Short-term volcano-tectonic earthquake forecasts based on a moving Mean-Recurrence-Time algorithm: the El Hierro seismo-volcanic crisis experience

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Abstract. Under certain conditions volcano-tectonic (VT) earthquakes may pose significant hazards to people living in or near active volcanic regions, especially on volcanic islands; however, hazard arising from VT activity caused by localized volcanic sources is rarely addressed in the literature. The evolution of VT earthquakes resulting from a magmatic intrusion shows some orderly behavior that may allow forecasting the occurrence and magnitude of major events. Thus governmental decision-makers can be supplied of warnings of the increased probability of larger-magnitude earthquakes in the short term time-scale. We present here a methodology for forecasting the occurrence of large-magnitude VT events during volcanic crises; it is based on a Mean-Recurrence-Time (MRT) algorithm that translates the Gutenberg-Richter distribution parameter fluctuations into time-windows of increased probability of a major VT earthquake. The MRT forecasting algorithm was developed after observing a repetitive pattern in the seismic swarm episodes occurring between July and November 2011 at El Hierro (Canary Islands). From then on, this methodology has been applied to the consecutive seismic crises registered at El Hierro, achieving a high success rate in the real-time forecasting, within 10 day time-windows, of volcano-tectonic earthquakes

1 Introduction

Volcano-tectonic (VT) earthquakes are considered to be low-magnitude compared to tectonic earthquakes, even though in some cases (three in the 20th century) they have reached M$\geq$7 (Zobin, 2001). Volcanic earthquakes occurring near active subduction zones, which may often reach magnitudes in the range 4-6, rarely cause the same degree of damage or concern among the population that stronger tectonic earthquakes cause. However, in volcanic regions with low tectonic activity,

and consequently with a higher vulnerability to strong ground motions, events exceeding M4 may produce significant damage. Such a situation may become quite serious when that type of VT activity occurs in volcanic islands with unstable topographies, prone to land-slides, as is the case of El Hierro, the westernmost, youngest (< 2 Ma, Ancochea et al, 1994), and smallest (269 km^2) of the Canary Islands.

In general, earthquake forecasting requires answers to four questions: where, when, how likely and how large? In VT earthquake forecasting, the answer to where is constrained by the extent of the volcanic system. The answer to the second question on timing is related to the onset and evolution of a volcanic crisis. Such crises are generally characterized by VT seismic swarms, lasting an average of 5.5 days in the case of El Hierro, concentrated in regions within or around the volcanic system, and generally defined as "a sequence of events closely clustered in time and space" (Benoit and McNutt, 1996). Since such swarms may include events of damaging magnitudes, it is important to detect the non-random components of the swarm evolution, as it contains factors linking different stages of the process that may allow major VT events to be forecast. We assume that such "causal factors" are related to the nature of the magmatic intrusion process at depth that involves an increasing accumulation of localized stress, which produces the VT earthquake when released. In particular, the magmatic intrusions may produce clustered sources of stress in which pressure increases over relatively short time-scales.

We picture the situation at El Hierro as voluminous bodies of dense magma intruding into the mantle under the crust from a deeper magma generation region (Martínez-Arevalo et al, 2013). That magma is dense enough to remain in almost isostatic equilibrium at the base of the crust in a process of magmatic underplating (Leahy et al, 2010). As it evolves under the local conditions at mantle-crust boundary depths, the diffusive assimilation of crustal minerals causes an increase in the magma buoyancy over the time-scale of centuries as the assimilation diffusivity is at least one order of magnitude higher than the thermal diffusivity (McLeod and Sparks, 1998; Portnyagin et al, 2008). The increasing buoyancy causes additional stresses and deformations in the overlying crust. Such processes may induce a causative evolution of the seismicity, reflected as an increased rate of seismic energy release, and a changing distribution in the magnitudes of the VT events, as discussed in the following sections. However, at this point, it is important to note that the analysis of such evolution may enable scientists to forecast the occurrence of major VT events in the short-term time scale; nevertheless, in some cases this analysis may not foretell the occurrence of an eruption, as the magma injection and migration process that causes the stress concentration may never reach the surface (Bell and Kilburn, 2012), although an increase in the probability of such an event must be considered. We present next this methodology, developed and used during the El Hierro volcanic process (2011-2015), which is aimed at detecting the precursory behavior of the seismicity before the occurrence of major, potentially damaging, VT earthquakes.

2 El Hierro volcanic process

The morphology of El Hierro island (27.7^o N; 18.0^o W) has been attributed to a triple volcanic rift with the NE, NW and S axes of these rifts diverging by about 120° from each other (Carracedo et al, 1999). The island landscape displays abundant dikes and fissures (Gee et al, 2001), as well as major landslides (Masson et al, 2002). The subaerial island displays a high concentration of volcanoes with a spatial distribution that may be explained by the model proposed by Stroncik et al (2009), in which the volcanic activity at El Hierro is controlled by a complex array of magma pockets. Magma injections from the pockets through dikes or sills may generate VT seismicity. In July 2011, a sudden increase of seismicity was detected at El Hierro Island, prompting several Spanish institutions to deploy recording instrumentation. In addition to the official seismic network operated by the Instituto Geográfico Nacional (IGN), in September 2011, the IGEO-CSIC Institute (see authors' affiliations) installed, for research purposes, a seismic network consisting of 3 permanent, real-time, vertical, short-period stations, and 5 similar, temporary, manual-access stations. Seismicity, deformations and diffuse gas emissions increased persistently until October 2011, when a submarine eruption at 27° 37.18' N; 17° 59.58' W was first detected (López et al, 2012; Ibáñez et al, 2012; Prates et al, 2013). The eruptive activity persisted for months, until March 2012. However, neither the seismic activity nor the deformations stopped, and have in fact continued to the time of this submission (García et al, 2014b, a).

During the whole episode (2011-2015), only two types of seismicity have been observed: short-period volcano-tectonic (VT) earthquakes, with well-defined P and S phases, and a syn-eruptive long period tremor, patently related to the submarine magma effusion. No long-period (LP) earthquakes have been observed at any time. Here, we analyze the time evolution of the VT earthquakes occurrence rates, as they seem to have similar origins, related to rapid stress concentrations caused by magma intrusions. The VT events do not show significant changes in their waveforms or spectral contents along the duration of the whole episode, as illustrated in Figure 1.

Figure 1 near here

The evolution of the seismic activity at El Hierro island for the whole period of unrest (2011-2015) is summarized in Figure 2, in terms of the time distribution of earthquake magnitudes, the number of earthquakes exceeding M 1.5 per day, the cumulative number of events, and the cumulative seismic energy released, estimated from the IGN public earthquake catalog (http://www.ign.es/ign/layoutIn/sismoFormularioCatalogo.do as downloaded on 2015-08-29), and from records of the above-mentioned IGEO-CSIC seismic research network. The uncertainties in calculating the duration and magnitude of very low-amplitude signals recorded by the IGEO-CSIC have been treated according to Del Pezzo et al (2003).

Figure 2 near here

Inspection of Figure 2 reveals that the seismicity, deformations and eruption evolution observed during the 2011 unrest episode not only is consistent with the model of Stroncik et al (2009) (Gar-

cía et al, 2014b), but it also reveals some other interesting features of the volcanic unrest process

95   dynamics. First, as expected, a marked rise of the VT event occurrence rate preceded the onset of the 10 October 2011 eruption. However, during the continuing seismic unrest, the event rate and the cumulative number of events have also markedly increased before the occurrence of major VT earthquakes. But it is the cumulative release of seismic energy, shown in the uppermost plot of Figure 2, the parameter that best illustrates the precursory character before major VT events. Ad-

100   ditionally, the M-T diagram in the lower plot of Figure 2 shows a peculiar behavior. The minimum magnitude rises as the number of higher-magnitude events increases. This may be caused by completeness fluctuations of the catalog, derived from the difficulties in counting very small events when larger earthquakes are concurrent, or it may be an actual condition related to the physical process of seismic energy release. Several other cases in which the completeness is maintained at the lowest

105   measurable value during the duration of the VT swarm suggest that the latter condition may be real. For example, Benoit and McNutt (1996) report an increase of the minimum magnitude when the VT activity approaches a mean magnitude 3. Likewise, De la Cruz-Reyna et al (2008) and Hurst et al (2014) report a similar behavior for the VT seismicity of Popocatépetl and Tongariro volcanoes respectively.

110   To date, five seismo-volcanic crises or VT earthquake swarms have been identified at El Hierro (García et al, 2014b, a), showing in all cases an increasing trend of the maximum detected magnitudes, as shown in Figure 3. It is significant that the acceleration of the seismic energy release rate begins in all cases when the cumulative seismic energy exceeds the 10^{11}J energy threshold criterion of Yokoyama (1988). Hours to days after the onset of this acceleration stage, the swarm sequences

115   culminated with earthquakes exceeding magnitude 4 (Figure 4). Currently, VT earthquake swarms are classified according to three family types proposed by Benoit and McNutt (1996), and later updated by Farrell et al (2009) and Brumbaugh et al (2014): Type A- mainshock and aftershocks; type B- foreshocks, mainshock and aftershocks; and type C- swarms without a mainshock. Further examination of the lower part of Figure 3 reveals that the evolution of the daily rate of seismicity does not

120   correspond to any of these established earthquake families. We thus introduce a fourth family, type D, characterized by an increasing number of growing magnitude foreshock events culminating with a mainshock and followed by a rapid decay of seismicity lasting just a few hours. The differences between these models are illustrated in Figure 5. Therefore, a type D sequence does not follows an ETAS model (Ogata, 1992), nor follows the Omori law (Utsu and Ogata, 1995), but it reveals a

125   causal process that allows forecasting of major VT events.

Figure 3 near here

Figure 4 near here

Figure 5 near here

2.1 Forecasting major VT earthquakes at El Hierro

130 The Gutenberg-Richter Law (GRL, Gutenberg and Richter, 1944) scales the seismic activity, with respect to its magnitude, as:

Equation 1 here

where $N(M)$ is the number of earthquakes with magnitude M or larger detected within a given region, in a certain time interval (Bender, 1983). In a process that remains stationary over a time

135 interval ΔT, the Gutenberg-Richter Parameters (GRP) a and b remain constant. Here, we use a time-dependent GRP to estimate the Mean-Recurrence-Time (MRT) of volcanic earthquakes having or exceeding given magnitudes, and thus the likelihood of major events occurring in the shorter time-scale (hours to days). The MRT (τ_T) between events with magnitude equal or greater than M may thus be estimated from Equation 1 as:

140 **Equation 2 here**

The MRT may thus be calculated as:

Equation 3 here

Increasing likelihood of major events may thus be estimated from the increasing rates of occurrence of smaller earthquakes. In practice this may prove to be a difficult task since the available

145 seismic catalogs frequently present completeness uncertainties derived from technical factors such as the stability of the seismic networks and links, weather conditions, background noise, event counting and magnitude assignment routines, among others. Problems of catalog completeness in general mean an under-counting of the lowest magnitudes (Bell and Kilburn, 2012) that define a low-end Magnitude Cutoff (MC) above which the GRL holds. A second major problem is is the bias in-

150 troduced by the use of binned magnitudes and errors of the magnitudes (Bender, 1983; Tinti and Mulargia, 1985, 1987; Marzocchi and Sandri, 2003). These problems have been amply discussed in the literature about seismicity from different origins (e.g. Wiemer et al, 1998; Lombardi, 2003; Marzocchi and Sandri, 2003; Helmstetter et al, 2007; Amorese et al, 2010; Bengoubou-Valerius and Gibert, 2013; Alamilla et al, 2015; Márquez-Ramírez et al, 2015). In our case, an additional problem

155 is that the development of the VT seismicity in the El Hierro crisis shows strong and rapid variations, and the estimates for the MC and the GRP may vary in time and space, causing temporary distributions of shocks quite different from those of the full catalog. We have addressed those problems considering a moving and variable time-window ΔT in equations 2 and 3. In most cases, an acceleration of the seismicity occurs when the cumulative energy released by a VT swarm reaches a

160 value near the 10^{11}J energy threshold of Yokoyama (1988). Experience has shown that at El Hierro such swarms precede a stage of accelerated seismicity with increasing magnitudes that culminate in major (M>4) VT events.

The MRT algorithm starts a forecast when a swarm of at least 200 earthquakes with M$\geq$1.5 are detected in a time span of 5 days. Then, a completeness magnitude MC is calculated using the

165 Maximum Curvature Method (MCM, Wiemer and Wyss, 2000). The GRP are estimated for each

time-window using a Maximum Likelihood Estimator (MLE) (Peishan et al, 2003; Bengoubou-Valerius and Gibert, 2013). In the final standard-C version of the software, we implemented a fast subroutine based on the equations of Marzocchi and Sandri (2003) to calculate the b-value:

Equation 4 here

where

Equation 5 here

and μ is the sampling average of the magnitudes, Mc is the cut-off (threshold) magnitude. We used a magnitude binning interval $\Delta M = 0.1$. If the seismicity rate drops below 200 earthquakes in 5 days, the MRT algorithm would stop running. In successive swarms, some patterns appear as the time to a mainshock approaches: Mc may increase from the initial 1.5 to as much as 3 or more, and the time window shortens. Algorithm 1 shows a schematic description (pseudocode) of the MRT calculation. The algorithm has been implemented in a batch processing mode that is fast and relatively simple to program.

Algorithm 1 near here

Table 1 shows the main features of the swarms detected at El Hierro, and Figure 6 shows the evolution of the MRT for the initial four cycles of El Hierro activity. A warning window for the likely occurrence of an earthquake exceeding M4 is issued when the calculated MRT for that magnitude drops below 10 days, and a statement saying that there is an increased likelihood of an M4 (or higher) earthquake in the following 10 days is delivered to the decision-makers. The warning remains active until the MRT returns to a value exceeding 10 days. This method has been incorporated into a Volcanic Alert System, (described in García et al, 2014a), where the continuous evolution of the MRT over the whole unrest process is described.

Figure 6 near here

Table 1 near here

An 8-month lull followed those four cycles, and as frequently happens, a belief that the seismo-volcanic crisis had ended spread throughout the island's population. Additional factors, such as a particularly strong winter storm and the Christmas holidays, caused failures of the IGN official seismic network that translated into a rather incomplete seismic catalog. When a new seismic swarm began on 2013-12-20, the MRT could only be calculated using predominantly data from the IGEO-CSIC seismic research network. Figure 7 shows the MRT evolution using magnitudes from both catalogs. On 2013-12-24 a new warning was issued communicating to decision-makers the increased likelihood of a M5 or larger earthquake occurring in the following days. On 2013-12-27, at 17:46:02 UTC, the largest earthquake of the entire episode, with magnitude 5.4, caused numerous landslides across the island, fortunately without casualties. It is interesting to note that no M4 earthquakes occurred in this stage.

Figure 7 near here

3 Discussion and Conclusions

Earthquake forecasting is a problem that has been addressed in the past from various different per-
spectives. Significant advances were obtained after the introduction of complexity theory (Lorenz,
1963; Mandelbrot, 1977) and the development of predictive algorithms (Gabrielov et al, 1986;
Molchan, 1990; Keilis-Borok, 1996; Turcotte, 1997). Currently, the need to implement operational
short-term earthquake forecasting based on predictive and forecasting algorithms has been stated
by Jordan et al (2011). The MRT is one of such algorithms, based on a property that is typical of
complex systems: seismic events cluster according to a simple scaling law, the Gutenberg-Richter
relationship (Equation 1). This empirical relationship contains information about the occurrence of
large magnitudes embedded in the number of small-magnitude events (Helmstetter et al, 2007), and
the time variations of the distribution of the small-magnitude events provides information about the
time-scale of large-magnitude occurrences. In the case of VT earthquakes, two additional factors
help to simplify the forecasting process: one is the limited geographic extent of the volcanic source
of seismicity, confining the spatial extension of the forecast. The other factor is the short time-scale,
measured in days, at which orderly fluctuations of the GRPs evolve reflecting stress accumulations
induced by the magma injections, and allowing rapid recognition of significant changes of the MRT
as defined in Equation 3, and therefore viable short-term forecasts (García et al, 2014a). In contrast, a
similar method for tectonic earthquakes would require recognizing orderly evolution patterns of the
GRPs over times scales of years to decades, making short-term forecasting non-viable (e.g. Jordan
et al, 2011).

We envision the El Hierro process as the result of magma injections causing rapid stress concen-
trations capable of triggering seismic swarms. Such swarms culminate with mainshocks that release
stress concentrations, and are thus not followed by aftershock sequences. Further magma migrations
cause new swarms and mainshocks, in repeating, but non-periodic cycles of activity. For example,
the largest earthquakes of the March and December 2013 swarms (see Table 1), were located at
less than 20 km West from the westernmost shore of the island, suggesting a nearby localized stress
source possibly resulting from subsurface magma injections under that region (Figure 8). From the
initial stage of unrest in July 2011, five earthquake swarm cycles have been identified, but only the
first of these culminated in an eruption. The subsequent cycles show two main features: first, the
swarms are separated by increasingly longer lull intervals, and second, they tend to culminate in
mainshocks of increasing magnitudes (see Figure 3).

Figure 8 near here

The forecasting algorithm we are proposing here is based on the above-mentioned envisioning
of the process that is causing the seismic swarms, and begins when the background seismic energy
exceeds the 10^{11}J energy threshold criterion of Yokoyama (1988). The acceleration of the earth-
quake rate (Figure 5-D) is interpreted in terms of piecewise estimations of the Gutenberg Richter
parameters. The variations of those parameters are, in turn, translated as time-windows of increased

likelihood of a large-magnitude earthquake. The MRT algorithm may be, and has been, used in real time. It took the initial VT swarm crises to interpret the process and to recognize and develop the procedures and set the parameters of the MRT algorithm, which was first tested during the third crisis, when a significant reduction of the MRT was detected on 2012-06-05. A M4.2 VT earthquake occurred on 2012-07-03. From then on, the MRT algorithm run continuously in the background. It was not until the fourth crisis that a formal warning was issued on 2013-03-26 communicating to the island authorities and to the Civil Protection officials the increased probability of a M5 earthquake for the following 8 days, as described in García et al (2014a). On 2013-03-31 a M4.9 occurred. In the next volcano-tectonic seismic crisis another formal warning was issued on 2013-12-22, communicating the increased probability of an earthquake exceeding M5 in the next 15 days. Further formal warnings were issued daily afterwards also indicating the increased probability of landslides and other eruption. On 2013-12-27, an M5.4 caused numerous landslides (García et al, 2014a).

In the absence of swarms, the GRPs are calculated with a long database of the seismic catalog, and updated on a daily basis (Algorithm 1), usually yielding fluctuating, but always very long values of the MRT (that may exceed 106 days). At the onset of a seismic swarm, the MRT drops rapidly to values of the order of 103 days. When this happens the GRPs are calculated from shorter time-windows of variable duration, provided that they contain a large enough number of events (at least 200) to yield stable values of the GRPs. When the MRT for events of magnitude 4 or higher is less than 10 days, a warning is issued to the decision makers, expressed as a 10-day window of increased likelihood for larger, potentially damaging earthquakes. Up to the time of this submission, all the recent earthquakes of M$\geq$4 at El Hierro have been forecasted several days in advance. Application of the MRT to other volcanoes may be relatively simple to implement, provided that the observed seismicity corresponds to swarms of type D (Figure 5): increasing number of VT events with increasing magnitudes followed by a mainshock, and by a rapid decay of the seismicity afterwards. The algorithm may be readily adapted to any real-time monitoring system. In addition, the concept of time-windows for the increased likelihood of a large-magnitude earthquake should be easily understood and accepted by governmental decision-makers, making the management of risk more effective.

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FIGURES
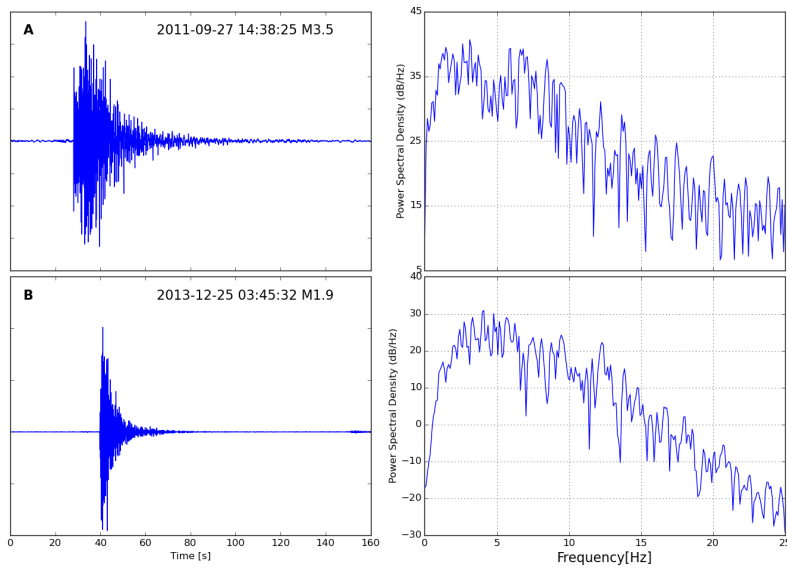
Figure 1. Characteristic VT earthquakes of the El Hierro seismo-volcanic process and their spectra. (A) Event recorded on 2011-09-27, before the eruption, at $\sim$ 6.3 km to the SE of the island center. (B) Event recorded on 2013-12-24, after the eruption at $\sim$ 10.4 km SW of the island center.
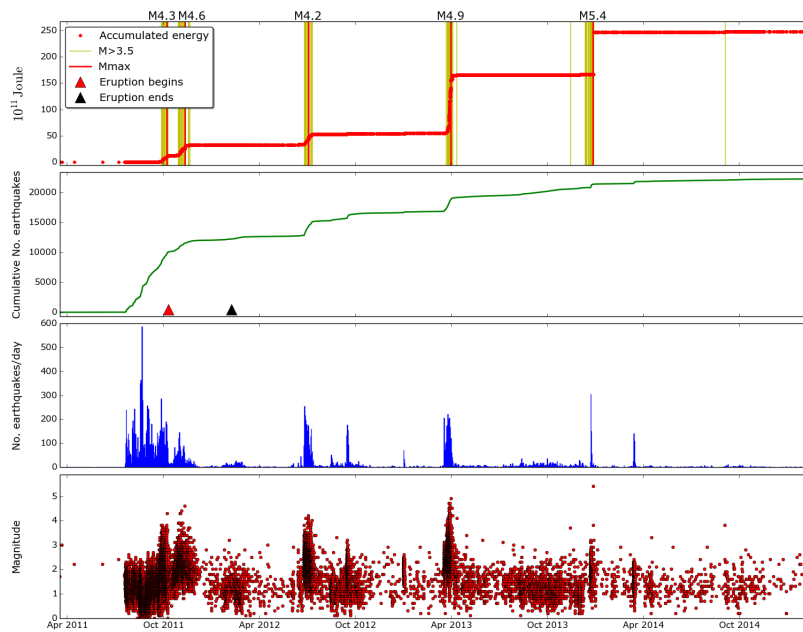
Figure 2. Evolution of the seismic activity at El Hierro Island between 2011-03-18 and 2015-02-12. Data are from the IGN public earthquake catalog and the IGEO-CSIC seismic research network.
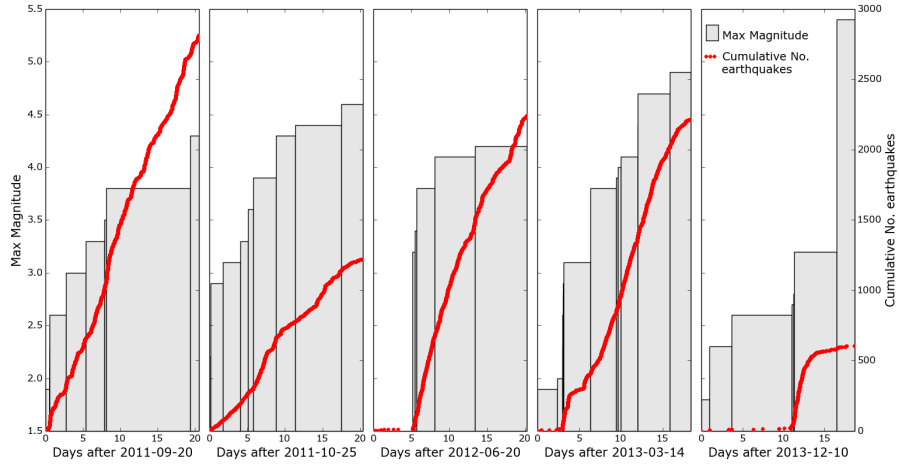
Figure 3. Time evolution of the daily count of VT events (red dots) and maximun magnitudes (gray bars) during the earthquake swarms of the El Hierro seismo-volcanic process.
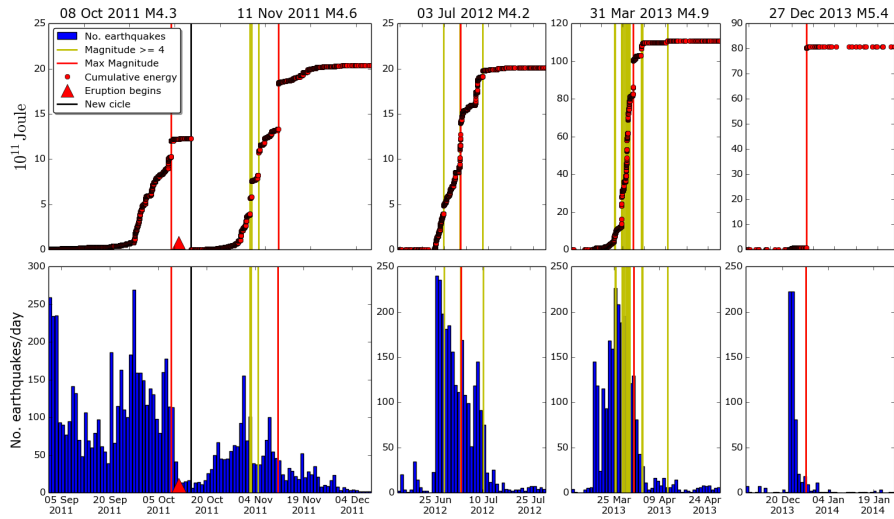
Figure 4. Seismo-volcanic crises identified at El Hierro Island (2011-2014). The upper plots show the evolution of seismic energy for each of the cycles of unrest. The lower plots show the daily event count. The plots illustrate how the seismic activity drops rapidly after the largest magnitude earthquakes. Particularly significant is the absence of aftershocks after the largest (M5.4) earthquake of 2013-12-27. Data are from IGN public earthquake catalog and the IGEO-CSIC seismic research network.
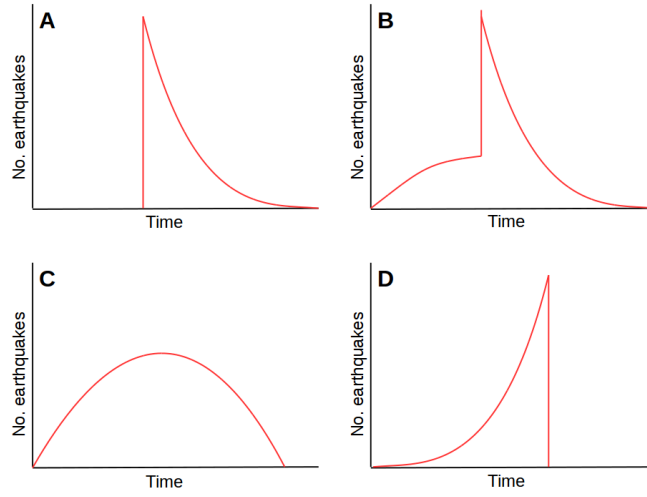
Figure 5. Seismic swarms are usually classified in three family types (A, B, C, Farrell et al, 2009; Brumbaugh et al, 2014). From our results at El Hierro in 2011-2015, we propose a fourth family type D, characterized by an increasing number of VT earthquakes and their magnitudes with time, and by a quick decay of the seismicity, in a matter of hours after a mainshock usually exceeding M4.
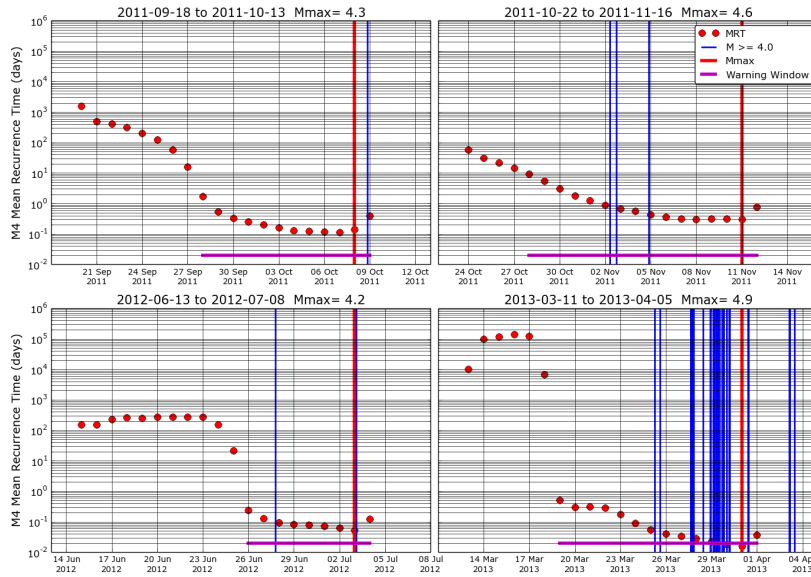
Figure 6. MRT evolution (computed using MLE) for four periods: 2011-08-18 to 2011-10-10; 2011-10-22 to 2011-11-13; 2012-06-13 to 2012-07-05; and 2013-03-11 to 2013-04-02. The warning windows were triggered when MRT dropped below 10 days.
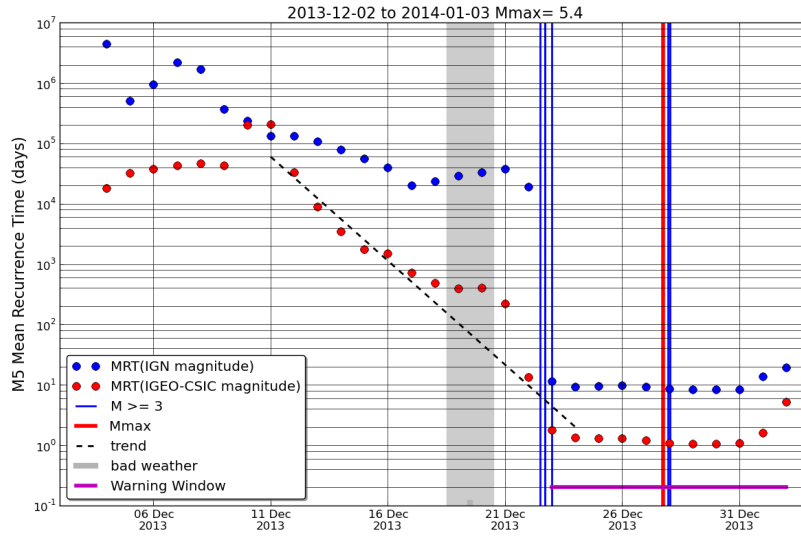
Figure 7. MRT evolution (computed using MLE) in December 2013 calculated from the IGN official catalog (blue) and from the IGEO-CSIC catalog (red). The magnitude of the earthquake on 2013-12-27 17:46:02 was estimated by IGN as 5.1, and as 5.4 by the IGEO-CSIC network and other international catalogs.
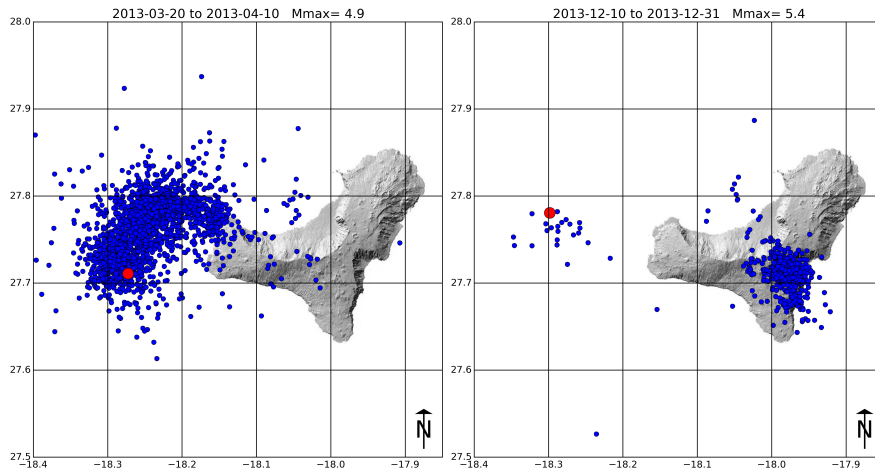
Figure 8. Swarms and mainshock epicentres of the March and December 2013 seismicity cycles. The M5.4 mainshock of 2013-12-27, at 17:46:02 UTC is located in the same region of the March 2013 cycle.

385   TABLES

Table 1. Characteristics of El Hierro swarms.

Mainshock Date	Magnitude		Swarm duration (days)	Number of events
	Mean	Max		
2011-10-08	2.33	4.3	10	934
2011-11-11	2.27	4.6	8	354
2012-07-03	2.35	4.2	5	635
2013-03-31	2.75	4.9	4	651
2013-12-27	2.09	5.4	4	466

EQUATIONS

$$\log_{10}(N(M)) = a - bM \tag{1}$$

$$N(M) = \frac{\Delta T}{\tau_T} = 10^{(a-bM)} \tag{2}$$

390 $$\tau_T = \Delta T \cdot 10^{(bM-a)} \tag{3}$$

$$b = \frac{1}{\ln(10)\Delta M}\ln(p) \tag{4}$$

$$p = 1 + \frac{\Delta M}{\mu - Mc} \tag{5}$$

ALGORITHM

Algorithm 1 Pseudocode of the MRT algorithm developed to forecast mainshocks applied during the El Hierro seismo-volcanic process (2011-2015).

1: *Get seismic catalog* ← `download from IGN website`

2: *Count number of events* ← `In the last 5 days`

3: **if** *earthquakes M1.5 > 200 events* **then**

4:     *Compute current MC* ← `Magnitude Cutoff, using`

5:     `Maximum Curvature Method (MCM)`

6:     *Compute Time window* ← `Use constant MC`

7:     *Compute number of events where M>MC*

8:     **if** *Number of events (M>MC) > 200 events* **then**

9:         *Select all events where M>MC*

10:         *Compute Gutenberg-Richter Parameters* ← `Using`

11:         `Maximum Likelihood Estimator (MLE)`

12:         *Compute Mean-Recurrence-Time (MRT) for M4 events*

13:         **if** *MRT for M4 events < 10 days* **then**

14:             **Activate Warning Window**

15:         **end if**

16:     **end if**

17: **end if**