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Radon emissions from mud volcanoes in Northern Italy: possible connection with local seismicity.

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Abstract. Data concerning Radon emission in waters filling mud volcanoes of Northern Apennines (Northern Italy) sampled from 1986 until 1989 have been analyzed. Possible connections between shallow environmental conditions and Rn emission from mud volcanoes have been explored. A linear relationship between air temperature and Rn count rates has been determined. After the removal of temperature related Rn variations, a significant correlation has been pointed out between anomalous spike-like Rn emissions at one of the station considered and the occurrence of low magnitude (M<4.5) local earthquakes.

Introduction

Mud volcanoes are a typical manifestation of accretionary complexes and are widely observed all over the world, mainly along continental margins (Higgins and Sanders, 1974; Le Pichon et al., 1990). Faults associated with shale diapirism processes seem to strongly influence mud volcano occurrences (Barber et al., 1986). Extrusion products are clay muds, connate salty waters and gases (mainly methane). Temperature of extruded fluids in general reflects shallow environmental temperature but, in some cases, thermal anomalies have been observed in connection with paroxysmal eruptions. Mud is driven upward by buoyancy forces arising from the bulk density contrast between an overpressured muddy mass and an overburden of greater density (Brown, 1990). Morphostructural features and geochemical evidence allow us to consider mud volcanoes as confined fluid reservoirs, located along tectonic disturbancies. Tamrazyan (1982) identified a particular sensitivity of mud volcanism to earth tides. This led to the hypothesis that physical changes in the earth strain field, e.g. the ones induced by seismogenic processes, could be expressed as fluctuations in mud volcano activity. Bouleguè et al. (1985) first proposed monitoring the expulsion of pore fluids from mud volcanoes with the aim of predicting seismic events in Japan. With the same purpose, Martinelli et al. (1987), Gorgoni et al. (1988) and Martinelli and Ferrari (1991), following Wakita et al. (1988), proposed the monitoring of Radon emissions from mud volcanoes.

The data set considered in this work consists of Rn 222 measurements carried out using an alpha-counter RD-200 Radon Detector (EDA instruments, Toronto, Canada). Sampling has been performed in waters filling cones of mud volcanoes at Nirano and Ospitaletto, two sites located about 10 km away from each other in the northern Apennines (Northern Italy, see Fig. 1), a large accretionary complex whose neogenic activity is widely documented (e.g., Castellarin and Vai, 1986). Isotopic analyses (Gorgoni et al., 1988) show the connate dominating origin of the Nirano mud volcano waters. No isotopic data is at present available about waters filling the Ospitaletto mud volcano.

The most extended sample of these measurements concerns the Nirano station where, from 30 May 1986 until 11 April 1989, Rn count rates were sampled from the fluid phase along with the fluid temperature, environmental barometry and temperature. The sampling had a sparse character until 12 March 1988 when a most frequent and regular sampling campaign (3 observations per week) began. During the first period of observation, some sparse estimates (30 values) of the chloride ion content had also been performed along with the Rn sampling. From 4 November 1987 until 18 March 1989 observations had also been carried out at Ospitaletto, at a rate of 3 observations per week since 12 March 1988. At this site, Rn count rates in the fluid phase along with the fluid temperature, barometry and air temperature, have been sampled.

In order to check the possible dependence of Radon data on meteorological noise, a spring source (Pavullo) clearly connected with phreatic recharge and located within few km from both Nirano and Ospitaletto has been monitored from 4 November 1987 until 18 March 1989 (with regular sampling since 12 March 1988). In this case, Rn data in the fluid phase have been sampled along with the water flow and temperature, environmental temperatures and barometries.

These data have been partially published and qualitatively commented upon (Martinelli et al.,1987; Gorgoni et al.,1988; Martinelli and Ferrari, 1991; Ferrari et al., 1991) but without statistical assessment. The purpose of this work is to explore, by using a statistical approach, the possible dependence of fluctuations in Rn emission on local seismogenic processes as suggested for other areas of the world (see, e.g., Hauksson, 1981; Igarashi et al., 1994).

Data Analysis

As a first step, each series of observations performed at each site (Fig. 2) has been analyzed independently. In particular, possible interrelations between the Rn count rates and the pattern of the other monitored parameters at each station (pressure, flow and temperature) have been explored. To this

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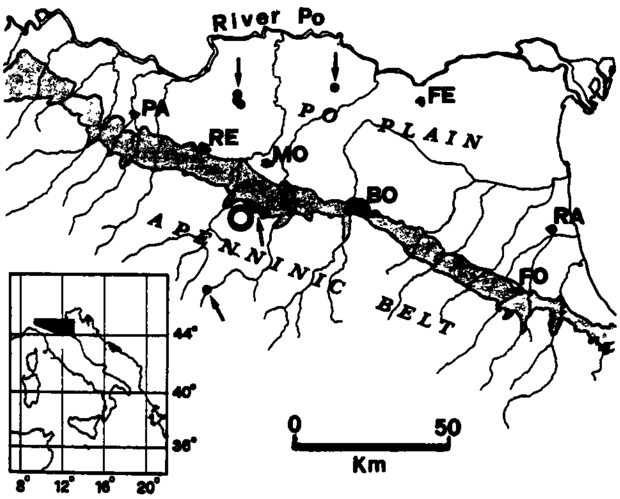

Figure 1. Area considered in this study. The open circle indicates the location of the sampling area considered for Rn monitoring. Dots indicated by arrows are the epicenters of the earthquakes in the Table. Shaded area represents the alluvial fans located at the boundary between the Po plain and the Apenninic belt. Major water courses are shown along with the location of most important towns (irregularly shaped black areas: BO = Bologna; FE = Ferrara; FO = Forli; MO = Modena; PA = Parma; RA = Ravenna; RE = Reggio Emilia).

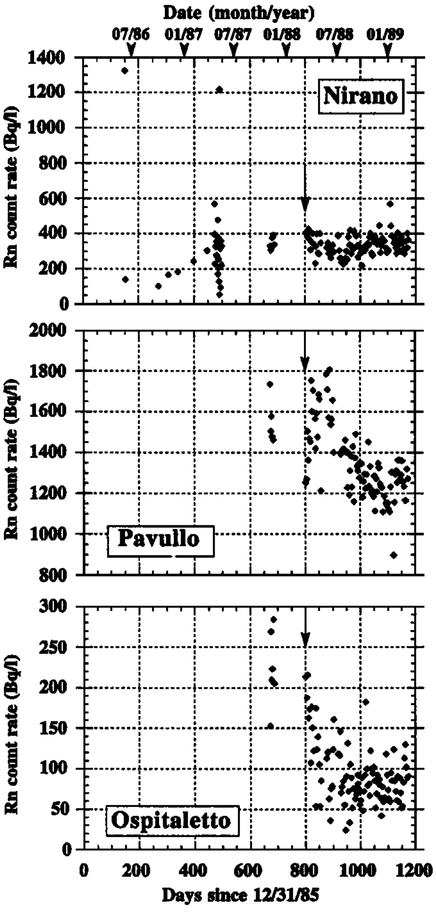

Figure 2. Time pattern of raw Rn count rates monitored at the sites of Nirano, Pavullo and Ospitaletto. Arrows indicate the beginning of the period of Rn regular sampling.

purpose, both parametric (Pearson) and distribution-free (Kendall) correlation analyses (see, e.g., Kendall, 1955) have been performed. In the following, only correlation values associated to significance levels lower than 0.05 have been considered as significant.

As stated above, the data collected at the Pavullo station can be considered as representative of the phreatic recharge. Thus, the comparison between these data and the ones obtained at the other two stations can be used to assess the possible presence of metoclimatic contamination. In order to make this comparison effective, possible "spurious" effects have to be detected and removed from the original data sets. In the case of the Pavullo station, the correlation analysis suggests the presence of a significant degree of interrelation between Rn count rates and water flow. This effect has been modelled by assuming a linear relationships between Rn count rates and water flow as suggested by the relatively high Pearson correlation (0.67). The parametrization of this relationships has been performed by a least squares regression analysis. Figure 3 reports Rn count rate fluctuations around the average emission at the Pavullo spring, after the removal of the water flow effect.

Correlation analysis performed on the data sampled at the Ospitaletto mud volcano, showed that no significant correlation is revealed by both parametric and distribution-free analyses between Rn count rates in the fluid phase and the other monitored parameters. A correlation analysis between these Rn data and the processed Rn observations at the Pavullo spring, indicates the presence of a significant degree of interrelation. This suggests that meteoclimatic contamination could affect the Rn measurements at Ospitaletto and thus, these data cannot be safely considered as representative of deep conditions. The effect can be explained by mixing phenomena of a clearly recognizable local phreatic aquifer with the possible deep contribution.

With regards to the Nirano station, Pearson correlation analysis showed that a significant correlation (0.40) exists only between Rn count rates and both water and air temperatures. A significant and very high (0.93) correlation also exists between the temperatures in water and air suggesting that water temperature is mainly conditioned by shallow environment. These results are fully confirmed by a distribution-free correlation analysis performed on the same data set. In order to insulate the effects potentially linked to

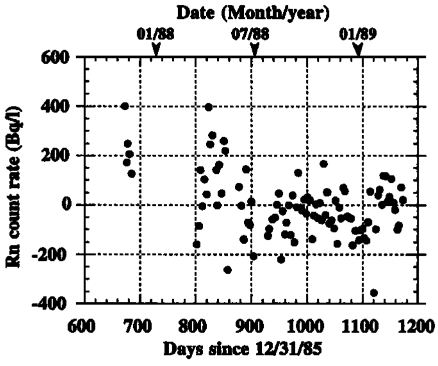

Figure 3. Time pattern of processed Rn values at the Pavullo station. Data represent fluctuation of Rn count rates around the average emission after the removal of the water flow effect (see text).

deep phenomena, the effect of air temperature has been removed from the series of Rn count rates by modelling this relationship as a linear function (as suggested by the relatively high value of Pearson correlation) whose parameters have been determined by least squares regression. Figure 4 shows fluctuations of Rn count rates around the average emission after the removal of the temperature effect. Probably due to the small amount of available chloride data, no significant correlation has been noted between fluctuations in Rn and chloride ion content.

The lack of significant correlation between processed Rn data at Nirano (Fig. 4) and Pavullo (Fig. 3) confirm, as suggested by isotope data (Gorgoni et al., 1988; Martinelli and Ferrari, 1991), that Rn emission at Nirano can be considered as representative of deep water circulation only which, in its turn, may reflect perturbations in the crustal strain field induced by seismogenic processes. A possible model which could account for this kind of phenomenon has been proposed by Sibson (1981).

Seismic activity from April 1986 until December 1989 has been analyzed on the basis of seismic bulletins supplied by the Italian National Institute of Geophysics (ING). No earthquake with magnitude greater than 5 has been detected in the whole Italian territory in the time span considered. Taking into account this fact and the results obtained by Dobrovolsky et al. (1979) and Hauksson (1981) about the dependence between the earthquake magnitude and the size of the area which could be affected by strain perturbation around the seismic source (range of detectability), only earthquakes which occurred within 50 km from the Nirano have been taken into account. A speditive completeness analysis of the available seismic catalogue has been performed using the approach proposed by Bath (1983). This analysis suggests that, in the period considered, the seismic data set can be considered complete for earthquakes with magnitude ≥2.5. This result is coherent with theoretical estimates proposed by De Simoni (1987). By following theoretical relationships obtained by Dobrovolsky et al. (1979) and experimental results reported by Hauksson (1981), the range of detectability for earthquakes magnitude≥4.0 has been fixed to 50 km from the test site. Following the same approach, the ranges of detectability for events with magnitude ≥3.5, ≥3.0 and ≥2.5 have been respectively fixed to 20, 10 and 5 km. Taking these limits into account, 9 seismic events have been selected (see the Table and Fig. 1).

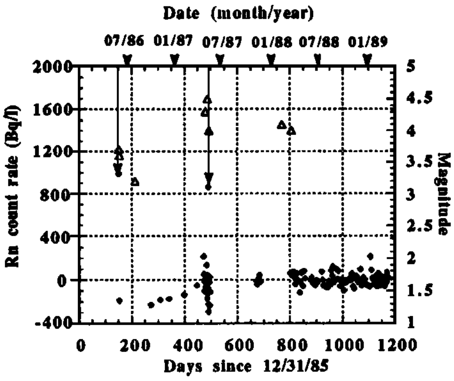

Figure 4. Comparison between seismicity (triangles) and Rn observations (dots) at Nirano. Rn values are the fluctuations in Rn count rates around the average emission after the removal of the temperature effect. Arrows indicate the two Rn "anomalies" (see text).

Table. Earthquakes occurred from April 1986 until December 1989 in the range of detectability (see text for details) of the Nirano station. Md is the duration magnitude (ING bulletins) except in the case of the earthquake which occurred on 1988/2/8. In this case, Local Magnitude (Ml) has been considered due to the lack of the Md value. For each earthquake, days since 1985/12/31 are reported. Epicentral distance (R) from the site located at 44.5°N and 10.9°E, representative of the test site area, are reported.

Date (y/m/d)	Lat. (° N)	Lon. (° E)	Mag. (Md)	Days	R (Km)
86/5/31	44.47	10.76	3.7	151	12
86/6/2	44.47	10.77	3.6	153	11
86/8/1	44.45	10.80	3.2	213	10
87/4/24	44.82	10.70	4.3	479	39
87/5/2	44.80	10.72	4.5	487	37
87/5/8	44.86	11.17	4.0	493	46
88/2/8	44.17	10.57	4.1	769	45
88/3/15	44.83	10.70	4.0	805	40
89/5/21	44.44	10.84	3.0	1237	8

The data in the Table indicates that no earthquake occurred in the area of detectability between April 1988 and April 1989. Thus, Rn observations concerning this time span have been considered as representative of undisturbed Rn activity. These data can be used to assess the statistical properties of "normal" Rn emissions to be compared with possible "anomalous" emissions near the occurrence of earthquakes. In particular, the values whose probability of occurrence is much less than 0.01, will be considered as "anomalous". This probability can be estimated through the assessment of statistical features of frequency distribution of "normal" Rn emission.

The analysis of frequency distribution of the 81 Rn values obtained during the time interval ranging from March 1988 to March 1989 shows that Rn fluctuations around the average emission have an overall range spanning from -111 to 222 Bq/l. These fluctuations are characterized by a standard deviation (σ) of 53 Bq/l. If the frequency distribution of Rn fluctuations is assumed to be Normal, values >220 Bq/l (>4σ) can be considered "anomalous". However, the sample values of Skewness and Coefficient of excess (1.15 and 2.30 respectively) suggest that the distribution of Rn values is slightly non Normal (see, e.g., Rock, 1988) and thus that the limit of 220 Bq/l cannot safely considered as a threshold to discriminate "anomalous" fluctuations. In this case, an upper limit for the threshold value can be obtained by the Chebyshev inequality statement (see, e.g., Gnedenko, 1982) which allows us to assess that, whatsoever parent distribution is considered for the sample, the probability of observing Rn fluctuations greater than 800 Bq/l (>15σ) can be safely assumed as much less than 0.01. Only twice did Rn fluctuations overcome this threshold (see Fig. 4): on 30 May 1986 (992 Bq/l) and 5 May 1987 (866 Bq/l). In the first case two shocks occurred in the detectability range (see Tab.) respectively 1 and 3 days after the Rn anomaly. In the second case, three shocks occurred respectively 11 and 3 days before and three days after the anomaly (see the Table). Unfortunately, all the seismic events occurred during the period in which Rn values were irregularly sampled. Thus, no data is available to detect possible anomalies occurred close to the seismic events on 1 August 1986 and 8 February 1988, while the event on 21 May 1989 occurred out of the sampling period which ended in April 1989. As concerns the earthquake which occurred on 15 March 1988 no anomaly was detected after the earthquake, i.e., in the period regularly sampled. In the period immediately preceding this earthquake only one Rn measurement (3 days before) is available. Due to this lack of data the presence of a possible "anomaly" preceding the earthquake could not have been detected.

On the basis of these observations, it seems possible to hypothesize that a correlation exists between the occurrence of large Rn anomalies (>800 Bq/l) at the Nirano mud volcano and earthquakes (M>2.5) occurring in the range of detectability in a time window of 25 days centred on the anomaly occurrence. In order to check the statistical significance of this correlation, the probability of observing at least one event in a time window of 25 days can be assessed by assuming a Poisson distribution for seismic events (see, e.g., Lomnitz, 1974) and data in the table. This probability results equal to 0.15. The probability of observing by chance what has been actually observed, i.e. that at least one earthquake occurs in both the two 25 days time windows centred around the Rn anomalies, can be estimated by the binomial distribution. It results equal to 0.02 and this value can be assumed as preliminary assessment of the statistical significance of the correlation observed between Rn anomalies at Nirano and earthquakes.

Conclusions

The results obtained suggest that Rn 222 activity, monitored in the liquid phase which fills the Nirano mud volcano in the northern Apennines, is sensitive to seismogenic processes which take place near this site. The "anomalous" Rn activity has been identified in the series of Rn count rates, after the removal of the temperature effects, in the form of spike-like values overcoming by more than 800 Bq/l the average emission. This suggests that Rn monitoring in the area of the northern Apennines could be a useful tool for geodynamic analyses. Furthermore, a continuous (daily or multi-daily) sampling performed over time periods of time (>1 years) seems to be necessary for a correct analysis of "anomalous" patterns.

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