Joint analysis of electric and gravimetric data for volcano monitoring: Application to data acquired at Vulcano Island (southern Italy) from 1993 to 1996

Rosa Di Maio[1*], Giovanna Berrino[2]

[1] *Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse, Università di Napoli Federico II, Largo San Marcellino, 10, Napoli 80138, Italy, e-mail: rosa.dimaio@unina.it*

[2] *Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli "Osservatorio Vesuviano", Via Diocleziano, 328, Napoli 80124, Italy, e-mail: giovanna.berrino@ingv.it*

*** Corresponding author: Rosa Di Maio**

Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse
Università di Napoli Federico II
Largo San Marcellino, 10
80138 Napoli (Italy)
Tel: +39 081 2538377
E-mail: rosa.dimaio@unina.it

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Abstract

Understanding the dynamics of volcanic-hydrothermal systems is a key factor for discriminating between ~~volcanic unrest and eruptive~~ **magmatic and hydrothermal nature of the sources responsible for the unrest phenomena observed in active volcanic areas.** Numerous ~~experiences~~ **studies** of geophysical data monitoring in volcano-geothermal districts ~~have~~ **has indeed** proven that close relationships exist between the volcanic and hydrothermal fluid~~s~~ circulation and the anomalous geophysical signals observed at the ground surface. In this paper~~, in particular,~~ a simultaneous analysis that integrates resistivity and gravity data is suggested as a useful tool to infer a consistent conceptual model of hydrothermal volcanic systems and their evolution. An application of the proposed analysis to repeated resistivity and gravity measurements performed on ~~the~~ Vulcano Island (Aeolian Archipelago, Sicily, southern Italy) is presented with the aim ~~to~~ of gaining information on the dynamics of the volcanic-hydrothermal system. The examined period ranges from December 1993 to September 1996, when significant changes in chemical properties, temperatures and emission rates of La Fossa crater fumaroles were observed, all indicating an increase in the flux of hot deep magmatic gases. The results of our analysis, which refers to a profile located at the foot of the northwest flank of La Fossa cone, suggest that underground cyclic water-to-vapour transformations govern the shallow hydrothermal system dynamics, generally described by a negative correlation between the monitored resistivity and gravity data. The occurrence of positive correlations between the two analysed parameters~~, instead,~~ could be ascrib~~able~~**ed** to ~~the~~ volcanic dynamics, which would mask the **normal** hydrological and hydrothermal system behaviour.

Keywords: electrical resistivity **variations**; gravity changes; volcano monitoring; hydrothermal systems; Vulcano Island (Italy)

1. Introduction

Many geophysical studies performed in active hydrovolcanic areas have proven a close relationship between hydrothermal system dynamics and anomalous geophysical signals observed at the ground surface. In particular, cyclic variations of physical parameters, most likely correlated to shallow aqueous fluid migration, ~~have been~~ **are** detected during unrest periods ~~at~~ **in** volcano-geothermal areas (e.g., Todesco and Berrino, 2005; Todesco et al., 2003; Gottsmann et al., 2007; Hermans et al., 2014). Thus, ~~the~~ knowledge of the physical processes responsible ~~of~~ **for** the observed anomalous signals may be ~~a~~ key ~~factor~~ for understanding the hydrothermal system dynamics and, hence, for discriminating ~~between volcanic unrest and eruptive activity~~ **whether the observed anomalies have to be attributed to hydrothermal features or to volcanic unrest phenomena, i.e. behaviors that could prelude an eruption (Phillipson et al., 2013).** Although such a distinction represents the main goal of any monitoring system of active volcanic areas, forecasting eruptive events is a difficult task as volcanic edifices generally are very heterogeneous structures characterised by complex hydrothermal and eruptive dynamics. They are usually formed by **alternances** of lava flow units, volcanoclastic deposits, ash layers, hydrothermal alteration materials and significant fracture systems, which constitute the permeable zone **that allows** rain **and sea** water infiltration and hydrothermal fluid and/or magma **ascent**. In calderic collapse areas, as for some Italian volcanic complexes, the thermal fluid circulation is substantially guided by the border and/or intracalderic faults (e.g. Wohletz and Heiken, 1992; Pribnow et al., 2003; Revil et al., 2004) as well as by the permeability of the volcanic deposits, which, in particular, ~~lets a~~ **permit** diffuse degassing of the magmatic fluids (e.g. Allard et al., 1991; Chiodini et al., 2003).

A wide range of geophysical parameters ~~are~~ **is** currently used for monitoring ~~the~~ on-going volcanic activity, such as density, gravity, magnetic susceptibility, electrical resistivity and seismic velocity. Unfortunately these parameters, **when interpreted independently,** can**not always** provide **an unambiguous interpretation of the relationship between the hydrothermal activity and magmatic activity due to the non-uniqueness in the data inversion, which** generally leads to more than one model **being** consistent with the observed signals. ~~ambiguity in modeling the volcanic activity when interpreted independently, because of the intrinsic uncertainty in the data interpretation process that generally lead to more than one model consistent with the observed signals. Therefore,~~ In the last decades, many efforts ~~have been~~ **were** made to develop multi-methodological geophysical approaches, as well as integrated data interpretation schemes (e.g., Berrino, 1994; Sasai et al., 1997; Di Maio et al., 1998a, 1998b; Di Maio et al., 2000; Sasai et al., 2001; Todesco and Berrino, 2005; Zlotnicki et

al., 2003; Gottsmann et al., 2007; Zlotnicki et al., 2009; Rinaldi et al., 2011). In this paper, ~~in particular,~~ a study that integrates electric and gravity data is proposed as a ~~useful~~ tool **for the monitoring of** volcanic activity ~~monitoring~~. The main aim is to jointly interpret resistivity and gravity time variations in terms of changes (or evolution) of the hydrovolcanic system dynamics. The proposed approach is tested on a series of repeated electrical resistivity tomographies and gravimetric surveys performed on the island of Vulcano (Sicily, southern Italy). It ~~represents~~ **is** one of the most ~~prominent~~ active volcanic districts ~~of~~ **in** the Italian territory **undergoing a significant hydrothermal and fumarolic activity,** ~~due to the progressive increase in activity~~, which has become particularly relevant ~~from~~ **since** 1987 (Barberi et al., 1991). ~~For our study the examined~~ The **study** period ranges from December 1993 to September 1996, when significant changes in chemical properties, temperatures and emission rates of La Fossa crater fumaroles were observed, all indicating an increase in the flux of hot deep magmatic gases (Diliberto et al., 2002 and references therein).

2. Joint interpretation of resistivity and gravity time variations for volcano monitoring: a conceptual physical model

Numerous ~~experiences of~~ studies involving geophysical ~~data~~ monitoring in volcano-geothermal areas ~~give~~ **provid**e evidence of time variations of monitored parameters ascribable to **either** hydrothermal fluid flow **or** magma movement, as either can ~~originate~~ **produce** similar anomalous patterns ~~of~~ **in** the observed signals (e.g. Berrino, 1994; Bonafede and Mazzanti, 1998; Battaglia et al., 2006; Gottsmann et al., 2007). Thus, multimethodological and/or multidisciplinary studies ~~have been~~ **are** proposed for identifying the most likely physical ~~model~~ **processes** responsible ~~of~~ **for** the recorded anomalies.

In this paper, ~~in particular, a simultaneous~~ **an integrated** analysis that ~~integrates~~ **combines** resistivity and gravity data is ~~suggested as a useful tool~~ **used** to infer a ~~consistent~~ conceptual model of the volcanic hydrothermal dynamics and its evolution. The idea is based on the following considerations: **T**he hydrothermal fluid circulation is strongly dependent on the geo-structural characteristics of the volcanic ~~districts~~ **area** as well as on the physical properties of the pore fluids. It is well known~~, in fact,~~ that rock porosity and permeable fracture systems represent the main patterns for the transport of both magma and hydrothermal fluids from the reservoir to the surface~~,~~ and that salinity, temperature and ~~phase~~ **state** (gas and/or liquid) of the pore fluids heavily influence the volcanic dynamics. All these factors in turn greatly affect the resistivity and gravity parameters; indeed, their variations can induce resistivity changes up to **a maximum of five orders** of magnitude (e.g. Di Maio et al., 1997; **Utada, 2003; Zlotnicki et**

al., 2003; ~~Finizola et al., 2006; Revil et al., 2008; Richards et al., 2010~~ **Aizawa et al., 2011**) and well-detectable gravity signals **from tens to hundreds of microGals** (e.g. **Eggers, 1987 and references therein; Berrino et al., 1992; Rymer, 1994 and references therein;** Todesco and Berrino, 2005; ~~Todesco et al., 2006;~~ Gottsmann et al., 2007; Crider et al., 2008; Berrino et al., 2013; Prutkin et al., 2014). ~~Because of~~ **Due to** this large potential range in values, an integrated study of resistivity and gravity time variations is very effective in monitoring the volcano activity. There is no doubt that the presence of empty (or gas filled) pores and/or fracture systems gives rise to a negative correlation between the monitored resistivity and gravity values, i.e. high resistivity patterns as well as negative gravity change**s** ~~fields~~ are likely observed with respect to the surrounding areas. At the same time, the ingression of fluid flows in the ~~filling of~~ ~~the mentioned~~ lithological (pores) or structural (fractures) discontinuities ~~by fluid flows~~, most likely induced by strong pressure and temperature gradients due to deep volcanic processes, may cause strong resistivity decreases and appreciable density increases. ~~Therefore, a negative correlation between the recorded resistivity and gravity values is still observed.~~ Consequently, a joint monitoring of resistivity and gravity data should show alternat**ing** periods of resistivity highs/gravity lows and resistivity lows/gravity highs if ~~a~~ hydrothermal system dynamics governed by underground cyclic water-to-vapour transformations is ~~supposed~~ **expected** in areas characterised by significant surface volcanic manifestations. The first phase of this cycle could be correlated with the ascent of gaseous magmatic fluids coming from the fracture network representing the volcanic feeding system. These high temperature ~~gaseous~~ masses would tend to migrate towards the Earth's surface and, ~~when in~~ **upo**n contact with the water-saturated surrounding rocks, would cause a water-to-vapour phase transformation, ~~originating in such a way~~ ~~an uprising~~ **causing the ascent of a** pressurised vapour-rich gaseous mixture. At the end of this second phase, in terms of resistivity/gravity anomalies, a resistivity high/gravity low (vapour-gas dominated system) would substitute a previous resistivity low/gravity high (water dominated system). A notable amount of the uprising vapour-gas mixture would feed the fumarolic system, while the remaining part should condense beneath the coldest lateral zones of the volcanic edifice. Both mechanisms would cause a pressure release and hence a recall of water in those pores and fractures ~~where~~from **which** it was previously removed by the gas uprising mechanism. Accordingly, the decrease (or the outage at most) of the fumarolic flow would indicate the presence of a highly pressurised underground system or, alternatively, the arrest of hot gas uprising. The first hypothesis could suggest a hazard scenario, i.e. a possible volcanic eruption

~~is forecasted~~, while the second ~~guess~~ could indicate a depletion or collapse of the heat source responsible ~~of~~ **for** the assumed cyclic phase transformation process.

3. Application to Vulcano Island (Sicily, southern Italy)

~~In this section,~~ **Here, we present t**he results of a joint interpretation of ~~concurrent~~ resistivity and gravimetric data acquired at ~~the~~ Vulcano Island (Sicily, southern Italy) ~~in~~ **during** a three-year~~s~~ period (1993-1996) of intense volcanic surface manifestations. ~~are **here** shown.~~ It is worth ~~to point out~~ **noting** that this application does not represent a testing of the proposed conceptual physical model that, as it is well known, ~~implies~~ **requires** a validation with a more long period of observations and/or with monitoring data acquired ~~in~~ **from** more than one active volcanic area. The shown example ~~would just~~ **merely** outline**s** the ~~effectiveness~~ **usefulness** of the proposed conceptual approach ~~in the volcanic forecasting, in other words its feasibility~~ in ~~describing~~ **characterising** the volcano-hydrothermal system dynamics in terms of resistivity and gravity time variations.

3.1. Geological, volcanological and hydrogeological background

The Aeolian Archipelago is a volcanic arc formed by seven islands and **is** located **in the** south ~~of~~ Tyrrhenian Sea (southern Italy) in a transition zone between two different tectonic domains (Fig. 1a): compressional ~~in~~ **on** the northwestern side of ~~the~~ Sicily~~,~~ and extensional ~~in~~ **on** ~~the~~ northeastern Sicily and southern Calabria (Scarfi et al., 2016 and references therein). In particular, Vulcano is the third largest and the southernmost island of the Aeolian arc. It is placed along the well-known Tindari-Letojanni fault system, which is associated with minor faults, craters and volcanic tectonic depressions, like La Fossa cone (i.e., a modest volcanic edifice situated in the northern sector of the island) (Fig. 1). Its morphology, formed in the last 6000 years (Dellino ~~and La Volpe, 1997~~ **et al., 2011**; De Rosa et al., 2004), substantially reflects five main periods of volcanic activity (Frazzetta et al., 1983): Punte Nere (PN), Palizzi (PA), Forgia Vecchia (FV), Pietre Cotte (PC) and Gran Cratere (GC) (Fig. 2). These activities were characterised by both explosive phreatic eruptions and eruptions producing pyroclastic products, pumice fall deposits and lava flows (**e.g. Santacroce et al., 2003; De Rosa et al., 2004; Dellino et al., 2011** ~~Revil et al., 2010~~). After the last eruptive event (1888-1890), the volcanic activity on the island ~~was~~ manifested through two significant fumarolic crises: the first lasted about a decade (1913-1923) (**Granieri et al., 2006; Aubert et al., 2008** ~~Revil et al., 2010)~~~~,~~ and the second, which began in 1977 (e.g. Bukumirovic et al., 1997 and reference

therein), is still ongoing and is expressed in terms of thermal manifestations and fumarole exhalations, observable both within the crater and in pericrateric areas. In particular, the main high-temperature fumarolic field ~~develops at~~ **is found in** the northern sector of La Fossa crater, where, during the last fumarolic crisis, a progressive increase of ~~the~~ fumarole~~s~~ temperature**s**, reaching values of about 700 °C in 1993, was observed. Gas emissions at relatively low temperatures (about 100 °C) are instead observed at Porto di Levante (Fig. 1b), where the activity is displayed both on the beach and in submarine fumarolic fields. The chemical composition of La Fossa crater fumaroles is typical of high-temperature magmatic fluids (i.e., CO_2 as **the** main component and high concentrations of H_2S, HCl, HF, SO_2 and CO), while the main components that characterise the Baia di Levante fumaroles are representative of hydrothermal systems (i.e., higher CH_4 and H_2S contents and lower CO contents with respect the crater fumaroles **and an** absence of SO_2) (Capasso et al., 2001). The observed time and space variations of temperature and chemical composition of the fumaroles, often accompanied by increasing seismicity (Alparone et al., 2010), have been attributed to the state of the volcanic activity (Chiodini et al., 1995 and reference therein) as well as to the existence of active tectonic structures, in particular of weak structural patterns that favour the upward migration of fumarolic and/or magmatic fluids (Capasso et al., 1992 and references therein). Indeed, during the last fumarolic crisis, magmatic fluid inputs were observed, many times in combination with increases in seismic activity (Revil et al., 2010).

With regard**s** to the aquifer systems that feed the fumarolic activity, geophysical and geochemical studies performed in the Vulcano Porto area (e.g. Di Maio et al., 1998a; Capasso et al., 2001; Madonia et al., 2015 and references therein) identified a shallow coastal aquifer, dipping northward, resulting from the mixing of seawater, meteoric recharge and volcanogenic fluids. In addition, two deeper boiling hydrothermal aquifers, reached at depths of about 90 m and 220 m by geothermal explorative drillings performed in the 1950s, are present underneath the Baia di Levante beach (Sommaruga, 1984; Chiodini et al., 1995; Capasso et al., 2001). Finally, a freshwater aquifer (Dall'Aglio et al., 1994), which fed the Vulcano Porto phreatic aquifer (Favara et al., 1997), is located ~~at~~ **in** the Vulcano Piano area in the southern part of the island (see Fig. 1) at about 400 m elevation above sea level.

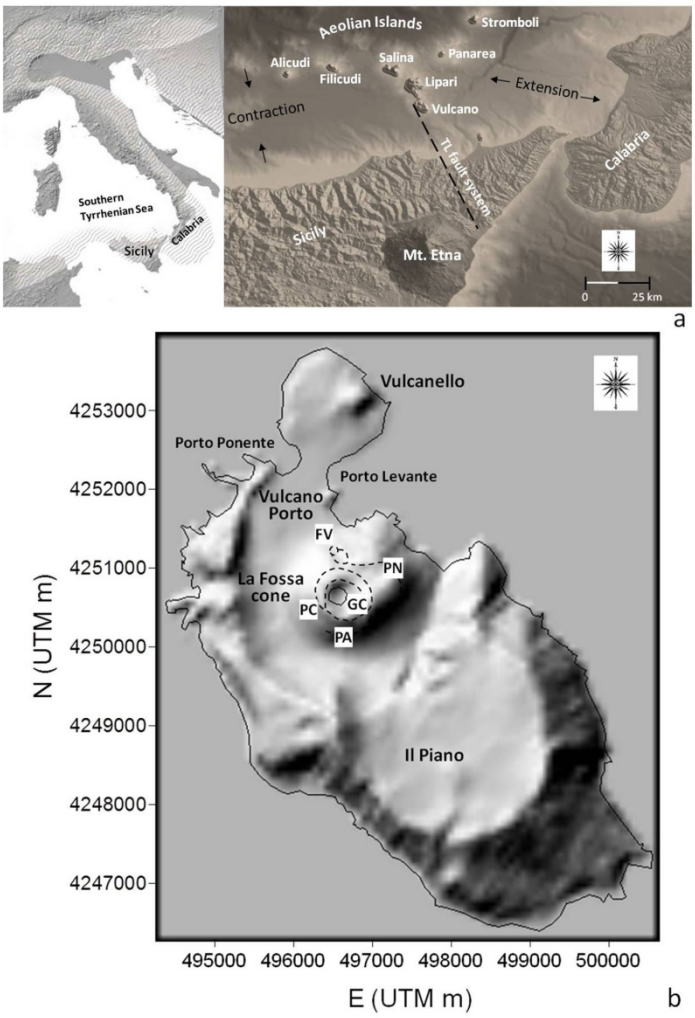

Fig. 1. a - Simplified map of the Aeolian Arc in the Tyrrhenian Basin (modified from Scarfi et al., 2016). Black dashed line indicates the Tindari-Letojanni (TL) Fault System. b - Map of the Vulcano Island. Dashed lines represent the main crater rims of La Fossa Cone, i.e. PN (Punte Nere), Pa (Palizzi), FV (Forgia Vecchia), PC (Pietre Cotte), and GC (Gran Cratere).

Based on the past history of the volcanic edifice, the length of the quiescence period and the growing urban development, Vulcano is considered the most dangerous island of the Aeolian Archipelago. This explains the ~~many~~ numerous studies in geology, volcanology, geophysics and geochemistry performed on the island in the last decades, as well as the need ~~of~~ **for** continuous monitoring of geophysical and geochemical parameters, aimed at understanding the dynamics of the magmatic hydrothermal system and predicting possible future scenarios (e.g. Granieri et al., 2006; Blanco-Montenegro et al., 2007; Revil et al., 2010). In this context, numerous models of hydrothermal fluid circulation ~~at~~ **on** Vulcano Island have been proposed in ~~the last~~ **recent** years, mainly based on simultaneous analysis of different geophysical and/or geochemical data. ~~In this work, in particular, a joint interpretation of resistivity and gravity variations, observed in a period of intense exhalative activity, is provided with the specific~~

~~intent to verify the effectiveness of the proposed conceptual model of hydrothermal system at Vulcano in the framework of volcanic surveillance programs.~~ **Here, we propose a combined analysis of resistivity and gravimetric data.**

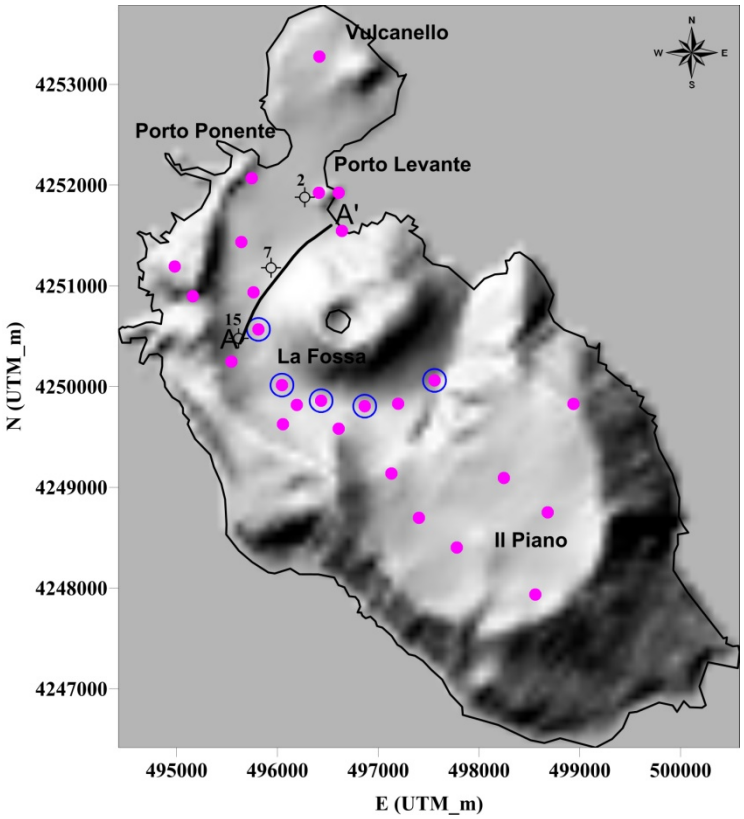

Fig. 2. Geophysical survey map at the island of Vulcano. Black continuous line AA': resistivity tomography (ERT) profile; magenta dots: gravity benchmarks belonging to the network operating from December 1993 to September 1996. The five benchmarks located in La Fossa-Palizzi area (rounded by on open blue circle) were set up in September 1994 following the significant fumarolic crisis of the summer 1994. **Numbered black circles: wells considered for the estimate of the shallow groundwater level variations observed in the analyzed time interval (from Madonia et al., 2015).**

3.2. Analysis of temporal variations of electrical resistivity and gravity data

~~For the present study,~~ We focus on **the** electrical resistivity and gravimetric dataset collected ~~at the~~ **on** Vulcano Island from 1993 to 1996 ~~in time intervals nearly coincident or, as in 1995, simultaneously acquired during a joined experiment.~~ During this three-year period, ~~in fact,~~ the volcanic monitoring of the island was intensified due to the occurrence of an earthquake (local magnitude ML= 4) with **an** epicenter located about 2 km south of Vulcano (Gulf of Patti)~~,~~ and to the strong modification of La Fossa crater fumarolic field, in terms of chemical composition, temperature and emission rate, which reached the highest recorded values in the middle of 1994 (Badalamenti et al., 1996; Bukumirovic et al., 1996; Diliberto et al., 1996).

3.2.1. Electrical resistivity tomographies

The geoelectrical monitoring of La Fossa area started in 1992 and consisted of repeated electrical resistivity tomographies (ERT) along profiles located in the northern sector of the Vulcano Island (Di Maio and Patella, 1994). ~~In particular, in this work~~ We refer only to measurements performed along a profile located at the foot of the northwest flank of La Fossa cone (AA' in **Fig. 2**), where the most striking resistivity time variations were observed.

Eleven 2D resistivity tomographies were ~~carried out~~ **performed during** ~~in~~ the analysed period (December 1993 **to** June 1996) along the AA' profile, **which extends** 1.6 km ~~extended~~. **The resistivity measurements were performed using the ABEM Terrameter SAS 300C together with the SAS 2000 Booster, which allows a maximum transmitter output of 400 V or 500 mA**. A dipole-dipole electrode array, with a dipole spacing of 100 m, **was chosen, as it is very sensitive to resistivity changes between the electrodes in each dipole pair. Unusual apparent resistivity changes, from values less than 10 Ωm to values greater than 10^5 Ωm (see Di Maio et al., 1997), were recorded in the central part of the profile between two consecutive periods. Likewise, this wide range of resistivity variation was also observed in some pseudo-sections. Therefore, special care was devoted to the data inversion process. Specifically, the collected apparent resistivity data were inverted with RES2DINV software (Loke and Barker, 1996; Loke and Dahlin, 2002; Loke, 2004) using the finite element method to link the model parameters to the 2D model response and the complete Gauss-Newton technique to determine the change in the model parameters. Moreover, due to the presence of very large resistivity contrasts, an appropriate mesh grid density was chosen in order to improve the inversion resolution (Zhang et al., 2015). The latter was tested by comparing the obtained resistivity models shown in Fig. 3 with the results of the probability tomography imaging applied to the analyzed apparent resistivity dataset (Mauriello and Patella, 1999). The general agreement between the models shown in Fig. 3 and the corresponding images of the most probable location of the underground resistivity anomalies shown in Mauriello and Patella (1999) provides evidence of the reliability of the performed inversions.**

Looking at the whole sequence of the resistivity models in Fig. 3, we **note that for the ERT surveys from December 1993 to December 1994 the maximum exploration depth was fixed at about 200 m below ground level (b.g.l.). Since the depth of investigation is strictly linked to the distance between the nearest current and potential electrodes (e.g. Loke, 2004), the most distant position between these electrodes was set equal to six-times the dipole spacing. This maximum distance was increased for the tomographies from**

January 1995 to June 1996 in order to achieve a greater exploration depth (about 300 m b.g.l.) and, thus, to obtain ~~more~~ information on the ~~geometry~~ **possible root** of the very-high resistivity body that cyclically appeared in the deep central portion of the resistivity sections. **As we can see in Fig. 3, a such greater depth was not reached for the ERT in May 1996 by virtue of technical troubles during the data acquisition process.**

The time variations of the resistivity models ~~of~~ in Fig. 3 show a general tendency of the resistivity to increase with depth, independent~~ly~~ of ~~month and year~~ **time** of observation, and a clear alternation of increasing and decreasing phases of the monitored resistivity values. This is particularly noticeable in the central sector of the tomographies, where resistivity variations up to five orders of magnitude ~~(from values less than 10 Ωm to values greater than 10^5 Ωm)~~ are observed in the same positions of the investigated ~~soil~~ section. Even though the ERT surveys were not performed with a constant time sampling interval, a periodicity of about 13-14 months seems to characterise two-consecutive resistivity lows. **In fact, the two ERT sequences, from December 1993 to December 1994 and from May 1995 to June 1996, respectively, show a very similar increasing trend of resistivity values separated by an abrupt decrease of the resistivity values in the interval January to February 1995.**

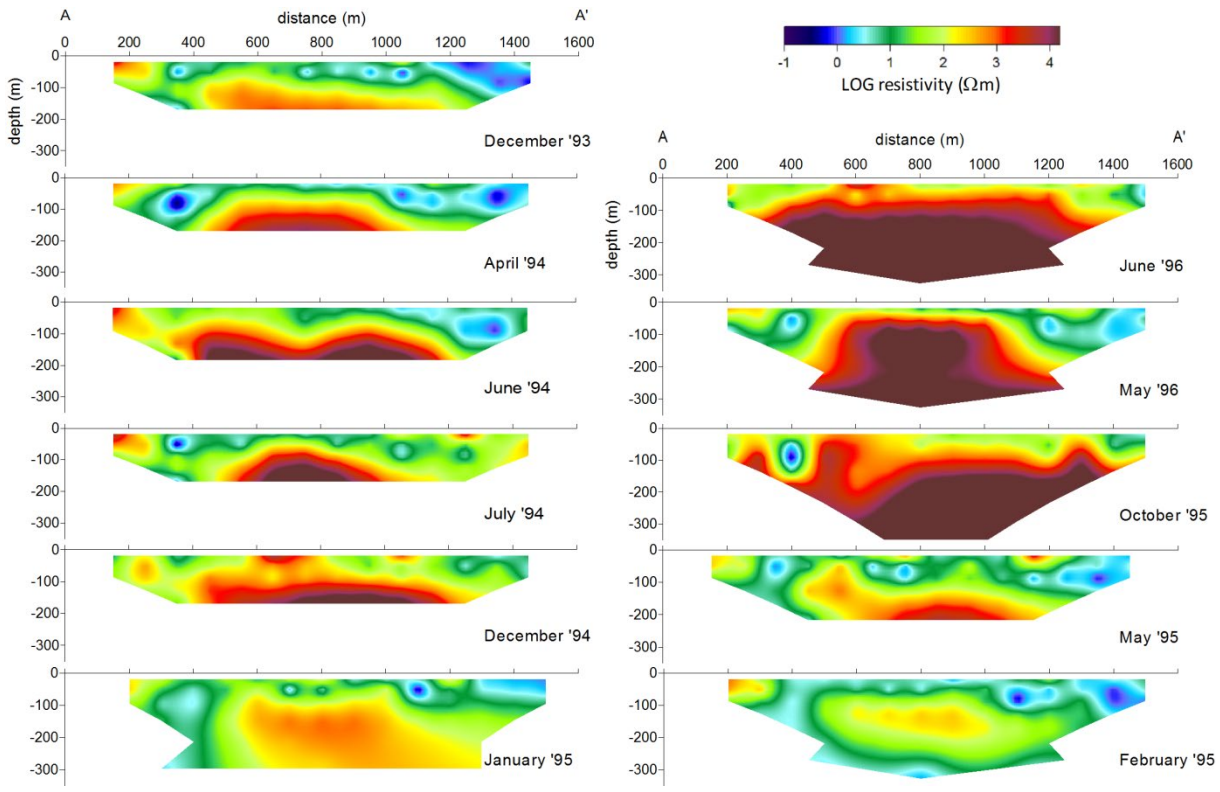

Fig. 3. Resistivity models along the profile AA' of Fig. 2 obtained from the inversion of the electrical resistivity tomographies carried out from December 1993 to June 1996.

3.2.2. Gravity surveys

The high-precision gravity measurements at Vulcano started in 1982 on a network initially formed by 11 benchmarks (Berrino et al., 1988) and increased over time (Berrino, 2000). In particular, for the period considered in this paper, the network consisted of 26 benchmarks located as shown in **Fig. 2**. The network is linked to an external reference station, situated in Milazzo (Sicily north coast), that ~~is~~ **has been** a site of absolute measurement since 1990 (Berrino, 1995).

From December 1993 to September 1996, ten gravity field surveys were carried out: eight realised on the whole network and two limited to the north-central part of the island. Gravity data were acquired ~~with~~ **using** two LaCoste and Romberg gravimeters (LCR, mods D, n. 62 and 136); the average errors for each survey range from ± 3 μGal to ± 12 μGal. The space gravity changes observed between two consecutive surveys, for the whole analysed period, are shown ~~by~~ **on** the maps ~~of~~ **in Figs. 4a-h**. To facilitate ~~the~~ comparison between different observation periods, the maps are drawn with **a** 15 μGal contour interval, which represents the largest error computed for the gravity variations related to the examined time intervals. **Figs. 4a-h** clearly show that the most significant gravity changes occurred in the following periods: December 1993 **to** July 1994 (Δg_{max} +30 μGal and -60 μGal, **Fig. 4a**); May **to** September 1995 (Δg_{max} +30 μGal and -75 μGal, **Fig. 4f**); September 1995 **to** April 1996 (Δg_{max} +45 μGal and -70 μGal, **Fig. 4g**). It is worth ~~to underline~~ **highlighting** that the ~~remarkable~~ gravity variations ~~observed~~ **detected** in the time interval December 1993 **to** July 1994 ~~took place~~ **were observed when** ~~during the~~ **an increase** of seismic **activity** ~~crisis~~ ~~of~~ **(Revil et al., 2010)**~~, when also~~ **and** ~~an increase of~~ temperature of the crater fumaroles was **also** recorded; in particular, values greater than 500 °C were measured in the following October (Harris et al., 2012). ~~Moreover,~~ An inversion of the gravity change fields during most of the consecutive analysed periods is also evident, particularly from May 1995 to April 1996 (**Figs. 4f and 4g**). As formerly suggested by Berrino (2000), the reversals of the gravity change field may be ascribable to significant seasonal effects as well as to seawater ingression/regression processes that control the hydrological system of the island. Such phenomena may produce changes ~~of~~ **in** both water table level and density, which could be responsible for most of the observed seasonal gravity variations. **In order to estimate the gravity effect due to the shallow groundwater level variations during the analysed time intervals, data from wells located close to our survey area (Madonia et al., 2015) were considered. In particular, with reference to the water table elevation data from wells located along the ERT profile (wells 7 and 15 in Fig. 2), the gravity effect was found to be less than ± 1 μGal; while a value of about 2 μGal was**

estimated for the gravity effect due to the larger water table changes (0.25 m at most) observed at well 2, which is located to the north of the ERT profile (see Fig. 2). As the extent of the water-table fluctuations in observation wells does not significantly modify the observed gravity change fields, we ascribe their reversal to density changes substantively due to cyclic processes of seawater ingression/water-to-vapour transformation as hypothesised by our conceptual model of hydrothermal system dynamics (see Section 3.4).

With the ~~sole~~ aim of better underlining the space gravity changes along the ERT profile (AA' in **Fig. 2**) ~~in~~ **during** the examined period, **Fig. 4** also illustrates the gravity variation maps, drawn with a contour interval of 2 μGal (**Fig. 4i-o**), limited~~ly~~ to the central-northern sector of the island and for time intervals approximately concurrent with those of the ERT surveys (see next section).

3.4. Integrated interpretation of resistivity and gravity time variations

In order to provide a joint interpretation of the anomalous resistivity and gravity time variations observed at Vulcano in the considered period (December 1993 **to** September 1996), a gravimetric profile coincident with the ERT profile ~~of~~ **in Fig. 2** ~~has been~~ **was** extracted from the gravimetric maps of **Fig. 4i-o**. Such maps correspond to gravity variations, Δg, observed for fixed time intervals, while the electrical tomographies show the underground resistivity distributions at the time of the prospecting. Therefore, resistivity differences, $\Delta\rho$, between two consecutive ERT surveys ~~have been~~ **were** calculated with the aim ~~to~~ of retriev**ing** tomographic sections in term of resistivity variations. In order to ~~make consistent the~~ **allow a** comparative analysis, these sections refer to time intervals coincident, or approximately coincident, with those indicated in **Fig. 4i-o**.

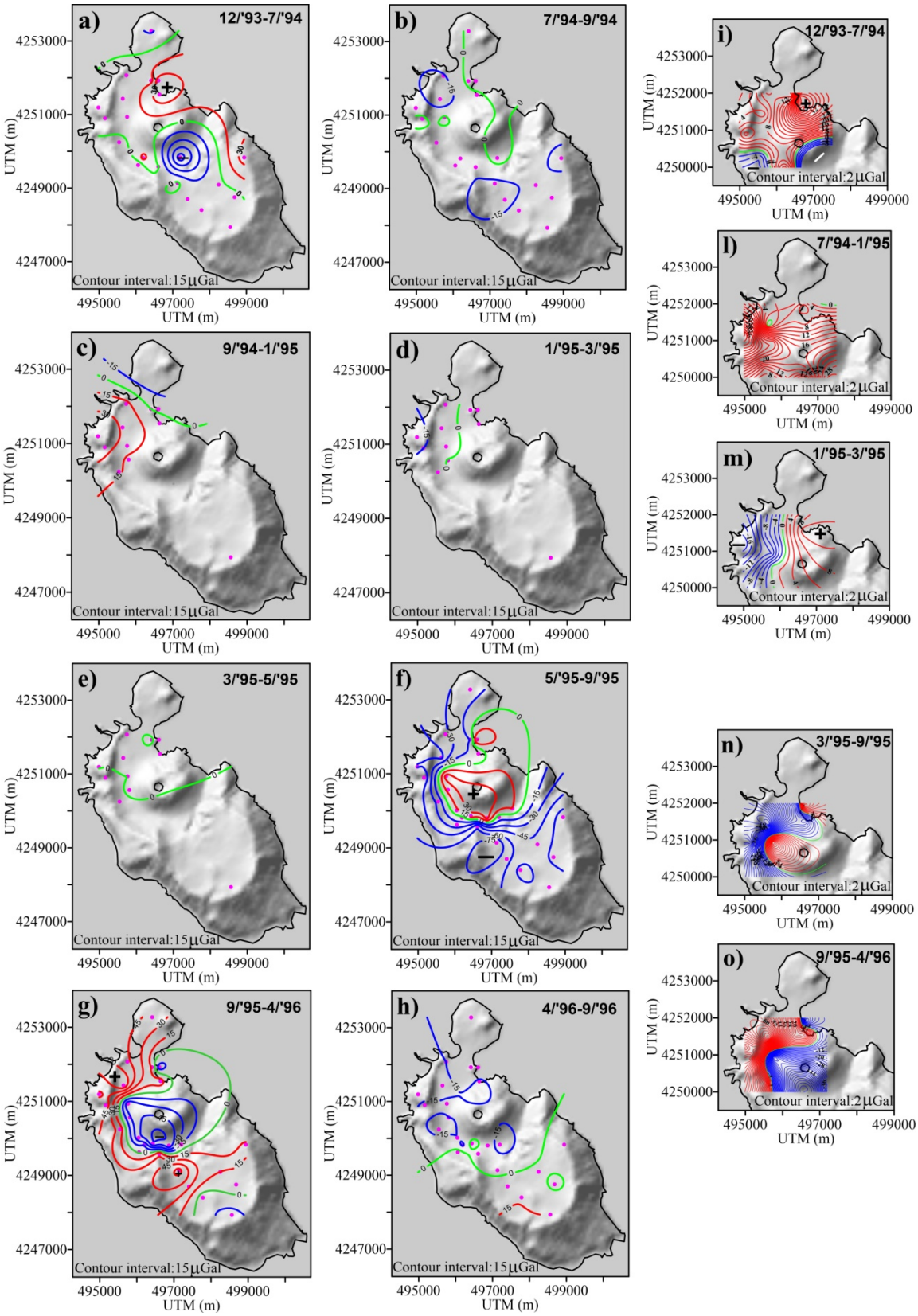

Fig. 4 Space distribution of the gravity change field observed at the island of Vulcano from December 1993 to September 1996. Images **a-h:** gravity change maps between two consecutive surveys drawn with a contour interval of 15 µGal. Images **i-o:** zoom of the gravity change fields in the area of the ERT profile related to time intervals approximately coincident with those of the ERT surveys. These maps are drawn with a contour interval of 2 µGal for underlining the gravity changes pattern along the ERT profile in the examined time intervals (see text for details). **The red, blue and green contour lines indicate, respectively, positive, negative and null gravity changes.**

Fig. 5 shows the sections of resistivity variations, $\Delta\rho$, and the profiles of gravity changes, Δg, ~~in~~ **for** time intervals where negative correlations were observed in the central portion of the profile. ~~An a~~ **A**lternate phase**s** characterised by increase/decrease and decrease/increase of the resistivity/gravity ~~observed~~ parameters~~, always inversely related,~~ **are** ~~also~~ eviden**ced**. According to the proposed conceptual model ~~(see~~ **of** Section 2~~)~~, such evidences are likely ascribable to the dynamics of the hydrothermal system. ~~Specifically,~~ The significant time variations of resistivity and gravity values observed at the foot of the north flank of La Fossa cone seem to outline an almost periodic phase transformation process ~~underground~~. ~~Indeed, these~~ **The** changes suggest that a cyclic heat source uprising/water-to-vapour transformation/seawater inland invasion mechanism could likely occur in this zone of intense volcanic manifestations. The first phase of the cycle could be correlated with the ascent of gaseous magmatic fluids coming from the area below Vulcano Porto located to the north of La Fossa cone (see **Fig. 1b**), where a weakness zone, probably responsible ~~of~~ **for** a new alignment of the volcanic feeding system, ~~has been~~ **is** observed (Frazzetta et al., 1983). The ascent towards the ~~earth's surface~~ **ground** of the~~se~~ high-temperature gaseous masses and the consequent contact with the seawater permeating the rocks would cause a water-tovapour phase transformation, giving rise to an uprising **of a** pressurised vapour-rich gaseous mixture. ~~Such a~~ **This** second phase would infer a higher electrical resistance and a mass deficiency with respect to the first phase of the process. This means that in terms of resistivity and gravity changes, positive $\Delta\rho$ values and negative Δg values would be observed. **Figs. 5a and 5b** could well represent these two phases of the hypothesised hydrothermal system dynamics (i.e., the transition from a seawater dominated system to a vapour-gas dominated system). At this stage, part of the uprising vapour-gas mixture would feed the intense fumarolic flow observable along the La Fossa crater rim, as supported by the results of geochemical and geothermal studies (e.g. Chiodini et al., 1995; Capasso et al., 2001; Diliberto et al., 2002; Madonia et al., 2015). The remaining part should condense beneath the coldest lateral zones of the volcano, as ~~it emerged from~~ **shown in** the study ~~of~~ **by** Revil et al. (2010). Both mechanisms would cause a pressure release below La Fossa crater~~,~~ and hence a recall of seawater in those pores and fractures ~~where~~from **which** it was previously removed by the gas uprising mechanism. This process would cause both **a** strong decrease of electrical resistivity and **an** increase of density, since the fracture voids and/or the rock pores are now filled with mineralised fluids, which consequently induce an increase of both electric conduction and mass. The results shown in **Fig. 5c** could well describe such a physical status ~~of~~ **in** the studied hydrothermal system.

A possible confirmation of the proposed hydrothermal system dynamics at Vulcano is provided by the geochemical models of mixing between magmatic and hydrothermal gases developed by Nuccio et al. (1999), Paonita et al. (2002) and Leeman et al. (2005) for the fumarolic emissions of the La Fossa crater during a time interval that includes the period analysed in the present work. These models hypothesise a hydrothermal system fed by seawater infiltrating at depth and evolving toward high pressure and temperature conditions. In particular, based on boron isotopic temporal variations in fumarolic condensates collected between 1970 and 1996 from La Fossa crater, selected well and thermal waters from the northern base of the volcano and samples of volcanic rocks and local sea water, Leeman et al. (2005) assumed that three distinct reservoirs, all likely present throughout the entire monitoring period, fed the La Fossa hydrothermal system: a deeper dominantly magmatic fluid; an intermediate mixing zone of moderately modified seawater with magmatic fluid; a shallow reservoir (likely at less than 1 km depth) of aqueous fluid (AF) produced from highly modified seawater that, infiltrated the base of the volcano, then underwent progressive heating, evaporation and boiling in low permeability zones. Ingress and circulation of such AF fluids would be a quasi-continuous process such that they would be available continuously, at least over the several decades of monitoring (Leeman et al., 2005). The recognised shallowest reservoir could well justify the three-stage cyclic mechanism that we suggest to govern the shallow hydrothermal system dynamics in the analysed period (1993-1996). In addition, the cycle length, which we find to be approximately of 13-14 months, seems to be in good agreement with the annual periodicity of the hydrological cycle observed in the monitored wells (Madonia et al., 2015). Indeed, a strong 12-month component dominates the power spectrum obtained by the Fast Fourier Transform analysis applied to the water table elevation data from well number 2 (i.e., the well located close to the sea) (Fig. 2). This component diminishes upslope and it is still visible, though with a much lower amplitude, in well 7 (Madonia et al., 2015). Interestingly, a weak 13-month component appears at the upslope well number 15 (i.e., the closest to the ERT Profile).

It is worth noting that the occurrence of positive correlations between resistivity and gravity changes in some of the examined time intervals seems to contradict the suggested physical model. Indeed, as shown in **Fig. 6**, during the periods December 1993 to July 1994 and July 1994 to January 1995 an increase of resistivity corresponds to an increase of gravity (and consequently of density) (**Fig. 6a**) and vice versa (**Fig. 6b**). These apparently anomalous correlations may be justified by considering the following two mechanisms: The simultaneous

increase of the two analysed parameters (**Fig. 6a**) could be due to the increase of the fluid temperature recorded in the period 1993 to 1994 (Badalamenti et al., 1996) **causing boiling phenomena in shallow water bodies,** such as to induce precipitation of salts dissolved in the water~~s~~ permeating fractures and/or pores of the rock formation. This phenomenon ~~has~~ can give~~n~~ rise to ~~well-known~~ **a** self-sealing process~~es~~ that ~~have led~~ **leads** to a **closure of the pore/fracture** system (Zlotnicki et al., 2009), as the number of interconnected pores (i.e., the effective porosity of the system) is reduced, with **a** subsequent increase of ~~its~~ electrical resistance and density. **This hypothesis agrees well with the steam-heating model proposed by Federico et al. (2010) based on a comprehensive study of major-ion chemistry, dissolved gases and stable isotopes measured in water wells selected from those monitored in the Vulcano Porto area (see Fig. 1) during the period 1989 to 1996. These authors, in fact, suggest that enhanced inputs of deep volcanic vapour during the 1988 to 1993 unrest period could be responsible of further boiling in the shallow thermal aquifer.** The behavior of the resistivity and gravity changes observed in the following time interval (**Fig. 6b**) may instead be attributed to seawater ingression forced by pressure gradients, likely generated by micro-fracturing processes induced by the earthquake of July 1994. The invasion of seawater in turn may have caused ~~the~~ salt dissolution, giving rise to the decrease of the resistivity and density values visible in the central-eastern part of the profile and to the recovery of the cyclic behaviour that governs the surface hydrothermal system. This hypothesis is supported by the inverse correlation between resistivity and gravity observed just ~~later~~ **after** the seismic event (**Fig. 5a**) and in the whole **of** 1995 (**Fig. 5b and 5c**), as well as by the subsequent volcanic activity ~~diminishing~~ decline. The latter **is** testified by the decrease of temperature and emission rate of the fumaloric flow and by the CO_2 soil degassing, observed until the end of 1995 (e.g. Badalamenti et al., 1996; Diliberto et al., 1996).

Further support of the proposed interpretation for the observed positive correlations is provided by the self-potential (SP) temporal changes detected in the study area during a nearly coincident time interval (Di Maio et al., 1997). Indeed, the positive SP change trend shown in the bottom graph of Fig. 6a, agrees well with the positive electric potential anomalies of electrokinetic origin observed in many volcano-geothermal areas and attributed to hot fluid upflow along fractures and/or pore networks (e.g., Revil and Pezard, 1998; Finizola et al., 2006; Richards et al., 2010; Hermans et al., 2014). Likewise, the negative electric potential anomaly observed in the westernmost part of the lower graph of Fig. 6b can be associated with the recharge area of the hydrothermal system (Revil and Pezard, 1998), as also suggested by the small gravity increase in the same

portion of the profile. It is worth to note that the location of the negative SP anomaly corresponds well with the topographically closed depression of the La Fossa crater that, according to Inguaggiato et al. (2012), contributes to the recharge of the Vulcano Porto aquifer. Moreover, the positive SP trend displayed in the remnant part of the profile could be justified by the proposed salt dissolution process, which is responsible for anomalous electric charge accumulation.

In conclusion, the direct correlation between the two analysed parameters could be ascrib~~able~~**ed** to the volcanic dynamics, which would mask the hydrological and hydrothermal system dynamics generally described by an inverse correlation between the recorded resistivity and gravity variations. **This suggestion is in full agreement with the above mentioned geochemical model of Leeman et al. (2005), which states that during the analysed period *i)* the processes that controlled the mixing between the three recognized fluid domains contributed to differing degrees over different time intervals, and *ii)* episodes of local seismicity presumably triggered reorganisation of hydrothermal circulation patterns, after which the hydrothermal system resumed its common dynamics.**

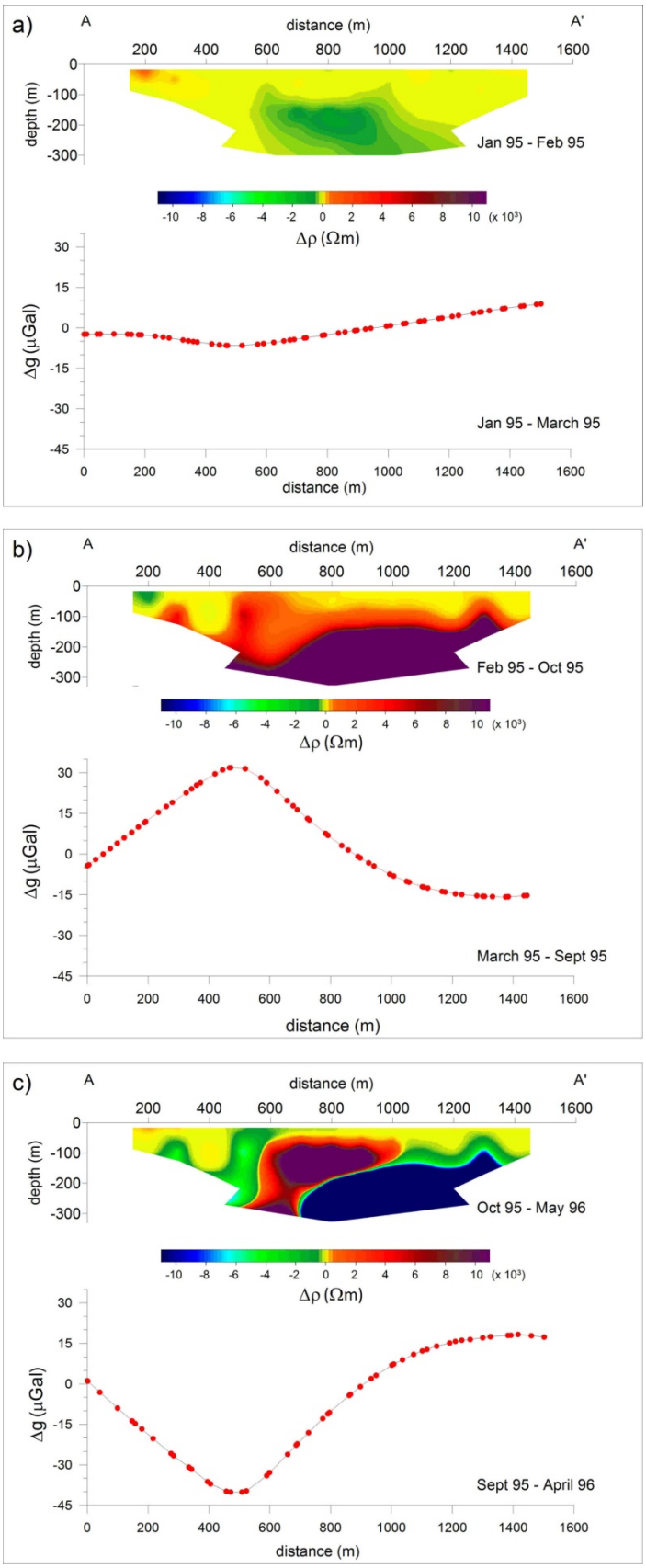

Fig. 5. Sections of resistivity variations, *Δρ*, and profiles of gravity changes, *Δg*, related to time intervals where negative correlations were observed along the resistivity tomography profile AA' of **Fig. 2**. The three *Δg* profiles of **Fig. 5a**, **5b** and **5c** have been extracted by the maps of **Fig. 4m**, **4n** and **4o,** respectively, along an alignment coincident with the geoelectrical profile.

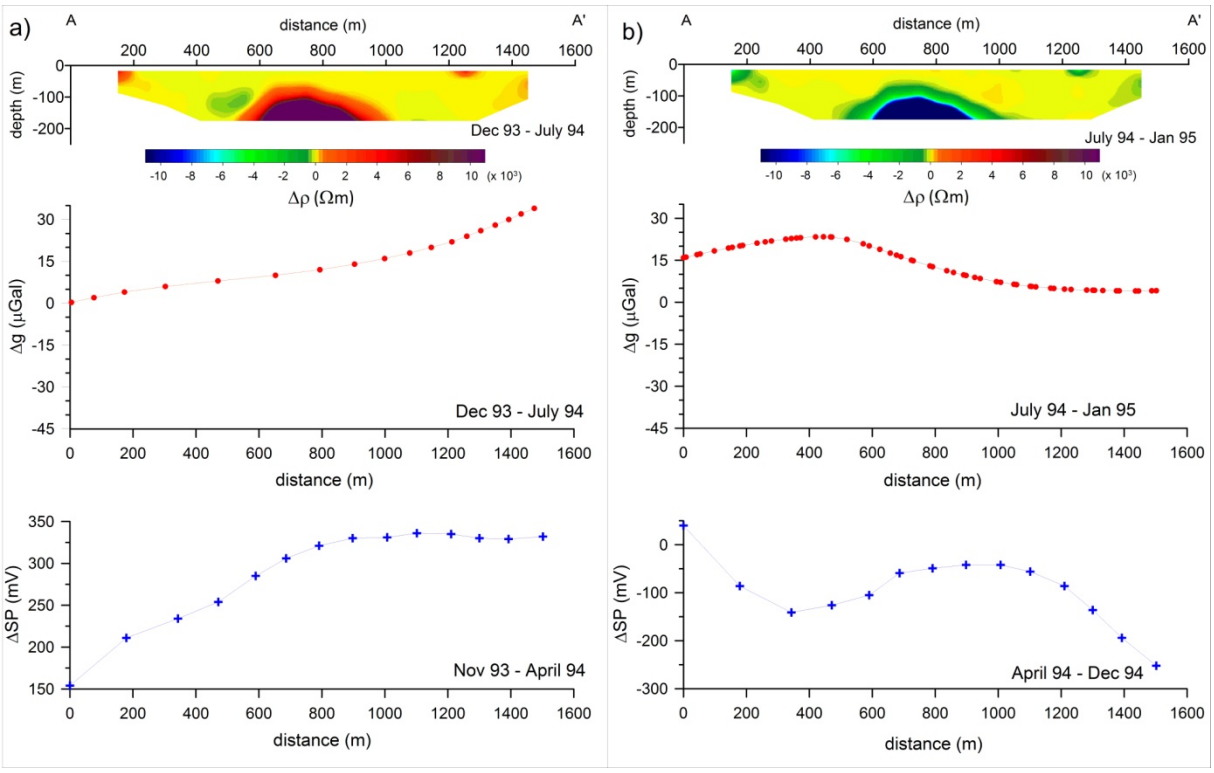

Fig. 6. Sections of resistivity variations, *Δρ*, and profiles of gravity, *Δg*, and self-potential, *ΔSP*, changes related to time intervals where positive correlations were observed along the resistivity tomography profile AA' of Fig. 2. The *Δg* profiles have been extracted by the maps of Fig. 4 along an alignment coincident with the geoelectrical profile. **The *ΔSP* profiles have been retrieved by three SP surveys performed at Vulcano Island on November 1993, April 1994 and December 1994 (Di Maio et al., 1997). In particular, the profiles show the self-potential temporal changes observed along the AA' profile.**

4. Conclusions

A conceptual physical model based on simultaneous analysis of electrical resistivity and gravity monitoring datasets is proposed to describe volcanic-hydrothermal systems and their ~~time~~ **temporal** behaviour. The model ~~essentially founds~~ **is based** on the assumption that water-to-vapour transformations occur in areas of intense surface volcanic manifestations. These phase transitions would explain the large variations observed ~~for~~ **in** the monitored resistivity and gravity values. The effectiveness of the proposed approach in volcanic forecasting is shown by the joint analysis of electrical resistivity and gravimetric datasets collected at the island of Vulcano from 1993 to 1996, in nearly coincident (or simultaneous) time intervals. Indeed, alternate phases characterised by increase/decrease of the two observed parameters, always inversely related, correlate well with a cyclic mechanism typified by three stages: heat source uprising/water-to-vapour transformation/sea water inland invasion. ~~Significantly, the performed~~ **Our** analysis shows that this negative correlation, which should describe the shallow hydrothermal system dynamics, disappears in some considered time intervals, **thus** making

way for positive correlation between the two analysed parameters. Such a ~~type of~~ correlation has been associated ~~to the~~ with volcanic dynamics, which would mask the hydrological and hydrothermal system dynamics. **The combined analysis used in this research could be useful in the future for interpreting the behaviour of the fumarolic/hydrothermal system at La Fossa in case of volcanic unrest.**

Finally, we should point out that our findings indicate that the monitoring of both resistivity and gravity data on the same spatial distribution and time basis is a promising tool for modeling hydrothermal volcanic systems and their evolution related to the mixing among fluids coming from different sources in any volcano-hydrothermal system.

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References

Aizawa K, Kanda W., Ogawa Y., Iguchi M., Yokoo A., Yakiwara H., Sugano T., 2011. Temporal changes in electrical resistivity at Sakurajima volcano from continuous magnetotelluric observations. J. Volcanol. Geotherm. Res. 199, 165-175, doi: 10.1016/j.jvolgeores.2010.11.003.

Allard, P., Carbonnelle, J., Dajlevic, D., Le Bronec, J., Morel, P., Robe, M.C., Morenas, J.M., Faivre-Pierret, R., Martin, D., Sabroux, J.C., Zettwoog, P., 1991. Eruptive and diffuse emissions of CO_2 from Mount Etna. Nature 351, 387-391, doi:10.1038/351387a0.

Alparone, S., Cannata, A., Gambino, S., Gresta, S., Milluzzo, V., Montalto, P., 2010. Time-space variation of volcano-seismic events at La Fossa (Vulcano, Aeolian Islands, Italy): new insights into seismic sources in a hydrothermal system. Bull. Volcanol. 72, 803-816, doi:10.1007/s00445-010-0367-6.

Aubert M., Diliberto S., Finizola A., Chébli Y., 2008. Double origin of hydrothermal convective flux variations in the Fossa of Vulcano (Italy). Bull. Volcanol. 70, 743-751, doi: 10.1007/s00445-007-0165-y.

Badalamenti, B., Calderone, L., Di Gangi, F., 1996. Vulcano island: continuous monitoring (temperature, reducing capacity, CO_2 in soil gases). Acta Vulcanologica 8(2), 200-202.

Barberi F., Neri G., Valenza M., Villari L., 1991. 1987-1990 unrest at Vulcano. Acta Vulcanologica 1, 95-106.

Battaglia, M., Troise, C., Obrizzo, F., Pingue, F., De Natale, G., 2006. Evidence for fluid migration as the source of deformation at Campi Flegrei caldera (Italy). Geophysical Research Letters 33, L01307, doi:10.1029/2005GL024904.

Berrino, G., 1994. Gravity changes induced by height-mass variations at the Campi Flegrei caldera. J. Volcanol. Geotherm. Res. 61, 293-309, doi:10.1016/0377-0273(94)90010-8.

Berrino, G., 1995. Absolute gravimetry and gradiometry on active volcanoes of Southern Italy. Bollettino di Geofisica Teorica ed Applicata, XXXVII, 146, 131-144.

Berrino, G., 2000. Combined gravimetry in the observation of volcanic processes in Southern Italy. Journal of Geodynamics 30, 371-388, doi:10.1016/S0264-3707(99)00072-1.

Berrino, G., Corrado, G., Luongo, G., 1988. Gravity changes and dynamics of the Aeolian Islands. Rendiconti della Società Italiana di Mineralogia e Petrografia 43(4), 935-946.

Berrino, G., d'Errico, V., Ricciardi, G., 2013. Thirty years of precise gravity measurements at Mt. Vesuvius: an approach to detect underground mass movements. Annals of Geophysics, 56(4), S0436; doi:10.4401/ag-6442.

Berrino, G., Rymer, H., Brown, G.C., Corrado, G., 1992. Gravity-height correlations for unrest at calderas. J. Volcanol. Geotherm. Res. 53, 11-26.

Blanco-Montenegro, I., De Ritis, R., Chiappini, M., 2007. Imaging and modelling the subsurface structure of volcanic calderas with high-resolution aeromagnetic data at Vulcano (Aeolian Islands, Italy). Bull. Volcanol. 69, 643-659, doi:10.1007/s00445-006-0100-7.

Bonafede, M., Mazzanti, M., 1998. Modelling gravity variations consistent with ground deformation in the Campi Flegrei caldera (Italy). J. Volcanol. Geotherm. Res. 81, 137-157, doi:10.1016/S0377-0273(97)00071-1.

Bukumirovic, T., Italiano, F., Nuccio, P.M., Pecoraino, G., Principio, E., 1996. Evolution of the fumarolic activity at La Fossa crater of Vulcano. Acta Vulcanologica 8(2), 210-212.

Bukumirovic, T., Italiano, F., Nuccio, P.M., 1997. The evolution of a dynamic geological system: the support of a GIS for geochemical measurements at the fumarole field of Vulcano, Italy. J. Volcanol. Geotherm. Res. 79, 253-263, doi:10.1016/S0377-0273(97)00032-2.

Capasso, G., Dongarrà, G., Hauser ,S., Favara, R., Valenza, M., 1992. Isotope composition of rain water, well water and fumarole steam on the island of Vulcano, and their implications for volcanic surveillance. J. Volcanol. Geotherm. Res. 49, 147-155, doi:10.1016/0377-0273(92)90010-B.

Capasso, G., D'Alessandro, W., Favara, R., Inguaggiato, S., Parello, F., 2001. Interaction between the deep fluids and the shallow groundwaters on Vulcano island (Italy). J. Volcanol. Geotherm. Res. 108, 187-198, doi:10.1016/S0377-0273(00)00285-7.

Chiodini, G., Cioni, R., Marini, L., Panichi, C., 1995. Origin of the fumarolic fluids of Vulcano Island, Italy and implications for volcanic surveillance. Bull. Volcanol. 57, 99-110.

Chiodini, G., Todesco, M., Caliro, S., Del Gaudio, C., Macedonio, G., Russo, M., 2003. Magma degassing as a trigger of bradyseismic events: The case of Phlegrean Fields (Italy). Geophysical Research Letters 30, doi:10.1029/2002GL016790.

Crider, J.G., Hill Johnsen, K., William-Jones, G., 2008.Thirty-year gravity change at Mount Baker Volcano, Washington, USA: Extracting the signal from under the ice. Geophysical Research Letters 35, L20304, doi:10.1029/2008GL034921.

Dall'Aglio, M., Fornaseri, M., Brondi, M., 1994. New data on Thallium in rocks and natural waters from central and southern Italy. Miner. Petrogr. Acta 38, 103-112.

~~Dellino, P., La Volpe, L., 1997. Stratigrafia, dinamiche eruttive e deposizionali, scenario eruttivo e valutazioni di pericolosità a La Fossa di vulcano. In: La Volpe, L., Dellino, P., Nuccio, M., Privitera, E. & Sbrana, A. (eds), Progetto Vulcano: Risultati dell'attività di ricerca 1993-1995. Felici Ed., Pisa, pp. 214-237.~~

Dellino, P., De Astis, G., La Volpe, L., Mele, D., Sulpizio, R., 2011. Quantitative hazard assessment of phreatomagmatic eruptions at Vulcano (Aeolian Islands, Southern Italy) as obtained by combining stratigraphy, event statistics and physical modeling. J. Volcanol. Geotherm. Res. 201, 364-384, doi: 10.1016/j.jvolgeores.2010.06.009.

De Rosa, R., Calanchi, N., Dellino, P.F., Francalanci, L., Lucchi, F., Rosi, M., Rossi, P.L., Tranne, C.A., 2004. Geology and volcanism of Stromboli, Lipari, and Vulcano (Aeolian Islands). Proceeding 32nd International Geological Congress, Firenze 20-28 August, 2004, Field Trip Guide Book − P42, vol. 5.

Diliberto, I.S., Gurrieri, S., Valenza, M., 1996. Relationships between diffuse CO2 emissions and volcanic activity on the island of Vulcano (Aeolian Islands, Italy) during the period 1984–1994. Bull. Volcanol. 64, 219-228, doi:10.1007/s00445-001-0198-6.

Diliberto, I.S., Gurrieri, S., Valenza, M., 2002. Diffuse CO2 degassing from the ground. Acta Vulcanologica 8(2), 203-204.

Di Maio, R., Patella, D., 1994. Vulcano: Self-potential and dipole-dipole geoelectrical measurements. In L.Villari (Ed.), Data related to eruptive activity, unrest phenomena and other observations on the Italian active volcanoes in 1992. Acta Vulcanologica 6, 64-66.

Di Maio, R., Mauriello, P., Patella, D., Petrillo, Z., Piscitelli, S., Siniscalchi, A., Veneruso, M., 1997. Self-potential, geoelectric and magnetotelluric studies in Italian active volcanic areas. Annals of Geophysics 40(2), 519-537.

Di Maio, R., Gerundo, M., Giammetti, S., Patella, D., Piscitelli, S., Veneruso, M., 1998a. Vulcano and Stromboli: Self-potential mapping and dipolar geoelectric tomography. In P.Gasparini (Ed.), Data related to eruptive activity, unrest phenomena and other observations on the Italian active volcanoes - 1993-1995. Acta Vulcanologica 10(1), 133-136.

Di Maio, R., Mauriello, P., Patella, D., Petrillo, Z., Piscitelli, S., Siniscalchi, A., 1998b. Electric and electromagnetic outline of the Mount Somma-Vesuvius structural setting. J. Volcanol. Geotherm. Res. 82, 219-238, doi:10.1016/S0377-0273(97)00066-8.

Di Maio, R., Patella, D., Petrillo, Z., Siniscalchi, A., Cecere, G., De Martino, P., 2000. Application of electric and electromagnetic methods to the definition of the Campi Flegrei caldera (Italy). Annals of Geophysics 43, 375-390.

Eggers, A.A., 1987. Residual gravity changes and eruption magnitudes. J. Volcanol. Geotherm. Res. 33, 201-216.

Favara, R., Francofonte, S., Madonia, P., Valenza, M., 1997. Modello idrogeologico dell'Isola di Vulcano e suo significato per la sorveglianza geochimica. In: C.N.R./G.N.V., Convegno Annuale 1996, Roma 3-5 Marzo 1997, pp. 162-163.

Finizola, A., Revil, A., Rizzo, E., Piscitelli, S., Ricci, T., Morin, J., Angeletti, B., Mocochain, L., Sortino, F., 2006. Hydrogeological insights at Stromboli volcano (Italy) from geoelectrical, temperature, and CO2 soil degassing investigations. Geophysical Research Letters 33, L17304, doi:10.1029/2006GL026842.

Federico, C., Capasso, G., Paonita, A., Favara, R., 2010. Effects of steam-heating process on a stratified volcanic aquifer: stable isotopes and dissolved gases in thermal waters of Vulcano Island (Aeolian archipelago). J. Volcanol. Geotherm. Res. 192, 178-190, doi:10.1016/j.jvolgeores.2010.02.02.

Frazzetta, G., La Volpe, L., Sheridan, M.F., 1983. Evolution of the Fossa cone, Vulcano. J. Volcanol. Geotherm. Res. 17, 329-360, doi:10.1016/0377-0273(83)90075-6.

Gottsmann, J., Carniel, R., Coppo, N., Wooller, L., Hautman, S., Rymer, H., 2007. Oscillations in hydrothermal systems as a source of periodic unrest at caldera volcanoes: Multiparameter insights from Nisyros, Greece. Geophysical Research Letters 34, L07307, doi: 10.1029/2007GL029594.

Granieri, D., Carapezza, M.L., Chiodini, G., Avino, R., Caliro, S., Ranaldi, M., Ricci, T., Tarchini, L., 2006. Correlated increase in CO_2 fumarolic content and diffuse emission from La Fossa crater (Vulcano, Italy): Evidence of volcanic unrest or increasing gas release from a stationary deep magma body?. Geophysical Research Letters 33, L13316, doi:10.1029/2006GL026460.

Harris, A., Alparone, A., Bonforte, A., Dehn, J., Gambino, S., Lodato, L., Spampinato, L., 2012. Vent temperature trends at the Vulcano Fossa fumarole field the role of permeability. Bull. Volcanol. 74, 1293-1311, doi: 10.1007/s00445-012-0593-1.

Hermans, T., Nguyen, F., Robert, T., Revil, A., 2014. Geophysical Methods for Monitoring Temperature Changes in Shallow Low Enthalpy Geothermal Systems. Energy 7, 5083-5118, doi:10.3390/en7085083.

Inguaggiato, S., Mazot, A., Diliberto, I.S., Inguaggiato, C., Madonia, P., Rouwet, D., Vita, F., 2012. Total CO2 output from Vulcano island (Aeolian Islands, Italy). Geochem. Geophys. Geosyst. 13, Q02012, doi:10.1029/2011GC003920.

Leeman, W.P., Tonarini, S., Pennisi, M., Ferrara, G., 2005. Boron isotopic variations in fumarolic condensates and thermal waters from Vulcano Island, Italy: Implications for evolution of volcanic fluids. Geochim. Cosmochim. Acta 69-1, 143-163.

Loke, M.H., 2004. Tutorial: 2-D and 3-D electrical imaging surveys. https://sites.ualberta.ca/~unsworth/UA-classes/223/loke_course_notes.pdf (accessed 28 July 2016).

Loke, M.H., Barker, R.D., 1996. Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method. Geophysical Prospecting 44, 131-152, doi:10.1111/j.1365-2478.1996.tb00142.x.

Loke, M.H., Dahlin, T., 2002. A comparison of the Gauss-Newton and the quasi-Newton methods in resistivity imaging inversion. J. Appl. Geophys. 49, 149-162.

Madonia, P., Capasso, G., Favara, R., Francofonte, S., Tommasi, P., 2015. Spatial distribution of field physico-chemical parameters in the Vulcano Island (Italy) coastal aquifer: volcanological and hydrogeological implications. Water 7, 3206-3224, doi:10.3390/w7073206.

Mauriello, P., Patella, D., 1999. Resistivity anomaly imaging by probability tomography. Geophysical Prospecting 47, 411-429.

Nuccio, P.M., Paonita, A., Sortino, F., 1999. Geochemical model of mixing between magmatic and hydrothermal gases: the case of Vulcano Island (Italy). Earth Planet. Sci. Lett. 167, 321-333.

Paonita, A., Favara, R., Nuccio, P.M., Sortino, F., 2002. Genesis of fumarolic emission as inferred by isotope massa balances: CO2 and water of Vulcano Island, Italy. Geochim. Cosmochim. Acta 66-5, 759-772.

Phillipson, G., Sobradelo, R., Gottsmann, J., 2013. Global volcanic unrest in the 21st century: An analysis of the first decade. J. Volcanol. Geotherm. Res. 264, 183-196.

Pribnow, D.F.C., Schütze, C., Hurter, S.J., Flechsig, C., Sass, J.H., 2003. Fluid flow in the resurgent dome of Long Valley Caldera: implications from thermal data and deep electrical sounding. J. Volcanol. Geotherm. Res. 127, 329-345, doi:10.1016/S0377-0273(03)00175-6.

Prutkin, I., Vajda, P., Gottsmann, J., 2014. The gravimetric picture of magmatic and hydrothermal sources driving hybrid unrest on Tenerife in 2004/5. J. Volcanol. Geotherm. Res. 282, 9-18, doi: 10.1016/j.jvolgeores.2014.06.003

Revil, A., Finizola, A., Sortino, F., Ripepe, M., 2004. Geophysical investigations at Stromboli volcano, Italy: implications for groundwater flow and paroxysmal activity. Geophys. J. Int. 157, 426-440, doi: 10.1111/j.1365-246X.2004.02181.x.

~~Revil, A., Finizola, A., Piscitelli, S., Rizzo, E., Ricci, T., Crespy, A., Angeletti, B., Balasco, M., Barde Cabusson, S., Bennati, L., Bolève, A., Byrdina, S., Carzaniga ,N., Di Gangi, F., Morin, J., Perrone, A., Rossi, M., Roulleau, E., Suski, B., 2008. Inner structure of La Fossa di Vulcano (Vulcano Island, southern Tyrrhenian Sea, Italy) revealed by high resolution electric resistivity tomography coupled with self potential, temperature, and CO_2 diffuse degassing measurements. Journal of Geophysical Research 113, B07207, doi:10.1029/2007JB005394.~~

Revil, A., Johnson, T.C., Finizola, A., 2010. Three-dimensional resistivity tomography of Vulcan's forge, Vulcano Island, southern Italy. Geophysical Research Letters 37, L15308, doi:10.1029/2010GL043983.

Revil, A., Pezard, P.A., 1998. Streaming electrical potential anomaly along faults in geothermal areas. Geophysical Research Letters 25(16), 3197-3200.

Richards, K., Revil, A., Henderson, F., Batzle, M., Haas, A., 2010. Pattern of shallow ground water flow at Mount Princeton Hot Springs, Colorado, using geoelectrical methods. J. Volcanol. Geotherm. Res. 198, 217-232, doi:10.1016/j.jvolgeores.2010.09.001.

Rinaldi, A.P., Todesco, M., Vandemeulebrouck, J., Revil, A., Bonafede, M., 2011. Electrical conductivity, ground displacement, gravity changes, and gas flow at Solfatara crater (Campi Flegrei caldera, Italy): Results from numerical modeling. J. Volcanol. Geotherm. Res. 207, 93-105, doi:10.1016/j.jvolgeores.2011.07.008.

Rymer, H., 1994. Microgravity changes as precursor to volcanic activity. J. Volcanol. Geotherm. Res. 61, 311-328.

Santacroce, R., Cristofolini, R., La Volpe, L., Orsi, G., Rosi, M., 2003. Italian active Volcanoes. Episodes 26, 227-234.

Sasai, Y., Zlotnicki, J., Nishida, Y., Yvetot, P., Morat, P., Murakami, H., Tanaka, Y., Ishikawa, Y., Koyama, S., Sekiguchi, W., 1997. Electromagnetic monitoring of Miyake-jima volcano, Izu-Bonin Arc, Japan: A preliminary report. J. Geomag. Geoelectr. 49, 1293-1316.

Sasai, Y., Zlotnicki, J., Nishida, Y., Uyeshima, M., Yvetot, P., Tanaka, Y., Watanabe, H., Takahashi, Y., 2001. Evaluation of electric and magnetic field monitoring of Miyake-jima Volcano (Central Japan): 1995-1999. Annals of Geophysics 44, 239-260, doi:10.4401/ag-3585.

Scarfì, L., Barberi, G., Musumeci, C., Patanè, D., 2016. Seismotectonics of northeastern Sicily and southern Calabria (Italy): New constraints on the tectonic structures featuring in a crucial sector for the central Mediterranean geodynamics. Tectonics 35, doi:10.1002/2015TC004022.

Sommaruga, C., 1984. Le ricerche geotermiche svolte a Vulcano negli anni ′50. Rend. Soc. It. Min. Petrol. 39, 355-366.

Todesco, M., Berrino, G., 2005. Modeling of hydrothermal fluid circulation and gravity signals at the Phlegraean Fields caldera. Earth and Planetary Science Letters 240, 328-338, doi:10.1016/j.epsl. 2005.09.016.

Todesco, M., Chiodini, G., Macedonio, G., 2003. Monitoring and modelling hydrothermal fluid emission at La Solfatara (Phlegrean Fields, Italy). An interdisciplinary approach to the study of diffuse degassing. J. Volcanol. Geotherm. Res. 125, 57-79, doi:10.1016/S0377-0273(03)00089-1.

~~Todesco, M., Chiodini, G., Berrino, G., 2006. Modeling of gas composition and gravity signals at the Phlegrean Fields Caldera. Proc. TOUGH Symposium, Berkeley, California, May 15-17, 6 pp.~~

Utada, H., 2003. Interpretation of time changes in the apparent resistivity observed prior to the 1986 eruption of Izu-Oshima volcano, Japan. J. Volcanol. Geotherm. Res. 126, 97-107, doi:10.1016/S0377-0273(03)00119-7.

Zhang, G., Zhang, G.B., Chen, C.C., Jia, Z.Y., 2015. Research on Inversion Resolution for ERT Data and Applications for Mineral Exploration. Terrestrial, Atmospheric & Oceanic Sciences 26(5), 515-526.

Zlotnicki, J., Sasai, Y., Yvetot, P., Nishida, Y., Uyeshima, M., Fauquet, F., Utada, H., Takahashi, Y., Donnadieu, G., 2003. Resistivity and self-potential changes associated with volcanic activity: The July 8, 2000 Miyake-jima eruption (Japan). Earth Planet. Sci. Lett. 205 (3-4), 139-154, doi:10.1016/S0012-821X(02)01025-7.

Zlotnicki, J., Sasai, Y., Toutain, J.P., Villacorte, E., Harada, M., PHIVOLCS team, Yvetot, P., Fauquet, F., Bernard, A., Nagao, T., 2009. Electromagnetic and geochemical methods applied to investigations of hydrothermal/volcanic unrests: Examples of Taal (Philippines) and Miyake-jima (Japan) volcanoes. Physics and Chemistry of the Earth 34, 394-408, doi:10.1016/j.pce.2008.09.012.

Wohletz, K., Heiken, G., 1992. Volcanology and Geothermal Energy, Berkeley, University of California Press, ISBN : 0-520-07914-0.