Innovative developments in the identification and forecasting of volcanic and volcano-tectonic activity: Experiences from different volcanoes

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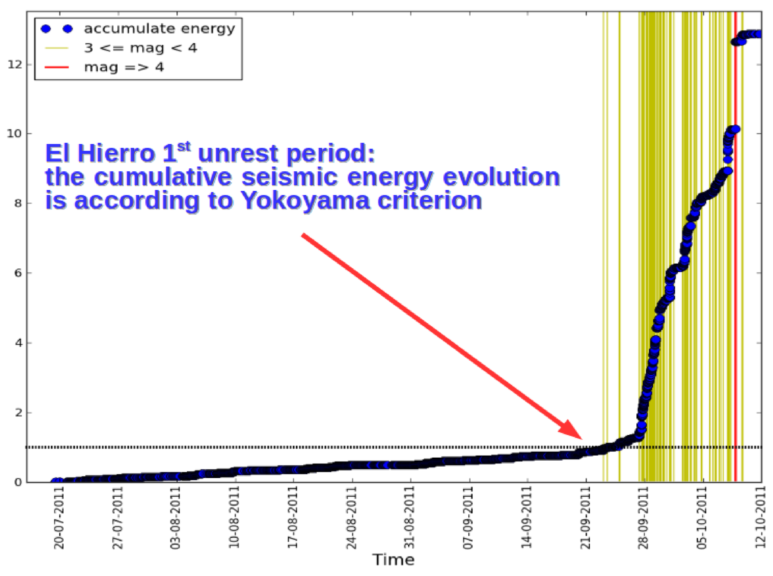
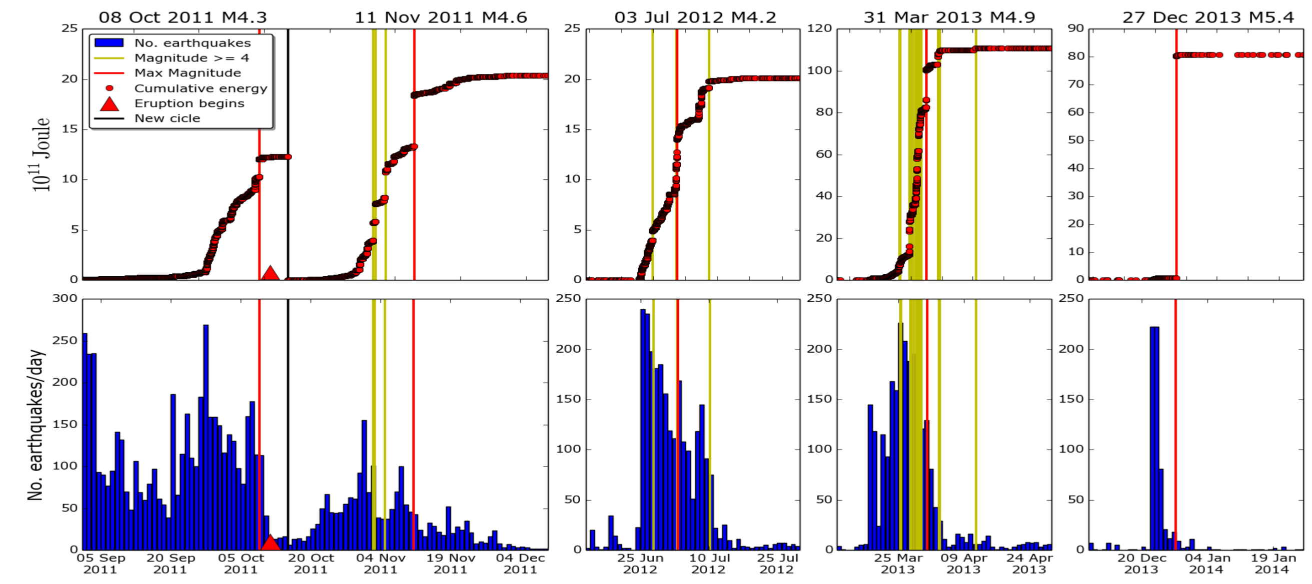
Yokoyama (1988) proposed an empirical relationship for a thresh-old of cumulative seismic energy released preceding magmatic eruptions in closed volcanic systems, after long periods of repose. He concluded that eruptions may occur when the cumulative seismic energy released during the precursory stage exceeded the 10^{11} J threshold. This threshold energy may be related to the volume of rock fractured by the magma that will erupt, and may be valid for central andesitic volcanoes and for monogenetic volcanoes. In addition, the cumulative seismic energy evolution shows a behaviour similar to the evolution of the observables of the volcano activity proposed by Voight (1988): *FFM Failure Forecast Method*. Magma induces additional stresses on the confining country rock in which it is intruding. When the combination of this stress with the regional tectonic stress reaches a critical value, the induced fracturing, or reactivation of pre-existent fractures, allows magma, and magma-related fluids to find their paths to the surface (De la Cruz-Reyna & Yokoyama 2011). The unrest episode at El Hierro occurred after a long repose period (over 200 yr), and after the seismic energy exceeded the 10**11 J threshold. Accordingly, using cumulative VT energy from the earliest stages of the unrest may be a more reliable parameter, as it is controlled by the largest magnitude events, unlike the statistics of the number of events, controlled by the smallest, more frequent, events.





When a seismic swarm responds to ***Yokoyama criterion***, the acceleration of the earthquake rate can be interpreted in terms of piece-wise estimations of the Gutenberg-Richter parameters. The variations of those parameters are translated as time windows of increased likelihood of a large-magnitude earthquake.

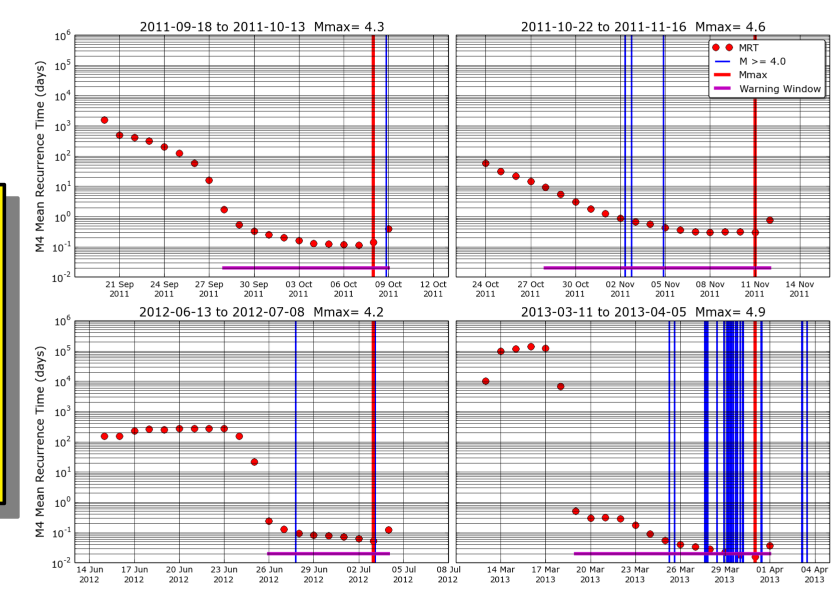
Under certain conditions, volcano-tectonic (VT) earthquakes may pose significant hazards to people living in or near active volcanic regions, especially on volcanic islands. The evolution of VT earthquakes resulting from a magmatic intrusion shows some orderly behaviour that may allow the occurrence and magnitude of major events to be forecast. Thus governmental decision makers can be supplied with warnings of the increased probability of larger-magnitude earthquakes on the short-term timescale. We present 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 (Spain). From then on, this methodology has been applied to the consecutive seismic crises at El Hierro, achieving a high success rate in the real-time forecasting, within 10-day time windows, of volcano-tectonic earthquakes

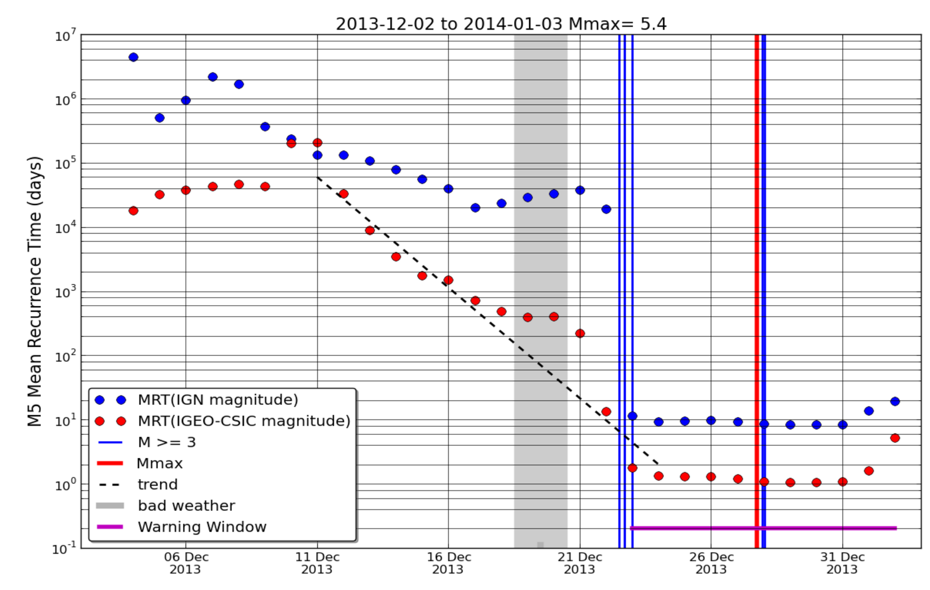
Gutenberg-Richter

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

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

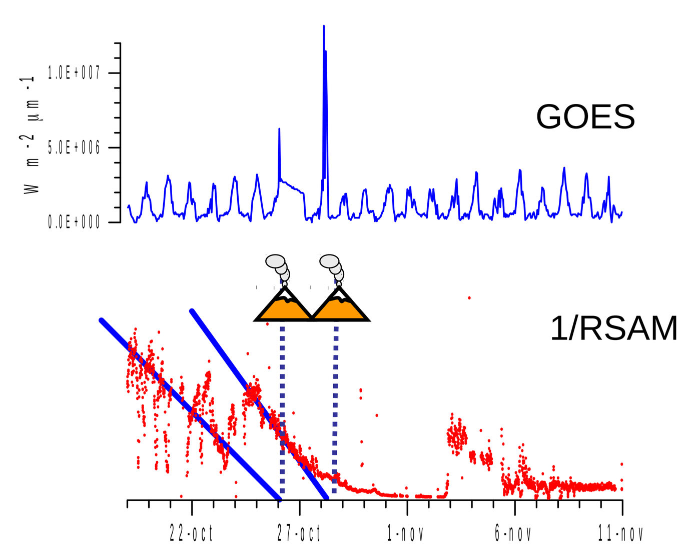
$$\tau_T = \Delta T \cdot 10^{(bM-a)}$$



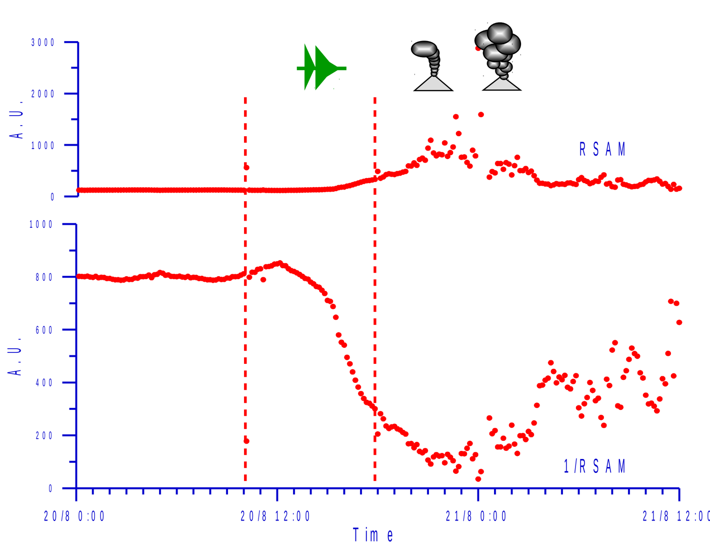


The Failure Forecast Method

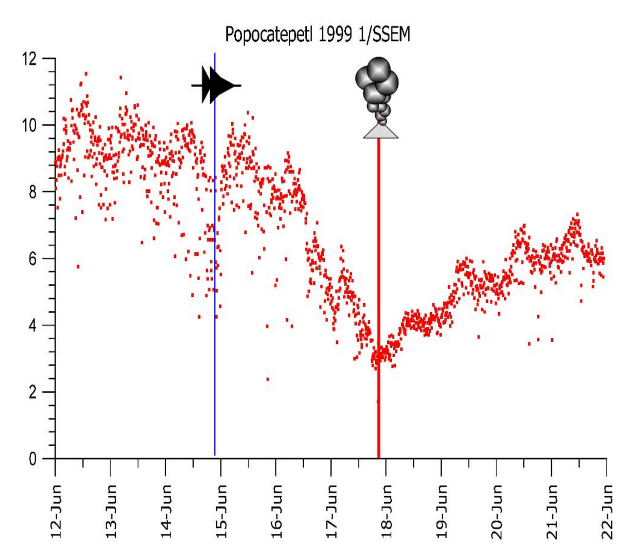
Voight (1988) proposed a general law of material failure governed by accelerating creep in order to characterize precursory phenomena. This gave birth to the material failure forecast method (FFM). The underlying hypothesis of this methodology is that deterministic models can be applied to volcanic systems. Pressurisation of a magma reservoir results in material failure, due to fracturing of the host rock. Voight's (1988) original approach has subsequently been applied and further developed in a number of studies in order to forecast eruptions or volcano-related seismic events at a number of different volcanoes (Voight and Cornelius, 1991; Cornelius and Voight, 1994, 1996; Kilburn and Voight, 1998; De la Cruz-Reyna and Reyes-Dávila, 2001; Kilburn, 2003; Ortiz et al., 2003; Carniel et al., 2006; Tárraga et al., 2006). The practical application of FFM as a real-time forecasting tool has been made possible in the 1990s — thanks to a marked increase in CPU speed.



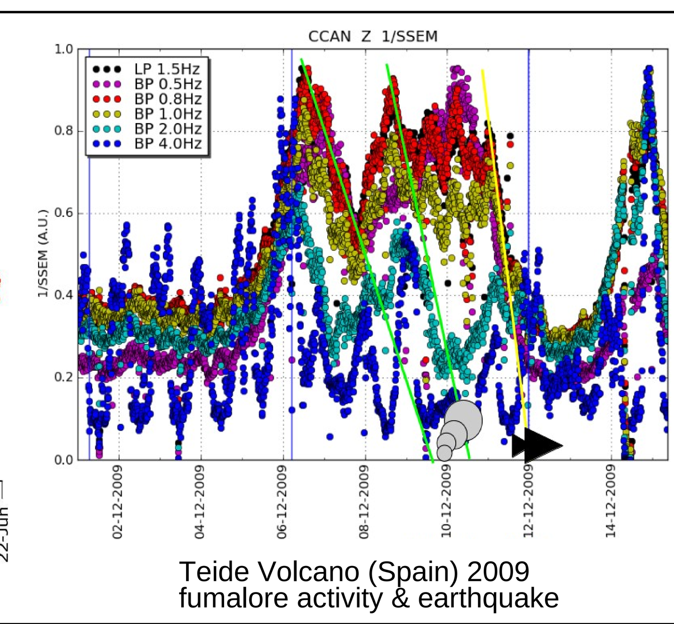
Villarrica Volcano (Chile)2000



Tungurahua Volcano (Ecuador)2008

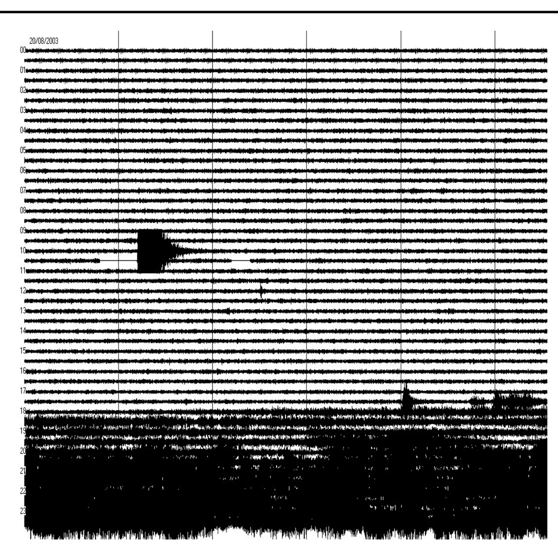


Popocatepetl Volcano (Mexico) 1999

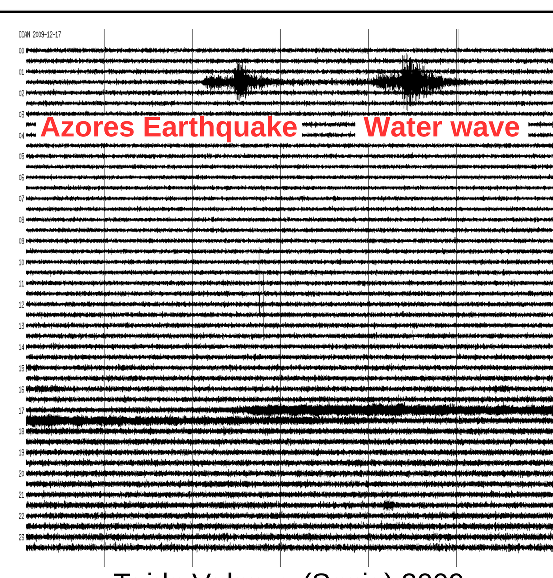


Teide Volcano (Spain) 2009 fumalore activity & earthquake

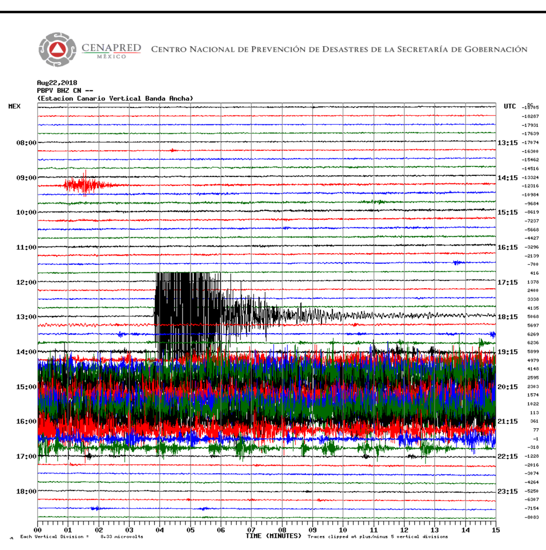
Small changes in the stress fields acting on active volcanoes can trigger volcanic seismicity and in some cases eruptions. The material failure process produces a characteristic release of strain that may be detected by nearby monitoring stations as an accelerated rate of seismic energy release. Real-time monitoring devices at Tungurahua, Teide and Popocatépetl have detected some cases in which the onset of the pattern was marked by regional tectonic earthquakes. The analysis of the seismic energy released at each volcano suggests that the regional earthquakes transferred a stress signal that increased almost linearly with time at the site, producing a logarithmic growth of the seismic rate associated to a first stage of material failure. The duration of the increasing stress stage is interpreted as related to the relaxation time of a viscoelastic shell surrounding the magmatic system. The behavior in those shells is consistent with a bulk viscosity component of the order of 10^5-10^6 Gpa s.



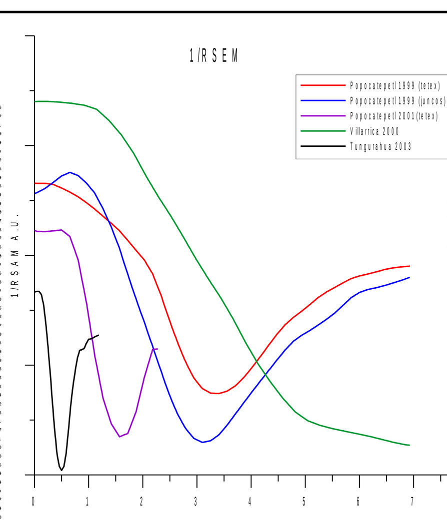
Tungurahua Volcano (Ecuador)2008



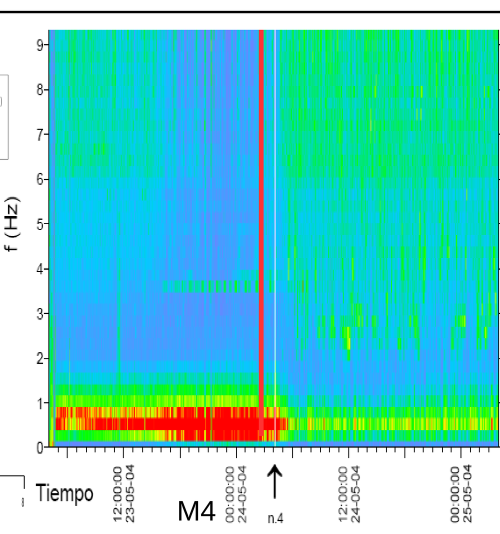
Teide Volcano (Spain) 2009



Popocatepetl Volcano (Mexico) 2018



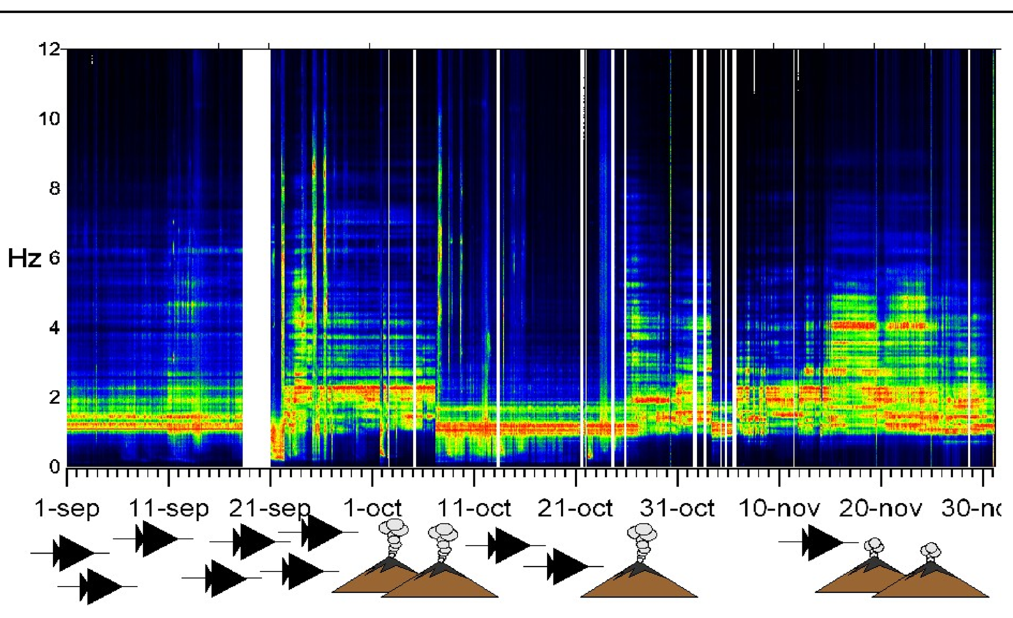
Days after seismic event

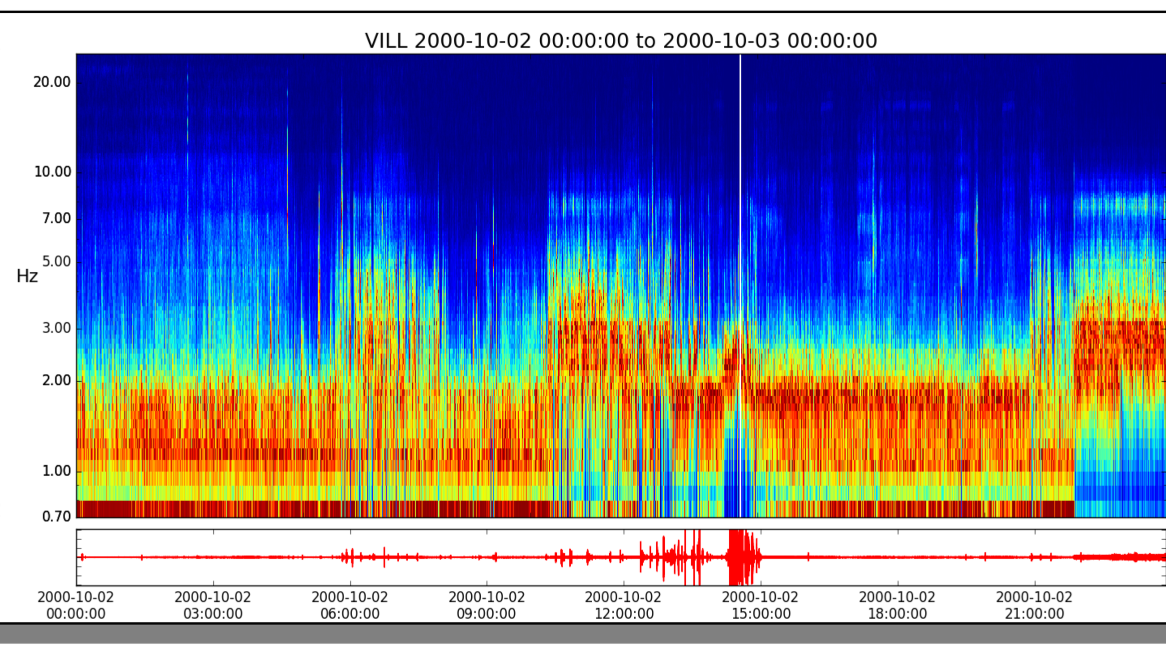


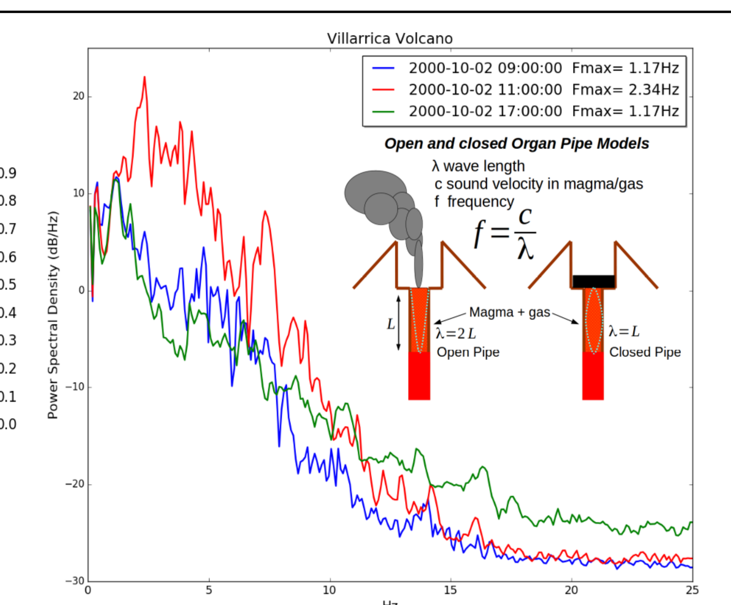
Inverse process: regional earthquake stop Teide (Spain) volcano tremor

Spectrogram

A spectrogram is a visual way of representing the signal strength, or "loudness", of a signal over time at various frequencies for a site. Not only can one see whether there is more or less energy at a particular frequency, but one can also see how energy levels vary over time. Using this spectrogram representation we also look at five different classification strategies in combination with a large number of different classifiers such as volcanic tectonic earthquakes, tectonic earthquakes, rockfalls etc…

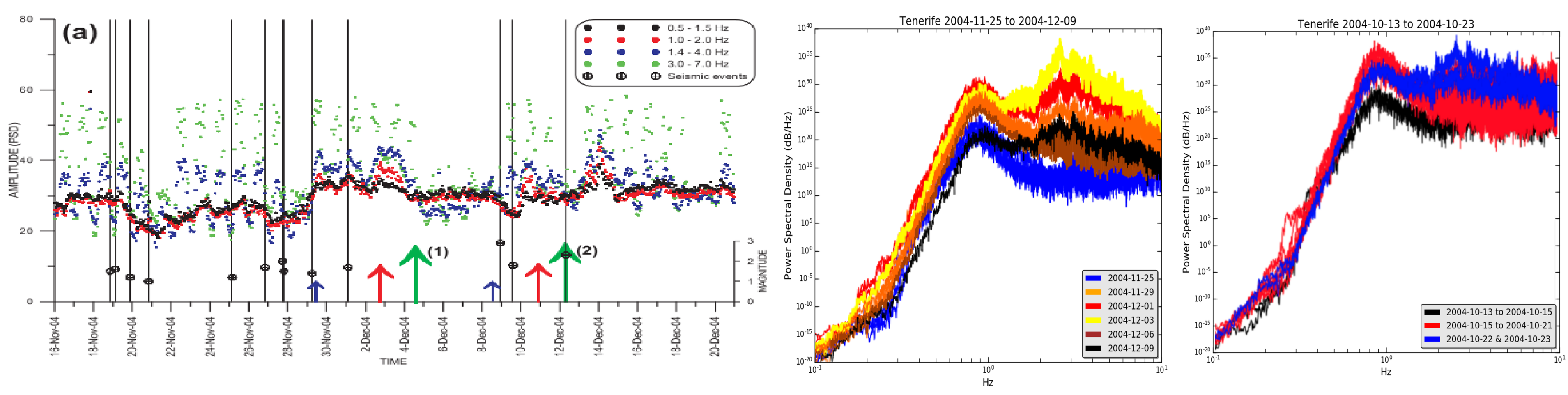




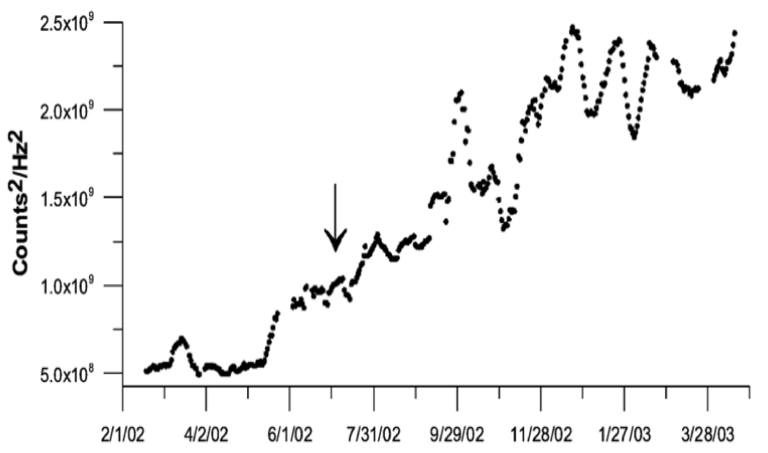


Base Level Noise Seismic Spectrum (BLNSS).

The volcano's base level activity can easily be determined by continuous monitoring of the minimum amplitude of all spectral components, and thus indicates the volcanic activity which is always present on fixed-segment waveforms. The selection of comparative time intervals also eliminates transitory signals related to weather/environmental conditions, thus avoiding the misinterpretations in terms of predominant frequencies found in short term analysis. The application to data recorded at the Soufriere Hills, Llaima and Villarrica volcanoes demonstrates the methodology's ability to clearly distinguish volcanic background activity from signals of re-activation and provides information related to the behavior and dynamics of volcanic unrest.



A relevant example of the utility of RT monitoring can be appreciated from the output series on 29 November 2004, which shows a systematic increase of energy in every frequency band. On 5 December 2004, a fumarole emission (largest green arrow 1) appeared in La Orotava valley (north-eastern flank of Teide volcano) and several local seismic events with magnitudes from 1.4 to 2.0 were registered during the following days. Thanks to the RT monitoring, warnings were issued in advance of the occurrence of the two phenomena.



Llaima volcano: Evolution of the integrated spectral squared amplitude of the BLNSS at the frequency band: 3.0–6.0 Hz. The arrows point to when the increment of seismic activity was reported.

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