Time dynamics of background noise in geoelectrical and geochemical signals: An application in a seismic area of Southern Italy

G. DI BELLO (1), M. RAGOSTA (1), J. HEINICKE (2), U. KOCH (2), V. LAPENNA (3)
S. PISCITELLI (3), M. MACCHIATO (4) and G. MARTINELLI (5)

(1) *Dipartimento di Ingegneria e Fisica dell'Ambiente, Università della Basilicata - Potenza, Italy*
(2) *Research Group Freiberg, Bad Brambach, Saxon Academy of Sciences - Leipzig, Germany*
(3) *Istituto di Metodologie Avanzate di Analisi Ambientale-CNR - Tito Scalo (PZ), Italy*
(4) *INFM-Dipartimento di Scienze Fisiche, Università Federico II - Napoli, Italy*
(5) *Servizio Cartografico e Geologico della Regione Emilia Romagna - Bologna, Italy*

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Summary. — We analyse geoelectrical and geochemical time series jointly measured by means of a multiparametric automatic station close to an anomalous fluid emission in Val d'Agri (Basilicata, Italy). The investigated area is located on Southern Apennine chain that in past and recent years was interested by destructive earthquakes. After a complete pre-processing of time series, we analyse the fluctuations triggered by the seasonal cycles and focus our attention on the possible link between geoelectrical and geochemical signals. In order to extract quantitative dynamical information from experimental time series, we detect scaling laws in power spectra that are typical fingerprints of fractional Brownian processes. After this analysis, the problem of the identification of extreme events in the time series has been approached. We consider significant anomalous patterns only when more consecutive values are above/below a fixed threshold in almost two of the time series jointly measured. We give the first preliminary results about the comparison between anomalous patterns detected in geoelectrical and geochemical parameters and the local seismic activity and, finally, analyse the implications with the earthquake prediction problem.

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1. – Introduction

The deterministic approach to the earthquake prediction problem has attracted many scientists for a long time. In many seismic areas experimental activities were carried out to detect anomalous changes in geophysical and geochemical parameters related to earthquakes [1-5]. Many models have been proposed to describe the anomalous patterns of precursory phenomena measured close to epicentral areas [6-10];

however, a comprehensive model to describe the physics underlying the generation mechanism of geophysical and geochemical precursory signals in focal area is still not available. Furthermore, in many cases precursory phenomena of geophysical and geochemical nature are not jointly analysed and linked.

The matter becomes extremely complicate when correlations between observed anomalies and seismic sequences are performed only by means of qualitative methods and without robust statistical tests. A preliminary analysis of the background and a detailed study on the possible correlations between anomalous patterns in precursory time series and climatological cycles are generally omitted. In this way, we may have the reasonable doubt that detected anomalies could be intrinsic fluctuations and they are not effectively connected with tectonic activity [11-14].

When we approach the short-term earthquake prediction, a key point is the identification of extreme events with respect to background fluctuations: it is necessary to detect anomalies in geoelectrical and geochemical time series with objective methods. This result can be obtained only when the time dynamics of these signals is well known: the study must be carried out by analysing time series measured over a very long period in order to better characterise the background noise. In this phase it is not necessary to analyse experimental data measured by monitoring network with an high number of remote stations spatially distributed in a seismic area. We will not deal with the earthquake prediction problem, but with the improvement of the knowledge about the time dynamics of geoelectrical and geochemical parameters that could have great implications in the earthquake prediction.

Taking into account these considerations and according to the recommendations of the European Seismological Commission that suggest to measure a wide range of non-seismometric parameters, to apply advanced statistical methods, to identify extreme events in precursory time series and to compare the results obtained in different geological and seismological environments, we started with a systematic monitoring activity in a focal region, based on multiparametric stations and combined with advanced time series analysis. This is an optimal approach to remove ambiguities connected with the interpretation of precursory signals in earthquake prediction researches.

Recent studies [15-18] pointed out that signals related to processes in the Earth's crust can be found by means of geochemical pathfinders, often connected to electrical phenomena (self-potential anomalies, resistivity changes, electromagnetic emissions). This means that deep geodynamic processes can simultaneously produce shallow geochemical anomalies (CO_2, radon and other ionic concentrations) and electrokinetic phenomena, and suggest the need to carry out simultaneous monitoring of geochemical and geoelectrical parameters. Furthermore, some recent laboratory experiments confirmed the existence of a link between anomalous streaming potentials and geochemical changes [19, 20]. Finally, many research activities regarding the monitoring of geophysical and geochemical parameters in active volcanic and seismic areas have been carried out in Central and Southern Italy. In fact, in this region there are favourable conditions to study the possible link between tectonic activity, geochemical and geophysical changes [21-26].

After a preliminary screening of spatial and temporal patterns of geochemical and geophysical phenomena observed in the Southern Apennines chain [27], since 1994 a multiparametric station, able to measure geophysical and geochemical parameters, has been set up close to a thermal area in Tramutola, Basilicata region, Italy (fig. 1). From

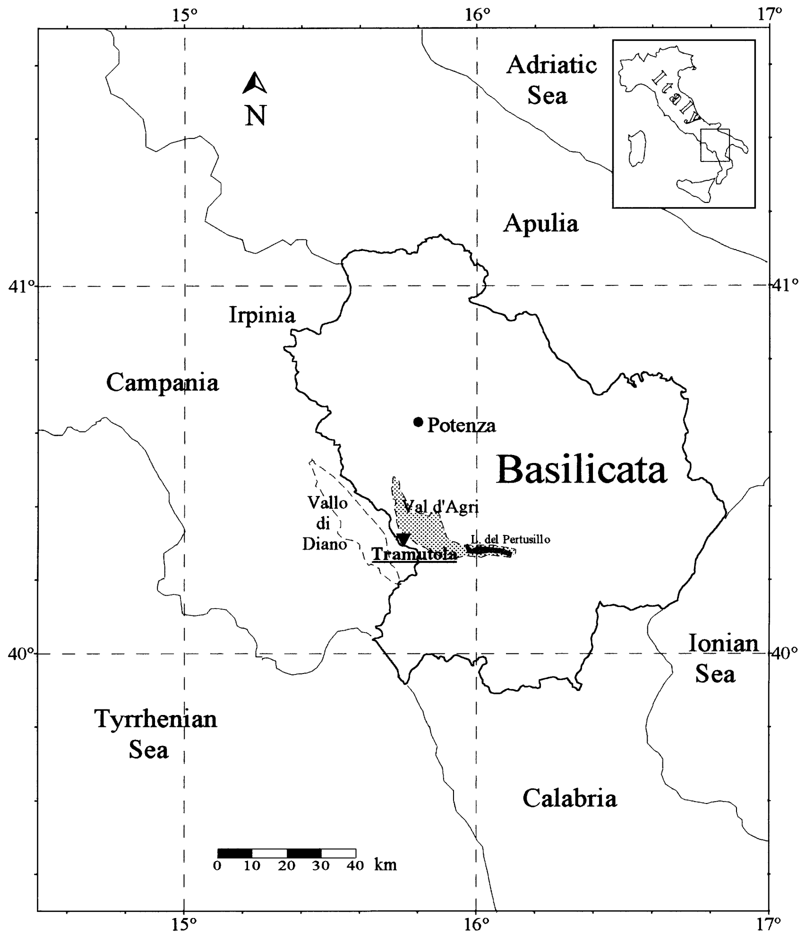

Fig. 1. – Location of the multiparametric station in the Southern Apennine chain.

historical records it is recognisable that in this region very strong earthquakes happened periodically throughout the centuries [28].

The purpose of this work is to study the background fluctuations of geoelectrical and geochemical time series recorded in Tramutola site during the period January 1995-December 1996. In particular, we analyse geoelectrical data (*i.e.* self-potential changes measured on Earth surface), geochemical data measured near a fluid emission (CO_2 and ^{222}Rn concentrations, electrical conductivity in water and water temperature) and meteoclimatic parameters (ambient temperature and rainfalls). The paper is organised as follows: in sect. **2** we describe the geological and seismological settings of the investigated area; in sect. **3** we show the results of the statistical analysis in the time and frequency domain and identify extreme events in geoelectrical and geochemical parameters; finally, in sect. **4** we discuss, only as an example, the time fluctuations of the geoelectrical and geochemical parameters before and after the occurrence of seismic events in the investigated area.

2. – Geological and seismological setting

The geological and structural setting of the investigated area (fig. 2) clearly reflects the complex history of the Southern Apennines, whose framework consists of a pile of thrust sheets, resulting from a complex sequence of tectonic events associated with the collision between Africa and Europe along the southern margin of the oceanic Tethys.

During the Mesozoic and early Cenozoic along this margin different large and thick carbonate platforms surrounded by deeper terrigenous basins developed. Starting in the middle Miocene up to upper Pliocene, five or more compressional tectonic phases [29, 30] caused progressive thrusting and piling of different tectonic units, corresponding to different paleogeographic domains, toward stable external domains of the Apulian-Adriatic foreland. The deformation front direction was NW-SE and migrated toward NE. During the Quaternary, the Southern Apennines have been

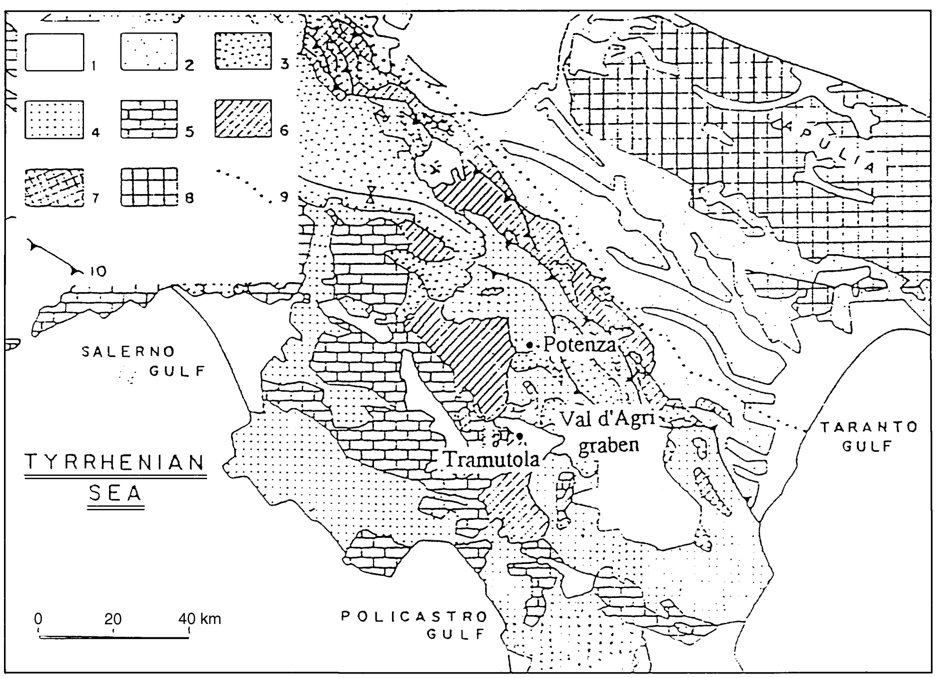

Fig. 2. – Simplified geological sketch of the Southern Apennines. 1) Middle Pleistocene to Holocene continental deposits; Quaternary volcanoes. 2) Upper Pliocene-Lower Pleistocene marine to continental deposits. 3) Upper Tortonian to Upper Pliocene clastic deposits accumulated in piggyback basins formed on top of the advancing nappes. 4) Apenninic nappes derived from internal paleogeographic domains, originally located between the European plate margins and the western carbonate-platform system. 5) Apenninic nappes derived from the western carbonate-platform system and related marginal areas. They include shallow-water and deep-water Mesozoic-Tertiary carbonates, as well as Upper Tortonian-Messinian siliciclastic flysch deposits. 6) Apenninic nappes derived from a basinal realm originally located between the western platform and the eastern platform (Inner Apulia Platform) domains. They include the Mesozoic-Tertiary Lagonegro sequence. 7) Monte Alpi units. 8) Mesozoic-Tertiary carbonates of the Apulia foreland. 9) Frontal ramp of the Apennine thrust sheets. 10) Out-of-sequence thrust (from ref. [29]).

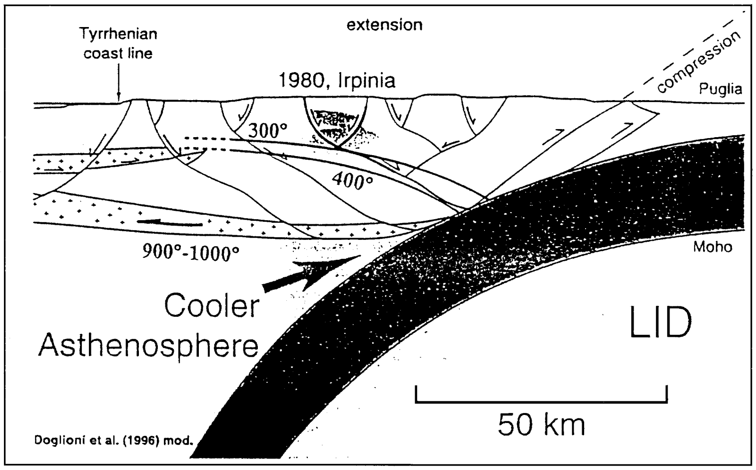

Fig. 3. – Schematic cross-section of geodynamic and lithospheric features of the Apennine chain (from ref. [31]).

affected by an important extensional tectonic phase, with NE-SW extensional trend, that caused further chain fragmenting into several isolated blocks.

Figure 3 shows a schematic cross-section of the geodynamic and lithospheric features, along a profile crossing Apennine chain from Tyrrhenian Sea to Adriatic Sea and passing through the seismogenetic structure that caused the Irpinia-Basilicata seismic event in 1980 [31].

The historical seismicity pattern confirms intense regional seismic activity and related complexity in crustal faulting. The November 23, 1980 earthquake ($M = 6.9$), one of the most destructive events in Southern Italy, occurred in this area. One of the most historically relevant events, the December 16, 1857 earthquake [32], occurred in Val d'Agri where the multiparametric station is located. The seismic activity occurred after the 1980 event consisted of medium-intensity events ($M < 5.5$) located close to the border between the Campania and Basilicata regions [33, 34].

The May 5, 1990 ($M_D = 5.0$, ING-National Institute of Geophysics) and the May 26, 1991 ($M_D = 4.5$) earthquakes may be considered the strongest events after the Irpinia 1980 earthquake [35, 36] occurred in this area. These events have been followed by aftershocks sequences that identify a fault structure located near the Potenza town. The seismological analysis of the above-mentioned remarkable events demonstrated that such earthquakes have been provoked by a strike-slip fault in WE direction [37]. This fault lies North of Potenza and is located in such a way to limit toward North and South two great seismogenetic faults that caused the earthquakes of 1857 in Val d'Agri and of 1980 in Irpinia, respectively [38] (fig. 4).

The South Apennine fault structure and the connected complex rupture events of the surface are strictly linked with deeply originated fluid occurrences, such as geothermal manifestations or mofettes, strongly affected by preseismic phenomena reported in the historical seismicity studies [32, 39]. In this region, indeed, we have favourable conditions for studies on interactions and correlations between tectonic activity, variations of the chemical and isotopic compositions in fluids and gases and electrokinetic processes possibly induced by geochemical/electrochemical anomalies.

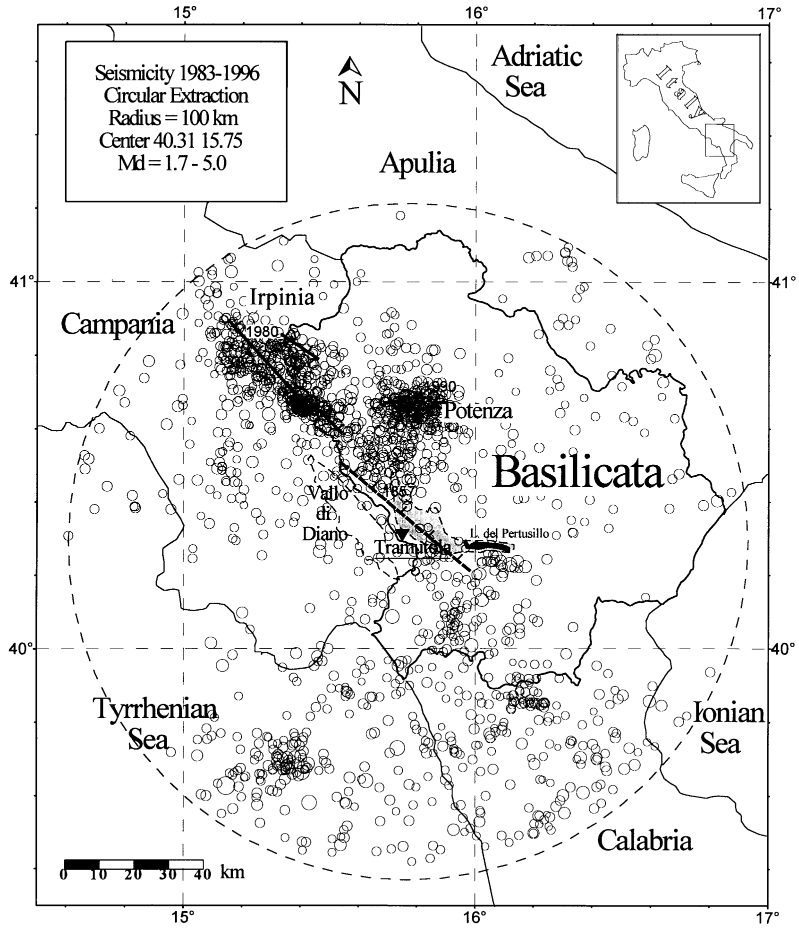

Fig. 4. – Main active faults and seismicity pattern observed during the period 1983-1996.

3. – Data analysis

Since April 1994 a prototype of a multiparametric station was installed close to a thermal-water well area located at Tramutola, a small town in Val d'Agri (Southern Italy). The artesian-well waters are characterized by a constant temperature of 27.8 °C, constant flow rate, macroscopic CH_4 (87 vol.%) and CO_2 (1.3 vol.%) bubbling activity, anomalous $^3He/^4He$ ratio and previously reported sensitivity of flow rate and chemical composition to seismic events [40].

The remote station is equipped with suitable sensors for measuring carbon dioxide concentration (CO_2), ^{222}radon concentration (^{222}Rn), electrical conductivity in water (C_W), water temperature (T_W) and with self-potential probes (in North-South direction, V_X, and in East-West direction, V_Y) to detect the electrical field variations on the Earth's surface (fig. 5). Sensors are connected with A/D converter to a personal computer; a software package provides pre-processing of collected data. The selected sampling interval is $\Delta t = 15$ min. Furthermore, we monitor the ambient temperature

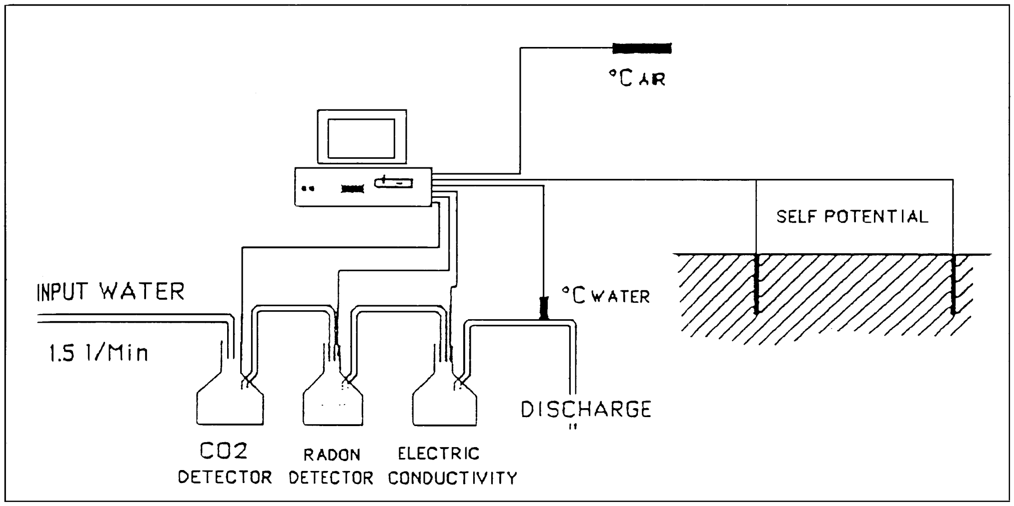

Fig. 5. – Scheme of the multiparametric station used at Tramutola to detect geoelectrical and geochemical parameters.

(T_A), measured close to the spring source, and the rainfall data (Rf) recorded by a meteo-climatic station of the Istituto Idrografico e Mareografico located less than 1 km far from the measuring site. In this way all recorded data can be constantly checked with meteo-climatic parameters. An example of geophysical and geochemical data measured during June 1995 is reported in fig. 6. Figure 7 shows the mean daily values of geophysical, geochemical and meteo-climatic data recorded during 1995.

3˙1. *Explorative data analysis*

3˙1.1. Univariate analysis. For each variable, starting from mean daily values, the statistical parameters of data distribution, relatively to location, spread and shape, have been calculated (table I). The explorative statistical study of data is the first important task in all experimental activity; in our case the knowledge of the statistical parameters has strong implications for the characterisation of intrinsic fluctuations. Self-potential and conductivity in water show a bimodal distribution reflecting a long-period shift towards lower values. CO_2 and water temperature have a very small range of fluctuations ($CV = 3\%$) and the distribution function is quite similar to a Gaussian curve. Radon measurements show high-frequency fluctuations caused by the radioactive decay process and data distribution is strongly affected by a positive asymmetric shape ($S = 2.3$ and mean, mode and median are lower than the range middle point). Finally, meteo-climatic data are characterised by well-known distributions, the environmental temperature is normally distributed while rainfall values follow a Poisson distribution.

3˙1.2. Bivariate and multivariate analysis. By means of scatter plots at lag 1, a preliminary screening to identify the influence of meteoclimatic variables on geoelectrical and geochemical data recording has been carried out. In table II the values of Pearson's correlation coefficient (ϱ) are shown. We note that the

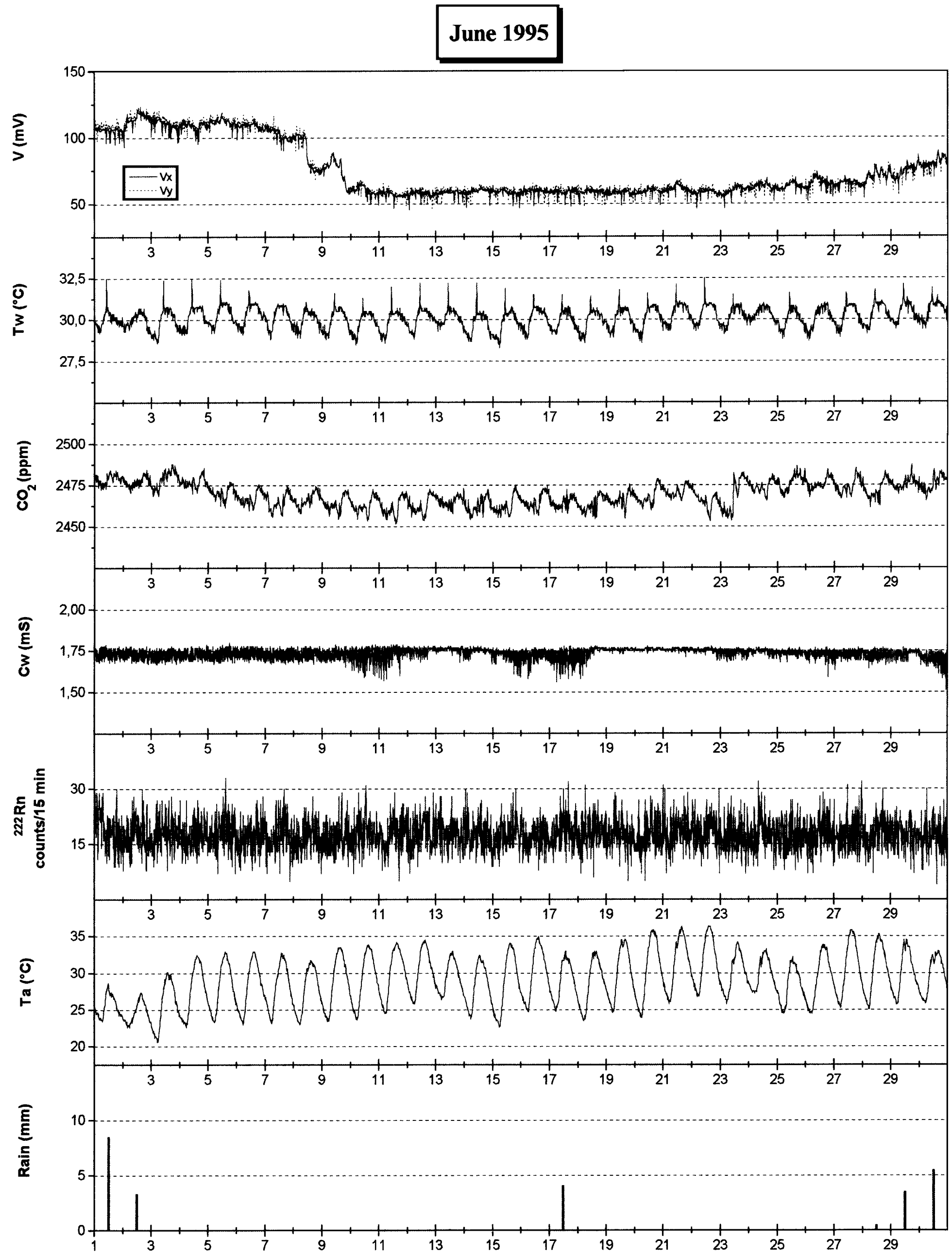

Fig. 6. – Plots of geophysical and geochemical data measured during June 1995 (the sampling interval is $\Delta t = 15$ min). Starting from top we have: self-potential data along N-S direction (V_X); water temperature values (T_W); CO_2 concentrations (CO_2); conductivity in water (C_W); radon counts (^{222}Rn); ambient temperature (T_a) and rainfall.

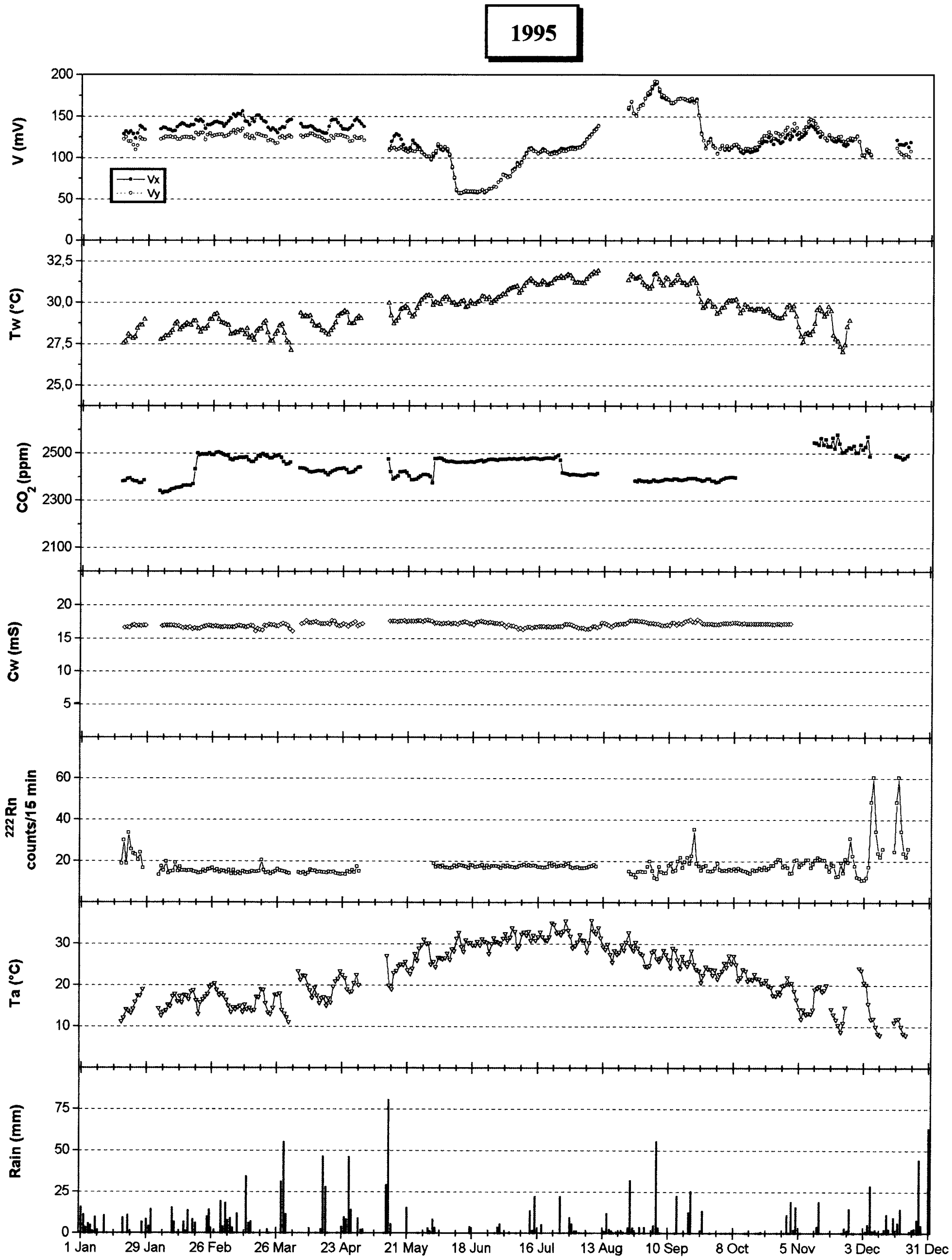

Fig. 7. – Plots of mean daily values of geophysical and geochemical parameters (V_X, V_Y, T_W, CO_2, C_W, ^{222}Rn) and mean daily values of the ambient temperature measurements and the rainfall (T_A, Rf) recorded during 1995.

TABLE I. – *Explorative statistical parameters calculated on two years* (1995-1996). *Legend:* n = *data percentage*, M = *mean*, Mn = *median*, Md = *mode*, St.D. = *standard deviation*, CV = *coefficient of variation* (*% ratio between standard deviation and mean*); S = *skeweness*; K = *kurtosis*; R = *range* (*in parenthesis the central value is shown*).

	n (%)	M	Mn	Md	St. D.	CV (%)	S	K	R
V_X (mV)	73	105	115	48	41	39	− 0.5	− 1.0	22–190 (106)
V_Y (mV)	69	101	111	48	36	36	− 0.4	− 0.3	18–192 (105)
T_W (°C)	66	30	30	27.7	1	3	− 0.3	− 0.5	24.6–32.1 (28.3)
CO_2 (ppm)	67	2452	2470	2479	73	3	− 1.4	4.2	2064–2618 (2341)
C_W (mS)	64	1.3	1.7	1.7	0.5	38	− 0.8	− 1.2	0.4–1.9 (1.1)
^{222}Rn (count)	57	17	17	14	8	47	2.3	12.6	1–80 (40.5)
T_A (°C)	70	20	20	19	7	35	− 0.1	− 0.8	2.0–35.7 (18.8)
Rf (mm)	100	4	0	0	11	275	4.1	19.6	0–82 (41)

self-potential measurements are not apparently related with temperature cycles and precipitations (only $\varrho(T_A - V_X) = -0.33$ is significant). Water temperature data (T_W) show a cyclic component triggered by environmental temperature (T_A) ($\varrho = 0.87$). The monitoring station, in fact, is at present located 5 meters away from spring source and linked to it by a plastic material tube, subject to ambient temperature variations. The CO_2 and ^{222}Rn time series are affected by daily changes related to water temperature ($\varrho(T_A - CO_2) = -0.29$ and $\varrho(T_A - {}^{222}Rn) = -0.30$). The electrical conductivity in water is not affected by external influence. All data recorded seem to be not contaminated by rainfall, only the self-potential values show a very slow increase after a rain period.

To complete our analysis, we estimate the correlation coefficients for each couple of geoelectrical and geochemical time series. The scatter plots point out different relationships among the couples of variables that the only linear correlation coefficient

TABLE II. – *Pearson's correlation coefficient values calculated between meteoclimatic variables and geochemical and geophysical parameters. In parentheses, for each couple of variables, the number of degrees of freedom is shown.*

	V_X	V_Y	T_W	C_W	CO_2	^{222}Rn
T_A	− 0.33 (497)	0.18 (497)	0.87 (478)	0.13 (463)	− 0.29 (458)	− 0.30 (408)
Rf	0.08 (531)	0.11 (505)	− 0.10 (480)	0.04 (466)	0.03 (490)	0.12 (416)

TABLE III. – *Correlation matrix of geochemical and geophysical parameters. In the upper part Pearson's correlation coefficient values and the number of degrees of freedom are reported; in the lower part Kendall's correlation coefficient values.*

	V_X	V_Y	T_W	CO_2	C_W	Rn
V_X	1	0.97 (505)	− 0.50 (480)	0.04 (489)	0.75 (435)	0.20 (410)
V_Y	0.92	1	− 0.36 (480)	0.05 (464)	0.80 (452)	0.18 (410)
T_W	− 0.53	− 0.40	1	− 0.26 (441)	− 0.31 (451)	− 0.29 (386)
CO_2	− 0.14	− 0.13	− 0.23	1	− 0.05 (421)	0.39 (373)
C_W	0.54	0.66	− 0.17	− 0.30	1	0.16 (358)
^{222}Rn	0.19	0.12	0.31	0.27	0.09	1

cannot take into account. So we use both a parametric test, based on the estimate of Pearson's coefficient (ϱ), and a non-parametric test, based on the estimate of Kendall's rank-order coefficient (τ) (table III). We note that self-potential time series are strongly correlated with electric conductivity in water (for example, $\varrho(V_X - C_W) = 0.75$ or $\tau(V_Y - C_W) = 0.66$) and the ^{222}Rn counts are weakly correlated with CO_2 concentration ($\varrho = 0.39$ and $\tau = 0.27$). However, because of the high number of degrees

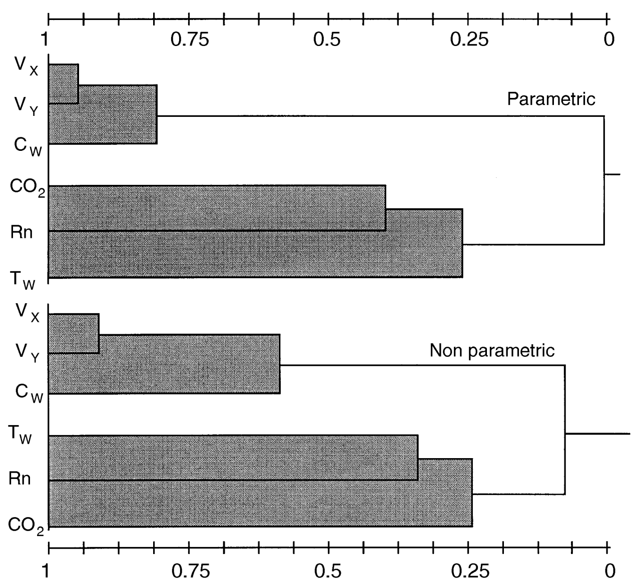

Fig. 8. – Dendrograms of clustering algorithm applied to ϱ-correlation matrix (parametric) and to τ-correlation matrix (non-parametric).

of freedom, at standard significance level (1%) almost all couples show a significant correlation. Thus, to obtain more informative results, we apply a multivariate technique to highlight the interrelation between the different parameters. A clustering algorithm [41], applied to the correlation matrices (ϱ-matrix and τ-matrix), allows us to discriminate two separate groups of variables (V_X, V_Y, C_W) and (T_W, CO_2, ^{222}Rn). The dendrograms are shown in fig. 8. This procedure allows us to point out a hierarchic classification in which we note the correlation between CO_2 and ^{222}radon and their link with the temperature. Furthermore, self-potential values are linked with electrical conductivity of fluids giving us a signature of a possible electrokinetic effect.

3·2. *Scaling laws in power spectra.* – To gain insight into the inner dynamics of geoelectrical and geochemical signals, we investigate the presence of scaling laws in the power spectra. It is widely accepted that the power law index can give information about the physics underlying the processes that produce the observed signals [42]. In particular, the relationship between the scaling exponent in power spectra and a tuning parameter of a wide class of fractional Brownian motions (fBm) has been analysed. These processes are a generalisation of Brownian process and in recent years they have been applied in modelling series of observations in a wide range of natural phenomena [43, 44].

It is well known that the distance covered by a random particle undergoing random collisions from all sides is directly related to the square root of time:

$$X(t) - X(t_0) \sim \xi |t - t_0|^H, \tag{1}$$

where t and t_0 are two different times, ξ a Gaussian variable with zero mean and unit variance and H a scaling exponent that is equal 1/2. In this case the displacement of the particle in one time interval is independent of the displacement at another. The concept of fractional Brownian motion is a generalisation of the random function $X(t)$ in which the exponent H can assume any real number in the range $0 < H < 1$ [45].

This theory can be applied to study the irregularity of experimental time series. In fact, following an independent way, Hurst investigated many time series (*i.e.* river discharges, rainfalls) using the dimensionless ratio R/S, where R is the range (difference between maximum and minimum values of variable) and S the standard deviation [46]. He found that the rescaled time series are well described by the following empirical relation $R/S = (\tau/2)^H$, where τ is the considered period and H a scaling exponent, the so-called Hurst exponent. It is evident that the theory of fractional Brownian process can be easily applied to describe experimental time series: the trace of random particle becomes a record in time.

The estimate of the Hurst exponent is a robust statistical tool that has a wide variety of interesting applications. The Hurst exponent is a useful measure of the fractal dimension of the time series ($D = 2 - H$) and there is an interesting relation between the rate of decay of power spectrum and the H value:

$$P(f) = f^{-\alpha} = f^{-(2H+1)}, \tag{2}$$

where f is the frequency and α the scaling exponent in the power spectrum [47].

The knowledge of this exponent allows us to well describe the time fluctuations of experimental data: for $H = 1/2$ the past and future increments are completely independent; for $0.5 < H < 1$ we have a persistent series (the series covers more distance that a random walk and, thus, if the system increases in one period, it is more

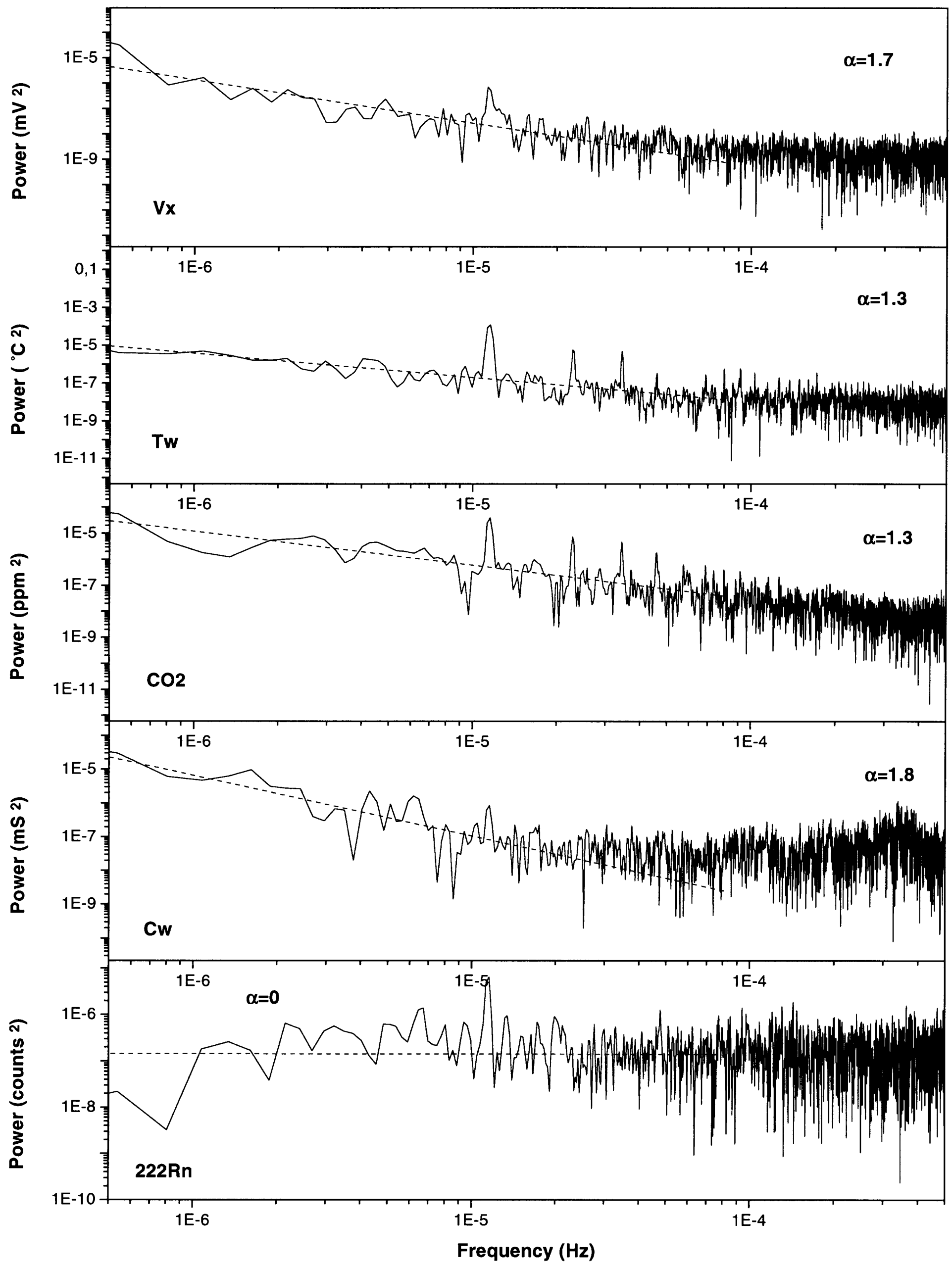

Fig. 9. – Power spectra of data recorded during the period June 1995-July 1995. To estimate the power spectra with FFT technique we use $N = 4096$ experimental values.

likely to keep increasing in the immediately following period); for $0 < H < 0.5$ we have an antipersistent series (the system is covering less distance that a random walk, it has the tendency to reverse itself often).

In this work we estimate the power spectrum of geoelectrical and geochemical time series using the classical FFT technique. First of all, we normalise the time series subtracting the mean value and dividing by the standard deviation; in a successive step, we plot the spectrum using a log-log scale (fig. 9). In order to estimate the scaling exponent α, we use a classical least-square method for the linear fit, but, in order to avoid the influence due to the high-frequency noise clearly visible in power spectra, we do not consider the contribute of $P(f)$ values for $f > 10^{-4}$ Hz.

With the only exception of radon counts, our findings point out that all the time series are characterised by antipersistent dynamics. In fact, the α values vary from 1.3 to 1.8 and, consequently, the H coefficient is varying in the range $0.15 < H < 0.4$. On the contrary, the radon counts are characterised by a flat spectrum (white noise) that is a typical feature of Poissonian process related to radioactive decaying.

3·3. *Identification of extreme events.* – In this subsection the problem of the identification of extreme events in geoelectrical and geochemical time series has been approached. This is one of the more controversial aspects of short-term prediction, the assessment of well-defined criteria to extract abnormal values from background noise in precursory geophysical time series is a very complex problem that is generally omitted or approached with empirical methods [11, 13].

A suitable tool to analyse the probability of abnormal events is the crossing theory or theory of runs [24]. Strictly speaking, in the run theory abnormal events are treated as rare or unlikely events. Assuming that the experimental time series is a stationary and Gaussian process, the number of crossings below/above some truncation level becomes a Poissonian process. Considering the number of observations to be large enough to permit a good estimation of the empirical curves of probabilities of the abnormal events, it is possible to fit the theoretical probability curves with curves coming from the observations. Unfortunately, in many applications the size of the records is large enough to assess the structure of the empirical time series of interest, but not enough to have good statistics about extreme events. This is our case, where only two years of observations are available.

To overcome this drawback, it is necessary to define an optimal criterium to detect abnormal values modelling the time fluctuations of experimental values. A possible procedure is the following: a) a time interval is selected; b) the mean value and the standard deviation are estimated; c) the time series are standardised (*i.e.* zero mean and unit variance); d) values above/below $\pm 2\sigma$ are detected; e) the simultaneous appearance of extreme events in two series at least is analysed.

Unfortunately, also in this method there is a non-objective point: the selection of time interval. A large time interval (the maximum allowed is the length of the series) introduces the influence of meteoclimatic fluctuations; on the contrary, a smaller time interval could introduce the influence of high-frequency noise (man-made noise; local electrical disturbances etc.) and produces biased estimates of the standard deviation (the error on the estimate depends upon the number of data points). To overcome this problem we use the results obtained in subsects. **3·1** and **3·2** that allow us to consider the experimental time series weakly correlated with meteoclimatic variables and characterised by anti-persistent time dynamics (constant change in the sign of increments) at short scales ($10^{-6}\,\text{Hz} < f < 10^{-4}\,\text{Hz}$). An optimum choice is a time interval with a length of one month.

Starting from the first portion of recorded time series, for each month and for each signal, we normalise the values obtaining new time series with zero mean and unit variance and select only more consecutive values above/below $\pm 2\sigma$. Furthermore, we consider as significant extreme events the contemporary occurrence of abnormal sequences of events in almost two different geoelectrical and/or geochemical time series. This choice allows us to have a period so long to have a good estimate of the standard deviation σ and so short to consider negligible the σ fluctuations with time.

Obviously, this is not the best solution to the problem of the identification of extreme events, but it represents an objective criterium that could be systematically applied to process all records available. We apply this method to analyse our geoelectrical and geochemical time series selecting only one significant extreme event during April 1996.

4. – Pre- and post-seismic fluctuations of geoelectrical and geochemical signals

In this last section we approach the study of the possible correlation between anomalous patterns in geoelectrical and geochemical time series and local seismic activity. Also in this case, we apply an objective criterium to select the sequence of seismic events to be used in the correlation analysis.

As concerns the seismic sequences, because the earthquake precursors are variations in geophysical fields, caused by local earthquake preparation processes, only earthquakes that could be responsible for strain effects in the investigated area are to be selected. It is necessary to discriminate the useful events (*i.e.* an earthquake responsible for significant geophysical and geochemical variations in a rock volume of the investigated area) from all seismic events occurred in the surrounding area of Tramutola. To this purpose an empirical formula introduced by Dobrovolsky [47] has been used:

$$r = 10^{0.43M}, \tag{3}$$

where r is the radius of the area in which the effects of the earthquake are in principle detectable and M is the magnitude. An estimate of the strain at the measuring station can be obtained using the following formula:

$$\varepsilon = (10^{1.45M - 9.18})/\Delta^3, \tag{4}$$

where ε is the strain, M is the magnitude and Δ the epicentral distance.

The seismic events are extracted by the Catalogue of the National Institute of Geophysics (ING) and selected by applying the Dobrovolsky rule. In this phase we do not consider the earthquakes with $M < 3$, because the number of small earthquakes detected in the investigated area is strongly affected by the distribution of seismometric stations and by the improvements of the Italian seismograph network.

During the monitoring period only two events satisfy the Dobrovolsky algorithm (fig. 10). The selected seismic events are characterised by a strain value of 10^{-8} that is of the same order as the tidal strain.

In figs. 11 and 12 geophysical and geochemical parameters observed before and after the selected shocks are reported. We note that the event detected on May 29, 1995 ($M_D = 4.0$, origin time: 20.44.24, $\Delta = 32.5$ km, depth = 9.3 km) was not preceded or followed by any anomalies. On the contrary, the event detected on April 3, 1996 ($M_D = 4.5$, origin time: 13.04.35, $\Delta = 44.8$ km, depth = 11.8 km) was preceded by marked self-potential anomalies in both the measuring arrays. It is interesting to note that also electrical conductivity shows a spike-like increase three days before the

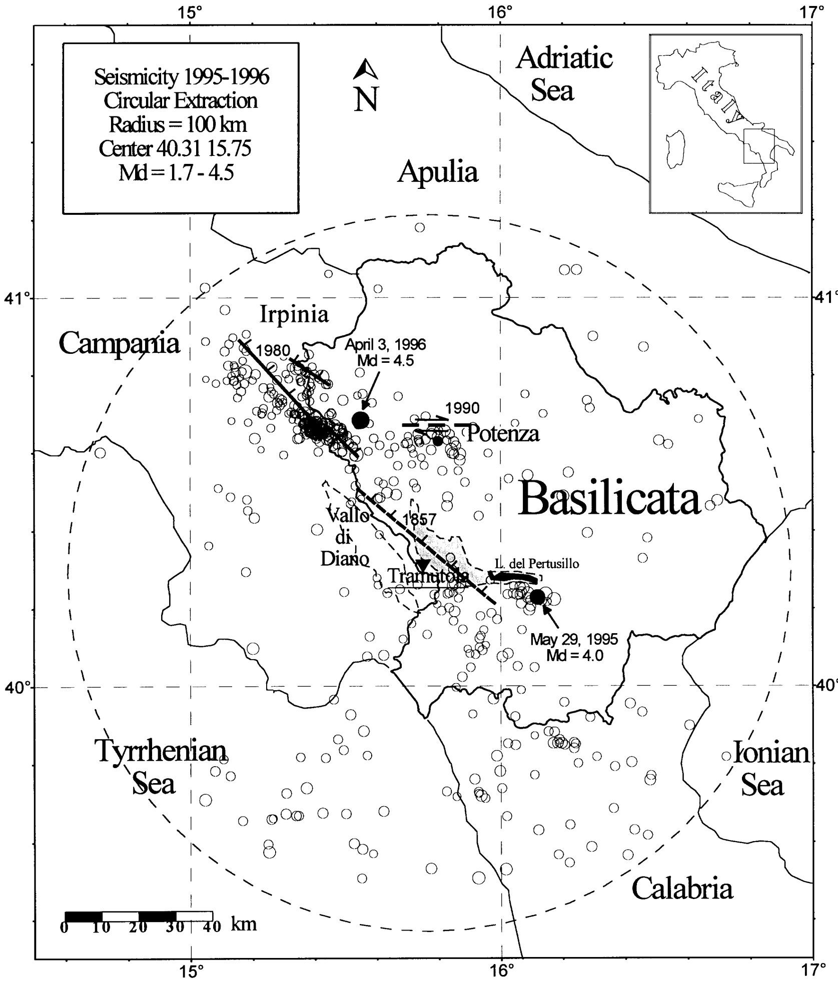

Fig. 10. – Seismicity pattern observed during the period January 1995-September 1996. The seismic events selected using the Dobrovolsky algorithm are indicated with dot circles.

seismic event. As we can see from figs. 11 and 12, the influence of the climatic parameters produces long-term fluctuations in electrical signals. No other anomalous behaviours were recorded in the remaining parameters. It is noticeable that a strong post-seismic fluctuation affected radon measurements; this behaviour could be probably due to changes in the deep fluids close the thermal area. In fact the anomalous record has been confirmed by fluctuations detected in some chemical components dissolved in the liquid phase and in some gaseous component (He, 3He/4He) monitored during the postseismic period [48].

To complete our analysis, the presence of false alarms in experimental time series has been checked. During the monitoring period there are not other significative anomalous patterns in geophysical and geochemical time series. As a consequence, we do not have false alarms.

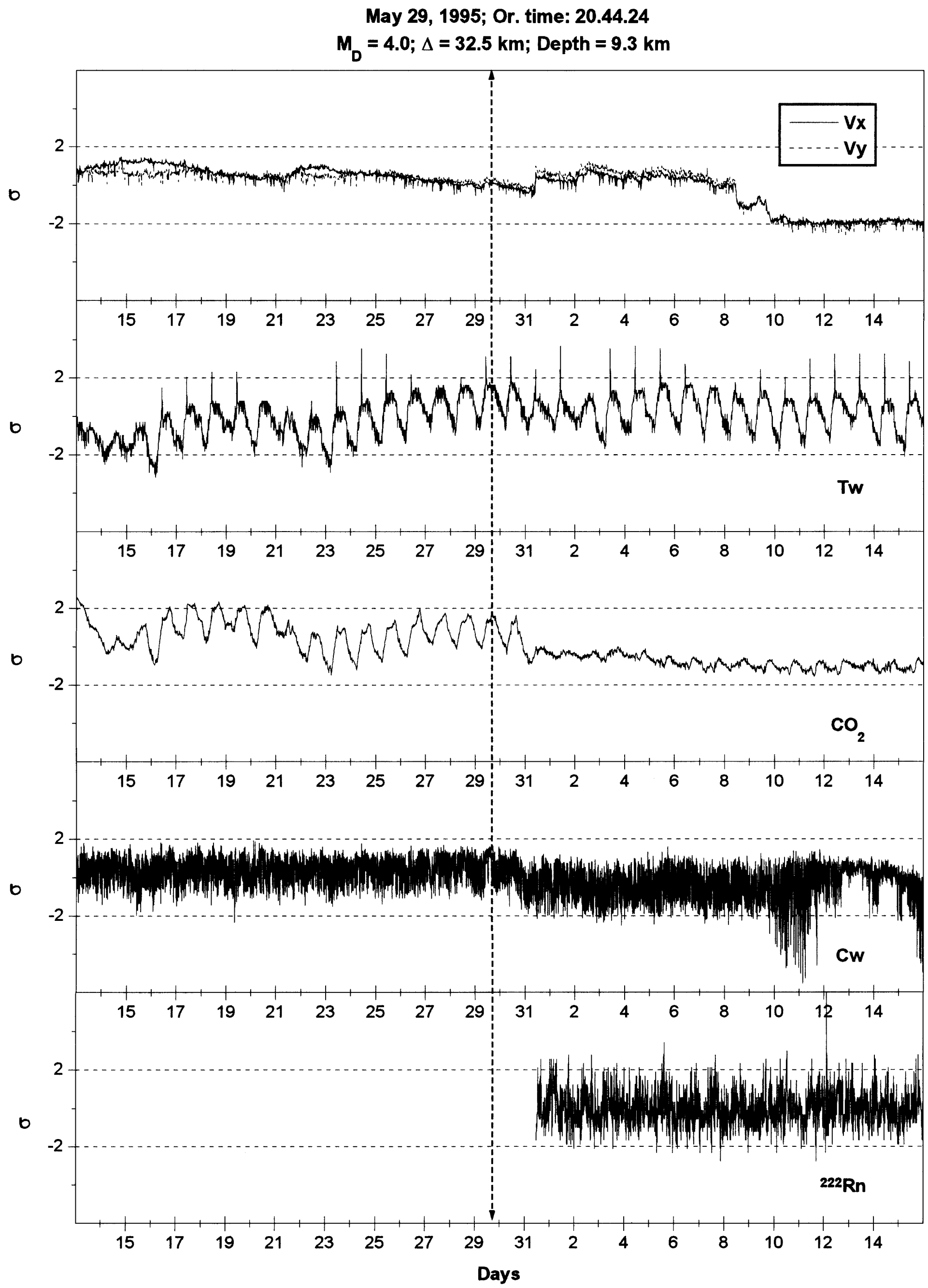

Fig. 11. – Geoelectrical and geochemical time series jointly monitored during the period May 13-June 16, 1995. The experimental values plotted in the graph are normalized (time series with zero mean and unit variance). The dashed line shows the seismic event selected by Dobrovolsky algorithm.

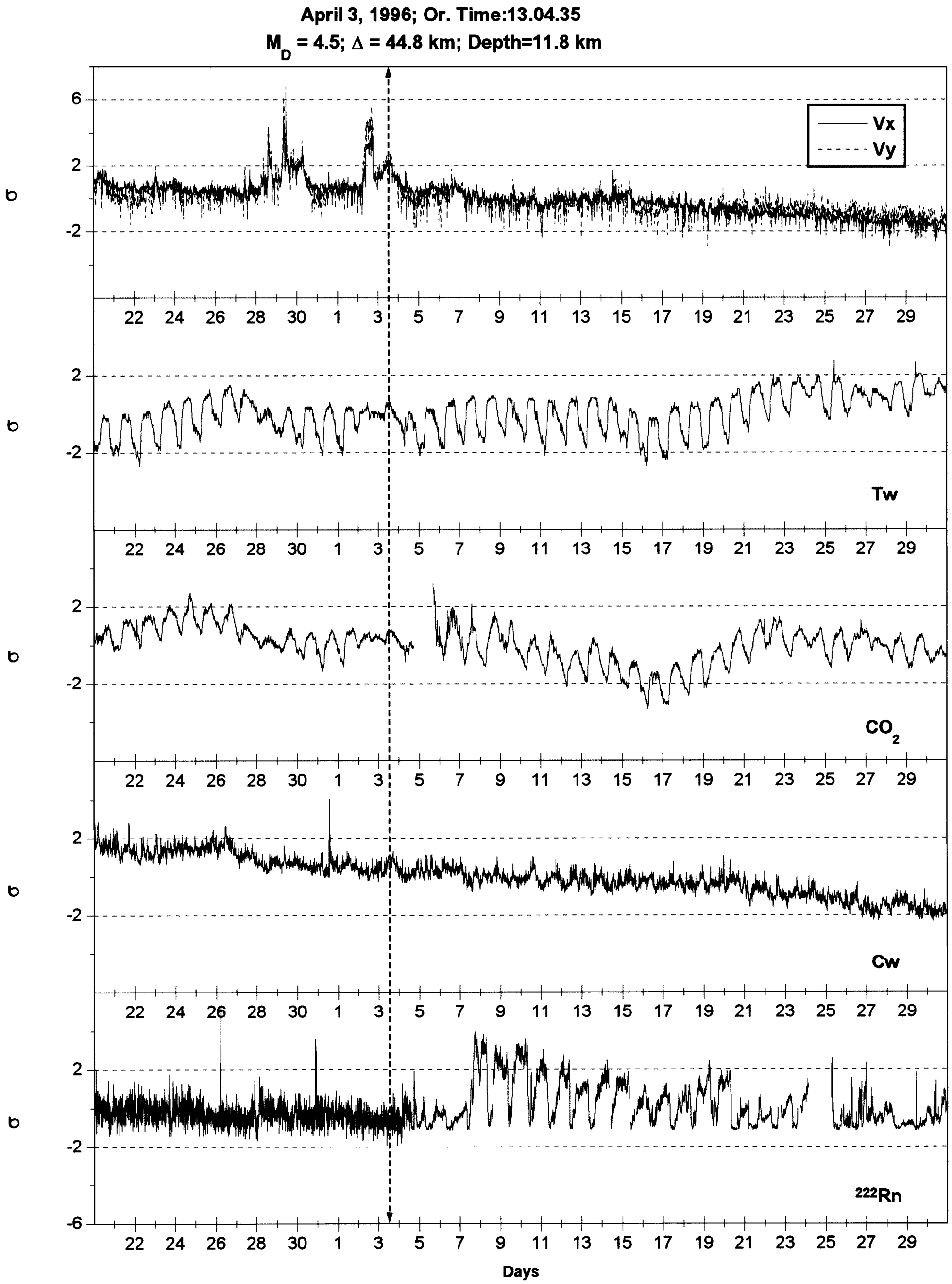

Fig. 12. – Geoelectrical and geochemical time series jointly monitored during the period March 20-April 30, 1996. The experimental values plotted in the graph are normalized (time series with zero mean and unit variance). The dashed line shows the seismic event selected by Dobrovolsky algorithm.

As a preliminary comment we infer that the observed anomalies in both the geophysical and geochemical parameters could have been generated by the stress variation preceding the earthquake. Thus, a possible electrokinetic effect [49] could be considered responsible for the detected anomalies. In fact an increase in the salt concentration of local deep seated fluids could fit both the detected anomalous signals. It is remarkable to note that, in spite of the comprehensive statistical treatment of data, no definitive conclusion can still definitely be drawn. While the event of $M_D = 4.5$ was preceded by anomalies in self-potential and electric conductivity, no anomalies in any parameters were detected in concomitance with the event of $M_D = 4$ even if closest to monitoring station.

Finally, we specify that the number of the earthquakes occurred in the investigated area is not sufficient to have firm conclusion about the application of these signals in the short-term earthquake prediction problem [50]. Our analysis may be considered a first preliminary step to better investigate the time dynamics of the signals recorded in the Southern Apennine chain.

5. – Conclusions

In spite of the lack of a completely representative time series of data, some preliminary results are obtained. Our findings allow us to obtain information about the intrinsic fluctuations of geophysical and geochemical experimental data measured close to an anomalous fluid emission in the Southern Apennine chain. Furthermore, our analysis gives more information about the possible link between geoelectrical and geochemical parameters: self-potential measurements and electric conductivity in water seem correlated and ^{222}Rn counts are weakly linked with CO_2 concentration. With the only exception of radon counts, all the experimental time series can be considered as a realization of a fractional Brownian process with anti-persistent dynamics. Before the seismic event occurred on April 3, 1996 ($M_D = 4.5$) anomalous patterns in signals of electrical nature have been observed. Furthermore, in the post-seismic period some fluctuations in radon measurements have been detected. Firm conclusions will be possible when a more complete data set of geophysical and geochemical time series and seismic sequences are available. A correct approach to the earthquake prediction problem is based on intense monitoring activities and on the application of advanced methods for time series analysis. Finally, it is necessary to better characterise the source physics of seismic events observed in the investigated area. This last feature seems even more important considering the peculiar seismotectonic complexity of the Southern Apennine chain. Furthermore, the variability of seismic source generation processes confirms the need for a dense monitoring array based on multiparametric stations.

* * *

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