Geostatistical analysis for the assessment of rare-gas soil distribution in detecting concealed faults: The Ofanto clay basin (*)(**)

G. CIOTOLI and S. LOMBARDI

Fluid Geochemistry Laboratory, Earth Sciences Department, Università di Roma "La Sapienza" Piazzale A. Moro 5, 00185 Roma, Italy

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

Summary. — An integrated geochemical, morphological and structural analysis was applied to a clay basin in Southern Italy (Ofanto valley) to delineate tectonic features. the resulting distribution of previous soil-gas surveys (helium and radon) and the location and orientation of field-observed brittle deformations (faults and fractures) were compared with air-photo interpreted morphotectonic features. The results show that the highest helium and radon values occur preferentially along elongated features shown by mesostructural and geomorphological analyses, *i.e.* anti-Apennine, Apennine and, secondarily, N-S orientations. Furthermore, the application of geostatistical techniques in a testing area has enhanced the semi-quantitative evaluation of this anisotropic soil-gas distribution (linked to the gas-bearing properties of the local brittle deformations). The correspondence between soil-gas distribution and mesostructural/geomorphological features, as well as the results from the geostatistical analysis, suggest that gas leakage towards the surface is controlled by the same structural pattern which created some morphological features. Geostatistical analysis of the geochemical data combined with the other geological techniques has been shown to improve the interpretation of soil-gas results for neotectonic studies in clay basins where tectonic discontinuities have no surface expression.

PACS 91.30.Px – Phenomena related to earthquake prediction.
PACS 91.45 – Physics of plate tectonics.
PACS 91.45.Fj – Convection currents.
PACS 01.30.Cc – Conference proceedings.

1. – Introduction

Earth degassing is the process whereby deep-origin gases migrate to the soil surface through the mantle and crust. The analysis of these naturally occurring gases in the soil has been shown to be a useful method for the detection of faults and fracture systems which act as preferential pathways for ascending deep gases (Sugisaki, 1987; Zhiguan 1991; Ciotoli *et al.*, 1993; Klusman, 1993; King, 1996). Generally, atmosphere

(*) 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.

and soil air can be considered to have similar gas concentrations which can be referred to a background value. In correspondence with faults and fractures, however, gas values are very different from those in the atmosphere and the spatial distribution of these anomalous concentrations generally reflect the location and orientation of these more permeable zones which act as conduits for deep seated gases. He and Rn have been shown to be the most reliable fault tracers. Recent efforts indicate that the soil-gas method seems to provide good information on gas-bearing faults, even in clayey basins where the homogeneity and plastic behavior of the clayey cover prevent the mapping of tectonic discontinuities by direct methods (Lombardi *et al.*, 1996). Although soil-gas distribution can be affected by pedological, biogenic and meteorological factors (Hinkle, 1994), these are considered subordinate to fault-related transport mechanisms. It is therefore necessary to collect a large number of samples during periods of stable meteorological conditions (*i.e.* during dry season), and to use an appropriate statistical treatment. The rapidity, reliability and low-cost make this method a powerful tool for geological investigations. This paper focuses on a soil-gas survey conducted in a clay basin in southern Italy (Ofanto valley) (fig. 1) to map faults whose presence had only been suggested by indirect stratigraphic and morphological

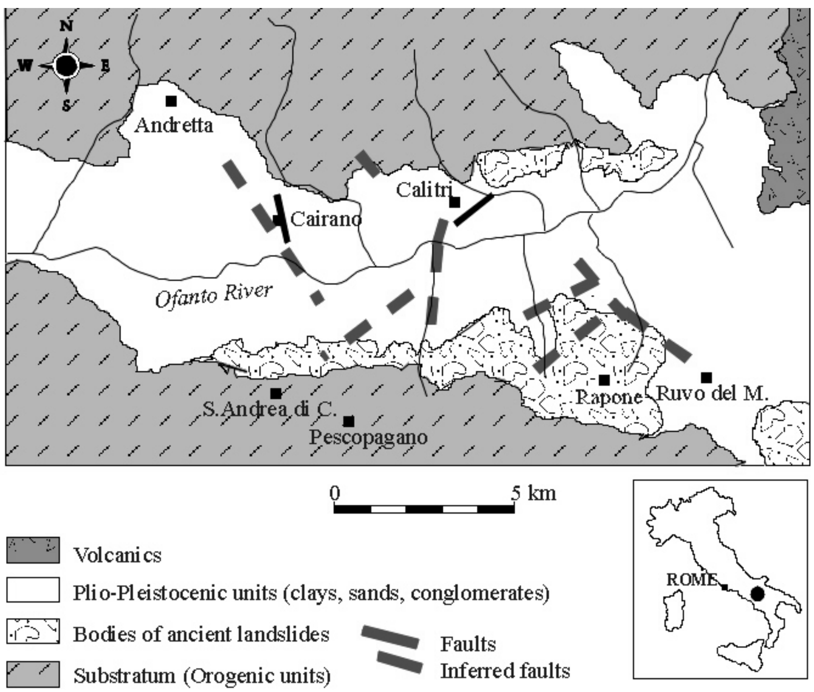

Fig. 1. – Geological map of the Ofanto basin (Southern Italy) (Ciotoli *et al.*, 1994). The Ofanto Valley is located in the Southern Apennine sector which was hit by a strong earthquake ($M_s = 6.9$) on November 23, 1980. It is a piggy-back basin mainly filled with over-consolidated Plio-Pleistocene clayey sediments which has a maximum outcropping thickness of about 600 meters. Recently detected Plio-Pleistocene compressional structures have been observed to be displaced by important dip-slip and transcurrent Apennine and anti-Apennine tectonic discontinuities. Some of these elements have been inferred on stratigraphic and morphological bases. Still-active Pleistocene extensional tectonics created the Ofanto Basin, as shown by the presence of normal faults linked to the growth of Vulture volcano in the eastern sector of the area.

evidences. To better understand the influence of buried structures on gas migration and concentrations in the shallow soil, He and Rn soil-gas data were compared with geo-structural data obtained by photo-interpretation and field-based structural mapping, and geostatistics were applied to assess the spatial continuity of soil-gas concentrations in an effort to identify a possible fault-linked anisotropy in their surficial distribution.

2. – Results

Geostatistics may be defined as the statistical study of spatial correlation and it has greatly enhanced the modeling of geological phenomena. Soil-gas concentrations usually show: i) a structural aspect related to the overall gas distribution (*i.e.* the presence of zones with, on average, elevated concentrations); ii) an erratic aspect

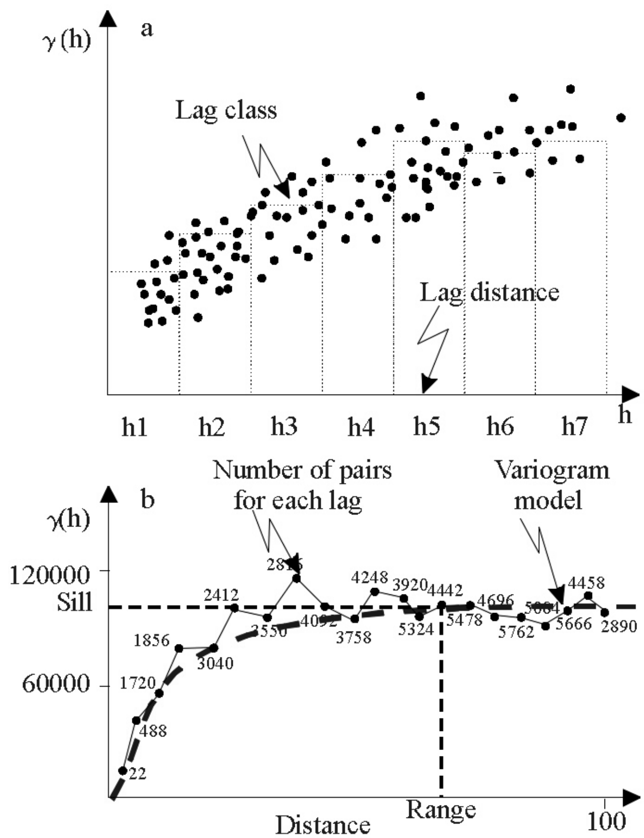

Fig. 2. – Figures show an example of the variogram cloud (a) and the calculated experimental variogram (b). Variogram cloud represents the scatterplot of the experimental variogram. The sorted data is partitioned into lag classes such that at least twenty lag distances are in each lag class, then the difference between each pair value (γ) in the lag class is averaged. The average g value for each class, plotted against distance, constitutes the points in the experimental variogram plot (b). The experimental variogram is modeled by a simple curve (*i.e.* mathematical function) that reaches a sill value at a definite distance (range). The range represents the distance beyond which data are not spatially correlated (the spatial domain of the phenomenon) (Ciotoli, 1997).

TABLE I. – *Main statistics of soil gas data from regional survey in the Ofanto basin. 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. The so-defined anomaly thresholds agree with those obtained from the change in slope of the probability plot following Sinclair* (1974).

	Count	min	max	mean	std. dev.	5th%	95th%	mean*	std. dev.*	anomaly threshold
Regional sampling										
Rn (Bq/L)	110	0.74	100	17	17.2	2.22	52.54	15	12	21
He (ppb)	110	−509	402	20	131.3	−163	230	18	92	64

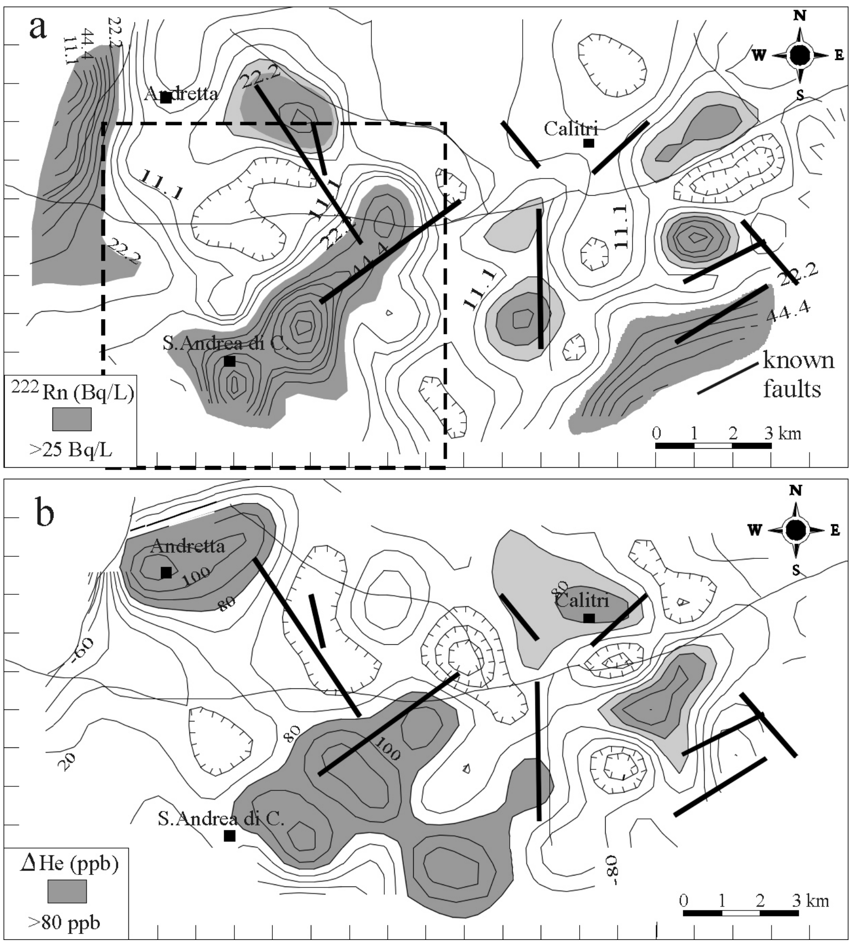

Fig. 3. – Soil-gas distribution in the Ofanto basin; a) radon (Bq/L), b) helium (ppb). Maps also show faults known in literature. The dotted square in fig. 3a highlights the test area used for geostatistical analysis (after Ciotoli *et al.*, 1994).

related to the local behavior of the phenomenon (*i.e.* in an anomalous zone the gas concentrations seem to fluctuate randomly). The geostatistical analysis can provide new insight in the geological and structural control (fault-related aspects) of the soil-gas data distribution. For example, variography is the geostatistical tool which assesses, in aggregate, how soil-gas content at any given two locations varies as a function of their distance, assuming that the spatial correlation within a data set may be modeled using a function termed the variogram (γ). Probability theory defines the variogram in terms of the variance (Var) of the difference between two sample values. The variogram is defined as follows: $\gamma(h) = (1/2)\,\mathrm{Var}\,[Z(x+h) - Z(x)]^2$, where $Z(x)$, $Z(x+h)$ are pairs of values at the sampled locations separated by the lag distance h (fig. 2a, b) (see Isaaks and Srivastava, 1989). A contour map of the variogram surface clearly displays directional soil-gas anisotropies and allows the computation of the anisotropy ratio using the max. and min. axes of the isovariance-closed contour lines (see fig. 6). This step provides the assessment of the spatial continuity of gas anomalies and useful parameters for the construction of a contour-line map which corrects false elongated anomalies caused by the gridding procedure (Isaaks and Srivastava, 1989). Some environmental factors (*i.e.* soil type, organic content and weathering) which isotropically affect the spatial correlation (distance only) of shallow soil-gas concentrations tend to mask the anisotropic pattern caused by aligned structural features. The anisotropy ratio enables the evaluation of the effectiveness and "strength" of anisotropic factors *vs.* random ("background") factors.

Sampling was carried out over an area of about 120 km^2 (≈ 1 sample/km^2). More

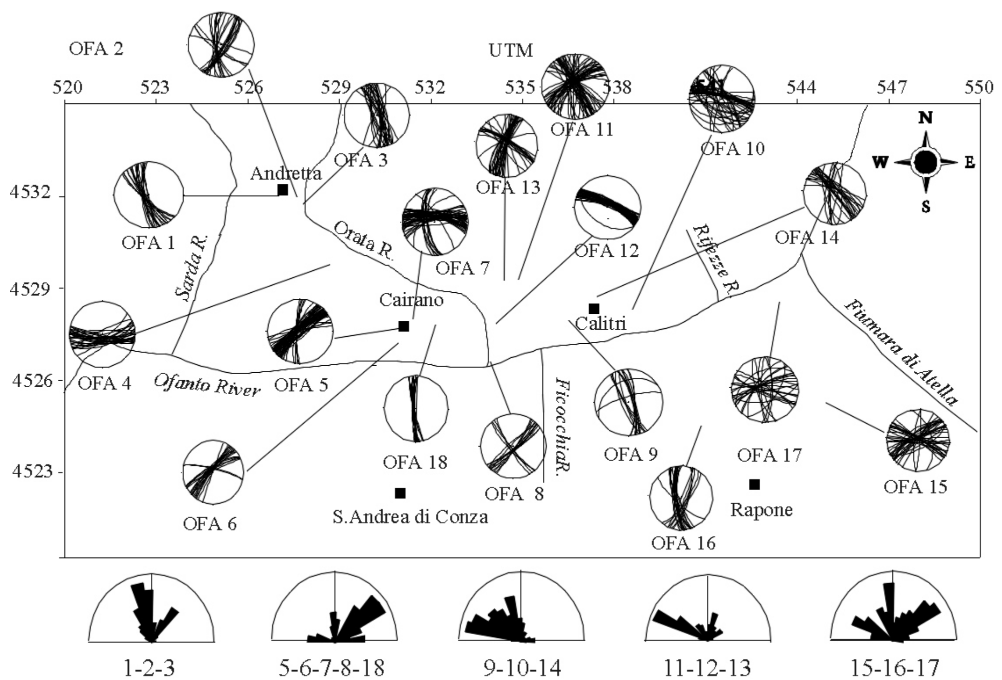

Fig. 4. – Field-based fracture field analysis of the Ofanto basin. Data from nearby stations are grouped and plotted in rose diagrams to obtain the most representative directions for comparison with geochemical results (after Ciotoli *et al.*, 1994).

than one hundred soil-gas samples were collected from a depth of 0.5–0.8 meters, depending on the soil thickness, using a well-tested technique. Soil-gas statistics are summarized in table I and the contour maps (figg. 3a and b) show Rn and He soil-gas distribution, respectively, as elaborated with "kriging" interpolation method. Results obtained in the previous work (Ciotoli *et al.*, 1994) show that the highest helium and radon values occur preferentially along anti-Apennine, Apennine and, secondarily, N-S elongated zones as defined statistically using data from field-based brittle deformation (fig. 4). The comparison with the new geomorphological data (air-photo lineaments) confirms these statistical trends in the S. Andrea di Conza, Calitri and Andretta sub-areas as shown in the rose diagrams (fig. 5). In order to enhance the interpretation of the elongated anomalies, variogram surface maps were elaborated where a strong radon and helium anomalies occurred (between S. Andrea di Conza and Calitri villages). The maps stress the following features (fig. 6a and b): i) minimum γ values for radon, corresponding to the directions of maximum data continuity, extending along the anti-Apennine direction (N45E) in correspondence with a fault zone recognized by previous geological surveys (Gambino, 1993); and ii) two main perpendicular directions of anisotropy which approximate Apennine and anti-Apennine trends for helium. The

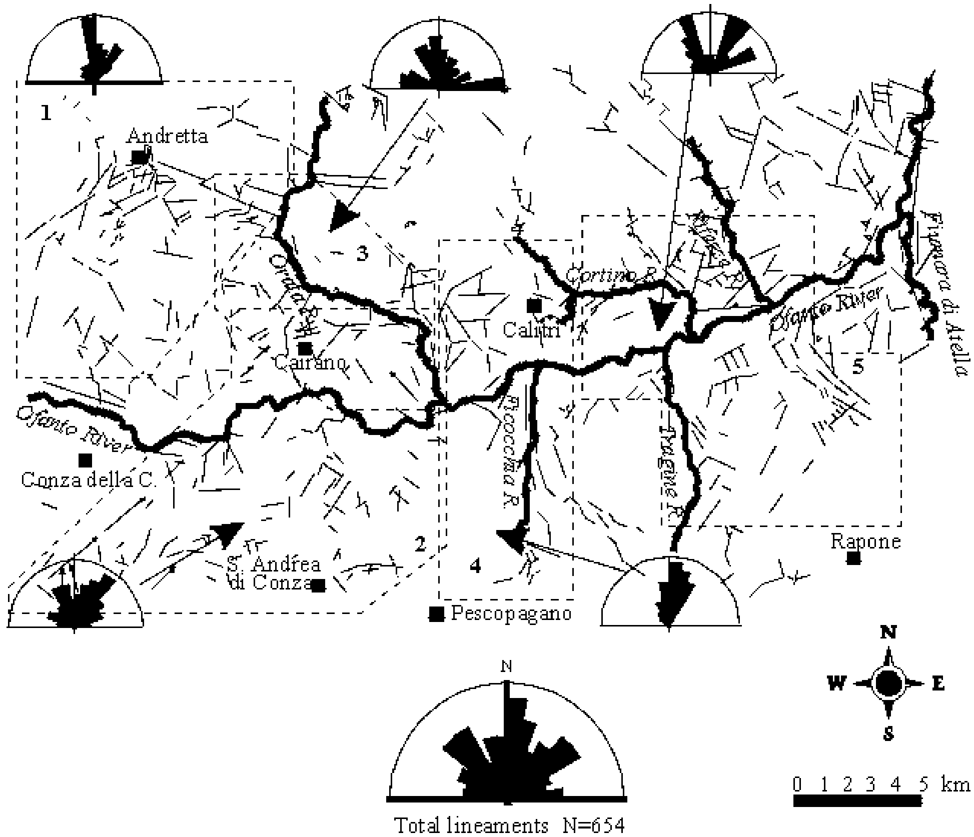

Fig. 5. – Photo-lineaments within the Ofanto basin. Rose diagrams include the recognized elements in the marked areas.

Apennine anisotropic trend is poorly represented in the contour maps of fig. 3a and b, suggesting that a variogram surface highlights anisotropic trends better than contour-line maps. Helium spatial continuity (fault-related) according to these orientations can be inferred. The "hole effect" (Armstrong, 1995) observed in the radon variogram surface map, marked by a depression (decreasing of variance) along the N-S direction (point H in fig. 6a), stresses the interaction of two or more faults having different directions, or the presence of discontinuous gas-bearing fault properties (*e.g.*, self-sealing phenomena along the structure). The ratio between the max. and min. anisotropy semi-axes (R) in the variogram surface map for Rn (6.25) and He (5.6)

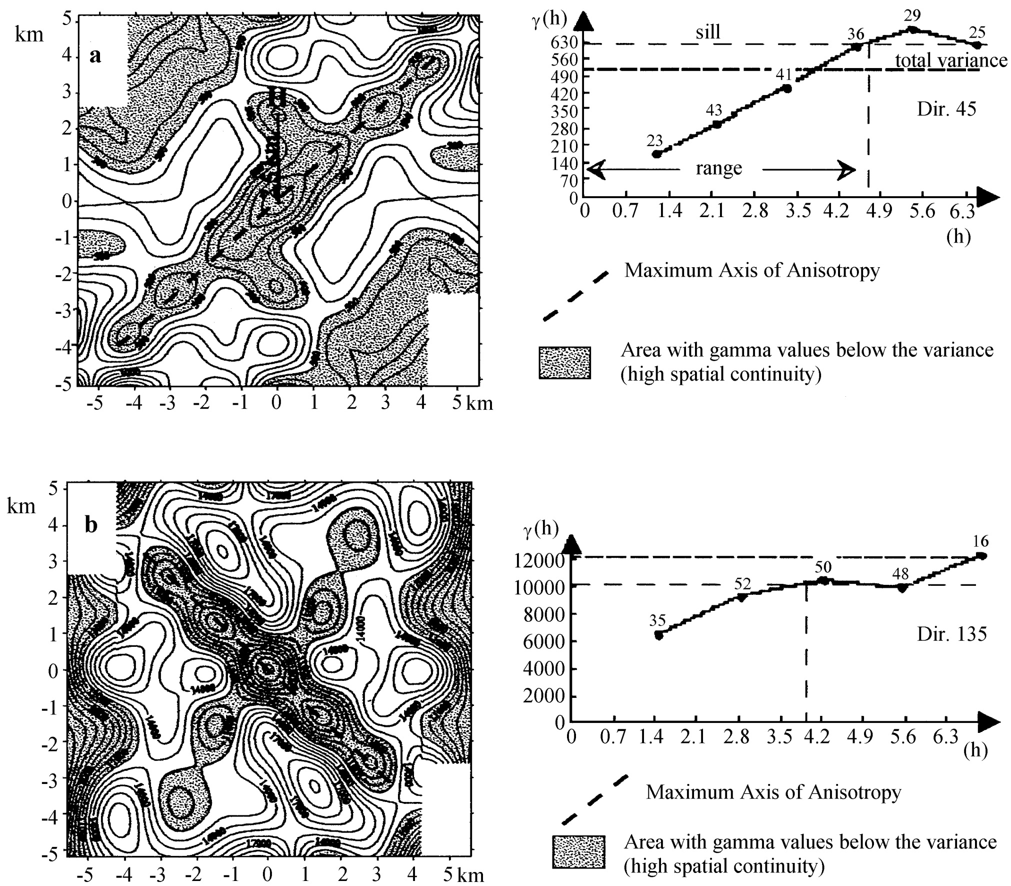

Fig. 6. – Contour maps of the variogram surface from the selected area between S. Andrea di Conza and Calitri for Rn (a) and He (b). Contour lines depict the function $g(h)$ of sample pairs grouped according their distance (lag $h = 1$ km) and the direction of the segment connecting the points of pair. The elongated shape and the direction of the closed contour line highlight the presence of a spatial anisotropy in data distribution and identify the preferential directions along which experimental variograms should be calculated. For each gas, the directional variogram was derived from the maximum axis of anisotropy (directions 45°, 135°, for Rn and He, respectively). The modeling of the experimental variograms along these (and other) directions provides the evaluation of parameters (nugget, range, sill) necessary to describe the continuity of the investigated variable in the 2D space (Ciotoli, 1997).

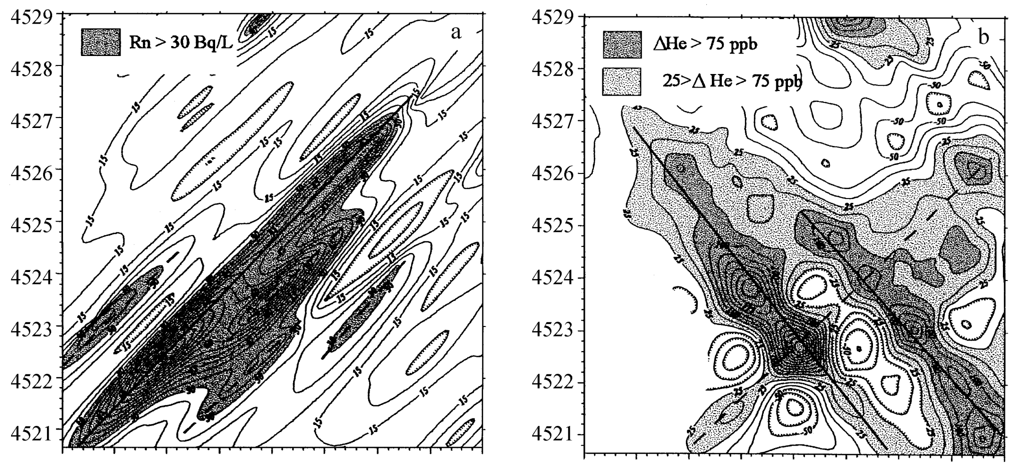

Fig. 7. – Contour-line maps for radon (a) and helium (b) distribution in soil gas. The modeling of experimental variograms calculated along the orientation of anisotropy provides the construction of maps corrected for the elongated anomalies due to gridding. Maps show anomalous areas (dark gray) according to the statistic threshold (table I) and weak anomalies (light gray). Furthermore, observed (continuous lines) and inferred (dotted lines) fault-related elongations are reported.

suggests that fault-induced anisotropy factors affect gas distribution over the entire selected area. The modeling of the experimental variograms calculated for radon and helium data in the selected area has provided the calculation of useful parameters for the construction of new contour-line maps (fig. 7a, b) corrected for the appearance of elongated anomalies due to the gridding procedure rather than to the effective anisotropy (Isaaks and Srivastava, 1989). Contour-line maps (fig. 7a, b) highlight that the distribution of radon and helium anomalies in the area shows a more complex pattern as inferred from the variogram surface maps (*i.e.* anisotropic distribution) (fig. 6a, b). Both radon and helium elongated distributions stress the possible existence of some brittle deformations (dotted lines) not observed in the field by means of geological method and probably linked to the main discontinuities NW-SE and NE-SW oriented (continuous lines) (fig. 7a and b). The different chemical and physical parameters (*i.e.* mobility, solubility) may explain the different but complementary behaviour of these gases that provide information about the gas-bearing role of field-observed faults and the location of brittle deformations with no surface expression.

3. – Conclusion

In spite of the above-mentioned limitations, a main dominating factor must be invoked wherever soil-gas distribution is similar for the two gases. Since geochemical trends coincide with geomorphological and structural features in the investigated area, it is suggested that tectonics control the leakage and distribution of soil gas along permeable zones (*i.e.* faults and fractures). The application of geostatistical techniques in the test area confirms an anisotropic soil-gas distribution along the anti-Apennine trend, and emphasizes the presence of an Apennine trend for He. Furthermore, it provides the semi-quantitative evaluation of the anisotropic soil-gas distribution and the calculation of useful parameters for the construction of contour-line maps. Anisotropic factors were found to be linked to gas leakage along fault systems whereas isotropic factors were mainly related to shallow background phenomena. The length of the maximum anisotropy axis is more than 6 km, suggesting that the fault influences radon distribution over the entire selected area. The geostatistical modeling of the soil-gas data helps in producing soil-gas maps that enhance the interpretation of fault-related anomalies highlighting a more realistic and detailed pattern of brittle deformations. As such, the clay sequence, if fractured, does not form an impermeable barrier to terrestrial gases in spite of its great thickness, plasticity and low intrinsic permeability.

* * *

We wish to thank A. BACCANI and E. GRILLANDA for technical support, A. CORAMI and L. PALTRINIERI for their help in the field and Dr. S. BEAUBIEN for the precious suggestions and the correction of the manuscript. This research was partially funded by EC (contract number F12W-CT91-0064).

REFERENCES

ARMSTRONG M., *CFSG course notes: mining geostatistics* (Centre de geostatistique, Ecole des Mines de Paris, Fontainebleau) 1995.

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., ETIOPE G., GAMBINO P. and LOMBARDI S., *Elio e radon nei gas del suolo quali traccianti di discontinuità tettoniche: confronto con l'analisi del campo di fratturazione nella valle dell'Ofanto* (*Appennino meridionale*), *Geol. Rom.*, **30** (1994) 761-768.

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).

GAMBINO P., *La geologia della media valle del F. Ofanto e i caratteri geotecnici delle successioni argilloso-sabbiose plio-pleistoceniche in relazione ai fenomeni di frana*, Tesi di dottorato, Dipartimento di Scienze della Terra, Università di Roma "La Sapienza" (1993).

HINKLE M., *Environmental conditions affecting concentrations of* He, CO_2, O_2 *and* N_2 *in soil gases*, *Appl. Geochem.*, **9** (1994) 53-63.

ISAAKS E. H. and SRIVASTAVA R. M., *An Introduction to Applied Geostatistics* (Oxford University Press, New York) 1989.

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

KLUSMAN R. W., *Soil Gas and Related Methods for Natural Resource Exploration* (J. Wiley & Sons, New York) 1993.

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* (*1996*). *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.

SINCLAIR A. J., *Selection of threshold values in geochemical data using probability graphs*, *J. Geochem. Expl.*, **3** (1974) 129-149.

SUGISAKI R., *Behavior and origin of helium, neon, argon and nitrogen from active fault*, *J. Geophys. Res.*, **92/B12** (1987) 12523.

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