Viable Precursors of Paroxysmal Phenomena as Detected by Applying RQA to Acoustic Emission Time Series

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Abstract

Recurrence quantification analysis (RQA) represents a recent method for processing non-linear time series, already addressed to different topics concerning earth sciences and others. RQA is applied in this work to analyze time series of acoustic emission (AE) triggered by Earth’s crust phenomena, so to detect feasible precursors of catastrophic events. The AE records of rms values were acquired at two different sites, placed close to the Peteroa volcano (Argentina) and at Valsinni (Matera, Italy), considering two ultrasound frequencies (25 and 150 kHz) with 30-sec sampling rate. The preliminary results of the application of RQA to the AE data of Valsinni with respect to the L’Aquila earthquake (Italy, on April 6, 2009), and to those related to the activity of the Peteroa volcano (Argentina) are described and appear suited to stress relationships with an impending catastrophic event.

Keywords: AE sensor, AE time series, signal analysis, RQA, precursors, paroxysmal events.

1. Introduction

Humankind often faces the hazard due to catastrophic natural phenomena, such as earthquakes and volcanic eruptions. They occur mostly with no feasible warning and cause often victims, serious damage to buildings and civil structures according to the involved energy. As regards the seismic events, the best protection is to plan earthquake-resistant dwellings, while against volcanic eruptions, especially for the explosive ones, the main safety suggestion is related to the definition of an appropriate escape strategy and of a land planning that foresees an urban development enough far away from the volcanic edifice.

Hence, reduction of danger for people, goods and structures should be a main task of society having available tools addressed to highlight impending earthquakes or volcanic eruptions. This is possible by identifying a so-called precursor, that is, a timely index providing a warning for approaching paroxysmal events. One of such parameters yielding suitable results is based on monitoring and analysing acoustic emission (AE) signals [1]. The AEs are elastic waves, in ultrasound frequencies (25 - 800 kHz), due to the energy release within natural or manmade structures affected by mechanical stress [2]. AE frequencies lower progressively almost up to the infrasound when the collapse occurs (Fig. 1).

The catastrophic stage is preceded (months, weeks, days, hours in advance) by the occurrence of ultrasonic AE according to the force that yields the structural stress and to its strength. A constant monitoring of AE signals and their time-series analysis allows to achieve anticipated information on the collapse risk choosing appropriate threshold values, defined on the basis of laboratory studies [3]. This way, the AE technique can be applied to geological structures, providing information about impending seismic, volcanic and hydrogeological (landslides, mudflows) events.
Fig. 1. The decrease of the frequencies sequence of the observed AE vs. time [1].

Fig. 2. Present configuration of an AE acquisition station.

Consequently, a suitable surveillance service for early warning handling can be provided by an AE recording equipment connected to an ICT network (Fig. 2), thus exhibiting AE as a challenging precursor. AE signal amplitude varies with the acoustic impedance, related to local rock stress conditions and particularly sensitive to fracture density and water content; therefore, the

- As a first order approximation, the phenomenon can be depicted in terms of Dirac $\delta$-functions.
- Upon closer physical consideration, every $\delta$-function ought to be substituted by a lognormal distribution.
- An eventual externally applied additional effect (such as e.g. tidal modulation) sometimes results into an apparent trend looking like a damped oscillation.
application of a method such as *Recurrence Quantification Analysis* (RQA) [4-6] to the AE time series is particularly suited; in fact, RQA is focused on pinpointing peculiar recurrence pattern without taking into account the amplitude. RQA allows studying the change in correlation structure of the observed phenomenon; a relevant increase of correlation is known to precede the catastrophic event in many different systems ranging from physiology to economy [7].

This technique belongs to a category of recent methods of analysis of so-called *disordered systems*. Such methods show that many objects and processes that earlier were considered as completely random reveal clear evidence of having some ordered structure in both time and space [8]. Hence, this paper shows the absolutely new application of RQA to AE time series recorded in areas undergoing earthquakes and volcanic eruptions. The RQA method is applied to the non-stationary AE signals, in order to investigate the evolution features of the quiescence and activation status of the crustal system. Two case histories, recorded at Valsinni (Matera, Italy) and at Peteroa volcano (on the Argentina – Chile border), are presented.

### 2. RQA Method

#### 2.1 RQA general description

In the study of the numerical series, among various statistical analysis techniques, the "dynamic" techniques are relatively new. They are generally based on representing, in a multi-dimensional space, a one-dimensional or time-dependent signal, through the technique of *embedding* [5]. This way, with the same analytical techniques, it is possible to identify in the numerical series members, i.e. the profile of hydrophobicity of the protein sequences or the variation over time of biopotentials such as the ECG (electrocardiogram), those 'hidden' variables, which are supposed to help define the dynamic characteristics of the system. These characteristics are analyzed individually, and this allows detecting subtle periodicities and recurrences not caught by the traditional methods (e.g. Fourier analysis or wavelet analysis [9]). A further advantage is that the reliability of the results is not conditioned by any assumptions of stationary or minimum length of the signal [5, 10].

Among these methods, the RQA includes an embedding procedure that allows expanding a mono-dimensional signal into multi-dimensional space, thus permitting the identification of fine peculiarities of the sampled series that in turn are described by few global parameters allowing for a synthetic description. RQA has been recently applied in medicine for the analysis of time series of oto-acoustic emissions [11, 12]. It introduces some parameters of the overall complexity of the signal, derived from the so-called "*Plot of Recurrence*" (RP). The trend of the original signal over time is represented by a set of \( n \) points equally spaced (e.g. \( \{a_1 \ a_2 \ldots \ a_n\} \), where \( a_i \) is the signal value at time \( i \). Next, the series is copied into successive columns (the number of columns is defined as a dimension of *embedding*, \( N \)), each one shifted by a given number of points (*lag*): this way, the *embedding* matrix is created. Finally, the graph of recurrence is built by drawing a *dot* in the space that represents the distances between the corresponding rows if the distance between the \( j_{th} \) and the \((j + 1)_{th} \) rows of the *embedding* matrix is less than a fixed value (called *radius*), producing a graph pattern. In the so obtained plot, the horizontal and vertical axes represent the relative position of the \( n \) points of the time series. The presence of horizontal and vertical lines in the recurrence plot shows that part of the considered signal matches closely with a sequence farther along the time.
The RQA descriptors are calculated based on the number and location of dots on the plot. In particular, percent of recurrence (%Rec) is the percentage of recurrence points in a recurrent plot; percent of determinism (%Det) is the percentage of recurrence points, which form diagonal lines and it indicates the degree of deterministic structure of the signal. Entropy (Ent) is the Shannon entropy of the probability distribution of the diagonal line lengths and is linked to the richness of deterministic structure [11]. Laminarity (LAM) is the percentage of recurrent points that are included in line segments vertical to the upward diagonal and whose length meets or exceeds the minimum length threshold. It measures chaotic transitions and is related to the amount of laminar phases in the system (intermittency) [6, 10].

Within this framework, Chelidze’s team applied RQA to study the dynamics of earthquakes’ temporal distribution by considering the inter-arrival times between two events of Caucasian earthquakes with Magnitude 3 [13]. They calculated the correlation dimension of the integral time series (14,100 time intervals) for a large period of observations; the possible control of dynamics of a complex seismic process by strong electromagnetic impacts in the temporal domain was observed. The result obtained by Chelidze et al. was that the qualitative methods testify the presence of some non-random nonlinear structure in energetic, spatial and temporal distributions of earthquakes. The predictive potential of complexity analysis of seismological time series is recently considered in the review by Chelidze and Matcharashvili [8].

2.2 RQA input parameters for AE application

For this work an average on 120 points (1 hour) as a first smoothing of the recorded AE signals is reckoned, reminding that sampling rate was 30 seconds. Then, the optimization procedure suggested the following parameters: the delay (lag) is set to 1; the number of the embedding matrix columns (embedding dimension) is set to 10 and the cut-off distance (radius) is set to 15.

If RQA is carried out by the computation of many small distance matrices corresponding to consecutive and overlapping sliding windows (epochs) along the series, the changing values of RQA variables in the subsequent windows allow for the detection of abrupt changes in the dynamical regime of the signal. This procedure, *Recurrence Quantification over Epochs* (RQE) was used to test the presence of phase changes in AEs.

RQE analysis was carried out by adopting the same parameters setting as for the global mode (RQA), plus the definition of windows having length of 24, 150 and 300 points (1 point = 1 hour) and shifting of 24, 150 or 300 points between consecutive windows, respectively (to obtain non-superimposed windows).

3. Case Histories

Figure 1 shows how a quite extensive range of frequencies in the ultrasound spectrum must be monitored in order to collect a satisfactory AE data set. This is an enough hard task taking into account the difficulty of simultaneously handling different piezoelectric sensors in the natural world. However, the skill acquired on laboratory experiments has allowed to define the best selection of transducer frequencies in correspondence of 25 and 150 kHz that depict the crack evolution in different materials [14]. Figure 2 shows the instrument sequence for AE data collection as well as a typical installation case, at Valsinni site.
In the present configuration of an AE acquisition site the two sensors are connected to a rocky outcrop through a glass bar, transparent to ultrasonic signals; then, the AE acquisition apparatus’ chain includes a pre-amplifier, an amplifier, a data logger and a remote connection module based on GPRS protocol. The incoming AE signals are sampled at 3 kHz, averaged and then recorded at 30-seconds time steps as rms values.

Within this context, two case studies of AE recording sites are described: one is Valsinni, Italy (Basilicata region; 40°10’05” Lat. and 16°26’35” Long.), a highly seismogenetic area, and the other, along the Argentina/Chile boundary, the Peteroa volcano (35º15´S Lat. and 70º35´ W Long.), exhibiting either seismic events or explosive eruptions. By analyzing both AE time-series, quite remarkable anomalies of paroxysm precursors showed up. Henceforth, the AE data collected at 25 kHz will be termed as LF AE, while the AEs recorded at 150 kHz as HF AE.

![Fig. 3. Input AE signals recorded at Valsinni acquisition site during Springs 2008-2009 period. Blue line depicts LF AE data, while red one shows HF AE data. L’Aquila earthquake (Magnitude = 6.3) occurrence is also reported.](image)

The AE time series acquired at Valsinni site between May 2008 and April 2009, just after the L’Aquila seismic event, are depicted in Fig. 3. In this plot the HF AEs (red line) show a considerable activity up to November 2008 and a subsequent depletion until March 2009, one month before L’Aquila earthquake; later, they start to increase again. Conversely, LF AEs exhibit evident activity from May to July 2008 and a following depletion up to the end of September 2008 when a rather remarkable activity begins, decreasing only when the seismic event comes up [15].

Next, the two AE time series acquired at the HF and LF frequencies on Peteroa volcano between April 2009 and March 2011 are depicted in Fig. 4. The plots show a periodic pattern of the LF AEs (right), as long as six months, perhaps related to Earth’s tide force [16]. The HF AEs (left), instead, show a more subdued periodic trend, and exhibit, as main characteristic, an abrupt
increase on November 2011, in correspondence to the first eruption phase. Better pictures of the two whole AE temporal distributions are shown in the left panels of Figs. 5 and 6.

Fig. 4. The AE collected on Petroea volcano between 17 April 2009 and 23 March 2011. (Left) HF AE; (Right) LF AE data. The green vertical lines point out the end of every year.

Fig. 5. (Left) Time-series of HF AE (red lines) collected on Petroea volcano between Falls 2009 and 2011. Black lines point out the earthquakes (1/10 of Magnitude values larger than 0.3) occurred within 300 km from Petroea volcano (USGS catalogue). Blue line refers to the very strong earthquake of Maule (Magnitude = 8.8), while the orange lines identify the explosive eruptions periods of Petroea. (Right) RQA parameters calculated from the HF AE series: the green line points out the %DET descriptor, while the brown line the %LAM (51 non-overlapping epochs; 1 epoch=300 hours).

4. Results of the RQA Application to AE Data

4.1 Valsinni case history

The RQA application to LF AE data collected at Valsinni site during the Springs 2008-2009 period (see Fig. 3) has yielded four RP, depicted in Fig. 7, relative to four different time lags. The top-left and bottom right graphs score low values (%DET ~70) before, about six months, and just after the L’Aquila earthquake and, moreover, exhibit much similar patterns, which appear to resemble the one of a sinusoidal trend. On the contrary, the other two RP, related to a
%DET ~90, exhibit quite complex patterns quite different from the other two. Thus, the incoming catastrophic event is observed in terms of a change in dynamic regime of AEs.

Fig. 6. (Left) Time-series of LF AE (magenta lines) acquired on Peteroa volcano between Falls 2009 and 2011. Black lines point out the seismic events (1/10 of Magnitude values larger than 0.3) recorded within 300 km from Peteroa volcano (USGS catalogue). Blue line is referring to the greatest earthquake of Maule (Magnitude = 8.8), while the orange lines define the explosive eruptions periods of Peteroa. (Right) RQA parameters calculated from the LF AE series: the green line points out the %DET descriptor, while the brown line the %LAM (51 non-overlapping epochs; 1 epoch= 300 hours).

Fig. 7. Comparison of the RP of the LF AEs recorded at Valsinni site in four different time periods, between September 2008 and April 2009. (Top left) Sep. 26-Oct. 03, 2008; (Top right) Dec. 12-Dec. 28, 2008; (Bottom left) Feb. 27-Mar. 09, 2009; (Bottom right) Apr. 13-Apr. 19, 2009.
Modification in dynamic regime of AEs is observed in Fig. 8, where the trend of the $\%DET$ values since the installation of the Valsinni AE station (May 2008) is reported. It can be noted that there is an almost continuous raise of $\%DET$ values until the occurrence of L’Aquila earthquake (Apr. 6, 2009) and a successive sudden depletion afterward.

![Fig. 8. Trend of the RQA $\%DET$ values for the LF AEs recorded at Valsinni station since June 2008 to middle April 2009. The red line indicates the occurrence of the L’Aquila earthquake. The time intervals reflect the different periods in which the $\%DET$ has been calculated.](image)

Fig. 8. Trend of the RQA $\%DET$ values for the LF AEs recorded at Valsinni station since June 2008 to middle April 2009. The red line indicates the occurrence of the L’Aquila earthquake. The time intervals reflect the different periods in which the $\%DET$ has been calculated.

![Fig. 9. Peteroa volcano. Top: An early record of LF AEs (150 hours: 17-23 April 2009). Bottom: Corresponding Recurrence plot (RP): the inset on 300 epochs (1 epoch=24 h=24 points). A periodic signal and the very regular pattern of RP can be observed.](image)

Fig. 9. Peteroa volcano. Top: An early record of LF AEs (150 hours: 17-23 April 2009). Bottom: Corresponding Recurrence plot (RP): the inset on 300 epochs (1 epoch=24 h=24 points). A periodic signal and the very regular pattern of RP can be observed.
4.2 Volcano Peteroa case history

As already mentioned in Sec. 2.2, the volcano Peteroa AE time series were analyzed in different time windows, in order to fine-tune its RQA parameters and to examine events at various time scales (Figs. 5, 6, 9, 10). In particular, the results obtained for the LF AE data with two different non-superimposed windows (termed epochs), of 24 and 300 points, are described. In the upper panel of Fig. 9, the pattern of the earlier record (the first 150 epochs corresponding to 6.25 days) of LF AEs is reported, while the upper panel of Fig. 10 shows the pattern of the entire recording period (16,146 points; corresponding to 2 years) of LF AEs. The lower panels of both Figs. 9 and 10 exhibit the corresponding RP.

Figure 9 points out a daily Earth’s tide oscillation in the AEs while its RP shows the typical pattern of sinusoidal trend, well observed plotting only the first 150 points (top of Fig. 9). Conversely, Fig. 10 for the whole monitored period shows a seasonal fluctuation of the LF AE data. The corresponding RP (lower panel of Fig. 10) exhibits a blank area around the middle, placed between two complex patterns, probably reflecting some modification in the internal structure of the volcano. It could correspond to sharp transition of the regime, probably being a threshold value in the AE time series, quite coinciding with the Chile Maule earthquake (Magnitude = 8.8; Feb. 27, 2010).

A better interpretation of RQA results about Peteroa volcano has been obtained by overlapping the time distribution of the RQA descriptors %DET and %LAM to the original AE time series and to the earthquakes occurred in the neighborhood of the volcano within a radius of 300 km. In Figs. 5 and 6, respectively, these data for HF and LF AEs are shown with the date of the Maule seismic event and the volcanic eruption periods. The HF AEs (right panel of Fig. 5) exhibit three significant patterns of both %DET and %LAM for different periods. The first one, lasting about seven months, shows uniform patterns of high values for both parameters, in accord-
ance with the smoothed sequence of seismic events. Then, the %DET and %LAM trends, about after middle December 2009, drop suddenly until the Maule earthquake occurrence, followed by a subsequent increase of both parameters. Next, after the intense Maule aftershocks seismic series, the RQA parameters present both remarkable fluctuations, perhaps driven by the explosive eruption sequences occurred on Spring 2010 and Easter-Fall 2011.

The LF AEs (Fig. 6) show a less evident pattern. The %DET and %LAM trends before the occurrence of the Maule earthquake appear less uniform than those exhibited by the HF AEs with strong fluctuations; they show (particularly %LAM) a remarkable decrease of values as the earthquake is approaching. Next, after the Maule earthquake, both RQA parameters exhibit a quite variable trend achieving a relative maximum during the Spring 2010 eruption period and a strong value depletion (especially the %LAM) during the inter-period between the two eruption phases and a successive abrupt increase before the second eruption period.

These results seem to confirm the capabilities of RQA method to depict the modifications in the volcanic edifice due to the combined action of seismic and volcanic activities. Particular interest has to be devoted to the relations between the RQA parameters trends and the occurrence of the Maule earthquake (Magnitude = 8.8), while it is difficult to define peculiar relations with the volcanic explosive activity.

5. Concluding Remarks

The results of the application of RQA technique to AE time series within two frequencies (HF = 150 kHz and LF = 25 kHz) in seismogenetic and volcanic areas are given considering different time scales. The temporal distribution of the obtained RQA parameters (Figs. 5, 6, 8) exhibits remarkable variations as a paroxysmal event is approaching.

Despite any possible warning due to the uncertainty of the underlying relationships with volcanic activity and earthquakes and to the merely episodic nature of the observations (more case studies are to be analyzed to confirm the obtained results), the anomalies detected in the RQA parameters could represent a likely signature of an incoming catastrophic event in terms of AE dynamic regime modifications, possibly providing a remarkable finding. The arrangement of dynamical processes can be analyzed, so reckoning noteworthy “predictive” RQA parameters. The obtained results appear quite interesting, but a fine-tuning of the analysis and more data sets from different seismic and volcanic areas are needed to assess the impact.

Acknowledgements

The authors are very thankful to Dr. J. Ruzzante and his team of ICES-CNEA (Argentina) for providing the AE data collected on Peteroa volcano monitoring site within the framework of the project PICT 2007-2009 “Emisión Acústica y precursors sísmicos”. They also thank the Civil Protection of Basilicata for the financial support for the installation of the Valsinni AE monitoring station in the framework of the Research Agreement between Regional Civil Protection of Basilicata and CNR IDASC. They are grateful to G. Ventrice of the SME P.M.E. srl (Italy) for his contribution to the instrument development, installation and maintenance at Valsinni site.
References


