ANNALI DI GEOFISICA, VOL. 44, N. 2, April 2001

Investigating the temporal fluctuations in geoelectrical and geochemical signals jointly measured in a seismic area of Southern Apennine chain (Italy)

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Abstract

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, Southern Italy). In the investigated area some destructive seismic events occurred in past and recent years. We analysed the temporal fluctuations of the signals by spectral tools. We detected scaling behaviours in the power spectra of the time series recorded, that are typical fingerprints of fractional Brownian motions. The estimated values of the spectral indices reveal the presence of antipersistent behaviour in the time dynamics of all geoelectrical and geochemical data recorded. This work intends to improve our knowledge of the inner time dynamics of geophysical non-seismometric parameters.

Key words *geoelectrical and geochemical signals – scaling – power spectral analysis*

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 (Rikitake, 1988; Thomas, 1988; Park and Fitterman, 1990; Tsunongai and Wakita, 1995; Chu *et al.*, 1996). Many models have been proposed to describe the anomalous patterns of precursory phenomena measured close to epicentral areas (Scholz *et al.*, 1973; Mizutani *et al.*, 1976; Park *et al.*, 1993), but 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 complicated when correlations between observed anomalies and seismic sequences are performed only by means of qualitative methods and without robust statistical tests. In this way, we may have

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reasonable doubt that detected anomalies could be intrinsic fluctuations and they are not effectively connected with tectonic activity (Patella, 1988; Mulargia and Gasperini, 1992; Geller, 1996).

The identification of possible anomalies in geoelectrical and geochemical time series must be viewed as the second step of a procedure that has as a first step the knowledge of the time dynamics of these signals. We will not deal with the earthquake prediction problem, but with the improvement of knowledge, by using advanced time series tools, of the time dynamics of geoelectrical and geochemical parameters that could have great implications in earthquake prediction.

An important aspect in time series analysis is to recognise in signal variability the only presence of purely random fluctuations or the existence of a «memory» in the process generating the signal itself. Using the Rescaled Range (R/S) analysis, Hurst (1951), generalising the concept of Brownian motion, introduced an exponent, Hurst exponent (H), as a meaningful measure of the «memory» of the system. Indicating by R the range (difference between maximum and minimum values of variable) and by S the standard deviation, Hurst found that the rescaled time series are well described by the following power-law empirical relation $R/S = (\tau/2)^H$, where τ is the considered period and H is the Hurst exponent. There are three possibilities for values of H. If $H = 0.5$, the system follows a random walk, the observations are independent and non-correlated. If $0 \leq H < 0.5$, the time series is characterised by antipersistent behaviour; this means that the system has the tendency to reverse itself often; if increasing, it is more likely to be decreasing next period; if decreasing, it is more likely to be increasing. If $0.5 < H \leq 1$, the time series is characterised by persistent behaviour; if the signal increases, it is more likely to be increasing in the immediately following period.

The power spectrum analysis of time series is a well-known method to measure the persistence of a time series. The power spectrum is defined as the square of the coefficients in a Fourier series representation of the time series. It measures the average variation of the function at different time lags. If adjacent data points are totally uncorrelated then the power spectrum will be constant as a function of the frequency, like white noise. If adjacent points are strongly correlated relative to points far apart in time the power spectrum will be large at small frequencies (long time lags) and small at high frequencies (short time lags) (Pelletier, 1997). If the power spectrum follows a $1/f^\beta$ power-law behaviour, a relation between β and H exists, $\beta = 2H + 1$ (Voss, 1989). Therefore, from the knowledge of spectral index β it is possible to extract information on the persistence of the signal.

We took into account these considerations and according to the recommendations of the European Seismological Commission that suggests measuring a wide range of non-seismometric parameters. To apply advanced statistical methods, identify extreme events in precursory time series and compare the results obtained in different geological and seismological enviroments, 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 (Fitterman, 1981; Dobrovolsky *et al.*, 1989; Di Maio and Patella, 1991; Balderer *et al.*, 1994a) 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 geodymanic processes can simultaneously produce shallow geochemical anomalies (CO_2, radon and other ionic concentrations) and electrokinetic phenomena, and suggests 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 (Joaniux and Pozzi, 1995; Revil and Pezard, 1999). 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 (Di Bello *et al.*, 1994; Cuomo *et al.*, 1996, 1998; Albarello and Martinelli, 1997). After a preliminary screening of spatial and temporal patterns of geochemical and geophysical phenomena observed in the Southern Apennines chain (Balderer *et al.*, 1994b), since 1994 a multiparametric station, able to measure geophysical and geochemical parameters, has been operating close to a thermal area in Tramutola, Basilicata region, Italy (fig. 1). From historical records, it is recognisable that in this region very strong earthquakes occurred periodically throughout the centuries (Westway and Jackson, 1987).

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

The purpose of this work is to study the temporal fluctuations of geoelectrical and geochemical time series recorded at Station Tramutola during the period from January 1995 to December 1995. In particular, we analyse geoelectrical data (self-potential signals measured on Earth surface), geochemical data measured near a fluid emission (CO_2 and ^{222}Rn concentrations, water temperature) and the meteoclimatic ambient temperature. The paper is organised as follows: in Section 2 we describe the geological and seismological settings of the investigated area; in Section 3 we show the experimental equipment of the multiparametric station; in Section 4 the results of the spectral analysis are discussed; finally the conclusions are depicted in Section 5.

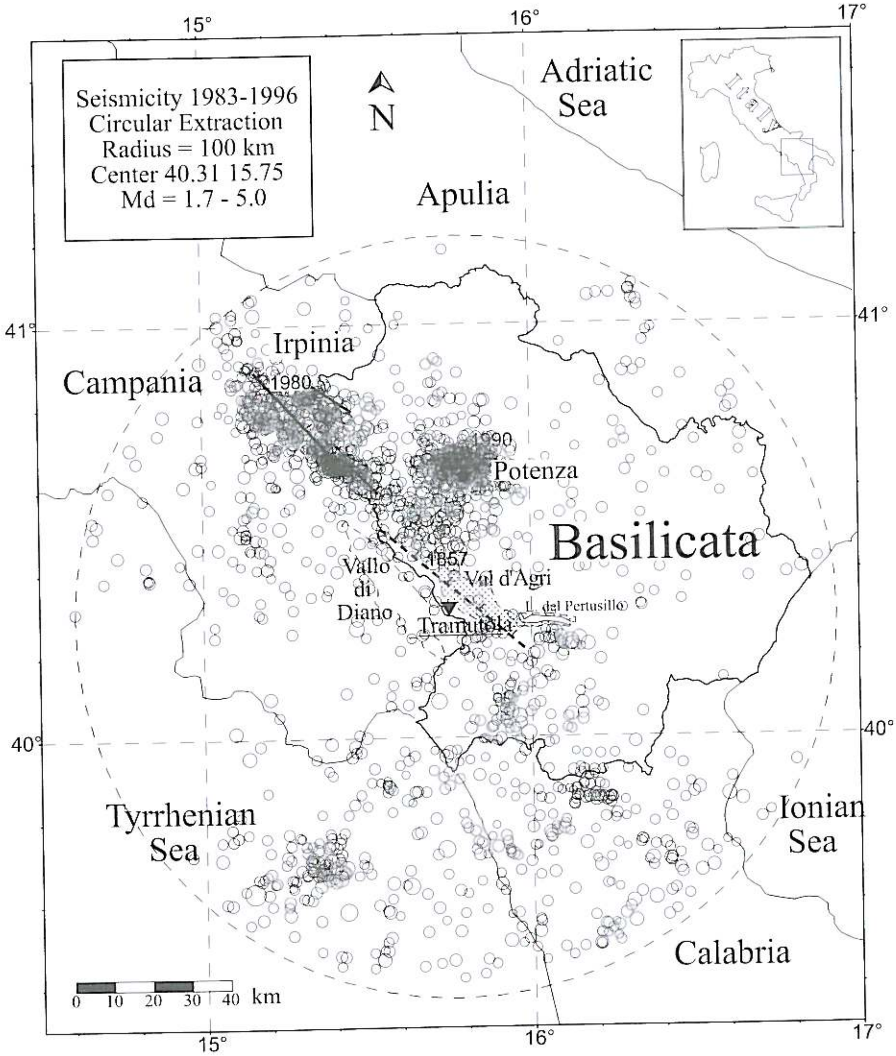

Fig. 2. Seismicity pattern observed on the Southern Apennine chain during the period 1983-1996 (data extracte from ING catalog).

2. Geological and seismological settings

The measuring station is located on the Southern Apennine chain, an African-verging fold and thrust belt built on during the Neogene tectogenesis (Cinque *et al.*, 1993). Starting in the middle Miocene up to the upper Pliocene, several compressional tectonic phases (Patacca *et al.*, 1988), associated with the collision between Africa and Europe, caused progressive thrusting and piling of different tectonic units, corresponding to different limestone platforms and siliceous basins, toward stable external domains of the Apulo-Adriatic foreland. During Plio-Pleistocene, the Southern Apennines were affected by an important neotectonic distensive phase, with NE-SW extensional axis, that caused chain fragmenting into several active kinematic isolated blocks (Pantosti and Valensise, 1990). In the same period, counter-apenninic regional transcurrent faults were generated.

From a seismologic point of view, the Southern Apennine chain is one of the most seismically active areas of the Mediterranean region. In particular, in this area major earthquakes are generally related to the great Apenninic normal faults, while moderate seismic events are generated by faults perpendicularly oriented with respect to the Apenninic chain (Pantosti and Valensise, 1990). Most moderate and large earthquakes show a dip slip mechanism, consistent with the actual extensional tectonics of the region (Westaway and Jackson, 1987).

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 (Mallet, 1987), occurred in Val d'Agri where the multiparametric station is located. The seismic activity that occurred after the 1980 event consisted of medium intensity events ($M < 5.5$) located close to the border between the Campania and Basilicata regions (Alessio *et al.*, 1995) and to north of town of Potenza (Tertulliani *et al.*, 1992; Ekström, 1994) (fig. 2).

The South Apenninic fault structure and the connected complex rupture events of the surface are strictly linked with deep originated fluid occurrences, such as geothermal manifestations or mofettes, strongly affected by preseismic phenomena reported in the historical seismicity studies (Battista, 1858). In this region, indeed, due also to a very low level of cultural noise, 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.

3. Data

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 characterised 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 (Balderer and Martinelli, 1994).

The remote station is equipped with suitable sensors for measuring carbon dioxide concentration (CO_2), ^{222}radon concentration (^{222}Rn), water temperature (T_W) and self-potential probes (in N-S direction, V_X, and E-W direction, V_Y) to detect the electrical field variations on the Earth's surface. Sensors are connected with an 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 (T_A), measured close to the spring source. The geophysical and geochemical data measured during 1995 are reported in fig. 3. The self-potential signals V_X, and V_Y present similar temporal variations, but V_X is characterised by greater variance. The ambient temperature T_A and the water temperature T_W follow very similar patterns with the visible annual periodicity. The CO_2 seems to alternate between two approximately constant values, with abrupt changes from one state to another. The ^{222}Rn seems to be characterised by strong irregularity with spikes occurring over a purely random fluctuating behaviour. Figure 4 shows the measure-

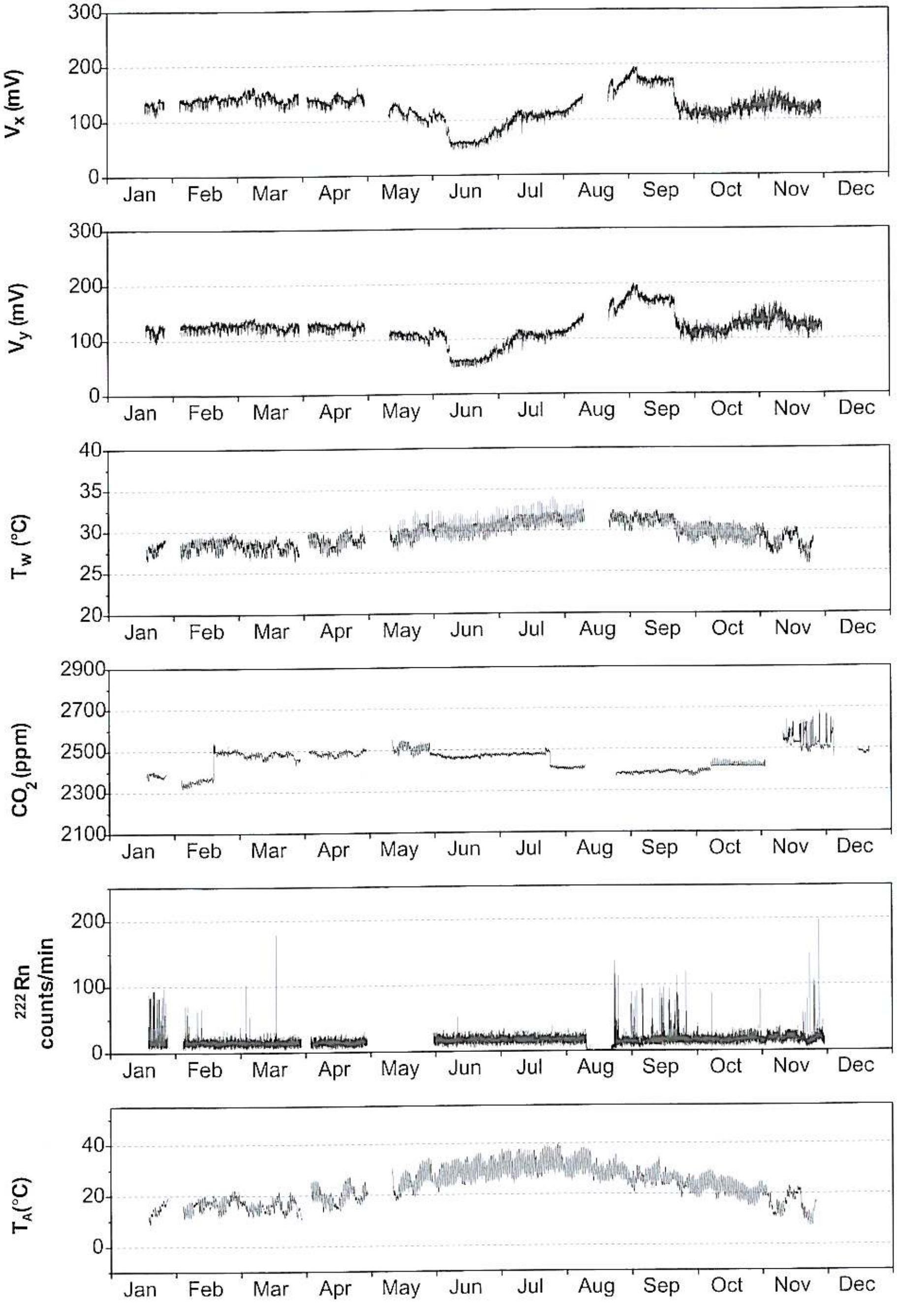

Fig. 3. Plots of the geophysical, geochemical and meteoclimatic signals recorded at a sampling interval $\Delta t = 15$ min during 1995. Starting from top we have: self-potential data along N-S and E-W directions (V_x,V_y); water temperature values (T_w); CO_2 concentration (CO_2); radon counts (^{222}Rn), and ambient temperature (T_A).

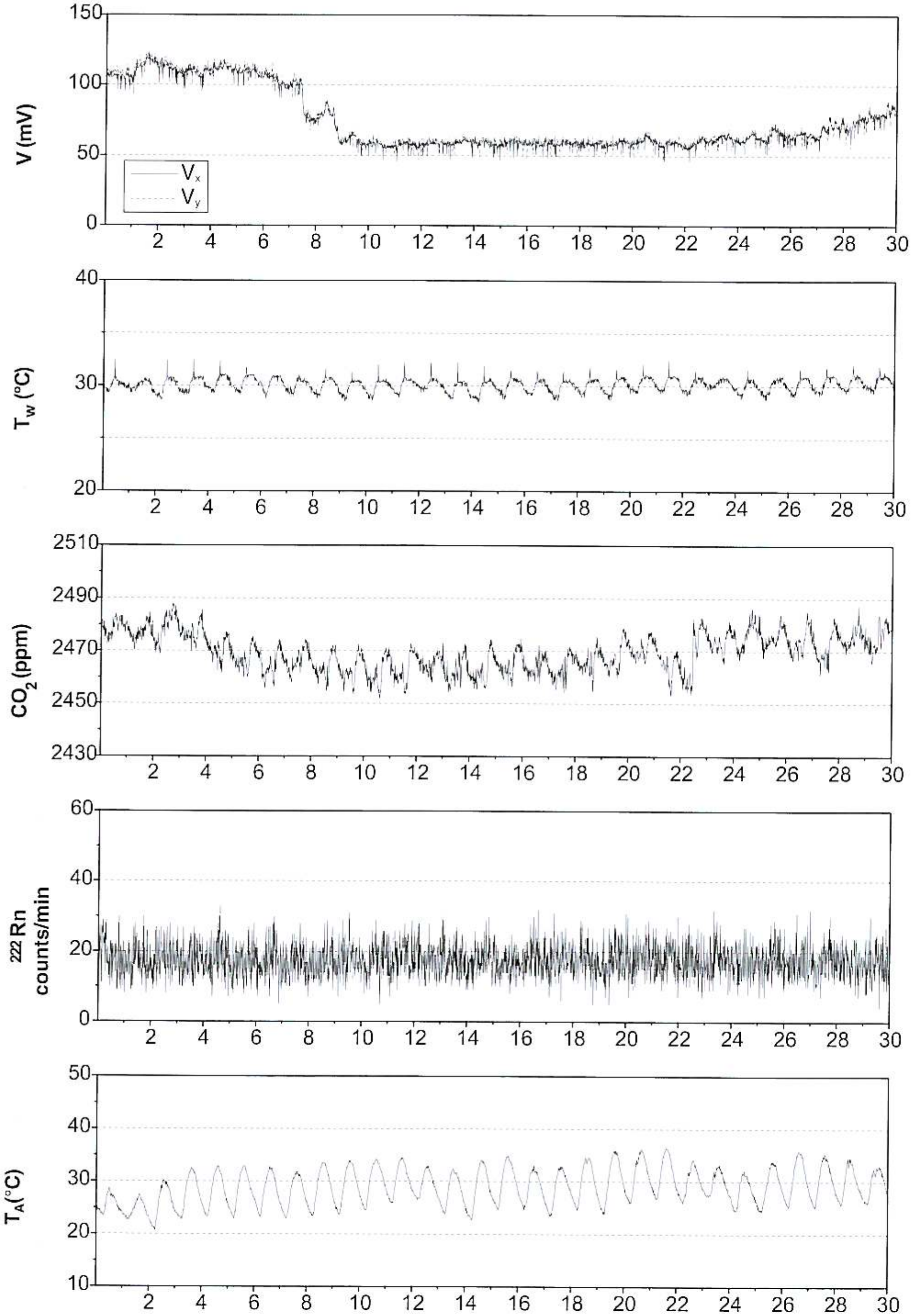

Fig. 4. A one month (June 1995) example of the data plotted in fig. 3.

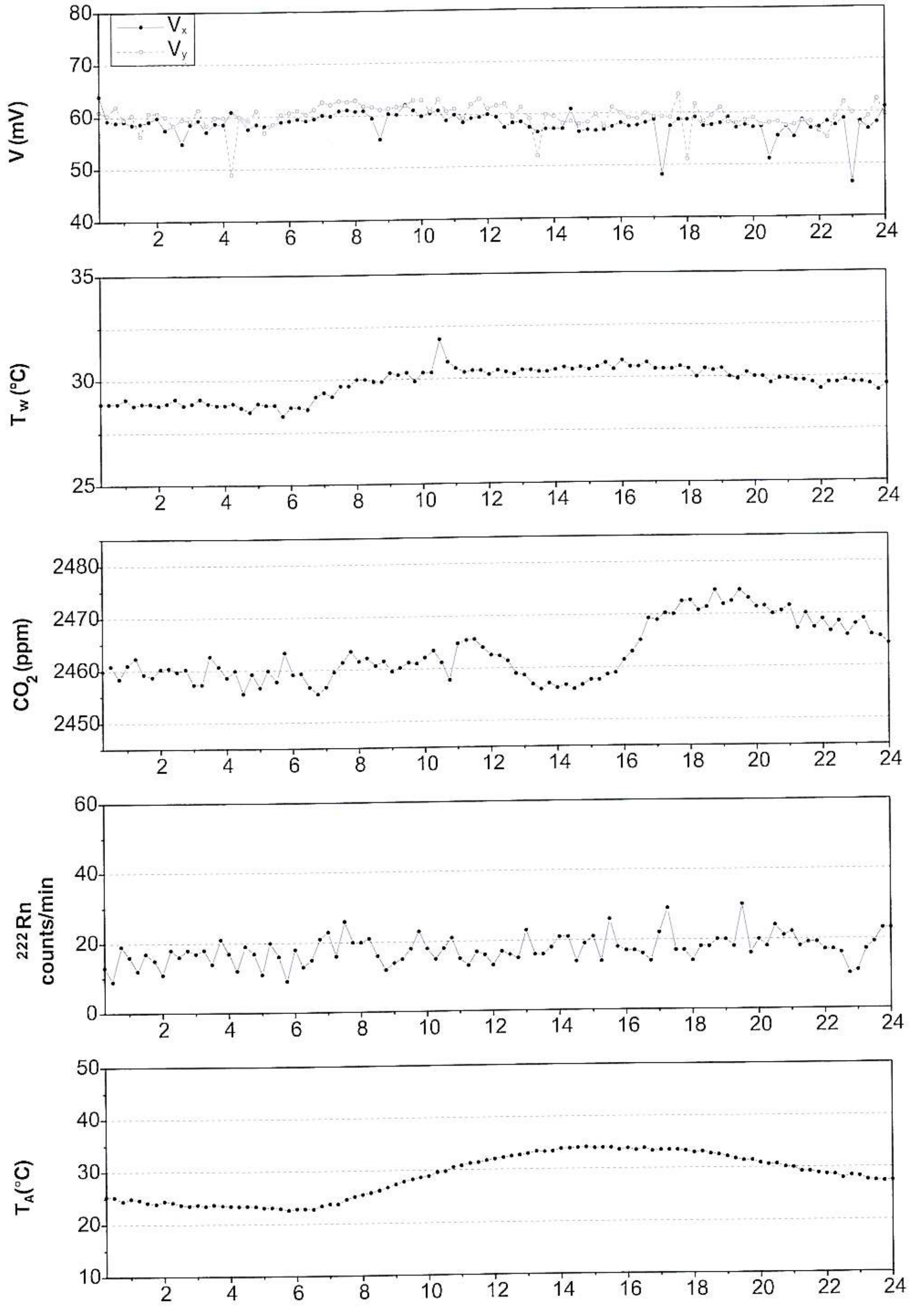

Fig. 5. A one day (15th June 1995) example of data plotted in fig. 3.

ments over the period of one month (June 1995): the self-potential signals present slightly smooth variations with a high frequency component superimposed; the T_A and T_W signals evidence the presence of the diurnal component, that influences the pattern of the CO_2 concentration; the radon counts are characterised by very high frequency variation with a typical feature of white noise. Figure 5 shows an example of recording a 1-day period (15th June). It is possible to observe a very different behaviour of the ambient temperature from those of the other signals: T_A varies persistently with the time; the other signals seem to fluctuate more or less regurlarly around an average value, with a clear indication of antipersistent behaviour at the 24-h-timescale.

4. Spectral analysis of the data

The power spectral densities of the signals are calculated with the Lomb Periodogram Method (Lomb, 1976) because the data are unevenly spaced. Indicating with the $\bar{x}$ mean value of the time series and with σ^2 its variance, the power spectrum is defined by the following formula:

$$S(\omega)=\frac{1}{2\sigma^2}\left\{\frac{\left[\sum_n (x_n-\bar{x})\sin\omega(t_n-\tau)\right]^2}{\sum_n \sin^2\omega(t_n-\tau)}+\right. \tag{4.1}$$

$$\left.+\frac{\left[\sum_n (x_n-\bar{x})\cos\omega(t_n-\tau)\right]^2}{\sum_n \cos^2\omega(t_n-\tau)}\right\}$$

where $\omega = 2\pi f$ and τ is defined by

$$\tan(2\omega\tau)=\frac{\sum_n \sin(2\omega t_n)}{\sum_n \cos(2\omega t_n)}. \tag{4.2}$$

Figure 6 presents the power spectra of geoelectrical and geochemical signals recorded at Tramutola station and the power spectrum of the ambient temperature. All the power spectra presented in this paper are plotted after taking the logarithm of the power spectrum and of the frequency against which the spectrum is plotted. All the power-law functions appear as straight lines with slopes equal to the exponent of the power-law. The frequency unit of all observational data is $(15\ \text{min})^{-1}$. In all the spectra the diurnal component is visible: less evident in the V_X, V_Y and ^{222}Rn, more in T_A, in water temperature T_W and in CO_2 concentration. In the spectra of V_X, V_Y, ^{222}Rn and T_W two frequency regimes are present: a scaling region, involving the low frequency part of the spectra, and a flat region at high frequencies. The CO_2 concentration presents a scaling behaviour over almost all frequencies. The crossover frequency for the V_X, V_Y and T_W is approximately given by $f \approx 1/24$ h, corresponding to the diurnal component. In the ^{222}Rn spectrum the scaling range is smaller and the crossover frequency is less than 24 h. The spectral exponents lie between 1.45 and 1.94, and this indicates an antipersistent behaviour for all the data; in fact, the Hurst exponents are less than 0.5. While the power spectrum of the ambient temperature T_A is characterised by a persistent behaviour, as the spectral exponent $\beta = 2.13$ suggests. This is in accordance with studies on the Lorentian form of the power spectrum of the temperature variations (Lovejoy and Schertzer, 1986; Pelletier, 1997). The behaviour of the ambient temperature indicates that the geoelectrical and geochemical variations are controlled by a geophysical mechanism different from that governing the ambient temperature fluctuations. For frequencies (corresponding to short time scales) greater than the crossover frequency, all the data display a white noise behaviour, typical of signals characterised by purely random fluctuations.

5. Conclusions

The power spectrum of one-year long geoelectrical and geochemical time series, measured at station Tramutola (Southern Italy), has a power-law dependence of frequency f in some range of frequencies. In almost all the spectra two frequency regimes are found with different values of β. The first corresponds to a scaling regime with $\beta < 2.0$, typical of signals character-

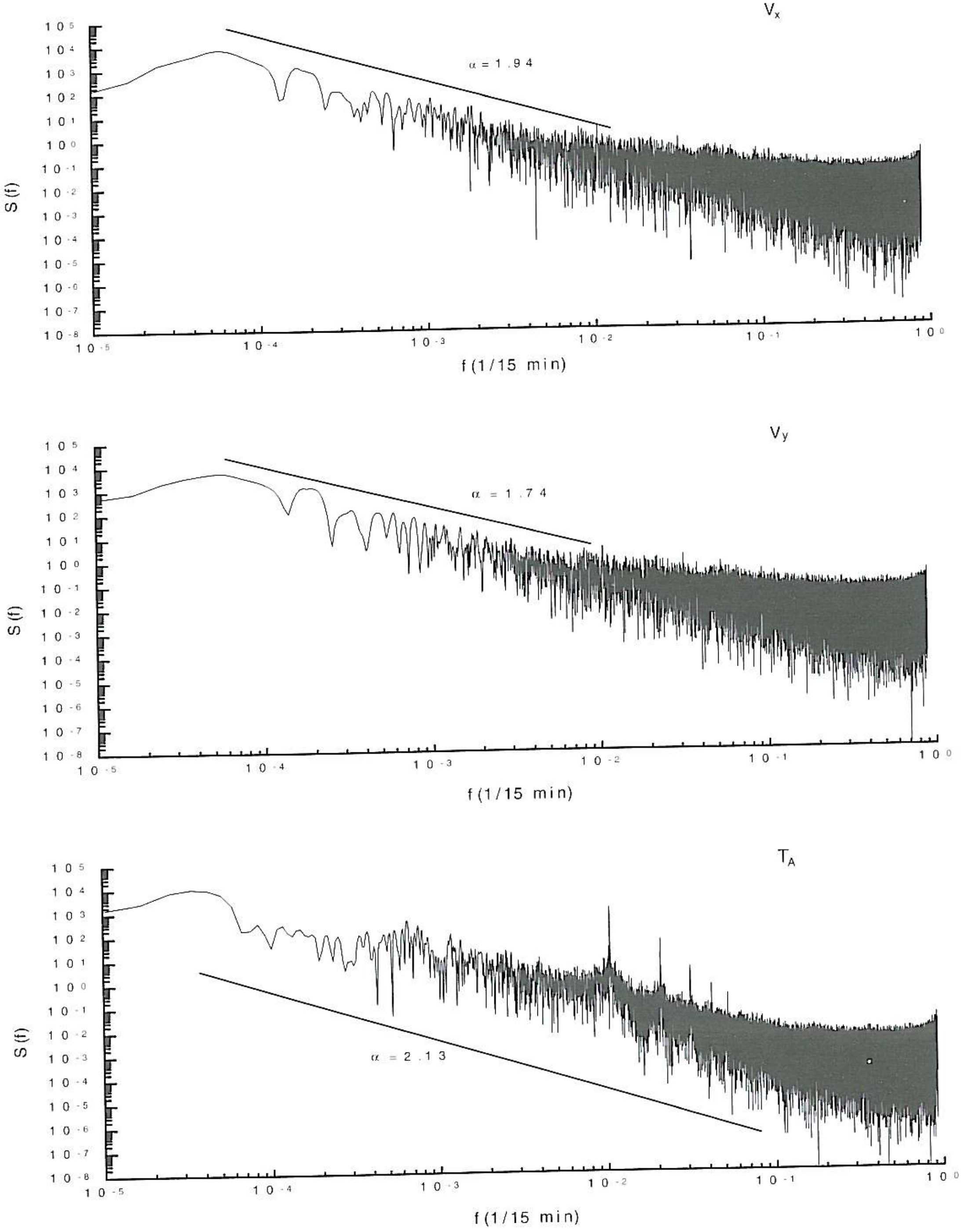

Fig. 6. Power spectra of data plotted in fig. 3.

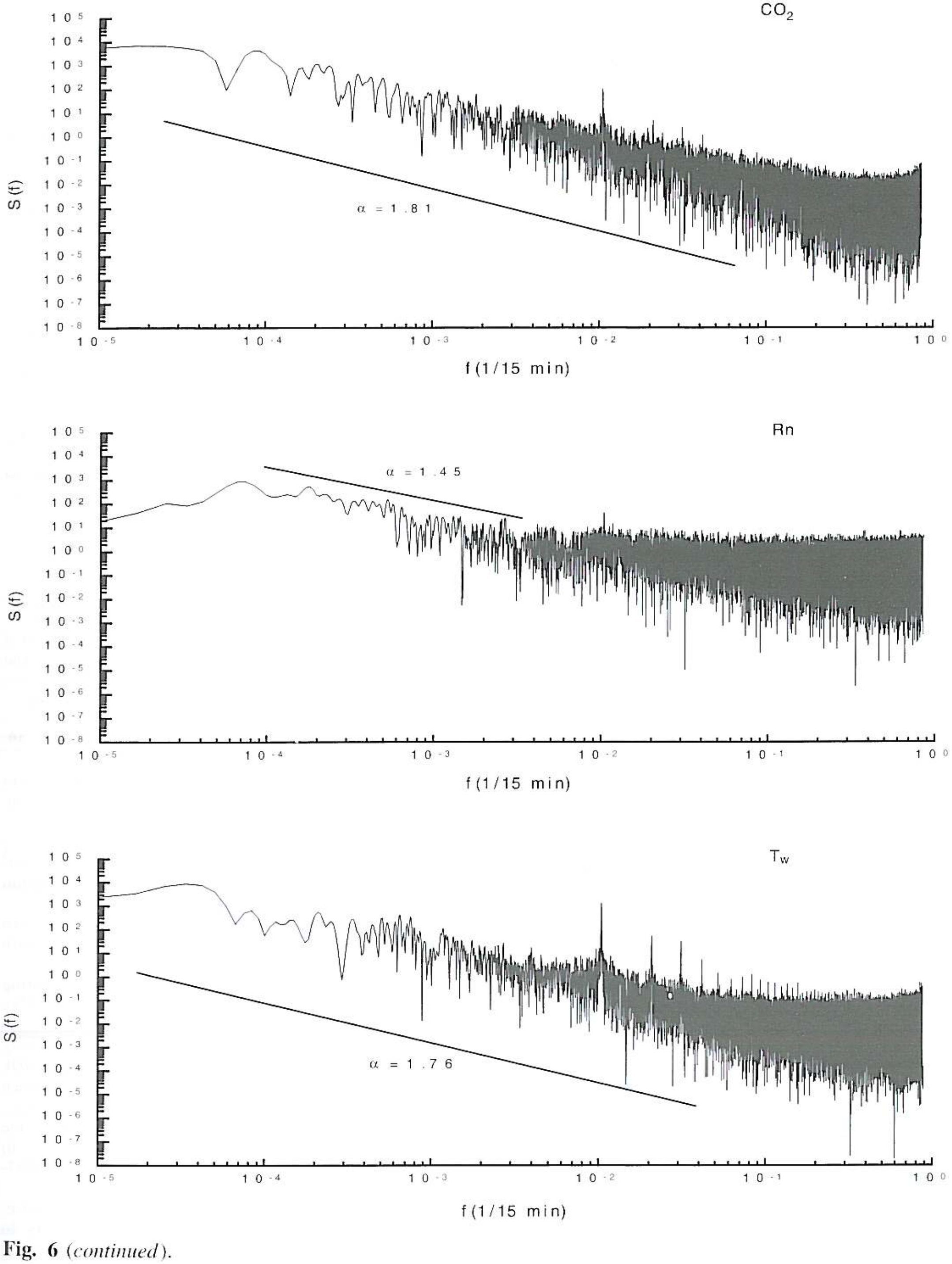

Fig. 6 (*continued*).

ised by antipersistent temporal fluctuations, the second to a white noise behaviour: thus, the signals for timescales longer than approximately 24 h display anticorrelated temporal fluctuations. The exception to this behaviour is represented by T_A, whose power spectral density suggests the presence of persistent temporal fluctuations in its dynamics. Therefore, in the scaling region of the geochemical and geoelectrical signals we cannot recognise the influence of the ambient temperature, whose variations are controlled by a persistent mechanism of generation. This work intends to improve the knowledge of time dynamics of non-seismometric parameters monitored in seismic areas, giving a background for the further more detailed analysis of the time series structure in relation to seismic activity.

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