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Observation of the Dynamics of Hydrothermal Activity in La Soufrière of Guadeloupe Volcano with Joint Muography, Gravimetry, Electrical Resistivity Tomography, Seismic and Temperature Monitoring

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1 Chapter 5
2 Observation of the Dynamics
3 of Hydrothermal Activity in
4 La Soufrière of Guadeloupe
5 Volcano with Joint
6 Muography, Gravimetry,
7 Electrical Resistivity
8 Tomography, Seismic and
9 Temperature Monitoring

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34 Muography uses muons contained in the natural cosmic rays to deter-
35 mine the density of rock volumes. The measurements consist in counting
36 the muons emerging from the target to determine the screening effect pro-
37 duced by the rock. Because the larger the rock thickness, the smaller the
38 number of muons able to cross, the time resolution that can be achieved by
39 muography to monitor density changes is on the order of one or two weeks
40 for kilometer-sized volcanoes. This limitation of the method can be reduced
41 by joining muography with high time-resolution measurements like passive
42 seismic monitoring. In the case of structural imaging, muography benefits
43 from the fact that muon trajectories are linear, making the tomography
44 problem simpler than for other geophysical techniques like electrical resis-
45 tivity tomography. Experiments performed on La Soufrière of Guadeloupe
46 volcano are described to show how muography can be used to contribute
47 to structural imaging of an highly heterogeneous lava dome and to detect
48 abrupt transient hydrothermal phenomena likely to produce dangerous ex-
49 plosive events.

Keywords: volcanic hydrothermal systems, muon tomography, geophys-
ical methods, gravimetry, electrical resistivity tomography, seismic moni-
toring, fumerole temperature

50 1.1. Objectives

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- 51 • Present the interest of hydrothermal systems monitoring
 - 52 • Discuss the characteristics of muography for hydrothermal systems moni-
53 toring
 - 54 • Present the various geophysical experiments performed on La Soufrière of
55 Guadeloupe
 - 56 • Discuss the results and propose a model of hydrothermal phenomena
-

57 1.2. Introduction

58 A significant amount of applications that made muography popular during the
59 last decade concern volcanoes [Tanaka et al., 2007, 2009a,b, 2010, Gibert et al.,
60 2010, Lesparre et al., 2011, Carbone et al., 2014, Jourde et al., 2016a]. Actu-
61 ally, muography possesses several key advantages for volcano imaging: i) the
62 possibility to radiograph the emerging part of the volcano from a single re-
63 mote viewpoint allows to study active dangerous unapproachable volcanoes; ii)
64 high density contrasts are often present in volcanoes, making muography par-
65 ticularly relevant; iii) the fact that muon trajectories may be considered linear
66 makes the tomography inverse problem simpler; iv) continuous measurements
67 offer the possibility to monitor density changes caused by either hydrothermal
68 phenomena and lava ascent.

69 Among the many phenomena observed on volcanoes, phreatic and hy-
70 drothermal explosions in volcanic geothermal fields [Rouwet et al., 2014, Erfurt-
71 Cooper, 2017] are subject to a growing attention in response to the occurrence
72 of the recent laterally-directed explosions that caused at least 58 fatalities at
73 Ontake volcano (Japan) in 2014 [Kaneko et al., 2016]. Other eruptions occurred
74 in New Zealand at the Te Maari Crater in Mount Tongariro (2012) [Jolly et al.,
75 2014] and in Whakaari/White Island (2019) [Dempsey et al., 2020]. Presently,
76 these catastrophic events are considered unpredictable [Kaneko et al., 2016],
77 and identifying precursors of unrest in shallow hydrothermal systems [Tonini
78 et al., 2016] is made difficult because of the specificity of each volcanic system
79 [Phillipson et al., 2013]. Detecting transient early warning signals of imminent
80 destabilization [Sano et al., 2015, Oikawa et al., 2016] among the many signals
81 produced by the long-standing activity of well-developed hydrothermal systems
82 constitutes a formidable challenge. Muography can significantly contribute to
83 make progress by bringing spatial and temporal information about the parts
84 of shallow hydrothermal system that may destabilize.

85 In this chapter, we present a series of long-term experiments conducted
86 on the La Soufrière volcano in Guadeloupe to document the detection of very
87 short-term warning signals (i.e. time scales of hours and days) of possible hy-
88 drothermal destabilization in an active lava dome of moderate activity. La
89 Soufrière is one of a few volcanoes very well suited for this kind of study
90 [Boudon et al., 2007, 2008]. Its moderate activity allows safe field work but
91 is sufficient to produce internal density variation that could be detected with
92 various methods and especially muography. The dome being less than 1 km
93 wide, it can be crossed by enough cosmic muons to give pertinent images of
94 its internal structure. The size scale of the internal heterogeneities is on the
95 order of a few meters to a few tens of meters so they are large enough to be
96 detected. Since the last 1976-1977 eruption, considered as a failed magmatic
97 event [Feuillard et al., 1983, Villemant et al., 2014], degassing first decreased to

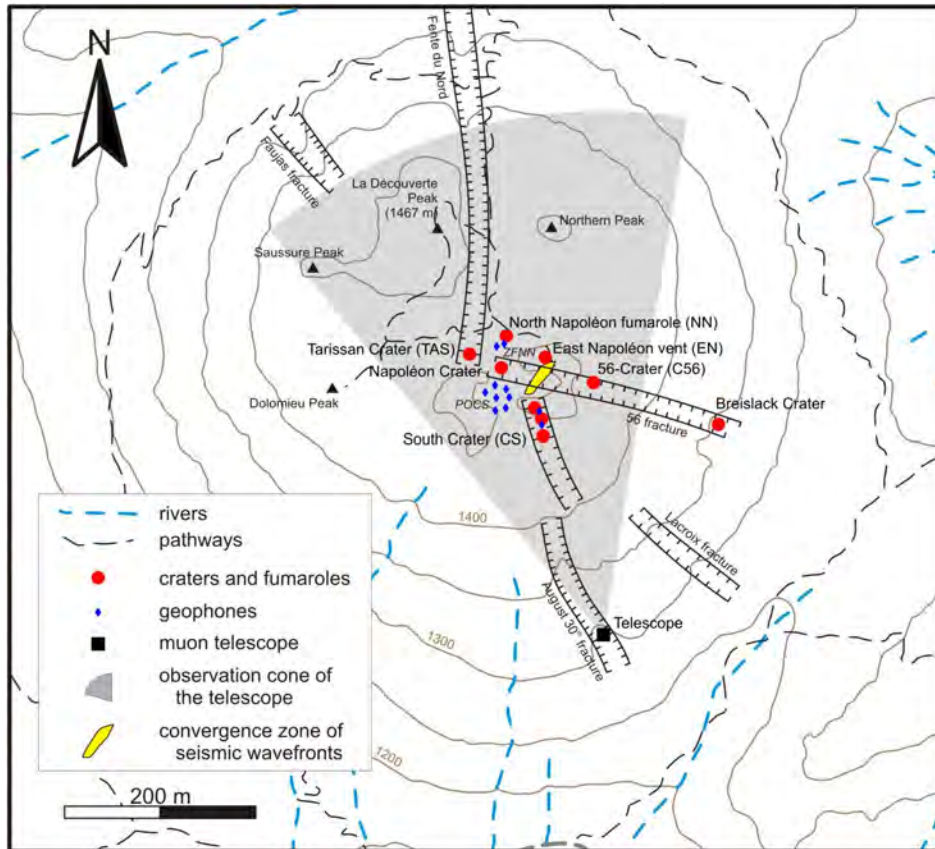


Figure 1.1: Main structures of the La Soufrière lava dome with sensor emplacements. The gray sector represents the view field of the muon telescope (black square) placed in the 30 August fracture at its apex. Vents are shown as red dots, geophones as blue diamonds, and the yellow patch is the plan view of the source of seismic noise (see Fig. 1.9). Reprinted from Le Gonidec et al. [2019].

98 a minimum in 1991 before increasing again with an intense fumarolic activity
99 at the summit since 1992 in the South Crater vents area (Fig. 1.1). Since 2014,
100 new active regions appeared to the East of the Tarissan and Dupuy craters (Fig.
101 1.1) perhaps due to flow paths rearrangement caused by the progressive seal-
102 ing of open fractures [Rosas-Carbajal et al., 2016]. This hydrothermal activity
103 is compatible with an increasingly vapor-dominated system favorable to local
104 destabilization. At least two small explosions occurred in 2016 in the East-
105 Napoléon vent (Fig. 1.1) and an accelerated episode of unrest was observed
106 during April 2018, which resulted from increased heating and pressurization
107 of the hydrothermal system and a quick (order of days) excursion through the
108 critical point of water [Moretti et al., 2020]. Such hazardous environments re-
109 sult from rapid phenomena occurring inside the lava dome at time scales of
110 few hours or days.

111 **1.3. Muography for volcano applications**

112 We recall the muography characteristics either particularly relevant or specific
113 to volcano applications and, particularly, the monitoring of shallow hydrother-
114 mal systems. More detailed description of the muography method are given in
115 other chapters of this book.

116 The main concerns encountered when applying muography to the monitor-
117 ing of hydrothermal systems are:

- 118 • The resolution that can be achieved for density, space and time and results
119 from a trade off among these three quantities.
- 120 • The perturbing effects likely to corrupt the data.
- 121 • The practical difficulties encountered during field implementation and main-
122 tenance of the equipment.

123 These items are discussed in the next three sections.

124 **1.3.1. Field implementation and maintenance**

125 Volcanoes often constitute harsh environments where various aggressive or dif-
126 ficult conditions make the installations of the telescopes and their long-term
127 operation problematic. On tropical volcanoes like La Soufrière, the main prob-
128 lems come from tropical storms, heavy rains, lightning, and acidic gas emis-
129 sions, mainly from steam-rich fumaroles. On a volcano like Mount Etna, addi-
130 tional difficulties come from snow and ash falls that may destroy the equipment.
131 Beside these problems due to natural environment, rough installation condi-
132 tions must be accounted for: strong shocks during transportation either by



Figure 1.2: View of a field telescope in maintenance on La Soufrière at the Rocher Fendu location. The instrument counts 3 detection matrices (grey frames). A wall of lead bricks with a thickness of 5 cm is placed in front of the central detector. The telescope may easily be rotated to change both its azimuth and its inclination. When in operation, a tarpaulin covers the instruments to protect it against rain. Reprinted from Jourde et al. [2016b].

133 helicopter or by car, use of rope-access techniques. For these reasons, our tele-
 134 scopes are modular and rugged enough to support shocks and rain (Fig. 1.2).
 135 Electrical power units are necessary to make the telescope autonomous. On
 136 volcanoes like La Soufrière, poor weather conditions render photo-voltaic units
 137 poorly efficient and approximately 10 W of photo-voltaic power are needed for
 138 1 W of electrical power available 24 hours a day. These constraints prevent the
 139 use of large high-acceptance telescopes. The installation of WiFi links is neces-
 140 sary to both download the data and perform remote-control operations of the
 141 telescopes (e.g. reboot, change thresholds and coincidence criteria of on-board
 142 computers, etc.).

143 Another concern to consider during field implementation is the presence of
 144 secondary topography (e.g. other volcanoes, cliffs, etc.) behind the volcano of
 145 interest. Beside the fact that secondary topography reduces the flux of muons
 146 available to tomography the target, the effects of such secondary structures
 147 may be complicated to suppress when processing the data.

148 **1.3.2. Resolution in density, time, and space**

149 Muography shares the same principles than classical X-ray medical radiogra-
 150 phy, and consists in measuring the screening effect of a body of matter on an
 151 incident flux, Φ_0 , of cosmic muons. The loss of energy of the muons along their
 152 trajectories through rock results from bremsstrahlung, nuclear interactions,
 153 and e^+e^- pair production physical processes. Assuming that muons continu-
 154 ously loss their energy along along their way, the rate of energy loss may be
 155 written as (see e.g. Sokalski et al. [2001] for more details),

$$-\frac{\partial E}{\partial \varrho} [\text{MeV} \cdot \text{cm}^2 \cdot \text{g}^{-1}] = a(E) + b(E) \cdot E, \quad (1.1)$$

156 where the functions a and b depend on the material properties, mainly the
 157 atomic weight [Nagamine, 2003, Lesparre et al., 2011]. The flux, Φ_E , of emerg-
 158 ing muons is the part of the incident muons with an initial energy larger
 159 than the cut-off energy, $E_{\min}(\varrho)$, necessary to cross the opacity $\varrho [\text{kg} \cdot \text{m}^{-2}] =$
 160 $\int_{\mathcal{L}} \rho(x) dx$, where $\rho [\text{kg} \cdot \text{m}^{-3}]$ is the density distribution along the trajectory,
 161 \mathcal{L} , of the particle. Telescopes are designed to collect the flux of muons com-
 162 ing from a collection of trajectories (or lines of sight), $\{\mathcal{L}_k, k = 1, \dots, M\}$
 163 which may be considered as straight lines excepted for low-energy muons or
 164 very dense matter (e.g. Pb, U, W) where scattering may be non-negligible [e.g.
 165 Gómez et al., 2017]. Each line of sight is characterized by a solid angle and a
 166 detection area whose product is called the acceptance $\mathcal{T} [\text{sr} \cdot \text{cm}^2]$.

167 As a rule of thumb, a muon loses about 2.2 MeV when crossing 1 cm
 168 of water [Scheck, 1978] (i.e. $-dE/d\rho = 2.2 \text{ MeV/g/cm}^2$). A simple propor-

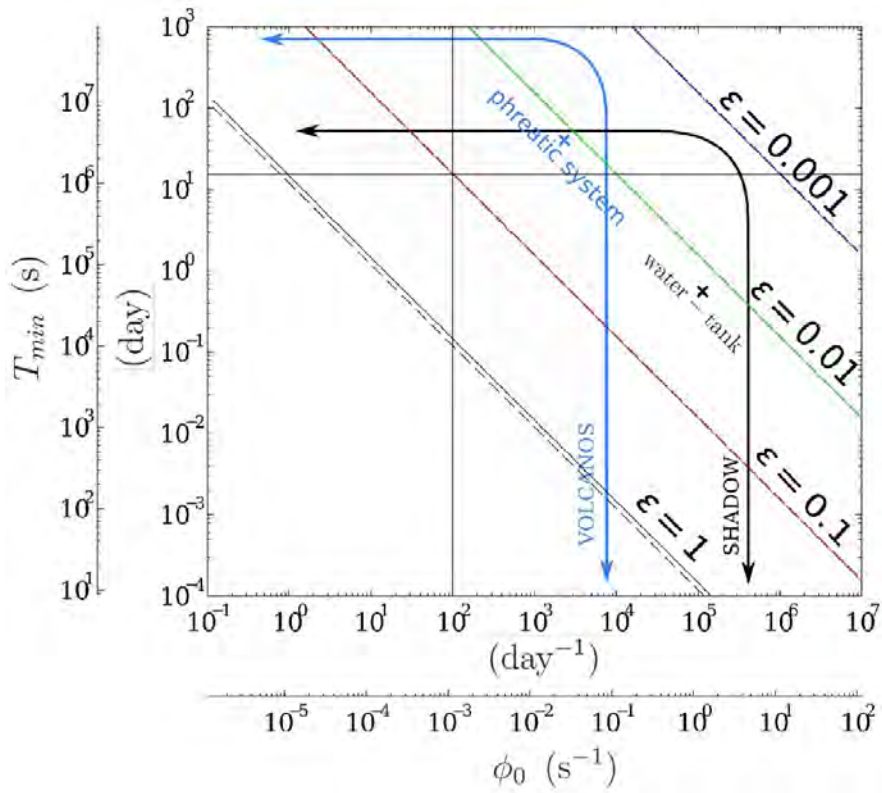


Figure 1.3: Minimum acquisition time T_{min} versus the average measured flux Φ_0 necessary to detect a relative flux variation of ϵ with a 95% confidence level. The blue curve delimits the resolution domain for typical volcano applications. Adapted from Jourde et al. [2016a].

169 tionality rule may be used to get a good estimate for other materials and
170 trajectory lengths. For instance, to cross the atmosphere whose weight per
171 surface unit equals 10 m of water, a muon loses about $E_{\min} = 2.2 \text{ MeV.cm}^{-1} \times$
172 $10^3 \text{ cm} = 2.2 \text{ GeV}$. For La Soufrière of Guadeloupe, taking an average density
173 $\rho = 2 \text{ g.cm}^{-3}$ (i.e. value for highly altered andesite lava blocks in Navelot
174 et al. [2018]) and typical trajectory lengths of 500 m, we obtain $E_{\min} =$
175 $2.2 \text{ MeV.cm}^{-1} \text{m}^3 \text{kg}^{-1} \times 5 \times 10^4 \text{ cm} \times 2 \text{ kg.m}^{-3} = 220 \text{ GeV}$.

176 Such a value for E_{\min} places the energy cut-off in the steep power-law part
177 of the energy spectrum of cosmic muons [Gaisser et al., 2016], and only a tiny
178 fraction of the incident muons will be able to cross the volcano to be detected
179 by the telescope. Consequently, in volcano applications, the number of muons
180 detected for a given trajectory is typically of the order of some tens per day
181 or even less, depending on the thickness of rock. Signal-to-noise ratio then
182 becomes a issue of critical importance, particularly in monitoring experiments
183 where density time-changes are to be detected. To illustrate this problem, let
184 us consider the case of a sudden opacity change $\delta\rho$ producing an increase of
185 10% of the number of muons able to cross the volcano. For a daily number
186 $N_b = 100$ (i.e. $\Phi_b = 10^2 \text{ day}^{-1}$) of muons detected before the occurrence of
187 the density change, we expect $N_a = 110$ (i.e. $\Phi_a = 1.1 \times 10^2 \text{ day}^{-1}$) after the
188 occurrence of the density change. Considering that the muon arrivals obey a
189 Poissonian process, the standard deviation $\sigma_N \approx 10$ for both N_b and N_a . Clearly,
190 this makes N_b and N_a statistically indistinguishable. To be able to detect the
191 density change, we have to consider longer periods of time to have better
192 statistics. For instance, for a time period of 10 days, we expect $N_b = 1000$,
193 $N_a = 1100$ with $\sigma_N \approx 32$, and N_b and N_a start to become distinguishable (at
194 a rather poor significance level).

195 Mathematical developments given by Lesparre et al. [2010] and Jourde et al.
196 [2016a] conduct to a feasibility formula where the statistical resolution, $\sigma_{\delta\rho}$ of a
197 given opacity change $\delta\rho$ is expressed as a function of the total opacity ρ of the
198 volcano, of the time resolution δT that can be achieved, and of the detection
199 characteristics of the telescope (Fig. 1.3). For a given telescope, the feasibility
200 formula indicates that the smaller the opacity variations to detect, the poorer
201 the time-resolution. Returning to the example of a 10% variation (i.e. $\epsilon = 0.1$
202 in Fig. 1.3) of a flux $\Phi_b = 10^2 \text{ day}^{-1}$, Figure 1.3 shows that a duration T_{\min}
203 slightly less than 20 days is necessary to detect the change à flux at the 95%
204 confidence level.

205 Another quantity considered in the feasibility formula is the telescope ac-
206 ceptance since the number of detected muons is proportional to \mathcal{T} . A way
207 to improve the time-statistical resolution is to augment the acceptance by in-
208 creasing the detection surface and/or the solid angle of capture of muons. An
209 increase of the detection surface may be obtained either by augmenting the
210 size of the pixellized detection matrices or by merging patches of lines of sight.

211 In the later case, this will reduce the number of effective pixels and decrease
212 the spatial resolution. Widening the solid angle of detection will also lead to a
213 decrease of the spatial resolution.

214 To give some practical insight to the reader about the performances of
215 muography for volcano applications, one can say that for the particular case of
216 La Soufrière of Guadeloupe, the spatial resolution is on the order of 10 to 50 m
217 depending on the distance from the telescope and due to the fan-like geometry
218 of the lines of sight. The time resolution corresponding to the observed opacity
219 changes is on the order of 1 to 3 weeks. As we shall see below, hydrothermal
220 phenomena with time constants as short as a fraction of day seem to occur in
221 the lava dome of La Soufrière. Such rapid phenomena cannot be detected with
222 muography alone, and other geophysical methods with short time-resolution
223 with a possibly poor spatial resolution (e.g. gravity measurements) can be used
224 in conjunction with muography to document this type of rapid phenomena.

225 **1.3.3. Perturbing effects**

226 A frequent situation encountered in muography applied to volcanoes is that
227 telescopes operate in open-sky conditions. This favors the occurrence of several
228 undesirable phenomena that somewhat complicate data acquisition and some
229 processing steps.

230 **Effects of open-sky flux.** The telescopes are exposed to the open-sky flux
231 of muons that is much larger than the flux of muons of interest and coming
232 from the target volcano. A very large number of detector hits are due to muons
233 coming from elsewhere than the volcano and these unwanted events must be
234 efficiently filtered out while preserving the particle trajectories coming from the
235 target to image. Filtering is performed through coincidence criterion applied
236 to at least three pixellized detectors as shown in Figure 1.2, and an event is
237 declared valid if three aligned pixels are simultaneously fired on three matrices.
238 Once applied, this filtering must be unbiased from missing-event probabilities.
239 A first type of missed events is caused by the imperfect efficiency of the scintil-
240 lator strips forming the matrices. A second type of missed events comes from
241 the dead time of the detection electronics which is not able to detect another
242 event during a period of time of about 200 ms following the detection of a
243 previous event. For both types of missed events, the bias correction results in
244 an increase of the flux of muons of interest. The parameters of the correction
245 formula are experimentally determined on the field through calibration sessions
246 where the telescopes are oriented toward the zenith. These dedicated calibra-
247 tion sessions may be completed with continuous re-calibrations performed by
248 using events coming from open-sky trajectories located above of beside the
249 volcano.

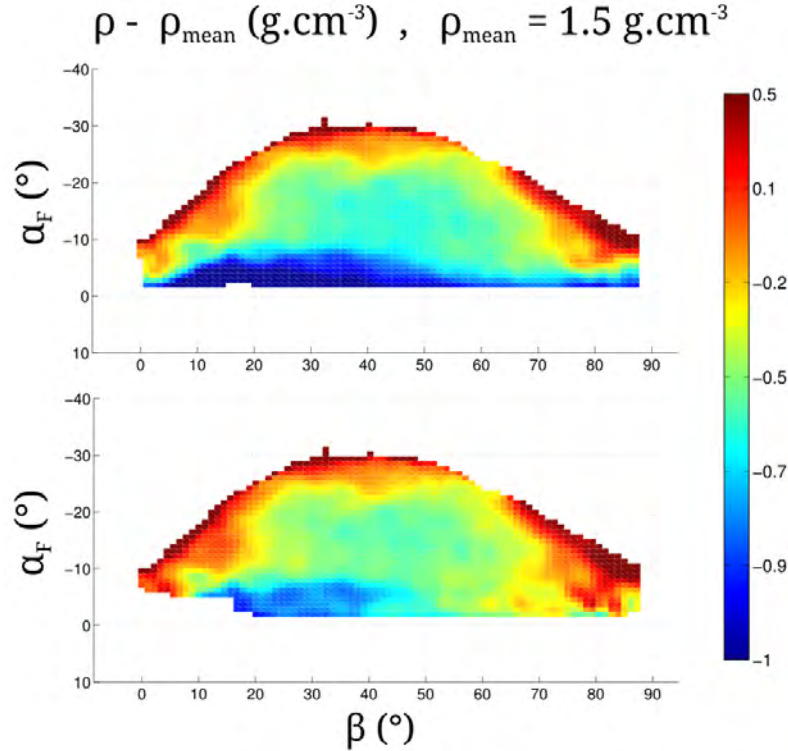


Figure 1.4: Example of upward flux correction in a muography of La Soufrière lava dome. Top: Uncorrected radiography with a spurious low-density layer at the bottom of the image (i.e. at near-horizontal inclinations). Bottom: Corrected image where the low-density layer has been suppressed. Reprinted from Jourde et al. [2013].

250 The open-sky flux of particles also counts high-energy electrons and positrons
 251 able to fire the detection matrices in a way similar to muons. These undesirable
 252 events may be eliminated by interposing a lead shield with a thickness of 5 cm
 253 in front of the center matrix of the telescopes.

254 **Upward flux.** This type of perturbing flux was discovered by us during ex-
 255 periments performed on Mount Etna and La Soufrière of Guadeloupe [Jourde
 256 et al., 2013]. This type of flux is composed of particles crossing the telescope in
 257 the reverse direction, i.e. hitting the rear matrix first, with trajectories identical
 258 to those of muons that crossed the volcano. In practice, particles forming the
 259 upward flux have trajectories with a small inclination below the horizontal and,
 260 consequently, only the trajectories with a small inclination above the horizon-
 261 tal when looking toward the volcano are biased (Fig. 1.4). These trajectories

262 generally correspond to the largest thickness of rock and, consequently, to the
263 smallest flux of muons crossing the volcano. The effects of the upward flux
264 are then particularly strong with a significant alteration of the signal-to-noise
265 ratio. If not corrected for, the upward flux produces an overestimation of the
266 flux coming from the volcano and the resulting densities are biased toward low
267 values. The correction of the upward flux needed an improvement of the clock
268 systems of our telescopes in order to determine the sense of propagation of the
269 particles through the measurement of their time-of-flight from one matrix to
270 another [Marteau et al., 2014].

271 **Scattered muons.** Muon scattering is another perturbing effect to consider
272 when doing muography of volcanoes and, more generally, in open-sky condi-
273 tions. Scattering of low-energy muons represents a potentially important source
274 of noise, particularly in transmission and absorption muography. The recon-
275 structed trajectories of scattered muons have trajectories that mimic those
276 of through-going particles. This results in an overestimate of the number of
277 detected particles and to an underestimate of the target opacity [Nishiyama
278 et al., 2016, Rosas-Carbajal et al., 2017, Gómez et al., 2017]. Contrarily to the
279 other perturbing flux discussed above, scattered muons cannot be rejected by
280 particle identification techniques, and data cleaning relies on models as given
281 by Gómez et al. [2017]. To be reliable, these models must account for the
282 topography of the geological structures and their surface density.

283 **1.4. Structural imaging of hydrothermal** 284 **reservoirs in La Soufrière lava dome** 285 **with joint muography, ERT and gravime-** 286 **try**

287 Structural imaging of volcanoes is important for monitoring hydrothermal sys-
288 tems because it gives the general arrangement of the different subsystems that
289 participate to the processes (e.g. reservoirs, fractures, barriers of massive lava).
290 However, imaging of lava domes remains a difficult task for most geophysic-
291 al methods because high-contrasts of material properties (e.g. several order
292 of magnitude for electrical conductivity, large variations of seismic velocities)
293 reinforce the non-linear nature of the associated inverse problems. Muographic
294 imaging is much simpler because of the straight pathways of the muons across
295 the rock.

296 1.4.1. Muography

297 **Survey characteristics.** The role of structural imaging is to provide an as
298 precise as possible 3D view of the volcano interior. In this respect, the more
299 the data we have, the better the resulting model and, in the case of muogra-
300 phy, this general principle translates into long acquisition times to have good
301 signal-to-noise ratio and as many a possible angles of view to constrain the 3D
302 tomography inversion. This later point is easily understood through the simi-
303 larity of muography and CT X-ray imaging and the fact that high-resolution
304 3D tomography implies a fine angular coverage to constrain the inverse Radon
305 transform. However, in the case of La Soufrière, only a small number of an-
306 gular views are possible because of both the harsh field conditions and the
307 expenditures inherent in the deployment of a large number of telescopes .

308 The first muography experiment performed on La Soufrière started in year
309 2008 with a single telescope. Since then, continuous measurements have been
310 made with at least one telescope and, in the best situation, with up to five
311 instruments located around the lava dome. Four of these telescopes are similar
312 to the one shown in Fig. 1.2 with three detection matrices of 16×16 pixels of
313 5×5 cm². These telescopes are configured with high angular aperture to image
314 the entirety of the lava dome. The fifth telescope is smaller with matrices of
315 10×10 pixels of 5×5 cm² and is located inside the 30 August Fault on the
316 South-Eastern flank of the volcano. This instrument is configured to provide a
317 close view of the most hydrothermally active region of the dome.

318 **Data analysis.** As explained in the preceding section, some processing steps
319 are necessary to obtain density radiographies from muon counts measured by
320 the telescopes.

321 The open-sky exposure of the telescopes makes some processing steps par-
322 ticularly critical. Such is the case of the filtering operations aimed at removing
323 the perturbing scattered and upward fluxes described in previous sections.
324 Other processing steps concern the filtering of fortuitous events, the bias cor-
325 rection of scintillator efficiency and the correction acceptance defects.

326 The resulting muographies as the one shown in Figure 1.4 display conspicu-
327 ous opacity contrasts that reveal the strong density heterogeneities in the lava
328 dome. In the particular case of La Soufrière, we recognize low-density domains
329 corresponding either to presently active areas (principally the South Crater) or
330 to ancient active areas. High-density domains indicate the presence of massive
331 lava volumes.

332 1.4.2. Electrical resistivity tomography (ERT)

333 The ERT experiments briefly presented below are discussed in details by Nicollin
334 et al. [2006], Lesparre et al. [2014] and Rosas-Carbajal et al. [2017].

335 **Complementarity of ERT compared to muography.** ERT brings infor-
336 mation about rock electrical conductivity, possibly complex-valued in the case
337 of electrical impedance tomography (EIT) measurements [Zimmermann et al.,
338 2008]. ERT measurements are highly sensitive to the presence of fluids as, in
339 general, their electrical conductivity is much higher than that of the rock ma-
340 trix. Even a small amount of liquid can increase the bulk rock conductivity by
341 several orders of magnitude [Archie, 1942], and ERT is an efficient method for
342 constraining the volume of fluid-saturated rocks in a volcano.

343 Contrarily to muography, ERT tomography cannot be performed from a
344 remote location and numerous electrodes must be placed on and around the
345 volcano to perform a 3D inversion such as the example shown in Fig. 1.5
346 [Rosas-Carbajal et al., 2017]. Although ERT is a potential-field method with
347 an infinite-distance sensitivity, one may reasonably assume that the electrical
348 current that flows from positive to negative injection electrodes (there may be
349 several electrodes of each type) is contained within a finite-size volume. How-
350 ever, contrarily to muography, the precise geometry of this volume is unknown
351 because it depends on the conductivity distribution which is precisely what we
352 look for. This makes ERT a highly non-linear inverse problem with a moderate
353 to low spatial resolution when compared to muography. Provided an array of
354 electrodes remains in place, ERT may be used to perform a monitoring with a
355 time resolution as fine as some minutes [e.g. Binley et al., 2015]. A joint anal-
356 ysis of ERT and muography data may be very helpful to resolve ambiguities
357 in interpretations. For instance, muography may be used to decide whether an
358 anomaly with a large electrical resistivity corresponds to a void or to a block
359 of massive andesite.

360 **Survey characteristics and data analysis.** The ERT data were collected
361 through experiments with electrode transects extending through La Soufrière
362 lava dome and around it [Rosas-Carbajal et al., 2017, Fig. 1]. Three-dimensional
363 protocols with non-aligned electrodes were used to better resolve the inner-
364 most regions of the lava dome [Lesparre et al., 2014]. Because of the harsh field
365 conditions, the ERT series of experiments was conducted from 2003 to 2011 to
366 collect about 23000 data points. The 3D inversion of the data was performed
367 with a least-squares algorithm with smoothness-constrained regularization of
368 the inversion for a model counting about 10^6 mesh cells [Johnson et al., 2010].

369 Several conductive regions ($\geq 0.1 \text{ S.m}^{-1}$) are found in the lava dome, the
370 largest located in the volcano's southern flank (Fig. 1.5). The southern con-
371 ductive body contains a sub-domain of 10^7 m^3 with a conductivity larger than

372 1 S.m^{-1} . Such high conductivities are likely to correspond to active pathways of
373 acid hydrothermal fluids emanating from deepest regions of the hydrothermal
374 system and rising toward the presently active parts on top of the lava dome.
375 Other conductive bodies located on the eastern and north-western sides of the
376 lava dome appear disjoint from the southern conductive reservoir and are likely
377 to correspond to fossil hydrothermal reservoirs with no visible present activity.

378 **1.4.3. Gravity survey**

379 A gravity survey performed on La Soufrière is presented by Rosas-Carbajal
380 et al. [2017]. Mathematical developments concerning the joint inversion of
381 muography and gravity data are given by Jourde et al. [2015] (see also [Nishiyama
382 et al., 2014, Barnoud et al., 2019, Cosburn et al., 2019]).

383 **Complementarity of gravimetry compared to muography.** Both gravity
384 measurements and muography bring direct information about the rock density
385 and, for this reason, joint inversion of both type of data appears natural. As ex-
386 plained in detail by [Jourde et al., 2015], the sampling kernels of both methods
387 strongly differ: gravity measurement are sensitive to the whole Earth’s den-
388 sity distribution with a r^{-2} weighting while muography data only depend on
389 the density distribution located inside bounded elongated and conical volumes
390 whose axis correspond to the lines of sight of the telescope. This difference
391 makes the gravity method a low-resolution in space while muography is po-
392 tentially a high-resolution method, depending on the telescope arrangement
393 used.

394 Despite the fact that muography actually samples a finite volume (i.e. the
395 union of the conical lines of sight) of the density distribution, it can be shown
396 that the information brought by muography improves the spatial resolution
397 outside this volume when a joint inversion with gravity data is performed
398 [Jourde et al., 2015]. Gravity data may also bring information useful to con-
399 strain the density distribution in gaps between lines of sight. Another interest
400 of gravity data is their usefulness to bring information to reduce the bias in
401 the density values determined by muography and caused by low-energy muon
402 scattering.

403 **Survey characteristics and data analysis.** The data set counts 103 grav-
404 ity measurements done between March 2014 and February 2015 with a Scin-
405 trex CG-5 gravimeter [Rosas-Carbajal et al., 2017]. The precision is about
406 $10 \mu\text{Gal}$. Methodological details for data processing prior to inversion, includ-
407 ing drift, tides, and ellipsoid and topography corrections are given by Jourde
408 et al. [2015]. The correlation between the topography and the Bouguer anomaly
409 [Jourde et al., 2015, Nettleton, 1939] is minimum for an optimal Earth den-

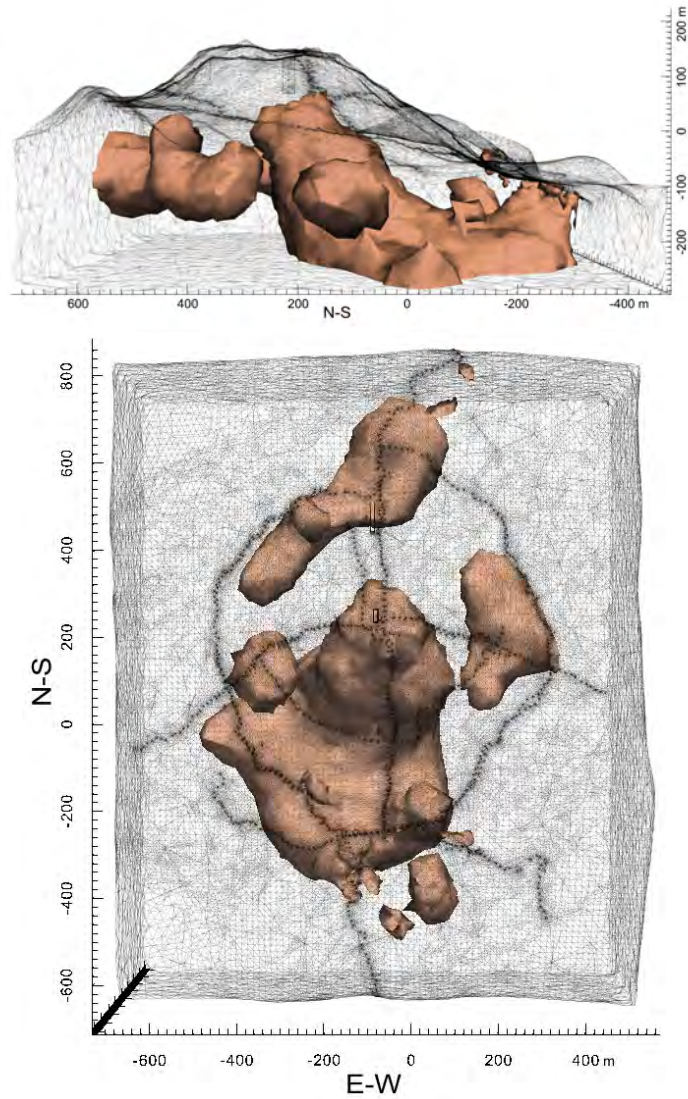


Figure 1.5: Main electrically conductive structures found with 3D ERT of La Soufrière lava dome (brown volumes) [Rosas-Carbajal et al., 2016]. (top) N-S section view, (bottom) plan view. The meshing of the numerical forward model is shown by the thin black lines. In the plan view, the black dots correspond to the electrode positions.

410 sity of 1.75 g.cm^{-3} [Parasnis, 1952]. This low value indicates that the lava
411 dome is highly heterogeneous and contains a significant fraction of voids and
412 of unconsolidated hydrothermally altered materials. The heterogeneity of the
413 lava dome is confirmed by a 3D model of the density distribution obtained by
414 jointly inverting gravimetry and muography data (Fig. 1.6).

415 **1.5. Functional imaging of sudden hy-** 416 **drothermal events with joint muog-** 417 **raphy, seismic noise and fumarole** 418 **temperature**

419 Functional imaging involves continuous measurements from an ensemble of
420 techniques providing complementary data to constrain the phenomena of in-
421 terest. In the present case, hydrothermal processes occurring in the lava dome
422 are likely to produce temperature variations at fumarole vents, density varia-
423 tions due to phase changes in hydrothermal reservoirs, and seismic noise caused
424 by multiphase flows and oscillations of fluids in conduits.

425 In the next sections, we present a field-experiment with an emphasis on the
426 detection of sudden events with time constants of hours and days. To detect
427 such events, we implemented a high time-resolution array of temperature (1 s
428 sampling interval) and seismic sensors (4 ms sampling interval) located on
429 the summit of the lava dome together with one telescope located inside the
430 30-August fracture (Fig. 1.1). We focus on a particular event that occurred
431 during a 3-day period of year 2017, from 28 March 12:00 UTC to 31 March
432 12:00 UTC. During this period, the weather conditions were very calm and
433 produced seismic data with a very high signal-to-noise ratio.

434 **1.5.1. Temperature at fumaroles**

435 **Experimental setup.** The temperature at the vents of the South crater was
436 measured every second by Pt1000 probes inserted several tens of centimeters
437 in the conduit of the vents. The Pt1000 were connected with a 4-wires protocol
438 to a Gantner A107 Analogue-to-Digital 19 bit module and the numerical data
439 were transferred to a Gantner QStation data concentrator through a RS485
440 serial data bus. All data were time-stamped through a GPS clock. The tem-
441 perature time-series of the Northern vent of the South Crater is shown in Fig.
442 1.7A. This vent is the northern most of the three fumaroles of the South Crater
443 (labelled CS in Fig. 1.1).

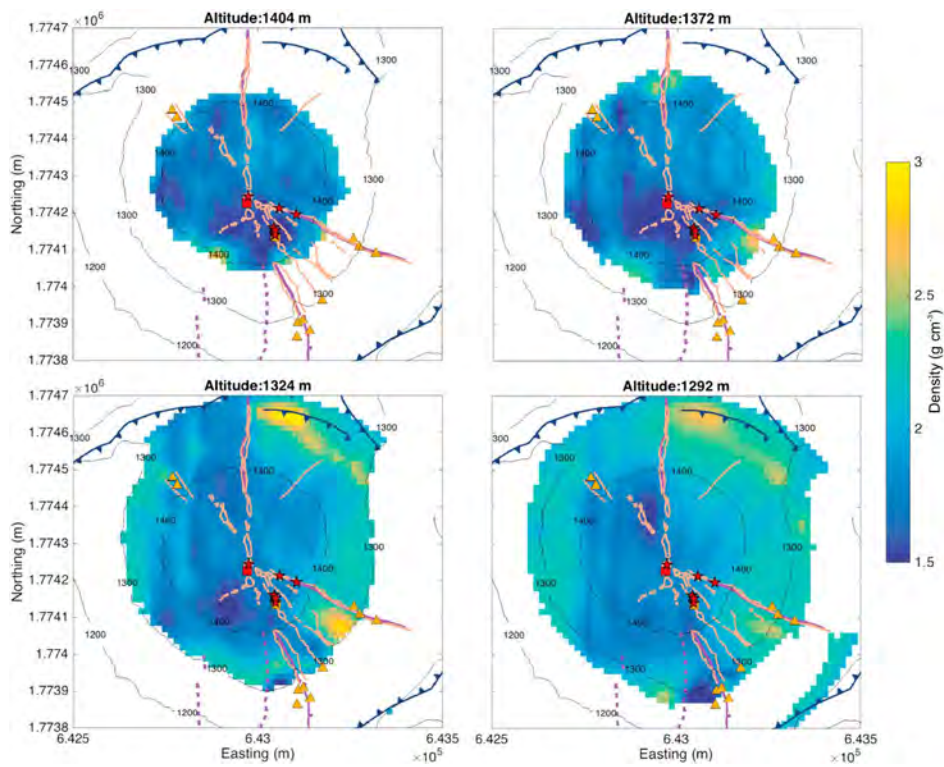


Figure 1.6: Horizontal slices of a 3-D density model at various altitudes within the dome of La Soufrière obtained from the joint inversion of muography and gravity data. Orange lines: fractures; violet lines: faults with triangles indicating fault direction; blue lines: collapse scars; orange symbols: past activity; red symbols: present activity; triangles: hydrothermal fluid springs; stars: active fumaroles; squares: boiling acid ponds. Reprinted from Rosas-Carbajal et al. [2017].

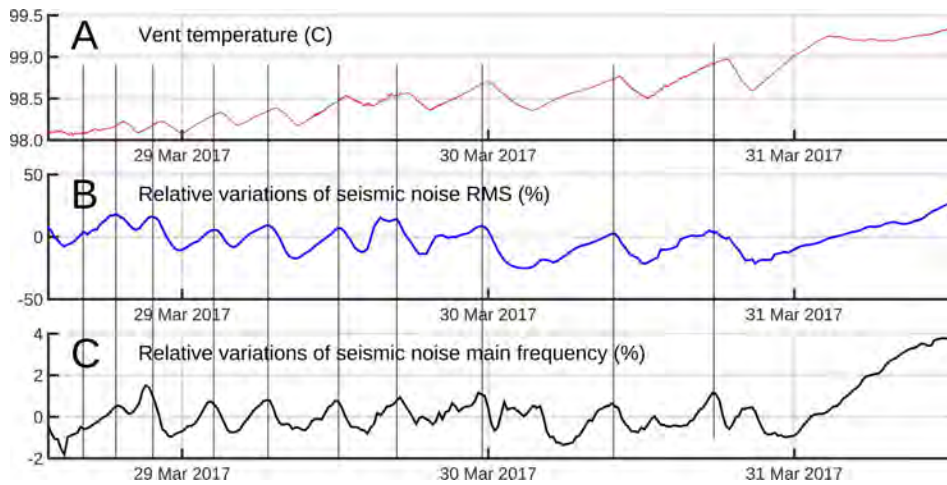


Figure 1.7: Time variations of vent temperature (in degrees Celsius) and seismic noise RMS and dominant frequency. a) Temperature in the North vent of the South crater. b) Relative variations (in percent) of the seismic noise energy in the 3-6 Hz frequency band. c) Relative variation (in percent) of the dominant frequency in the 3-6 Hz spectral band. The thin black vertical lines mark the relative maxima of seismic RMS that fall nearby temperature maxima. Observe the delay of about 45 mn of the temperature maxima with respect to those of the seismic noise RMS. The sampling interval of temperature data is 1s and the seismic attributes (RMS and dominant frequency) are computed for time windows of 20s. Reprinted from Le Gonidec et al. [2019].

444 **Data analysis.** Defining a cycle as the time period separating two successive
445 local minima in the temperature record, 10 such cycles may be identified in
446 the curve of Fig. 1.7A. Fig. 1.8 shows that the duration of the successive
447 cycles increased from 3 hours (cycle 1) to 8 hours (cycle 9). Splitting a cycle
448 into a fall and a rise period, one observes that the fall period remains almost
449 constant near 2 hours for all cycles (Fig. 1.8B). Conversely, the rise period
450 increases from 2 hours to 6 hours when progressing along the series of cycles
451 (Fig. 1.8C). The increase of the duration of the rise period explains the positive
452 trend visible in the total cycle duration (Fig. 1.8A). Another positive trend is
453 superimposed on the cycle sequence with an average temperature rise of 0.1 °C
454 between successive temperature minima (Fig. 1.8D). The temperature decrease
455 occur during the fall period steadily trends from 0.15 °C to 0.4 °C along the
456 cycle sequence (Fig. 1.8E), and the temperature increment in the successive rise
457 periods increases from 0.15 °C to 0.65 °C (Fig. 1.8F). The global positive trend
458 superimposed on the oscillation pattern produces a net increase of temperature
459 of about 1.2 C.

460 The oscillating pattern observed in the temperature time series resembles
461 to reverse log-periodic sequences as observed financial time series [Sornette
462 and Zhou, 2002]. The log-periodicity of the temperature cycles can be tested
463 by checking if the start dates, t_n , of the cycles obey:

$$t_n - t_c = \tau \times \lambda^n, \quad (1.2)$$

464 where t_c is the data marking the onset of the critical transition, n is the cycle
465 index increasing with time, τ is the time unit (e.g. hour or day), and λ is the
466 scaling ratio such that,

$$\lambda = \frac{t_{n+2} - t_{n+1}}{t_{n+1} - t_n}. \quad (1.3)$$

467 For the temperature data of Fig. 1.7, we obtain $\lambda = 1.3$. Using a Shanks
468 transformation, [Shanks, 1955, Bender and Orszag, 2013],

$$t_c = \frac{t_{n-1} \times t_{n+1} - t_n^2}{t_{n-1} + t_{n+1} - 2t_n}, \quad (1.4)$$

469 we obtain $t_c \approx -15$ h, indicating that the sequence of temperature cycles
470 critically converges backward in time to a date approximately half a day before
471 the appearance of the visible oscillations.

472 1.5.2. Seismic noise measurements

473 **Experimental setup..** The ambient seismic noise is sampled at a frequency of
474 250 Hz with an array of Geo Space GS-11D vertical geophones with a low-pass

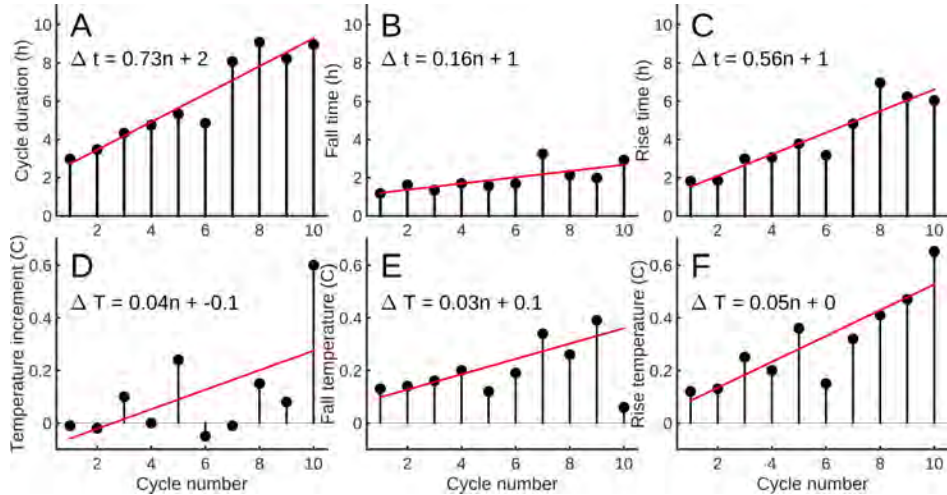


Figure 1.8: Characteristics of the temperature cycles identified (separated by thin vertical lines) in Figure 1.7 represented as a function of cycle number. A) Cycle duration; B) fall-time; C) Rise time; D) Temperature increment; E) Fall temperature; F) Rise temperature. Reprinted from Le Gonidec et al. [2019].

475 cut-off frequency of 3 Hz. Gantner A108 Analogue-to-Digital 19 bit modules
 476 are used to convert the analog signals to numerical data transferred to a Gant-
 477 ner QStation data concentrator. A common GPS time base is used for both
 478 temperature and seismic data. Two groups of 8 geophones form heptagonal
 479 arrays located East of the Tarissan crater and North of the Napoléon crater
 480 (NN array) and midway between Tarissan and South craters (POCS array
 481 (Fig.1.1). Three geophones are aligned along the fracture of the South crater
 482 (SC). Because of their location on top of the lava dome, the geophones are very
 483 sensitive to noise induced by meteorological conditions and anthropogenic noise
 484 (e.g. tourists walking on the summit).

485 **Data processing..** The SC and NN data were discarded because of a too low
 486 signal-to-noise ratio, and only the POCS data have been used to compute the
 487 RMS and the dominant frequency time-series of Fig. 1.7B,C. Both the RMS
 488 and the dominant frequency were computed for data segments of 20 s and for
 489 the 3–6 Hz range where the spectral coherency is maximum [Le Gonidec et al.,
 490 2019]. Both the seismic RMS and dominant frequency time series display the
 491 same oscillating pattern as observed in the temperature time series of Fig. 1.7A.
 492 The oscillations of the seismic RMS are advanced by 43 ± 11 min with respect
 493 to the temperature oscillations. Similarly, the dominant frequency curve is
 494 advanced by 48 ± 14 min. These delays eliminate the possibility that the vents

495 themselves are the source of the seismic noise.

496 The source of seismic noise is localized by back-propagating the delayed
497 seismic traces recorded by the geophones (POCS array geophones, 2 NN geo-
498 phones and 2 SC geophones). Time lags are determined by searching the maxi-
499 mum value of the cross-correlation between all pairs of seismic time-series. The
500 time lags are averaged for the 3-day period of data. Prior to cross-correlating,
501 the raw data are band-pass filtered in the $3\text{Hz} \leq f \leq 25\text{Hz}$ frequency band
502 where significant spectral coherency is observed for most pairs of seismic time-
503 series. Because of the lack of published seismic-velocity model for the lava
504 dome, we use a constant velocity to back-propagate the delayed wavefronts. In
505 the present study, the best refocusing of the wave-fronts is obtained for a seis-
506 mic wave velocity around 500 m/s in good agreement with the recent model of
507 volcano seismic velocities proposed by Lesage et al. [2018]. The source volume
508 is defined as the ensemble of voxels where at least 8 wavefronts refocus simul-
509 taneously. The source volume is represented in yellow in Fig. 1.9 and is rather
510 small, i.e. 10^4 m^3 , but apparently connected to one of the major fracture and
511 fumarole systems of the volcano.

512 1.5.3. Muography experiment

513 **Experimental setup.** The telescope used in the present study was equipped
514 with three parallel detection matrices of 10×10 pixels of $5 \times 5 \text{ cm}^2$. The two
515 extreme matrices were 1 m apart. All matrices were synchronized by the same
516 master clock signal with a timing resolution better than 1ns. No lead shield was
517 used since the telescope lay deep in a fault where surrounding rocks naturally
518 filter low-energy scattered particles that constitute the dominant source of
519 noise [Gómez et al., 2017]. For this telescope, the view field counted $M =$
520 $19 \times 19 = 361$ lines of sight, and the solid angle spanned by each line \mathcal{L}_k could
521 be adjusted by tuning the distance between the front and the rear matrices. The
522 telescope setup was: azimuth = 345° ; inclination = 28.5° ; $X_{UTM} = 20N643115$;
523 $Y_{UTM} = 1773938$; above m.s.l. In order to increase the acceptance and improve
524 the space- and time-resolution we merged lines of sight (see Extended Data Fig.
525 1 in Le Gonidec et al. [2019]).

526 **Monitoring with cosmic muons.** The source of the seismic noise associated
527 to the oscillation sequence (Fig. 1.7) was located inside the observation cone
528 of the muon telescope (Fig. 1.1). The time-resolution is about 10-20 days and
529 the variance of the muons counts was reduced by merging adjacent lines of
530 sight to increase the acceptance [Jourde et al., 2016a]. The muons count time-
531 series (Fig. 1.10) extends from 8 January to 14 April 2017 to largely encompass
532 the 3-day period where we evidenced the correlated events in the temperature
533 and seismic data. Fig. 1.10 displays the muon count time series in 4 areas:

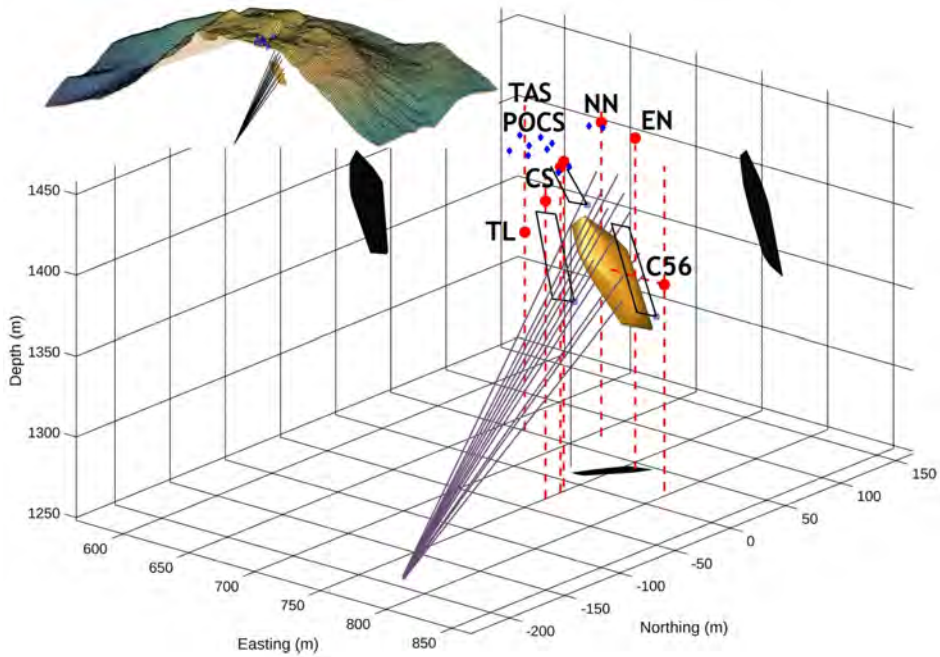


Figure 1.9: Location of the seismic noise source volume. The yellow body represents the 3D convergence zone of the seismic wavefronts recorded by the geophones of the POCS, CS and NN areas on top of the lava dome (blue dots). This volume is reconstructed by back-propagating the time lags of seismic signals and is likely to contain the sources of the seismic noise. The red dots represent the main active vents. The black patches are the projections of the source volume onto the faces of the 3D block diagram. The fan-like bundle of straight lines represents the lines of sight of the muon telescope crossing the active hydrothermal region and used to obtain the red curve in Fig. 1.10. The 3 black rectangles located above and on each sides of the source zone show the 3 adjacent areas corresponding to the curves labeled 2, 3 and 4 in Fig. 1.10. The telescope is located at the apex of the fan-like pattern. The inset shows the position of the seismic source zone in the lava dome (see Extended Data Fig. 6 for an enlarged version). The red dots mark the main fumaroles TAS = Tarissan crater, TL Tarissan acid pond, C56 = 56-crater fumaroles, CS = South crater fumaroles, NN = North Napoléon fumarole, EN = East Napoléon fumarole. POCS = main array of geophones used in the present study. The vertical dashed red lines passing through the fumaroles markers are upward-continued to the top of the lava dome to better show that TL and G56 are located in pits about 80 m below the surface. Reprinted from Le Gonidec et al. [2019].

534 one centered on the source of the seismic noise (red curve of Fig. 1.10), and
535 three areas located to the left, the right and above (blue curves in Fig. 1.10).
536 On 4 April 2017, we see a sharp increase in the muon count occurring in the
537 region of the seismic source while the other three areas remain stationary. The
538 time-resolution of the curves displayed in Fig. 1.10 is not as fine as in Fig.
539 1.7. However, we remark that a possible moderate increase may occur as soon
540 as 31 March when the descending phase of the flux oscillation is interrupted.
541 Consequently, there is possibly a delay of up to two days between the beginning
542 of the temperature and seismic oscillations shown in Fig. 1.7 and the onset on
543 increase of muon flux.

544 **1.5.4. Dynamics of the shallow hydrothermal** 545 **system**

546 The remarkable correlation observed in the oscillating time series of both tem-
547 perature and seismic noise attributes (Fig. 1.7) suggests a causal link between
548 the temperature measured in the vents and the activity of the source of seis-
549 mic noise localized using both the seismic and the muons data (Fig. 1.9 and
550 1.5). This source volume appears vertically elongated over more than 50m and
551 slightly inclined southward. Such a shape is partly a consequence of the ge-
552 ometry of the geophone array which is located only on the western side of the
553 source. Its lower part is connected to the 56-fracture which extends West-East
554 from the Napoléon to the Breislack craters (Fig. 1.1 and 1.11a). The sharp de-
555 crease in opacity observed in the source volume located within the lava dome
556 may be explained by the rapid invasion of steam flushing a liquid phase (Fig.
557 1.11b). This is likely due to the convective destabilization of hydrothermal flu-
558 ids triggering an ascent of hot fluids with increased gas fraction in the deep
559 part of the 56-fracture network. These hot fluids are likely to reside in the lava
560 dome and in the first hundreds of meters below. In this scenario, the oscilla-
561 tions shown on Fig. 1.7 are early-warning phenomena that occur at the very
562 beginning of the process with the first signs of destabilization within the source
563 volume (Fig. 1.11a). We check this idea by analyzing the temperature oscil-
564 lations as a log-periodic sequence [Sornette, 2006] to estimate the occurrence
565 time of an eventual singular event marking the destabilization. We find this
566 occurrence about 15 hours before the appearance of the first visible oscillation.

567 The time-variations in the dominant frequency of the seismic noise (Fig.
568 1.7C) may reflect long-period changes of the physical conditions in a resonator
569 formed by a fracture network filled with a liquid-bubble mixture of high bulk
570 compressibility, high density and low sound velocity (Fig. 1.11). The small
571 variations of the dominant frequency may be reproduced by varying the sound
572 velocity in a Helmholtz-like resonator system. Using the data modeling results

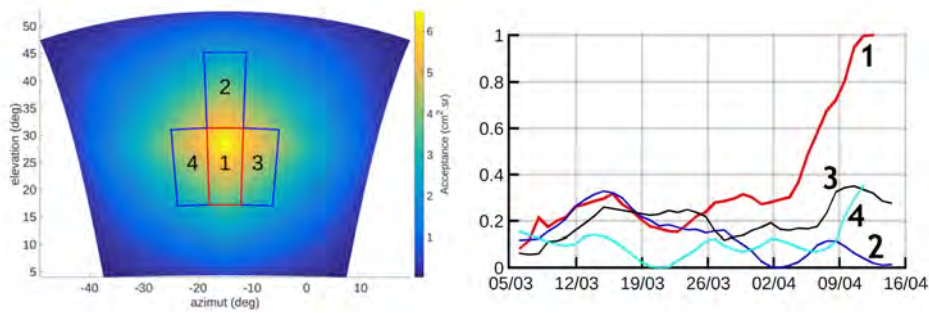


Figure 1.10: Time variations of the muon flux across different domains of the dome of La Soufrière. The red curve is for the bundle of lines of sight covering the seismic source zone of Fig. 1.9. The other three curves are for adjacent areas labeled 2, 3 and 4 in the inset showing the acceptance function of the telescope's view-field. Oscillation amplitudes are arbitrarily set to a common value. The total acceptance of bundles of lines of sight crossing the source area 1 is $54.3 \text{ cm}^2.\text{sr}$. The acceptances of the merged lines of sight in the areas 2, 3 and 4 are respectively $34.8 \text{ cm}^2.\text{sr}$, $40.3 \text{ cm}^2.\text{sr}$, and $45.8 \text{ cm}^2.\text{sr}$. For comparison, the maximum acceptance of the axial line of sight of the telescope equals $6.5 \text{ cm}^2.\text{sr}$. Adapted from Le Gonidec et al. [2019].

573 shown if the Fig. 9b of the article published by Kieffer [1989], we derive the
574 mass fraction φ of steam necessary to reproduce the observed frequency vari-
575 ations. We find that a minimum mass fraction $\varphi = 11\%$ is necessary to obtain
576 a physical solution and that variations of 0.25% above this value are sufficient
577 to reproduce the data. The frequency jump visible after 31 March (Fig. 1.7C)
578 requires a φ increase of 0.75%. Such a mass fraction corresponds to a volume
579 fraction of steam around 97% at pressures less than 10 bars. This would imply
580 a steam flow in either a slug or annular flow regime [Abdulmouti, 2014]. These
581 types of flow are known for their violent dynamics [Lane et al., 2001]. and
582 thus for their efficient seismic emissivity [Hellweg, 2000]. Two-phase flows in
583 conduit networks are reported to be intrinsically unstable and prone to oscilla-
584 tions sustained by turbulent movements and density waves [Fujita et al., 2011,
585 Dartevelle and Valentine, 2007]. In many instances, the period of the density
586 waves is proportional to the wave time-of-flight required to cross the system
587 [Kakac and Bon, 2008]. Within this phenomenological context, the observed
588 increase of the oscillation period in the temperature and seismic times series
589 (Fig. 1.7) may reflect a progressive extension of the size of the fracture network
590 occupied by the two-phase flow (Fig. 1.11A). This extension may result from
591 an enhanced extraction of the gaseous phase caused by the pressure oscilla-
592 tions [Luo et al., 1999] that may produce local negative pressure anomalies in
593 the deep parts of the draining network. This kind of positive feedback could
594 eventually lead to an abrupt jump of steam production exceeding the trans-
595 port capacity of the surface vents and leading to explosive events. Owing to
596 these observations, we consider that the 56-fracture of La Soufrière lava dome
597 is prone to destabilization and represents an area of potentially high risk level.
598 The fact that this fracture was the first to activate at the very onset of the two
599 last phreatic eruptions in 1956 and 1976 ([Rosas-Carbajal et al., 2016, Moretti
600 et al., 2020] and references therein); further confirms this argument The tem-
601 perature trend observed along the cycle of temperature oscillations may be
602 due to a constant steam supply causing a progressive increase of the pressure
603 in the source zone of Fig. 1.9. As revealed by gas geothermobarometry from
604 fumarolic fluid chemistry, this increase peaked in the April-May 2018 excursion
605 through the water critical point of water of the boiling hydrothermal portion
606 feeding summit fumaroles [Moretti et al., 2020]. Our integrated methodology
607 could then represent a monitoring technique able to track the hydrothermal
608 evolution well before that changes of P, T and composition are recorded by
609 fumarolic fluids.

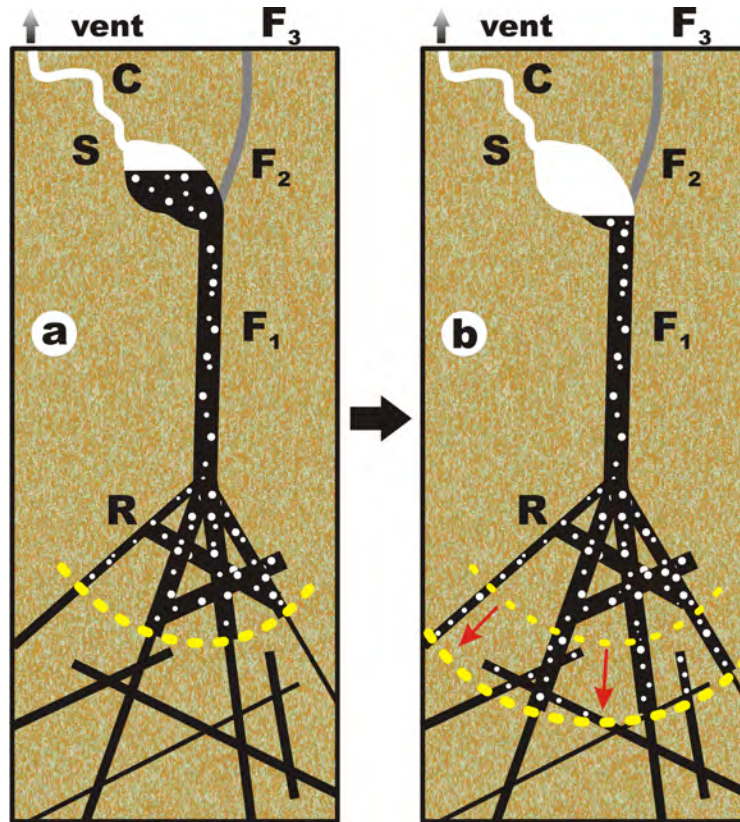


Figure 1.11: Conceptual view of the destabilization process as documented by the temperature, seismic and muon data. a) The lower part of the 56-fracture (F1) is filled with a mixture of liquid and rising bubbles coming from a lower feeding reservoir R. The two-phase flow is subject to density-waves oscillations causing hammering in the upper part S of the system corresponding to the yellow elongated volume of Fig. 1.9. S emits seismic noise and transmits pressure oscillations in the vent through the tortuous conduit C. As the volume of R increases (symbolized by red arrows and expanding yellow dashed lines), the period of the density waves increases as observed in Fig. 1.7. b) The increase of steam production causes an overpressure that flushes the liquid from S. This produces a huge decrease of density as seen in the muon telescope data of Fig. 1.10. F2 = low-permeability segment of the 56-fracture preventing strong surface emissions in the upper open segment F3 and favoring a deviation of the flux toward the South Crater vents through S and C. Adapted from Le Gonidec et al. [2019].

1.6. Conclusion

During the past decade, muography has progressively acquired a state of the art that makes this technique operational in many domains of Earth Sciences like, for instance, civil engineering, hydrology, archaeology and volcanology. This latter domain was among the firsts to be explored and it is now considered that muography belongs to the toolbox of imaging techniques available to study processes at work in active volcanoes. In the present chapter, with help of the case study of La Soufrière volcano, we show how muography can be used to obtain information both for structural imaging and functional imaging problems. We also show all the benefits that can be obtain by joining muography with other geophysical techniques like electrical resistance tomography, passive seismic monitoring, gravimetry and temperature measurements.

In the particular case of transient signals caused by rapid fluid movements and phases changes occurring in the shallow hydrothermal system described above, the time-resolution of muography is not sufficient to unambiguously detect the emergence of the phenomena at work. However, by joining muography data with high time-resolution data like temperature measurement in vents and passive seismic data, both a good space and time resolution can be obtained.

Further improvements could be obtained by using larger muon telescopes with high acceptance to improve the time resolution [Lesparre et al., 2010, Jourde et al., 2016a]. Coupling several telescopes placed at different stations around the volcano will also improve the 3D location of active hydrothermal focus. Other types of measurements like multi-gas and high time-resolution deformation, could also help to better constrain models and improve our understanding of rapid phenomena that might produce dangerous events.

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