

# NATURAL LEAKAGE OF HELIUM FROM ITALIAN SEDIMENTARY BASINS OF THE ADRIATIC STRUCTURAL MARGIN

*Perspectives for geological sequestration of carbon dioxide*

G. Ciotoli<sup>1</sup>, S. Lombardi<sup>1</sup> and F. Zarlenga<sup>2</sup>

<sup>1</sup>Earth Sciences Department, University of Rome "La Sapienza", Rome, Italy; <sup>2</sup>ENEA-Cr-Casaccia-Prot/Prev, Italy

**Abstract:** Soil gas surveys were performed along the Adriatic foredeep (Vasto, Ferrandina, Pisticci basins), in order to evaluate the relationship between neotectonics and gas leakage from hydrocarbon reservoirs. More than 4000 soil gas samples were collected in the area and analyzed for helium, which is a good fracture tracer due to its chemical inertness and high mobility. Furthermore, helium is enriched in more than 90% of known reservoirs, and displays many characteristics of the ideal geochemical tracer for buried faults and gas and oil reservoirs (abiogenic, non-reactive, and mobile). Statistical analysis shows an average helium concentration of 5.7 ppm in the foredeep basin areas (atmospheric value is 5.2 ppm). This value is higher than that calculated using over 30,000 soil gas samples collected throughout Italy in different geological scenarios (about 5.4 ppm). Results obtained using a geostatistical approach are consistent with the presence of high helium concentrations as linear or spot anomalies due to irregular, channelled flow along faults above hydrocarbon accumulations. Considering the Plio-Miocene age of the Adriatic foredeep reservoirs, the magnitude of these diffuse gas microseepages highlights that losses from hydrocarbon reservoirs should be low. Results indicate that despite the fact that the area is heavily faulted and that gas seepage has occurred from the reservoir over geological periods of time, no environmental effects are observed at surface. This fact lends support to the idea that geological sequestration of CO<sub>2</sub> within a less structurally-active area would result in the safe, long-term isolation of this green-house gas.

**Key words:** soil gas geochemistry, tracer, helium, safety and monitoring of CO<sub>2</sub> geological sequestration sites

## 1. INTRODUCTION

In this research helium soil gas concentrations have been considered as a tracer of gas microseepage through thousands of meters of fractured and/or faulted overburden. Helium is a good fracture tracer because it is chemically inert, physically stable, highly insoluble in water, and as such it is highly mobile (Pogorski and Quirt, 1981; Oliver et al., 1984). Helium migration, as well as other gases, occurs primarily by advection or diffusion from deep accumulations (geothermal fluids, uraniumiferous ore and in 90% of known hydrocarbon reservoirs) towards the surface along permeable fault and fracture systems (Eremeev et al., 1973; Lombardi and Reimer, 1990; Duddridge et al., 1991; Ciotoli et al., 1998). Its distribution in soil gas depends on the permeability of the rocks, depth of origin, the presence of intersecting structures, and the influence of near-surface conditions such as groundwater flow, weathering, etc. The concentration of helium in the atmosphere is constant (5220 $\pm$ 15 ppb; Holland & Emerson, 1990) as the result of the dynamic budget between degassing helium and helium diffusion into space.

Extensive experience in soil-gas prospecting by the authors indicates that helium soil-gas anomalies generally occur as linear, fault-linked anomalies, irregularly-shaped diffuse or "halo" anomalies and irregularly-spaced plumes or "spot anomalies" (Lombardi et al., 1996; Ciotoli, 1997; Ciotoli et al., 1997, 1999). These features reflect gas migration dominated by brittle deformation, both at the macro and/or micro scale. Linear anomalies longer than several hundreds of meters are often taken as strong evidence of tectonic control of gas migration along gas-bearing faults, (Ciotoli et al., 1998). It is important to realize that most faulted areas consist of fault intersections and extensive microfractures that allow gases to escape laterally and vertically, producing "halo" or diffuse anomaly. Furthermore, recent research has demonstrated how the gas-bearing properties of faults are not necessarily continuous along a tectonic structure (Ciotoli et al., 1998). In these cases isolated points with high concentration values ("spotty anomalies") are frequently observed in soil gas distributions. When multiple "spot" anomalies occur along a linear trend, one can infer that they lie along a structural feature which has spatially discontinuous gas-transport properties (Lombardi et al., 1996; Ciotoli et al., 1998) (Fig.2).

Since helium is more soluble in oil than in water, oil-water mixing will result in the preferential partitioning of helium into oil, thus the surface distribution of helium (similarly to those for hydrocarbon gases) can indicate the presence of underground helium reservoirs in which petroleum may also be found (Zartman et al., 1961; Cunningham, 1988). For example, the helium distribution above the Eldingen oil field in Germany is thought to be

controlled by a combination of structural and hydrogeological conditions (Roberts, 1981; Van den Boom, 1987).

A further aspect in the interpretation of helium values considers their magnitude, which can be reduced to the following main populations:

- negative or near zero concentrations that indicate zones of weathering processes (i.e. high moisture, good soil aeration, or zones where the fractures are water-conducting);
- normal soil-air content, which ranges between about -100 to +100 ppb in Italy (determined statistically using more than 32,000 data values collected in central and southern Italy by the authors since 1970);
- anomalous values that represent the subsurface presence of a deep helium source.

## **2. GAS MICROSEEP DIFFERENCES BETWEEN THE THYRRHENIAN AND ADRIATIC COASTS**

From a geological point of view Italy is characterized by active and recent volcanoes (from the Pliocene to Present) and geothermal fields along the Tyrrhenian margin. Two mountain chains (the Alps and the Apennines) transect the country and sedimentary basins (the Padanian Foredeep, Adriatic sea and other small peri-tyrrhenian basins) host oil and natural gas reservoirs and saline aquifers. Therefore there is a very strong geological complexity which controls the gas leakage from deep reservoirs (Ciotoli et al., 1997; 1998; 1999; 2002). Within this framework various CO<sub>2</sub> reservoirs are located throughout the different geological domains, and many are considered as natural analogues of the geological storage of anthropogenic CO<sub>2</sub>. These are characterized by different pressures, temperatures and leakage rates, and thus represent a large range of situations which may eventually occur in an engineered system. This combination of great depths and long time periods mean that the natural analogue sites can help us better understand eventual system evolution, which is difficult to model or to represent experimentally.

The experience accumulated in Italy has shown widespread macro-scale (gas vents, fumaroles, mineralised aquifers) and micro-scale (micro seeps) gas leakage from oil, natural gas and geothermal reservoirs along active faults (Ciotoli et al., 1998; Etiope and Lombardi, 1994). In active volcanic areas the CO<sub>2</sub> flux from degassing activity ranges from 25 at Etna, to 1-2 at Stromboli to 0.066 Mton y<sup>-1</sup> at Vulcano (Morner and Etiope, 2002). In the sedimentary basins along the Tyrrhenian coast, where geothermal reservoirs also occur, the flux of CO<sub>2</sub> derives from diffuse soil degassing and from gas

vents. The output of diffuse degassing ranges from 7300 ton  $y^{-1}km^{-2}$  (Cava deSelci, Alban Hills Volcanic District), to  $> 73,000$  ton  $y^{-1}km^{-2}$  (Latera, Sabatinian Volcanic District), to 0.83-1,123 kg  $m^{-2} y^{-1}$  (in the sedimentary basins of the Siena Graben). In the case of gas vents the measured output ranges from 1,800 ton  $y^{-1}$  (at Massa Martana and Montecastello Vibio) to 310,000 ton  $y^{-1}$  (Mefite d'Ansanto). The regionally evaluated output of the central Apennine chain is  $4.4-13.2 \times 10^6$  ton  $y^{-1}$  (over 12,564  $km^2$ ) (Chiodini et al., 2000).

### **3. SOIL GAS DATA FROM THE SEDIMENTARY BASINS OF THE ADRIATIC FOREDEEP**

Soil gas surveys were carried out in different sedimentary basins located along the Adriatic foredeep (Vasto, Ferrandina, Pisticci basins) in order to evaluate the relationship between neotectonics and gas leakage from hydrocarbon reservoirs. In these areas about 5,000 soil gas samples were collected and analysed. Statistical analysis of soil gas data collected in the foredeep basins (FB) shows a mean helium concentration of 5.7 ppm (atmospheric value is 5.2 ppm; Holland and Emerson, 1990). This value is higher than the mean value (about 5.4 ppm) calculated using over 30000 samples collected throughout Italy in different geological settings (Tab. 1). Furthermore, it is worth noting that intermontane basins (IB) show the highest maximum value (315.22 ppm) and have a higher mean value (5.55 ppm) than that of volcanic areas (VA) and neogenic basins (NB) (Tyrrhenian sedimentary basins). This characteristic is probably linked to the presence in these zones of active tectonics and seismogenic faults that provide a vertical pathway for gas migration towards the surface.

Elevated outlier values shift the data distribution toward higher concentrations, as suggested by the high skewness values (FB, VA and IB). In contrast, NB shows a more symmetrical data distribution, as suggested by the low values of standard deviation (0.31) and skewness (0.52), and by the similar values of the mean (5.39 ppm) and the median (5.37 ppm). The lower quartile values indicate atmospheric content, and the upper quartile values generally correspond to the anomaly threshold. Considering the similar values of the interquartile range (IQR) (50% of data) it is possible to conclude that in Italy He concentrations higher than about 0.25 -0.30 ppm can be considered as anomalies.

Figure 1 compares helium concentrations in the Italian peri-Adriatic basins (Vasto, Pisticci, Agri, Pescara and Ferrandina basins) with data from the NB and VA. The box plot highlights that the high helium values observed in the investigated areas are probably linked to deep hydrocarbon

reservoirs, as suggested by the similar mean helium values for the various Vasto and Agri basin sectors. It is worth noting that high helium concentrations were measured in the Agri basin before the discovery of the oil field in 1986.

Table 1. Main statistical parameters of helium concentrations in soil gas from different investigated geological scenarios.

	Foredeep Basins (FB)	Volcanic areas (VA)	Neogenic Basins (NB)	Intermontane Basins (IB)
<b>N</b>	4893	13255	6597	4338
<b>Mean</b>	5.74	5.42	5.39	5.55
<b>Median</b>	5.31	5.34	5.37	5.26
<b>Min</b>	3.82	2.12	1.76	1.2
<b>Max</b>	146.81	127.52	8.82	315.22
<b>LQ</b>	5.22	5.22	5.22	5.15
<b>UQ</b>	5.48	5.5	5.51	5.45
<b>IQR</b>	0.26	0.28	0.29	0.29
<b>Std Dev</b>	5.13	1.51	0.31	5.8
<b>Skewness</b>	20.05	50.83	0.52	42.29

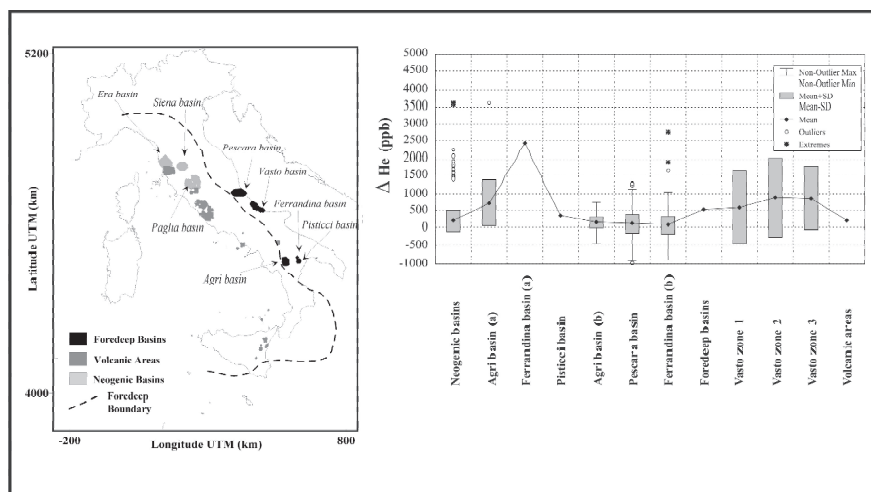


Figure 1. The figure to the right makes a statistical comparison of helium data from different surveys conducted in Italy by the authors since the 1970's; survey locations are shown to the left (modified after Ciotoli et al., 2004). The high helium concentrations detected in the Vasto basin are comparable to those measured in the Agri basin, in which hydrocarbon accumulations occur. Note that the mean helium values at Vasto are higher than those measured in volcanic areas where helium migration and high concentrations are well known in the literature.

Finally, a comparison of helium anomaly magnitudes with the different thicknesses of the sedimentary covers occurring in the central and southern

sectors shows that the soil-gas distribution does not seem to be affected by lithology changes and/or thickness. These results could, however, be affected by the different permeability of the fracture systems due to different activation age and/or self-sealing phenomena, and by different soil moisture content. In conclusion, the overall spatial association of geochemical data with geomorphological and structural features suggests the presence of zones of enhanced gas permeability (with gas microseeps) resulting from neotectonic activity in the area.

#### **4. HELIUM GAS MICROSEEPS IN THE ADRIATIC FOREDEEP: THE VASTO BASIN**

The Vasto basin is located between the Sangro river to the north and the Biferno river to the south, and covers part of the Adriatic foredeep which constitutes the extensive NW-SE trending structural and morphological depression along the eastern side of the Italian peninsula (Fig 2). This is the only domain of the Apennines where folding and thrusting are still active, associated with progressive eastward shifting of the Adriatic foredeep and migration of the foreland peripheral bulge at rates of 1.5-3 cm y<sup>-1</sup> (Patacca and Scandone, 1989).

The outcropping formations consist of more than 2,500 m (8,300 ft) of Plio-Pleistocene sandy-clays and a pre-Pliocene substratum of Lower and Middle Miocene biogenic limestones which are transgressive over Cretaceous carbonates.

The structural evolution of the area involved different phases. Middle Pliocene compressional tectonics caused a translation of the Apennine chain towards the east, which formed thrust faults (characterized by strike-slip movement) which have been active since the Plio-Pleistocene. In the northern-central sector of the studied area Pleistocene extensional tectonics caused the formation of structural highs (e.g. the Cupello anticline) that are often characterized by the presence of hydrocarbon reservoirs. About 100 small hydrocarbon fields have been discovered in the entire foredeep region since 1950. In 1955 the largest gas field, with an area of 10 km<sup>2</sup>, was discovered SW of Vasto ("Cupello-S Salvo"). This is mainly a gas province where most of the hydrocarbon reservoirs occur in a belt that parallels the contact between the outer thrust front and the Adriatic foredeep (Carlin and Dainelli, 1998). Hydrocarbons are generally trapped at the top of the Middle Miocene and Mesozoic carbonates, or in structural (thrust-faulted anticlines) and stratigraphic (pinch-outs) traps located within different Pliocene sand bodies. The youngest reservoirs are confined to the outermost position, in Middle-Late Pliocene-Pleistocene sands (Casnedi, 1983).

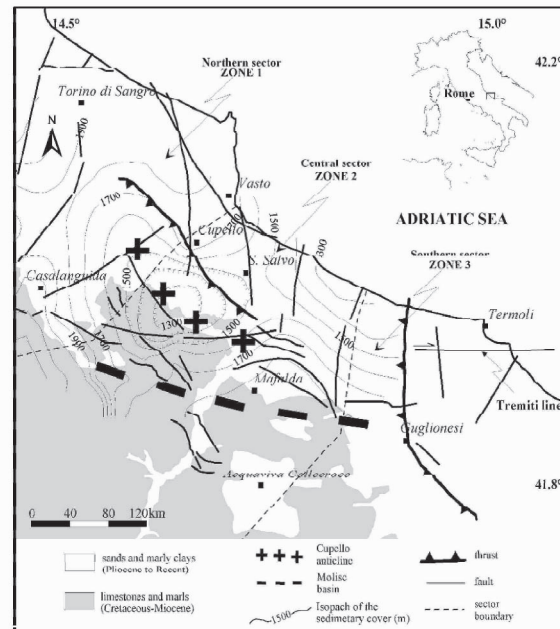


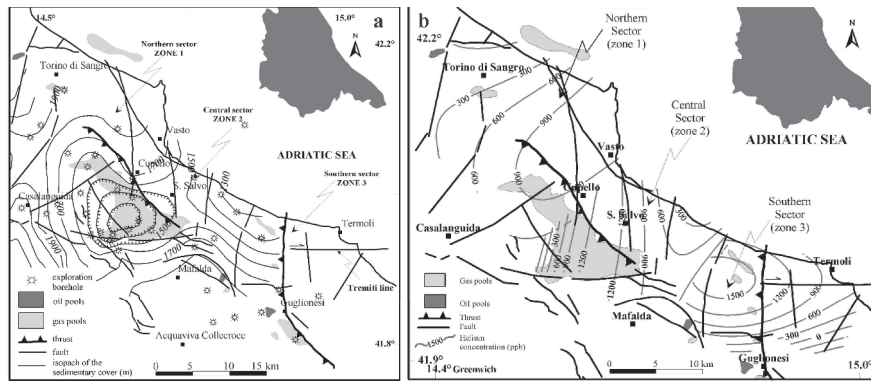
Figure 2. Geological map of the investigated area. Figure also shows the boundaries of the three sectors (zone 1 - northern sector; zone 2 - central sector; zone 3 - southern sector) defined to better interpret the helium distribution.

Drilling in the hydrocarbon fields indicates the occurrence of overpressures up to lithostatic in compartmentalized domains, which are laterally bounded by thrust faults and vertically trapped by low-permeability beds. This closed circulation in low-permeability domains is indicative of thrust faults acting as barriers to meteoric and deep fluids (and to hydrocarbons) (Ghisetti et al., 2000; Ghisetti and Vezzani, 2002). Progressive eastward fluid expulsion, connected with the eastward migration of shortening, is suggested by the west to east migration of gas reservoirs, and by geochemical indicators like helium.

## 5. RELATIONSHIPS BETWEEN TECTONICS AND REGIONAL HELIUM DISTRIBUTION

Helium trend surfaces were calculated (using a 2<sup>nd</sup>-degree polynomial regression) in order to highlight large-scale trends and patterns related to regional tectonics, such as basins and/or structural highs (Fig 3). The map shows a clear anisotropic helium distribution, consisting of:

- mainly NE-SW-oriented anomalies in the northern sector;
- N-S-oriented anomalies in the central sector ;
- E-W-oriented anomalies in the southern sector.



*Figure 3.* Location map of the hydrocarbon reservoirs and some of the producing and / or exploration wells (a). The map also shows the thickness of the sedimentary cover, as isopach lines, calculated using borehole data. The figure also shows soil-gas helium-trend surfaces (b) that may be related to regional tectonic features. The figure shows a clear anisotropic helium distribution in the central (N-S oriented) and southern (E-W oriented) sectors probably related to the Cupello anticline and the Molise Basin (modified after Ciotoli et al., 2004).

The anisotropic spatial behavior of regional helium anomalies are probably linked to the different orientations of the main fault systems which characterize these sectors. In particular, in the northern sector the regional helium distribution is influenced by the NE-SW trending faults related to the extensional tectonics phase, which controls the direction and abrupt deviation of the major rivers in this zone. In the central sector the N-S trend of the regional helium anomalies may be related to the most recent fault systems which defined the morphology of the coastline, as well as the orientation of some river courses. In the southern sector the regional helium anomalies agree well with the right-lateral transfer zone of the Tremiti fault line (Doglioni et al., 1994), which is also suggested by the orientation of the isopach lines (Fig. 3a). Furthermore, a comparison of helium trends versus sedimentary cover thickness (Fig. 3b) shows high values even where the carbonate substratum is structurally lowered and overlain by a clay-rich sedimentary cover that is up to 1500 m thick in the southern sector. In these sectors structural hydrocarbon traps also occur at different depths. This fact suggests a possible deep source for the helium in the hydrocarbon reservoirs, with leakage and distribution influenced by the presence of more permeable pathways, such as regional faults and associated fractures.

The map shows E-W contour lines which reflect the general helium trend in this sector, as reported in Figure 3. The eastward shifting and the N-S distribution of the high helium residual spots away from the location of the recognized small gas fields is consistent both with the N-S reservoir distribution and with the idea of gas migration along more recent and permeable fault systems (i.e. low-angle N-S thrust faults).

The map of residual anomalies (Figure 4a), calculated from the helium values measured in the southern sector of the investigated area, highlights high fault-related helium anomalies probably associated with the hydrocarbon reservoirs as shown in Figure 4b. The map shows east-west contour lines that reflect the general helium trend in this sector, as reported in Figure 3. The eastward shifting and the north-south distribution of the high helium residual spots from the location of the recognized small gas fields is consistent with both the north-south distribution of the reservoirs and with the idea of gas migration along more recent and permeable fault systems (i.e., low-angle north-south thrust faults).

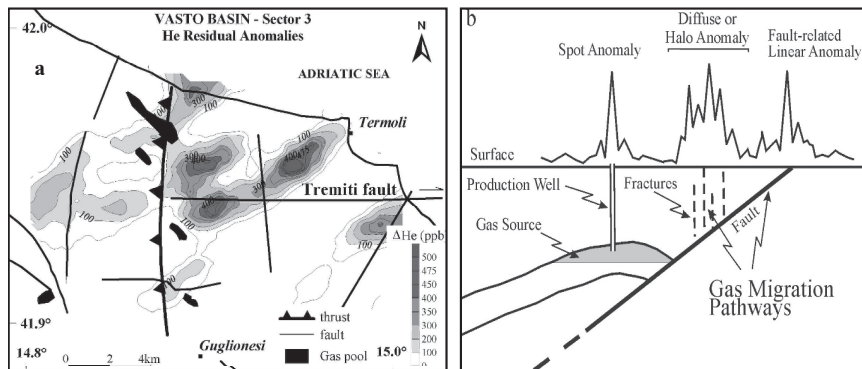


Figure 4. Residual anomalies map for the southern sector (a). This map shows the N-S distribution of the spotty residual anomalies (above 300 ppb), which is congruent with N-S thrust fault systems in the sector. A further spotty anomaly near the village of Termoli may indicate the existence of another pool. The slight eastward shifting of the residual anomalies seem to be well correlated with the location of the pools to the west, as illustrated in the schematic diagram (b) (modified after Ciotoli et al., 2004).

## 6. IMPLICATIONS OF GAS MICROSEEPS FOR THE GEOLOGICAL SEQUESTRATION OF CO<sub>2</sub>

Soil gas surveys and flux measurements carried out in Italy in different geological settings show that gas leakage occurs mainly along recently-activated faults and fractures. Even in this case it only occurs along preferred

pathways and is strongly localized (channelling effects) (Ciotoli et al., 1997, 2002; Lombardi et al., 1996; Lombardi et al., 1993). Even if the quantitative study of flux across faults is not complete, research performed in clayey basins, characterized by both extensional and compressive tectonics, suggests only minor gas escape along the above-mentioned channels. This hypothesis is also supported by a limited number of gas injection tests carried out in shallow, faulted and unfaulted clayey sequences (Etiopie et al., 1995; Lombardi et al., 1996; Ciotoli et al., 2003). Considering these results discussed above the following work is needed to better apply this method for the geological sequestration of CO<sub>2</sub>:

- define background values of the natural soil gas emissions, in case the area is eventually used for CO<sub>2</sub> storage;
- develop new monitoring systems to detect in real time increases in CO<sub>2</sub> escaping along vertical migration pathways

## **7. CONCLUSIONS**

Results outlined in the present work show how the integration of near-surface gas geochemistry with lithology, structural geology and geomorphology data can be used to better understand the subsurface distribution of oil and gas reservoirs, even in areas where thick sedimentary sequences cover and isolate them. However the very fact that gas anomalies originating from great depths are observed in the shallow soil horizon implies that, although the structural and stratigraphic traps have resulted in hydrocarbon accumulation, small scale leakage does occur along the numerous faults and fractures in this tectonically active and complex area. That said, these leaks have been found to be spatially restricted and to result in relatively low levels of gas release to the atmosphere. In regards to the field of CO<sub>2</sub> geological storage these results have three very important implications. First, leakage is slow and isolated even in a highly faulted area, giving confidence to the idea that sequestration within un-faulted areas will be even more safe. Second the soil gas method has been shown to be well adapted to the twin tasks of site-assessment prior to installation of a CO<sub>2</sub> sequestration site (to look for gas permeable structures) and for eventual monitoring of the site once injection begins (for carbon credit auditing and public assurance). Finally although the Italian foredeep region is clearly not ideal, these results indicate that CO<sub>2</sub> sequestration in the aging hydrocarbon reservoirs of this region (due to various economic and logistical advantages) may still be feasible if eventual small leakage rates are acceptable. This conclusion does not, however, take into account the potential for an earthquake in this region which might result in a larger

release, although the long term isolation of the hydrocarbons does not support this idea.

## REFERENCES

- Carlin, S., and Dainelli, J., 1998, Pressure regimes and pressure systems in the Adriatic foredeep (Italy), *AAPG Memoire* **70**: 145-160.
- Casnedi, R., 1983, Hydrocarbon-bearing submarine fan-system of Cellino formation, central Italy: *AAPG Bulletin*, **67**:359-370.
- Chiodini, G., Frondini, F., Cardellini, C., Parello, F., Peruzzi, L., 2000, Rate of diffuse carbon dioxide Earth degassing estimated from carbon balance of regional aquifers: the case of central Apennine, Italy. *J. Geophys. Res.* **105**(B4): 8423–8434.
- Ciotoli, G., 1997, Introduzione di metodi geostatistici nell'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", Roma, Italy, 226 p.
- Ciotoli, G., Lombardi, S., Serafini, S., and Zarlenga, F., 1997, The refinement of geomorphological and geochemical statistical techniques in the study of clay-basin tectonics: the Era basin (Central Italy): *Italian Journal of Quaternary Sciences*, **10**(2):231-246.
- Ciotoli, G., Guerra, M., Lombardi, S., and Vittori, E., 1998, Soil gas survey for tracing seismogenic faults: a case-study the Fucino basin (central Italy): *Journal of Geophysical Research*, **103**(B10):23,781-23,794.
- Ciotoli, G., Etiopè, G., Guerra, M., and Lombardi, S., 1999, The detection of concealed faults in the Ofanto basin using the correlation between soil-gas fracture surveys: *Tectonophysics*, **299**(3-4):321-332.
- Ciotoli G., Lombardi S., Morandi S., and Zarlenga F.(2004) – A Multidisciplinary Statistical Approach to Study the Relationships between Helium Leakage and Neo-tectonic Activity in a Gas Province: The Vasto Basin, Abruzzo-Molise (Central Italy). *AAPG Bull.*, 88/3, 355-372.
- Dogliani, C., Mongelli, F., and Piero, P., 1994, The Puglia uplift (SE Italy): an anomaly in the foreland of the Apenninic subduction due to buckling of a thick continental lithosphere: *Tectonics*, **13**(5):1309-1321.
- Duddridge, G. A., Grainger, P., and Durrance, E. M., 1991, Fault detection using soil gas geochemistry: *Quatern. Journal of Engineering Geology*, **24**:427-435.
- Eremeev, A. N., Sokolov, V. A., and Solovov, A. P., 1973, Application of helium surveying to structural mapping and ore deposit forecasting: *London Symposium Volume*, p. 183-192
- Etiopè, G., and Klusman, R. W., 2002, Geologic emission of methane to the atmosphere: *Chemosphere*, **49**:777-789.
- Etiopè, G. and Martinelli, G., 2002, Migration of carrier and trace gases in the geosphere: an overview: *Physics Earth Planetary Interior*, **129**:185-204.
- Ghisetti, F., and Vezzani, L., 2002, Normal faulting, transcrustal permeability and seismogenesis in the Apennines (Italy), *Tectonophysics*, **348**:155-168.
- Ghisetti, F., Kirschner, D., and Vezzani, L., 2000, Tectonic controls on large scale fluid circulation in the Apennines (Italy): *Journal Geochemical Exploration*, **69/70**:533-537.
- Lombardi, S., and Reimer, G. M., 1990, Radon and helium in soil gases in the Phlaegrean Fields, central Italy: *Geophysical Research Letters*, **17**:849-852.

- Lombardi, S., Etiope, G., Guerra, M., Ciotoli, G., Grainger, P., Duddridge, G. A., Gera, F., Chiantore, V., Pensieri, R., Grindrod, P., and Impey, M., 1996, The refinement of soil gas analysis as a geological investigative technique: Final Report. CEC, Programme on Radioactive Waste Management (1990-1994) Part A, Task 4, Eur 16929 En, 194 p.
- Oliver, B. M., Bradley, J. G., and Farrar IV, H., 1984, Helium concentration in the Earth's lower atmosphere: *Geochimica et Cosmochimica Acta*, **48**:1759-1469.
- Patacca, E., and Scandone, P., 1989, Post-Tortonian mountain building in the Apennines. The role of the passive sinking of a relic lithospheric slab: In *The Lithosphere in Italy*, eds. A. Boriani, M. Bonafede, G.B. Piccardo, and G.B. Vai, Accademia Nazionale dei Lincei, v. 80, p. 157-176.
- Pogorsky, L. A., and Quirt, G. S., 1981, Helium emanometry in exploring for hydrocarbons: Part I. In: *Unconventional Methods in Exploration for Petroleum and Natural Gas II*. Southern Methodist University Press, p. 124-135.
- Roberts, A.A., 1981, Helium emanometry in exploring for hydrocarbons: Part II. In: *Unconventional Methods in Exploration for Petroleum and Natural Gas II*. Southern Methodist University Press, p. 135-149.
- Van Den Boom, G.P., 1987, Helium distribution pattern of measured and corrected data around the "Eldingen" Oil Field, Nw Germany. *J. Geophys.Res.*, **92b**:12547-12555.