ANNALI DI GEOFISICA, VOL. XL, N. 5, October 1997

Isochronal maps at Mt. Etna volcano (Italy): a simple and reliable tool for investigating large-scale heterogeneities

Giuseppe Patanè(1), **Concetta Centamore**(2) **and Santo La Delfa**(1)
(1) *Istituto di Geologia e Geofisica, Università di Catania, Italy*
(2) *Dipartimento di Geofisica e Vulcanologia, Università di Napoli «Federico II», Napoli, Italy*

Abstract
This paper analyses twelve etnean earthquakes which occurred at various depths and recorded at least by eleven stations. The seismic stations span a wide part of the volcanic edifice; therefore each set of direct *P*-wave arrival times at these stations can be considered appropriate for tracing isochronal curves. Using this simple methodology and the results obtained by previous studies the authors make a reconstruction of the geometry of the bodies inside the crust beneath Mt. Etna. These bodies are interpreted as a set of cooled magmatic masses, delimited by low-velocity discontinuities which can be considered, at present, the major feeding systems of the volcano.

Key words *isochronal curves – Mt. Etna*

1. Introduction

Volcano-tectonic studies on Mt. Etna developed in concomitance with the application of advanced methods (deep seismic refraction profiles, instrumental analyses of seismic activity) in order to improve the knowledge on deep structures of the volcano.

The obtained results have confirmed on the one hand the absence of extended superficial magmatic reservoirs, on the other, they have changed, sometimes in radical way, the criteria adopted to explain the genesis and the evolution of eruptive phenomena; in other words, the role played by some tectonic structures in the uprising of magma and the mechanisms of eruptions at Mt. Etna are now better understood.

In recent years various approaches have been adopted to explain Mt. Etna dynamics. Cristofolini *et al.* (1979), taking into account geological, volcanological and geophysical data, reconstructed a nearly NS cross-section which points out the relations between the geological bodies and the low velocity layers detected by deep seismic refraction sounding studies of the crust beneath Mt. Etna (Cosentino *et al.*, 1982). The section also clearly shows an uprise of the mantle inside the deep crust under the volcanic area; this agrees with the low-velocity structure modelled by Sharp *et al.* (1980) as a tri-axial ellipsoidal body with longer horizontal axis oriented NE-SW, centred at 15 km depth below Mt. Etna and formed by a complex series of veins of melt running through a highly fractured crust.

Mailing address: Prof. Giuseppe Patanè, Istituto di Geologia e Geofisica, Università di Catania, Corso Italia 55, 95129 Catania, Italy; e-mail: patane@alp9ct.infn.it

Subsequently, the hypothesis of a diapiric upwelling of the mantle, first suggested by Cristofolini *et al.* (1988), was confirmed by Tanguy *et al.* (1997) who, on the basis of petrological and geochemical results, suggest that various stages of evolution in the diapir can justify the gradual shift in composition from tholeiitic to alkaline magmas observed at Mt. Etna in the last 500000 years.

Seismic tomography results obtained by Hirn *et al.* (1991) and Cardaci *et al.* (1993) have provided the researchers with new important elements for detailing the 3D structure of the upper crust under Etna. In fact high *P*-wave velocity anomalies, interpreted as magmatic bodies now completely cooled, were found in the upper portion of the volcano; these bodies seem to be delimited by two main regional tectonic discontinuities, generally oriented N-S and E-W. On the contrary low-velocity bodies, maybe linked to magmatic reservoirs, have been identified at depths greater than 10 km.

Recent studies (Patanè *et al.*, 1994; Montalto *et al.*, 1996; Patanè *et al.*, 1996) show that, if the tectonic forces produce favourable conditions, the above regional discontinuities can favour the uprising of magma. In particular, since the behaviour of the etnean shallower crust seems to be governed by a compressive stress field (Patanè *et al.*, 1994; Centamore *et al.*, 1997) which is part of the regional stress field induced by the pushing of the African plate against the Central Mediterranean basin, the dyke intrusions could be considered a «passive» phenomenon driven by temporal fluctuations in this compressive stress field. This is confirmed by the detailed studies of the 1984 eruption (La Delfa *et al.*, 1997) and the 1991-1993 eruption (Patanè *et al.*, 1996), which point out the fundamental role played by the temporal fluctuations in the direction of the principal compressive stress.

This paper shows that the large-scale regional structural heterogeneities crossing Mt. Etna, together with the high-velocity bodies of the crust under the volcano, are well highlighted by simple isochronal maps (*i.e.*, loci of equal arrival time) contoured starting from the set of arrival times at local seismic stations of direct *P*-waves radiated by etnean sources.

2. Data set and analysis

The seismic events analysed in this study are listed in table I; earthquakes No. 1, 3, 4, 5, 6 and 10 were collected by both the permanent network of Catania University and the temporary ARGOS network of IRIGM of Grenoble (fig. 1), whereas events No. 2, 7, 8, 9, 11 and 12 were recorded by the Poseidon seismic network (fig. 2).

Table I also reports the hypocentral parameters of earthquakes, located by means of the HYPO71PC computer program (Lee and Lahr, 1975) adopting the 1D velocity model deduced from Hirn *et al.* (1991); the resulting map of epicentres, the N-S and the E-W cross-sections of hypocentres are shown respectively in fig. 3a-c.

Figure 4 (No. 1-5) represents the isochronal maps relative to the shallower ($H < 4$ km, No. 1-4) and intermediate-depth ($4 < H < 8$ km, No. 5) seismic events. The maps are listed in the same order as events in table I. Earthquakes located in the eastern sector of the volcano (No. 2 and 4) show isochronal maps elongated mainly in the NE and NW trends and, in a minor part, toward the SW trend. Events in the northern sector, near to the summit craters (No. 1 and 3) are characterised by peripheral isochronal curves elongated especially in the EW and NNW directions, while curves close to the summit craters have an almost circular shape. In the isochronal curves relative to the intermediate-depth event (No. 5), two low-velocity trends, nearly WSW and SSE, delimit two high-velocity lobes, oriented respectively NW and SSW. It is noteworthy that the epicentres of all these events are placed outside the curve relative to the minimum arrival time.

Figures 4 (No. 6) and 5 plot the isochronal curves of deeper events (from No. 6 to No. 12, with depth > 10 km). For all these maps, if the high-velocity structures are considered, a «four-lobes» geometry is recognisable; referring to the summit craters the lobes are elongated, on the average, in the NNE, SE, SW and NW directions, while the low-velocity zones coincide approximately with the NNW-SSE and ENE-WSW trends. In particular, the map

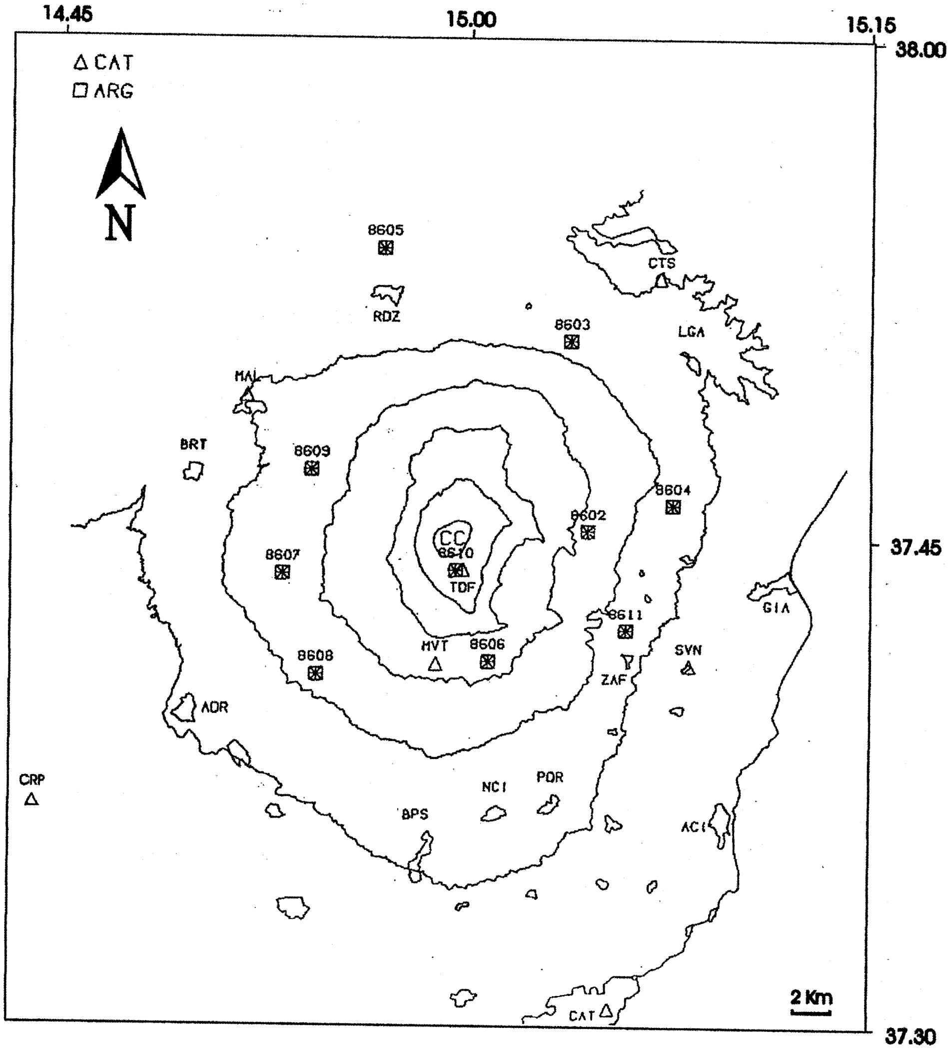

Fig. 1. Map of seismic networks of Catania University (triangles) and Grenoble IRIGM (squares) operating at Mt. Etna in 1984; CC = Central Craters.

relative to event No. 6 highlights the lobes of the northern sector quite well. The curves of event No. 10 show in the western sector two high-velocity lobes, oriented respectively WNW and SSW; in the eastern sector the outer curves are elongated in the ESE trend, whereas the inner curves lengthen toward ENE. Clearly, all the computed epicentres of deeper events are placed inside the curves corresponding to the minimum arrival time.

The fault-plane solutions of the analysed events are shown in fig. 6; the nodal planes have prevalently NNW-SSE, NNE-SSW, WNW-ESE and ENE-WSW directions, according to the morphostructural lineaments emerging at middle-high altitudes of the volcanic edifice.

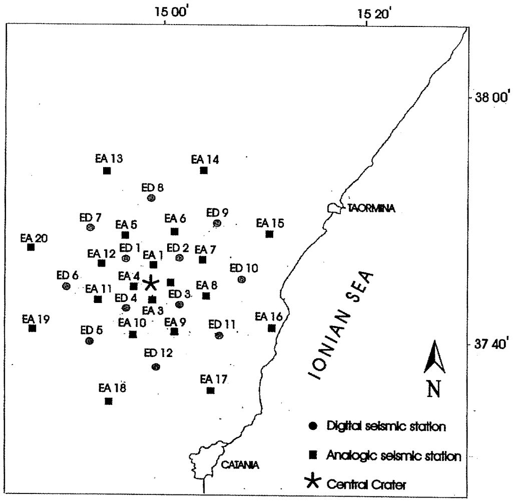

Fig. 2. Map of seismic stations belonging to the Poseidon network and operating at Mt. Etna in 1995.

3. Discussion and conclusions

As observed by previous studies (Hirn *et al.*, 1991; Cardaci *et al.*, 1993), the geological structures inside the crust beneath Etna show a very complex pattern, confirmed by the present analysis performed by means of isochronal maps. In particular, for both shallower and deeper events the observed curves agree very well with the velocity anomalies pointed out by the seismic tomography of Mt. Etna (fig. 7a-f); it must be emphasised that our results have been obtained without adopting velocity models for the crust or numerical algorithms.

The foci of analysed earthquakes are located prevalently inside the high-velocity bodies; this fact can be interpreted as a consequence of the different mechanical behaviour, respectively ductile and brittle, of lower and higher velocity bodies, determined probably by a different temperature. As a confirmation of this, in figs. 4

Table I. Focal parameters of analysed earthquakes; negative depths correspond to foci above sea level. ERH = standard error on epicentre (km); ERZ = standard error on hypocentre (km); RMS = root mean square error of time residuals (s); GAP = maximum angle among stations as seen from the epicentre.

No.	Date	h min (GMT)	Origin	Long. (°E)	Lat. (°N)	Depth (km)	ERH	ERZ	RMS	GAP (deg.)
1	28/08/84	4.46	49.84	14-58.47	37-45.88	−0.50	0.3	0.3	0.11	98
2	27/02/95	11.33	2.30	15-07.05	37-44.07	0.94	0.5	0.7	0.32	146
3	31/08/84	21.06	25.43	14-59.87	37-45.59	2.72	0.9	0.7	0.20	95
4	28/10/84	15.17	42.53	15-02.91	37-47.38	2.84	1.7	2.2	0.46	76
5	27/09/84	16.17	51.07	14-58.57	37-45.36	7.65	1.5	1.8	0.35	92
6	29/03/84	23.07	59.52	14-57.31	37-43.18	10.02	1.1	1.4	0.22	88
7	10/02/95	5.06	14.08	14-59.05	37-41.73	10.75	0.5	0.4	0.19	69
8	10/02/95	13.45	50.94	14-59.05	37-40.99	11.60	0.6	0.5	0.23	81
9	10/02/95	8.50	23.33	15-00.89	37-42.13	11.89	0.7	0.6	0.21	62
10	04/06/84	22.56	45.51	14-57.77	37-40.10	12.20	0.9	1.3	0.17	110
11	10/02/95	3.46	25.37	14-59.76	37-43.38	12.83	0.8	0.7	0.21	86
12	10/02/95	4.44	49.53	14-59.24	37-41.39	14.75	0.8	0.7	0.25	56

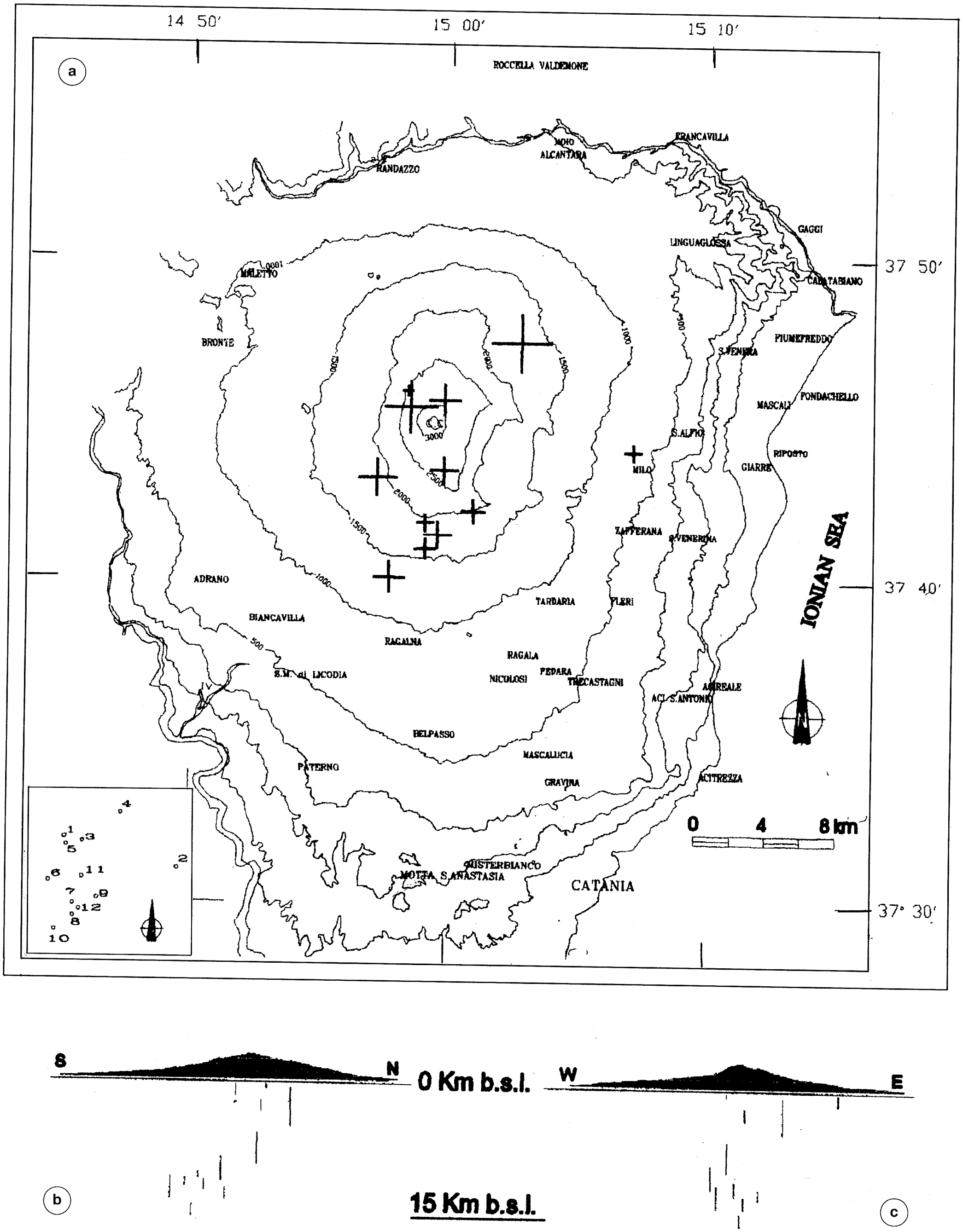

Fig. 3a-c. Epicentral distribution of selected events (a), N-S (b) and E-W (c) vertical sections of hypocentres. Error bars on epicentral (a) and hypocentral (b, c) determinations are superimposed.

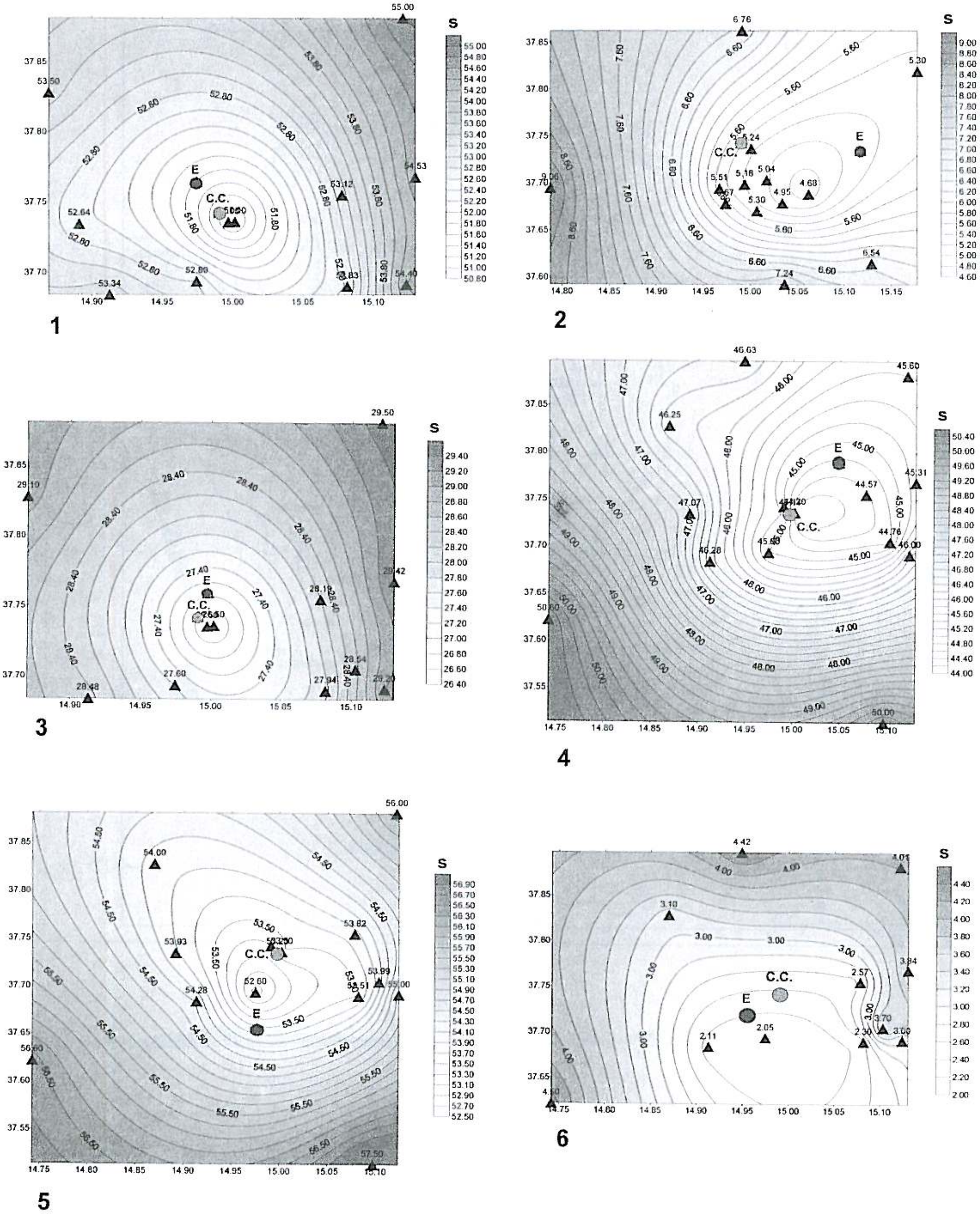

Fig. 4. Isochronal maps of events with No. 1-6 in table I.

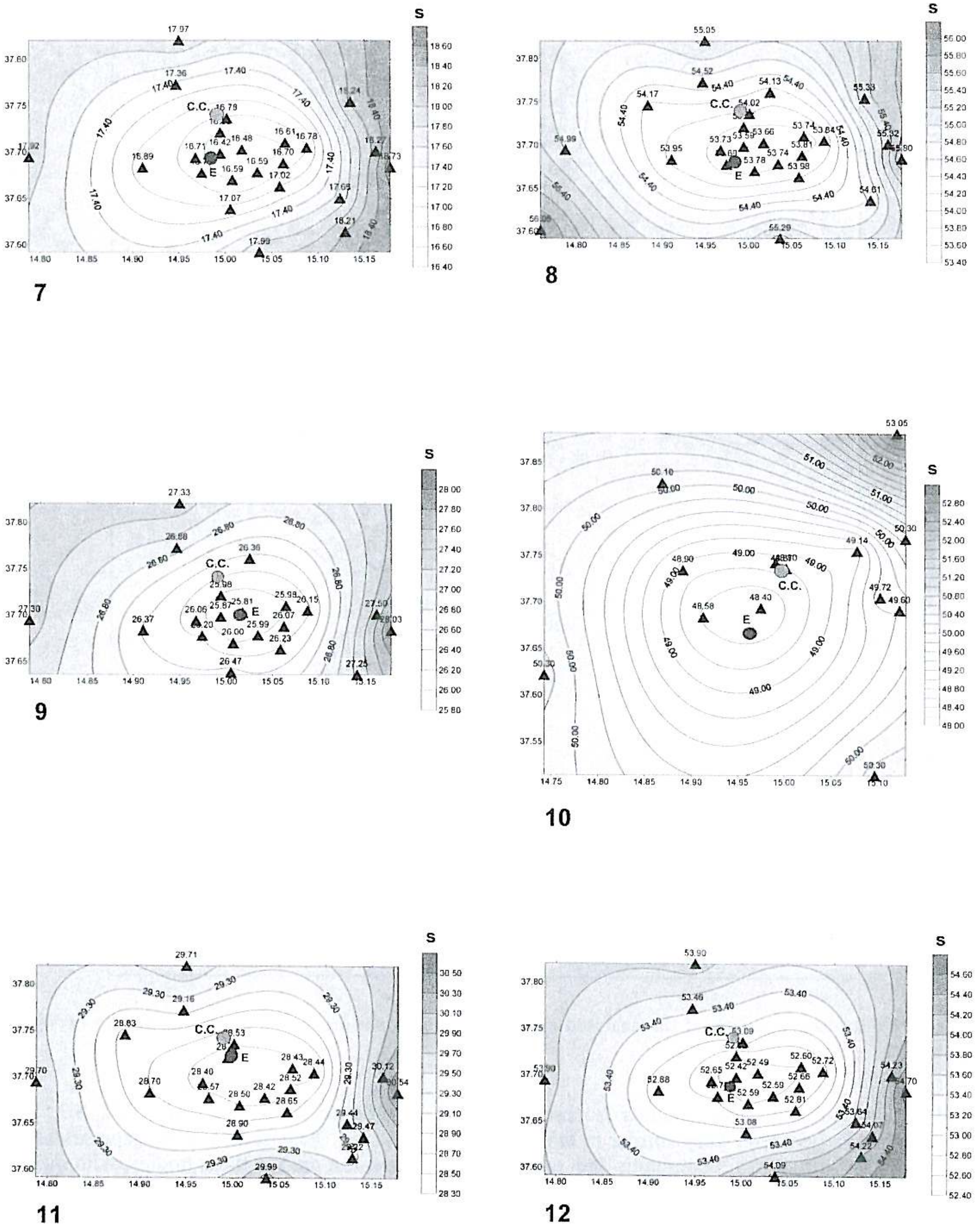

Fig. 5. Isochronal maps of earthquakes with No. 7-12 in table I.

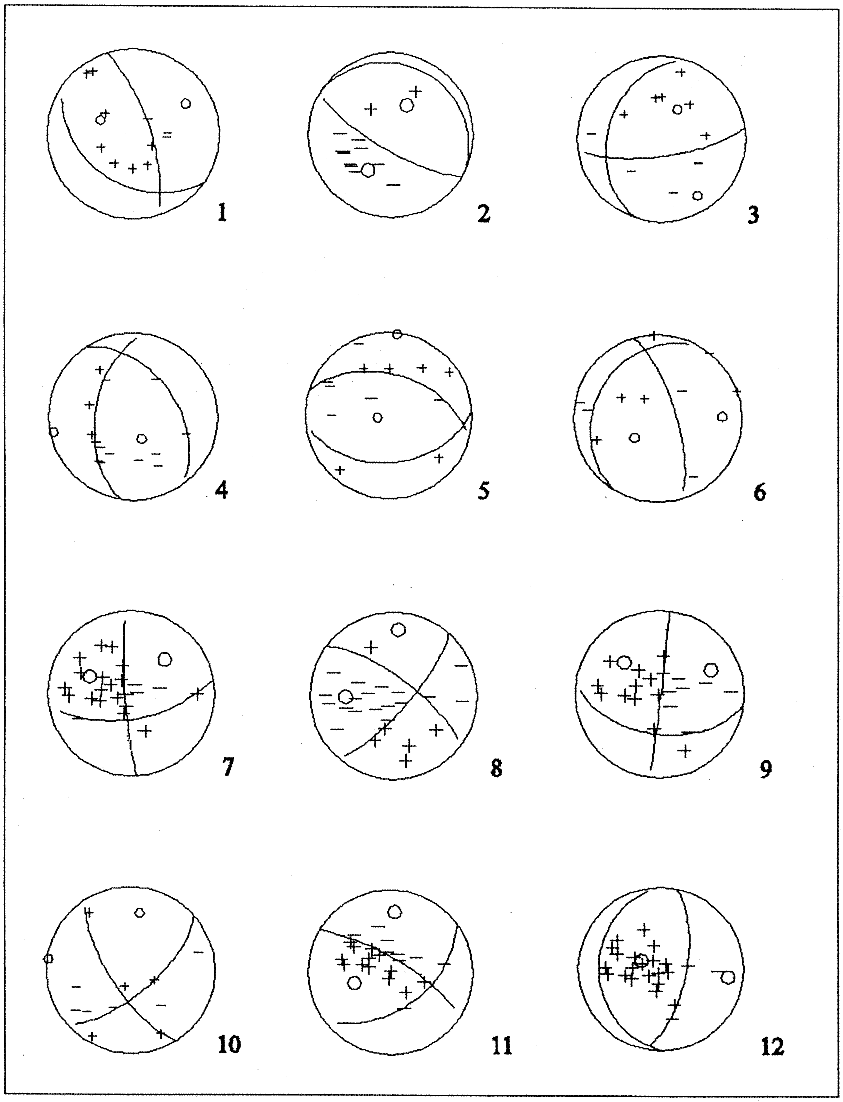

Fig. 6. Fault plane solutions of the analysed events; the projections are in the upper hemisphere of Wulff net.

and 5 it can be noted that the inner isochronal curves show a geometry very similar to that of high-velocity structures containing the same hypocentres.

Moreover, on the basis of analogous considerations, it can be inferred that high-velocity lobes correspond to congealed magmatic masses lengthened nearly toward NNE, SE, SW and NW; fig. 8a,b shows a 3D representation of the greatest among these bodies, with different trends and at various depths. In particular, a continuous migration of magma which lasted up to the recent past, may have occurred in the southern sector of the volcano along the N-S

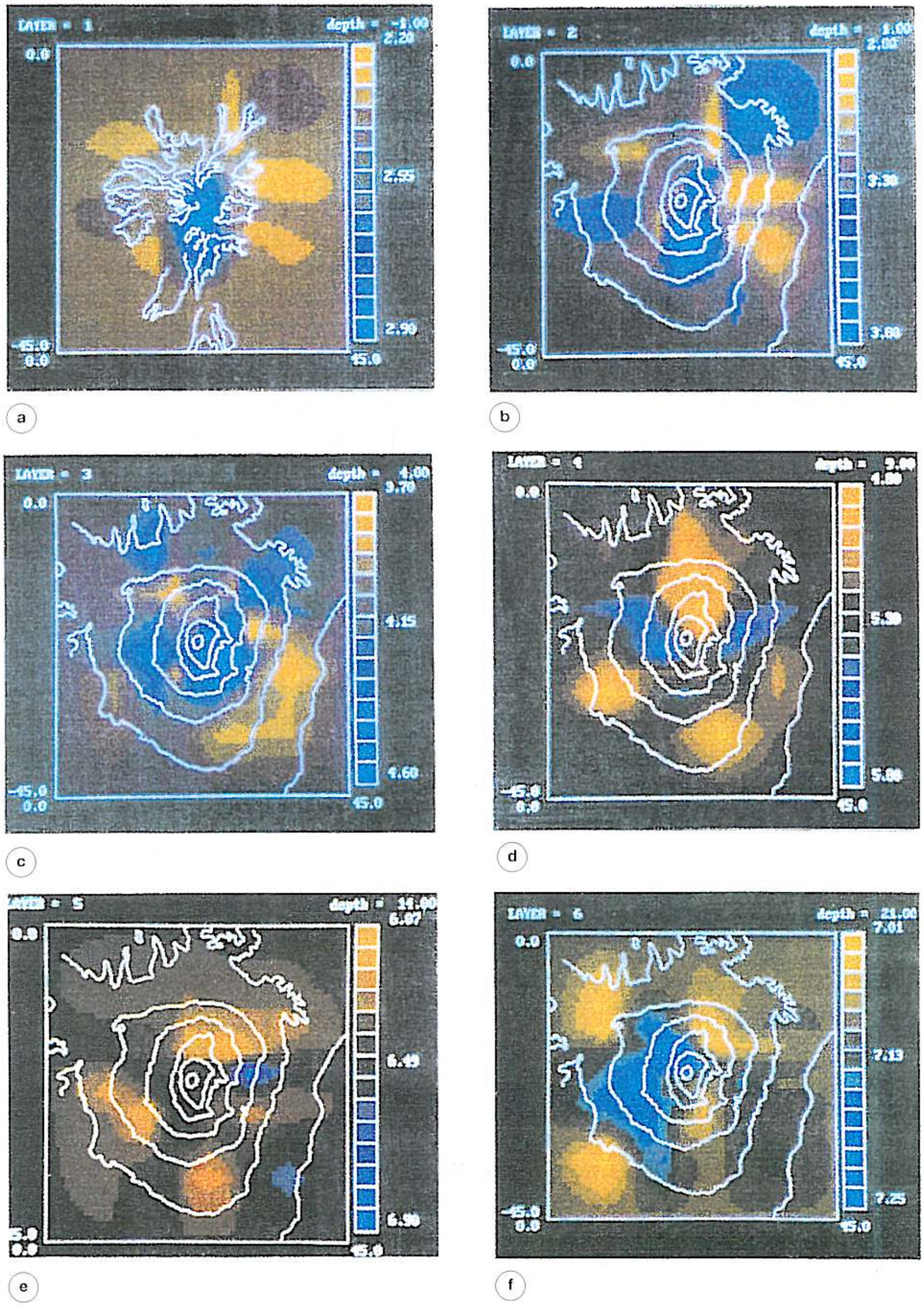

Fig. 7a-f. Sections showing the 3D velocity model beneath Etna determined by Cardaci *et al.* (1993). The depths of sections are – 1.0 km (a); 1.0 km (b); 4.0 km (c); 9.0 km (d); 14.0 km (e) and 21.0 km (f), respectively. Negative depths are above sea level.

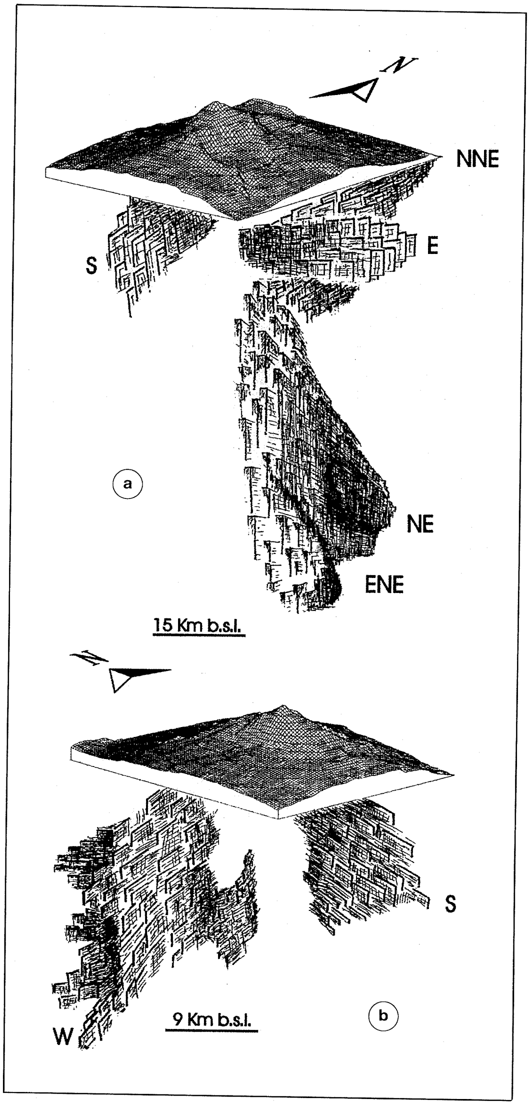

Fig. 8a,b. 3D sketch of high-velocity bodies under Mt. Etna volcano, as seen from SE (a) and SW (b) sectors, respectively.

trend, inside a shallow layer about 4-5 km thick. In the north-eastern sector analogous migrations probably happened along the NNE-SSW and E-W trends for the shallower levels, while for the deeper ones they involved the ENE-WSW and NE-SW trends. In the central western sector cooled magmatic bodies are placed prevalently along the E-W trend; moreover, some «apophyses» stretched torward N and S are located at various depths. All the described bodies seem to have a remarkable lateral continuity and common roots connected with the central eruptive pipe.

The low-velocity zones, with nearly NNW-SSE and ENE-WSW directions, are generally in agreement with the orientation of nodal planes computed for the analysed events; we assume that these velocity anomalies are related with an intricate network of fractures mostly filled with magma.

Finally, the discrepancy between computed epicentres of shallower events and the centres of the corresponding inner isochronal curves suggests that the 1D velocity model generally adopted for the location of etnean seismic events (Hirn *et al.*, 1991) overestimates the velocity of the first layers; on the contrary, for deeper earthquakes the centre of the inner isochronal curve can give a reliable estimation of epicentral coordinates.

Acknowledgements

This research was carried out by means of grants MURST 40% and 60%.

REFERENCES

CARDACI, C., M. COVIELLO, G. LOMBARDO, G. PATANÈ and R. SCARPA (1993): Seismic tomography of Etna volcano, *J. Volcanol. Geotherm. Res.*, **56**, 357-368.

CENTAMORE, C., G. PATANÈ and T. TUVÈ (1997): Maximum entropy estimation of *b* values at Mt. Etna: comparison with conventional least squares and maximum likelihood results and correlation with volcanic activity, *Ann. Geofis.* (in press).

COSENTINO, M., G. LOMBARDO, G. PATANÈ, R. SCHICK and A.D.L. SHARP (1982): Seismological researches on Mt. Etna: state of art and recent trends, *Mem. Soc. Geol. It.*, **23**, 159-202.

CRISTOFOLINI, R., F. LENTINI, G. PATANÈ and R. RASÀ (1979): Integrazione di dati geologici, geofisici e petrologici per la stesura di un profilo crostale in corrispondenza dell'Etna, *Boll. Soc. Geol. It.*, **98**, 239-247.

CRISTOFOLINI, R., S. GRESTA, S. IMPOSA and G. PATANÈ (1988): Feeding mechanism of eruptive activity at Mt.

Etna based on seismological and petrological data, in *Modelling of Volcanic Processes*, edited by C.Y. KING and R. SCARPA, *Earth Evol. Sci.*, 73-93.

HIRN, A., A. NERCESSIAN, M. SAPIN, F. FERRUCCI and G. WITTLINGER (1991): Seismic heterogeneity of Mt. Etna: structure and activity, *Geophys. J. Int.*, **105**, 139-153.

LA DELFA, S., G. PATANÈ and C. CENTAMORE (1997): The geodynamics of Mt. Etna volcano during and after the 1984 eruption, *Ann. Geofis.* (in press).

LEE, W.H.K. and J.C. LAHR (1975): Hypo71: a computer programme for determining hypocenter, magnitude, and first motion pattern of local earthquakes, *US Geological Survey Open-file Report*, 75-311.

MONTALTO, A., S. VINCIGUERRA, S. MENZA and G. PATANÈ (1996): Recent seismicity of Mount Etna: implications for flank instability, in *Volcano Instability on the Earth and Other Planets*, edited by W.J. MCGUIRE, A.P. JONES and J. NEUBERG, *Geol. Soc., Spec. Publ.*, **110**, 169-177.

PATANÈ, G., A. MONTALTO, S. IMPOSA and S. MENZA (1994): The role of regional tectonics, magma pressure and gravitational spreading in earthquakes of the eastern sector of Mt. Etna volcano (Italy), *J. Volcanol. Geotherm. Res.*, **61**, 253-266.

PATANÈ, G., A. MONTALTO, S. VINCIGUERRA and J.C. TANGUY (1996): A model of the onset of the 1991-1993 eruption of Etna (Italy), *Phys. Earth Planet. Inter.*, **97**, 231-245.

SHARP, A.D.L., P.M. DAVIS and F. GRAY (1980): A low-velocity zone beneath Etna and magma storage, *Nature*, **287**, 587-591.

TANGUY, J.C., M. CONDOMINES and G. KIEFFER (1997): Evolution of the Mount Etna magma: constraints on the present feeding system and eruptive mechanism, *J. Volcanol. Geotherm. Res.*, **75**, 221-250.