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Monitoring ^{222}Rn in soil gas of Garfagnana (Tuscany) aimed at earthquake prediction

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Abstract
^{222}Rn concentration in soil gas from nineteen stations of Garfagnana valley (Central Italy) was continuously monitored from December 1990 to May 1993. ^{222}Rn activity was measured by solid state nuclear track detector (SSNTD). Tracks detected by spark-counter and by optical microscope were proportionally constant for track densities lower than 2500 tracks/cm^2. Since time variations in track density both for the same monitoring station and for different stations are significantly higher than fluctuations in the experimental conditions, the validity of spark-counter for radon activity measurements is confirmed. Data collected in the period of monitoring indicate significant seasonal variations in radon concentration for every monitoring station. Moreover, the soil characteristics play an important role in determining the observed patterns. No significant correlation could be found between radon emission and seismicity. However, it should be noted that no earthquake with a magnitude higher than 3.5 occurred in Garfagnana during the monitoring period.

Key words *radon – track – soil gas – monitoring – earthquake prediction*

1. Introduction

The Earth at present is degassing in a showy way from volcanoes but in a more quantitatively important way from soils. The degassing process is controlled by stress conditions and by the distribution of fracture systems in the shallower part of the Earth's crust. High concentrations of some gases and volatiles, such as He, ^{222}Rn, H_2, CO_2, CH_4 and Hg, have been measured in the soil near zones affected by fault systems (Wakita *et al.*, 1978; Wakita *et al.*, 1980; Sugisaki *et al.*, 1983; King, 1986). Anomalous degassing from soil in relation to local and regional seismic activity has been observed in various regions of the Earth (King, 1986).

Among different gaseous species utilized in the study of geochemical precursors of earthquakes, ^{222}Rn has received particular attention for its peculiar characteristics. ^{222}Rn, in fact, is a chemically inert gas, with quite a high solubility in water which decreases with temperature; it is a radioactive isotope belonging to the decay family of ^{238}U, with a half-time of 3824 days. This short half-time makes radon particularly suitable for studying phenomena during their evolution, while its high radioactivity makes it detectable at minimum levels. Moreover, its chemical inertness allows radon to make the run between its production zone and the measuring station undisturbed. ^{222}Rn is continuously produced by rocks containing uranium. It remains in the sites occupied by uranium atoms or diffuses in interstitial pores. Then, radon can reach the surface by diffusive and/or convective flow.

For more than 30 years the association between earthquakes and radon anomalies in soil gases has been studied. Usually, the mean activity in the superficial layer of the soil, integrated over the exposure time, was measured by using nitrocellulose films sensitive to α particles emitted during radon decay (Fleischer and Mogro-Campero, 1978). Radon anomaly mostly consists in an increase or decrease of its activity before or at the same time as seismic events. The anomaly is generally comprised within a factor two to a factor ten with respect to the background (King, 1978; Mogro-Campero *et al.*, 1980; Thomas *et al.*, 1986; Humanante *et al.*, 1990; Igarashi *et al.*, 1993). However, a clear univocal correlation between radon anomalies and seismicity has not been yet established. Local conditions probably affect variations in the radon soil degassing-seismicity relationship. Therefore, the potentiality of radon in monitoring seismic events has to be studied locally by long-term observation in areas showing relevant seismic activity.

The physical mechanisms responsible for the geochemical anomaly are not well known. Many different models have been suggested (see Thomas, 1988, for review). Among these the IRSA model (Increase Reactive Surface Model) seems to better explain the observed phenomena. According to this model, gas trapped in a rock matrix is released during microfracturing associated with changes in regional stress accompanying the preparation process of an earthquake (Sugisaki *et al.*, 1983; Thomas *et al.*, 1986).

This work reports the initial results concerning radon emission values recorded during over two years in different places of Garfagnana, a valley extending for about 30 km N-NE of Lucca (Tuscany), along the «Serchio graben» NW-SE tectonic structure. In the past, destructive earthquakes occurred in this region, which at present is a site of significant seismic activity. For this reason Garfagnana is particularly suitable for studying the relations existing between radon emanation, structural lineaments and seismicity. Studying a new area, such as Garfagnana, requires background variation in ^{222}Rn emission to be known at each monitoring station. This can only be achieved with several years of data collection.

2. Geology and seismicity of the Garfagnana area

Northern Apennines are characterized by a passive subduction plate margin in which the retreating rate of the flexuring axis is approximately equal to the opening rate of the back-arc region. This setting involves the «Po-Adriatic foreland» that is progressively deformed by flexuring underneath the NE-migrating Apenninic chain. The back-arc basin, represented by the Tyrrhenian Sea, opens behind the chain. The lateral continuity of the system is interrupted by transversal elements that play a role of extension-extension, compression-compression or extension-compression transforms. These elements operate as transfer faults that disengage the whole system.

Within this tectonic setting (fig. 1), the Garfagnana area (so-called Serchio graben) is thought to represent the inner margin of the Apennines that was reached by the extensional front during Ruscinian-Villafranchian times and evolved into a graben. Because of this, its structural geometry consists of SW-dipping stair-like normal faults and NE-dipping antithetic faults, making part of a unique extensional system. It is along these latter faults that the blocks of the Serchio graben tilted and remained bound by the Apuane Massif to the W and by the Apennines to the NE.

Towards the NW, this graben basin is limited by a transversal element that, from Fivizzano to the south along the Secchia valley, separates the Garfagnana from the Lunigiana area. The basin ends towards SE to the south of Barga, with no evidence of major transversal structural elements. There is firm evidence, however, that the same extension has been transferred to the Mugello basin, NW-SE elongated too, which is positioned externally with respect to the Garfagnana. In addition, the macroseismic field reconstruction of the 6/03/1740 earthquake shows a clear elongation of the isoseismals along a direction perpendicular to the Apenninic trend (Iaccarino, 1968).

The Garfagnana area is the *locus* of seismicity mainly related to the major normal faults that constitute the Serchio graben (Eva *et al.*, 1978; Boccaletti *et al.*, 1985; Patacca and

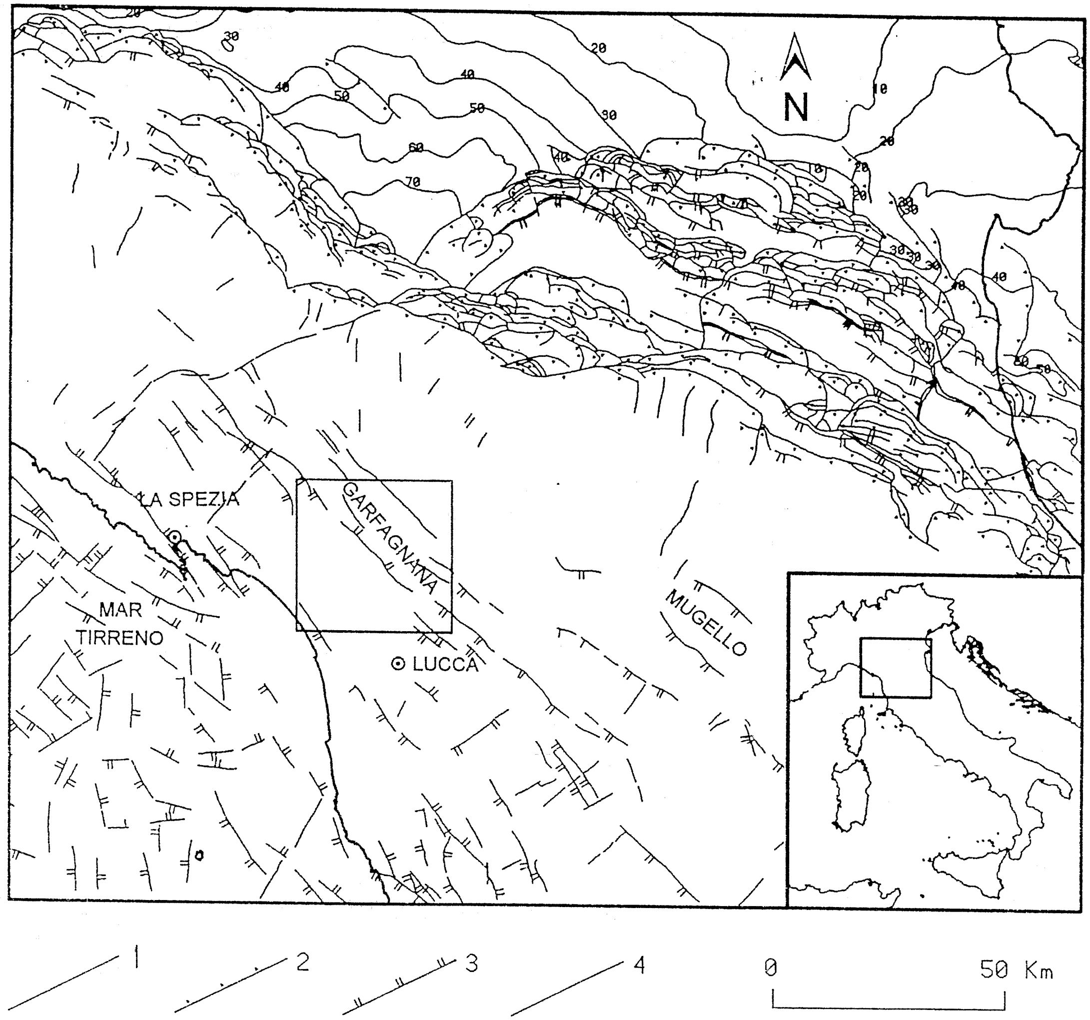

Fig. 1. Structural map of the Northern Apennines (after a Structural Model of Italy, CNR/PFG, 1990). 1) Isobaths at the top of pre-Pliocene (in hundred metres) highlight the foreland flexuring; 2) main thrusts correspond to the fold and thrust belt; 3) main normal faults outline the inner margin of the Apennines affected by the extensional front; 4) main vertical faults, interpreted as transfer faults when they trend NE-SW.

Scandone, 1985). The biggest disastrous event was the earthquake on September 9th, 1920, with an epicentral intensity of IX-X MCS, after which only low-intensity events were recorded. Previously, some other destructive earthquakes struck this region (1481 and 1837), with epicentral intensities of VIII and IX MCS, respectively (Postpischl, 1985).

The few fault-plane solutions available give no clear-cut indications about the nature of the ruptures that generate the earthquakes. The macroseismic field reconstructions, conversely, show a clear elongation of the isoseismals with respect to the expected seismic faults: 1) isoseismals grouped along the major extensional faults of the graben (1481, 1920, etc.); 2) isoseismals elongated perpendicularly to the graben axis, and related to the transversal fault systems (1740).

With reference to the Neogene sedimentary infill of the Garfagnana area, lacustrine basins developed over depressed areas between the end of the Pliocene and the beginning of the Quaternary (fig. 2). Two Villafranchian sedimentary basins, including two equivalent fluviolacustrine sedimentary cycles, were identified

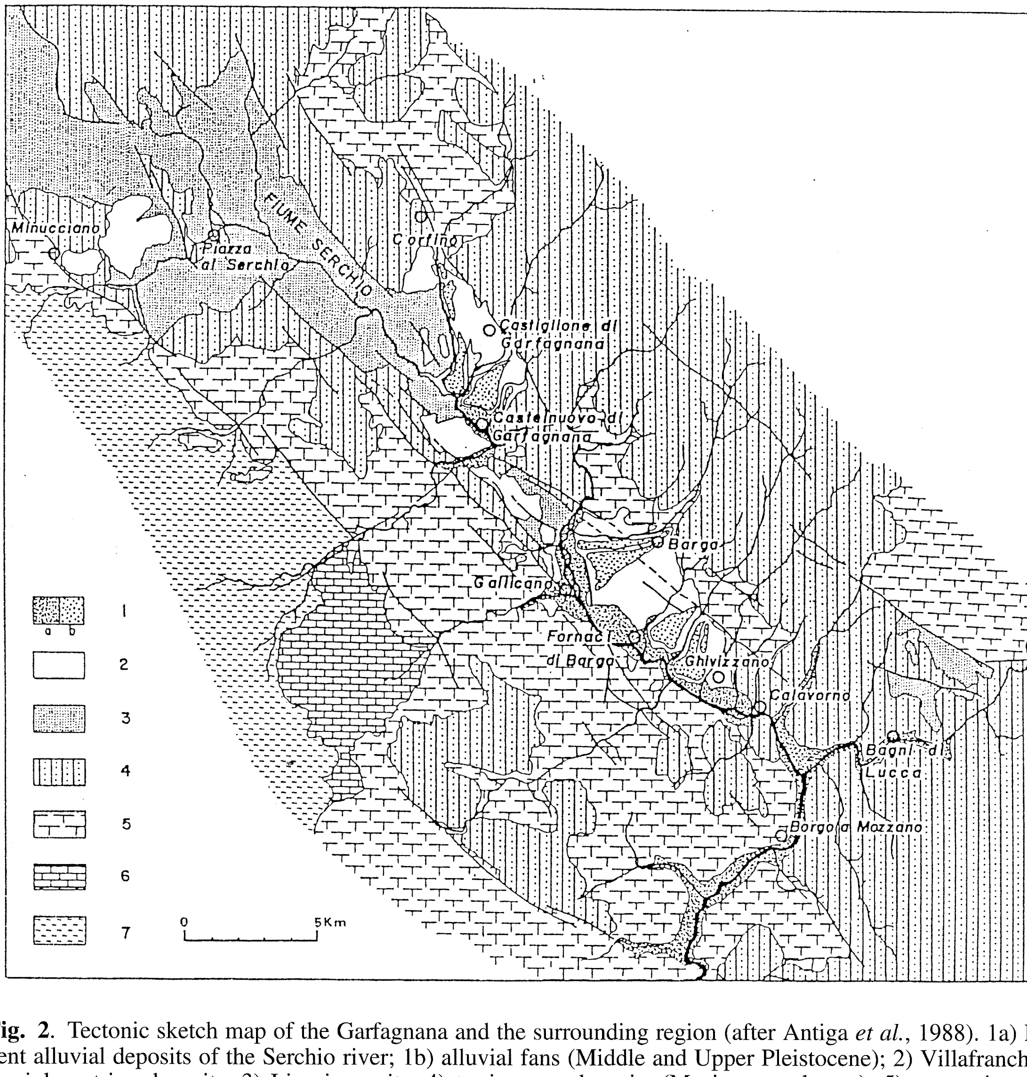

Fig. 2. Tectonic sketch map of the Garfagnana and the surrounding region (after Antiga *et al.*, 1988). 1a) Recent alluvial deposits of the Serchio river; 1b) alluvial fans (Middle and Upper Pleistocene); 2) Villafranchian fluviolacustrine deposits; 3) Ligurian units; 4) terrigenous deposits (Macigno sandstone); 5) pre-terrigenous deposits of the Tuscan nappe; 6) Panie unit (part of the Apuane Massif complex); 7) Apuane units. Main normal and strike-slip faults are represented by solid lines.

at Barga and at Castelnuovo Garfagnana. The Monte Perpoli gully, interposed between these two basins, represents an emerged area where the Villafranchian sedimentary record is exclusively made up of fluvial polymictic conglomerates and alluvial fan deposits.

The Villafranchian fluviolacustrine deposits are unconformably covered, in angular and erosional unconformity, by deposits that are regarded as alluvial fan conglomerates. These sediments may have derived from alluvial sedimentation acting over the Apennine chain (Antiga *et. al.*, 1988). These authors focused on the structural elements indicating recent tectonic activity, and therefore affecting the Villafranchian and post-Villafranchian sediments.

For the Garfagnana area, the available hydrochemical information reveals the existence of a deep regional water circulation. Temperature and composition of deep waters are related to the depth of water circuits (Fancelli *et al.*, 1976). Moreover, in this area helium and radon contents in waters are quite high, especially in springs close to fault systems. This fact has suggested that the tectonic conditions (active stress field observed at regional level, kinematic evolution in this sector of Northern Apennines, predominant extensional regime and presence of very recent faults) of the studied area play a leading role in determining chemical characteristics of the water bodies at depth, essentially as regards gaseous species (Bencini *et al.*, 1990). Therefore fractures and fault zones represent the main channels for deep gas migration toward the surface. For these reasons, structural analysis has been chosen as a tool for selecting the four areas of geochemical monitoring of radon in soil gases. They are the Coreglia, Loppia, Ponte di Campia and Castiglione Garfagnana areas (fig. 3).

The Coreglia faults, between the localities of Ghivizzano and Coreglia Antelminelli, mark the northeastern boundary of the Garfagnana depression. They have a N132 direction and separate alluvial fan deposits from pre-Villafranchian basement.

The fault located in the vicinity of Loppia has the same direction as the Coreglia faults and corresponds, underneath the Quaternary and Villafranchian deposits, to the major normal faults bounding the Garfagnana basin (Moretti, 1987). Here, the fluviolacustrine deposits of the first cycle, together with the fluviatile deposits of the Loppora river, are exposed.

The fault exposed at Ponte di Campia has a N100 direction. It is regarded as one of the youngest structures, and is responsible for unbalancing the equilibrium profile of the Serchio river. Vertical erosive regression has been estimated in the order of 100 metres (Moretti, 1992). The Macigno sandstone and the Ligurian units outcrop in the area, but the Villafranchian deposits are not exposed.

The Castiglione Garfagnana fault is located immediately below the walls of the town, to the north. It has a N120 direction and intersects sediments of the second fluviolacustrine cycle.

3. Materials and methods

3.1. *Radon measurements*

Most of the methods for radon analysis are based on the detection of α particles emitted by ^{222}Rn (5.49 MeV) and its decay products such as ^{218}Po (6.00 MeV) and ^{214}Po (7.69 MeV). Measurements can be either active, which involves pumping gas into or through a detecting instrument, or passive, when radon concentration is measured *in situ* under natural conditions.

Among passive methods, solid state nuclear track detectors (SSNTDs) are the most widely used in the applications regarding Earth sciences. SSNTDs are constituted by specific materials such as nitrocellulose and polymers. The passage of an ionizing particle, such as an alpha particle, creates a permanently damaged region on an atomic scale, called «track». The damage may be enlarged by chemical treatment which preferentially removes the damaged material («latent track»). The result of the etching is a track visible under an optical microscope. This track may pass through the whole thickness of the detector (through hole).

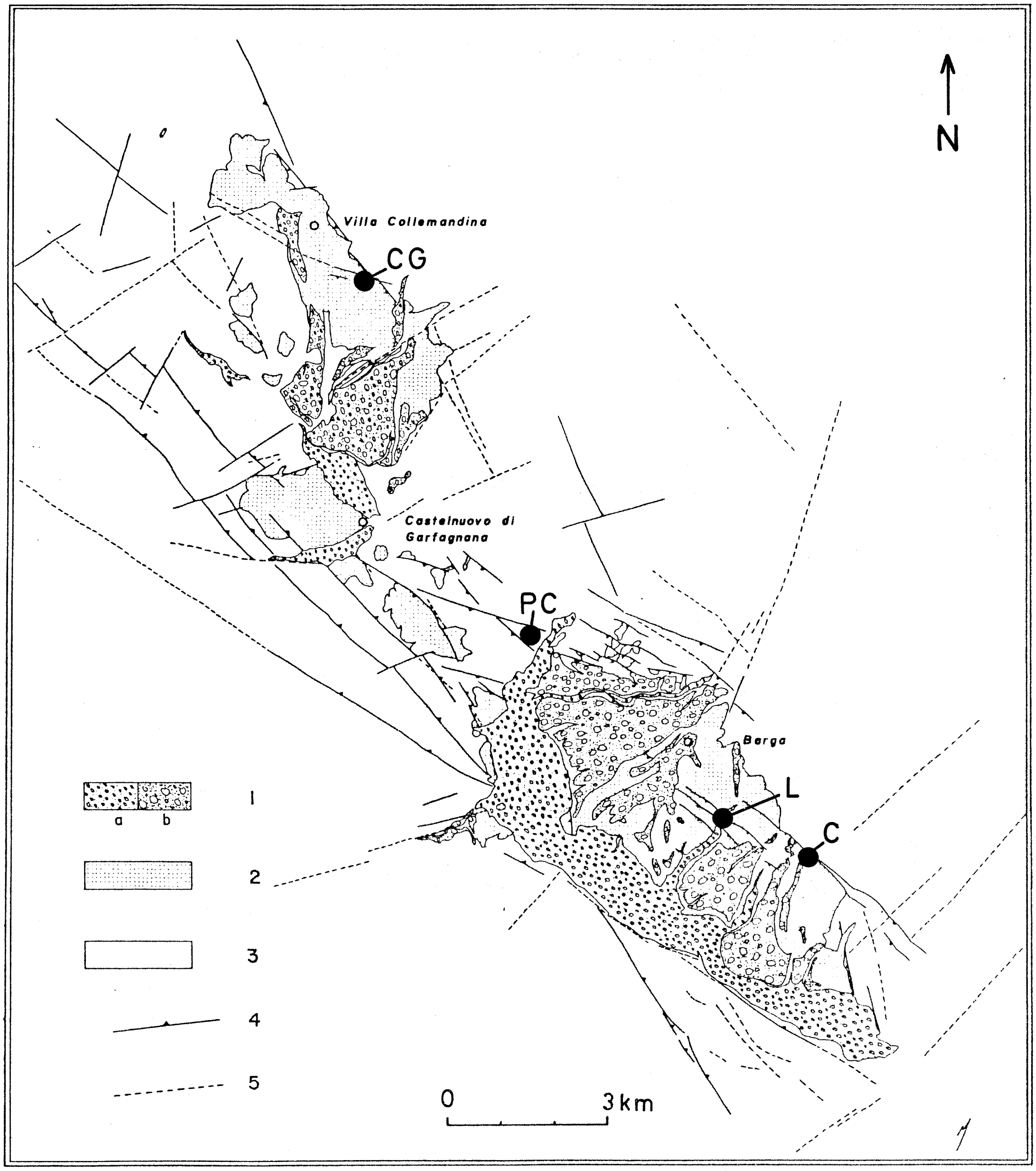

Fig. 3. Main tectonic lineaments of the Garfagnana area (after Antiga *et al.*, 1988). 1a) Recent alluvial deposits; 1b) alluvial fans; 2) Villafranchian deposits; 3) pre-Villafranchian basement; 4) proven faults; 5) lineations derived from aerial photo interpretation. Circles represent the areas chosen for geochemical monitoring: L) Loppia area; PC) Ponte di Campia area; CG) Castiglione Garfagnana area; C) Coreglia area.

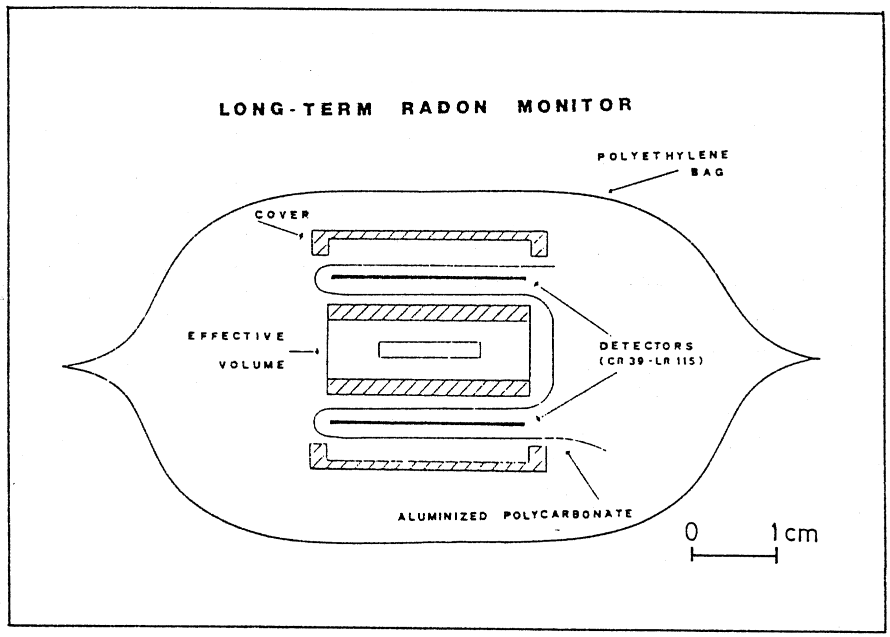

Fig. 4. Cross-section of the radon gas sampler dosimeter developed at the ENEA (after Torri, 1990).

The number of tracks is related to the exposure time and to the radionuclide concentration.

3.2. *LR-115 detector*

In the present work a SSNTD was used consisting in a 12 μm thick cellulose nitrate (manufactured by Kodak under the trade name of LR-115) placed on a 100 μm polyester backing. Only α particles with energies between 2.25 and 3.5 MeV produce detectable tracks on the LR-115 film (Bonetti *et al.*, 1991), so that the α particles must be slowed down to allow their detection. In our case slowing down was achieved with a thin foil (20 μm) of aluminized polycarbonate.

The radon dosimeter contains two detectors and is placed in a heat-sealed plastic bag made of polyethylene, with a thickness of 40 μm, permeable to radon (fig. 4). The polyethylene bag slows down gas run so that thoron (^{220}Rn), with a 55 s half-time, decays before reaching the sensitive volume of the dosimeter (Torri, 1990).

The monitoring stations planned for this study consist of a PVC tube (diameter 8 cm, 50 cm long) inserted in the ground. The dosimeter is placed 20 cm above the bottom inside the tube over a support constituted by a 30 cm long PVC tube, closed at both ends (fig. 5). Sealing with insulating tape prevents contact with the atmosphere. After exposure, LR-115 detectors are etched in a 2.5 N NaOH solution at 60°C for 70 minutes. The solution is stirred to ensure complete homogeneity. Etching creates tracks, some of which are through holes, in the area where *α* particles have passed through the film. These holes are counted using a spark-counter (Cross and Tommasino, 1970), see fig. 6. Track counting was performed at 500 V for 10 s. It has been shown (Azimi-Garakani, 1990) that a pre-sparking treatment at higher voltage optimizes counting conditions: we used 900 V for 10 s.

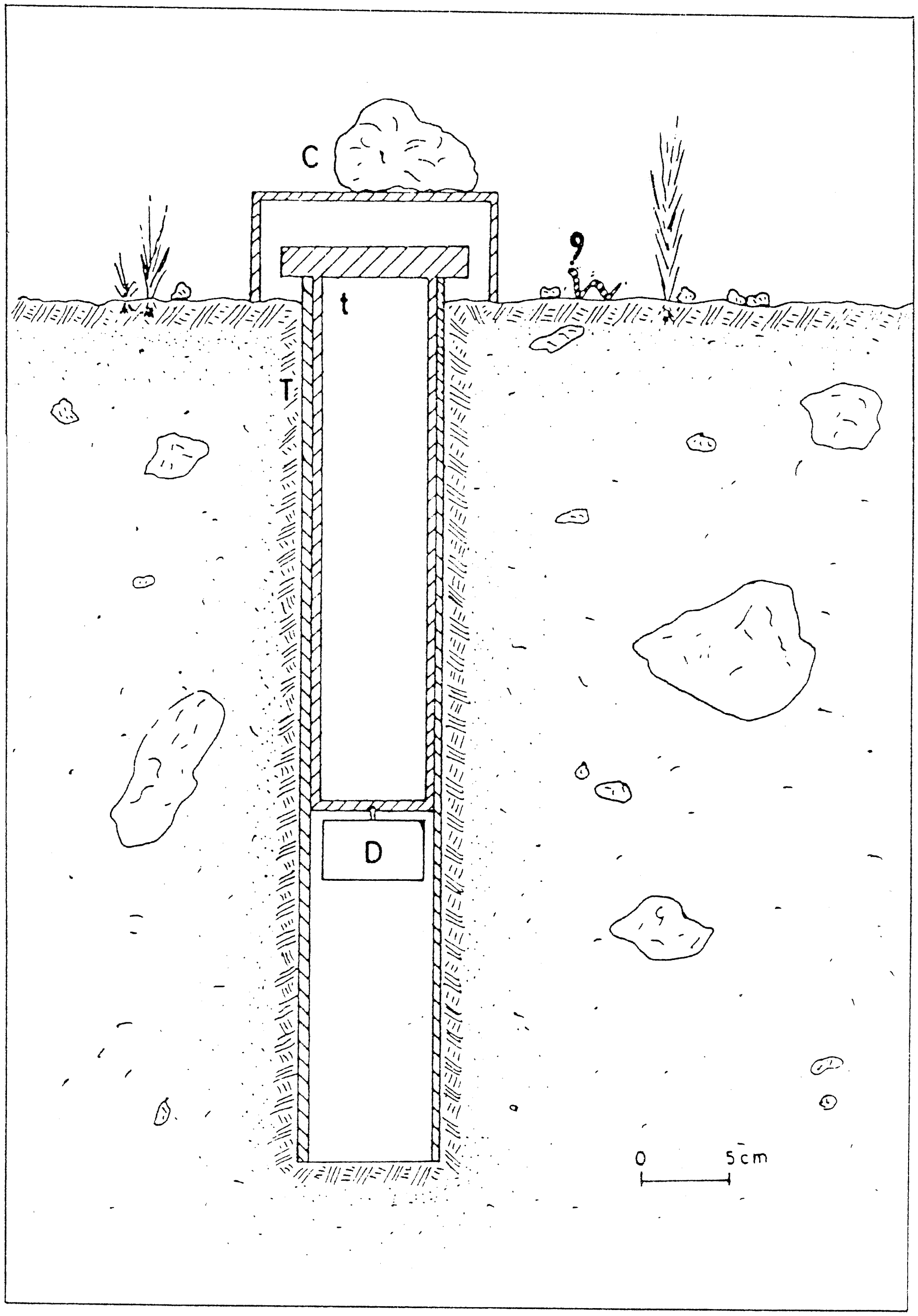

Fig. 5. Radon monitoring device used in all measuring stations (after Leonardi, 1991): D) dosimeter; T) external PVC tube; t) internal PVC tube; C) protection cover of monitoring station.

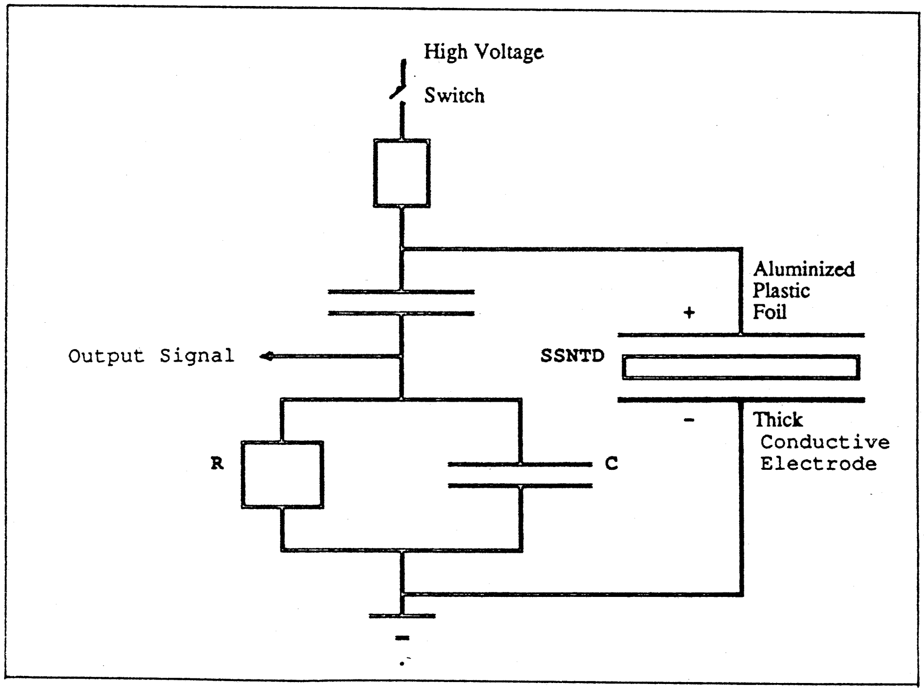

Fig. 6. Schematic diagram of the spark-counter (after Azimi-Garakani, 1990); C) capacitor; R) resistor. The SSNTD, placed between the electrode, forms a capacitor. When high voltage is applied across the capacitor (C), an electrical discharge (or spark) takes place through a track hole. The voltage pulse produced across the resistor (R) can easily be counted electronically.

LR-115 thickness after chemical etching (residual thickness) is about 6-7 μm. The number of counted tracks per cm^2 is a function of the residual thickness; the lower the residual thickness, the higher the number of counted tracks. Track counts were normalized to a reference thickness of 6.5 μm, using the following equation:

$$R_{6.5} = N_t/[1 + \beta(t - 6.5)] \qquad (3.1)$$

where $R_{6.5}$ are tracks/cm^2 normalized to the reference thickness, N_t is the track density measured with the spark-counter, t is the residual thickness and β is the correction coefficient (ENEA-DISP Technical Report, in press). In this work a β value of -0.391 was used. Normalization of track density is necessary because even small variations in residual thickness may result in remarkable changes in the number of through holes. For example, a difference of ± 1μm in the residual thickness may cause a correction of $+60\%$ and -40% of measured value. The normalized data were then divided by the exposure time, generally between 20 and 30 days, to obtain the final value expressed in tracks/cm^2/day.

3.3. *Reproducibility of track density with LR-115*

When using LR-115 films to measure time variations of radon activity, it is necessary to evaluate when a difference in the number of counted tracks is significant and represents an actual variation in ^{222}Rn concentrations at the monitoring site. Theoretically, one may assume that the tracks are distributed according to Poisson statistics. This is to say that ^{222}Rn is uniformly distributed in the space of survey and that the detector shows no fluctuations in registration efficiency. The measurement error would be, in this case, the square root of counted tracks ($N_t^{1/2}$). This happens only under ideal conditions. Actually, many unknown factors may determine a deviation of the experimental conditions from the ideal ones.

In this work, measurement reproducibility at a given site was experimentally validated by calculating the standard deviation of N_t counting obtained with different detectors, exposed in theory to the same conditions, i.e. the same monitoring station and for the same exposure time. Unlike averages, experimentally evaluated standard deviations show an asymmetrical, larger Chi-type distribution. Consequently, an experimental evaluation of reasonable precision requires a suitable number of data; however, only few individual monitors are commonly exposed for the same time in a single station. In this experiment we collected 58 data regarding detectors exposed in Calabria (Southern Italy) in different monitoring stations, containing four detectors at the same time. N_t values were normalized for thickness and the average was considered equal to one. The standard deviation for the 58 normalized data was 11.8% (with a 95% confidence interval between 10.1 and 13.3%). This standard deviation is much higher than the one estimated from Poisson statistics (for N_t values between 1000 and 2500, a value of about 2.5% would be expected). This means that unknown factors, such as the spatial variation of ^{222}Rn concentration, variations in LR-115 recording efficiency, the slowing down of polycarbonate and the polyethylene bag and, mostly, errors in the measurement of thickness play a dominant role. The counting system should not be included among these factors: 14 measurements on the same detector performed by spark-counter showed a comparably negligible standard deviation (about 1%).

This experiment shows that differences below about 20% should not be considered significant when only one detector for every monitoring station is exposed. This uncertainty, however, is much lower than the temporal track density variation observed both in the same station and at different sites.

3.4. *LR-115 efficiency: a comparison between spark-counter and optical microscope*

Conversion of measured track density on LR-115 films into absolute radon mean activity values during the monitoring period is not a trivial task. Only particles that reach the LR-115 with energies in the above-mentioned range leave a detectable track on the detector; furthermore, only tracks that pass through the film are counted by the spark-counter. Assuming that N_t is proportional to the mean radon activity, track density may be converted into ^{222}Rn concentration values by calculating an efficiency factor (E) from detector exposure to a known radon concentration.

The assumption that the N_t values, measured by the spark-counter, are proportional to the mean radon activity is based on the premise that the through holes represent a constant fraction of the detected tracks. Although in this work we are interested in spatial and temporal relative radon flux variations, rather than in absolute activity determination, the premise is likewise important. Unexplored E fluctuations might simulate radon emission variations.

To assess the percentage of through holes as a function of superficial density, 33 detectors exposed at different monitoring sites, and/or for different exposure times, were counted under a Leitz orthoplan microscope. The results were compared with N_t values obtained with a spark-counter (counting with the microscope was performed before the pre-sparking, as this treatment produces a certain degree of surface damage which might prevent optimal observation). Under the optical microscope, besides the total number of detected tracks, those which passed through the film were also counted.

Figure 7 shows N_t counting versus the number of through holes observed at the microscope. Experimental data suggest a curve (full line)

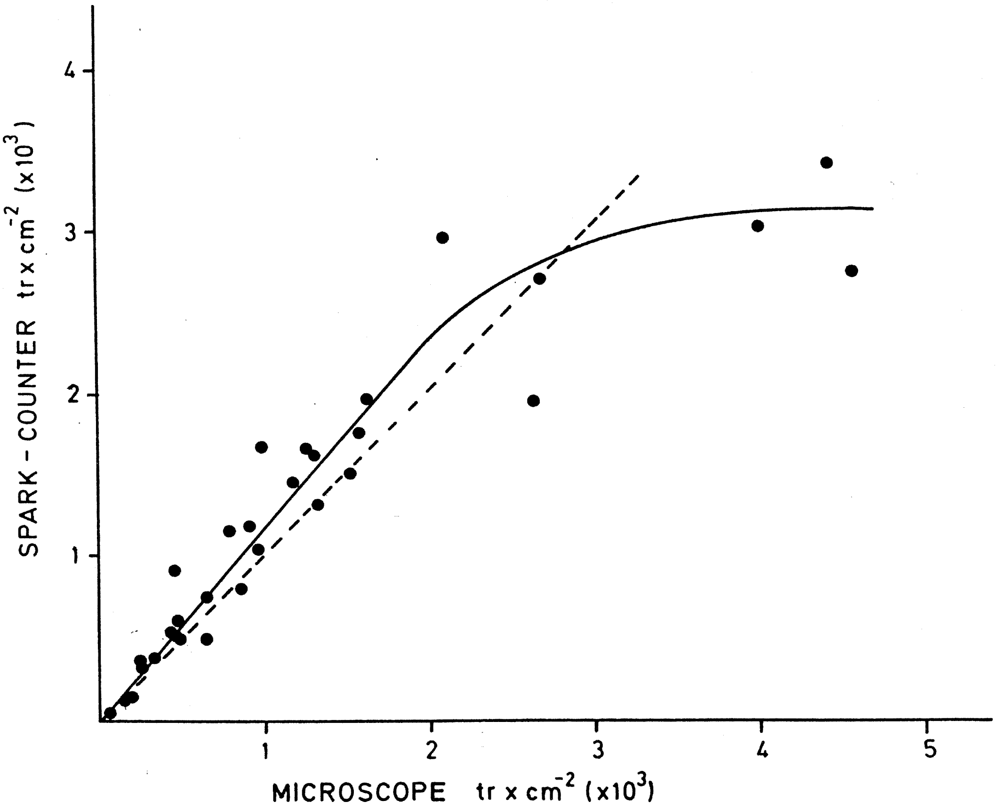

Fig. 7. Comparison between the number of through holes measured with the spark-counter (N_t) and with the microscope.

that for $N_t < 2500$ tracks/cm^2 follows a straight line with a slope greater than 1 (dashed line). The curve then crosses the dashed line and tends to become parallel to the abscissa axis. Thus, for N_t values below 2500, the number of through holes counted with the spark-counter exceeds the number counted using the microscope. This is probably due to the pre-sparking treatment which may eliminate the small thickness of residual film in those tracks that pass through the detector almost completely. For higher track densities the spark-counter resolution decreases and the saturation effect occurs.

The dispersion of the experimental points around the curve is partially due to the relatively large experimental error (>10%) in track density measurement by optical counting, especially for low track densities. This unexpected wide scattering of the points in fig. 7 is consistent with the observed wide standard deviation mentioned above and further confirms that unknown factors produce extra-Poissonian fluctuations of N_t counts.

Data processing of performed measurements shows that:

1) the distributions of optical counts on individual unit areas of the detectors by Chi-

square test are consistent with Poisson distributions;

2) the number of through holes for areal densities < 2500 tracks/cm^2 represents 20% of all detected tracks;

3) the ratio of through holes to total tracks (and, likewise, the ratio of N_t to total tracks) is inversely related to residual thickness.

This latter result is substantially obvious and points to the importance of normalizing the track densities obtained with the spark-counter to a reference thickness.

Finally, measurements of track density performed with a spark-counter are suitable for the purposes of this work, provided that significant radon emission variations are greater than 20%.

4. Results and discussion

Track density patterns related to selected sampling surveys along ideal sections perpendicular to fault directions are reported in fig. 8a-d. These patterns show that the highest values of radon emission do not always coincide with morphological evidence of a fault. The different pattern shapes are probably related to the climatic conditions (dry or moist)

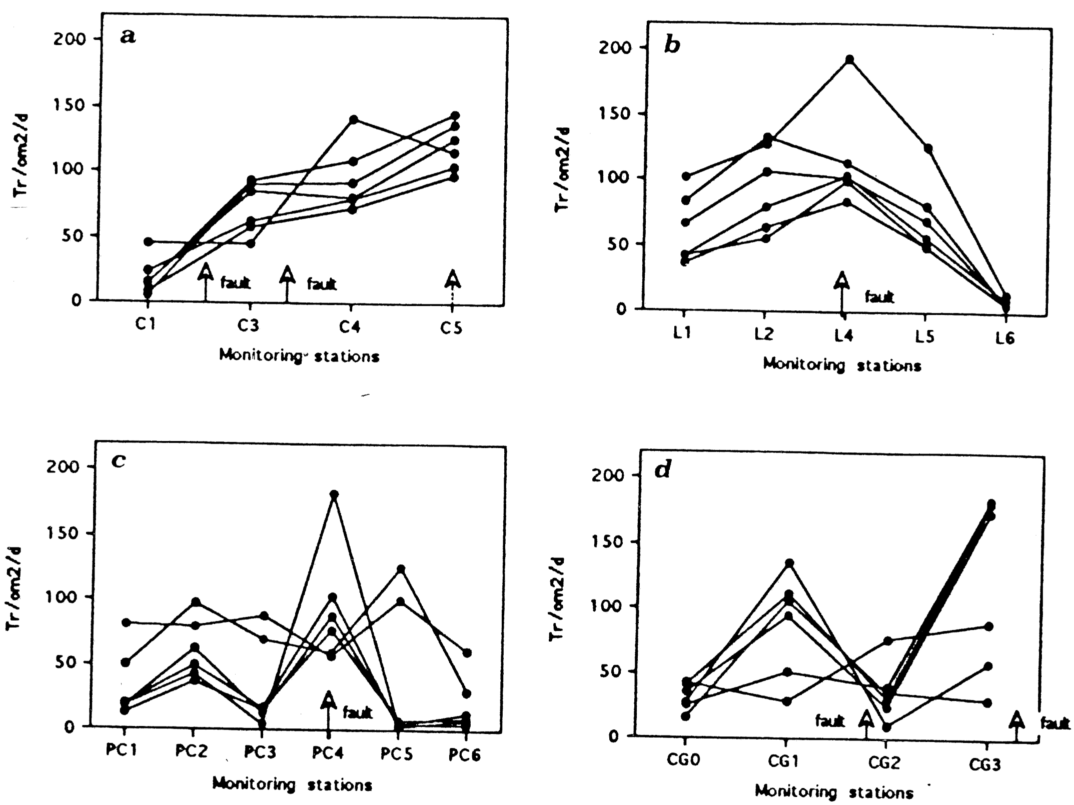

Fig. 8a-d. Track density patterns, related to selected surveys, along ideal sections perpendicular to fault directions. a) Coreglia; b) Loppia; c) Ponte di Campia; d) Castiglione Garfagnana.

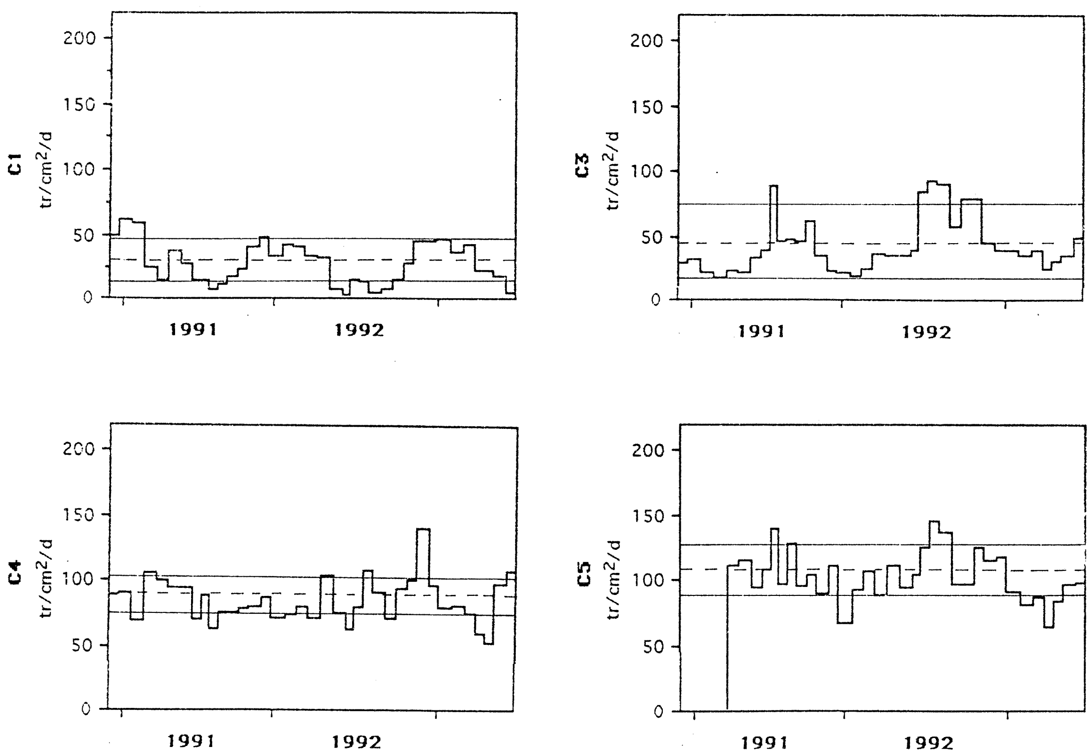

Fig. 9a. Time variations of soil gas radon concentration for each monitoring station in the Coreglia area, during the period December 1st 1990-May 19th 1993. The mean value of ^{222}Rn activity (dashed line) is also reported; solid lines are drawn at ± 1 standard deviation distance.

under which measurements were performed. This observation indicates that radon concentration in soil gas is affected both by parameters related to the location of the station (such as the existence of high vertical permeability zones and the characteristics of soil) and by seasonal factors such as atmospheric conditions (temperature, pressure, rainfall, etc.).

The temporal variation of radon concentration in soil gas monitored at every station is shown in figs. 9a-d for the period December 90-May 93. Concentration data are expressed in tracks/cm^2/day (tr/cm^2/d). In the same figure lines representing the mean value of activity and the standard deviation ($\pm 1\sigma$) for each station are also drawn. The graphs of figs. 9a-d show a wide range of variation for all stations during two and a half years of monitoring.

At Coreglia (fig. 9a) mean activity values range from about 30 tr/cm^2/d at C1 station to about 110 tr/cm^2/d at C5 monitoring site, although the latter is the farthest station from mapped faults (see fig. 8a). However, the highest value measured at C5 station can be explained by the fact that this station is located on the ideal prolongation of the Loppia faults, even if there is no geological evidence of these faults in the Coreglia zone.

In the Loppia zone (fig. 9b), the highest value of radon emission was measured close to the fault (see fig. 8b). Mean activity values are very high in L1, L2 and L4 monitoring sites

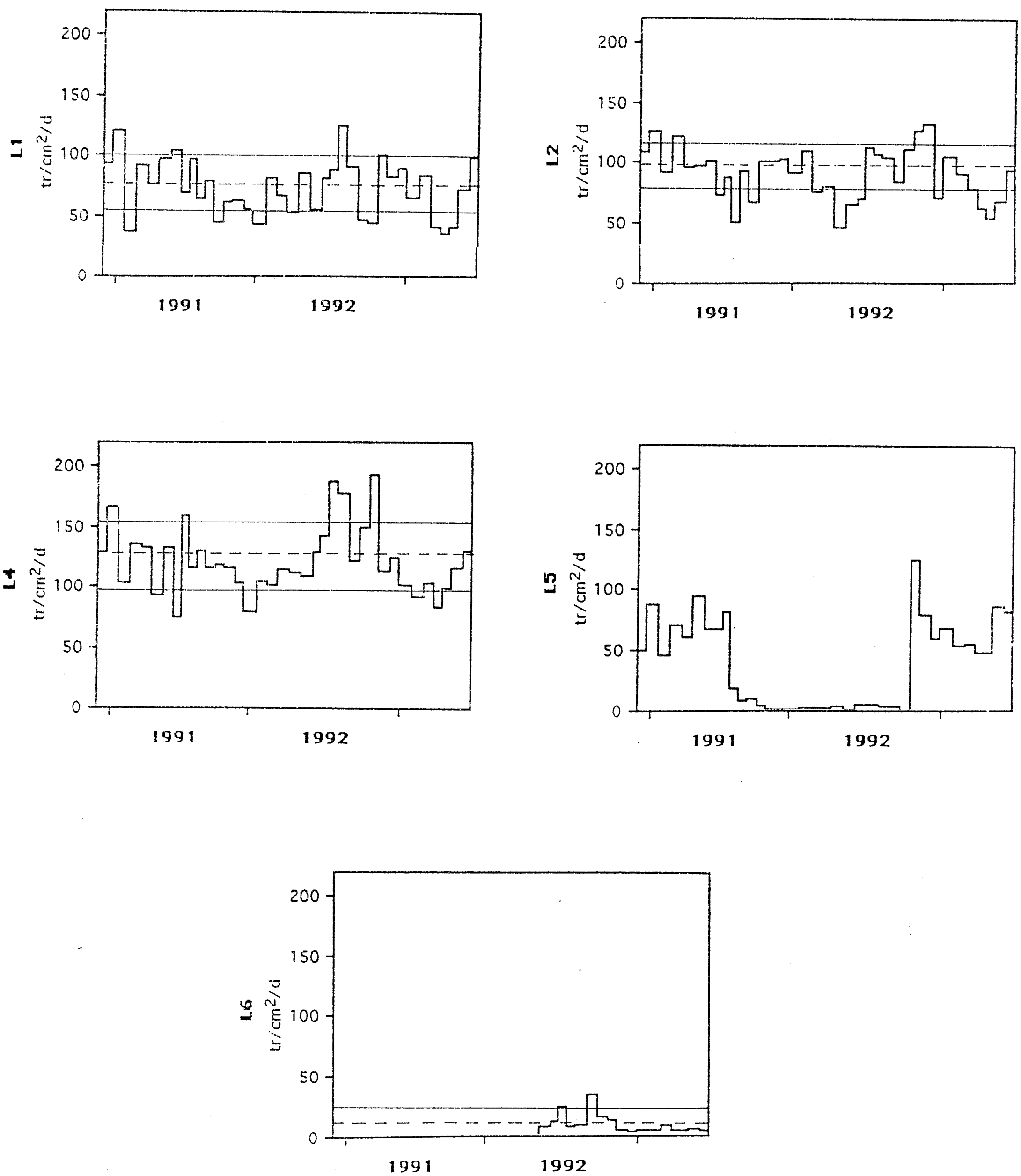

Fig. 9b. Time variations of soil gas radon concentration for each monitoring station in the Loppia area, during the period December 1st 1990-May 19th 1993. The mean value of ^{222}Rn activity (dashed line) is also reported; solid lines are drawn at ± 1 standard deviation distance.

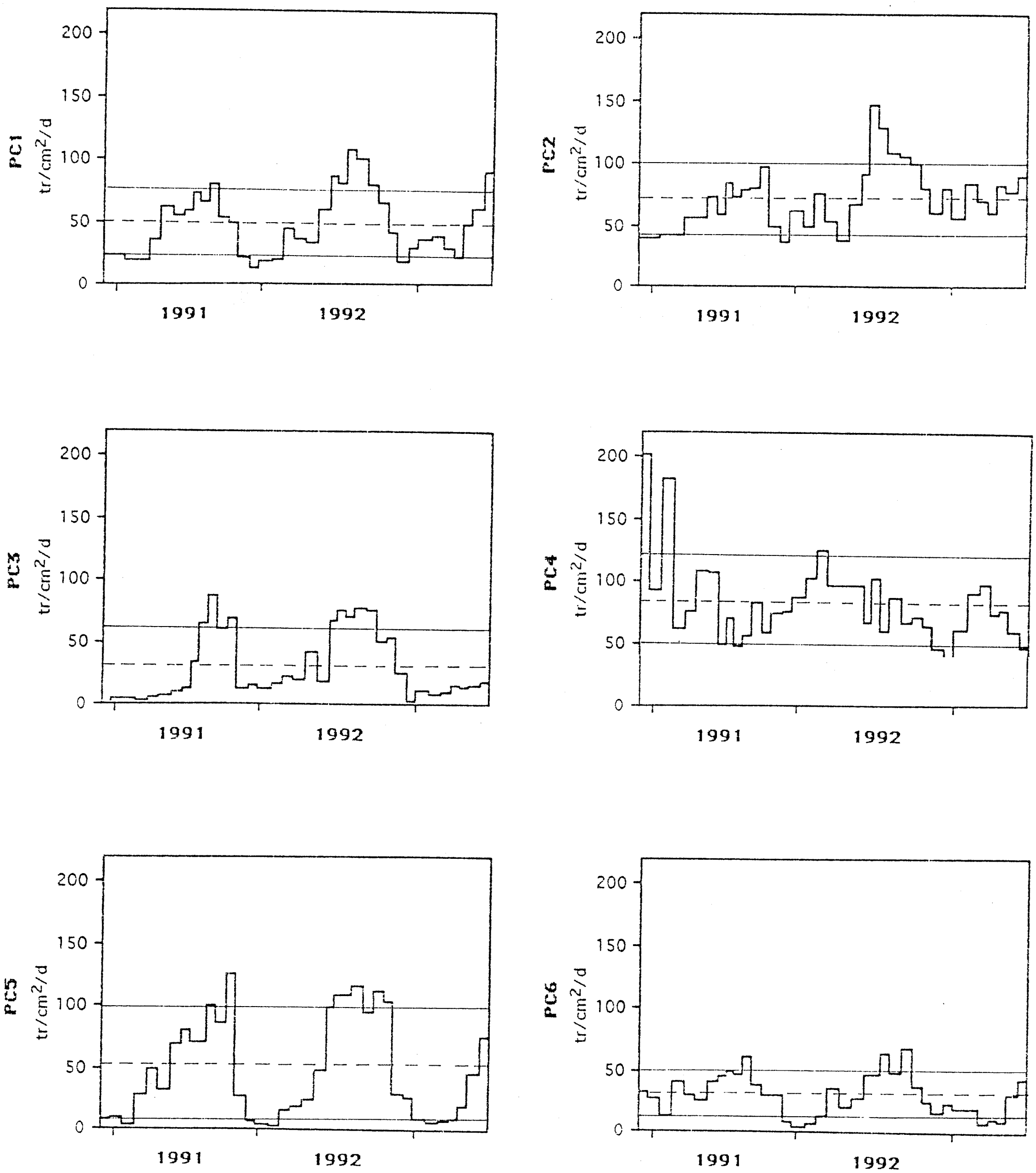

Fig. 9c. Time variations of soil gas radon concentration for each monitoring station in the Ponte di Campia area, during the period December 1st 1990-May 19th 1993. The mean value of ^{222}Rn activity (dashed line) is also reported; solid lines are drawn at ± 1 standard deviation distance.

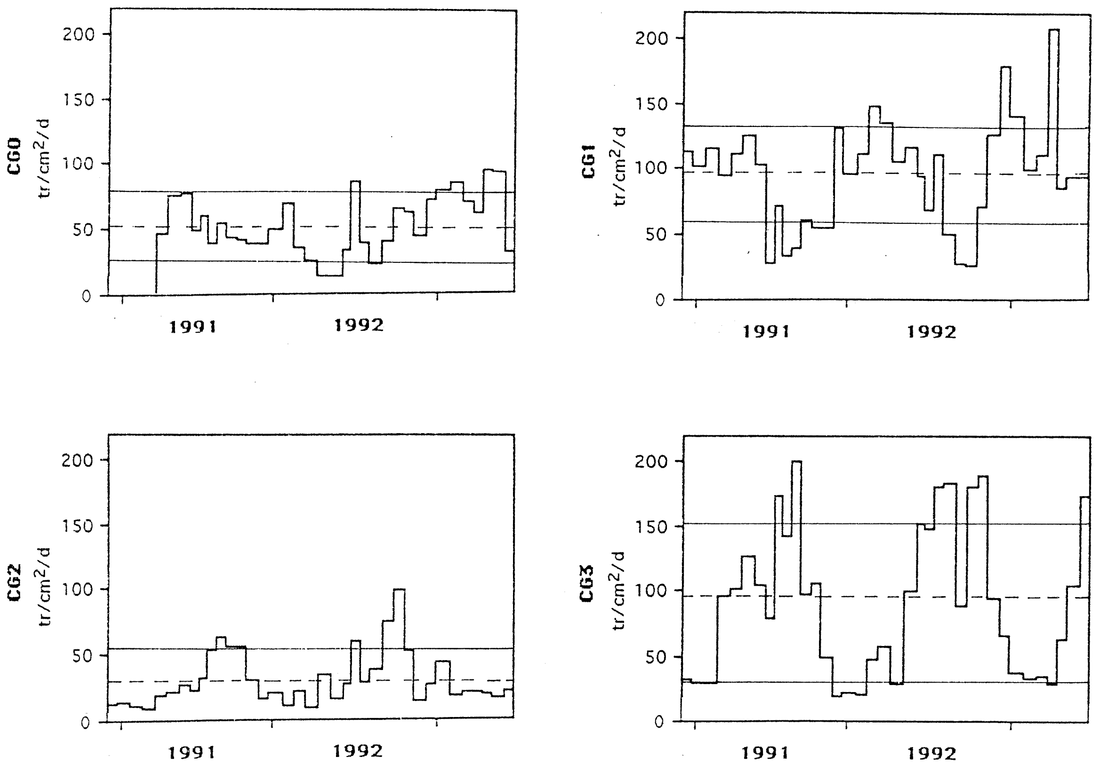

Fig. 9d. Time variations of soil gas radon concentration for each monitoring station in the Castiglione Garfagnana area, during the period December 1st 1990-May 19th 1993. The mean value of ^{222}Rn activity (dashed line) is also reported; solid lines are drawn at ± 1 standard deviation distance.

(80-125 tr/cm^2/d). This is very probably related to the high density faulting that characterizes this zone. The mean value for L5 station could not be calculated because anomalously low values were recorded in the period among 200 and 650 days, due to the presence of water at the bottom of the sampling tube.

In the Ponte di Campia zone (fig. 9c), a relative maximum in radon concentration was observed at PC4 station, located near the fault with N100 direction (see fig. 8c). Mean activity values range from about 30 tr/cm^2/d, in the stations far from the fault, to about 85 tr/cm^2/d at PC4 station.

Soil radon values in the Castiglione di Garfagnana area are characterized by an increase from CG0 to CG3 stations (fig. 9d), with the exclusion of CG2 station placed on the fault plane. Mean concentrations for the four stations vary from 30 to 95 tr/cm^2/d. The low value at CG2 station may be due to atmospheric air circulation in the shallower part of soil, close to the fault plane. The high values measured at CG3 station are probably related to the presence of a second fault near the station (see fig. 8d).

Radon emission for each station changes remarkably with time. These variations appear to be quite regular (at least at the frequency of measurements) and, at some sites, they are positively correlated with atmospheric temperature trends (temperature is measured daily at a

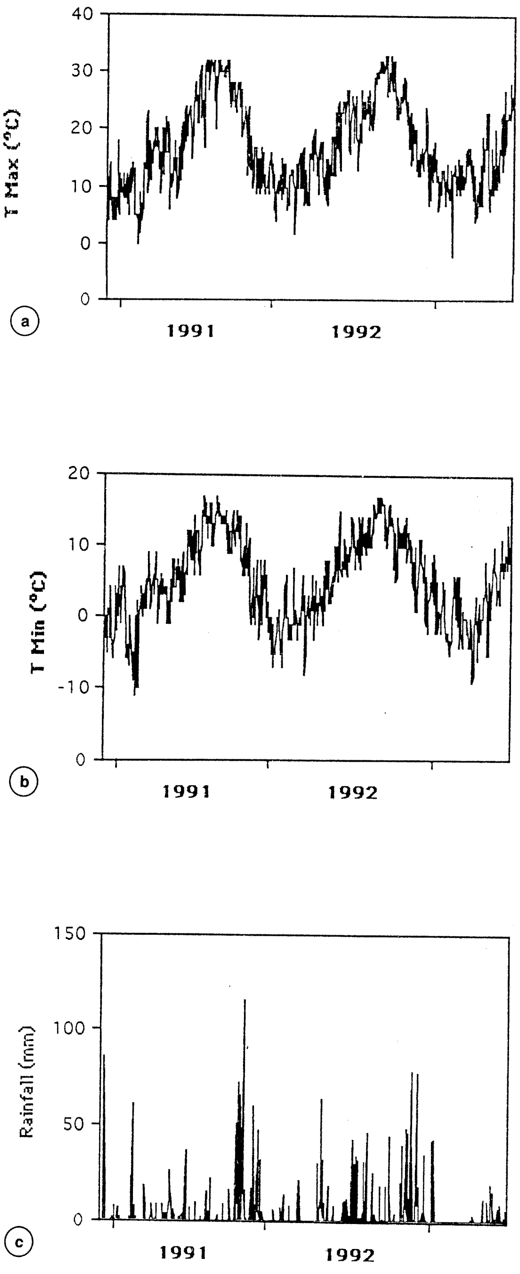

Fig. 10a-c. Time variation of maximum (a) and minimum (b) atmospheric temperatures measured at Villa Collemandina meteorologic station; c) daily rainfall data (in mm) of Villa Collemandina pluviometric station.

height of 150 cm from soil). Other monitoring stations exhibit a negative correlation between radon and atmospheric temperature, while in other cases there is no observable relationship. Trends of maximum (a) and minimum (b) atmospheric temperatures in the studied area are reported in fig. 10a-c. As 20-30 day exposure times were used, as written above, impulsive variations in ^{222}Rn activity in water or gas samples may be missed if the track-etch method is used (King, 1984, 1985). However, it can be reasonably argued that longer variations in ^{222}Rn activity in soil gases have to occur as a consequence of strain accumulation leading to an earthquake. The different monitoring stations are grouped according to the relationship existing between radon emission and atmospheric temperature:

– A group: in these stations radon concentration and temperature are inversely related;
– B group: for these stations there is no evident relation with temperature;
– C group: stations showing a positive correlation between radon and temperature.

For each measurement station maximum and minimum values of radon emission and their Δ ratio (to evaluate the entity of signal variation) are reported in table I. Since radon flux may be influenced by granulometric and structural properties of the soil in which the station is placed, the characteristics of the geological substratum are also reported in the same table. The relationship with the geological substratum is complex and the latter plays a substantial role (Abdoh and Pilkington, 1989). This finding is confirmed in this study. In fact, monitoring stations in the Loppia area, placed above recent coarse alluvium, show very low Δ values; conversely, monitoring sites in the Ponte di Campia area, located above sandstone belonging to both Ligurian and Tuscan units, show the highest Δ values.

A relationship between ^{222}Rn activity and external temperature was observed in caves and soils near Budapest, in the thermal karst region (Csige *et al.*, 1990; Hunyadi *et al.*, 1991; Geczy *et al.*, 1993). These authors explained the recorded variation as due to the in-

Table I. List of the monitoring stations. For each station the following data are reported: relation between radon emission and atmospheric temperature (stations are classified into 3 groups: A = inversely related, B = without correlation, C = correlated); minimum and maximum activity values; ratio of the previous values (Δ); a brief description of the geological substratum.

Station	Group	^{222}Rn track range density (tr/cm^2/d)	Δ	Characteristics of geological substratum underlying the station
C1	A	5-60	≈ 12	Pre-Villafranchian basement (Scaglia Toscana formation)
C3	C	20-90	≈ 4	Pre-Villafranchian basement (Scaglia Toscana formation)
C4	B	70-140	2	Alluvial fan deposits of Villafranchian age
C5	C (*)	75-140	≈ 2	Alluvial fan deposits of Villafranchian age (rich in sandy fraction)
L1	C (*)	40-120	3	Recent coarse alluvium
L2	A (*)	45-140	≈ 3	Recent coarse alluvium
L4	C	75-190	≈ 2.5	Villafranchian fluvial deposits
L5	(**)			Recent coarse alluvium
L6	C	5-35	≈ 7	Villafranchian fluviolacustrine sediments
PC1	C	15-110	≈ 7.5	Pre-Villafranchian basement (Ligurian units)
PC2	C	35-150	≈ 4	Pre-Villafranchian basement (Ligurian units)
PC3	C	5-90	18	Terrigenous cover overlying pre-Villafranchian basement (Macigno sandstone)
PC4	A	40-200	5	Terrigenous cover overlying pre-Villafranchian basement (Macigno sandstone)
PC5	C	5-125	25	Terrigenous cover overlying pre-Villafranchian basement (Macigno sandstone)
PC6	C	5-70	14	Terrigenous cover overlying pre-Villafranchian basement (Macigno sandstone)
CG0	B	15-60	4	Villafranchian fluvial conglomerates
CG1	A	30-180	6	Villafranchian fluvial conglomerates
CG2	C	10-100	10	Villafranchian fluviolacustrine sediments
CG3	C	20-200	10	Villafranchian fluviolacustrine sediments

(*) The relationship between temperature and radon emission is not very clear. (**) This station could not be evaluated due to the prolonged presence of water at the bottom of the tube.

fluence of ventilation induced by the difference between internal and external temperatures. A similar model might be applied to our case; however, an unambiguous explanation will only be possible when a better knowledge of subsoil air circulation conditions is attained.

Time variations in radon activity (figs. 9a-d) were also compared with daily rainfall values of Villa Collemandina pluviometric station (fig. 10c). The correlation between radon emission and rainfall is not quite clear, although in different areas some authors found a negative correlation (Steele, 1984, 1985; Tidjani *et al.*, 1990). It should be pointed out that the rela-

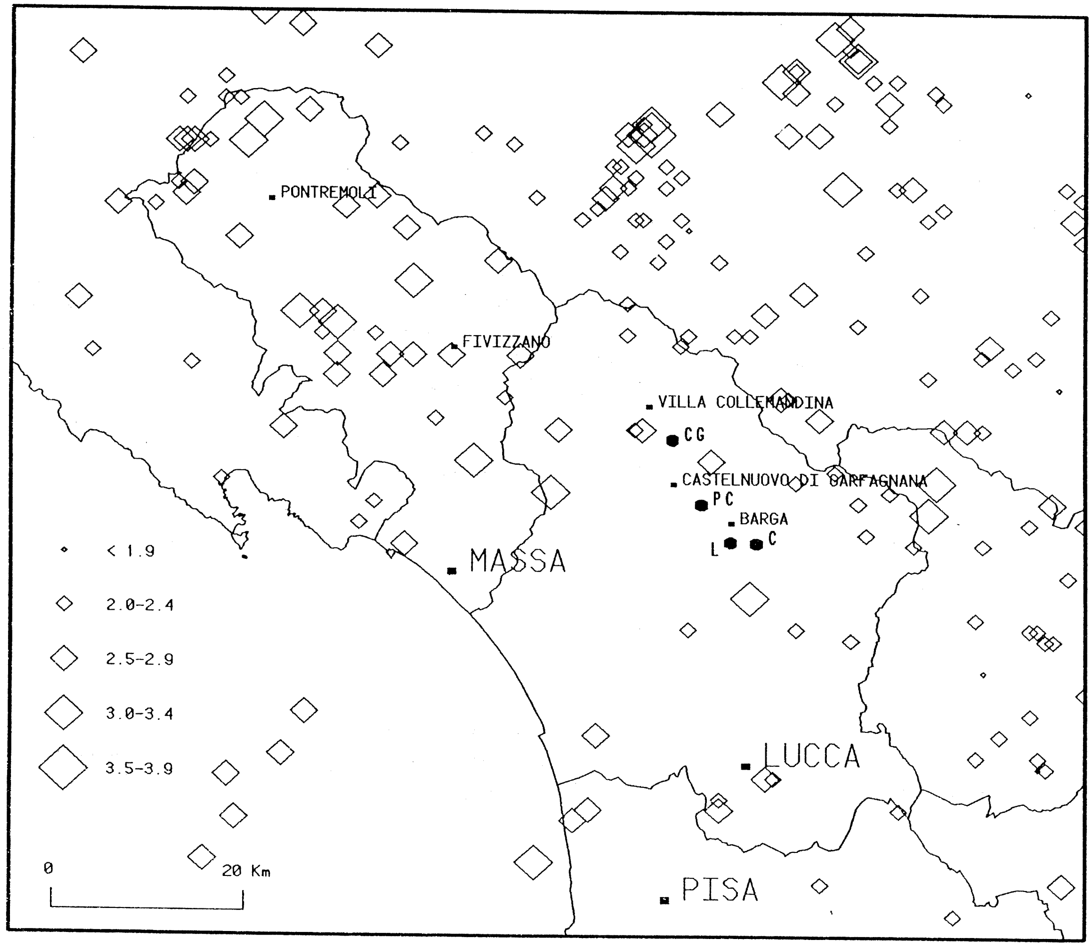

Fig. 11. Seismicity recorded in the Northern Apennines during the time period December 1990-May 1993, extracted from the ING catalogue. The locations of the four monitored areas, Coreglia (C) Loppia (L) Ponte di Campia (PC) and Castiglione Garfagnana (CG), are reported.

tionship between these two parameters is affected by many factors. For instance, radon emission data are not recorded daily like the pluviometric ones and rainfall affects coefficients of ^{222}Rn migration in soil, etc.

In the period of radon monitoring the level of seismic activity in Garfagnana was quite low (fig. 11). Maximum recorded magnitude was 3.5 for local seismic events; only an earthquake of $M = 4.2$ occurred about 100 km NE from the studied area. No significant correlation between radon emission and seismic activity could be observed. This is in accordance with the results of a model (Dobrovolsky *et al.*, 1979) that allows the precursor epicentral distance to be evaluated as a function of the magnitude of an earthquake. In fact, on the basis of the seismic energy of recorded earthquakes, no anomalous radon emission would be expected in the monitored areas. Hence, radon activity values measured during December 1990 – May 1993 represent the background for every station of the four zones studied in Garfagnana.

5. Conclusions

Experimentation of Kodak LR-115 film both in the laboratory and in the field confirmed its reliability as an α activity detector of ^{222}Rn in soil gas. Tracks were counted with a spark-counter and, in a few cases, with an optical microscope as well. The comparison between the two different systems of measurement showed a lower efficiency of the spark-counter. However, the ratio between the two measurements remains practically constant up to about 2500 tr/cm^2. Observed time variations in track density for the same monitoring station, as well as for different stations, are much higher than those related to fluctuations in the experimental conditions. Thus, LR-115 film (detector) and spark-counter (automatic instrument for track density measurement) are suitable for evidencing any variation in soil gas radon concentration.

During the two and a half years of monitoring in Garfagnana, significant variations in radon activity were observed in every station. Such variations follow regular temporal trends which may be attributed to seasonal factors (temperature of soil air and rainfall) and/or to characteristics of the soil in which each station is located. A clear-cut relationship between radon emission and atmospheric temperature was identified. Monitoring sites were classified into A, B and C groups, corresponding to negative, absent and positive correlation between radon concentration and atmospheric temperature, respectively .

During the monitoring period no significant correlation was observed between radon emission and seismic events recorded in the area. Thus, concentrations measured in this period represent the background of radon emission in every site of the four monitored zones in Garfagnana. This background will be taken into account in the future monitoring programme planned by our group.

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