IL NUOVO CIMENTO VOL. 22 C, N. 3-4 Maggio-Agosto 1999

The behavior of rare soil gases in a seismically active area: The Fucino basin (central Italy) (*)(**)

G. CIOTOLI (^{1}), M. GUERRA (^{2}), S. LOMBARDI (^{1}) and E. VITTORI (^{3})

(^{1}) *Laboratorio di Chimica dei Fluidi, Dipartimento di Scienze della Terra*
Università di Roma "La Sapienza", Piazzale A. Moro 5, 00185 Roma, Italy
(^{2}) *Istituto Nazionale di Geofisica (ING) - Via di Vigna Murata 605, 00143 Roma, Italy*
(^{3}) *Agenzia Nazionale per la Protezione dell'Ambiente*
Via Vitaliano Brancati 48, 00148 Roma, Italy

(ricevuto il 9 Giugno 1998; approvato il 18 Dicembre 1998)

Summary. — Soil-gas (He, Rn) concentrations were performed to test their sensitivity for locating fault or fracture systems also when masked by non-cohesive lithologies, and to investigate about the gas-bearing properties of seismogenic faults. The Fucino basin (central Italy) was chosen as test site because it displays a network of surface and shallow-buried active faults within the valley floor that were partially reactivated during the 1915 Avezzano earthquake ($M_s = 7.0$). The highest radon values were found aligned along the most important faults bordering the eastern and the north-western sides of the plain. Moderately anomalous values of radon activity occur along the faults located in the depression of the historical lake. Highest helium values prevail in the western part of the plain, in correspondence of a horst structure inferred to be as the prolongation of the Vallelonga-Trasacco ridge. The study provides constraints on the spatial influence of tectonics and geology on deep-seated gas migration toward the surface.

PACS 91.30.Px – Phenomena related to earthquake prediction.
PACS 91.45.Fj – Convection currents.
PACS 47.55.Mh – Flows through porous media.
PACS 01.30.Cc – Conference proceedings.

1. – Introduction

The systematic observation and recording of the gas-releasing crustal phenomena can reveal channeling migration along enhanced permeability pathways (*i.e.* tectonic discontinuities) and give important information about earthquake prediction studies. All types of faults and fracture zones should be considered as belts of increased

---

(*) Paper presented at the "Fourth International Conference on Rare Gas Geochemistry", Rome, October 8-10, 1997.
(**) The authors of this paper have agreed to not receive the proofs for correction.

permeability which can readily transmit a variety of fluids, including gases, to the surface. Subsurface gases (Rn, He, CO_2, CH_4, H_2, H_2S) stored in or around fault zones are referred to as "fault-soil gases" (Zhiguan, 1991; Chengmin and Xuanhu, 1994). In seismic areas the increase in the regional stress field causes changes in fluid pore pressure resulting in a mobilization and re-distribution of various gaseous species via advection (for a detailed review see Holub and Brady, 1981). This mobilization produces shallow soil-gas anomalies due to increased upward mobility along new faults and fractures and/or the reactivated pre-existing brittle deformations (King *et al.*, 1996). Field data also showed the reliability of the soil-gas method for detecting faults buried or cutting unconsolidated sediments which may prevent the recognition of brittle deformations in the field by traditional means of geological investigation (Duddridge *et al.*, 1991; Ciotoli *et al.*, 1993 and references therein; Lombardi *et al.*, 1996). This relatively new technique has great potential for geological investigation due to its low cost, ease of operation and rapid deployment. In this work soil-gas (He, Rn) regional survey (about 5 sample/km^2), and high-resolution sampling (about 80-100 samples/km^2) were carried out in the Fucino basin (central Italy), a seismically active and fault-bounded intramontane depression, filled with a thick sequence of sandy-clayey continental deposits, within the central Apennine orogenic belt (fig. 1). The area was selected as the test site because it displays: *a*) surface and shallow-buried seismogenic faults partially reactivated during the 1915 Avezzano earthquake ($M_s = 7.0$) (San Benedetto-Gioia dei Marsi fault, SBGMF and Trasacco fault, TF) (Michetti *et al.*,

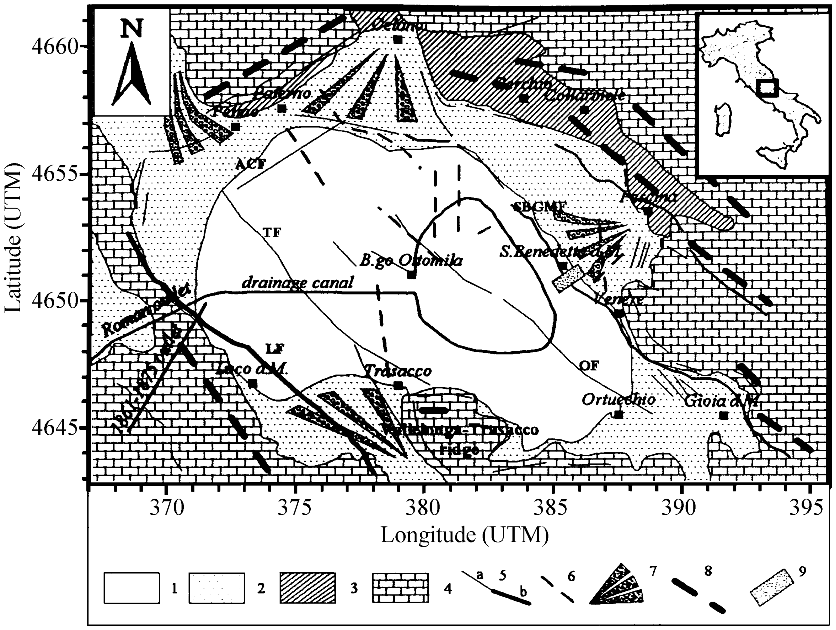

Fig. 1. – Geological map of the Fucino basin. Legend: 1 area covered by the Fucino Lake in 1861 A.D.; 2 latest glacial to Holocene fluvio-lacustrine terrace, about 20 kyr to present; 3 lower to middle Pleistocene terrace; 4 Meso-Cenozoic mainly carbonate bedrock; 5 Holocene normal fault marked as b) where coseismically re-activated; 6 coseismic ruptures; 7 latest Pleistocene to Holocene alluvial fan; 8 range front (modified from Michetti *et al.*, 1996).

1996 and references therein); *b*) coseismic phenomena: ruptures, liquefaction, as well as gas and water emissions along the fractures elsewhere in the plain (Oddone, 1915; Galadini *et al.*, 1995). The primary goals of this research are: to test the sensitivity of the method for locating fault or fracture systems, in an area where unconsolidated lacustrine sediments occur; to investigate the gas-bearing properties of the seismogenic faults related to the 1915 earthquake (SBGMF) and hidden structural features recognized by seismic surveys and remote sensing techniques (Ortucchio fault, OF; Luco dei Marsi fault, LF; Trasacco fault, TF; Avezzano-Celano fault, ACF) (Giraudi, 1989) in the valley floor and in the western sectors of the area.

2. – Results

2˙1. *Regional survey.* – The main statistics of soil-gas data in the Fucino plain is reported in table I. Radon and helium average concentrations are within the mean values (about 20 Bq/L and about 50 ppb, respectively) coming from previous surveys carried out in different Italian basins (Lombardi *et al.*, 1996). Analysis of soil samples provided the determination of ^{222}Rn activity at the equilibrium with parent radionuclides (radium) according to Akerblom (1993). The obtained mean value for soil samples (26.41 Bq/L) is nearly the same (26.5 Bq/L) as the radon anomaly threshold defined by statistical assumptions (table I). Radon samples exceeding the calculated value are not supported by *in situ* production, but they can be linked to upward migration processes through enhanced permeability pathways. The dot-map of radon distribution shows that in the eastern sector of the plain higher radon values occur aligned along SBGMF, as well as in the north-western sector where the ACF crosses a WNW-ESE prolongation of a 1915 coseismic rupture (Michetti *et al.*, 1996). Anomalous values of radon also occur along the faults located in the depression of the historical lake (OF and TF). Further, North of the Borgo Ottomila village in correspondence of coseismic scarps mapped by Oddone (1915) an area of high radon and helium values occurs. This area is marked also by anomalies of the other analyzed gases (CO_2, CH_4)

TABLE I. – *Main statistics of soil gas data from regional and high-resolution surveys. As the presence of a few outliers* (*isolated values at the tails of frequency distribution*) *may provide non-representative statistical parameters, gas values greater than* 95 *percentile and lower than* 5 *percentile were excluded. The mean* (*) *and standard deviation* (*) *of the corrected set were used to define the statistical anomaly threshold fixed at the mean plus* 1/2 *standard deviation.*

	Regional sampling									
	Count	min	max	mean	std. dev.	5th%	95th%	mean*	std. dev.*	anomaly threshold
Rn (Bq/L)	548	0.37	119.5	21.8	16.65	4.07	55.55	20.25	12.5	26.5
He (ppB)	548	−497	8238	64	552.76	−278	303	19	125	82
	High-resolution survey (S. Benedetto dei Marsi site)									
	count	min	max	mean	std. dev.	5th%	95th%	mean*	std. dev.	anomaly threshold
Rn (Bq/L)	84	2.58	93.98	29.88	19.83	5.18	68.82	28.7	16.21	36.8
He (ppB)	84	−528	1044	64	255	−364	419	55	173	141

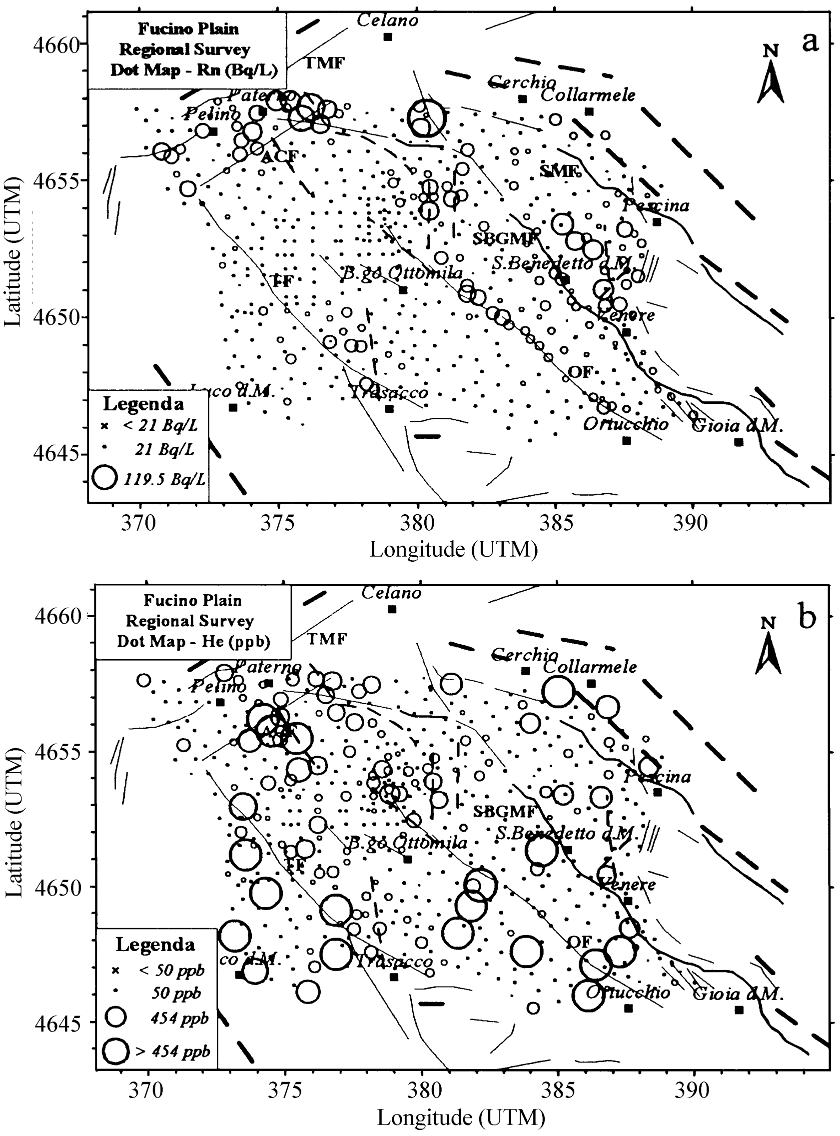

Fig. 2. – Dot maps of soil-gas concentration obtained from regional survey. (a) Rn; (b) He distribution. The diameter of the dots is proportional to concentration values.

and is characterized by a pervasive brittle deformation of the surface layers induced by liquefaction phenomena caused by the 1915 earthquake (Galadini *et al.*, 1995). Helium highest values prevail in the central (B.go Ottomila village) and north-western part of the plain (fig. 2b) in the area where liquefaction-induced brittle deformations occur and in correspondence of TF and ACF, respectively.

2·2. *High-resolution survey.* – South of the S. Benedetto dei Marsi village a detailed survey was performed across two fault scarps originated during the 1915 earthquake

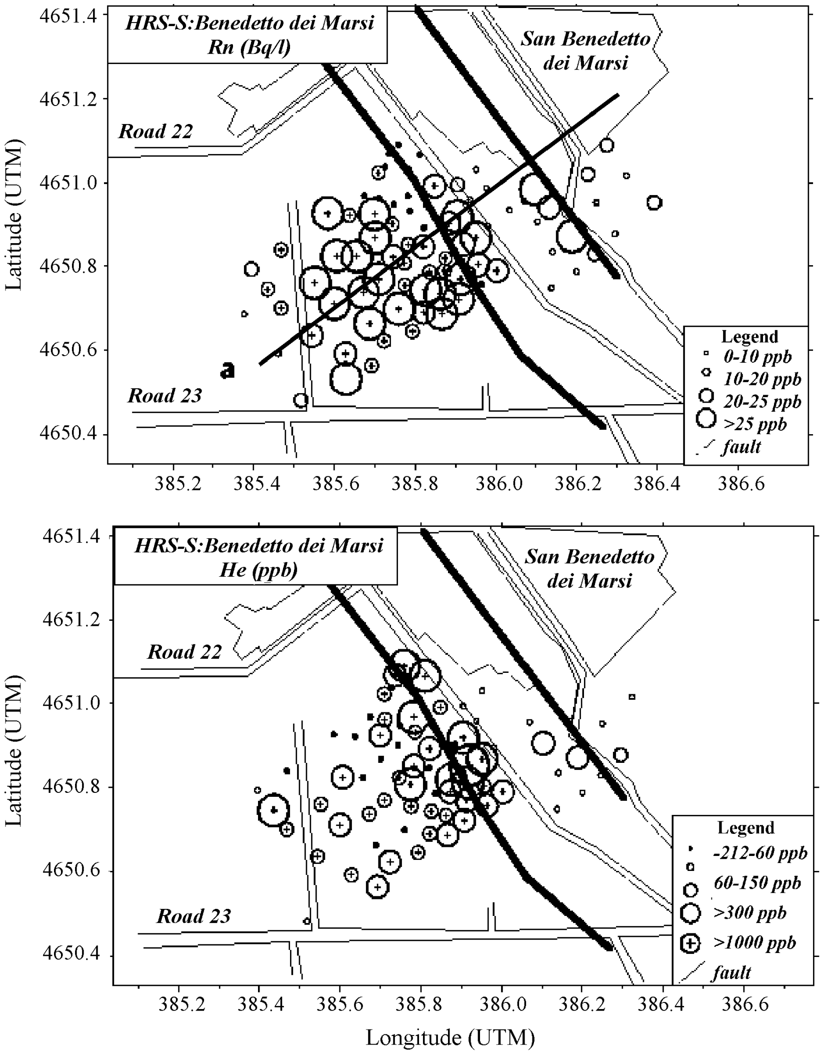

Fig. 3. – High-resolution survey at S. Benedetto dei Marsi site.

and belonging to an active segment of the SBGMF (fig. 3). Sample locations were projected along a middle-longitudinal line to the transect and moving-average-transformed values were plotted against the distance from a reference point (fig. 4). Generally, at high-resolution scale, the different contribution of phenomena acting along specific directions (*i.e.* fault-related anisotropy effects) *vs.* phenomena acting randomly (*i.e.* isotropic field of background) is less apparent than at a regional scale. This may originate because of a "scale-effect", when sampling is performed within the influence range of a structure (Ciotoli, 1997). In this case, field data provide a sharp soil-gas pattern for Rn and He due to the recent activity and a well-defined interception of fault plane with the surface. In the soil-gas profile the occasional displacement between radon peaks (signed with **F?**) may indicate the location of a

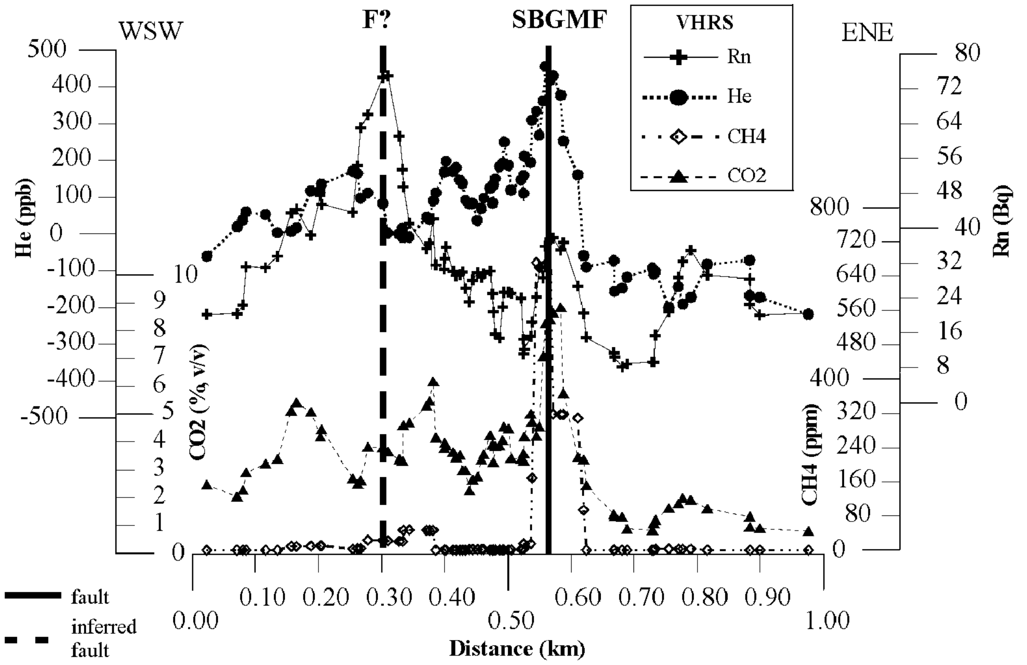

Fig. 4. – Profiles of soil-gas radon and helium concentrations along the HRS at the S. Benedetto dei Marsi site. Samples were projected along a middle-longitudinal line to the transect and moving-average-transformed values were plotted against the distance from a reference point (a in fig. 3). The figure also shows profiles of methane and carbon dioxide soil-gas concentrations. As radon and helium, these gases highlight sharp peaks in correspondence of the SBGM fault.

further buried fault parallel to the main fault scarp. Moreover, the presence of a shallow water table (groundwater movement) can add a horizontal component to the escaping gas producing the peak displacement in the figure.

3. – Discussion

Regional soil-gas survey (fig. 2a, b) shows different gas-bearing properties of faults either bordering and cutting the Fucino plain. Basically, soil-gas anomalies are clustered around specific locations or they mark belts of enhanced permeability along the main NW-SE structural elements, known or inferred on the basis of morphological interpretation. In this case, radon appears as the most sensitive tracer of structural features. The sharper anomalies are associated to the SBGMF and to the N-S fault recognized by Oddone (1915) South of the Pescina village. These fault segments, characterized by extensive kinematics and reactivated during the earthquake in 1915, caused in the field a set of fault scarps up to few meters high. Also the OF, recognized only at some discrete points by previous structural surveys (*e.g.*, Giraudi, 1989), is marked by a continuous, well-defined Rn "ridge". In the western-central side of the plain, helium values seem to characterize the shallow carbonate horst that was inferred to be the north-western prolongation of the carbonatic Vallelonga-Trasacco ridge (fig. 2b). The pervasive fracturing associated with this narrow structure may enhance helium leakage from deeper strata, therefore causing the helium to be distributed along a belt instead of a line. Furthermore, helium high values characterize the coseismic ruptures in the northern sector (ACF). On the contrary, the observation that Rn anomalies more effectively outline faults (re)activated during the 1915 earthquake in the eastern sector of the plain is consistent with an enhanced emanation power due to the micro-fracturing and crushing phenomena induced by stress-strain field variations (Holub and Brady, 1981). Moreover, along the fault zone the relatively high gas permeability and the action of carrier gas (possible relationship with the occurrence of gas bubbling (CH_4) in wells, gas vents and "mud-volcanoes" throughout the Fucino plain) produce a suitable rate of migration required to obtain anomalies of short-life Rn in the soil pores. Sampling at a regional scale showed that in this case Rn is very well related to fault in fine-grained deposits especially when freshly faulted. In order to study the radon spatial continuity, a first geostatistical approach was performed in the eastern sector of the plain where radon well detects the SBGMF and the OF. Figure 5 shows the variogram surface and the contour-line maps of radon distribution in this area, respectively. The variogram surface map highlights an anisotropic radon distribution, as well as identifies preferential orientations along which directional variograms should be calculated to obtain the spatial model. The map stresses minimum γ values (high spatial continuity) trending about N 135 and

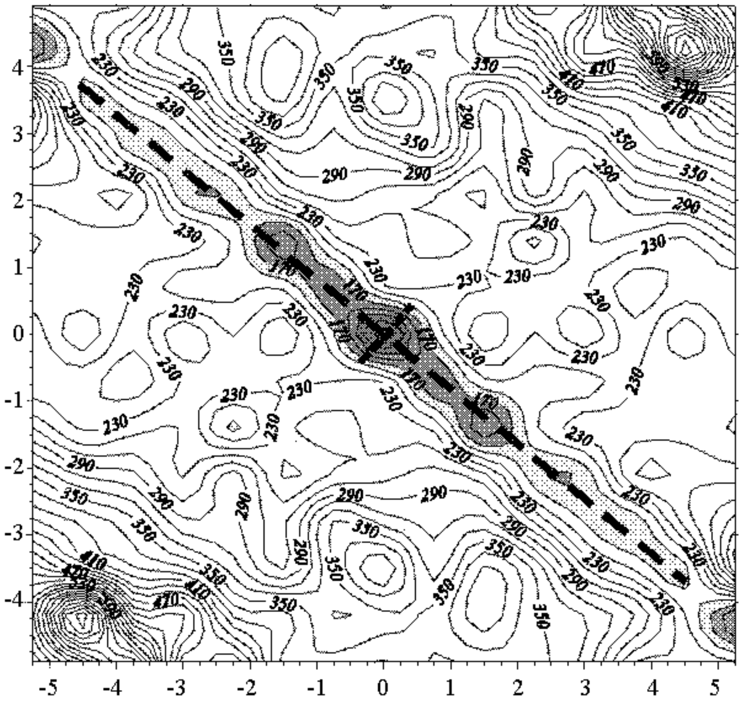

Fig. 5. – The figure shows the variogram surface map calculated for the selected area. The map provides an effective way to visualise the presence of radon distribution anisotropies and identifies preferential orientations along which directional variograms should be calculated. The dotted line indicates the direction maximum anisotropy axis, as well as the spatial domain of the phenomenon (*i.e.* the distance along which the fault influences the radon distribution).

corresponding to the orientations of the SBGMF and the OF. The anisotropy ratio ($R \cong 5$), given by the relation $A_{\max}/A_{\min}$, suggests the effective influence of anisotropy-inducing factors (faults) as well as a quantitative measure of the distance along which the fault influences the Rn distribution. A more complete geostatistical analysis (*i.e.* calculation and modeling of experimental variograms, computing contour maps) will be performed in a future work.

4. – Conclusions

The comprehensive approach followed in this study has provided remarkable insights on the spatial influence of tectonic discontinuities on deep-seated gas migration towards the surface. The geometry of soil-gas anomalies at the surface reflects the different gas-bearing properties of the seismogenetic faults (SBGMF, OF), and the shallow-buried faults (LF and TF) of the Fucino plain. In particular, such an approach demonstrates that Rn can better identify freshly broken ruptures associated with seismogenic faults and the simple-geometry faults of the eastern sector (SBGMF and OF), as high helium values characterize the western side where a more pervasive fracturing induced by the complex geometry of the TF (listric fault) and the occurrence of coarser deposits produce wider soil-gas anomalies making the fault location less clear. Independent of gas origin, the results show that gases migrate preferentially through brittle deformations by advective processes as suggested by the relatively high rate of migration needed to obtain anomalies of short-life ^{222}Rn in the soil pores. Geostatistics (*i.e.* the study of the variogram surface) stresses the presence of a sharp fault-related anisotropy of radon distribution in the eastern sector of the plain. In a further work a more detailed geostatistical study will be performed.

* * *

We are very grateful to Dr. S. Beaubien for the revision of the manuscript and his helpful suggestions. We wish to thank Mrs. A. Baccani for her help in the laboratory analyses. This research was partially funded by EC (contract number ENV4-CT96-0291).

REFERENCES

Akerblom G., *Ground radon: Monitoring procedure in Sweden*, paper presented at the *Jag* Disc. Meeting on *Radon Workshop, Geology, Environment, Technology*, Royal Astronomical Society, London, February 12, 1993.

Chengmin W. and Xuanhu L., *Application of fracture gas measurement to the earthquake studies in China, Earthquake Res. in China*, 8/2 (1994) 167-180.

Ciotoli G., Etiope G., Lombardi S., Naso G., and Tallini M., *Geological and soil-gas investigations for tectonic prospecting: preliminary results over the Val Roveto Fault* (*Central Italy*), *Geol. Rom.*, **29** (1993) 483-493.

Ciotoli G., *Introduzione di metodi geostatistici nella interpretazione della distribuzione dei gas endogeni nei suoli quale contributo alle indagini strutturali: la piana del Fucino. Tesi di dottorato*, Dipartimento di Scienze della Terra, Università di Roma "La Sapienza" (1997).

Duddridge G. A., Gringer P. and Durrance E. M., *Fault detection using soil gas geochemistry, Quaterly J. Engin. Geol.*, 24 (1991) 427-435.

Galadini F., Galli P., Giraudi C. and Molin D., *Il terremoto del 1915 e la sismicità della Piana del Fucino* (*Italia centrale*), to be published in *Boll. Geol. It.*

GIRAUDI C., *Lake levels and climate for the last 30,000 years in the Fucino area (Abruzzo, Central Italy) - A review, Palaeogeogr., Palaeoclimatol., Palaeoecol.*, **70** (1989) 249-260.

HOLUB R. F. and BRADY B. T., *The effect of stress on radon emanation from rock, J. Geophys. Res.*, **86** (1981) 1776-1784.

KING C.-K., KING B.-S., EVANS W. C. and ZANG W., *Spatial radon anomalies on active faults in California, App. Geochem.*, **11** (1996) 497-510.

LOMBARDI S., ETIOPE G., GUERRA M., CIOTOLI G., GRAINGER P., DUDDRIDGE G. A., GERA F., CHIANTORE V., PENSIERI R., GRINDROD P. and IMPEY M., *The refinement of soil gas analysis as a geological investigative technique. Final Report*, Work carried out under a cost sharing contract with the European Atomic Energy Community in the framework of its 4th R&D programme on *Management and Storage of Radioactive Waste* (1990-1994) Part A, Task 4: "Disposal of Radioactive Waste", EUR 16929 EN (1996).

MICHETTI A. M., BRUNAMONTE F., SERVA L. and VITTORI E., *Trench investigations of the 1915 Fucino earthquake fault scarps (Abruzzo, Central Italy): geological evidence of large historical events, J. Geophys. Res.*, **101** (1996) 5921-5936.

ODDONE G., *Gli elementi fisici del grande terremoto marsicano-fucense del 13 gennaio 1915, Boll. Soc. Sism. It.*, **19** (1915) 71-215.

ZHIGUAN S., *A study on the origin of fault gases in Western Yunnan. Earthquake Res. China*, **5/1** (1991) 45-52.