GRUPPO NAZIONALE DI GEOFISICA DELLA TERRA SOLIDA

32° convegno nazionale

GNGTS

Trieste

19-21 novembre 2013
Stazione Marittima

ATTI
Tema 1: Geodinamica

OGS

ISTITUTO **NAZIONALE DI**
OCEANOGRAFIA E DI
GEOFISICA SPERIMENTALE

SPACE-TIME CHANGES OF SEISMIC ACTIVITY AT MT. ETNA VOLCANO (ITALY) OBSERVED THROUGH STATISTICAL APPROACHES

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Introduction. Volcanic processes can locally modify the normal stress state of a volcano, which generally is connected to the regional stress field. Volcanic eruptions are often preceded by changes both in the rate and the location of local volcano-tectonic earthquakes so that a statistical approach can give a clue to investigate about precursors (Alparone *et al.,* 2011; Bell and Kilburn, 2012). The analysis of the space-time variations of the hypocentral distribution during pre-eruptive and inter-eruptive periods, could provide important constrains for a better understanding of the link between seismicity and eruptive processes (Lombardo and Cardaci, 1994; Vinciguerra *et al.,* 2001). Besides, some authors have pointed out that, in a volcano, the analysis of the inter-event times (IETs) distribution pattern could represent an important tool to distinguish among sectors affected by different stress fields (e.g. Bell and Kilburn, 2008; Traversa and Grasso, 2010). An IET is defined as the waiting time between two consecutive earthquakes, related to a specific interval of time and a particular threshold of magnitude. The waiting time distribution of global or national size catalogues is usually modelled using a gamma law (Corral, 2003). This single-peaked distribution, typical of tectonic areas, is clearly different from the IET distribution for regional or local catalogues that generally has a bimodal shape deriving from the combination of two distributions, one due to correlated events (which have short inter-event time) and the other due to independent events (which tend to be separated by longer gaps) (Naylor *et al.,* 2010). Therefore, for a small region, the bimodal shape of IET distribution is heavily influenced by the high percentage of correlated events (aftershocks). IET analysis in the Etnean area was already performed by Sicali *et al.* (2012) investigating the seismic events occurred during the time interval 1988-2011 (Patane *et al.,* 2004; Gruppo Analisi Dati Sismici, 2011). The authors, aimed to identify the existence of either a periodicity or a stationary behaviour of the seismic activity and tried to correlate it with the volcano-tectonic features of the region. As a result of this study, the presence of different volcano sectors showing specific behaviour was set into evidence. The comparison between the spatial variation of Etna IET distributions with those obtained for Sicily and Italy, showed that at a large scale the IETs are well-modelled by a gamma distribution, whereas at the local Etnean scale the IETs are characterized by a bimodal curve. The two peaks are related to: (i) the background regional stationary seismicity, (ii) the contribution of the local seismic swarms with very short inter-event times, which considerably modify the usual seismic rate. Sicali *et al.* (2012) concluded that the seismicity taking place at depth shallower than 5 km is almost entirely represented by short IETs and is mainly confined to the Etna summit area. On the other hand, earthquakes deeper than 5 km, appear mainly linked to the regional tectonic setting. In particular, the eastern flank seismicity is influenced by the extensional regional tectonics typical of the eastern Sicily, whereas the western flank seismicity seems consistent with the compressional processes observed at a regional scale. Such findings further support the evidences that Mt. Etna is located at the boundary of two different tectonic domains (Neri *et al.,* 2005; La Vecchia *et al.,* 2007; Palano *et al.,* 2012).

In the present study a more thorough analysis, at a scale of the sectors previously identified, is performed in order to investigate about possible correlations between the occurrence of Etnean eruptions and its seismicity. The dataset used is now extended back to the period 1976-1987, matching the date coming from the IIV, Poseidon and INGV-CT seismic networks (Gruppo Analisi Dati Sismici, 2011) with those recorded by the seismic network run by University of Catania. This allow us to analyze a longer and more significant range of time which spans from 1976 to 2011, evaluating both the space-time IET distributions and the earthquake cumulative patterns in different sectors of the volcano.

Seismic data and method. The used catalogue consists of 12,645 earthquakes occurred at Mt. Etna from January 1976 to December 2011, which were recorded through the permanent seismic networks run by the University of Catania (1976-1987) and by the IIV-CNR (Istituto Internazionale di Vulcanologia), Sistema Poseidon and INGV-CT (Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania) from 1988 up to 2011 (Patane *et al,* 2004; Gruppo Analisi Dati Sismici, 2011). Moreover, in addition to the permanent network, data recorded by several temporary seismic networks, held by different institutions, were added when available in order to reduce the gap in the azimuthal distribution of the recording stations. With the aim of having an homogenous catalogue, all recorded earthquakes were relocated using the HypoEllipse algorithm (Lahr, 1989) and the velocity model proposed by Him *et al.* (1991). The sensitivity of the seismic monitoring network at Mt. Etna (gap, erh, erz, rms, etc.) was gradually enhanced several times between 1976 and 2011 so that, the minimum magnitude of earthquakes located in the study area, varied over the time following the network upgrade.

Tests have been performed to evaluate the completeness of the catalogue and consequently a completeness magnitude Md = 2.5 has been obtained. According to this result, all further analysis have been carried out by selecting the earthquakes having such magnitude threshold and an hypocentre location uncertainty lower than 2.5 km, therefore obtaining a revised final dataset consisting of 2,762 earthquakes (Fig. la). Three different patterns of hypocenter distributions can be observed (Fig. 1b), therefore in order to obtain information about the

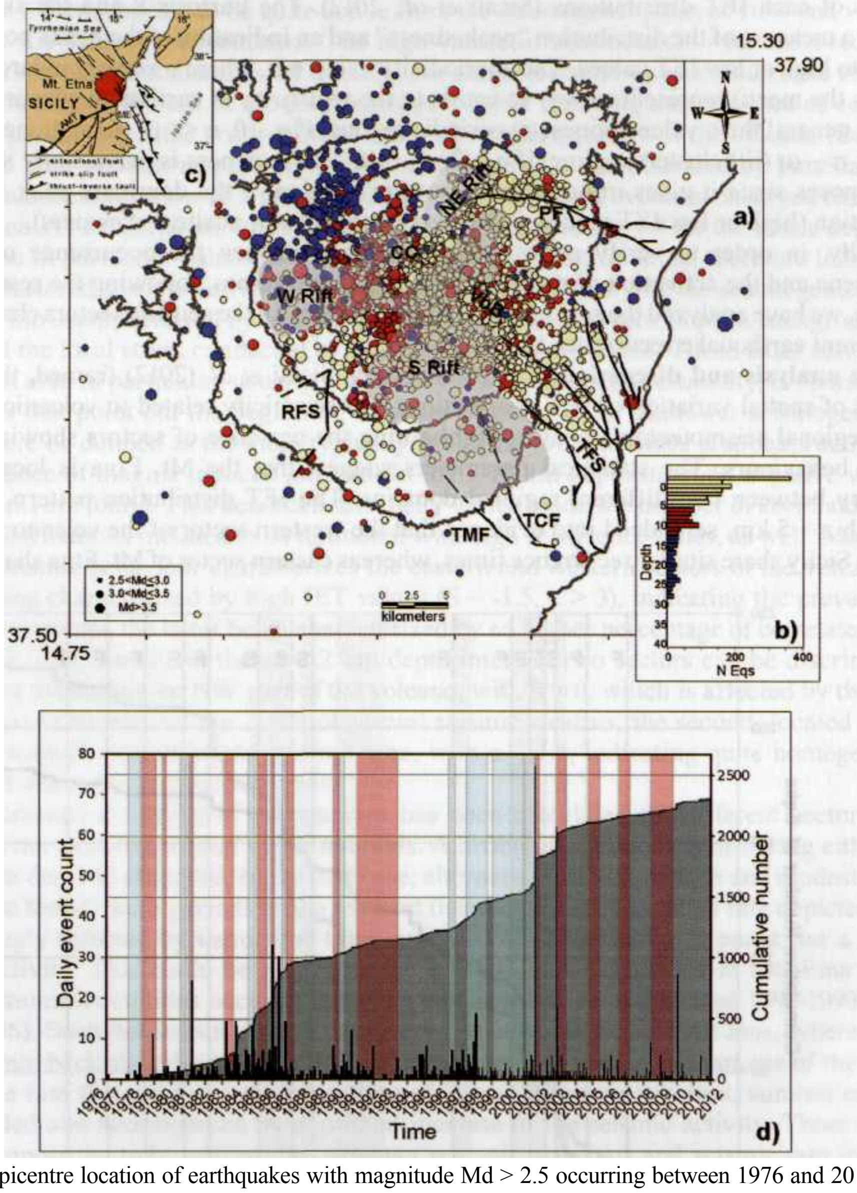

Fig. 1 - a) Epicentre location of earthquakes with magnitude Md > 2.5 occurring between 1976 and 2011 at Mt. Etna; circle size indicates magnitude classes; colours indicate the depth range (see inset b for details); black lines indicate the main faults: PF (Pernicana fault system), RFS (Ragalna fault system), TFS (Timpe fault system), TCF (Trecastagni fault), TMF (Tremestieri fault) (modified from Azzaro *et al.*, 2012); b) number of earthquakes vs. focal depth; c) structural settings of eastern Sicily; d) daily and cumulative number of earthquakes during the study period; the size of the red and blue bands indicates the duration of the flank and the summit eruptions, respectively (Andronico and Lodato, 2005; Bullettin data from http://www.ct.ingv.it/it/banca-dati-delle-eruzioni/eruzioni-etna.html).

seismic behaviour of different crustal volumes, a space-time analysis of the IETs has been performed by sub-grouping the earthquakes into three depth classes: 1) from the surface to 5 km b.s.l., 2) between 5 km and 12 km b.s.l. and 3) below 12 km b.s.l. We then have calculated the IET distributions and some associated statistical parameters (aperiodicity α, skewness S, kurtosis k) for all the earthquakes located within 3.5 km around each node, in a grid map having inter-node distance of 2 km. The statistical parameters allow quantifying the shape features of each IET distributions (Sicali *et al.,* 2012). The kurtosis k and the skewness S, provide a measure of the distribution "peakedness" and an indication of the peaks position with respect to high or low IET values. The aperiodicity α ($\alpha = \sigma/\mu$, where σ is the standard deviation and μ is the mean) represents a way to estimate the regularity of earthquake occurrence over time. In general the a value defines: (i) periodic regime, if $\alpha \sim 0$, $\sigma \ll \mu$ (ii) stationary regime, if $\alpha \sim 1$, $\sigma \sim \mu$.; (iii) clusters regime, if $\alpha > 2$, $\sigma \gg \mu$. The skewness is particularly suitable for our purposes since it gives information about the position of the dominant peak in the IET distribution (high or low IET values, in relation to negative or positive skewness).

Finally, in order to verify a possible correlation between the occurrence of eruptive phenomena and the activation of particular seismogenic volumes, following the results of IET analysis, we have analyzed the seismic rate - time variations of the seismic sectors characterized by different earthquake recurrence time.

Data analysis and discussion. In a recent study, Sicali *et al.* (2012) framed, through the analysis of spatial variation of IET distributions, the seismicity related to volcanic processes in the regional seismotectonic context highlighting the presence of sectors showing specific seismic behaviours. The statistical parameters suggest that the Mt. Etna is located at the boundary between two different regional domains. The IET distribution pattern, evaluated for depth z > 5 km, set indeed into evidence that the western sector of the volcano and north-western Sicily share similar recurrence times, whereas eastern sector of Mt. Etna shares similar

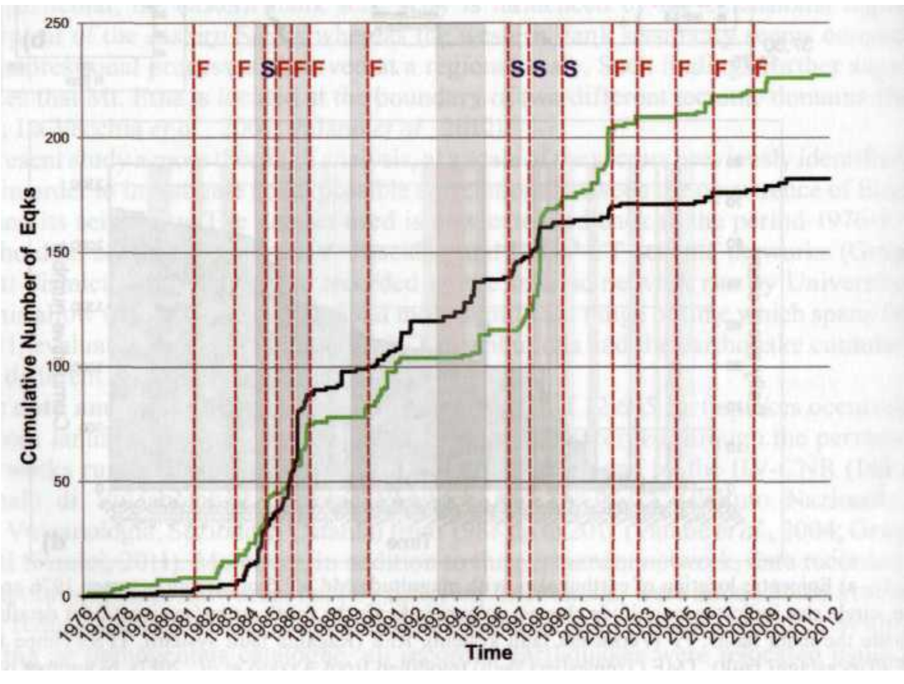

Fig. 2 - Cumulative number of earthquakes during 1976-2011 in the western flank of Mt. Etna. Black curve refers to earthquakes occurring at depth z > 12 km green curve refers to earthquakes occurring at depth 5 < z < 12 km. The grey bands indicate the periods during which the increase of deeper crustal volume seismicity precede the shallower ones. Dashed lines indicate the beginning of either flank F or summit S main eruptions.

features with eastern Sicily. Present study aims to carry out a more detailed analysis about the seismic features of different sectors of Mt. Etna volcano and for this purpose a seismic catalogue covering a longer span time has been adopted.

Spatial Analysis of Seismicity. The IETs distributions within the main seismogenic depth intervals identified at Mt. Etna (Fig. 1b) have been computed, for the time interval 1976-2011, with the aim of obtain information about the seismic behaviour of different crustal volumes. The level $z \leq 5$ km appears to be quite active from the seismogenic point of view and very well defined by the statistical parameters. The high values of skewness ($S > 0$), observed in this depth interval, point out that most of the IETs are characterized by short recurrence times and are concentrated on the left of the distribution, therefore implying the existence of correlated events. In particular, in the north-eastern and south-eastern sectors of the volcano (Pernicana and Timpe fault systems respectively) IET distributions are characterized by bimodal shape, while a peaked curve at low IET values and therefore correlated events is observed close to the summit area. As concerns the aperiodicity values, we observe $\alpha > 1.5$ for the whole depth level that assume in particular values $\alpha > 3$ in proximity of the summit area, therefore indicating a strongly clustered seismic activity. In our opinion, the seismicity of the seismogenic volume with $z \leq 5$ km seems affected by both the regional stress field, which imply a background seismicity and the local stress connected to the magma rising processes. These latter activities, in the summit area in particular, usually with a very low background seismicity, is characterized by swarms that point out the beginning of some eruptions. The shallower seismogenic level can therefore be defined as the more typically "volcanic" volume since it appears activated as a consequence of magma induced stresses. In the 5-12 km depth interval, negative values of the skewness are found. This denotes a seismicity with a moderate number of correlated events and IET distributions inclined to be unimodal with high recurrence times, as well. Moreover a different seismic behaviour characterizes the eastern and western sectors of the volcano. The former being characterized by high IET values ($S \sim -1.5$, $k > 3$), indicating the prevalence of independent events, the latter being characterized by an higher percentage of correlated events ($S \sim -0.5$, $k \sim 2$). Finally, in the $z > 12$ km depth interval, two sectors can be discriminated: the first one located in the N W part of the volcano, with $S > 0$, which is affected by the occurrence in recent time (after the 2009) of several seismic swarms; the second, located towards the south-western portion of the summit area, with $\alpha \sim 1.5$, indicating quite homogeneously distributed seismicity recurrence times.

The cumulative number of earthquakes has been calculated for different sectors of the volcano at the afore-mentioned depth intervals. A different behaviour considering either $z < 5$ or $z > 5$ km depth is observed. In the first case, alternating periods of high and modest seismic activity are found; these periods are so relevant that the global cumulative rate depicted in Fig. Id is strongly affected by them. The time interval 1991-2001 shows in particular a reduced seismic activity. This could be related to the lack of lateral eruptions at Mt. Etna and the prevalent summit activities occurred after the end of the flank eruption of 1991-1993 (Allard *et al,* 2006). Such behaviour is particularly evident close to the summit area, where usually the moderate background seismic activity is interrupted by sudden increments of the seismic occurrence rate that point out the beginning of lateral eruptions whereas, summit eruptions are preceded and accompanied by a gradual increase of the seismic activity. These findings further support the tight relationship between volcanic activities and seismic rate inside the first 5 km beneath the volcano. When the cumulative number of earthquakes is calculated for depth $z > 5$ km no significant sharp increments of the seismic activity are observed during the whole considered time interval (1976-2011). Only in a few instances slight increments of the seismic activity in the western sector of the volcano precede the onset of some flank eruptions. Such behaviour continues to be observed at depth greater than 12 km, although seldom seismic swarms without a clear correlation with eruptive episodes are detected. A detailed analysis of the number of intermediate ($5 < z \leq 12$ km) and the deep ($z > 12$ km) earthquakes in the western sector of the volcano highlights that an increment of the occurrence frequency of the events precedes by some days (sometimes months) the unrest of several flank eruptions and some summit eruptions (Fig. 2). It is indeed quite clear that the increase of seismic activity starts in the deeper seismogenic level and continues in the shallower one. We are keen to interpret these results as a first sign of the deep ($z > 12$ km) recharging of the volcanic system that is soon after followed by the increment of the seismic rate at shallower levels which seems to mark a sort of magma migration ($5 < z \leq 12$ km). When the magma rising process keeps going it triggers shallow seismic swarms ($z \leq 5$ km) indicating the opening of eruptive fractures. It has however to be specified that such tendency towards a magma migration is not observed in some instances (i.e. before the 2002 and 2004 eruptions). In such cases it could be hypothesized (Andronico *et al.,* 2005; Collins *et al.,* 2013) that magma was already still standing in the shallower part of the volcano consequently to a previous uprising.

Temporal Analysis of Seismicity. Trying to describe the time evolution of the seismicity recorded on Mt. Etna in the study period, it appears clear (Fig. 1d) a change in the seismic style of the volcano. The cumulative curve shows indeed a significant difference in dip before and after 1987. Moreover it is noticeable that all summit eruptions, except the 1998 one, occur without significant increments of the seismic rate whereas most of the flank eruptions are marked by a sharp increase of the seismic activity. Inspection of Fig. Id shows that the dataset 1976-2011 can be subdivided into four time intervals characterizing both periods of intense volcanic activity with lateral eruptions and periods with summit activities without flank episodes. The IET distributions was therefore carried out during the following periods: 1976-1987, 1988-2000, 2000-2003, 2003-2011. In Fig. 3 the values of skewness (S) for each period are reported since they better represent the different seismic styles and the IET distribution patterns. During the 1976-1987 time interval several eruptive events, both of lateral and summit kind, occurred. The chiefly active seismogenic level, as defined by the statistical parameters, is the one at depth $z < 5$ km. It shows high S values (Fig. 3a) pointing out that we deal with several correlated events especially in the summit area. At $z > 5$ km the skewness assume slightly negative values ($S < -0.5$) indicating seismicity characterized by independent events with relatively long recurrence times. During the second time interval (1988-2000) only summit eruptions occurred, except the 1991-1993 flank activity. In this case all the seismogenic levels appear equally affected by the seismic activity and the observed statistical parameters are those typical of time stationary activities represented by independent events ($S < 0$) linked to the background seismicity (Fig. 3b). It is in particular noticeable that, as already observed when the whole dataset has been analyzed (1976-2011), a marked difference between the seismic style of the western and eastern sectors of the volcano is set into evidence particularly at depths $z > 5$ km, the former showing some correlated events. The values of the statistical parameters calculated for the time interval 2000-2003, for the depth level $z < 5$ km are quite pronounced ($0.5 < S < 2.5$, Fig. 3c), pointing out in this way the tight relation existing between seismic and volcanic activities, relationship that is set into evidence by IET distributions with a lot of correlated events (seismic swarms preceding eruptive activities). Although the analyzed interval is particularly short, the small number of data anyway allows us to observe, similarly to the findings obtained when the whole dataset was analyzed, that below 5 km depth a distinct different behaviour of the western and eastern sectors of Mt. Etna is still detectable (Fig. 3c). The dataset concerning the period 2003-2011 is also formed by a few data so that information regarding only small sectors of the volcano can be inferred from the IET distributions. Similarly to the 1988-2000 period, low values of the statistical parameters are obtained for the depth interval $z \leq 5$ km, therefore indicating the presence of background seismicity only without earthquake swarms (Fig. 3d). Below 5 km depth, in the NW sector of the volcano high values of skewness ($S \sim 1.5$) are obtained, suggesting the occurrence of seismic swarms. Such seismic activity occurred in recent time (after 2009) and appears not linked to any eruptive phenomenon.

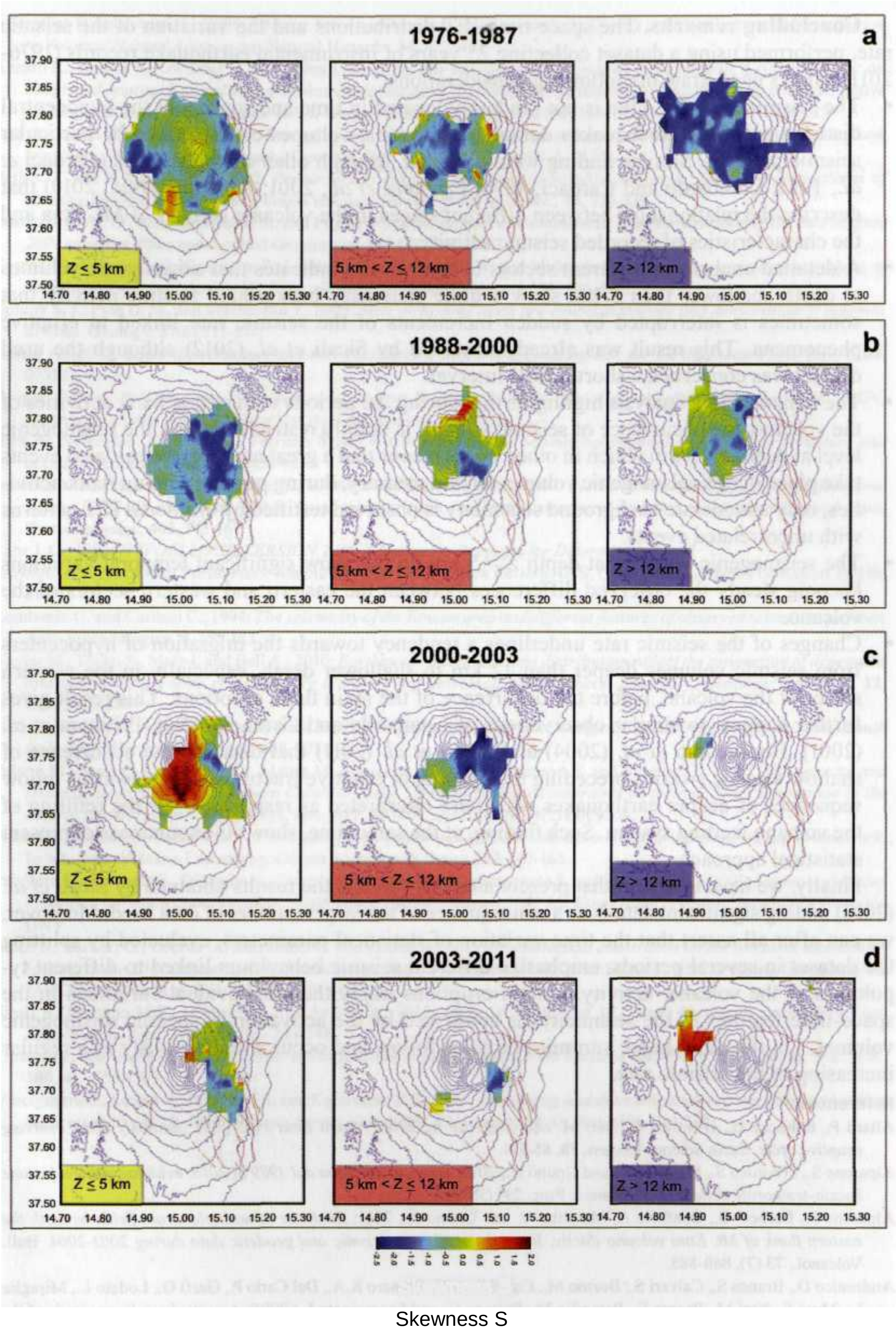

Fig. 3 - Areal distribution of skewness values during different time intervals.

Concluding remarks. The space-time IET distributions and the variation of the seismic rate, performed using a dataset collecting 25 years of instrumental earthquake records (1976-2011), allows us to draw the following considerations:

- The seismicity at Mt. Etna is not randomly located in time and space, but the hypocentral distribution of the earthquakes defines seismogenic volumes characterized by particular seismic patterns. Similar finding were obtained, through other methodologies (Cardaci *et al.,* 1993; Lombardo and Cardaci, 1994; Privitera *et al.,* 2001; Alparone *et al.* 2010) that describe the relationships between different stages in the volcanic activity of Mt. Etna and the characteristics of recorded seismic activity.
- A detailed analysis of different sectors of the volcano indicates that seismogenic volumes at depth shallower than 5 km show a quite stationary background seismic activity that sometimes is interrupted by sudden increments of the seismic rate linked to eruptive phenomena. This result was already observed by Sicali *et al.* (2012) although the used dataset was concerned a shorter time interval.
- The temporal IET analysis highlights that during the periods with strong flank activities of the volcano, the occurrence of seismic swarms is mainly restricted within the seismogenic level at depth $z \leq 5$ km which in other words means that a great number of correlated events take place in this seismogenic volume. On the contrary, during periods without flank activi ties, only a moderate background seismicity is observed testified by unimodal IET patterns with uncorrelated events.
- The seismogenic volumes at depth $z > 5$ km do not show significant temporal variations keeping steady the observed differences between the eastern and western sectors of the volcano.
- Changes of the seismic rate underlines a tendency towards the migration of hypocenters from seismic volumes deeper than 12 km to shallower depth, especially in the western sector of the volcano, before the occurrence of the main flank eruptions. This result gives further support to similar observations of Lombardo and Cardaci (1994), Privitera *et al.* (2001), Bonaccorso *et al.* (2004) and Sicali *et al.* (2011) that describe the occurrence of shallow seismic swarms preceding the opening of eruptive fractures. These swarms follow sequences of deeper earthquakes which are interpreted as responsible for the refilling of the volcano feeding system. Such finding, at the same time, shows the soundness of present statistical approach.

Finally, we have to affirm that present analysis validate the results obtained by Sicali *et al.* (2012) adding significant details as a consequence of the larger number of data used. Moreover, we can after all assert that the time variation of statistical parameters, evaluated by splitting the dataset in several periods, emphasize different seismic behaviours linked to different typologies of the volcanic activity. Lateral eruptions imply the most evident variations in the space-time features of the seismicity, as confirmed by the activation of specific seismogenic volumes. On the other hand, summit eruptions follow and occur simultaneously to a regular increasing of the seismic rate. References

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