Journal of Volcanology and Geothermal Research 200 (2011) 1–17

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Detecting imminent eruptive activity at Mt Etna, Italy, in 2007–2008 through pattern classification of volcanic tremor data

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ARTICLE INFO

Article history:
Received 14 April 2010
Accepted 25 November 2010
Available online 7 December 2010

Keywords:
volcanic tremor
volcano monitoring
pattern recognition
Self Organizing Maps
fuzzy clustering
Mt. Etna

ABSTRACT

Volcano monitoring aims at the recognition of changes in instrumentally observable parameters before hazardous activity in order to alert governmental authorities. Among these parameters seismic data in general and volcanic tremor in particular play a key role. Recent major explosive eruptions such as Okmok (Aleutians) and Chaitén (Chile) in 2008 and numerous smaller events at Mt Etna (Italy), have shown that the period of premonitory seismic activity can be short (only a few hours), which entails the necessity of effective automatic data processing near on-line. Here we present a synoptic pattern classification analysis based on Self Organizing Maps and Fuzzy Cluster Analysis which is applied to volcanic tremor data recorded during a series of paroxysmal eruptive episodes and a flank eruption at Etna in 2007–2008. In total, eight episodes were analyzed; in six of these significant changes in the dynamic regime of the volcano were detected up to 9 h prior to the onset of eruptive activity, and long before changes in volcanic tremor amplitude and spectral content became evident in classical analysis. In two cases, the state transition was <1 h before the onset of eruptive activity, which we interpret as evidence for very rapid magma ascent through an open conduit. We further detected twenty failed paroxysms, that is episodes of volcanic unrest that did not culminate in eruptive activity, between March and April 2007. As the application of the software for this synoptic pattern classification is straightforward and requires only moderate computational resources, it was possible to exploit it in an on-line application, which was tested and now is in use at the Istituto Nazionale di Geofisica e Vulcanologia in Catania for the monitoring of Etna. We believe that the pattern classification presented here may become a powerful addition to the repertoire of volcano monitoring tools and early warning techniques worldwide.

1. Introduction

Instrumental monitoring of volcanoes is vital for capturing and recognizing geophysical, geochemical, thermal, and visual premonitory phenomena of potentially hazardous eruptions. Yet, in spite of decades of progress and rapidly improving knowledge and techniques, modern volcanology continues to face a multitude of challenges. Some of the most vexing issues are whether eruption precursors will be recognized early enough to allow Civil Defense and authorities to take precautionary measures, and whether the unrest will be followed by an eruption at all. A number of recent volcanic events has shown the limits of instrumental data even at well-monitored volcanoes, such as Okmok in the Aleutian Islands, which erupted violently in July 2008 after less than 5 h of premonitory seismicity that was identified as such only in hindsight (Neal et al., 2009). Extremely rapid ascent (>5 km in ~4 h) of rhyolitic magma was documented by Castro and Dingwell (2009) in the case of the 2008 Plinian eruption of Chaitén volcano in Chile, and recent basaltic-andesitic eruptions at Hekla (Iceland) have shown remarkably short periods of precursory seismicity (Soosalu and Einarsson, 2002; Soosalu et al., 2005). Similarly, episodes of intense and potentially disruptive volcanism at Mt Etna in eastern Sicily (Italy) are often preceded by periods of changes in geophysical signals heralding the volcano unrest as short as a few hours to a few tens of minutes (e.g., Behncke and Neri, 2003; Neri et al., 2005, 2006). The central feeder conduit system of Mt Etna is open and virtually poses no resistance to ascending magma, whereas the aforementioned cases of other volcanoes were characterized by different sets of physical conditions (including closed conduits). Nonetheless, the outcome is essentially identical. This observation implies that the problem is not a regional issue but of general importance.

On the other hand, increased attention is now being paid by the volcanological community to episodes of evident anomalies in the instrumentally acquired data, which, however, do not culminate in eruptions. These "non-eruptions" (Poland, 2010) bring along the problem of possible false alarms that can have high social and

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doi:10.1016/j.jvolgeores.2010.11.019

economic costs, as seen in 1976 at La Soufrière volcano on the island of Guadeloupe (West Indies) (Fiske, 1984; Komorowski et al., 2005). The consequences of a false alarm on a densely populated volcano of a developed country, such as Mt Etna and Vesuvius in Italy or Fujiyama in Japan, would be of dimensions difficult to envisage.

Mt Etna is situated in a densely populated area with a long cultural history, and is one of the best documented and monitored volcanoes worldwide (Chester et al., 1985; Bonaccorso et al., 2004). Mt Etna's eruptions have a strong socio-economic impact, in particular for the threat of lava invasion of inhabited and agricultural areas. More explosive volcanism is also common, often resulting in tall ash clouds and widespread tephra falls, as in 2001 and 2002–2003, when long-lasting ash emission caused weeks-long disruption of air traffic around the volcano.

Seismic data from the volcano and adjacent areas play a key role in volcano surveillance. They are continuously recorded in digital format and routinely processed (e.g., Patanè et al., 2004). A wide variety of seismic signals is recorded on a basaltic stratovolcano like Etna. Transient signals, such as explosion quakes along with long and very long period events, are directly linked to the volcanic activity (e.g., Di Grazia et al., 2009). Earthquakes often herald and accompany the opening of eruptive fractures at the onset of flank eruptions. However, summit eruptions at Mt Etna—which are commonly more violently explosive and occur more frequently than flank eruptions—are often preceded by a rapid increase in tremor amplitude, sometimes only a few tens of minutes prior to the onset of eruptive activity. As a consequence, such paroxysms represent a serious threat to tourists, mountain guides, and scientists in the summit area, and warning times regarding the possibility of volcanic ash plumes affecting air traffic are very short.

Monitoring of the seismic background signal—commonly referred to as volcanic tremor—has become decisive for the surveillance of Mt Etna. Indeed, changes in the state of activity as well as in the eruptive style of the volcano are mirrored in the seismic signature of volcanic tremor, such as amplitude and spectral content (e.g., Alparone et al., 2003; Falsaperla et al., 2005; Langer et al., 2009). The continuous acquisition of seismic signals requires the processing of huge amounts of data accumulated every day. A possible way to tackle the problem resides in automatic classification of the signals. This has been demonstrated in various cases. One of the first papers in this context was presented by Falsaperla et al. (1996) who applied multilayer perceptrons to explosion quakes recorded on Stromboli, Italy, using a supervised classification scheme, which trained the classifier to learn from given examples. On the basis of spectral characteristics of volcanic tremor recorded on the same volcano, Langer and Falsaperla (1996) identified activity regimes using cluster analysis in an unsupervised classification. Esposito et al. (2008) applied unsupervised classification based on Self Organizing Maps to "Very Long Period Events" recorded on Stromboli investigating the relationship of these signals to infrared images of the active vents. An automatic classification of volcanic signals based on Hidden Markov Models was proposed by Ibanez et al. (2009). Langer et al. (2009) analyzed patterns derived from volcanic tremor data recorded during the July–August 2001 flank eruption of Mt Etna, applying both concepts of supervised (support vector machines and multilayer perceptrons) and unsupervised classification (Self Organizing Maps and crisp clustering), and identifying various regimes of patterns matching volcanological observations. The results of the classification with supervision confirmed the a-priori distinction of different regimes of volcanic activity, i.e., pre-eruptive, eruptive, post eruptive and lava fountains (Masotti et al., 2006). On the other hand, unsupervised classification brought out subtle internal structures within the data, adding valuable information to the results of the a-priori classification. The encouraging results by Langer et al. (2009) led Messina and Langer (Submitted for publication to Computers & Geosciences) to the development of a software package for unsupervised classification, which uses the so-called Kohonen or Self Organizing Maps (SOM hereafter) as well as various techniques for clustering. Based on that software, we exploit here the synoptic unsupervised classification potential in an application to volcanic tremor data recorded on Etna in 2007 and 2008. As visualization is a critical issue in multivariate data analysis, we use the colors of the nodes of the SOM and the class membership vectors inferred from fuzzy clustering for monitoring the development of volcanic tremor characteristics. This kind of synoptic view proved indeed to be especially useful for the large number of patterns to analyze and the identification of transitional regimes between clusters, which are of paramount interest for surveillance purposes. The choice of this kind of visualization was also motivated by the fact that the selected time intervals represent various activity stages of Etna, ranging from quiescence to Strombolian activity, lava fountains and lava emissions.

2. Data

2.1. Volcanological observations

Information on the state of Mt Etna is collected by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) Sezione di Catania through periodical field and aerial surveys, satellite observations as well as permanent video cameras. Continuous video surveillance provides images in the visible band and in the long-wave infrared acquired by a network of five cameras located to the south and east of the volcano, at a distance between 5 and 21 km from the summit craters (Andò and Pecora, 2006). Reports on the volcanic activity are regularly published on the web site of the INGV Catania at http://www.ct.ingv.it/ > Monitoraggio sismico e vulcanico > Rapporti > Vulcanologia.

The time span from March 2007 to May 2008 was characterized by eruptive events that marked the transition of the volcano from a relatively quiescent state to intense summit activity consisting of a series of relatively brief paroxysms with violent Strombolian activity, lava fountains, and high-rate lava emission (Andronico et al., 2008). This period was followed by a long-lasting, low-effusion rate flank eruption, which started on the morning of 13 May 2008 on the upper E flank of the volcano, and continued at a slowly decreasing rate until 6 July 2009 (Fig. 1; Aloisi et al., 2009; Di Grazia et al., 2009). During the year 2007 there were six paroxysmal episodes, namely on 29 March, 10–11 April, 29 April, 6–7 May, 4–5 September and 23–24 November. These events had durations ranging from 45 min (29 March) to over 10 h (4–5 September). A further and exceptionally violent episode of lava fountaining occurred on 10 May 2008, shortly before the 2008–2009 flank eruption.

2.2. Seismic data

Volcanic tremor data are recorded by the permanent seismic network of INGV equipped with Nanometrics Trillium™ seismometers having corner period of 40 s. The dynamic range of the digitizer is 24 bit and the sampling rate is 100 Hz. Among the stations close to the eruptive theatres, we chose ESPC for our application (Fig. 1) as this station offered high reliability and continuity of data acquisition, as well as good signal quality over the studied period. ESPC is located at about 6 km from the summit craters and is equipped with three components. In the following, we focus on the vertical component of the station, although the proposed data processing held on whatever chosen component.

For our application, we selected 2-day long continuous time series for each eruptive episode of 2007, starting several hours before each episode (i.e., 28–29 March, 10–11 April, 28–29 April, 6–7 May, 4–5 September, and 23–24 November). A further longer seismic record (seven days) covers a continuous time series from 0000 UT on 9 May 2008 to 2400 UT on 15 May 2008, and includes both the summit