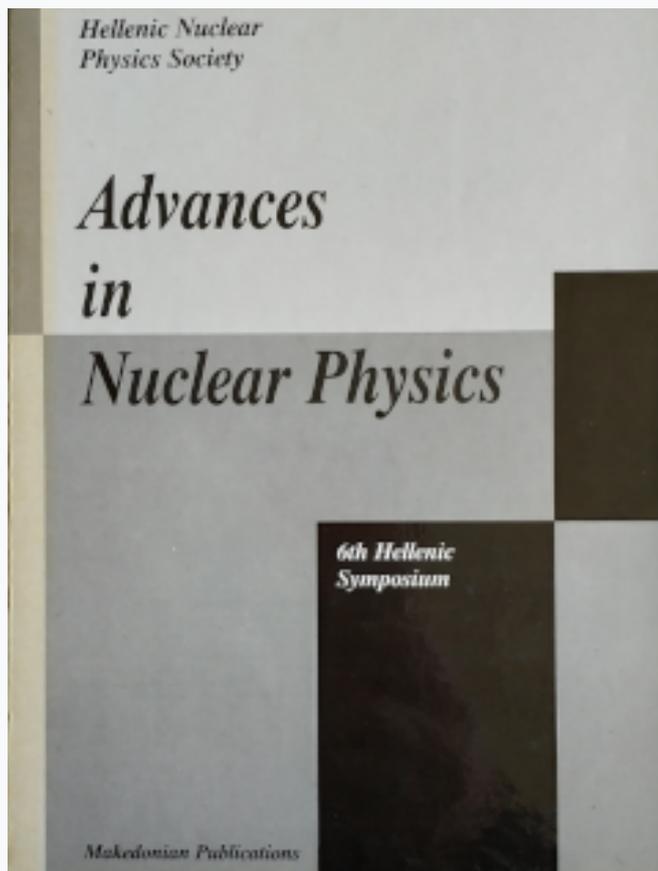


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# Assessment of arrangements for the detection of radon emanating from soil

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## Abstract

CR-39 solid state nuclear track detectors were used to measure radon ( $^{222}\text{Rn}$ ) concentration in the soil near ground surface. The measurements were performed in the campus of the University of Ioannina, using PVC tubes at 0.25 m intervals down to depths of 1.25 m. The track detectors were etched in 7N NaOH solutions at 80°C. The tracks were counted using a microscope - camera - computer system, developed for automatic counting. The results provide evidence for the non-diffusive transport of radon in soils. A transport length of  $(46.9 \pm 3.2)$  cm was estimated for radon transport near ground surface. Also the variation of soil's radon was correlated to meteorological variations.

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## 1 Introduction

Radon ( $^{222}\text{Rn}$ ) is an inert radioactive gas, formed as progeny of uranium and emanated from soil and rocks in various concentrations. Radon and its decay products are the most important sources of radiation, contributing approximately half of the total effective dose equivalent received from artificial and natural radioactivity sources [1]. Levels of radon progeny in houses depend on the geology underlying house foundations and the mechanisms of radon transport. The sheared fault zones are known to cause high indoor radon concentrations. Radon moves upwards in soil partly by diffusion and partly by bulk flow caused by changes in air pressure at the surface. The purpose of the work presented here was to study the radon concentrations in soil with arrangements that may be used for geological research, especially for the detection of geological faults.

## 2 Experimental methods

The measurements of radon concentrations were carried out with CR-39 solid state nuclear track detectors [2] (Pershore Mouldings Ltd). The detectors were placed in 10 cm intervals, inside PVC tubes with lengths 25 to 125 cm (Fig. 1). The tubes were buried in the soil, distanced 25 cm one tube from the other. The detection arrangements were calibrated in the radon calibration chamber of NRPB laboratories in Didcot, UK.

The CR-39 detectors were etched in a solution of 7N NaOH at 80°C for 8 h. Then they were measured using a semi-automatic track measuring arrangement, employing a microscope-CCD camera-frame grabber-computer chain (Fig. 2). The computer program TRACKA [3] was used to count the number of tracks per optical field by counting the picture elements (pixels) of certain grey-scale values (Fig. 3). Preceding the enumeration of the tracks, the system was calibrated to assign the appropriate grey scale values to the mean number of pixels of a track image.

## 3 Results and discussion

The detectors were exposed to radon soil for periods of 15 d. Typical measurements of radon concentration as a function of depth from the soil surface are presented in Fig. 4. To explain this sort of behaviour for radon emanation, Fick's first law may be used:

$$J = -D \vec{\nabla} C \quad (1)$$

where  $C$  [ $\text{Bq m}^{-3}$ ] and  $[J \text{ m}^{-2} \text{ s}^{-1}]$  are the concentration and current density of activity in the interstitial volume and  $D$  [ $\text{m}^2 \text{ s}^{-1}$ ] is the diffusion coefficient. The rate of change of activity concentration is predicted by the diffusion equation

$$\frac{\partial C}{\partial t} = D \vec{\nabla}^2 C - \lambda C + S \quad (2)$$

where  $\lambda$  is the decay constant of  $^{222}\text{Rn}$  and  $S$  is the generation rate of  $^{222}\text{Rn}$  available for diffusion per interstitial volume.

According to the steady state model

$$\frac{\partial C}{\partial t} = 0 \text{ and } S = \text{constant} \quad (3)$$

Then the solution of Eqn. (2) can be written as

$$C(z) = C_0[1 - \exp(-\sqrt{\frac{\lambda}{D}}z)] \quad (4)$$

$$C(z) = C_0[1 - \exp(-z/L)] \quad (5)$$

where  $C(z)$  is the radon concentration at a depth  $z$  from the surface,  $C_0$  is the maximum concentration in soil and

$$L = \sqrt{\frac{D}{\lambda}} \quad (6)$$

is the diffusion length.  $L$  ranges from 1.6 m to 1.9 m for dry silt, sand and gravel materials. For wet clay materials, diffusion lengths of about 0.01 m were reported [4].

From the inspection of Eqns. (1)-(6) and the fact that the motion of radon in the ground is limited by its decay ( $t_{1/2} = 3.82$  d), it is concluded that according to the diffusion theory, measurable quantities of radon do not originate from distances more than 10-15 m. However, radon from ores at even greater distances can be detected if a transport mechanism, other than diffusion, is assumed active. Thus it is accepted that radon is transported not only by diffusion but also by fluid flow.  $^{222}\text{Rn}$  fluxes from the combined diffusive and advective transport in an isotropic region are defined by the combination of Fick's law (for diffusion) and Darcy's law (for air flow) as [5]:

$$J = -Dp \vec{\nabla} C - \frac{\kappa}{\mu} \vec{\nabla} PC \quad (6)$$

where  $p$  is the total porosity,  $\kappa[\text{m}^2]$  is the soil gas permeability,  $[\text{Pa s}]$  is the viscosity of soil gas and  $P$  is the soil gas pressure. The one-dimensional (1-D) form of the transport Eqn. (6) with constant production, diffusion and flow velocity has the following solution [6]:

$$C(z) = C_1 \exp \left[ \sqrt{\left(\frac{vp}{2D}\right)^2 + \frac{\lambda p}{D} - \frac{vp}{2D}} z \right] + C_2 \left\{ 1 - \exp \left[ -\sqrt{\left(\frac{vp}{2D}\right)^2 + \frac{\lambda p}{D} + \frac{vp}{2D}} z \right] \right\} \quad (7)$$

where  $z$ , is the coordinate chosen perpendicular to the surface,  $C_1$  and  $C_2$  are constants and  $v$  is the flow velocity in the soil.

Following Kristiansson and Malmqvist [6], the second term of Eqn. (9) is small implying that the local production of free radon has only a small influence on depth dependence. To a good approximation

$$\frac{\ln 2}{L_{1/2}} \approx \sqrt{\left(\frac{vp}{2D}\right)^2 + \frac{\lambda p}{D} - \frac{vp}{2D}} \quad (8)$$

and the depth dependence can be described by the expression:

$$C(z) = C_0 e^{\left(\frac{\ln 2}{L_{1/2}}\right)z} \quad (9)$$

where  $C(z)$  is the radon concentration at depth  $z$ , and  $c(0)$  and  $L_{1/2}$  are constants. Eqn. (9) seems to describe well the measured radon emanation displayed in Fig. 4. From our measurements,  $L_{1/2}$ , the distance in soil which corresponds to the half of the initial radon concentration, was estimated equal to  $(46.9 \pm 3.2)$  cm. The observed behaviour of radon concentration cannot be explained by single diffusion transport. The observed deviation from diffusion may be attributed to long distance transport mechanisms.

Inside the tubes, radon tends to remain near the soil. A typical profile of radon concentration inside the 1.25 m tube is shown in Fig. 5.

Soil radon was monitored with parallel measurements of meteorological conditions, such as temperature and soil humidity. Temporal variation of radon concentration in the 1.25 m tube compared to temperature and soil humidity variations are presented in Figs. 6-7. The correlation of radon concentration with soil humidity is shown in Fig. 8.

The above radon measurement techniques were applied for the detection of geological faults. Fig. 9 shows preliminary measurements of radon emanation across the Manoliassa fault, a fault near the town of Ioannina in north-western Greece. The pronounced peak suggests the presence of the fault. The applied method technique relies on the assumption that there is a higher temperature reservoir underneath and the high temperature causes the migration of radon through faults. The observation of considerably higher radon concentrations indicates the presence of a fault. If the existence of a long distance transport mechanisms is assumed, a model such as the one described by expression (9) should be adapted. Yet, the present results do not rule out the diffusion component of radon's migration through soil. According to the models described by Eqns. (1) to (9), radon moves upwards in soil partly by diffusion in soil gas and partly by flow caused by changes in air pressure at the surface. The diffusion flux may be estimated if one assumes that the radioactivity, porosity and density of the soil are independent of depth.

From the present results it is evident that meteorological changes such as rainfall which increases soil's humidity or pressure variation have a direct effect on radon emanation. The rain water while invading the pore spaces inhibits radon's escape. Also the pressure variations affect the radon's emanation rate. However, the effect of pressure is averaged out because passive detectors are exposed for relatively long periods.

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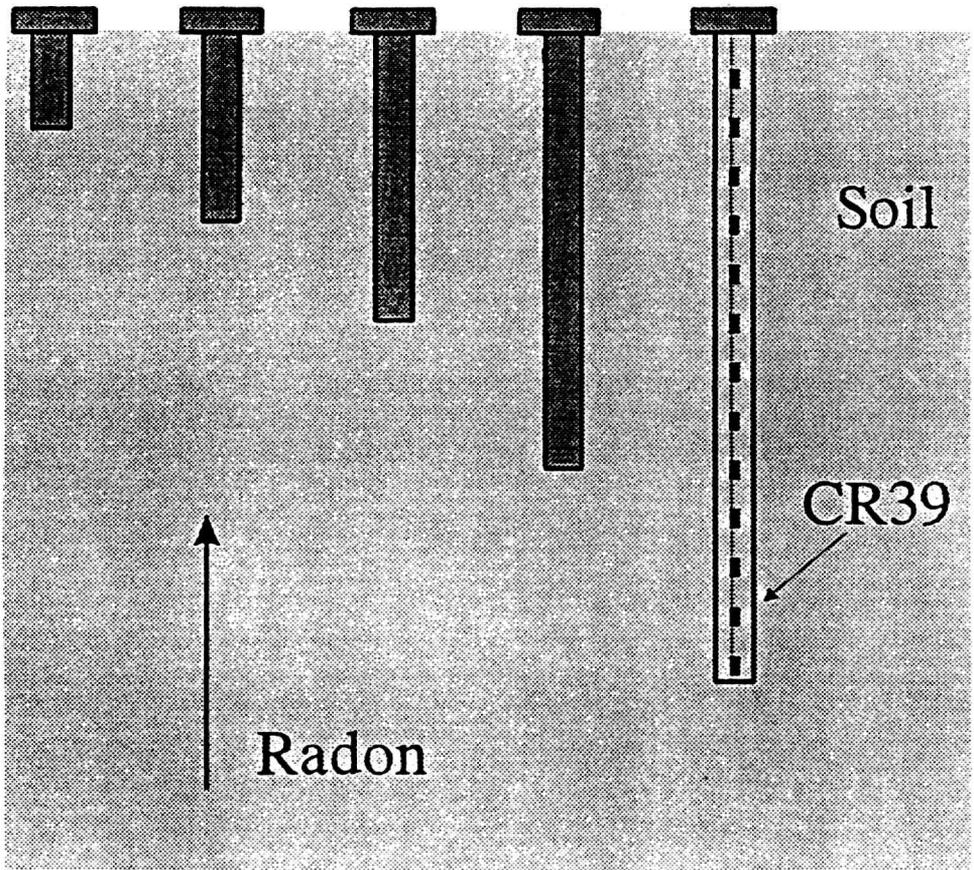


Fig. 1 Radon measurements arrangement.

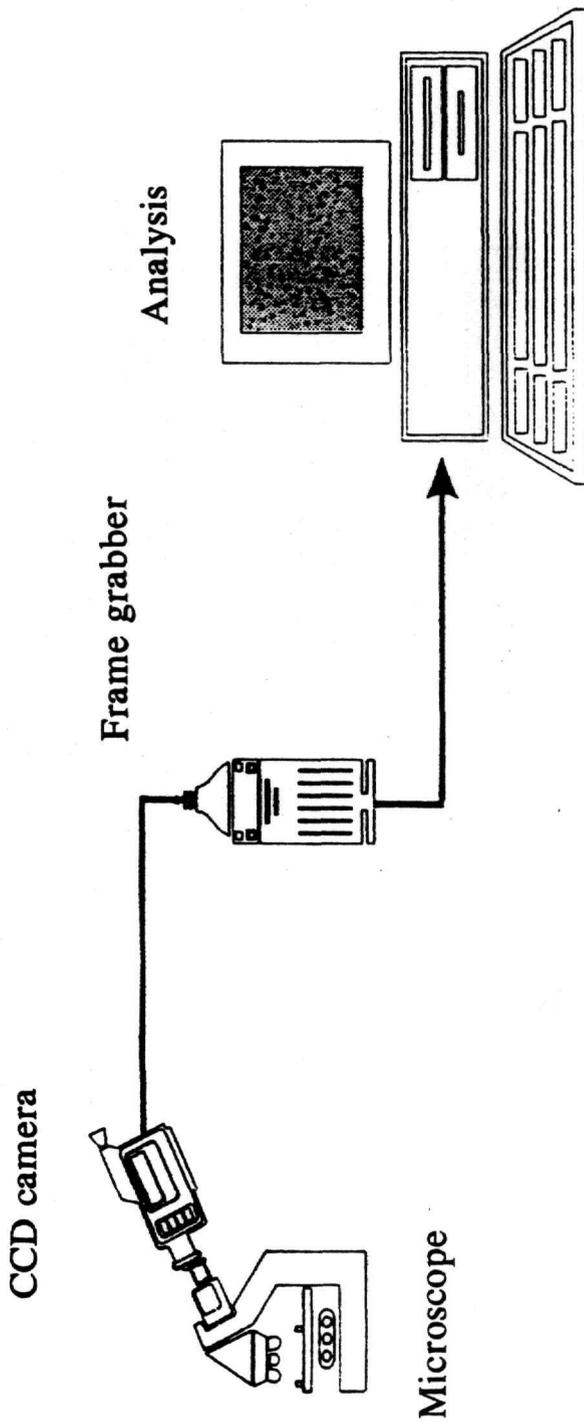


Fig. 2 Semi-automatic track measuring arrangement, employing a microscope-CCD camera-frame grabber-computer chain

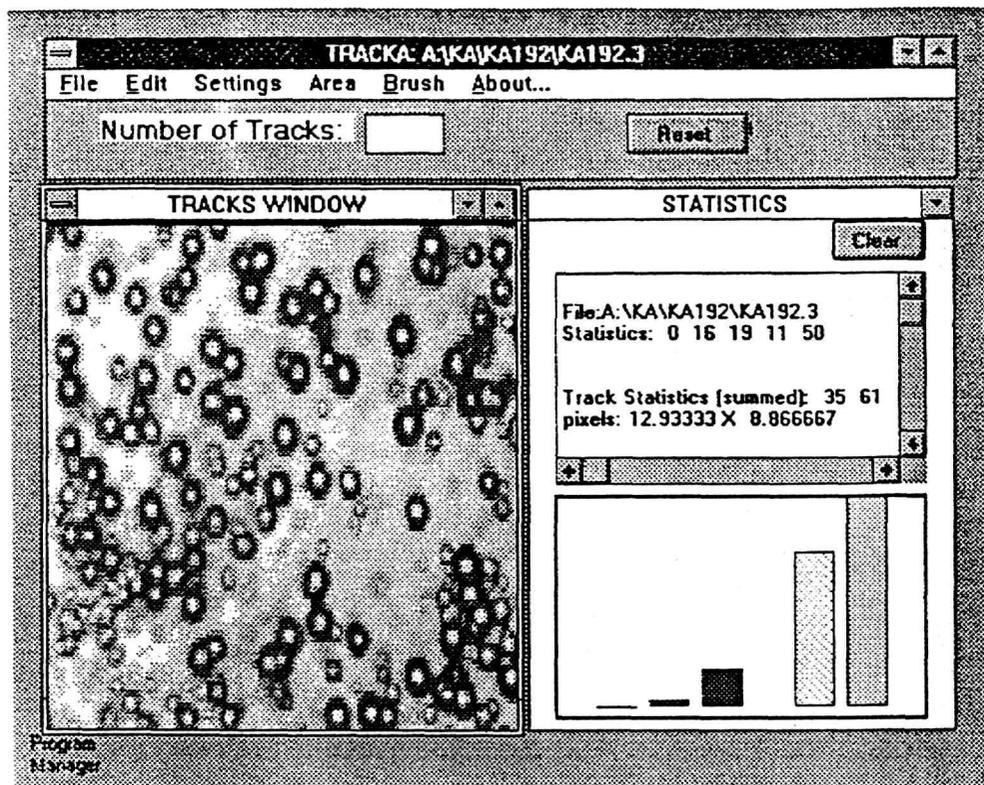


Fig. 3. Track analysis screen of program TRACKA.

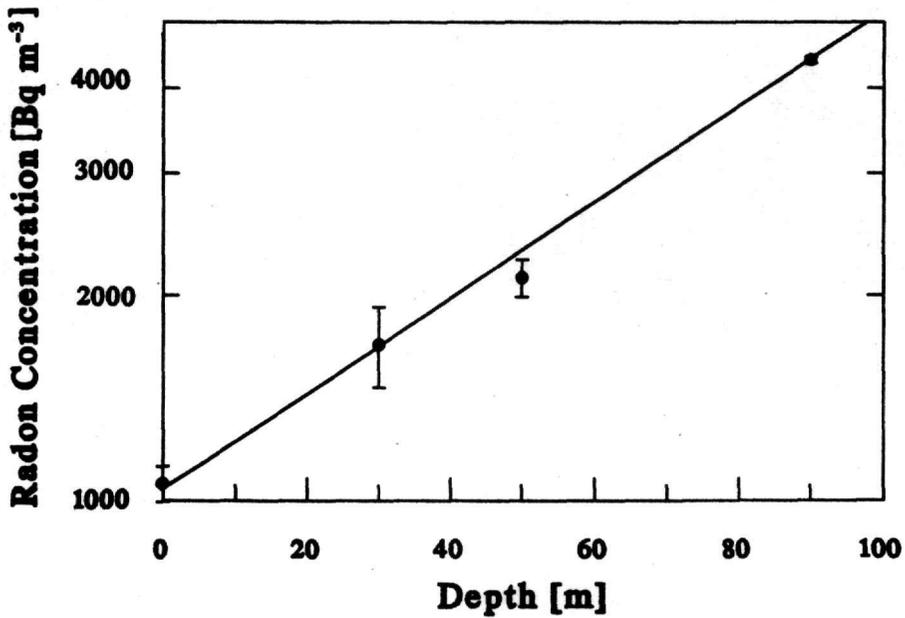
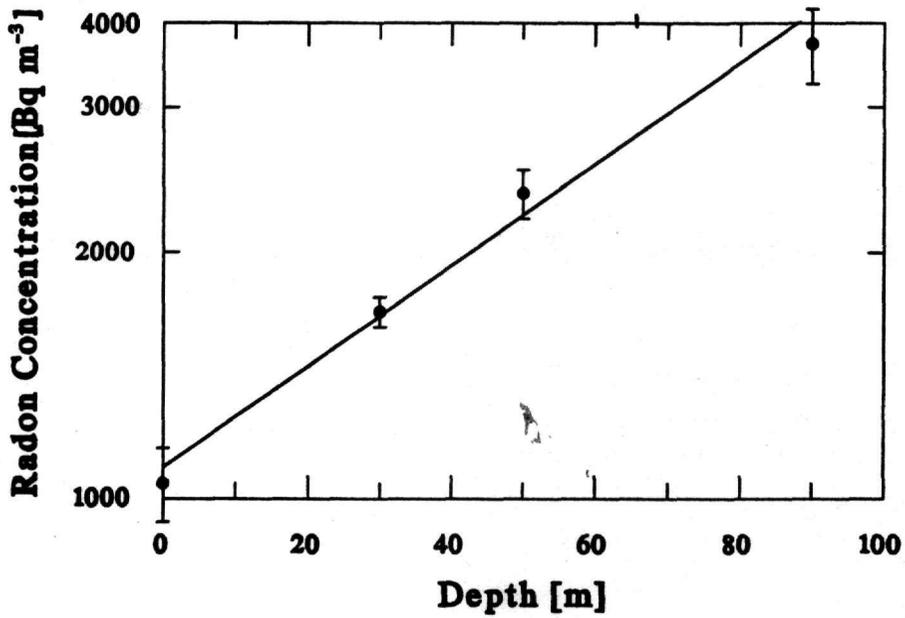


Fig. 4 Typical sets of measurements of radon concentration as a function of depth from the soil surface.

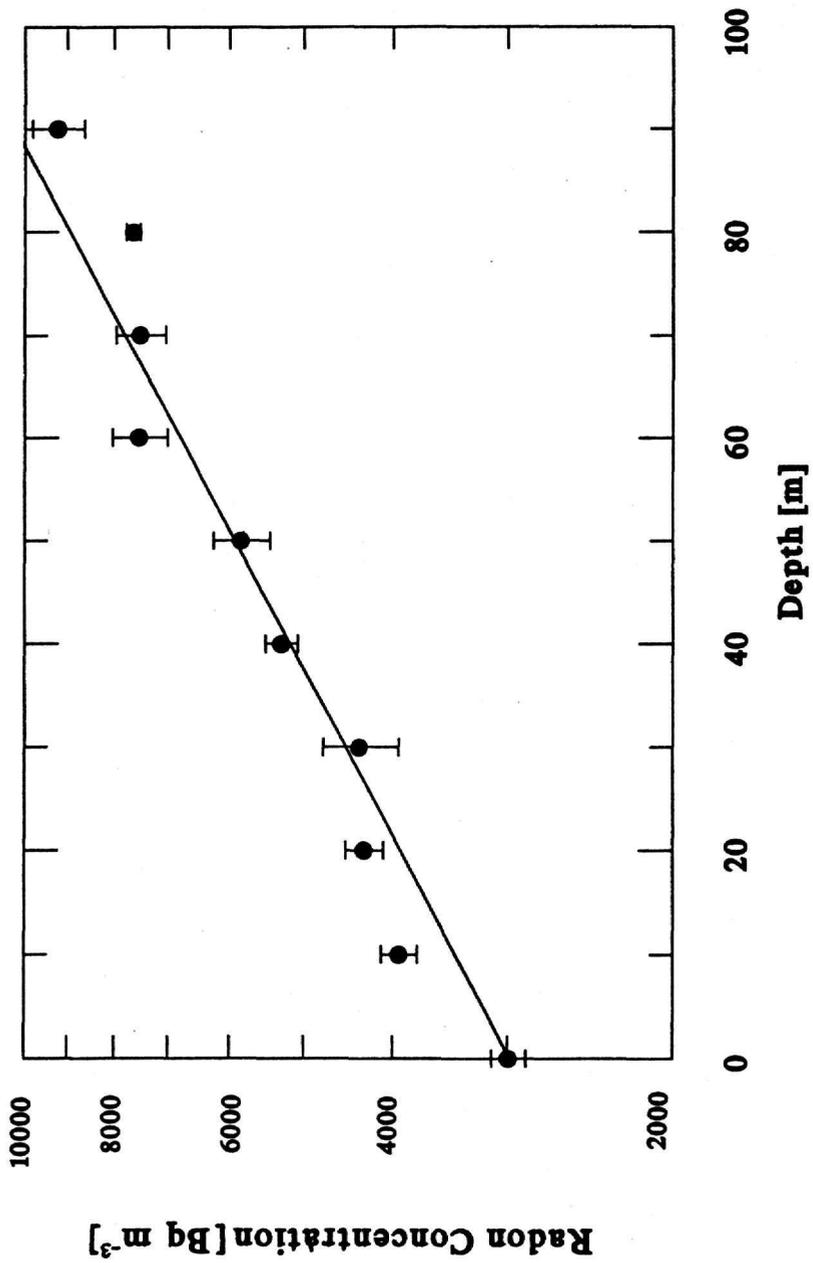


Fig. 5 Radon concentration profile in the 1.25 m tube.

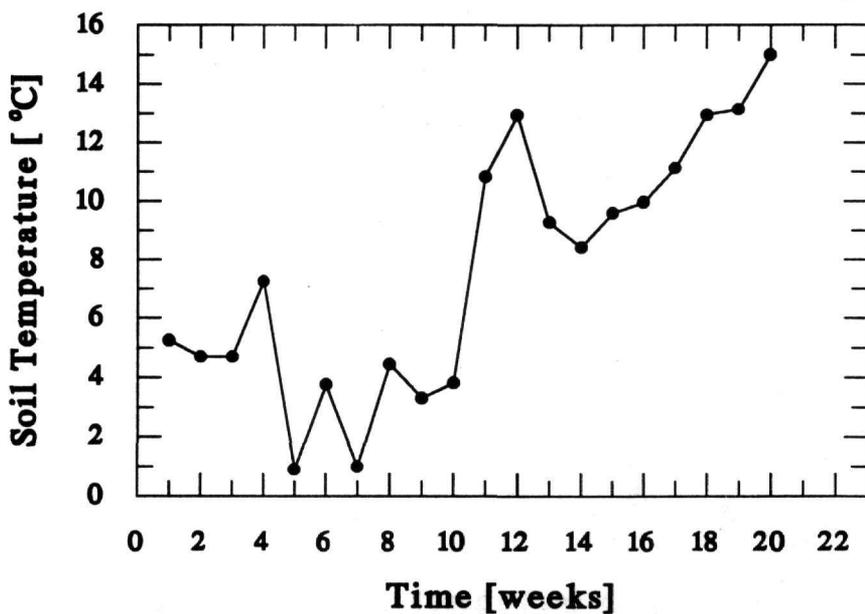
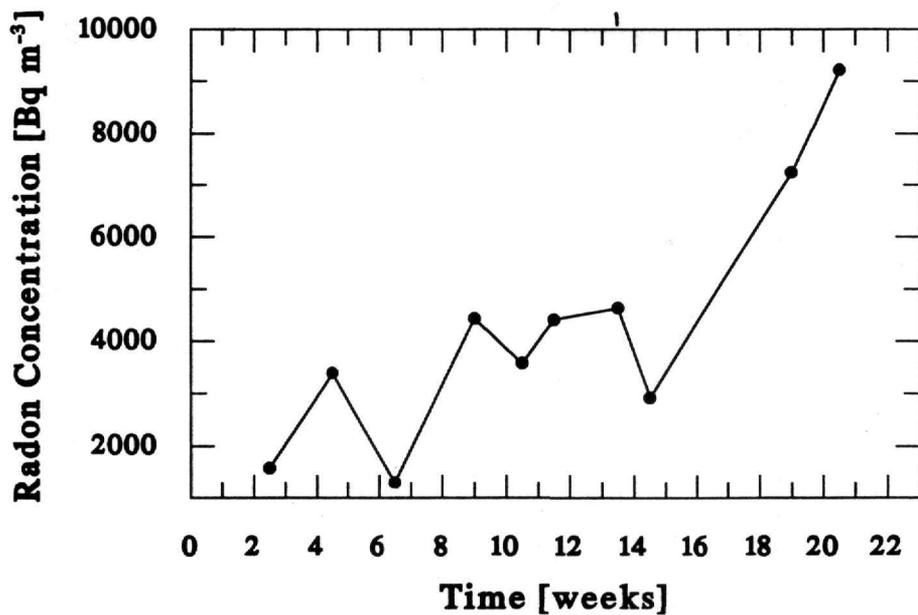


Fig. 6 Temporal variation of radon concentration in the 1.25 m tube compared to temperature variations.

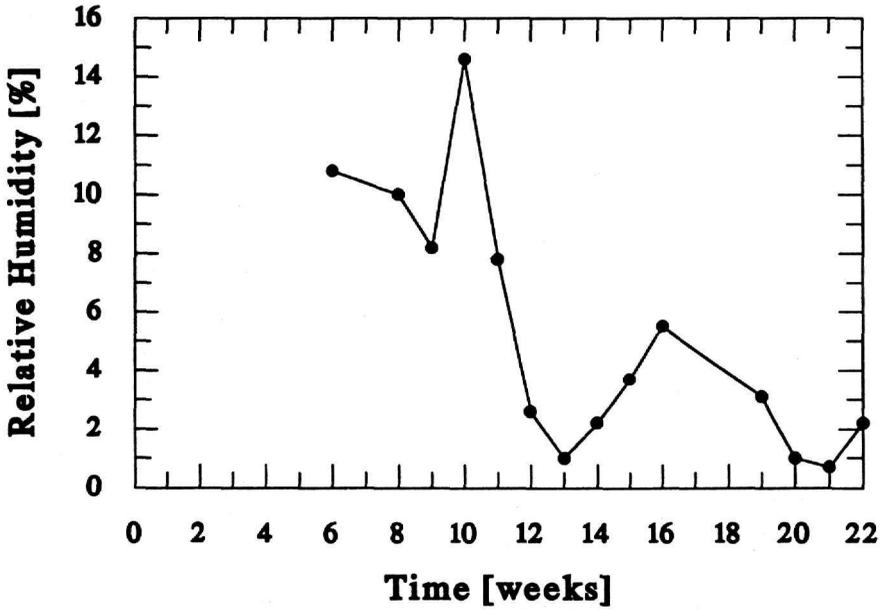
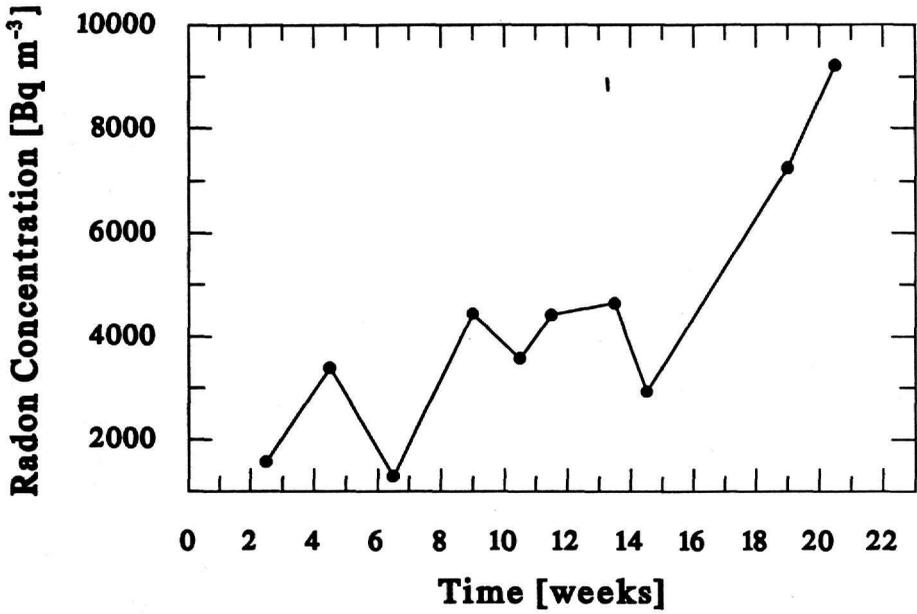


Fig. 7 Temporal variation of radon concentration in the 1.25 m tube compared to soil humidity variations.

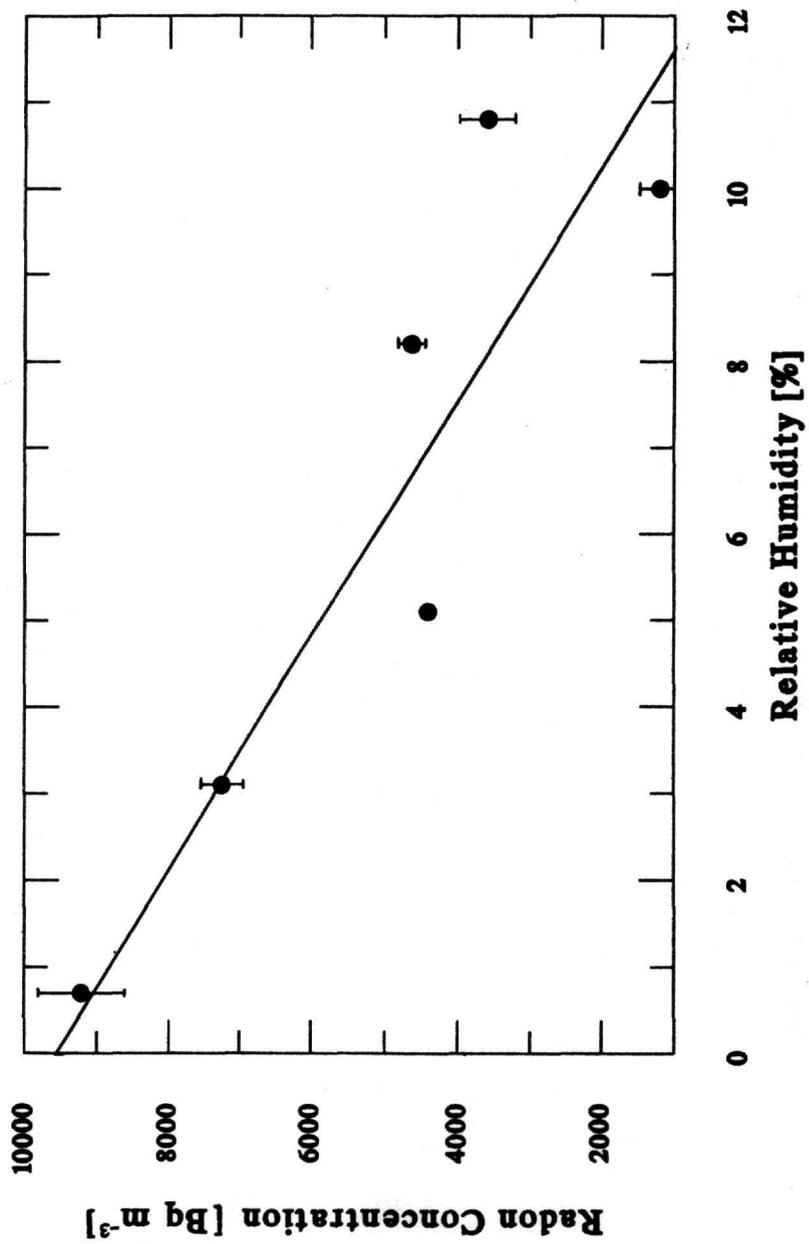


Fig. 8 Correlation of radon concentration with soil humidity.

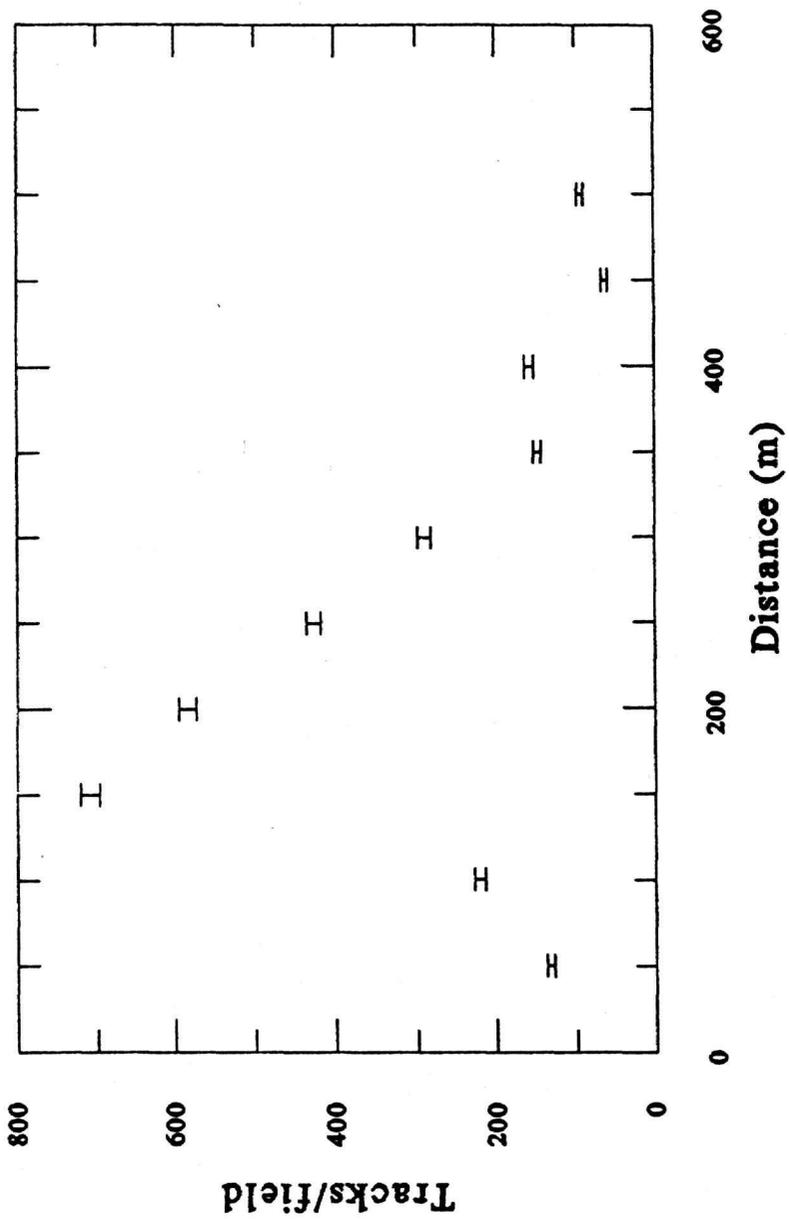


Fig. 9 Radon emanation across the Manoliassa fault.