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Fracto-emissions as seismic precursors

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ABSTRACT

Three different forms of energy might be used as earthquake precursors for environmental protection against seismicity. At the tectonic scale, Acoustic Emission (AE) prevails, as well as Electro-Magnetic Emission (EME) at the intermediate scales, and Neutron Emission (NE) at the nano-scale. TeraHertz pressure waves are in fact produced at the last extremely small scale, and fracture experiments on natural rocks have recently demonstrated that these high-frequency waves are able to induce nuclear fission reactions with neutron and/or alpha particle emissions. Very important applications to earthquake precursors can be proposed. The authors present the results they are obtaining at a gypsum mine located in Northern Italy. In this mine, to avoid interference with human activities, the instrumental control units have been located at one hundred metres underground. The experimental results obtained from July 1st, 2013 to December 31, 2015 (five semesters) are analysed by means of a suitable multi-modal statistics. The experimental observations reveal a strong correlation between the three fracto-emission peaks (acoustic, electromagnetic, and neutron emissions) and the major earthquakes occurred in the surrounding areas.

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1. Introduction

Solids that break in a brittle way are subjected to a rapid emission of energy involving the generation of pressure waves that travel at a characteristic speed with an order of magnitude of 10^3 m/s. Considering the very important case of earthquakes, it is possible to observe that, as fracture at the nanoscale (10^{-9} m) emits pressure waves at the frequency scale of TeraHertz (10^{12} Hz), so fracture at the microscale (10^{-6} m) emits pressure waves at the frequency scale of GigaHertz (10^9 Hz), at the scale of millimetre emits pressure waves at the scale of MegaHertz (10^6 Hz), at the scale of metre emits pressure waves at the scale of kiloHertz (10^3 Hz), and eventually faults at the kilometre scale emit pressure waves at the scale of the simple Hertz, which is the typical and most likely frequency of seismic oscillations (Fig. 1) [1].

The animals with sensitive hearing in the ultrasonic field (frequency > 20 kHz) "feel" the earthquake up to one day in advance, when the active cracks are still below the metre scale. Ultrasounds are in fact a well-known seismic precursor [2,3]. With frequencies between Mega- and GigaHertz, and therefore cracks between the micron and the millimetre scale, pressure waves can generate electromagnetic waves of the same frequency, which turn out to be even a more advanced seismic precursor (up to a few days before) [4,5]. When pressure waves show frequencies between Giga- and TeraHertz, and then with cracks below the micron scale, we are witnessing a phenomenon partially unexpected: pressure waves resonate with the crystal lattices and, through a complex cascade of events (acceleration of electrons, bremsstrahlung gamma radi-

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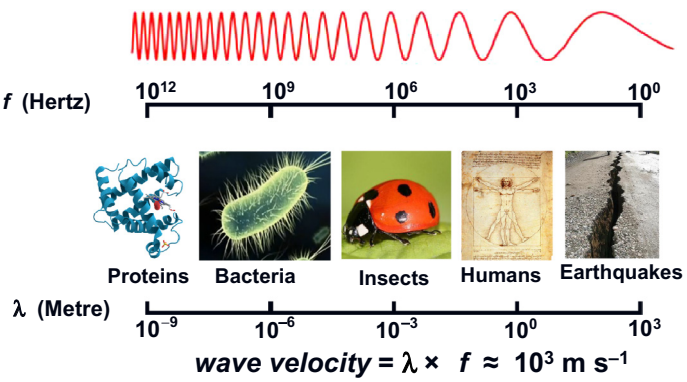

Fig. 1. Correlation between wavelength (forming crack) scale and frequency scale by assuming a constant pressure wave velocity.

ation, photo-fission, etc.), may produce nuclear fission reactions [6–16]. It can be shown experimentally how such fission reactions can emit neutrons [17–19] like in the well-known case of uranium-235 but without gamma radiation and radioactive wastes. Note that the Debye frequency, i.e., the fundamental frequency of free vibration of crystal lattices, is around the TeraHertz, and this is not a coincidence, since it is simply due to the fact that the inter-atomic distance is just around the nanometre, as indeed the minimum size of the lattice defects. As the chain reactions are sustained by thermal neutrons in a nuclear power plant, so the piezonuclear reactions are triggered by pressure waves that have a frequency close to the resonance frequency of the crystal lattice and an energy close to that of thermal neutrons [8]. Neutrons therefore appear to be as the most advanced earthquake precursor (up to three weeks before) [20–27].

In the present work, after summarizing the results obtained during two different experimental investigations at "Testa Grigia" laboratory (Plateau Rosa, Cervinia, Italy) and at the seismic district of "Val Trebbia" (Bettola, Piacenza, Italy) [28,29], the authors describe the preliminary results acquired at a gypsum mine situated in Northern Italy (Murisengo, Alessandria) and related to the evaluation of acoustic, electromagnetic, and nuclear phenomena. The monitoring system, based on the simultaneous acquisition of the various physical quantities, controls the structural stability of the mine carrying out, at the same time, the environment monitoring for the seismic risk evaluation. The preliminary results obtained during the in-situ monitoring revealed a strong correlation between AE/EME/NE emissions and the major earthquakes occurring in the surrounding areas.

2. Seismic precursors: acoustic, electromagnetic, neutron emissions

Seismic precursors are phenomena that take place well in advance than the occurrence of an earthquake. These parameters are of various kind, such as ground deformation, changes in tilt and strain and in Earth tidal strain, changes in the geoacoustic and geomagnetic field, in radon and carbon dioxide content, in environmental radioactivity and so on.

The monitoring and the correct interpretation of these phenomena provide the basis for the assessment of the three main parameters of an earthquake: place and time of occurrence, as well as magnitude of the quake.

Moreover, the prediction strategy has to take into account an integral approach that includes the evaluation of several physical quantities and that discriminates true signals from the environmental background or noise.

In addition, it is very important to consider that, in the period before the earthquake occurrence, a very wide area of cracking rocks is active and in a critical condition around the future earthquake focal zone under the influence of tectonic stresses. In particular, Dobrovolsky et al. [30] tried to calculate the dimension of this earthquake preparation area as a function of the magnitude of the incoming earthquake considering an arbitrary heterogeneity and anisotropy of the Earth's surface. Assuming that the zone of effective manifestation of the precursor deformations is a circle with the centre in the epicentre of the next earthquake, the radius R of this 'strain zone' may be up to hundreds kilometres for earthquakes with a magnitude M equal to 5 degrees in the Richter scale and can tend to the whole Earth surface for a M = 9 seismic event (for example, Sumatra 2004, Chile 2010, Japan 2011). Comparison between theoretical and field results showed a satisfactory agreement [30]. In addition, it was also observed that all the precursors tend to fall into this circle.

In the last decades a great number of laboratory tests and experimental observations evidenced that mechanical, electromagnetic, and neutron emissions, together with radon levels, carbon dioxide emanations and temperature variations, are the most reliable natural phenomena that can be linked to earthquake preparation.

In particular, the experimental tests carried out since 2008 at the Politecnico di Torino have demonstrated how the monitoring of the different forms of energy (Acoustic Emission AE, Electro-Magnetic Emission EME, and Neutron Emission NE), emitted during the failure of natural and artificial brittle materials, enables an accurate interpretation of mechanical damage and fracture, not only at the scale of the laboratory, but also at the Earth's crust scale [31–38].

Nowadays, the AE technique is well-known in the scientific community and applied for structural monitoring purposes [3,39–43]. In addition, the relation between AE and geological structure has been investigated for several years in order to study their implications as a precursor of earthquakes and volcanic eruptions [2,44–46]. For example, an AE paroxysm, i.e. a large and almost abrupt increase in the AE signals, was observed at about 400 km of distance from the epicentral area before the occurrence of the Assisi earthquake [44,45].

Moreover, considering that earthquakes always affect structural stability, an interpretation in which AE and seismic events are considered to be linked both in space and time seems to be possible. With this approach a correlation between bursts of AE activity in a masonry building and regional seismicity can be investigated [2,39,40,47].

In another recent work [48] a new method for evaluating seismic risk in regional areas based on the acoustic emission (AE) technique is proposed. In this research two important constructions of the Italian cultural heritage were considered: a chapel of the "Sacred Mountain of Varallo" and the "Asinelli Tower" in Bologna. The structures were monitored during earthquake sequences in their relative areas and by using the Grassberger-Procaccia algorithm, a statistical method for space-time correlation between AE and seismic events was developed. The study emphasized how under certain conditions it was observed that AEs precede earthquakes. In particular a constant AE activity in the 24 h prior to an earthquake was monitored.

On the other hand, the EM signals are related to brittle materials in which the fracture propagation occurs suddenly and is accompanied by abrupt stress drops in the stress–strain diagram. A number of laboratory studies revealed the existence of EM signals during fracture experiments carried out on a wide range of materials [5,49–54]. It was also observed that the EM signals detected during failure of materials are analogous to the anomalous radiation of geoelectromagnetic waves observed before major earthquakes [54], reinforcing the idea that the EM effect can be applied as a forecasting tool for seismic events.

In particular, several scientific reports emphasized that experimental evidences between anomalous electromagnetic signals and earthquakes become more and more plausible [55–60]. As an example, the Kobe earthquake, occurred in Japan in 1995, is considered as the "big impact" in terms of pre-seismic electromagnetic changes monitored by a lot of scientists working independently all around the World [58].

Moreover, kHz and MHz electromagnetic (EM) anomalies were also recorded before the L'Aquila (Italy) earthquake occurred on April 6, 2009 [61,62]. Clear anomalies were revealed between 2 and 8 days before the occurrence of the quake.

As regards the neutron emissions, the detections performed by Russian researchers [20–27] have led to consider also the Earth's crust, in addition to cosmic rays, as a relevant source of neutron flux variations.

In particular, quoting from Volodichev, neutron emissions measured in seismic areas of the Pamir region (4200 m a.s.l.) exceeded the usual neutron background "up to two orders of magnitude in correspondence to seismic activity and rather appreciable earthquakes, greater than or equal to the 4th degree in the Richter scale magnitude" [27]. In addition, considering the altitude dependence of neutron radiation (Pfotzer profile [63]), values approximately ten times higher than natural background at sea level are generally detected at 5000 m altitude. Therefore, the same earthquakes occurring at sea level should produce a neutron flux up to 1000 times higher than the natural background.

Anomalous neutron measurements were also carried out by Sigaeva et al. [23] before the Sumatra earthquake of December 26, 2004. Variations in the neutron flux were observed in different points (Crimea and Kamchatka) some days before the earthquake. The variations' peak reached hundreds of percentage.

3. In-situ monitoring of seismic risk: preliminary experimental investigations

An additional analysis carried out by the authors after those by the Russian research groups is presented. The studies start from recent data acquired at the "Testa Grigia" laboratory of Plateau Rosa, Cervinia (Italy), during an experimental campaign on the evaluation of neutron radiation from cosmic rays [28,29]. Even more recent data refer to a dedicated experimental trial carried out in Northern Italy, at the seismic district of "Val Trebbia", Bettola, Piacenza [28,29].

3.1. Experimental campaign at "Testa Grigia" laboratory (Plateau Rosa, Italy)

Since 1997, dedicated experimental campaigns [64–66] have been performed at High Altitude Observatories (HMOs), in the Northern as well as Southern Hemisphere, to obtain information on the variability of atmospheric neutron spectra with solar activity.

In particular, in the period from July 30 to August 3, 2008, an experimental campaign was conducted at the "Testa Grigia" laboratory (Plateau Rosa, Italy). During the data acquisition, an evident increase by about 6 times in neutron radiation with respect to the average natural background was monitored between July 31 and August 1st. This phenomenon was monitored for a period of about two hours. Then the values decreased to the usual background level (Fig. 2).

As usual, the assumptions made for the explanation of this event have firstly focused on possible effects of cosmic origin. However, from the analysis of data relating to solar and galactic events, apparently, no event of such great intensity was found. As a matter of fact, no significant sunspot activity was recorded during the data acquisition time window. As well as, during the same period, no anomalies in the cosmic ray flux were detected [67].

On the other hand, considering the phenomenon of neutron emission before seismic events, a searching of earthquakes occurred in the immediate vicinity of the laboratory and during the weeks following the experimental campaign was carried

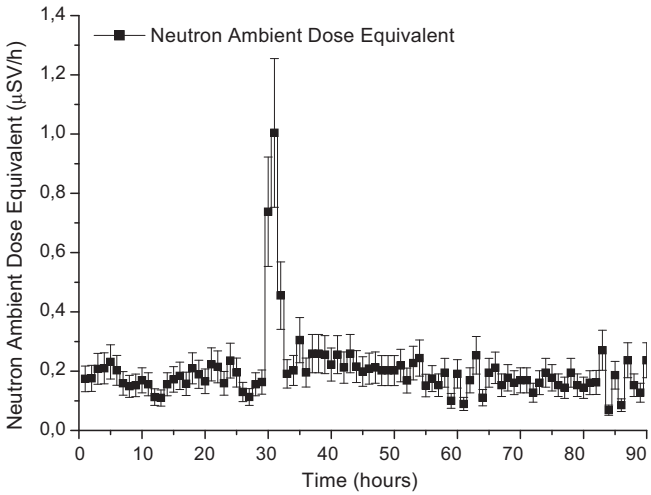

Fig. 2. Neutron ambient dose equivalent measured at "Testa Grigia" laboratory during the experimental campaign of July-August 2008.

out. A discrete seismic activity [68] occurred during the period July-August 2008 in a region a few hundred kilometres away from the laboratory. In particular, starting from 8 days after the anomalous increase in neutron radiation, seismic events up to the 3rd degree in the Richter scale of magnitude were observed. This interpretation is consistent with the observations of Russian groups and it provides further experimental evidence of the correlation between neutron emissions and seismic events of appreciable intensity.

3.2. Experimental campaign at "Val Trebbia" (Piacenza, Italy) seismic district

From December 28, 2012, to January 6, 2013, a dedicated experimental campaign was conducted at Villanova Chiesa, Bettola, Piacenza, located in Northern Italy, at the "Val Trebbia" seismic district [28,29]. The seismic risk level of this geographical area is changed after the disastrous earthquakes that have stricken the Emilia Romagna region in Spring 2012. At this moment the area is considered a medium-high seismic zone.

During the experimental trial three evident peaks in neutron radiation field were monitored between December 30, 2012, and January 2, 2013. An increase by about 6 times in the neutron dose with respect to the average natural background was observed in two cases (Fig. 3). These phenomena were monitored for a period of at least three hours. Then the values decreased to the usual background level.

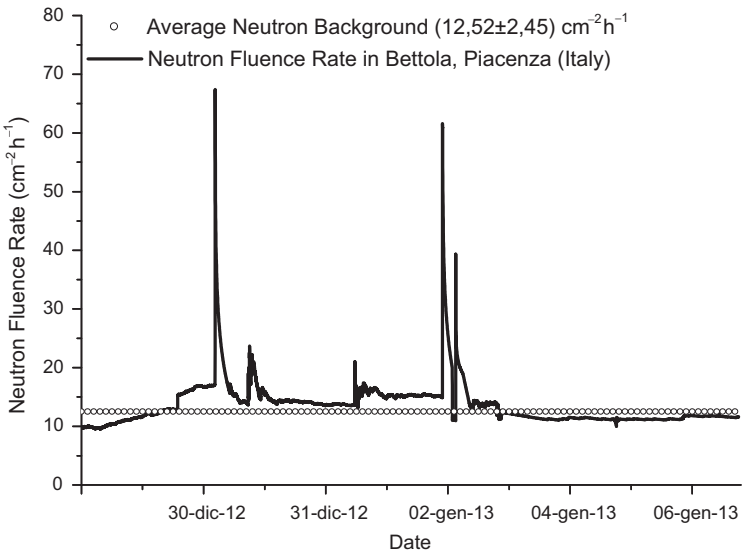

Fig. 3. Neutron ambient dose equivalent measured at Villanova Chiesa, Bettola, Piacenza during the period December 2012 – January 2013.

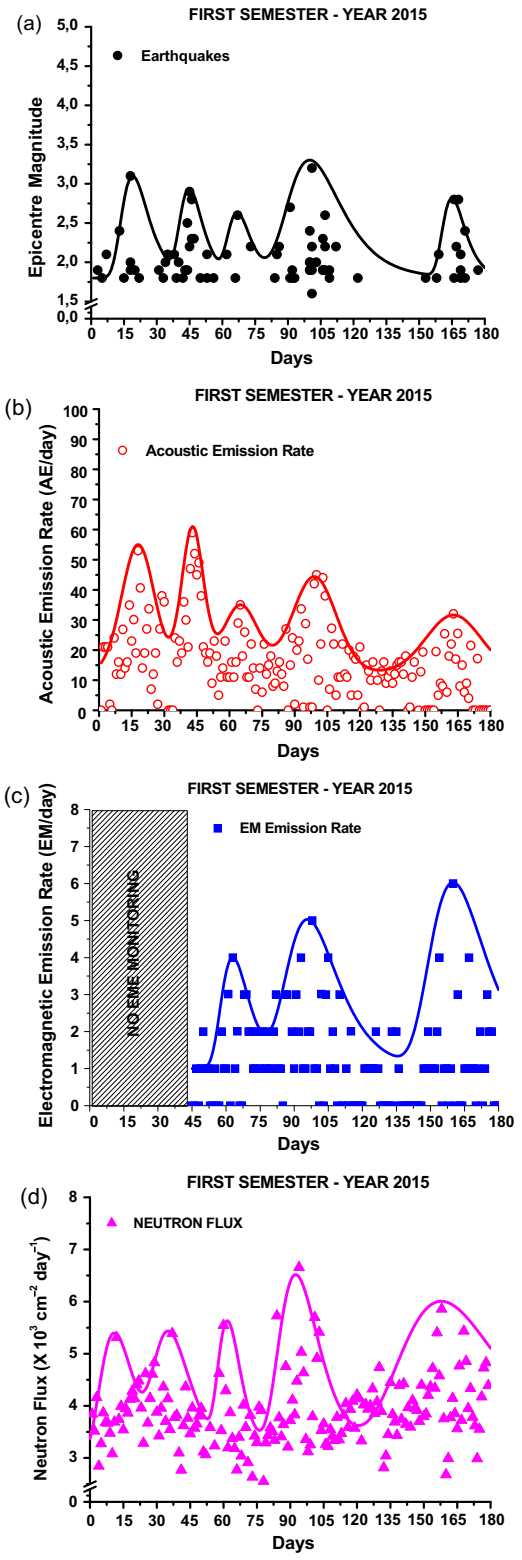

Fig. 4. Multi-modal Gaussian distribution during the first semester 2015 for earthquakes (a), acoustic emissions (b), electromagnetic emissions (c), and neutron emissions (d).

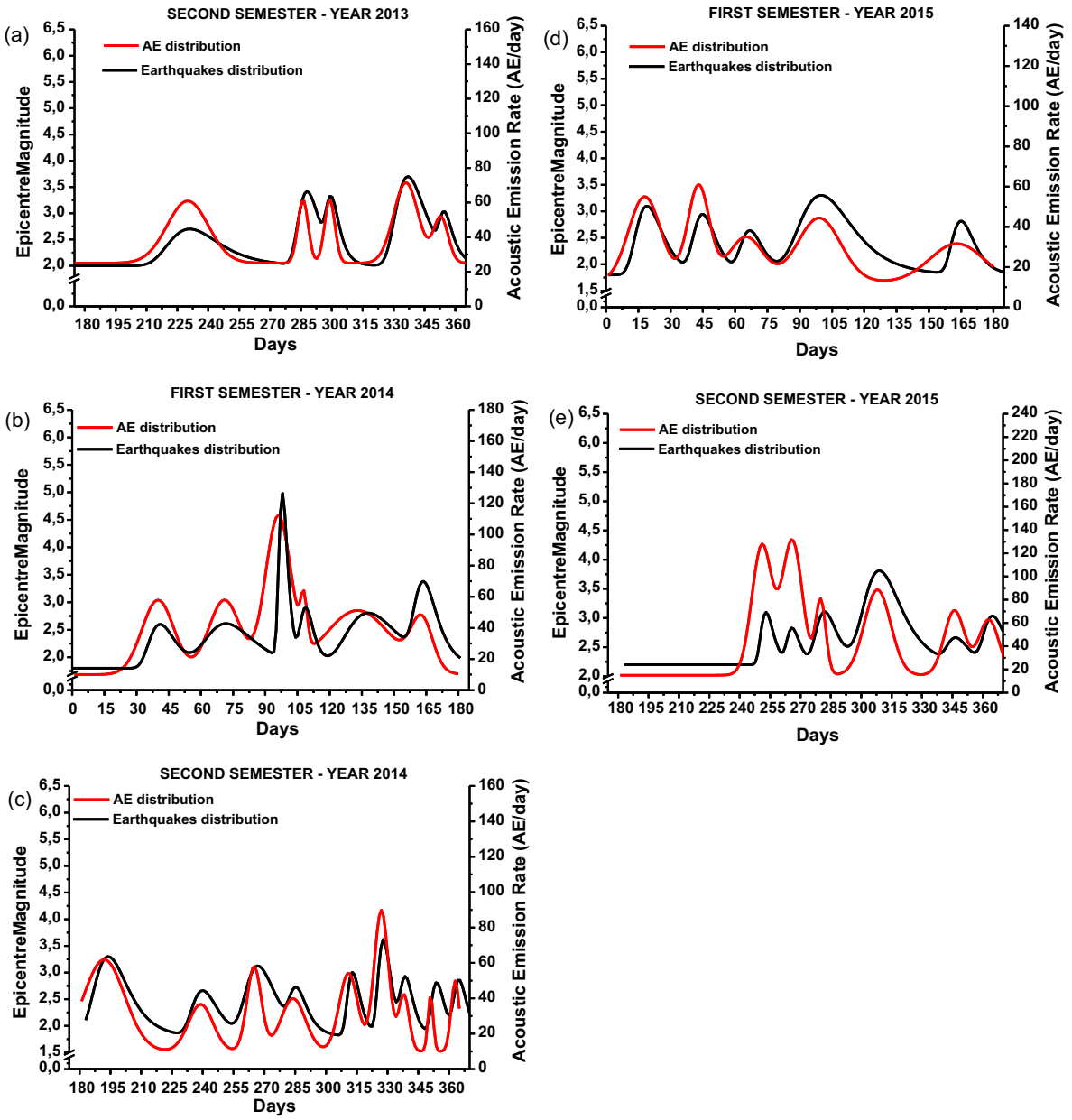

Fig. 5. (a)–(e) Earthquakes vs acoustic emissions temporal distributions for the five semesters of monitoring.

As in the case of "Testa Grigia" laboratory, no plausible explanation of a cosmic or galactic origin was found. As a matter of fact, only small fluctuations of few percentages in the cosmic ray flux were detected [67].

Moreover, a searching of earthquakes occurred in the immediate vicinity of the monitored area and during the weeks following the experimental campaign was carried out.

In particular, about one week later than the anomalous increase in neutron radiation a seismic swarm, the main shock of which was of the fifth degree in the Richter scale of magnitude, occurred in the "Garfagnana" district, less than 100 km far from Bettola.

4. Case study of "San Pietro-Prato Nuovo gypsum mine: multi-modal statistical analysis

Nowadays several seismic monitoring networks, just based on seismic accelerations, are being utilized all over the World, in California, Mexico, Taiwan, Turkey, Romania, and Japan [69]. However, any sort of multi-parametric monitoring method that takes into account the simultaneous observation of different precursory phenomena does not exist yet.

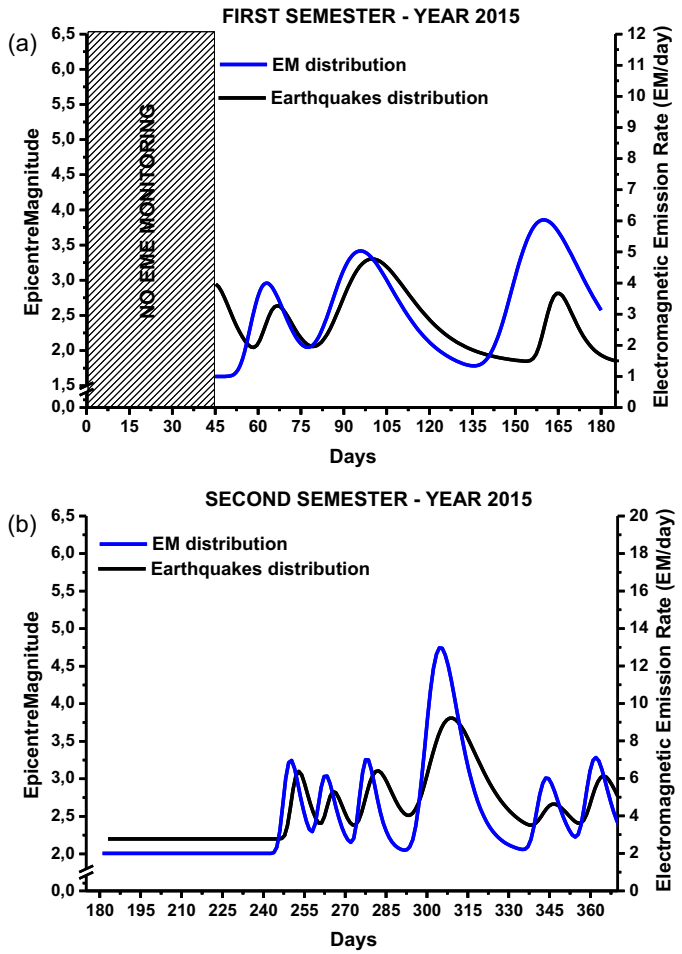

Fig. 6. (a) and (b) Earthquakes vs electromagnetic emissions temporal distributions for the two semesters of monitoring.

In this framework, since July 1st, 2013 a dedicated in-situ monitoring at the San Pietro - Prato Nuovo gypsum mine, located in Murisengo (Alessandria, Northern Italy) has started and it is still in progress.

Currently, a rock pillar of the mine, located at about 100 m below the ground level, is subjected to a multi-parameter monitoring in order to evaluate the seismic risk of the surrounding area and, at the same time, to assess its structural stability. The structural monitoring is principally conducted by the AE technique, whereas the seismic risk of the surrounding area by the detection of the AE/EME fluctuations, as well as by the environmental neutron field.

Thanks to the position of the monitoring station (100 m under the ground level), the acoustic and electromagnetic noise of human origin is greatly reduced, as well as the neutron background is between one and two orders of magnitude lower than that on the Earth surface. These aspects make the mine an appropriate place for the monitoring of all the events correlated to seismic phenomena.

The AE equipment consists of six USAM® units, that can be synchronized for multi-channel data processing. Each unit contains a preamplified wideband piezoelectric sensor (PZT) sensitive to the frequency range between 50 kHz and 800 kHz. The AE signals are preamplified, filtered through a bandpass filter in order to have a high signal to noise ratio and a flat frequency response over a broad range.

On the other hand, the EM device consists of a telescopic antenna, having a maximum length of 125 cm. By pulling to the right length, the antenna can be tuned to operate at different frequencies. For this reason, it is a "wide band" device in the sense that it is possible to adjust its length according to the frequency/wavelength that the operator wants to receive. Moreover, the antenna is coupled with an Agilent DSO1052B oscilloscope (50 MHz, 2 channels) that allows appropriate monitoring of EM signals with frequencies up to tens of MHz.

As regards neutrons, it is well known that they are electrically neutral particles, so they cannot directly produce ionization in a detector, and therefore cannot be directly detected. This means that neutron detectors must rely upon a conversion process where an incident neutron interacts with a nucleus to produce a secondary charged particle. These charged particles are then detected, and from them the neutrons presence is deduced. In particular, during the experimental trial at the gypsum mine, the environmental neutron field monitoring was carried out by means of the AT1117M (ATOMTEX, Minsk, Repub-

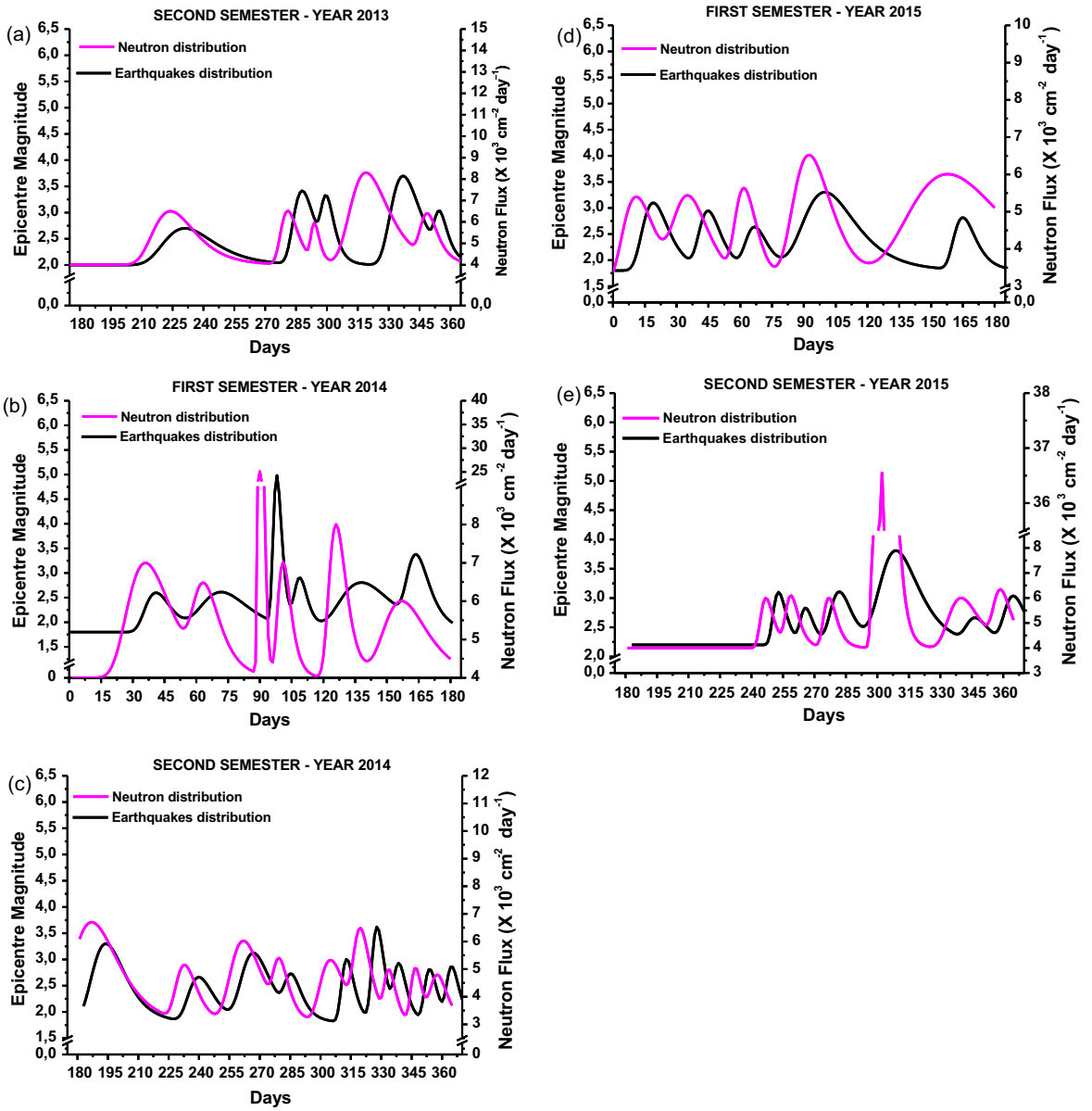

Fig. 7. (a)–(e) Earthquakes vs neutron emissions temporal distributions for the five semesters of monitoring.

lic of Belarus) neutron device. This type of device provides a high sensitivity and wide measuring ranges (neutron energy range 0.025 eV–14 MeV), with a fast response to radiation field change ideal for any environmental monitoring purpose.

From July 1st, 2013, the acquisition of acoustic and neutron environmental radioactivity parameters was performed, whereas only from February 15, 2015 the measuring platform has been also integrated with the acquisition of electromagnetic emissions by means of the telescopic antenna coupled with the Agilent oscilloscope.

The acquisition of the experimental data of acoustic emissions, electromagnetic emissions, neutron environmental flux and seismic activity, was carried out on a monthly basis. Moreover, the period of monitoring has been divided for convenience into five distinct semesters.

The statistical analysis of the distribution of seismic events and of the three fracto-emissions was performed by means of a multi-modal (multi-peak) approach. The software used for the statistical analysis was Microcal Origin. Given a specific discrete distribution of points and applying suitable computational routines, the software determines the relative maxima of the distribution and evaluates the best Gaussian fitting by symmetrical or non-symmetrical bell-shaped curves.

Regarding the seismic activity, during the 921 days (five semesters) of the preliminary investigation, 242 earthquakes of magnitude greater than 1.8 degrees in the Richter scale, within a geographical area of 100 km radius, were observed [70].

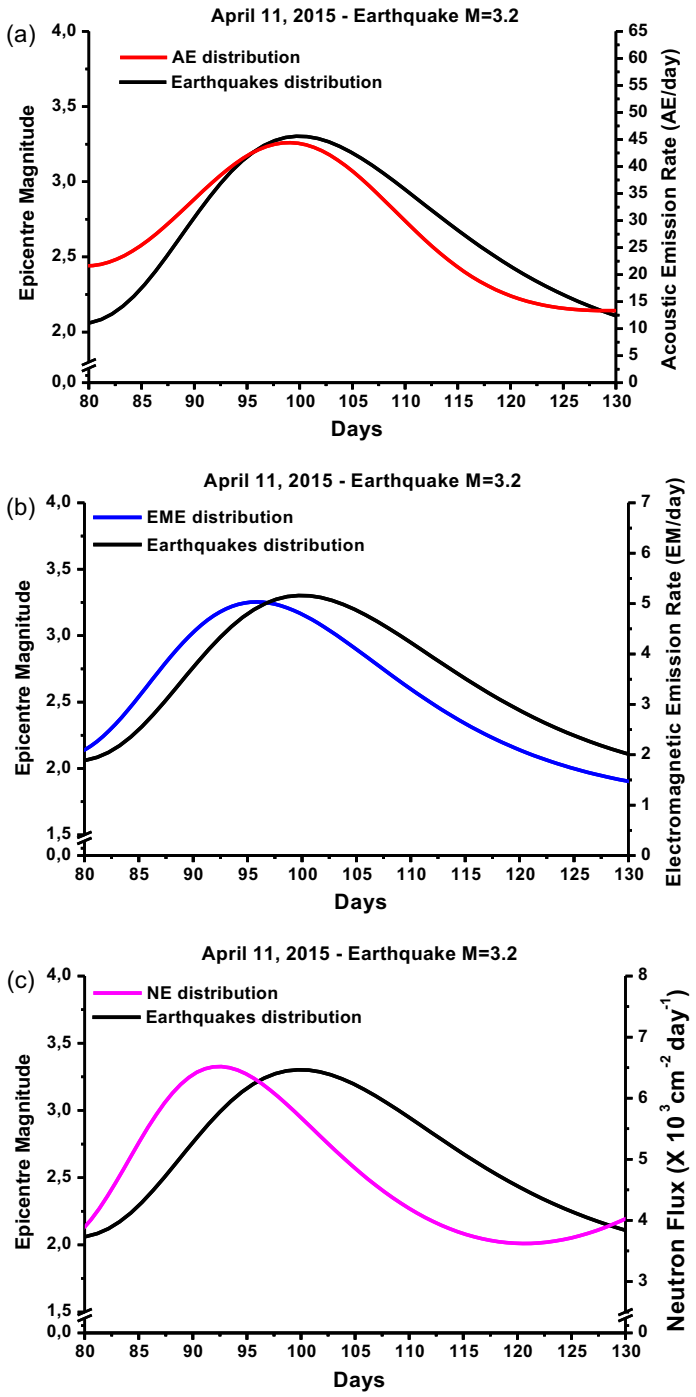

Fig. 8. (a)–(c) Anticipated and differently shifted Gaussian distributions of AE/EME/NE emissions for the earthquake of April 11, 2015.

The threshold of 1.8 has been selected since, considering the experimental evidences, this was found to be a sort of seismic off-set below which no significant change in the neutron flux was observed.

By applying the multi-modal statistics to the temporal distribution of the 242 earthquakes detected during the 5 semesters of monitoring, 31 distinct seismic swarms with a maximum magnitude between 2.5 and 4.7 degrees in the Richter scale were identified. Moreover, these earthquakes tend to generate a preparation area, estimated by the criteria proposed by

Dobrovolsky et al. [30], characterised by a radius between several tens and some hundreds kilometres and therefore within the monitoring area in the surroundings of Murisengo.

Similar multi-modal evaluations were also performed for acoustic, electromagnetic, and neutron emissions.

In the case of AE emissions, it was considered the discrete distribution of the total daily number of observed acoustic events so that 31 AE Gaussian distributions over the 921 days of monitoring were clearly identified, exactly one for each correlated swarm.

For what concerns the electromagnetic emissions, the same multi-modal statistical analysis was performed considering the total daily number of anomalous electromagnetic events. In this case, the data processing is limited only to the two semesters of year 2015. Being the time period of the electromagnetic monitoring of just 320 days, only 9 EM Gaussian distribution peaks were obtained.

Eventually, also for neutron radiation the multi-peak analysis was performed. As for the previous fracto-emissions, the total daily neutron flux was considered and 31 NE Gaussian distribution peaks over the 5 semesters of monitoring were obtained.

As an example, the statistical distributions of seismic swarms and related fracto-emissions for the first half of the year 2015 are shown in Fig. 4(a)–(d).

Besides the multimodal statistical analysis of earthquakes distribution and of the three fracto-emissions, a further temporal correlation between the semester distributions of seismic activity and each related fracto-emission was carried out. The comparison between the temporal distribution of seismic swarms and that of each fracto-emission is given in the following for the five semesters of monitoring (Figs. 5(a)–(e), 6(a) and (b), 7(a)–(e)).

From the comparison between the different diagrams, it is evident the strong correlation between acoustic, electromagnetic, neutron signals and the seismic swarms occurring in the surrounding areas. The three fracto-emissions tend to anticipate the next seismic event with an evident and chronologically ordered shifting.

As a matter of fact, this behaviour was observed in an extremely systematic way for all the 31 detected seismic swarms. In particular, it was noted how AE regularly anticipate the earthquakes by about one day, EME by 3–4 days, whereas NE by about one week. Therefore, they should be considered as precursors of the next major earthquake rather than aftershocks of the previous one, on the basis of the statistical signal processing and of the different temporal distances.

As a further example, in Fig. 8(a)–(c) it is reported the comparison between one of the 31 seismic swarms and the correlated fracto-emission distributions. The seismic event refers to the swarm of April 2015 whose main event of 3.2 degrees in the Richter scale occurred on April 11, 2015. From the comparison it can be seen that AE/EME/NE anticipate very clearly the seismic activity.

5. Conclusions

The experimental results obtained at the San Pietro - Prato Nuovo gypsum mine emphasize the close correlation between acoustic, electromagnetic, and neutron emissions and seismic activity. In particular, it was observed that the three different fracto-emissions regularly anticipate the seismic event by approximately one day, 3–4 days, and one week, respectively.

This preliminary experimental investigation can be considered as a starting point for the design and installation of additional monitoring stations in other geographical areas where the seismic activity is significantly greater than that of Murisengo, such as in Sicily (Italy), Greece, California, and Japan.

Then, applying the methodology and the experimental approach used in the gypsum mine, it will be possible to realize suitable monitoring platforms to prevent well in advance the effects of seismic events and to identify the epicentre of the earthquakes. An undoubtable impact onto seismology can be produced.

Moreover, the installation of the experimental devices for the acquisition of the energy parameters in geographical regions characterised by a higher seismicity could be performed at the ground level and not necessarily underground as in the case of the Murisengo quarry. More intense fracto-emissions, well distinguishable from the background environmental level, are supposed in those cases.

In this way, it will be possible to define more accurately the seismic off-set (currently assumed equal to 1.8 degrees in the Richter scale) and to better evaluate the time correlation between each fracto-emission, and the incoming earthquake. A longer temporal shifting of each fracto-emission peak with respect to the seismic event is in fact expected.

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