GEOTHERMAL FLUIDS MONITORING BY TIME LAPSE ELECTRICAL RESISTIVITY TOMOGRAPHY: THE PISCIARELLI DISTRIBUTE DEGASSING TESTSITE (CAMPI FLEGREI - SOUTHERN ITALY)

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Introduction. The Pisciarelli area (Campi Flegrei) is characterised by an active distribute degassing site , which is affected by near- surface secondary processes of seasonal character that look as if they mask the deeper signals related to the temperature-pressure changes occurring in the shallow feeding hydrothermal system.

Starting from 2003, the Pisciarelli field has experienced an evident increase of activity, which has been marked by a sequence of temperature peaks of the ephemeral fumaroles well above the average background temperature of 95 °C, each lasting up to half a year until early 2011, and exceptionally about one year, from mid-2011 to mid-2012, the last recorded peak. Furthermore, a nearly linear trend of the peak temperatures, from about 97 °C up to around 112 °C, has been recorded from 2003 up to date. The increase of degassing activity has also been marked by the opening of new vigorous vents and enlargement of degassing pools, also accompanied by intense local seismic activity and ground uplift.

In order to evaluate the fluids dynamics in the shallow hydrothermal systems and to interpret its eventual periodicity, we perform DC electrical tomography at fixed period of time. The repeated Electrical Resistivity Tomography (ERT) should allow us to identify the main end member sources such as the meteoric component, and/or the eventual evolution of the deep fluids.

ERT recently is receiving an increasingly interest in environmental and hydrogeological studies to well suited to 2-D and 3-D field data acquisition and interpretation, and can be adapted to various scales.

Time-lapse ERT consists in performing an identical ERT survey several times in the same place, to characterize different hydrological/geothermal process during time. Time-lapse ERT can also be used to monitor changes in electrical resistivity linked to groundwater flows, because they create variations in water content and/or water conductivity.

Many applications are discussed in literature (e.g., White, 1994; Daily *et al.*, 1995; Barker and Moore, 1998; Ramirez and Daily, 2001; Carter, 2002; Slater *et al.*, 2002; Singha and Gorelick, 2005; Cassiani *et al.*, 2006; Swarzenski *et al.*, 2006; de Franco *et al.*, 2009). However all these experiments are devoted to the use of the ERT for tracer tests or in contaminant hydrology and are characterized by a short monitoring period due to the complexity and problems of long-time instrument operational maintenance.

In this work we propose a first geophysical monitoring by time lapse electrical resistivity in a distributed degassing site. A long period (about 12 months) time lapse monitoring will allow us to understand the behaviour of hydrothermal fluids in the lower 20-m of the phreatic aquifer and will supply fundamental evidences on the possible seasonal resistivity fluctuations or whether the resistivity changes are indicative of an increase in volcanic gases present in the hydrothermal system.

Campi Flegrei geological background. Located in the Campanian region (South Italy), the Phlegraean Volcanic District (PVD) is a densely populated active volcanic area, including the Campi Flegrei (CF) caldera, the islands of Procida and Ischia, plus a number of submerged volcanoes. Volcanological, geophysical and geochemical evidences (De Vita *et al.*, 1998, 1999) support the hypothesis that remnants of the magma source feeding the two large eruptive events of Campanian Ignimbrite (37 ky BP) and Neapolitan Yellow Tuff (14.9 ky BP) are involved in more recent volcanic episodes (e.g. Agnano-Monte Spina eruption, 4 ky BP). Volcanic risk has increased in time due to the rapid population expansion in such active and active volcanic areas of the Earth. The reconstruction of the temporal evolution and the definition of the present state of the magmatic system feeding an active volcano are essential data for hazard assessment. Therefore the restless Campi Flegrei caldera (CFc) is one of the most dangerous volcanic areas on Earth. It is inhabited by more than 1.5 million people, most of whom concentrated in the city of Naples, as also recently indicated by the upcoming emergency evacuation plan for the Campi Flegrei area which as included different neighbourhood (i.e. Chaia, Fuorigrotta, Bagnoli, a part of Vomero). The magmatic system is still active as demonstrated by the widespread fumaroles and thermal springs (Allard *et al.*, 1991), and by bradyseismic episodes that occurred in 1969–1972 and 1982–1984 (Corrado *et al.*, 1977; Barberi *et al.*, 1984, 1989; Orsi *et al.*, 1999). The maximum ground uplift and the earthquakes location during the crises are focused in the center of the Campi Flegrei caldera, near the fumarolic field of Solfatara volcano. The Solfatara volcano is a tuff cone that consists of hydrothermally altered breccias and dunebedded ash to lapillus beds (Rosi and Sbrana, 1987). The tuff cone was formed between 3.8 and 4.1 ka (Di Vito *et al.*, 1999), and historical chronicles report that a phreatic event occurred in the 12th century. At the present moment, the Solfatara area is affected by an intense, diffuse degassing and fumarolic activity. Detailed geochemical study of Solfatara fumaroles (Caliro *et al.*, 2007), coupled with soil diffuse degassing measurements (Chiodini *et al.*, 2001) and with physical numerical simulations of the hydrothermal system (Todesco *et al.*, 2003; Troiano *et al.,* 2011) suggests that magma degassing episodes have a relevant role in triggering the volcanic unrest periods that periodically affect the area (Chiodini *et al.*, 2003). The Solfatara volcano is located inside the CF caldera, at about 2 km east–northeast of the town of Pozzuoli. A low-magnitude explosive eruption in 1198 AD ejected tephra over a small area (Di Vito *et al.*, 1999). The crater has a roughly elliptical shape with axes of 580 and 770 m, and the highest relief along its rim reaches 199 m asl. The Solfatara crater is located very close to the area of maximum ground uplift and is the most active seismic area. It hosts large and spectacular fumarole vents, with maximum flow temperatures in the range of 150–160 °C at the Bocca Grande (BG) and Bocca Nuova (BN) fumaroles and approximately 100 °C at Le Stufe (LS) and La Fangaia (LF) ones (Chiodini *et al.*, 2001). Systematic measurements of the gas fluxes from the soil evidenced up to 1500 tonnes/day of CO2 emission through the main fault system and temperature up to 95 °C far from the fumaroles (Granieri *et al.*, 2010). During the first 16 years of systematic monitoring of the geochemical composition of the BG and BN fumaroles, from 1984 to 2000, the CO_2/H_2O concentration ratio has shown three clear peaks, in 1986, 1991 and 1995–96, respectively of 0.30, 0.26 and 0.34 over a background average value of 0.17, peaked about one year later of related peaks in ground deformation. Since 2000 to nowadays the CO_2/H_2O concentration ratio has progressively increased with a nearly linear trend from the background value of 0.17 up to about 0.32 (Chiodini *et al.*, 2010).

Pisciarelli field site and experimental set-up. The Pisciarelli area is a fault-related fumarolic field located slightly outside the caldera rim of the Solfatara crater (Fig. 1a). This area is characterized by the presence of fractures and is affected by phenomena of emission of gases and fluids. The fumaroles are mainly composed by H_2O followed by CO_2 and H_2S and with a range of temperature between 100-110 °C (Chiodini, 2009). Currently the increasing temperature of the fumaroles above the average background temperature, local seismicity and occurrence of fumaroles mixed with jets of boiling water, show an evident increase of the activity compared to previous inspections. During field surveys made in the year 2006 in Pisciarelli area, compared to similar surveys conducted in the past (the year 2005), changes in the phenomena of gases and fluids emissions were observed. In addition, along the eastern side of the small hill to the east of this place pool the points of greenhouse gas emissions have increased. Fractures are mostly trending N110-120E and the area is dominated by two main features NW-SE and NE-SW. Also accumulations of material from surface gravitational movements of recent formation were not observed.

a

b

Fig. 1 – a) The Phlegraean Volcanic District; b) the ERT profiles at Pisciarelli.

The presence of a very shallow aquifer seem to have the control on the behavior and composition of the fumaroles. The emission of gases and fluids are affected by near-surface secondary processes of seasonal character that seem to mask the deeper signals related to the temperature-pressure changes occurring in the hydrothermal system, clearly observed, instead, inside the Solfatara crater at the BG and BN fumarole vents (Chiodini *et al.*, 2011). In the January 2013 the disappearance of the main fumarole recently opened and the appearance of a vent that emits high-pressure steam and liquid water up to 3-4 meters high were observed. It could be a phenomenon partly due to heavy rains during the last week of January (INGV – Osservatorio Vesuviano). This fumarolic field is still largely unknown regarding geophysical surveys mainly because of its limited space, surrounded on the eastern side by intense urbanization inside the large Agnano crater (Troiano *et al.,* 2014). Currently it is mainly affected by geochemical, thermal and seismic monitoring which may not fully explain the behaviour of fluids surface.

The geophysical characterization of the Pisciarelli structure is a crucial step for improving our capability to forecast pre-eruptive scenarios. In particular, electrical and electromagnetic (EM) methods are among the most suitable tools in volcano-geothermal areas (e.g., Di Maio *et al.*, 1997; 1998; Legaz *et al.*, 2009; Zeyen *et al.*, 2011; Fikos *et al.*, 2012). The resistivity parameter has, indeed, a so large variability as to allow the great majority of buried structures of volcanological interest to be distinguished. To enhance the resolution power, great help is provided by the Electrical Resistivity Tomography (ERT) approach, which implies handling of

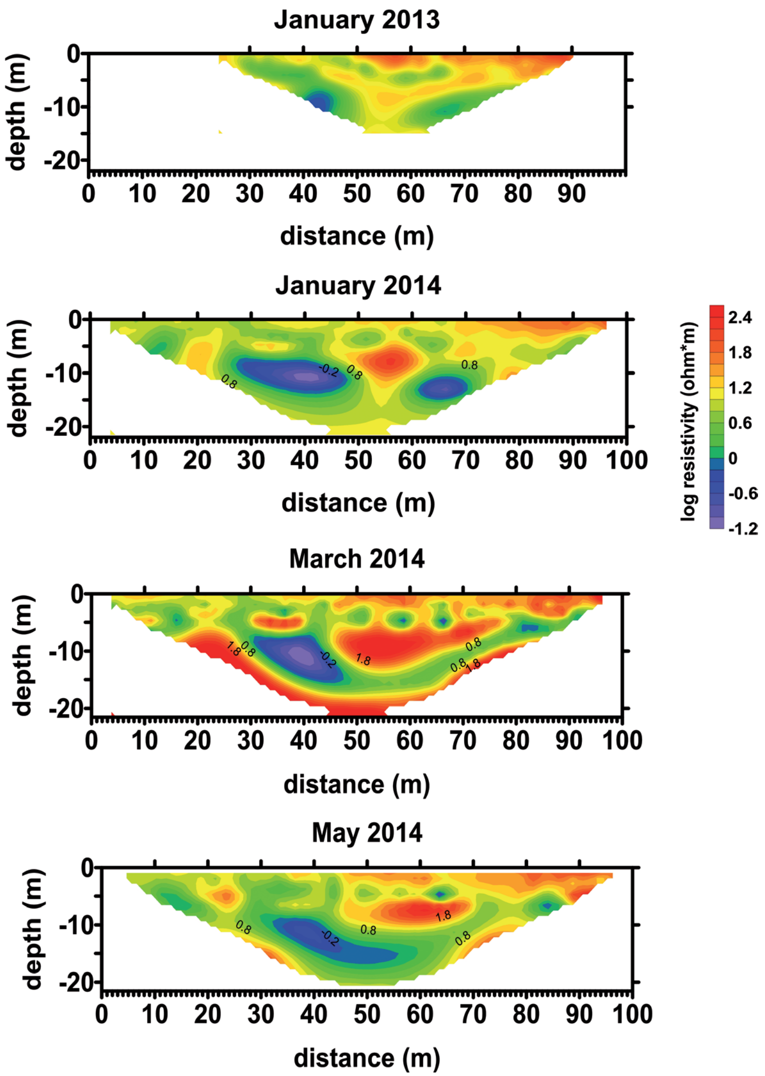

Fig. 2 – Resistivity sections related to a repeated profile in SW-NE direction carried out at four different times. All the profiles show a complex electrical distribution, presenting, in particular a resistive overburden on the whole length of the section overlaying more conductive anomalies. Moreover, a strong resistivity body (several hundred of Ohm m) appears in the central part of the survey. for all the times, localized at about 10 m depth from the surface.

large datasets, now easly collected by modern computer-assisted, multichannel resistivitymeters. Moreover, refined 2D and 3D inversion codes (e.g., Tripp *et al.*, 1984; Shima, 1990; Park and Van, 1991; Li and Oldenburg, 1992; Sasaki, 1994; Loke and Barker, 1995; Dahlin and Zhou, 2004; Mauriello and Patella, 2009) make of ERT a must for the imaging of volcanic structures down to a few hundred meters depth.

A dedicated time lapse ERT system has been developed for the long-term monitoring of the geothermal fluid circulation in the shallow aquifers at Pisciarelli fumarolic field (Campi Flegrei).

Six ERT profiles have been realized in the Pisciarelli area by a dipole-dipole configuration with a full array of maximum 42 electrodes.

The dipole-dipole electrode array consists of two sets of electrodes, the current (source) and potential (receiver) electrodes. A dipole is a paired electrode set with the electrodes located

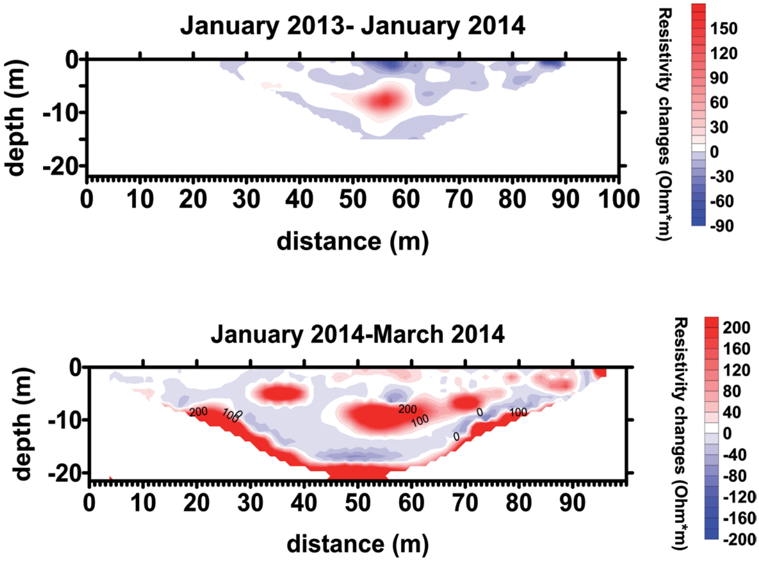

Fig. 3 – Two distinct sections evidencing the resistivity changes related to analyzed times are shown. Annual changes are reported in the first section, whereas in the second section a two-months interval has been considered.

relatively close to one another; if the electrode pair is widely spaced it is referred to as a bi-pole. The convention for a dipole-dipole electrode array is to maintain an equal distance for both the current and the potential electrodes (spacing = *a*), with the distance between the current and potential electrodes as an integer multiple of *a*. The electrodes do not need to be located along a common survey line. A primary advantage of the dipole-dipole electrode array is the ease of deployment in the field due to shorter wire lengths. However, a large generator may be needed to transmit a greater current magnitude for the measurement, especially for deep soundings. The dipole-dipole source-receiver coupling has been chosen because of its greater compactness and sensitivity to both lateral location and depth evaluation of anomaly source bodies (Ward, 1990).

As source we used the IRIS Syscal Pro ® system with maximum output voltage and current of 800 V and 2 A, respectively.

The profiles were acquired in January 2013, in January, March, May, July and September 2014 respectively. They cross the Pisciarelli area following approximately the NS direction and were characterized by a 2.5 m electrode spacing (Fig. 1b) and maximum penetration depth of about 20 m.

The ERT lines have singularly been inverted using the RES2DINV ® commercial software (Loke and Barker, 1996; Loke, 2012). The resulting 2D resistivity sections are shown in Fig. 2.

In order to highlight the dynamic of Pisciarelli area, we show in Fig. 3 two distinct sections evidencing the resistivity changes related to some of analysed times. Annual changes are reported in the first section, whereas in the second section a two-months interval has been considered.

A zone where resistivity increase appears at about 10 m depth in the central part of the survey. This feature appears in both sections mud pool resulting more evident in the period January-March 2014. In the proximity of the principal vent of Pisciarelli, an ulterior resistivity increasing emerges.

Finally, in an almost uniform layer, at bottom of the second section, a further resistivity enhancement is present.

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