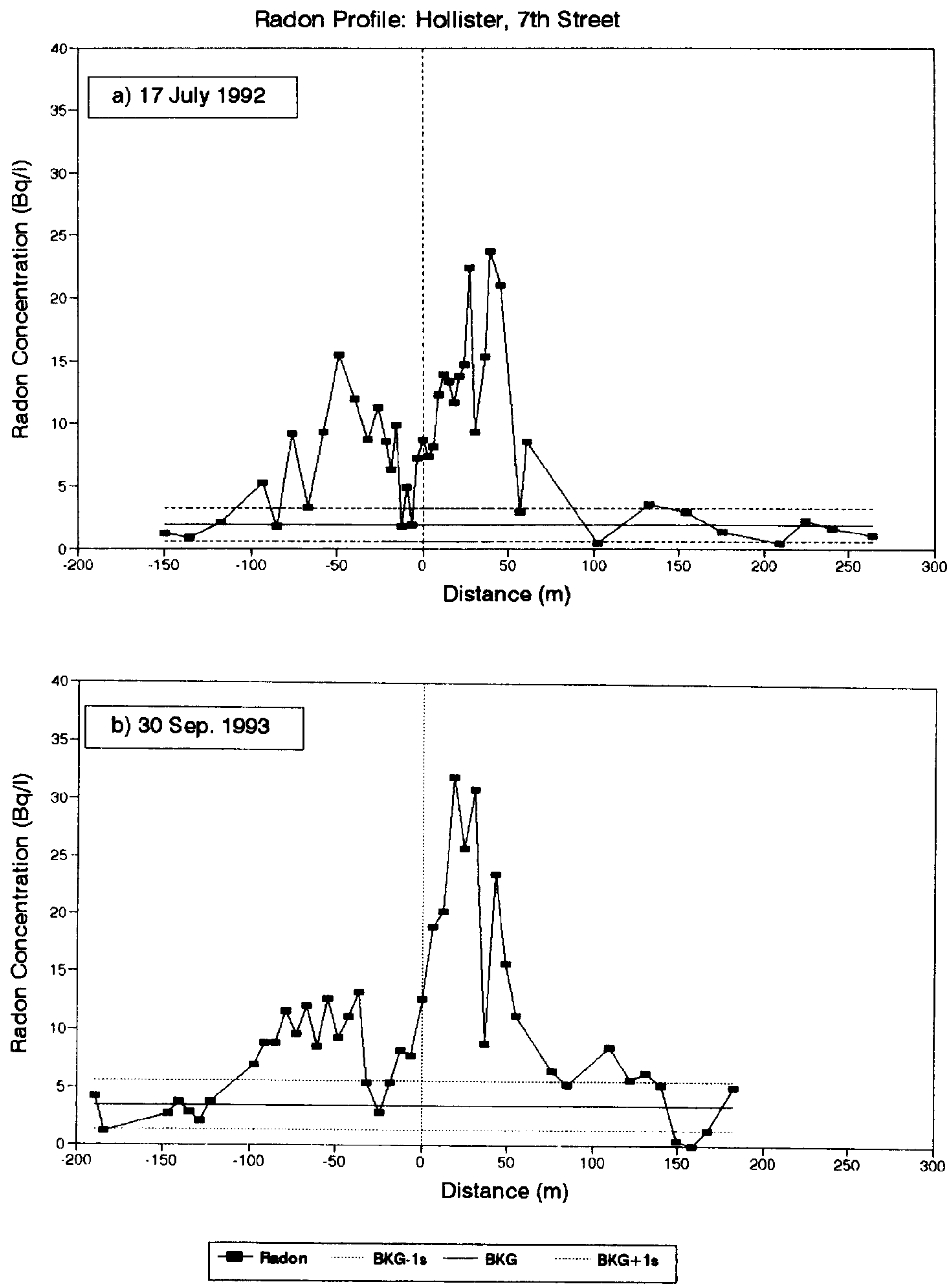


Fig. 3. Radon concentration vs. distance along a survey line crossing the creeping Calaveras fault near Seventh Street in Hollister observed on 17 July 1992 (a); 30 September and 1 October 1993 (b).

*Fresh fault breaks*

Figures 8 and 9 show the results obtained three weeks after the magnitude 7.5 Landers earthquake of 28 June 1992. The survey was conducted alongside two parallel roads which are about 1.7 km apart and were both offset nearly 3 m by the earthquake ruptures. The measurements were made along a 300-m line beside Encantado Road and a 420-m line beside Reche Road in Landers. The background values here were very low. The high permeability of the sandy surface soil in this dry desert area possibly permitted easy mixture of the radon-poor atmospheric air with the soil air. In the two major fault breaks, however, the radon values were an order of magnitude higher than background. At the Encantado site, there was a smaller break in the middle, where the radon concentration was also somewhat (about 4 times) higher than the background values.

The survey at Encantado Road was repeated two days later. As shown in Fig. 8b, a similar radon anomaly was observed but the amplitude was some-

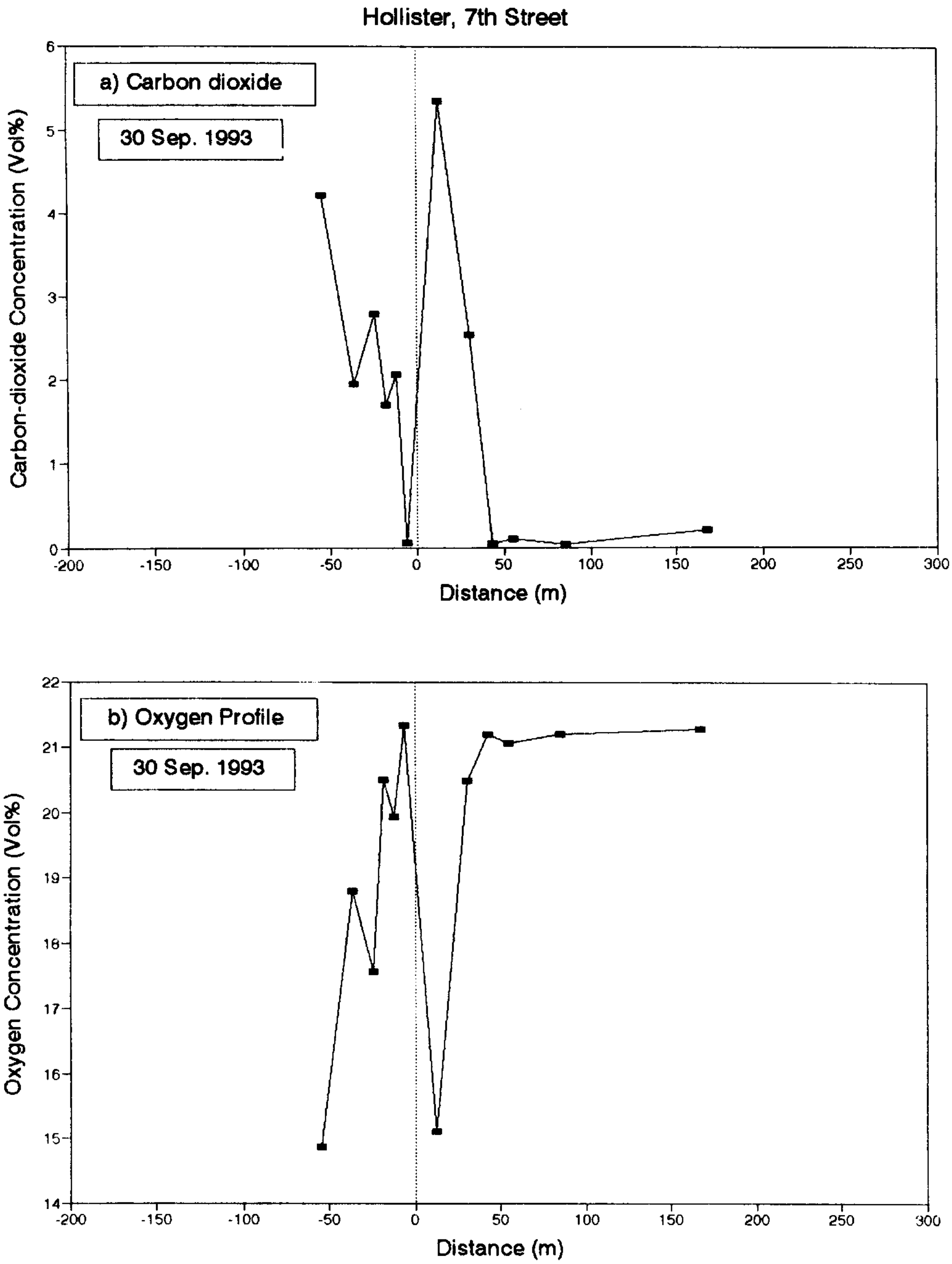


Fig. 4. Concentrations of carbon dioxide (a) and oxygen (b) vs. distance along the survey line crossing the creeping Calaveras fault near Seventh Street in Hollister observed on 30 September 1993.

what diminished. This diminution may be partly due to statistical fluctuation in counting. It may also be partly the result of a flow of radon-poor atmospheric air into the soil after the first survey, caused by the partial vacuum created by the gas sampling process. When the second survey was conducted, the sampled spaces might not have had enough time to receive sufficient fresh supply of radon from below.

A survey was also conducted in and along two 600 m-long fault breaks that crossed Reche Road (Fig. 10). The radon values at most points along the breaks were much higher than the above-mentioned background values recorded on either side of the fault.

## DISCUSSION

Our surveys in California showed anomalously high radon emanations (up to an order of magnitude above the background values) on four active fault zones. These anomalies have features that may be indicative of the structures of the fault zones. Environmental

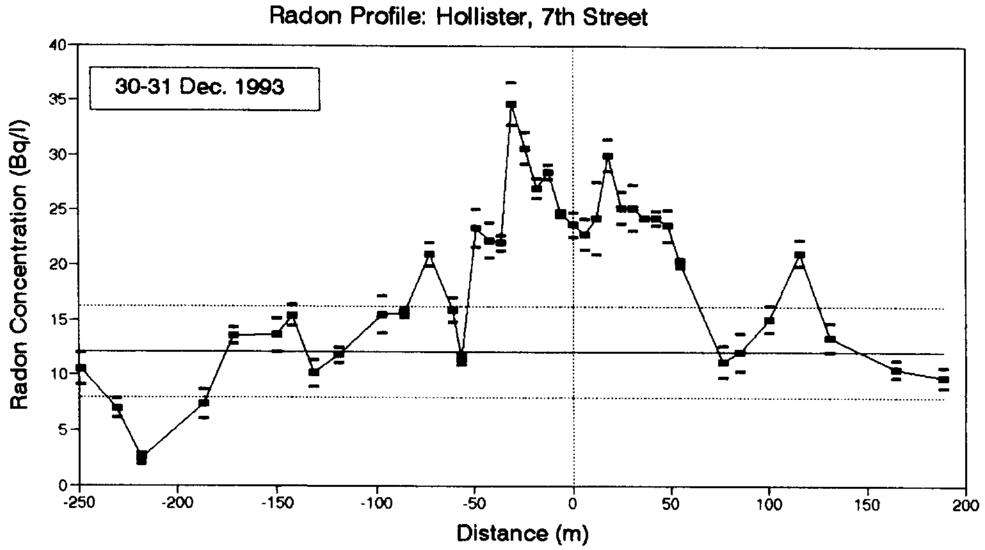


Fig. 5. Radon concentration vs. distance along the survey line crossing the creeping Calaveras fault near Seventh Street in Hollister, observed on 30 and 31 December 1993. The horizontal bars indicate one standard deviation above and below the mean value of three measurements made at each point.

changes, such as rainfall, were able to affect the radon concentrations, but most of the fault-associated anomalies were able to persist.

What are the possible causes for the fault-related radon anomalies? They are unlikely to be due to radon originated from depths of one kilometer or more, because of radon's short half-life of 3.8 days and slow speed of migration in the ground (Tanner, 1980). Nor are these anomalies likely to be caused by barometric-pressure or elevation changes, because such changes were very small during most surveys. One possible perturbation is non-uniform watering in Hollister, but this was done only in the vicinity of Dunne park where the background data were measured; the anomalies were recorded in the park itself where watering was quite uniform.

Another possible cause is different soil porosity between fault zones and their side areas. For a closed soil system (i.e. no gas outflow), the radon concentration $C$ is given by (Tanner, 1980):

$$C = 37(\rho K Ra)/3\varepsilon, \text{ Bg/l}$$

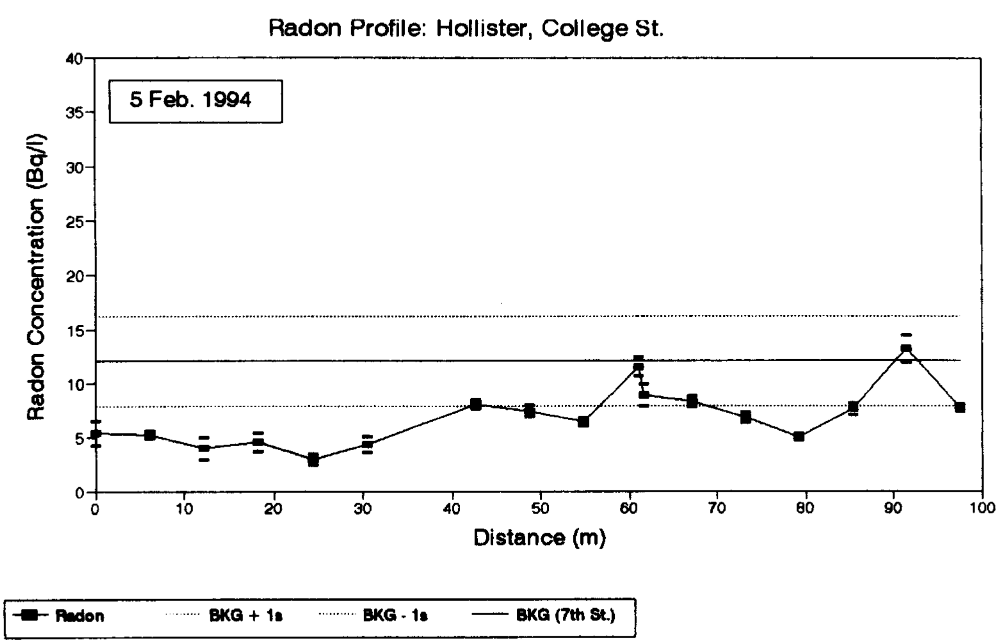


Fig. 6. Radon concentration vs. distance observed on 5 February 1994 along a survey line parallel to and 270-m west of the Calaveras fault in Hollister. The distance shown is from the cross-fault survey line (Fig. 5) toward north. The background levels are those measured alongside 7th St. on 30 and 31 December 1993.

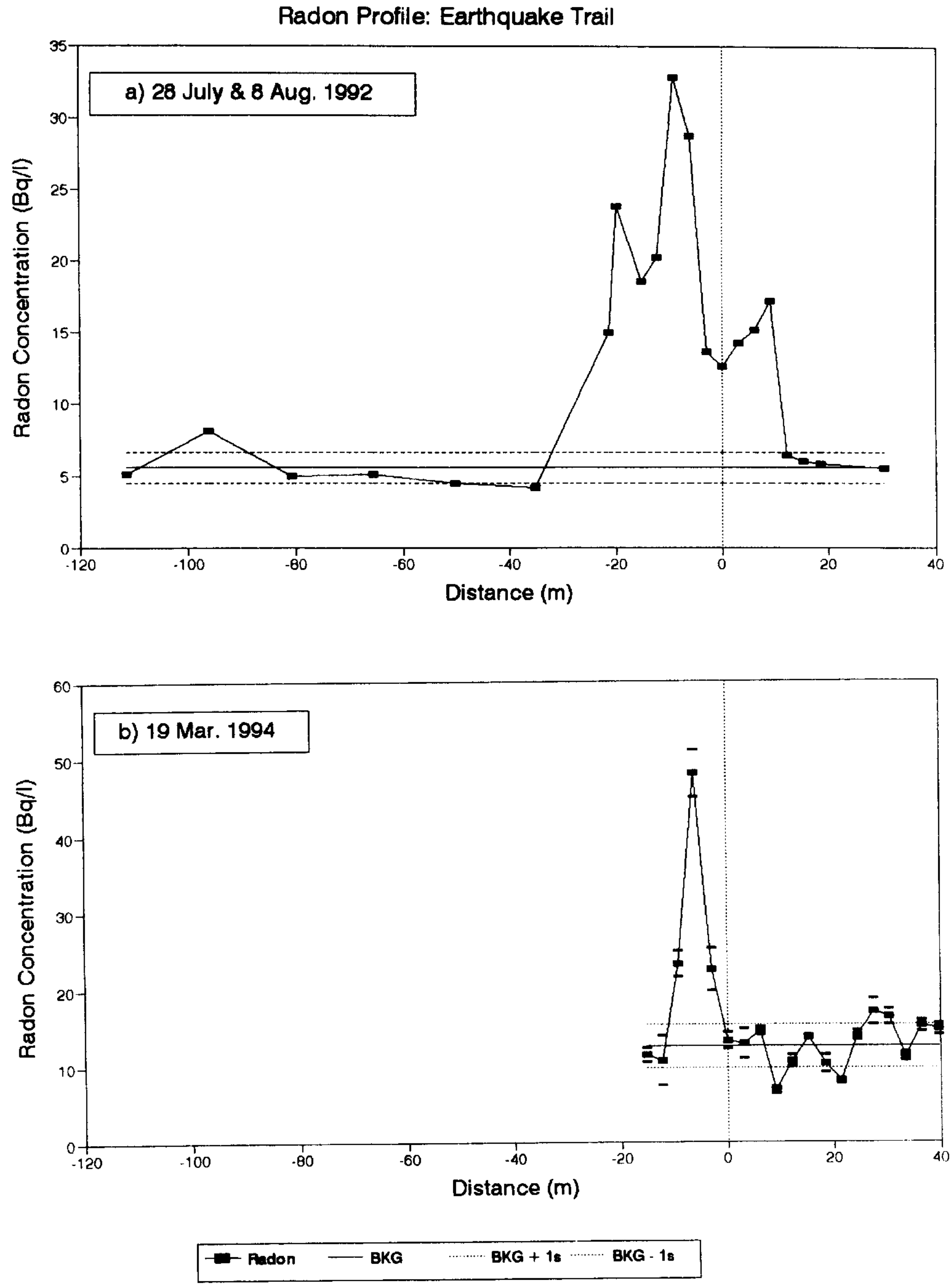


Fig. 7. Radon concentration vs. distance along a line across the locked San Andreas fault at Earthquake Trail in Point Reyes National Seashore, observed on 28 July and 8 August 1992 (a); and 19 March 1994 (b).

where $\rho$ is the soil density (gm/cm$^3$), $K$ is the radon-emanation efficiency, $\varepsilon$ is the soil porosity, and $Ra$ is the $^{238}U$ equivalent at equilibrium (ppm) of the activity of $^{226}Ra$ present. Since radon concentration is inversely proportional to porosity, one would expect the soil in the mechanically disturbed fault-zone to have higher porosity and lower radon emanation than soil on country rocks, not higher emanation as observed. Furthermore, the soil porosity along any survey line does not appear likely to vary by more than a factor of two or three, significantly less than the observed order-of-magnitude radon variations.

One possible cause for the fault-associated radon anomalies is higher outgassing rate in the fault zones where the gas permeability is relatively high. Because subsurface radon concentration is known to increase with depth greatly (by three orders of magnitude) over a range of only several meters (Fig. 11, from Junge, 1963), a slightly higher outgassing rate tends to bring up slightly deeper soil air which contains significantly more radon to the detection level and thus can cause

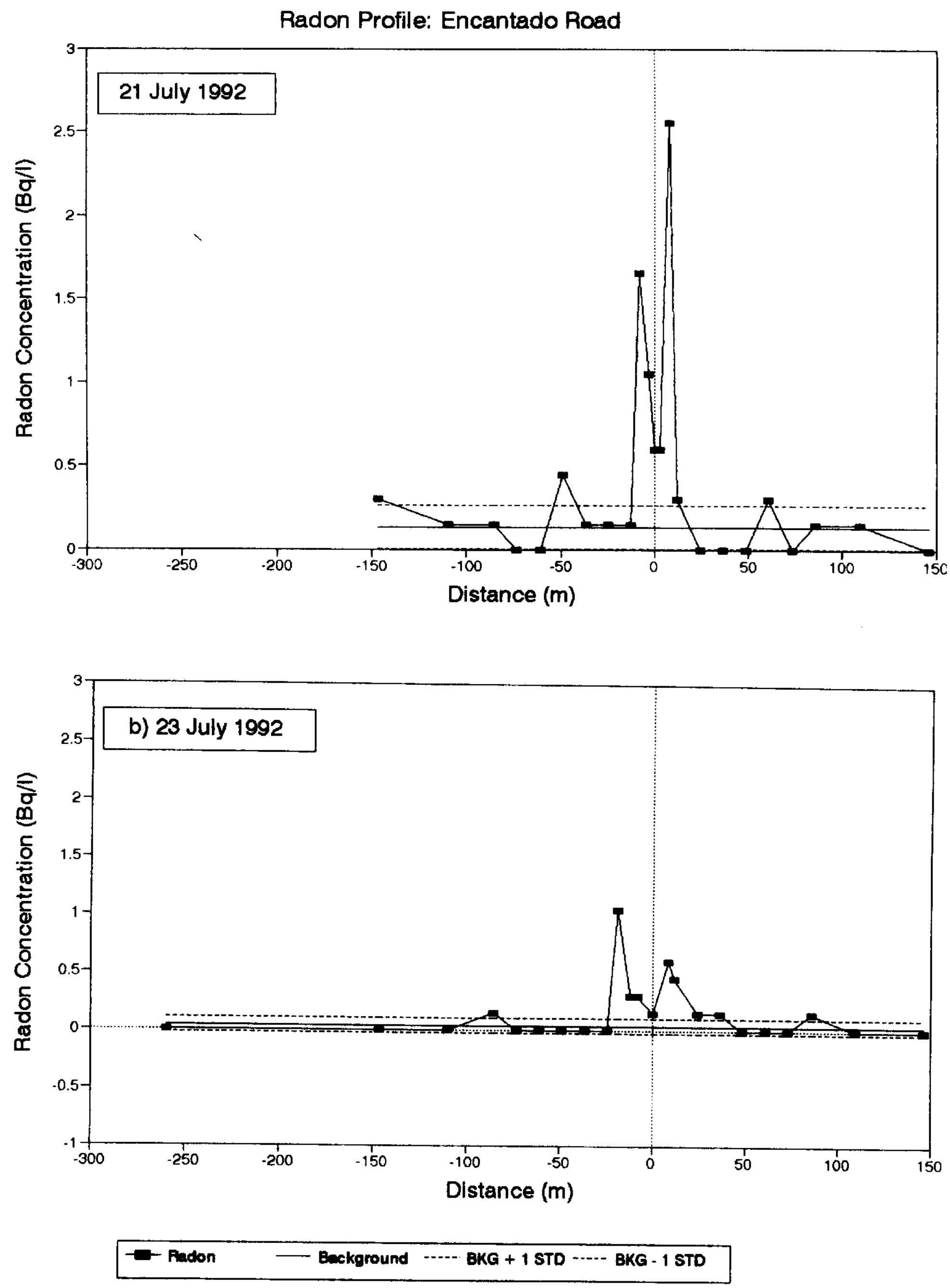


Fig. 8. Radon concentration vs. distance alongside Encantado Road, crossing the fault zone broken during the 1992 Landers earthquake. The surveys were conducted on 21 July (a) and 23 July (b), 1992.

the anomalies. King (1978) proposed a one-dimensional model in which the soil is treated as a homogeneous porous half-space with uniform radium distribution (thus uniform radon production rate). On the assumption that radon migrates by molecular diffusion in the soil governed by Fick's law and by soil–air flow governed by Darcy's law under a vertical pore-pressure gradient (which is known to exist in the crust), and that the radon concentration is negligibly small at the surface, it was shown that the steady-state radon concentration $C$ is a function of depth, $-z$, as follows (e.g. Clements, 1974):

$$C = \frac{\phi}{\lambda}\left\{1 - \exp\left(\gamma\left(\frac{\varepsilon\lambda}{D}\right)^{1/2} z\right)\right\}$$

where

$$\gamma = \frac{\nu}{2(\varepsilon\lambda D)^{1/2}} + \left(\frac{\nu^2}{4\varepsilon\lambda D} + 1\right)^{1/2}$$

$\phi$ is radon production rate, $\lambda$ is its decay constant, $\varepsilon$ is soil porosity, $D$ is the molecular diffusion coefficient of

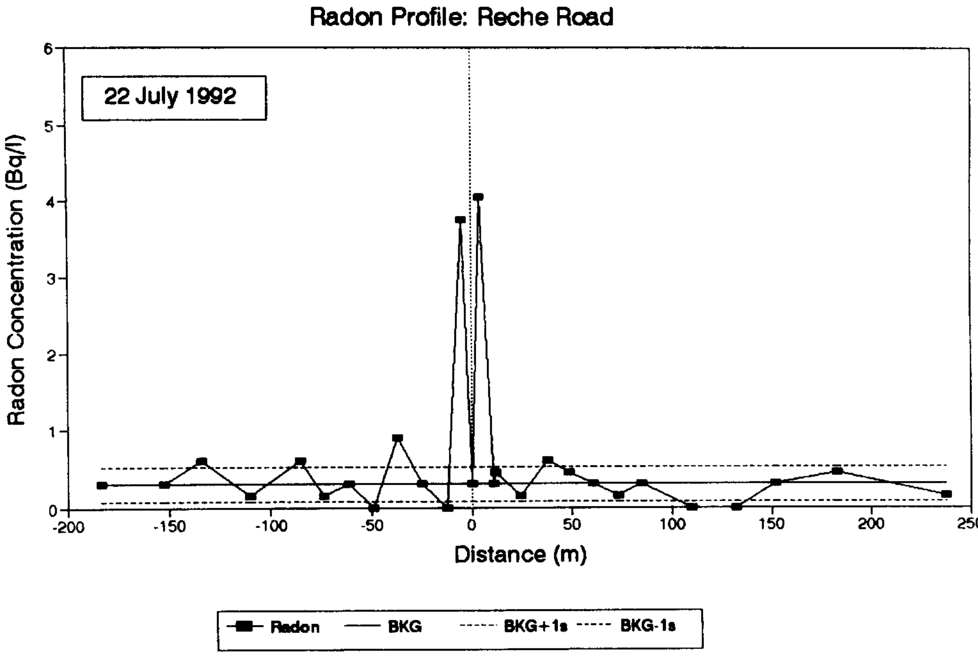


Fig. 9. Radon concentration vs. distance alongside the Reche Road, crossing the fault zone broken during the 1992 Landers earthquake. The survey was conducted on 22 July 1992.

radon in the soil, and $v$ is the apparent soil–air flow velocity (volume of flow per unit time per unit area). Figure 12 shows the results for five different flow velocities (0, $\pm 3 \times 10^{-4}$, $\pm 10^{-3}$ cm/s, positive upward) and assumed material constants appropriate for typical dry soils. It is evident that a relatively small upward or downward flow is fully capable of increasing or decreasing the subsurface radon concentration at shallow depths (of about 32 cm) by as much as an order of magnitude. To check whether the subsurface radon concentration profile varies as predicted by the model, King (1978) made measurements in boreholes of several different depths separated by several meters at a site. Figure 13 shows the depth profiles for a three-

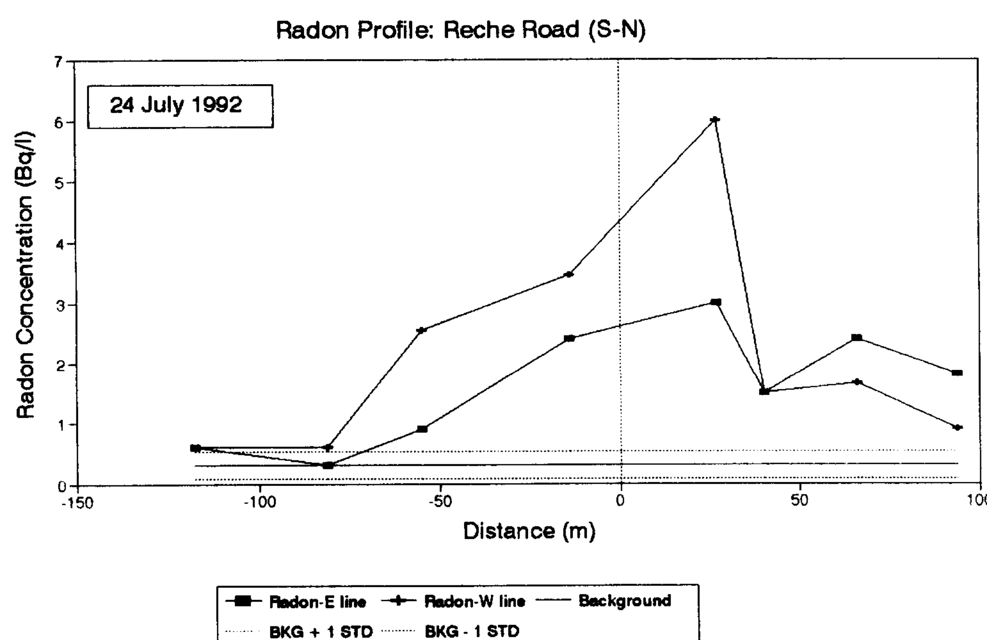


Fig. 10. Radon concentration vs. distance in and along the two fault breaks associated with the 1992 Landers earthquake. The distance is measured from the center of Reche Road; north is to the right of the figure. The background values are from the cross-fault survey shown in Fig. 9.

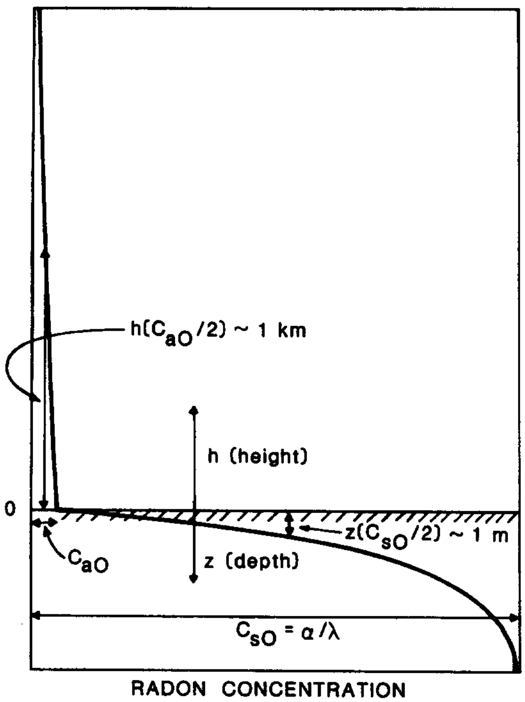


Fig. 11. Schematic diagram of radon concentration in atmosphere and soil air near the ground surface as a function of elevation and depth. $C_{so}$ is concentration in undisturbed soil air at great depth; $C_{ao}$, concentration at surface. (After Junge, 1963.)

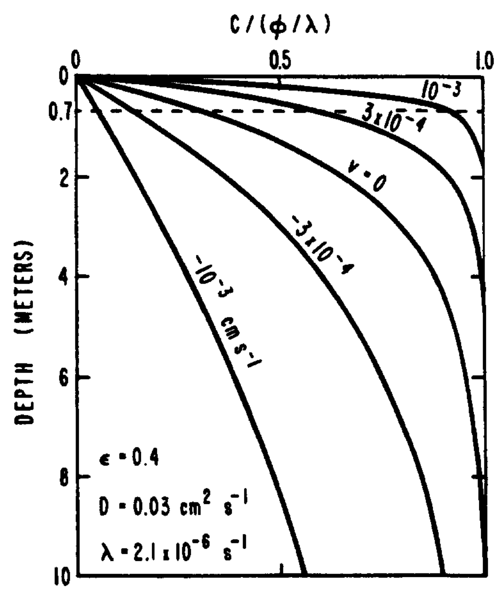


Fig. 12. Radon concentration as a function of depth calculated for a homogeneous, porous half-space with uniform radon production rate and parametric values appropriate for typical dry soils for five different vertical gas-flow velocities. Sampling depth in the present study is 32 cm, about half as indicated by the dashed line. (After King, 1990.)

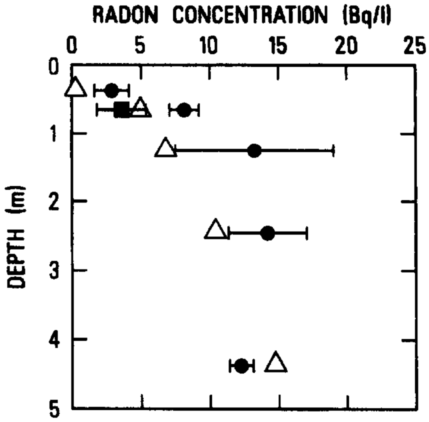


Fig. 13. Radon concentration as a function of depth observed by King (1978) during two different periods in a cluster of holes of different depths. The square indicates a long-term average value at a depth of 0.7 m; the solid circles indicate the measured radon profile for an anomalous period; the triangles the result for a nearly normal period. (Modified from King, 1978.)

week period during which the radon emanation was anomalously high and for a two-week period during which the emanation was near background level. It is evident that during the anomalous period radon concentration increased at the shallower depths only, in agreement with the model. We plan to do a similar study at some of our survey sites.

To calculate radon concentrations expected from the above-mentioned model, we need to measure the uranium content and the emanation efficiency of local soil. Being unable to do such measurement with soil at the survey sites due to lack of funds, we use the results of King (1980) who did such measurements on soil samples collected at about 30 other sites in central California during 1975–1978. As shown in Figs 14a and b, the uranium contents differed at most by a factor of three from one site to another, and the corresponding radon concentrations differed by an order of magnitude with no obvious correlation with the uranium contents of the soil, even with the emanation efficiency taken into consideration (Fig. 14b). The soils at most of the presently surveyed sites appear to be quite uniform in composition, and the variations of uranium contents at any such site should be far less than a factor of three (see King, 1985 for measured values at another site). Thus the observed anomalies are not likely to be caused by possible non-uniform uranium distribution.

From the previously obtained values of uranium content (Fig. 14) and with the assumption of soil density of 1.5 g/cm$^{-3}$ and porosity of 0.4, we calculated the maximum soil–air radon contents to be in the range of 7–52 Bq/L, which is consistent with the peak values observed in the present surveys (1–50 Bq/L).

Radon activity in subsurface soil air is known to show weather-related seasonal variation (e.g. King

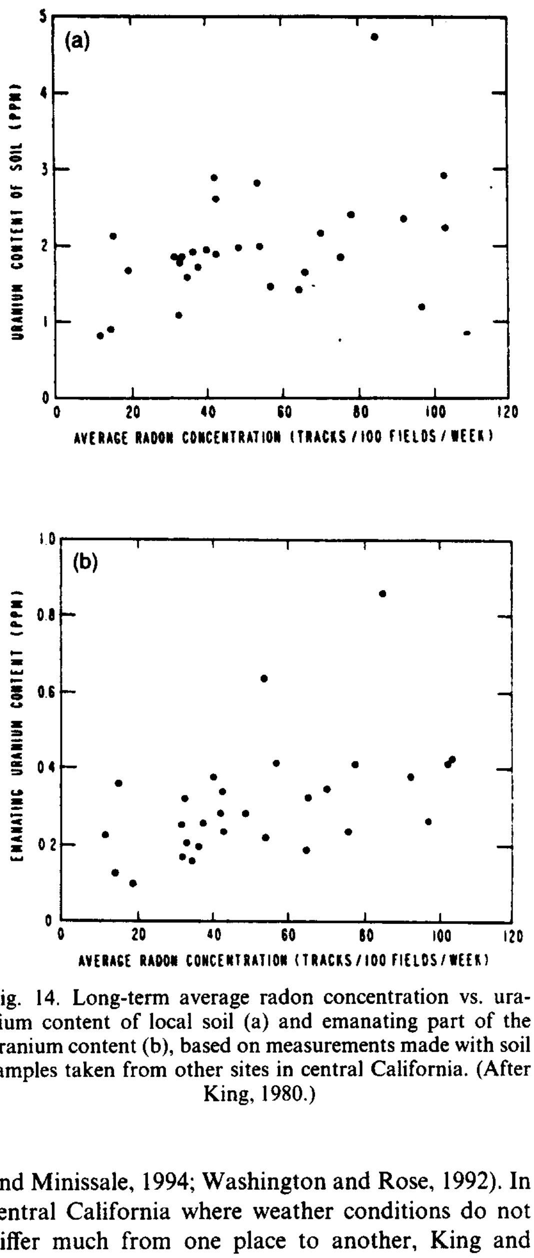


Fig. 14. Long-term average radon concentration vs. uranium content of local soil (a) and emanating part of the uranium content (b), based on measurements made with soil samples taken from other sites in central California. (After King, 1980.)

and Minissale, 1994; Washington and Rose, 1992). In central California where weather conditions do not differ much from one place to another, King and Minissale observed several different patterns of seasonal variation among 60 sites they studied. They attribute the different patterns largely to the water-saturation and moisture-retention characteristics of the shallow part of the soil. During the rainy season, radon tends to be confined underground by the water-saturated surface soil which has much reduced gas permeability (and available porosity). The thickness of this confining layer at any particular time differs from one site to another, depending on the topography and water permeability of the soil. At a sloping or low-permeability site where the confining layer is relatively thin, radon concentration measured below the layer tends to show increased values. On the other hand, at a flat high-permeability site where the confining layer is thicker than the detection depth and thus preventing deeper and radon-richer air from reaching the detector, the measured radon value tends to be reduced. The same explanation is applicable to the observation of the relatively lower radon peaks observed during the rainy season at Nyland (Figs 2a and b) where the permeability is relatively high (short sampling time), and corresponding increase in background values in Hollister (Figs 3a,b and 5) where the permeability is relatively low, or at the Earthquake Trail (Figs 7a and b) on a slope. This model can also explain why the peak values did not show much increase in a rainy season, because they were already near the maximum levels during the dry seasons.

The twin-peak feature of the observed radon anomalies across the creeping faults can be understood on the basis of the above-mentioned model as follows. The low radon values in the sliding zones may be due to the low permeability of the fault-gouge materials in the zones. The anomalously high values observed on the adjacent sides may be due to the existence of shear zones containing inter-connected fractures in rocks where the permeability is anomalously high, thus providing easy paths for outgassing. Such fault structures were observed by Wallace and Morris (1986) in deep mines (Fig. 15). The outgassing hypothesis is also supported by the increased $CO_2$ and decreased $O_2$ concentrations observed at places where radon values were found to be high (Figs 3b, 4a and

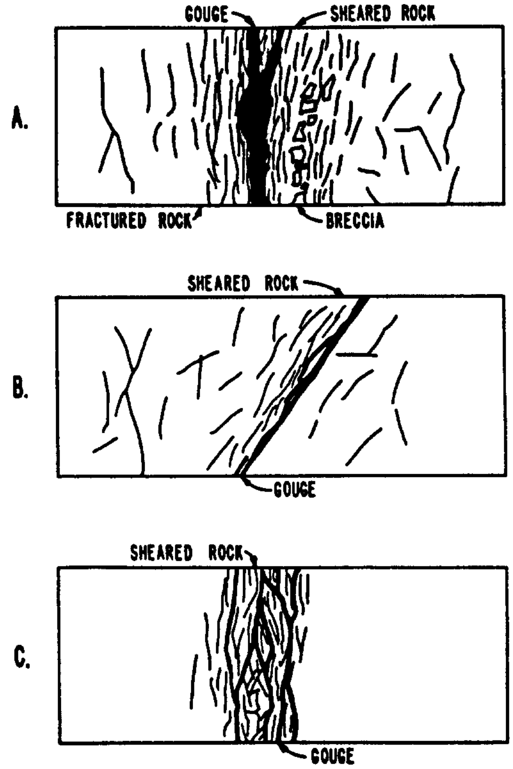


Fig. 15. Diagrams showing different positions of gouge materials in the fault zones. (A) Gouge zone near center of fault zone. (B) Gouge localized at one boundary of fault zone. (C) Thin gouge seams forming anastomosing pattern through fault zone. (After Wallace and Morris, 1986.)

b), because deeper soil air is known to contain more $CO_2$ and less $O_2$.

The outgassing model requires a higher gas-outflow rate for anomalous radon emanation, but does not specify the ultimate sources of the gases. They could come from earth's deep interior, or laterally from surrounding country rocks, or both. To ascertain the sources, we need to make more detailed measurements of the chemical and isotopic compositions of the soil air. For example, in addition to carbon dioxide and oxygen, it is desirable to measure hydrogen, helium and carbon isotopes, because deeper gas tends to have less tritium and carbon-14, and mantle gas has a higher $^3He/^4He$ ratio than crustal gas and atmospheric air (see King, 1986).

## SUMMARY

(1) Radon emanations on four active fault zones in California were measured to be higher than background values by as much as an order of magnitude, as has been observed by other investigators on other faults.

(2) The radon anomalies show characteristic features which may be structurally controlled. These features may be modified in time by other environmental changes, particularly rainfall.

(3) A possible cause for the anomalies is a higher outgassing rate in the anomaly zones, which probably have higher gas permeability.

This work suggests that radon measurement may possibly be used for measuring vertical gas-flow rate in the ground, for mapping (unknown) faults, and for studying radon pollution in buildings on fault zones.

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