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Key Points:
- Thousands of low-frequency seismic events are detected in many regions of Italy
- The origin source is related to the activity of huge cement plants
- Results lead us to revise the previous interpretation as natural phenomena

Supporting Information:
- Readme
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Figure S6
- Figure S7
- Table S1

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Man-induced low-frequency seismic events in Italy

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Abstract Unconventional seismic events in Italy are detected by scanning three years of continuous waveforms recorded by the Italian National Seismic Network. Cross correlation of signal templates with continuous seismic records has evidenced unusual events with similar low-frequency characteristics in several Italian regions. Spectral analysis and spatiotemporal distribution of these events, some of which are previously interpreted as tectonic long-period transients, suggest that they are not natural, but produced by huge cement factories. Since there are at least 57 full-cycle cement plants operating in Italy, each affecting areas of about 1250 to 2800 km^2, we argue that significant portions of the Italian territory (23% to 51%) can be affected by this man-made noise. Seismic noise analyses, such as those used for microzonation or crustal structure investigations, as well as data mining techniques used to retrieve anomalous transient signals, should thus take into account this peculiar and pervasive source of seismic waves.

1. Introduction

Italy is one of the most seismically active regions of the Mediterranean. Thanks to a very efficient continuous seismic monitoring of the Italian National Seismic Network [*Amato and Mele*, 2008] operated by the Istituto Nazionale di Geofisica e Vulcanologia (INGV), several thousands of microearthquakes are recorded every year in the country. Seismic activity is due to ongoing subduction of both oceanic and continental lithosphere, and to the effects of past subduction, continental collision, and delamination of the Adria microplate, which led to the present crustal extension of the Apennine belt [*Chiarabba et al.*, 2005].

In the last decade, several studies in the world have shown that subduction zones are candidate regions for the occurrence of peculiar seismic phenomena, such as deep tectonic tremors and low-frequency (LF) earthquakes [e.g., *Obara,* 2002; *Rogers and Dragert*, 2003; *Shelly et al.*, 2006, among many others]. Compared to classical earthquakes, these seismic events are characterized by a low-frequency spectral content (about 1–5 Hz) and amplitudes decreasing at frequencies larger than 6 Hz [e.g., *Shelly et al.*, 2007]. Recently, anomalous low-frequency signals have been discovered in Italy and interpreted as the result of fluid movements in the upper crust [*Piccinini and Saccorotti*, 2008; *Saccorotti et al.*, 2011]. According to *Piccinini and Saccorotti* [2008], these signals have spectral characteristics similar to volcanic long-period (LP) events, but they do not occur in volcanic setting.

A difficult task for seismologists is the discrimination between the several seismic sources originated by natural and artificial processes. Italy is a highly industrialized and strongly urbanized country, resulting in a variety of seismic events and tremors caused by human activity. Many sources are non-stationary, such as railways and highways, whereas others are located at specific sites and repeatedly induce vibrations in the ground, such as quarries [*Mele et al.*, 2010; *Cattaneo et al.*, 2014] or sources related to the industrial activity [*Cara et al.*, 2010]. Currently, the INGV seismic network, which includes more than 350 seismometers with data archived in continuous mode, is capable to identify very low-magnitude events down to a local magnitude Ml = 0.5 in the Umbria region, central Italy [*Chiaraluce et al.*, 2014]. Figure 1 shows the epicenters of more than 26,000 earthquakes with local magnitude equal or lower than 1, recorded in Italy in the last eight years. To improve an efficient and massive use of such a large data set, seismic waveform classification and events source characterization represent a basic prerequisite.

In this framework, we have analyzed three years of continuous seismic records of the INGV network to study recurrent seismic signals having characteristics that differ from classical earthquakes. During our analysis we have identified swarms of several thousands of unusual seismic events in many regions of Italy. Signal spectral properties (mainly constituted of low frequencies in the range of 1–5 Hz) are different from classical earthquakes or quarry blast recordings, while they are more similar to those reported by *Piccinini and Saccorotti* [2008].

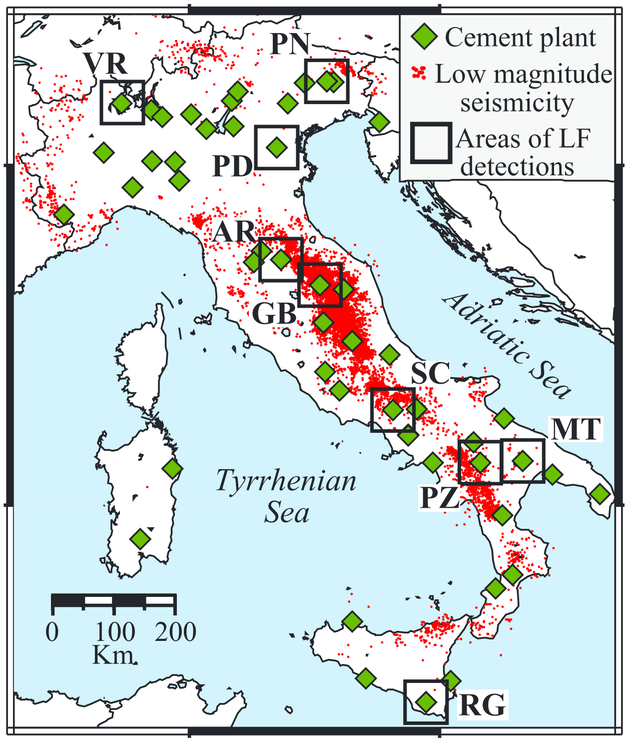

Figure 1. Epicentral map of earthquakes with magnitude lower than 1.0, recorded in Italy by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) network from 2005 to date (red dots, 26,460 events). Black boxes indicate the location of the regions where we detected low-frequency (LF) events from 2010 to 2012: Varese (VR), Pordenone (PN), Padova (PD), Arezzo (AR), Gubbio (GB), Sesto Campano (SC), Potenza (PZ), Matera (MT), and Ragusa (RG). Green diamonds are the location of the 57 full-cycle cement factories active in Italy in 2010 [source AITEC, Associazione Italiana Tecnico Economica Cemento, http://www.aitecweb.com, last accessed August 2014].

Here, we present the main characteristics of LF events detected in several sites from the Alps to Sicily. We compare these signals with an example of deep tectonic LF earthquake recorded in Shikoku region, Japan [*Shelly et al.*, 2007] and a volcanic LP event recorded at Stromboli volcano, Italy [*Martini et al.*, 2007]. Then, we focus our analysis on three areas where the seismic stations are close enough to the source to perform a spatiotemporal analysis of these events. Finally we discuss our interpretation about the possible origin of the LF events recorded in Italy, in light of their hypocenter location and temporal distribution.

2. Signal Characterization

LF signals are identified in several regions of Italy, which belong to different tectonic settings (Figure 1). From North to South, we recorded LF events along the compressional fronts of Southern Alps (northern Italy), the extensional Apennines belt (central Italy), the foredeep area (southern Italy), and the African foreland in Sicily. In northern Italy, LF signals are recognized in the Varese area (VR), Pordenone (PN), and Padova (PD). In central Italy, LF events occur near the city of Arezzo (AR), in the Gubbio area (GB), and near Sesto Campano (SC). In southern Italy, we found similar signals around Matera (MT), Potenza (PZ), and Ragusa (RG). A detailed list of seismic stations of the INGV network that recorded these events is reported in the supplementary information, Table T1 and Figure S1. Due to the low amplitude of these signals, we could perform detailed source locations only in two regions: the Gubbio area where the INGV network is very dense [*Chiaraluce et al.*, 2014], and the Arezzo area. In the other regions we analyzed the spectral characteristics of the LF signals and their temporal occurrence, which appears to be always peculiar if we look at the hourly, weekly, and yearly distribution.

Figure 2 shows three representative examples of LF waveforms. In spite of their original geological setting, signals share very similar characteristics. The P onset is quite clear, while the signature of the *S* wave arrival is not evident. Signal duration ranges from 10 s (MURB station, Figure 2b and VARE station, Figure 2h) to about 25 s (ASQU station, Figure 2e). The velocity spectrum has harmonic character with two main narrow frequency bands (approximately 1–2 Hz and 4–5 Hz), evidenced by the spectral ratio computed between the signals of the LF events and the noise (Figures 2c, 2f, and 2i). Both signal and noise spectra are computed on time windows of different lengths depending on event duration (i.e., from 10 s to 25 s); then, they are smoothed with a half-width window size of 5 points. The highest frequency band of the spectral ratio is centered on 4–5 Hz (4 Hz at ASQU station, 4.5 at MURB, and 5 Hz at VARE) and corresponds to the first phase arrival. The lower frequency band characterizes the event coda and extends in a range between 1 and 2.5 Hz (about 1 Hz at ASQU, 2 Hz at MURB, and 2.5 Hz at VARE) with amplitudes lower (about half size) than the higher frequency band. Lower frequencies are probably associated to surface wave trains resulting from the local velocity structure. LF signals detected in other Italian areas maintain the same spectral

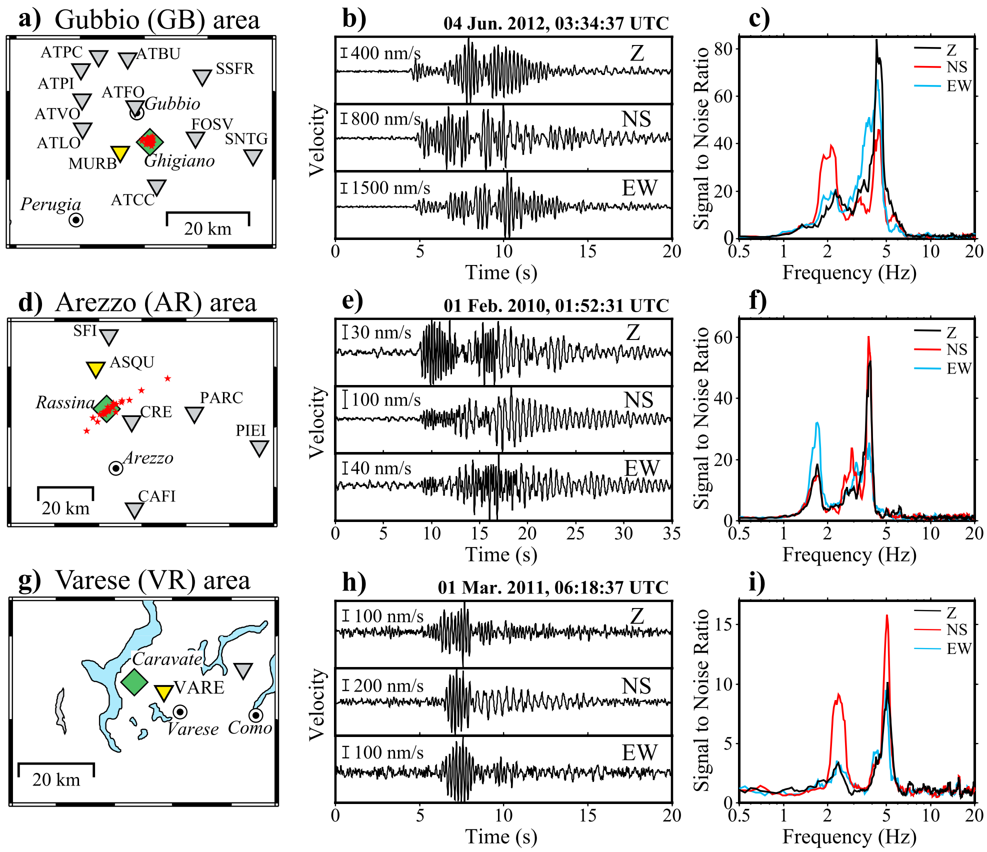

Figure 2. Examples of LF events recorded in three study areas: Gubbio (GB), Arezzo (AR), and Varese (VR) (refer to Figure 1 for their location). (a), (d), and (g) Map views of the three regions and location of the seismic stations (yellow triangles) whose record samples of LF signals are plotted in the central panels. Gray triangles represent the other seismic stations at which we detect LF signals in these areas. Green diamonds indicate the position of the huge cement plants operating in the same areas (Ghigiano in Gubbio area, Rassina in the Arezzo area, and Caravate in the Varese area). Red stars in Figures 2a and 2d are the hypocenter location of some LF events analyzed in this study (see text for further details). (b), (e), and (h) Three-component velocity signals of LF events, bandpass filtered between 1 and 10 Hz and recorded at the stations MURB, ASQU, and VARE, respectively. (c), (f), and (i) Signal to noise velocity spectral ratio computed for the three components Z, NS, and EW, on windows of 20 s of LF signal and 20 s of noise.

characteristics of those described above (see their location in Figure 1). Further examples of these signals are reported in the supporting information, Figures S2–S4. Since we observe the same spectral ratio at all the stations, we suggest that these signals are indicative of very similar sources.

Figure 3 shows a comparison between seismic events characterized by low-frequency spectral content, but having different source origin: (1) a tectonic LF earthquake recorded in the Shikoku region of Japan at the borehole station KWBH of the Hi-net seismic network (data published in *Shelly et al.* [2007]; Figure 3a), (2) a volcanic LP event recorded at the STR6 station of the INGV network located around the Stromboli volcano [*De Cesare et al.*, 2009] (Figure 3c), and (3) a LF event recorded at MURB station (Gubbio area, central Italy, Figure 3e). We observe that signals of both tectonic LF earthquake and volcanic LP event have dominant spectral content centered on the lower frequencies (in our example, 2 Hz for LF earthquake and 1 Hz for the LP event, Figures 3b and 3d). Their signatures in spectrum are broadband, with rapid decay toward high frequencies. Differently, the signature of the LF signal in the Gubbio area exhibits much narrow bands with only two main frequencies: a main pick at 5 Hz and a smaller pick at 2 Hz, with a total absence of higher frequency content (Figures 2c and 3f). It is worth noting that in some cases, signals with a monochromatic character can be generated by sources related to volcanic activity (see *Chouet and Matoza* [2013], and references therein). Nevertheless, such spectral characteristics are not comparable to that of the LF seismicity observed in tectonic settings [e.g., *Obara*, 2002; *Rogers and Dragert*, 2003].

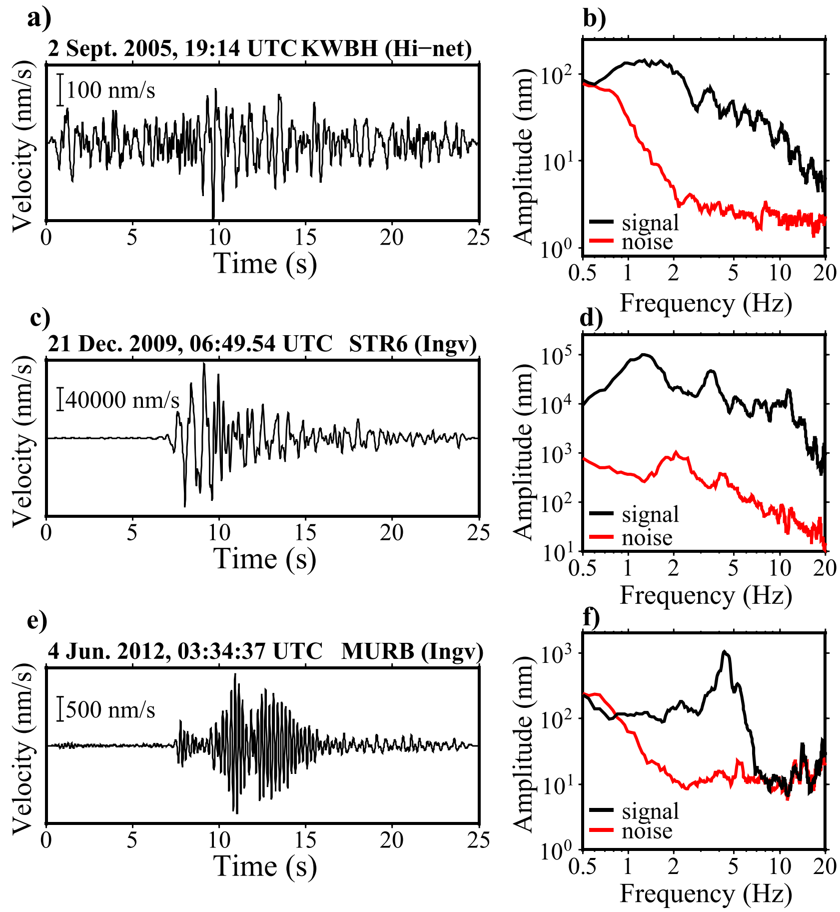

Figure 3. Comparison between an example of LF event analyzed in this study and other natural events characterized by low-frequency spectral content. (a) Example of tectonic LF earthquake recorded at the station KWBH of the Hi-Net in the Shikoku region (Japan) and presented in the study of *Shelly et al.* [2007]. The signal (vertical component) is filtered between 1 and 10 Hz. (b) Comparison between the spectrum of the LF signal of figure (a) (black line) and the noise (red line). (c) Example of volcanic LP event at the Stromboli Volcano, Italy, recorded at the station STR6. The signal is filtered between 1 and 10 Hz. (d) Velocity spectra of the LP signal (black line) and the noise (red line). (e) Vertical component of LF signal recorded at MURB station (also presented in Figure 2b). (f) Velocity spectra of the pre-event noise (red line) and the LF event (black line).

3. Spatiotemporal Distribution

We searched for accurate hypocenter location of repeated LF events and temporal distribution of their occurrence. The former was obtained (where possible) by using both absolute and double-difference hypocenter location. The latter was performed by applying a classical matched-filter technique [*Turin*, 1960], in which template event waveforms were isolated at each station and cross correlated with continuous seismic signals. Both template signals and continuous seismograms were bandpass filtered between 1 and 10 Hz. When cross-correlation values exceed a given threshold, a repeated event is detected and the associated time of the maximum cross correlation value is stored. If the time difference of the detected signals at each station of the area is the same as for the template event, we consider that both detected and template events have the same source location.

In the Gubbio area, we selected about 1000 LF events recorded from March to July 2012 on at least six stations. Due to the signal characteristics, only the *P* wave arrival was picked. Absolute hypocenter locations were computed with the Simulps14 code [*Thurber*, 1983] by adopting a local 3-D velocity model [*Carannante et al.*, 2013]. Then, we performed a double difference location [*Waldhauser and Ellsworth*, 2000] using the cross-correlation delay of the previously located events. We found that 393 events were well cross correlated at enough stations to guarantee a stable location (cross-correlation values larger than 0.85). After double

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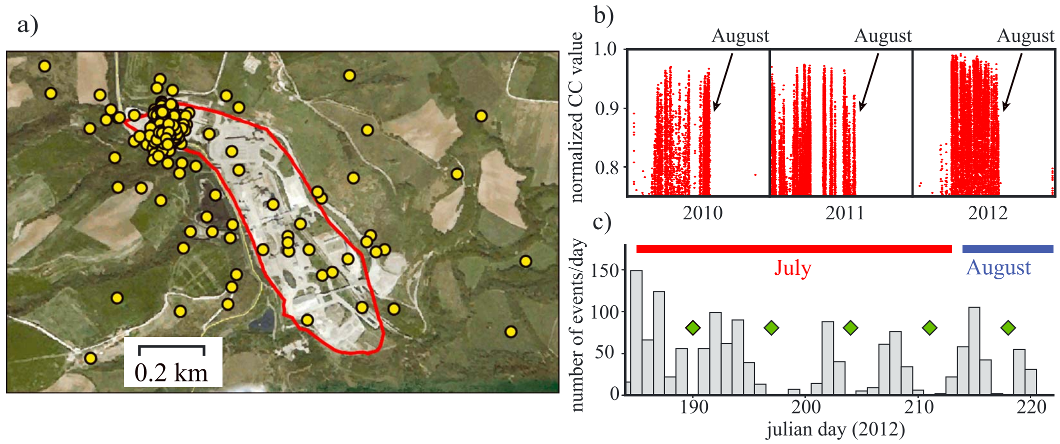

Figure 4. (a) Map of the cement factory of Ghigiano near Gubbio (the gray area with red contour) and epicenter locations (yellow dots) of 393 similar LF-events recorded from March to August 2012 (see the text for further details). (b) Normalized cross-correlation values (red dots) of LF-events detections similar to that presented in Figure 2b (cross-correlation value greater than 0.75) and recorded during the three years of observation: black arrows indicate the stops of activity that occurs every year during the first week of August. (c) Graphics representing the daily occurrence of similar LF events (i.e., cross-correlation values greater than 0.8) from July to August 2012; Sundays are highlighted by green symbols and correspond to weekly stops of activity.

difference location, most of the source positions (342) collapse in a unique cluster with a volume of $0.3 \times 0.3 \times 0.3\ km^3$, located beneath the cement factory of Ghigiano (Figures 2a and 4a). Dealing with locations of very shallow events without *S* wave pickings, the absolute depth of the locations' centroid is not well constrained. This centroid is located at a depth of about 1.2 km, but we observe that any value between 0 and 2 km depth would produce the same fit to the data. The most important result is the relative position among the events below the cement plant: about 96% of the hypocenters cluster in a depth range smaller than 0.3 km from the centroid position.

From January 2010 to December 2012, similar signals were detected by cross correlating the template event of Figure 2b with continuous seismic records. Two graphics representing the LF detections (cross-correlation values greater than 0.8) as a function of time are shown in Figures 4b and 4c. We register a large amount of very similar LF events, up to 250 events/day with normalized cross-correlation values greater than 0.8. The main characteristic is that events do not occur randomly, but show a seasonal recurrence, with intense activity during the winter season and periods of no-activity starting in August and lasting for some months (Figure 4b). Moreover, in some periods as from July to August 2012, we observe peculiar gaps of LF events in correspondence of the weekends (Figure 4c). We note that the results shown in Figure 4 are related to one specific type of LF event (i.e., one template), that is the most frequent and evident. We are aware that other LF signals may occur in the periods where we do not find the signals described above. However the main finding is the peculiar recurrence of LF events, located beneath the industrial site of Ghigiano, which seems to be more related to human activity than natural processes.

LF events recorded in the Arezzo area (Figure 2d) show very similar waveforms to the Gubbio ones. Unfortunately, their hypocenter locations are more difficult to constrain due to less dense station coverage. In an attempt to identify the source location, we selected a sample of 25 LF events and handpicked the *P* wave arrival times on the available seismic stations. As in the Gubbio area, only *P* wave arrival times are used for event location because there is no evidence of *S* waves. However, the seismic network is less dense than in the previous example: the distribution of epicenters is rather widespread (Figure 2d) and depicts the elongation of the error ellipsoid. Nonetheless, we note that the barycenter of their distribution corresponds to the location of a huge cement plant located in Rassina, near Arezzo. More details about the hypocenter location in this area are reported in the supplementary information, Figure S5.

In northern Italy (VR area in Figure 1), hundreds of similar LF events are recorded at VARE station, which is about 7 km far from the cement factory of Caravate (Figure 2g). Although we do not have sufficient stations to locate the LF sources, signals were so clear that we successfully applied the template matching filter over the period of three years. Even accounting for only very strong similarity between signals (cross-correlation values greater than 0.8) we detected up to one hundred of events/day, concentrated in limited periods of activity (1–3 months). We observe a regular occurrence of LF events with respect to the daily and nightly hours, and as in the case of the Gubbio area, we detected systematic gaps at the weekends (for more details, see the supporting information, Figure S6). This temporal distribution suggests a close relation between LF-event occurrence and human activity.

4. Discussion and Conclusions

In this work we have analyzed a type of seismic signal that is repeatedly detected in the continuous seismic records of the INGV network. We have shown that these signals are not due to earthquakes neither to quarry blasts since they have different spectral properties with clear harmonic signature and low-frequency content (Figure 2). In recent studies, some authors have found a strong similarity between LF signals recorded in the Gubbio area and waveforms of LP seismicity usually recorded in volcanic settings [*Piccinini and Saccorotti*, 2008]. According to these authors, LF events are interpreted as the acoustic resonance of fluid filled cracks in the upper crust, repeatedly triggered by time-localized pressure steps. This interpretation was supported by the fact that LF events were only observed in a sector of the Apennines chain where previous studies suggest both the presence of CO_2 circulation of deep origin [*Chiodini et al.*, 2004] and the possible role of these fluids in triggering the intense microseismicity recorded in the northern Apennines [*Collettini and Barchi*, 2002; *Miller et al.*, 2004].

After spectral analysis of several LF signals observed over a long period of time (three years), we find that events recorded in the Gubbio area have very similar spectral characteristics to that of LF events observed in many other regions in Italy. This new result indicates that these particular events are not related to a particular geologic setting, regardless of the ongoing tectonic regimes. Compared to two examples of tectonic LF earthquakes or volcanic LP events (Figure 3), we have shown that spectral properties of the LF events recorded in Italy cannot be correlated to those of known natural sources observed in tectonic settings. On the other hand, we find that industrial activity is very intensive in the studied regions, all hosting huge industrial factories for cement production (Figure 1). Therefore, the detection of similar signals in areas where the same typology of cement factories is installed, calls into question the natural origin of the LF events previously identified in Italy.

The correlation between LF events and industrial plants is supported by event hypocenter locations in the areas where the spatial density of the INGV network allows us to perform this kind of analysis. In the Gubbio region, most of the analyzed LF epicenters collapse in a very small area (with a diameter of about 300 m) at the site of the Ghigiano cement factory (Figure 4a). Although less accurate, similar results are observed in the Arezzo region where the barycenter of the LF sources is located at the site of the Rassina cement plant (Figure 2 and supporting information, Figure S5). In the other areas of study (Figure 1), where we do not have enough stations to compute hypocenter locations, the relation between LF events and industrial activity is suggested by the evidence that all the seismic stations in which we identified LF signals are always located close (0–20 km) to one of the 57 full-cycle cement factories operating in Italy (e.g., VARE station near the cement factory of Caravate in Figure 2g, and other examples reported in the supporting information, Table S1 and Figures S2–S4).

Looking at the time distribution, it appears that LF event occurrence is often characterized by a regular behavior suggesting a human control of these sources. Regular temporal distribution is found in: (1) daily alternation of activity, with stops during the nights (e.g., Varese area, supporting information Figure S6) or, inversely, with prevalent activity during the nights and low activity during the days (e.g., near Ragusa, Sesto Campano, Arezzo, see supporting information, Figures S3, S4, and S5, respectively), (2) weekly alternation of activity and gaps coinciding with the weekend (e.g., Gubbio and Varese areas, Figure 4 and supporting information, Figures S6–S7), and (3) seasonal recurrence observed over a period of three years (Gubbio region, Figure 4).

It is worth noting that the temporal distribution of LF events has not been always regular during the three years of analysis and shows different patterns at the different industrial sites. In some cases, the activity is continuous and concentrates in few days without any interruptions (e.g., Figure S2 of supporting information). However, the differences found among the studied industrial sites possibly reveal different sources (i.e., machines) and different production procedures (i.e., working hours, weekly, and yearly periods of activity and stand-by). In a single cement plant, there are several machines capable of inducing tremors to the ground. Cement manufacturing processes generally include, after mining, the crushing of raw material, the mixing of different rock types, the milling of rocks (during which three conical rollers move over a turning milling), the calcination (involving huge rotary kilns that can have a length of hundreds meters), and the cement milling, in which the clinker (a semi-product of the process) is ground in big mill chambers with steel balls. Each of these machineries involves strong vibrations; some of them are installed underground to minimize the outdoor effect, possibly increasing the coupling to the ground below. Unfortunately, very limited information on production strategies is publicly available, since industries do not like (and have not) to release details on them. Concerning the working time of these plants, we argue that the cement production is not a continuous process but rather factories tend to concentrate the different operational phases in limited time frames. Different industrial choices can explain the variety of the temporal distribution of industrial activity deduced in the studied region. We can only hypothesize some of the reasons for this: they may include availability of raw material, commercial need, water supply, energy cost, environmental impact, and engagement with local communities.

Italy is the first producer of concrete in Europe, with at least 57 full cycle cement plants that cover the whole country (Figure 1, [http://www.aitecweb.com/Portals/0/pub/Repository/Area%20Economica/Pubblicazioni%20AITEC/Mappa_delle_Cementerie_2011.PDF, last accessed August 2014]). If we assume that every cement factory produces seismic vibrations detectable in an area of at least 1250 km^2 (i.e., a circle of 20 km radius) to 2800 km^2 (radius 30 km), we find that a very significant portion of Italy (23% to 51%) is affected by industrial noise as that analyzed in our study. We still believe that in Italy geological processes might generate unconventional earthquakes/tremors due to fluid mobilization in the mantle and in the crust [*Collettini and Barchi*, 2002; *Chiodini et al.*, 2004; *Miller et al.,* 2004; *Antonioli et al.*, 2005; among many others]. However, in such a complex and noisy environment, ongoing investigations searching for natural tremors, as well as other analyses based on seismic noise propagation (site response, velocity structure studies, etc.), should take into account and isolate all possible sources of man-made noise, including those described in this paper.

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