An analytic expression for the volcanic seismic swarms occurrence rate

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Abstract

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Abstract

Seismic swarms are defined as a group of earthquakes occurring very close in time and space but without any larger event triggering their occurrence. Up to now no simple law has been found to describe the swarm occurrence rate. Here we find an expression able to fit the average occurrence rate on some volcanic areas. Such an expression exhibits some differences in respect of the usual Omori law. Namely the c parameter of the Omori law is equal to zero and the power law decay of the average occurrence rate of the earthquakes is followed by an exponential decaying regime. Both the results can be interpreted in term of fluid injection and/or movements. Indeed this is a more impulsive phenomenon, in respect to the occurrence of a large earthquake, with a duration compatible with a $c = 0$. The exponential decay following the power law one could explained by a viscoelastic relaxation of the stress induced by the injection and/or movements of fluids in the earth crust.

1 Introduction

When an earthquake occurs the stress released by its occurrence is redistributed to the surrounding rocks causing the occurrence of a number of aftershocks which depends on the magnitude of the triggering event (Helmstetter, 2003). The rate of occurrence is governed by the Omori law (Omori, 1894)

$$n = \frac{k}{(t+c)^p} \tag{1}$$

where n is the number of aftershock, t is the time elapsed from the mainshock occurrence and k, c and p are experimental constant. k depends exponentially on the mainshock magnitude (Helmstetter, 2003), c makes the Omori law normalizable, whereas p controls the velocity of aftershocks rate decay.

The Omori law is one of the principal ingredients for the ETAS model (Ogata, 1985, 1998) which views the earthquake occurrence as the superposition of a constant rate of occurrence μ and the aftershocks occurrence rate. They occur in a cascade process: a parent earthquake can generate some offspring who can, in turn, generate other offspring. This is a very general characteristic of aftershocks occurrence.

Differently from mainshock - aftershock sequences, earthquake swarms are defined as earthquakes clustered in space and time without a triggering events of higher magnitude (Hainzl, Fischer, & Dahm, 2012). Swarm activity has been associated to stress changes induced by aseismic processes such as pore pressure changes (Miller et al., 2004) or fluid intrusion (Toda, Stein, & Sagiya, 2002). Mogi (1963) firstly suggested that swarms occur in regions characterised by high heterogeneity in terms of material properties and stress concentration. Swarms are indeed recorded in volcanic, geothermal or tectonic environments (Hainzl & Fischer, 2002; Tramelli et al., 2021; White & McCausland, 2015) and their triggering mechanism is interpreted as due to volcanic processes or fluid injection and/or movements (Chouet, 1996; Glazner & McNutt, 2021; Hainzl, 2003; Tramelli et al., 2021). Volcanic swarms are usually the main reported seismic precursor for volcanic eruptions especially for volcanoes that have been silent for decades or more (White & McCausland, 2015).

A mechanical model to simulate the swarm occurence was obtained modifying the Burridge and Knopoff (1967) original one introduced by Hill (1977) and Hainzl (2003). They were able to explain some of the characteristics of earthquake swarms occurring in seismogenic structures driven by fluid injection and/or movements.

Some statistical models for swarm occurence modified the original ETAS one (Ogata, 1985, 1998) introducing a non stationary background seismic occurrence. The simplest approach was introduced by Lombardi, Marzocchi, and Selva (2006) who use the stationary ETAS model in moving time windows explaining the fluctuations of the ETAS model parameters. Marsan, Prono, and Helmstetter (2013) and Reverso, Marsan, and Helmstetter (2015) took into account of seismic transients like fault interactions, fluid and dike injections being able to recover, both in duration and in intensity, the changes in fault loading rates. Kumazawa and Ogata (2014) expressed $\mu(t)$ as a piece wise linear function, whereas Kattamanchi, Tiwari, and Ramesh (2017) made use of a spline function which allowed them to identify slow slip earthquakes occurring on subduction zones The authors enlighten as their approach could model earthquake sequences triggered by fluid/magma injections.

Even if many of these models can reproduce some statistical feature of the seismic swarms, it was not possible the fitting of the occurrence rate and neither the Omori law nor a simple relationship can well describe the temporal evolution of the volcanic earthquake swarms.The reason for such a difficulty must be sought in the duration of the swarms which are often very short and not provide a sufficient number of events for a reliable statistical analysis.

In the following we will show that, stacking many swarms in an average rate of occurrence, an analytic expression for the earthquake swarms time evolution can fit the experimental observations.

2 The data

Here we analyse five earthquake catalogues of corresponding volcanic areas: Campi Flegrei (CF) (1982-1984), Campi Flegrei (2000-2019), Etna (S. et al., 2015), Hawaii, Costa Rica. The web sites where the catalogues can be downloaded are reported in Table 1, whereas Table 2 reports the time periods of the catalogues, the earthquake number in each one of them and the completeness magnitude here adopted. This quantity has been estimated by using the goodness of fit method (Wiemer & Wyss, 2000) and the method introduced by Godano (2017). In most of cases the two methods estimate the same value and, when there are differences, we adopted the larger value between the two estimations.

Table 1. The areas and the web sites from where the earthquake catalogues can be downloaded.

Catalogue	web site
Costa Rica	`https://doi.org/10.5281/zenodo.6383911`
CF 1982-1984	`https://doi.org/10.5281/zenodo.6376561`
CF 2000-2019	`sismolab.ov.ingv.it/sismo/CATALOGO_STATICO/FLEGREI/fle_2000_2019.html`
Etna	`ct.ingv.it/index.php/monitoraggio-e-sorveglianza/banche-dati-terremoti/terremoti`
Hawaii	`https://earthquake.usgs.gov/fdsnws/event/1/`

3 Individuating the seismic swarms and defining the rate of occurrence

The first step of our investigation is to separate the earthquake swarm from the background seismic activity. This result can be obtained using the clustering properties of earthquake occurrence. In order to characterise these properties we use the distribu-

Table 2. The temporal periods, the number of events in the catalogues and the completeness magnitude of the catalogues here analysed.

Catalogue	initial date	final date	N	m_c
Costa Rica	2005/01/03	2021/12/31	19372	2.4
CF 1982-1984	1982/02/04	1984/12/31	5775	1.0
CF 2000-2019	2000/08/22	2019/12/31	1489	0.4
Etna	2000/01/01	2016/12/31	8983	2.6
Hawaii	2000/01/01	2018/05/31	64076	1.8

tion of the time interval between two successive events. In the following we refers at this quantity as the inter-event time Δt. Let us, firstly, to recall the fundamental results obtained on this distribution.

3.1 The inter-event time distribution

The main result obtained on the inter-event time distribution during the last twenty years, is that the Δt distribution $p(\Delta t)$ can be considered universal when the inter-event times Δt are rescaled by the mean occurrence rate, R (A. Corral, 2003, 2004, 2006). Namely, $p(\Delta t)$ is independent of the geographic zone and the magnitude threshold. This implies that R defines a 'local' time scale that characterises the earthquake occurrence whereas their clustering properties can be considered universal. This result was firstly obtained for pseudo-stationary periods revealing that earthquakes tend to cluster even if their occurrence is apparently Poissonian (A. Corral, 2004). The universality of $p(\Delta t)$ has been also observed for non-stationary periods (A. Corral, 2009) and for aftershock sequences (Bottiglieri, Lippiello, Godano, & De Arcangelis, 2011; Shcherbakov, Yakovlev, Turcotte, & Rundle, 2005). However the universal behaviour of $p(\Delta t)$ has been questioned (Hainzl, Scherbaum, & Beauval, 2006; Lindman, Jonsdottir, Roberts, Lund, & Bödvarsson, 2005; Molchan, 2005; Saichev & Sornette, 2006, 2007; Sornette, Utkin, & Saichev, 2008; Touati, Naylor, & Main, 2009). In particular, deviations from universality at small Δt have been related to interplay between correlated earthquakes, which follow a Gamma distribution (see appendix for more details), and uncorrelated events, which follow pure exponential decay. The departure from universality has been solved by Bottiglieri, de Arcangelis, Godano, and Lippiello (2010) who showed that four typical time scales are relevant for the interevent time distribution scaling: the inverse rate of independent events, λ, the mean inverse rate of correlated events, the time parameter c defined in the Omori law, and the catalogue duration T (the last one is irrelevant for the analysis here presented).

3.2 The role of the space

Earthquake swarms can be characterised also by their spatial clustering. In order to take into account the role of the space we evaluate the conditioned probability density of Δt given a $\Delta r < \delta$, where Δr is the epicentral distance between the same successive events with an inter-event time Δt and δ is a fixed value. More precisely, if Δt is the inter-event time between the ith earthquake and the $1{+}i$th one, it is counted in the distribution only if Δr (the inter-distance between the ith earthquake and the $1+$ ith one) assumes a value $\leq \delta$. δ has been fixed in different ranges depending on the size of the investigated areas. The δ values can be found in the legends of figure 1 showing the conditioned probability density $p(\Delta t|\Delta r \leq \delta)$.

As can be seen $p(\Delta t|\Delta r \leq \delta)$ does not depend on δ with the exception of Etna and Hawaii for the smallest values of δ. This implies that, for Etna and Hawaii, no background activity is included in the analysis when δ assumes very small values. Nevertheless, here we need to include some background activity in order to individuate the swarms as an increase of the seismic activity as compared to the background occurrence rate.

The $p(\Delta t|\Delta r \leq \delta)$ follows a Gamma distribution characterised by two parameters: α controlling the power law decay of the distribution and Θ representing the Δt value after which the exponential decay becomes dominant. The two parameters have been estimated using a maximum likelihood method (see Appendix). In table 3 we report only the values of Θ because it will be useful in the swarm individuation (see next section).

3.3 The earthquakes swarms and the Omori law

As stated before we use the value of Θ for discriminating between the background activity and the swarms occurrence. More precisely the swarm starts when $\Delta t \leq \Theta|\Delta r \leq \delta$ and ends when $\Delta t > \Theta|\Delta r \leq \delta$. Indeed Θ^{-1} can be viewed as the largest observable occurrence rate of the background earthquakes (where observable means not hid-

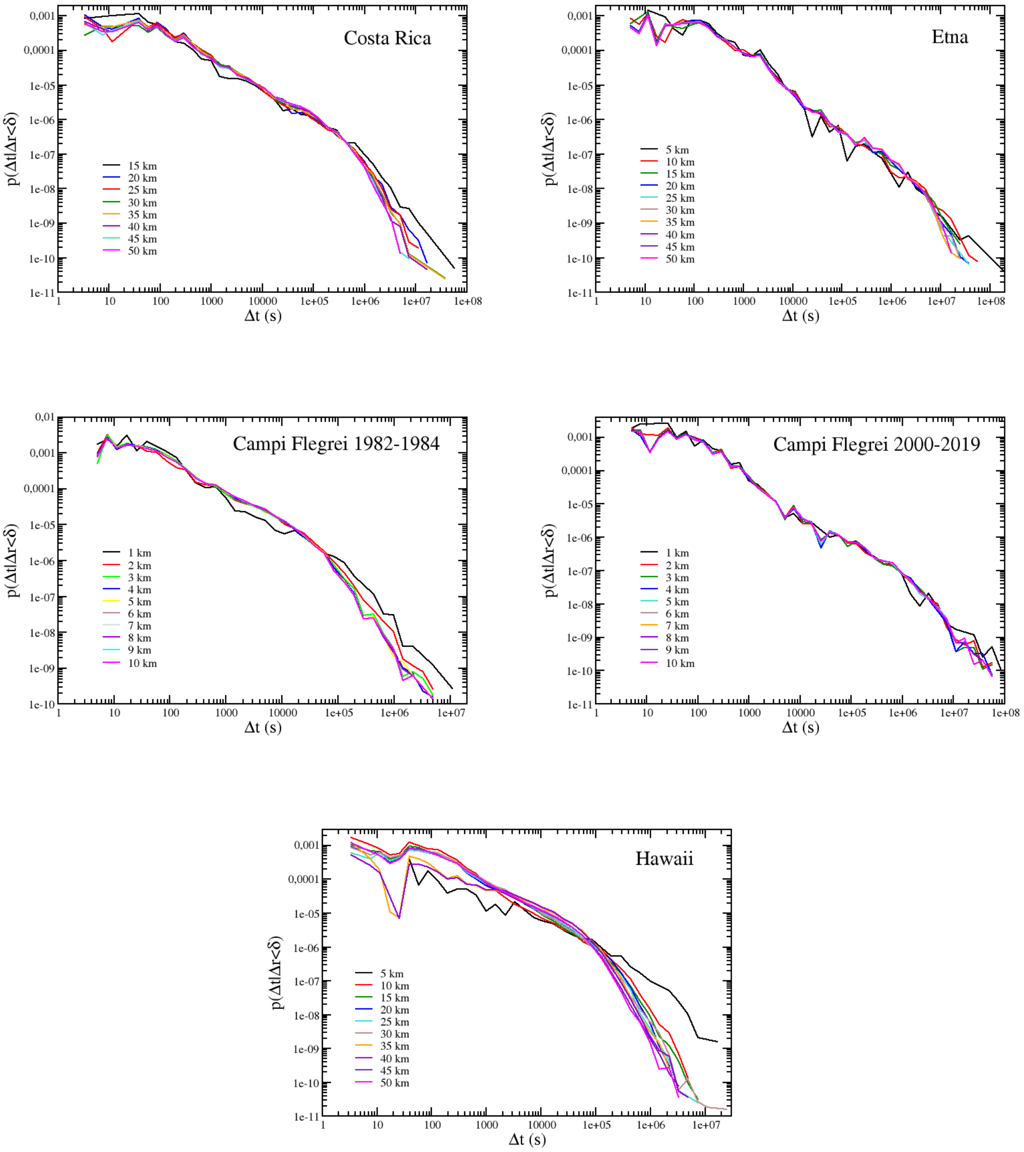

Figure 1. The conditioned probability density $p(\Delta t|\Delta r \leq \delta)$ for the five volcanic catalogues here analysed. The minimum δ value has been obtained under the request of at least 150 events satisfying the condition $\Delta t|\Delta r \leq \delta$).

Table 3. The values of θ for the earthquake catalogues here analysed.

Catalogue	Θ
Costa Rica	450000 (s)
CF 1982-1984	55000 (s)
CF 2000-2019	500000 (s)
Etna	200000 (s)
Hawaii	80000 (s)

den by the swarm events occurrence rate). Conversely the $\Delta t \leq \Theta$ intertime values characterise the occurrence of clustered events in the earthquake swarms. In order to have a qualitative feedback of our choice, figure 2 shows the cumulative number of events for the whole catalogue (black squares) and for the events selected as swarms (red circles). As can be seen the rate of occurrence increases significantly in correspondence of the individuated swarms revealing that the method recognise the seismic swarms efficiently. In figure 2 we use the largest δ value reported in the figure 1 labels. However the δ value do not influence the selection of the swarms simply because Θ is δ independent.

As a counter proof of the goodness of our choice for the earthquake swarms, we show (figure 3) the intertime distribution during the periods outside the swarms. As expected the distribution appear to be exponential for all the catalogues here analysed revealing their Poissonian occurrence and confirming the goodness of our choice.

The great part of the individuated swarms are very short and do not allow the investigation of their time behaviour. As a consequence we have stacked all of them in a unique average Omori law for each catalogue. Namely we count the number of events occurred at the time t elapsed from the beginning of the swarm and for each class t the different $n(t)$ are summed and divided by the number of classes with $n(t) \neq 0$ building an average rate of occurrence $\nu(t|\Delta r \leq \delta)$ for each catalogue here analysed. Figure 4 shows $\nu(t|\Delta r \leq \delta)$ opportunely rescaled in order to have a collapse on a unique master curve and to better evidence their independence of the δ value.

For all the catalogues we obtain a $\nu(t|\Delta r \leq \delta)$ that can be described as a power law tapered by an exponential decrease after a given value of t. However the Campi Fle-

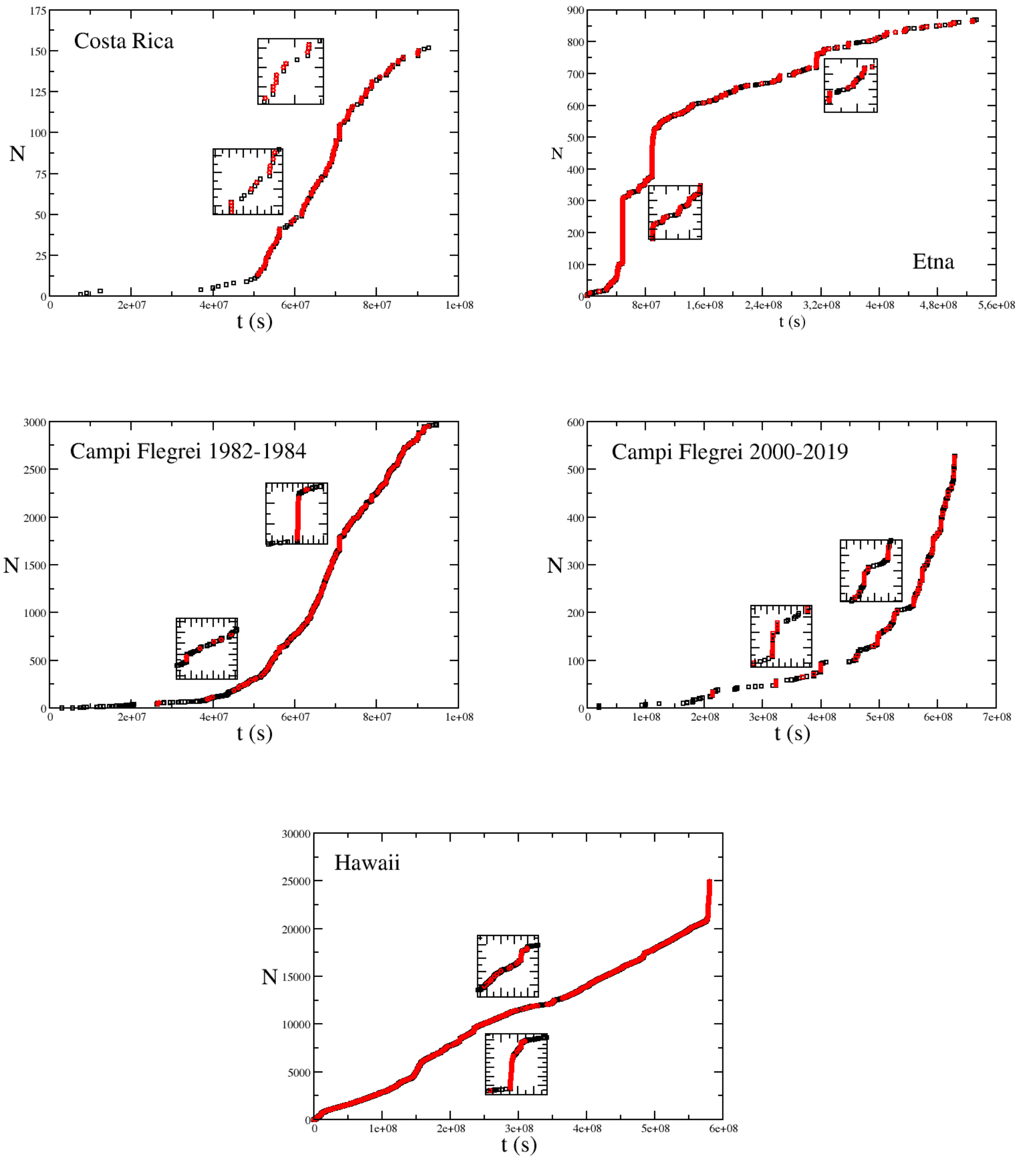

Figure 2. The cumulative number of earthquakes as a function of time for the whole catalogues (black squares) and for the individuated swarms (red circles). The insets represent a zoom of the curve in proximity of the square corner closest to the curve.

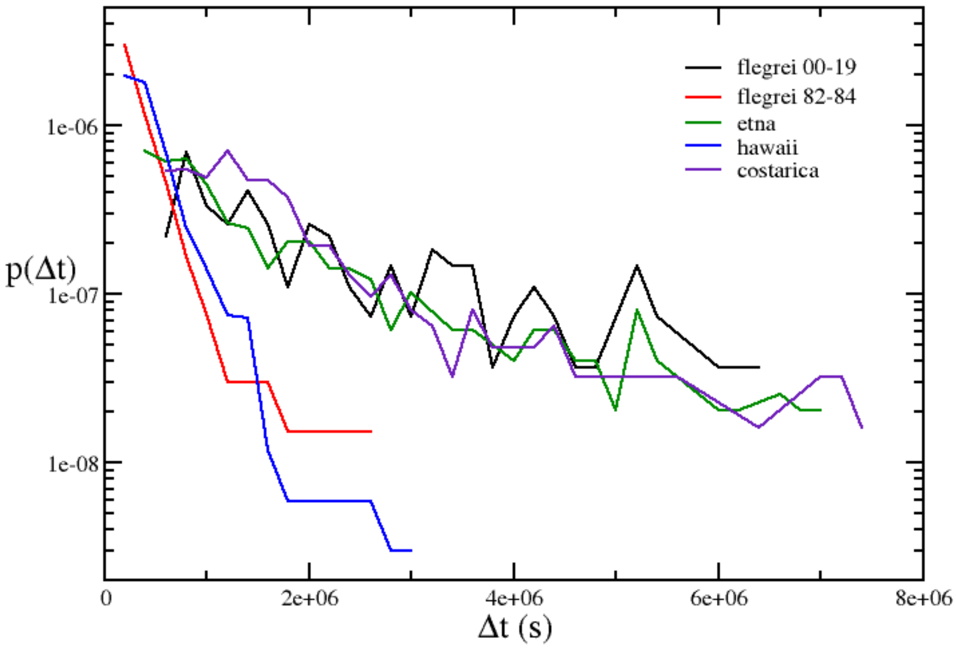

Figure 3. The intertime between two successive events occurring during periods outside the swarms.

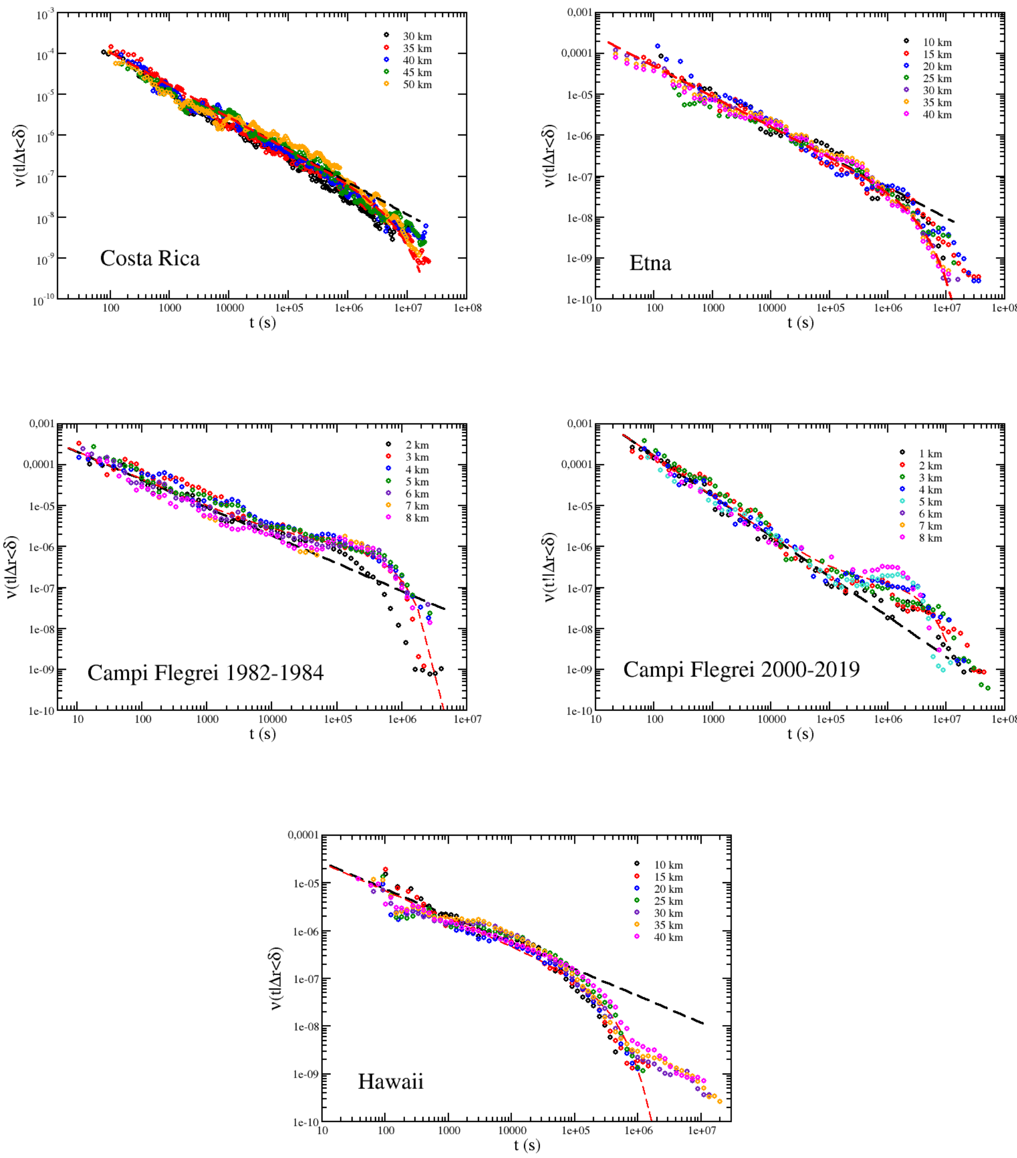

Figure 4. The conditioned rate of occurrence $\nu(t|\Delta r \leq \delta)$ for the five volcanic catalogues here analysed. The standard deviation is of the same order of magnitude of the symbol size.

grei catalogues after the power law decay presents a bump in the average occurrence rate eventually followed by an exponential decay whereas the Hawaii catalogue exhibits a more flat regime at $t > 10^6$(s) for δ=30, 35 and 40 km.

An interpretation and the fit of these behaviour will be provided in the next section.

3.4 The productivity law

We have verified that the volcanic swarms occurrence rate can be assimilated to an Omori law. Let us to verify if the productivity law holds also for volcanic earthquakes. As suggested by Helmstetter (2003) the number of events in a seismic sequence, grows exponentially with the magnitude of the mainshock. However, for the earthquake swarms, it is not possible to speak of a mainshock. As a consequence, we evaluate the number of events in a swarm as a function of the largest event magnitude, m_L, in the swarm. Figure 5 shows that the productivity laws are independent of the δ values with the exception of the Hawaii catalogue.

Following Shebalin, Narteau, and Baranov (2020) we also investigated the productivity through the distribution $p(n)$ of the number of earthquakes per swarm. Figure 6 confirms the results of Shebalin et al. (2020): $p(n)$ follows a power law distribution. However the smallest value of n is, in our case, 2 simply because it is impossible to have swarms with $n < 2$.

As expected the distribution of occurrence time t_L of the largest earthquake in the swarm in respect to the beginning time t_b of the swarm reveals that in all the cases $t_L > t_b$ (figure 6) confirming that the mechanism of triggering the earthquake swarms is different by the one of the tectonic sequences which are triggered by the mainshock.

This result confirms the idea that earthquake swarms are not triggered by the occurrence of a large events.

4 Discussion

In the previous section we have shown that many of the results obtained for the earthquake sequences can be extended to the volcanic earthquakes with some substantial difference.

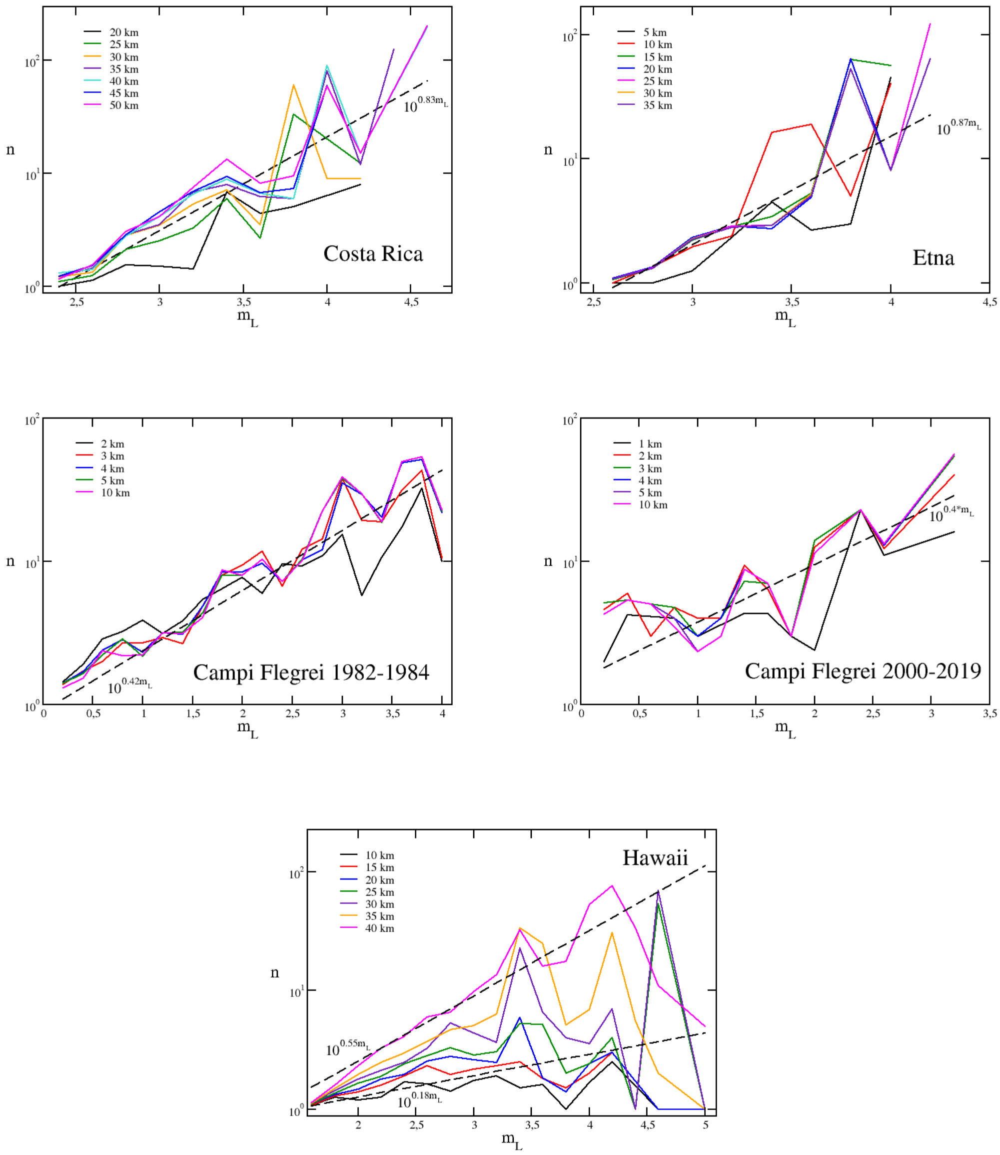

Figure 5. The conditioned productivity laws for the five volcanic catalogues here analysed.

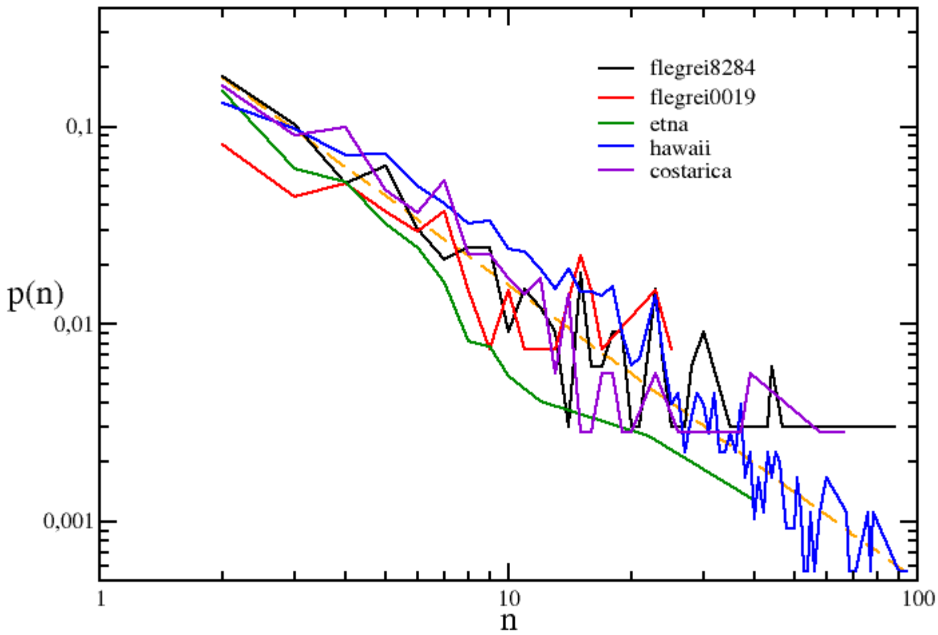

Figure 6. The distribution of the number of events per swarm n for the five volcanic catalogues here analysed.

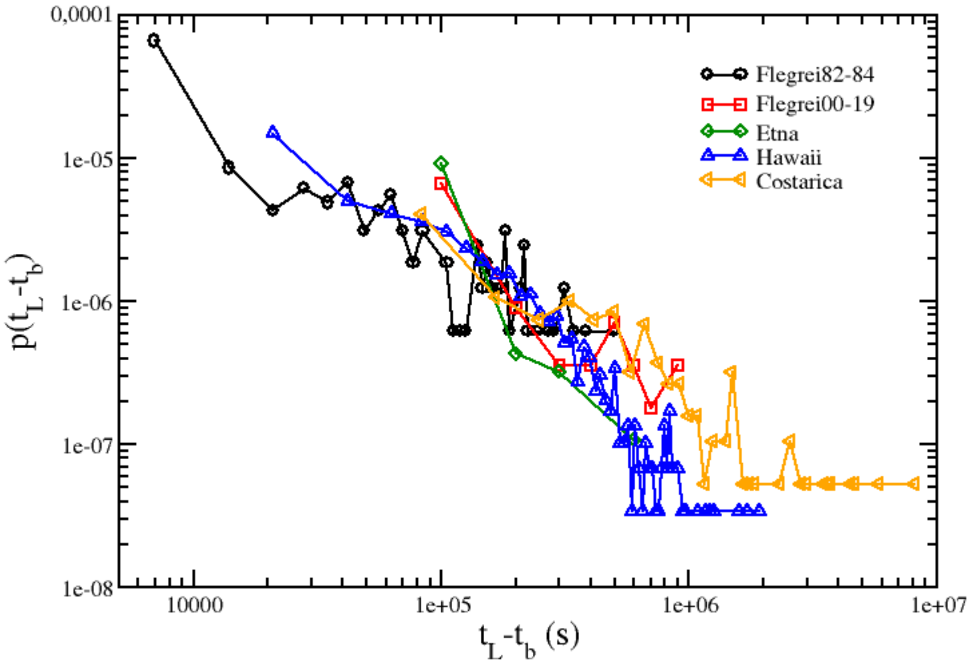

Figure 7. The distribution of $t_L - t_b$ for the five volcanic catalogues here analysed.

The intertime distribution follows, as for the earthquake sequences, a Gamma one. As well known this is characterised by a power law decreases with Δt followed by an exponential one. The first regime is characteristic of earthquakes clusters, whereas the exponential regime characterises the occurrence of the background seismic activity (Bottiglieri et al., 2010; A. Corral, 2003, 2004, 2006; Godano, 2015; Molchan, 2005). The parameter Θ separate the two regimes and has been here used for successfully individuate the seismic swarms. The Δt distribution appears to be independent of the δ value revealing that it is not influenced by the spatial occurrence properties. This result was unexpected because the spatial proximity is part of the definition of earthquake swarms. However it simply reveals that the occurrence probability of simultaneous swarms at different zone of the same volcanic area is very small, even if the area is characterised by the presence of many volcanoes as in Costa Rica or Hawaii.

The analysis of the Δt distribution allows us to individuate the seismic swarms and to build for each catalogue an average swarm rate of occurrence. Figure 4 shows as this occurrence rate exhibits some differences in respect to the Omori law. The first one is that the parameter c appears to be equal to zero. However the presence of an exponential tapering at high values of t allows the normalisation of the occurrence rate expression:

$$\nu(t) \propto (t^{-p} + \mu)e^{-\frac{t}{\tau}} \tag{2}$$

where p assumes the same meaning of the usual Omori law p value and τ is the elapsed time from the beginning of the swarm at which the exponential decay becomes dominant. The parameter μ is the constant rate of background occurrence seismicity here introduced to explain the bump in the rate of occurrence just before the exponential regime (Figure 4) observed for the Campi Flegrei catalogues.

We have fitted the parameters of Eq.s (2) through the minimisation of the χ^2. More precisely we explore the parameter space looking for the minimum value of the χ^2. The estimated parameters are reported in table 4.

Let us to provide an interpretation of the three main differences with the standard Omori law. Namely the c is equal to zero and the power law rate regime is followed by an exponential one.

Table 4. The estimated values of the parameters p, τ and μ for the five catalogues here analysed.

Catalogue	p	τ	μ
Costa Rica	0.79	$5.8 \cdot 10^6$ (s)	0 (s^{-1})
CF 1982-1984	0.68	$5 \cdot 10^5$ (s)	10^{-3} (s^{-1})
CF 2000-2019	0.98	$2.8 \cdot 10^6$ (s)	10^{-5} (s^{-1})
Etna	0.74	[$2.8 \cdot 10^6$,$82 \cdot 10^6$] (s)	0 (s^{-1})
Hawaii	0.58	$3.1 \cdot 10^5$ (s)	0 (s^{-1})

1. The c value represents a physical time during which aftershocks do not yet occur or are not recorded. It can be explained in terms of many physical processes, namely the faulting duration, a not perfectly elastic behaviour of the rock introducing a delay in the mechanism of stress release, higher resistance of the unbroken patches of the fault delays the occurrence of the aftershocks, etc. In the case of the seismic swarms the triggering phenomenon is not the occurrence of a large earthquake, but the intrusion and/or movements of fluids (see, among the others, Chouet (1996); Glazner and McNutt (2021); Hainzl (2003); Hill (1977); Tramelli et al. (2021)). This can be considered a more impulsive phenomenon, moreover the presence of fluids lubricates the existing faults making more rapid the response to the stress impulse. As a consequence the c value becomes negligible.
2. We interpret the exponential decay after the power law regime as due to a viscoelastic effect in the hypothesis that the occurrence rate is proportional to the stress rate. Indeed the higher temperature of the volcanic rocks makes their rheological behaviour more viscous than the rocks of the tectonic areas. As a consequence, when the fluid is not injected or moved anymore, the induced stress on the surrounding rocks is released following a viscous relaxation causing the exponential decay of the occurrence rate.
3. The presence of the μ constant term here introduced for explaining the bump in the occurrence rate for the Campi Flegrei catalogues deserves a short discussion. Indeed it should not be confused with the background activity which is a constant rate of occurrence to be added to the swarms activity and represent a Poissonian

process independent of the swarm triggering mechanism. Conversely μ should be considered as an integral part of the swarm that ceases when the fluid intrusion and/or movements stops. In this sense the triggering mechanism causes an increase of the stress generating the swarm activity and, moreover, causes a Poissonian occurrence of other earthquakes that could be generated by a mechanism of fault lubrication due to the presence of fluids. The observation of μ only at Campi Flegrei is easy to explain noting that the m_c values are significantly higher for the other volcanoes. Indeed the background seismicity is dominated by smaller events and, as a consequence, the background activity, occurring during the swarms, cannot be observed for the catalogues with a large value of m_c (see table 2).

Finally the Hawaiian greater productivity for δ=30, 35 and 40 km can be explained observing that for those δ values the rate of occurrence exhibits an approximately flat regime (for $t > 10^6$ s) evidencing that, in these cases, some background activity has been included in the analysis.

5 Conclusions

The general interpretation of earthquake occurrence is that the stress induced by the plate tectonics drives the crustal rocks at a critical state which allows the occurrence of random earthquakes whose magnitude follows the Gutenberg-Richter distribution. Moreover, when an earthquake occurs, it diffuses, in the crust, the accumulated strain generating new stress able to give rise to the occurrence of other earthquakes. Generally the two classes of earthquakes are called mainshocks and aftershocks. The number of aftershocks depends on the magnitude of their mainshock (Helmstetter, 2003) and decreases in time as t^{-p} (Omori, 1894). However such a behaviour is not observed for seismic swarms occurring on volcanic, geothermal or tectonic environments where fluids injections and/or movements generate an instant increase of the stress.

Up till now neither the Omori law nor any other simple law has been found to fit the swarm occurrence rate. However the earthquake distribution within swarm has been found to be fractal and the intertime distribution and their spatio-temporal spreading was fitted by power laws at least for the swarm recorded in the Vogtland region (Hainzl, 2003; Hainzl & Fischer, 2002).

We have shown that, stacking the occurrence rate of many swarms it is possible to express the earthquake swarms occurrence rate as a power law decay tapered by an exponential decay allowing its normalisation. The definition of such an expression could also aim at boosting some debate on the swarms definition and could be useful in the definition of the seismic risk where the triggering mechanism is represented by fluids injections and/or movements.

6 Appendix

The Gamma distribution can be defined as:

$$p(\Delta t) = \frac{1}{\Gamma(\alpha)} \Delta t^{\alpha-1} e^{-\Delta t/\Theta} \tag{3}$$

The two parameters of this distribution can be easily estimated by the maximum likelihood method. The log-likelihood for the 3 distribution is:

$$LL = (\alpha - 1) \sum_i \Delta t_i - N \frac{\langle \Delta t \rangle}{\theta} - NK \log \Theta - N \log \Gamma(\alpha) \tag{4}$$

A correct estimation of the parameters involves the derivative of $\Gamma(\alpha)$, however an approximated estimation is provided by $\alpha = \frac{3-s+\sqrt{(s-3.)^2+24s)}}{12s}$ with $s = \log\langle \Delta t \rangle - \langle \log \Delta t \rangle$ and $\Theta = \frac{\langle \Delta t \rangle}{\alpha}$.

7 Declarations

The authors declare that there is no conflict of interest.

8 Ethical statements

All materials and results here presented have not been previously published elsewhere. The paper properly credits the meaningful contributions of co-authors.

9 Data availability

Data here used can be found and downloaded at the web-sites: `https://doi.org/10.5281/zenodo.6383911`, `https://doi.org/10.5281/zenodo.6376561`, `sismolab.ov.ingv.it/sismo/CATALOGO_STATICO/FLEGREI/fle_2000_2019.html`, `ct.ingv.it/index`

.php/monitoraggio-e-sorveglianza/banche-dati-terremoti/terremoti, https://earthquake.usgs.gov/fdsnws/event/1/

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