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# Statistical analysis of the volcano seismicity during the 2007 crisis of Stromboli, Italy: a 3-day oscillatory signal as onset of the activity

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**Abstract.** We analyze the volcano seismicity recorded during the 2007 eruption of Stromboli. Data-set is composed of the continuous recordings of a three-component broad-band seismometer and of a strainmeter. Starting from the characterization of the standard activity as a stationary phase of equilibrium, we investigate the non-equilibrium phase of the effusive process. A statistical analysis of the explosions reveals that the occurrence is always driven by a Poisson process as for the standard activity, even approaching the effusion phase, with the only difference in shortening the inter-times just during the effusion. A slightly different process can be advocated for the swarms of the explosions, because a maximum in the distribution of inter-times can be evidenced. Regarding the amplitudes of the explosion-quakes, they have a log-normal distribution until the effusion onset as in the standard Strombolian activity. The actual departure from that stationarity seems to be traced by an early deformative response at very long period. It appears as a transient oscillating signal characterized by a period of about three days that modulates the explosion amplitudes. In a conceptual organ pipe-like model it is related to the chocking of the pipe. The successive activity can be interpreted as the response of volcano to restore the equilibrium condition.

## 1. Introduction

Stromboli is a strato-volcano located in Tyrrhenian sea on the homonomous island at North of the Sicilian coasts (Italy). It is characterized by a persistent activity made of explosions emitting gas and scorie every 5-10 minutes superimposed to a continuous volcanic tremor. This activity is so characteristic to be named "Strombolian" also when appearing on other volcanoes [see, e.g., referring to Erebus volcano, Antarctica, Aster et al., 2003; De Lauro et al., 2009a; Etna volcano, Patané et al., 2008; Popocatepetl, Chouet et al., 2005]. Sometimes, it is interrupted by effusive phases and/or by big explosive events; the last two occurred on December 2002 and February 2007.

The study of how this volcano leaves and returns to its state of stationary equilibrium is of great interest not only from a volcanological point of view but also in the more general framework of physics of fluid systems; in fact, the physics of non-equilibrium systems can be considered one of the major challenge of theoretical and experimental researchers.

In this paper, we take advantage from very intensive seismological observations of the volcano, to study the effusive phase occurred in 2007 looking at seismic recordings of one broadband three-component seismometer of "Istituto Nazionale di Geofisica e Vulcanologia (INGV)- Osservatorio Vesuviano (Naples)" network . We also take into account some months of recordings of a borehole strainmeter of "Analysis and Monitoring of Environmental Risk" center (AMRA).

Our aim is to establish experimentally how and when the non-equilibrium phase of the volcano culminating into the effusive phase starts, and which are its characteristics in terms of the occurrence of the explosions, spectral properties, waveforms. In Section 2,

we will give a brief summary of the characteristics of the stationary activity. In Section 3, we will describe the effusive phase and the analyses performed, whereas a discussion on the results and the conclusions are drawn in the final sections.

## 2. Standard Strombolian activity

A quantitative description of the stationary phase from a seismological point of view is necessary to understand when and how the system has a transition to a non-stationary phase. The persistent activity of volcanic tremor is characterized by a broadband spectrum in the band 0.1-7 Hz. Decomposition in time domain shows that the volcanic tremor is a linear superposition of four signals that can be recognized as dynamical systems in limit cycle regime [De Lauro et al., 2008]. The four signals are characterized by frequencies in specific ratios and with a clear radial polarization, supporting the results of previous works revealing the presence of P-waves [see, e.g., Falsaperla et al., 1998, 2002]. The lowest band (0.1-0.5 Hz) with a characteristic peak close to 0.3 Hz contains the best polarized signal, sometimes masked by contributes coming from oceanic microseismic noise [De Lauro et al., 2005, 2006; Patanè et al., 2007], whereas scattering prevails at higher frequencies.

The explosion-quakes are an enhancement of the volcanic tremor amplitude [De Martino et al., 2002; Ciaramella et al., 2006] induced by the formation, ascent and bursting of gas slugs. As well as tremor, they can be decomposed into well characterized seismic signals [Acernese et al., 2003] displaying a radial polarization pointing to the crater area [Acernese et al., 2004]. The inter-occurrence times between two successive explosion-quakes (hereafter, inter-time) is a measure of the waiting time between successive slugs. The explosions occurrence is driven by a Poissonian process, whose rate is related to the apparent repetitivity of the phenomenon [Bottiglieri et al., 2005].

The stationary phase of Stromboli including both tremor and explosions is well reproduced at macroscopic level in terms of low turbulent systems displaying intermittence [Venkataramani et al., 1996; Bottiglieri et al., 2008]. In fact, the system is generally quiescent (background volcanic tremor) with sudden bursts of activity (explosion-quakes). The switching between bursts and quiescent states occurs following a Poissonian process. In this unified scheme, both tremor and explosions share a common source to be seeked in the thermodynamics of the volcano.

As established in a variety of papers [e.g. Burton et al., 2007], the thermodynamical conditions of the magmatic system of Stromboli imply that at suitable depths (0.7-2 Km) magma must degas. The exsolved gas, driven by a diffusive dynamics, hits the wall of the volcanic conduit. By the coupling between the gas flux and the rock, volcanic tremor is produced as self-sustained oscillations, which are the background seismic signals recorded by seismometers. In fact, confined jets exhibit well-organized oscillation patterns contrary to the convective instability of a free jet [Maurel et al., 1996] and the appearance of this globally organized phenomenon observed in confined geometries is due to a feedback effect. This pattern is reported in literature as self-oscillations. The gas particles, due to the low diffusion coefficient, are confined in a very thin volume (with respect to the whole depth of volcano conduit), favoring the coalescence and then the formation of the slugs [Chandresekar, 1943; Binder and Stauffer, 1976; De Lauro et al., 2009a]. Once a suitable size is matched (fixed by the conditions of equilibrium), the slugs rise along the volcanic conduit very rapidly, exploding then at the air-free surface. To remain coherent during the ascent they are expected to oscillate with the same frequency of the background signal reinforcing it. This mechanism can describe the transition from tremor to explosion.

A detailed theoretical description of the vibrations would require two coupled sets of field equations: one for the solid and another for the fluid oscillations [Lane et al., 2001]. Actually, in the framework of the theory of the dynamical systems, the problem can be simplified and the ground vibrations can be reproduced in time and frequency domains by very simple systems of nonlinear oscillators in the regime of self-oscillations [Konstantinou, 2002; De Lauro et al., 2008; De Lauro et al., 2009b]. The Andronov oscillator [Andronov et al., 1966] is one of the simplest examples: looking at a standard analogical description, it consists in a valve oscillator with the oscillating circuit in the anode circuit and inductive feedback. Nonlinearity is produced by the mutual dependence between grid voltage and anodic current by inductive feedback. Mathematically, the system can be cast into a set of piece-wise linear second order differential equations. A suitable modification of that model to take into account the observed Poissonianity at Stromboli is reported in De Lauro et al. [2008].

## 3. Effusive phase

The common source process underlying the generation of both tremor and explosion-quakes - relative to the stationary phase - is reflected into a similar spectral content of the seismic vibrations. We check whether this basic property is preserved during a non-stationary activity such as the effusive phase. Our data set is composed of seismic data acquired by STR1 station (equipped with a Guralp CMG-40T three-component broadband seismometer) in the period 07/10/2006 - 31/03/2007 (see map in Fig. 1). This station is part of seismic network of INGV-OV; for major details regarding the network, the data and real-time analyses, refer to *http://eolo.ov.ingv.it*.

That period contains the effusive phase, which started on 27/02/2007. In Fig. 2 we plot examples of the recordings. In Fig. 3, spectra of tremor and explosion-quakes before the onset are reported. The two spectra are clearly comparable, as expected for the standard Strombolian activity. Specifically, they show standard bell-shape and main peaks in the range [1-5] Hz with the most energetic centered at about 2.5 Hz. Further lower frequencies can be easily recognized in the spectra: the standard 10s-signal related to the explosions, and the 3s-signal related to the volcanic tremor [De Lauro et al., 2005].

Moving towards the effusive event, volcanic tremor and explosion-quakes retain their comparable bell-shaped spectra with the peak at 2.5 Hz that becomes more and more relevant, as shown by the daily average spectrogram of the events (Fig. 4c). We note also an overall increase in the amplitude of tremor and explosions until the effusion onset (Figs. 4a,b), which is consistent with the results of Patanè et al. [2007]. An accurate analysis of the amplitude distribution will be reported in the next section.

The spectra change when the end of the effusion is approaching. In fact, an interesting case is reported in Fig. 5a, where the overall bell-shape is no more visible and it is replaced by an exponential decreasing shape. Moreover, the fundamental peak is located close to 0.3 Hz, suggesting a change in the vibrating structure that can involve a different geometry and/or size or depth of the plumbing system. The events extracted from the swarms of explosion-quakes (swarms, hereafter) recorded on March 7th and 22th show a clear shift towards higher frequencies with a dominant spectral peak at 3.5 Hz (see Fig. 5b). Another element that can indicate a departure from the stationary state can be a change of the properties of the explosions occurrence. A variation of the dynamic system, ruling the occurrence of the explosions, may induce a different statistical distribution of

the inter-occurrence times. Namely, a crucial point is to establish if some correlations between the explosions emerge before or during the effusive phase or if the standard properties of independence of the stationary phase are basically preserved. In that case, we have to expect only a variation in thermodynamical state.

The series of the inter-times is obtained by applying a suitable picking method of the explosion-quakes to the continuous seismic signal. Specifically, we low-pass filter the continuous signal with a frequency corner equal to 3.5 Hz in order to reduce the effect of non-volcanic signals. We estimate the absolute maximum in a not-overlapping time-window of 12 seconds sliding all along the filtered signal. An explosion-quake is detected when the ratio between two adjacent maxima is greater than a certain threshold and fixing a minimum amplitude equal to 2.5 the background tremor. Window's length and thresholds were chosen in empirical way to optimize the detection of all the explosions and to take into account also multiple explosions. We have checked "a posteriori" the real occurrence of slug-induced explosions looking at their waveforms in order to verify the absence of volcano-tectonics, tectonic earthquakes and spurious signals. As an additional check, we have verified the computed occurrence-times applying another automatic procedure based on the estimation of the root mean square envelope [Cannata et al., 2009]. The results match in 99% of the cases.

In Fig. 6a, the inter-times are represented as a function of time. The evolution of the statistical properties of the inter-times has been evaluated on not-overlapping time-windows lasting 16 hours. The choice of the duration guarantees a significant statistics of events and a time-resolution suitable to evidence eventual changes in distribution. Fig. 6b contains the inter-time distributions in a semi-log scale; this function does not change

its exponential form, thus allowing the estimate of a characteristic rate as best-fit. The different slopes are related to different rates, ranging within [0.001-0.016]1/s.

It is interesting to compare the inverse of the mean values of the inter-times with the estimated rates: the time-evolution of both the parameters is very similar (Fig. 7). This is a further indication that the mechanism driving the occurrence of the explosions is well described by a Poissonian process. It is supported by the variability coefficient Cv (defined as the ratio between the standard deviation and the mean value of the inter-time series), namely according with the curves of Figs. 8a,b, Cv is meanly centered at 0.8, whereas it lowers to 0.6 in correspondence to the swarms. This value indicates that the swarms are ruled by an eventual different process, which is represented by the distributions of Figs. 8c,d. The shape is not exponential anymore and a maximum appears indicating a most frequent inter-time of about 30 s. Looking at Fig. 7, one can see that the most significant change - both in the mean value and occurrence rate - is located at the onset of the effusive phase, where the rates grow considerably. Indeed, during the effusive phase the occurrence rates are twice the rates of the Standard activity on average, i.e., from 0.004 to 0.009 1/s.

### 3.1. Evidence of an early deformative response in tidal frequency range: a 3-day signal

In the stationary phase, the similarity of the waveforms among the explosions provides an energy distribution with a log-normal shape. This implies a preferred length scale in the source mechanism [De Martino et al., 2004]. According with the cited coalescence Landau-Chandrasekar model [Chandrasekar, 1943], the scale has been identified with the size of the bursting slugs; it depends on specific rheologic parameters and on the rate of inter-times

distribution [Bottiglieri et al., 2005]. As is shown in Fig. 9, until the onset of the effusion, the analysis of the amplitude distributions of the explosion-quakes shows that at every time they continue to retain a classical log normal behaviour, even when a slight growth is observed at the beginning of January. The growth in amplitude does not correspond to a simultaneous growth of the occurrence rate, which remains indeed constant (see Fig. 7), while in stationary equilibrium conditions we expect that longer inter-times would provide more energetic explosions. During the effusive phase, the amplitude distribution shape drastically changes, from a Gaussian to a flatter shape, reflecting the strong variability of the explosions. This is a further indication that the system is out of equilibrium and many scales are reliable. The evolution of such phenomenology can be traced by looking at surrogated data, obtained selecting the highest amplitude among all the explosions occurring in sliding time windows 3 hours long. The surrogated data are reported in Fig. 10: the amplitudes' growth is clearly visible as a step function in correspondence of February 7th; the energy involved in the dynamics changes abruptly. This plot clearly shows that this change is preceded by an oscillatory signal with a period of about three days that lasts about 13 days, appearing as a modulation in the explosion amplitudes. In other words, from January 25th the amplitudes of the explosions are modulated by a 3-day signal that ends on February 7th. This signal is in the tidal regime and requires to be better investigated by instrument suitable to detect these low frequencies.

Two strainmeters were installed in 2006 at Stromboli, the first at the Timpone del Fuoco site (TDF), close to the small village of Ginostra, and the second close to the local Civil Defense Centre (SVO). After the period of stabilization, they are properly working from 19/01/2007. For our aim, we use the recordings of the borehole strainmeter of SVO and

relative to the period 19/01/2007 - 30/06/2007 (for strainmeter location see Fig. 1). Since the two systems measure different physical variables (velocity and strain), we normalize one to each other. On the other hand, our interest is only to observe the correspondence of such a 3-day signal on the two instruments. The superposition between the surrogated data from seismic series and the strain signal is reported in Fig. 11. As one can see, the best overlap occurs just in the identified period, highlighted by a black box. This correspondence means that a deformation is associated with this early oscillatory signal.

Signals in the tidal frequency range are not usually considered as eventual volcanic precursors, although some relations between tides and seismic vibrations have been studied [see, e.g., Cochran et al., 2004]. Basically, these studies searched an eventual triggering of the fortnightly component of earth tides on clusters of increasing seismicity. To clarify the contribution and the link between the tides and the volcanic activity, we analyze the energy of the standard tidal constituents and that of the 3-day signal during the non-equilibrium phase.

Fig. 12 shows the time evolution of the spectral peaks of earth tides: specifically diurnal, semidiurnal and 3-day constituents recorded by the strainmeter. Each behaviour is compared with the mean value and the mean value plus 3 $\sigma$ (standard devation), red and green lines respectively, both evaluated one year after the end of the effusion (i.e. February-March 2008). Diurnal and semidiurnal constituents oscillate around the mean value which is basically constant and not connected to the volcanic activity. In addition, both components are always contained in the variability (lower than green line). The evident oscillations are mainly related to the lunar and semilunar tides. On the contrary, the 3-day component shows a clear growth at the end of January 2007 and it returns to

the stationary value well before the end of the effusion. This is another indication that it is related to the volcanic activity and precedes the volcanic eruption.

## 4. Summary

The overall episode of the activity of Stromboli volcano from the end of January to April 2007 can be described by salient dates. On the basis of the experimental evidences, we can reconstruct the dynamics:

- the onset of the entire process is underlined by the insurgence of the evidenced 3-day periodicity transient, which starts on January 25th and persists for several days, i.e. it ends on February 7th;
- at the end of the 3-day signal an increase of 35% of the amplitudes of the explosions is detected on a statistical basis. This is, indeed, calculated on the main peaks of the amplitude distributions as relative variation. This growth interrupts when effusion starts.
- after 20 days from the end of the 3-day signal, on February 27th, the effusion process starts;
- the inter-times of the explosions decrease from a constant value of 5.5 minutes within 30% to 2 minutes;
- a first swarm occurs on March 7th and introduces the subsequent parossistic phase;
- the parossistic phase occurs on March 15th;
- two other episodes of swarms occur on March 20th and 22nd, respectively;
- the effusion phase ends on April 2nd.

The occurrence of the explosions, even during the effusive phase, is described by a Poissonian process, indicating that the degassing layer emits bubbles with the same dynamics,

just changing the rate, which increases approaching the effusion phase from a mean value of 0.004 to 0.009 ($1/s$). This increase of the rate (i.e. shortening the inter-times) is in line with the depressurization due to the effusion. A departure from the Poissonian description of the occurrence of the explosions regards the swarms. In fact, the variability coefficient approaches 0.6 indicating the existence of a most probable inter-time of 30s.

## 5. Discussion and Conclusions

In conclusion, a possible picture of whole phenomenon can be derived in the framework of the conceptual model provided in Section 2.

All the stages of the eruption can be basically seen as the response of the system to a variation of the state due to an eventual ascent magma. The 3-day signal, chronologically, seems to underline the onset of the all processes. It is a slow response of the system in the tidal range, revealing a possible correlation between earth tides and this phenomenon of non-equilibrium. We remind that the study of correlation between earth tides and seismicity is still matter of discussion; for a review see, e.g., Mauk and Jonhston [1973]. In particular, the case of Stromboli volcano is studied in Jonhston and Mauk [1981], who correlated the major eruptions to the fortnightly component.

In this paper, we have observed a different and new phenomenon: the insurgence of a 3-day periodic signal as onset of a non-equilibrium phase of Stromboli. The observed earth tides periodicities are basically due to a synchronization mechanism between the global Earth motions, the gravitational attraction, and the local characteristics, including rheology, geometry and basin effects [see, e.g., Melchior, 1978]. Variations in these characteristics can induce changes in the amplitude ratios among the standard frequency peaks and/or enrichments in the tidal spectrum, both at lower and higher frequencies.

This can be also the case of Stromboli volcano during the crisis. In details, we can think of Stromboli plumbing system as a sort of reservoir that during stationary activity receives and ejects, on average, the same quantity of magma. If the loading rate of that reservoir rapidly increases, the system tends to be choked at a certain depth as observed also in Burton et al. [2009]. The theory of vibrating cavities envisages that closed fluid-filled cavities develop lower harmonics than open ones. This should explain in an heuristic way the insurgence of the 3-day signal. In other words, the cavity along which magma rises, being choked at some depth, becomes closed in contrast to the previous open state, then the 3-day signals starts. The chocking has the consequence to modify the pressure conditions along the volcanic conduit, i.e. the system de-pressurizes. The following overall observed phenomenon appears as the response of volcano to restore an equilibrium condition.

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**Figure 1.** Map of location of both seismometer labeled STR1 and strainmeter labeled SVO.

**Figure 2.** Examples of waveforms recorded during the different phases of the volcano activity.

**Figure 3.** Spectral amplitude of tremor (red) and explosion-quakes (blue) estimated considering four representative days before the effusion. The graphs have been computed by averaging the spectral content of tremor and explosions occurring within 40 minutes. The number of analyzed explosions ranged between 4 and 20, according with the variable occurrence rate. Note also the increasing amplitude of the explosions moving towards the effusion onset.

**Figure 4.** Upper panel: time evolution of the number of explosions per hour; middle panel: the root mean square is reported as an effective estimate of the seismic amplitude. It increases approaching the effusion onset; lower panel: Averaged spectrogram of the continuous seismic signal.

**Figure 5.** a)Spectra of tremor (red) and explosion-quakes (blue) estimated about one month after the effusion onset and few days before the end; b) Spectra of swarms.

**Figure 6.** a)Inter-times (in seconds) as function of time; b) Distributions of the inter-times plotted in semi-log scale. Each curve is relative to the events occurring within 16 hours time window.

**Figure 7.** Reciprocal of the mean values of the inter-times (blue line) and rates (red line) of the explosive process. The rate is computed as the best fit of the exponential decrease.

**Figure 8.** Evolution (a) and distribution (b) of the variability coefficient of the inter-time series; distribution of the inter-times of the swarms of 07/03/2007 (c) and 22/03/2007 (d).

**Figure 9.** Mean density distributions of the explosions' amplitude estimated within the periods indicated in the legend. Frequency is the mean number of events occurring in 16 hours.

**Figure 10.** Logarithm of the maximum amplitude of the seismic signal estimated in non-overlapping windows of three hours. The highest value represented in the figure corresponds to the big explosion occurred on 15th of March during the effusion.

**Figure 11.** Evolution of the amplitude of the seismic signal (red line) along with the signal of the dilatometer filtered between the frequencies corresponding to the periods of two and four days, respectively (blue line). Both the signals have been normalized to facilitate the comparison. Dilatometer's recordings start on January 19th. In this representation, the match between the curves evidenced by a black rectangle lasts approximately from the beginning of the dilatometers' recordings to February 7th, when an increase of the explosions' amplitude occurs and leads to the effusion.

**Figure 12.** Power Spectral Density (PSD) of the frequencies corresponding to periods of (a) 3 days, (b) 24 hours and (c) 12 hours of the dilatometer in the period January-June 2007 (blue lines). They have been computed by Fourier analysis on windows of 12 days with an overlap of 75%. All values fall within the statistical variability except the 3-day component in the period January 25th - February 5th 2007, suggesting a significant deviation of the energy of this frequency only in this period. This has been verified by evaluating the mean values (red line) and the variability (mean value plus three standard deviation - green line) of PSD along two months of standard strombolian activity, namely one year after the end of the effusion.


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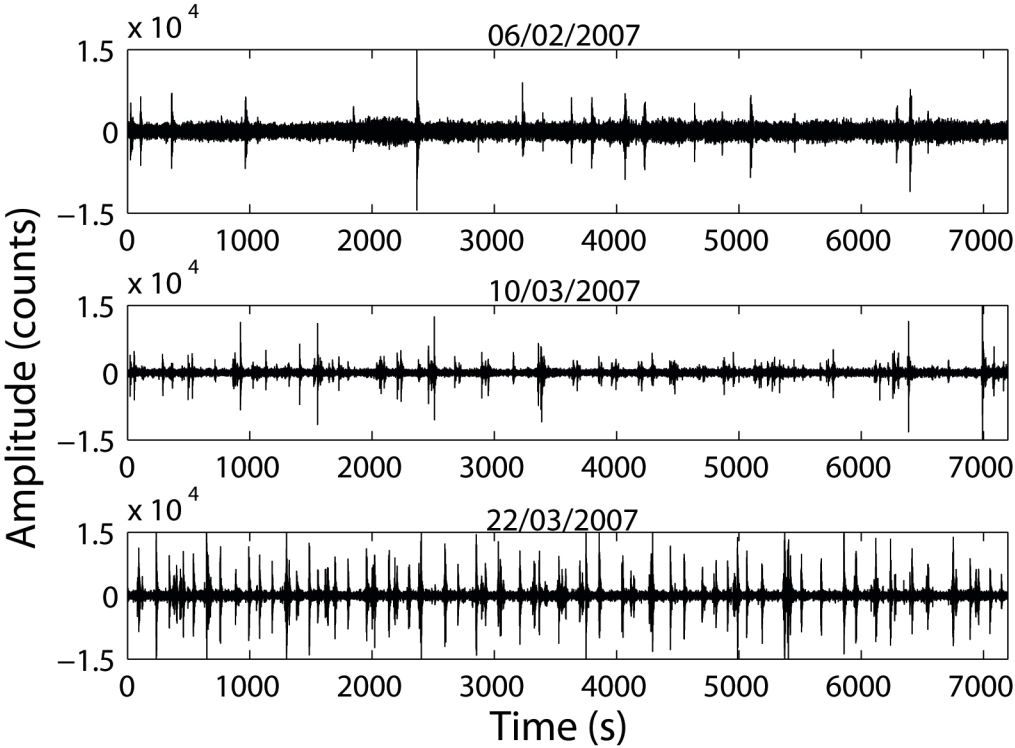
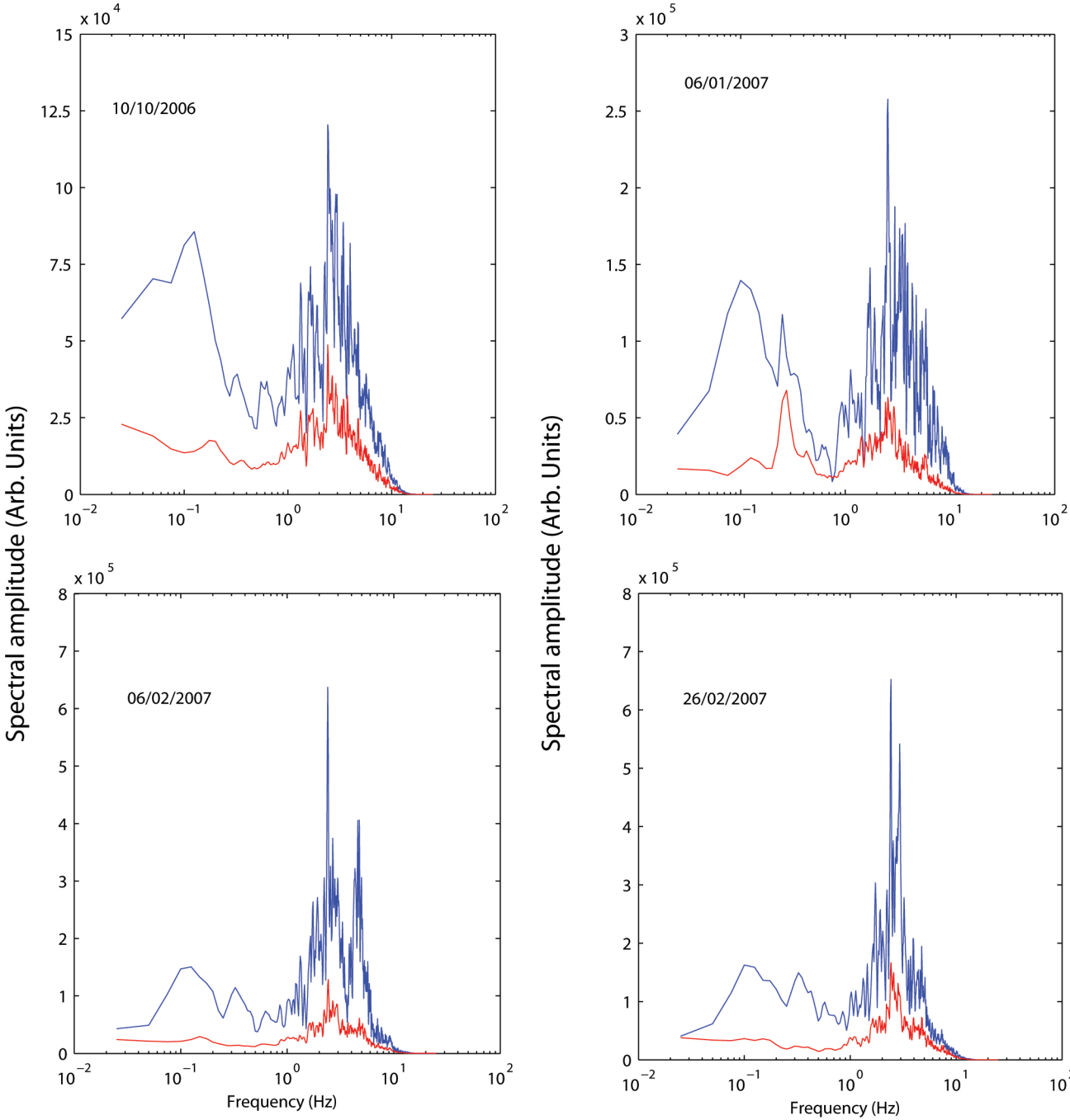
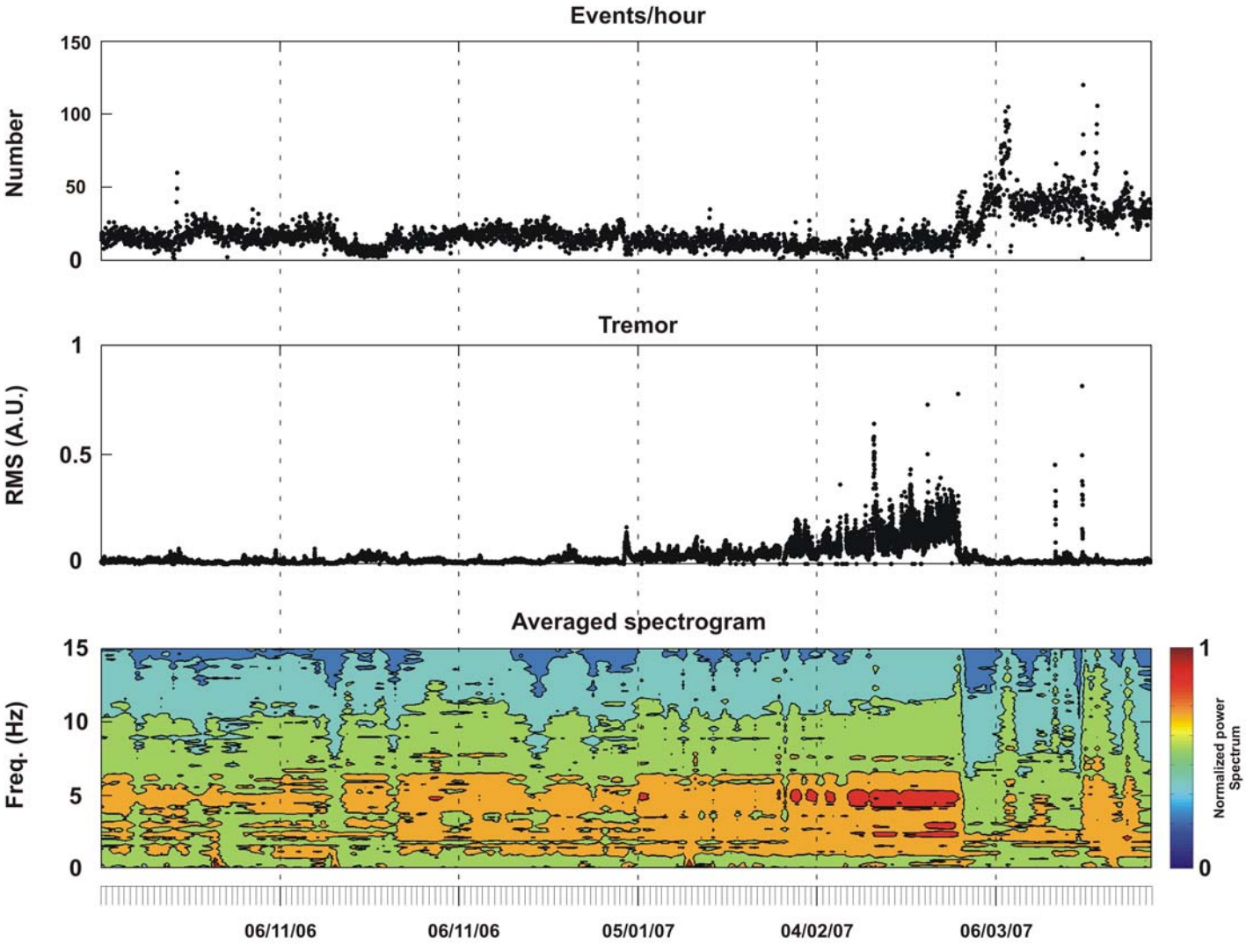
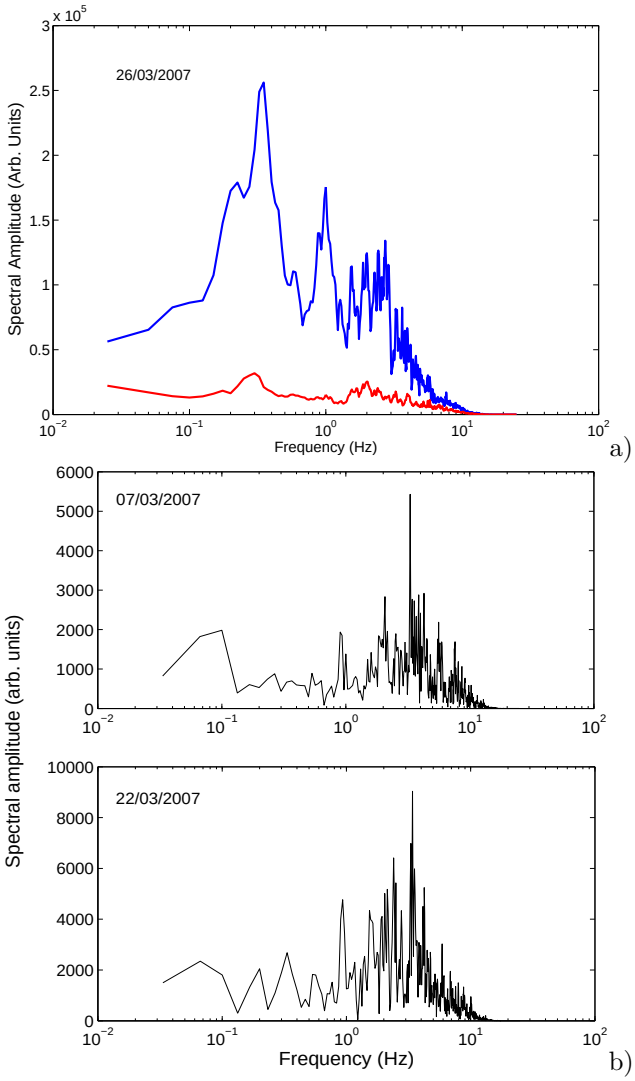
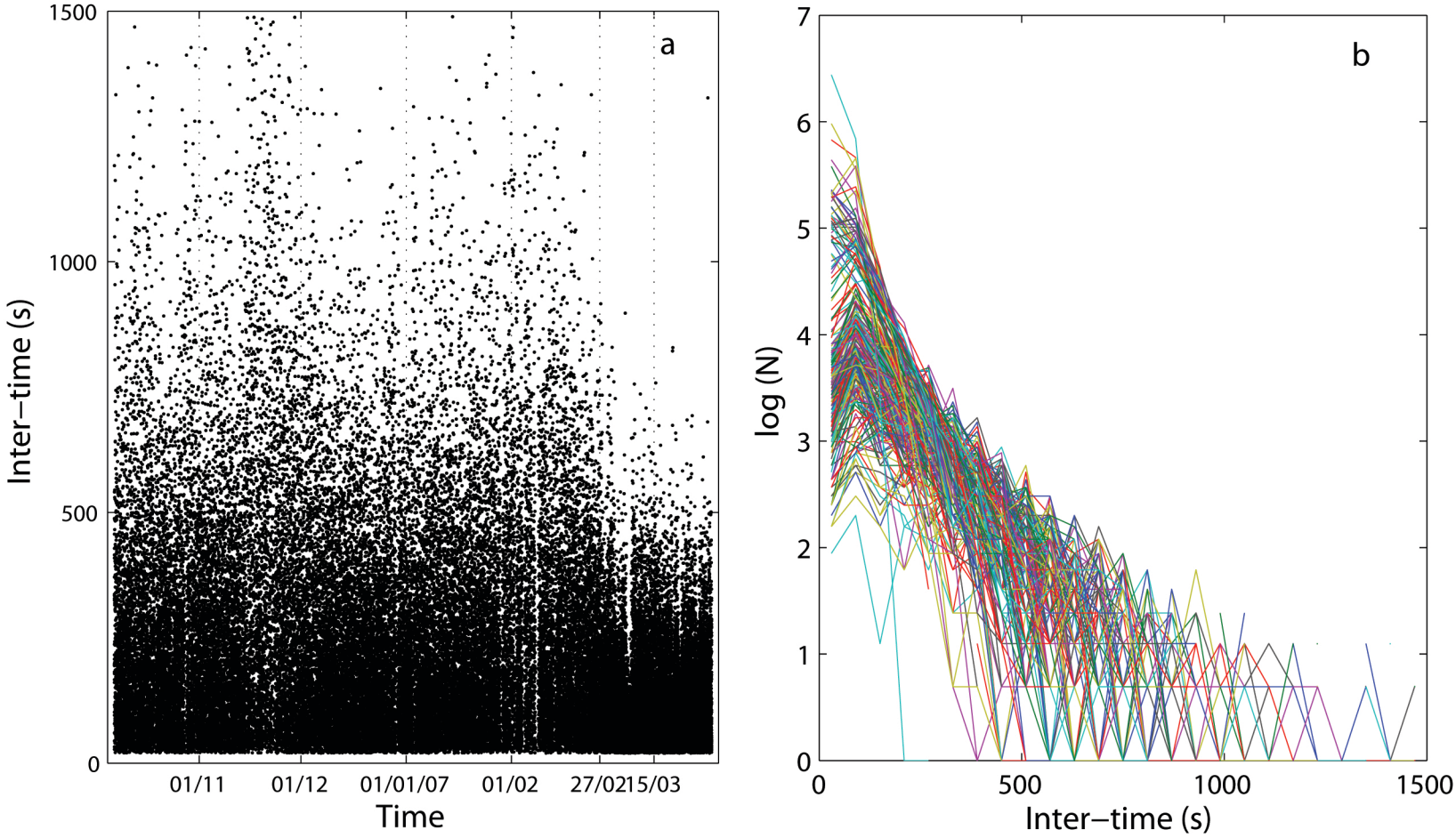
Stromboli
Google

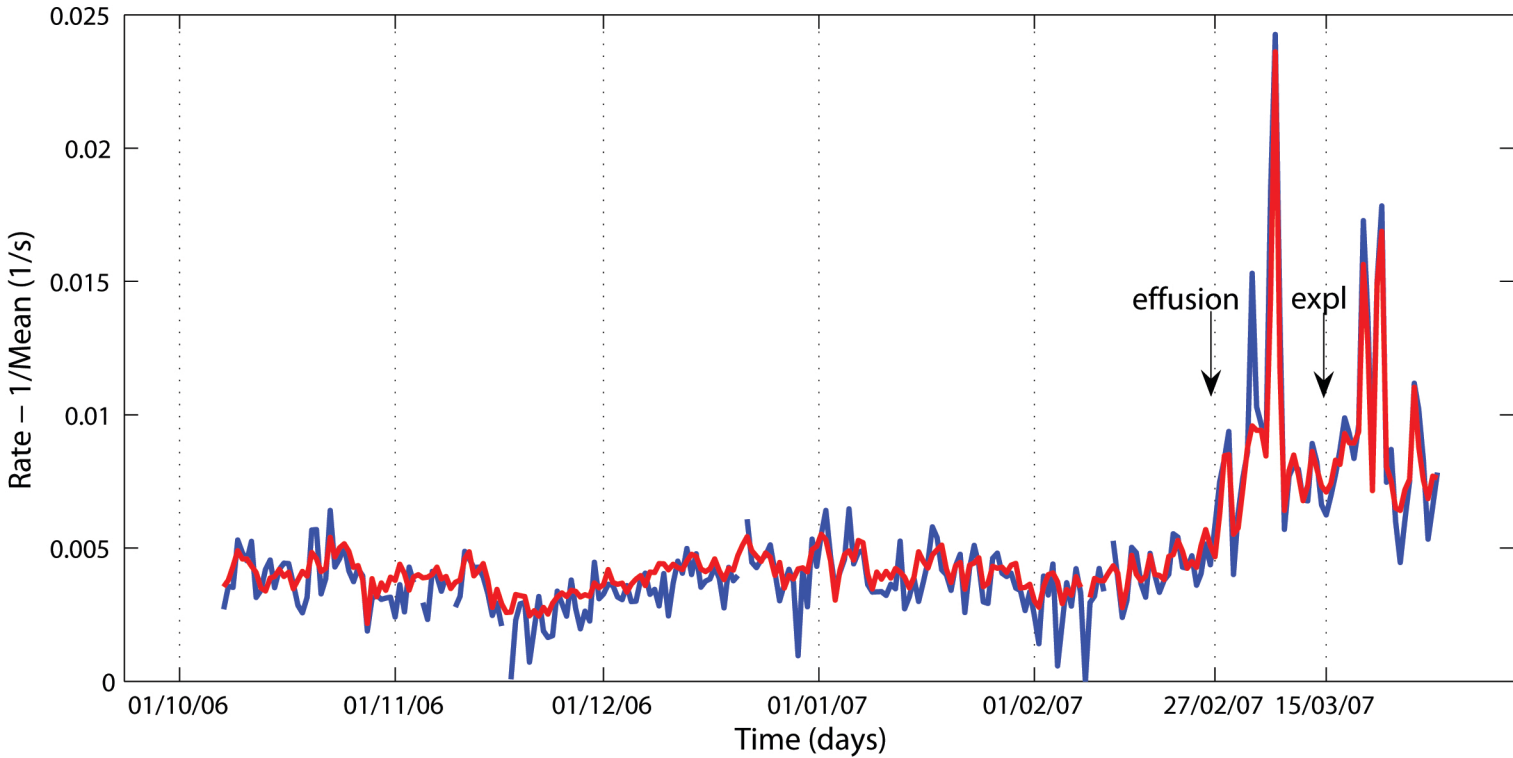

x 10^4
06/02/2007
1.5
0
−1.5
0
1000
2000
3000
4000
5000
6000
7000
x 10^4
10/03/2007
1.5
0
−1.5
0
1000
2000
3000
4000
5000
6000
7000
x 10^4
22/03/2007
1.5
0
−1.5
0
1000
2000
3000
4000
5000
6000
7000
Amplitude (counts)
Time (s)

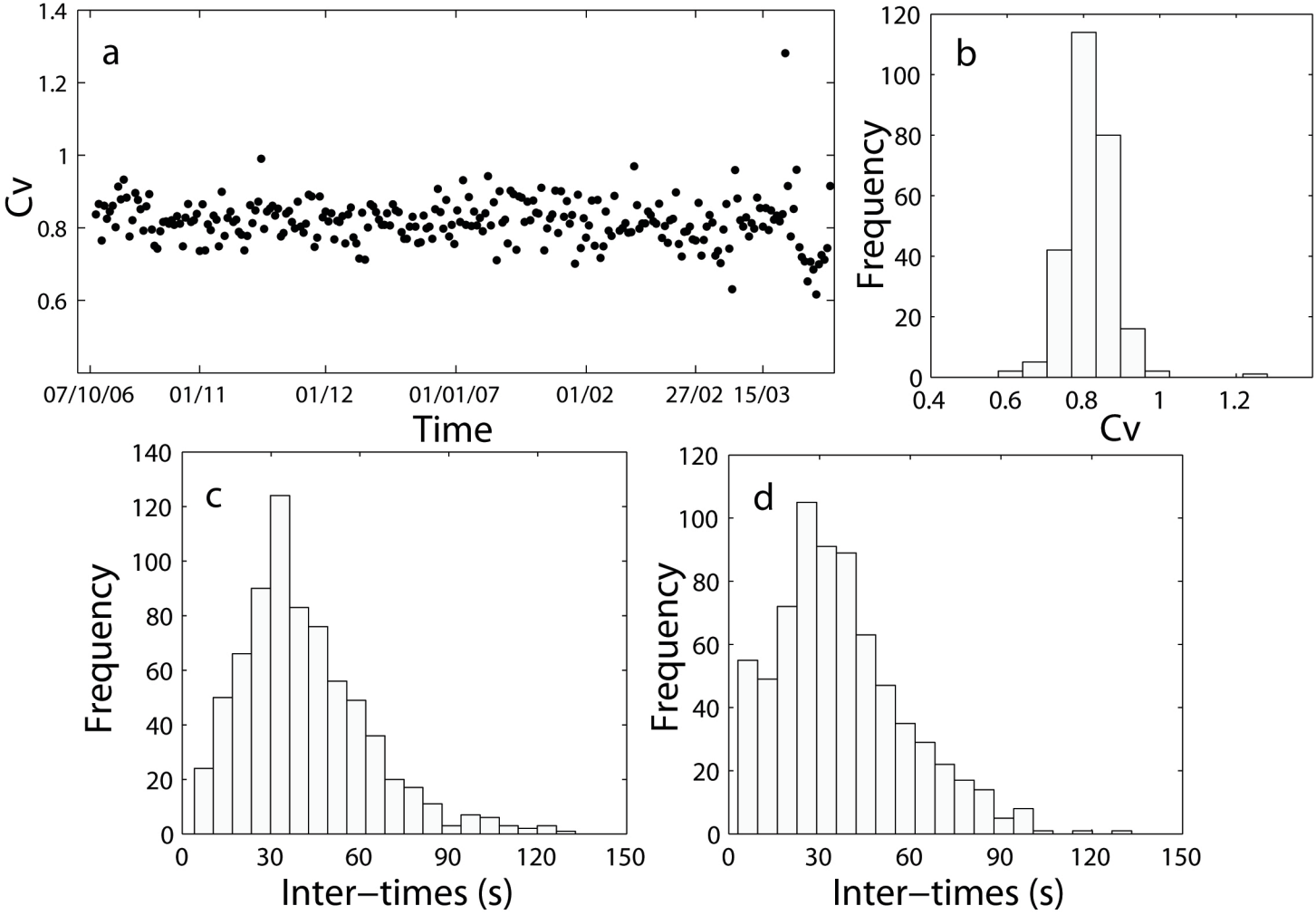

10/10/2006
06/01/2007
06/02/2007
26/02/2007
Spectral amplitude (Arb. Units)
Spectral amplitude (Arb. Units)
Frequency (Hz)
Frequency (Hz)
x 10^4
x 10^5
x 10^5
x 10^5

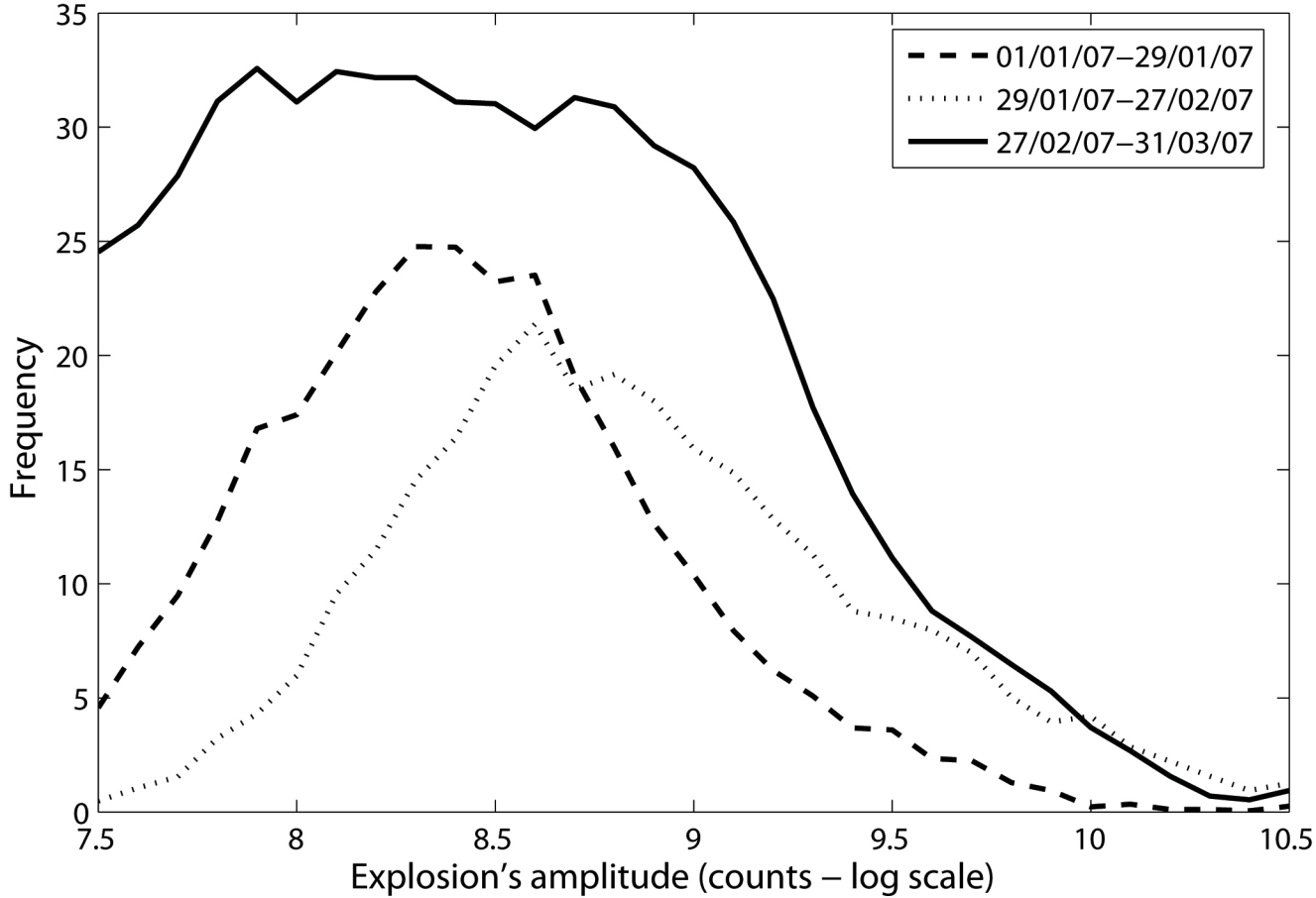

Events/hour
Number
150
100
50
0
Tremor
RMS (A.U.)
1
0.5
0
Averaged spectrogram
Freq. (Hz)
15
10
5
0
1
0
Normalized power Spectrum
06/11/06
06/11/06
05/01/07
04/02/07
06/03/07

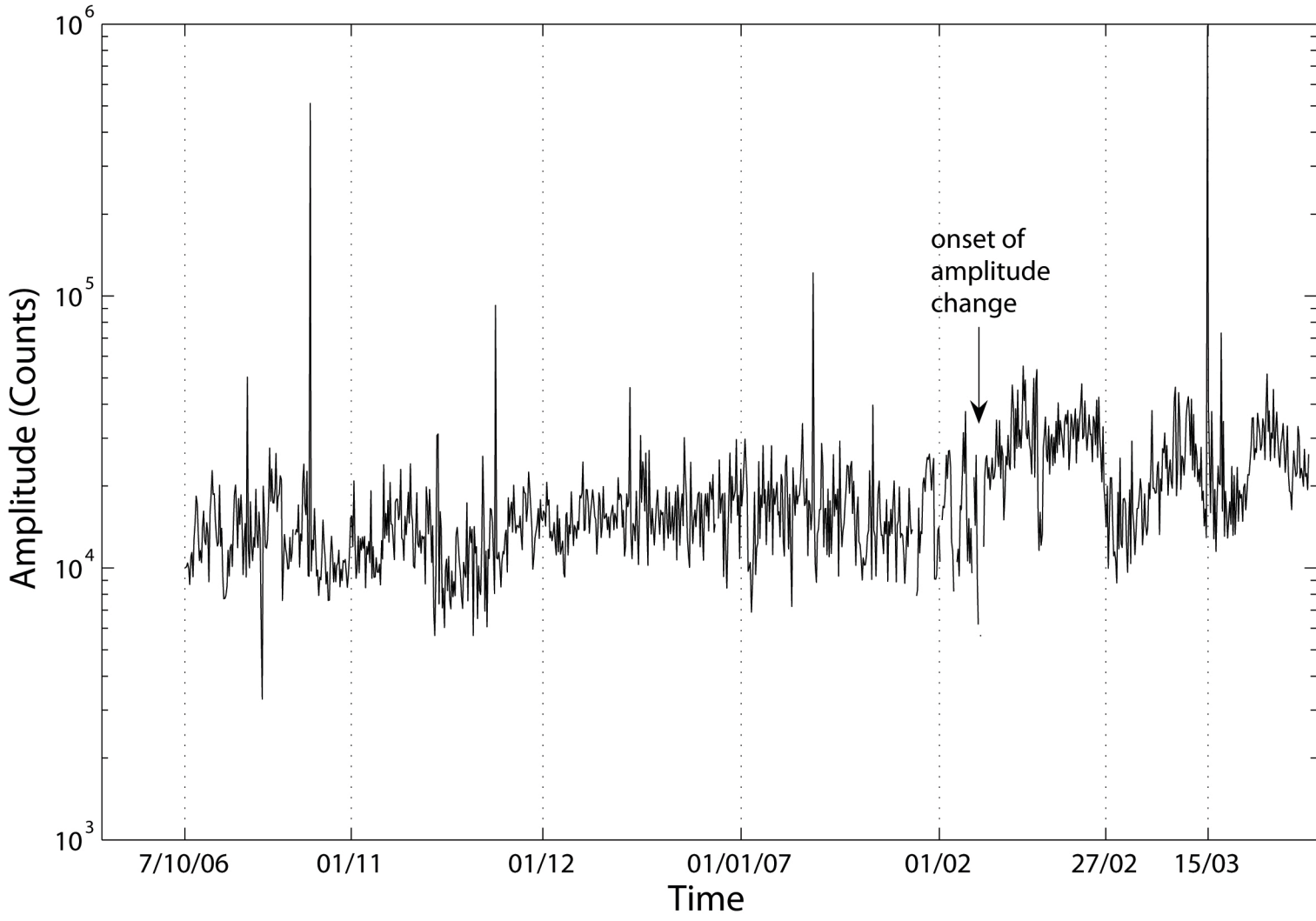

x 10^5
26/03/2007
Spectral Amplitude (Arb. Units)
Frequency (Hz)
a)
07/03/2007
22/03/2007
Spectral amplitude (arb. units)
Frequency (Hz)
b)

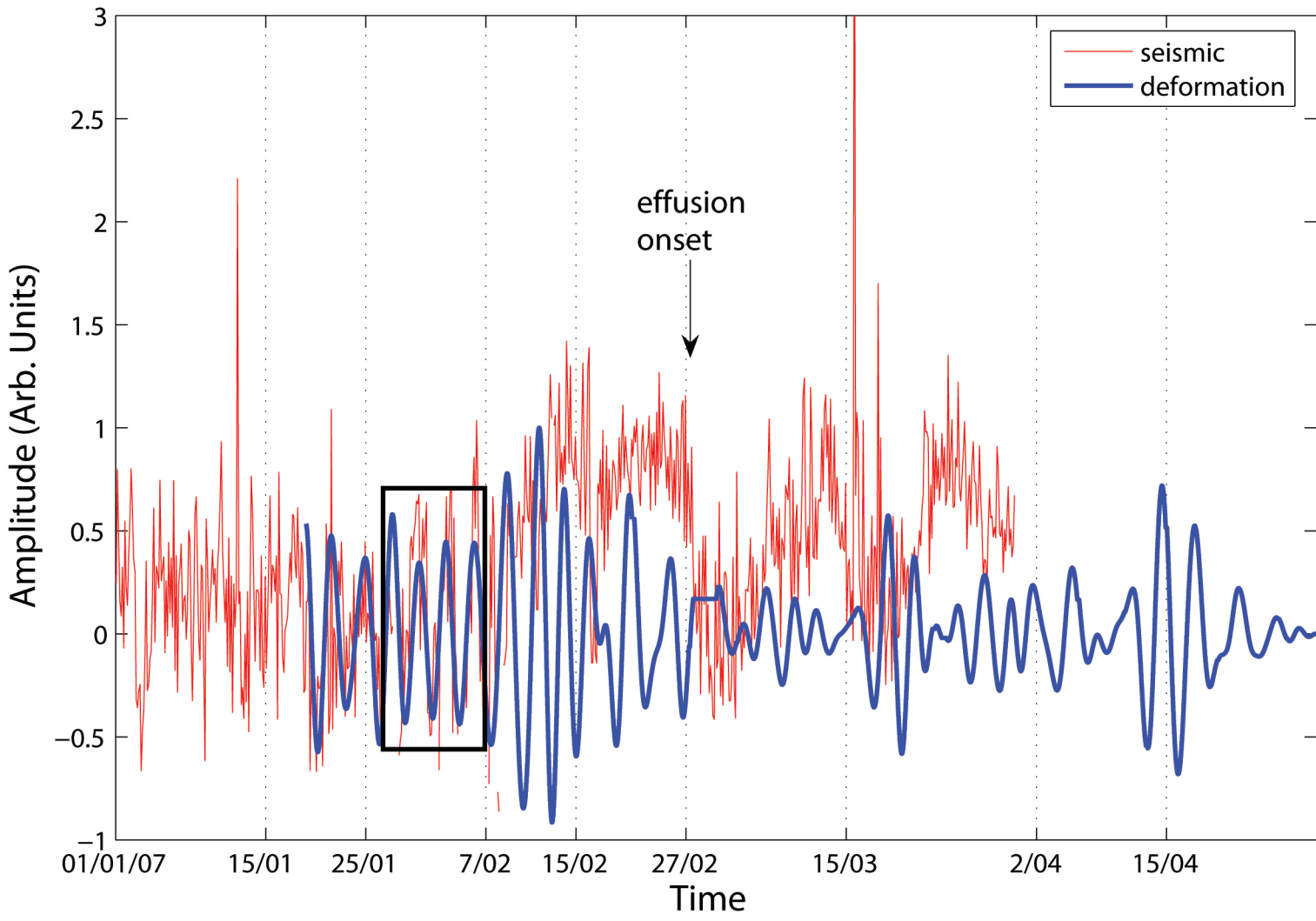

a
1500
1000
500
0
Inter−time (s)
01/11
01/12
01/01/07
01/02
27/02
15/03
Time
b
7
6
5
4
3
2
1
0
log (N)
0
500
1000
1500
Inter−time (s)

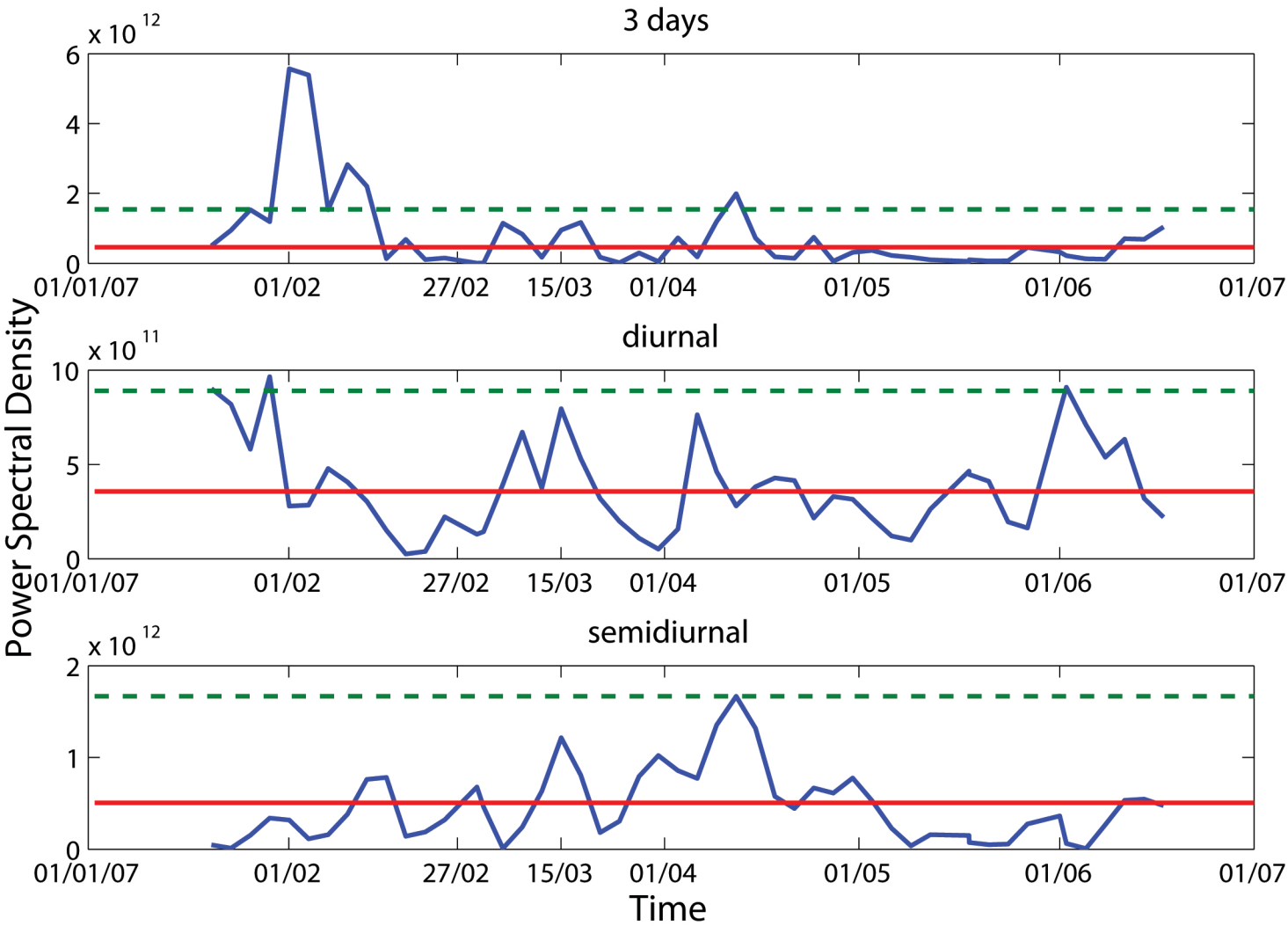

0.025
0.02
0.015
0.01
0.005
0
Rate – 1/Mean (1/s)
effusion
expl
01/10/06
01/11/06
01/12/06
01/01/07
01/02/07
27/02/07
15/03/07
Time (days)


a
Cv
1.4
1.2
1
0.8
0.6
07/10/06
01/11
01/12
01/01/07
01/02
27/02
15/03
Time
b
Frequency
120
100
80
60
40
20
0
0.4
0.6
0.8
1
1.2
Cv
c
Frequency
140
120
100
80
60
40
20
0
0
30
60
90
120
150
Inter−times (s)
d
Frequency
120
100
80
60
40
20
0
0
30
60
90
120
150
Inter−times (s)


01/01/07–29/01/07
29/01/07–27/02/07
27/02/07–31/03/07
Frequency
Explosion's amplitude (counts – log scale)
0
5
10
15
20
25
30
35
7.5
8
8.5
9
9.5
10
10.5


Amplitude (Counts)
$10^6$
$10^5$
$10^4$
$10^3$
onset of
amplitude
change
7/10/06
01/11
01/12
01/01/07
01/02
27/02
15/03
Time


seismic
deformation
effusion
onset
Amplitude (Arb. Units)
3
2.5
2
1.5
1
0.5
0
−0.5
−1
01/01/07
15/01
25/01
7/02
15/02
27/02
15/03
2/04
15/04
Time


3 days
x 10 12
6
4
2
0
01/01/07
01/02
27/02
15/03
01/04
01/05
01/06
01/07
diurnal
x 10 11
10
5
0
semidiurnal
x 10 12
2
1
0
Power Spectral Density
Time