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Identifying seismicity patterns leading flank eruptions at Mt. Etna Volcano during 1981-1996

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Abstract. Seismicity time properties of the Etna Volcano (Italy) are investigated through a systematic pattern recognition analysis. Mean Hypothesis Testing (MHT) has been applied to a long time database of instrumental data recorded from 1981 to 1996 to identify relevant correlation among seismic patterns, main seismogenic volumes and the eight flank eruptions occured in the same period. Time evolution of the test statistic (T-Ratio), calculated on a temporal window starting 75 days prior to a volcanic eruption and extending 25 days after, reveals that there is a pattern of seismic activity prior to the eruptions that can be used as a diagnostic tool as well as a physical modeling support in eruption forecasting.

Introduction

The Etna volcano is located on the east coast of Sicily, close to the boundary between the continental crust of Hyblean Plateau and the Mesozoic oceanic crust of Ionian basin. As one of the planet's few continously-active volcanoes, Etna constitutes one of the most important natural volcanic laboratories. The complex stress field affecting the volcano results from the combined effects of regional tectonics associated with the interaction between the African and Eurasian plates, the rise of magma into the crust and the gravitative seaward sliding of the eastern sector of the volcano. Magma ascent through the crust takes place as large diapiric bodies along a number of megafaults [*Armienti et al.*, 1989; *Ferrucci et al.*, 1993; *McGuire et al.*, 1990]. The interaction between the regionally important NNW-SSE and NE-SW aligned master faults are suspected of controlling magma transport within the volcanic edifice, although the precise mechanisms by which this is achieved are not yet fully understood. Currently, the roles of the different forces controlling magma transfer remain unresolved, and there is no consensus on the precise form of the broad geodynamic framework of the volcano. Seismicity is unquestionably the most useful indicator of the state of an active volcano. Over a century of seismological observations testify that seismicity, in the form of discrete earthquakes, volcanic tremors, or both, nearly always precedes, accompanies, or follows unrest at all type of volcanoes (andesitic, dacitic and basaltic, central volcanoes, and restless caldera). Etnean earthquakes usually show both small average magnitude (2.5 - 3.0) and swarm occurrence with peculiar features in space and time. Recent seismological studies of Etnean seismicity have identified the migration of seismic foci beneath and within the volcanic edifice prior the last two main eruptive episodes (1989 and 1991-1993) at both medium [*Castellano et al.*, 1993] and short time scales [*Ferrucci et al.*, 1993]. Moreover fractal analysis of the earthquakes time and spatial distributions [*De Rubeis et al.*, 1997; *Latora et al.*, 1998], revealed a link between variations of clustering properties (fractal dimension D) and eruptions occurrence. The aim of the present paper is a systematic pattern recognition analysis of the seismicity temporal distribution affecting the main seismogenic etnean volumes during 1981-1996. The main interest is in the differentiation of eruptive and non-eruptive periods and in the characterization of a precursory activity.

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Data

The 1981-1996 period has been characterized by intense volcanic and seismic activity affecting different eruptive systems. The seismic data set available consists of 5000 earthquakes recorded between 1st January 1981 and 31st December 1996 by the networks of the University of Catania, International Institute of Volcanology (Catania), National Group for Volcanology, University of Cambridge (1982), and ARGOS (1983). Hypocentral locations of the events were estimated using the standard location routine HYPO71 with the velocity model proposed for the Etnean area by [*Lombardo et al.*, 1983]. Earthquakes with angular gap less than

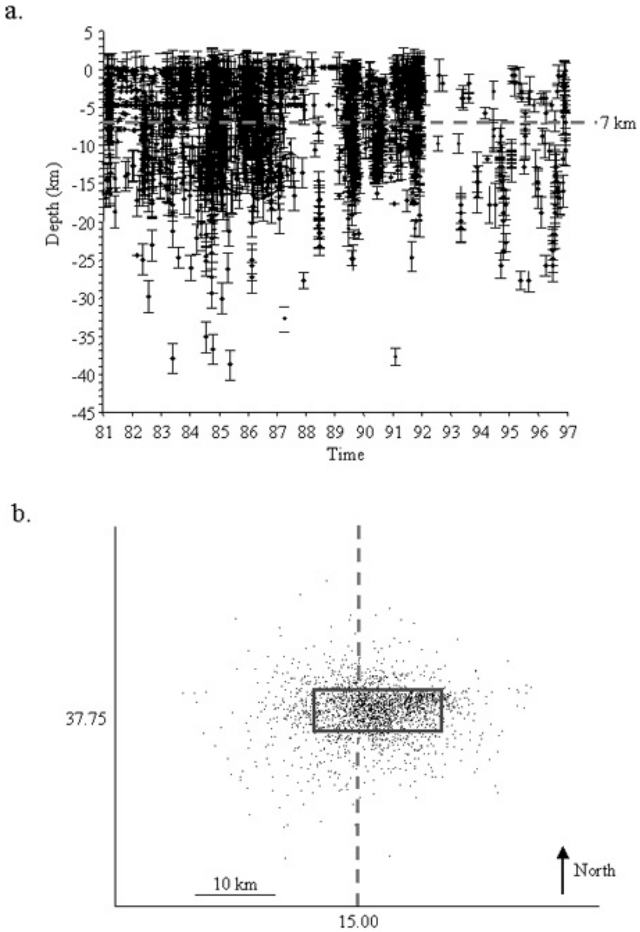

Figure 1. a) Depth vs. time section. The dashed line marks the 7km depth threshold adopted to distinguish shallow from deep events. b) Epicenters map. The dashed line marks the boundary between eastern (left) and western (right) flanks. The rectangle area corresponds to the summit events.

180^o, localization horizontal error less than 3.0 km and localization vertical error less than 3.0 km have been considered. Magnitude has been estimated from the Serra La Nave station seismograms by the following equation: $M = 2.2 \log t + 0.3 \log d - 1.5$, where t is the earthquake duration in seconds, and d the hypocentral distance from the SLN station in kilometers. The test of completeness, performed according to Tinti and Mulargia's procedure [*Tinti and Mulargia*, 1985], shows that the data set can be considered complete for magnitude greater than 2.5. The earthquake catalogue obtained after this double selection (2500 events) allows associating the events according to the depth threshold stress inversion recognised at 7 km of depth [*Scarpa et al.*, 1983; *Gresta and Patané*, 1987]. The shallow earthquakes are subgrouped according to the different mechanics between eastern and western flank [*Gresta et al.*, 1990] and to the opening of fracture systems affecting the summit area (see fig.1). As a consequence four seismogenic volumes can be identified, where the latter three comprise shallow earthquakes, i.e. earthquakes with depth less than 7 km:

1) *deep* earthquakes, characterized by depth greater than 7 km;

2) *eastern* flank earthquakes, associated mainly to the activity of the NNW-SSE fault system;

3) *summit* earthquakes, affecting the craters area;

4) *western* flank earthquakes related mainly to the NE-SW regional fault system.

As an example in fig.2 is reported the number of *deep* earthquakes per day between 1981 and 1996. Eight main flank eruptions occurred during this time span; the duration of eruptive episodes is highlighted in gray in figure. To determine what patterns of physical phenomena distinguish eruptive from non-eruptive periods, two classes of 125-day time intervals are created:

1) the *eruptive* class consisting of 8 samples, one for each eruptive episode in the revised catalog, with the eruption occurring at day 76;

2) the $non-eruptive$ class, created by randomly selecting 8 time intervals of 125 points during non-eruptive periods. Multiple random selections of the non-eruptive class (duplicates 1, 2, and 3) have been considered to ensure a sufficient degree of generalization.

The choice of 125 points for the time window length is determined by the fact that the period analyzed should be long enough to describe intermediate time-scale events. Moreover, the principle that intervals should not overlap sets the maximum time length of the interval.

Method

Mean Hypothesis Testing (MHT) is a statistical method to characterize a system's behavior. It is used to identify variables that are discriminating among different classes of system behavior as well as the relevant time windows when such discrimination is possible [*Kamimura et al.*, 1997]. Utilizing the mean as a measure of the class's behavior, MHT seeks out those measurements that violate the null hypothesis that the means of two classes are similar. The method has been previously applied to other complex systems such as biological and chemical processes [*Kamimura et al.*, 1997]. In this paper MHT has been adapted to identify the seismic measurements that are able to discriminate between eruptive and non-eruptive volcanic periods. We consider the two

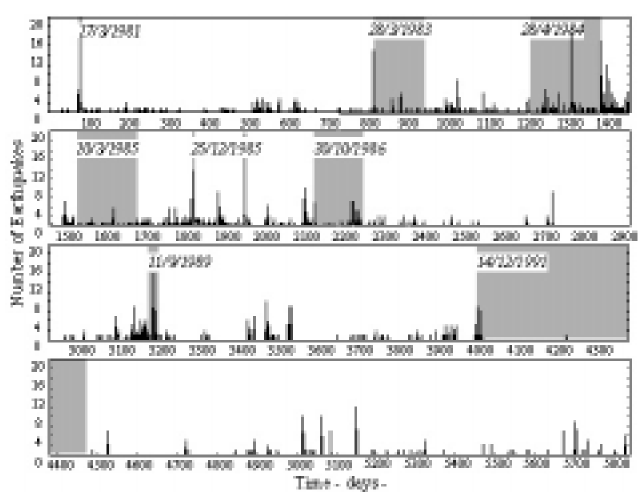

Figure 2. Number of *deep* earthquakes vs time (days) during 1981-1996. The marked dates refer to eruption onsets; eruptions duration is highlighted in gray.

classes, *eruptive* and *non − eruptive*, as previously defined in the data section. Each class contains 8 different samples and for each class we consider 4 variables, or seismic data subgroup (i.e. number of *deep*, *eastern*, *summit*, *western* earthquakes). By $(x_{ij}(t))_k,\ 1 \le t \le 125$ we indicate number of earthquakes at day t in the seismic data subgroup j, ($j = 1, 2, 3, 4$), i.e. respectively number of *deep*, *eastern*, *summit* or *western* earthquakes. Index $i = 1$ labels the *eruptive* class and $i = 2$ labels the *non − eruptive* one; k labels the kth sample of class i, ($k = 1, ..., 8$). For each class i and seismic data subgroup j, a mean number of earthquakes is calculated averaging over the number of different samples:

$$\mu_{ij}(t) = \frac{1}{n_i} \sum_{k=1}^{n_i} (x_{ij}(t))_k \qquad (1)$$

where $n_i = 8$ both for the *eruptive* class $i = 1$ and for the *non − eruptive* class $i = 2$. These quantities are subject to a hypothesis test at each time t to determine if the overall behavior of the *eruptive* and *non − eruptive* classes is statistically different. For a fixed t and j the null hypothesis is:

$$\mu_{1j}(t) - \mu_{2j}(t) = 0 \qquad j = 1, 2, 3, 4 \qquad (2)$$

and it states that the two classes' means are not statistically different and that the subgroup j is not discriminating. The decision to reject or to accept the null hypothesis is made using a T-statistic [*Mardia et al.*, 1979]; the number of samples making up each class is small, so the T-statistic is employed rather than the Z-test which is designed for large sample sizes. The applicability of the statistical test is confirmed by a check for normality of the data. The two means are used to construct the T-statistic, which is then compared to a tabulated (threshold) T-value, with a selected significance level of 95%. In this paper we report the quantity T-Ratio, i.e. the ratio of the T-statistic to the threshold T-value. The null hypothesis is rejected or accepted whether or not the T-Ratio exceeds 1 (details of the entire hypothesis test can be found in [*Mardia et al.*, 1979] and [*Kamimura et al.*, 1997]). If T-Ratio > 1 the difference in the means is significant; this indicates the variable (subgroup) considered is significant to discriminate among *eruptive* and *non − eruptive* period at time t.

Discussion

Mean Hypothes Testing results are reported in fig.3; the results are similar for the other two non-eruptive duplicates. It can be noted that:

1) For the *deep* earthquakes the T-Ratio has a value clearly greater than 1, 15 to 0 days before the eruption onset. This result demonstrates that, although the shallow dynamics of the flank eruptive processes can be different (opening fracture systems at different quotas and with different extension), the presence of *deep* earthquakes prior to an eruption is a persistent feature. A recent study on deep seismic migration before the 1989 eruption [*Castellano et al.*, 1993] excluded the existence of intermediate or deep magma chambers. These authors justified the existence of this seismicity as a response of the local stress field in response to change in external (regional) stress field. We can add on the basis of this systematic analysis that this process seems to occur before every flank eruption. In other words, we believe that a stress transfer occurs before each eruptive episode considered. This is probably due to the extraction of the magma from the depth, and the statistical analysis suggests that this process act with a surprising regularity as well as a magma chamber.

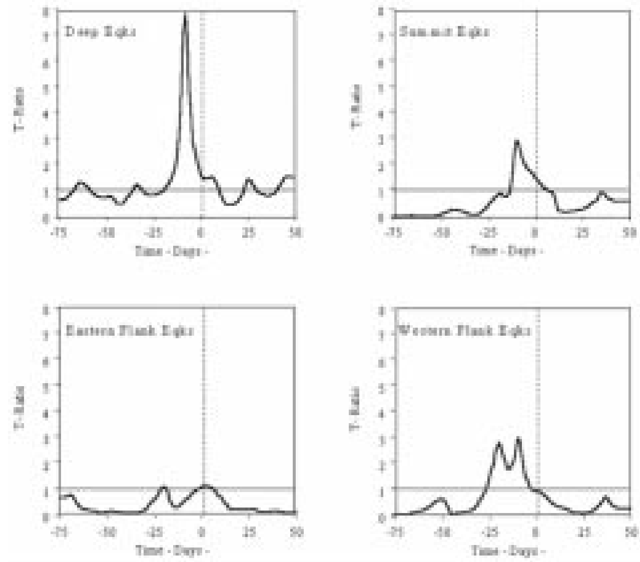

Figure 3. T-Ratio temporal evolution for the four different seismic data subgroups, considering duplicate 1 as the non-eruptive class. Onset of the eruption is at day 0; the negative values on the time axes indicate days preceding the eruption.

2) The *eastern* flank earthquake variable has a T-Ratio less than 1 for all the time points and hence is not likely to play a significant role. Despite of the significant microseismic swarms ($M < 2$) of low eastern flank before the 1989 and 1991-93 [*Latora et al.*, 1998; *Vinciguerra et al.*, 1998], located earthquakes with higher magnitude ($M > 2.5$) as well as the ones considered in this analysis do not appear directly linked to the eruptive processes, but rather with the activity of the well-known fault systems affecting this volcano sector [*Montalto et al.*, 1996; *Gresta et al.*, 1997]. As a consequence the structural systems affecting this volcano sector (mainly trending NNW-SSE), play a passive response role to the deep magma transfer processes and for this reason the time distribution properties do not show any significant pattern [*De Rubeis et al.*, 1997].

3) The *summit* earthquakes are characterized by a marked T-Ratio greater than 1 ranging from 15 to 0 days before the eruptive episode. This is in accordance with the T-Ratio computed for the *deep* group. This behavior is due to the fact that the events cluster around the conduits in the summit area, accompanying magma transfer towards the opening fracture systems during the arise last phases. Thus, these earthquakes are strongly related to the *deep* earthquakes reflecting the focii upward migration linked with the eruption onsets.

4) The analysis of the *western* flank earthquakes gives a very interesting result. The T-Ratio is markedly greater than 1 from 15 to 5 days before the eruptive episodes, hence a significant feature. Swarm occurrences on the western flank have been observed before some eruptions, inducing some authors to suggest that tectonics affecting this volcano sector is related to the volcanic activity [*Gresta et al.*, 1990]. Nevertheless the clusteres features of these avents did

not allow to recognise clear links with eruptive processes [*De Rubeis et al.*, 1997]. These results suggest that activation of shallow structures (mainly trending NE-SW) can be considered a marker of flank eruption occurrence and particularly that the western shallow sector plays a basic role in the eruptive feeding system acting (by magmatic batches or simple intrusions) in a systematic way.

Conclusions

A pattern recognition analysis of Etna volcano recent seismicity (1981-1996), has been performed in order to identify seismicity patterns preceding flank eruptions occurrence. The time evolution of the test statistic (MHT T-Ratio), calculated on a temporal window starting 75 days prior to an eruption, provides a systematic interpretation of the seismic distributions of the Etnean area. Results obtained suggest that:

1) *Deep* and *summit* earthquakes show a typical behavior with a statistical significance before every flank eruption, although the shallow dynamics of the flank eruptive processes can be different. This is probably due to the extraction of the magma from the depth; the pattern recognition analysis suggests that this process acts with a surprising regularity as well as a magma chamber.

2) *Eastern* flank earthquakes, characterized by a very shallow nature, do not show any significant relation with the eruptive episodes, suggesting that the structural systems affecting this area are not related to magma transfer processes and confirming the different mechanics of the eastern flank area with respect to the whole volcano edifice.

3) The analysis of the *western* flank earthquakes suggests that the tectonics of this sector play a basic role, acting in a systematic way in relation to the eruptive feeding system.

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