

Bulletin of Volcanology

Magnetotelluric imaging of the resurgent caldera on the island of Ischia (Southern Italy): inferences for its structure and activity

--Manuscript Draft--

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| Manuscript Number: | BUVO-D-17-00072R4 |
| Full Title: | Magnetotelluric imaging of the resurgent caldera on the island of Ischia (Southern Italy): inferences for its structure and activity |
| Article Type: | Research Article |
| Corresponding Author: | Stefano Carlino Istituto Nazionale di Geofisica e Vulcanologia Sezione di Napoli ITALY |
| Corresponding Author Secondary Information: | |
| Order of Authors: | Maria Giulia Di Giuseppe Antonio Troiano Stefano Carlino |
| Funding Information: | |
| Abstract: | <p>The island of Ischia (located in the Bay of Naples, Italy) represents a peculiar case of a well-exposed caldera that has experienced a large (>800 m) and rapid resurgence, accompanied by volcanic activity. What drives the resurgence of calderas is a crucial issue to investigate, because this process is associated with potential eruptions and high risk to people living within and around such large active volcanic systems. To improve the knowledge of volcano-tectonic processes affecting the caldera of Ischia electromagnetic imaging of the structures associated with its resurgence was performed and integrated with available geological information. A magnetotelluric (MT) survey of the island was carried out along two main profiles through the central-western sector, providing an electrical resistivity map to a depth of 3 km. These resistivity cross-sections allowed us to identify the presence of a very shallow magmatic intrusion, possibly a laccolith, at a depth of about 1 km, which was responsible for both the resurgence and the volcanic activity. Furthermore, the tectonic structures bordering the resurgent area and the occurrence of a large thermal anomaly in the western sector of the caldera also provided a signature in the resistivity cross-sections, with the magma intrusion producing advection of hot fluids with high geothermal gradients (>150 °C km⁻¹) in the southern and western sectors. All of these data are fundamental for the assessment of the island's volcano-tectonic dynamics and their associated hazards. The structure and activity of the island have been controlled by the process of resurgence associated with the arrival of new magma and the progressive intrusion of a laccolith at a shallow depth. The reactivation of such a shallow system may imply imminent eruption which would pose a major volcanic hazard.</p> |
| Response to Reviewers: | <p>Dear Editor</p> <p>We would like to thank you for your further revision that greatly improved the quality of the work. All your corrections and comments have been reported and followed in the new text. Figure and captions have also been changed. You can find all the changes in the tracking copy of the paper. We cannot reported the vertical scale in the figure 8 because it is difficult to read due to the points of view. We avoid this problem reporting the height of the Mt. Epomeo.</p> <p>Regards</p> |
| Author Comments: | <p>In this work we provide new data about the active volcanic island of Ischia (Gulf of Naples, Italy) inferred from a geophysical survey. In particular, a magnetotelluric survey of the island has been performed along two main profiles of the central-western sector, obtaining the first electrical resistivity map down to a depth of 3km. The island undergone to a resurgence process, of at least 800m, forming a central uplifted block around which explosive and effusive volcanic activity occurred during the last 55ka (last eruption occurred in 1302). The island is still active and is characterized by a large</p> |

hydrothermal system with high heat flow and geothermal gradient up to 250°Ckm⁻¹. The presence of a stable population of about 65.000 units, and more than 1.500.000 visitors during the spring-summer season, makes the volcanic risk of this area very high. The volcano dynamic of the island is thus necessarily to be evaluated, firstly by improving the knowledge of shallow and deep geology of the island. The interpretation of resistivity variations allow us to recognize the main volcano-tectonic features of central-western part of the island, along the two profiles, such as the presence of a possible very shallow magmatic intrusion to a depth of about 1km, the tectonic structures bordering the resurgent area and the occurrence of large thermal anomaly of the western sector. All these data are fundamental for the assessment of volcano-dynamic of the island and associated risk.

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1 **Magnetotelluric imaging of the resurgent caldera on the island of Ischia (Southern Italy):**
2 **inferences for its structure and activity**

3 Di Giuseppe, M. G., Troiano, A. and *Carlino, S.

4 Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli – Osservatorio Vesuviano (Italy)

5 *Corresponding author: stefano.carlino@ingv.it

6

7 **Abstract**

8 The island of Ischia (located in the Bay of Naples, Italy) represents a peculiar case of a well-
9 exposed caldera that has experienced a large (>800 m) and rapid resurgence, accompanied by
10 volcanic activity. What drives the resurgence of calderas is a crucial issue to investigate, because
11 this process is associated with potential eruptions and high risk to people living within and around
12 such large active volcanic systems. To improve the knowledge of volcano-tectonic processes
13 affecting the caldera of Ischia electromagnetic imaging of the structures associated with its
14 resurgence was performed and integrated with available geological information. A magnetotelluric
15 (MT) survey of the island was carried out along two main profiles through the central-western
16 sector, providing an electrical resistivity map to a depth of 3 km. These resistivity cross-sections
17 allowed us to identify the presence of a very shallow magmatic intrusion, possibly a laccolith, at a
18 depth of about 1 km, which was responsible for both the resurgence and the volcanic activity.
19 Furthermore, the tectonic structures bordering the resurgent area and the occurrence of a large
20 thermal anomaly in the western sector of the caldera also provided a signature in the resistivity
21 cross-sections, with the magma intrusion producing advection of hot fluids with high geothermal
22 gradients (>150 °C km⁻¹) in the southern and western sectors. All of these data are fundamental for
23 the assessment of the island's volcano-tectonic dynamics and their associated hazards. The structure
24 and activity of the island have been controlled by the process of resurgence associated with the
25 arrival of new magma and the progressive intrusion of a laccolith at a shallow depth. The
26 reactivation of such a shallow system may imply imminent eruption which would pose a major
27 volcanic hazard.

28

29 **Introduction**

30 The resurgence of calderas was defined by Smith and Bailey (1969) as the process of uplift that
31 usually occurs in the form of a structural dome that takes place after a caldera collapse. The uplift
32 and bending of both the floor and roof of the caldera produce fracturing, faulting and, thereby,
33 enhance the development of permeability channels (Kennedy *et al.*, 2012). While generation of

34 highly permeable network promotes the circulation of hot fluids, forming magmatic-hydrothermal
35 systems (Hulen *et al.*, 1987), faulting and fracturing can also facilitate the migration of magma to
36 the surface and, eventually, an eruption (Kilburn, 2003). Thus, resurgence plays a central role in the
37 evolution of calderas, but the processes involved are still unclear, in particular with regard to the
38 causes and the timing of uplift. The most common process associated with the resurgence of
39 calderas is the influx or intrusion of magma at various depths (Fridrich *et al.*, 1991; Saunders, 2001;
40 Jellinek and De Paolo, 2003; Kawakami *et al.*, 2007). Other mechanisms contributing to resurgence
41 have been suggested, such as combination of regional detumescence and viscous rebound (Smith
42 and Bailey, 1969; Marsh, 1984), volatile exolution and gas overpressure (Marsh, 1984), thermal
43 expansion of the caldera fill (Kennedy and Stix, 2003) and the disturbance of geothermal fluids
44 (Hurwitz *et al.*, 2007; Chang *et al.*, 2010, Troiano *et al.*, 2011).

45 A crucial question is thus, what drives resurgence within calderas and (if magma is involved in this
46 process), at what depths and of what volumes are the resultant intrusions? In the latter case,
47 depending on the volcano-tectonic setting, the rate of uplift of the area and magma viscosity
48 (Pollard and Johnson, 1973; Smith and Bailey, 1969; Acocella *et al.*, 2001; Carlino, 2012), the
49 magmatic intrusion may evolve in a range of ways (e.g. to be emplaced as sills, dikes or laccoliths)
50 producing a variable amount of uplift and a variety of resurgence structures (Paige, 1913; Orsi *et al.*,
51 1991; Henry *et al.*, 1997; Acocella *et al.*, 2001 and references therein). The recognition of such
52 differences is fundamental in the understanding a caldera structure and any associated hazard. As a
53 result the shallow and deep structures of calderas need to be better investigated through the
54 application of effective geophysical methods. Among the geophysical surveys that can improve the
55 knowledge of the deep structures of calderas, electrical resistivity mapping represents a reliable tool
56 in the assessment of the buried structures in volcanic settings (Troiano *et al.*, 2008; Troiano *et al.*,
57 2009; Revil *et al.*, 2010; Troiano *et al.*, 2014; Di Giuseppe *et al.*, 2015; Di Giuseppe *et al.*, 2017b).
58 In this work, a magnetotelluric (MT) survey was applied to the active volcanic caldera of Ischia,
59 whose resurgence is thought to be associated to a sill intrusion, possibly developed in the form of a
60 laccolith (Rittman, 1930; Sbrana *et al.*, 2009; Carlino *et al.*, 2006; Carlino, 2012 and references
61 therein). The resurgence, which is estimated as at least 800 m (Vezzoli, 1988), was accompanied by
62 volcanic activity and by the exhumation of the geothermal system (Sbrana *et al.*, 2009), with the
63 occurrence of a large diffuse heat flow and very high geothermal gradients ($>180^{\circ}\text{C km}^{-1}$) in the
64 shallow crust (Vezzoli, 1988; Carlino, 2012; Carlino *et al.*, 2014; Carlino *et al.*, 2015). Although a
65 numbers of local geophysical investigations have been performed at Ischia (Di Napoli *et al.*, 2009,
66 2011; Paoletti *et al.*, 2013), a wider geophysical imaging of the island is not yet available. Such
67 knowledge represents a crucial task in supporting physical modeling (Rinaldi *et al.*, 2011), to

68 improve the understanding of the caldera's structure and activity, and to assess the associated
69 hazard on the island.

70 The MT survey was carried out in the central-western sector of the island. Through this survey, the
71 electrical resistivity distribution was reconstructed in correspondence to two separate profiles
72 (deployed in a N-S and a WSW-ENE direction respectively) (Figure 1). In this fashion two
73 resistivity sections, respectively about 5 km and 3 km long, were obtained and interpreted to
74 highlight the main geological features of the crust to a depth of 3 km including its thermal state, as
75 well as location of fluid circulations and structural discontinuities within both the collapsed and the
76 uplifted areas. The results provide new insights regarding both the thermal situation pertaining on
77 the central-western sector of the island and the circulation of geothermal fluids. We find presence of
78 a crystalline structure (intrusive rocks with very low permeability) located beneath the Mount
79 Epomeo block (Figure 1), which possibly represents the apical part of a degassed and cooling
80 magmatic source (laccolith). The results obtained are important, not only because of the volcanic
81 risk on the island (which has about 65,000 inhabitants and more than 1,500,000 visitors during the
82 spring and summer months) but also for the volcano-tectonic evolution observed in many calderas
83 worldwide, during resurgence.

84

85 **Main geological features of the island**

86 The volcanic field of Ischia is part of the Phlegrean Volcanic District (Figure 1). The rim of Ischia
87 caldera, which formed after the Mount Epomeo Green Tuff (MEGT) eruption, 55 ka (Vezzoli,
88 1988), is not well documented, although there are a few signs of the rim in the NW, SW and SE
89 sectors (Tibaldi and Vezzoli, 1998). The caldera, it would seem, has an elliptical shape with its
90 major axis running ENE-WSW (Vezzoli, 1988). The island's most important structural element is
91 the 4x4 km² resurgent block of Mount Epomeo (formed mainly by the MEGT), located in the centre
92 of the caldera, which has been uplifted over the last 55 ka by a magmatic intrusion (Rittman, 1930;
93 Sbrana *et al.*, 2009). The edges of this block are marked by a system of sub-vertical faults with
94 NW-SE, NE-SW and N-S strike (Vezzoli, 1988; Acocella and Funiciello, 1999; Tibaldi and
95 Vezzoli, 1998) (Figure 1). The existence of a possible magmatic intrusion, associated with the
96 resurgence and post-caldera volcanic activity, was first inferred from gravity surveys by Carrara *et*
97 *al.*, (1983) and Nunziata and Rapolla (1987). More recently, the model of laccolith intrusion
98 (proposed by Rittman, 1930) has been taken up again by interpreting stratigraphy, deep
99 temperature, geochemical, magnetic, electric and gravity data (Carlino *et al.*, 2006; Sbrana *et al.*,
100 2009; Carlino 2012; Paoletti *et al.*, 2013). Sbrana *et al.* (2009) provided a model of resurgence of
101 the island by using an integrated analysis of melt and fluid inclusions, mineralogy and stable

102 isotopic compositions of pumices, tuffs and syenitic xenoliths. In this model the engine of the
103 hydrothermal system of Ischia can be identified as being a shallow magmatic system (at a depth of
104 2 km) that hosts hot trachytic magma. Accordingly, Carlino *et al.*, (2006) and Carlino (2012)
105 showed, through analytical modeling of the bending and fracturing of an elastic plate, that the
106 resurgence of Mount Epomeo block may be associated to a sill-like intrusion which developed,
107 during its later stages, into a laccolith, the top of which is located at a depth of about 2 km. Paoletti
108 *et al.* (2013), using an integrated analysis of geophysical data, highlighted the presence of a possible
109 magmatic intrusion, with a temperature below the Curie point, a density of about 2.4 g cm^{-3} and its
110 top at a depth of about 2 km. The top of this magma body is slightly off-center, being in the
111 southwestern part of Ischia where fumaroles emissions are focused (Chiodini *et al.*, 2004). The total
112 estimated uplift of the Mount Epomeo block, deduced from the present height of marine deposits
113 and eustatic variations, is 710 m in the southern sector and 920–970 m in the northern sector, with
114 average rate of uplift ranging from 2.3 to 3.3 cm a^{-1} (Barra *et al.* 1992; Tibaldi and Vezzoli 2004;
115 Carlino *et al.* 2006). During the resurgence over the last 28 ka, most of the eruptive centres have
116 been aligned along the caldera structure (Vezzoli, 1988). Between 28 ka and 18 ka the volcanic
117 activity migrated to the SW and SE sectors of the island (Fusi *et al.*, 1990). However, during the
118 most recent period of activity, from 10 ka to 1302 A.D., the eruptive centers have become clustered
119 in the eastern and northern sector, with the emission of domes and lava flows (de Vita *et al.*, 2010).
120 The last eruption in the island took place in 1302 A.D. (de Vita *et al.*, 2010)

121 The circulation of hydrothermal fluids on the island is linked to its volcano-tectonic structural
122 setting, whose permeability is controlled by the relative location of lavas and pyroclastic deposits.
123 Fluid circulation is thus correlated with the occurrence and interlayering of different deposits, and
124 mostly takes place at pathways of high permeability such as at fractures and faults in welded tuffs
125 and lavas and within the pores of unconsolidated pyroclastic deposits (Celico *et al.*, 1999; Carlino *et al.*,
126 2014). The shallow stratigraphy of the western sector (down to a depth of 1 km) has been
127 inferred from borehole measurements (Penta and Conforto, 1951; see figure 1 for borehole
128 locations). In the central zone of Mt. Epomeo and along its boundary while coarse volcanic deposits
129 form a shallow permeable layer, fractured tuffs, lavas and marine clay deposits make up semi-
130 permeable and impermeable layers, respectively. In the western area of the island the aquifer
131 generally has a lower transmissivity than in the eastern sector (Celico *et al.*, 1999). The effect of
132 volcano-tectonic structures is noticeable above the main faults bordering Mt. Epomeo, where the
133 shallow aquifers have been pushed upward in correspondence to the uplift of the block (Sbrana *et al.*,
134 2009; Carlino *et al.*, 2014). Along the western faults hot springs are located about highly
135 permeable path ways associated with high thermal energies (Chiodini *et al.*, 2004) (Figure 1). Also

136 inferred in the western sector is the occurrence of mixing processes between marine water and
137 hydrothermal fluids, testified to by the high salinity of the fluids sampled close to the coast (Celico
138 *et al.*, 1999; Di Napoli *et al.*, 2011). In the southwestern sector of the island the shallow resistivity
139 model obtained by Di Napoli *et al.* (2011) highlights the presence of a zone of high conductivity,
140 whose top is located at a depth of about 100 m and which is related to the superficial hydrothermal
141 reservoir. Geothermal gradients of the island are typically very high, ranging in the hottest areas
142 (south-western sector) from $180\text{ }^{\circ}\text{C km}^{-1}$ to $200\text{ }^{\circ}\text{C km}^{-1}$ (AGIP, 1987). These high gradients are
143 associated with an efficient heat transport from the reservoir through an advection-dominated
144 system (Carlino *et al.*, 2012; Carlino *et al.*, 2014). Taking into account these gradients, the
145 transition from a brittle to semi-brittle regime should take place at a depth of about 2-3 km (Carlino
146 *et al.*, 2014), while the depth of the brittle crust is possibly deeper in the north with respect to the
147 southern sector (Carlino *et al.*, 2006). At present time the island is subject to slow subsidence,
148 reflecting a gradual depressurization of the magmatic or hydrothermal system beneath Mount
149 Epomeo (Sepe *et al.*, 2007; De Martino *et al.*, 2011).

150

151 **MT data collection, analysis and inversion.**

152 To characterize the first few kilometers of the crust of the island of Ischia a magnetotelluric survey
153 was performed. Magnetotellurics is an electromagnetic geophysical method for measuring the
154 resistivity of the earth's interior by recording the natural electric (**E**) and magnetic (**H**) fields on the
155 surface (Vozoff, 1991) as they vary over time. In the present application, fluctuations of the
156 orthogonal components of these fields were recorded at 20 measurement sites (see figure 1 for
157 locations). Measurements were carried out using a Stratagem EH4 instrument, produced by
158 Geometrics. Only the horizontal components of the **E** and **H** fields were recorded, neglecting the
159 sampling of Hz which is usually considered as only providing limited additional information
160 regarding the dimensionality of the Earth's local structure (Vozoff, 1991; Simpson and Bahr, 2005).
161 Once data set of field fluctuations over time had been collected, the underground resistivity
162 complexity was obtained as a rank-2 tensor, **Z**, correlating the two orthogonal pairs (E_x , E_y) and
163 (H_x , H_y) at the Earth's surface in the frequency-domain. This tensor is correlated with the MT
164 apparent resistivity and phase curves, which compose the final dataset. To estimate such curves, the
165 collected time series spectra have been estimated using a short period Fourier transform performed
166 over the $10^{-4} \sim 10^1$ s range. Such a period was examined to investigate the structures located across
167 the first few kilometers of depth below ground level. The investigated depth of the electromagnetic
168 waves depends on their capacity to penetrate into the Earth. This, in turn, is directly related to rock
169 resistivity. In a uniform substrate the electric and magnetic fields weaken exponentially with depth,

170 the more conductive the rock, the lower the penetration. The depth at which the fields decline to e^{-1}
171 of their values at the surface is termed the skin depth $\delta = (2\rho/\omega\mu)^{1/2} \approx 500(\rho/f)^{1/2}$ (in meters)
172 where, ρ is the resistivity, f is the frequency of the wave, $\omega = 2\pi f$ and μ is the permeability. The
173 latter is usually taken as being equal to μ_0 (free space permeability), except in highly magnetic
174 materials. Frequency enters into the equations because the magnitudes of the induced telluric
175 currents depend on the rate of change of the magnetic fields over time (Vozoff, 1991, Simpson and
176 Bahr, 2005).

177 After the application of short period Fourier transform, data belonging to each of the MT surveys
178 were analyzed using the algorithm of Egbert and Booker (1986). This was used to avoid the
179 distortion in the estimated MT curves, which might emerge from the time series due to the presence
180 of anthropic noise, especially for surveys in urban environments. This kind of algorithm has proven
181 to be effective in the case of single station MT surveying (Egbert and Livelybrooks, 1996; Bai *et*
182 *al.*, 2001; Brasse *et al.*, 2001; Pous *et al.*, 2002). Its application in such a context was tested during
183 the electromagnetic imaging of the nearby Campi Flegrei area (Troiano *et al.*, 2014; Di Giuseppe *et*
184 *al.*, 2017a) to analyze MT soundings. Its performance also proved to be adequate in the case of
185 Ischia and the MT curves obtained do not appear affected by anomalous behavior, such as a strong
186 scattering of the points, strong oscillations or rises in the apparent resistivity, etc., that might signal
187 the presence of coherent noise. Finally, the MT curves were analyzed using both MT-corrector[®] and
188 Winglink[®] commercial software (Figure 2).

189 One of the first issues concerning magnetotelluric data is the *static-shift* (Jones, 1988). The data
190 may suffer a sort of indetermination in the level of the apparent resistivity curves, due to the
191 galvanic effects of shallower bodies. Such an issue, that does not affect the phase curves, was taken
192 into account by carrying out Local Electrical Resistivity Tomographies (ERT). ERT, being based on
193 a DC current source, does not suffer such issues and it is possible to use tomography of this kind to
194 synthetically reconstruct the correct level of the MT apparent resistivity at high frequency. Two
195 separate profile lines, which were oriented along N-S and the WSW-WNE transects were set up.
196 These profiles, 5 km and 3 km long respectively, covered the central-western sector of the island
197 (figure 1). For each of the two profiles the apparent resistivity and phase curves relative to both the
198 TM (Transverse magnetic) and TE (Transverse electric) modes are shown in figure 3, under
199 pseudosection form (Vozoff, 1991).

200 As an initial step, the MT data dimensionality was analyzed. The introduced \mathbf{Z} , which correlates the
201 electric and magnetic fields on the Earth surface, presents peculiar characteristics in the case of 1D
202 or 2D symmetries actually present in the data (Vozoff, 1991; Simpson and Bahr, 2005; Troiano *et*
203 *al.*, 2009) and several approaches exist in the literature to investigate this issue, namely the Wal

204 method (Weaver *et al.*, 2000), phase tensor analysis method (Caldwell *et al.*, 2004) and Groom and
205 Bailey's method (McNeice and Jones, 2001).

206 In the present case, phase tensor analysis has been applied. This method, introduced by Caldwell *et*
207 *al.* (2004) was well-described in Berdichevsky and Dmitrev (2010), where it is possible to retrieve
208 details regarding the methodology, the definition of the phase tensor $[\Phi] = \begin{bmatrix} \Phi_{xx} & \Phi_{xy} \\ \Phi_{yx} & \Phi_{yy} \end{bmatrix}$ and all the
209 derived quantities. Figure 4 reproduces the behavior of the orientation of the phase tensor ellipse,
210 i.e. the $\alpha_1 = \frac{1}{2} \sin\left(\frac{\Phi_{xy} + \Phi_{yx}}{\Phi_{xx} + \Phi_{yy}}\right)$ angle, defined in Berdichevsky and Dmitrev (2010); it is also
211 reproduced the Caldwell-Bibby-Brown Skew angles, $skew_{CBB} = \frac{1}{2} \arctan\left(\frac{\Phi_{xy} - \Phi_{yx}}{\Phi_{xx} + \Phi_{yy}}\right)$, for every
212 survey, over four distinct frequency bands, respectively centered on 0.9, 9, 90 and 900 Hz. In a
213 model with the two-dimensional regional background, $skew_{CBB} = 0$ and the principal directions of
214 the phase tensor coincide with the α_1 angle. In the case of a 3D asymmetric regional background
215 $skew_{CBB} \neq 0$. This angle represents a correction for the regional background asymmetry, which can
216 be neglected if small, so that we can rely on the 2D approximation of the regional background. As
217 expected in a volcanic context, the $skew_{CBB}$ does not seem to present a behavior adequate to support
218 a 2D inversion and a different approach has to be pursued. It is worth noting that this step is the
219 basis on which to choose one of the possible strategies that might prove to be more satisfactory for
220 the data inversion.

221 Despite the well-tested 2D approach generally being thought of as the optimal to choose in terms of
222 a compromise between the numerical complexities of the task and the affordability of the results, its
223 incorrect application can lead to very misleading results and examples exist in literature where the
224 differences originating from a 3D reinterpretation of previously analyzed MT data have led to
225 models having very different implications (Booker, 2014). On the other hand, even if various 3D
226 inversion codes have been proposed in the literature (Siripunvaraporn *et al.*, 2005a; Kelbert *et al.*,
227 2014) and if 3D inversion has been actually developed in MT surveying (Rosenkjaer *et al.*, 2015;
228 Yang *et al.*, 2015), such a procedure is still not totally stable and requires a high number of
229 sampling sites to be applied. In the Ischia survey work, the morphological conditions limited the
230 number of sites and imposed the alignment of the sites along two crossed lines. This configuration
231 has to be taken into account when the inversion strategy is questioned.

232 Many papers in the literature consider 3D inversion of 2D profiles (e.g. Ledo *et al.*, 2002;
233 Siripunvaraporn *et al.*, 2005b). These highlight the limits of this approximation when the TM and
234 TE apparent resistivity and phase are considered separately. Such a situation has also already been
235 dealt with in Troiano *et al.* (2014), who presented a 3D inversion of an electromagnetic survey
236 carried out in the Campi Flegrei area. In this case, the 1D inversion of the Z determinant has proved

237 to be a useful tool to set up a strategy to interrogate the effects of buried structures in 3D based on
238 2D survey profiles. Such considerations prove to be particularly significant in volcanic
239 environments (Ranganayaki, 1984; Pedersen and Engels, 2005; Troiano *et al.*, 2014) and the
240 resistivity model that can be obtained through this step, despite the strong limitation linked to the
241 1D approximation.

242 The likely indetermination related to the effects due to the eventual presence of lateral anomalies on
243 the MT sections were here taken into account through a 3D based trial-and-error procedure
244 (Troiano *et al.*, 2014). The latter was carried out through the use of the subroutines of the
245 WingLink® commercial code in order to estimate the apparent resistivity and phase curves. The
246 subsoil was divided up into $76 \cdot 79 \cdot 36$ cells, with dimensions ranging from 50 m (in the core of the
247 modeled area) up to 1 km (in the external zones) and an objective function was derived, based on
248 the misfit between measured and reconstructed apparent resistivity and phases. This trial-and-error
249 procedure begins with the resistivity model obtained using the 1D inversion of the Z determinant. A
250 wide range of alternative models were then compared, taking as the most adequate that related to
251 the lowest root mean square (r.m.s.). At the end of the procedure, an optimal model, corresponding
252 to an r.m.s. less than seven, was selected. We note that the r.m.s. value obtained here was
253 compatible with those presented for similar applications (e.g. Schwalenberg *et al.*, 2002; Abdul
254 Azeez and Harinarayana, 2007; Rao *et al.*, 2007; Heise *et al.*, 2008; Arango *et al.*, 2009; Troiano *et*
255 *al.*, 2009 and Troiano *et al.*, 2014).

256 An error threshold of 5% was considered for both the apparent resistivity and phase curves. More
257 details for the data analysis and inversion procedures can be found in Troiano *et al.* (2008) and
258 Troiano *et al.* (2014). The sections corresponding to the two profiles of figure 1 are represented in
259 figure 5 and figure 6, respectively. The main electrical anomalies have been labeled with capital
260 letters and will be interpreted geologically in the following section.

261 Considering a mean electrical resistivity for the medium of about $100 \Omega\text{m}$, the maximum period of
262 10 s was found to be associated with a wave penetrating more than 15 km into the crust. The
263 models of figure 5 and figure 6 resolve to a maximum depth of about 3 km.. A full sensitivity
264 analysis was also carried out, following Schwalenberg *et al.* (2002). In figure 7 the sensitivity maps
265 are reported, relative to the resistivity cross-sections of both figures 5 and 6. Sensitivity represents
266 an estimate of the changes induced in the data by infinitesimal variations in the underground
267 electrical resistivity. There is no univocal threshold for the sensitivity required to indicate that a
268 structure is well resolved, but the procedure presented in Troiano *et al.* (2008) and Troiano *et al.*
269 (2009) supports the conclusion that both our resistivity cross-sections are reliable. The consistency
270 of the main bodies retrieved in the sections was further questioned by removing the anomaly from

271 the model and recalculating the relative r.m.s. Significant r.m.s. variations with respect to the error
272 thresholds can be considered as an indicator that the investigated part of the model exhibits good
273 resolution. For example, in the NS section of figure 5, the resolution of the zones labeled as A, B1,
274 B2 and C was tested. When the resistivity of the model was modified only zone A, substituting the
275 few tens of Ωm retrieved with the data inversion using the 200 Ωm identified in the surrounding
276 area, a 13.4% change in the r.m.s. was obtained. This indicates that the A zone exhibits good
277 resolution. Analogous results were obtained for all other zones.

278

279 **Results**

280 The resistivity imaging of the island of Ischia has allowed us to recognize a number of sectors,
281 down to a depth of 2-3 km, with resistivity anomalies that are ascribable to distinctive processes and
282 physical conditions of the hydrothermal system below the caldera. From the S-N profile (Figure 5),
283 moving from south to north, it is possible to highlight a relatively high resistivity zone extending to
284 station I6 (Ischia6) (this is zone A where resistivity values of thousands of Ωm). There is then a
285 lower resistivity channel (zone B, with a few tens to hundreds of Ωm) between the measurement
286 stations I7 and I8, and a high resistivity zone (C) beneath the Mt. Epomeo resurgent block (several
287 thousands Ωm at a depth below 1000 m, between stations I5 and I13). A further zone of lower
288 resistivity (zone D) occurs on the northern coast ($<50 \Omega\text{m}$).

289 Along the WSW-ENE profile (figure 6) a rapid change in resistivity (from several thousands of Ωm
290 to a few tens of Ωm) is observed to the WSW. Beyond the anomaly beneath Mt. Epomeo (C1, a few
291 thousand Ωm), four other zones can be characterized. The first one is a channel with lower resistivity
292 between the stations I20 and I21 (E) which is well developed down to the bottom of the profile (at a
293 depth of 2.5 km). Within the interior of this channel, two lower resistivity zones (a few tens Ωm)
294 appear: the first one (E1) is located at shallower depths, up to 500 m below the surface, and the
295 second one (E2) develops from a depth of about 1500 m to the bottom of the profile. Finally, a
296 roughly circular shallow area (F) with very low relative resistivity (less than ten Ωm) can be
297 identified ENE to station I18 (figure 6).

298 The agreement between the two resistivity cross-sections of figures 5 and 6 have been evaluated in
299 figure 8, where a stereographic view of the retrieved anomalies is provided. In the area where the
300 two profiles intersect our magnetotelluric imaging detects a coherent resistive structure in
301 correspondence to the Mt. Epomeo resurgent block.

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305 **Interpretation of the resistivity cross-sections**

306 The sensitivity of electrical resistivity to the presence of groundwater provides electrical and
307 electromagnetic methods with a high detectability power for resolving buried structures. However,
308 once the presence of the electrical resistivity anomalies have been inferred in volcanic settings, the
309 interpretation of the geophysical imaging remains inherently difficult. Because the resistivity of
310 rocks is generally affected by the water content, alteration (through their clay content and clay
311 mineralogy), salinity of the pore water and temperature, the physical properties of porous rocks in
312 geothermal and volcanic areas remain poorly known (e.g. Revil *et al.* 2002, Revil *et al.* 2017a and
313 Revil *et al.* 2017b). Groundwater in volcanic settings flows within porous materials, which may
314 undergo a greater or lesser degree of alteration. This alteration is due to a chemical weathering of
315 the minerals by the hot hydrothermal fluids, including hydration-dissolution processes of the
316 volcanic glass and the formation of aluminosilicates such as clays and zeolites (Schön, 2015).
317 Hydroelectric coupling in these porous rocks is influenced by the presence of these aluminosilicate
318 minerals due to their role in blocking the connected pore space. Electrical conductivity provides two
319 contributions. The first is associated with conduction within the pore water. The second is termed
320 surface conductivity and is associated with conduction in the electrical double layer coating the
321 surface of grains (Berdichevsky and Dmitriev, 2010; Schön, 2015)). Both of these processes can
322 bring about an increase in conductivity and, using only resistivity data, it is not easy to separate
323 surface from bulk conductivities at a given pore water conductivity. In our case, a numbers of
324 ambiguities in the interpretation of our data were reduced by correlating the resistivity anomalies
325 with data provided from drilling (see figure 1 for locations), down to depth of 1150 m, and with
326 previous geophysical and geochemical modeling of the island provided by Nunziata and Rapolla
327 (1987), Chiodini *et al.* (2004), Paoletti *et al.* (2005), Di Napoli *et al.* (2009), Di Napoli *et al.*, (2011),
328 Carlino (2012), Paoletti *et al.*, (2013), Carlino *et al.* (2014).

329 The resistivity contrasts between zones A, B, C and D of N-S profile (Figure 5) present a good
330 correlation with the known volcano-tectonic features of the island, such as the boundary of caldera
331 and the Mount Epomeo resurgent block. In particular, the structural limit of the caldera is
332 recognizable in the southern sector, close to the station I6. A normal fault, with a NW-SE strike
333 affecting the south-western sector of the resurgent block (see figure 1 for fault location) (Vezzoli,
334 1988), coincides with the resistivity contrast between stations I5 and I8. In addition, north of station
335 I4, the resistivity variation pattern can be interpreted as the occurrence of minor faults facilitating
336 the block uplift in the period since 33 ka ago (Vezzoli *et al.*, 2009). In the northern sector (figure 5)
337 a low resistivity zone, which deepens to about 700-800 meters down, between the coast to the inner

338 part of the island, is perhaps attributable to the interface between saline water and fresh water due to
339 the latter's buoyancy.

340 Between measurement stations I7 and I8 a lower resistivity channel can be identified (B in figure
341 5). In particular, two major anomalies (B1 and B2) have been detected along this channel. The
342 shallower one, B1, has a vertical extent of up to about 450 m b.s.l., while the deeper one, B2,
343 develops from about 1100 m to 2500 m b.s.l. Following hydrothermal studies of the island (Di
344 Napoli *et al.*, 2009, 2011) and drilling data (Penta and Conforto, 1951; Penta, 1963; AGIP, 1987),
345 we can interpret the resistivity anomalies B1 and B2 as two aquifers, the former with a temperature
346 of about 150°C, and the latter with a temperature of 250 °C (Chiodini *et al.*, 2004). These are
347 formed by mixing of liquid and vapour (Chiodini *et al.*, 2004). The lower levels of the aquifer B1
348 and the upper level of the aquifer B2 are in good agreement with the hydrothermal model proposed
349 by Di Napoli *et al.* (2011). Along the WSW-ENE profile (Figure 6) two zones, E1 and E2, have
350 been interpreted as two aquifers similar to those inferred along the N-S profile (B1 and B2). In
351 accordance with the vertical tectonic movement of the island (resurgence), the top of aquifer B2 (N-
352 S profile of figure 5) is closer to the uplift block and has been dislocated upwards with respect to
353 the aquifer E2. The bottom of the aquifers are possibly sealed by argillification processes which took
354 place before resurgence. Furthermore, as shown in Figure 9, the shape and location of the whole
355 channel exhibiting low resistivity is possibly reconcilable with a thermal anomaly (a plume)
356 associated with advection of hydrothermal fluids. This is an interpretation also supported by drill
357 hole data and by the presence of fumaroles and a hot-spring field (with temperatures up to 100°C),
358 immediately north and west of stations I20 and I21, respectively (Citara site, figure 1) (Penta and
359 Conforto, 1951; AGIP, 1987; Chiodini *et al.*, 2004; Di Napoli *et al.*, 2011; Carlino *et al.*, 2014).
360 The presence of such a thermal plume should leave a clear geophysical signature and the further
361 surveys might allow it to be fully characterized (Jardani *et al.*, 2008).

362 One of the main features of the resistivity images is the occurrence of a high resistivity zone (>1000
363 Ωm) in both the N-S and WSW-ENE sections (see zones C and C1 in figures 5 and 6, respectively,
364 as well as figure 8). This anomaly is delimited by the faults bordering the resurgent block.
365 Considering the high heat flow and the elevated geothermal gradient of the area (Carlino *et al.*,
366 2014), the relatively high resistivity anomaly (C and C1) can be explained in terms of permeability.
367 High resistivity can be associated with a lower flow of hot hydrothermal fluids. This process,
368 typical of many volcanic areas (Marsh, 1984), is related to the occurrence of crystalline rocks such
369 as intrusive bodies with very low permeability (k) which ranges from 10^{-17} to 10^{-21} m² for granite,
370 for example (Brace, 1980). Such low permeabilities would inhibit the passage of fluids because the
371 minimum permeability for volatiles to transfer into the shallow crust is 10^{-20} to 10^{-18} m², while for

372 fluid transfer the figure is $\geq 10^{-16} \text{ m}^2$ (Ingebritsen *et al.*, 2010). Furthermore, geochemical and
373 isotopic investigations (Tedesco, 1996) have highlighted the presence of magmatic fluids, which
374 probably escape laterally from below to the magma body because they encounter a permeability
375 barrier in a higher more crystalline part. The presence of a shallow magmatic body ($\approx 2 \text{ km}$ in
376 depth) beneath the Mount Epomeo resurgent structure, has already been inferred by other authors
377 from interpretation of magnetic and gravity data (Nunziata and Rapolla, 1987; Paoletti *et al.*, 2013
378 and references therein). For instance, the contemporary presence of a magnetic minimum and a
379 gravimetric maximum (slightly decentred to the SW with respect to the centre of the island), might
380 be explained by the existence of an intrusion or several intrusions and/or by partially melted zones
381 to create pockets of crystal mush. This hypothesis is supported by the high temperature gradient
382 measured in the central-western sector of the island (Penta and Conforto, 1951; Penta, 1954;
383 Ippolito and Rapolla, 1982; Panichi *et al.*, 1992; Paoletti *et al.*, 2009). Furthermore, an undated
384 intrusive rock was found at the bottom of the 1050 m deep drilling, located west of Mount Epomeo
385 (well 2 in Figure 1) (Penta and Conforto, 1951; AGIP, 1987). Our findings seem to confirm the
386 presence of such a shallow magmatic body with a bulge penetrating up to about 1 km below the
387 surface. Furthermore, taking into account the geothermal gradient of the island (about $200^\circ\text{C km}^{-1}$)
388 (see Carlino *et al.*, 2012, 2014 for details) the solidus temperature (onset of melting) may be
389 encountered at a depth $>3 \text{ km}$.

390 As a whole, we are confident that this magmatic body represents an intrusion and cannot be related
391 to other high resistivity structures, such as an uplifted basement or unfractured rocks filling the
392 caldera. Further observations supporting our statement include: the high rate of resurgence of Mt.
393 Epomeo, which indicates a magmatic process (injection) as driving mechanism (Tibaldi and
394 Vezzoli, 2004; Sbrana *et al.*, 2009) as driving mechanism; the observed pattern of deformation that
395 can be associated with a shallow magmatic source with its top at about 2 km b.s.l. (Carlino, 2012);
396 the observation that new trachybasaltic magma arrived in the shallow magmatic system before the
397 volcanic activity 28-18 ka (Civetta *et al.*, 1991); the melt inclusion data that reveal that the eruptive
398 products of 73-59 ka came from a magmatic storage region located at a depth of about 2 km
399 (Sbrana *et al.*, 2009) and, finally, the very high geothermal gradient and high temperature
400 hydrothermal system, associated with the presence of a shallow magmatic body (Sbrana *et al.*,
401 2009; Carlino *et al.*, 2012, 2014).

402 The resistivity anomaly (figure 8) perhaps thus represents the apex of a laccolith (or alternatively a
403 series of cone sheets) (Westerman *et al.*, 2004) intruded into the shallow crust of the island
404 (Rittman, 1930; Sbrana *et al.*, 2009; Paoletti *et al.*, 2013; Carlino *et al.*, 2006; Carlino, 2012), over
405 the least 33 ka (Carlino, 2012 and references therein). Considering both the N-S and WSW-ENE

406 profiles, the intrusion seems to have a branch that is elongated NS in the western sector of Mt.
407 Epomeo.

408 Finally, we can compare the WSW-ENE profile with the geology of the island (*Carta Geologica*
409 *dell'isola d'Ischia*, CARG project), which in this sector is mainly constrained by the stratigraphy
410 revealed from the drilling (figure 10). As we seen in figure 10, around station I20 the resistivity
411 anomaly ($>2000 \Omega\text{m}$) corresponds to the Punta Imperatore lavas and to the eruptive center of
412 Campotese (see also figure 1). These lavas, dated to about 177 ka (Gillot *et al.*, 1982), are dissected
413 by faults that possibly do not involve the more recent, overlying, deposits and that are associated
414 with collapse of the caldera rim. The contrast in resistivity highlights the difference between the
415 lower consolidated deposit of the inner caldera and the structural domes at the caldera rim. ENE to
416 station I18 a very low resistivity area coincides with the most important fumarole field of the island
417 (Bocca di Serra, Donna Rachele fumaroles). The fumarole field covers about 0.80 km^2 (80
418 hectares), with emissions totaling $\approx 9 \text{ td}^{-1}$ (volume) of CO_2 that rise along a system of vertical faults
419 (Chiodini *et al.*, 2004). This system is perhaps partly fed by a relatively deep hydrothermal aquifer
420 (about 600 m deep) (Chiodini *et al.*, 2004), whose fluids take advantage of the structural
421 discontinuity (faults and fractures system) located at the boundary of the uplifted block. We also
422 note a coincidence between the variation in lithology encountered in the stratigraphy of the drillings
423 (drillings 2 and 4, see figure 1 for location) (AGIP, 1987) and the variation in resistivity
424 encountered in our cross-sections (figure 11a, b). Finally, in order to assess the influence of the
425 intrusion on the tilting of the Mt. Epomeo block (Acocella and Funiciello, 1999) we need to
426 improve our measurements to get a wider 3D imaging, because the resistivity anomalies seem to
427 have a complex shape that cannot be well constrained by 2D inversion.

428

429

430 **Discussion**

431 Of the varying interpretations of the caldera resurgence process, the most common is that of
432 magmatic intrusion which can evolve in a range of ways, from sills, to dikes or laccoliths (Paige,
433 1913; Henry *et al.*, 1997; Acocella *et al.*, 2001 and references therein). This process is generally
434 associated with the formation of well-developed geothermal systems (Hulen *et al.*, 1987). One
435 implication of this study involves the mechanism producing resurgence of calderas. As in the case
436 of Ischia, the relatively high rate of uplift, which provides a strain rate of at least one order of
437 magnitude larger than tectonic processes (Carlino, 2012), excludes a regional tectonic contribution.
438 The long-term rate of uplift makes it possible also to exclude any non-purely magmatic contribution
439 to the resurgence, such as the oversaturation of volatile species in a shallow and crystallising

440 magma body (Tait *et al.*, 1989) or a fluid contribution (Hurwitz *et al.*, 2007). These processes are
441 typically associated to relative small-scale (metres) and short-term (months to years) disturbances
442 and, as in the case of the contribution of fluids, a partial recovery of the deformation occurring will
443 take place (see, for instance, the example of Campi Flegrei caldera; Troiano *et al.*, 2011 and
444 references therein). The long-term resurgence of Ischia (from at least 33 ka to 5 ka) was punctuated
445 by phases of quiescence (de Vita *et al.*, 2010), which possibly corresponded to periods of volcanic
446 activity (Carlino *et al.*, 2006). However a large proportion of the magma arriving in the shallow
447 system (Civetta *et al.*, 1991) has not been erupted, and merely contributes to the uplift of Mt.
448 Epomeo (Carlino *et al.* 2012), forming a very shallow intrusion whose occurrence seems to be
449 confirmed by resistivity data. This behaviour is different when compared to that of the nearby
450 Campi Flegrei caldera, (where some caldera sectors were uplifted by less than 100 m, while larger
451 eruptions occurred). It is instead similar to the Grizzly Peak caldera (Colorado) (Fridrich *et al.*,
452 1991) and Pantelleria (Southern Italy) (Orsi *et al.*, 1991). In these cases, the rheology of the shallow
453 magma sources and the response of the surrounding rock walls to the stress induced by the pressure
454 of the magma possibly control the different evolutions of caldera resurgence. For instance, the
455 temperature of the intruded magma and of the surrounding rock, together with the injection rate,
456 strongly affect the behaviour of the system (Jellinek and DePaolo, 2003). Large geothermal
457 gradients and low magma injection rates enhance creep processes instead of catastrophic failure,
458 increasing the accretion of magma at depth and inhibiting eruptions (Jellinek and DePaolo, 2003).
459 Overall, when the magma is the primary source of the resurgence of calderas, it is crucial to
460 estimate its volume, thermal state and thermal history (Cooper and Kent, 2014), while the rheology
461 of the magma itself and of the surrounding rock is critical in the evolution of the resurgence
462 (Carlino and Somma, 2010). For the island of Ischia, if we assume a roughly radial symmetry of the
463 resistivity anomaly associated with the magma intrusion (about 2 km in radius and 2 km in vertical
464 extension), at least for the crust down to 3 km, that we obtain a magma volume of about 6 km³. If
465 this has been gathering since 33ka (Tibaldi and Vezzoli, 1998), then the accumulation rate is about
466 $1.8 \cdot 10^{-4} \text{ km}^3 \text{ a}^{-1}$. This possibly represents a lower limit of the volume of magma (and the magma
467 rate) intruded into the shallow crust, which, in its present state (having been gathering over 33ka), is
468 not likely to prove eruptible due to its thermal condition. That is the magma will be highly degassed
469 and the maximum temperature is possibly $\leq 600^\circ\text{C}$ (Carlino *et al.*, 2014).

470

471 **Conclusions**

472 Our magnetotelluric survey carried out in the southern and western sector of the island of Ischia,
473 detected several electrical resistivity anomalies, down to a depth of 3 km. The interpretation of the

474 resistivity cross-sections and comparison with other geological, geophysical and geochemical data
475 allow the following conclusions and inferences:

- 476 - a large thermal anomaly has been found in the southern and western sector of the island and
477 is associated with a zone of heat advection and circulation of hydrothermal fluids (figures 5
478 and 6). The presence of two major hot aquifers, previously hypothesized by geochemical
479 studies (Chiodini *et al.*, 2004, Di Napoli *et al.*, 2011), has also been located in the
480 southwestern sector of the caldera. The aquifers reside at different depths, with the depths
481 being controlled by tectonic movements, which have caused deformation of the resurgent
482 block of Mt. Epomeo over at least the last 33 ka (Vezzoli, 1988). The top of the deeper
483 aquifers feed the main south-western fumarole fields, and are located at a depth of about
484 1000 m to 1500 m, respectively;
- 485 - a large resistivity anomaly is located below the resurgent structure of Mt. Epomeo. It is
486 interpreted as the apical part of a crystalline (and very low permeability) magmatic body
487 intruded below the central part of the island (and slightly dislocated towards the south-west)
488 and whose apex reaches a depth of about 1 km b.s.l. This body is bounded by an abrupt
489 resistivity drop corresponding to the faults around to the resurgent block of Mt. Epomeo;
- 490 - we propose that this high resistivity body is associated with the laccolith of Ischia (Rittman,
491 1930; Sbrana *et al.*, 2009; Carlino, 2012), which produced the bending, fracturing and
492 faulting of the overlying crust, and which witnessed magma intrusion during the most recent
493 stage of the resurgence (5 ka) (Civetta *et al.*, 1991; Vezzoli *et al.*, 2009). As result, the
494 uplifted block has been broken up into minor blocks, with the underlying laccolith possibly
495 developing as a complex structure. This laccolith is the engine of the robust geothermal
496 system of the island, and -to be consistent with a high resistivity - is likely dominated by a
497 highly crystalline mush;
- 498 - the existence of such a shallow magma body is critical in terms of volcanic hazard
499 assessment. The volcanism of Ischia seems, in fact, to be strictly correlated to the resurgence
500 process that, in turn, is reliant on the dynamics of the laccolith (Carlino, 2012). A renewal of
501 resurgence will be related to reactivation of the laccolith by arrival of new magma (Civetta
502 *et al.*, 1991). This may possibly produce a large disturbance of the geothermal system at a
503 depth of between 1 km and 2 km. A reactivation of such a shallow magmatic system may
504 imply imminent eruption and would pose high volcanic hazard (e.g. Cooper & Kent, 2014);
505 certainly it would cause hydrothermal emissions to evolve towards magmatic (Vaselli *et al.*,
506 2010).

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Figures captions

Figure 1. Structural and geological map of Ischia Island (after Di Napoli *et al.*, 2011). The MT measurement stations along the N-S profile are given as blue points; the MT measurement stations along the WSW-ENE profile are green points; the blue-green points are stations belonging to both the profiles; Drilling sites are given as red points numbered 1 to 5. The shaded grey circular area indicates the resurgence zone and black lines are mapped faults (Di Napoli et al. 2011). The dotted red lines indicate the resistivity section profiles.

Figure 2. Three examples of apparent resistivity and phase diagrams pertaining to the Ischia MT survey work.

Figure 3. (a) S-N Magnetotelluric profiles of apparent resistivity (above) and phase (below) pseudosections relative to the TM mode. (b) S-N Magnetotelluric profiles of apparent resistivity (above) and phase (below) pseudosections relative to the TE mode. (c) WSW-ENE magnetotelluric profiles of apparent resistivity (above) and phase (below) pseudosections relative to the TM mode. (d) WSW-ENE Magnetotelluric profiles of apparent resistivity (above) and phase (below) pseudosections relative to the TE mode (see text for details).

Figure 4. Results of the data dimensional analysis carried on the MT dataset using the phase tensor approach. The data have been divided up into four contiguous frequency bands, respectively centered on 0.9, 9, 90 and 900 Hz. The phase- tensor ellipse orientation (in degrees) and the Caldwell-Bibby-Brown Skew angles are given, for each MT survey, in (panel a) and (panel b), respectively.

Figure 5. S-N resistivity profile obtained from the inversion of the MT survey (panel b). Dotted lines are the faults associated with the caldera boundary and to the dislocation of the resurgent block (see text for details). It is also reported (panel a) the topographic profile along the section.

Figure 6. WSW-ENE resistivity profile obtained from the inversion of the MT survey (panel b). The resistivity anomalies (marked as E, E1 and E2) is coincident with a thermal plume producing high geothermal gradients and very high temperatures (~100°C) at the surface (Carlino et al., 2014). It is also reported (panel a) the topographic profile along the section.

Figure 7. Sensitivity cross-sections relative to the resistivity models (S-N profile, above and WSW-ENE profile, below).

Figure 8. Topography in shaded relief of Ischia draped over the DEM (INGV web-GIS source), perspective views from W (a), NE (b), SW (c), S (d). Beneath each are the resistivity data for the two profiles so as to set in context the variations we record with depth, as well as distance from Mt. Epomeo."

552 Figure 9. Magnification of the central part of the WSW-ENE profile compared with the geotherms
553 (after Carlino et al., 2014)

554

555 Figure 10. Comparison of the shallower part of WSE-ENE resistivity profile with a geological
556 section of the island (from *Carta Geologica dell'Isola d'Ischia*, CARG project). Legend: PZE =
557 *Pizzone Tuffs (~61 ka)*; TFS = *Frassitelli Tuffs (~62 ka)*; VNU = *dike and tabular intrusions*; TME
558 = *Mount Epomeo Green Tuff (~55 ka)*; PIM-FGN = *Punta Imperatore ancient lavas (~117 ka)*;
559 *ELF = Elephant pyroclastic deposits*; TCT = *Citara Tuffs (~45 Ka)*; SUN = *debris and mud flow*
560 *deposits*; PPI = *Punta Imperatore pyroclastic deposits (~ 18 ka)*; PUS = *Punta Soccorso debris*
561 *avalanche*; *a_{ta} = alluvial deposits. (from CARG project)*

562

563 Figure 11 (a, b). Magnification of the sections given in figures 5 and 6 with the position of drill
564 sites 2 and 4 (see figure 1 for location) from which stratigraphic data are taken. Legend: (drill n. 4)
565 VB = Volcanic Breccia; GT = Green Tuff; GTL = Green Tuff interlayered with trachytic lava. (drill
566 n. 2) RT = Reworked Tuffs and Alluvium; TYT = Trachytic Yellow Tuffs; PLD = Pyroclastic and
567 Lava deposits; GrT = Green Tuff; TL = Trachytic lava

568

569 **Acknowledgements:** This work was carried out in the framework of the INGV-DPC Research
570 Agreement 2012–2021 "All. A". We are grateful to the Associate Editor, V. Acocella, the
571 Executive Editor, A. Harris, and to the Referees, J. Stix and A. Revil, for their helpful comments
572 that have greatly improved the quality of the work.

573

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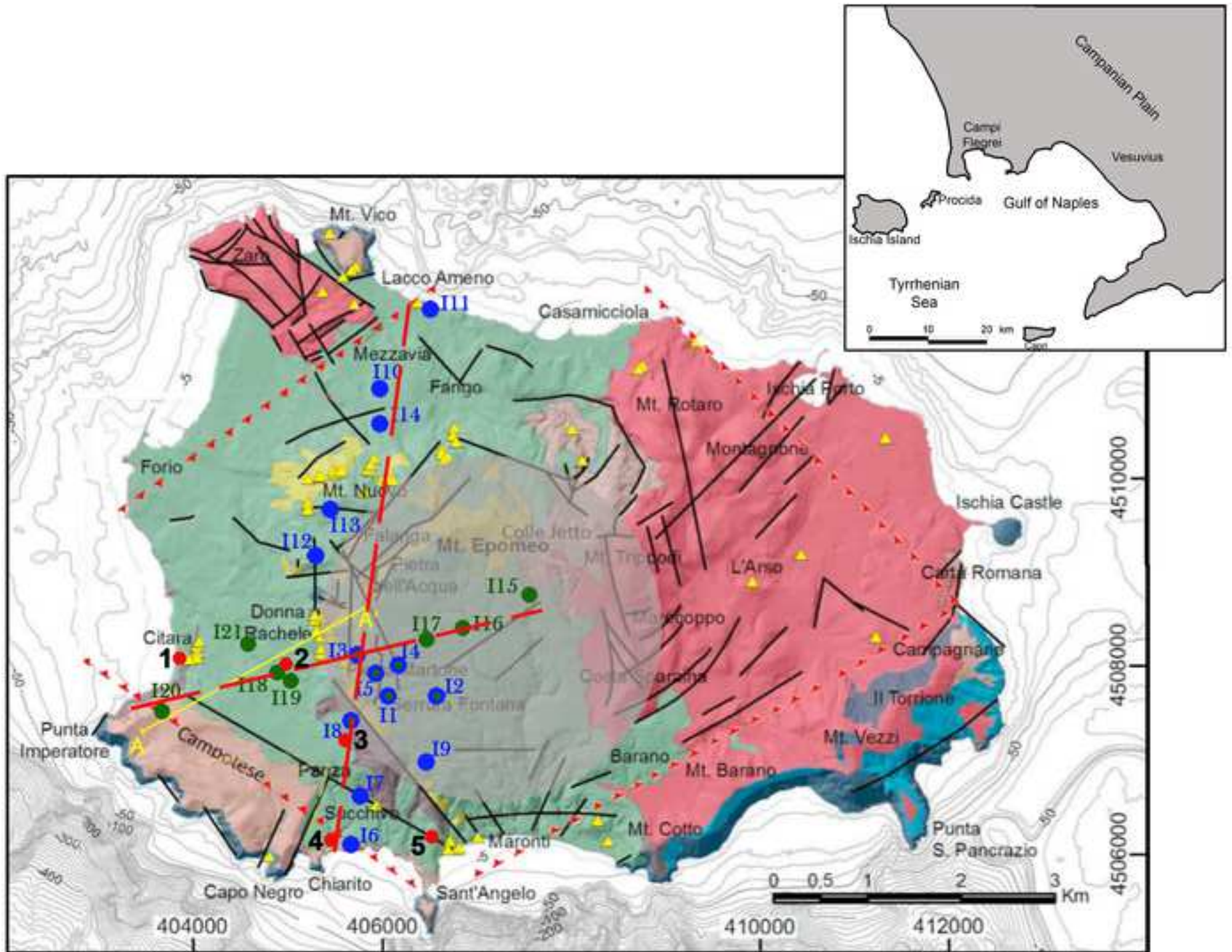
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Figure 1

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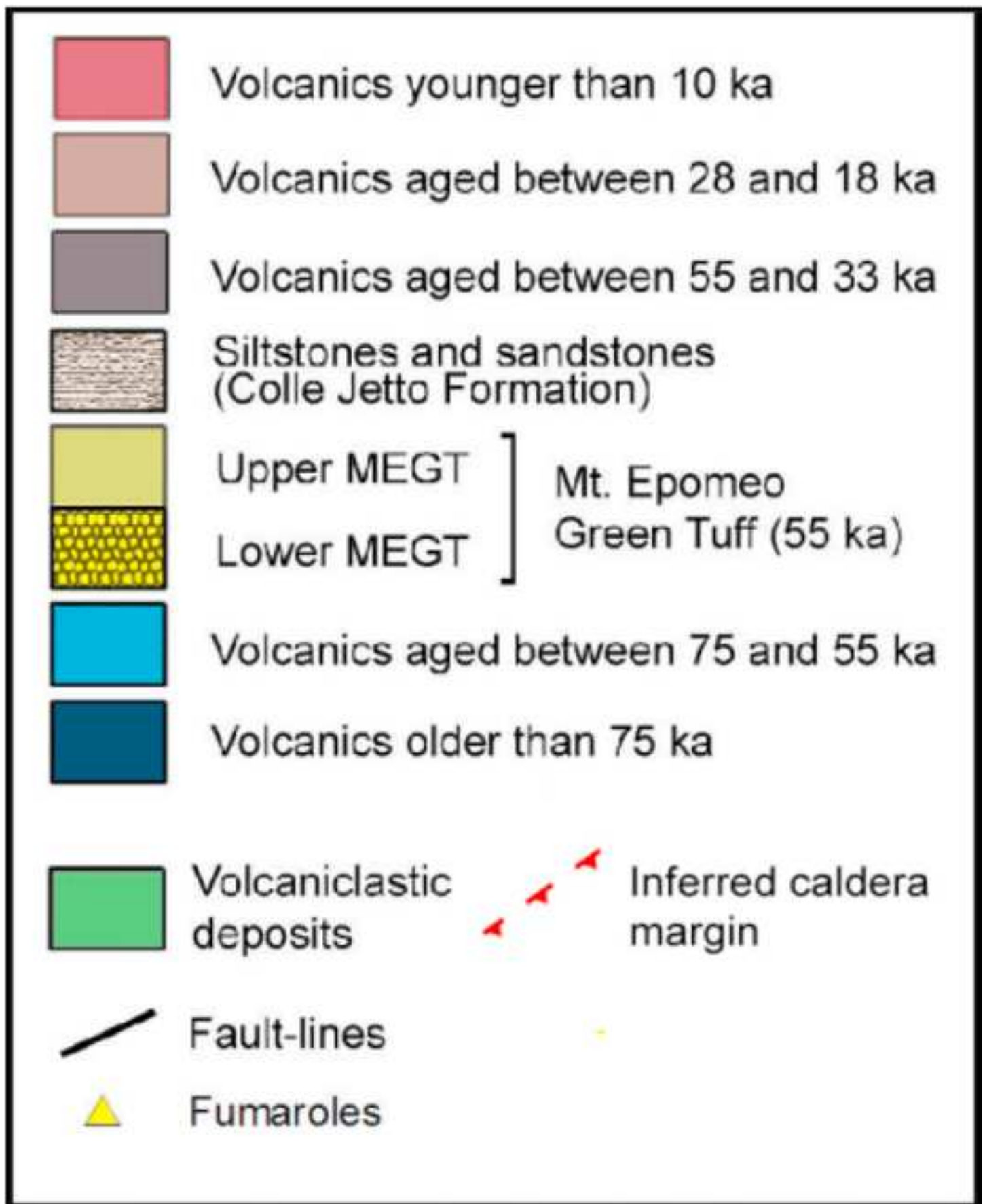
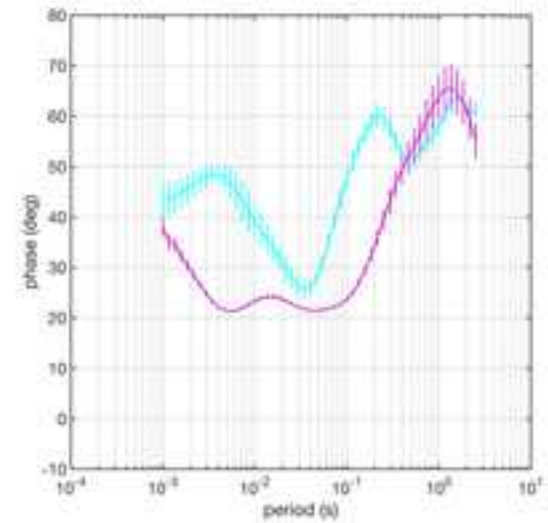
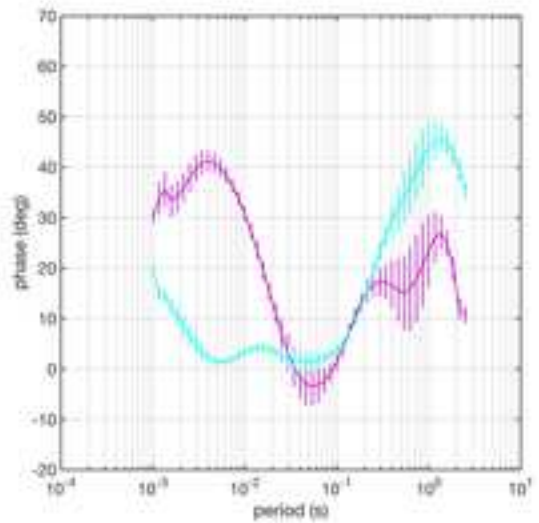
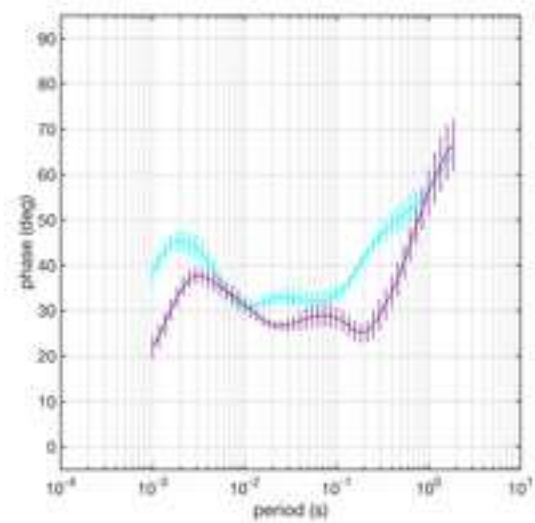
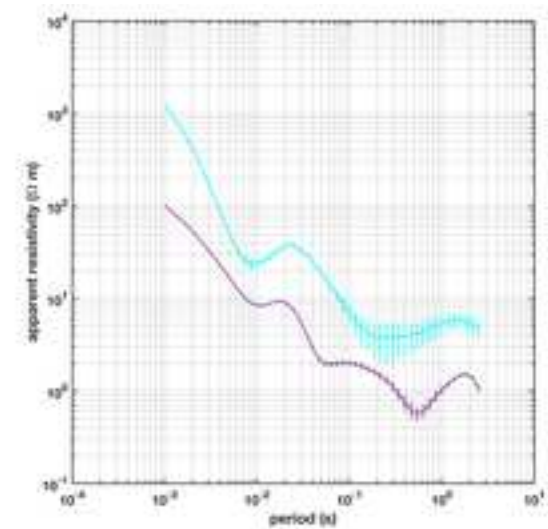
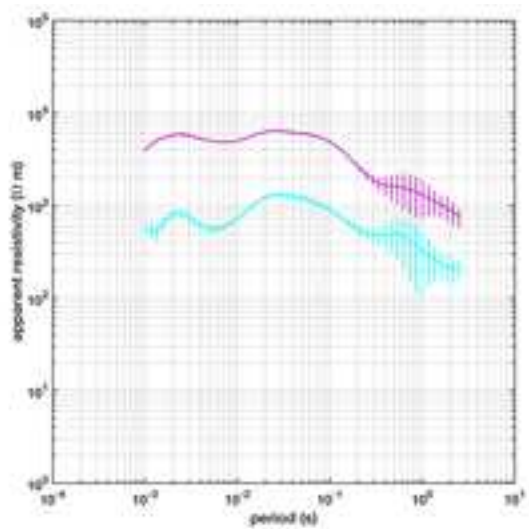
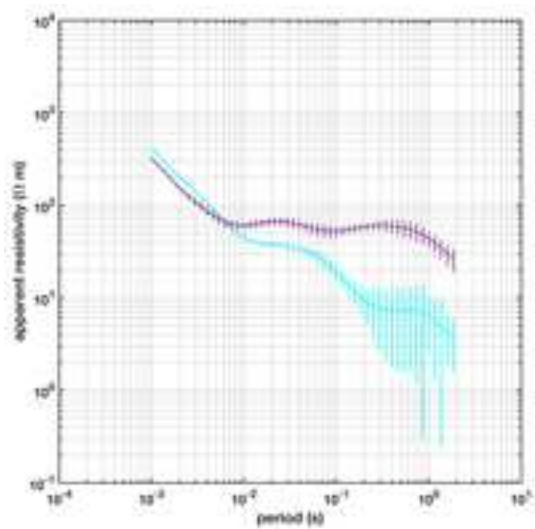
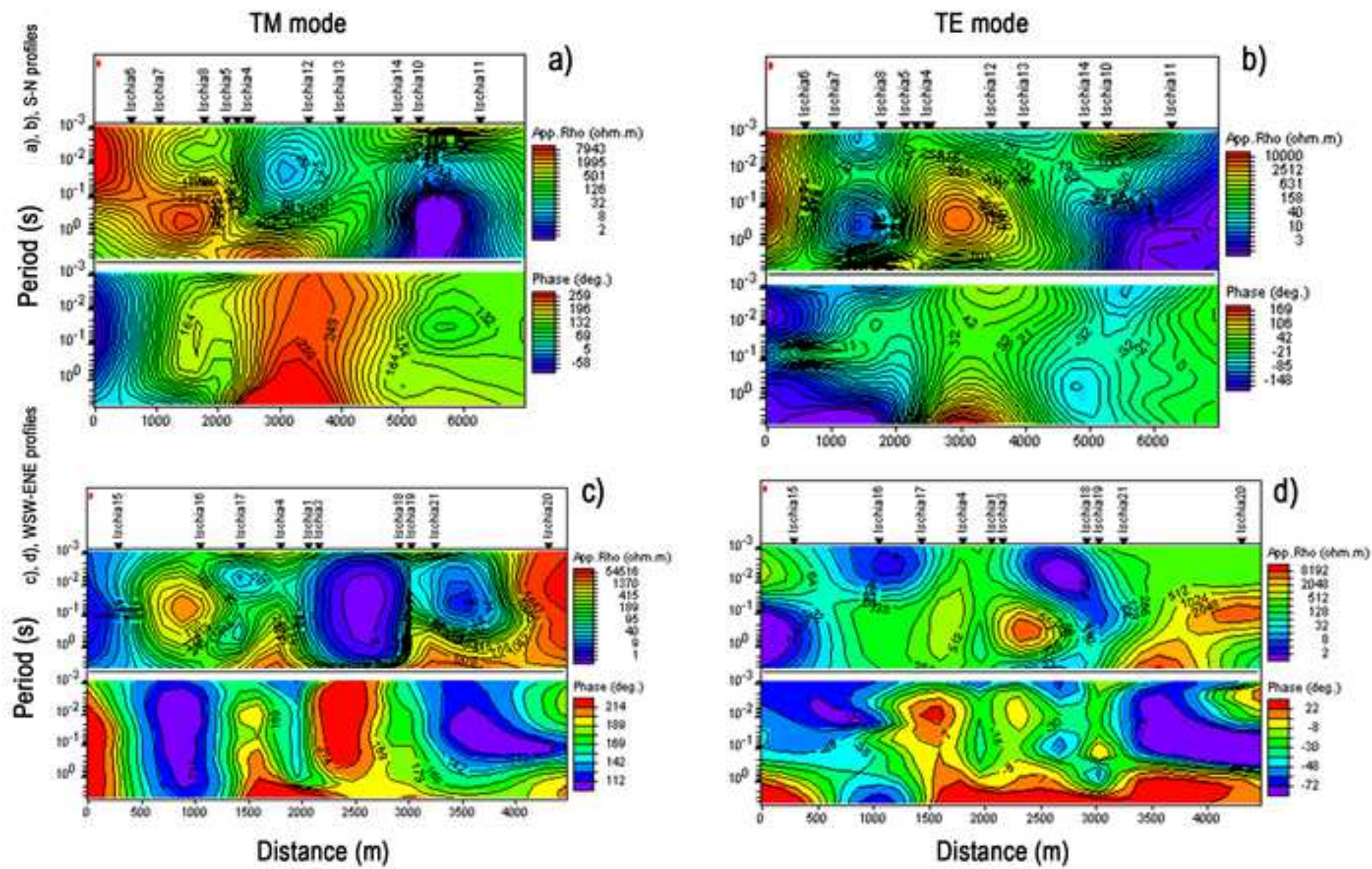


Figure 2

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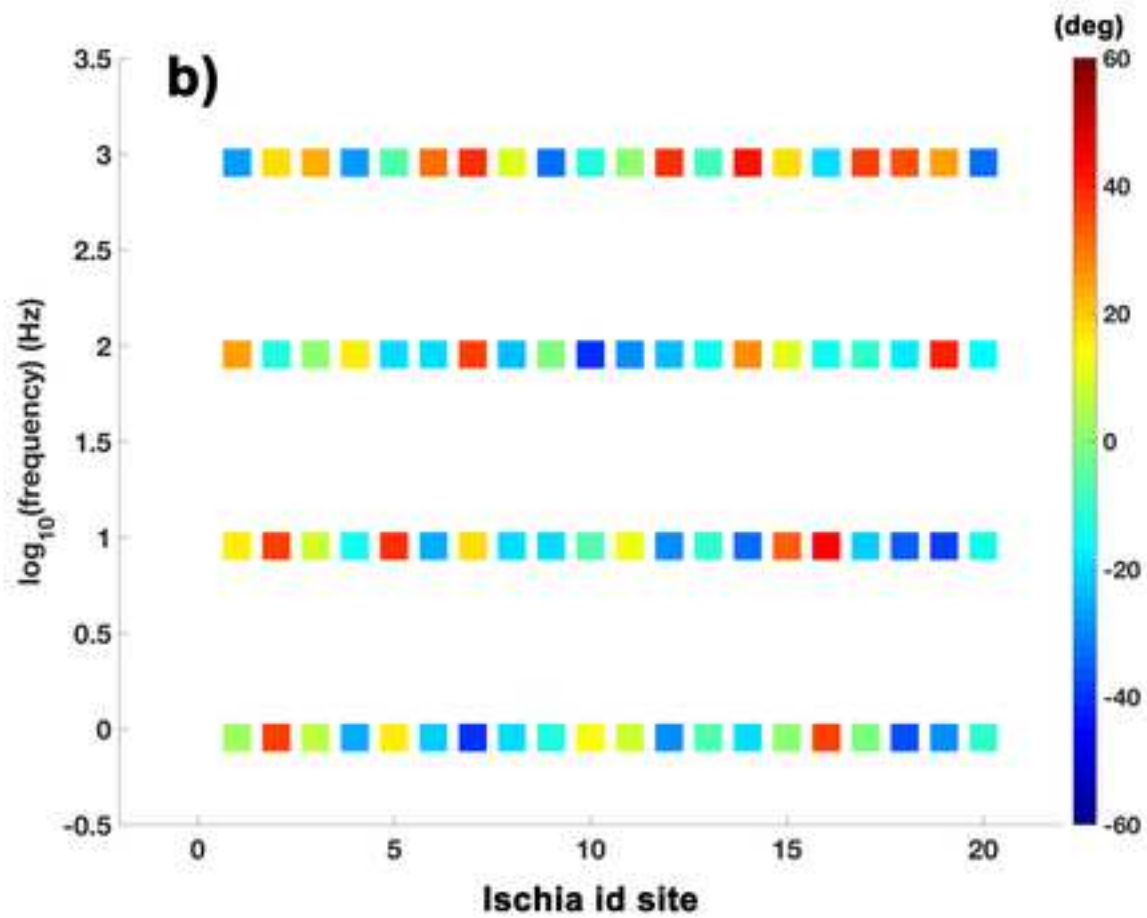
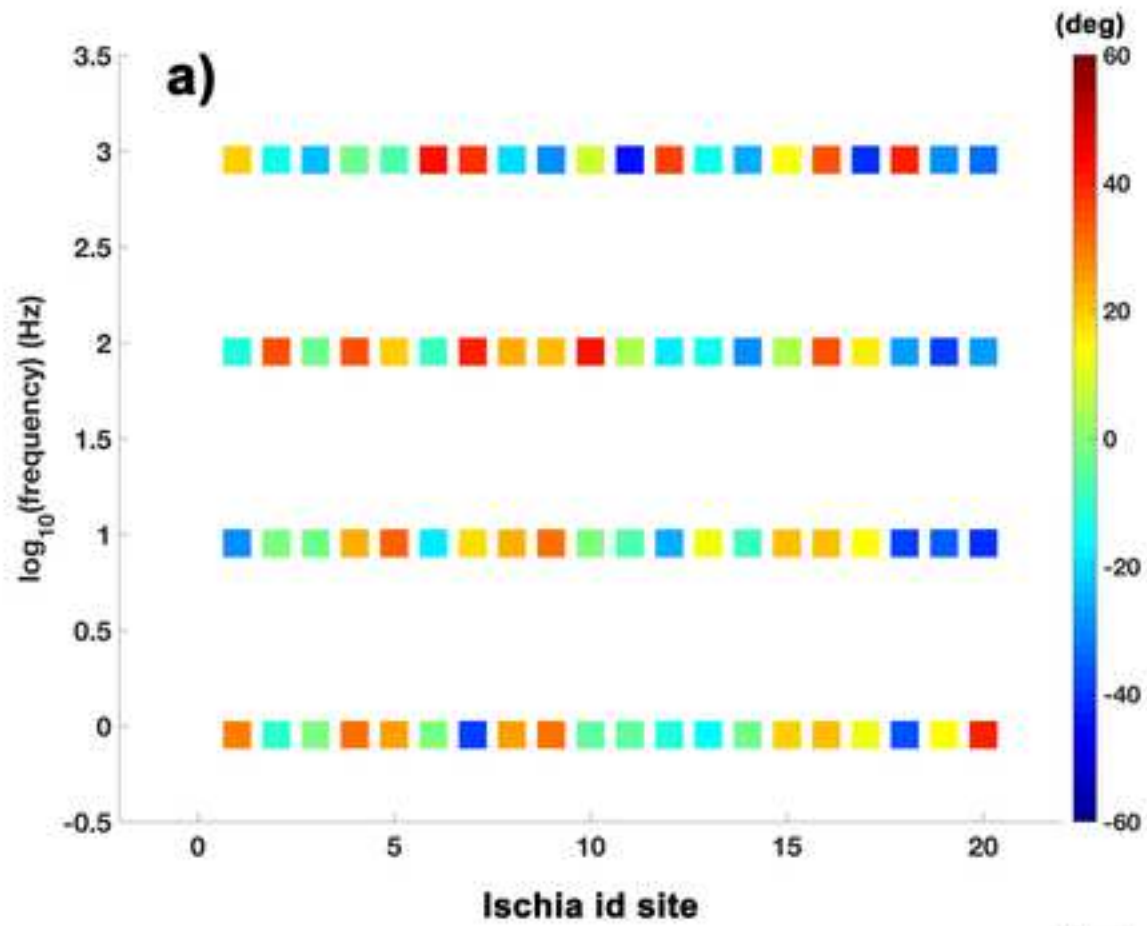


Figure 5

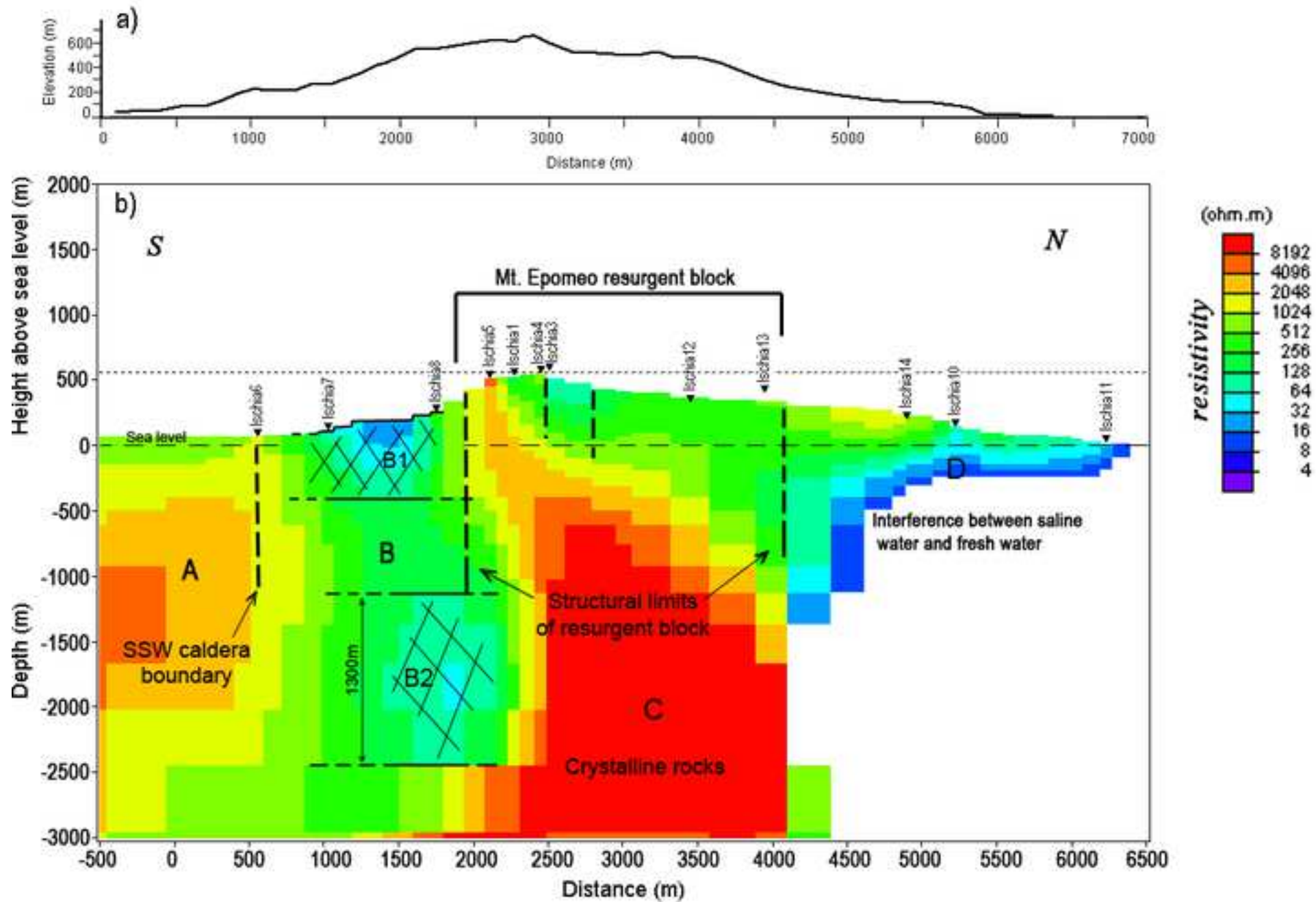
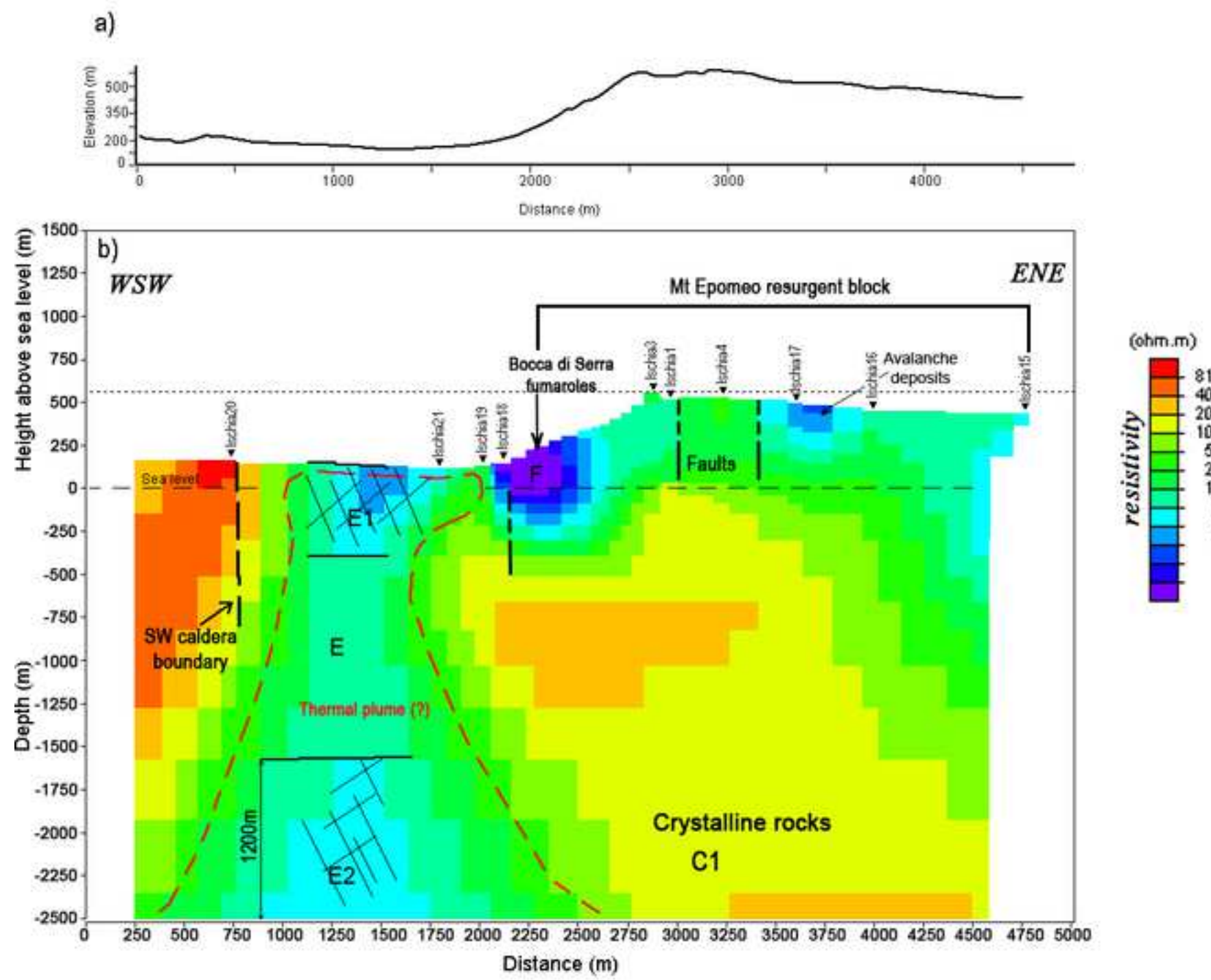
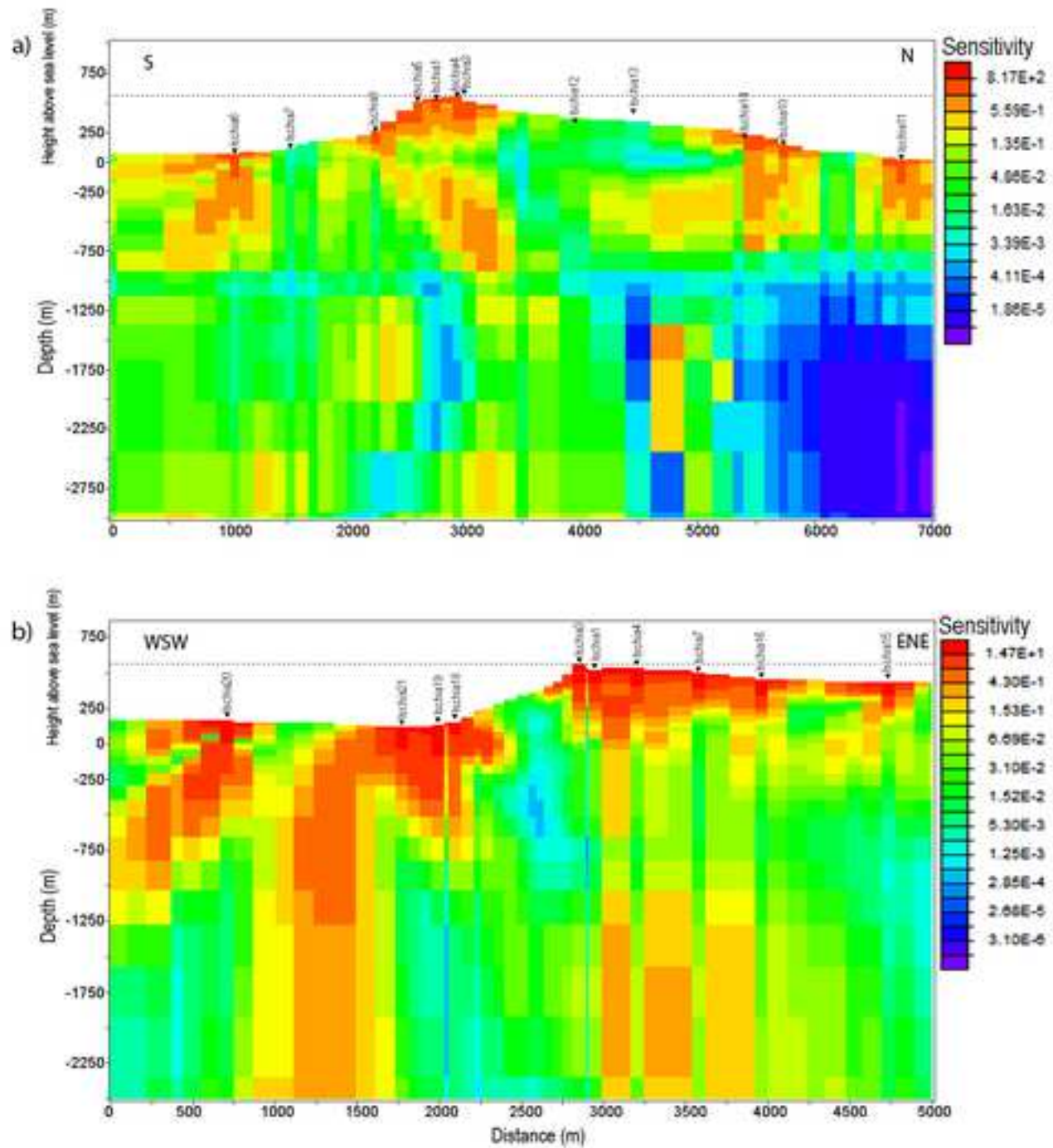


Figure 6





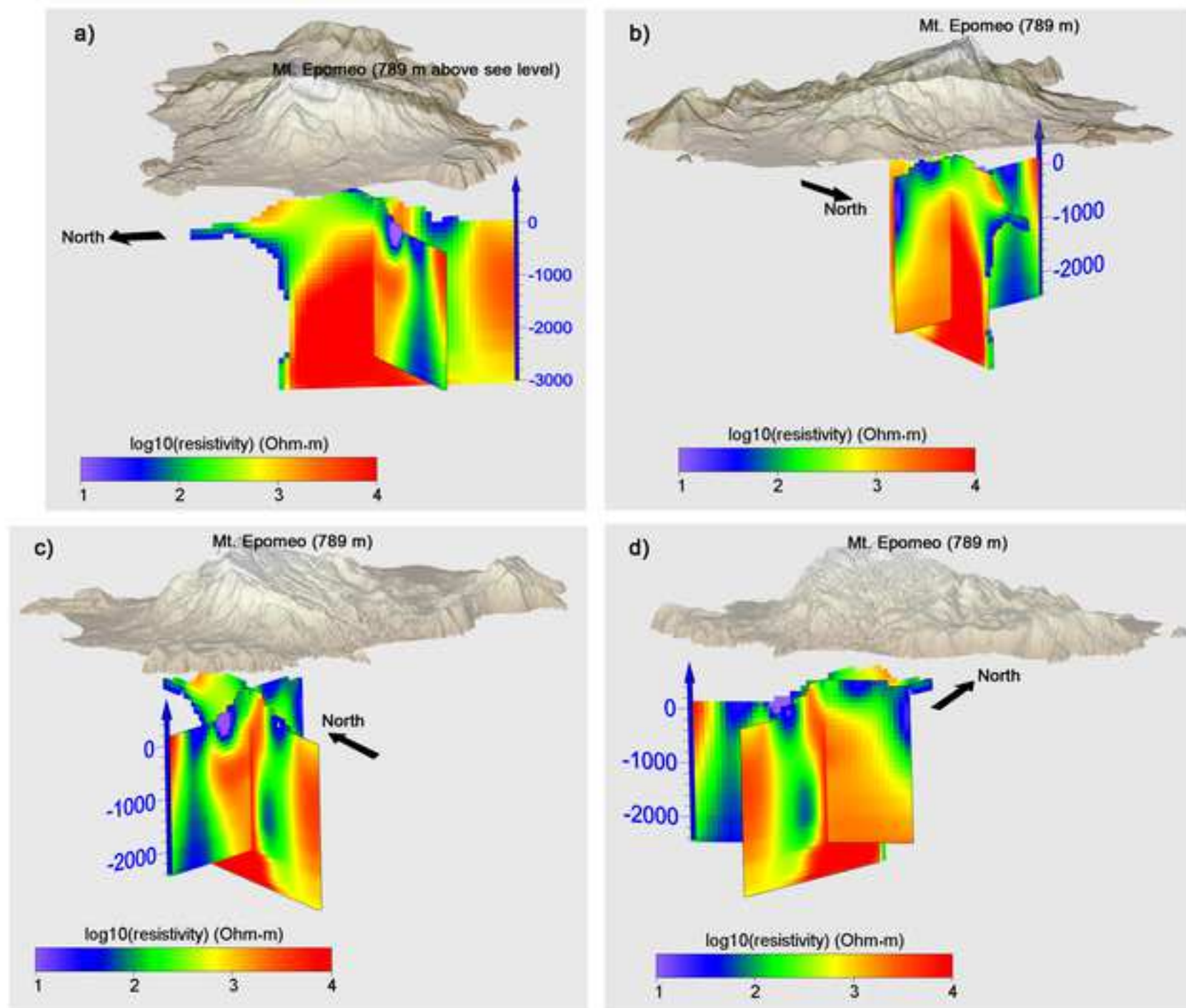
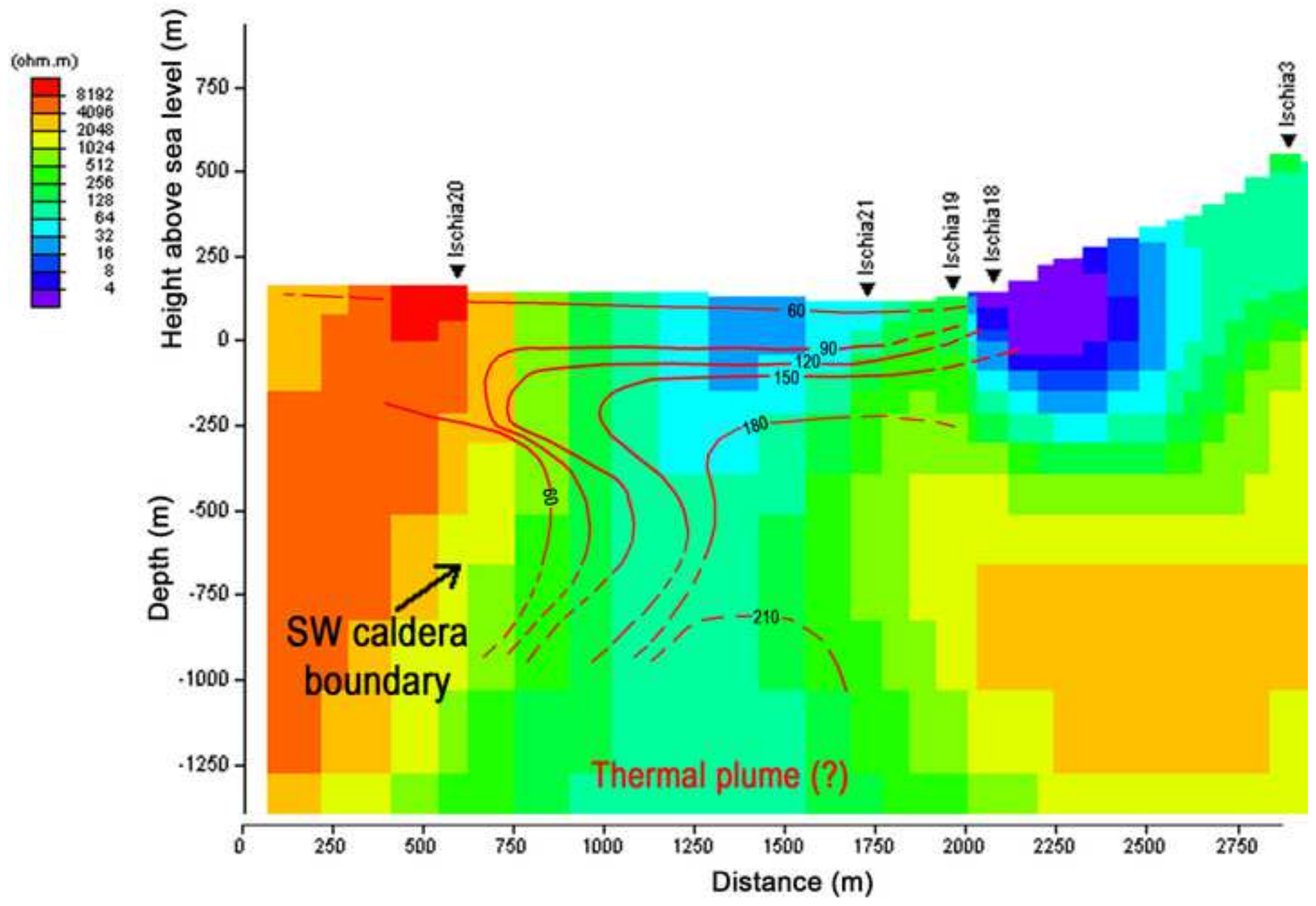
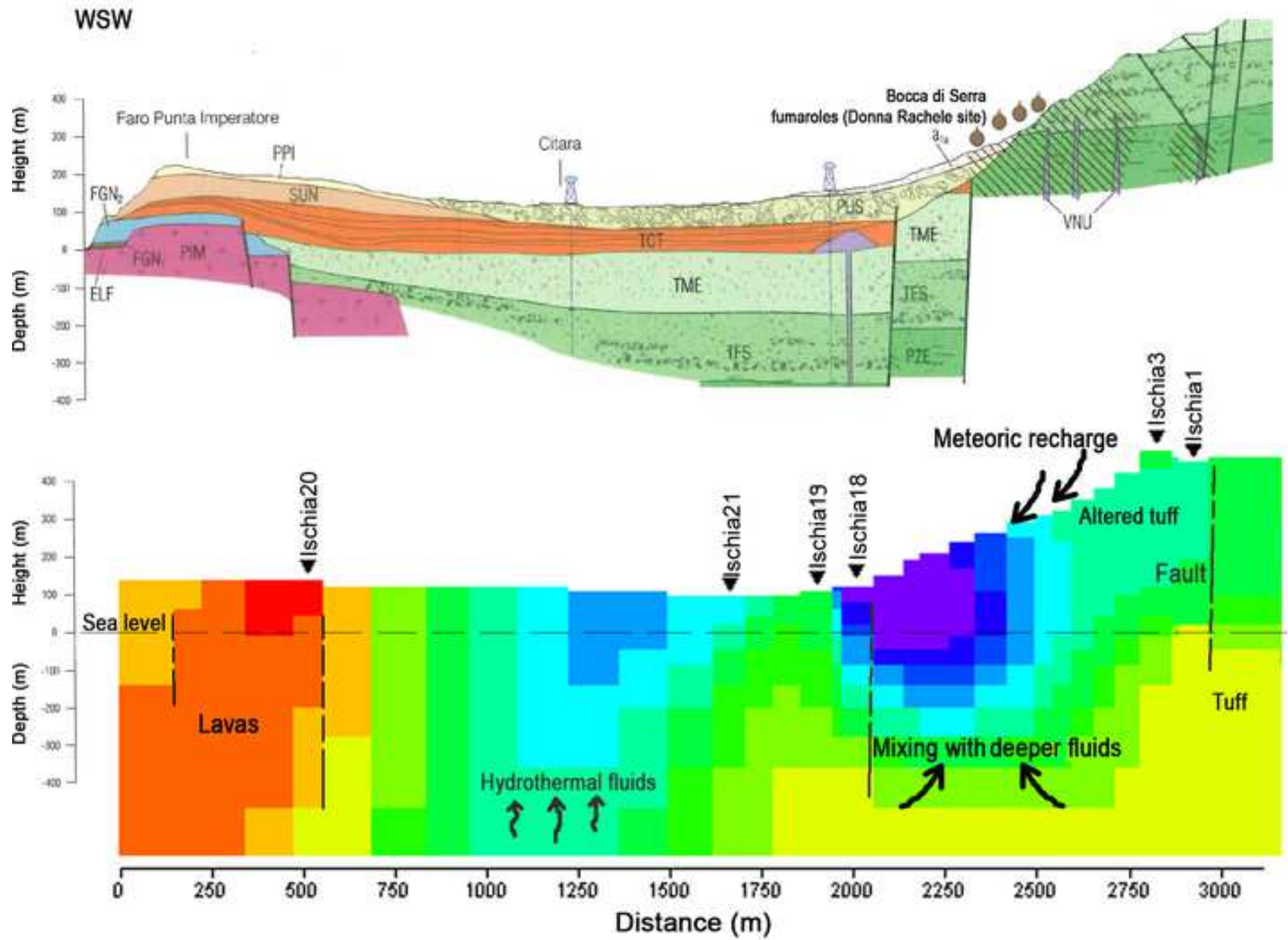
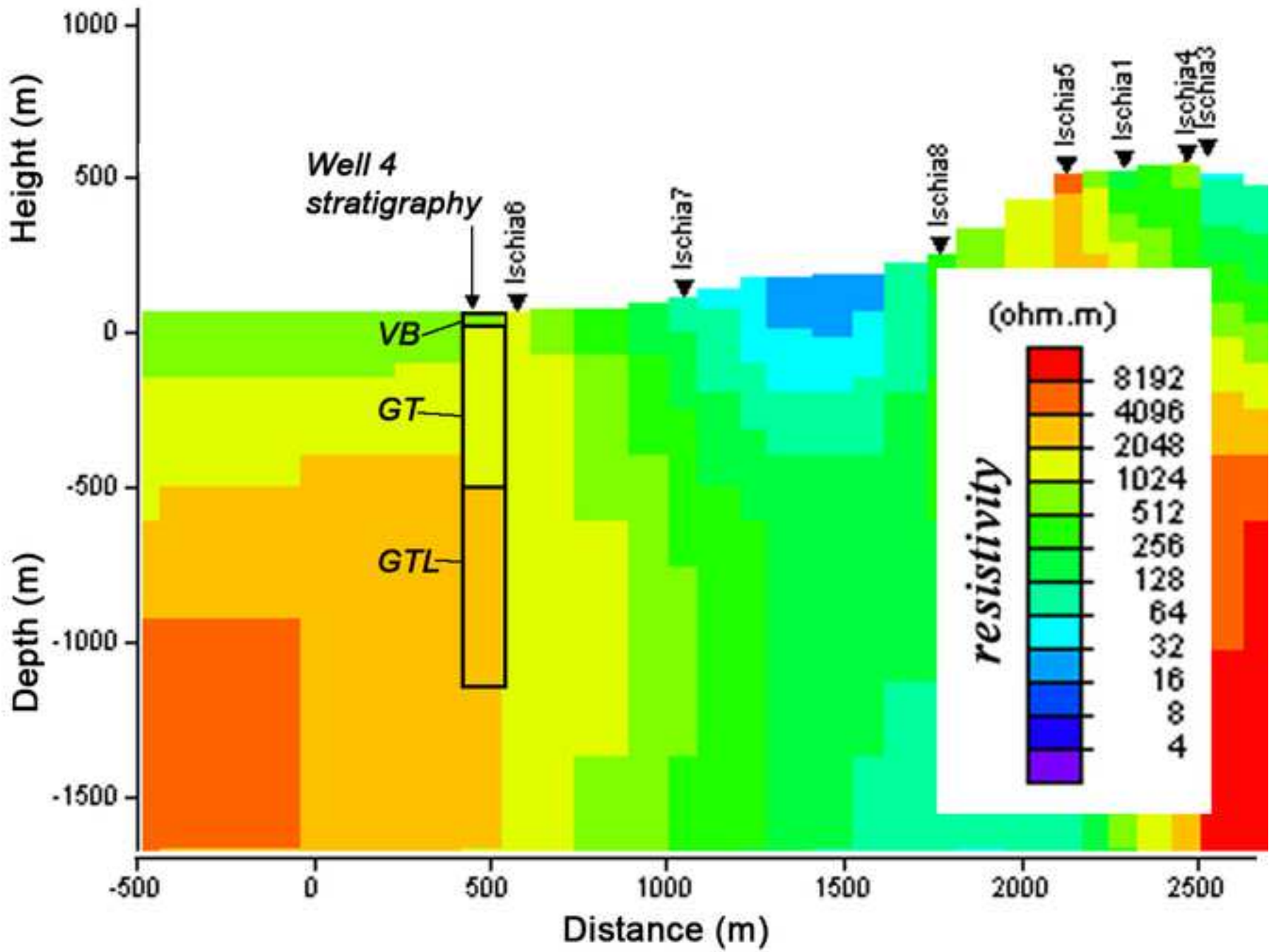
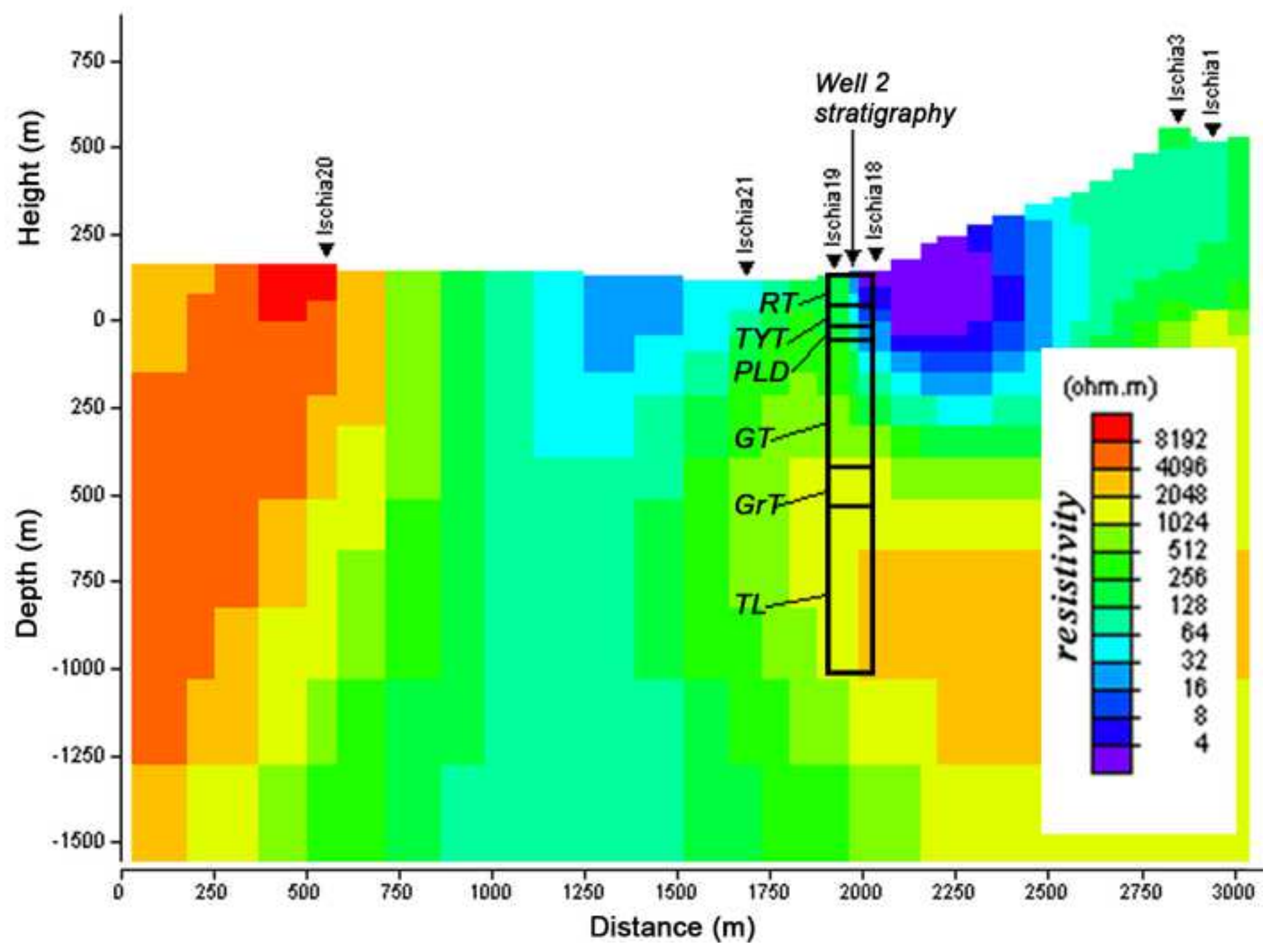


Figure 9









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1 **Magnetotelluric imaging of the resurgent caldera on the island of Ischia (Southern Italy): ~~the~~**
2 **inferences for its structure and activity ~~volcano-tectonics and dynamics~~.**

3 Di Giuseppe, M. G., Troiano, A. and *Carlino, S.

4 Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli – Osservatorio Vesuviano (Italy)

5 *Corresponding author: stefano.carlino@ingv.it

6
7 **Abstract**

8 The island of Ischia (located in the Bay of Naples, Italy) represents a peculiar case of a well-
9 exposed caldera that has experienced a large (>800 m) and rapid resurgence, accompanied by
10 volcanic activity. What drives the resurgence of calderas is a crucial issue to investigate, because
11 this process is associated with potential eruptions and high risk ~~for the~~ people living within and
12 around ~~these such~~ large ~~volcanoes~~ active volcanic systems. To improve the knowledge of volcano-
13 tectonic processes affecting the caldera of Ischia ~~a new~~ electromagnetic imaging of the structures
14 associated with ~~the its~~ resurgence was performed and integrated with ~~the available~~ geological
15 information ~~available~~. A magnetotelluric (MT) survey of the island was carried out along two main
16 profiles through the central-western sector, providing ~~the an first~~ electrical resistivity map to a depth
17 of 3 km. These resistivity cross-sections ~~thus obtained~~ allowed us to identify the presence of a very
18 shallow magmatic intrusion, possibly a laccolith, ~~to at~~ a depth of about 1 km, which was responsible
19 for both the resurgence and the volcanic activity. Furthermore, the tectonic structures bordering the
20 resurgent area and the occurrence of a large thermal anomaly in the western sector of the caldera
21 also provided a signature in the resistivity cross-sections, with the magma intrusion producing ~~a~~
22 ~~vigorous~~ advection of hot fluids with high geothermal gradients (>150 °C km⁻¹) in the southern and
23 western sectors. All of these data are fundamental for the assessment of the island's volcano-
24 tectonic dynamics and their associated hazards. The ~~dynamics-structure and activity~~ of the island
25 have been ~~influenced-controlled~~ by the process of resurgence ~~that is~~ associated with the arrival of
26 new magma and the progressive intrusion of ~~the a~~ laccolith at ~~a shallower~~ depth. The reactivation of
27 such a shallow system may imply imminent eruption ~~and which would pose~~ a major volcanic
28 hazard.

29
30 **Introduction**

31 The resurgence of calderas was defined by Smith and Bailey (1969) as the process of uplift that
32 usually occurs in the form of a structural dome that takes place after a caldera collapse. The uplift
33 and bending of both the floor and roof of the caldera produce fracturing, faulting and,

34 ~~Furthermore~~thereby, enhance the development of permeability channels (Kennedy *et al.*, 2012).
35 While generation of A-highly permeable network promotes the circulation of hot fluids, forming
36 magmatic-hydrothermal systems (Hulen *et al.*, 1987), ~~while~~-faulting and fracturing can also
37 facilitate the migration of magma to the surface and, eventually, an eruption (Kilburn, 2003). Thus,
38 resurgence plays a central role in the evolution of calderas, but the processes involved are still
39 unclear, in particular with regard to the causes and the timing of ~~any~~-uplift. The most common
40 process associated with the resurgence of calderas is the influx or intrusion of magma at various
41 depths (Fridrich *et al.*, 1991; Saunders, 2001; Jellinek and De Paolo, 2003; Kawakami *et al.*, 2007).
42 Other mechanisms contributing to ~~the~~-resurgence have been suggested, such as combination of
43 regional detumescence and viscous rebound (Smith and Bailey, 1969; Marsh, 1984), volatile
44 exolution and gas overpressure (Marsh, 1984), thermal expansion of the caldera fill (Kennedy and
45 Stix, 2003) and the disturbance of geothermal fluids (Hurwitz *et al.*, 2007; Chang *et al.*, 2010,
46 Troiano *et al.*, 2011).

47 A crucial question is thus, what drives resurgence within calderas and (if magma is involved in this
48 process), at what depths and of what volumes are the resultant intrusions? In the latter case,
49 ~~(depending on the volcano-tectonic setting, the~~ dynamic rate of uplift of the area and ~~the~~-magma's
50 viscosity (~~(~~-Pollard and Johnson,1973; Smith and Bailey, 1969; Acocella *et al.*, 2001; Carlino,
51 2012), the magmatic intrusion may evolve in a range of ways (e.g. to be emplaced as sills, dikes, or
52 laccoliths) producing a variable amount of uplift and a variety of resurgence structures (Paige,
53 1913; Orsi *et al.*, 1991; Henry *et al.*, 1997; Acocella *et al.*, 2001 and references therein). The
54 recognition of such differences is fundamental in the understanding ~~of~~ a caldera's dynamic structure
55 and any associated hazard. As a result ~~and thus~~ the shallow and deep structures of calderas need to
56 be better investigated through the application of effective geophysical methods. Among the
57 geophysical surveys that can improve the knowledge of the deep structures of calderas, electrical
58 resistivity mapping represents a reliable tool in the assessment of the buried structures in volcanic
59 settings. ~~This is supported by the relevant results obtained during many applications of electrical~~
60 ~~and electromagnetic geophysical methods, carried out in the last decade on both volcanic and~~
61 ~~tectonic structures~~ (Troiano *et al.*, 2008; Troiano *et al.*, 2009; Revil *et al.*, 2010; Troiano *et al.*,
62 2014; Di Giuseppe *et al.*, 2015; Di Giuseppe *et al.*, 2017b). In this work, a magnetotelluric (MT)
63 survey was applied to the active volcanic caldera of Ischia, whose resurgence is thought to be
64 associated to a sill intrusion, possibly developed in the form of a laccolith (Rittman, 1930; Sbrana *et*
65 *al.*, 2009; Carlino *et al.*, 2006; Carlino, 2012 and references therein). The resurgence, which is
66 estimated as at least 800_m (Vezzoli, 1988), was accompanied by volcanic activity and by the
67 exhumation of the geothermal system (Sbrana *et al.*, 2009), with the occurrence of a large diffuse

68 heat flow and very high geothermal gradients ($>180^{\circ}\text{C km}^{-1}$) in the shallow crust (Vezzoli, 1988;
69 ~~Sbrana et al., 2009~~; Carlino, 2012; Carlino et al., 2014; Carlino et al., 2015). ~~Beyond-Although~~ a
70 numbers of ~~specific-local geophysical~~ investigations ~~have been performed~~ at Ischia (~~see Nunziata~~
71 ~~and Rapolla, 1987~~; Di Napoli et al., 2009, 2011; Paoletti et al., 2013), a wider geophysical imaging
72 of the island is not yet available. Such knowledge represents a crucial task in supporting ~~the~~
73 physical modeling (~~Rinaldi et al., 2011~~), to improve the understanding of the caldera's
74 ~~dynamic structure and activity~~, and to assess the associated hazard on the island.

75 The MT survey was carried out in the central-western sector of the island. Through this survey, the
76 electrical resistivity distribution was reconstructed in correspondence to two separate profiles
77 (deployed in a N-S and a WSW-ENE direction respectively) (Figure 1). In this fashion two
78 resistivity sections, respectively about 5 km and 3 km long, were obtained and interpreted ~~in order~~
79 to highlight the main geological features of the crust to a depth of 3 km including its thermal state,
80 ~~as well as location of~~ fluid circulations and structural discontinuities ~~along-within~~ both the collapsed
81 and the uplifted areas. ~~The results provide new insights. In particular, new evidences emerged~~
82 regarding both the thermal situation pertaining on the central-western sector of the island and the
83 circulation of geothermal fluids. ~~The main finding was the~~~~We find~~ presence of a crystalline
84 structure (intrusive rocks with very low permeability) located beneath the Mount Epomeo block
85 (~~Figure 1~~), which possibly represents the apical part of a degassed and cooling magmatic source
86 (laccolith). The results obtained are important, not only because of the volcanic risk on the island
87 (which has about 65,000 inhabitants and more than 1,500,000 visitors during the spring and summer
88 months) but also for the volcano-tectonic evolution observed in many calderas worldwide, during
89 resurgence ~~processes~~.

90

91 **Main geological features of the island**

92 The volcanic field of Ischia is part of the Phlegrean Volcanic District, ~~which is the most important~~
93 ~~quaternary active volcanic area of the Mediterranean region~~ (Figure 1). The rim of ~~the~~ Ischia
94 caldera, ~~which~~ formed after the Mount Epomeo Green Tuff (MEGT) eruption, 55 ka (~~Vezzoli,~~
95 ~~1988~~), is not well documented, ~~although there are even though~~ a few signs of the rim ~~have been~~
96 ~~identified~~ in the NW, SW and SE sectors (~~Tibaldi and Vezzoli, 1998~~). The caldera, it would seem,
97 has an elliptical shape with its major axis running ENE-WSW (Vezzoli, 1988). The ~~most~~ island's
98 ~~most~~ important structural element is the ~~roughly~~ 4x4 km² resurgent block of Mount Epomeo
99 (formed mainly by the MEGT), located in the centre of the caldera, which has been uplifted over
100 the last 55 ka by a magmatic intrusion (Rittman, 1930; Sbrana et al., 2009). The edges of this block
101 are marked by a system of sub-vertical faults with NW-SE, NE-SW and N-S strike (Vezzoli, 1988;

102 Acocella and Funicello, 1999; Tibaldi and Vezzoli, 1998) (Figure 1). The existence of a possible
103 magmatic intrusion, associated with the resurgence and post-caldera volcanic activity, was first
104 inferred from gravity surveys by Carrara *et al.*, (1983) and Nunziata and Rapolla (1987). More
105 recently, the model of laccolith intrusion (proposed by Rittman, 1930) has been taken up again by
106 interpreting stratigraphy, deep temperature, geochemical, magnetic, electric and gravity data
107 (Carlino *et al.*, 2006; Sbrana *et al.*, 2009; Carlino 2012; Paoletti *et al.*, 2013). Sbrana *et al.* (2009)
108 provided a model of resurgence of the island by using an integrated analysis of melt and fluid
109 inclusions, mineralogy and stable isotopic compositions of pumices, tuffs and syenitic xenoliths.
110 ~~The authors have shown that~~In this model the engine of the hydrothermal system of Ischia can be
111 identified ~~as being a in its~~ shallow magmatic system (at ~~around a depth of~~ 2 km ~~depth~~) that hosts hot
112 trachytic magma. Accordingly, Carlino *et al.*, (2006) and Carlino (2012) showed, ~~through by the~~
113 analytical modeling of the bending and fracturing of an elastic plate, that the resurgence of Mount
114 Epomeo block may be associated to a sill-like intrusion which developed, during its later stages,
115 into a laccolith, the top of which is located at a depth of about 2 km. Paoletti *et al.*, (2013), using an
116 integrated analysis of geophysical data, highlighted the presence of a possible magmatic intrusion,
117 with a temperature below the Curie point, a density of about 2.4 g cm⁻³ and its top at a depth of
118 about 2 km. The top of this magma body is slightly ~~off-center, being decentred~~ in the southwestern
119 part of Ischia, where a ~~fumarolic emissions are focused (Chiodini et al., 2004) robust geothermal~~
120 ~~circulation takes place~~. The total estimated uplift of the Mount Epomeo block, deduced from the
121 present height of ~~the~~ marine deposits and eustatic variations, is 710 m in the southern sector and
122 920–970 m in the northern sector, with average ~~rate of~~ uplift ranging from 2.3 to 3.3 cm a⁻¹ (Barra
123 *et al.* 1992; Tibaldi and Vezzoli 2004; Carlino *et al.* 2006). During the resurgence over the last 28
124 ka, most of the eruptive centres have been aligned along the caldera structure (Vezzoli, 1988).
125 Between 28 ka and 18 ka the volcanic activity migrated to the SW and SE sectors of the island (Fusi
126 *et al.*, 1990). ~~while~~ However, during the most recent period of activity, from 10 ka to 1302 A.D.,
127 the eruptive ~~centres~~ centers ~~were~~ have become clustered in the eastern and northern sector, with the
128 emission of domes and lava flows (Vezzoli, 1988; Fusi *et al.*, 1990; de Vita *et al.*, 2010). The last
129 eruption in the island took place in 1302 A.D. (de Vita *et al.*, 2010), ~~while the resurgence has~~
130 ~~probably been taking place actively since about 5ka (Vezzoli et al., 2009)~~.
131 The circulation of ~~underground hydrothermal~~ fluids on the island is linked to its volcano-tectonic
132 ~~dynamie~~ structural setting, whose permeability is controlled ~~which was characterized~~ by the
133 ~~positioning relative location~~ of lavas and pyroclastic deposits. ~~F~~The fluid circulation is thus
134 correlated ~~with~~ the occurrence and interlayering of different deposits, and mostly takes place ~~at~~
135 ~~pathways of high permeability such as at~~ through the fractures and faults ~~in~~ of welded tuffs and lavas

136 and within the pores of unconsolidated pyroclastic deposits (Celico *et al.*, 1999; Carlino *et al.*,
137 2014). The shallow stratigraphy of the western sector (down to a depth of 1 km) has been inferred
138 from ~~a range of~~ borehole measurements ~~s~~ (Penta and Conforto, 1951; see figure 1 for borehole
139 locations). In the central zone of Mt. Epomeo and along its boundary ~~the while~~ coarse volcanic
140 deposits ~~represent form a the~~ shallow permeable layer, ~~while~~ fractured tuffs, ~~and~~ lavas and marine
141 clay deposits ~~characterize~~ make up the semi-permeable and impermeable layers, respectively. In the
142 western area of the island the aquifer generally has a lower transmissivity than in the eastern sector
143 (Celico *et al.*, 1999). The effect of volcano-tectonic structures is noticeable above the main faults
144 bordering Mt. Epomeo, where the shallow aquifers have been ~~pushed dislocated~~ upward in
145 correspondence to the uplift of the block (Sbrana *et al.*, 2009; Carlino *et al.*, 2014). Along the
146 western faults ~~are located the~~ hot springs are located about highly permeable path ways associated
147 with high thermal energies with larger capacity and greater thermal energy (Chiodini *et al.*, 2004)
148 (Figure 1). Also inferred in the western sector is the occurrence of mixing processes between
149 marine water and hydrothermal fluids, testified to by the high salinity of the ~~fluids sampled latter~~
150 close to the coast (Celico *et al.*, 1999; Di Napoli *et al.*, 2011). In the southwestern sector of the
151 island the shallow resistivity model obtained by Di Napoli *et al.*, (2011) highlights the presence of a
152 zone of high conductivity, whose top is located at a depth of about 100 m and which is related to the
153 superficial hydrothermal reservoir. Geothermal gradients of the island are typically very high,
154 ranging in the hottest areas (south-western sector) from 180 °C ~~kKm~~⁻¹ to 200 °C ~~kKm~~⁻¹ (AGIP,
155 1987). These high gradients are associated with an efficient heat transport from the reservoir
156 through an advection-dominated system (Carlino *et al.*, 2012; Carlino *et al.*, 2014). Taking into
157 account ~~the above these~~ gradients, the transition from a brittle to semi-brittle regime should take
158 place at a depth of about 2-3 km (Carlino *et al.*, 2014), while the depth of the brittle crust is possibly
159 ~~higher deeper~~ in the north with respect to the southern sector (Carlino *et al.*, 2006).

160 At present time the island is subject to slow subsidence, reflecting a gradual depressurization of the
161 magmatic or hydrothermal system beneath Mount Epomeo (Sepe *et al.*, 2007; De Martino *et al.*,
162 2011).

163

164 **MT data collection, analysis and inversion.**

165 ~~In order to~~ characterize the first few ~~km~~ kilometers of the crust of the island of Ischia a
166 magnetotelluric survey was performed. Magnetotellurics is an electromagnetic geophysical method
167 for measuring the resistivity of the earth's interior by recording the natural electric (**E**) and
168 magnetic (**H**) fields on the surface (Vozoff, 1991) as they vary over time. In the present application,
169 fluctuations of the orthogonal components of these fields ~~have been were~~ recorded ~~in~~

170 ~~correspondence to the~~ at 20 measurement sites (see figure 1 for locations). Measurements were
171 carried out using a Stratagem EH4 instrument, produced by Geometrics ~~and lasted as long as a few~~
172 ~~hours. Only the horizontal components of the E and H fields were recorded, neglecting the~~
173 ~~sampling of Hz which is usually considered as only providing limited additional information~~
174 ~~regarding the dimensionality of the Earth's local structure (Vozoff, 1991; Simpson and Bahr, 2005).~~
175 Once ~~the series of the~~ data set of field fluctuations over time had been collected, the underground
176 resistivity complexity was obtained as a rank-2 tensor, \mathbf{Z} , correlating the two orthogonal pairs
177 (E_x, E_y) and (H_x, H_y) at the Earth's surface in the frequency-domain. This tensor is correlated ~~with~~
178 the MT apparent resistivity and phase curves, which compose the final dataset. To estimate such
179 curves, the collected time series spectra have been estimated using a short ~~time-period~~ Fourier
180 transform performed over the $[10^{-4} \sim 10^1]$ s ~~period-range~~. Such a period was examined ~~in order~~ to
181 investigate the structures located across the first few ~~km-kilometers of~~ depth below ground level.
182 ~~In fact, the investigated~~ depth of the electromagnetic waves depends on their capacity to
183 penetrate into the Earth. This, in turn, is directly related to rock resistivity. In a uniform substrate
184 the electric and magnetic fields weaken exponentially with depth, the more conductive the
185 ~~earthrock~~, the lower the penetration. The depth at which the fields ~~had declined~~ to e^{-1} of their values
186 at the surface is ~~called-termed~~ the skin depth $\delta = (2\rho/\omega\mu)^{1/2} \approx 500(\rho/f)^{1/2}$ (in metres) where, ρ is
187 the resistivity, f is the frequency of the wave, $\omega = 2\pi f$ and μ is the permeability. The latter is
188 usually taken as being equal to μ_0 (~~free space permeability~~), except in highly magnetic materials.
189 Frequency enters into the equations because the magnitudes of the induced telluric currents depend
190 on the rate of change of the magnetic fields over time (Vozoff, 1991, Simpson and Bahr, 2005). ~~To~~
191 ~~record the electrical and magnetic fields fluctuations on the Earth's surface over such a time period,~~
192 ~~measurements were carried out through the use of Stratagem eh4[®] instruments, made by~~
193 ~~Geometrics, which were equipped with a couple of low frequency BF4 magnetometers. Only the~~
194 ~~horizontal components of the E and H fields were recorded, neglecting the sampling of Hz which is~~
195 ~~usually considered as only providing limited additional information regarding the dimensionality of~~
196 ~~the Earth's local structure (Vozoff, 1991; Simpson and Bahr, 2005).~~
197 After the ~~application of~~ short ~~time-period~~ Fourier transform, data belonging to each ~~one~~ of the MT
198 surveys were analyzed using the ~~robust~~ algorithm ~~presented in~~ of Egbert and Booker (1986). This
199 was used to avoid the distortion in the estimated MT curves, which might emerge from the time
200 series due to the presence of anthropic noise, especially for surveys in urbanized environments. This
201 kind of algorithm has proven to be effective in the case of single station MT surveying (Egbert and
202 Livelybrooks, 1996; Bai *et al.*, 2001; Brasse *et al.*, 2001; Pous *et al.*, 2002). Its application in such a
203 context was tested during the electromagnetic imaging of the nearby Campi Flegrei area (Troiano *et*

204 *al.*, 2014; Di Giuseppe *et al.*, 2017a) ~~in order~~ to analyze ~~the~~ MT soundings. Its performance also
205 proved to be adequate in the case of Ischia and the MT curves obtained do not appear affected by
206 anomalous behaviour, such as a strong scattering of the points, strong oscillations or rises in the
207 apparent resistivity, etc., that might signal the presence of coherent noise. Finally, the MT curves
208 were analyzed using both MT-corrector[®] and Winglink[®] commercial software (Figure 2). ~~Some of~~
209 ~~the curves thus obtained are displayed in figure 2, as example of their general behavior.~~
210 Furthermore, ~~One~~ of the first issues concerning magnetotelluric data is ~~so-called~~ the static-shift
211 (Jones, 1988). The data may suffer a sort of indetermination in the level of the apparent resistivity
212 curves, due to the galvanic effects of shallower bodies. Such an issue, that does not affect the phase
213 curves, was taken into account by carrying out Local Electrical Resistivity Tomographies (ERT).
214 ERT, being based on a DC current source, does not suffer such issues and it is possible to use
215 tomography of this kind to synthetically reconstruct the correct level of the MT apparent resistivity
216 at high frequency. ~~In the following the dataset has been arranged considering t~~Two separate profile
217 lines, which were oriented along N-S and the WSW-WNE transects ~~were set up~~. These profiles, 5
218 km and 3 km long respectively, covered the central-western sector of the island (figure 1). For each
219 of the two profiles the apparent resistivity and phase curves relative to both the TM (Transverse
220 magnetic) and TE (Transverse electric) modes are shown in figure 3, under pseudosection form
221 (Vozoff, 1991).

222 As an initial step, the MT data dimensionality was analyzed. ~~As is well known, t~~The introduced **Z**,
223 which correlates the electric and magnetic fields on the Earth surface, presents peculiar
224 characteristics in the case of 1D or 2D symmetries actually present in the data (Vozoff, 1991;
225 Simpson and Bahr, 2005; Troiano *et al.*, 2009) and several approaches exist in ~~the~~ literature to
226 investigate this issue, namely the Wal method (Weaver *et al.*, 2000), ~~the~~ phase tensor analysis
227 method (Caldwell *et al.*, 2004) and ~~the~~ Groom and Bailey's method (McNeice and Jones, 2001).
228 In the present case, ~~the~~ phase tensor analysis has been applied. This method, introduced by
229 Caldwell, *et al.* (2004) was ~~successively~~ well-described in Berdichevsky and Dmitrev (2010), where
230 it is possible to retrieve details regarding the ~~overall~~ methodology, the definition of the phase tensor
231 $[\Phi] = \begin{bmatrix} \Phi_{xx} & \Phi_{xy} \\ \Phi_{yx} & \Phi_{yy} \end{bmatrix}$ and all the derived quantities. Figure 4 reproduces the ~~behaviour~~ behavior of the
232 orientation of the phase tensor ellipse, i.e. the $\alpha_1 = \frac{1}{2} \sin \left(\frac{\Phi_{xy} + \Phi_{yx}}{\Phi_{xx} + \Phi_{yy}} \right)$, e.g. the α_1 -angle, defined in
233 Berdichevsky and Dmitrev (2010); ~~it is also reproduced,~~ and the Caldwell-Bibby-Brown Skew
234 angles, $skew_{CBB} = \frac{1}{2} \arctan \left(\frac{\Phi_{xy} - \Phi_{yx}}{\Phi_{xx} + \Phi_{yy}} \right)$, for every survey, over four distinct frequency bands,
235 respectively ~~centred~~ centered on 0.9, 9, 90 and 900 Hz. In a model with the two-dimensional
236 regional background, $skew_{CBB} = 0$ and the principal directions of the phase tensor coincide with the

237 α_1 angle. In the case of a ~~3D the three-dimensional~~ asymmetric regional background $\text{skew}_{\text{CBB}} \neq 0$.
238 This angle represents a correction for the regional background asymmetry, which can be neglected
239 if small, ~~so that we can rely on the resorting to the two-dimensional-2D~~ approximation of the
240 regional background. As expected in a volcanic context, the skew_{CBB} does not seem to present a
241 ~~behaviour/behavior~~ adequate to ~~support~~ a 2D inversion ~~in the present case~~ and a different approach
242 ~~has~~ to be pursued. It is worth noting that this step is the basis on which to choose one of the
243 possible strategies that might ~~turn out/prove to be~~ more satisfactory for the data inversion.
244 Despite the well-~~consolidated-tested~~ 2D approach generally being thought of as the optimal to
245 choose in terms of a compromise between the numerical complexities of the task and the
246 affordability of the results, its incorrect application can lead to very misleading results and
247 examples exist in literature where the differences originating from a 3D reinterpretation of
248 previously analyzed MT data have led to models having very different implications (Booker, 2014).
249 On the other hand, even if various 3D inversion codes have been proposed in the literature
250 (Siripunvaraporn *et al.*, 2005a; Kelbert *et al.*, 2014) and ~~if~~ 3D inversion ~~is-has been~~ actually
251 developed in MT surveying (Rosenkjaer *et al.*, 2015; Yang *et al.*, 2015), such a procedure ~~is~~ still
252 ~~turns out to be~~ not totally stable and requires a high number of sampling sites to be applied. In the
253 Ischia survey work, the ~~logistical-morphological~~ conditions limited the number of ~~surveys-sites~~ and
254 imposed the alignment of the sites along two crossed lines. This configuration has to be taken into
255 account when the inversion strategy is questioned.
256 Many papers in the literature ~~concern-consider 3D the three-dimensional~~ inversion of ~~two-~~
257 ~~dimensional-2D~~ profiles (e.g. Ledo *et al.*, 2002; Siripunvaraporn *et al.*, 2005b), ~~which~~
258 ~~highlight~~ ~~These highlighted~~ the limits of this approximation when the TM and TE apparent
259 resistivity and phase are considered separately. Such a situation has also already been dealt with in
260 Troiano *et al.* (2014), ~~which-who~~ presented ~~the three-dimensional a~~ 3D inversion of an
261 electromagnetic survey carried out in the Campi Flegrei area. In this ~~last~~ case, the ~~one-~~
262 ~~dimensional-1D~~ inversion of the Z determinant has ~~proven-proved~~ to be a useful tool to set up a
263 strategy to interrogate the effects of ~~three-dimensional~~ buried structures ~~in 3D based~~ on ~~two-~~
264 ~~dimensional-2D~~ survey profiles. Such ~~quantities-considerations prove turn out~~ to be particularly
265 significant in volcanic environments (Ranganayaki, 1984; Pedersen and Engels, 2005; Troiano *et*
266 *al.*, 2014) and the resistivity model that can be obtained through this step, despite the strong
267 limitation linked to the 1D approximation, ~~may be an optimal starting model~~.
268 The likely indetermination related to the effects due to the eventual presence of lateral anomalies on
269 the MT sections ~~have been/were here successively~~ taken into account through a 3D ~~based forward~~
270 trial-and-error procedure (Troiano *et al.*, 2014). The latter ~~is-was~~ carried out through the use of the

271 subroutines of the WingLink® commercial code in order to estimate the apparent resistivity and
272 phase curves. The subsurface was divided up into 76 ~~79~~ ~~36~~ cells, with dimensions ranging from
273 50 m (in the core of the modeled area) up to 1 km (in the external zones) and an objective function
274 was ~~evaluated~~ derived, based on the misfit between measured and reconstructed apparent resistivity
275 and phases. This trial-and-error procedure begins with the resistivity model obtained using the 1D
276 inversion of the Z determinant. A wide range of alternative models were then compared, taking as
277 ~~the most adequate~~ that the one related to the lowest root mean square (r.m.s.). At the end of the
278 procedure, an optimal model, corresponding to an r.m.s. less than seven ~~lower than 7 r.m.s. value~~,
279 was selected. We note that ~~such a procedure is well founded in the literature and that~~ the r.m.s.
280 value obtained here was compatible with ~~ones those~~ presented ~~in literature~~ for similar applications
281 (e.g. Schwalenberg *et al.*, 2002; Abdul Azeez and Harinarayana, 2007; Rao *et al.*, 2007; Heise *et*
282 *al.*, 2008; Arango *et al.*, 2009; Troiano *et al.*, 2009 and Troiano *et al.*, 2014).

283 An error threshold of 5% was considered for both the apparent resistivity and phase curves. More
284 details for the data analysis and inversion procedures can be ~~retrieved~~ found in Troiano *et al.* (2008)
285 and Troiano *et al.* (2014). The sections corresponding to the two ~~crossed~~ profiles of figure 1 are
286 represented in figure 5 and figure 6, respectively. The main electrical anomalies have been labeled
287 with capital letters and will be interpreted geologically in the following section.

288 ~~Considering At this point one last issue should be discussed concerning the description of the~~
289 ~~reliability of the results obtained from the MT data analysis. As an initial concern, taking into~~
290 ~~account the rule of thumb's for skin depth and considering~~ a mean electrical resistivity for the
291 medium of about 100 Ωm, the maximum period of 10 s was found to be associated with a wave
292 penetrating more than 15 km into the crust. The models of figure 5 and figure 6 resolve to a
293 maximum depth of about 3 km, ~~which then prove to be completely determined. A~~ Apart from such
294 ~~empirical considerations, a~~ full sensitivity analysis was also carried out, following Schwalenberg *et*
295 *al.* (2002). In figure 7 the sensitivity maps are reported, relative to the resistivity cross-sections of
296 both figures 5 and ~~figure~~ 6. Sensitivity represents an estimate of the changes induced in the data by
297 infinitesimal variations in the underground electrical resistivity. There is ~~not an~~ univocal threshold
298 for the sensitivity required to indicate that a structure is well resolved, but the procedure presented
299 in Troiano *et al.* (2008) and Troiano *et al.* (2009) supports the conclusion that both ~~the our~~
300 resistivity cross-sections are reliable. The consistency of the main bodies retrieved in the sections
301 was further questioned by removing the anomaly from the model and recalculating the relative
302 r.m.s. ~~The absence of significant changes in this parameter implies a lack of resolution of the~~
303 ~~analyzed zone. On other hand,~~ Significant r.m.s. variations with respect to the error thresholds
304 ~~could~~ can be considered as an indicator that the investigated part of the model exhibits good

305 resolution. For example, in the NS section ~~displayed in of~~ figure 5, the resolution of the zones
306 labeled as A, B1, B2 and C was tested. When the resistivity of the model was modified only ~~in the~~
307 ~~A-zone A~~, substituting the few tens of Ωm retrieved with the data inversion using the 200 Ωm
308 identified in the surrounding area, a 13.4% change in the r.m.s. was obtained. This indicates that the
309 A zone exhibits good resolution. Analogous results were obtained for ~~the remaining bodies all other~~
310 ~~zones~~.

312 Results

313 The resistivity imaging of the island ~~of Ischia has allowed~~ allows us to recognize a number of
314 sectors, down to a depth of 2-3 km, with resistivity anomalies that are ascribable to ~~the~~ distinctive
315 processes and physical conditions of ~~the hydrothermal system below the caldera the crust~~. From the
316 S-N profile (Figure 5), moving from south to north, it is possible to highlight a relatively higher
317 resistivity zone ~~south-extending~~ to station I6 (Ischia6) (~~this is zone A with where resistivity~~ values
318 of thousands of Ωm). ~~There is then~~ a lower resistivity channel (zone B, with a few tens to hundreds
319 ~~of~~ Ωm) between the measurement stations I7 and I8, ~~and~~ a high resistivity zone (C) beneath the Mt.
320 Epomeo resurgent block (several thousands Ωm at a depth below 1000 m, between stations I5 and
321 I13). ~~A and a~~ further zone of lower resistivity (~~zone D~~) ~~occurs~~ on the northern coast ($<50 \Omega\text{m}$).

322 Along the WSW-ENE profile (figure 6) a rapid change in resistivity (from several thousands ~~of~~ Ωm
323 to a few tens of Ωm) is observed ~~in to~~ the WSW ~~zone~~. Beyond the anomaly beneath Mt. Epomeo
324 (C1, a few thousand ~~of~~ Ωm), ~~four~~ other zones ~~were can~~ characterized. ~~The first one is Aa~~ channel
325 with lower resistivity between the stations I20 and I21 (E) ~~which is well~~ developed down to the
326 bottom of the profile (~~at a depth of 2.5 km~~). ~~W and within its the interior of this channel~~, two lower
327 resistivity zones (a few tens Ωm) appear: the first one (E1) is located at shallower depths, up to 500
328 m below ~~the surface level~~, ~~and~~ the second one (E2) develops from a depth of about 1500 m to the
329 bottom of the profile. ~~Furthermore~~ Finally, a roughly circular shallow area (F) with very low relative
330 resistivity (less than ten Ωm) can be identified ~~uphill ENE~~ to station I18 (~~figure 6~~).

331 The agreement between the two resistivity cross-sections of figures 5 and ~~figure 6~~ have been
332 evaluated in ~~Figure 8~~, where a stereographic view of the retrieved anomalies is provided. In the
333 area where they ~~two profiles~~ intersect ~~the our~~ magnetotelluric imaging detects a coherent resistive
334 structure in correspondence to the Mt. Epomeo resurgent block.

337 Interpretation of the resistivity cross-sections

338 ~~As is well known, the peculiar~~ sensitivity of electrical resistivity to the presence of groundwater
339 provides electrical and electromagnetic methods with a high detectability power ~~with respect to~~
340 ~~resolving~~ buried structures. However, once the presence of the electrical resistivity anomalies have
341 been inferred, in volcanic settings, the interpretation of the geophysical imaging remains inherently
342 difficult. ~~As~~ ~~Because~~ the resistivity of rocks is generally affected by the water content, alteration
343 (through their clay content and clay mineralogy), salinity of the pore water and temperature, the
344 physical properties of porous rocks in geothermal and volcanic areas remain poorly known (e.g. ~~A~~
345 ~~digression regarding such issues can be read in~~ Revil *et al.*, (2002), Revil *et al.* (2017a) and Revil *et*
346 *al.* (2017b) ~~and the references therein. Summarizing their considerations,~~ Groundwater in volcanic
347 settings flows within porous materials, which may ~~present~~ ~~undergo~~ a greater or lesser degree of
348 alteration. This alteration is due to a chemical weathering of the minerals by the hot hydrothermal
349 fluids, including hydration-dissolution processes of the volcanic glass and the formation of
350 aluminosilicates ~~such as~~ (clays and zeolites (Schön, 2015)). Hydroelectric coupling in these porous
351 rocks is influenced by the presence of these aluminosilicate minerals ~~due to their role in blocking as~~
352 ~~a result of their key position inside~~ the connected pore space. Electrical conductivity provides two
353 contributions. The first is associated with conduction within the ~~bulk~~ pore water. The second
354 ~~contribution, called~~ ~~is termed~~ surface conductivity ~~and~~ is associated with conduction in the
355 electrical double layer coating the surface of ~~the~~ grains (Berdichevsky and Dmitriev, 2010; Schön,
356 2015). Both ~~of~~ these processes ~~could~~ ~~can~~ bring about an increase in conductivity~~ies~~ and, using only
357 resistivity data, it is not easy to separate surface from bulk conductivities at a given pore water
358 conductivity. In our case, a numbers of ambiguities in the interpretation of ~~our~~ data were reduced by
359 correlating the resistivity anomalies with data provided ~~by~~ ~~from~~ drillings (see figure 1 for
360 locations), down to ~~a maximum~~ depth of 1150 m, and with previous geophysical and geochemical
361 modeling of the island ~~provided by Nunziata and Rapolla (1987), Chiodini et al. (2004), Paoletti et~~
362 ~~al. (2005), Di Napoli et al (2009), Di Napoli et al., (2011), Carlino (2012), Paoletti et al., (2013),~~
363 ~~Carlino et al. (2014).~~

364 The resistivity contrasts between ~~the zones~~ A, B, C and D ~~zones~~ of N-S profile (Figure 5) present a
365 good correlation with the known volcano-tectonic features of the island, such as the boundary of
366 caldera ~~collapse~~ and the Mount Epomeo resurgent block. In particular, ~~the~~ structural limit of the
367 caldera is ~~perhaps~~ recognizable in the southern sector, close to the station I6. A normal fault, with a
368 NW-SE strike affecting the south-western ~~uplift sector~~ of the resurgent block (see ~~also~~ figure 1 for
369 fault location) (Vezzoli, 1988), ~~corresponds to~~ ~~coincides with~~ the resistivity contrast between
370 stations I5 and I8. In addition, north ~~to~~ ~~of~~ station I4, the resistivity variation pattern can be
371 interpreted as the occurrence of minor faults facilitating the block uplift in the period since 33 ka

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ago (Vezzoli *et al.*, 2009). In the northern sector (figure 5) a low resistivity ~~surface zone~~, which deepens to about 700-800 meters down, ~~from-between~~ the coast to the inner part of the island, is perhaps attributable to the interface between saline water and fresh water due to the latter's buoyancy.

Between ~~the~~ measurement stations I7 and I8 a lower resistivity channel can be identified (B in figure 5). In particular, two major anomalies (B1 and B2) have been detected along this channel. The shallower one, B1, has ~~a~~ vertical extent ~~of~~ up to about 450 m b.s.l., while the deeper one, B2, develops from about 1100 m to 2500 m b.s.l. ~~According to the following~~ hydrothermal studies of the island (Di Napoli *et al.*, 2009, 2011) and ~~from~~ drilling data (Penta and Conforto, 1951; Penta, 1963; AGIP, 1987), we ~~have can~~ interpreted the resistivity anomalies B1 and B2 as two aquifers, the former with a temperature of about 150°C, ~~and~~ the latter with a temperature of 250°C (~~Chiodini et al., 2004~~). ~~These are~~ formed by ~~a~~ mixing of liquid ~~and~~ vapour (~~Chiodini et al., 2004~~). The lower levels of the aquifer B1 and the upper level of the aquifer B2 are in good agreement with the hydrothermal model proposed by Di Napoli *et al.*, (2011). Along the WSW-ENE profile (Figure 6) two zones, E1 and E2, have been interpreted as two aquifers similar to those inferred along the N-S profile (B1 and B2). In accordance with the vertical tectonic movement of the island (resurgence), the top of ~~the~~ aquifer B2 (N-S profile of figure 5), ~~that~~ is closer to the uplift block ~~and~~ has been dislocated upwards with respect to the aquifer E2. The bottom of the aquifers are possibly sealed by argillification processes which took place before ~~the~~ resurgence. Furthermore, as shown in Figure 9, the shape and location of the whole channel exhibiting low resistivity is possibly reconcilable with a thermal anomaly (a plume) associated with ~~a robust~~ advection of hydrothermal fluids. ~~This is~~ an interpretation also supported by ~~the drill hole~~ data ~~from drillings~~ and by the presence of large fumaroles and a hot-spring field (with temperatures up to 100°C), immediately north and west of ~~the~~ stations I20 and I21, respectively (Citara site, ~~see also~~ figure 1) (Penta and Conforto, 1951; AGIP, 1987; Chiodini *et al.*, 2004; Di Napoli *et al.*, 2011; Carlino *et al.*, 2014). ~~As is well known~~, ~~the~~ presence of such a thermal plume should leave a clear geophysical signature and the ~~carrying out of new~~ further surveys might allow it to be fully characterized (Jardani *et al.*, 2008).

One of the main features of the resistivity images is the occurrence of a high resistivity zone (>1000 Ωm) ~~identified~~ in both the N-S and WSW-ENE sections (see zones C and C1 in figures 5 and 6, respectively, ~~as well as~~ and figure 8). This anomaly is delimited ~~in the upper part~~ by the faults bordering the resurgent block. Considering the high heat flow and the elevated geothermal gradient of the area (Carlino *et al.*, 2014), ~~which generally tends to lower the resistivity of rocks~~, the relatively high resistivity anomaly (C and C1) can be ~~debated~~ explained in terms of ~~rock type and texture and their associated~~ permeability. ~~An initial remark is that the~~ high resistivity is

406 ~~possibly can be~~ associated with a lower flow of hot hydrothermal fluids ~~into the rocks~~. This process,
407 typical of many volcanic areas (Marsh, 1984), is related to the occurrence of crystalline rocks such
408 as intrusive bodies with very low permeability (k) ~~or impermeable (e.g. k ranging~~ which ranges
409 10^{-17} to 10^{-21} m² for granite, ~~for example~~) (Brace, 1980). ~~Such low permeabilities would~~ These
410 inhibit the passage of fluids because the minimum permeability for volatiles to transfer into the
411 shallow crust is 10^{-20} to 10^{-18} m², while for fluid transfer the figure is $\geq 10^{-16}$ m² (Ingebritsen *et al.*,
412 2010). Furthermore, geochemical and isotopic investigations (Tedesco, 1996) ~~have~~ highlighted the
413 presence of magmatic fluids ~~(with small crustal contamination)~~, which probably escape laterally
414 from below to the magma body because they encounter a permeability barrier in ~~a higher its upper~~
415 ~~and~~ more crystalline part. The presence of a shallow magmatic body (≈ 2 km in depth) beneath the
416 Mount Epomeo resurgent structure, ~~has~~ already been inferred by others authors ~~from interpretation~~
417 ~~of mag~~ magnetic and gravity data (Nunziata and Rapolla, 1987; Paoletti *et al.*, 2013 and references
418 therein). For instance, the contemporary presence of a magnetic minimum and a gravimetric
419 maximum (slightly decentred to the SW with respect to the centre of the island), might be explained
420 by the existence of an intrusion or several intrusions and/or by partially melted ~~zones to create~~
421 ~~pockets of crystal mush~~ spots (mush). This hypothesis is supported by the high temperature gradient
422 measured in the central-western sector of the island (Penta and Conforto, 1951; Penta, 1954;
423 Ippolito and Rapolla, 1982; Panichi *et al.*, 1992; Paoletti *et al.*, 2009). Furthermore, an undated
424 intrusive rock was found at the bottom of the 1050 m deep ~~well~~ drilling, located west of Mount
425 Epomeo (well 2 in Figure 1) (Penta and Conforto, 1951; AGIP, 1987). Our findings seem to
426 confirm the presence of such a ~~shallow~~ magmatic body, ~~suggesting an even shallower one~~, with a
427 bulge penetrating up to about 1 km below the surface. Furthermore, taking into account the
428 geothermal gradient of the island (about 200°C km⁻¹) (see Carlino *et al.*, 2012, 2014 for details) the
429 solidus temperature (onset of melting) may be encountered at a depth >3 km.

430 As a whole, we are confident that this magmatic body represents an intrusion and cannot be related
431 to other ~~different high resistivity~~ structures, such as an uplifted ~~resistive~~ basement or unfractured
432 rocks filling the caldera. Further observations supporting our statement include ~~the following~~: the
433 high rate of resurgence of Mt. Epomeo, ~~clearly which~~ indicates ~~ing~~ a magmatic process (injection)
434 ~~as driving mechanism~~ (Tibaldi and Vezzoli, 2004; Sbrana *et al.*, 2009) as driving mechanism; the
435 observed pattern of deformation that can be associated with a shallow magmatic source ~~with its top~~
436 ~~at about 2 km b.s.l.~~ (Carlino, 2012), ~~with the top at about 2 km b.s.l.~~; the ~~observation that arrival of~~
437 new trachybasaltic magma ~~arrived in into~~ the shallow magmatic system before the volcanic activity
438 28-18 ka (Civetta *et al.*, 1991); the melt inclusion ~~data that reveal that the of~~ eruptive products ~~of~~
439 ~~(73-59 ka) that were within~~ came from a magmatic storage region located at a depth of about 2 km

440 (Sbrana *et al.*, 2009) and, finally, the very high geothermal gradient and high temperature
441 hydrothermal system, associated with the presence of a shallow magmatic body (Sbrana *et al.*,
442 2009; Carlino *et al.*, 2012, 2014).

443 The ~~structure of the~~ resistivity anomaly (figure 8) perhaps thus represents the apex of a laccolith (or
444 alternatively a series of cone sheets) (Westerman *et al.*, 2004) intruded into the shallow crust of the
445 island (Rittman, 1930; Sbrana *et al.*, 2009; Paoletti *et al.*, 2013; Carlino *et al.*, 2006; Carlino, 2012),
446 ~~since at over the~~ least 33 ka (Carlino, 2012 and references therein). Considering both the N-S and
447 WSW-ENE profiles, the intrusion seems to have a branch that is elongated N-S in the western
448 sector of Mt. Epomeo.

449 Finally, we can compare the WSW-ENE profile ~~has been compared~~ with the geology of the island
450 (*Carta Geologica dell'isola d'Ischia*, CARG project), which in this sector is mainly constrained by
451 the stratigraphy revealed from the drilling ~~stratigraphy~~ (figure 10). ~~From As we seen in~~ figure 10,
452 ~~some correlations can be highlighted,~~ around the station I20, ~~where~~ the resistivity anomaly (>2000
453 Ωm) corresponds to the Punta Imperatore lavas and to the eruptive centrecenter of Campotese (see
454 also figure 1). These lavas, dated to about 177 ~~ka~~ (Gillot *et al.*, 1982), are dissected by faults that
455 possibly do not involve the more recent, overlying, deposits and that are associated with ~~the~~
456 collapse of the caldera rim. ~~As already mentioned above,~~ The contrast in resistivity highlights the
457 difference between the lower consolidated deposit of the inner caldera and the structural domes at
458 the caldera rim. Uphill-ENE to the station I18 a very low resistivity area coincides is well matched
459 with the most important fumarole field of ~~n~~ the island (Bocca di Serra, Donna Rachele fumaroles);
460 ~~which we correlated to the argillification processes of the rocks as a result of hydrothermal~~
461 alteration. The fumarole field covers about 0.80 km² (80 hectares), with emissions totaling ≈ 9 td⁻¹
462 (volume) of CO₂ ~~rising that rise along from~~ a system of vertical faults (Chiodini *et al.*, 2004). This
463 system is perhaps partly fed by a relatively deep hydrothermal aquifer (about 600 m deep) (Chiodini
464 *et al.*, 2004), whose fluids take advantage of the along the structural discontinuity (faults and
465 fractures system) located at the boundary of the uplifted block. ~~It is~~ We also remarkable that we note
466 a coincidence quite good agreement between the variation in ~~the~~ lithology encountered in the
467 stratigraphy of the wells drillings (wells drillings n-2 and n-4, see figure 1 for location) (AGIP,
468 1987) and the variation in resistivity encountered in ~~the our~~ cross-sections (figure 11a, b). Finally,
469 in order to assess the influence of the intrusion on the tilting of the Mt. Epomeo block (Acocella and
470 Funicello, 1999) we need to improve our measurements to get a wider 3D imaging, because the
471 resistivity anomalies seem to have a complex shape that cannot be well constrained by 2D
472 inversion.

473

474

475 Discussion

476 ~~Among the worldwide caldera systems, the active volcanic island of Ischia represents a good case~~
477 ~~study to investigate the processes generating resurgence and associated volcanic activity.~~ Of the
478 varying interpretations of the caldera resurgence process, the most common is that of magmatic
479 intrusion which can evolve in a range of ways, from sills, to dikes or laccoliths, ~~producing a~~
480 ~~variable amount of uplift and structures within the resurgent area~~ (Paige, 1913; Henry *et al.*, 1997;
481 Acocella *et al.*, 2001 and references therein). This process is generally associated with the
482 formation of well-developed geothermal systems (Hulen *et al.*, 1987).
483 ~~A One broader~~ implication of this study involves the mechanism producing ~~the~~ resurgence of
484 calderas. As in the case of Ischia, the relatively high rate of uplift, which provides a strain rate of at
485 least one order of magnitude larger than tectonic processes (Carlino, 2012), ~~excludes a regional~~
486 ~~tectonic contribution.~~ The ~~large and~~ long-term rate of uplift makes it possible also to exclude any
487 non-purely magmatic contribution to the resurgence, such as the oversaturation of volatile species
488 in a shallow and crystallising magma body (Tait *et al.*, 1989) or ~~a~~ fluid contribution (Hurwitz *et al.*,
489 2007). These processes are typically associated to relative small-scale (metres) and short-term
490 (months ~~to~~ years) disturbances and, as in the case of the contribution of fluids, a partial recovery~~ing~~
491 of the deformation occurring ~~will takes~~ place (see, for instance, the example of Campi Flegrei
492 caldera; Troiano *et al.*, 2011 and references therein). The long-term resurgence of Ischia (from at
493 least 33 ka to 5 ka) was punctuated by phases of quiescence (de Vita *et al.*, 2010), which possibly
494 corresponded ~~to the periods~~ of volcanic activity (Carlino *et al.*, 2006), ~~while However~~ a larger
495 proportion of the magma arriving ~~into~~ the shallow system (Civetta *et al.*, 1991) has not been
496 erupted, and merely contributed ~~ed~~ to the uplift of Mt. Epomeo (Carlino *et al.* 2012), forming a very
497 shallow intrusion whose occurrence seems to be confirmed by resistivity data. This behaviour ~~that,~~
498 ~~for instance,~~ is different when compared to ~~that of~~ the nearby Campi Flegrei caldera, (where some
499 caldera sectors were uplifted by less than 100 m, while larger eruptions occurred). ~~It,~~ is instead
500 similar to ~~other volcanoes, as observed for~~ the Grizzly Peak caldera (Colorado) (Fridrich *et al.*,
501 1991) and ~~for the volcanic island of~~ Pantelleria (Southern Italy) (Orsi *et al.*, 1991). In ~~the~~
502 ~~above these~~ cases, the rheology of ~~the~~ shallow magma sources and the response of the surrounding
503 rock walls to the stress induced by the pressure of the magma possibly control the different
504 evolution~~s~~ of caldera resurgence ~~(total uplift vs. erupted volumes)~~. For instance, the temperature of
505 the intruded magma and of the surrounding rock, ~~walls~~ together with the injection rate, strongly
506 affect the behaviour of the system (Jellinek and DePaolo, 2003). Large geothermal gradients and
507 low magma injection rates enhance creep processes instead of catastrophic failure, increasing the

508 accretion of magma at depth and inhibiting eruptions (Jellinek and DePaolo, 2003). Overall, when
509 the magma is the primary source of the resurgence of calderas, it is crucial to estimate its volume,
510 thermal state and thermal history (Cooper and Kent, 2014), while the rheology of the magma itself
511 and of the surrounding rock ~~walls~~ is critical in the evolution of the resurgence (Carlino and Somma,
512 2010). For the island of Ischia, if we assume a roughly radial symmetry of the resistivity anomaly
513 associated with the magma intrusion (about 2 km in radius and 2 km in vertical extension), at least
514 for the crust down to 3 km, ~~that we obtain get~~ a magma volume of about 6 km³. ~~If this has been~~
515 ~~gathering since 33ka (Tibaldi and Vezzoli, 1998), then the accumulation rate is about 1.8·10⁻⁴ km³~~
516 ~~a⁻¹. This possibly represents a lower limit of the volume of magma (and the magma rate) intruded~~
517 ~~into the shallow crust, which, in its present state (having been gathering over 33ka), is not likely to~~
518 ~~prove eruptible due to its thermal condition. That is (the magma is will be highly degassed and the~~
519 ~~maximum temperature is possibly ≤ 600°C (and is below the melting point; see also Carlino et al.,~~
520 ~~2014).~~

521

522 Conclusions

523 ~~The Our~~ magnetotelluric survey carried out in the southern and western sector of the island of
524 ~~Ischia~~, detected several electrical resistivity anomalies, ~~up-down~~ to a depth of 3 km. The
525 interpretation of the resistivity ~~cross-sections~~ and ~~the~~ comparison with ~~previous-other~~ geological,
526 geophysical and geochemical ~~studies-data provide allow~~ the following ~~main findings conclusions~~
527 ~~and inferenes~~:

528 ~~— a good correlation, according to data in the literature (Schön, 2015), has been observed~~
529 ~~between the known geological information (stratigraphy inferred from drilling data) and the~~
530 ~~range of variation in the area's resistivity anomalies (see figure 11a, b).~~

531 - a large thermal anomaly has been ~~inferred-found~~ in the southern and western sector of the
532 island and is associated with a ~~sustained-zone of~~ heat advection ~~of-and~~ circulation of
533 hydrothermal fluids (Figure 5 and 6). The presence of two major hot aquifers, previously
534 hypothesized by geochemical studies (Chiodini *et al.*, 2004, Di Napoli *et al.*, 2011), has ~~also~~
535 been ~~definitely-located/lized~~ in the southwestern sector ~~of the caldera~~. The aquifers ~~are~~
536 ~~found/reside~~ at different depths, ~~with the depths being controlled by/depending on the vertical~~
537 tectonic movements, which have ~~affected-caused deformation of~~ the resurgent block of Mt.
538 Epomeo ~~for-over~~ at least the last 33 ka (Vezzoli, 1988). The top of the deeper aquifers,
539 feeding the main south-western fumarole fields, ~~and~~ are located at a depth of about 1000 m
540 to 1500 m, respectively.

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- 541 - a large resistivity anomaly is located below the resurgent structure of Mt. Epomeo, ~~along~~
 542 ~~both the N-S and WSW-ENE profiles~~. It is interpreted as the apical part of a crystalline (and
 543 very low permeability) magmatic body intruded below the central part of the island (and
 544 slightly dislocated towards the south-west) and whose apex reaches a depth of about 1 km
 545 b.s.l. (~~in the central-western part~~) and the bulk body of which is This body is bounded by an
 546 abrupt resistivity drop corresponding to the faults ~~close-around~~ to the resurgent block of Mt.
 547 Epomeo.
- 548 - we ~~suppose~~ propose that this high resistivity body is associated with the laccolith of Ischia
 549 (Rittman, 1930; Sbrana *et al.*, 2009; Carlino, 2012), which produced the bending, fracturing
 550 and faulting of the overlying crust, and ~~which witnessed a further~~ magma intrusion during
 551 the ~~final-most recent~~ stage of the resurgence (5 ka) (Civetta *et al.*, 1991; Vezzoli *et al.*,
 552 2009). As result, the uplifted block ~~h~~ was been broken up into minor blocks, with the
 553 underlying laccolith possibly developing as a complex structure, ~~formed by various~~
 554 ~~protrusions on its apex~~. This laccolith is the engine of the robust geothermal system of the
 555 island, and -to be consistent with a high resistivity - is likely dominated by a highly
 556 crystalline mush.
- 557 - ~~finally, the finding~~ the existence of such a shallow magma body is critical in terms of
 558 volcanic hazard assessment ~~on the island~~. The volcanism of ~~the island~~ Ischia seems, in fact,
 559 to be strictly correlated to the resurgence process that, in turn, is reliant on the dynamics
 560 of the laccolith (Carlino, 2012). A renewal of ~~the~~ resurgence ~~is thus will be~~ related to ~~the~~
 561 reactivation of the laccolith (~~e.g. the~~ by arrival of new magma) (Civetta *et al.*, 1991); This
 562 ~~which~~ may possibly produce a large disturbance of the geothermal system at a depth of
 563 between 1 km and 2 km. A reactivation of such a shallow magmatic system may imply
 564 imminent eruption and ~~a~~ would pose high volcanic hazard (e.g. Cooper & Kent, 2014);
 565 certainly it would cause hydrothermal emissions to evolve towards magmatic (Vaselli et al.,
 566 2010).

571 Figures captions

573 Figure 1. Structural and geological map of Ischia Island (after Di Napoli *et al.*, 2011). Indicated are
 574 the MT measurement stations along the N-S profile are given as (blue points); the MT
 575 measurement stations along the WSW-ENE profile are (green points; the blue-green points are the
 576 stations belonging to both the profiles); Drilling sites are given as the geological section A-A' used

577 ~~in the text; the deep wells on the island~~ (red points numbered ~~from~~-1 to 5). The shaded grey circular
578 area indicates the resurgence zone ~~and black lines are mapped faults~~ (Di Napoli et al. 2011). The
579 dotted red lines indicate the resistivity section profiles.

580

581 Figure 2. Three examples of apparent resistivity and phase diagrams pertaining to the Ischia MT
582 survey work.

583 Figure 3. (a) ~~NS-S-N~~ Magnetotelluric profiles of apparent resistivity (above) and phase (below)
584 pseudosections relative to the TM mode. (b) ~~NS-S-N~~ Magnetotelluric profiles of apparent resistivity
585 (above) and phase (below) pseudosections relative to the TE mode. (c) WSW-ENE
586 ~~m~~Magnetotelluric profiles of apparent resistivity (above) and phase (below) pseudosections relative
587 to the TM mode. (d) WSW-ENE Magnetotelluric profiles of apparent resistivity (above) and phase
588 (below) pseudosections relative to the TE mode (see text for details).

589

590 Figure 4. Results of the data dimensional analysis carried on the ~~Ischia~~-MT dataset using the phase
591 tensor approach. The data have been divided up into four contiguous frequency bands, respectively
592 centered on 0.7 9, 90 and 900 Hz. The phase- tensor ellipse orientation (in degrees) ~~(e.g. the α_1~~
593 ~~angle defined in Berdichevsky and Dmitrev, 2010)~~ and the Caldwell-Bibby-Brown Skew angles are
594 ~~reported given~~, for each MT survey, ~~respectively in~~ (panel a) and (panel b), respectively.

595

596 Figure 5. S-N resistivity profile obtained from the inversion of the MT survey (panel b). ~~It is~~
597 ~~possible to recognize different resistivity contrasts associated with volcano tectonics and~~
598 ~~geothermal features of the island~~. Dotted lines are the faults associated with the caldera boundary
599 and to the dislocation of the resurgent block (see text for details). It is also reported ~~(top panel a)~~ the
600 topographic profile along the section.

601

602 Figure 6. WSW-ENE resistivity profile obtained from the inversion of the MT survey (panel b). The
603 resistivity anomalies ~~(indicated marked~~ as E, E1 and E2) ~~has been associated~~ is coincident with a
604 thermal plume producing high geothermal gradients and very high temperatures (~100°C) at the
605 surface ~~(see also figure 7~~ Carlino et al., 2014). It is also reported ~~(top panel a)~~ the topographic
606 profile along the section.

607

608 Figure 7. Sensitivity cross-sections relative to the resistivity models ~~shown in figure 5~~ (NS-S-N
609 profile, above) and ~~figure 6~~ (WSW-ENE profile, below).

610

611 Figure 8. Topography in shaded relief of Ischia draped over the DEM (INGV web-GIS source),
612 perspective views from W (a), NE (b), SW (c), S (d). Beneath each are the resistivity data for the
613 two profiles so as to set in context the variations we record with depth, as well as distance from Mt.
614 Epomeo. ~~Summarizing figure for resistivity profiles from different point of views. It is possible to~~
615 ~~infer the shape of the intrusion which exhibits a complex structure formed by very shallow~~
616 ~~protrusions.~~

617

618 Figure 9. Magnification of the central part of the WSW-ENE profile compared with the geotherms
619 (after Carlino et al., 2014) ~~Comparison of a detail of figure 6 (WSW-ENE resistivity profile) with~~

620 the isotherms obtained from the temperatures measured inside the wells down to a depth of 1000m
621 (see figure 1 for well locations)

622
623 Figure 10. Comparison of the shallower part of WSE-ENE resistivity profile with a geological
624 section of the island (from *Carta Geologica dell'Isola d'Ischia*, CARG project). Legend: PZE =
625 Pizzone Tuffs (~61 ka); TFS = Frassitelli Tuffs (~62 ka); VNU = dike and tabular intrusions-;
626 TME = Mount Epomeo Green Tuff (~55 ka); PIM-FGN = Punta Imperatore ancient lavas (~117
627 ka); ELF = Elephant pyroclastic deposits; TCT = Citara Tuffs (~45 Ka); SUN = debris and mud
628 flow deposits; PPI = Punta Imperatore pyroclastic deposits (~ 18 ka); PUS = Punta Soccorso
629 debris avalanche; a_{al} = alluvial deposits. (from CARG project)

630
631 Figure 11 (a, b). ~~Detail Magnification~~ of the sections ~~given in~~ figures 5 and 6 with the position ~~of~~
632 ~~drill sites and stratigraphy of well numbers~~ 2 and 4 (see figure 1 for location) ~~from which~~
633 ~~stratigraphic data are taken. The comparison has been carried out to correlate the variation in the~~
634 ~~resistivity with the different layering of buried rocks.~~ Legend: (~~well-drill~~ n. 4) VB = Volcanic
635 Breccia; GT = Green Tuff; GTL = Green Tuff interlayered with trachytic lava. (~~well-drill~~ n. 2) RT =
636 Reworked Tuffs and Alluvium; TYT = Trachytic Yellow Tuffs; PLD = Pyroclastic and Lava
637 deposits; GrT = Green Tuff; TL = Trachytic lava

638
639 **Acknowledgements:** This work was carried out in the framework of the INGV-DPC Research
640 Agreement 2012–2021 "All. A". ~~This paper does not necessarily represent DPC official opinion and~~
641 ~~policies.~~ We are grateful to the Associate Editor, V. ~~Acocella~~ ~~Acocella~~, the Executive Editor, A.
642 ~~Harris~~, and to the Referees, J. Stix and A. Revil, for their helpful comments that have greatly
643 improved the quality of the work.

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