

# “VOLCANIC AND VOLCANO-TECTONIC ACTIVITY FORECASTING: A REVIEW ON SEISMIC APPROACHES”

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## ABSTRACT

Forecasting volcanic activity is a difficult problem that is being addressed worldwide from different perspectives. Significant advances have been made after the introduction of non-linear dynamical systems theory and the use of power-law distributions of different geophysical parameters in the Earth Sciences. In particular, frequency-magnitude power-law statistics evidences the scale-invariance and self-organization of seismicity, and brittle fracture models show that under certain conditions, a precursory causal evolution characterized by an accelerating strain rate culminates in a catastrophic failure of the system under stress. The precursory organization of the seismicity and the distinct characteristics of the seismic events have allowed the development of forecasting tools. In this work we present some examples of forecasting methods based on seismic observations at different volcanoes in the world, and how results and experiences has been used to improve both hardware and software tools developed for short-term forecasting of volcanic and seismo-volcanic activity.

## 1. INTRODUCTION

Forecasting volcanic eruptions is one of the most controversial issues in volcanology. Historically there are evidences that people abandoned hazardous areas before eruptions, even before the existence of modern instrumental monitoring methods. For example, the excavations conducted by Marinatos since 1967 in the Greek island Santorini found that little or no loss of lives occurred in the settlement of Akrotiri during the Thera eruption that destroyed the city around 1627 BC, thus suggesting that the town was evacuated be-

fore the eruption [Pellegrino, 1991]. Similarly, the relatively small number of corpses found in Herculaneum, destroyed by the Plinian eruption of Mt. Vesuvius in 79 AC, suggests a similar situation [Scandone and Giacomelli, 2014]. A move to prevent a tragedy such as abandoning endangered settlements depends on three basic factors: the capacity of observation to recognize significant changes in the patterns of volcanic activity, the perception that eruptive activity may cause fatal damage, and the capability of making a political decision resulting in a complex move as in the case of the evacuation of a community. Failure in any of these

three factors may lead to a complete disaster, as it was the case in St. Pierre (Martinique) in 1902 [Tanguy, 1994], or in Armero (Colombia) in 1985 [Voight, 1990]. These three basic factors have been addressed for a long time in Japan. For example, the 1910 Usu volcano eruption was studied by scientists at that time, in particular by Omori and Satō [Omori, 1903, 1911, 1912; Satō, 1913; Yokoyama and Matsushima, 2018], and the management of the emergency situation was properly handled. With this background Noguchi and Kamiya [1963], Mogi [1963] and Minakami [1964] purported the concept of volcano observatory as a mean for forecasting volcanic eruptions. Similarly, the analysis of the 1975 eruption of Tolbachik [Fedotov and Markhinin, 1983], the successive eruptions of Etna [e.g. Vinciguerra et al., 1999] and the 1980 eruption of Mt. St. Helens [Lipman and Mullineaux, 1981], provided evidence in setting some physical basis on the nature of eruptions and their precursors [De Natale et al., 1999]. An important boost of world-wide research works on forecasting and modeling of pre-eruptive processes from different perspectives followed afterwards.

The theory of nonlinear dynamic systems and the power-law distribution attributed to the energy released by different geophysical phenomena have greatly helped to deal with and model the complex nature of forecasting hazardous activity [e.g. Pshenichny et al., 2003, 2009]. It is very important to emphasize that the nature of the causal forecasting methods based on the concatenated increase of a geophysical observable implies dynamic time scales that decrease as the monitored system evolves (hours-days). In contrast, non-concatenated causal phenomena only provide “stationary” information on the state of a geophysical system which can only be used for the long-term (years-decades) assessment of the related hazard [Jones, 1996]. In a volcanic region, this may be exemplified as the difference between an accelerated release of seismic energy, probably leading to some type of volcanic or seismo-volcanic manifestation, and a volcanic hazards map.

In this work we aim to describe the evolution of the precursory unrest activity of active volcanoes and its relevance in forecasting eruptions through causal forecasting models and methods based on changes in the seismicity observed. Our experience is focused mainly on the measurement and data processing of volcano seismicity, and to a lesser extent, in real-time defor-

mation measurement using GPS L1 and L2. In addition, we believe that these seismic models and methods are adequate for volcanoes where the assessment of new unrest detected with provisional monitoring equipment are critical for risk management, but due to the lack of resources, the deployment and maintenance of a comprehensive volcano monitoring network is not always possible.

## 2. METHODS BASED ON CHANGES IN SEISMICITY

As stated in the previous section, historical evidence indicates that the perception of a relationship between seismic and eruptive activity may be as old as humanity. However, in the XX century the advent of electronics, computers, more sensitive motion transducers, and the capabilities to program elaborate signal analysis tools, allowed the recognition of multiple types of signals produced by internal processes of active volcanoes, most of them with precursory value [Omori 1911, 1912; Schick and Riuscetti, 1973; Schick 1981]. For example, during the 1982-1984 Campi Flegrei bradyseismic crisis [Barberi et al., 1984], the introduction of real-time digital instruments [Ortiz et al., 1984; 1992] not only permitted a follow-up of the ongoing activity, but also initiated the development of hardware and software specifically designed for volcano monitoring that is still used [Barberi et al., 2008].

In general, seismic forecasting methods may be grouped in two types: those based on the time evolution of volcano-tectonic earthquakes, and those based on the analysis of waveform signals of volcanic origin.

### 2.1 PRECURSORY TIME EVOLUTION OF VOLCANO TECTONIC EARTHQUAKES

The rapid increase of the rate of volcano tectonic (VT) earthquakes before an eruption is one of the earliest manifestations recognized as an eruption precursor [Benoit and McNutt, 1996]. However, since many earthquake swarms in volcanic areas are not followed by eruptive activity, the causality between these signals and eruptions is weak [Gudmundsson, 2002; García et al., 2014a]. Migration of seismic foci has also been used since the 1960's as a forecasting technique but sometimes eruptions are not preceded by migrations and vice versa [Wiemer et al., 1998]. The time evolution of the seismic energy release by VT earthquakes and par-

ticularly its cumulative value provides a more reliable tool for the eruption forecasting. Yokoyama [1988] found that VT cumulative seismic energy reaching a threshold of  $10^{11}$  J has significant forecasting value. It is also a relatively simple observable to evaluate because it requires only a basic seismic catalog with a magnitude of completeness of the catalogue  $M_c=2$  or lower [García et al., 2014a]. Examples of such behavior are shown in Figure 1, where a clear increase of the seismic activity near the Teide volcano (Tenerife, Canary islands, Spain) in 2004 contrasts with the uniformity of the seismicity at regional level. Similarly, Figure 2 shows an example of how different seismic parameters evolved before and after an eruption during the El Hierro 2011 precursory unrest. The daily data processing allowed forecasting the eruption and the higher magnitude VT events [García et al., 2014a,b; 2016] using some of the methods described below. The daily data processing using different methods of analysis ((Mean Recurrence Time MRT, García et al. 2016, Real-time Seismic Amplitude Measurement RSAM, Endo and Murray, 1991, etc.) allowed to forecast the volcanic activity and pro-

vide the authorities and relevant bodies with pertinent technical input [García et al., 2014b]. We implemented a variety of methods because the appropriateness (and inherent precision) of a given method depends on the type of changes in the volcanic behavior. The MRT based in the seismic catalogue is the most used method.

## 2.2 MAGNITUDE DISTRIBUTION

The distribution of earthquake magnitudes in a volcanic region may also be described by the frequency-magnitude distribution of tectonic earthquakes based on the Ishimoto and Iida [1939] and the Gutenberg-Richter [1944] law

$$\text{Log}_{10} N = a - bM$$

where  $N$  is the cumulative number of earthquakes with magnitude  $\geq M$ , and  $a$  and  $b$  are constants that describe the power law decay of occurrence frequency with increasing magnitude. The  $b$ -value is the slope of the line which best fits the earthquake-magnitude distribution data above the magnitude of completeness  $M_c$ , defined

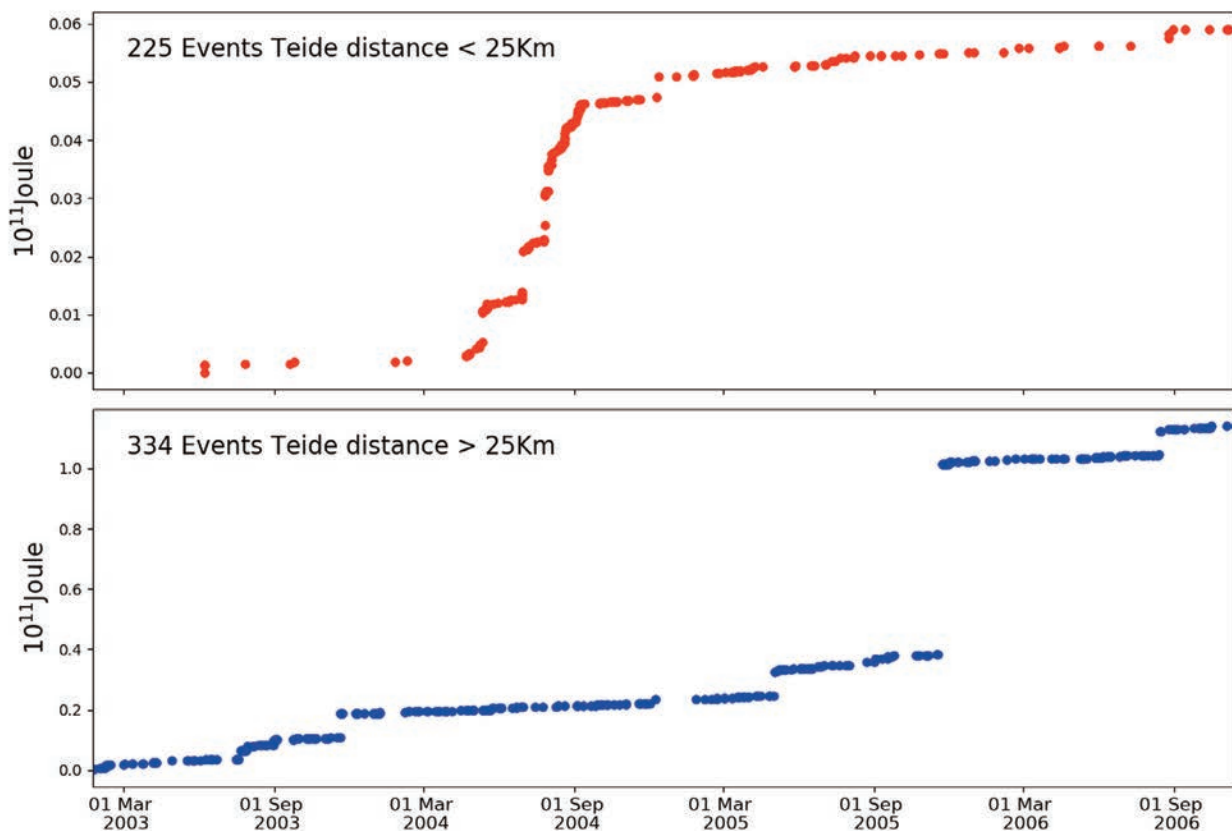


FIGURE 1. Near and far field seismicity at Tenerife island during the 2004 Teide volcano seismic crisis: The cumulative seismic energy release plots reveal a significant difference between the local VT seismicity and the seismicity at distance greater than 25 km from the volcano.

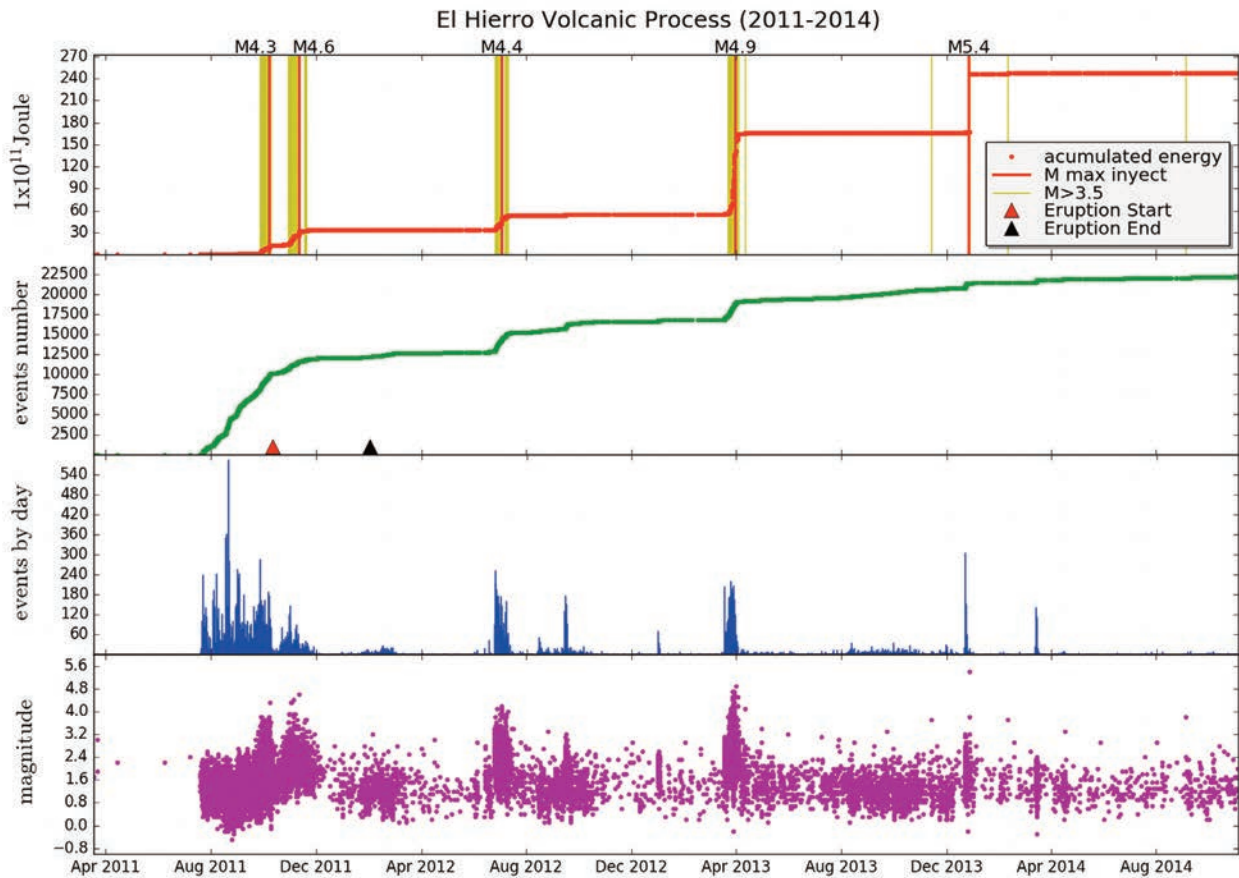


FIGURE 2. Evolution of different geophysical parameters at El Hierro during the volcano-tectonic and eruptive activity in 2011-2014 [in García et al., 2016].

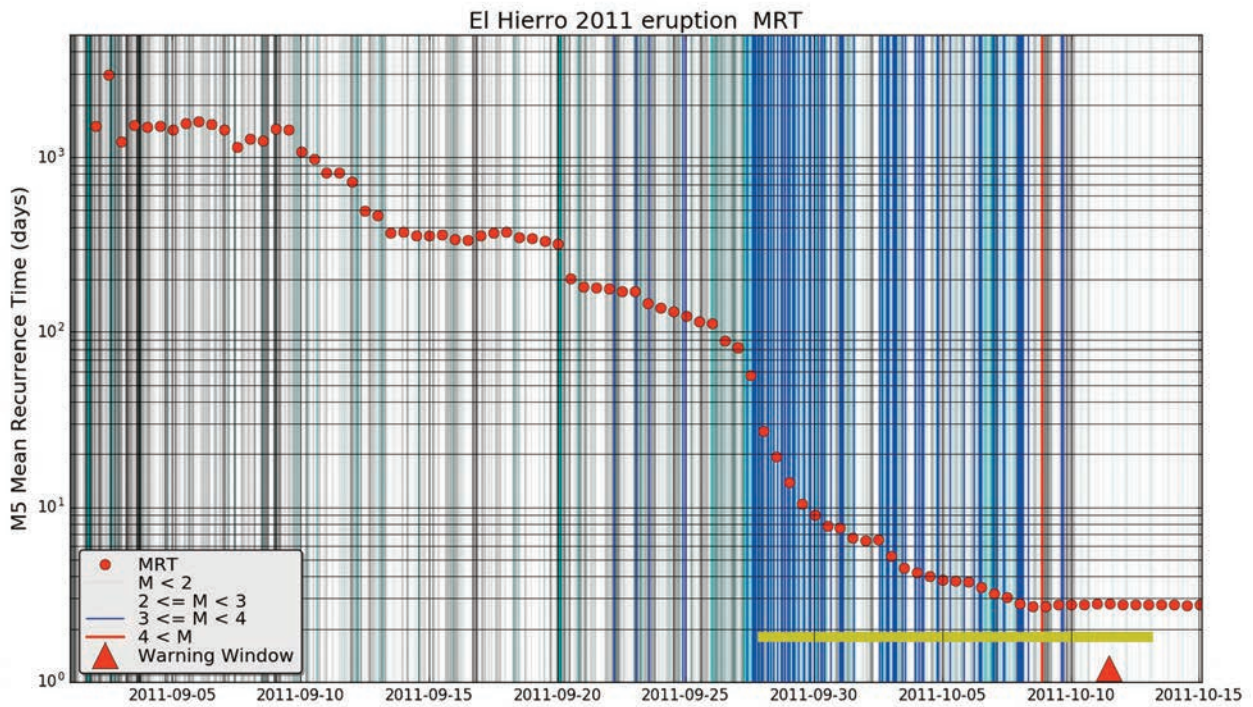


FIGURE 3. Evolution of the MRT from 01 September to 12 October 2011. The calculated value of the MRT remains stable (about 103 days) during the first 10 days of September, and, rapidly decays afterwards reaching a value of about 10 days on 28 September, when a warning was issued. The eruption began on 11 October 2011.

as the lowest magnitude at which 100% of the events are detected [Rydelek and Sacks, 1989; Taylor et al., 1990; Wiemer and Wyss, 2000]. The  $b$ -value mostly depends on the properties of the seismic medium and on the nature of the stress source causing the earthquakes. Areas where seismicity is caused by extensive regional stress show  $b$ -values near 1.0 [Frohlich and Davis, 1993]. Stress concentration leading to clustering of seismicity and fracture over distances of a few kilometers seems to have a strong effect on the value of  $b$  [Ogata and Katsura, 1993; Wiemer and McNutt, 1997; Wiemer and Wyss, 1997]; particularly, stress concentration produced by increased thermal gradients, or rock fracturing caused by hydraulic stresses [Grasso and Sornette, 1998] cause a significant increase in  $b$  [Warren and Latham, 1970]. Both of the former processes are common in volcanic regions, and  $b$ -values larger than 1 are commonly associated to some type of internal volcanic activity [De la Cruz-Reyna et al., 2008]. The analysis of the  $b$ -values calculated over short time windows in a volcanic region permits calculating the changing “mean recurrence time” (MRT), a parameter measuring the probability of a VT earthquake exceeding a given (relatively high) magnitude. An application of this methodology is illustrated in Figure 3. The methodology was developed as a forecasting tool for the expected largest-magnitude earthquake in each magma injection process during the El Hierro seismo-volcanic crisis [García et al., 2016]. Combining the MRT with an associated alert level procedure (VAL) provides a robust method to objectively communicate the seismo-volcanic hazard [García et al., 2014b].

### 3. METHODS BASED ON CHANGES IN SEISMIC WAVEFORMS

#### 3.1 ANALYSIS OF CONTINUOUS SEISMIC SIGNALS

The seismic signals recorded by a seismometer result from the superposition of multiple signals from different sources, including those generated by the volcanic activity. A main goal is to discriminate the signals generated by the volcanic activity from the rest. This is done by means of decomposition techniques such as Singular Value Decomposition [Carniel et al., 2006a], Independent Component Analysis and Non-negative Matrix Factorization [see Carniel, 2014 for a review]. This task can be particularly difficult at the onset of volcanic activity that is, when the signals of volcanic origin are relatively weak. In such a situation, relevant

information may be disregarded as “noise”. The analysis of noise acquires then a particular importance [Peterson, 1993]. Recent developments in noise analysis based on continuous assessment of noise levels for quality control purposes [Sleeman and Vila, 2007], variations of signal-to-noise ratios [Bormann, 2002; McNamara et al., 2009], or specific applications to geology [Ladina, 2012], resulted in useful tools for the recognition of subtle changes in the internal state of a volcano. Changes systematically altering the amplitude and/or predominant frequencies of the background seismic noise can be detected using these methods of analysis in a given volcanic region. It is particularly important to mention the Base Level Noise Seismic Signal (BLNSS) [Vila et al., 2006, 2008], which proved to be very useful in monitoring the 2003-2005 unrest episode of the Teide volcano. Through this method it was possible to report changes in the internal process of the Teide volcano. As an example, Figure 4 shows the base level noise spectra computed for different days. A significant increase of noise energy in the 1-10 Hz frequency band from 2004-12-01 through 2004-12-03 preceded by nine days a new fissure with fumarole emissions that appeared in La Orotava valley in the northeastern flank of Teide volcano, which returned to the normal levels a few hours after the fissure aperture [see García et al., 2006 for details].

To assess the capabilities of the method, we performed BLNSS analyses on other active volcanoes such as Soufriere Hills in Montserrat, West Indies, and in Llaima and Villarrica in Chile [Vila et al., 2006]. Generally speaking, the BLNSS proved to be a powerful tool that also provides relevant information on the status of volcanic unrest.

It is important to emphasize that the methods based on the characterization of background noise detect changes in the evolution of a volcanic seismic signal but they do not provide any a-priori information about the sources, nor about the structures traveled through by transitory seismic waves. However, new developments adapted from neurosciences like the Self-Organizing Maps, SOM [Kohonen, 1982] have been recently applied in geophysics along with decomposition techniques such as the Singular Spectrum Analysis to identify specific evolutionary patterns [Carniel et al., 2006b, 2009; Roden et al., 2015]. Similar techniques were applied in volcanology to identify states of the volcanic activity from continuous tremor data [Carniel et al., 2006a; Langer et al., 2009; Carniel et al., 2013]. The

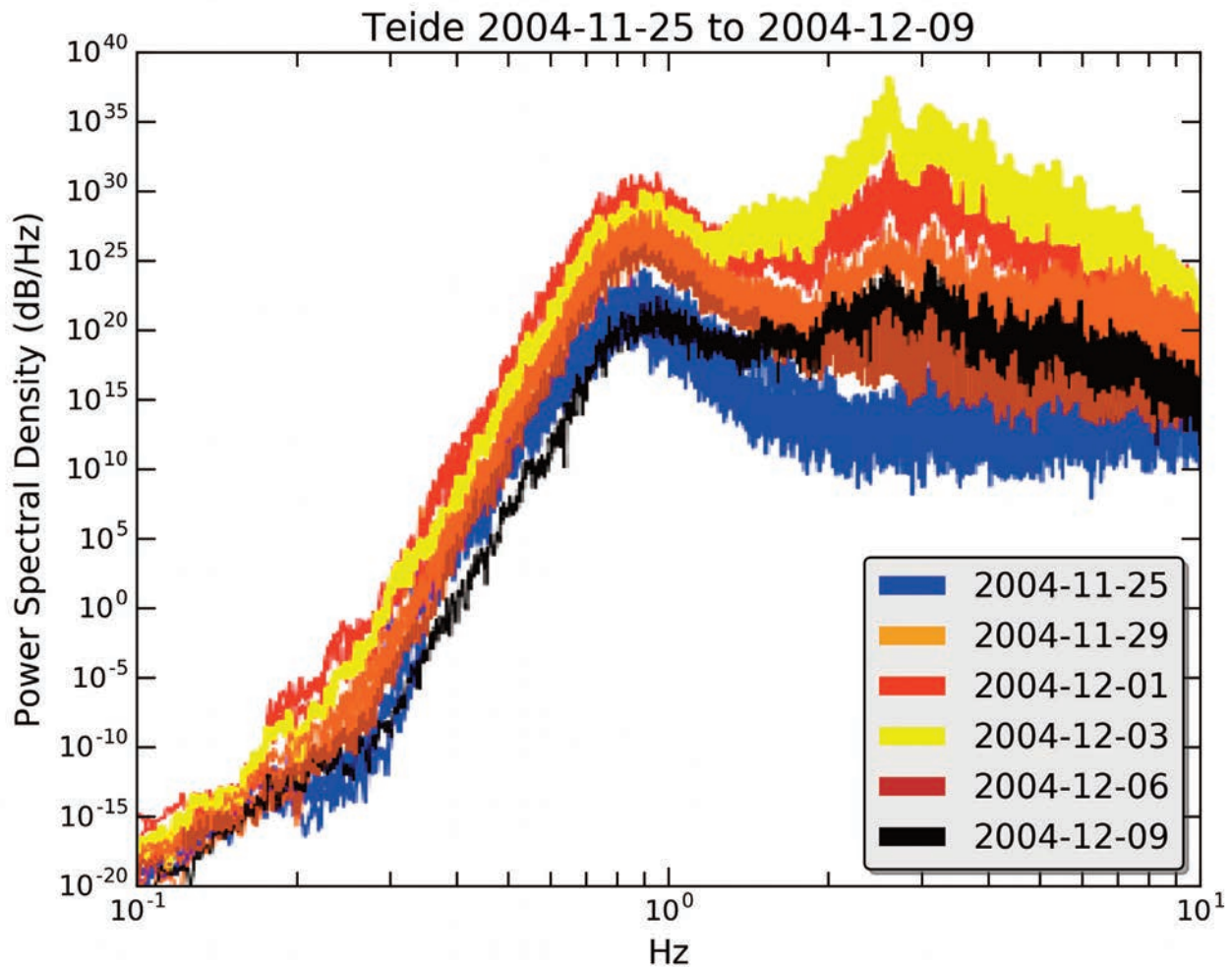


FIGURE 4. Evolution of the Base Level Noise Seismic Signal (BLNSS) in Tenerife during the 2004 seismo-volcanic crisis (2004-11-25 to 2004-12-09). Seismic energy release in the band 1-10 Hz significantly increases between 25 November and 03 December 2004, and decreases afterwards. On 03 December 2004 a fracture with fumaroles opened close to Benijos village ( $28^{\circ}34' 20''$  N;  $16^{\circ} 11' 14''$  W) (Garcia et al, 2006; Vila et al, 2006, 2008).

geostatistical approach at different time scales is also promising [Jaquet and Carniel, 2003; Jaquet et al., 2006].

The Failure Forecast Method (FFM; Voight 1988) provides a simple tool that under certain conditions (closed volcanic systems) permits forecasting volcanic activity from the precursory accelerating release rate of different strain-related parameters. Some of such (analogous) parameters are the RSAM [Real-time Seismic Amplitude Measurement; Endo and Murray, 1991], the RSEM [Real-time Seismic Energy Measurement; De la Cruz-Reyna and Reyes-Davila, 2001], the SSAM [Spectral Seismic Amplitude Measurement; Stephens et al., 1990], the SSEM [Spectral Seismic Energy Measurement; Tarraga et al., 2008] and the SSW [Similar Seismic Waveforms; Salvage and Neuberg, 2016]. In particular, the analysis of accelerating RSAM rates permitted real-time forecasting of eruptions at Tun-

gurahua volcano, Ecuador (Figure 5a) [De la Cruz-Reyna et al., 2010], and at Villarrica volcano (Chile) [Ortiz et al., 2003] (Figure 5b). Also in Villarrica, some results with the seismic signal spectrogram showed the open-close transitions of the conduit systems (Figure 6a and 6b), and interactions between tectonic events, seismic noise and volcanic activity [Ortiz et al., 2003; Tarraga et al., 2006; Carniel et al., 2006a; Tarraga et al., 2012].

Similarly, during the 2004-2005 seismic crises at Teide volcano (Tenerife island), the analysis of SSEM series allowed us to forecast local earthquakes [Tarraga et al., 2006]. The RSEM analysis used at Colima volcano in Mexico [De la Cruz-Reyna and Reyes-Davila, 2001; Reyes-Davila and De la Cruz-Reyna, 2002], allowed the identification of the nature of the stress evolution at the source. The forecasting accuracy of these methods has been improved with the use

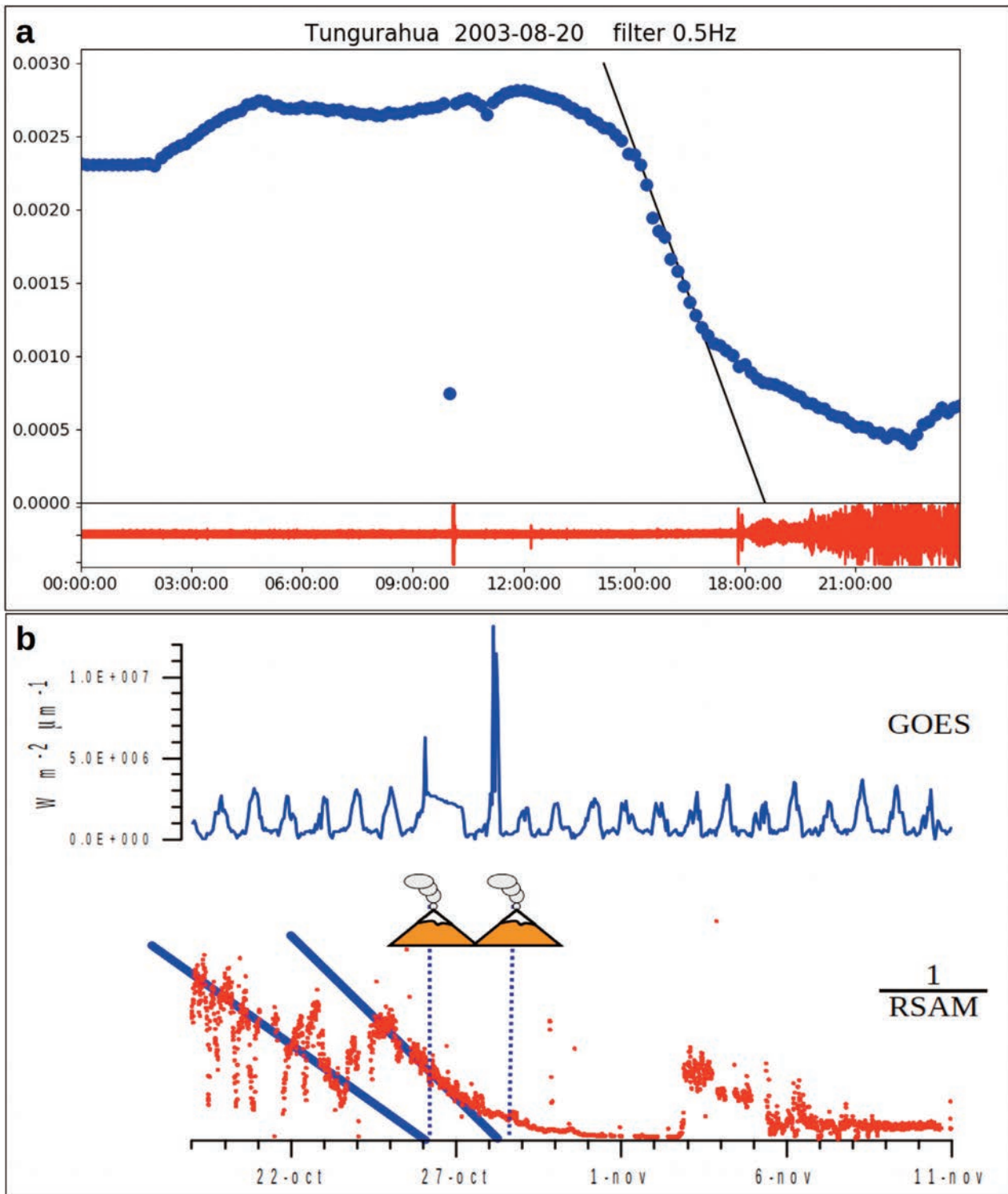


FIGURE 5. a) Evolution of the inverse low-pass filtered SSEM at Tungurahua volcano (Ecuador). At 10 hours of 20 Aug 2003 a M 4.5 regional tectonic earthquake located at 34.5 km from the volcano (isolated dot near the center of the plot) marks the onset of a rapid decrease of the inverse SSEM pointing to the time of the eruption [De la Cruz-Reyna et al., 2010]. b) Two moderate explosions at Villarrica volcano (Chile) on 27 and 29 October 2000 were forecasted with the inverse FFM. The upper plot shows the radiance peaks caused by the explosions (Hot Spot Monitoring Program , Hawaii Institute of Geophysics and Planetology. [Harris et al., 2001].

of Kalman filtering [Kalman, 1960], particularly when applied to other strain-rate related parameters such as

the terrain deformation, as it was the case in the recent volcanic process at the Canary island of El Hierro in

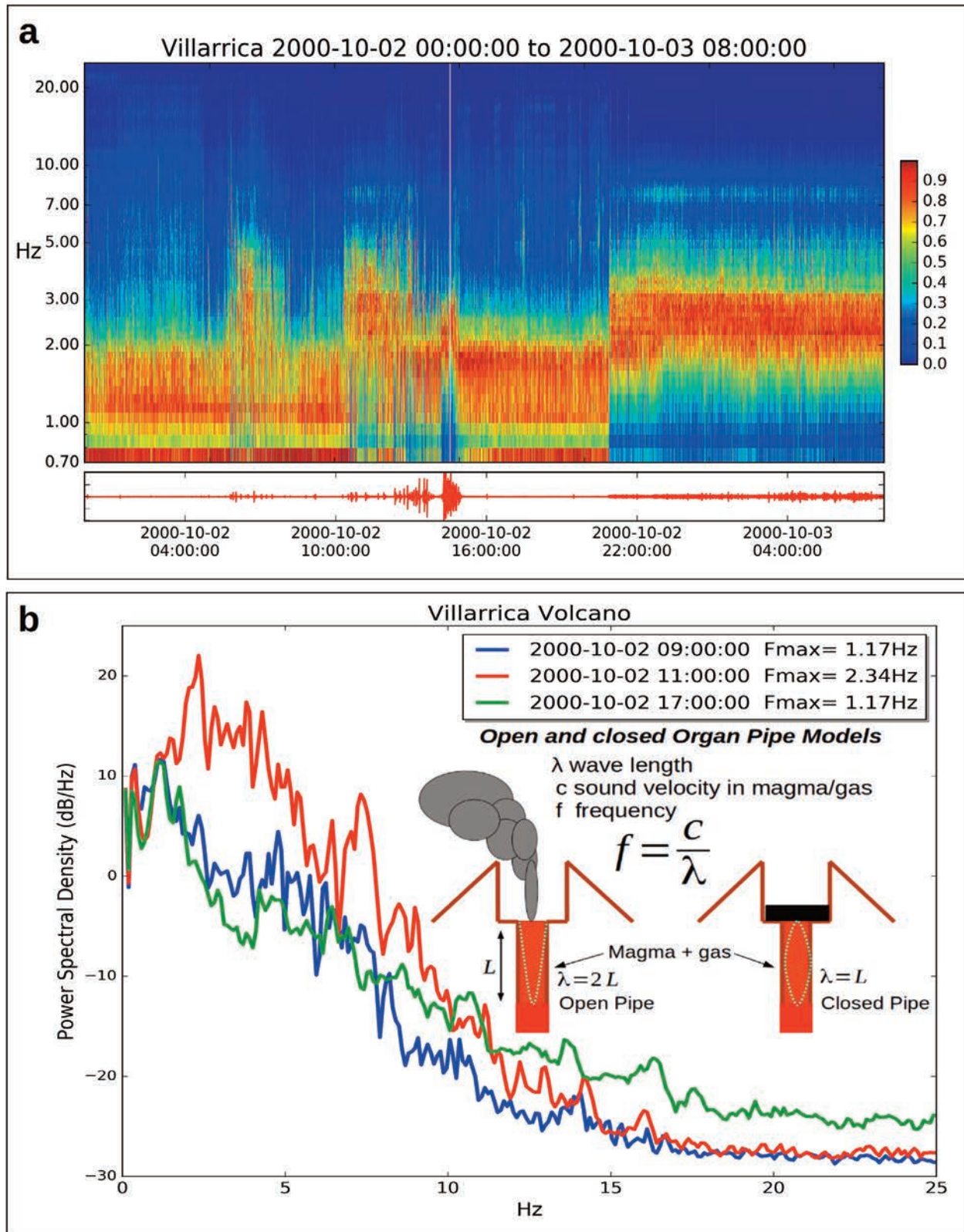


FIGURE 6. a) 24-hour spectrogram of a seismic signal at Villarrica volcano (Chile) obtained on 02 Oct 2000. A sharp transition of the dominant frequency may be clearly seen around hour 21:00. This type of transition is attributed to sudden openings or closings of the volcano conduit. b) The seismic signal spectrogram of this eruptive activity shows that the dominant frequency of a closed conduit (red) is twice the frequency of an open conduit (blue and green).



each case on a preliminary assessment of the physics controlling the volcanic activity and the type of available data. This sometimes requires developing new methods to deal with particular situations [see e.g. Salvage and Neuberg, 2016].

A review of other methods of data reduction to characterize volcanic activity can be found in Carniel [2014], where particular emphasis is put on approaches based on the time evolution of parameters that consider the volcano as a non-linear dynamical system.

### 3.2 ANALYSIS OF SEISMIC WAVEFORMS AND RECOGNITION OF EVENT FAMILIES

Since late XIX and through the XX century, earthquakes of volcanic origin have been differentiated from tectonic earthquakes [e.g. Mercalli, 1883; Omori, 1903, 1911, 1912; Davison, 1921; Noguchi, 1963; Mogi, 1963; Minakami, 1964], and different source mechanisms have been associated to each type.

The identification and follow up of the evolution of different volcanic signals may have a high forecasting value. However, monitoring and recognition of the different signals is a difficult task, particularly during unrest periods, when signals of many coexistent processes are recorded. Recently, some methods of automatic recognition and selection of families of signals in real or quasi-real time have been developed. For example, the Hidden Markov Models, that have been applied to several volcanoes such as Merapi [Ohrnberger, 2001; Wassermann and Ohrnberger, 2001], Las Cañadas caldera [Beyreuther et al., 2008], Popocatepetl [Cortés et al., 2009], Stromboli, Etna [Ibáñez et al., 2009] and Volcán de Colima, where the results of automatic recognition accuracy, reported by the group in charge of the monitoring activities amount to 82% [Cortés et al., 2009; Arámbula-Mendoza et al., 2018].

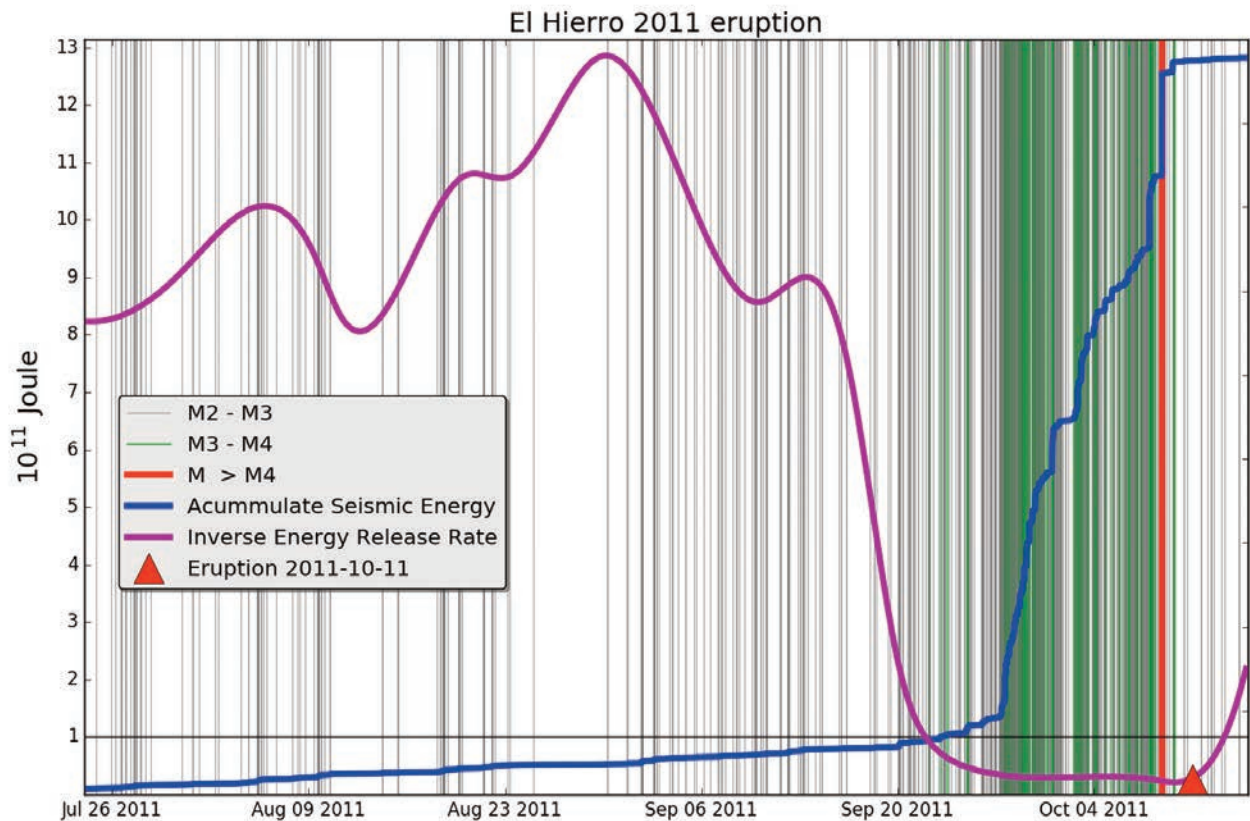
Other examples of signal classification methods are the Artificial Neural Networks [Falsaperla et al., 1996] applied for example to Vesuvius volcano [Scarpetta et al., 2005], the Support Vector Machines [Masotti et al., 2006], Parallel System Architectures based on HMM [Cortés et al., 2014], Deep Neural Networks [Titos et al., 2018a] and Recurrent Neural Networks [Titos et al., 2018b]. Currently, the EU-funded project VULCAN.ears (Volcano-seismic Unsupervised Labelling and Classification Embedded in A Real-time Scenario) aims to develop a volcano-independent [Cortés et al., 2019], HMMs-based software to classify events ([https://cordis.europa.eu/project/rcn/210584\\_en.html](https://cordis.europa.eu/project/rcn/210584_en.html)).

## 4. A CASE HISTORY: EL HIERRO 2011-2014 VOLCANIC ACTIVITY AFTER A LONG REPOSE PERIOD

The recent volcanic and seismic unrest observed at El Hierro (Canary islands; 2011-2015) provided with an opportunity to observe its complex evolution since its onset in July 2011 using some of the methods described in previous sections, and collect relevant forecast information data to assist decision-making. Seismic data, including earthquake magnitudes and locations were obtained from the on-line official catalog of the Spanish Geographical Institute (<http://www.ign.es/ign/layout/sismoFormularioCatalogo.do>). To process this information, we first implemented a real-time calculation of the cumulative seismic energy and a stepwise estimate of the Gutenberg-Richter  $b$ -value [Gutenberg and Richter, 1944] on intervals showing stability in the rate of occurrence of different earthquake magnitudes [García et al., 2016]. From the beginning of the seismic analysis, the evolution of the seismic energy conformed to the Yokoyama criterion [Yokoyama, 1988] showing significant increments in the number and magnitude of earthquakes when the cumulative energy exceeded  $10^{11}$ J (Figure 7).

Kalman- filtered data were used to track the SSEM evolution. In the initial stages of unrest, the  $b$ -value provided information about the process of magma migrations causing the unrest, but difficulties with the stability of the low-cut-off magnitude made it difficult to continuously track changes of the  $b$ -value. The Kalman-SSEM based forecasting of major earthquakes provided useful results until the onset of the submarine eruption (2011-10-10), when the strong tremor caused by the eruption masked most of the other signals. Nevertheless, the SSEM method still allowed forecasts using distant stations.

Volcano-tectonic seismicity at El Hierro stopped when the eruption began, resuming some days later, on 2011-10-29, when a new seismic swarm and significant deformations developed in a way similar to the pre-eruptive unrest. The new unrest episode culminated with the largest earthquake with magnitude 4.6. Figure 8 shows the improved inverse SSEM forecast of this new unrest episode using the Kalman-filtered data. This activity could be explained by a new deep magma injection process. Afterward, a sequence of similar episodes of seismicity and deformation were recorded, with temporal and spatial evolutions that are consistent with the



**FIGURE 7.** Evolution of the cumulative seismic energy from the onset of unrest at El Hierro island, to the onset of the submarine eruption. The rate of cumulative seismic energy release (blue thick line) clearly accelerates after reaching the Yokoyama threshold level of  $10^{11}$  J. The purple line represents the inverse of the smoothed derivative of the cumulative seismic energy (inverse energy release rate), which clearly shows the increased rate of energy release just above (below in the inverse curve) that energy threshold.

model of magma injections along paths defined by stress controlled conical surfaces [De la Cruz-Reyna and Yokoyama, 2011; García et al., 2014a]. The model allows detection of shallow regions of increased seismic and related landslide hazard. The similarities among the different episodes of seismicity motivated the definition of a new family of magma-migration related seismic swarms [Farrell et al., 2009; García et al., 2016].

### 5. VOLCANIC ACTIVITY FORECASTING AND RISK MANAGEMENT

The assessment and management of developing volcanic activity evolve in two parallel lines; one is specifically scientific, while the other is focused on the management of the risk posed by the activity. The latter must provide decision factors in near real time and include criteria and communication procedures to advise authorities and warn the population sufficiently in advance of a critical situation. Timely needs are determined by the type of necessary preventive actions (e.g.

hours in the case of closing of a road in a zone of probable landslides, or days in cases requiring to evacuate). Marrero et al. [2010] presented a new tool for simulating and optimizing large-scale evacuation processes: The Variable Scale Evacuation Model (VSEM), which allows simulating an evacuation considering different strategies for diverse impact scenarios. The decision to evacuate is one of the critical issues in managing a crisis. In order to make such an important decision, it is essential to estimate the potential loss of lives for each of the expected impact scenarios. To improve the emergency response planning and facilitate the decision-making process we also developed a methodology to estimate the number of potential fatalities, which has been applied to the Central Volcanic Complex of Tenerife and to El Chichón volcano (México) [Marrero et al., 2012, 2013].

Employing several of the above mentioned forecasting tools, and according to a time window defined by the expected impact scenarios, it was possible to design an automatic “watchdog” system capable to detect actual data trend changes, and reject spurious signals re-

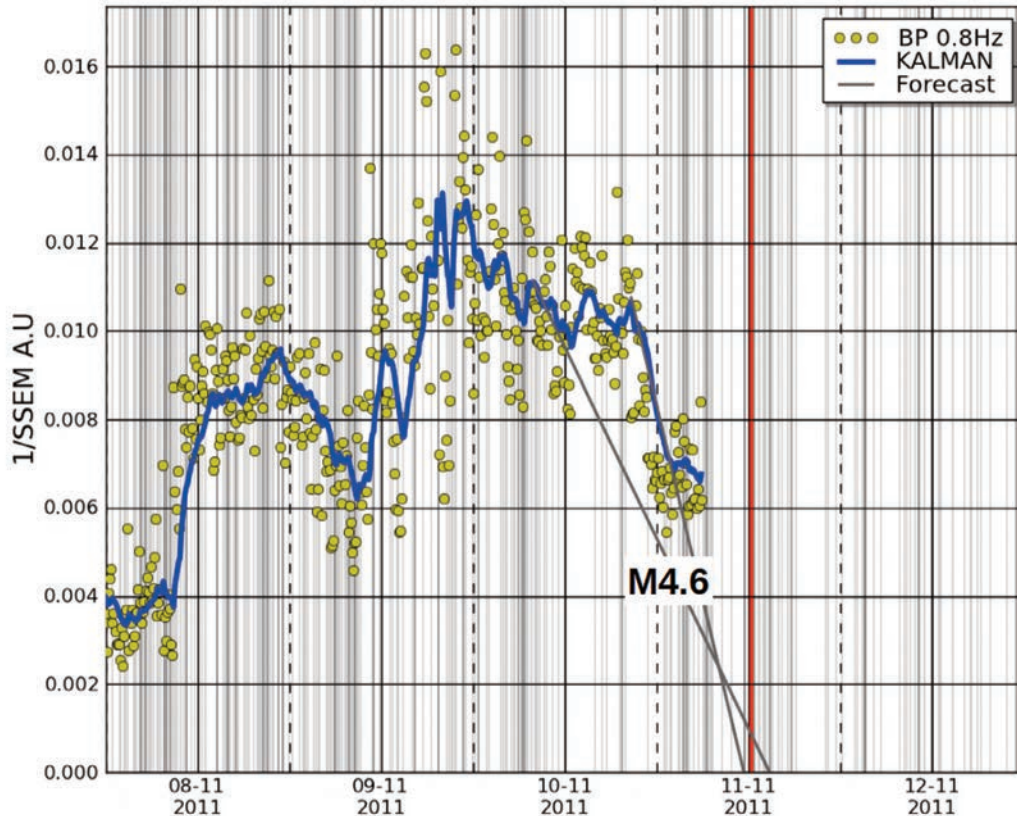


FIGURE 8. Inverse Kalman-filtered SSEM forecasts issued at El Hierro about one day and about half day before the M 4.6 VT earthquake of 11 Nov 2011.

lated to instrumental failure. Such “watchdog” system operates in steps according to the following routine:

1. Automatic and/or visual daily examination of the available seismic data
2. Computation of earthquake magnitudes.
3. VT hypocentral/epicentral locations or at least estimation of distance to station.
4. Cumulative seismic energy calculation, and assessment of the seismic energy release rate.
5. 24-hour spectral analysis of the continuous signal.
6. RSAM calculation and/or derived methods: SSAM, SSEM, BLNSS.
7. MRT calculation using VT located at less than 10–20 km from the volcano.
8. Identification of VT families.

In this way unrelated signals are rejected, and only changes related to volcanic activity may be translated into a specific Volcanic Alert System (VAS) that is easy to understand and use by scientists, technicians, and decision-makers [García et al., 2014b]. Although this procedure has been tested, its effectiveness is highly dependent on the cultural, political and social background of the area in which a crisis develops [Marrero et al., 2015].

## 6. DISCUSSION

There are indeed many more methods for volcano monitoring and eruption forecasting with increasing degrees of sophistication. However, a common problem, particularly in developing countries, or in regions with volcanoes with low rates of high-magnitude eruptions, is the difficulty and sometimes impossibility to obtain funding for extensive and permanent monitoring, particularly when other basic social and economic issues must be addressed. The methods discussed here may render useful results even with data obtained with low-cost instruments, like those designed for educational purposes. For example, the Arietta ([www.acmesystems.it](http://www.acmesystems.it)), Raspberry ([www.raspberrypi.org](http://www.raspberrypi.org)) or Arduino ([www.arduino.cc](http://www.arduino.cc)) embedded micro-computers allow assembling seismic monitoring stations at very low cost. Affordable 4.5 Hz geophones with a pre-amplifier can generate valuable data extending their signal response to 5 seconds [Ortiz et al., 2001; Havskov and Alguacil, 2006]. Data may be transmitted to a processing center by GSM, Ethernet or WIFI in quasi-real time or by specific time-periods depending on the available links, and following

the procedure described in the previous section. These methods have been used at El Hierro and El Chichón volcanoes with good results

## 7. CONCLUSIONS

Awareness of manifestations precursory to eruptions has existed for a long time. Disasters happen when precursors are not recognized, or misunderstood, or ignored, and a wrong decision follows. It is thus necessary to increase the reliability of the precursor's recognition and interpretation, and improve the communication of the hazards and the confidence of the decision-makers. This task is not simple, as the number of parameters involved in a volcanic process exceeds the number of measurable quantities that can be accurately measured at the surface. It is now recognized that even simple dynamical systems can show a complex behavior when they become non-linear [Lorenz, 1963; Mandelbrot, 1977; Turcotte, 1987; Newman, 2011] and this triggered the introduction of novel methods to characterize [Carniel, 2014] and model [Pshenichny et al., 2003, 2009] the time series representing the dynamics of volcanic systems. For instance, the determination of power-law distributions for different parameters, in particular frequency-magnitude power-law statistics, may reveal some general scale-invariance and self-organization characteristics of the magmatic systems. Such information can help to recognize a process that will culminate as a catastrophic failure. Considering the technical developments of sensors, transducers, computers and communication devices, and the persistently increasing capabilities of software to process that type of information, it is presently feasible to monitor volcanoes and maintain a sound forecasting capability at an affordable cost. What is needed is to promote the political will to invest in such systems.

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## REFERENCES

- Arámbula-Mendoza, R., Reyes-Dávila, G., Vargas-Bramontes, D.M., González-Amezcuca, M., Navarro-Ochoa, C., Martínez-Fierros, A. and Ramírez-Vázquez, A. (2018). Seismic monitoring of effusive-explosive activity and large lava dome collapses during 2013-2015 at Volcán de Colima, Mexico. *J. Volcanol. Geoth. Res.*, 351, 75-88, doi: 10.1016/j.jvolgeores.2017.12.017.
- Barberi, F., Corrado, G. and Innocenti, F. (1984). Phlegraean Fields 1982-1984: Brief chronicle of a volcano emergency in a densely populated area. *Bull. Volcanol.*, 47: 175, doi: 10.1007/BF01961547.
- Barberi, F., Casale, R. and Fratta, M. (1995). The European laboratory volcanoes. Workshop proceedings Aci Castello (Catania), 18-21 June 1994, ECSC-EC-EAEC, Brussels, Luxembourg, ISBN 92-827-4985-1.
- Barberi, F., Civetta, L., Rosi, M. and Scandone. (2008). Chronology of the 2007 eruption of Stromboli and the activity of the Scientific Synthesis Group. *J. Volcanol. Geoth. Res.*, 182 3-4 123-130, doi: 10.1016/j.jvolgeores.2008.09.019.
- Benoit, J. P. and McNutt, S. R. (1996). Global volcanic earthquake swarm database 1979-1989. Open-file report 96-69, US Department of the Interior, US Geological Survey.
- Beyreuther M. Carniel R., and Wassermann J. (2008). Continuous Hidden Markov Models: Application to automatic earthquake detection and classification at Las Cañadas caldera, Tenerife. *J. Volcanol. Geoth. Res.*, 176, 4, 513-518, doi: 10.1016/j.jvolgeores.2008.04.021.
- Bormann, P. (2002). Seismic signals and noise. In Bormann, P. (Ed.) *New Manual of Seismological Observatory Practice*. IASPEI, vol. 1, chap. 4, pp: 1-33, GeoForschungsZentrum, Potsdam, Germany.
- Carniel, R., Ortiz, R., and Di Cecca, M. (2006a) Spectral and dynamical hints on the timescale of preparation of the 5 April 2003 explosion at Stromboli volcano. *Canad. J. Earth. Sci.* 43:41-55, doi: 10.1139/E05-093.
- Carniel, R., Barazza, F., and Pascolo, P. (2006b), Improvement of Nakamura technique by singular spectrum analysis. *Soil Dyn. Earthq. Eng.* 26, 1, 55-63, doi: 10.1016/j.soildyn.2005.08.005.
- Carniel, R., Tarraga, M., Barazza, F. and García, A. (2008). Possible interaction between tectonic events and seismic noise at Las Cañadas Volcanic

- Caldera, Tenerife, Spain. *Bull. Volcanol.* 70, 9: 1113-1121, doi: 10.1007/s00445-007-0193-7.
- Carniel, R., Barbui, L. and Malisan, P. (2009). Improvement of HVSR technique by self-organizing map (SOM) analysis. *Soil Dyn. Earthq. Eng.* 29, 6: 1097-1101, doi: 10.1016/j.soildyn..11.008.
- Carniel, R., Barbui, L. and Jolly, A.D. (2013). Detecting dynamical regimes by Self-Organizing Map (SOM) analysis: an example from the March 2006 phreatic eruption at Raoul Island, New Zealand Kermadec Arc. *Bollettino di Geofisica Teorica ed Applicata*, 54, 1:39-52, doi: 10.4430/bgta0077.
- Carniel, R. (2014). Characterization of volcanic regimes and identification of significant transitions using geophysical data: a review. *Bull Volcanol* (2014) 76:848, doi: 10.1007/s00445-014-0848-0.
- Cortés, G., Arámbula, R., Gutiérrez, L.A., Benítez, C., Ibáñez, J., Lesage, P., Alvarez, I. and García, L. (2009). Evaluating robustness of a HMM-based classification system of volcano-seismic events at Colima and Popocatepetl volcanoes. *Geoscience and Remote Sensing Symposium, IEEE International, IGARSS*, doi: 10.1109/IGARSS.2009.5418275.
- Cortés, G., García, L., Álvarez, I., Benítez, C., de la Torre, A. and Ibáñez, J. (2014). Parallel System Architecture (PSA): An efficient approach for automatic recognition of volcano-seismic events. *J. Volcanol. Geoth. Res.*, 271:1-10. doi: 10.1016/j.jvolgeores.2013.07.004.
- Cortés, G., Carniel, R., Mendoza, M.A., Lesage, P. (2019). Standardization of Noisy Volcanoseismic Waveforms as a Key Step toward Station- Independent, Robust Automatic Recognition. *Seismological Research Letters*, 90 (2 A), pp. 581-590. doi: 10.1785/0220180334
- Davison C. (1921). Volcanic Earthquakes. *The Journal of Geology*, 29, 2: 97-124.
- De la Cruz-Reyna, S. and Reyes-Dávila, G.A. (2001). A model to describe precursory material-failure phenomena: applications to short-term forecasting at Colima volcano, Mexico. *Bull Volcanol* 63:297-308, doi: 10.1007/s004450100152.
- De la Cruz-Reyna S, Yokoyama I, Martínez-Bringas A., Ramos E. (2008). Precursory Seismicity of the 1994 Eruption of Popocatepetl Volcano, Central Mexico. *Bull Volcanol* 70(6): 753-767, doi:10.1007/s00445-008-0195-0.
- De la Cruz-Reyna, S., Tárraga, M., Ortiz, R. and Martínez-Bringas, A. (2010). Tectonic earthquakes triggering volcanic seismicity and eruptions. Case studies at Tungurahua and Popocatepetl volcanoes. *J. Volcanol Geoth. Res.*, 193:37-48, doi:10.1016/j.jvolgeores.2010.03.005.
- De la Cruz-Reyna, S. and Yokoyama, I. (2011). A geophysical characterization of monogenetic volcanism, *Geofis. Int.*, 50, 465-484, ISSN 0016-7169.
- De Natale G., Gasparini P. and Coppa U. (Eds) (1999). *Physics of volcanic phenomena and eruption precursors*. Special Issue *Annali di Geofisica*, 42 (3).
- Endo, E.T. and Murray, T. (1991). Real-time Seismic Amplitude Measurement (RSAM): a volcano monitoring and prediction tool. *Bull. Volcanol*, 53: 533-545, doi: 10.1007/BF00298154.
- Falsaperla, S., Graziani, S., Nunnari, G. and Spampinato, S., (1996). Automatic classification of volcanic earthquakes by using multi-layered neural networks. *Natural Hazards* 13 (3), 205-228, doi: 10.1007/BF00215816.
- Farrell, J., Husen, S. and Smith, R.B. (2009). Earthquake swarm and b-value characterization of the Yellowstone volcano-tectonic system, *J. Volcanol. Geoth. Res.*, 188, 260-276, doi: 10.1016/j.jvolgeores.2009.08.008,
- Fedotov, S.A. and Markhinin, Ye.K. (Eds) (1983). *The Great Tolbachik Fissure Eruption: Geological and Geophysical Data, 1975-1976*. Cambridge University Press, 341 p. ISBN 0-521-24345-9.
- Frohlich C. and Davis, S. (1993) Teleseismic b-values: or, much ado about 1.0. *J Geophys Res* 98:631-644
- García, A., Vila, J., Ortiz, R., Marcía, R., Sleeman, R., Marrero, J.M., Sánchez, N., Tárraga, M. and Correig, A.M. (2006) Monitoring the reawakening of Canary Islands' Teide Volcano. *Eos Trans AGU* 87:61-65. doi:10.1029/2006E0060001.
- García, A., Fernández-Ros, A., Berrocoso, M., Marrero, J.M., Prates, G., De la Cruz-Reyna, S. and Ortiz, R. (2014a). Magma displacements under insular volcanic fields, applications to eruption forecasting: El Hierro, Canary Islands, 2011-2013. *Geophys. J. Int.*, 196:1-13, doi:10.1093/gji/ggt505.
- García, A., Berrocoso, M., Marrero, J.M., Fernández-Ros, A., Prates, G., De la Cruz-Reyna, S. and Ortiz, R. (2014b). Volcanic Alert Level System (VALS) developed during the (2011-2013) El Hierro (Canary Island) volcanic process. *Bull. Volcanol.*, 76:825, doi:10.1007/s00445-014-0825-7.
- García, A., De la Cruz-Reyna, S., Marrero, J.M. and Ortiz, R. (2016). Short-term volcano-tectonic

- earthquake forecasts based on a MRT algorithm: the El Hierro seismo-volcanic crisis experience. *Nat. Hazards Earth. Syst. Sci.*, 16, 1135–1144. doi: 10.5194/nhess-16-1135-2016.
- Grasso, J.R. and Sornette, D. (1998). Testing self-organized criticality by induced seismicity. *J. Geophys. Res. Solid Earth*, doi: 10.1029/97JB01344.
- Gudmundsson, A. (2002). Emplacement and arrest of sheets and dykes in central volcanoes, *J. Volc. Geotherm. Res.*, 116(3-4): 279-298, doi: 10.1016/S0377-0273(02)00226-3.
- Gutenberg, B. and Richter, C.F. (1944). Frequency of earthquakes in California, *B. Seismol. Soc. Am.*, 34, 185–188.
- Havskov, J. and Alguacil, G. (2006) *Instrumentation in earthquake seismology*. Springer, 312p, ISBN-10 1-4020-2968-3 (HB)
- Harris, A.J.L., Pilger, E. and Flynn, L.P. 2001. Web-based hot spot monitoring using GOES: What it is and how it works. *Adv. Environ. Monit. Model.* 1, 3-31.
- Ibáñez, J.M., Benitez, C., Gutierrez, L.A., Cortes, G., Garcia-Yeguas, A. and Alguacil, G. (2009) The classification of seismo-volcanic signals using Hidden Markov Models as applied to the Stromboli and Etna volcanoes. *Journal of Volcanology and Geothermal Research* 187 (2009) 218–226, doi:10.1016/j.jvolgeores.2009.09.002.
- Ishimoto, I. and Iida, K., (1939). Observations of earthquakes registered with the microseismograph constructed recently. *Bull. Earthq. Res. Inst. Univ. Tokyo.*, 17, 443–478.
- Jaquet, O. and Carniel, R. (2003). Multivariate stochastic modelling: Towards forecasts of paroxysmal phases at Stromboli. *J. Volcanol. Geoth. Res.*, 128, 1-3, 261-271, doi: 10.1016/S0377-0273(03)00259-2.
- Jaquet, O., Carniel, R., Sparks, S., Thompson, G., Namar, R., Di Cecca, M. (2006). DEVIN: A forecasting approach using stochastic methods applied to the Soufrière Hills Volcano. *J. Volcanol. Geoth. Res.*, 153, 1-2, 97-111 doi: 10.1016/j.jvolgeores.2005.08.013
- Jones, L.M. (1996). Earthquake prediction: the interaction of public policy and science. *Proc. Nat. Acad. Sci. USA.* 93, 3721-3725.
- Kalman, R.E. (1960). A new approach to linear filtering and prediction problems. *Journal of Fluids Engineering*, 82(1): 35–45, doi: 10.1115/1.3662552.
- Kohonen, T. (1982). Self-Organized Formation of Topologically Correct Feature Maps. *Biological Cybernetics*, 43, 59-69, doi: 10.1007/BF00337288.
- Ladina, C. (2012). Information from seismic ambient noise: techniques to investigate geological properties. *Tesi di Dottorato. Università di Genova*, 189 pp.
- Langer, H., Falsaperla, S., Masotti, M., Campanini, R., Spampinato, S. and Messina, A. (2009). Synopsis of supervised and unsupervised pattern classification techniques applied to volcanic tremor data at Mt Etna, Italy. *Geophysical Journal International*, 178(2-1): 1132-1144, doi: 10.1111/j.1365-246X.2009.04179.x.
- Lipman, P.W. and Mullineaux, D.R. (1981) *The 1980 eruptions of Mount St. Helens, Washington*. Geological Survey Professional Paper 1250. 844 pp., doi: 10.3133/pp1250
- Lorenz, E.N. (1963). Deterministic nonperiodic flow. *J. Atmos. Sci.* 20 (2): 130–141, doi: 10.1175/1520-0469(1963)020<0130:DNF>2.0.CO;2
- Mandelbrot, B.B. (1977). *Fractals: Form, Chance and Dimension*. W. H. Freeman and Co. San Francisco.
- Marrero, J.M., García, A., Llinares, A., Rodríguez-Losada, J.A. and Ortiz, R., (2010). The Variable Scale Evacuation Model (VSEM): a new tool for simulating massive evacuation processes during volcanic crises. *Natural Hazards and Earth System Sciences* 10: 747–760, doi: 10.5194/nhess-10-747-2010
- Marrero, J.M., García, A., Llinares, A., Rodríguez-Losada, J.A., and Ortiz, R. (2012). A direct approach to estimating the number of potential fatalities from an eruption: application to the central volcanic complex of Tenerife Island. *J. Volcanol. Geotherm. Res.*, 219: 33–40, doi: 10.1016/j.jvolgeores.2012.01.008.
- Marrero, J.M., García, A., Llinares, A., De la Cruz-Reyna, S., Ramos, S. and Ortiz, R. (2013) Virtual Tools for volcanic crisis management, and evacuation decision support: applications to El Chichón volcano (Chiapas, México). *Nat. Hazards*, 68:955–980, doi:10.1007/s11069-013-0672-4.
- Marrero, J.M., García, A., Llinares, A., Berrocoso, M. and Ortiz, R. (2015). Legal framework and scientific responsibilities during volcanic crises: the case of the El Hierro eruption (2011–2014). *Journal of Applied Volcanology*, 4:13, doi: 10.1186/s13617-015-0028-8.
- McNamara, D.E., Hutt, C.R., Gee, L.S., Benz, H.M. and Buland, R.P. (2009). A Method to Establish Seismic

- Noise Baselines for Automated Station Assessment. *Seismological Research Letters* Volume 80 (4):628-637, doi: 10.1785/gssrl.80.4.628.
- Masotti, M., Falsaperla, S., Langer, H., Spampinato, S. and Campanini, R. (2006). Application of support vector machine to the classification of volcanic tremor at Etna, Italy. *Geophysical Research Letters*, 33, L20304, doi: 10.1029/2006GL027441.
- Mercalli, G. (1883). Vulcani e fenomeni vulcanici in Italia. In: Negri, G., Stoppani, A. and Mercalli, G. (eds) *Geologia d'Italia*. Vallardi, pp 217-218.
- Minakami, T. (1964). On possibility or impossibility of standardizing the observations in volcanological observatories. *Bull. Volcanol.*, 27(1): 411-414.
- Mogi, K. (1963). Experimental study on the mechanism of the earthquake occurrences of volcanic origin. *Bull. Volcanol.*, 26(1): 197-208, doi: 10.1007/BF02597286.
- Newman, M.E.J. (2011). Complex Systems: A Survey. *Am. J. Phys.* 79: 800-810, doi: 10.1119/1.3590372.
- Noguchi, K. and Kamiya, H. (1963). Prediction of volcanic eruption by measuring the chemical composition and amounts of gases. *Bull. Volcanol.*, 26(1): 367-378, doi: 10.1007/BF02597298.
- Ogata, Y. and Katsura, K. (1993) Analysis of temporal and spatial heterogeneity of magnitude frequency distribution inferred from earthquake catalogues. *Geophys. J. Int.* 113,727-738, doi: 10.1111/j.1365-246X.1993.tb04663.x
- Ohrnberger, M. (2001). Continuous automatic classification of seismic signals of volcanic origin at Mt. Merapi, Java, Indonesia. Ph.D. dissertation, Mathematisch naturwissenschaftlichen Fakultät der Universität Potsdam.
- Omori, F. (1903). Preliminary report of an eruption of Tori-shima. *Journal of the Seismological Society of Japan* (First series), 43: 4-20 (in Japanese)
- Omori, F. (1911). The Usu-san eruption and earthquake and elevation phenomena. *Bull. Imp. Earthquake Inv. Com.*, 5: 1-38.
- Omori, F. (1912). The eruptions and earthquakes of the Asama-Yama. *Bulletin of the Imperial Earthquake Investigation Committee*, 6.
- Ortiz, R., Araña, V., Astiz, M. and Valentin (1984). Magnetotelluric survey in the bradyseismic area of Phlegraean Fields. *Bull Volcanol* 47: 239-246, doi: 10.1007/BF01961554.
- Ortiz, R., Correig, A.M., Diez, J.L. and Muñoz, M.L. (1992). Apparent Variation of Coda Q in Phlegraean Fields During the Bradyseismic Crisis of 1982-1984. In: Gasparini, P., Scarpa, R. and Aki, K. (eds). *Volcanic Seismology*. IAVCEI Proceedings in Volcanology, vol 3. Springer, Berlin, Heidelberg, doi: 10.1007/978-3-642-77008-1\_31.
- Ortiz, R., García, A., Astiz, M. (2001) Instrumentación en volcanología. Lanzarote. Cabildo. Servicio de Publicaciones. 347pp ISBN 84-87021-84-0
- Ortiz, R., Moreno, H., García, A., Fuentealba, G., Astiz, M., Peña, P., Sánchez, N. and Tárraga, M. (2003). Villarrica volcano (Chile): characteristics of the volcanic tremor and forecasting of small explosions by means of a material failure method. *J. Volcanol. Geotherm. Res.*, 128:247-259, doi: 10.1016/S0377-0273(03)00258-0.
- Pellegrino, Ch. (1991). *Unearthing Atlantis: An Archaeological Odyssey*. Random House Publishing Group: 336pp. ISBN 10: 0394575504 / ISBN 13: 9780394575506.
- Peterson, J. (1993). *Observations and Modelling of Seismic Background Noise*, US Department of Interior Geological Survey, Albuquerque, New Mexico, USA, Open-File Report 93-322, 95 pp.
- Prates, G., García, A., Fernández-Ros, A., Marrero, J.M., Ortiz, R. and Berrocoso, M. (2013). Enhancement of sub-daily positioning solutions for surface deformation surveillance at El Hierro volcano (Canary Islands, Spain). *Bull. Volcanol.*, 75(6):1-9, doi:10.1007/s00445-013-0724-3.
- Pshenichny, C.A., Moukhachyov, V.P. and Khrabrykh, Z.V. (2003). Logical assessment of observational knowledge in volcanology. *Journal of Volcanology and Geothermal Research*, 128, 287-298.
- Pshenichny, C.A., Nikolenko, S.I., Carniel, R., Vaganov, P.A. and Rezyapkin, A.A. (2009) The event bush as a semantic-based numerical approach to natural hazard assessment (exemplified by volcanology) . *Computers & Geosciences*, 35 (2009) 1017-1034, doi: 10.1016/j.cageo.2008.01.009
- Reyes-Davila, G.A. and De la Cruz-Reyna, S. (2002). Experience in the short-term eruption forecasting at Volcán de Colima, México, and public response to forecasts. *J. Volcanol. Geotherm. Res.*, 117(1-2): 121-127, doi: 10.1016/S0377-0273(02)00240-8.
- Roden, R., Smith, T. and Sacrey, D. (2015). Geologic pattern recognition from seismic attributes: Principal component analysis and self-organizing maps. *Interpretation*, 3 (4): SAE59-SAE83, doi 10.1190/INT-2015-0037.1.

- Rydelek, P.A. and Sacks, I.S. (1989). Testing the completeness of earthquake catalogs and the hypothesis of self-similarity. *Nature*, 337:251–253.
- Salvage, R.O. and Neuberg, J.W. (2016). Using a cross correlation technique to refine the accuracy of the Failure Forecast Method: Application to Soufrière Hills volcano, Montserrat. *J. Volcanol. Geotherm. Res.*, 324:118–133, doi:10.1016/j.jvolgeores.2016.05.011.
- Satō, D. (1913). Preliminary report on the explosion of Usu Volcano. *Rep. Geol. Surv. Jp*, 22, 6–46 (in Japanese).
- Scandone, R. and Giacomelli, L. (2014). Vesuvius, Pompei, Herculaneum: a lesson in natural history. *Journal of Research and Didactics in Geography*, 2-3: 33–41, doi: 10.4458/4403-03.
- Scarpetta, S., Giudicepietro, F., Ezin, E., Petrosino, S., Del Pezzo, E., Martini, M. and Marinaro, M. (2005). Automatic classification of seismic signals at Mt. Vesuvius volcano Italy using neural networks. *Bull. Seismol. Soc. Amer.*, 95(1): 185–196, doi: 10.1785/0120030075.
- Schick, R. and Riuscetti, M. (1973). An analysis of volcanic tremors at South Italian volcanoes, *Z. Geophys.*, 39: 247–262.
- Schick, R. (1981). Source mechanism of volcanic earthquakes. *Bull. Volc.*, 44-3: 491–497, doi: 10.1007/BF02600579.
- Sleeman, R. and Vila, J. (2007). Towards an Automated Uniform Quality. Control of the Virtual European Broadband Seismograph Network (VEBSN). *Orfeus Electronic Newsletter*, 7(1):5.
- Stephens, C.D., Marso, J.N. and Lahr, J.C. (1990). Real-time Seismic Spectral Amplitude monitoring during the 1989–1990 eruptions at Redoubt volcano. Alaska. *EOS, Trans. Am. Geophys. Union*, 71: 1709.
- Tanguy, J.C. (1994). The 1902–1905 eruptions of Montagne Pele, Martinique: anatomy and retrospection. *J. Volcanol. Geotherm. Res.*, 60: 87–107, doi: 10.1016/0377-0273(94)90064-7.
- Tárraga, M., Carniel, R., Ortiz, R., Marrero, J.M. and García, A. (2006). On the predictability of volcano-tectonic events by low frequency seismic noise analysis at Teide-Pico Viejo volcanic complex, Canary Islands. *Nat. Hazards Earth Syst. Sci.*, 6:365–376, doi: 10.5194/nhess-6-365-2006.
- Tárraga, M., Carniel, R., Ortiz, R. and García, A. (2008). The Failure Forecast Method: review and application for the real-time detection of precursory patterns at reawakening volcanoes, *Dev. Volcanol.*, 10, 447–469, doi: 10.1016/S1871-644X(07)00013-7.
- Tárraga, M., Mendoza-Rosas, A.T., Carniel, R., De la Cruz-Reyna, S., Martínez-Bringas, A., García, A. and Ortiz, R. (2012). Dynamical analysis of the Popocatepetl volcano (central Mexico) continuous seismic signals: a case of tectonic earthquakes influencing volcanic activity, *Acta Geophys.*, 60, 3, 37–48, doi: 10.2478/s11600-012-0020-1
- Taylor, D.W.A., Snoke, J.A., Sacks, I.S. and Takanami, T. (1990). Non-linear frequency-magnitude relationship for the Hokkaido corner, Japan. *Bull. Seismol. Soc. Am.*, 80: 340–353.
- Titos, M., Bueno, A., Garcia, L., Benitez, C. (2018a). A Deep Neural Networks Approach to Automatic Recognition Systems for Volcano-Seismic Events. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 11 (5):1533–1544. doi: 10.1109/JSTARS.2018.2803198
- Titos, M., Bueno, A., Garcia, L., Benitez, M.C., Ibañez, J. (2018b). Detection and Classification of Continuous Volcano-Seismic Signals With Recurrent Neural Networks. *IEEE Transactions on Geoscience and Remote Sensing*, in press. doi: 10.1109/TGRS.2018.2870202
- Turcotte, D.L. (1987). *Fractals and chaos in geology and geophysics*. Cambridge University Press. ISBN: 9780521567336, 416pp.
- Vila, J., Macià, R., Kumar, D., Ortiz, R., Moreno, H. and Correig, A.M. (2006). Analysis of the unrest of active volcanoes using variations of the base level noise seismic spectrum. *J. Volcanol. Geotherm. Res.*, 153: 11–20, doi: 10.1016/j.jvolgeores.2005.10.01.
- Vila, J., Ortiz, R., Tárraga, M., Macià, R., García, A., Kumar, D. and Correig, A.M. (2008). Near-Real time analysis of seismic data of active volcanoes: Software implementations of time sequence data analysis. *Natural Hazards and Earth System Sciences* 8: 789–794, doi: 10.5194/nhess-8-789-2008.
- Vinciguerra, S., Garozzo, S., Montalto, A. and Patane, G. (1999). Eruptive and seismic activity at Etna Volcano (Italy) between 1977 and 1991. *Geological Society, London, Special Publications*, 161, 89–107, doi: 10.1144/GSL.SP.1999.161.01.07.
- Voight, B. (1988). A method for prediction of volcanic eruptions, *Nature*, 332, 125–130.
- Voight, B. (1990). The 1985 Nevado del Ruiz volcano catastrophe: anatomy and retrospection. *J. Vol-*



- canol. Geotherm. Res., 44: 349-386, doi: 10.1016/0377-0273(90)90027-D.
- Warren, N.W. and Latham, G. (1970). An experimental study of thermally induced microfracturing and its relation to volcanic seismicity. *J. Geophys. Res.*, 75: 4455-4464, doi: 10.1029/JB075i023p04455.
- Wassermann, J. and Ohrnberger, M. (2001) Automatic hypocenter determination of volcano induced seismic transients based on wavefield coherence - an application to the 1998 eruption of Mt. Merapi, Indonesia. *J. Volcanol. Geotherm. Res.* 110(1-2):57-77, doi: 10.1016/S0377-0273(01)00200-1.
- Wiemer, S. and McNutt, S. (1997). Variations in frequency-magnitude distribution with depth in two volcanic areas: Mount St. Helens, Washington, and Mt. Spurr, Alaska, *Geophys. Res. Lett.* 24, 189-192, doi: 10.1029/96GL03779.
- Wiemer, S. and Wyss, M. (1997). Mapping the frequency-magnitude distribution in asperities: An improved technique to calculate recurrence times? *J. Geophys. Res.* 102, 15.115-15.128 doi: 10.1029/97JB00726.
- Wiemer, S., McNutt, S.R. and Wyss, M.(1998). Temporal and three-dimensional spatial analyses of the frequency-magnitude distribution near Long Valley Caldera, California, *Geophys. J. Int.*, 134: 409-421, doi: 10.1046/j.1365-246x.1998.00561.x.
- Wiemer, S. and Wyss, M. (2000). Minimum magnitude of completeness in earthquake catalogs: examples from Alaska, the western United States and Japan. *Bull. Seismol. Soc. Am.*, 90: 859-869, doi: 10.1785/0119990114.
- Yokoyama, I. (1988). Seismic energy releases from volcanoes, *Bull. Volcanol.*, 50: 1-13, doi: 10.1007/BF01047504.
- Yokoyama, I. and Matsushima, N. (2018). Understanding active volcanoes: the case of Usu Volcano, Japan, with emphasis on the 1977 summit eruption. *Geofísica Internacional* 57(1): 13-37.
- D.M. Johnston, J.W. Cole, J.B. Wardman, G. Wilson and S.T. Barnard (2012). Volcanic ash impacts on critical infrastructure. *Physics and Chemistry of the Earth*, 45-46, 5-23.
- Wilson, G., T.M. Wilson, N.I. Deligne and J.W. Cole (2014). Volcanic hazard impacts to critical infrastructure: a review. *Journal of Volcanology and Geothermal Research*, 286(1), 148-182.

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