The paper deals with a relatively new technique, the Recurrence Quantification Analysis (RQA), a non-linear time series processing approach already utilized in different disciplines such as Economy, Physiology, Neurosciences, Earth Sciences, Astrophysics and Engineering. Here this method is applied to time series of Acoustic Emissions (AE) signals due to crustal movements, in order to show up possible precursors of catastrophic events. The AE records have been collected, at two different ultrasound frequencies (25 and 150 kHz) and with 30 sec. of sampling rate, in two sites located at Valsinni (Potenza, Italy) and nearby the Peteroa volcano (Argentina). The preliminary results of RQA applied to these AE time series before the earthquake of L’Aquila (Italy, on April 6, 2009), and those concerning the activity of the Andean volcano are shown and seem quite suitable for highlighting incoming paroxysms.

**Keywords:** Acoustic Emissions, AE sensor, Signal Analysis, condition monitoring / RQA, AE time series, precursors, catastrophic events

1. Introduction

Earthquakes are among the most hazardous natural events for the civil communities. They show up seemingly without warnings and, depending on their energy (Richter scale), modify landscapes, destroy buildings and civil structures. Nowadays, the only defence is to set up earthquake-resistant buildings. Furthermore, many people live close to volcanoes, and their eruptions, especially the explosive ones, turn out very dangerous for the persons and manmade structures.

Figure 1. The frequencies shift in AE, from [2].
Therefore, it could be challenging for the research to handle tools allowing to perceive impending earthquakes or volcanic eruptions in order to reduce risks of damages for persons, goods and structures. A parameter depicting the paroxysm risk’s timing trend is termed precursor. Among the techniques developed to define early catastrophes’ warning, an approach that seems to yield suitable results is based on monitoring and analysing Acoustic Emissions (AE) [1]. The AE are waves, in ultrasound frequencies (25 - 800 kHz), due to the release of energy inside structures affected by geomechanic stresses. AE’s frequencies downgrade gradually up to the infrasonic band when the collapse is approaching (fig. 1).

The AE occur long before (months, weeks, days, hours) the collapse moment, depending on the cause that produced the structural stress and its intensity. By keeping AE under continuous monitoring and analyzing their timing, it is possible to have information on the collapse risk approaching using threshold values, defined in advance by laboratory studies [2]. Thus, the application of the AE technique in geological structures allows to obtain information about incoming earthquake, volcanic and hydrogeological (landslides, mudflows) events.

Accordingly, instruments for AE monitoring connected in an ICT networking (fig. 2) can provide a surveillance service for early warnings management, that is AE can be considered a precursor. The signals of AE do not exhibit periodic events; in addition, the intensity of the signal depends on many factors and the instrumentation does not need to be calibrated. Furthermore, these signals are largely non-stationary and strictly context dependent so asking for a non-linear and very largely assumptions-free technique as Recurrence Quantification Analysis (RQA) for their investigation.

Figure 2. AE recording instruments installed on a rocky outcrop.
This paper shows as RQA can be applied to case studies involving seismic events and volcanic eruptions. As it will be explained in the next section, the analysis is focused on pinpointing peculiar recurrence patterns of the series and in the case of AE the main advantage of RQA is that it can provide information without being affected by amplitude variations of the signal. From a purely theoretical point of view, it is worth noting that the ability of RQA to predict catastrophic changes is in line with the fact RQA is based upon the change in correlation structure of the observed phenomenon that is known to precede the actual event in many different systems ranging from physiology to economy and genetics [3].

2. RQA analysis

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 [4]. 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 to detect subtle periodicities and recurrences not caught by the traditional methods (e.g. Fourier analysis). A further advantage is that the reliability of the results is not conditioned by any assumptions of stationarity or minimum length of the signal [5].

Among these methods the RQA is a relatively recent technique used also for the analysis of time series of otoacoustic emissions [6]. 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. \( \{ a_1, a_2, ..., a_n \} \)), 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 \( j_{th} + 1 \) rows of the embedding matrix is less than a fixed value (called radius), producing a graph pattern. In the so obtained graph, the horizontal and vertical axes represent the relative position of the \( n \) points of the time series. The RQA descriptors are calculated based on the number and location of dots on the graph.

The most common RQA descriptors are percent of recurrence (\%REC), which represents the fraction of dots on the graph occupied by recurrence points, percent of determinism (\%DET), which represents the fraction of occurrence of consecutive dots parallel to the main diagonal [3, 7] and percent laminarity (\%LAM) which is the percentage of recurrence points that are included in line segments vertical to the upward diagonal and whose length meets or exceeds the minimum length threshold [8].

3. Case studies

As shown in fig. 1, the acquisition of a suitable AE record needs to monitor a large frequency spectrum in the ultrasound bands, but this operation appears quite difficult considering the complexity of the simultaneous management of various piezoelectric transducers in the natural environment. This has been overcome, on the basis of the experience acquired on laboratory, choosing only two sensors working at 25 and 150 kHz, which describe well the
development of cracks in materials. In fig. 2 the scheme of the AE acquisition instrumentation is shown together to a typical installation example, at Valsinni site (Mt, Italy).

The connection between sensors and rocky outcrop is carried out through a glass rod, transparent to ultrasound; then, pre-amplifier, amplifier, data logger and GPRS unit complete the AE acquisition chain. The incoming AE signals are sampled at 3 kHz, averaged and then recorded every 30 seconds as RMS data.

Figure 3. Locations of the case study sites: (Left) Valsinni (Mt, Italy); (Right) Peteroa volcano (Argentina/Chile border).

In this framework, the paper deals with some case studies of AE monitoring stations on Italy, Valsinni, site of the Basilicata region (40°10’05” Lat. and 16°26’35” Long.) which undergoes severe seismic events, and at Argentina/Chile border, the Peteroa volcano (35°15´S Lat. and 70º35´ W Long.), area characterized by both earthquakes and explosive eruptions (fig. 3). On both sites the analysis of AE signals has shown interesting features of paroxysm precursors. Hereafter, the AE recorded at 25 kHz will be recalled as LF AE, while the AE acquired at 150 kHz as HF AE.

Figure 4 shows the AE recorded at Valsinni monitoring site since May 2008 to middle April 2009, just after the L’Aquila earthquake. It is possible to note that the HF AE (red line)
exhibit quite remarkable activity until November 2008 and successive values depletion up to March 2009, one month before L’Aquila seismic event, when they start again to rise. LF AE present, instead, evident activity between May and July 2008 with a subsequent values depletion until the end of September 2008 when a very strong activity starts, dropping only as the earthquake is approaching [9].

Figure 5 shows the HF and LF AE recorded on Peteroa volcano in the period between Apr. 17, 2009 and Mar. 23, 2011. It can be noted that the LF AE (right panel) exhibit a periodic pattern, lasting about 6 months, due probably to Earth’s tides forcing [10]. Conversely, the HF AE (left panel), still keeping a much subdued periodic pattern, show, as main feature, a sudden increase on November 2011, just after the first eruption period (see left panels of figs. 8 and 9 for a better view of the whole AE trends).

4. Results of the RQA application to AE

As far as the Peteroa volcano AE time-series are concerned, different time windows and steps were selected to apply the RQA method in order to fine-tune its parameters and to examine events at various time scales (figs. 6 to 9). In particular, the results obtained with not superimposed windows (termed epochs) of 24 and 300 points are here reported for the LF AE data. In the upper panel of fig. 6 the pattern of the earlier record (the first 150 epochs corresponding to 6.25 days from 17 to 23 April 2009) of LF AE is depicted. In the upper panel of fig. 7 the pattern of the whole recording period (16146 points; corresponding to 2 years) of LF AE is shown. The lower panels of both figures 6 and 7 represent, instead, the corresponding RP. Figure 6 points out a tide oscillation in the AE while the RQA pattern exhibits the typical shape of sinusoidal trend, well observed in windows of 150 points. Figure 7, concerning the whole monitored period, shows instead a seasonal fluctuation of the LF AE data set. The corresponding RP (lower panel of fig. 7) shows a blanked area around epoch 300 preceded and followed by two complex patterns. This means that this time period (epoch 300) could reflect some modification in the internal structure of the volcano, the singularity (no recurrences, in the middle) corresponding to a sharp transition of the regime, probably being a threshold value in the AE time series, quite coinciding with the Chile Maule earthquake (M=8.8, Feb. 27, 2010).
Moreover, in order to get a better interpretation of RQA results about Peteroa, the time distribution of the RQA descriptors %DET and %LAM have been overlapped to the raw AE time series and to the seismic events occurring in the neighborhoods (at most within 300 km) of the volcano. Figures 8 and 9 show respectively these data for HF and LF AE together to the date of the Maule earthquake and the eruption periods.

The HF AE (right panel of fig. 8) appear showing three peculiar patterns of both %DET and %LAM in different periods. In the first one, about seven months long, both parameters exhibit a uniform pattern of high values, in agreement with the smooth earthquakes sequence. After middle December 2009, the %DET and %LAM trends drop abruptly until the Maule earthquake occurrence, then both parameters increase again. Afterwards, following the dense Maule aftershocks seismic sequence, the RQA parameters exhibit both strong fluctuations, perhaps driven by the two periods of explosive eruption activities of Spring 2010 and Easter-Fall 2011.

The LF AE (fig. 9) exhibit a less evident pattern. The %DET and %LAM trends before the occurrence of the Maule earthquake seem less uniform than the ones exhibited by the HF AE with large fluctuations, showing (especially %LAM) a strong value depletion as the earthquake is approaching. After the Maule earthquake both RQA parameters show a quite variable trend reaching a relative maximum during the Spring 2010 eruption period and a strong value decrease (especially the %LAM) during the inter-period between the two eruptions stages and a subsequent abrupt increase before the second eruption period.

These results seem to confirm the capabilities of RQA method to depict the modifications in the volcano apparatus due to the combined actions of seismic and volcanic activities. Particu-
lar interest has to be devoted to the relations between the RQA parameters trends and the occurrence of the M8.8 Maule earthquake, while it is difficult to define peculiar relations with the volcanic explosive activity.

Figure 7. Peteroa volcano, (Top) LF AE during emission in the whole period Apr. 17, 2009 - Mar. 23, 2011 (16146 points). (Bottom) RP on 600 epochs (1 epoch = 24 points = 24 h).

Figure 8. (Left) Time series of HF AE (red lines) acquired on Peteroa volcano between Falls 2009 and 2011. Black lines point out the seismic events (M/10 larger than 0.3) recorded within 300 km from Peteroa volcano (USGS catalogue). Blue line is referring to the greatest earthquake of Maule (M=8.8), while the orange lines define the explosive eruptions periods of Peteroa. (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).
Figure 9. (Left) Time series of LF AE (magenta lines) acquired on Peteroa volcano between Falls 2009 and 2001. Black lines point out the seismic events (M/10 larger than 0.3) recorded within 300 km from Peteroa volcano (USGS catalogue). Blue line is referring to the greatest earthquake of Maule (M=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).


The application of RQA to AE recorded at Valsinni site during the Springs 2008-2009 period (see fig. 4) has yielded four RP shown in figure 10 referring as to four different time lags. The global %DET in the four RP of figure 10 scores low value before (two month, indicatively) and after the earthquake (%DET= 70) (plots on top left and bottom right panels). On the contrary, it is approximately %DET= 90 in the other two panels: the incoming catastrophic event is observed in terms of a change in dynamic regime of AE. Moreover, figure 11 depicts the trend of the %DET values since the beginning of AE acquisition at Valsinni station (May
As already shown in figure 10, there is an almost continuous increase of %DET values till the occurrence of L’Aquila earthquake (Apr. 6, 2009) and a subsequent depletion after it. As already pointed out for Peteroa volcano, this result seems to confirm the utility of this RQA descriptor as possible precursor for paroxysmal events.

Figure 11. Trend of the RQA %DET values for the LF AE recorded at Valsinni station since June 2008 to middle April 2009. The red line points out the occurrence of the L’Aquila earthquake. The shown time intervals reflect the different periods in which the %DET has been calculated.

5. Concluding remarks

The results described in this paper point out the feasible applications of RQA method to AE signals in seismogenetic and volcanic areas with different time scales and with a comparison between HF AE and LF AE. Looking at the obtained results (figs. 7 to 11) it is evident how the changes in RQA parameters are visible much before the earthquake actually happens. Even with all the caveats coming from the still uncertain status of the causal relations between volcanic activity and earthquakes as well as from the purely episodic character of the observations (these results must be confirmed by the analysis of other cases), the fact that there is approximately two months anticipated signature of the catastrophic event in terms of a change in dynamic regime of AE constitutes an extremely interesting finding.

The configuration of dynamical processes can be analyzed and significant predictive parameters can be reckoned. The results appear quite encouraging, but a fine-tuning and a greater amount of new data sets (data recorded from different seismic areas and volcanic sites) are necessary to assess the impact satisfactorily. Moreover, it will be needed to define the most valuable descriptors for this kind of applications and their consistency.
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