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Acoustic, electromagnetic, and neutron emissions as seismic precursors: The lunar periodicity of low-magnitude seismic swarms

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ABSTRACT

Fracto-emission signals (Acoustic Emission AE, Electromagnetic Emission EME, and Neutron Emission NE), triggered by high-frequency pressure waves at the different scales, can be used as a promising tool for environmental protection against seismicity. So far, no reliable method has been developed yet for the successful application of earthquake prediction because the physical mechanism of earthquakes and precursors is at present poorly understood, as well as the estimation of the so-called "earthquake preparation zone". On the other hand, recent studies are also re-evaluating the possible correlation between seismic activity and lunar periodicity. Since July 2013 an in-situ experimental campaign has started at a gypsum mine located in Northern Italy, revealing the strong seismic forecasting potentialities of the fracto-emission peaks by means of a dedicated monitoring platform and a multi-modal statistical analysis. In the present paper, an innovative interpretation of the earthquake preparation area is proposed, and the new experimental evidences obtained at the gypsum mine are reported confirming the previous results (Carpinteri and Borla, 2017). Finally, the relationship between small magnitude earthquake swarms occurred in the surroundings of the mine and the Moon phases is also investigated.

1. Introduction

In the last decades several laboratory tests and experimental observations have shown that acoustic (AE), electromagnetic (EME), and neutron (NE) emissions, together with radon and carbon dioxide anomalous levels, are the most common physical phenomena that can anticipate the seismic activity [1–12].

On the other hand, since 2008, numerous fracture experiments on different type of rocks [13–21] have demonstrated that high-frequency pressure waves (up to THz, 10^{12} Hz), produced by mechanical instabilities, can induce low energy fission reactions on medium weight elements with neutron and/or alpha particle emissions [22–24]. Similarly, pressure waves with lower frequency, i.e. at the MHz and kHz frequency bands, may trigger the emission of electromagnetic and acoustic signals, respectively [13].

The same phenomenon can take place during the early stages of an earthquake. As a matter of fact, at the tectonic scale cracking is a multi-scale phenomenon, as well as the frequencies of pressure waves cover a broad spectrum [1,13], from the THz frequency range for fracture at the nanoscale down to the Hz frequency range at the kilometre scale, which is the typical and most likely frequency of seismic oscillations (Fig. 1 up).

At present, a reliable method for forecasting earthquakes has not been developed yet because the physical mechanisms that generate them and their precursors are very complex and still not completely understood.

In general, a seismic precursor is a phenomenon that can take place well before to the quake occurrence, and also at large

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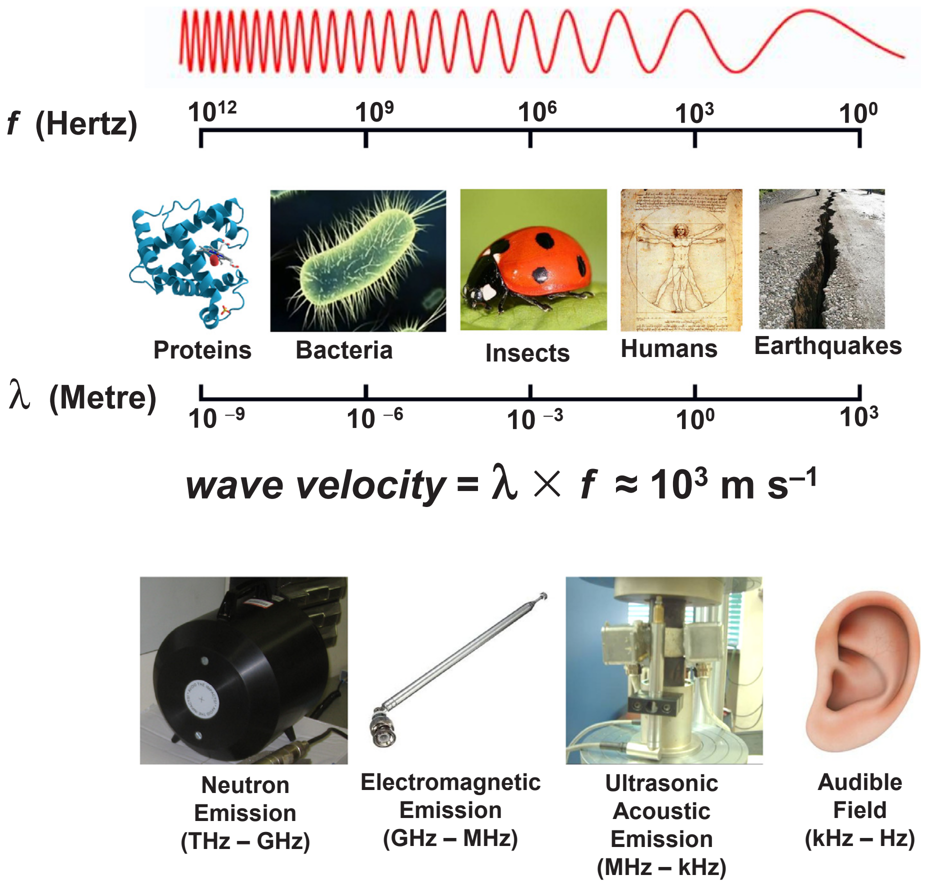

Fig. 1. Correlation between wavelength (forming crack) scale and frequency scale by assuming a constant pressure wave velocity (up); Fracto-emissions measurement (down).

distances from the epicentre. However, a single precursor may not be useful, thus the forecasting strategy must involve an integral approach that includes several parameters.

The main idea is that, if all the precursory phenomena are simultaneously analyzed in suitable monitoring sites, they could provide the basis for the prediction of the three main data of an earthquake: place and time of occurrence, as well as magnitude of the seismic event. In this framework, the use of the fracto-emission precursors (AE, EME, and NE) can represent a huge step forward, not only for their monitoring capabilities during the earthquake, but also for their forecasting potentialities before the event [1].

Hence, ad-hoc measuring devices have to be used for the correct acquisition of the three types of fracto-emission in the respective ranges of frequency: proportional counter for environmental neutron evaluation, antenna and oscilloscope for electromagnetic waves, and piezoelectric transducers for ultrasonic acoustic emissions. Finally, during the seismic event low frequencies prevail, typically in the audible field (Fig. 1 down).

Another very important aspect of earthquake forecasting is the assessment of the so-called “earthquake preparation zone”.

As a matter of fact, in the period before the earthquake occurrence, a very wide area of cracking rocks is active and reaches the critical condition around the future earthquake focal zone under the influence of tectonic stresses.

In particular, Dobrovolsky et al. [25] tried to calculate the dimension of this earthquake preparation area as a function of the magnitude of the incoming earthquake. 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 thousands kilometres. Moreover, all the precursors of non-mechanical nature (i.e. physical, geochemical, etc.) tend to fall into this circle [25].

An innovative assumption about the earthquake preparation zone could be that, in addition to being proportional to the magnitude of the incoming quake [25], it could also depend on the crack size forming in the Earth's crust before the seismic event. Approaching the earthquake occurrence, this area would shrink because of the closure of the pre-existing smaller cracks, resulting in a new preparation area where the remaining small cracks coalesce to form larger ones. Therefore, the day of the earthquake, the area will coincide with the quake epicentre.

Accordingly, it can be supposed that in the early stages of evolution of a seismic event the preparation area has the maximum size extension. The nano- and micro-cracks, as well as the THz and GHz pressure waves, will prevail and, as a consequence, the neutron

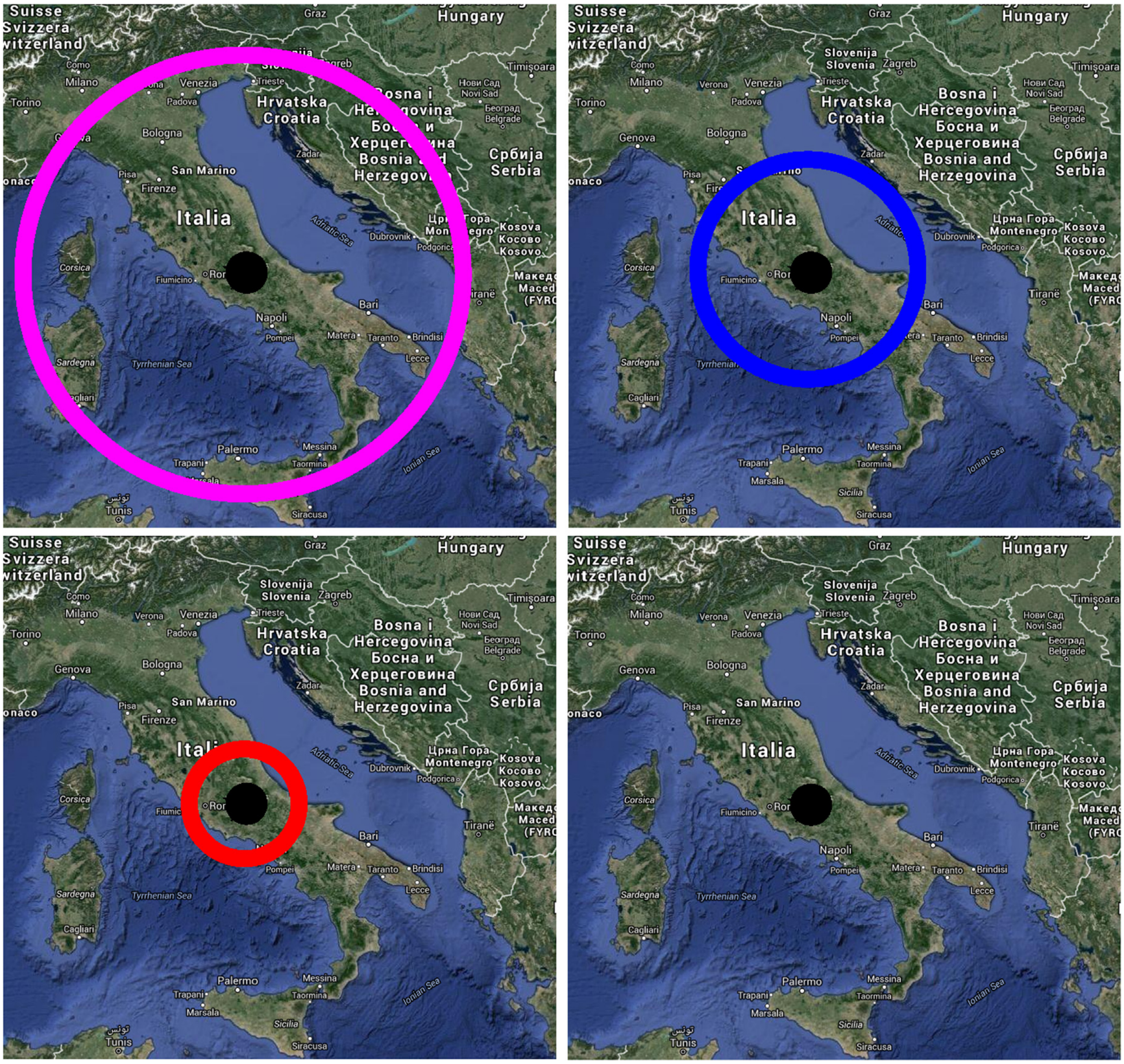

Fig. 2. Evolution of the earthquake preparation zone. Each circle represents the border of the preparation area inside which the fracto-emissions can be generated and monitored: NE (violet), EME (blue), AE (red). The black dot identifies the earthquake epicentre. Equivalent crack size from 10^{-9} m to 10^{-6} m (violet), from 10^{-6} m to 10^{-3} m (blue), from 10^{-3} m to 10^{0} m (red), and bigger than 10^{0} m in the last stage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

emission will be more likely. This means that the neutron component can be even monitored at a considerable distance from the epicentre of the future earthquake. As an example, this experimental evidence was observed for the Sumatra earthquake of 2004 when, some days before the earthquake occurrence, significant anomalies in the neutron environmental flux were measured in Crimea and Kamchatka [8].

In the following step, tectonic stress will tend to focus closer to the earthquake epicentre. As a result, the dimension of the preparation area will shrink, in the new area the crack size will increase (from the micro up to the millimetre scale) and the electromagnetic emissions in the GHz-MHz frequency range will occur [26–30].

Approaching the seismic event, a further size reduction of the preparation zone, characterized by larger fractures (from the millimetre up to the metre scale) able to generate ultrasonic acoustic waves (up to several hundreds of kHz), are expected.

Finally, at the last stage, the preparation area will collapse to the earthquake epicentre, macro-cracks along the seismic faults will coalesce and the propagation of the quake will take place. In Fig. 2, a graphic representation of the conjectured model of preparation zone localization is illustrated. Each circle represents the border of the preparation zone inside which the fracto-emissions can be generated and monitored: NE (violet), EME (blue), and AE (red). The black dot, instead, identifies the epicentre of the incoming earthquake.

Fig. 3. The monitoring station equipped with the AE piezoelectric sensors, the telescopic antenna and oscilloscope for EME evaluation, and the NE proportional counter.

From the experimental point of view, starting from July 2013, an in-situ monitoring campaign has been started at the "San Pietro - Prato Nuovo" gypsum mine in Murisengo (Alessandria, Italy) by using dedicated instrumentation located at about 100 m below the ground level.

The novelty of this experimental investigation consists in the simultaneous acquisition of the three forms of fracto-emission and in their temporal correlation with the incoming seismic event by means of an appropriate multi-modal statistical analysis [1].

From the early experimental evidences obtained during a period of five semesters (July 2013–December 2015), it was observed a strong correlation between acoustic, electromagnetic, neutron peaks and the seismic swarms occurring in the surrounding area of Murisengo mine. In particular, it appears very clearly how the three fracto-emissions tend to anticipate the next seismic swarm peak with an evident and chronologically ordered shifting [1].

In the present paper, after summarizing the preliminary results obtained in the first period of monitoring [1], the authors discuss about the new experimental evidences. The fracto-emissions monitored in an additional period from January 1, 2016 to June 30, 2017 confirm the strong correlation between AE, EME, NE peaks and the major earthquakes occurred in the geographical area close to the gypsum mine.

Moreover, the correlation between the seismic activity observed in the area of the quarry and lunar phases was also taken into account. As a matter of fact, some studies have emphasized that a large number of earthquakes seems to take place during the periods of full or new Moon, when the gravitational forces acting on the Earth's surface are at their maximum level [31–36]. The gravitational force, behaving as an additional stress applied to a fault system with a tensional level near to the failure, could trigger the cracking process that brings to the earthquake evolution and propagation. In this framework, the correlation between Moon cycle and seismicity in the surrounding area of Murisengo is reported.

2. The case study of "San Pietro-Prato Nuovo" gypsum mine: Review on preliminary results

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 [1].

The seismic risk assessment of the area around the gypsum mine is carried out with a multi-parametric monitoring by detecting the AE/EME/NE fluctuations at about 100 m below the ground level.

The underground position of the monitoring station provides a significant reduction in the acoustic and electromagnetic noise, as well as an extremely low neutron environmental background. For these reasons, the Murisengo mine is a very appropriate location for measuring all those physical and mechanical parameters related to seismic activity.

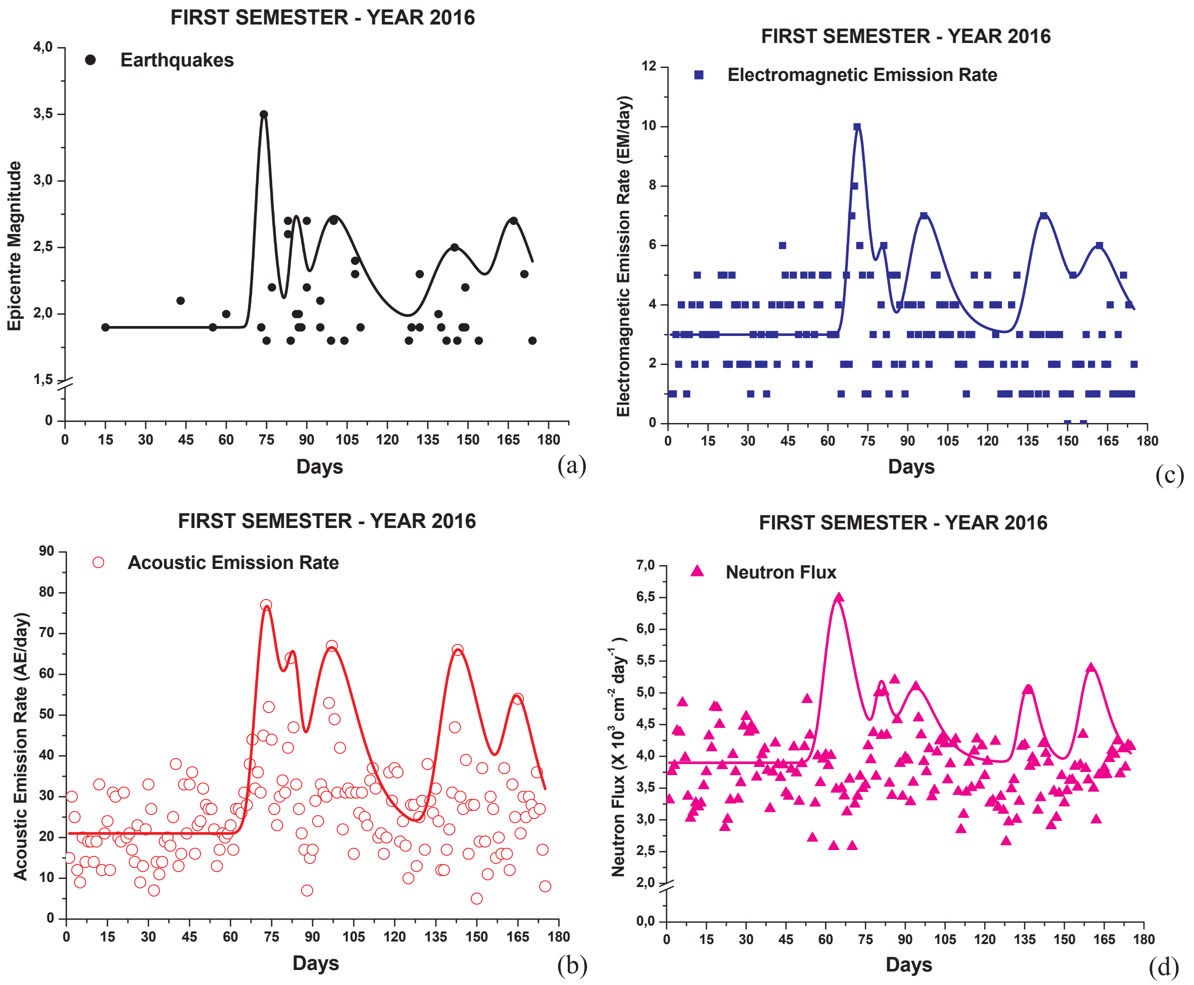

Fig. 4. a–d: Multi-modal Gaussian distribution during the first semester 2016 for earthquakes (a), acoustic emissions (b), electromagnetic emissions (c), and neutron emissions (d).

The AE equipment consists of six preamplified wideband piezoelectric sensor (PZT) sensitive to the frequency range between 50 kHz and 800 kHz. In addition, before the beginning of the acoustic emission monitoring, specific tests were carried out in order to exclude any sort of interference induced by the excavation activity (i.e. drilling and blasting) [37]. In particular, no type of noise was detected, because the shock-wave frequency spectrum produced by such activities was observed to be outside of the sensitivity range of the instrumentation used.

On the other hand, a telescopic antenna coupled with an Agilent Microwave300 oscilloscope is used for the acquisition of EM signals with frequencies up to 300 MHz.

As regards neutrons, the AT1117M (ATOMTEX, Minsk, Republic of Belarus) proportional counter is employed. This type of device provides a high sensitivity and wide measuring range (energy range 0.025 eV–14 MeV), with fast response to radiation field change ideal for environmental monitoring purpose. In Fig. 3 the monitoring set-up of the underground station is reported.

The preliminary experimental results [1], which refer to a five-semester monitoring period from July 1st, 2013 to December 31, 2015, showed a strong correlation between the three fracto-emission peaks and the most important quakes recorded in the closest areas.

A multi-modal (multi-peak) approach was used for the statistical analysis of seismic events, and fracto-emission temporal distributions [1]. In particular, the software (Microcal Origin) determines the relative maxima of a given discrete distribution of points and evaluates the best Gaussian fitting by symmetrical or non-symmetrical bell-shaped curves.

During the first five semesters of monitoring, 242 earthquakes of magnitude M higher than or equal to 1.8 degrees in the Richter scale, within a radius of 100 km, were recorded [38]. For lower magnitude, no significant variation in the neutron flux was observed. Thus, 1.8 it is considered a sort of seismic threshold. Moreover, these seismic events tend to generate a preparation area, estimated by the criteria proposed in [25], large enough to include the Murisengo monitoring station.

The multi-modal statistics applied to the 242 earthquakes observed during the preliminary investigation, identified 31 main

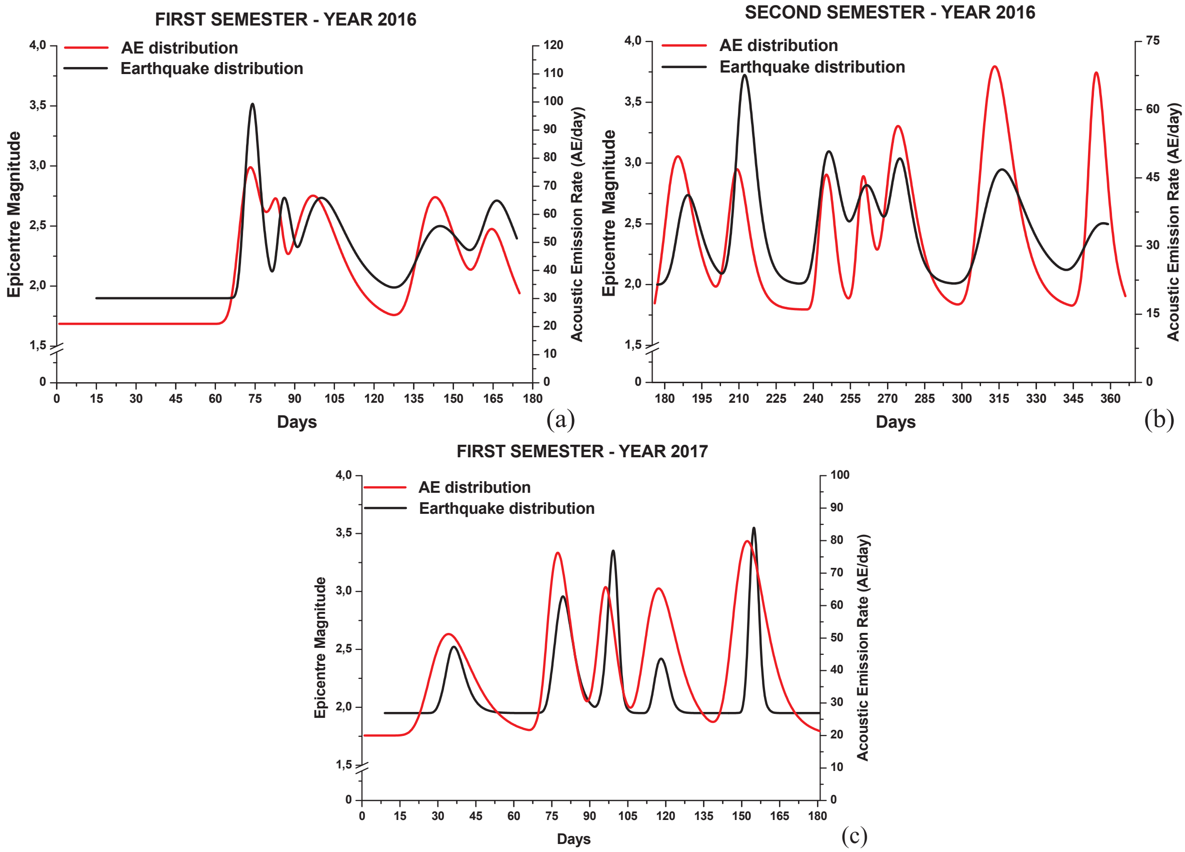

Fig. 5. a–c: Earthquakes vs acoustic emissions (AE) temporal distributions for the three semesters of monitoring.

seismic swarms with a magnitude M between 2.5 and 4.7 degrees in the Richter scale. Similar multi-modal statistical analyses were also performed for acoustic, electromagnetic, and neutron emissions, showing also in this case 31 main emission peaks for each type of fracto-emission [1].

The temporal correlation between the distributions of seismic activity and each fracto-emission revealed a strong correlation among them. In particular, it was observed how AE, EME, and NE regularly anticipate the next seismic swarm peak of about one day, three-four days, and one week respectively. Hence, fracto-emissions should be considered as precursors of the next earthquake of relatively high magnitude rather than aftershocks of the previous one.

3. New experimental evidence from San Pietro-Prato Nuovo gypsum mine

In addition to the experimental results obtained during the preliminary investigation [1], new important experimental evidences have been observed in the period from January 1st, 2016 to June 30, 2017, confirming the close correlation between seismicity and fracto-emissions.

As done for the first five semesters, the data acquisition was carried out on a monthly basis.

As regards the seismic activity monitored during the new three semesters, 154 earthquakes of magnitude greater than or equal to the considered seismic threshold (magnitude M of 1.8 degrees in the Richter scale), within a distance of 100 km, were recorded [38].

By means of Microcal Origin software, the multimodal statistical analysis was carried out on the 154 seismic events, identifying 17 distinct seismic swarms of magnitude M between 2.5 and 3.7 degrees in the Richter scale. The same statistical analysis was performed for the acoustic, electromagnetic, and neutron activity. Also in those cases, exactly 17 main emission peaks for each fracto-emission were obtained.

As an example, in Fig. 4a–d, the results of the multi-modal statistical analyses performed on the first semester of the year 2016 of monitoring for the earthquakes temporal distribution and for the AE/EME/NE emissions are reported.

Then, similarly to the first monitoring period, a correlation analysis between the temporal distributions of seismic activity and each related fracto-emission is carried out (Figs. 5a–c, 6a–c, 7a–c).

Considering the various diagrams, it is evident that the forecasting potentialities of the fracto-emissions is confirmed by the new experimental observations. As for the preliminary measurement campaign, AE/EME/NE tend to anticipate the next seismic swarm

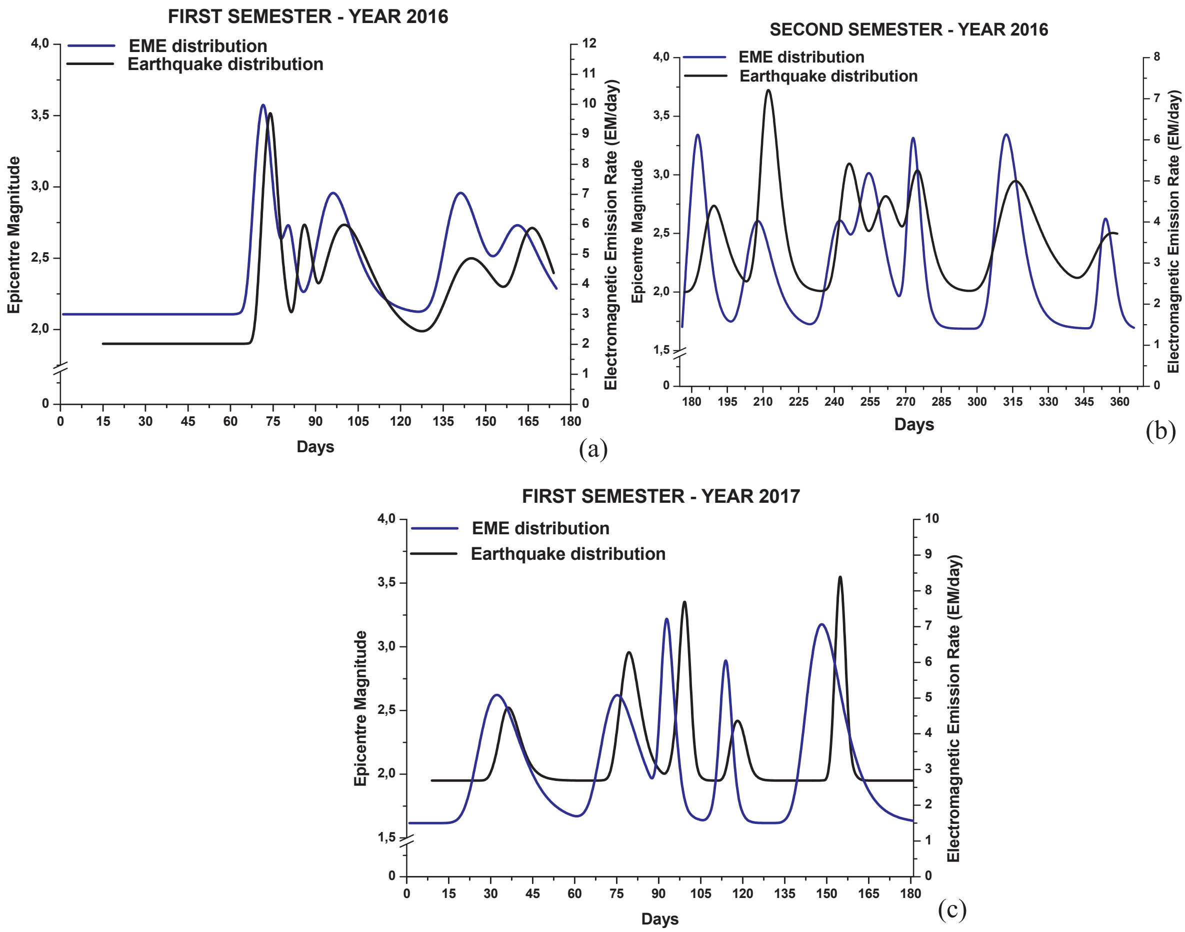

Fig. 6. a–c: Earthquakes vs electromagnetic emissions (EME) temporal distributions for the three semesters of monitoring.

peak with an evident and chronologically ordered shifting, by about 1–2 day, 3–4 days, and about one week, respectively. As an example, in Fig. 8a–c, it is reported the comparison between the seismic swarm of November 11, 2016, whose main event was of M = 3.0 degrees in the Richter scale, and the correlated fracto-emission distributions.

Moreover, the lead-time standard deviation of each fracto-emission, equal to 31% for AE, 29% for EME, and 17% for NE, indicates a rather little statistical dispersion of the experimental data (Fig. 9a–c).

On the other hand, as regards the correlation between the amplitude of the fracto-emission peaks and the seismic swarms magnitude, some preliminary considerations can be also made.

As explained in the Introduction, acoustic, electromagnetic, and neutron emissions are generated within the earthquake preparation area in the days before the quake occurrence. Actually, due to the signal attenuation trough the Earth's crust, only the fracto-emissions coming from the fractures located in the superficial layers of the ground in the vicinity of the mine can be acquired.

Therefore, considering the fracto-emission peak values and the estimated local seismic magnitude in Murisengo (not the epicentre one) a power-law can be obtained. In particular, by increasing the magnitude, also AE, EME, and NE increase. A very preliminary discussion about this topic was already published in a previous work of the authors [39]. Further analyses are now in progress and will be discussed in future publications.

In addition, a frequency shifting, from higher to lower values, was also monitored for each fracto-emission. A decrement of the EME frequencies from several tens to few MHz, as well as for the AE frequencies from about 650 to several tens of kHz, was detected. Hence, this observed frequency reduction strengthens the assumed increasing size of the newly formed cracks within the earthquake preparation zone in the days preceding the seismic event.

4. Possible correlation between seismic activity and lunar phases

Since the end of the 19th century many investigations have been carried out concerning the question if gravitational forces induced by Moon and Sun can trigger earthquakes or volcanic activities [31–36].

In particular, these studies have emphasized that the relationship between earthquake occurrence and lunar phases seems to be

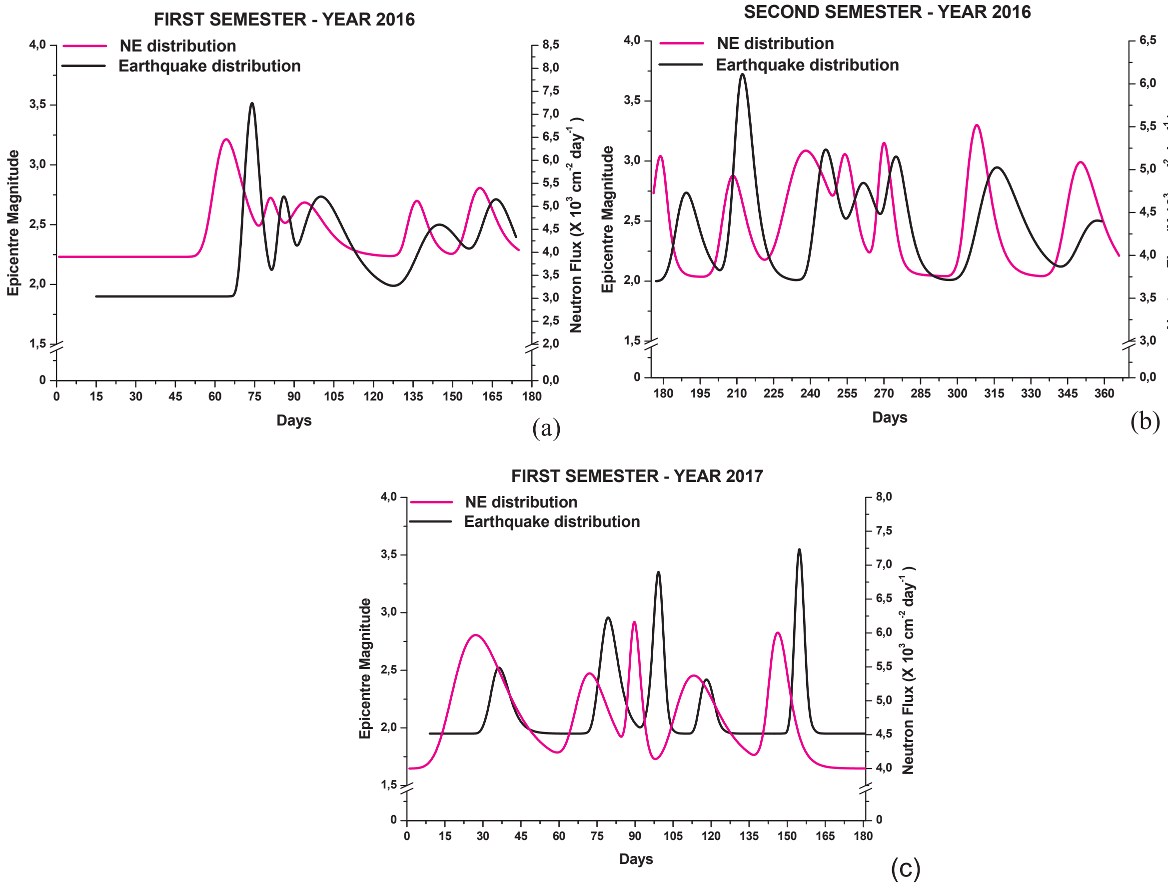

Fig. 7. a–c: Earthquakes vs neutron emissions (NE) temporal distributions for the three semesters of monitoring.

stronger during periods of full or new Moon, that is when Sun, Moon, and Earth are aligned. As a matter of fact, in this case the gravitational attraction and the tidal forces acting on the Earth's surface are more intense. On the contrary, at first and third quarter Moon phases, lunar and solar tides are in opposition and the tidal force is at its minimum.

In general, two different types of tide can generate elastic deformation on the Earth's crust: the solid Earth's tide and the oceanic tide [40]. The first one is due to the gravitational forces exerted by the Sun and the Moon that induce strains and, consequently, lead the surface of the Earth to yield radially up to tens of centimetres. This phenomenon happens inadvertently since the wavelength of the ground oscillation is of the order of thousands Km. However, if this occurs in a critical area where a great amount of strain energy (stress) is accumulated and the pressure gradient is close to the breakpoint, the tidal effect can trigger the nucleation of failure processes. Then, the crack growth along the seismic faults will accelerate until the earthquake propagation.

The second term, instead, is caused by the effect of the oceanic tides on the Earth's crust. Furthermore, considering the individual effects of the Sun and the Moon, the latter has a larger gravitational pull on the Earth than the Sun because, even if the Sun has a greater mass, the Earth-Sun distance is much larger than that of Earth-Moon.

Although the assumption that tidal forces can trigger earthquakes is still debated, it is becoming more plausible thanks to some research studies conducted along the San Andrea fault in California, USA [36,41,42]. By detecting the several seismic events occurred in the surrounding area of the fault, the researchers observed that, when the gravitational forces caused by the Sun and the Moon are added to the tectonic force that pushes the Pacific Ocean plaque against the American continent, more earthquakes occurred.

A further experimental evidence was recently published in Nature Geoscience journal [43].

In particular, the authors assess that, when tides are very large, small earthquakes tend to grow because the strong variation in the tides intensity can accelerate the tectonic movement along a fault and increase the probability of seismic events. Then, the gravitational forces acting on the Earth crust can change the stress along the faults leading to small seismic tremors to grow into significant or up to very large earthquakes. As a matter of fact, the research carried out by Ide et al. [43] reports that the Sumatra earthquake of 2004, with a magnitude of 9.1, and the seismic event of Maule (Chile) in 2010, with a magnitude of 8.8, took place during the full Moon phase, when the tidal stress level was maximum [43].

Hence, although these stress variations due to gravitational forces (stress jumps of about 10^3 Pa) are much smaller than typical stress drops of a seismic event (up to 10^7 Pa) [44], their combined effect, applied to a fault system that is close to failure could induce

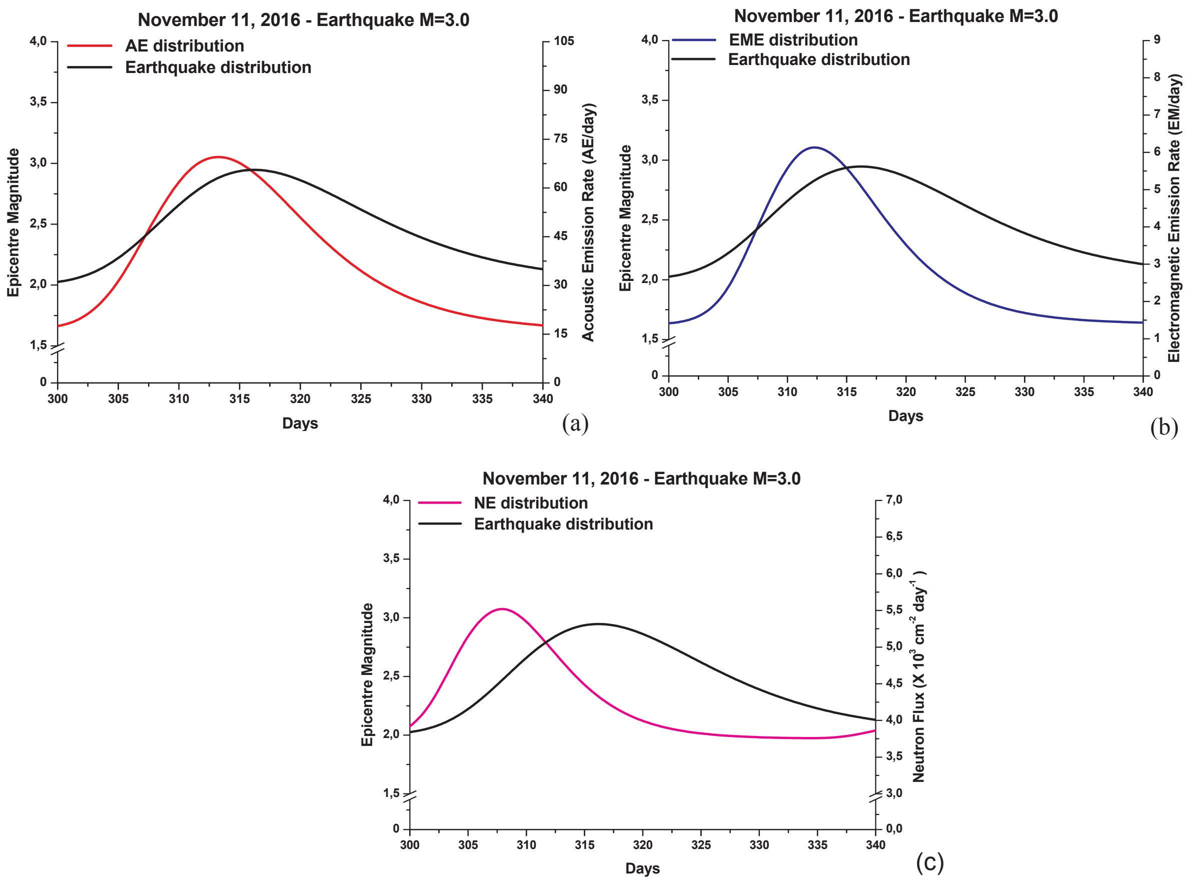

Fig. 8. a–c: Anticipated and differently shifted Gaussian distributions of AE/EME/NE fracto-emissions for the earthquake of November 11, 2016.

the earthquake.

Moreover, also sunspots, and in turn the solar activity, could influence the earthquake occurrence [45]. As a consequence, the solar-terrestrial interaction could play a role on seismicity, involving a sort of coupling between the Sun, solar wind, magnetosphere, and lithosphere. In addition, geomagnetic storms, caused by Coronal Mass Ejections (CMEs) might induce eddy electric currents in rocks along faults, reducing their shear resistance [46,47], and thus possibly increasing the seismic activity.

4.1. Experimental correlation between seismicity and lunar periodicity at the "San Pietro-Prato Nuovo" gypsum mine

A possible correlation between lunar phases and seismic activity in the surrounding area of Murisengo gypsum mine was explored considering the 48 main seismic swarms occurred during the eight semesters of monitoring, from July 1st, 2013 to June 30, 2017.

Firstly, it was observed that the mean waiting time between two consecutive seismic swarms is of about 30 days (48 seismic swarms in 48 months), that is also the average duration of a synodic month (i.e. the typical period of the Moon's revolution). Therefore, this experimental evidence appears to be not a simple coincidence.

Thus, comparing the seismic swarms occurrence with the different periods of full and new Moon, an appreciable temporal correlation can be observed.

In the following diagrams (Fig. 10a–h) the temporal distribution of the 48 seismic swarms together with the lunar phases are reported. A sinusoidal curve is used to represent the lunar cycle. In particular, the maximum and minimum of the sinusoidal function represent the full and new Moon, respectively. On the other hand, the occurrence of the seismic swarm peak is identified by means of a black dot.

Considering the various diagrams, it is evident the close correlation between lunar periodicity and seismic activity. As a matter of fact, it was observed that, for the majority of the cases, the main event of each seismic swarm takes place the same day, or within 2–3 days before or after the occurrence of new or full Moon.

Therefore, the experimental observation carried out at Murisengo seems to show that, not only high magnitude earthquakes can be affected by the gravitational forces exerted by the Sun and the Moon [43], but also seismic swarms and low magnitude earthquakes tend to grow under the influence of our Star and our Satellite.

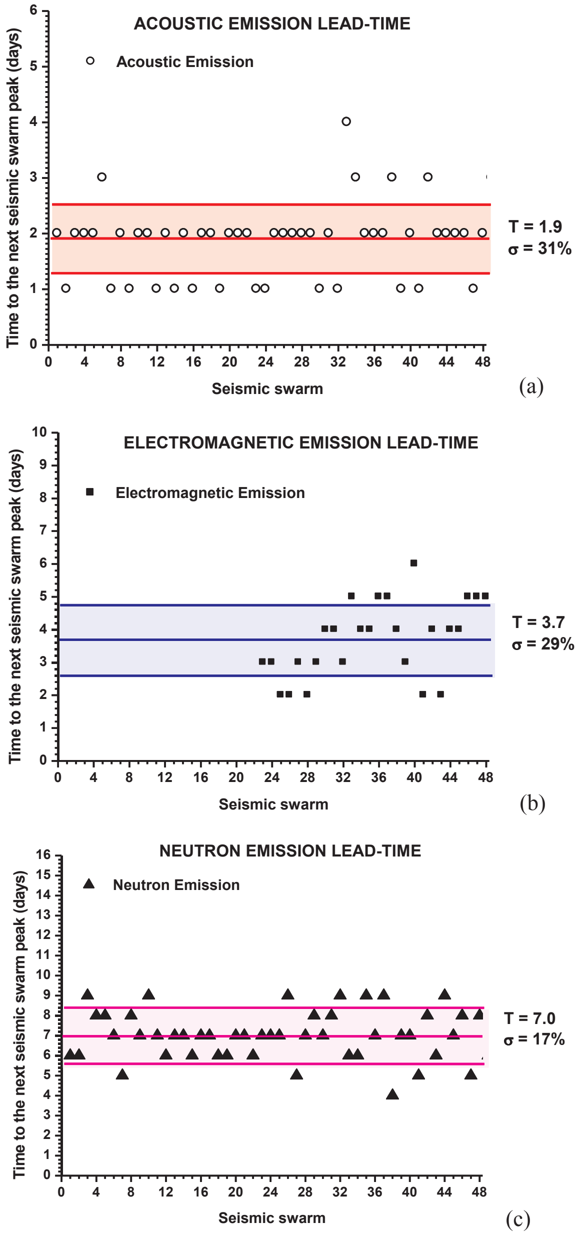

Fig. 9. a–c: Lead-time statistical dispersion of each fracto-emission.

5. Conclusions

The new experimental evidences obtained by the monitoring of fracto-emissions at the San Pietro - Prato Nuovo gypsum mine in Murisengo (Alessandria, Italy) confirm the close correlation between acoustic, electromagnetic, neutron emissions and seismic activity. In particular, as already published in a recent paper [1], it was observed that the three different energy emissions regularly anticipate the seismic swarm peak by approximately one day, 3–4 days, and one week, respectively.

An innovative estimation about the dimension and temporal evolution of the earthquake preparation zone has been also proposed. It is supposed that it could depend not only on the magnitude of the incoming earthquake, but also on the crack size development over the Earth's crust. Approaching the earthquake occurrence, this area would shrink because of the closure of the pre-existing smaller cracks, resulting in a new preparation area where the remaining small cracks coalesce to form larger ones. Accordingly, the preparation area will continue to reduce in size until it will coincide with the epicentre of the imminent quake.

Finally, a possible correlation between lunar phases and seismic activity monitored in the surroundings of Murisengo was conducted. As a matter of fact, during the eight semesters of monitoring 48 major seismic swarms were observed, approximately one seismic swarm every 30 days, that is the typical duration of a synodic month. The experimental observations have evidenced that the seismic swarm peaks take place the same day, or within 2–3 days before or after the occurrence of new or full Moon, when the gravitational forces acting on the Earth's surface are at their maximum level. So, similarly to the observation that high magnitude earthquakes can be linked to lunar cycle, also seismic swarms or low magnitude earthquakes can be influenced by the tidal forces exerted by the Sun and the Moon.

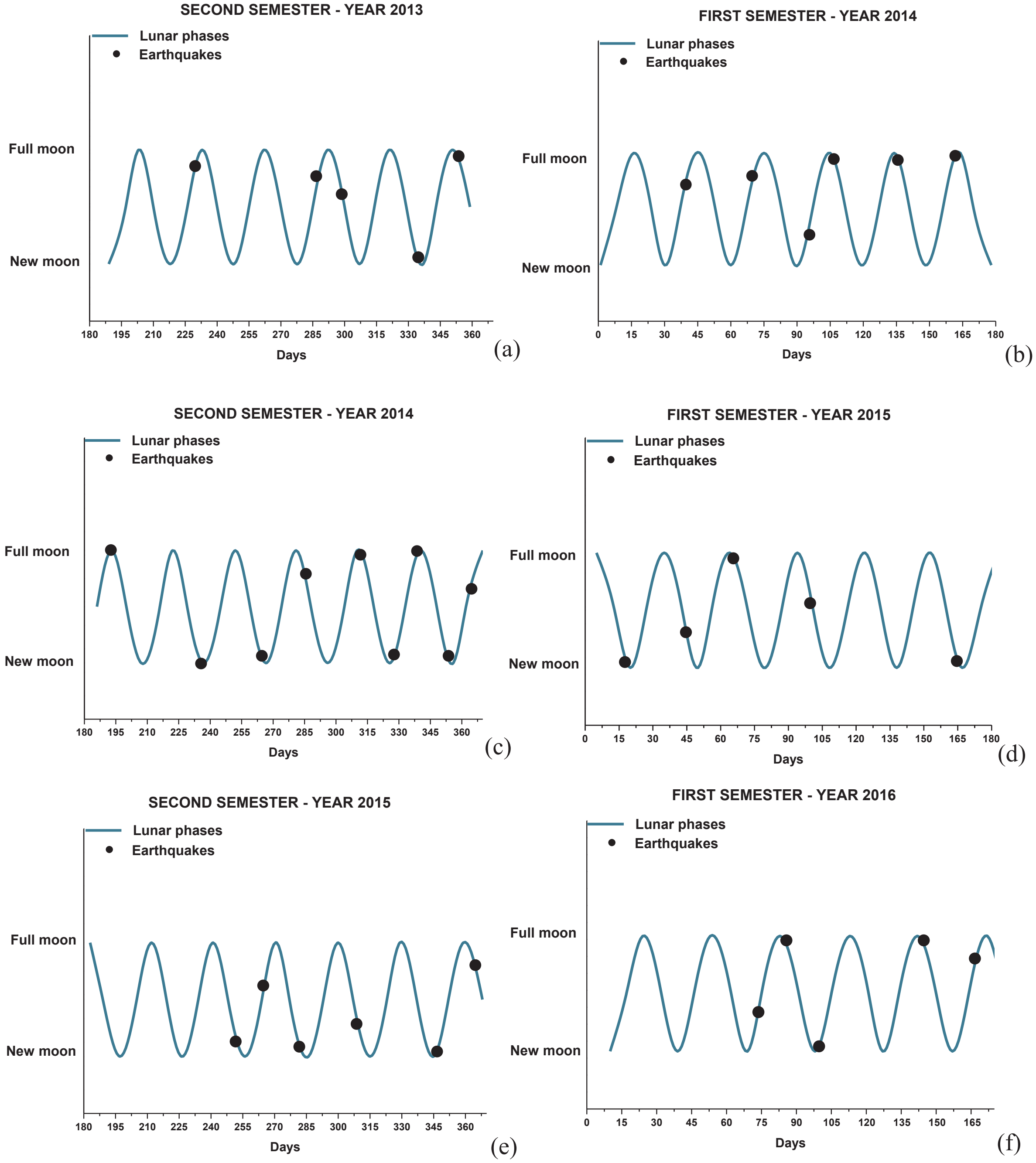

Fig. 10. a–h: Correlation between lunar phases and earthquakes occurrence for the eight semesters of monitoring (July 2013–June 2017).

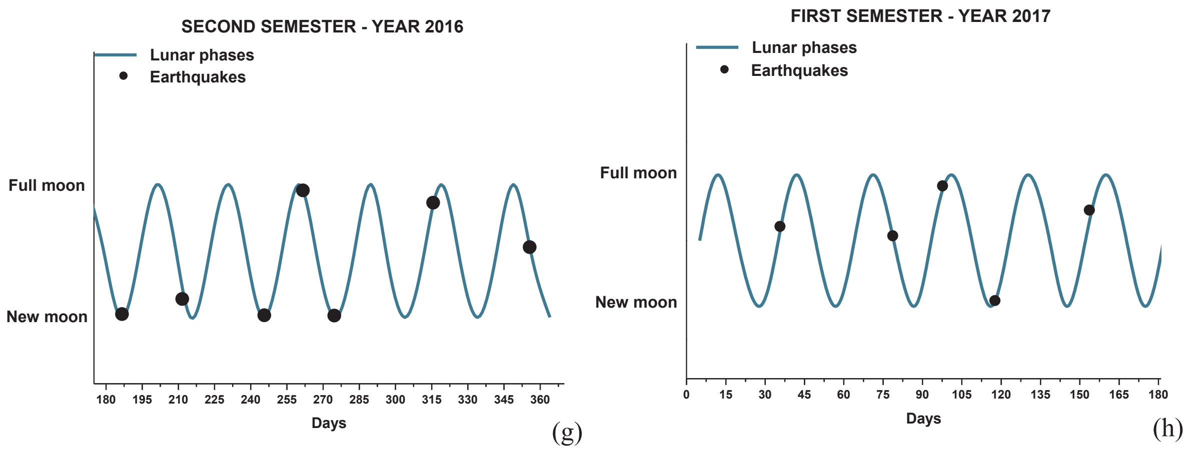

Fig. 10. (*continued*)

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