GEOLOGICA CARPATHICA, 54, 4, BRATISLAVA, AUGUST 2003
251–260

CORRELATION BETWEEN LOCAL STRESS FIELD AND SUMMIT ERUPTION OF MOUNT ETNA: THE 27 MARCH 1998 EVENT

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(Manuscript received February 28, 2002; accepted in revised form March 11, 2003)

Abstract: The eruption on 27 March 1998 at the NE Crater, from 21h22 to 23h59 GMT, with Strombolian explosions and lava fountains, was the first of a long series of eruptive manifestations with relatively high energy, which affected the volcano after the 1991–1993 lateral event. The seismic activity occurred late in 1997 and the first months of 1998 constitutes, in the authors' opinion, a precursor of this eruption and the successive eruptive events at the SE Crater, since it is believed to be associated with a conspicuous magma uprise. The continuous epicentre migration, in a brief time span, in various sectors of the volcano owing to the dynamics of different tectonic trends, is considered related to a rapid fluctuation in the local stress field, probably responsible for the sudden onset and rapid end of the eruptive event.

Key words: stress field, focal mechanisms, earthquakes, eruption, Mt Etna.

Introduction

Etna is a volcano, circa 3300 m a.s.l., with a 40 km mean diameter, located on the convergence between the African and Eurasiatic plates. Its eruptive behaviour has evolved over the last 500 ka, from a prevalently fissure type eruptive activity to a central type one (Chester et al. 1985; Kieffer 1985; Tanguy et al. 1997).

Monitoring the eruptive phenomena and the morphological variations of the summit craters, was carried out carefully from the second decade of the 20th century on; in fact, vulcanologists understood that the eruptive activity at the Central Crater (where both the Voragine Centrale or "Chasm" and the Bocca Nuova are located) and the NE Crater (Fig. 1), in many cases, represented precursors of very high energy volcanic phenomena, like the lateral eruptions.

Monitoring of seismic activity began much later, in 1967 (Bottari & Riuscetti 1967). The data quality was improved in time and good reliability has been achieved since 1977. Most of the data collected over the last 20 years, allowed the working out of various approaches, including statistical ones, to studiyng the relationships between earthquakes and eruptions. On the basis of statistics, Sharp et al. (1981) found an important correlation between lateral eruptions and earthquakes. Instead, Gasperini et al. (1990) stated a contrasting opinion. These researchers, by applying an algorithm developed by Gasparini & Mulargia (1989) to the sequences of earthquakes and eruptions in the period 1978–1987, concluded that there is no correlation between lateral or summit events and seismicity.

According to Cardaci et al. (1993), the summit eruptions are preceded by an increase in the number of low-frequency events and seismic transients with spectral characteristics equal to those of tremors; the source of low-frequency events (spindle) is associated by Montalto et al. (1992) to slug breaking at the top of the magma column, which generates impulsive type pressure.

Cosentino et al. (1989) attempted to characterize the summit and lateral eruptions from a seismological point of view. These researchers conclude that there is no effective change in seismicity close to an eruptive event at the summit craters, but rather that the latter is the precursor of lateral eruptive activity, an observation carried out by vulcanologists in the first half of the 20th century only on the basis of the development of volcanic phenomena. Lastly, Vinciguerra et al. (1999), studying the relationship between the main phases of seismic energy release and the principal eruptive episodes between 1977 and 1991, conclude that summit eruptions usually take place without any preceding sudden change in seismic patterns. However, the modest seismic activity some months before the onset, suggests that the magma rises slowly, stopping temporarily in a shallow magmatic batch, before the eruptive event.

This work considers the correlation between seismic and eruptive activity occurring at the NE Crater on March 27th 1998, through a detailed analysis of the spatial and temporal fluctuations in seismic activity and the local stress field.

This eruptive phenomenon, as well as the other eruptions at the NE Crater, was not immediately preceded by considerable seismicity. Nevertheless, numerous earthquake swarms of modest magnitude (MD ≤ 3.5) took place between October 1997 and March 1998 and affected the whole volcanic area.

A seismic activity maximum was recorded during January 1998 and, in the authors' opinion, was associated with magma 'uprise', which caused the eruptive event at the NE Crater and the volcanic manifestations at the other summit craters during 1998.

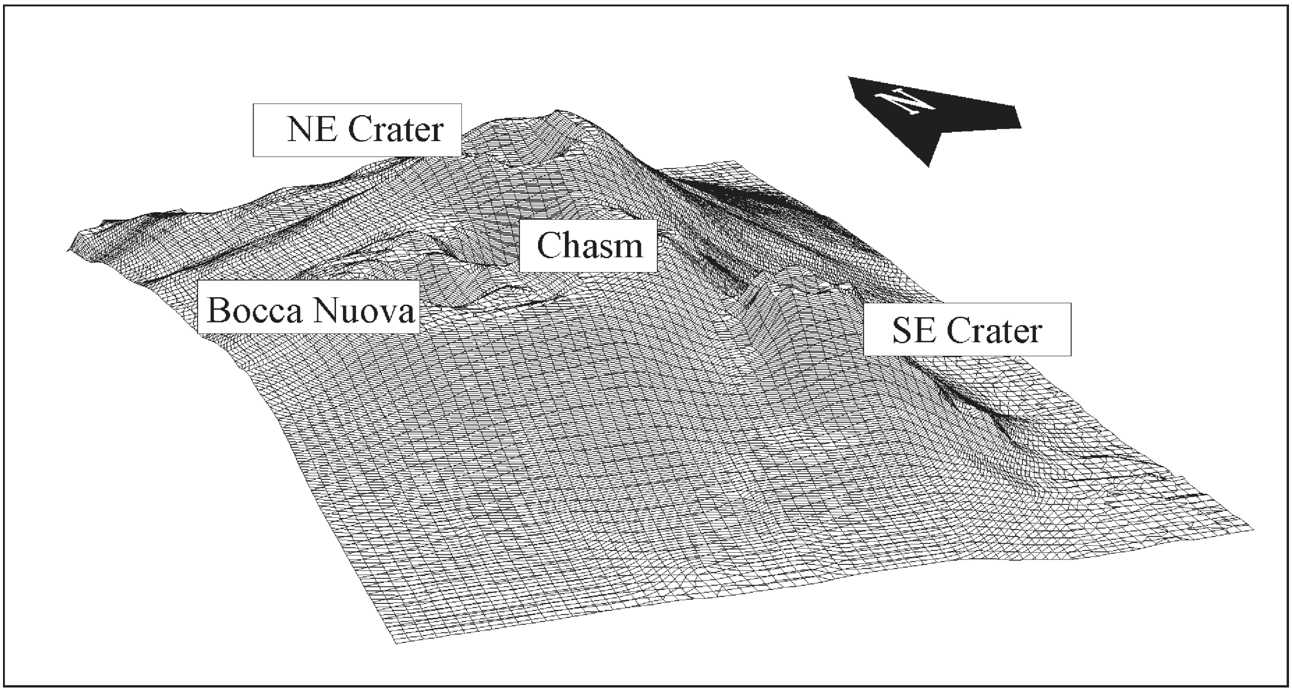

Fig. 1. 3D schematic picture of the summit craters.

History of the NE Crater

The creation of the NE Crater (NEC) took place on 27 May 1911 through the non-eruptive collapse of the lower part of the central cone, at about 3100 m elevation, 3.5 months before a lateral eruption on the NNE flank of the mountain (Riccò 1911, see details in Tanguy 1981). During the following two years, the NEC merely appeared as a steaming chasm. Weak explosive activity was noticed for the first time on 15 July 1913 (Riccò et al. 1917). However, Strombolian explosions occurred only from March 1915 onwards, either jointly with, or independently of, similar activity at the Central Crater. On 24 June 1917 an 800 m high lava fountain gushed forth for twenty minutes from the NEC, but the first sluggish, «subterminal» lava flows occurred in March–July 1918 (Tanguy & Patanè 1996). Strombolian explosive activity was renewed in June 1922 and a typical lava effusion in May-June 1923 preceded another lateral eruption on the NNE flank. On the other hand, the 2 November 1928 eruption (ENE flank) was heralded by only one hour of explosive activity from the NEC, and both NEC and Central Crater showed intermittent lava fountains in the weeks before the 1947 eruption on the Northern flank.

Conversely, and although intermittent weak explosions occurred there between 1931 and 1941, no activity from the NEC happened during the 1942 eruption on the Southern flank, nor during the 1949 one (S, N and NW flanks) or during the large Eastern flank 1950–51 eruption (125×10^6 m^3, Murray 1990).

From 1955 to 1971, the NEC was in almost continuous, or «persistent» explosive and effusive activity, producing more than 350×10^6 m^3 of flows that covered the Northern and Eastern summit area, sometimes in connection with strong explosions at the Central Crater (e.g., 1960, 1964). However, no lateral eruption occurred before 1971 (Southern and NE flanks), when all activity at the NEC had already ceased (Tanguy & Patanè 1996).

Explosions resumed at the NEC on 28 September 1974, followed by lava outflows and, in February 1975, by opening of a new fissure on the Northern flank (Kieffer et al. 1975). Alternation of lateral and subterminal (NEC) activity lasted in this region until January 1977. On 16 July of the same year, a series of strong lava fountains began and very fast outflows occurred at irregular intervals (a few days to several weeks) between July 1977 and March 1978, no connection being evident with the 1978 (April–June, August, November) and 1979 lateral eruptions (SE and NE flanks). Paroxysms similar to those of the 1977–78 period were renewed at the NEC in September 1980 and February 1981, perhaps heralding the violent March 1981 eruption on the NNW flank (Tanguy & Patanè 1984). Then the NEC was quiet for several years, although other lateral eruptions occurred in 1983 and 1985 (S and E flanks).

In September 1986, a renewal of subterminal explosive and effusive activity at the NEC eventually culminated in a violent phreatomagmatic paroxysm (on the 24th), perhaps related to the opening of new fissures leading to the November 1986–February 1987 Eastern flank eruption. Then the NEC was dormant for a long period, although large lateral eruptions occurred in 1989 (NE flank) and 1991–93 (SE flank, this latter producing 235×10^6 m^3, Calvari et al. 1994).

In recent years, the activity of the NEC was rather sporadic, alternating between quiet long-lasting degassing and violent paroxysms, usually of a few hours, namely in 1995 and 1996. A peculiar effusive event was a lava outflow cascading within the neighbouring Voragine of the Central Crater (21/7 to 19/8 1996). Since then, only occasional explosions have occurred from time to time, as in October 1999. Finally, continuous abundant degassing took place at the NEC before, during and after the July 2001 lateral eruption (Tanguy et al. 2001).

The lava fountaining of 27 March 1998 was one of the last significant events of the NEC. After moderate and transient explosive activity in the early afternoon on this day, Strombolian jets started again at about 21h30 GMT (22h30 Local Time) and evolved into a lava fountain between 22h50 and 23h50 GMT, accompanied by two phases of unusually high amplitude tremor. Strong detonations were heard all around the volcano as large lava blocks and scoriae were thrown 300 to 400 m above the crater rim, but relatively little material was found outside the large chasm. During this paroxysmal event, the other summit craters (especially Bocca Nuova and SE Crater) continued their moderate magmatic activity without significant change (Tanguy et al. 1999).

As a conclusion to this brief summary, it seems that the NEC, although clearly related to the lateral eruptions of 1911 and 1923 and, to a lower degree, than the 1928 and 1947 one, subsequently evolved as an independent summit vent. This is particularly true since the appearance of the Bocca Nuova (or West Chasm of the Central Crater) in 1968, and that of the new subterminal South-East Crater in 1971–78.

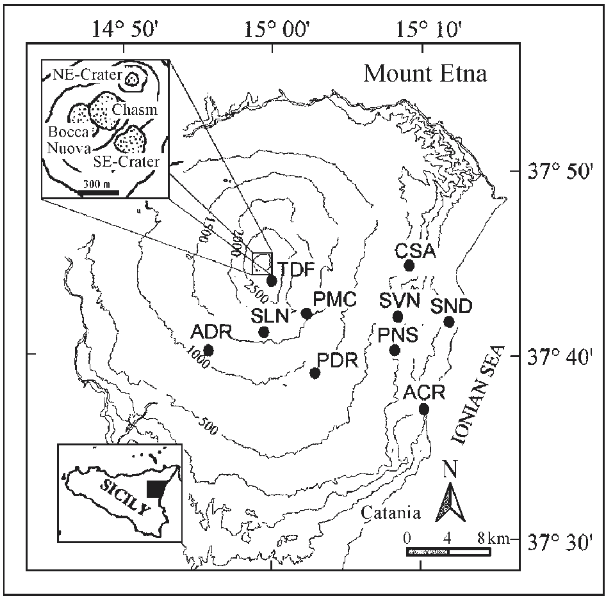

Fig. 2. Mt Etna map: location and names of the seismic stations. The inset on the upper-left corner offers a schematic picture of the summit crater.

Data analysis

Seismic activity before the 27th March 1998 eruptive event at NE Crater prevalently affected the top of the volcano and, only moderately, the other sectors.

The local magnitudes of the events are in the range 2 to 3. Earthquakes were recorded by University of Catania seismic stations and by the Seismological Observatory of Acireale.

Seismic signals are acquired by 1 Hz 3D digital seismometers located in Adrano (ADR) and Acireale (ACR) and by 1 Hz single-component seismometers in S. Venerina (SVN), Pennisi (PNS), S. Leonardello (SND), S. Alfio (CSA), and Mount Pomiciaro (PMC), in the eastern sector of Mount Etna, and Serra La Nave (SLN), Pedara (PDR) and Torre del Filosofo (TDF), in the southern sector (Fig. 2).

A selection of the data has been performed by considering the earthquakes recorded at a minimum number of 7 stations and the standard errors of the coordinates ERH, ERZ ≤ 3 km and RMS < 0.3 sec. This selection meant a dramatic reduction in the number of the events, from more than a thousand to a few hundred. The hypocentre location was performed by the calculation program Hypo71 (Lee & Lahar 1975) and the velocity model used is that of Hirn et al. (1991).

The seismic activity, in the considered period (October 1997–March 1998), is located in the summit area, in the eastern, western and southern sectors. In October and in November, the epicentre distribution is associated with the NE-SW, NNE-SSW and NW-SE structural trends and also affected the middle-low altitudes (Fig. 3a,c). In December the seismic activity decreased, and was located at middle-high altitudes with two evident trends, NE-SW and NNW-SSE, (Fig. 3e). In January 1998 about 500 events were recorded, only 138, with MD > 2.0, were located and affected almost the whole volcanic area (Fig. 4a). Two main structural trends were associated with the seismic swarms: NNE-SSW and WNW-ESE. In the following months, February and March, the seismicity decreased and the structural trends involved were NE-SW, NW-SE and NNE-SSW, NNW-SSE respectively (Fig. 4c,e). The vertical sections (Figs. 3–4: b,d,f) show that the hypocentres were distributed in a depth range between 0 and 24 km; a reduction of the seismic foci density was observed below 12 km. The highest focal depths are to be found in the western sector and in relation to the main axis of the magma uprise; the highest hypocentre density was located at a depth lower than 9 km.

Similar eruptions occurred between July 1977 and March 1978 at the NE Crater (Vinciguerra et al. 1999), and seismic activity preceded the 27th March 1998 eruption by a few months. In fact, in January about 500 earthquakes with MD < 3.5 (Fig. 5) occurred over the whole volcanic area along the NNE-SSW regional tectonic trend and the WNW-ESE volcano-tectonic one (Romano 1982).

Similar considerations were made on occasion of other summit phenomenologies (Tanguy & Patanè 1984; Cosentino et al. 1989); this may mean that the source mechanisms of eruptive phenomena are substantially unchanged over time.

Between January and April 1998, the macroseismic activity with intensity Io ≤ IV–V (M.S.K.), mainly affected the southwest and southern sectors of the volcano (Fig. 6). The mesoseismic areas of some events are prevalently aligned in a NE-SW direction (events No. 1 and 2), in agreement with the orientations of the eruptive fractures opened up in the NE Crater and along the NW-SE structural trend (events 4 and 5). Fig. 6 shows all the macroseisms occurring in 1998; all these events show the particular dynamism of the southern sector of Etna, where all the summit eruptions following the NE one

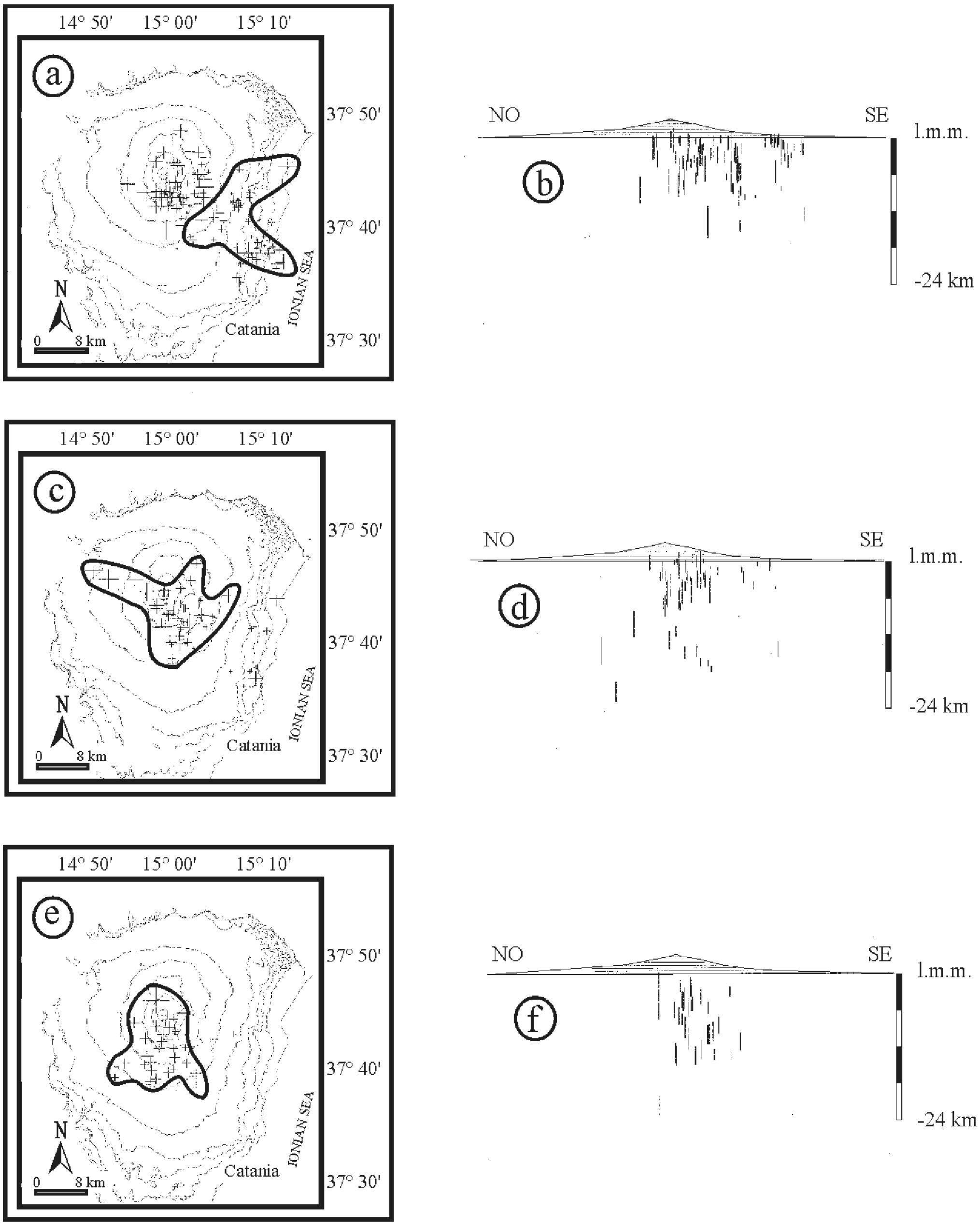

Fig. 3. Maps indicating the seismic activity at Mt Etna in October, November and December 1997: (**a, c, e**) epicentres and principal trends (inside delimitate areas); (**b, d, f**) hypocentres.

and the eruption of July 2001 took place (La Delfa et al. 2001).

By using the earthquake data collected during March, 19 reliable Fault-Plane Solutions (F.P.S.) have been evaluated (Table 1 and Fig. 7a). As can be seen from this figure, 9 events show a focal mechanism linked mainly to thrust faulting and only 6 of them show mechanisms connected with normal faulting (Fig. 7b); 2 events are linked to strike-slip faults and lastly, only 2 of them show a sub-vertical focal plane.

Generally, it can be observed that the Fault-Plane Solutions (F.P.S.) are in good agreement with the outcropping structures (Fig. 7a,b; Fig. 8); in some cases this correspondence seems ambiguous, in particular in the sites where faults and fractures outcrop with variable orientations; lastly, there is a complete lack of correspondence for the F.P.S. No. 3, 7 and 15.

From the comparison between the focal mechanisms and the tectonic structures outcropping in the area it may be seen that the most active structural trend is the NNW-SSE one (events No. 2, 4, 11, 12, 13, 14, 15, 18, 19). The WNW-ESE (events No. 3, 5, 7, 8, 17), NNE-SSW (events No. 1, 6, 10) and ENE-WSW (events No. 9 and 16) trends are less active, at least in the studied period.

The eruption at the NE Crater is associated with the opening of an eruptive fracture, oriented circa NE-SW (Fig. 9a), the distribution of the azimuthal direction of the P-axes fluctuates prevalently around an average value of roughly 45°–50°

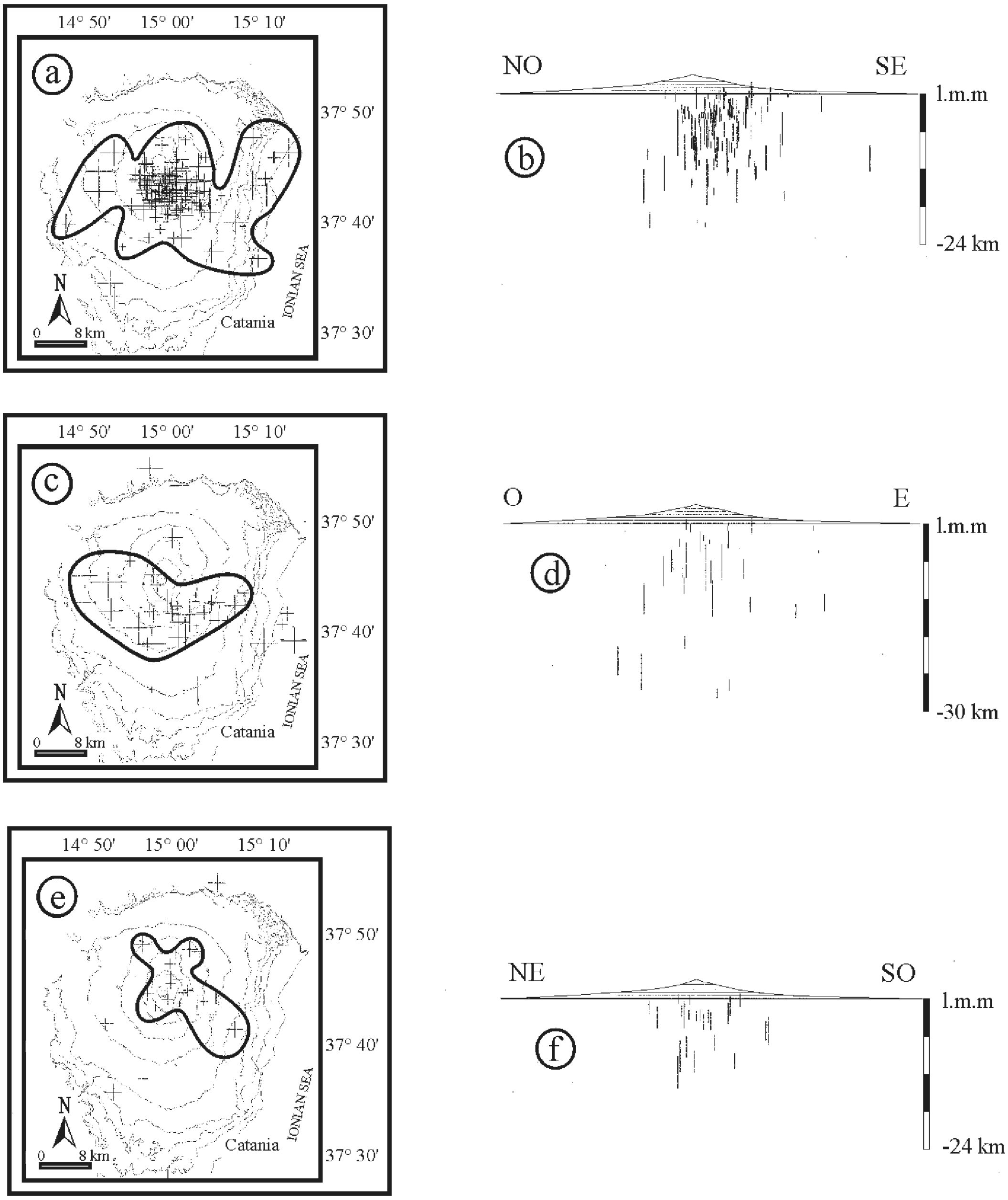

Fig. 4. Maps indicating the seismic activity at Mt Etna in January, February and March 1998: (**a, c, e**) epicentres and principals trends (inside delimitate areas); (**b, d, f**) hypocentres.

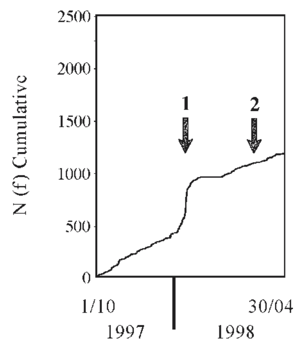

Fig. 5. Cumulative curve concerning the earthquakes recorded in the period between October 1997 and April 1998; **1** — seismic swarm in January 1998; **2** — NE Crater eruption (March 27, 1998).

(Fig. 9b), in agreement with the direction of the same fracture. In particular, during the third week of March, the orientation of the P-axis is very close to the above mentioned discontinuity (Fig. 7a: F.P.S. Nos. 17, 18, 19; Fig. 9b).

Discussion and conclusions

It is known that seismic energy release before an eruptive event, during the final phase and after its end, can give different information about the origin and evolution of the eruptive event (Yokoyama 1988; Patanè et al. 1996; La Delfa et al. 1999).

Table 1: Focal parameters of main earthquakes during March 1998. A.P. — pressure axis; A.T. — tension axis; P.A. and P.B. are the nodal planes from fault-plane solutions.

No.	Date	h:min (GMT)	Origin	Long (°)	Lat (°)	Depth (km)	A.P. - strike	A.P. - dip	A.T. - strike	A.T. - dip	P.A. - strike	P.A. - dip	P.A. - slip	P.B. - strike	P.B. - dip	P.B. - slip
1	2.3.1998	6.10	49.38	14-53.96	37-35.59	1.39	194.5	35.7	299.4	19.6	243.68	79.88	41.25	342.43	49.53	13.35
2	2.3.1998	6.17	32.5	14-57.18	37-36.83	0.3	62.1	18.4	285.4	65.4	344.93	65.2	72.65	128.26	29.95	57.17
3	2.3.1998	12.32	36.56	15-01.03	37-45.73	3.07	30	1.8	210	88.2	120	75	90	300	15	90
4	3.3.1998	0.28	20.44	14-59.90	37-43.88	4.2	70	0	270	90	340	75	90	160	15	90
5	3.3.1998	0.57	52.66	15-03.87	37-43.76	2.64	184.2	41	16.4	48.4	99.9	86.22	83.87	221.45	7.2	31.75
6	3.3.1998	10.36	57.01	15-02.14	37-44.69	4	291.9	41.1	161.5	36.6	312.89	27.57	5.28	47.57	87.56	62.53
7	3.3.1998	21.21	48.49	14-53.31	37-41.73	10.15	190.8	3.3	92.5	68.2	259.05	45.22	58.84	119.7	52.6	62.46
8	10.3.1998	19.15	9.02	15-05.32	37-44.05	10.93	20.1	52.9	205.7	37	312.76	8.15	70.71	113.29	82.31	87.29
9	11.3.1998	2.02	42.21	15-00.80	37-47.95	0.13	317.3	70.7	172.6	15.9	277.86	30.64	68.94	73.75	61.6	77.99
10	12.3.1998	2.16	9.23	14-57.09	37-48.84	1.77	257.7	64.8	131.7	15.4	168.58	83.87	36.92	263.17	53.33	7.65
11	14.3.1998	23.24	3.3	15-05.06	37-39.73	5.76	0.1	50.2	95.1	4.2	36.26	60.58	43.15	150.98	53.44	37.7
12	15.3.1998	19.49	34.58	15-00.23	37-45.33	11.06	200.6	69.4	43.2	19.2	307.14	64.56	81.86	145.57	26.63	73.42
13	15.3.1998	20.08	44.77	15-01.58	37-44.53	3.1	256.2	18.1	2.2	40	31.06	47.58	18.56	133.83	76.41	43.95
14	18.3.1998	3.12	49.32	14-57.71	37-44.38	8.49	258.7	52.1	79.4	37.9	171.85	7.03	87.28	349.11	82.98	89.66
15	18.3.1998	3.25	22.04	15-00.21	37-47.05	2.35	68.1	18.5	246.7	71.5	337.73	63.49	89.55	158.75	26.51	89.09
16	18.3.1998	3.26	4.41	15-00.24	37-46.11	2.96	129.8	34.4	28	16.7	163.6	52.92	14.27	262.31	78.66	37.95
17	19.3.1998	1.05	39.12	15-01.27	37-43.50	7.77	38.4	34.6	176.5	47.2	289.5	83.18	67.87	183.22	23.11	17.62
18	21.3.1998	5.30	5.82	14-53.02	37-41.73	12.92	241.9	52.1	96.3	32.7	232.33	19.98	31.11	351.88	79.83	72.71
19	31.3.1998	7.34	7.34	14-58.57	37-43.27	3	58.5	15.5	299.8	60.1	117.41	36.72	45.2	348.5	64.89	62.27

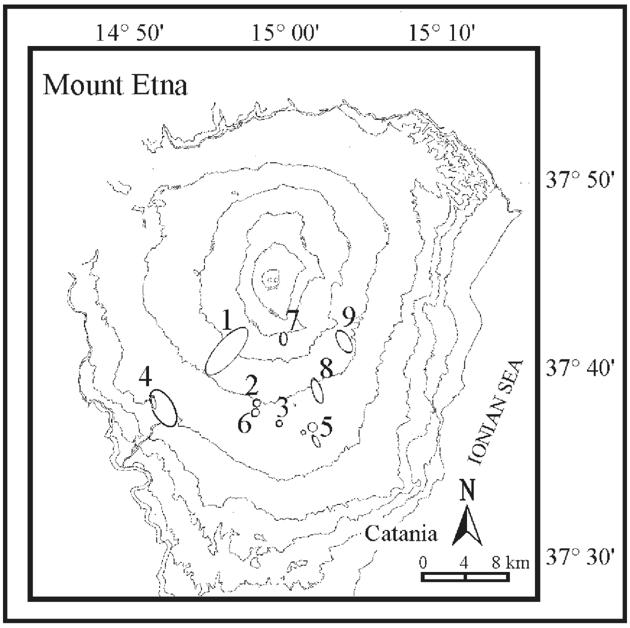

Fig. 6. Map indicating the mesoseismic areas of some earthquakes during 1998. The macroseismic scale used is MSK. **1** — 01.10.1998, 08h46m (GMT), I_o — IV–V; **2** — 03.02.1998, 06h10m, 06h27m (GMT), I_o — III; **3** — 03.02.1998, 21h10m (GMT), I_o — III–IV; **4** — 03.03.1998, 21h21m (GMT), I_o — IV–V; **5** — 04.01.1998, 07h29m (GMT), I_o — IV; 05.22.1998, 11h54m (GMT), I_o — V; 07.21.1998, 21h24m (GMT), I_o — IV; 07.22.1998, 14h19m (GMT), I_o — IV–V; **6** — 08.27.1998, 06h59m (GMT), I_o — IV–V; **7** — 10.26.1998, 11h54m (GMT), I_o — IV; **8** — 11.03.1998, 15h26m (GMT), I_o — IV; **9** — 12.05.1998, 04h38m (GMT), I_o — V (La Delfa et al. 2001).

Similarly to the eruptions at the NE Crater in 1977–1978, no seismic event of significant energy occurred shortly before the 27 March 1998 eruption.

This eruption, like those in the second half of 1998 at the SE Crater (La Delfa et al. 2001), justifies the hypothesis that the magma migration towards higher crustal levels, began between the second half of 1997 and the first half of 1998, a time interval within which numerous seismic swarms took place.

The hypocentres affected both the surface crustal as well as relatively deeper layers, constituted by the carbonate units cropping out to the south in the Iblean area (Cristofolini et al. 1979). In such a way one may hypothesize that the volcanic phenomenon at the NE Crater, albeit to a modest degree, represents the manifestation of a dynamism, associated with a very unstable stress field, which affects a large crustal thickness. Cocina et al. (1997) have arrived at the same considerations; according to these researchers, the trend of the stress is rather heterogeneous in the Etnean crust eastwards from the fifteenth meridian which is the eastern sector of the volcano where the eruptive phenomenon of the NE Crater is located. The analysis of the causes about the stress field and its variability in the Etnean area, is still a matter of debate among researchers, since it is not well defined if the convergence between the African and European plates is still active and what is the role of volcanism about the mentioned stress field. However the researches carried out in the last thirty years (Cristofolini et al. 1979; Sharp et al. 1980; Tanguy et al. 1997, to quote some of them) have underlined the mantle uprising at the deep crust correspondence, which may be a component responsible for the stress field and therefore for the magma uprising towards the surface. Furthermore the south-vergences nappe chain outcropping in the North of the volcano, with clear gravitate balance loss, could represent another component of the tangential type stress field, with North-South orientation, acting on Etna. The intensity and direction of time variation about these two strengths combination could be responsible for the local stress field fluctuation and therefore the volcano geodynamics having different time scale (La Delfa et al. 2000).

In particular, the main results obtained in this research, may be listed as follows:

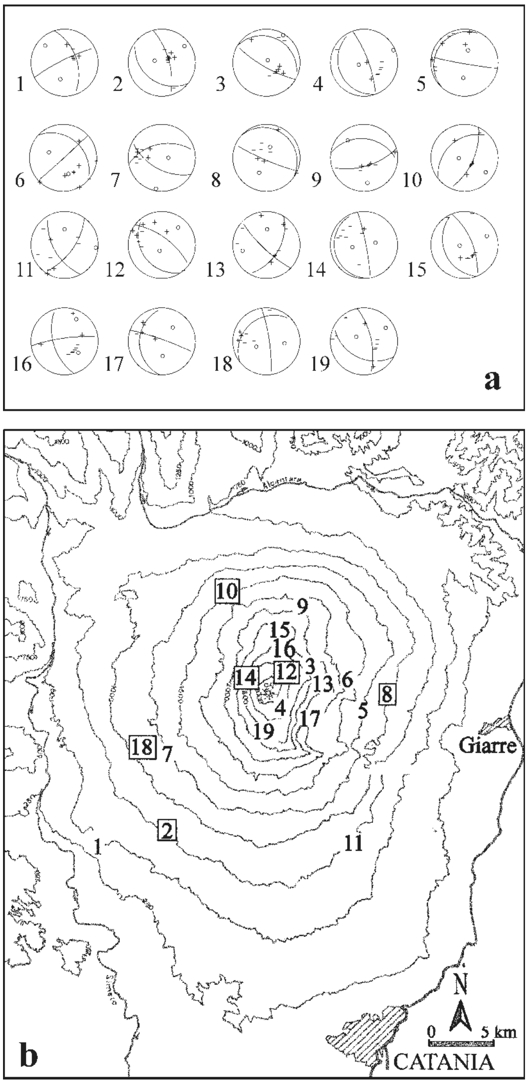

Fig. 7. (**a**) Fault-plane solution plots of the main earthquakes which occurred during March 1998 and (**b**) relative enumerated epicentres. The numbers inside the squares relate to the normal fault-plane solutions (see Table 1 for the list of focal parameters associated with each event).

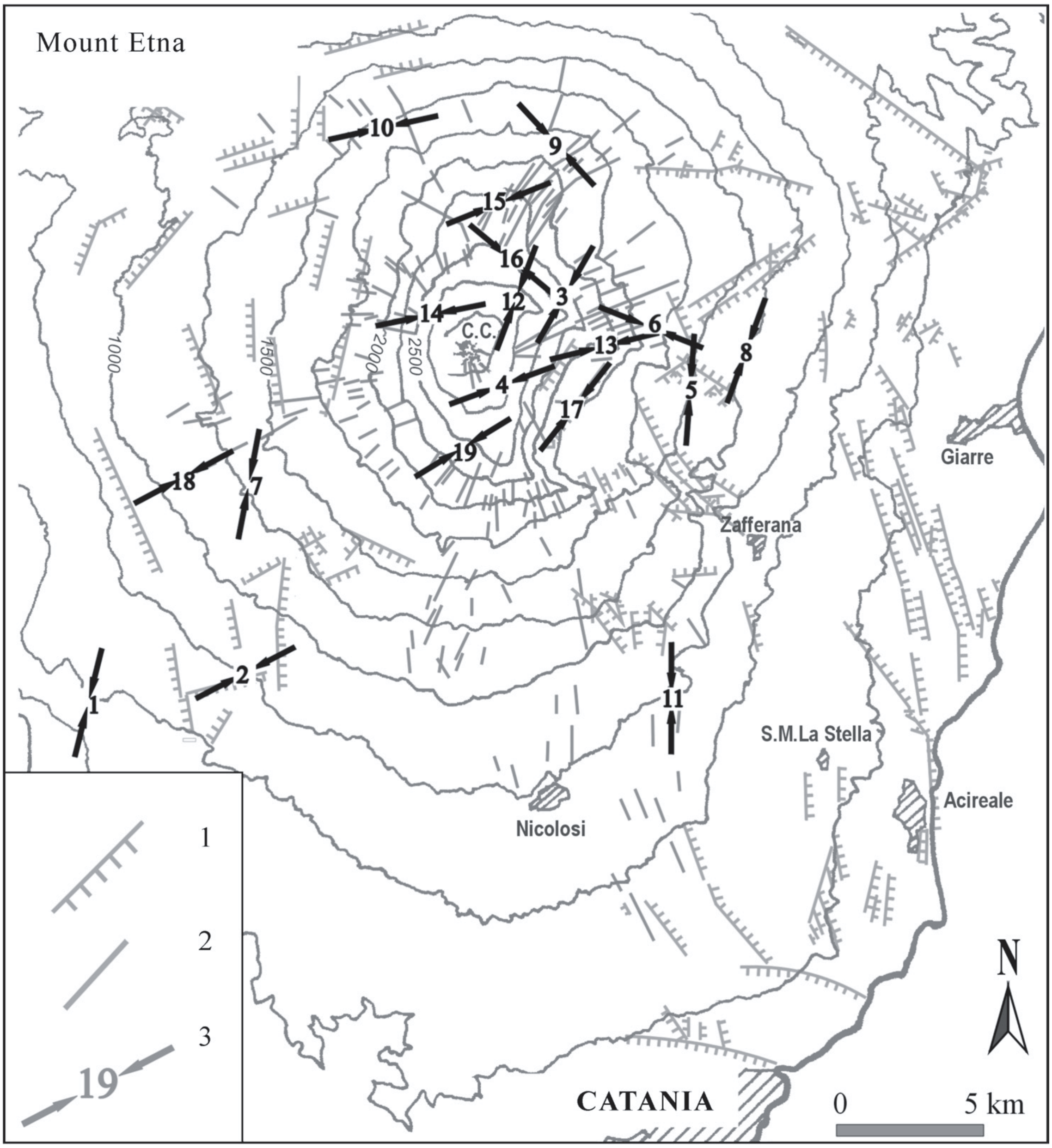

Fig. 8. Structural map of Mt Etna (from Romano et al. 1979, modified). This map emphasized faults (**1**), fractures (**2**) and P-axis (**3**). The numbers represent the progressive order of the associated F.P.S.

• The eruptive style of the NE Crater on 27 March 1998 does not differ from that observed in this century many times.

• The epicentral pattern preceding the eruptive phase of this volcano suggests that the terminal activity is related in a more complex way to the seismic activity. Analysis of seismicity between October 1997 and March 1998 in fact shows that before the eruption at the NE Crater, numerous earthquake swarms affected all sectors of Etna along different tectonic and volcano-tectonic trends; however, most seismic events are located in the summit area and the eastern sector (Figs. 3–4: a,c,e), where the crust shows the greatest degree of fracturing (Fig. 8).

In addition, in the studied period there were two seismic peaks, in October 1997, before a moderate eruptive activity at the SE Crater begun in November, and in January.

All these considerations allow us to conclude that the magma uprise is associated with a marked crustal deformation in the volcanic area; however, the release of elastic energy is higher in the more brittle zones.

• The migration of the magma to the surface is slowed down by a notable hysteresis of the crust, probably determined by a non-favourable stress field; in fact the time interval separating the summit eruptive event from seismic paroxysms is generally in the order of a reduced number of months.

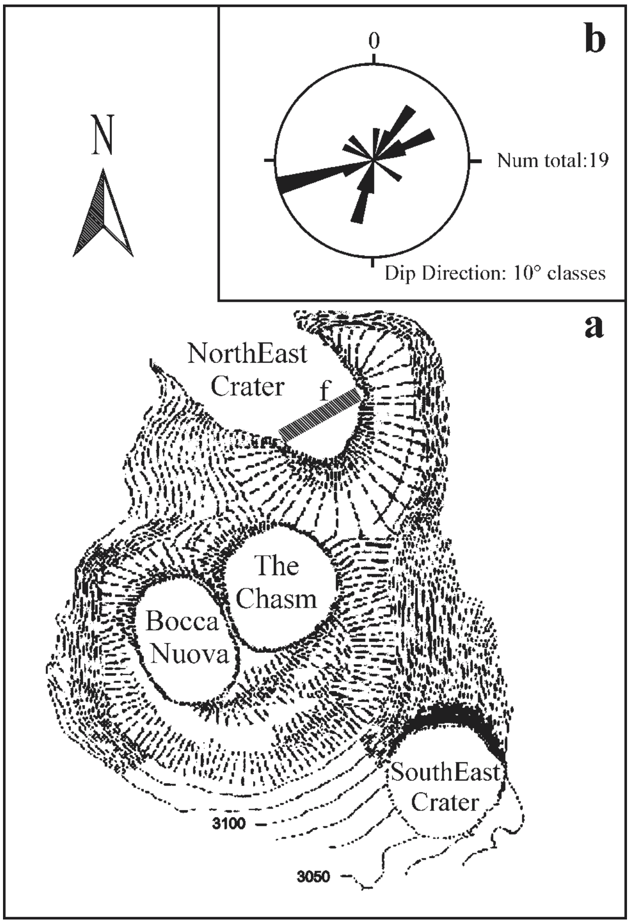

Fig. 9. (**a**) Schematic picture of the summit craters, f = eruptive fracture inside NE Crater; (**b**) diagram showing the principals trends of P-axes dip direction (see Fig. 7a).

However Centamore et al. (1999), show through the analysis of the 'b' coefficient of the Gutemberg-Richter curve, that the genesis of an eruptive event, at Etna, is also compatible with a compressional type stress field. Indeed, the opening up of the fractures and the penetration of the magma may occur following a decrease in the intensity of the main stress module σ_1. In agreement with this result, the focal mechanisms obtained show fault processes both of normal and inverse type, but the latter are predominant and located close to the summit (Fig. 7b).

• The fault-plane solutions show that in the same area of the volcano, both normal and inverse faults may exist (e.g., F.P.S. Nos. 5, 8 and 12, 13) and that the fault planes may have the same orientation. Therefore, the stress field acting on the pre-existing structural discontinuities, when it varies locally, can cause different source mechanisms in the same structures.

• The eruptive activity of Mt Etna varies from periods of relative calm to periods in which there are violent eruptions. This trend suggested to Scarpa et al. (1983) the hypothesis of the existence of a temporal rotation of the axes of the stress field acting on the volcano. La Delfa et al. (1999), through the study of the focal mechanisms of earthquakes accompanying and following the eruption at the SE Crater in 1984, have further confirmed these hypotheses.

The results in this work demonstrate a notable analogy with those obtained by these last authors. In fact, the opening up of eruptive fractures oriented circa NE-SW, accords well with the orientation of the P-axis, which shows the same direction at least during the last ten days of March (F.P.S. Nos. 17, 18, 19). The instability of the local stress field was most likely responsible for the brief duration of the eruptive phenomenon.

Acknowledgments: The authors wish to thank the referees and particularly Dr. M. Ripepe for the improvement of the early version of the paper. This work was carried out by means of 60 % MURST grants.

References

Bottari A. & Riuscetti M. 1967: Serra La Nave seismic station on Mt Etna. *Ann. Geophys.* 20, 243–264 (in Italian).

Calvari S., Coltelli M., Neri M., Pompilio M. & Scribano V. 1994: The 1991–1993 Etna eruption: chronology and flow-field evolution. *Acta Vulcanol.* 4, 1–14.

Cardaci C., Falsaperla S., Gasperini P., Lombardo G., Marzocchi W. & Mulargia F. 1993: Cross-correlation analysis of seismic and volcanic data at Mt. Etna volcano, Italy. *Bull. Volcan.* 55, 596–603.

Centamore C., Patanè G. & Tuvè T. 1999: Maximum entropy estimation of *b* values at Mt. Etna: comparison with conventional least squares and maximum likelihood results and correlation with volcanic activity. *Ann. Géophys.* 42, 515–528.

Cocina O., Neri G., Privitera E. & Spampinato S. 1997: Stress tensor computations in the Mount Etna area (Southern Italy) and tectonic implications. *K.J Geodinamics* 23, 109–127.

Chester D.K., Duncan A.M., Guest J.E. & Kilburn C.R.J. 1985: Mount Etna. The anatomy of a volcano. *Chapman and Hall,* London, 1–404.

Cosentino M., Lombardo G. & Privitera E. 1989: A model for internal dynamical processes on Mt. Etna. *Geophys. J.* 97, 367–379.

Cristofolini R., Lentini F., Patanè G. & Rasà R. 1979: Geologic, geophysic and petrological data integration for the drawing up of a crust outline at Etna volcano. *Boll. Soc. Geol. Ital.* 98, 239–247 (in Italian).

Gasperini P. & Mulargia F. 1989: A statistical analysis of seismicity in Italy: the clustering properties. *Bull. Seismol. Soc. Amer.* 79, 973–988.

Gasperini P., Gresta S. & Mulargia F. 1990: Statistical analysis of seismic and eruptive activities at Mt. Etna during 1978-1987. *J. Volcan. Geotherm. Res.* 40, 317–325.

Guest J. 1973: The summit of Mt. Etna prior to the 1971 eruptions. *Phil. Trans R. Soc. Lond.,* A 274, 63–78.

Hirn A., Nercessian A., Sapin M., Ferrucci F. & Wittlinger G. 1991: Seismic heterogeneity of Mount Etna: structure and activity. *Geophys. J. Int.* 105, 139–153.

Kieffer G. 1985: Evolution structurale et dynamic d'un grand volcan polygénique: stades d'édification et activité actuelle de l'Etna (Sicile). *Ph. D. thesis,* Univ. Clermont-Ferrand, 1–497.

Kieffer G., Nicolosi A. & Tanguy J.C. 1975: Sur le réveil du Cratère Nord-Est de l'Etna (29.9.74) et le mécanisme de l'activité volcanique persistante. *C. R. Acad. Sci.* 280 D, 701–704.

La Delfa S., Patanè G. & Centamore C. 1999: The geodynamics of Mt. Etna volcano during and after the 1984 eruption. *Ann. Géo-*

phys. 42, 545–563.

La Delfa S., Patanè G. & Tanguy J.C. 2000: Kilometer-scale heterogeneities inside volcanoes revealed by using a set of geophysical methods: variable stress field at Mount Etna, Sicily. *Physics of the Earth and Planetary Interiors* 121, 157–173.

La Delfa S., Patanè G., Clocchiatti R., Joron J.L. & Tanguy J.C. 2001: Activity of Mt. Etna February 1999 fissure eruption: inferred mechanism from seismological and geochemical data. *J. Volcan. Geotherm. Res.* Vol. 105 (1–2), 121–139

Lee W.H. & Lahr J.C. 1975: HYPO71PC (revised): a computer program for determining hypocenter, magnitude and first-motion pattern of local earthquakes. *U. S. Geol. Surv. Open-File Rep.* 75–311.

Montalto A., Di Stefano G. & Patanè G. 1992: Seismic patterns and fluid-dynamic features preceding and accompanying the January 15, 1990 eruptive paroxism on Mt. Etna (Italy). *J. Volcan. Geotherm. Res.* 51, 133–143.

Murray J.B. 1990: High level magma transport at Mount Etna volcano, as deduced from ground deformation measurements. In: Ryan (Ed.): Magma transport and storage. *Wiley,* New York, 357–383.

Patanè G., Montalto A., Vinciguerra S. & Tanguy J.C. 1996: A model of the onset of the 1991–1993 eruption of Etna (Italy). *Phys. Earth Planet. Inter.* 97, 231–245.

Riccò A. 1911: The new vent at north-east of the central crater of Mt. Etna. *Atti Acc. Gioenia Sc. Nat. Catania*, serie 5, 4, mem. 11 (1–6 + 1PL) (in Italian).

Riccò A., Platania Giov., Platania Gaet. & De Fiore O. 1917: About recent revival of active volcanoes Etna, Stromboli, Vulcano. *Boll. Soc. Sismol. Ital.* 21, 28–36 (in Italian).

Romano R. 1979: Geological map of Mount Etna. *CNR* , Roma.

Romano R. 1982: Succession of the volcanic activity in the Etnean area. *Mem. Soc. Geol. Ital.* 23, 27–48.

Scarpa R., Patanè G. & Lombardo G. 1983: Space-time evolution of seismic activity at Mt. Etna during 1974–1982. *Ann. Geophys.* 1 (6), 451–462.

Sharp A.D.L., Davis P.M. & Gray F. 1980: A low velocity zone beneath Etna and magma storage. *Nature*, 287, 587–591.

Sharp A.D.L., Lombardo G. & Davis P. M. 1981: Correlation between eruptions of Mount Etna, Sicily, and regional earthquakes as seen in historical records from AD 1582. *Geophys. J. Royal Astron. Soc.* 65, 507–523.

Tanguy J.C. 1981: Les éruptions historiques de l'Etna: chronologie et localisation. *Bull. Volcan.* 44–3, 585–640.

Tanguy J.C. & Patanè G. 1984: Activity of Mount Etna, 1977–1983: volcanic phenomena and accompanying seismic tremor. *Bull. Volcan.* 47, 965–976.

Tanguy J.C. & G. Patanè 1996: L'Etna et le monde des volcans. *Diderot éditeur, art? sciences,* Paris, New York.

Tanguy J.C., Condomines M. & Kieffer G. 1997: Evolution of the Mount Etna magma: constraints on the present feeding system and eruptive mechanism. *J. Volcan. Geotherm. Res.* 75, 251–250.

Tanguy J.C., La Delfa S. & Patanè G. 1999: Present activity of Mount Etna. *International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI),* 2, 10–13.

Tanguy J.C., R. Clocchiatti, S. La Delfa & G. Patanè 2001: Etna (Italy): Strong June eruptions, a M 3.9 earthquake, copious July-August flank lavas, and a new cone. *Bull. Global Volcanism Network,* 26, N. 9; *Smithsonian Institution.*

Vinciguerra S., Garozzo S., Montalto A. & Patanè G. 1999: Eruptive and seismic activity at Etna Volcano (Italy) between 1977 and 1991. *Geol. Soc. London* 161, 89–107.

Yokoyama I. 1988: Seismic energy releases from volcanoes. *Bull. Volcan.* 50, 1–3.