Self-potential, geoelectric and magnetotelluric studies in Italian active volcanic areas

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Abstract

We present the results of self-potential, geoelectric and magnetotelluric studies in Italian active volcanic areas as essential contributions both to structural modeling and to hazard evaluation. On Mt. Etna and Mt. Somma-Vesuvius complexes structural modeling was emphasized due to a lack of global information involving the whole apparatuses, at least from the electrical point of view. Hazard investigation was, instead, investigated with high resolution techniques on the island of Vulcano, where intense unrest phenomena have long been recorded.

Key words *self potential – dipolar geoelectrics – magnetotellurics – volcanoes*

1. Introduction

Italy is characterized by the presence of many important volcanic districts, of which Mt. Etna in Sicily, Mt. Somma-Vesuvius close to Naples and the Vulcano island in the Aeolian arc are the ones of major concern, being considered the most active areas on account of their recent volcanic history and present manifestations.

The geophysical investigations in these areas, coordinated by the Italian Group of Volcanology (GNV), National Research Council (CNR), have by long addressed both structural modeling and hazard evaluation. The first objective aims at giving the most reliable geometrical and multi-parameter physical image of the volcanic plumbing systems. The second is approached by frequent monitoring of those geophysical parameters that more than others may undergo variations in time due to endogeneous dynamics.

We adopted for the first time and still make systematic use of the Self-Potential (SP), Dipolar Geoelectric (DG) and Magneto-Telluric (MT) geophysical methods to have a thorough picture of the electrical behaviour in volcanic areas from a few hundred metres to some kilometres of depth.

In the above quoted volcanic areas, we programmed at least two of the three mentioned methods for both mutual control and integrated interpretation of the data. Special care was taken to make a combined analysis of DG and MT investigations, which, wherever possible, were performed in station sites very close to each other. The comparison between DG and MT data is of paramount importance for two reasons. Firstly DG data allow us to solve uncertainties in the MT impedance estimates due to static shift (Jones, 1988). Secondly possible

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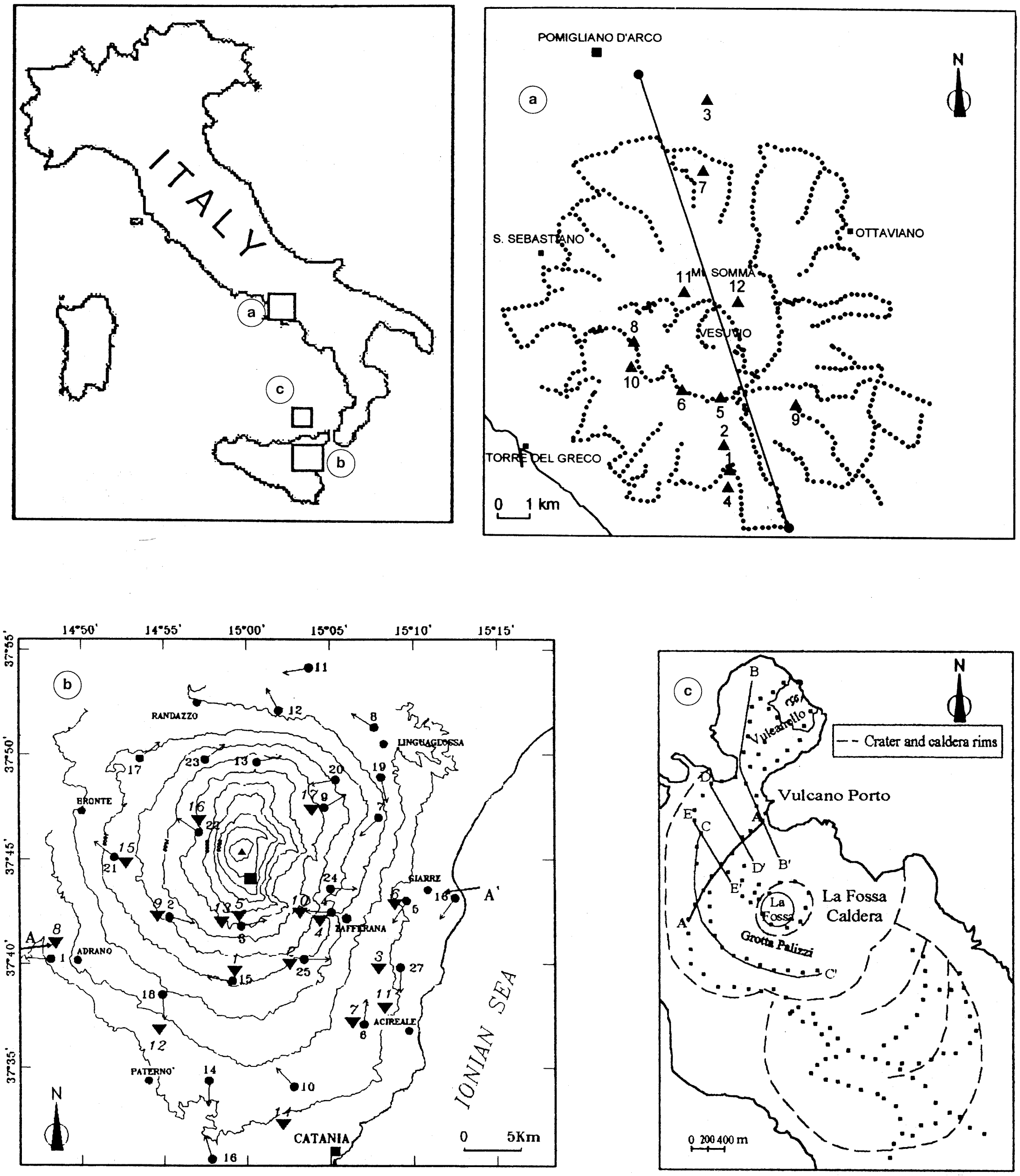


Fig. 1a-c. Location maps of the investigated areas. a) Mt. Somma-Vesuvius: dots, full line and triangles indicate the SP areal survey circuits, the DG tomography profile and the MT sounding sites, respectively; b) Mt. Etna: triangles and square indicate the MT sounding sites and the combined DG-MT sounding station, respectively, dots with arrows indicate DG sounding sites; c) Vulcano island: dots and full lines indicate the SP areal survey circuits and the DG tomography profiles, respectively.

discrepancies between DG and MT data in the common depth of exploration (the final and the initial parts in the DG and MT diagrams, respectively) can be explained as a resistivity frequency dispersion effect (Patella, 1987) and hence provide information on the degree of fracturation and mineral particle deposition, due to hydrothermal activity (Patella *et al.*, 1991).

Figure 1a-c shows the location map of the survey areas. In the following sections, we set forth an integrated examination of all the most important results obtained so far. Details of data acquisition and processing can be found in previous papers (Di Maio and Patella, 1994b; Di Maio *et al.*, 1994; Di Maio *et al.*, 1996a-d).

2. Application to structural studies

The main goal of the structural studies of a volcanic complex is to detect the plumbing and feeding systems and to analyse their physical and geometrical features. This is a generally complex problem due to surface inhomogeneities, rough topography and scant accessibility that characterize a volcanic landscape. The solution requires a detailed recognition of the shallower portion of the volcanic body, such as can be obtained by SP and DG methods. A wide-band (0.001-250 Hz) MT surveying, on the other hand, well constrained by the SP and DG methods, may retrieve information from the deeper region, thus, on the primary feeding system.

2.1. *Mt. Somma-Vesuvius*

The Mt. Somma-Vesuvius volcanic complex is located inside one of the most densely populated areas in the world. The last event, which occurred in 1944, was classified as a final eruption, the main characteristic of which is many subsequent years of repose (Scandone *et al.*, 1993). Both these circumstances now make the Vesuvian area one with the highest volcanic risk in the world.

As indicated in fig. 1a, we performed in this area an SP areal survey, a deep DG pseudosection and twelve wide-band MT soundings.

2.1.1. Self-potential

Figure 2 shows the results of the SP areal survey which refers to the circuitry network reported in fig. 1a. The SP data were collected as potential drops across a passive dipole 100 m in length, continuously displaced along the interconnected circuits. The map in fig. 2 was obtained after first attributing an SP arbitrary zero value to a reference point in the area, then subtracting in each point of the net the average value of the whole set of SP data. This survey follows a previous one, in which the N-S and E-W components of the natural steady electric field were measured in a set of discrete points, roughly covering the entire Vesuvian area, with dipoles only 10 m in length (Di Maio *et al.*, 1996a). As the previous survey did not sufficiently clarify the low wavenumber content of the SP field, we decided to repeat the survey with the technique outlined above.

Observing the map in fig. 2, a long wavelength N-S oriented double polarization SP field is now particularly evident. Its most interesting signatures over the whole area are, to the north, the sharp transition from negative to positive SP values, partly in close correspondence with the Mt. Somma caldera northern boundary, and to the south, a similar, but less intense and with opposite direction, SP steep gradient, coinciding with the Mt. Somma caldera southern boundary.

Another important feature is the lack of complete circular symmetry in the SP isoline crowding effect in the central western and eastern parts of the map, which would have better delineated the whole Mt. Somma caldera rim. On the contrary, an E-W elongated strip of higher positive SP values, crossing the whole central volcanic area, better represents the large scale behaviour of the SP field. Referring to the inward opposite polarization double plane source model (Fitterman, 1983) as to a reasonable physical scheme of the disclosed SP anomaly pattern, we suggest that a confined

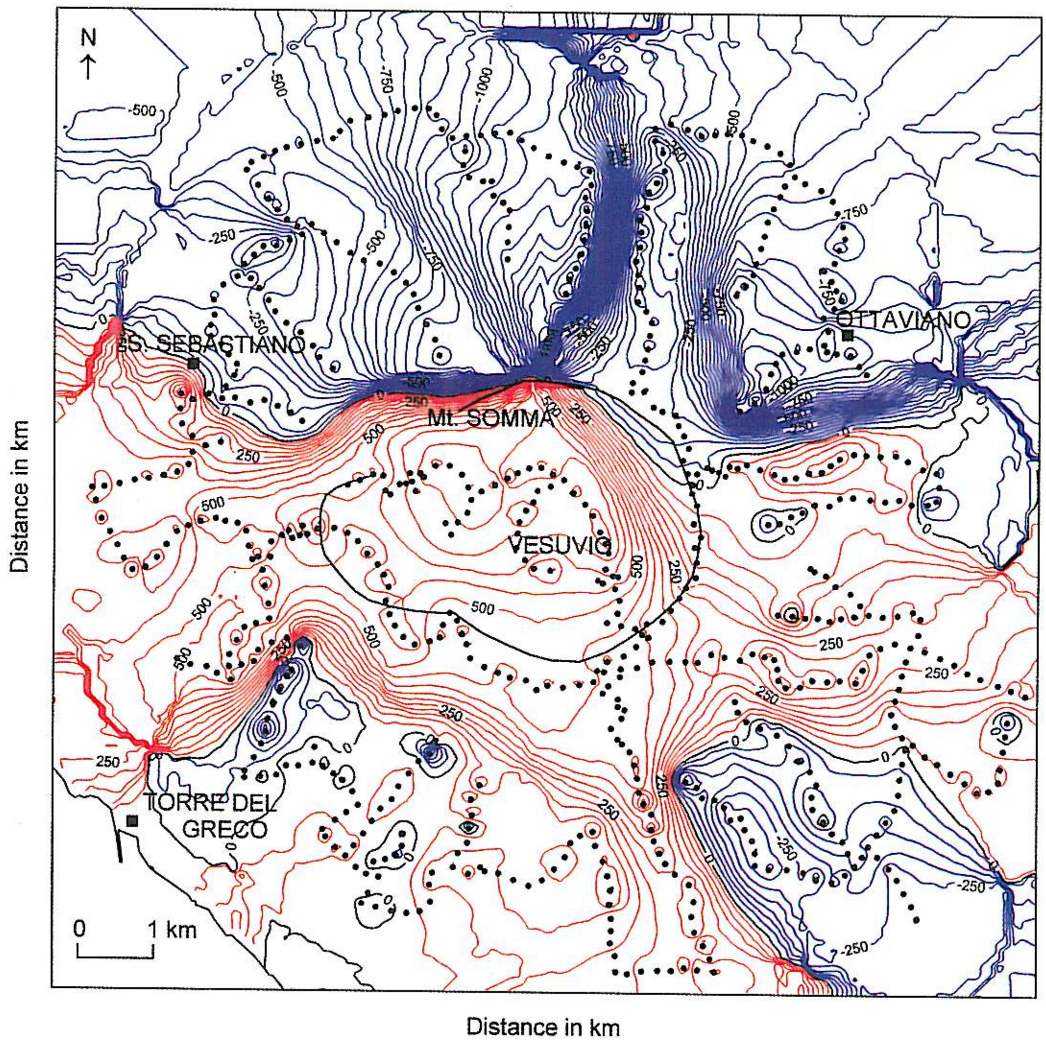


Fig. 2. SP anomaly map in the Mt. Somma-Vesuvius area relative to the survey circuitry of fig. 1a. Contour interval is 50 mV. The heavy circular line delineates the Mt. Somma caldera rim.

«graben-like» structural feature, with a likely deeply-rooted bounding fracture system and nearly E-W strike, dominates the whole central sector of Vesuvius. Local, strongly polarized patches, mostly marking here and there the Mt. Somma caldera rim, outline electrical effects originated by much more intense thermal and/or kinetic primary fluid flows (Sill, 1983).

Further SP evidence deserving some comment is the SP high roughly enclosing the whole Vesuvius cone. Both the SP amplitude and the horizontal gradient of this anomaly are markedly less than those of the companion plume-shaped negative anomaly, stretching northward from the northern caldera rim toward the foothills of Mt. Somma. In conjunction with Fitterman's double plane source model referred to above, such further evidence would be indicative of a marked lower resistivity of the volcanic materials just below the SP high (Fitterman, 1983), *i.e.* within the Vesuvius main plumbing system.

Finally, by a closer inspection of the general trend of the isolines, we also note the existence of a nearly N-S alignment, which is emphasized by the negative isolines N-S elongated narrow weakening between the two strong SP lows to the north, the W-E directed steep gradient of the positive isolines in the central region and the same gradient from positive to negative isolines to the south. Again, such a feature could be indicative of a polarized, length-limited N-S fracture system, wherein fluid circulation could be enhanced.

2.1.2. Geoelectrics

Figure 3 shows the DG pseudosection along the N-S profile indicated in fig. 1a. The DG data were obtained with dipoles 500 m in length and the dipole apparent resistivity data were as usual attributed to the mid-point of the distance between the emitting and the receiving dipole, at a pseudo-depth equal to half the spacing between the centres of the two dipoles. Continuous displacement of the dipoles along the selected profile about 13 km in length provided a very dense network of experimental apparent resistivity values in the vertical pseudosection.

Looking at the picture in fig. 3, a lateral sequence of alternated conductive-resistive bodies is clearly evident across the pseudosection. Following the interpretation given in Di Maio *et al.* (1996d), the northern and southernmost conductive bodies may be associated with sea-water invaded volcano-clastic sediments. In this model, the northern dike system-like very resistive body, located beneath the Mt. Somma caldera rim, would behave as a huge impermeable hydrological barrier. The next internal conductive body corresponds to the Vesuvius cone zone, where the volcanics there are probably filled with fluids and a large amount of hydrothermally altered products. Finally, the southern resistive block may be associated with the faulted carbonatic basement. In this area, there is close correspondence in depth to the top of the calcareous substratum (about

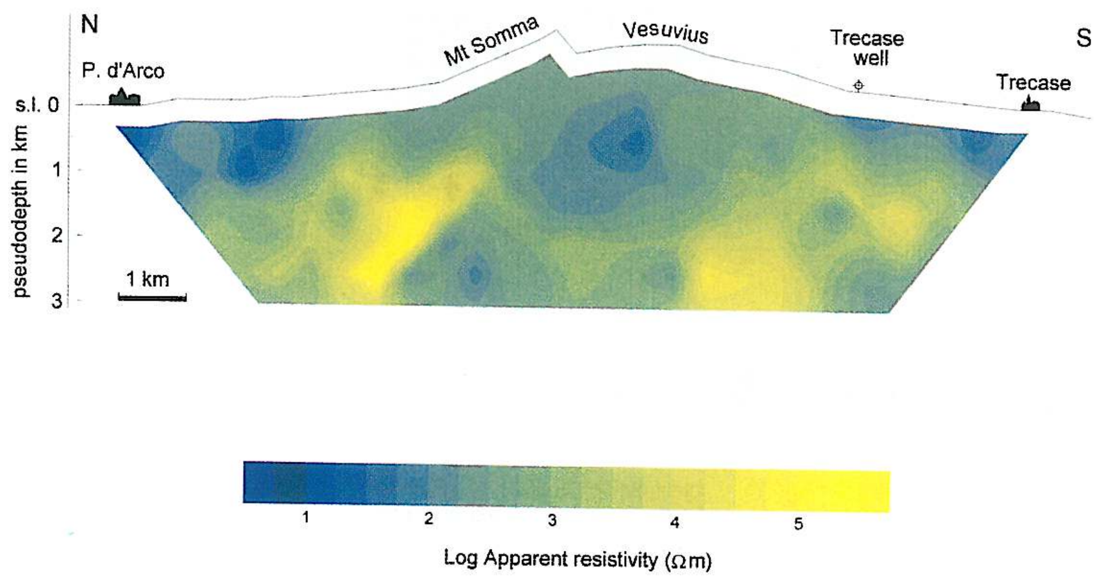


Fig. 3. DG tomography in the Mt. Somma-Vesuvius area relative to the N-S profile of fig. 1a.

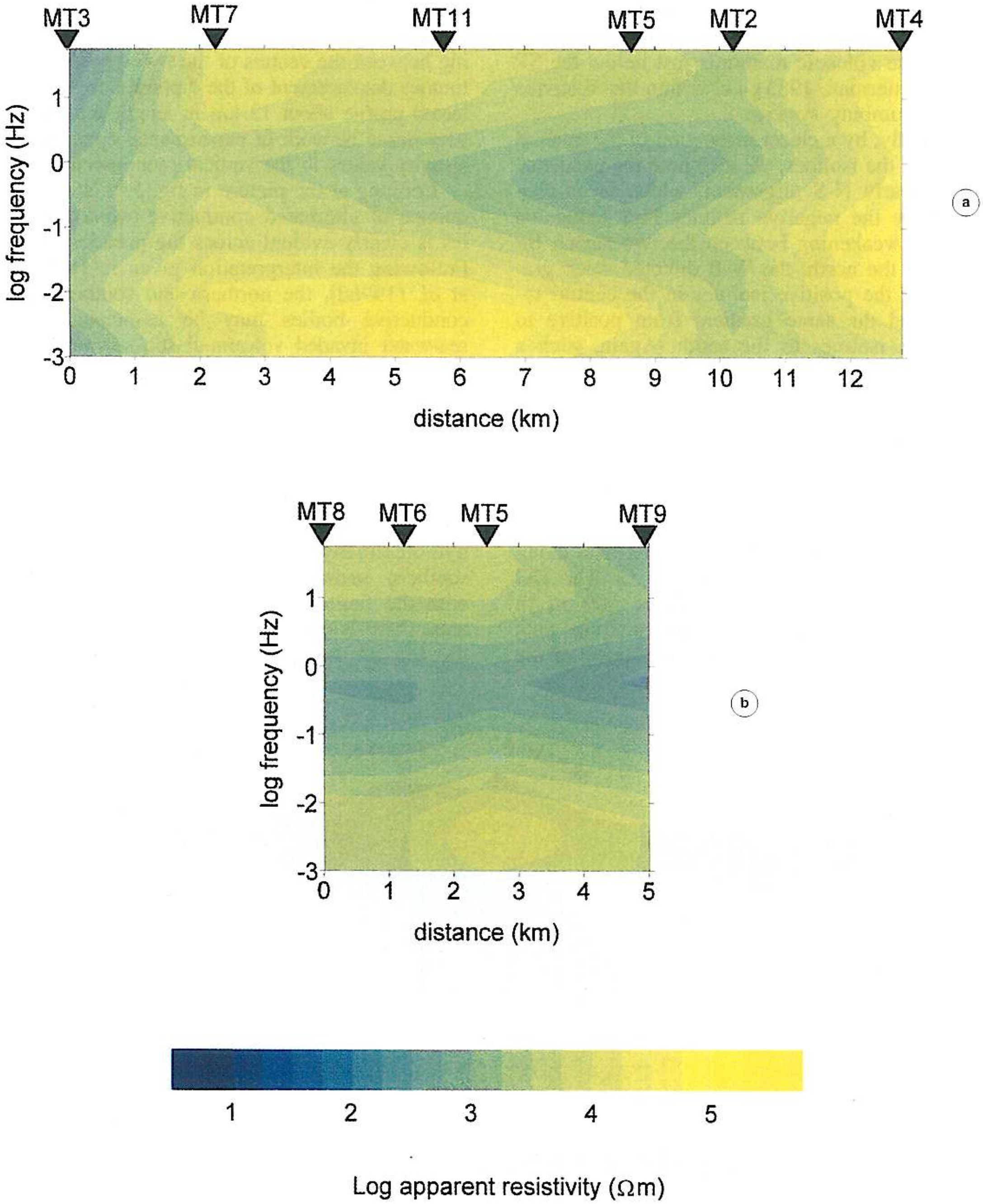


Fig. 4a,b. MT determinant apparent resistivity pseudosections along a nearly N-S (a) and W-E (b) profile in the Mt. Somma-Vesuvius area relative to the soundings of fig. 1a.

1300 m b.g.l.) with the Trecase deep well drilled by AGIP (Bernasconi *et al.*, 1981).

The DG pseudosection in fig. 3 is in good accord with the previously analysed SP map and also, to a large extent, with the preliminary interpretation by Zollo *et al.* (1996) of a recent 2D seismic tomography experiment.

2.1.3. Magnetotellurics

Almost all MT soundings were located on volcanic rock outcrops. We noted a notable difference in the behaviour of the apparent resistivity diagrams between the soundings close to the central Vesuvius conduit and all the others. This occurrence is well evident in fig. 4a,b, where we show two pseudosections of the rotationally invariant determinant apparent resistivity (Ranganayaki, 1984), relative to two profiles, respectively along a roughly N-S (fig. 4a) and W-E direction (fig. 4b).

The first profile, nearly coincident with the DG transect, exhibits in the high frequency interval (greater than a few Hz) a general correspondence with the DG pseudosection of fig. 3, namely the common evidence of a conductive-resistive lateral transition in the distance range from sounding MT11 to sounding MT4.

The most relevant deep information contained in the MT data seems to be the rather regular conductive central zone, the top level of which, evaluated from a preliminary 1D inversion, may be located at a depth of 6-7 km in correspondence with the Vesuvius edifice (MT5). In the depth range 4-10 km, by analysis of fluid injections in ejected nodules and other geochemical evidence, Belkin and De Vivo (1993) postulated a pressure of $1 \div 2.5$ kbar and a temperature in the range 1000-1200°C crystallization trapping zone of a silicate melt. It is known that at such pressure and temperature conditions quartz inclusive melts are characterized by resistivities not greater than 100 Ωm (Parkhomenko, 1967), and hence it seems reasonable to admit that the whole rock-melt system may have resistivities of the order of a very few hundred Ωm, as now deduced from our MT interpretation.

2.2. *Mt. Etna*

Mt. Etna is located in Eastern Sicily between two main structural units: the Iblean foreland to the south and the northern chain to the north. This singular position makes information on its structural setting an important topic to understand the geodynamics of that region. Figure 1b shows the details of our investigation program, consisting of a network of MT sounding stations closely corresponding to the station sites of dipole geoelectrical soundings, previously performed by Loddo *et al.* (1989). This site coincidence was imperative, for it only could help virtually eliminate electromagnetic noise from MT data.

Indeed, by least squares methods one can usually obtain a set of four different stable estimates of the tensor impedance elements (Sims *et al.*, 1971), which are in principle all coincident in absence of noise. However, in the presence of random noise in the magnetic field, it is known that biased down impedance elements are obtained from those estimates containing autopowers of the magnetic field, and, in case of random noise in the electric field, upward biased impedance elements are obtained from those estimates containing autopowers of the electric field. In the Mt. Etna survey, we acquired MT data in four frequency bands, partially overlapping each other (band 1: $0.0005 \div 0.25$ Hz; band 2: $0.01 \div 2.5$ Hz; band 3: $0.2 \div 50$ Hz; band 4: $1 \div 250$ Hz) and deduced that in the two higher frequency bands the data could have been affected by electric noise only, whereas in the two lower frequency bands only the magnetic noise would have been predominant. The first conclusion was strongly supported by the nearby DG data, which constrain the MT apparent resistivity behaviour in the high frequency part of the spectrum. The second conclusion, instead, was maintained by the almost continuous alignment over the entire frequency interval of those impedance estimates containing only cross-powers of electric and magnetic fields.

To outline the general agreement between DG and MT soundings, we give in fig. 5a a pseudosection of synthetic MT data along the profile AA′ of fig. 1b, as deduced from the DG

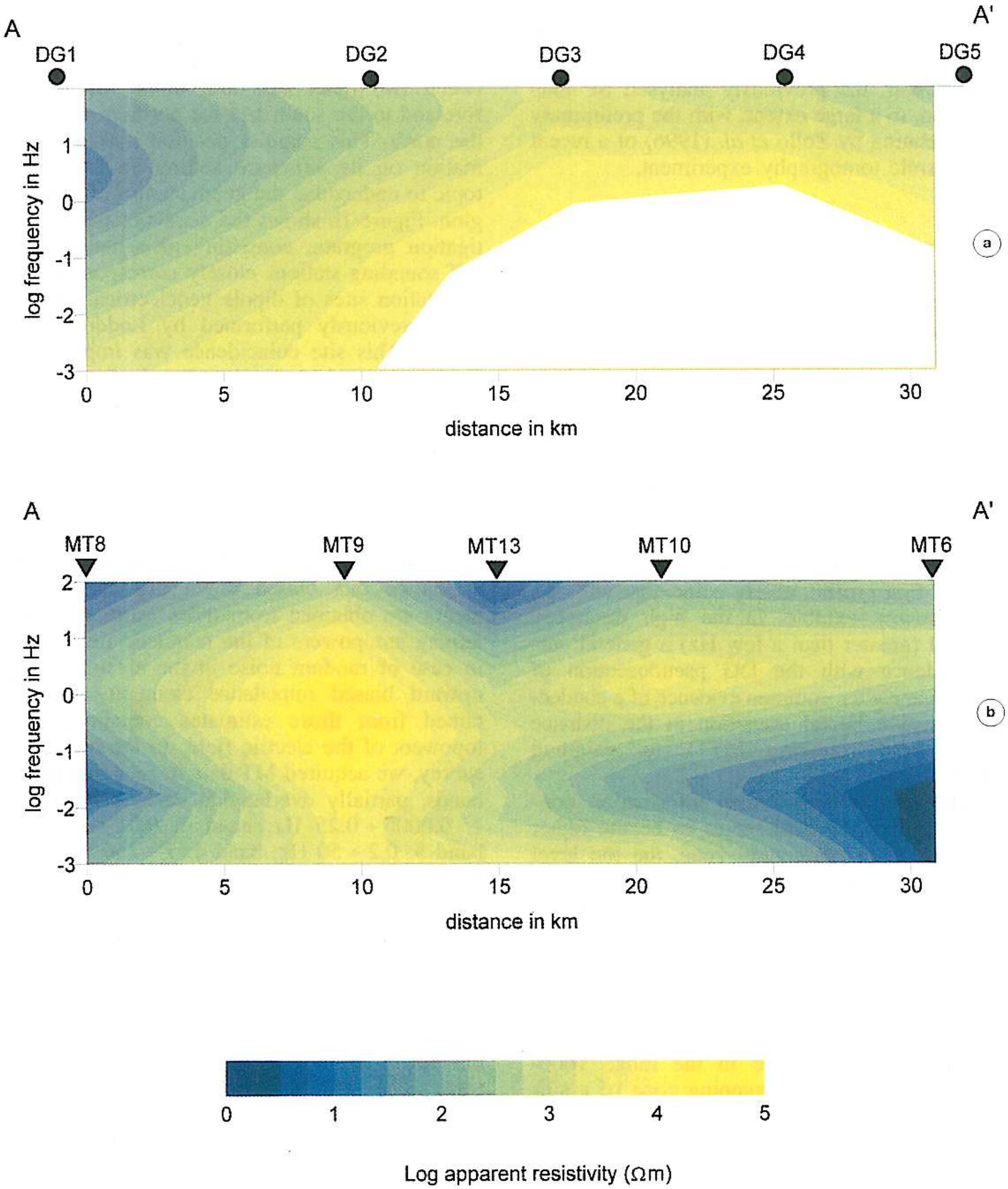


Fig. 5a,b. Mt. Etna experiments: a) synthetic MT pseudosection constructed on the basis of previous DG soundings along the profile AA′ of fig. 1b; b) real MT determinant apparent resistivity pseudosection along the same profile AA′.

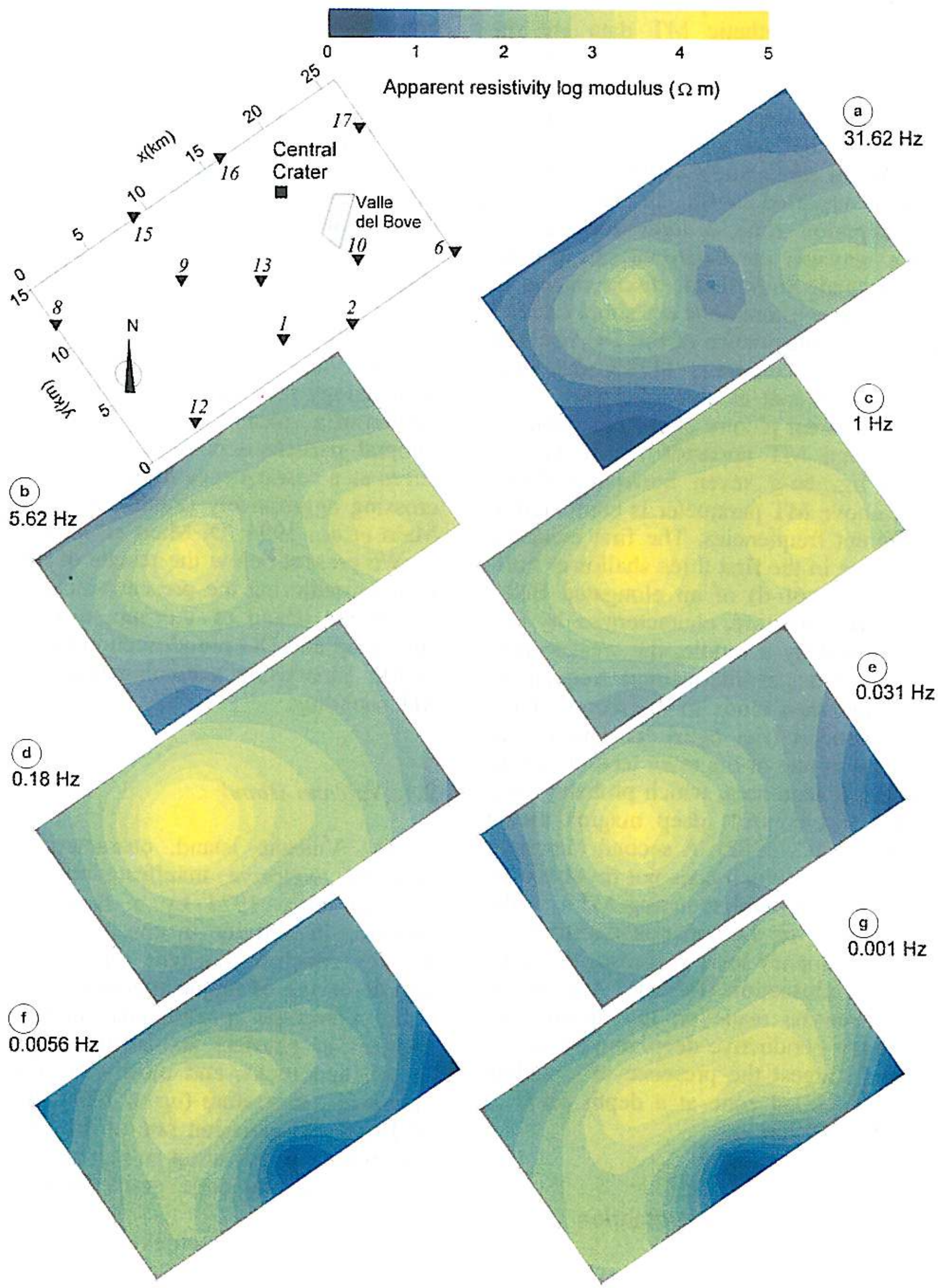


Fig. 6a-g. MT determinant apparent resistivity horizontal slices at seven different frequencies in the Mt. Etna area: a) 31.62 Hz; b) 5.62 Hz; c) 1 Hz; d) 0.18 Hz; e) 0.031 Hz; f) 0.0056 Hz; g) 0.001 Hz.

soundings along the same profile. Below each DG station, the synthetic MT data are restricted to the lowest frequency limit compatible with the maximum information depth of the DG signal. This pseudosection is to be compared with the true MT pseudosection of the determinant apparent resistivity along the same profile reported in fig. 5b. In the common investigation zone, a large scale correspondence between the two data sets can be easily envisaged. Some local discrepancies in the mid and the western zone are simply due to the not perfect coincidence of the DG and MT station sites (the compared MT13 and DG3 stations are as distant as about 1.5 km).

To give an areal picture of the behaviour of the determinant MT apparent resistivity, we present in fig. 6a-g seven horizontal slices, where the above MT parameter is contoured at seven different frequencies. The first evidence is the presence in the first three shallower horizontal cuts (fig. 6b-d) of an elongated ENE-WSW resistive structure, characterized by two nuclei separated by a saddle, the westernmost one of which fades at intermediate frequencies (fig. 6e,f) and then tends to re-emerge at the lowest frequencies (fig. 6g,h). This trend can be associated to one of the main tectonic alignments in the Etnean area, which probably controlled and still controls deep magma ascent (Lo Giudice *et al.*, 1982). A second important piece of evidence, which does not involve only a restricted area around sounding MT9, is the general tendency of the apparent resistivity to decrease as frequency lowers, starting from the 0.031 Hz pseudosection (fig. 6f). Among the hypotheses can be made on the meaning of such emerging conductive deep zone, it seems plausible to suggest the presence of a widely extended fluid-filled zone at a depth equal to or larger than 10 km.

3. Application to hazard evaluation

The transition from quiescence to activity generally involves migration of high temperature and high pressure volcanic fluids from a deep reservoir towards the Earth's surface. The thrust exerted by the pressurized fluids on the overlying rocks may induce formation and propagation of cracks or fractures, which may then facilitate magma ascent. Invasion of groundwaters or sea water in the new cracks and fractures and their interaction with volcanic fluids are expected to generate local time variations of electrical parameters, which can easily be detected at the ground surface, as is the case of SP anomalies (Di Maio and Patella, 1994a; Di Maio *et al.*, 1996a) and resistivity changes (Di Maio and Patella, 1994b; Di Maio *et al.*, 1996b).

In addition, as already mentioned in the introduction, the resistivity dispersion phenomenology may be observed in the plumbing system of a volcanic edifice, essentially due to mineral particle deposition across rock interstices as a consequence of hot magmatic fluids crossing aggressively (Patella *et al.*, 1991; Di Maio *et al.*, 1994; Di Maio *et al.*, 1996c).

We present below the results of our experiments monitoring the present volcanic dynamics on the island of Vulcano, using SP areal surveying and DG pseudosection profiling, and at Mt. Etna using a combination of DG and MT sounding.

3.1. *Vulcano island*

The Vulcano island, characterized in the past by explosive manifestations, has been affected since 1977 by a slow progressive increase in activity in the Fossa zone (see fig. 1c), which has become particularly relevant and deserving of major attention from 1987 to date. Observed phenomena include many changes in physical and chemical parameters in soil and rocks, and mostly the notable increase in temperature (up to 700°C by the end of 1993) and emission rate of the Fossa crater fumaroles, all indicating an increase in the flux of hot deep magmatic gases (Barberi *et al.*, 1991).

On the basis of such evidences, in 1991 we planned a geoelectric study consisting of repeated SP areal surveys extended over the whole island (dots in fig. 1c) and DG tomographies along profiles located in the northern sector of the island (full lines in fig. 1c).

3.1.1. Self-potential

The seven SP areal surveys performed to date are displayed in fig. 7a-g. The time variations of the SP anomalies, ascribable to variable conditions of underground fluid flows, are clearly evident.

By comparing all the maps in fig. 7a-g, a large-scale, long period variation of a roughly NW-SE oriented SP quasi-regional field can be observed. It which can be associated to a long-term variable electrokinetic flow along the whole southern rim of the Fossa caldera, which is very well delineated by the sometimes intensive crowding of the SP isolines, due to a local steep SP horizontal gradient. Likely flow direction reversals can also be foreseen, as the clear SP field polarity inversions in the map in fig. 7f and to a lesser extent in the map of fig. 7d seem to indicate.

Comparing this anomalous SP isoline crowding effect with the similar one experienced in the Mt. Sommà-Vesuvius area, we can safely conclude that locally pervious, more or less extended patches of a caldera boundary in a volcanic active area are the zones where the most intense, even long-lasting SP effects are observed. In the specific case of the island of Vulcano, at the southern Fossa caldera rim, a huge mass of intrusive bodies is hypothesized to stand at a depth of $1 \div 1.5$ km of depth b.s.l., across the normal fault system representing the embryonic stage of the Fossa depression (Gioncada and Sbrana, 1991). However, the time variable crowding effect, which may even be lacking, as can be seen mainly in the maps in fig. 7b,d, does further support, the already estimated limited geothermal potential in this zone of the island (Gioncada and Sbrana, 1991).

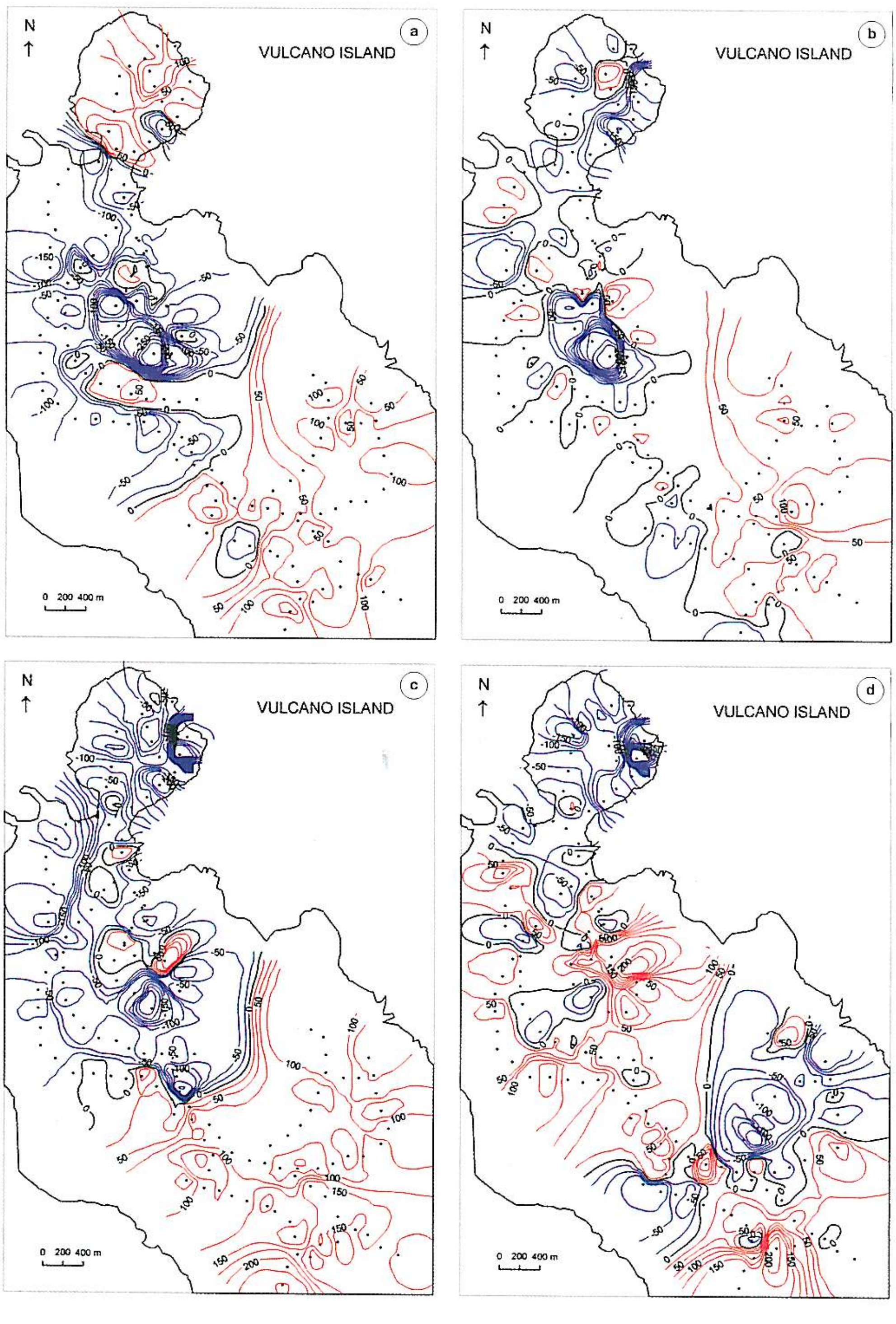
Superimposed on the above quasi-regional field, a lot of local SP anomalies are also present, the largest and most intense of which are located in the Fossa caldera zone, especially around the Fossa cone rim, and on the eastern side of the Vulcanello headland. Time migrations and space dislocations of the local fields inside the Fossa caldera can be most likely ascribed to the present volcanic activity, whose most impressing surface evidence is the mentioned Fossa crater fumarole system, still easily visible on the northern high slopes of the Fossa cone. There are good reasons to maintain that such effects would be of thermoelectric nature, on account of the extremely high yield and temperature of the outpouring vapour-gas mixture.

A further noteworthy low wavenumber anomaly appears located close to the Grotta Palizzi area, amidst the southern foothills of the Fossa cone and Fossa caldera rim. It is very evident only in the maps in fig. 7a,g, where, again, the polarity reversal represents a distinctive feature.

3.1.2. Geoelectrics

As regards the DG investigation, we present only the results relative to profile AA′ of fig. 1c, for that is where we have always observed the most striking resistivity time variations. The results related to the other profiles indicated in fig. 1c can be found in Di Maio and Patella (1994b).

Figure 8a-o displays the thirteen tomographies performed to date. At a glance, one can readily observe, independently of month and year of observation, a general stable tendency of resistivity to increase with depth. It is locally disturbed by scattered resistive or conductive nuclei, always appearing about in the same positions, proceeding from the eastern (point A′) to the western (point A) edge of the profile. By closely inspecting the whole time sequence, alternate sequences of resistivity decrease and resistivity increase phases are evident, especially in the central sector of the profile, where unusual resistivity changes are recorded in some points even of five orders of magnitude, from values as low as 10 Ωm to values as high as 10^5 Ωm. It is difficult to assign a steady periodicity to this striking phenomenon, as we did not use a constant and shorter sampling time interval of the full profile. Approximately, with a rate of one complete tomography every two months the periodicity seems very close to $9 \div 14$ months between two consecutive resistivity lows.


N
a
VULCANO ISLAND
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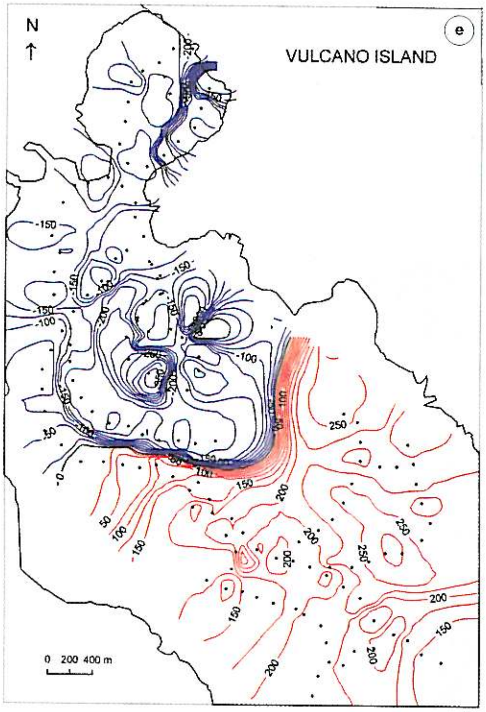
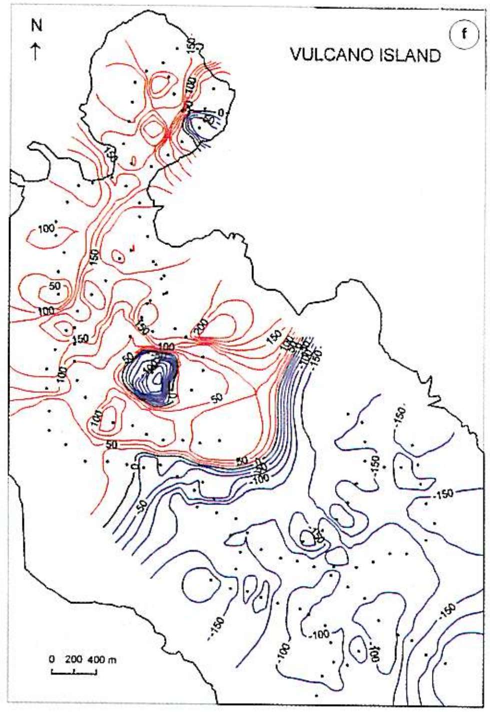




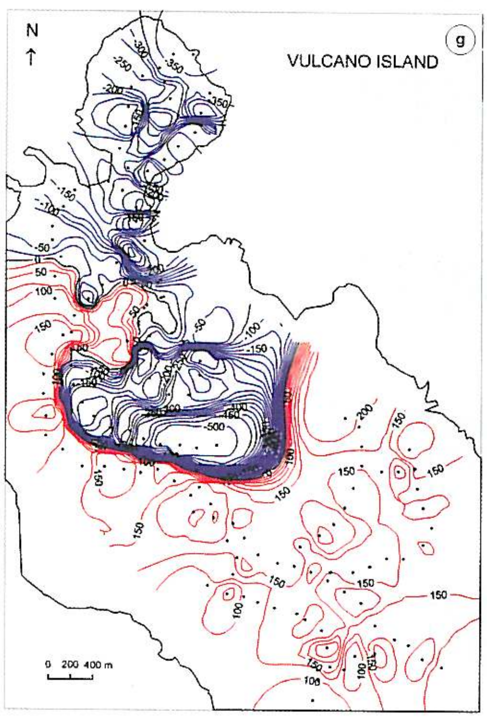
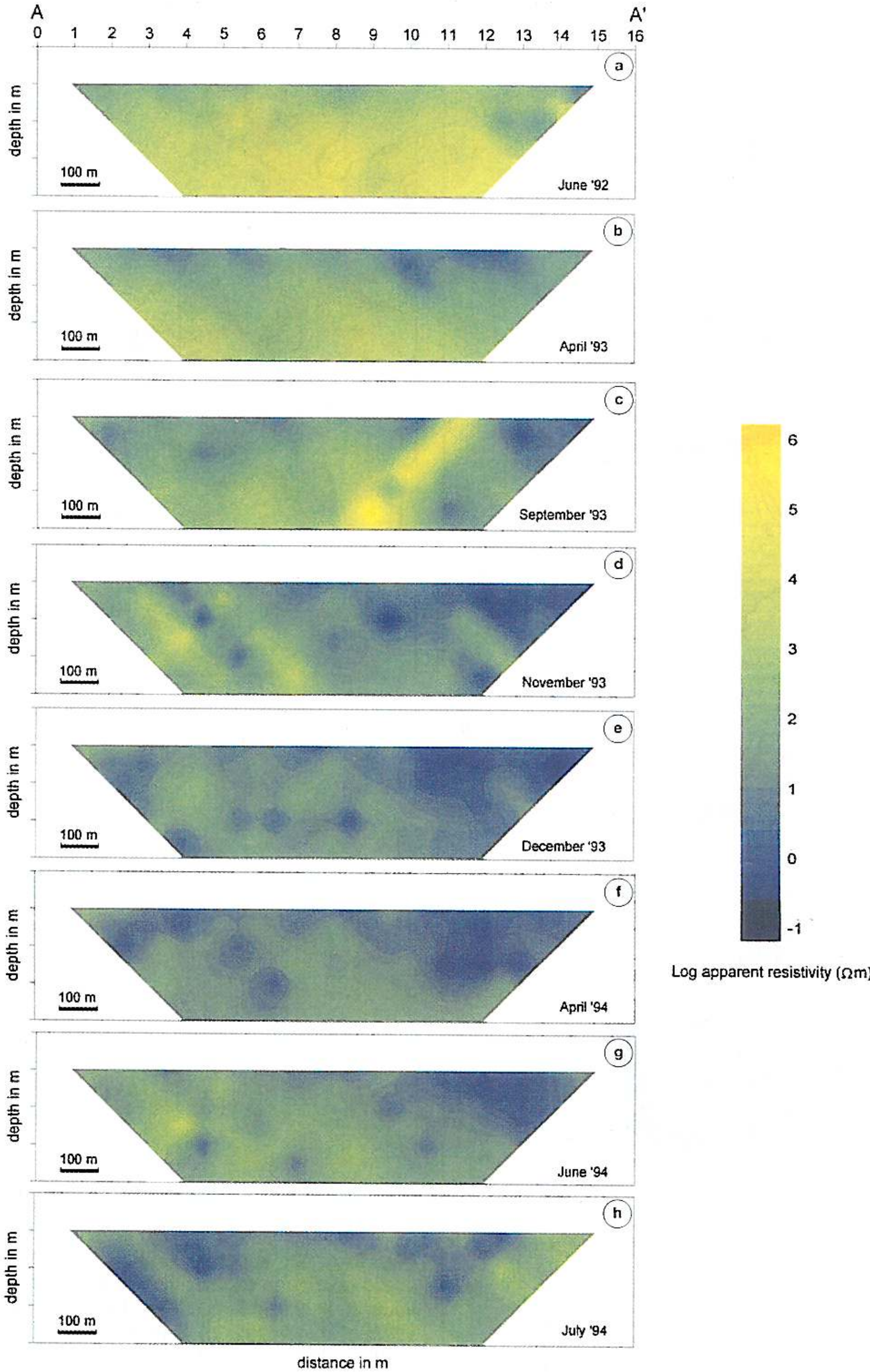


Fig. 7a-g. SP anomaly maps in the Vulcano island relative to the circuitry of fig. 1c. Contour interval is 25 mV. a) May 1991; b) January 1992; c) June 1992; d) September 1993; e) November 1993; f) April 1994; g) December 1994.


A
A'
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
a
depth in m
100 m
June '92
b
April '93
c
September '93
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e
December '93
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Log apparent resistivity (Ωm)

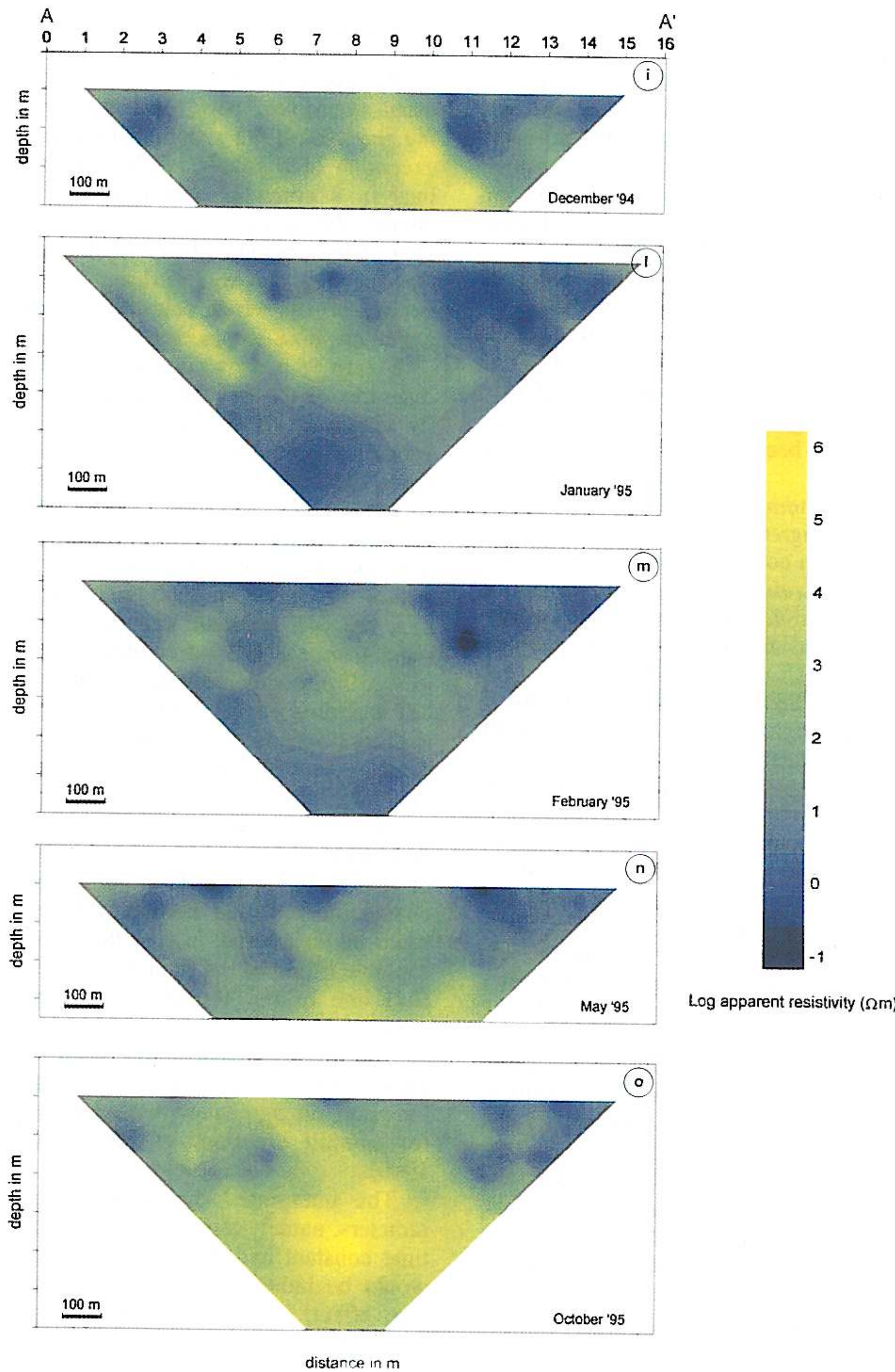

Fig. 8a-o. DG tomographies along the profile AA′ of fig. 1c.

The significant time and space variations of the SP and DG anomalies in the Fossa area seem to outline an almost periodic phase transformation process underground. Indeed, the observed resistivity changes suggest that a cyclic *heat source uprising/water-to-vapour transformation/sea water inland invasion* mechanism could occur in this zone of intense volcanic activity.

The first phase of the above cycle could be correlated with the gaseous magmatic fluid uprising, probably coming from the area below Vulcano Porto located to the north of the Fossa, where a weakness zone, probably responsible for a new alignment of the volcanic feeding system, has been noted (Frazzetta *et al.*, 1983).

These high temperature gaseous masses would tend to migrate towards the Earth's surface and, when in contact with the rock permeating sea water, would cause a water to vapour phase transformation, originating in such a way an uprising pressurized vapour-rich gaseous mixture.

At the end of this second phase, in terms of geoelectric tomography, a resistivity high (vapour-gas dominated system) would substitute a previous resistivity low (sea water dominated system).

A notable amount of the uprising vapour-gas mixture would feed the fumarolic system, as supported by the results of geochemical and geothermal studies (Capasso *et al.*, 1993; Carapezza and Diliberto, 1993; Italiano *et al.*, 1993). The remaining part should condense beneath the lateral coldest zones of the volcano. Both mechanisms would cause a pressure release below the Fossa crater and hence a recall of sea water in those pores and fractures, wherefrom it was previously removed by the gas uprising mechanism.

Looking at the DG tomographies of December 1993 (fig. 8e) and February 1995 (fig. 8m), presumably performed after periods of intense activity, one can observe low resistivity values exactly where high values were previously monitored, except for some small residual resistive nuclei very likely ascribable to temporary self-sealed confined sacks of gas-vapour mixture.

3.2. *Mt. Etna*

We discuss now the results of a very unusual experiment performed at Mt. Etna, during the 1989-1993 eruption, consisting of the execution of a couple of DG and MT soundings in a common data reference station at about 2600 m a.s.l., very close to the eruptive vent of the copious effusive manifestation (see fig. 1b). The aim was to detect resistivity dispersion effects which could be correlated with a shallow dike emplacement.

Figure 9a,b shows the processed sounding diagrams of the DG and MT apparent resistivity functions versus dipole spacing and wave period, respectively. The geoelectrical interpretation displays a layering sequence, reported in fig. 9a, which becomes compatible with the common station MT data, provided that we admit the existence of resistivity dispersion within the very thin shallow second layer. In fact, the MT synthetic sounding curve elaborated from the DG interpretation (dashed line in fig. 9b), compared with the field TM-mode MT sounding curve (squares in fig. 9b), shows a shears-opening effect in the short period band, typical of a very shallow frequency-domain induced charge polarization mechanism. By introducing in the second layer a frequency dependent resistivity, characterized by the set of Cole-Cole parameters (time constant τ, chargeability m and frequency factor c) indicated by an asterisk in fig. 9b, a complete acceptable fitting of the field MT data is obtained (full line in fig. 9b) with the same layered model.

The resistivity dispersion effect seems very likely ascribable to a plate-like magma dyke intrusion, in agreement with Murray's model for summit eruptions at Mt. Etna (Murray, 1990).

The interpreted dispersion Cole-Cole parameters, namely the very long relaxation main time constant and the very high chargeability, would be indicative of a very intense dispersion effect, caused by both the magma high temperature state and the large deposition of pore occluding mineral particles during magma intrusion (Mauriello *et al.*, 1996).

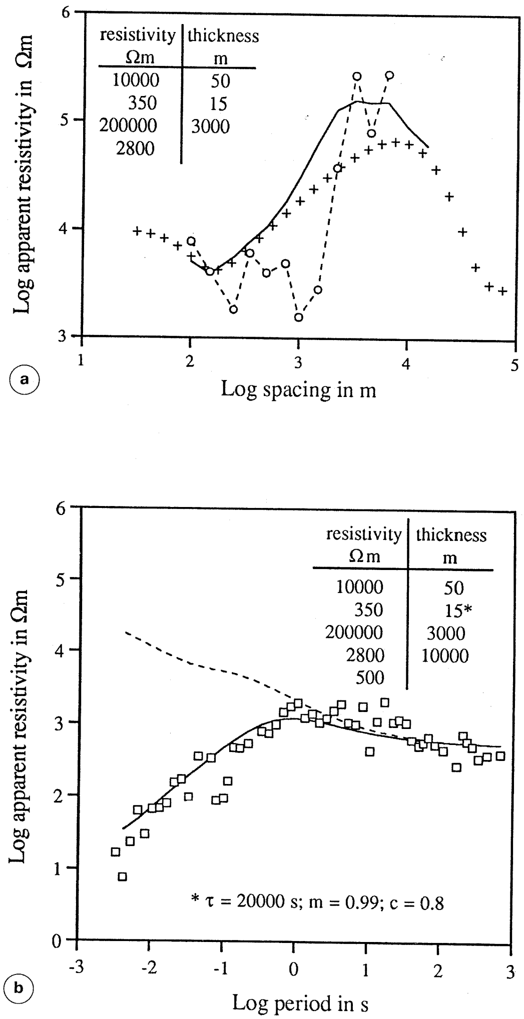

Fig. 9a,b. Combined DG-MT sounding experiment at Mt. Etna. a) DG apparent resistivity *versus* spacing diagrams and layering interpretation. The dot-dashed and continuous lines are the original field dipole diagram and the Schlumberger transformation diagram, respectively. The sequence of crosses is the Schlumberger fitting model curve. b) MT apparent resistivity *versus* period diagrams and layering interpretation. The dashed line is the synthetic diagram reconstructed from the DG interpretation reported in picture (a). The squares and the continuous line are the real MT field data and the fitting theoretical curve including resistivity dispersion in the second layer. Cole-Cole dispersion parameters are reported close to the asterisk.

Experimental evidence of resistivity frequency dispersion effects in volcanic areas are becoming more and more frequent, and this would shed new light on the possibility of using such effects to monitor volcanic activity and possibly forecast magma outpouring episodes. By repeated DG and MT sounding experiments in some reference stations, one might, in principle, observe onset, growth, evolution and upward migration of the dispersive phenomenon, and relate it to magma uprises towards the Earth's surface.

4. Conclusions

The above analysis has pointed out that, notwithstanding the many objective difficulties which characterize data acquisition in volcanic areas, the integrated use of quite different electromagnetic and electric geophysical methods may provide very useful information on the space distribution of the electric parameters and also permit a careful control of the time modification of the same and/or other parameters, connected with the typical volcanic structural settlement and dynamics. Furthermore, the combined analysis virtually eliminates typical interpretative ambiguities inherent in each single method.

Among the many results obtained so far, which have been detailed in the previous sections, we emphasize the prominent role of the magnetotelluric method in disclosing the deep, otherwise inaccessible electrical structures and of the self-potential and dipole geoelectrical methods in disentangling the rather complex surface manifestations.

In particular, in the Vesuvian and Etnean areas the MT soundings revealed the existence of deep conductive zones in the crust, which in volcanic regions assume major relevance for they are most probably correlated with the presence of extended fluid-filled horizons. On the other hand, the SP and DG surveys in the Vesuvian area and the island of Vulcano contoured the most important shallow electric variations, very likely related to hot fluid circulation, water-magma and rock-magma interactions.

A final noteworthy conclusion is addressed to the DG-MT combined interpretation for retrieving resistivity dispersion effects and related Cole-Cole parameters. The Etna experiment has once more highlighted the fact that the importance of this approach rests on the circumstance that resistivity dispersion is a clearly temperature-dependent and mineral deposition affected physical phenomenon, which can be observed even down to some hundreds of metres in depth. As monitoring the time evolution and upward space migration of this effect is only a matter of a nearly continuous field observation, we are of the opinion that resistivity dispersion will in the near future be included in the list of reliable volcanic activity precursory effects.

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