

Manuscript Details

Manuscript number	VOLGEO_2018_184_R2
Title	Monitoring active fumaroles through time-lapse electrical resistivity tomograms: an application to the Pisciarelli fumarolic field (Campi Flegrei, Italy).
Article type	Research Paper

Abstract

Volcanoes are usually monitored through observations of many physical and chemical phenomena. In the most dangerous cases, as the one of the Campi Flegrei caldera (Italy), great amount of data are collected, both in discrete or continuously, and regularly stored. However, how to transform such mass of data in a deeper understanding of the volcano dynamics is still an open question. Dissimilar information are in fact always hard to compare, but just integrating all the available knowledge hazardous events could be prevented in a reliable way. Fluids, as water and gasses mobilized in the subsoil by the heat induced by deep magmatic sources, are widely recognized as the first engine of similar occurrences and the volcanic gas emissions represent, together with the seismic activity, one of the most considered precursors. At the same time, the electrical geophysical methods are the most applied in order to detect and characterize the fluid patterns in the subsoil. So, the integration of geoelectrical and geochemical observations should represents one of the most pursued approach in volcanoes monitoring. On the contrary, standard way to compare such data have been not yet codified. The ERT tomograms capability to individuate that parts of the subsoil where gasses cumulate is well understood in literature. However, we look for indications about its proficiency in associating the electrical resistivity changes relative to these zones, once compared to the geochemical time series, to deep related contributes, distinguishing them from the seasonal ones. The electrical signature of the fluid patterns, reconstructed through a time-lapse ERT approach, could be of relevance to better characterize the volcanic phenomena and their origins. In this paper a first test of ERT and geochemical time series integration was performed to enhance the understanding of the Pisciarelli fumarolic field evolution, now the most active area in the whole Campi Flegrei caldera.

Keywords	time lapse ERT tomography; Fumarolic vent; Campi Flegrei;
Corresponding Author	Maria Giulia Di Giuseppe
Order of Authors	Maria Giulia Di Giuseppe, Antonio Troiano
Suggested reviewers	Andre Revil, Vincenzo Lapenna, Yoichi Sasai, Jacques Zlotnicki
Opposed reviewers	agata siniscalchi

Submission Files Included in this PDF

File Name [File Type]

Editor.pdf [Cover Letter]

Comments from the reviewer.pdf [Response to Reviewers]

PaperI1rev_TC.pdf [Revised Manuscript with Changes Marked]

highlights.pdf [Highlights]

PaperI1rev.pdf [Manuscript File]

fig1.jpg [Figure]

fig2.jpg [Figure]

fig3.jpg [Figure]

fig4.jpg [Figure]

fig5.jpg [Figure]

fig6.jpg [Figure]

fig7.jpg [Figure]

fig8a.jpg [Figure]

fig8b.jpg [Figure]

fig8c.jpg [Figure]

fig8d.jpg [Figure]

fig8e.jpg [Figure]

fig9.jpg [Figure]

To view all the submission files, including those not included in the PDF, click on the manuscript title on your EVISE Homepage, then click 'Download zip file'.

Research Data Related to this Submission

There are no linked research data sets for this submission. The following reason is given:
Data will be made available on request

Dear Editor,

we are now sending a revised version of the manuscript "Monitoring active fumaroles through time-lapse electrical resistivity 1 tomograms: an application to the Pisciarelli fumarolic field (Campi Flegrei, Italy)." By M. G. Di Giuseppe and A. Troiano.

We considered your invite to take into account the observations of reviewer nr.2 and we added some sentences to the text. However, we cannot avoid pointing out the differences between our approach and that of the reviewer. On one side, we understand that in previous versions of the text there was no mention of the main mechanisms contributing to electrical conduction in rocks and the factors that influence the same. On the other hand, we believe that the core of our paper is the presentation of a specific application, considering a more detailed discussion about that to be out of focus. Also with regard to the position of the reviewer with respect to the autonomous value of electrical tomography, we disagree on both issues raised. On the one hand, direct petrophysical information would certainly be useful to support the interpretation of the sections, but for us it cannot be considered a necessary condition. The subsoil model obtained through time-lapse ERT, although essential because based just on the electrical picture of the subsoil (let's say univariate), is self-standing, at least in our opinion. On the other hand, although more surveys certainly mean more knowledge, we believe that a method such as ERT has shown, in decades of applications, its validity independently of IP surveys, even in volcanic environments.

We really hope that you could consider favourably this version of the manuscript and we wish to thank you for your attention.

Best regards

The authors.

1
2
3 **-Reviewer 2**
4
5
6
7

8 Review of “Monitoring active fumaroles through time-lapse electrical resistivity 1
9 tomograms: an application to the Pisciarelli fumarolic field (Campi Flegrei, Italy).” By M. G.
10 Di Giuseppe and A. Troiano. I will let the editor decide if he wants this manuscript to be
11 published but I do not see new research in this work. The time lapse inversion approach is
12 very crude, there is not discussion of the underlying petrophysics (with the fact that ERT
13 cannot be independently interpreted) and there is a lack of coupling the geophysics with
14 the process at play (a currently hot subject of research in hydrogeophysics). However this
15 paper has been significantly improved with respect to the first version. I think this paper
16 could be saved if it would contain a strong discussion between the time lapse ERT
17 observations and the final plot corresponding to Figure 9. This implies a discussion on how
18 the differential environmental variables (saturation, temperature, salinity) affect the
19 resistivity.
20

21 1. Many statements are too strong Example: “just integrating all the available knowledge
22 hazardous events could be prevented in a reliable way.”. This is not demonstrated in the
23 paper. This is only a wish from the authors.
24

25
26 2. The summary is not a summary with the exception of the last sentence. It just
27 provides vague statements about volcanological crisis forecasting. Please rewrite the
28 summary so that it reflects and summarize the content of the manuscript.
29

30
31 3. Intro: replace “Di Giuseppe et al., 2015;), » by « Di Giuseppe et al., 2015) » . Change
32 « complicat ed.” By “complicated.” All these errors show that the manuscript has not been
33 polished enough.
34

35
36 4. The following sentence is not substantiated enough “A mapping of the electrical
37 resistivity changes through ERT should be indicative of potentially hazardous dynamics in
38 the area”.

39
40 5. Regarding the sentence “The geophysical surveys based upon the electrical resistivity
41 estimations are very effective tools for imaging tectonic and volcanic structures, and
42 several contribution regarded the Campanian district (Di Maio et al., 1998; Bruno et al.,
43 2007; Troiano et al., 2008, 2009; Byrdina et al., 2014; Di Giuseppe et al., 2015, 2017;
44 Gresse et al., 2017).” Actually in a recent series of papers in JVGR (Soueid Ahmed et al.,
45 2018, Ghorbani et al., 2018; Revil et al., 2018a, b), it was advocated that ERT is not a
46 stand alone technique because surface conductivity cannot be separated from the bulk
47 conductivity and that surface conductivity usually is dominant in most volcanic setting. ERT
48 requires IP (induced polarization) to be properly interpreted. I think this point should be
49 discussed in details since the paper, in its actual form, completely oversell what ERT can
50 accomplish especially without a description of the underlying petrophysics.
51

52
53 6. Line 200-205: it is shown in MANY papers that time lapse ERT required imperatively the
54 use of dedicated inversion algorithm like sequential inversion or 4D inversion (including a
55 regularization in time). Examples include: Karaoulis M., A. Revil, D.D. Werkema, B.
56 Minsley, W.F. Woodruff, and A. Kemna, Time-lapse 3D inversion of complex conductivity
57 data using an active time constrained (ATC) approach, Geophysical Journal International,
58
59

60
61
62 187, 237–251, doi: 10.1111/j.1365-246X.2011.05156.x, 2011. Karaoulis, A. Revil, J.
63 Zhang, and D.D. Werkema, Time-lapse joint inversion of cross-well DC resistivity and
64 seismic data: A numerical investigation, *Geophysics*, 77(4), D141–D157 doi:
65 10.1190/GEO2012-0011.1, 2012. Meyerhoff S.B., M. Karaoulis, F. Fiebig, R.M. Maxwell,
66 A. Revil, J.B. Martin, W. D. D. Graham, Visualization of conduit-matrix conductivity
67 differences in a karst aquifer using time-lapse electrical resistivity, *Geophys. Res. Lett.*, 39,
68 L24401, doi:10.1029/2012GL053933, 2012. Karaoulis M., A. Revil, D.D., Werkema, P.
69 Tsourlos, and B.J. Minsley, IP4DI: A software for time-lapse 2D/3D DC-resistivity and
70 induced polarization tomography, *Computers & Geosciences*, 54, 164-170, 2013. This is
71 just to cite few examples in my realm. It is well known and demonstrated in many papers
72 that inverting the snapshots independently and looking at the difference does not work
73 because of the noise level in the data and inversion artefacts. This point should be
74 discussed because again it gives the bad feeling that the authors oversell what they do
75 and the implications of their work. Consequently I totally disagree with the statements in
76 lines 224-229. Lines 228-229: this is not a good way to proceed. A better way is the
77 sequential inversion is to take the result of the inversion of the previous snapshots as a
78 starting model for the inversion of the next one. However it is demonstrated in the papers
79 above that even this approach can propagate artefacts in the sequence of inverted
80 snapshots. It is also behind the 2.5+ time or 4D inversion proposed in the papers above or
81 time lapse regularization on the Kalman filter approach. The sentence “As a final, and
82 likely more corrected, option, the dataset could be inverted jointly, adopting a minimizing
83 function, which reflects a metric function of both space and time (Johnson et al., 2010).” is
84 grossly wrong since this paper does not deal with this issue indicating that the authors
85 never read the paper they cite.
86
87
88

89 A few sentences have been added to the text, in order to mention of the main mechanisms contributing to
90 electrical conduction in rocks and the factors that influence the same. We understand that in previous
91 versions of the text there was no references to such issues. However, we consider a more detailed
92 discussion about that to be out of focus, believing that the core of our paper is the presentation of a
93 specific application.
94

95 Although direct petrophysical information would certainly be useful to support the interpretation of the
96 sections, in our opinion it cannot be considered a necessary condition. The same for IP. We consider the
97 model of Fig.9 a self-standing result, even if based just on the electric tomography of the subsoil.
98

99 For what concerns the inversion procedure, we changed the citation of Johnson et al., 2010 and slightly
100 modified the related sentence.
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118

1
2
3 1 Monitoring active fumaroles through time-lapse electrical resistivity tomograms: an application to
4
5 2 the Pisciarelli fumarolic field (Campi Flegrei, Italy).
6
7

8 3 M. G. Di Giuseppe and A. Troiano
9

10 4 Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli 'Osservatorio Vesuviano'
11
12

13 5 **Abstract**
14

15
16 6 Volcanoes are usually monitored through observations of many physical and chemical phenomena.
17
18 7 In the most dangerous cases, as the one of the Campi Flegrei caldera (Italy), great amount of data are
19
20 8 collected, both in discrete or continuously, and regularly stored. However, how to transform such
21
22 9 mass of data in a deeper understanding of the volcano dynamics is still an open question. Dissimilar
23
24 10 information are in fact always hard to compare, but just integrating all the available knowledge
25
26 11 hazardous events could be prevented in a reliable way. Fluids, as water and gasses mobilized in the
27
28 12 subsoil by the heat induced by deep magmatic sources, are widely recognized as the first engine of
29
30 13 similar occurrences and the volcanic gas emissions represent, together with the seismic activity, one
31
32 14 of the most considered precursors. At the same time, the electrical geophysical methods are the most
33
34 15 applied in order to detect and characterize the fluid patterns in the subsoil. So, the integration of
35
36 16 geoelectrical and geochemical observations should represents one of the most pursued approach in
37
38 17 volcanoes monitoring. On the contrary, standard way to compare such data have been not yet codified.
39
40 18 The ERT tomograms capability to individuate that parts of the subsoil where gasses cumulate is well
41
42 19 understood in literature. However, we look for indications about its proficiency in associating the
43
44 20 electrical resistivity changes relative to these zones, once compared to the geochemical time series,
45
46 21 to deep related contributes, distinguishing them from the seasonal ones. The electrical signature of
47
48 22 the fluid patterns, reconstructed through a time-lapse ERT approach, could be of relevance to better
49
50 23 characterize the volcanic phenomena and their origins. In this paper a first test of ERT and
51
52 24 geochemical time series integration was performed to enhance the understanding of the Pisciarelli
53
54 25 fumarolic field evolution, now the most active area in the whole Campi Flegrei caldera.
55
56
57
58
59
60

61
62
63 **26 Introduction**
64
65

66 27 Electrical resistivity tomography (ERT) represents a well-established technique, widely employed to
67
68 28 investigate fluid-induced variations in volcanological settings (Revil et al. 2008; Byrdina et al. 2009;
69
70 29 Finizola et al. 2009; Finizola et al. 2010; Revil et al., 2011; Di Giuseppe et al. 2015). Many literature
71
72 30 publications describe electrical investigations devoted to the definition of the structural setting of
73
74 31 volcanoes (Finizola et al., 2006; Revil et al., 2008; Aizawa et al., 2009; Fikos et al., 2012; Barde-
75
76 32 Cabusson et al., 2013; DiGiuseppe et al., 2017). When applied in time-lapse mode, e.g. performing
77
78 33 tomograms reiteratively overtime, ERT maps the temporal changes in electrical resistivity, which
79
80 34 could be related to the changes in the fluid patterns in the subsoil (Singha et al., 2015; Slater, 2007).
81
82 35 Because fluids are often involved in relevant volcanic phenomena, time-lapse ERT should be
83
84 36 considered in the monitoring of active areas in order to investigate highly hazardous but ambiguous
85
86 37 phenomena. This particularly concern for silicic volcanoes, which commonly develop pervasive
87
88 38 hydrothermal systems during their long repose periods. The resulting magma-hydrothermal
89
90 39 interactions are still poorly understood (Chiodini et al. 2016). In active calderas, widely investigated
91
92 40 through electrical methods (Pribnow et al., 2003; Bruno et al., 2007; Di Giuseppe et al., 2015), the
93
94 41 hydrothermal circulation is extremely intense, indeed, due to the major structural control, which
95
96 42 makes the characterization of unrest phases even more complicated. In addition, the liquid and the
97
98 43 gas interactions between mixtures of different chemical species, the most relevant among them being
99
100 44 water and carbon dioxide, happen in the very shallowest part of the geothermal system, often creating
101
102 45 active fumaroles. Once injected into the shallower formations from deeper magmatic sources, the
103
104 46 CO₂ will tend to rise upward because of its low density until it is trapped by low-permeability
105
106 47 structures or by dissolution into the groundwater (Bachu et al., 1994). The electrical resistivity of the
107
108 48 mixture of grains and pores, which contain the fluids, changes over time, mainly due to fluid filling
109
110 49 the pores driven by the fumarole dynamics, and the literature points out that fluids in volcanic
111
112 50 environments affect electrical resistivity, generating detectable variations in the recordable signals
113
114 51 (Rinaldi et al., 2011). In effects, one of the most sensible parameters to detect the approach of a new
115
116
117
118
119
120

121
122
123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
178
179
180

52 eruptive phase is to examine the variations in the composition of discharged fluids. The isotopic
53 signature, however, is often difficult to interpret in terms of system evolution, because several
54 mechanisms may be responsible for differences in the proportion of magmatic gases and shallower
55 fluid components. Indeed, such proportions can be altered before the fluids reach the surface, due to
56 the mixing between fluids of different origin, or due to reactions that modify the original isotope
57 composition. Time-lapsed ERT can reconstruct these changes (Giese et al. 2009; Kiessling et al. 2010;
58 Würdemann et al. 2010; Schmidt-Hattenberger et al. 2011; Zhou et al. 2012), and help to characterize
59 the fumarole dynamics. The dissolution of CO₂ in groundwater and soil moisture indeed generates an
60 enlargement of the low resistivity area after CO₂ injection into the vent. An opposite relationship
61 between CO₂ concentration and electrical resistivity is observed when CO₂, rather than dissolving in
62 water, replaces the brine in the rock matrix, causing the apparent resistivity to increase (Le Roux et
63 al., 2013). The integration between time-lapse ERT and geochemical observations could help to
64 characterize the phenomena related to the mixing of different chemical species, and to reconstruct
65 interaction between fluids of magmatic origin and meteoric waters. The relationship between the
66 contributions of deeper magmatic sources and sources linked to seasonal fluctuations could be also
67 investigated in that manner. Here a similar application is presented, carried out in the Pisciarelli area,
68 which represents a part of the Campi Flegrei caldera (Italy) where vigorous gaseous emissions are
69 present. Repeated tomograms, performed bimonthly, furnished an image of the dynamics of fluids
70 contributing to the fumarolic vent. An approach to the comparison of the gaseous emission rates,
71 temperature and rainfall rates is suggested, to which end a characterization of the detected anomalies
72 is provided.

73 **The Campi Flegrei caldera.**

74 The Campi Flegrei caldera (CFc) is one of the most hazardous volcanoes in Europe (Orsi et al., 2004)
75 and it is inhabited by more than 300,000 people (Bevilacqua et al., 2015), including entire quarters
76 of Naples (Fig.1a). Vertical ground movements with rates ranging from centimetres to metres per
77 year are typical even during quiescent periods (Dvorak and Mastrolorenzo, 1991). Since 1950 the

181
182
183 78 area has been in a new phase of uplift after several centuries of subsidence dating back to 1538 A.D.,
184
185 79 when the last eruption occurred in the area (Di Vito et al., 1987). The most recent episodes of intense
186
187 80 ground uplift were during 1970-72 and 1982-84, which caused a cumulative maximum uplift of over
188
189 81 3.5 m, accompanied by intense seismicity. Apart from the ground uplift, the CFc unrest is
190
191 82 characterized primarily by shallow hydrothermal manifestations (such as the vigorous gas emissions),
192
193 83 which are most evident in the Solfatara crater and the nearby Pisciarelli areas (Fig.1b), with an
194
195 84 involvement of the seismic activity. In effect, the recent literature on the interpretation of the unrest
196
197 85 of the whole CFc points out the driving role played by processes involving these two areas (De Natale
198
199 86 et al., 1991; Chiodini et al., 2003; Troiano et al., 2011; Piochi et al., 2015a), which are continuously
200
201 87 monitored and under observation for the risk strictly related to their potential expansion into a high-
202
203 88 density urban area. Many studies involve the mechanical effect of overpressure on a shallow magma
204
205 89 chamber (Berrino et al., 1984; Bianchi et al., 1987; Amoruso et al., 2007;) or a sill-like deformative
206
207 90 source (D’Auria et al., 2011). Other studies suggest that the unrest periods affecting the whole caldera
208
209 91 could likely be related to the triggering of the local hydrothermal system caused by magma degassing
210
211 92 episodes centred below the Solfatara - Pisciarelli area (De Natale et al., 1991; Chiodini et al., 2003;
212
213 93 Todesco et al., 2003; De Natale et al., 2006; Gottsmann et al., 2006; Lima et al., 2009; Shirzaei and
214
215 94 Walter, 2010; Troiano et al., 2011).

216
217 95 Geophysical applications allowed a detailed imaging of the subsurface structure of the Solfatara crater
218
219 96 (Letort et al., 2012; Petrosino et al., 2012; Byrdina et al., 2014; Di Giuseppe et al., 2015; Isaia et al.,
220
221 97 2015; Gresse et al., 2017). The structure of the Pisciarelli site is less defined. Moreover, several
222
223 98 monitoring techniques (geodetic, thermal and geochemical) are currently applied to the CFc,
224
225 99 especially at the Solfatara and Pisciarelli areas (INGV, 2018), but a lack of knowledge persists about
226
227 100 the distribution and dynamics of the geothermal fluids present in the area. Specifically, the Pisciarelli
228
229 101 area has been the subject of a severe reactivation in the last few years, concomitant with an increase
230
231 102 of ground uplift. The main manifestations are as follows: an enlargement of the fumarolized area, the
232
233 103 opening of a new vent (which occurred in March 2008), the opening of a new boiling pool (which
234
235
236
237
238
239
240

241
242
243 104 occurred in March 2009 and which was probably accompanied by a small explosion because mud
244
245 105 sputter occurred, covering the soil slope up to 3–4 m above the emission point), a further vigorous,
246
247 106 roaring fumarole created (which appeared on the 20th of December, 2009, that represents the strongest
248
249
250 107 gas emission of the entire area to date), the seismic swarm of about 190 events (recorded in the area
251
252 108 during the 30th of March, 2010) and a new vent opened (during the 15th of November, 2010). Finally,
253
254 109 in the January of 2013 the disappearance of the main fumarole that was recently opened and the
255
256 110 appearance of a vent that emits high-pressure steam and liquid water up to 3-4 m high were observed.
257
258 111 These manifestations make the Pisciarelli unrest quite peculiar. It is indubitably linked to the global
259
260 112 CFc unrest, as evidenced by the geochemical species emitted (Chiodini et al., 2011). However, the
261
262 113 local aspect of the CFc dynamic in this area has to be carefully taken into account. The Pisciarelli
263
264 114 neighbourhood has a high degree of urban development and minor events could represent a high risk
265
266
267 115 for a great number of inhabitants.
268
269 116 A mapping of the electrical resistivity changes through ERT should be indicative of potentially
270
271 117 hazardous dynamics in the area. Such parameters are, in fact, sensitive to properties such as salinity,
272
273 118 porosity and phase changes of fluids flowing into the porous space, which contribute to the
274
275 119 characterization of the fluid circulation in the subsurface.
276
277 120
278
279 121 **The state of the Solfatara – Pisciarelli area.**
280
281 122 After the last major unrest period observed in the CFc, during 1982-1984, the ground deformation
282
283
284 123 trend showed a subsidence period until 2004-2005, when a new uplift phase started. Since 2010-2011
285
286 124 the deformation rate shows a further increase, leading to a cumulative uplift of more than 20 cm. The
287
288 125 ground uplift is also accompanied by widespread fumarolic activity occurring in the whole CF caldera
289
290 126 area. However, these unrest manifestation are all focused in the centre of the CFc (Figure1a), near
291
292 127 the Solfatara - Pisciarelli area (D'Auria et al., 2011), where the evidences of volcanic effects are
293
294 128 particularly present now. For such a reason, the ascription of a central role in the CFc unrest dynamic
295
296
297
298
299
300

301
302
303 129 for these two areas has grown, and has been the subject of the many detailed numerical studies,
304
305 130 mentioned earlier.

306
307
308 131
309
310 132 The geophysics surveys contributed to defining the structural outline of the Solfatara – Pisciarelli
311
312 133 area (SP), and represented a crucial task for understanding volcanic activity. Recent surveys
313
314 134 highlighted the main structural asset of the area. The first magnetotelluric surveys (Troiano et al.,
315
316 135 2014) detected a near-vertical steam/gas-saturated plume-like structure, which reaches the free
317
318 136 surface where the main fumarole fields are active, emerging from a high temperature (>300 °C), over
319
320 137 pressured, gas-saturated plate-like reservoir, which extends down to at least 3 km in depth.
321
322 138 Subsequent ERT surveys clarified the shallower structure of the Solfatara volcano, outlining a
323
324 139 complex hydrothermal system, formed by a mix of upwelling fluids, gases, and meteoric water
325
326
327 140 (Byrdina et al., 2014; Di Giuseppe et al., 2015; Gresse et al., 2017). Isaia et al. (2015), when
328
329 141 considering this structural framework, ended in the suggestion that the Solfatara volcano could be a
330
331 142 maar-diatreme structure, characterized by a shallow crater cut in the pre-eruptive basement, and a
332
333 143 deep diatreme (down to 2–3km).

334
335 144
336
337 145 Physical and chemical observations are now performed in the whole CFc as part of the volcanic
338
339 146 monitoring and both the Solfatara crater and the Pisciarelli area represent the great majority of the
340
341 147 areas surveyed. Regular thermic, seismic, gravimetric, geochemical and geodetic monitoring is
342
343
344 148 carried out in the area. In particular, the geochemical data had a central role in the debate on the CFc
345
346 149 unrest (Chiodini et al., 2012, 2016; Moretti et al., 2017). A general increase of the deep magmatic
347
348 150 component into the emitted volatiles was observed (INGV, 2018). In particular, for what concerned
349
350 151 the SP area, the following features were observed:

- 351
352 152
- an increasing trend in the CO₂/H₂O, generally indicating a growth in the magmatic component
- 353
354 153 into the fumarolic fluids
- 355
356
357
358
359
360

- an increasing CO concentration, that generally characterize volcanic systems at high temperature, whereas hydrothermal contributions would be usually related to lower levels of this component
- an increase of the CO-CO₂ equilibrium temperature, representing the shallower hydrothermal system conditions
- and an increasing trend in the CO₂/CH₄ ratio

Further considerations about the fluid dynamics in the area arise also from the geophysical observations. Di Giuseppe et al. (2015) discussed a migration of the shallow fluid volume eastwards during the few past decades, and supposed that water might have invaded spaces previously saturated with steam, gas or a combination thereof below the Solfatara main vents, at the same time as fluxes steam, gas or both were invading voids opening to the east. This last observation strictly followed the recent relocation of the fumarolic activity from the Solfatara area toward the Pisciarelli area, located eastward to the outer slopes of the Solfatara (Figure 1b) (Troiano et al., 2014). This relocation was marked by a temperature increasing, new vents and boiling pools opening, the occurrence of seismic activity and by the impressively fast changes in the morphology of this zone.

Unfortunately, the source of such relocation is yet largely unknown and a lack of knowledge persists about the fluid dynamics in that part of the CFc hydrothermal system. Current geophysical details of the connections between the Solfatara and Pisciarelli zones are still largely crude, and the geochemical data from Pisciarelli suffers of some criticism, as discussed in Chiodini et al. (2011), who suggested that these data could be heavily modified by seasonal cycles. They would then be not totally conclusive for investigations into the future changes caused by deep volcanic processes.

The ERT survey in the Pisciarelli area.

421
422
423
424
425
426
427
428
429
430
431
432
433
434
435
436
437
438
439
440
441
442
443
444
445
446
447
448
449
450
451
452
453
454
455
456
457
458
459
460
461
462
463
464
465
466
467
468
469
470
471
472
473
474
475
476
477
478
479
480

179 Two main electrical conductivity mechanisms characterize a fluid-saturated porous medium (Rinaldi
180 et al., 2011). The first one is caused by the fluid flow inside the pores, through electro-migration of
181 charges into the connected pore space. A second conduction mechanism occurs at the pore water–
182 mineral interface in the electrical double layer, that is caused by a migration of the weakly adsorbed
183 counterions (usually cations). The DC electrical conductivity of the porous rock can be expressed as
184 a combination of those two contribution, namely the surface electrical conductivity at the water–
185 mineral interface and the pore fluid electrical conductivity. Changes in those two quantities are
186 mainly due to variations into the fluid filling the pore, considering that wet rocks usually have
187 conductivities sensibly higher than dry rocks (Rinaldi et al., 2011 and references therein). Surface and
188 pore fluid conductivities depend linearly from temperature (Vaughan et al., 1993, Revil et al., 1998,
189 Roberts, 2002). Moreover, a dependence from the rock matrix permeability and from salinity of the
190 pore fluids is also observed (Jardani and Revil, 2009). Many mechanisms can be advocated when
191 changes are observed in the bulk conductivity of the rocks. The first element to consider is the
192 compositional nature of the fluids flowing into the system. The pore space of the rocks is indeed
193 occupied by a mixture of multiphase fluids, as water and CO₂ in liquid and vapour phase. Such
194 mixture is altered by the interaction between meteoric waters and fluids rising from the deep because
195 of volcanic effects, which has direct effects upon the underground resistivity. When fluid changes
196 their distribution into the shallower part of the hydrothermal system, the diffusion of the gas phases
197 (both water vapor and CO₂) and the temperature variations alter the electrical conductivity both at
198 the pore surface and within the porous space. Also the boiling phenomena into the fluids reinforce
199 the observed gradient in conductivity between liquid saturated and gas saturated areas, concentrating
200 the brine and increasing salinity in the remaining liquid part. As further effect, the fracturing induced
201 by the fluid dynamics and thermal expansion also alter the electrical conductivity of the subsoil,
202 modifying the rock permeability.

203 The geoelectrical surveys are very effective tools for unveiling the dynamics of tectonic and volcanic
204 settings, and several contributions already regarded the Campanian district (Di Maio et al., 1998;

481
482
483 205 Bruno et al., 2007; Troiano et al., 2008, 2009; Byrdina et al., 2014; Di Giuseppe et al., 2015, 2017;
484
485 206 Gresse et al., 2017).

487
488 207 For the first time, ERT surveys were carried out into the Pisciarelli fumarolic field after the January
489
490 208 2013 event, when a vent that emitted high-pressure steam and liquid water up to 3-4 metres high was
491
492 209 observed, in order to get an insight about the geothermal fluid circulation in the very shallow aquifer.
493
494 210 A first survey was performed along a 70 m long survey line, aligned with the main fumarole and the
495
496 211 permanent thermal pool in the west-east direction (Figure 2), while crossing the part of the area subject
497
498 212 to abrupt morphological changes and major emissive activity. A dipole-dipole electrode configuration
499
500 213 was adopted, with a 2.5 m spacing, which was compact and sensitive to both lateral location and
501
502 214 depth of bodies that are the source of anomalies (Ward, 1988). An Iris Syscal Pro instrument was
503
504 215 used as multichannel resistivity meter. The same instrument was employed as power source, being able
505
506 216 to output a direct current with a maximum voltage and current of 800 V and 2 A, respectively.
507
508 217 The selected survey arrangement took into account the morphology and harsh environment
509
510 218 characterizing the Pisciarelli area, which represented a limitation imposed on a classical ERT
511
512 219 application. It was only possible to arrange a short survey line, with a consequent limit in the expected
513
514 220 depth of investigation. Despite this restriction, the use of a time-lapse approach, which consists in
515
516 221 performing identical ERT surveys several times in the same place, makes the ERT useful to
517
518 222 investigate the evolution of the Pisciarelli structures. The time-lapse approach was followed in several
519
520 223 ERT applications presented in the literature. As an example, Wallin et al. (2013) imaged the inland
521
522 224 intrusion of river water in a contaminated aquifer. Nickschick et al. (2017) observed the changes in
523
524 225 the subsurface structure beneath heavily CO₂ degassing spots in the Hartsouf Mofete field (Czech
525
526 226 Republic). In the volcanic Pisciarelli environment, time-lapse ERT may possibly resolve the
527
528 227 modifications of fluid phases and/or distribution induced by the contribution of a heat component or
529
530 228 a hot gaseous component, both likely present if a magmatic source is active in the area.
531
532 229
533
534
535
536
537
538
539
540

541
542
543
544
545
546
547
548
549
550
551
552
553
554
555
556
557
558
559
560
561
562
563
564
565
566
567
568
569
570
571
572
573
574
575
576
577
578
579
580
581
582
583
584
585
586
587
588
589
590
591
592
593
594
595
596
597
598
599
600

The ERT survey was regularly repeated, starting in January 2014 ending April 2015. It is worth noting that the successive repetitions of the January 2013 survey were performed along a slightly longer survey line (100 m long) with respect to the first January 2013 survey and that the bimonthly interval was chosen in order to evaluate the possible influence of seasonal effects on the hydrothermal system, as indicated by the geochemical monitoring. The ERT lines were inverted using ERTlab3D[®] commercial software, including topography. The inverse algorithm, described by LaBrecque et al. (1999) uses a regularized solution, looking for the optimal value of the parameter vector \mathbf{P} and the stabilization parameter α for which minimizing the functional $Y(\mathbf{P})=\chi^2(\mathbf{P})+\alpha\mathbf{P}^T\mathbf{R}\mathbf{P}$ results in $\chi^2(\mathbf{P})=\chi^2_{\text{prior}}$. The parameters \mathbf{P} are the natural logarithms of the conductivity of the mesh elements and \mathbf{R} , the solution roughness, acts as the stabilizing functional. χ^2_{prior} is equal to the number of data points and χ^2 is given by $\chi^2 = (\mathbf{D} - \mathbf{F}(\mathbf{P}))^T\mathbf{W}(\mathbf{D} - \mathbf{F}(\mathbf{P}))$, where \mathbf{D} is the vector of known data values, $\mathbf{F}(\mathbf{P})$ is the forward solution and \mathbf{W} is a data weight matrix. The diagonal elements of \mathbf{W} are the reciprocals of the data variances and the off-diagonal elements are zero. This assumes non-correlated data errors. When ERT data was inverted in time-lapse mode, different approaches were contemplated. As first consideration, with every dataset collected independently of the others, each tomogram can be assumed to be a representation of a constant state of the shallower geothermal system at the collection time. With this in mind, it is possible to invert each dataset independently, isolating changes in the electrical resistivity by post inversion model differencing. A second option to consider is the inversion on the differences between the background and subsequent datasets, e.g. the resistivity obtained by the inversion of the first dataset, considered as background data, can be considered as the a priori model in the difference inversion. In this case systematic errors such as those errors due to in field configuration and discretization in the forward modelling algorithm tend to null and the result is that the difference data is likely fitted more closely than the individual potentials, resulting in fewer inversion artefacts (LaBrecque and Yang, 2001). A time-lapse regularization can also be considered (Oldenborger et al., 2007), whereby the reference model for the first inversion is an uniform model and the reference model for all subsequent experimental stages is

601
602
603 256 the model obtained via inversion of the data from the previous stage. Such approaches require, at
604
605 257 least in principle, fewer model modifications to fit the data and the objective function penalizes large
606
607
608 258 perturbations from previous models as opposed to large perturbations from background. Thus, such
609
610 259 inversion is ultimately able to build up more structure in the final models, while still satisfying the
611
612 260 data to the same level of the previous options. As a final, and likely more corrected, option, the dataset
613
614 261 could be inverted adopting 4D approaches (Kim et al., 2009; Karaoulis et al., 2011), which consider
615
616 262 a four-dimensional space–time model, introducing regularizations reflecting a metric function of both
617
618 263 space and time. In the present case, time-lapse minimization was adopted during the inversion of the
619
620 264 dataset. The final models for each dataset, are reported in Figure 3a. Average root-mean-squares
621
622 265 (RMS) varying from 1.1 up to 1.9 resulted, which we considered satisfactory. In order to support the
623
624 266 reliability of the images, it is common to look at \mathbf{S} , the so-called inverse problem’s sensitivity matrix,
625
626
627 267 which take into account the effects on the data by infinitesimal changes into the model resistivity.
628
629 268 The sensitivity has been estimated for all the tomograms presented in Figure 3.

630 631 269 632 633 270 **The ERT Dataset.**

634
635 271 The sequence of inverted resistivity images obtained in the timelapse survey is shown in Figure 3.
636
637 272 The tomograms showed diffuse lateral and vertical heterogeneities within a resistivity range of about
638
639 273 three orders of magnitude.

640
641
642 274
643
644 275 The bimonthly-recorded resistivity sections showed four main electrical anomalies:

- 645
646 276 A. the first anomaly lying at about 20 m along the profile (corresponding to the blue vertical
647
648 277 dashed line in the figure), located at depths varying between 60-70 m a.s.l.;
- 649
650 278 B. a second zone displaced at around 35 m along the profile (corresponding to the black dashed
651
652 279 line in the figure), located at depths between 50-65 m a.s.l.;
- 653
654 280 C. a third zone centred at around 55 m along the profile (corresponding to the red dashed line in
655
656 281 the figure), located between 50-65 m a.s.l.;

661
662
663 282 D. A fourth zone centred at around 70 m along the profile (corresponding to the green dashed
664
665 283 line in the figure), located at around 60 m a.s.l.;

667 284
668
669
670 285 A further anomalous zone appears at the very end of the profile. This last feature does not lie in the
671
672 286 vegetation-free zone and could likely be linked to some anthropic artefact. The anomalies' evolution,
673
674 287 in shape and resistivity, is reported in Figure 4, for each of the collected datasets.

675
676 288 Following the approach of Wallin et al. (2013), from the ERT tomograms, the time series of electrical
677
678 289 resistivity have been extracted for each of the electrical anomalies depicted in Figure 4, while taking
679
680 290 into consideration the mean values of the parameter in the elementary cells that compose the related
681
682 291 part of the tomograms. These resistivity time series are reported in Figure 5.

683 291
684 292 The anomalies observed in the subsurface underneath the Pisciarelli degassing site changed over time,
685
686
687 293 as a consequence of changes in several parameters on which the resistivity depends. In particular, the
688
689 294 high pressure of fluids (CO₂ and water carried along), likely mobilized by a deeper source, is capable
690
691 295 of altering the host rocks mechanically and/or chemically. The fluid's power is capable of moving
692
693 296 material from lower levels or widening the pores within materials. Moreover, according to
694
695 297 Annunziatellis et al. (2008), gases like CO₂ are capable of migrating not only vertically, but also
696
697 298 horizontally in soil as density-driven flows or advective forces, leading to horizontal changes in the
698
699 299 anomalies. In addition, temperature fluctuations, for instance induced by the inflow of deep-lying hot
700
701 300 fluids or by fluids mixing of in the uppermost part of the hydrothermal system, can induce significant
702
703
704 301 changes in resistivity. Considering such connections, a comparison between the changes of electrical
705
706 302 resistivity in the anomalous zones and some superficial observations was attempted. The parameters
707
708 303 considered here are the temperature, CO₂ fluxes and rainfall rates. The CO₂ fluxes and the
709
710 304 temperatures of the emitted gasses were recorded in the Pisciarelli main vent during 2007-2016
711
712 305 (INGV, 2018) in correspondence with the FLXOV3 measuring station. These quantities are reported
713
714 306 in Figure 6a and 6b, respectively, where are limited to the years 2014-2015. Also the long-term
715
716 307 temperature trend is reported in Figure 6a, which was deduced by applying the Seasonal Trend

721
722
723 308 Decomposition (STL) algorithm on the infrared imaging recorded in proximity of the upper part of
724
725 309 the west side of the vent (Vilaro et al., 2015; INGV, 2018). The two temperature estimates, which
726
727
728 310 refer to emitted gasses and surface thermal features of the area affected by diffuse degassing,
729
730 311 respectively, are biased. However, they show a very close relationship in pattern of variability. The
731
732 312 monthly rainfall rates, relative to the meteorological station of Pozzuoli (furnished by the ‘Protezione
733
734 313 Civile Regione Campania’) are reported in Figure 6c. All data are reported as recorded in the
735
736 314 corresponding measuring stations, but a brute comparison between these quantities can be misleading,
737
738 315 due to the very different nature and variability of such records. Therefore, the way to compare
739
740 316 information so different as the ERT tomograms and the surface observations (geochemical data,
741
742 317 temperature and rainfall rates) has to be carefully investigated and a normalization criterion has to be
743
744 318 adopted to result in a valid comparison. In order to place all these signals on a comparable scale, the
745
746
747 319 so-called z-score (Klemelä, 2009) was calculated for each record separately. The z-scores were
748
749 320 obtained by removing the mean value from each time series and dividing by the relative standard
750
751 321 deviation. In such way, samples having zero means and unit variances are obtained. The z-scores for
752
753 322 all the variables mentioned above (and shown in Figure 5 and 6) are reported in Figure 7.

754 755 323 **Discussion.**

756 324
757 325 The resistivity trends of the different anomalies over time, in terms of z-scores, are shown in Figure
758
759 326 8a. Thus emerges a peculiar behaviour of anomaly B, that shows a resistivity oscillating more in time
760
761 327 with respect to the other anomalies, all presenting a comparable increasing attitude. In Figure 8b, the
762
763 328 resistivity of anomaly B is compared with the rainfall rate and temperature. The B resistivity appears
764
765
766 329 to be correlated with the temperature and anti-correlated with the rainfall. This suggests that the
767
768 330 character of the B anomaly may be influenced by seasonal effects, probably driven by the influx of
769
770 331 cold rainwater into the system. The warmer and drier months see an increase in resistivity and vice
771
772 332 versa. Figure 8c shows, for anomaly C, how the linear increasing trend of resistivity instead appears
773
774 333 to be less correlated to temperature and rainfall rates.

781
782
783 334 Considering on turn the geochemical data, the main vent showed an increasing amount of CO₂
784
785 335 emission, varying by about one order of magnitude from 2007-2016 (INGV, 2018). Superimposed
786
787
788 336 on this accumulation tendency, a clear annual cyclic oscillation was distinguishable, that has been
789
790 337 stronger in more recent years. Chiodini et al. (2011), reporting on the CO content of the Pisciarelli
791
792 338 fumarole, until 2011, concluded that at Pisciarelli, strong seasonal effects and the possibility of re-
793
794 339 equilibration of the fumarolic fluids at very shallow depths concealed the deep geothermo-barometric
795
796 340 signals. In addition, the comparison of the z-scores of CO₂ emission, IR temperature and rainfalls,
797
798 341 reported in Figure 8d shows a strong correlation between CO₂ emission and rainfalls. The comparison
799
800 342 between CO₂ emission and resistivities, reported in Figure 8e, suggests a link between the
801
802 343 parameters. Such correlation could be likely due to a buffering and/or cumulation of the gas flowing
803
804 344 from the geothermal system to the atmosphere in those zones. At least in principle, the contribution
805
806
807 345 of chemical effects to observed changes in resistivity, such as fracture sealing or rock alteration,
808
809 346 cannot be excluded. However, we note that these effects should not show any periodicity. Moreover,
810
811 347 concerning the sealing, the dynamics of Pisciarelli allows a reasonable opening rather than closing of
812
813 348 fractures. On other hands, the dominants among the new chemical species, e.g. sulfur and alunite as
814
815 349 indicated in Piochi et al. (2015b), should induce a decrease in the bulk rocks resistivity. In contrast,
816
817 350 the non-cyclical anomalies retrieved through the time-lapse ERT imaging present an increasing
818
819 351 attitude. The comparison with the surface data helps to strengthen the hypotheses on the phenomena
820
821 352 that determine the observed variations in the electrical structures.

823
824 353 Recognizing the relevance and meaning of the anomalies and their evolution over time in electrical
825
826 354 images is not, however, trivial, especially considering the interplay between rainwater and
827
828 355 hydrothermal fluids, which can generate elaborate patterns. In the case of Pisciarelli, this interaction
829
830 356 has a feedback in the tomographic sections. The first element is the direct link between anomaly B
831
832 357 and the surface. The second element is the diffusion over time of a low resistivity zone along the top
833
834 358 of anomaly C, which interacts with a vertical conductive plume apparently rising up in the boundary
835
836 359 zone between the C and D anomalies. The B anomaly corresponds to the thermal pool and it shows a
837
838
839
840

841
842
843 360 seasonal character, while the boundary between the C and D anomalies corresponds to a fault zone
844
845 361 with surface manifestations and the maximum of fracture detected in the field (Isaia et al., 2015). In
846
847 362 our interpretation, rainwaters stored into the thermal pool penetrate into the subsoil through the
848
849
850 363 narrow channel, permeating the available space, the results of which are laterally confined by the C
851
852 364 anomaly, in turn acting as a permeability barrier. Moreover, part of the same waters dislocate also
853
854 365 along the top of the C anomaly, which again acts as a permeability barrier, ending to interact with
855
856 366 other fluids, of deeper origin, rising along the pre-existing fractures. This interpretative framework is
857
858 367 summarized in Figure 9, where a sketch map is superimposed over the tomographies.

860 368 **Conclusion**

861
862 369 In this paper the results of a time lapse ERT monitoring in the volcanically active Pisciarelli site are
863
864 370 shown. Being that pre-eruptive changes are frequently extremely rapid, and the Pisciarelli area is
865
866
867 371 extremely urbanized, this site represents one of the strong sources of volcanic risk in the whole CFC
868
869 372 and looking for pre-eruptive indicators could be relevant to prevent potentially highly destructive
870
871 373 consequences. This is particularly true due to the non-totally conclusive findings of the routine
872
873 374 monitoring performed in the area.

874
875 375 Even though the imaging we have performed brings only a small amount of large-scale information
876
877 376 about the feeding system, due to the limited resolution at depths, the ERT imaging highlighted several
878
879 377 anomalous zones. The interpretation of such patterns is quite difficult, being related to complex
880
881 378 phenomena such as the interaction between the fluid components of different origins present in the
882
883
884 379 vent. However, the comparison with other monitoring data (temperature, geochemical data and
885
886 380 rainfall rates) permitted us to discern the areas dominated by seasonal effects from the ones more
887
888 381 influenced by other, most significant contributions, linked to gas injected into the system from deep
889
890 382 locations which cumulates in the subsoil. Moreover, such comparison can be a guideline toward a
891
892 383 more confident interpretation of the patterns shown by fluids during such times, helping to understand
893
894 384 what features are more related to the apport of meteoric waters into the subsoil and what could be
895
896 385 more correlated to the inflow of fluids of deeper origins. The boundary surfaces along which the
897
898
899
900

901
902
903
904
905
906
907
908
909
910
911
912
913
914
915
916
917
918
919
920
921
922
923
924
925
926
927
928
929
930
931
932
933
934
935
936
937
938
939
940
941
942
943
944
945
946
947
948
949
950
951
952
953
954
955
956
957
958
959
960

386 fluids displace and the fractures where fluids rise are also revealed. The reconstruction of such
387 features, obtained through the imaging of the underground electrical resistivity changes reveal the
388 complex interactions between the environment and the deeper volcanic sources. In this sense, the
389 presented results point out some general aspects. The indirect information obtained through
390 geophysical imaging proves an vehicle to underline the underground phenomena, explaining the
391 dynamics of large volumes of subsoil without any arbitrary extrapolations, typical of techniques based
392 on surface observations. A further methodological aspect has to be underlined. No geophysical
393 method is self-consistent, in the sense that just the integration of information about all the physical
394 characteristics of rocks allows the understanding of the phenomena occurring and the creation of
395 unique lithological models. In spite of this, however, our results show how the single electrical
396 technique has a relevant proficiency. The model presented in Fig.9 evidence the self-standing ERT
397 capability to define and detail the phenomena at least in their essential lines. The results presented
398 here can be considered the first test about the aptitude of time-lapse ERT to understand the evolution
399 of an active fumarole, thanks to a significant contribution to the characterization of subsoil structures
400 and the understanding of their evolution during time. In any case, even if the tomograms indicate that
401 this promising approach of time-lapse ERT monitoring to sheds light on the potentially dangerous
402 evolution of the investigated system, because the phenomena involved are extremely complex, the
403 evaluation of such aspects deserves more effort and rigorous modelling. As further development, the
404 establishment of permanent and longer surveying lines could substantiate the results. In particular, a
405 continuous acquisition of the tomograms could end in longer time series of electrical resistivity
406 changes, which could be compared to the geochemical ones following combined statistical
407 approaches, such as wavelet coherence analysis.

Figure captions.

961
962
963
964 410 **Fig.1.** a) Map of the Campi Flegrei caldera (Italy). b) Map of the Solfatara-Pisciarelli complex,
965
966 411 framed with the black box in panel a). The ERT survey area is enclosed in the black box and the
967
968 412 survey profile is evidenced with the red line. The geodetic reference system is UTM-WGS84.
969
970 413
971
972 414 **Fig.2.** Aerial view of the Pisciarelli area, where the time-lapse ERT surveys were realized (red dashed
973
974 415 line). Locations of the main anomalies retrieved by ERT are indicated, with the colored capital letters.
975
976 416 The geodetic reference system is UTM-WGS84.
977
978 417
979
980
981 418 **Fig.3.** ERT resistivity sections relative to the profile sketched in Fig.2. For every section, the relative
982
983 419 date is indicated. A common logarithmic scale is used for all the resistivity sections. The main features
984
985 420 discussed into the text (already shown in figure 2) are also indicated with the coloured dotted lines;
986
987 421
988
989 422 **Fig.4.** Detail of the four main electrical anomalies retrieved through time-lapse ERT. For every
990
991 423 section, the relative date is indicated. A common logarithmic scale is used for all the resistivity
992
993 424 sections. The main features discussed into the text are also labelled with coloured capital letters.
994
995 425
996
997
998 426 **Fig. 5.** Comparison between the electrical resistivity time series (in Ωm) as function of time, which
999
1000 427 were obtained extracting the mean value of the parameter in correspondence of the four areas shown
1001
1002 428 in figure 4.
1003
1004 429
1005
1006 430 **Fig. 6.** a) temperature of the gas emitted at the Pisciarelli main vent (left axes, $^{\circ}\text{C}$) and temperature
1007
1008
1009 431 extracted from infrared thermal images through the application of the STL algorithm (right axis, $^{\circ}\text{C}$)
1010
1011 432 during 2014-2015. (b) CO₂ fluxes emitted at the Pisciarelli main vent (in $\text{gm}^{-2}\text{d}^{-1}$) during 2014-
1012
1013 433 2015. (c) Monthly rainfall rates (in mm month^{-1}) recorded at the Pozzuoli meteorological station of
1014
1015 434 the ‘Protezione Civile Regionale’ agency.
1016
1017
1018
1019
1020

1021
1022
1023
1024
1025
1026
1027
1028
1029
1030
1031
1032
1033
1034
1035
1036
1037
1038
1039
1040
1041
1042
1043
1044
1045
1046
1047
1048
1049
1050
1051
1052
1053
1054
1055
1056
1057
1058
1059
1060
1061
1062
1063
1064
1065
1066
1067
1068
1069
1070
1071
1072
1073
1074
1075
1076
1077
1078
1079
1080

Fig.7. The z-scores extracted by the variables mentioned in Figure 5 (electrical resistivity time series) and Figure 6 (temperature, CO₂ fluxes and rainfall rates). Z-scores were obtained by removing the mean value from each time series and dividing by the relative standard deviation.

Fig. 8. Z-scores extracted by the observed variables, compared as follow: (a) electrical resistivity time series relative to the four anomalous zones shown in Figure 2. (b) electrical resistivity time series relative to the B electrical anomaly, surface IR temperature and rainfall rates. (c) electrical resistivity time series relative to the C electrical anomaly, surface IR temperature and rainfall rates. (d) CO₂ fluxes, surface IR temperature and rainfall rates. (e) electrical resistivity time series relative to the four anomalous zones, CO₂ fluxes.

Fig.9. Conceptual model of the Pisciarelli fumarolic zone. This W-E model crosses the main vent and the thermal permanent pool. The interpretative elements are reported in the legend. Electrical resistivity isolines, relative to the April 2015 tomogram are superimposed, maintaining the same common logarithm scale of Figure 3.

References

Aizawa, K., Ogawa, Y., Ishido, T., 2009. Groundwater flow and hydrothermal systems within volcanic edifices: Delineation by electric self-potential and magnetotellurics. *J. Geophys. Res.* 114, B01208. doi:10.1029/2008JB005910

Amoruso, A., Crescentini, L., Linde, A.T., Sacks, I.S., Scarpa, R., Romano, P., 2007. A horizontal crack in a layered structure satisfies deformation for the 2004–2006 uplift of Campi Flegrei. *Geophys. Res. Lett.*

1081
1082
1083 460 34, L22313. doi:10.1029/2007GL031644
1084
1085
1086 461 Annunziatellis, A., Beaubien, S.E., Bigi, S., Ciotoli, G., Coltella, M., Lombardi, S., 2008. Gas migration
1087
1088 462 along fault systems and through the vadose zone in the Latera caldera (central Italy): Implications for
1089
1090 463 CO₂geological storage. *Int. J. Greenh. Gas Control* 2, 353–372. doi:10.1016/j.ijggc.2008.02.003
1091
1092
1093 464 Bachu, S., Gunter, W.D., Perkins, E.H., 1994. Aquifer disposal of CO₂: Hydrodynamic and mineral
1094
1095 465 trapping. *Energy Convers. Manag.* 35, 269–279. doi:10.1016/0196-8904(94)90060-4
1096
1097
1098 466 Barde-Cabusson, S., Bolós, X., Pedrazzi, D., Lovera, R., Serra, G., Martí, J., Casas, A., 2013. Electrical
1099
1100 467 resistivity tomography revealing the internal structure of monogenetic volcanoes. *Geophys. Res. Lett.*
1101
1102 468 40, 2544–2549. doi:10.1002/grl.50538
1103
1104
1105 469 Berrino, G., Corrado, G., Luongo, G., Toro, B., 1984. Ground deformation and gravity changes
1106
1107 470 accompanying the 1982 Pozzuoli uplift. *Bull. Volcanol.* 47, 187–200. doi:10.1007/BF01961548
1108
1109
1110 471 Bevilacqua, A., Isaia, R., Neri, A., Vitale, S., Aspinall, W.P., Bisson, M., Flandoli, F., Baxter, P.J.,
1111
1112 472 Bertagnini, A., Esposti Ongaro, T., Iannuzzi, E., Pistolesi, M., Rosi, M., 2015. Quantifying volcanic
1113
1114 473 hazard at Campi Flegrei caldera (Italy) with uncertainty assessment: 1. Vent opening maps. *J. Geophys.*
1115
1116 474 *Res. Solid Earth* 120, 2309–2329. doi:10.1002/2014JB011775
1117
1118 475 Bianchi, R., Coradini, A., Federico, C., Giberti, G., Lanciano, P., Pozzi, J.P., Sartoris, G., Scandone, R.,
1119
1120 476 1987. Modeling of surface deformation in volcanic areas: The 1970-1972 and 1982-1984 crises of
1121
1122 477 Campi Flegrei, Italy. *J. Geophys. Res. Solid Earth* 92, 14139–14150. doi:10.1029/JB092iB13p14139
1123
1124
1125 478 Bruno, P.P.G., Ricciardi, G.P., Petrillo, Z., Di Fiore, V., Troiano, A., Chiodini, G., 2007. Geophysical and
1126
1127 479 hydrogeological experiments from a shallow hydrothermal system at Solfatara Volcano, Campi Flegrei,
1128
1129 480 Italy: Response to caldera unrest. *J. Geophys. Res. Solid Earth* 112. doi:10.1029/2006JB004383
1130
1131
1132 481 Byrdina, S., Revil, A., Pant, S.R., Koirala, B.P., Shrestha, P.L., Tiwari, D.R., Gautam, U.P., Shrestha, K.,
1133
1134 482 Sapkota, S.N., Contraires, S., Perrier, F., 2009. Dipolar self-potential anomaly associated with carbon
1135
1136 483 dioxide and radon flux at Syabru-Bensi hot springs in central Nepal. *J. Geophys. Res.* 114, B10101.

1141
1142
1143
1144
1145
1146
1147
1148
1149
1150
1151
1152
1153
1154
1155
1156
1157
1158
1159
1160
1161
1162
1163
1164
1165
1166
1167
1168
1169
1170
1171
1172
1173
1174
1175
1176
1177
1178
1179
1180
1181
1182
1183
1184
1185
1186
1187
1188
1189
1190
1191
1192
1193
1194
1195
1196
1197
1198
1199
1200

484 doi:10.1029/2008JB006154

485 Byrdina, S., Vandemeulebrouck, J., Cardellini, C., Legaz, A., Camerlynck, C., Chiodini, G., Lebourg, T.,
486 Gresse, M., Bascou, P., Motos, G., Carrier, A., Caliro, S., 2014. Relations between electrical resistivity,
487 carbon dioxide flux, and self-potential in the shallow hydrothermal system of Solfatara (Phlegrean
488 Fields, Italy). *J. Volcanol. Geotherm. Res.* 283, 172–182. doi:10.1016/j.jvolgeores.2014.07.010

489 Chiodini, G., Avino, R., Caliro, S., Minopoli, C., 2011. Temperature and pressure gas geoindicators at the
490 Solfatara fumaroles (Campi Flegrei). *Ann. Geophys.*

491 Chiodini, G., Caliro, S., De Martino, P., Avino, R., Gherardi, F., U., T., E., B., G.P., R., P., R., C., R., 2012.
492 Early signals of new volcanic unrest at Campi Flegrei caldera? Insights from geochemical data and
493 physical simulations. *Geology* 40, 943–946. doi:10.1130/G33251.1

494 Chiodini, G., Paonita, A., Aiuppa, A., Costa, A., Caliro, S., De Martino, P., Acocella, V.,
495 Vandemeulebrouck, J., 2016. Magmas near the critical degassing pressure drive volcanic unrest
496 towards a critical state. *Nat. Commun.* 7, 13712.

497 Chiodini, G., Todesco, M., Caliro, S., Del Gaudio, C., Macedonio, G., Russo, M., 2003. Magma degassing as
498 a trigger of bradyseismic events: The case of Phlegrean Fields (Italy). *Geophys. Res. Lett.* 30.
499 doi:10.1029/2002GL016790

500 D’Auria, L., Giudicepietro, F., Aquino, I., Borriello, G., Del Gaudio, C., Lo Bascio, D., Martini, M.,
501 Ricciardi, G.P., Ricciolino, P., Ricco, C., 2011. Repeated fluid-transfer episodes as a mechanism for the
502 recent dynamics of Campi Flegrei caldera (1989–2010). *J. Geophys. Res.* 116, B04313.
503 doi:10.1029/2010JB007837

504 De Natale, G., Pingue, F., Allard, P., Zollo, A., 1991. Geophysical and geochemical modelling of the 1982–
505 1984 unrest phenomena at Campi Flegrei caldera (southern Italy). *J. Volcanol. Geotherm. Res.* 48,
506 199–222. doi:10.1016/0377-0273(91)90043-Y

507 De Natale, G., Troise, C., Pingue, F., Mastrolorenzo, G., Pappalardo, L., Battaglia, M., Boschi, E., 2006. The

- 1201
1202
1203
1204
1205
1206
1207
1208
1209
1210
1211
1212
1213
1214
1215
1216
1217
1218
1219
1220
1221
1222
1223
1224
1225
1226
1227
1228
1229
1230
1231
1232
1233
1234
1235
1236
1237
1238
1239
1240
1241
1242
1243
1244
1245
1246
1247
1248
1249
1250
1251
1252
1253
1254
1255
1256
1257
1258
1259
1260
- 508 Campi Flegrei caldera: unrest mechanisms and hazards. *Geol. Soc. London, Spec. Publ.* 269.
- 509 Di Giuseppe, M.G., Troiano, A., Fedele, A., Caputo, T., Patella, D., Troise, C., De Natale, G., 2015.
510 Electrical resistivity tomography imaging of the near-surface structure of the Solfatara crater, Campi
511 Flegrei (Naples, Italy). *Bull. Volcanol.* 77. doi:10.1007/s00445-015-0910-6
- 512 Di Maio, R., Mauriello, P., Patella, D., Petrillo, Z., Piscitelli, S., Siniscalchi, A., 1998. Electric and
513 electromagnetic outline of the Mount Somma–Vesuvius structural setting. *J. Volcanol. Geotherm. Res.*
514 82, 219–238. doi:10.1016/S0377-0273(97)00066-8
- 515 Di Vito, M., Lirer, L., Mastrolorenzo, G., Rolandi, G., 1987. The 1538 Monte Nuovo eruption (Campi
516 Flegrei, Italy). *Bull. Volcanol.* 49, 608–615. doi:10.1007/BF01079966
- 517 Dvorak, J.J., Mastrolorenzo, G., 1991. The mechanisms of recent vertical crustal movements in Campi
518 Flegrei caldera, southern Italy. pp. 1–47. doi:10.1130/SPE263-p1
- 519 Fikos, I., Vargemezis, G., Zlotnicki, J., Puertollano, J.R., Alanis, P.B., Pigtain, R.C., Villacorte, E.U.,
520 Malipot, G.A., Sasai, Y., 2012. Electrical resistivity tomography study of Taal volcano hydrothermal
521 system, Philippines. *Bull. Volcanol.* 74, 1821–1831. doi:10.1007/s00445-012-0638-5
- 522 Finizola, A., Aubert, M., Revil, A., Schütze, C., Sortino, F., 2009. Importance of structural history in the
523 summit area of Stromboli during the 2002–2003 eruptive crisis inferred from temperature, soil CO₂,
524 self-potential, and electrical resistivity tomography. *J. Volcanol. Geotherm. Res.* 183, 213–227.
525 doi:10.1016/j.jvolgeores.2009.04.002
- 526 Finizola, A., Revil, A., Rizzo, E., Piscitelli, S., Ricci, T., Morin, J., Angeletti, B., Mocochain, L., Sortino, F.,
527 2006. Hydrogeological insights at Stromboli volcano (Italy) from geoelectrical, temperature, and CO₂
528 soil degassing investigations. *Geophys. Res. Lett.* 33, L17304. doi:10.1029/2006GL026842
- 529 Finizola, A., Ricci, T., Deiana, R., Cabusson, S.B., Rossi, M., Praticelli, N., Giocoli, A., Romano, G.,
530 Delcher, E., Suski, B., Revil, A., Menny, P., Di Gangi, F., Letort, J., Peltier, A., Villasante-Marcos, V.,
531 Douillet, G., Avard, G., Lelli, M., 2010. Adventive hydrothermal circulation on Stromboli volcano

1261
1262
1263
1264 532 (Aeolian Islands, Italy) revealed by geophysical and geochemical approaches: Implications for general
1265 fluid flow models on volcanoes. *J. Volcanol. Geotherm. Res.* 196, 111–119.
1266
1267 534 doi:10.1016/j.jvolgeores.2010.07.022
1268
1269
1270 535 Giese, R., Hennings, J., Lüth, S., Morozova, D., Schmidt-Hattenberger, C., Würdemann, H., Zimmer, M.,
1271
1272 536 Cosma, C., Juhlin, C., 2009. Monitoring at the CO₂ SINK site: A concept integrating geophysics,
1273
1274 537 geochemistry and microbiology. *Energy Procedia* 1, 2251–2259. doi:10.1016/j.egypro.2009.01.293
1275
1276
1277 538 Di, Giuseppe, M.G. Di, Troiano, A., Vito, M.A. Di, Somma, R., Matano, F., 2017. Definition of small-scale
1278
1279 539 volcanic structures by Electrical Resistivity Tomography: the Trentaremi cone, an example from the
1280
1281 540 Campi Flegrei Caldera (Italy). *Ann. Geophys.* 60, S0552. doi:10.4401/ag-7397
1282
1283
1284 541 Gottsmann, J., Folch, A., Rymer, H., 2006. Unrest at Campi Flegrei: A contribution to the magmatic versus
1285
1286 542 hydrothermal debate from inverse and finite element modeling. *J. Geophys. Res.* 111, B07203.
1287
1288 543 doi:10.1029/2005JB003745
1289
1290
1291 544 Gresse, M., Vandemeulebrouck, J., Byrdina, S., Chiodini, G., Revil, A., Johnson, T.C., Ricci, T., Vilardo, G.,
1292
1293 545 Mangiacapra, A., Lebourg, T., Grangeon, J., Bascou, P., Metral, L., 2017. Three-Dimensional
1294
1295 546 Electrical Resistivity Tomography of the Solfatara Crater (Italy): Implication for the Multiphase Flow
1296
1297 547 Structure of the Shallow Hydrothermal System. *J. Geophys. Res. Solid Earth* 122, 8749–8768.
1298
1299 548 doi:10.1002/2017JB014389
1300
1301
1302 549 INGV, 2018. Bollettini di sorveglianza dei vulcani campani.
1303
1304
1305 550 Isaia, R., Vitale, S., Di Giuseppe, M.G., Iannuzzi, E., Tramparulo, F.D., Troiano, A., 2015. Stratigraphy,
1306
1307 551 structure, and volcano-tectonic evolution of Solfatara maar-diatreme (Campi Flegrei, Italy). *Bull. Geol.*
1308
1309 552 *Soc. Am.* 127, 1485–1504. doi:10.1130/B31183.1
1310
1311 553 **Karaoulis M., A. Revil, D.D. Werkema, B. Minsley, W.F. Woodruff, and A. Kemna, Time-lapse 3D**
1312
1313 554 **inversion of complex conductivity data using an active time constrained (ATC) approach, *Geophysical***
1314
1315 555 ***Journal International*, 187, 237–251, doi: 10.1111/j.1365-246X.2011.05156.x, 2011**
1316
1317
1318
1319
1320

1321
1322
1323 556 Kiessling, D., Schmidt-Hattenberger, C., Schuett, H., Schilling, F., Krueger, K., Schoebel, B., Danckwardt,
1324
1325 557 E., Kummerow, J., 2010. Geoelectrical methods for monitoring geological CO2 storage: First results
1326
1327 558 from cross-hole and surface–downhole measurements from the CO2SINK test site at Ketzin
1328
1329 559 (Germany). *Int. J. Greenh. Gas Control* 4, 816–826. doi:10.1016/j.ijggc.2010.05.001
1330
1331
1332 560 **Kim, J. H., Yi, M. J., Park, S. G., & Kim, J. G. (2009). 4-D inversion of DC resistivity monitoring data**
1333
1334 561 **acquired over a dynamically changing earth model. *Journal of Applied Geophysics*, 68(4), 522-532.**
1335
1336
1337 562 Klemelä, J., 2009. Smoothing of multivariate data : density estimation and visualization. John Wiley & Sons.
1338
1339
1340 563 LaBrecque, D.J., Morelli, G., Daily, W., Ramirez, A., Lundegard, P., 1999. 37. Occam’s Inversion of 3-D
1341
1342 564 Electrical Resistivity Tomography, in: *Three-Dimensional Electromagnetics*. Society of Exploration
1343
1344 565 Geophysicists, pp. 575–590. doi:10.1190/1.9781560802154.ch37
1345
1346
1347 566 LaBrecque, D.J., Yang, X., 2001. Difference Inversion of ERT Data: a Fast Inversion Method for 3-D In Situ
1348
1349 567 Monitoring. *J. Environ. Eng. Geophys.* 6, 83–89. doi:10.4133/JEEG6.2.83
1350
1351 568 Le Roux, O., Cohen, G., Loisy, C., Laveuf, C., Delaplace, P., Magnier, C., Rouchon, V., Cerepi, A., Garcia,
1352
1353 569 B., 2013. The CO2-Vadose project: Time-lapse geoelectrical monitoring during CO2 diffusion in the
1354
1355 570 carbonate vadose zone. *Int. J. Greenh. Gas Control* 16, 156–166. doi:10.1016/J.IJGGC.2013.03.016
1356
1357
1358 571 Letort, J., Roux, P., Vandemeulebrouck, J., Coutant, O., Cros, E., Wathelet, M., Cardellini, C., Avino, R.,
1359
1360 572 2012. High-resolution shallow seismic tomography of a hydrothermal area: application to the Solfatara,
1361
1362 573 Pozzuoli. *Geophys. J. Int.* 189, 1725–1733. doi:10.1111/j.1365-246X.2012.05451.x
1363
1364
1365 574 Lima, A., De Vivo, B., Spera, F.J., Bodnar, R.J., Milia, A., Nunziata, C., Belkin, H.E., Cannatelli, C., 2009.
1366
1367 575 Thermodynamic model for uplift and deflation episodes (bradyseism) associated with magmatic–
1368
1369 576 hydrothermal activity at the Campi Flegrei (Italy). *Earth-Science Rev.* 97, 44–58.
1370
1371 577 doi:10.1016/j.earscirev.2009.10.001
1372
1373
1374 578 Moretti, R., De Natale, G., Troise, C., 2017. A geochemical and geophysical reappraisal to the significance
1375
1376 579 of the recent unrest at Campi Flegrei caldera (Southern Italy). *Geochemistry, Geophys. Geosystems* 18,
1377
1378
1379
1380

1381
1382
1383 580 1244–1269. doi:10.1002/2016GC006569
1384
1385
1386 581 Nickschick, T., Flechsig, C., Meinel, C., Mrlina, J., Kämpf, H., 2017. Architecture and temporal variations
1387
1388 582 of a terrestrial CO₂ degassing site using electric resistivity tomography and self-potential. *Int. J. Earth*
1389
1390 583 *Sci.* 1–12. doi:10.1007/s00531-017-1470-0
1391
1392
1393 584 Oldenborger, G.A., Knoll, M.D., Routh, P.S., LaBrecque, D.J., 2007. Time-lapse ERT monitoring of an
1394
1395 585 injection/withdrawal experiment in a shallow unconfined aquifer. *GEOPHYSICS* 72, F177–F187.
1396
1397 586 doi:10.1190/1.2734365
1398
1399
1400 587 Orsi, G., Di Vito, M.A., Isaia, R., 2004. Volcanic hazard assessment at the restless Campi Flegrei caldera.
1401
1402 588 *Bull. Volcanol.* 66, 514–530. doi:10.1007/s00445-003-0336-4
1403
1404
1405 589 Petrosino, S., Damiano, N., Cusano, P., Di Vito, M.A., de Vita, S., Del Pezzo, E., 2012. Subsurface structure
1406
1407 590 of the Solfataro volcano (Campi Flegrei caldera, Italy) as deduced from joint seismic-noise array,
1408
1409 591 volcanological and morphostructural analysis. *Geochemistry, Geophys. Geosystems* 13, n/a-n/a.
1410
1411 592 doi:10.1029/2011GC004030
1412
1413
1414 593 Piochi, M., Mormone, A., Balassone, G., Strauss, H., Troise, C., De Natale, G., 2015a. Native sulfur, sulfates
1415
1416 594 and sulfides from the active Campi Flegrei volcano (southern Italy): Genetic environments and
1417
1418 595 degassing dynamics revealed by mineralogy and isotope geochemistry. *J. Volcanol. Geotherm. Res.*
1419
1420 596 304, 180–193. doi:10.1016/j.jvolgeores.2015.08.017
1421
1422
1423 597 Piochi, M., Mormone, A., Balassone, G., Strauss, H., Troise, C., De Natale, G., 2015b. Native sulfur, sulfates
1424
1425 598 and sulfides from the active Campi Flegrei volcano (southern Italy): Genetic environments and
1426
1427 599 degassing dynamics revealed by mineralogy and isotope geochemistry. *J. Volcanol. Geotherm. Res.*
1428
1429 600 304, 180–193. doi:10.1016/j.jvolgeores.2015.08.017
1430
1431
1432 601 Pribnow, D.F., Schütze, C., Hurter, S.J., Flechsig, C., Sass, J.H., 2003. Fluid flow in the resurgent dome of
1433
1434 602 Long Valley Caldera: implications from thermal data and deep electrical sounding. *J. Volcanol.*
1435
1436 603 *Geotherm. Res.* 127, 329–345. doi:10.1016/S0377-0273(03)00175-6
1437
1438
1439
1440

1441
1442
1443
1444
1445
1446
1447
1448
1449
1450
1451
1452
1453
1454
1455
1456
1457
1458
1459
1460
1461
1462
1463
1464
1465
1466
1467
1468
1469
1470
1471
1472
1473
1474
1475
1476
1477
1478
1479
1480
1481
1482
1483
1484
1485
1486
1487
1488
1489
1490
1491
1492
1493
1494
1495
1496
1497
1498
1499
1500

604 Revil, A., Cathles III, L.M., Losh, S., Nunn, J.A., 1998. Electrical conductivity in shaly sands with
605 geophysical application. *J. Geophys. Res.*, 103 (B10) (1998), pp. 23925-23936

606 Revil, A., Finizola, A., Piscitelli, S., Rizzo, E., Ricci, T., Crespy, A., Angeletti, B., Balasco, M., Barde
607 Cabusson, S., Bennati, L., Bolève, A., Byrdina, S., Carzaniga, N., Di Gangi, F., Morin, J., Perrone, A.,
608 Rossi, M., Roulleau, E., Suski, B., 2008. Inner structure of La Fossa di Vulcano (Vulcano Island,
609 southern Tyrrhenian Sea, Italy) revealed by high-resolution electric resistivity tomography coupled
610 with self-potential, temperature, and CO₂ diffuse degassing measurements. *J. Geophys. Res.* 113,
611 B07207. doi:10.1029/2007JB005394

612 Revil, A., Finizola, A., Ricci, T., Delcher, E., Peltier, A., Barde-Cabusson, S., Avard, G., Bailly, T., Bennati,
613 L., Byrdina, S., Colonge, J., Di Gangi, F., Douillet, G., Lupi, M., Letort, J., Tsang Hin Sun, E., 2011.
614 Hydrogeology of Stromboli volcano, Aeolian Islands (Italy) from the interpretation of resistivity
615 tomograms, self-potential, soil temperature and soil CO₂ concentration measurements. *Geophys. J. Int.*
616 186, 1078–1094. doi:10.1111/j.1365-246X.2011.05112.x

617 Roberts, J.J., 2002. Electrical properties of microporous rock as a function of saturation and temperature. *J.*
618 *Appl. Phys.*, 91 (3).

619 Schmidt-Hattenberger, C., Bergmann, P., Kießling, D., Krüger, K., Rucker, C., Schütt, H., Group, K., 2011.
620 Application of a Vertical Electrical Resistivity Array (VERA) for monitoring CO₂ migration at the
621 Ketzin site: First performance evaluation. *Energy Procedia* 4, 3363–3370.
622 doi:10.1016/j.egypro.2011.02.258

623 Shirzaei, M., Walter, T.R., 2010. Time-dependent volcano source monitoring using interferometric synthetic
624 aperture radar time series: A combined genetic algorithm and Kalman filter approach. *J. Geophys. Res.*
625 115, B10421. doi:10.1029/2010JB007476

626 Singha, K., Day-Lewis, F.D., Johnson, T., Slater, L.D., 2015. Advances in interpretation of subsurface
627 processes with time-lapse electrical imaging. *Hydrol. Process.* 29, 1549–1576. doi:10.1002/hyp.10280

628 Slater, L., 2007. Near Surface Electrical Characterization of Hydraulic Conductivity: From Petrophysical

1501
1502
1503
1504 629 Properties to Aquifer Geometries—A Review. *Surv. Geophys.* 28, 169–197. doi:10.1007/s10712-007-
1505 9022-y
1506 630
1507
1508 631 Todesco, M., Chiodini, G., Macedonio, G., 2003. Monitoring and modelling hydrothermal fluid emission at
1509
1510 632 La Solfatara (Phlegrean Fields, Italy). An interdisciplinary approach to the study of diffuse degassing.
1511
1512 633 *J. Volcanol. Geotherm. Res.* 125, 57–79. doi:10.1016/S0377-0273(03)00089-1
1513
1514
1515 634 Troiano, A., Di Giuseppe, M., Petrillo, Z., Troise, C., De Natale, G., 2011. Ground deformation at calderas
1516
1517 635 driven by fluid injection: Modelling unrest episodes at Campi Flegrei (Italy). *Geophys. J. Int.* 187, 833–
1518
1519 636 847. doi:10.1111/j.1365-246X.2011.05149.x
1520
1521
1522 637 Troiano, A., Di Giuseppe, M.G., Patella, D., Troise, C., De Natale, G., 2014. Electromagnetic outline of the
1523
1524 638 Solfatara-Pisciarelli hydrothermal system, Campi Flegrei (Southern Italy). *J. Volcanol. Geotherm. Res.*
1525
1526 639 277, 9–21. doi:10.1016/j.jvolgeores.2014.03.005
1527
1528
1529 640 Troiano, A., Di Giuseppe, M.G., Petrillo, Z., Patella, D., 2009. Imaging 2D structures by the CSAMT
1530
1531 641 method: Application to the Pantano di S. Gregorio Magno faulted basin (Southern Italy). *J. Geophys.*
1532
1533 642 *Eng.* 6, 120–130. doi:10.1088/1742-2132/6/2/003
1534
1535
1536 643 Troiano, A., Petrillo, Z., Di Giuseppe, M.G., Balasco, M., Diaferia, I., Di Fiore, B., Siniscalchi, A., Patella,
1537
1538 644 D., 2008. About the shallow resistivity structure of Vesuvius volcano, in: *Annals of Geophysics*.
1539
1540 645 doi:10.4401/ag-3043
1541
1542
1543 646 **Vaughan, P.J., Udell, K.S., Wilt, M.J., 1993. The effects of steam injection on the electrical conductivity of**
1544
1545 647 **an unconsolidated sand saturated with a salt solution. *J. Geophys. Res.*, 98 (B1) (1993), pp. 509-518**
1546
1547
1548 648 Vilardo, G., Sansivero, F., Chiodini, G., 2015. Long-term TIR imagery processing for spatiotemporal
1549
1550 649 monitoring of surface thermal features in volcanic environment: A case study in the Campi Flegrei
1551
1552 650 (Southern Italy). *J. Geophys. Res. Solid Earth* 120, 812–826. doi:10.1002/2014JB011497
1553
1554 651 Wallin, E.L., Johnson, T.C., Greenwood, W.J., Zachara, J.M., 2013. Imaging high stage river-water intrusion
1555
1556 652 into a contaminated aquifer along a major river corridor using 2-D time-lapse surface electrical

1561
1562
1563
1564
1565
1566
1567
1568
1569
1570
1571
1572
1573
1574
1575
1576
1577
1578
1579
1580
1581
1582
1583
1584
1585
1586
1587
1588
1589
1590
1591
1592
1593
1594
1595
1596
1597
1598
1599
1600
1601
1602
1603
1604
1605
1606
1607
1608
1609
1610
1611
1612
1613
1614
1615
1616
1617
1618
1619
1620

653 resistivity tomography. *Water Resour. Res.* 49, 1693–1708. doi:10.1002/wrcr.20119

654 Ward, S.H., 1988. The Resistivity and Induced Polarization Methods, in: *Symposium on the Application of*
655 *Geophysics to Engineering and Environmental Problems 1988. Environment and Engineering*
656 *Geophysical Society*, pp. 109–250. doi:10.4133/1.2921804

657 Würdemann, H., Möller, F., Kühn, M., Heidug, W., Christensen, N.P., Borm, G., Schilling, F.R., 2010.
658 CO2SINK—From site characterisation and risk assessment to monitoring and verification: One year of
659 operational experience with the field laboratory for CO2 storage at Ketzin, Germany. *Int. J. Greenh.*
660 *Gas Control* 4, 938–951. doi:10.1016/j.ijggc.2010.08.010

661 Zhou, X., Lakkaraju, V.R., Apple, M., Dobeck, L.M., Gullickson, K., Shaw, J.A., Cunningham, A.B.,
662 Wielopolski, L., Spangler, L.H., 2012. Experimental observation of signature changes in bulk soil
663 electrical conductivity in response to engineered surface CO2 leakage. *Int. J. Greenh. Gas Control* 7,
664 20–29. doi:10.1016/j.ijggc.2011.12.006

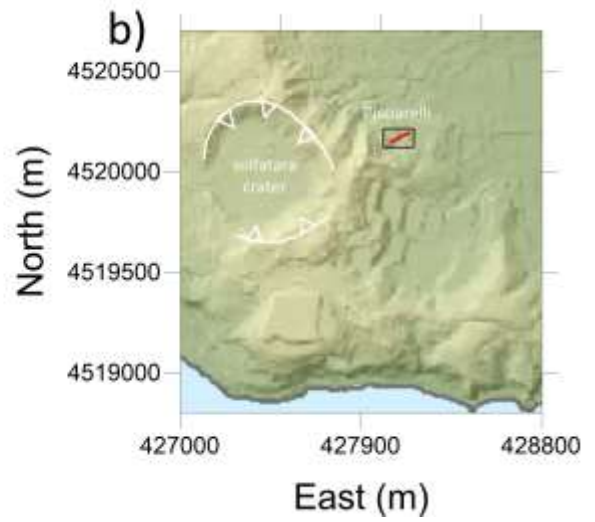
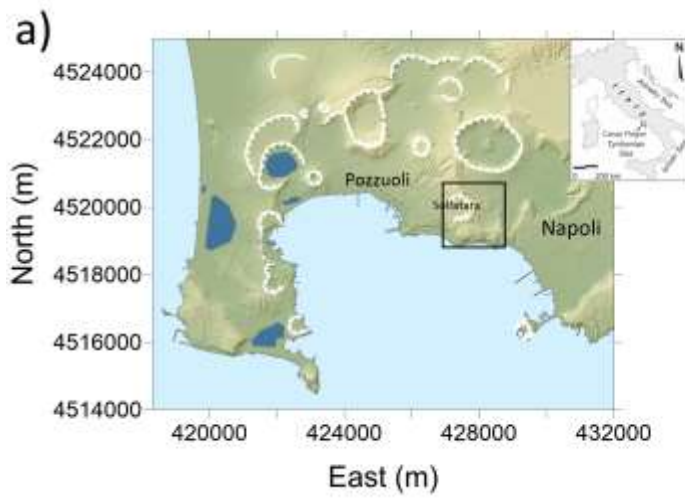


Figure 1.

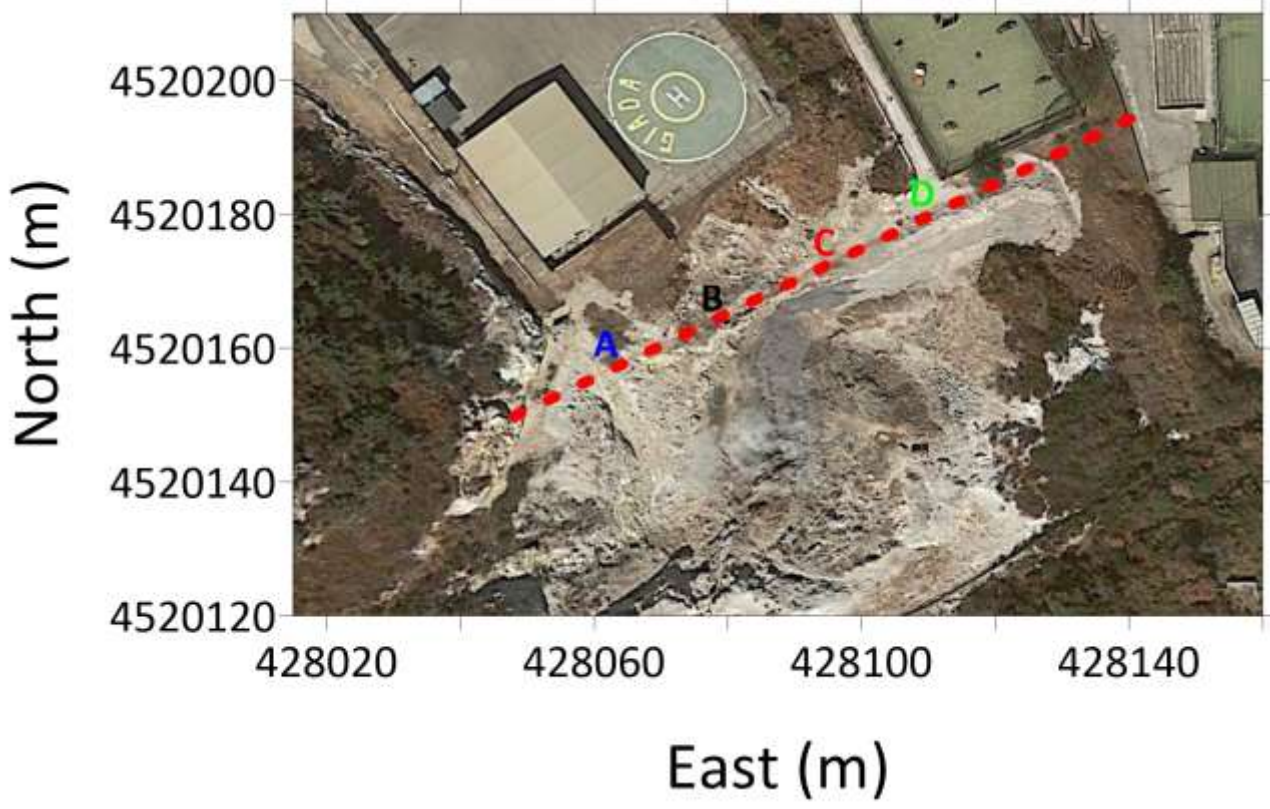
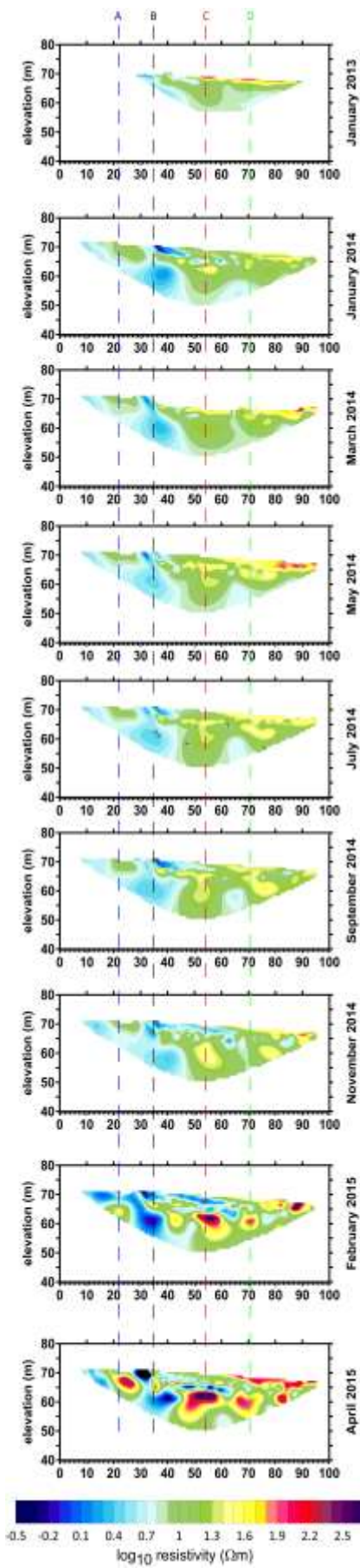


Figure 2.

1741
1742
1743
1744
1745
1746
1747
1748
1749
1750
1751
1752
1753
1754
1755
1756
1757
1758
1759
1760
1761
1762
1763
1764
1765
1766
1767
1768
1769
1770
1771
1772
1773
1774
1775
1776
1777
1778
1779
1780
1781
1782
1783
1784
1785
1786
1787
1788
1789
1790
1791
1792
1793
1794
1795
1796
1797
1798
1799
1800



675

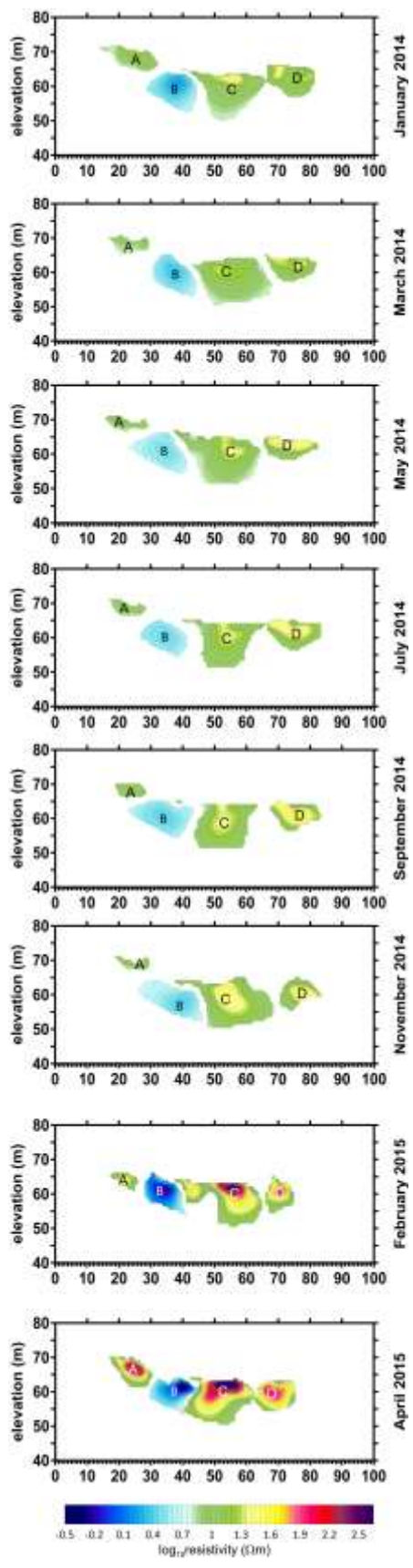
676

Figure 3

1801
1802
1803
1804
1805
1806
1807
1808
1809
1810
1811
1812
1813
1814
1815
1816
1817
1818
1819
1820
1821
1822
1823
1824
1825
1826
1827
1828
1829
1830
1831
1832
1833
1834
1835
1836
1837
1838
1839
1840
1841
1842
1843
1844
1845
1846
1847
1848
1849
1850
1851
1852
1853
1854
1855
1856
1857
1858
1859
1860

677

1861
1862
1863
1864
1865
1866
1867
1868
1869
1870
1871
1872
1873
1874
1875
1876
1877
1878
1879
1880
1881
1882
1883
1884
1885
1886
1887
1888
1889
1890
1891
1892
1893
1894
1895
1896
1897
1898
1899
1900
1901
1902
1903
1904
1905
1906
1907
1908
1909
1910
1911
1912
1913
1914
1915
1916
1917
1918
1919
1920



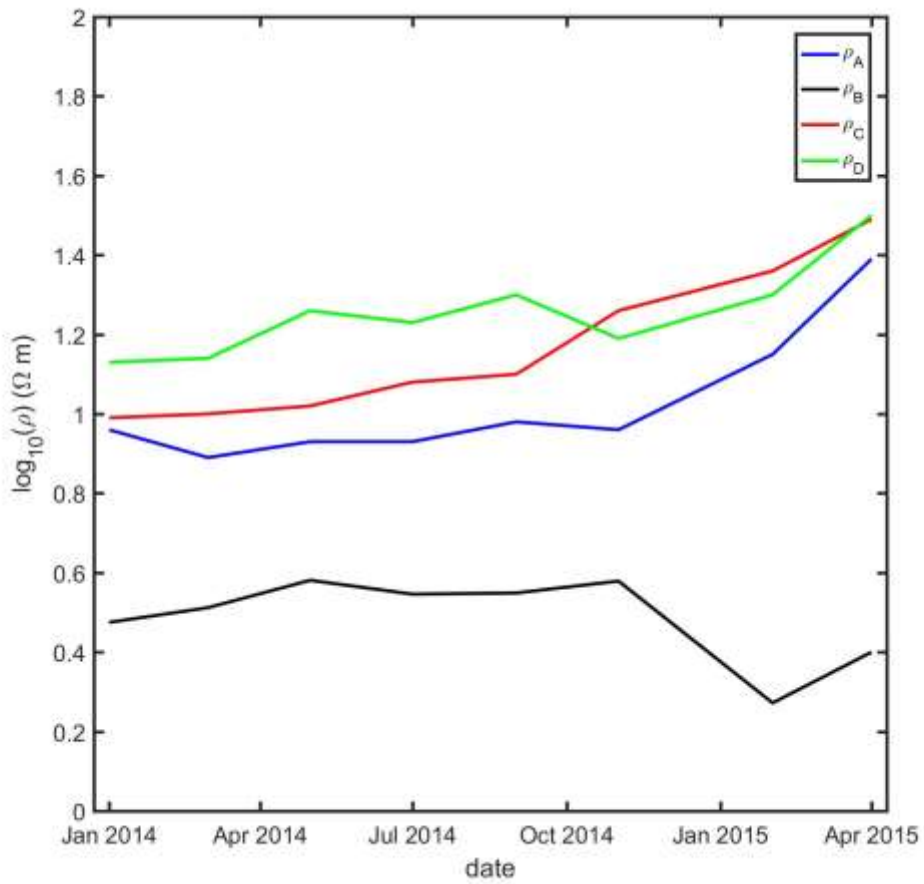
678

679

Figure 4.

680

1921
1922
1923
1924
1925
1926
1927
1928
1929
1930
1931
1932
1933
1934
1935
1936
1937
1938
1939
1940
1941
1942
1943
1944
1945
1946
1947
1948
1949
1950
1951
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980



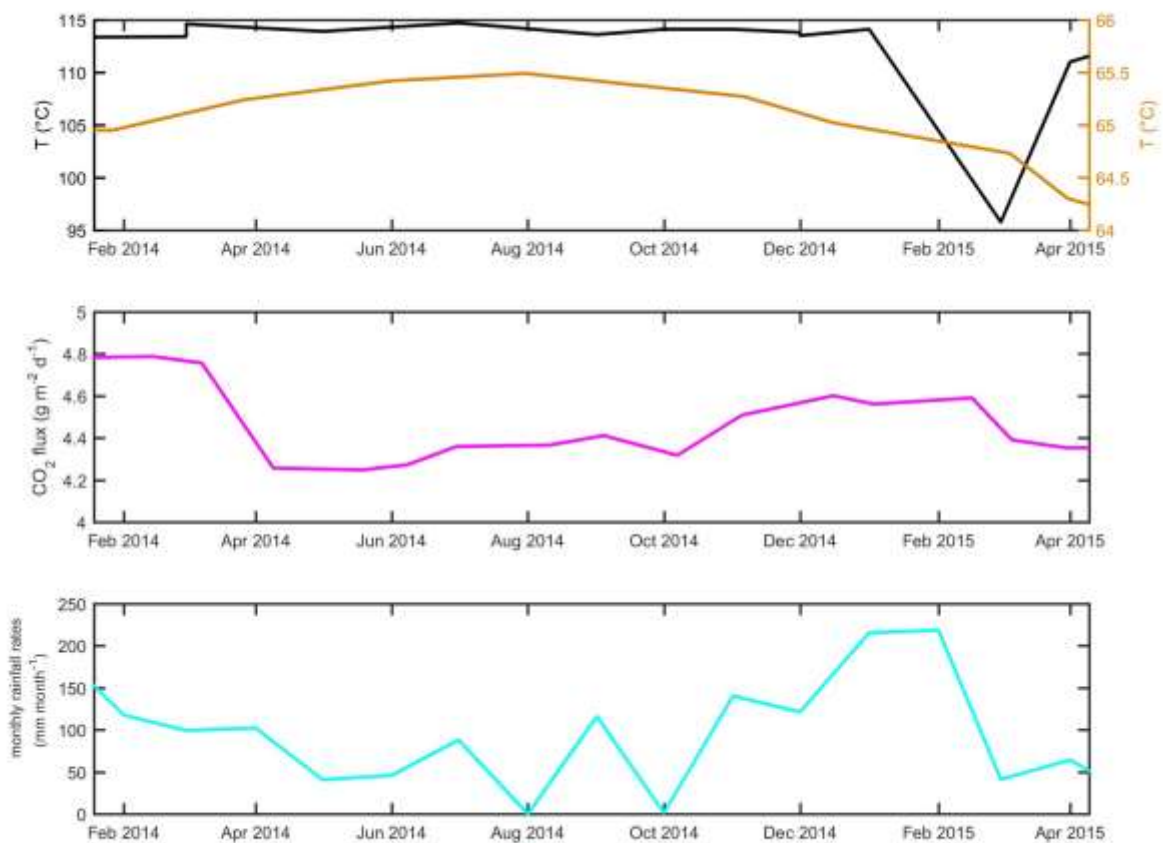
681

682

Figure 5.

683

1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040



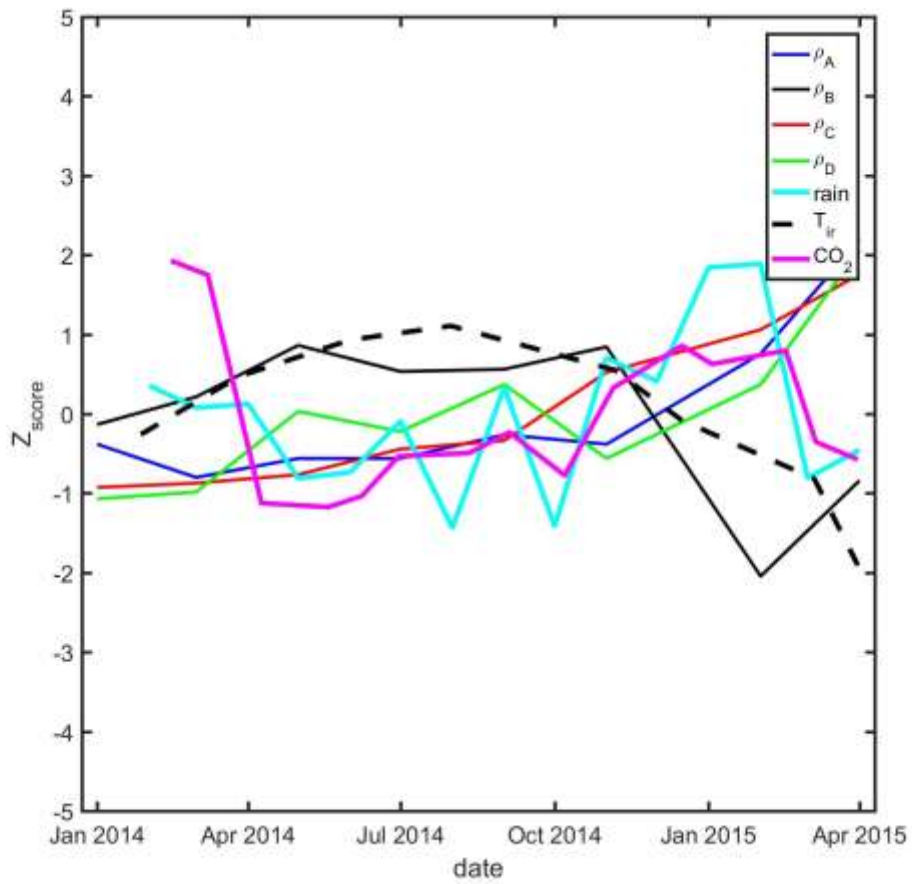
684

685

Figure 6.

686

687



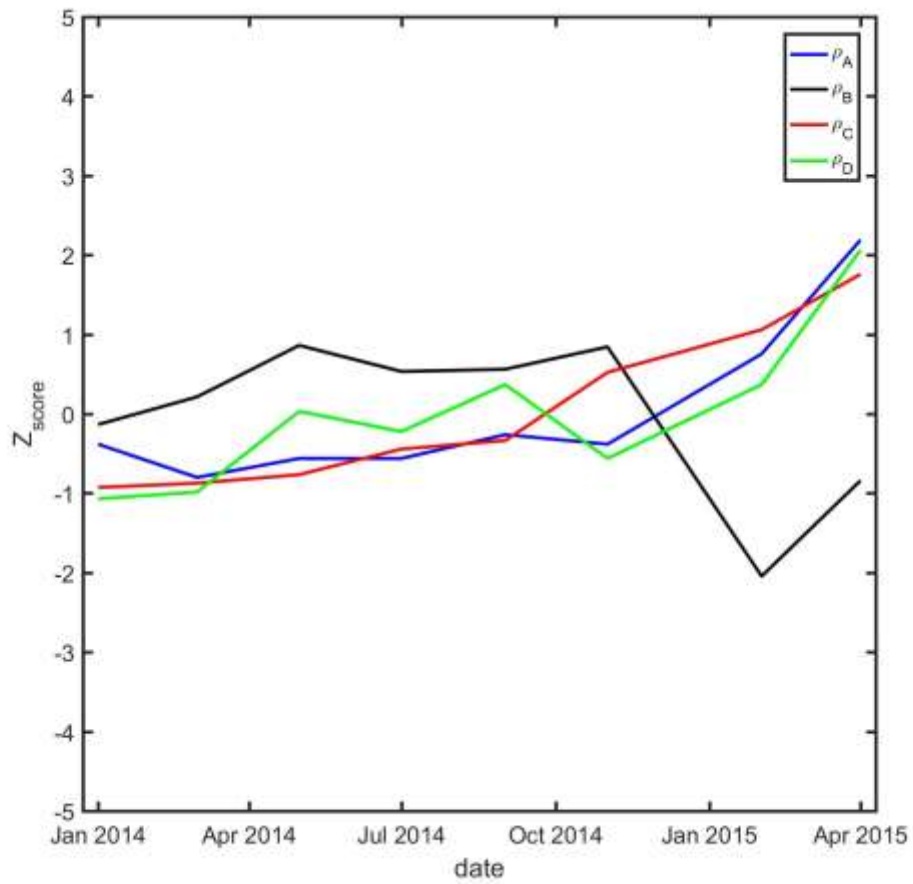
688

689 Figure 7.

690

691

2101
2102
2103
2104
2105
2106
2107
2108
2109
2110
2111
2112
2113
2114
2115
2116
2117
2118
2119
2120
2121
2122
2123
2124
2125
2126
2127
2128
2129
2130
2131
2132
2133
2134
2135
2136
2137
2138
2139
2140
2141
2142
2143
2144
2145
2146
2147
2148
2149
2150
2151
2152
2153
2154
2155
2156
2157
2158
2159
2160



692

2131

2132

693

Figure 8a.

2135

694

2137

2138

2139

695

2140

2141

2142

2143

2144

2145

2146

2147

2148

2149

2150

2151

2152

2153

2154

2155

2156

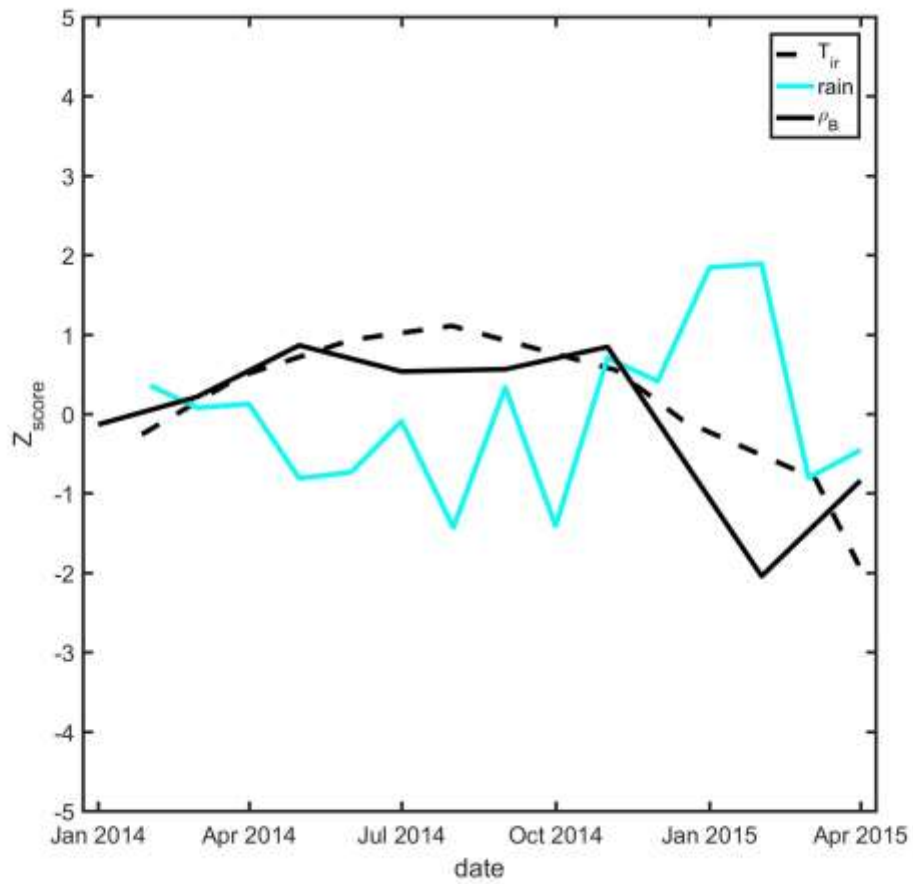
2157

2158

2159

2160

2161
2162
2163
2164
2165
2166
2167
2168
2169
2170
2171
2172
2173
2174
2175
2176
2177
2178
2179
2180
2181
2182
2183
2184
2185
2186
2187
2188
2189
2190
2191
2192
2193
2194
2195
2196
2197
2198
2199
2200
2201
2202
2203
2204
2205
2206
2207
2208
2209
2210
2211
2212
2213
2214
2215
2216
2217
2218
2219
2220



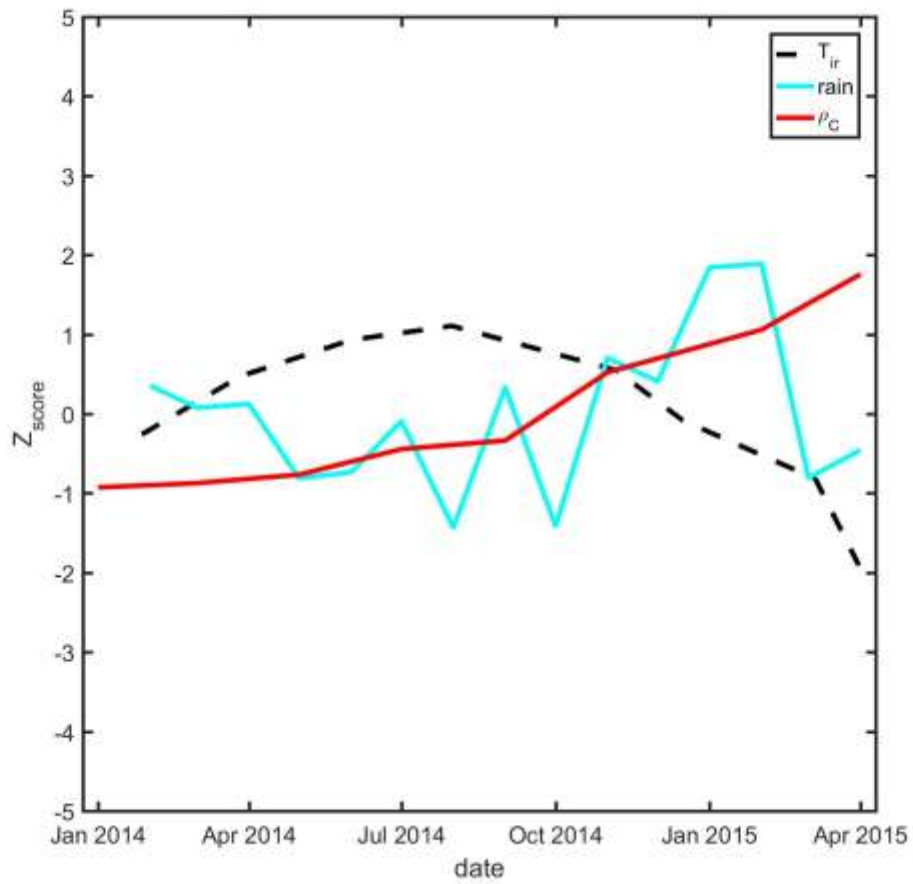
696

697 Figure 8b.

698

699

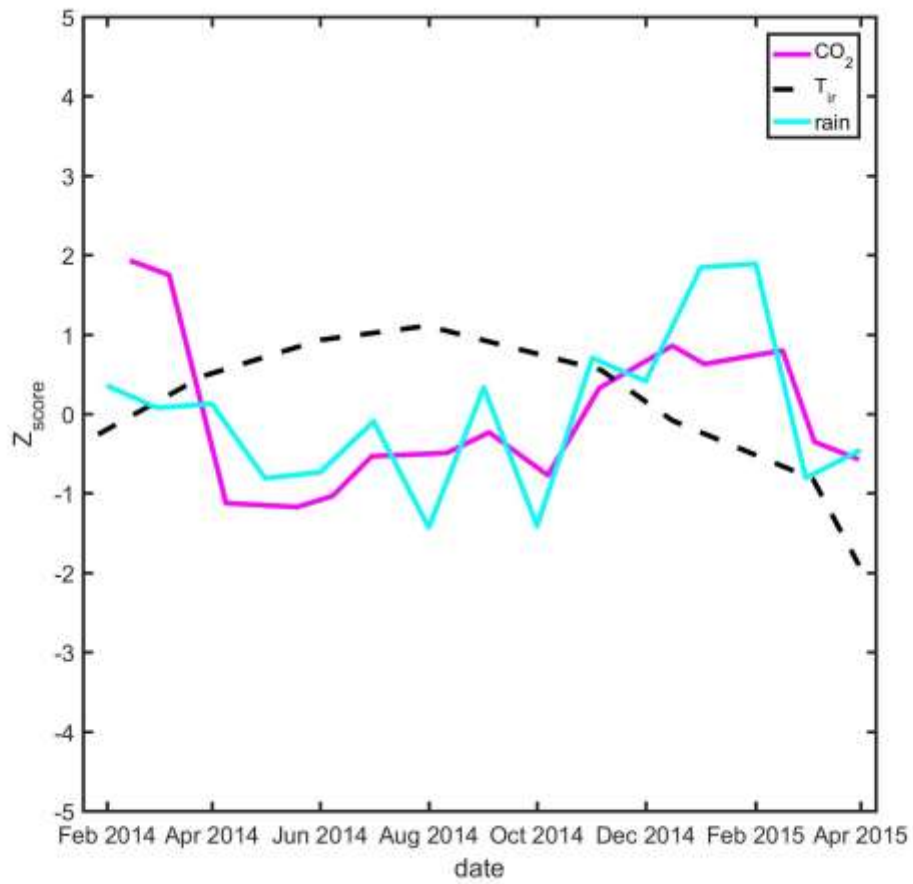
2221
2222
2223
2224
2225
2226
2227
2228
2229
2230
2231
2232
2233
2234
2235
2236
2237
2238
2239
2240
2241
2242
2243
2244
2245
2246
2247
2248
2249
2250
2251
2252
2253
2254
2255
2256
2257
2258
2259
2260
2261
2262
2263
2264
2265
2266
2267
2268
2269
2270
2271
2272
2273
2274
2275
2276
2277
2278
2279
2280



700
701 Figure 8c.

702
703

2281
2282
2283
2284
2285
2286
2287
2288
2289
2290
2291
2292
2293
2294
2295
2296
2297
2298
2299
2300
2301
2302
2303
2304
2305
2306
2307
2308
2309
2310
2311
2312
2313
2314
2315
2316
2317
2318
2319
2320
2321
2322
2323
2324
2325
2326
2327
2328
2329
2330
2331
2332
2333
2334
2335
2336
2337
2338
2339
2340



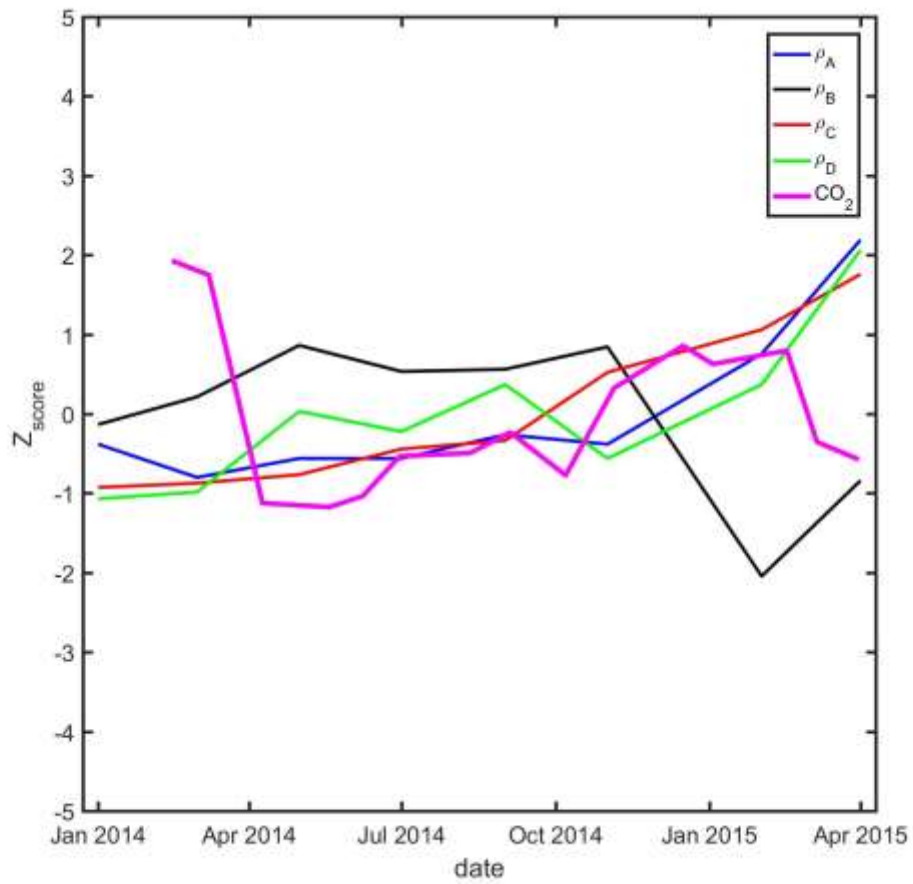
704

705 Figure 8d.

706

707

2341
2342
2343
2344
2345
2346
2347
2348
2349
2350
2351
2352
2353
2354
2355
2356
2357
2358
2359
2360
2361
2362
2363
2364
2365
2366
2367
2368
2369
2370
2371
2372
2373
2374
2375
2376
2377
2378
2379
2380
2381
2382
2383
2384
2385
2386
2387
2388
2389
2390
2391
2392
2393
2394
2395
2396
2397
2398
2399
2400



708
709 Figure 8e.

2401
2402
2403
2404
2405
2406
2407
2408
2409
2410
2411
2412
2413
2414
2415
2416
2417
2418
2419
2420
2421
2422
2423
2424
2425
2426
2427
2428
2429
2430
2431
2432
2433
2434
2435
2436
2437
2438
2439
2440
2441
2442
2443
2444
2445
2446
2447
2448
2449
2450
2451
2452
2453
2454
2455
2456
2457
2458
2459
2460

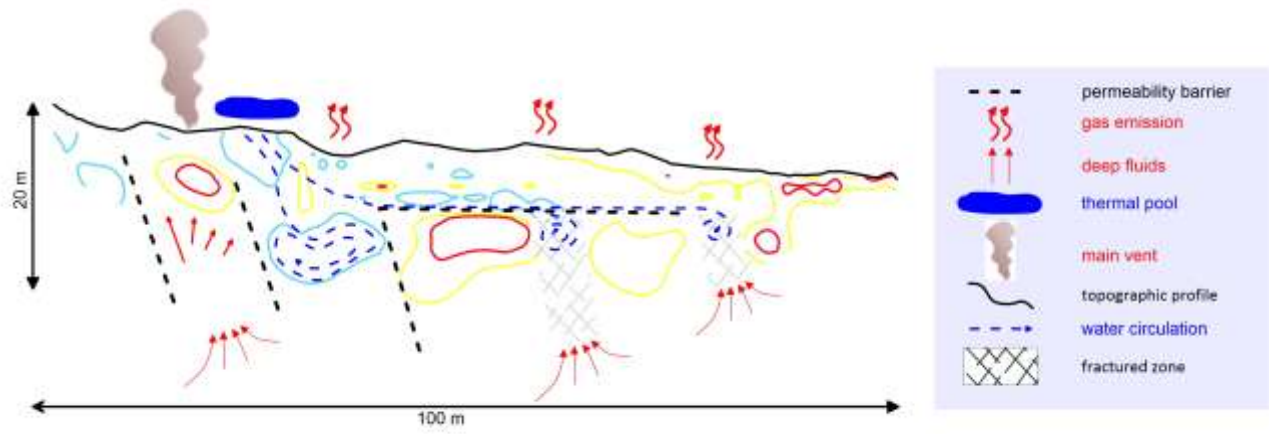


Figure 9.

- Time lapse ERT surveys were performed in the Pisciarelli site
- ERT and superficial data integration was performed to study the site
- Mutual relationship between the parameters and their interdependence is analysed
- Seasonal anomalies and features linked to volcanic contributions are marked
- A conceptual model of the fumarolized area is presented

1
2
3 1 Monitoring active fumaroles through time-lapse electrical resistivity tomograms: an application to
4
5 2 the Pisciarelli fumarolic field (Campi Flegrei, Italy).
6
7

8 3 M. G. Di Giuseppe and A. Troiano
9

10 4 Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli ‘Osservatorio Vesuviano’
11
12

13 5 **Abstract**
14

15
16 6 Volcanoes are usually monitored through observations of many physical and chemical phenomena.
17
18 7 In the most dangerous cases, as the one of the Campi Flegrei caldera (Italy), great amount of data are
19
20 8 collected, both in discrete or continuously, and regularly stored. However, how to transform such
21
22 9 mass of data in a deeper understanding of the volcano dynamics is still an open question. Dissimilar
23
24 10 information are in fact always hard to compare, but just integrating all the available knowledge
25
26 11 hazardous events could be prevented in a reliable way. Fluids, as water and gasses mobilized in the
27
28 12 subsoil by the heat induced by deep magmatic sources, are widely recognized as the first engine of
29
30 13 similar occurrences and the volcanic gas emissions represent, together with the seismic activity, one
31
32 14 of the most considered precursors. At the same time, the electrical geophysical methods are the most
33
34 15 applied in order to detect and characterize the fluid patterns in the subsoil. So, the integration of
35
36 16 geoelectrical and geochemical observations should represents one of the most pursued approach in
37
38 17 volcanoes monitoring. On the contrary, standard way to compare such data have been not yet codified.
39
40 18 The ERT tomograms capability to individuate that parts of the subsoil where gasses cumulate is well
41
42 19 understood in literature. However, we look for indications about its proficiency in associating the
43
44 20 electrical resistivity changes relative to these zones, once compared to the geochemical time series,
45
46 21 to deep related contributes, distinguishing them from the seasonal ones. The electrical signature of
47
48 22 the fluid patterns, reconstructed through a time-lapse ERT approach, could be of relevance to better
49
50 23 characterize the volcanic phenomena and their origins. In this paper a first test of ERT and
51
52 24 geochemical time series integration was performed to enhance the understanding of the Pisciarelli
53
54 25 fumarolic field evolution, now the most active area in the whole Campi Flegrei caldera.
55
56
57
58
59
60

61
62
63 **26 Introduction**
64
65

66 27 Electrical resistivity tomography (ERT) represents a well-established technique, widely employed to
67
68 28 investigate fluid-induced variations in volcanological settings (Revil et al. 2008; Byrdina et al. 2009;
69
70 29 Finizola et al. 2009; Finizola et al. 2010; Revil et al., 2011; Di Giuseppe et al. 2015). Many literature
71
72 30 publications describe electrical investigations devoted to the definition of the structural setting of
73
74 31 volcanoes (Finizola et al., 2006; Revil et al., 2008; Aizawa et al., 2009; Fikos et al., 2012; Barde-
75
76 32 Cabusson et al., 2013; DiGiuseppe et al., 2017). When applied in time-lapse mode, e.g. performing
77
78 33 tomograms reiteratively overtime, ERT maps the temporal changes in electrical resistivity, which
79
80 34 could be related to the changes in the fluid patterns in the subsoil (Singha et al., 2015; Slater, 2007).
81
82 35 Because fluids are often involved in relevant volcanic phenomena, time-lapse ERT should be
83
84 36 considered in the monitoring of active areas in order to investigate highly hazardous but ambiguous
85
86 37 phenomena. This particularly concern for silicic volcanoes, which commonly develop pervasive
87
88 38 hydrothermal systems during their long repose periods. The resulting magma-hydrothermal
89
90 39 interactions are still poorly understood (Chiodini et al. 2016). In active calderas, widely investigated
91
92 40 through electrical methods (Pribnow et al., 2003; Bruno et al., 2007; Di Giuseppe et al., 2015), the
93
94 41 hydrothermal circulation is extremely intense, indeed, due to the major structural control, which
95
96 42 makes the characterization of unrest phases even more complicated. In addition, the liquid and the
97
98 43 gas interactions between mixtures of different chemical species, the most relevant among them being
99
100 44 water and carbon dioxide, happen in the very shallowest part of the geothermal system, often creating
101
102 45 active fumaroles. Once injected into the shallower formations from deeper magmatic sources, the
103
104 46 CO₂ will tend to rise upward because of its low density until it is trapped by low-permeability
105
106 47 structures or by dissolution into the groundwater (Bachu et al., 1994). The electrical resistivity of the
107
108 48 mixture of grains and pores, which contain the fluids, changes over time, mainly due to fluid filling
109
110 49 the pores driven by the fumarole dynamics, and the literature points out that fluids in volcanic
111
112 50 environments affect electrical resistivity, generating detectable variations in the recordable signals
113
114 51 (Rinaldi et al., 2011). In effects, one of the most sensible parameters to detect the approach of a new
115
116
117
118
119
120

121
122
123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
178
179
180

52 eruptive phase is to examine the variations in the composition of discharged fluids. The isotopic
53 signature, however, is often difficult to interpret in terms of system evolution, because several
54 mechanisms may be responsible for differences in the proportion of magmatic gases and shallower
55 fluid components. Indeed, such proportions can be altered before the fluids reach the surface, due to
56 the mixing between fluids of different origin, or due to reactions that modify the original isotope
57 composition. Time-lapsed ERT can reconstruct these changes (Giese et al. 2009; Kiessling et al. 2010;
58 Würdemann et al. 2010; Schmidt-Hattenberger et al. 2011; Zhou et al. 2012), and help to characterize
59 the fumarole dynamics. The dissolution of CO₂ in groundwater and soil moisture indeed generates an
60 enlargement of the low resistivity area after CO₂ injection into the vent. An opposite relationship
61 between CO₂ concentration and electrical resistivity is observed when CO₂, rather than dissolving in
62 water, replaces the brine in the rock matrix, causing the apparent resistivity to increase (Le Roux et
63 al., 2013). The integration between time-lapse ERT and geochemical observations could help to
64 characterize the phenomena related to the mixing of different chemical species, and to reconstruct
65 interaction between fluids of magmatic origin and meteoric waters. The relationship between the
66 contributions of deeper magmatic sources and sources linked to seasonal fluctuations could be also
67 investigated in that manner. Here a similar application is presented, carried out in the Pisciarelli area,
68 which represents a part of the Campi Flegrei caldera (Italy) where vigorous gaseous emissions are
69 present. Repeated tomograms, performed bimonthly, furnished an image of the dynamics of fluids
70 contributing to the fumarolic vent. An approach to the comparison of the gaseous emission rates,
71 temperature and rainfall rates is suggested, to which end a characterization of the detected anomalies
72 is provided.

73 **The Campi Flegrei caldera.**

74 The Campi Flegrei caldera (CFc) is one of the most hazardous volcanoes in Europe (Orsi et al., 2004)
75 and it is inhabited by more than 300,000 people (Bevilacqua et al., 2015), including entire quarters
76 of Naples (Fig.1a). Vertical ground movements with rates ranging from centimetres to metres per
77 year are typical even during quiescent periods (Dvorak and Mastrolorenzo, 1991). Since 1950 the

181
182
183
184
185
186
187
188
189
190
191
192
193
194
195
196
197
198
199
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
221
222
223
224
225
226
227
228
229
230
231
232
233
234
235
236
237
238
239
240

78 area has been in a new phase of uplift after several centuries of subsidence dating back to 1538 A.D.,
79 when the last eruption occurred in the area (Di Vito et al., 1987). The most recent episodes of intense
80 ground uplift were during 1970-72 and 1982-84, which caused a cumulative maximum uplift of over
81 3.5 m, accompanied by intense seismicity. Apart from the ground uplift, the CFc unrest is
82 characterized primarily by shallow hydrothermal manifestations (such as the vigorous gas emissions),
83 which are most evident in the Solfatara crater and the nearby Pisciarelli areas (Fig.1b), with an
84 involvement of the seismic activity. In effect, the recent literature on the interpretation of the unrest
85 of the whole CFc points out the driving role played by processes involving these two areas (De Natale
86 et al., 1991; Chiodini et al., 2003; Troiano et al., 2011; Piochi et al., 2015a), which are continuously
87 monitored and under observation for the risk strictly related to their potential expansion into a high-
88 density urban area. Many studies involve the mechanical effect of overpressure on a shallow magma
89 chamber (Berrino et al., 1984; Bianchi et al., 1987; Amoruso et al., 2007;) or a sill-like deformative
90 source (D’Auria et al., 2011). Other studies suggest that the unrest periods affecting the whole caldera
91 could likely be related to the triggering of the local hydrothermal system caused by magma degassing
92 episodes centred below the Solfatara - Pisciarelli area (De Natale et al., 1991; Chiodini et al., 2003;
93 Todesco et al., 2003; De Natale et al., 2006; Gottsmann et al., 2006; Lima et al., 2009; Shirzaei and
94 Walter, 2010; Troiano et al., 2011).

95 Geophysical applications allowed a detailed imaging of the subsurface structure of the Solfatara crater
96 (Letort et al., 2012; Petrosino et al., 2012; Byrdina et al., 2014; Di Giuseppe et al., 2015; Isaia et al.,
97 2015; Gresse et al., 2017). The structure of the Pisciarelli site is less defined. Moreover, several
98 monitoring techniques (geodetic, thermal and geochemical) are currently applied to the CFc,
99 especially at the Solfatara and Pisciarelli areas (INGV, 2018), but a lack of knowledge persists about
100 the distribution and dynamics of the geothermal fluids present in the area. Specifically, the Pisciarelli
101 area has been the subject of a severe reactivation in the last few years, concomitant with an increase
102 of ground uplift. The main manifestations are as follows: an enlargement of the fumarolized area, the
103 opening of a new vent (which occurred in March 2008), the opening of a new boiling pool (which

241
242
243 104 occurred in March 2009 and which was probably accompanied by a small explosion because mud
244
245 105 sputter occurred, covering the soil slope up to 3–4 m above the emission point), a further vigorous,
246
247 106 roaring fumarole created (which appeared on the 20th of December, 2009, that represents the strongest
248
249
250 107 gas emission of the entire area to date), the seismic swarm of about 190 events (recorded in the area
251
252 108 during the 30th of March, 2010) and a new vent opened (during the 15th of November, 2010). Finally,
253
254 109 in the January of 2013 the disappearance of the main fumarole that was recently opened and the
255
256 110 appearance of a vent that emits high-pressure steam and liquid water up to 3-4 m high were observed.
257
258 111 These manifestations make the Pisciarelli unrest quite peculiar. It is indubitably linked to the global
259
260 112 CFc unrest, as evidenced by the geochemical species emitted (Chiodini et al., 2011). However, the
261
262 113 local aspect of the CFc dynamic in this area has to be carefully taken into account. The Pisciarelli
263
264 114 neighbourhood has a high degree of urban development and minor events could represent a high risk
265
266
267 115 for a great number of inhabitants.
268
269 116 A mapping of the electrical resistivity changes through ERT should be indicative of potentially
270
271 117 hazardous dynamics in the area. Such parameters are, in fact, sensitive to properties such as salinity,
272
273 118 porosity and phase changes of fluids flowing into the porous space, which contribute to the
274
275 119 characterization of the fluid circulation in the subsurface.
276
277 120
278
279 121 **The state of the Solfatara – Pisciarelli area.**
280
281 122 After the last major unrest period observed in the CFc, during 1982-1984, the ground deformation
282
283
284 123 trend showed a subsidence period until 2004-2005, when a new uplift phase started. Since 2010-2011
285
286 124 the deformation rate shows a further increase, leading to a cumulative uplift of more than 20 cm. The
287
288 125 ground uplift is also accompanied by widespread fumarolic activity occurring in the whole CF caldera
289
290 126 area. However, these unrest manifestation are all focused in the centre of the CFc (Figure1a), near
291
292 127 the Solfatara - Pisciarelli area (D'Auria et al., 2011), where the evidences of volcanic effects are
293
294 128 particularly present now. For such a reason, the ascription of a central role in the CFc unrest dynamic
295
296
297
298
299
300

301
302
303 129 for these two areas has grown, and has been the subject of the many detailed numerical studies,
304
305 130 mentioned earlier.

306
307
308 131
309
310 132 The geophysics surveys contributed to defining the structural outline of the Solfatara – Pisciarelli
311
312 133 area (SP), and represented a crucial task for understanding volcanic activity. Recent surveys
313
314 134 highlighted the main structural asset of the area. The first magnetotelluric surveys (Troiano et al.,
315
316 135 2014) detected a near-vertical steam/gas-saturated plume-like structure, which reaches the free
317
318 136 surface where the main fumarole fields are active, emerging from a high temperature (>300 °C), over
319
320 137 pressured, gas-saturated plate-like reservoir, which extends down to at least 3 km in depth.
321
322 138 Subsequent ERT surveys clarified the shallower structure of the Solfatara volcano, outlining a
323
324 139 complex hydrothermal system, formed by a mix of upwelling fluids, gases, and meteoric water
325
326
327 140 (Byrdina et al., 2014; Di Giuseppe et al., 2015; Gresse et al., 2017). Isaia et al. (2015), when
328
329 141 considering this structural framework, ended in the suggestion that the Solfatara volcano could be a
330
331 142 maar-diatreme structure, characterized by a shallow crater cut in the pre-eruptive basement, and a
332
333 143 deep diatreme (down to 2–3km).

334
335 144
336
337 145 Physical and chemical observations are now performed in the whole CFc as part of the volcanic
338
339 146 monitoring and both the Solfatara crater and the Pisciarelli area represent the great majority of the
340
341 147 areas surveyed. Regular thermic, seismic, gravimetric, geochemical and geodetic monitoring is
342
343
344 148 carried out in the area. In particular, the geochemical data had a central role in the debate on the CFc
345
346 149 unrest (Chiodini et al., 2012, 2016; Moretti et al., 2017). A general increase of the deep magmatic
347
348 150 component into the emitted volatiles was observed (INGV, 2018). In particular, for what concerned
349
350 151 the SP area, the following features were observed:

- 351
352 152
- an increasing trend in the CO₂/H₂O, generally indicating a growth in the magmatic component
353
354 153 into the fumarolic fluids
- 355
356
357
358
359
360

- an increasing CO concentration, that generally characterize volcanic systems at high temperature, whereas hydrothermal contributions would be usually related to lower levels of this component
- an increase of the CO-CO₂ equilibrium temperature, representing the shallower hydrothermal system conditions
- and an increasing trend in the CO₂/CH₄ ratio

Further considerations about the fluid dynamics in the area arise also from the geophysical observations. Di Giuseppe et al. (2015) discussed a migration of the shallow fluid volume eastwards during the few past decades, and supposed that water might have invaded spaces previously saturated with steam, gas or a combination thereof below the Solfatara main vents, at the same time as fluxes steam, gas or both were invading voids opening to the east. This last observation strictly followed the recent relocation of the fumarolic activity from the Solfatara area toward the Pisciarelli area, located eastward to the outer slopes of the Solfatara (Figure1b) (Troiano et al., 2014). This relocation was marked by a temperature increasing, new vents and boiling pools opening, the occurrence of seismic activity and by the impressively fast changes in the morphology of this zone.

Unfortunately, the source of such relocation is yet largely unknown and a lack of knowledge persists about the fluid dynamics in that part of the CFc hydrothermal system. Current geophysical details of the connections between the Solfatara and Pisciarelli zones are still largely crude, and the geochemical data from Pisciarelli suffers of some criticism, as discussed in Chiodini et al. (2011), who suggested that these data could be heavily modified by seasonal cycles. They would then be not totally conclusive for investigations into the future changes caused by deep volcanic processes.

The ERT survey in the Pisciarelli area.

421
422
423 179 Two main electrical conductivity mechanisms characterize a fluid-saturated porous medium (Rinaldi
424
425 180 et al., 2011). The first one is caused by the fluid flow inside the pores, through electro-migration of
426
427
428 181 charges into the connected pore space. A second conduction mechanism occurs at the pore water–
429
430 182 mineral interface in the electrical double layer, that is caused by a migration of the weakly adsorbed
431
432 183 counterions (usually cations). The DC electrical conductivity of the porous rock can be expressed as
433
434 184 a combination of those two contribution, namely the surface electrical conductivity at the water–
435
436 185 mineral interface and the pore fluid electrical conductivity. Changes in those two quantities are
437
438 186 mainly due to variations into the fluid filling the pore, considering that wet rocks usually have
439
440 187 conductivities sensibly higher than dry rocks (Rinaldi et al., 2011 and references therein). Surface and
441
442 188 pore fluid conductivities depends linearly from temperature (Vaughan et al., 1993, Revil et al., 1998,
443
444 189 Roberts, 2002). Moreover, a dependence from the rock matrix permeability and from salinity of the
445
446
447 190 pore fluids is also observed (Jardani and Revil, 2009). Many mechanisms can be advocated when
448
449 191 changes are observed in the bulk conductivity of the rocks. The first element to consider is the
450
451 192 compositional nature of the fluids flowing into the system. The pore space of the rocks is indeed
452
453 193 occupied by a mixture of multiphase fluids, as water and CO₂ in liquid and vapour phase. Such
454
455 194 mixture is altered by the interaction between meteoric waters and fluids rising from the deep because
456
457 195 of volcanic effects, which has direct effects upon the underground resistivity. When fluid changes
458
459 196 their distribution into the shallower part of the hydrothermal system, the diffusion of the gas phases
460
461 197 (both water vapor and CO₂) and the temperature variations alter the electrical conductivity both at
462
463
464 198 the pore surface and within the porous space. Also the boiling phenomena into the fluids reinforce
465
466 199 the observed gradient in conductivity between liquid saturated and gas saturated areas, concentrating
467
468 200 the brine and increasing salinity in the remaining liquid part. As further effect, the fracturing induced
469
470 201 by the fluid dynamics and thermal expansion also alter the electrical conductivity of the subsoil,
471
472 202 modifying the rock permeability.
473
474 203 The geoelectrical surveys are very effective tools for unveil the dynamics of tectonic and volcanic
475
476 204 settings, and several contribution already regarded the Campanian district (Di Maio et al., 1998;
477
478
479
480

481
482
483 205 Bruno et al., 2007; Troiano et al., 2008, 2009; Byrdina et al., 2014; Di Giuseppe et al., 2015, 2017;
484
485 206 Gresse et al., 2017).

487
488 207 For the first time, ERT surveys were carried out into the Pisciarelli fumarolic field after the January
489
490 208 2013 event, when a vent that emitted high-pressure steam and liquid water up to 3-4 metres high was
491
492 209 observed, in order to get an insight about the geothermal fluid circulation in the very shallow aquifer.
493
494 210 A first survey was performed along a 70 m long survey line, aligned with the main fumarole and the
495
496 211 permanent thermal pool in the west-east direction (Figure 2), while crossing the part of the area subject
497
498 212 to abrupt morphological changes and major emissive activity. A dipole-dipole electrode configuration
499
500 213 was adopted, with a 2.5 m spacing, which was compact and sensitive to both lateral location and
501
502 214 depth of bodies that are the source of anomalies (Ward, 1988). An Iris Syscal Pro instrument was
503
504 215 used as multichannel resistivity meter. The same instrument was employed as power source, being able
505
506 216 to output a direct current with a maximum voltage and current of 800 V and 2 A, respectively.
507
508 217 The selected survey arrangement took into account the morphology and harsh environment
509
510 218 characterizing the Pisciarelli area, which represented a limitation imposed on a classical ERT
511
512 219 application. It was only possible to arrange a short survey line, with a consequent limit in the expected
513
514 220 depth of investigation. Despite this restriction, the use of a time-lapse approach, which consists in
515
516 221 performing identical ERT surveys several times in the same place, makes the ERT useful to
517
518 222 investigate the evolution of the Pisciarelli structures. The time-lapse approach was followed in several
519
520 223 ERT applications presented in the literature. As an example, Wallin et al. (2013) imaged the inland
521
522 224 intrusion of river water in a contaminated aquifer. Nickschick et al. (2017) observed the changes in
523
524 225 the subsurface structure beneath heavily CO₂ degassing spots in the Hartsouf Mofete field (Czech
525
526 226 Republic). In the volcanic Pisciarelli environment, time-lapse ERT may possibly resolve the
527
528 227 modifications of fluid phases and/or distribution induced by the contribution of a heat component or
529
530 228 a hot gaseous component, both likely present if a magmatic source is active in the area.
531
532 229
533
534
535
536
537
538
539
540

541
542
543
544
545
546
547
548
549
550
551
552
553
554
555
556
557
558
559
560
561
562
563
564
565
566
567
568
569
570
571
572
573
574
575
576
577
578
579
580
581
582
583
584
585
586
587
588
589
590
591
592
593
594
595
596
597
598
599
600

230 The ERT survey was regularly repeated, starting in January 2014 ending April 2015. It is worth
231 noting that the successive repetitions of the January 2013 survey were performed along a slightly
232 longer survey line (100 m long) with respect to the first January 2013 survey and that the bimonthly
233 interval was chosen in order to evaluate the possible influence of seasonal effects on the hydrothermal
234 system, as indicated by the geochemical monitoring. The ERT lines were inverted using ERTlab3D®
235 commercial software, including topography. The inverse algorithm, described by LaBrecque et al.
236 (1999) uses a regularized solution, looking for the optimal value of the parameter vector \mathbf{P} and the
237 stabilization parameter α for which minimizing the functional $Y(\mathbf{P})=\chi^2(\mathbf{P})+\alpha\mathbf{P}^T\mathbf{R}\mathbf{P}$ results in
238 $\chi^2(\mathbf{P})=\chi^2_{\text{prior}}$. The parameters \mathbf{P} are the natural logarithms of the conductivity of the mesh elements
239 and \mathbf{R} , the solution roughness, acts as the stabilizing functional. χ^2_{prior} is equal to the number of data
240 points and χ^2 is given by $\chi^2 = (\mathbf{D} - \mathbf{F}(\mathbf{P}))^T\mathbf{W}(\mathbf{D} - \mathbf{F}(\mathbf{P}))$, where \mathbf{D} is the vector of known data values,
241 $\mathbf{F}(\mathbf{P})$ is the forward solution and \mathbf{W} is a data weight matrix. The diagonal elements of \mathbf{W} are the
242 reciprocals of the data variances and the off-diagonal elements are zero. This assumes non-correlated
243 data errors. When ERT data was inverted in time-lapse mode, different approaches were
244 contemplated. As first consideration, with every dataset collected independently of the others, each
245 tomogram can be assumed to be a representation of a constant state of the shallower geothermal
246 system at the collection time. With this in mind, it is possible to invert each dataset independently,
247 isolating changes in the electrical resistivity by post inversion model differencing. A second option
248 to consider is the inversion on the differences between the background and subsequent datasets, e.g.
249 the resistivity obtained by the inversion of the first dataset, considered as background data, can be
250 considered as the a priori model in the difference inversion. In this case systematic errors such as
251 those errors due to in field configuration and discretization in the forward modelling algorithm tend
252 to null and the result is that the difference data is likely fitted more closely than the individual
253 potentials, resulting in fewer inversion artefacts (LaBrecque and Yang, 2001). A time-lapse
254 regularization can also be considered (Oldenborger et al., 2007), whereby the reference model for the
255 first inversion is an uniform model and the reference model for all subsequent experimental stages is

601
602
603 256 the model obtained via inversion of the data from the previous stage. Such approaches require, at
604
605 257 least in principle, fewer model modifications to fit the data and the objective function penalizes large
606
607
608 258 perturbations from previous models as opposed to large perturbations from background. Thus, such
609
610 259 inversion is ultimately able to build up more structure in the final models, while still satisfying the
611
612 260 data to the same level of the previous options. As a final, and likely more corrected, option, the dataset
613
614 261 could be inverted adopting 4D approaches (Kim et al., 2009; Karaoulis et al., 2011), which consider
615
616 262 a four-dimensional space–time model, introducing regularizations reflecting a metric function of both
617
618 263 space and time. In the present case, time-lapse minimization was adopted during the inversion of the
619
620 264 dataset. The final models for each dataset, are reported in Figure 3a. Average root-mean-squares
621
622 265 (RMS) varying from 1.1 up to 1.9 resulted, which we considered satisfactory. In order to support the
623
624 266 reliability of the images, it is common to look at \mathbf{S} , the so-called inverse problem’s sensitivity matrix,
625
626
627 267 which take into account the effects on the data by infinitesimal changes into the model resistivity.
628
629 268 The sensitivity has been estimated for all the tomograms presented in Figure 3.

630 631 269 632 633 270 **The ERT Dataset.**

634
635 271 The sequence of inverted resistivity images obtained in the timelapse survey is shown in Figure 3.
636
637 272 The tomograms showed diffuse lateral and vertical heterogeneities within a resistivity range of about
638
639 273 three orders of magnitude.

640
641
642 274
643
644 275 The bimonthly-recorded resistivity sections showed four main electrical anomalies:

- 645
646 276 A. the first anomaly lying at about 20 m along the profile (corresponding to the blue vertical
647
648 277 dashed line in the figure), located at depths varying between 60-70 m a.s.l.;
- 649
650 278 B. a second zone displaced at around 35 m along the profile (corresponding to the black dashed
651
652 279 line in the figure), located at depths between 50-65 m a.s.l.;
- 653
654 280 C. a third zone centred at around 55 m along the profile (corresponding to the red dashed line in
655
656 281 the figure), located between 50-65 m a.s.l.;

661
662
663 282 D. A fourth zone centred at around 70 m along the profile (corresponding to the green dashed
664
665 283 line in the figure), located at around 60 m a.s.l.;

666
667 284
668
669
670 285 A further anomalous zone appears at the very end of the profile. This last feature does not lie in the
671
672 286 vegetation-free zone and could likely be linked to some anthropic artefact. The anomalies' evolution,
673
674 287 in shape and resistivity, is reported in Figure 4, for each of the collected datasets.

675
676 288 Following the approach of Wallin et al. (2013), from the ERT tomograms, the time series of electrical
677
678 289 resistivity have been extracted for each of the electrical anomalies depicted in Figure 4, while taking
679
680 290 into consideration the mean values of the parameter in the elementary cells that compose the related
681
682 291 part of the tomograms. These resistivity time series are reported in Figure 5.

683
684 292 The anomalies observed in the subsurface underneath the Pisciarelli degassing site changed over time,
685
686
687 293 as a consequence of changes in several parameters on which the resistivity depends. In particular, the
688
689 294 high pressure of fluids (CO₂ and water carried along), likely mobilized by a deeper source, is capable
690
691 295 of altering the host rocks mechanically and/or chemically. The fluid's power is capable of moving
692
693 296 material from lower levels or widening the pores within materials. Moreover, according to
694
695 297 Annunziatellis et al. (2008), gases like CO₂ are capable of migrating not only vertically, but also
696
697 298 horizontally in soil as density-driven flows or advective forces, leading to horizontal changes in the
698
699 299 anomalies. In addition, temperature fluctuations, for instance induced by the inflow of deep-lying hot
700
701 300 fluids or by fluids mixing of in the uppermost part of the hydrothermal system, can induce significant
702
703
704 301 changes in resistivity. Considering such connections, a comparison between the changes of electrical
705
706 302 resistivity in the anomalous zones and some superficial observations was attempted. The parameters
707
708 303 considered here are the temperature, CO₂ fluxes and rainfall rates. The CO₂ fluxes and the
709
710 304 temperatures of the emitted gasses were recorded in the Pisciarelli main vent during 2007-2016
711
712 305 (INGV, 2018) in correspondence with the FLXOV3 measuring station. These quantities are reported
713
714 306 in Figure 6a and 6b, respectively, where are limited to the years 2014-2015. Also the long-term
715
716 307 temperature trend is reported in Figure 6a, which was deduced by applying the Seasonal Trend

721
722
723 308 Decomposition (STL) algorithm on the infrared imaging recorded in proximity of the upper part of
724
725 309 the west side of the vent (Vilaro et al., 2015; INGV, 2018). The two temperature estimates, which
726
727 refer to emitted gasses and surface thermal features of the area affected by diffuse degassing,
728 310 respectively, are biased. However, they show a very close relationship in pattern of variability. The
729
730 311 monthly rainfall rates, relative to the meteorological station of Pozzuoli (furnished by the ‘Protezione
731
732 312 Civile Regione Campania’) are reported in Figure 6c. All data are reported as recorded in the
733
734 313 corresponding measuring stations, but a brute comparison between these quantities can be misleading,
735
736 314 due to the very different nature and variability of such records. Therefore, the way to compare
737
738 315 information so different as the ERT tomograms and the surface observations (geochemical data,
739
740 316 temperature and rainfall rates) has to be carefully investigated and a normalization criterion has to be
741
742 317 adopted to result in a valid comparison. In order to place all these signals on a comparable scale, the
743
744 318 so-called z-score (Klemelä, 2009) was calculated for each record separately. The z-scores were
745
746 319 obtained by removing the mean value from each time series and dividing by the relative standard
747
748 320 deviation. In such way, samples having zero means and unit variances are obtained. The z-scores for
749
750 321 all the variables mentioned above (and shown in Figure 5 and 6) are reported in Figure 7.
751
752 322

753 323 **Discussion.**

754
755 324 The resistivity trends of the different anomalies over time, in terms of z-scores, are shown in Figure
756
757 325 8a. Thus emerges a peculiar behaviour of anomaly B, that shows a resistivity oscillating more in time
758
759 326 with respect to the other anomalies, all presenting a comparable increasing attitude. In Figure 8b, the
760
761 327 resistivity of anomaly B is compared with the rainfall rate and temperature. The B resistivity appears
762
763 328 to be correlated with the temperature and anti-correlated with the rainfall. This suggests that the
764
765 329 character of the B anomaly may be influenced by seasonal effects, probably driven by the influx of
766
767 330 cold rainwater into the system. The warmer and drier months see an increase in resistivity and vice
768
769 331 versa. Figure 8c shows, for anomaly C, how the linear increasing trend of resistivity instead appears
770
771 332 to be less correlated to temperature and rainfall rates.
772
773 333
774
775
776
777
778
779
780

781
782
783 334 Considering on turn the geochemical data, the main vent showed an increasing amount of CO₂
784
785 335 emission, varying by about one order of magnitude from 2007-2016 (INGV, 2018). Superimposed
786
787
788 336 on this accumulation tendency, a clear annual cyclic oscillation was distinguishable, that has been
789
790 337 stronger in more recent years. Chiodini et al. (2011), reporting on the CO content of the Pisciarelli
791
792 338 fumarole, until 2011, concluded that at Pisciarelli, strong seasonal effects and the possibility of re-
793
794 339 equilibration of the fumarolic fluids at very shallow depths concealed the deep geothermo-barometric
795
796 340 signals. In addition, the comparison of the z-scores of CO₂ emission, IR temperature and rainfalls,
797
798 341 reported in Figure 8d shows a strong correlation between CO₂ emission and rainfalls. The comparison
799
800 342 between CO₂ emission and resistivities, reported in Figure 8e, suggests a link between the
801
802 343 parameters. Such correlation could be likely due to a buffering and/or cumulation of the gas flowing
803
804 344 from the geothermal system to the atmosphere in those zones. At least in principle, the contribution
805
806
807 345 of chemical effects to observed changes in resistivity, such as fracture sealing or rock alteration,
808
809 346 cannot be excluded. However, we note that these effects should not show any periodicity. Moreover,
810
811 347 concerning the sealing, the dynamics of Pisciarelli allows a reasonable opening rather than closing of
812
813 348 fractures. On other hands, the dominants among the new chemical species, e.g. sulfur and alunite as
814
815 349 indicated in Piochi et al. (2015b), should induce a decrease in the bulk rocks resistivity. In contrast,
816
817 350 the non-cyclical anomalies retrieved through the time-lapse ERT imaging present an increasing
818
819 351 attitude. The comparison with the surface data helps to strengthen the hypotheses on the phenomena
820
821 352 that determine the observed variations in the electrical structures.

823
824 353 Recognizing the relevance and meaning of the anomalies and their evolution over time in electrical
825
826 354 images is not, however, trivial, especially considering the interplay between rainwater and
827
828 355 hydrothermal fluids, which can generate elaborate patterns. In the case of Pisciarelli, this interaction
829
830 356 has a feedback in the tomographic sections. The first element is the direct link between anomaly B
831
832 357 and the surface. The second element is the diffusion over time of a low resistivity zone along the top
833
834 358 of anomaly C, which interacts with a vertical conductive plume apparently rising up in the boundary
835
836 359 zone between the C and D anomalies. The B anomaly corresponds to the thermal pool and it shows a
837
838
839
840

841
842
843 360 seasonal character, while the boundary between the C and D anomalies corresponds to a fault zone
844
845 361 with surface manifestations and the maximum of fracture detected in the field (Isaia et al., 2015). In
846
847 our interpretation, rainwaters stored into the thermal pool penetrate into the subsoil through the
848 362
849 narrow channel, permeating the available space, the results of which are laterally confined by the C
850 363
851 anomaly, in turn acting as a permeability barrier. Moreover, part of the same waters dislocate also
852 364
853 along the top of the C anomaly, which again acts as a permeability barrier, ending to interact with
854 365
855 other fluids, of deeper origin, rising along the pre-existing fractures. This interpretative framework is
856 366
857 summarized in Figure 9, where a sketch map is superimposed over the tomographies.
858 367
859

860 368 **Conclusion**

861
862 369 In this paper the results of a time lapse ERT monitoring in the volcanically active Pisciarelli site are
863
864 shown. Being that pre-eruptive changes are frequently extremely rapid, and the Pisciarelli area is
865 370
866 extremely urbanized, this site represents one of the strong sources of volcanic risk in the whole CFC
867 371
868 and looking for pre-eruptive indicators could be relevant to prevent potentially highly destructive
869 372
870 consequences. This is particularly true due to the non-totally conclusive findings of the routine
871 373
872 monitoring performed in the area.
873 374
874

875 375 Even though the imaging we have performed brings only a small amount of large-scale information
876
877 376 about the feeding system, due to the limited resolution at depths, the ERT imaging highlighted several
878
879 anomalous zones. The interpretation of such patterns is quite difficult, being related to complex
880 377
881 phenomena such as the interaction between the fluid components of different origins present in the
882 378
883 vent. However, the comparison with other monitoring data (temperature, geochemical data and
884 379
885 rainfall rates) permitted us to discern the areas dominated by seasonal effects from the ones more
886 380
887 influenced by other, most significant contributions, linked to gas injected into the system from deep
888 381
889 locations which cumulates in the subsoil. Moreover, such comparison can be a guideline toward a
890 382
891 more confident interpretation of the patterns shown by fluids during such times, helping to understand
892 383
893 what features are more related to the apport of meteoric waters into the subsoil and what could be
894 384
895 more correlated to the inflow of fluids of deeper origins. The boundary surfaces along which the
896 385
897
898
899
900

901
902
903 386 fluids displace and the fractures where fluids rise are also revealed. The reconstruction of such
904
905 387 features, obtained through the imaging of the underground electrical resistivity changes reveal the
906
907 388 complex interactions between the environment and the deeper volcanic sources. In this sense, the
908
909
910 389 presented results point out some general aspects. The indirect information obtained through
911
912 390 geophysical imaging proves an vehicle to underline the underground phenomena, explaining the
913
914 391 dynamics of large volumes of subsoil without any arbitrary extrapolations, typical of techniques based
915
916 392 on surface observations. A further methodological aspect has to be underlined. No geophysical
917
918 393 method is self-consistent, in the sense that just the integration of information about all the physical
919
920 394 characteristics of rocks allows the understanding of the phenomena occurring and the creation of
921
922 395 unique lithological models. In spite of this, however, our results show how the single electrical
923
924 396 technique has a relevant proficiency. The model presented in Fig.9 evidence the self-standing ERT
925
926
927 397 capability to define and detail the phenomena at least in their essential lines. The results presented
928
929 398 here can be considered the first test about the aptitude of time-lapse ERT to understand the evolution
930
931 399 of an active fumarole, thanks to a significant contribution to the characterization of subsoil structures
932
933 400 and the understanding of their evolution during time. In any case, even if the tomograms indicate that
934
935 401 this promising approach of time-lapse ERT monitoring to sheds light on the potentially dangerous
936
937 402 evolution of the investigated system, because the phenomena involved are extremely complex, the
938
939 403 evaluation of such aspects deserves more effort and rigorous modelling. As further development, the
940
941 404 establishment of permanent and longer surveying lines could substantiate the results. In particular, a
942
943
944 405 continuous acquisition of the tomograms could end in longer time series of electrical resistivity
945
946 406 changes, which could be compared to the geochemical ones following combined statistical
947
948 407 approaches, such as wavelet coherence analysis.

949
950 408
951
952 409 **Figure captions.**

953
954
955
956
957
958
959
960

961
962
963
964 410 **Fig.1.** a) Map of the Campi Flegrei caldera (Italy). b) Map of the Solfatara-Pisciarelli complex,
965
966 411 framed with the black box in panel a). The ERT survey area is enclosed in the black box and the
967
968 412 survey profile is evidenced with the red line. The geodetic reference system is UTM-WGS84.
969
970 413
971
972 414 **Fig.2.** Aerial view of the Pisciarelli area, where the time-lapse ERT surveys were realized (red dashed
973
974 415 line). Locations of the main anomalies retrieved by ERT are indicated, with the colored capital letters.
975
976 416 The geodetic reference system is UTM-WGS84.
977
978 417
979
980
981 418 **Fig.3.** ERT resistivity sections relative to the profile sketched in Fig.2. For every section, the relative
982
983 419 date is indicated. A common logarithmic scale is used for all the resistivity sections. The main features
984
985 420 discussed into the text (already shown in figure 2) are also indicated with the coloured dotted lines;
986
987 421
988
989 422 **Fig.4.** Detail of the four main electrical anomalies retrieved through time-lapse ERT. For every
990
991 423 section, the relative date is indicated. A common logarithmic scale is used for all the resistivity
992
993 424 sections. The main features discussed into the text are also labelled with coloured capital letters.
994
995 425
996
997
998 426 **Fig. 5.** Comparison between the electrical resistivity time series (in Ωm) as function of time, which
999
1000 427 were obtained extracting the mean value of the parameter in correspondence of the four areas shown
1001
1002 428 in figure 4.
1003
1004 429
1005
1006 430 **Fig. 6.** a) temperature of the gas emitted at the Pisciarelli main vent (left axes, $^{\circ}\text{C}$) and temperature
1007
1008
1009 431 extracted from infrared thermal images through the application of the STL algorithm (right axis, $^{\circ}\text{C}$)
1010
1011 432 during 2014-2015. (b) CO₂ fluxes emitted at the Pisciarelli main vent (in $\text{gm}^{-2}\text{d}^{-1}$) during 2014-
1012
1013 433 2015. (c) Monthly rainfall rates (in mm month^{-1}) recorded at the Pozzuoli meteorological station of
1014
1015 434 the ‘Protezione Civile Regionale’ agency.
1016
1017
1018
1019
1020

1021
1022
1023
1024
1025
1026
1027
1028
1029
1030
1031
1032
1033
1034
1035
1036
1037
1038
1039
1040
1041
1042
1043
1044
1045
1046
1047
1048
1049
1050
1051
1052
1053
1054
1055
1056
1057
1058
1059
1060
1061
1062
1063
1064
1065
1066
1067
1068
1069
1070
1071
1072
1073
1074
1075
1076
1077
1078
1079
1080

Fig.7. The z-scores extracted by the variables mentioned in Figure 5 (electrical resistivity time series) and Figure 6 (temperature, CO₂ fluxes and rainfall rates). Z-scores were obtained by removing the mean value from each time series and dividing by the relative standard deviation.

Fig. 8. Z-scores extracted by the observed variables, compared as follow: (a) electrical resistivity time series relative to the four anomalous zones shown in Figure 2. (b) electrical resistivity time series relative to the B electrical anomaly, surface IR temperature and rainfall rates. (c) electrical resistivity time series relative to the C electrical anomaly, surface IR temperature and rainfall rates. (d) CO₂ fluxes, surface IR temperature and rainfall rates. (e) electrical resistivity time series relative to the four anomalous zones, CO₂ fluxes.

Fig.9. Conceptual model of the Pisciarelli fumarolic zone. This W-E model crosses the main vent and the thermal permanent pool. The interpretative elements are reported in the legend. Electrical resistivity isolines, relative to the April 2015 tomogram are superimposed, maintaining the same common logarithm scale of Figure 3.

References

Aizawa, K., Ogawa, Y., Ishido, T., 2009. Groundwater flow and hydrothermal systems within volcanic edifices: Delineation by electric self-potential and magnetotellurics. *J. Geophys. Res.* 114, B01208. doi:10.1029/2008JB005910

Amoruso, A., Crescentini, L., Linde, A.T., Sacks, I.S., Scarpa, R., Romano, P., 2007. A horizontal crack in a layered structure satisfies deformation for the 2004–2006 uplift of Campi Flegrei. *Geophys. Res. Lett.*

1081
1082
1083 460 34, L22313. doi:10.1029/2007GL031644
1084
1085
1086 461 Annunziatellis, A., Beaubien, S.E., Bigi, S., Ciotoli, G., Coltella, M., Lombardi, S., 2008. Gas migration
1087
1088 462 along fault systems and through the vadose zone in the Latera caldera (central Italy): Implications for
1089
1090 463 CO₂geological storage. *Int. J. Greenh. Gas Control* 2, 353–372. doi:10.1016/j.ijggc.2008.02.003
1091
1092
1093 464 Bachu, S., Gunter, W.D., Perkins, E.H., 1994. Aquifer disposal of CO₂: Hydrodynamic and mineral
1094
1095 465 trapping. *Energy Convers. Manag.* 35, 269–279. doi:10.1016/0196-8904(94)90060-4
1096
1097
1098 466 Barde-Cabusson, S., Bolós, X., Pedrazzi, D., Lovera, R., Serra, G., Martí, J., Casas, A., 2013. Electrical
1099
1100 467 resistivity tomography revealing the internal structure of monogenetic volcanoes. *Geophys. Res. Lett.*
1101
1102 468 40, 2544–2549. doi:10.1002/grl.50538
1103
1104
1105 469 Berrino, G., Corrado, G., Luongo, G., Toro, B., 1984. Ground deformation and gravity changes
1106
1107 470 accompanying the 1982 Pozzuoli uplift. *Bull. Volcanol.* 47, 187–200. doi:10.1007/BF01961548
1108
1109
1110 471 Bevilacqua, A., Isaia, R., Neri, A., Vitale, S., Aspinall, W.P., Bisson, M., Flandoli, F., Baxter, P.J.,
1111
1112 472 Bertagnini, A., Esposti Ongaro, T., Iannuzzi, E., Pistolesi, M., Rosi, M., 2015. Quantifying volcanic
1113
1114 473 hazard at Campi Flegrei caldera (Italy) with uncertainty assessment: 1. Vent opening maps. *J. Geophys.*
1115
1116 474 *Res. Solid Earth* 120, 2309–2329. doi:10.1002/2014JB011775
1117
1118 475 Bianchi, R., Coradini, A., Federico, C., Giberti, G., Lanciano, P., Pozzi, J.P., Sartoris, G., Scandone, R.,
1119
1120 476 1987. Modeling of surface deformation in volcanic areas: The 1970-1972 and 1982-1984 crises of
1121
1122 477 Campi Flegrei, Italy. *J. Geophys. Res. Solid Earth* 92, 14139–14150. doi:10.1029/JB092iB13p14139
1123
1124
1125 478 Bruno, P.P.G., Ricciardi, G.P., Petrillo, Z., Di Fiore, V., Troiano, A., Chiodini, G., 2007. Geophysical and
1126
1127 479 hydrogeological experiments from a shallow hydrothermal system at Solfatara Volcano, Campi Flegrei,
1128
1129 480 Italy: Response to caldera unrest. *J. Geophys. Res. Solid Earth* 112. doi:10.1029/2006JB004383
1130
1131
1132 481 Byrdina, S., Revil, A., Pant, S.R., Koirala, B.P., Shrestha, P.L., Tiwari, D.R., Gautam, U.P., Shrestha, K.,
1133
1134 482 Sapkota, S.N., Contraires, S., Perrier, F., 2009. Dipolar self-potential anomaly associated with carbon
1135
1136 483 dioxide and radon flux at Syabru-Bensi hot springs in central Nepal. *J. Geophys. Res.* 114, B10101.

1141
1142
1143
1144
1145
1146
1147
1148
1149
1150
1151
1152
1153
1154
1155
1156
1157
1158
1159
1160
1161
1162
1163
1164
1165
1166
1167
1168
1169
1170
1171
1172
1173
1174
1175
1176
1177
1178
1179
1180
1181
1182
1183
1184
1185
1186
1187
1188
1189
1190
1191
1192
1193
1194
1195
1196
1197
1198
1199
1200

484 doi:10.1029/2008JB006154

485 Byrdina, S., Vandemeulebrouck, J., Cardellini, C., Legaz, A., Camerlynck, C., Chiodini, G., Lebourg, T.,
486 Gresse, M., Bascou, P., Motos, G., Carrier, A., Caliro, S., 2014. Relations between electrical resistivity,
487 carbon dioxide flux, and self-potential in the shallow hydrothermal system of Solfatara (Phlegrean
488 Fields, Italy). *J. Volcanol. Geotherm. Res.* 283, 172–182. doi:10.1016/j.jvolgeores.2014.07.010

489 Chiodini, G., Avino, R., Caliro, S., Minopoli, C., 2011. Temperature and pressure gas geoindicators at the
490 Solfatara fumaroles (Campi Flegrei). *Ann. Geophys.*

491 Chiodini, G., Caliro, S., De Martino, P., Avino, R., Gherardi, F., U., T., E., B., G.P., R., P., R., C., R., 2012.
492 Early signals of new volcanic unrest at Campi Flegrei caldera? Insights from geochemical data and
493 physical simulations. *Geology* 40, 943–946. doi:10.1130/G33251.1

494 Chiodini, G., Paonita, A., Aiuppa, A., Costa, A., Caliro, S., De Martino, P., Acocella, V.,
495 Vandemeulebrouck, J., 2016. Magmas near the critical degassing pressure drive volcanic unrest
496 towards a critical state. *Nat. Commun.* 7, 13712.

497 Chiodini, G., Todesco, M., Caliro, S., Del Gaudio, C., Macedonio, G., Russo, M., 2003. Magma degassing as
498 a trigger of bradyseismic events: The case of Phlegrean Fields (Italy). *Geophys. Res. Lett.* 30.
499 doi:10.1029/2002GL016790

500 D’Auria, L., Giudicepietro, F., Aquino, I., Borriello, G., Del Gaudio, C., Lo Bascio, D., Martini, M.,
501 Ricciardi, G.P., Ricciolino, P., Ricco, C., 2011. Repeated fluid-transfer episodes as a mechanism for the
502 recent dynamics of Campi Flegrei caldera (1989–2010). *J. Geophys. Res.* 116, B04313.
503 doi:10.1029/2010JB007837

504 De Natale, G., Pingue, F., Allard, P., Zollo, A., 1991. Geophysical and geochemical modelling of the 1982–
505 1984 unrest phenomena at Campi Flegrei caldera (southern Italy). *J. Volcanol. Geotherm. Res.* 48,
506 199–222. doi:10.1016/0377-0273(91)90043-Y

507 De Natale, G., Troise, C., Pingue, F., Mastrolorenzo, G., Pappalardo, L., Battaglia, M., Boschi, E., 2006. The

- 1201
1202
1203
1204
1205
1206
1207
1208
1209
1210
1211
1212
1213
1214
1215
1216
1217
1218
1219
1220
1221
1222
1223
1224
1225
1226
1227
1228
1229
1230
1231
1232
1233
1234
1235
1236
1237
1238
1239
1240
1241
1242
1243
1244
1245
1246
1247
1248
1249
1250
1251
1252
1253
1254
1255
1256
1257
1258
1259
1260
- 508 Campi Flegrei caldera: unrest mechanisms and hazards. *Geol. Soc. London, Spec. Publ.* 269.
- 509 Di Giuseppe, M.G., Troiano, A., Fedele, A., Caputo, T., Patella, D., Troise, C., De Natale, G., 2015.
510 Electrical resistivity tomography imaging of the near-surface structure of the Solfatara crater, Campi
511 Flegrei (Naples, Italy). *Bull. Volcanol.* 77. doi:10.1007/s00445-015-0910-6
- 512 Di Maio, R., Mauriello, P., Patella, D., Petrillo, Z., Piscitelli, S., Siniscalchi, A., 1998. Electric and
513 electromagnetic outline of the Mount Somma–Vesuvius structural setting. *J. Volcanol. Geotherm. Res.*
514 82, 219–238. doi:10.1016/S0377-0273(97)00066-8
- 515 Di Vito, M., Lirer, L., Mastrolorenzo, G., Rolandi, G., 1987. The 1538 Monte Nuovo eruption (Campi
516 Flegrei, Italy). *Bull. Volcanol.* 49, 608–615. doi:10.1007/BF01079966
- 517 Dvorak, J.J., Mastrolorenzo, G., 1991. The mechanisms of recent vertical crustal movements in Campi
518 Flegrei caldera, southern Italy. pp. 1–47. doi:10.1130/SPE263-p1
- 519 Fikos, I., Vargemezis, G., Zlotnicki, J., Puertollano, J.R., Alanis, P.B., Pigtain, R.C., Villacorte, E.U.,
520 Malipot, G.A., Sasai, Y., 2012. Electrical resistivity tomography study of Taal volcano hydrothermal
521 system, Philippines. *Bull. Volcanol.* 74, 1821–1831. doi:10.1007/s00445-012-0638-5
- 522 Finizola, A., Aubert, M., Revil, A., Schütze, C., Sortino, F., 2009. Importance of structural history in the
523 summit area of Stromboli during the 2002–2003 eruptive crisis inferred from temperature, soil CO₂,
524 self-potential, and electrical resistivity tomography. *J. Volcanol. Geotherm. Res.* 183, 213–227.
525 doi:10.1016/j.jvolgeores.2009.04.002
- 526 Finizola, A., Revil, A., Rizzo, E., Piscitelli, S., Ricci, T., Morin, J., Angeletti, B., Mocochain, L., Sortino, F.,
527 2006. Hydrogeological insights at Stromboli volcano (Italy) from geoelectrical, temperature, and CO₂
528 soil degassing investigations. *Geophys. Res. Lett.* 33, L17304. doi:10.1029/2006GL026842
- 529 Finizola, A., Ricci, T., Deiana, R., Cabusson, S.B., Rossi, M., Praticelli, N., Giocoli, A., Romano, G.,
530 Delcher, E., Suski, B., Revil, A., Menny, P., Di Gangi, F., Letort, J., Peltier, A., Villasante-Marcos, V.,
531 Douillet, G., Avard, G., Lelli, M., 2010. Adventive hydrothermal circulation on Stromboli volcano

1261
1262
1263
1264 532 (Aeolian Islands, Italy) revealed by geophysical and geochemical approaches: Implications for general
1265 fluid flow models on volcanoes. *J. Volcanol. Geotherm. Res.* 196, 111–119.
1266
1267 534 doi:10.1016/j.jvolgeores.2010.07.022
1268
1269
1270 535 Giese, R., Hennings, J., Lüth, S., Morozova, D., Schmidt-Hattenberger, C., Würdemann, H., Zimmer, M.,
1271
1272 536 Cosma, C., Juhlin, C., 2009. Monitoring at the CO₂ SINK site: A concept integrating geophysics,
1273
1274 537 geochemistry and microbiology. *Energy Procedia* 1, 2251–2259. doi:10.1016/j.egypro.2009.01.293
1275
1276
1277 538 Di, Giuseppe, M.G. Di, Troiano, A., Vito, M.A. Di, Somma, R., Matano, F., 2017. Definition of small-scale
1278
1279 539 volcanic structures by Electrical Resistivity Tomography: the Trentaremi cone, an example from the
1280
1281 540 Campi Flegrei Caldera (Italy). *Ann. Geophys.* 60, S0552. doi:10.4401/ag-7397
1282
1283
1284 541 Gottsmann, J., Folch, A., Rymer, H., 2006. Unrest at Campi Flegrei: A contribution to the magmatic versus
1285
1286 542 hydrothermal debate from inverse and finite element modeling. *J. Geophys. Res.* 111, B07203.
1287
1288 543 doi:10.1029/2005JB003745
1289
1290
1291 544 Gresse, M., Vandemeulebrouck, J., Byrdina, S., Chiodini, G., Revil, A., Johnson, T.C., Ricci, T., Vilardo, G.,
1292
1293 545 Mangiacapra, A., Lebourg, T., Grangeon, J., Bascou, P., Metral, L., 2017. Three-Dimensional
1294
1295 546 Electrical Resistivity Tomography of the Solfatara Crater (Italy): Implication for the Multiphase Flow
1296
1297 547 Structure of the Shallow Hydrothermal System. *J. Geophys. Res. Solid Earth* 122, 8749–8768.
1298
1299 548 doi:10.1002/2017JB014389
1300
1301
1302 549 INGV, 2018. Bollettini di sorveglianza dei vulcani campani.
1303
1304
1305 550 Isaia, R., Vitale, S., Di Giuseppe, M.G., Iannuzzi, E., Tramparulo, F.D., Troiano, A., 2015. Stratigraphy,
1306
1307 551 structure, and volcano-tectonic evolution of Solfatara maar-diatreme (Campi Flegrei, Italy). *Bull. Geol.*
1308
1309 552 *Soc. Am.* 127, 1485–1504. doi:10.1130/B31183.1
1310
1311 553 Karaoulis M., A. Revil, D.D. Werkema, B. Minsley, W.F. Woodruff, and A. Kemna, Time-lapse 3D
1312
1313 554 inversion of complex conductivity data using an active time constrained (ATC) approach, *Geophysical*
1314
1315 555 *Journal International*, 187, 237–251, doi: 10.1111/j.1365-246X.2011.05156.x, 2011
1316
1317
1318
1319
1320

1321
1322
1323 556 Kiessling, D., Schmidt-Hattenberger, C., Schuett, H., Schilling, F., Krueger, K., Schoebel, B., Danckwardt,
1324
1325 557 E., Kummerow, J., 2010. Geoelectrical methods for monitoring geological CO2 storage: First results
1326
1327 558 from cross-hole and surface–downhole measurements from the CO2SINK test site at Ketzin
1328
1329 559 (Germany). *Int. J. Greenh. Gas Control* 4, 816–826. doi:10.1016/j.ijggc.2010.05.001
1330
1331
1332 560 Kim, J. H., Yi, M. J., Park, S. G., & Kim, J. G. (2009). 4-D inversion of DC resistivity monitoring data
1333
1334 561 acquired over a dynamically changing earth model. *Journal of Applied Geophysics*, 68(4), 522-532.
1335
1336
1337 562 Klemelä, J., 2009. Smoothing of multivariate data : density estimation and visualization. John Wiley & Sons.
1338
1339
1340 563 LaBrecque, D.J., Morelli, G., Daily, W., Ramirez, A., Lundegard, P., 1999. 37. Occam’s Inversion of 3-D
1341
1342 564 Electrical Resistivity Tomography, in: *Three-Dimensional Electromagnetics*. Society of Exploration
1343
1344 565 Geophysicists, pp. 575–590. doi:10.1190/1.9781560802154.ch37
1345
1346
1347 566 LaBrecque, D.J., Yang, X., 2001. Difference Inversion of ERT Data: a Fast Inversion Method for 3-D In Situ
1348
1349 567 Monitoring. *J. Environ. Eng. Geophys.* 6, 83–89. doi:10.4133/JEEG6.2.83
1350
1351 568 Le Roux, O., Cohen, G., Loisy, C., Laveuf, C., Delaplace, P., Magnier, C., Rouchon, V., Cerepi, A., Garcia,
1352
1353 569 B., 2013. The CO2-Vadose project: Time-lapse geoelectrical monitoring during CO2 diffusion in the
1354
1355 570 carbonate vadose zone. *Int. J. Greenh. Gas Control* 16, 156–166. doi:10.1016/J.IJGGC.2013.03.016
1356
1357
1358 571 Letort, J., Roux, P., Vandemeulebrouck, J., Coutant, O., Cros, E., Wathelet, M., Cardellini, C., Avino, R.,
1359
1360 572 2012. High-resolution shallow seismic tomography of a hydrothermal area: application to the Solfatara,
1361
1362 573 Pozzuoli. *Geophys. J. Int.* 189, 1725–1733. doi:10.1111/j.1365-246X.2012.05451.x
1363
1364
1365 574 Lima, A., De Vivo, B., Spera, F.J., Bodnar, R.J., Milia, A., Nunziata, C., Belkin, H.E., Cannatelli, C., 2009.
1366
1367 575 Thermodynamic model for uplift and deflation episodes (bradyseism) associated with magmatic–
1368
1369 576 hydrothermal activity at the Campi Flegrei (Italy). *Earth-Science Rev.* 97, 44–58.
1370
1371 577 doi:10.1016/j.earscirev.2009.10.001
1372
1373
1374 578 Moretti, R., De Natale, G., Troise, C., 2017. A geochemical and geophysical reappraisal to the significance
1375
1376 579 of the recent unrest at Campi Flegrei caldera (Southern Italy). *Geochemistry, Geophys. Geosystems* 18,
1377
1378
1379
1380

1381
1382
1383 580 1244–1269. doi:10.1002/2016GC006569
1384
1385
1386 581 Nickschick, T., Flechsig, C., Meinel, C., Mrlina, J., Kämpf, H., 2017. Architecture and temporal variations
1387
1388 582 of a terrestrial CO₂ degassing site using electric resistivity tomography and self-potential. *Int. J. Earth*
1389
1390 583 *Sci.* 1–12. doi:10.1007/s00531-017-1470-0
1391
1392
1393 584 Oldenborger, G.A., Knoll, M.D., Routh, P.S., LaBrecque, D.J., 2007. Time-lapse ERT monitoring of an
1394
1395 585 injection/withdrawal experiment in a shallow unconfined aquifer. *GEOPHYSICS* 72, F177–F187.
1396
1397 586 doi:10.1190/1.2734365
1398
1399
1400 587 Orsi, G., Di Vito, M.A., Isaia, R., 2004. Volcanic hazard assessment at the restless Campi Flegrei caldera.
1401
1402 588 *Bull. Volcanol.* 66, 514–530. doi:10.1007/s00445-003-0336-4
1403
1404
1405 589 Petrosino, S., Damiano, N., Cusano, P., Di Vito, M.A., de Vita, S., Del Pezzo, E., 2012. Subsurface structure
1406
1407 590 of the Solfataro volcano (Campi Flegrei caldera, Italy) as deduced from joint seismic-noise array,
1408
1409 591 volcanological and morphostructural analysis. *Geochemistry, Geophys. Geosystems* 13, n/a-n/a.
1410
1411 592 doi:10.1029/2011GC004030
1412
1413
1414 593 Piochi, M., Mormone, A., Balassone, G., Strauss, H., Troise, C., De Natale, G., 2015a. Native sulfur, sulfates
1415
1416 594 and sulfides from the active Campi Flegrei volcano (southern Italy): Genetic environments and
1417
1418 595 degassing dynamics revealed by mineralogy and isotope geochemistry. *J. Volcanol. Geotherm. Res.*
1419
1420 596 304, 180–193. doi:10.1016/j.jvolgeores.2015.08.017
1421
1422
1423 597 Piochi, M., Mormone, A., Balassone, G., Strauss, H., Troise, C., De Natale, G., 2015b. Native sulfur, sulfates
1424
1425 598 and sulfides from the active Campi Flegrei volcano (southern Italy): Genetic environments and
1426
1427 599 degassing dynamics revealed by mineralogy and isotope geochemistry. *J. Volcanol. Geotherm. Res.*
1428
1429 600 304, 180–193. doi:10.1016/j.jvolgeores.2015.08.017
1430
1431
1432 601 Pribnow, D.F., Schütze, C., Hurter, S.J., Flechsig, C., Sass, J.H., 2003. Fluid flow in the resurgent dome of
1433
1434 602 Long Valley Caldera: implications from thermal data and deep electrical sounding. *J. Volcanol.*
1435
1436 603 *Geotherm. Res.* 127, 329–345. doi:10.1016/S0377-0273(03)00175-6
1437
1438
1439
1440

1441
1442
1443
1444 604 Revil, A., Cathles III, L.M., Losh, S., Nunn, J.A., 1998. Electrical conductivity in shaly sands with
1445
1446 605 geophysical application. *J. Geophys. Res.*, 103 (B10) (1998), pp. 23925-23936
1447
1448 606 Revil, A., Finizola, A., Piscitelli, S., Rizzo, E., Ricci, T., Crespy, A., Angeletti, B., Balasco, M., Barde
1449
1450 607 Cabusson, S., Bennati, L., Bolève, A., Byrdina, S., Carzaniga, N., Di Gangi, F., Morin, J., Perrone, A.,
1451
1452 608 Rossi, M., Roulleau, E., Suski, B., 2008. Inner structure of La Fossa di Vulcano (Vulcano Island,
1453
1454 609 southern Tyrrhenian Sea, Italy) revealed by high-resolution electric resistivity tomography coupled
1455
1456 610 with self-potential, temperature, and CO₂ diffuse degassing measurements. *J. Geophys. Res.* 113,
1457
1458 611 B07207. doi:10.1029/2007JB005394
1459
1460
1461 612 Revil, A., Finizola, A., Ricci, T., Delcher, E., Peltier, A., Barde-Cabusson, S., Avard, G., Bailly, T., Bennati,
1462
1463 613 L., Byrdina, S., Colonge, J., Di Gangi, F., Douillet, G., Lupi, M., Letort, J., Tsang Hin Sun, E., 2011.
1464
1465 614 Hydrogeology of Stromboli volcano, Aeolian Islands (Italy) from the interpretation of resistivity
1466
1467 615 tomograms, self-potential, soil temperature and soil CO₂ concentration measurements. *Geophys. J. Int.*
1468
1469 616 186, 1078–1094. doi:10.1111/j.1365-246X.2011.05112.x
1470
1471
1472 617 Roberts, J.J., 2002. Electrical properties of microporous rock as a function of saturation and temperature. *J.*
1473
1474 618 *Appl. Phys.*, 91 (3).
1475
1476 619 Schmidt-Hattenberger, C., Bergmann, P., Kießling, D., Krüger, K., Rücker, C., Schütt, H., Group, K., 2011.
1477
1478 620 Application of a Vertical Electrical Resistivity Array (VERA) for monitoring CO₂ migration at the
1479
1480 621 Ketzin site: First performance evaluation. *Energy Procedia* 4, 3363–3370.
1481
1482 622 doi:10.1016/j.egypro.2011.02.258
1483
1484
1485 623 Shirzaei, M., Walter, T.R., 2010. Time-dependent volcano source monitoring using interferometric synthetic
1486
1487 624 aperture radar time series: A combined genetic algorithm and Kalman filter approach. *J. Geophys. Res.*
1488
1489 625 115, B10421. doi:10.1029/2010JB007476
1490
1491
1492 626 Singha, K., Day-Lewis, F.D., Johnson, T., Slater, L.D., 2015. Advances in interpretation of subsurface
1493
1494 627 processes with time-lapse electrical imaging. *Hydrol. Process.* 29, 1549–1576. doi:10.1002/hyp.10280
1495
1496 628 Slater, L., 2007. Near Surface Electrical Characterization of Hydraulic Conductivity: From Petrophysical
1497
1498
1499
1500

1501
1502
1503
1504 629 Properties to Aquifer Geometries—A Review. *Surv. Geophys.* 28, 169–197. doi:10.1007/s10712-007-
1505 9022-y
1506 630
1507
1508 631 Todesco, M., Chiodini, G., Macedonio, G., 2003. Monitoring and modelling hydrothermal fluid emission at
1509
1510 632 La Solfatara (Phlegrean Fields, Italy). An interdisciplinary approach to the study of diffuse degassing.
1511
1512 633 *J. Volcanol. Geotherm. Res.* 125, 57–79. doi:10.1016/S0377-0273(03)00089-1
1513
1514
1515 634 Troiano, A., Di Giuseppe, M., Petrillo, Z., Troise, C., De Natale, G., 2011. Ground deformation at calderas
1516
1517 635 driven by fluid injection: Modelling unrest episodes at Campi Flegrei (Italy). *Geophys. J. Int.* 187, 833–
1518
1519 636 847. doi:10.1111/j.1365-246X.2011.05149.x
1520
1521
1522 637 Troiano, A., Di Giuseppe, M.G., Patella, D., Troise, C., De Natale, G., 2014. Electromagnetic outline of the
1523
1524 638 Solfatara-Pisciarelli hydrothermal system, Campi Flegrei (Southern Italy). *J. Volcanol. Geotherm. Res.*
1525
1526 639 277, 9–21. doi:10.1016/j.jvolgeores.2014.03.005
1527
1528
1529 640 Troiano, A., Di Giuseppe, M.G., Petrillo, Z., Patella, D., 2009. Imaging 2D structures by the CSAMT
1530
1531 641 method: Application to the Pantano di S. Gregorio Magno faulted basin (Southern Italy). *J. Geophys.*
1532
1533 642 *Eng.* 6, 120–130. doi:10.1088/1742-2132/6/2/003
1534
1535
1536 643 Troiano, A., Petrillo, Z., Di Giuseppe, M.G., Balasco, M., Diaferia, I., Di Fiore, B., Siniscalchi, A., Patella,
1537
1538 644 D., 2008. About the shallow resistivity structure of Vesuvius volcano, in: *Annals of Geophysics*.
1539
1540 645 doi:10.4401/ag-3043
1541
1542
1543 646 Vaughan, P.J., Udell, K.S., Wilt, M.J., 1993. The effects of steam injection on the electrical conductivity of
1544
1545 647 an unconsolidated sand saturated with a salt solution. *J. Geophys. Res.*, 98 (B1) (1993), pp. 509-518
1546
1547
1548 648 Vilardo, G., Sansivero, F., Chiodini, G., 2015. Long-term TIR imagery processing for spatiotemporal
1549
1550 649 monitoring of surface thermal features in volcanic environment: A case study in the Campi Flegrei
1551
1552 650 (Southern Italy). *J. Geophys. Res. Solid Earth* 120, 812–826. doi:10.1002/2014JB011497
1553
1554 651 Wallin, E.L., Johnson, T.C., Greenwood, W.J., Zachara, J.M., 2013. Imaging high stage river-water intrusion
1555
1556 652 into a contaminated aquifer along a major river corridor using 2-D time-lapse surface electrical
1557
1558
1559
1560

1561
1562
1563
1564
1565
1566
1567
1568
1569
1570
1571
1572
1573
1574
1575
1576
1577
1578
1579
1580
1581
1582
1583
1584
1585
1586
1587
1588
1589
1590
1591
1592
1593
1594
1595
1596
1597
1598
1599
1600
1601
1602
1603
1604
1605
1606
1607
1608
1609
1610
1611
1612
1613
1614
1615
1616
1617
1618
1619
1620

653 resistivity tomography. *Water Resour. Res.* 49, 1693–1708. doi:10.1002/wrcr.20119

654 Ward, S.H., 1988. The Resistivity and Induced Polarization Methods, in: *Symposium on the Application of*
655 *Geophysics to Engineering and Environmental Problems 1988. Environment and Engineering*
656 *Geophysical Society*, pp. 109–250. doi:10.4133/1.2921804

657 Würdemann, H., Möller, F., Kühn, M., Heidug, W., Christensen, N.P., Borm, G., Schilling, F.R., 2010.
658 CO2SINK—From site characterisation and risk assessment to monitoring and verification: One year of
659 operational experience with the field laboratory for CO2 storage at Ketzin, Germany. *Int. J. Greenh.*
660 *Gas Control* 4, 938–951. doi:10.1016/j.ijggc.2010.08.010

661 Zhou, X., Lakkaraju, V.R., Apple, M., Dobeck, L.M., Gullickson, K., Shaw, J.A., Cunningham, A.B.,
662 Wielopolski, L., Spangler, L.H., 2012. Experimental observation of signature changes in bulk soil
663 electrical conductivity in response to engineered surface CO2 leakage. *Int. J. Greenh. Gas Control* 7,
664 20–29. doi:10.1016/j.ijggc.2011.12.006

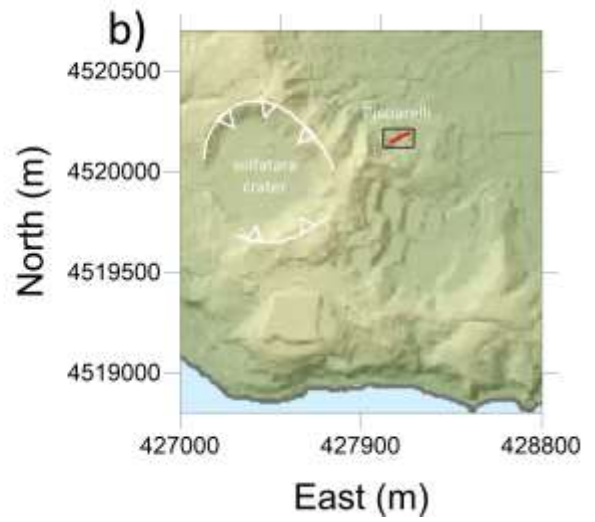
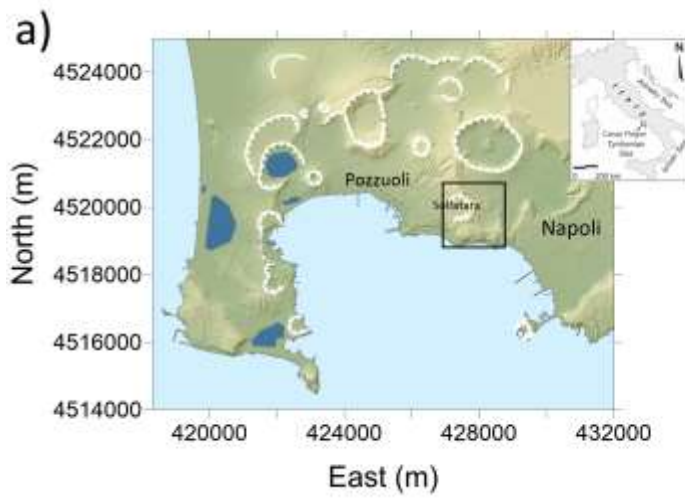


Figure 1.

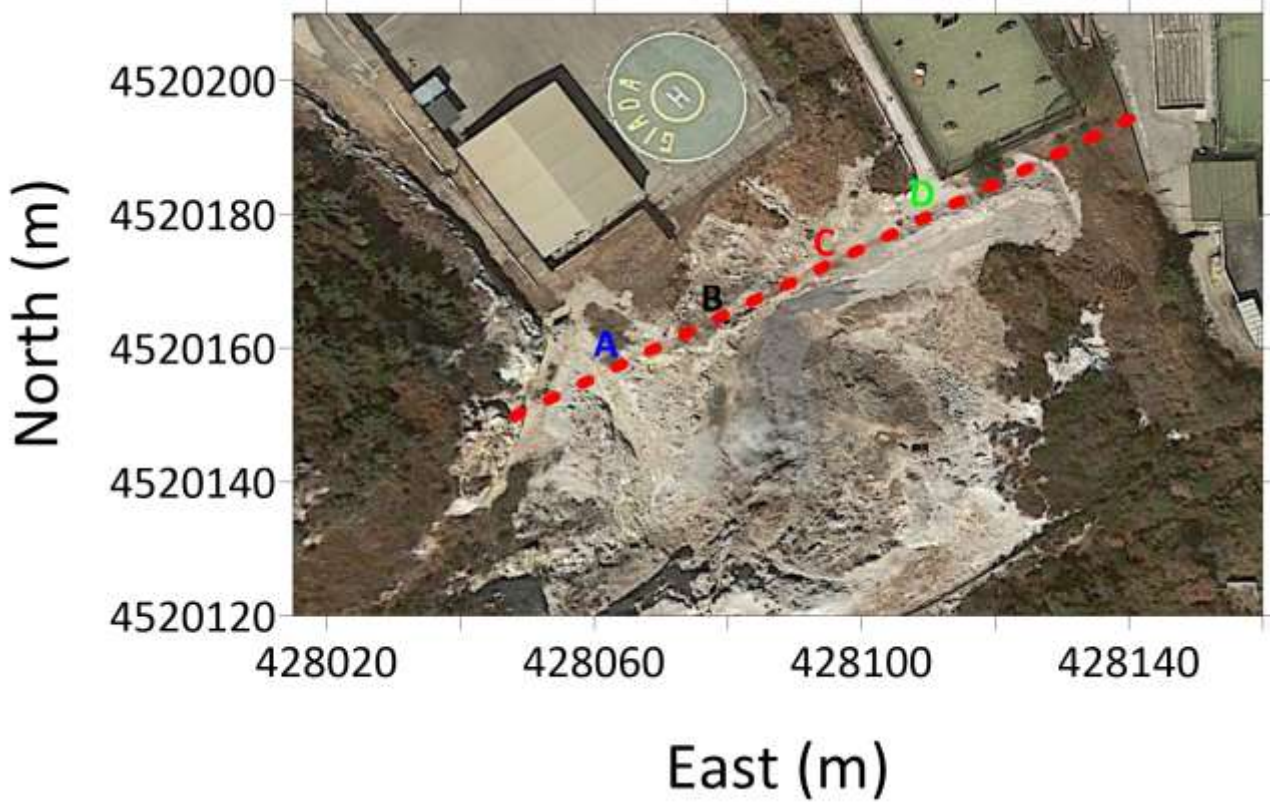
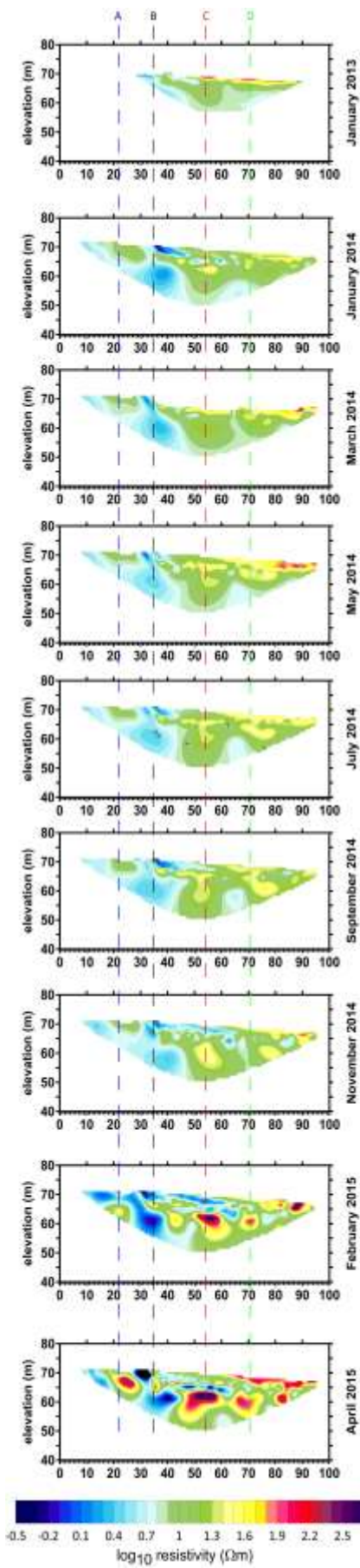


Figure 2.

1741
1742
1743
1744
1745
1746
1747
1748
1749
1750
1751
1752
1753
1754
1755
1756
1757
1758
1759
1760
1761
1762
1763
1764
1765
1766
1767
1768
1769
1770
1771
1772
1773
1774
1775
1776
1777
1778
1779
1780
1781
1782
1783
1784
1785
1786
1787
1788
1789
1790
1791
1792
1793
1794
1795
1796
1797
1798
1799
1800



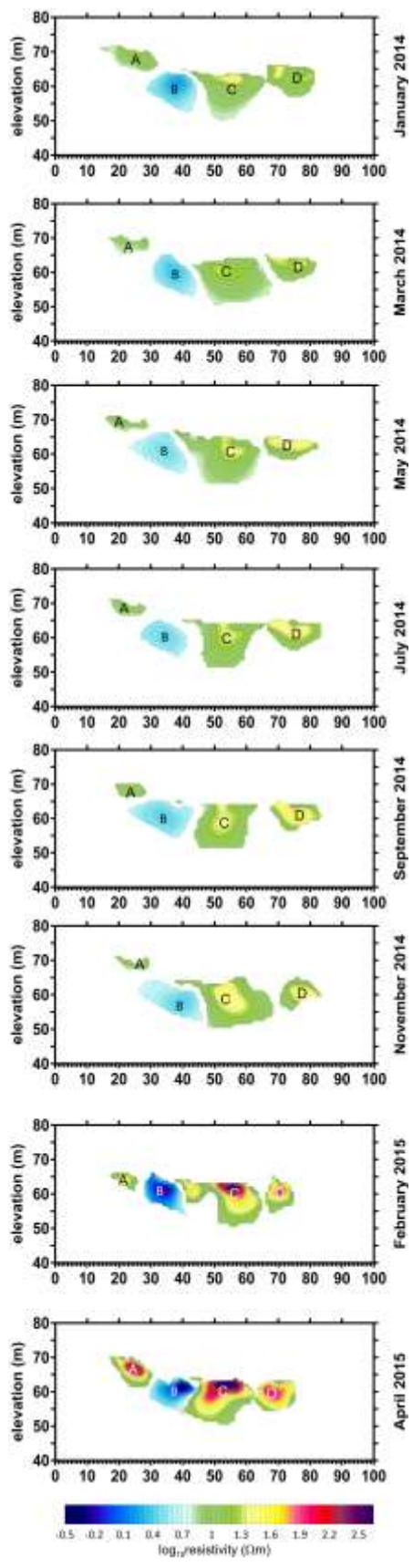
675

676

Figure 3

1801
1802
1803
1804
1805
1806
1807
1808
1809
1810
1811
1812
1813
1814
1815
1816
1817
1818
1819
1820
1821
1822
1823
1824
1825
1826
1827
1828
1829
1830
1831
1832
1833
1834
1835
1836
1837
1838
1839
1840
1841
1842
1843
1844
1845
1846
1847
1848
1849
1850
1851
1852
1853
1854
1855
1856
1857
1858
1859
1860

1861
1862
1863
1864
1865
1866
1867
1868
1869
1870
1871
1872
1873
1874
1875
1876
1877
1878
1879
1880
1881
1882
1883
1884
1885
1886
1887
1888
1889
1890
1891
1892
1893
1894
1895
1896
1897
1898
1899
1900
1901
1902
1903
1904
1905
1906
1907
1908
1909
1910
1911
1912
1913
1914
1915
1916
1917
1918
1919
1920



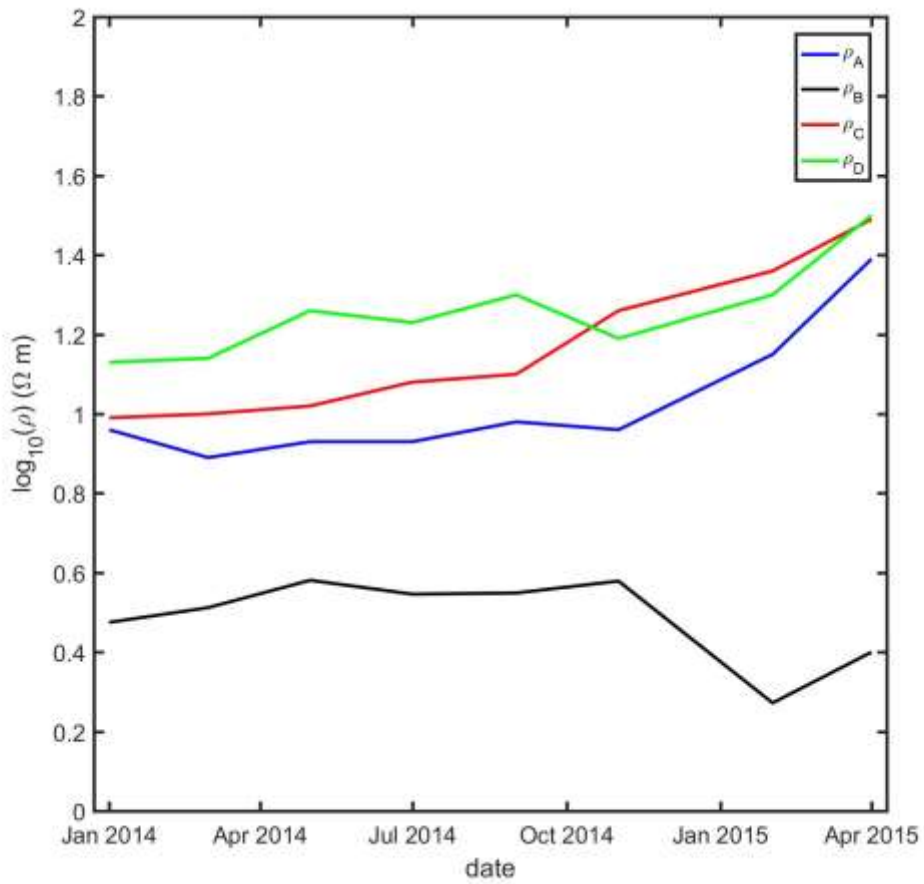
678

679

Figure 4.

680

1921
1922
1923
1924
1925
1926
1927
1928
1929
1930
1931
1932
1933
1934
1935
1936
1937
1938
1939
1940
1941
1942
1943
1944
1945
1946
1947
1948
1949
1950
1951
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980



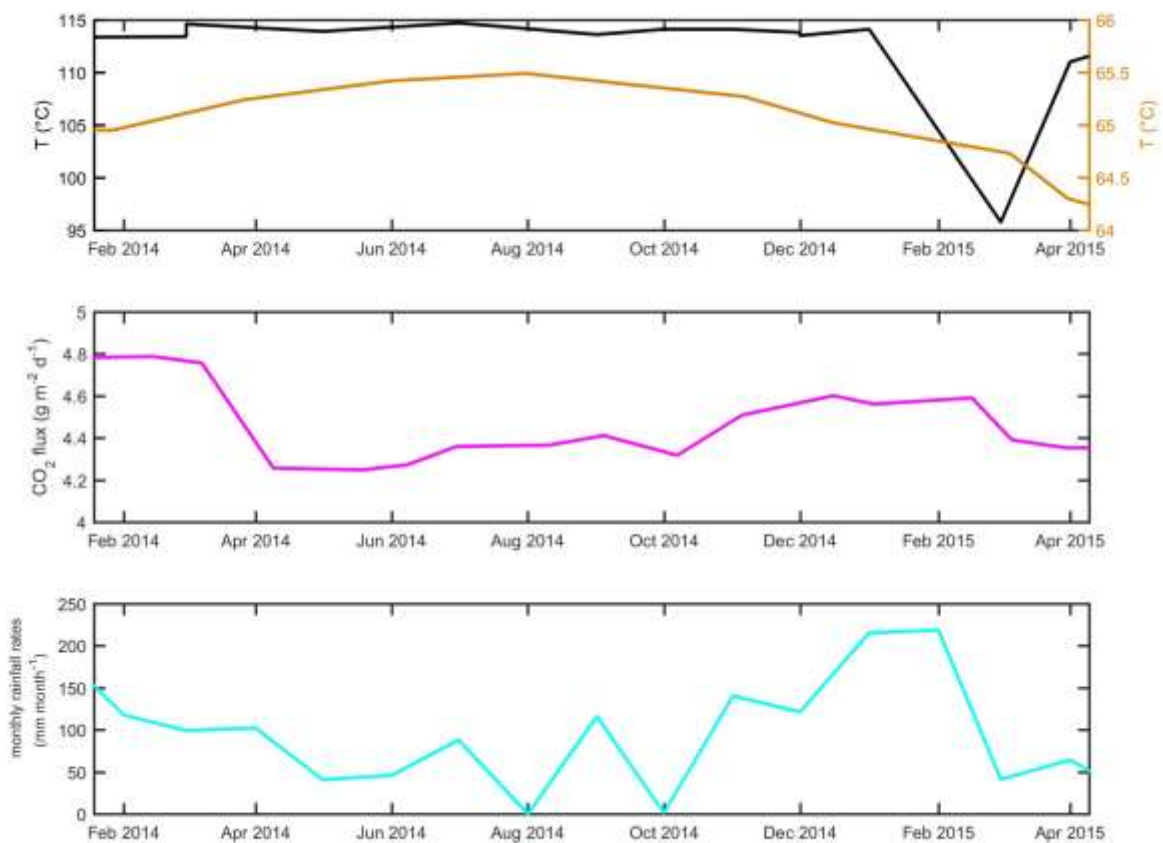
681

682

Figure 5.

683

1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040



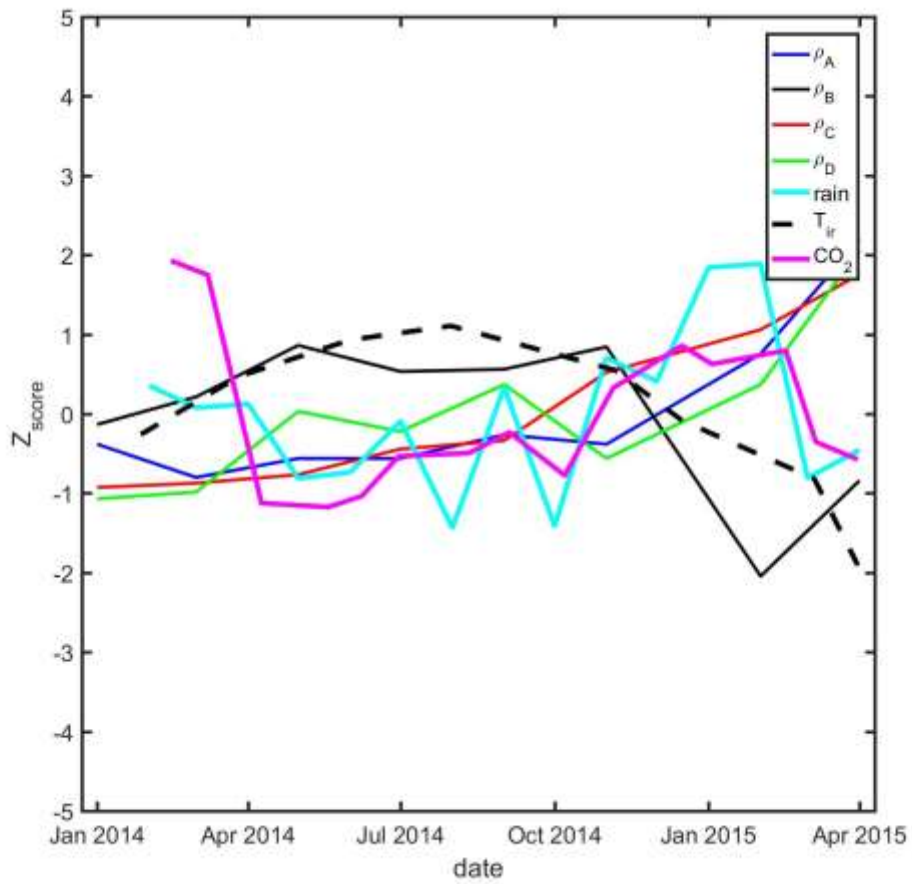
684

685

Figure 6.

686

687



688

689

Figure 7.

690

691

692

693

694

695

696

697

698

699

700

701

702

703

704

705

706

707

708

709

710

711

712

713

714

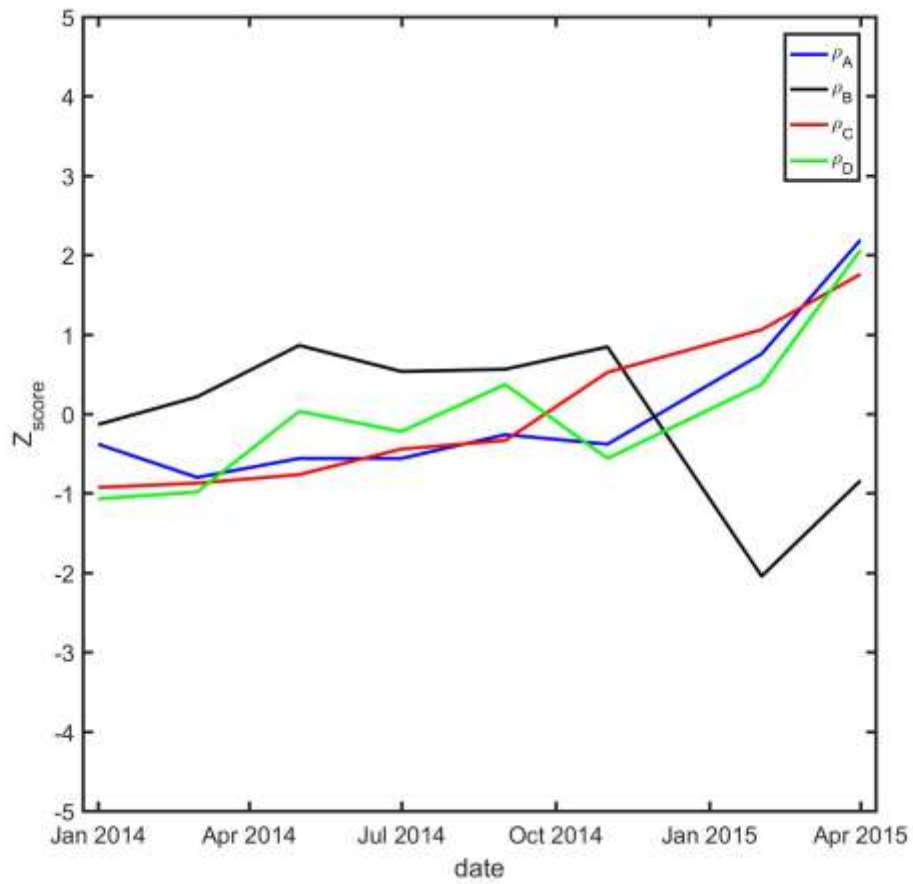
715

716

717

718

2101
2102
2103
2104
2105
2106
2107
2108
2109
2110
2111
2112
2113
2114
2115
2116
2117
2118
2119
2120
2121
2122
2123
2124
2125
2126
2127
2128
2129
2130
2131
2132
2133
2134
2135
2136
2137
2138
2139
2140
2141
2142
2143
2144
2145
2146
2147
2148
2149
2150
2151
2152
2153
2154
2155
2156
2157
2158
2159
2160



692

2131

2132

693

Figure 8a.

2135

694

2137

2138

2139

695

2140

2141

2142

2143

2144

2145

2146

2147

2148

2149

2150

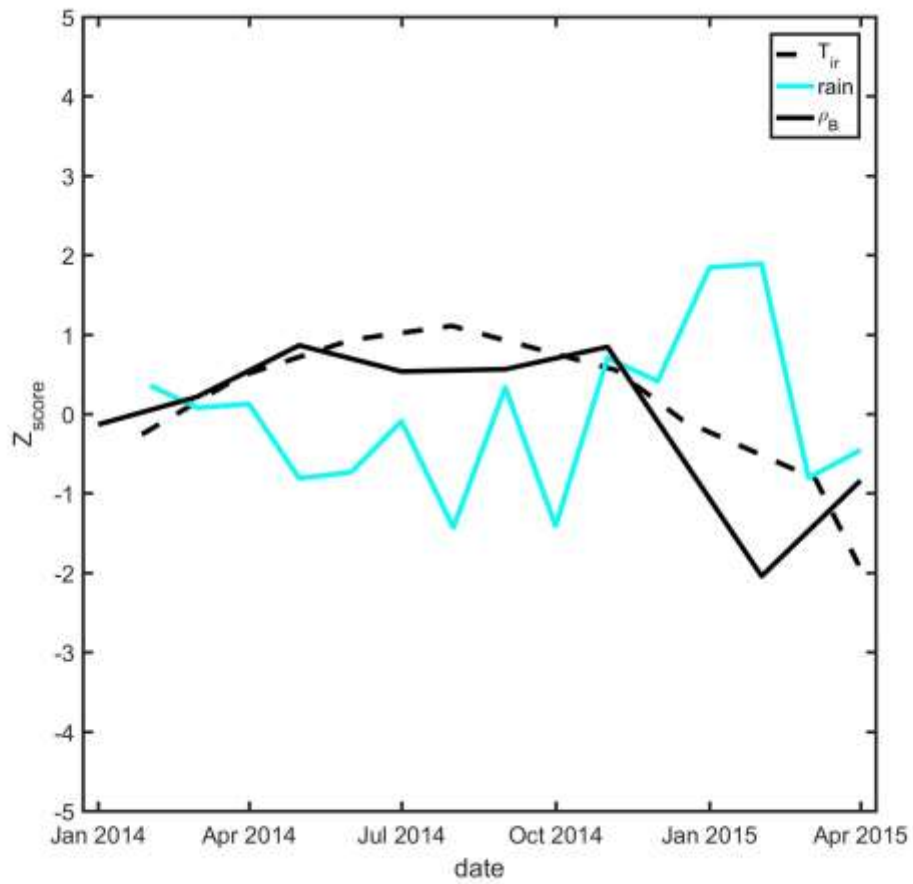
2151

2152

2153

2154

2161
2162
2163
2164
2165
2166
2167
2168
2169
2170
2171
2172
2173
2174
2175
2176
2177
2178
2179
2180
2181
2182
2183
2184
2185
2186
2187
2188
2189
2190
2191
2192
2193
2194
2195
2196
2197
2198
2199
2200
2201
2202
2203
2204
2205
2206
2207
2208
2209
2210
2211
2212
2213
2214
2215
2216
2217
2218
2219
2220



696

2191

2192

2193

2194

2195

2196

2197

2198

2199

2200

2201

2202

2203

2204

2205

2206

2207

2208

2209

2210

2211

2212

2213

2214

2215

2216

2217

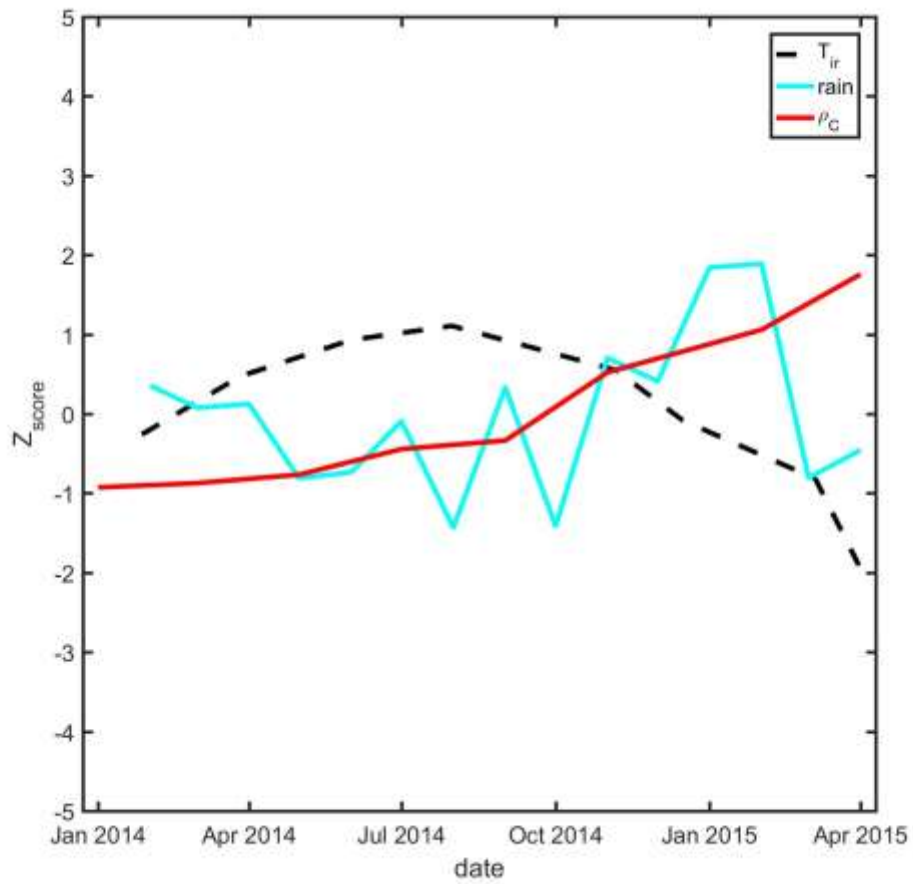
2218

2219

2220

Figure 8b.

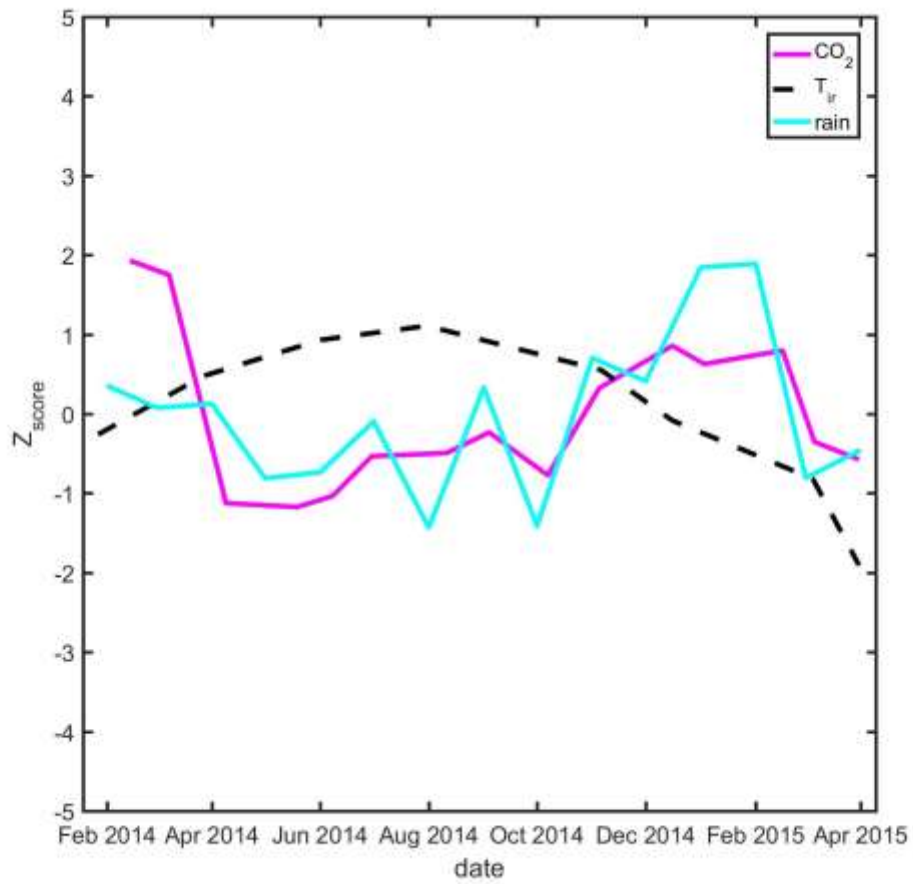
2221
2222
2223
2224
2225
2226
2227
2228
2229
2230
2231
2232
2233
2234
2235
2236
2237
2238
2239
2240
2241
2242
2243
2244
2245
2246
2247
2248
2249
2250
2251
2252
2253
2254
2255
2256
2257
2258
2259
2260
2261
2262
2263
2264
2265
2266
2267
2268
2269
2270
2271
2272
2273
2274
2275
2276
2277
2278
2279
2280



700
701 Figure 8c.

702
703

2281
2282
2283
2284
2285
2286
2287
2288
2289
2290
2291
2292
2293
2294
2295
2296
2297
2298
2299
2300
2301
2302
2303
2304
2305
2306
2307
2308
2309
2310
2311
2312
2313
2314
2315
2316
2317
2318
2319
2320
2321
2322
2323
2324
2325
2326
2327
2328
2329
2330
2331
2332
2333
2334
2335
2336
2337
2338
2339
2340



704

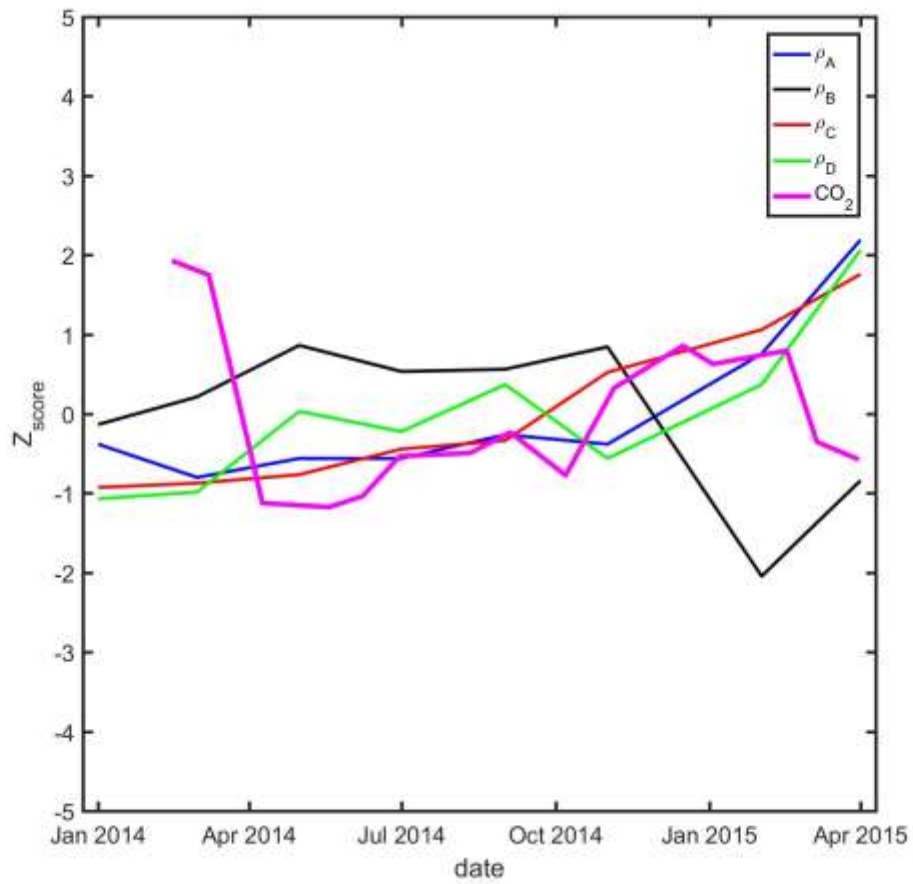
705

Figure 8d.

706

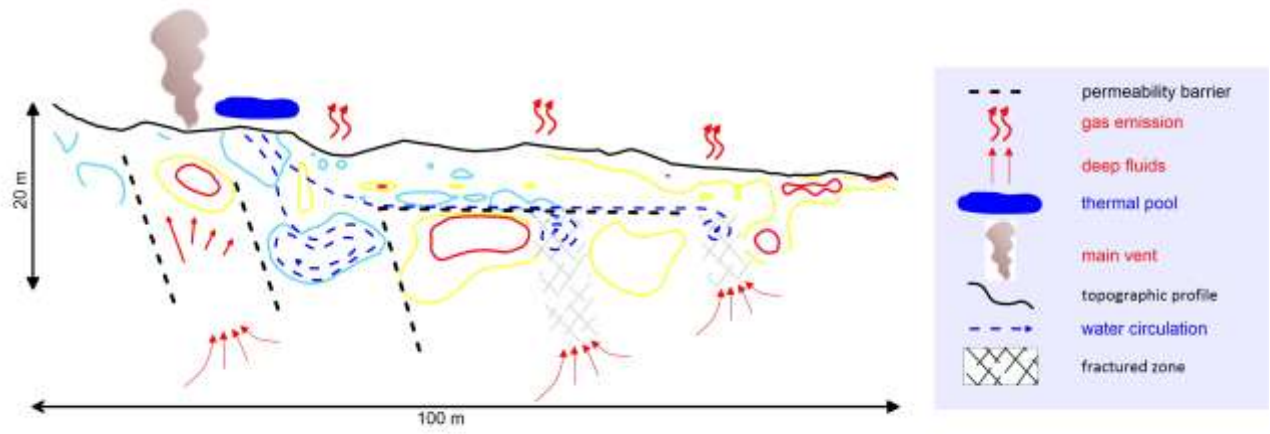
707

2341
2342
2343
2344
2345
2346
2347
2348
2349
2350
2351
2352
2353
2354
2355
2356
2357
2358
2359
2360
2361
2362
2363
2364
2365
2366
2367
2368
2369
2370
2371
2372
2373
2374
2375
2376
2377
2378
2379
2380
2381
2382
2383
2384
2385
2386
2387
2388
2389
2390
2391
2392
2393
2394
2395
2396
2397
2398
2399
2400



708
709 Figure 8e.

2401
2402
2403
2404
2405
2406
2407
2408
2409
2410
2411
2412
2413
2414
2415
2416
2417
2418
2419
2420
2421
2422
2423
2424
2425
2426
2427
2428
2429
2430
2431
2432
2433
2434
2435
2436
2437
2438
2439
2440
2441
2442
2443
2444
2445
2446
2447
2448
2449
2450
2451
2452
2453
2454
2455
2456
2457
2458
2459
2460



712

713 Figure 9.

714

