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1 Seismic-refraction field experiments on Galapagos Islands: a quantitative tool for hydrogeology

2
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8 9 **Abstract**

10 Due to their complex structure and the difficulty of collecting data, the hydrogeology of basaltic
11 islands remains misunderstood, and the Galapagos islands are not an exception. Geophysics allows
12 the possibility to describe the subsurface of these islands and to quantify the hydrodynamical
13 properties of its ground layers, which can be useful to build robust hydrogeological models. In this
14 paper, we present seismic refraction data acquired on Santa Cruz and San Cristobal, the two main
15 inhabited islands of Galapagos. We investigated sites with several hydrogeological contexts, located
16 at different altitudes and at different distances to the coast. At each site, a 2D P-wave velocity profile
17 is built, highlighting unsaturated and saturated volcanic layers. At the coastal sites, seawater
18 intrusion is identified and basal aquifer is characterized in terms of variations in compressional sound
19 wave velocities, according to saturation state. At highlands sites, the limits between soils and lava
20 flows are identified. On San Cristobal Island, the 2D velocity profile obtained on a mid-slope site
21 (altitude 150 m), indicates the presence of a near surface freshwater aquifer, which is in agreement
22 with previous geophysical studies and the hydrogeological conceptual model developed for this
23 island. The originality of our paper is the use of velocity data to compute field porosity based on
24 poroelasticity theory and the Biot-Gassmann equations. Given that porosity is a key parameter in
25 quantitative hydrogeological models, it is a step forward to a better understanding of shallow fluid
26 flows within a complex structure, such as Galapagos volcanoes.

27 28 **Keywords**

29 seismic-refraction, volcanic rocks, water table, acoustic velocities, porosity

30 31 **Highlights**

- 32 - Seismic-refraction acquisition on volcanic islands
- 33 - Shallow hydrogeological targets: salted wedge or fresh-water aquifers
- 34 - Discussion about the applicability of the poroelastic theory for such acquisition
- 35 - Interpretation of velocities in terms of porosity using Biot-Gassmann theory

36 - Sensitivity approach of mechanical parameters on inverted porosities

37

38 1. Introduction

39

40 The hydrogeology of volcanic island is complex and remains poorly understood. Their hydrodynamic
41 functioning relies on a disrupted geological setting up. Alternating active volcanic phases which
42 contribute to the building up of the main edifice, combining basaltic lava flows or pyroclasts events
43 with quiet periods, where weathering processes are dominant and alter the fresh outcropped
44 basalts. As a result, the internal structure of volcanic islands looks like a layer-cake; where massive or
45 fractured basaltic lavas are interlayered with weathered material (ashes, clayed soils, weathered
46 basalts or pyroclasts...). Building an efficient flow model at island scale requires a large set of data:
47 climatological and hydrological monitoring to constrain the water cycle on surface but also
48 hydrodynamic parameters of the multi-layered system. In this context, porosity is one of the key
49 parameters for such flow modelling as it controls to the groundwater storage.

50 On Galapagos Islands, a previous study provides porosity and permeability data of soils at different
51 elevation points [Adelinet et al., 2008]. However, data is limited to the surface. The present study
52 suggests a new approach, which allows the estimation of the field porosity of the substratum (at
53 deeper levels) using its acoustic properties.

54

55

56 In order to investigate acoustic and petrophysical properties of Galapagos subsurface, we chose to
57 use seismic-refraction methods. The advantage of seismic methods compared to electrical ones for
58 instance is the direct relationship between acoustic velocities and porosity whereas electrical
59 methods are generally only useful to determine position of water table in such complex geological
60 structures [Revil et al., 2004; 2008]. Indeed, accurate knowledge of seismic velocities helps to
61 estimate the porosity of the groundwater formations. For instance in Garambois et al. [2002]
62 porosity is inferred by using both P and S waves compared with GPR results. We are aware that only
63 combined geophysical approaches can provide well-constrained hydrogeological models. However, as
64 many studies have been performed on Galapagos islands during the last decade, we chose to focus
65 our study only on the acoustic and petrophysical behaviour of both studied islands, Santa Cruz and
66 San Cristobal.

67

68 Seismic refraction methods are generally used in oil industry for static corrections in processing of
69 seismic reflection., and commonly in engineering applications (e.g. see Khalil and Hanafy [2008]). In
70 hydrogeology, it is less employed due to the lack of resolution in depth and also due to the cost of an
71 intensive processing. Moreover, seismic-refraction has some limitations, such as, when low-seismic-
72 velocity layers are overlain by high-seismic-velocity layers [Haeni, 1981]. Nevertheless, seismic-
73 refraction surveys have been used to describe the velocity structure of some basaltic islands, such as
74 Canary Island [Bosshard & MacFarlane, 1970; Banda et al., 1981] or Faeroe Islands [Pálmason, 1965].
75 A very interesting study has been performed in Iceland combining seismic tomography field
76 experiments with laboratory ultrasonic measurements to obtain a comprehensive picture of the
77 velocity systematics according lithology [Grab et al., 2015]. Generally, refraction survey carried out
78 on 2D lines allows the mapping of velocities on a depth profile. Different limits could be seen as
79 refractors for volumetric waves: interface between weathered and unweathered rocks, fracture

80 areas and limits between dry and saturated layers [Mari, 1999]. Indeed, water table is a very
81 effective refractor with P-wave velocities in saturated rocks generally more than 1500 m/s [Kearey et
82 al., 2013]. In our case, seismic refraction is used to assess subsurface acoustic properties. In such
83 case, targets are close to the surface, less than 50 m deep, and therefore issues on depth resolution
84 and cost are overcome. Interpretation of layer velocity can be assured as we expect an increasing
85 gradient of velocity with depth at this scale. Indeed, if we consider the largest scale of the entire
86 island, this assumption could not be validate due to the structural alternating sequence of lava flow
87 deposits and soil/weathered rock, which could potentially results in a low velocity layer underlying a
88 high velocity layer.

89
90 In this paper, rather than just present the velocity structure of the subsurface, we propose to go a
91 step further by using velocity data to derive porosity. The present study is included into the
92 Galapagos Islands Integrated Water Studies project (GIIWS), which begins in 2003 [d'Ozouville, 2007;
93 d'Ozouville et al., 2008a, 2008b; Auken et al., 2009; Pryet, 2011a, 2011b; Pryet et al., 2012a, 2012b;
94 Violette et al., 2014; Dominguez et al., 2016]. Note that before this project, no baseline data existed
95 for hydrogeological understanding on Galapagos. The keypoint of the GIIWS is to use several datasets
96 in order to build robust conceptual hydrogeological models for Santa Cruz and San Cristobal islands.
97 Dataset are collected using in-situ measurements and indirect data, such as geophysical
98 measurements. The integration of a large datasets is very important to understand the
99 hydrogeological working of such complex structure as described on a Micronesian example by Ayers
100 & Vacher [1986], on La Reunion [Violette et al., 1997], on Mayotte island [Vittecoq et al., 2014]
101 andon Martinique Island [Vittecoq et al., 2015].

102
103 The present paper is structured as follow: First, the acquisition on sites and the layouts on both
104 islands are extensively presented. Second, we figure out the different 2D velocity profiles deduced
105 from raw seismic data. Third, we interpret our velocity data in terms of porosity data in the
106 poroelasticity framework. Finally we discuss the results in a global hydrogeological framework.

107

108

109 **2. Material and methods**

110

111 **2.1. Sites description**

112 The archipelago is located on the Ecuador at about 1000 km west from the South America continent.
113 Santa Cruz and San Cristobal Islands are respectively in the central and eastern part of the
114 archipelago. Geologically they belong to the central sub province [Mc Birney and Williams, 1969;
115 Bow, 1979; Geist et al., 1998]. Both islands are built from similar basaltic rocks and are exposed to
116 similar climate conditions. However there are some differences between islands. In terms of age, San
117 Cristobal is older than Santa Cruz with the more recently erupted lavas dated of 2.4 M.y. [Geist et al.,
118 1986] against 1.3/0.95-0.05 M.y. on Santa Cruz [White et al., 1993]. The weathered cover is also
119 different: 1 m on Santa Cruz compared to 10 m on San Cristobal [Geist et al., 1986]. On both islands,
120 physical properties of soils evolved according to the elevation and the rainfall regime [Adelinet et al.,
121 2008; Violette et al., 2014]. Soils are thicker, less porous and less permeable in altitude than near the
122 coast.

123

124 In the frame of this study, two seismic campaigns have been carried out on Galapagos Islands. Three
125 sites on Santa Cruz (SZ) Island were investigated in 2011 whereas six sites on San Cristobal (SC) Island
126 were done in 2013. Experiments were carried out at the same time of the year, in the beginning of
127 the cool season (July). Figure 1 presents maps of the sites location on both islands. Sites have been
128 chosen according to their altitude and distance to sea. We defined three types of location: coastal,
129 mid-slope and highlands (Table 1). Mid-slope and highland sites are always located on the windward
130 side of the islands. Ground floors of sites present also different aspects (Figure 2): unweathered or
131 weathered basalts, scoria cone, pyroclasts, soils, etc... Coastal sites have been chosen to estimate
132 wave velocities of basaltic rocks where water table position is known, *e.g.* limit between dry basalts
133 and basalts saturated with salt water due to ocean intrusion. Given the expecting layering in these
134 sites, interpretation should be much easier: dry versus water saturated basalts or scoria. Windward
135 highlands sites have been studied mainly to measure the thickness of soils, which is a key parameter
136 to quantify storage in the water cycle and water flow as a recharge to deep aquifers. Mid-slope sites
137 have only been investigated on San Cristobal because the perched aquifers depth is compatible with
138 the penetration depth of seismic-refraction method (several tens of meters). Indeed the emergence
139 of springs indicates the existence of shallow groundwater on San Cristobal [Pryet et al., 2012a;
140 Dominguez, 2016]. On the contrary, Santa Cruz Island presents a buried perched aquifer, identified
141 by helicopter borne geophysical method at more than 100 meters depth [d'Ozouville et al., 2008;
142 Auken et al., 2009; Pryet et al., 2012a], a depth that cannot be reached with sledge-hammer source.

143

144 Let now detailed the site location and the layout for both islands. SZ1 is very close to the seashore
145 (Figure 1), on a 6.5 m high cliff. The seismic line was deployed perpendicular to the seashore. SZ2 is
146 an urban site; the line follows the drawing of a future road that leads to a residential area. As
147 observed in the picture of figure 2, the road is without asphalt. The line was also deployed
148 perpendicularly to the seashore. SZ3 is located in a pasture with flourishing vegetation. This longest
149 investigated line was deployed south-eastward along the steepest slope. During acquisition, weather
150 was foggy and rainy on this last site. SC1 is a San Cristobal site, the nearest from the coast. The line
151 was deployed parallel to the seashore. SC2 is an urban site on a road without asphalt, the line was

152 deployed perpendicularly to the seashore. SC3 is close to the airport and to a scoria cone on which
 153 an open-pit mine is settled. Figure 3 presents a detailed map of windward mid-slope sites on San
 154 Cristobal (SC4 and SC5). SC4 is located downstream of a major water catchment of the island (Cerro
 155 Gato water catchment) and near a perennial stream of the same name. An outcrop of pyroclastic
 156 material has been described just above the seismic layout [Izquierdo et al., 2015]. SC5 is located on a
 157 watershed beside the one of SC4 (Figure 3b and c). The seismic line has been deployed near a
 158 temporary river-bed. We will discuss further the implication of the mid-slope sites locations in terms
 159 of velocities in section 3.2. SC6 is on the same watershed than SC4 but in the top of it (altitude
 160 around 600 m).

161 **Table 1 - Description of sites investigated by seismic-refraction on Santa Cruz and San Cristobal islands**

ISLAND	SITES	ALTITUDE m a.s.l.	DISTANCE TO SEA m	LOCATION TYPE	DESCRIPTION
Santa Cruz	SZ1	6.5	20	Coastal	Perpendicular to seashore, on a 6.5 m high cliff, basaltic lava flow without soil
	SZ2	20	1495	Coastal	Compact soil with scoria deposits
	SZ3	393	7950	Highlands	Thick clayed soil layer with abundant vegetation, humid condition for acquisition
San Cristobal	SC1	1	135	Coastal	Parallel to seashore, compact soil with scoria debris (probably substratum is scoria)
	SC2	8	350	Coastal	Compact soil with rock debris (the substratum is probably basaltic rock)
	SC3	10	915	Coastal	Close to a scoria cone (red mine), compact soil with debris (the substratum is probably scoria deposit)
	SC4	160	1295	Mid-slope	Soil and weathered basalt, near a pyroclastic outcrop
	SC5	230	1790	Mid-slope	Silty to clay soil
	SC6	590	3870	Highlands	Clayed soil (more than 4 m of thickness)

162

163

164 **2.2. Survey layout and processing for seismic-refraction**

165 As far as waves are generated by a sound source and travel across a layered media, different
 166 processes occur: wave can be diffracted, reflected or refracted on interfaces. Seismic-refraction
 167 methods measure the shortest time of a compressional wave to travel down from the source,
 168 through the ground, and back up to sensors placed on the land surface. By measuring the travel
 169 times of the sound wave and applying the Snell-Descartes's law that governs the propagation of
 170 sound, the geometry and characteristics of the subsurface geology and/or hydrogeology can be
 171 inferred. Therefore, field data consist of measured distances and seismic travel times. From this time-
 172 distance information, velocity variations and depths to individual layers can be calculated and
 173 modelled.

174
 175 The seismic-refraction survey carried out on Galapagos Islands involves a total of 9 lines. Figure 4
 176 describes the layout used on Santa Cruz (SZ) and San Cristobal (SC) sites. Each line was shot in both
 177 forward and reverse order. The sound source is a 4 kg sledge-hammer striking a Teflon plate. The
 178 shot points (SP on Figure 4) are spread on the lines with minimum 4 end-off and 1 central shots. 24
 179 geophones of natural frequency of 10 Hz are regularly spread on the lines and measure the wave
 180 acceleration in the vertical direction. The distance between two geophones (inter-trace IT on figure
 181 4) varies between 1 and 5 m, depending on the studied site. Table 2 summarizes the distances and
 182 acquisition parameters used for each site. No frequency filters were applied during data acquisition.
 183 Objectives were different according to the sites. For the coastal ones, the objective is to visualize the
 184 interface between dry and water saturated rocks having the visual control of the sea level. We know
 185 that P-wave velocities are not sensitive to varying salt content of the groundwater, however as soon
 186 as we are closed to the sea shore we can interpolate this interface as the top of the salty wedge. The
 187 objective in highland site (SZ3) is to estimate the soil thickness and the weathered basalt properties
 188 for highland sites, thus a longer line was used for SZ3. At San Cristobal sites, we had the experience of
 189 Santa Cruz experiments made 2 years before. In addition targets were shallower, thus long lines were
 190 not useful. As a consequence, we used the same layout with a line length of about 100 m and a 2 m
 191 inter-trace for all the sites on San Cristobal. The same layout allows us to compare results from one
 192 site to another in terms of depth penetration and P-wave velocities.

193
 194 **Table 2 - Layout description of seismic-refraction survey on Santa Cruz and San Cristobal islands**

ISLAND	SITES	geophone spacing (m)	Seismic spread (m)	Geophones	Strike bases	Acquisition system	Acquisition time / sample interval (ms)
Santa Cruz	SZ1	1	33	1C - 10 Hz	5	DAQLINK III	500 / 0.5
	SZ2	2	66	1C - 10 Hz	5	DAQLINK III	500 / 0.5
	SZ3	5	165	1C - 10 Hz	5	DAQLINK III	500 / 0.5
San Cristobal	SC1	2	96	1C - 10 Hz	9	GEODE GEOMETRICS	500 / 0.5
	SC2	2	96	1C - 10 Hz	9	GEODE GEOMETRICS	500 / 0.5
	SC3	2	96	1C - 10 Hz	9	GEODE GEOMETRICS	500 / 0.5

	SC4	2	96	1C - 10 Hz	9	GEODE GEOMETRICS	500 / 0.5
	SC5	2	96	1C - 10 Hz	9	GEODE GEOMETRICS	500 / 0.5
	SC6	2	96	1C - 10 Hz	9	GEODE GEOMETRICS	500 / 0.5

195

196 Samples shot gather of the raw data is given in Figure 5. Trace normalized amplitudes are used for
 197 display purpose. The data show good quality where first arrival refracted waves are easily identified.
 198 General workflow of seismic-refraction processing is presented on Figure 6. Data were analyzed using
 199 the software programs Pickwin (ver 5.1.1.2) and Plotrefa (ver 3.0.0.6) from the Seismager software
 200 package developed by Geometrics Inc. The first step consists in picking first break arrivals of each
 201 shot point (5 for Santa Cruz sites and 9 for San Cristobal sites). It corresponds to P-wave arrivals. The
 202 picking was performed manually (Figure 6.1) using Pickwin. Then arrival times are plotted against
 203 source-to-geophone distances, which results in time-distance or traveltimes curves (Figure 6.2). The
 204 tomographic method using Plotrefa [Zhang & Toksoz, 1998] involves the creation of an initial velocity
 205 model. Four parameters are required: the depth to top of the lowest layer, the minimum and
 206 maximum velocities and the number of layers. According geophone spacing, depth to top of the
 207 lowest layer is equal to 10, 20 or 40 meters (respectively for 1, 2 and 5 meters geophone spacing).
 208 Minimum and maximum velocities are fixed from the traveltimes curves, adding 30 % for the
 209 maximum value. Generally, these values are set to 300 m/s (propagation of the sound in air) and
 210 3000 m/s, respectively. The number of layers is always fixed to 20. Then, the tomographic method
 211 involves iteratively tracing rays through the model, comparing the calculated travel times to the
 212 measured travel times, modifying the model, and repeating the process until the difference between
 213 calculated and measured times is minimized.

214

215

216 At the end of the tomography process, a global Root Mean Square (RMS) error is calculated,
 217 integrating all errors between calculated and measured traveltimes in a least square meaning. This
 218 parameter assesses the quality of the workflow. Table 3 presents the final RMS errors obtained after
 219 the tomography processing of the nine studied profiles. The final RMS errors lie between 0 and 3 ms
 220 for most of the profiles (SZ1, SZ2, SC1, SC2, SC3, SC4 and SC5). Profiles SZ3 and SC6 show increased
 221 RMS errors, which can be related to poorer data quality caused by worse acquisition conditions (bad
 222 coupling due to wet clayey soils for these highland sites) compared to the other profiles. Moreover,
 223 RMS errors calculated for Santa Cruz sites are higher than the ones for San Cristobal. This can be
 224 consequence of the number of shot points : 5 for Santa Cruz and 9 for San Cristobal leading to a
 225 better convergence.

226

227 **Table 3 – Mean RMS errors obtained for the nine profiles after the tomography process. These values show that the**
 228 **models fit our travel time data well.**

Site	SZ1	SZ2	SZ3	SC1	SC2	SC3	SC4	SC5	SC6
RMS error (ms)	1.024	2.365	3.757	0.864	0.262	0.966	0.836	1.104	3.846

229

230 The final cell size of the tomography model depends on the geophone spacing for the horizontal
 231 component and on the resolution during raytracing processing for the vertical one. The vertical

232 resolution is globally equal to the half of the horizontal one. Table 4 summarizes the cell size
 233 obtained for the studied profiles according to the geophone spacing and also the total number of
 234 cells.

235
 236 **Table 4 - Horizontal (X size) and vertical (Z size) components of the tomography cell for each profile. The total number of**
 237 **cells is also mentioned.**

Site	SZ1	SZ2	SZ3	SC1	SC2	SC3	SC4	SC5	SC6
X size (m)	1	2	5	2	2	2	2	2	2
Z size (m)	0.5	1	2.5	1	1	1	1	1	1
Number of cells	486	630	517	432	432	432	432	432	432

238
 239 Using as example the SC2 profile, figure 6 provides the reliability of raytracing and the tomography
 240 processing of our study case. Observed and calculated traveltimes are very closed (Figure 6a) and
 241 raytracing is coherent (Figure 6b). Note that we compare the first arrivals only for the times that are
 242 inside the profiles. Indeed cells that are off sides are not covered by enough rays and then cannot be
 243 solved. Final RMS error is low, less than 1 ms, decreasing sharply just after one iteration (Figure 6c).
 244 Assessing the coherence of raytracing allows us to be confident with the penetration depth.
 245 Following results have been checked to be reliable in terms of depth.

246
 247
 248
 249

250 3. P-wave tomography results

251 Before our results are presented, we want to note once again that seismic-refraction is not the more
 252 efficient tool to study the variation of salt content into water. Therefore, we would infer the sea
 253 intrusion beneath island only for the coastal sites, where we know that the salty wedge is at the
 254 same depth that the groundwater level. Indeed, near the coast, the freshwater layer is very thin with
 255 only a few centimetres thick. At other sites, the visible water saturated layers can only be described
 256 as groundwater levels.

257 258 3.1. On Santa Cruz Island

259 Figure 8 presents the tomography profiles of the three sites investigated on Santa Cruz Island.
 260 Resolution in depths and in P-wave velocities is different due to the variable intertrace between
 261 geophones. All profiles are shown with a flat surface because we succeed to deploy the different
 262 profile without important topographic variations. SZ1 site is located on a cliff (6.5 m above the sea
 263 level) with a direct visual checking of the seawater level. Outcrops exhibit a massive basaltic lava flow
 264 with numerous metric fractures. The velocity profile precisely presents a strong refractor 6.5 m
 265 beneath the ground surface, which corresponds to the sea water level position. A first layer of very
 266 low velocity (around 500 m/s) is very thin (about 2 meters width) and corresponds to unconsolidated
 267 material. The second and third layers of velocity respectively around 1600 m/s and 2400 m/s, are
 268 separated by an interface located at the sea water level position. Thus, these layers correspond

269 respectively to dry and seawater saturated layers. This site allows the possibility to check the
270 application of seismic-refraction to visualize ocean intrusion.

271

272 On SZ2 profile, the seawater level is also visible, 20 m deep beneath the ground surface, which
273 corresponds to the altitude of the site. We have access to more information than for SZ1 concerning
274 the velocity layering thanks to a higher penetration depth (due to longer seismic line). The thickness
275 of the first layer of low velocity (500 m/s) is about 2 meters and it could correspond to embankment.
276 Indeed, the seismic line of SZ2 has been deployed on a future road. The second very low velocity
277 layer (around 1000 m/s) is several meters thick with a lateral variation from 2 to 6 meters thick. It
278 could correspond to burden unconsolidated material. Beneath this layer we find again a low velocity
279 layer with a magnitude similar to the one obtained on SZ1 (around 1600 m/s), which is considered as
280 a dry layer. Finally, beneath the seawater level, we identify a water saturated layer with higher
281 velocity (2400 m/s) which can be the top of the salty wedge.

282

283 The profile obtained on SZ3 site is the longest one of the present study. Distance between
284 geophones is 5 meters, and the total spread is about 200 m. Due to the poor signal to noise ratio, the
285 identification of the first break is more difficult in this profile. The global RMS error is quite high
286 (Table 3: less than 4 ms actually). However, results are coherent with the other ones and the
287 penetration depth is about 50 m. A first velocity layer with P-wave velocity around 350 m/s is
288 observed from the surface to about 15 m deep. This velocity value is closed to the one of P-waves
289 into the air (340 m/s), that is why we assume that this first layer is an unconsolidated one.. Beneath
290 this very low velocity layer, a medium of about 15 m deep with a velocity around 1500 m/s is visible.
291 This layer covers another velocity layer with a positive gradient according the depth, from 1500 m/s
292 to 2400 m/s at the deepest parts of the profile. Mostly In the western part of the profile, beneath
293 about 30-40 m depth we find a high velocity layer (about 2400 m/s). Regarding results obtained on
294 SZ1 and SZ2 we interpreted it as a water saturated layer. But the resolution is too low to be sure on
295 this last interpretation.

296

297 To conclude on Santa Cruz, we identified three layers, from top to bottom: unconsolidated material
298 with very low velocities near the surface, a dry layer associated to low velocities (around 1600 m/s)
299 and a water saturated one associated to high velocities (2400 m/s). The last one can be easily
300 identified at SZ1 and SZ2. Note that, even for the high velocity layer, the absolute velocity values
301 remain low. It is probably because of the high degree of fracturing in the basaltic rocks, which is in
302 agreement with the outcrop observations made on the cliff beneath SZ1. Compressive acoustic
303 waves are very sensitive to fractures, and their velocity decrease sharply with increasing fracture
304 density.

305

306 **3.2. On San Cristobal island**

307

308 Figures 9 and 10 present the P-waves velocity models obtained respectively at the three coastal sites
309 and at the three mid-slope and highland sites on San Cristobal Island. Similarly to Santa Cruz, three
310 velocity layers could be identified from the six profiles as follows:

- 311 - A very low velocity layer (around 500 m/s) interpreted as unconsolidated material
- 312 - A low velocity layer (between 1400 and 1700 m/s) interpreted as dry rocks

313 - A high velocity layer (between 2400 and 2700 m/s) interpreted as water saturated rocks,
314 note that water can be salty or fresh depending of the location, coastal or highland
315 respectively.

316

317 San Cristobal coastal sites (SC1, SC2, SC3) have a flat topography. The velocity models of these sites
318 present a thin unconsolidated layer near the surface (Figure 9). The thickness of this layer is less than
319 1 meter for SC2 and SC3 and about 2 meters for SC1. The ocean intrusion is visible for the three
320 coastal sites at sea level. As SC1 is the nearest site from the seashore, the saturation interface is a
321 strong refractor and could hide a limit of alteration located just above. Thus the first layer with low
322 velocity is probably in fact a mixed layer composed with unconsolidated material and unsaturated
323 rocks. This can explain its relative high thickness according to other coastal sites. Once again, at this
324 site the sea water intrusion appears beneath the real sea level. Moreover, as SC1 is the nearest site
325 from the seashore, it could be due to a tide effect. SC2 presents the typical layering made with a very
326 low velocity layer (less than 500 m/s) of unconsolidated material, a low velocity one (around 1600
327 m/s) of unsaturated fractured basalts and a high velocity one (around 2700 m/s) associated to a
328 water saturated layer. The saturation interface is shown at sea level as expected. SC3 presents the
329 same layering than SC2 with a smoother transition between water saturated and unsaturated layers.
330 Moreover, the velocity of the water saturated layer is lower for SC3 profile (around 2400 m/s) than
331 for the SC1 and SC2 ones(around 2700 m/s).

332

333 Results obtained for mid-slope and highland sites are contrasting (Figure 10). First, these profiles
334 present a topography (more than 15 % slope for SC5 and SC6 for instance). The velocity profile
335 deduced at the highest site (SC6) presents only one very low velocity layer associated to soil, with
336 one sublimit inside, at about 30 m depth. Site SC5 is located at a mid-slope on the windward side as
337 well. The first layer is thinner (about 3.5 meters). This soil layer is above a distinguishable low velocity
338 layer (around 1300 m/s), which could be associated to dry material according to the results obtained
339 at the coast. In the northern part of the profile, a layer with higher velocity (2000 m/s) is recognisable
340 in depth. It could be the top of a partially saturated level. The fully saturated layer would be located
341 below.

342

343 Finally, tomography profile obtained on SC4 is the most interesting one. From a hydrological point of
344 view, this site is located downstream of a major perennial spring of the island (Cerro Gato spring) and
345 near a stream fed from this spring. The spatial configuration of seismic layout regarding the
346 hydrological aspects is presented on figure 3. The first soil layer is about 3 m deep, comparable to
347 SC5. Beneath, the second velocity layer of about 10 m width corresponds probably to an unsaturated
348 layer. But on the contrary to SC5, there is clearly a third layer on the bottom part of the profile with
349 high velocity (about 2400 m/s). This layer might correspond to a saturated material. The velocity
350 value is indeed similar to the corresponding one measured on SC3.

351

352 **4. Interpretation of tomography results**

353

354 **4.1. Geological and hydrogeological interpretations**

355 From an acoustic velocity point of view, both islands present the same layering in the subsurface (i.e.
356 in the first dozen of meters): an unconsolidated level near the surface with very low velocities
357 associated to unconsolidated material, a low velocity layer associated to dry volcanic material and a
358 high velocity level in depth, associated to water saturated volcanic material.

359

360 The first layer located very close to the surface could be interpreted as debris at the coast
361 (embankment or desegregated volcanic material) and clayed soil in the highlands. For instance, on
362 SC6, It could be interpreted as a thick soil above highly weathered volcanic material. Indeed, at the
363 end of the formation of San Cristobal, the island was partially covered by pyroclastic deposits
364 according to Geist et al. [1986]. The alteration of such material may have formed the soil we see on
365 the seismic-refraction data. Coastal sites with visual controls on the geology and the saturation
366 interface allow the quantification and calibration of velocity in basalts, while it is water saturated or
367 not. This is the case of SZ1 and SC1, providing basaltic lava flows on outcrops. Variations in velocities
368 according to these calibration data supply new information. For instance, the saturated layers of SC3
369 and SC4 have lower velocities than the saturated layers of SC1 (2400-2500 m/s against 2700 m/s). It
370 could be explain by the nature of the basement, SC3 and SC4 are very close to a scoria deposit cone
371 where pyroclastic deposits can be observed around the areas (Figure 3). Now, if we compare both
372 islands, on Santa Cruz, the velocities respectively in dry and water saturated basalts are around 1400
373 and 2400 m/s whereas on San Cristobal they are 1400 and 2700 m/s, respectively. The velocity
374 difference between the two islands could be explained by the elder of each one. Indeed, as
375 mentioned in the introduction, Santa Cruz is younger than San Cristobal and probably their fractures
376 in basalts are fresher and not filled with other material (able to reduce the porosity). On San
377 Cristobal, cooling fractures should be filled by alteration material or oversaturated fluid precipitation.
378

379 From a hydrogeological point of view, SC4 shows important results. The existence of a high velocity
380 layer related to a water saturated level is clear. This could be interpreted as an aquifer.. This result is
381 in accordance with previous helicopter-borne geophysical study, which reveals that both islands have
382 prominent low resistivity layers in the range of 30-130 ohm.m beneath the windward highlands
383 [d'Ozouville et al., 2008b; Auken et al., 2009; Pryet et al., 2011b, 2012a]. These resistivity values are
384 of particular interest because they are characteristic of basalt saturated with water on other islands
385 [Lienert, 1991; Descloitres et al., 1997; Krivochieva and Chouteau, 2003; Vittecoq et al., 2014 and
386 2015]. The Cerro Gato stream is located 80 m away from the left limit of the profile (A). This layer
387 could be a saturated layer that corresponds to a freshwater perched aquifer supplying the
388 hydrographic network. The water table is quite horizontal with a very low slope (2° towards the SW).
389 corresponding to the direction of the topography. The orientation suggests that the aquifer is fed by
390 the stream. Compared to SC4, profile obtained on SC5 does not show any fully water saturated layer.
391 Figure 3 shows that SC5 is near from a temporary river bed. As we investigated sites during the end
392 of the hot season (in July), the river bed was dry. Consequently groundwater could be at deeper
393 levels and not supplied by surface network at this period of the year.

394

395

397 A key point to build quantitative hydrogeological model is the assessment of porosity of the different
 398 geological layers, porosity being the storage capacity of an unconfined aquifer. Acoustic velocities
 399 associated with effective medium modelling can bridge the gap between the geological lithology
 400 description and the porosity assessment at field scale [Adelinet et al., 2011; Adelinet & Le Ravalec,
 401 2015]. Indeed, P-waves (and also of course S-waves) are very sensitive to the rock heterogeneity,
 402 such as grain contacts, pores, cracks or fractures, and Galapagos volcanic islands are a highly
 403 fractured medium. However, according to the scale and to the geophysical method, we do not
 404 investigate the same size of heterogeneity, it depends on the wavelength. In our case, due to the
 405 acquisition layout (sledge-hammer source), we have a central frequency of about 100 Hz [Keiswetter
 406 and Steeples, 1995; Feroci et al., 2000]. Given an average P-wave velocity of 2000 m/s, it results in an
 407 average wavelength of 20 m for our seismic experiment. According to the standard test method for
 408 the determination of velocities [ASTM D2845-08, 2008], the wavelength should be at least three
 409 times the average heterogeneity size. Reversely, that means that our method provides velocities
 410 affected by heterogeneities of several meters length (fractures specially). Moreover, considering that
 411 seismic resolution is defined by a rule of thumb as the quarter of the wavelength, it means that our
 412 acquisition set-up would not be accurate to image anything with a thickness smaller than 5 meters.
 413 Besides, as seismic data reveal the existence of saturated layer in depth, we have to discuss another
 414 frequency effect on elastic properties of volcanic material. Indeed, at low frequency, the fluid
 415 pressure is constant and unaffected by the seismic waves, it is the drained regime. At higher
 416 frequencies, the assumption of fluid pressure equilibrium becomes invalid, the fluid pressure is
 417 locally uniform but changes when the waves pass through ; the regime is called the undrained
 418 regime. Both drained and undrained regimes are relevant of the poroelasticity theory [Gassmann,
 419 1951; Biot, 1956; Murphy, 1986]. According Cleary [1978], the cut-off frequency (f_c) between the
 420 drained and the undrained states depends on the rock intrinsic permeability k (m^2), the drained bulk
 421 modulus K_d (equal to the dry modulus, Pa), the fluid viscosity η ($Pa.s$) and a flow length L (m) as
 422 follows:

$$423$$

$$424 \quad f_c = \frac{4 \times k \times K_d}{\eta \times L^2} \quad (1)$$

$$425$$

426 The poroelasticity framework and the associated equations allow calculating the drained saturated
 427 moduli from the drained dry ones. To apply such theory we need to know in which frequency range
 428 the field experiments are. We can evaluate the cutoff frequency for our investigated sites
 429 considering a flow length, L , equal to a half wavelength (around 10 meters) and a drained dry bulk
 430 modulus around 10 GPa. The touchy parameter is the rock intrinsic permeability. At the laboratory
 431 scale, andesite basaltic and scoria flows may have the same permeability around $10^{-12} m^2$ [Saar and
 432 Manga, 1999]. We expect that on the field and due to fractures, the permeability is higher. Based on
 433 a hydrogeological modelling, Dominguez [2016] provide range between 10^{-9} and $10^{-11} m^2$ for San
 434 Cristobal sites, which are in agreement with literature on permeability in highly fractured basalts
 435 [Bear, 1972]. Furthermore, Ingrebitsen & Scholl [1993] provide near surface horizontal permeabilities
 436 around $10^{-10} m^2$ for the Hawaiian Kilauea volcano which is a good analogue for Galapagos islands
 437 [Violette et al., 2014]. Now, if we take an average value of $10^{-10} m^2$ for our field sites, we obtain a cut-
 438 off frequency of 0.4 Hz between the drained regime and the undrained one. This value is lower than
 439 the sledge-hammer frequency of 100 Hz and then validates our poroelastic approach that we will

440 describe now, *i.e.* we will assume that fluid pressure in the saturated basalts is affected by the
 441 seismic wave (undrained regime).

442

443 Our goal is to relate P-wave velocities to porosity for each investigated site. In an isotropic
 444 framework, P-wave velocity (VP) can be written as a function of bulk and shear moduli, respectively
 445 noted K and G, as follow:

$$446 \quad VP = \sqrt{\frac{K + \frac{4}{3}G}{\rho}} \Leftrightarrow K = \rho VP^2 - \frac{4}{3}G \quad (2)$$

447 Where ρ is the rock bulk density.

448 Given that our interest is the difference between dry (subscript _{dry}) and saturated (subscript _{sat}) state,
 449 we introduce ΔK as the difference between the saturated and the dry bulk modulus:

$$450 \quad \Delta K = K_{sat} - K_{dry} = \rho_{sat}VP_{sat}^2 - \frac{4}{3}G_{sat} - \rho_{dry}VP_{dry}^2 + \frac{4}{3}G_{dry} \quad (3)$$

451 Considering that we remain in the poroelasticity framework, we can use the first equation of Biot-
 452 Gassmann, which announces that the saturated shear moduli is equal to the dry one. So:

$$453 \quad \Delta K = \rho_{sat}VP_{sat}^2 - \rho_{dry}VP_{dry}^2 \quad (4)$$

454 So, the variation in bulk moduli is directly related to the variation of P-wave velocity according
 455 saturation state. Velocities in dry and saturated medium are available on sites where a water table is
 456 visible (sea water level or perched aquifer), *i.e.* sites SZ1, SZ2, SZ3, SC1, SC2, SC3 and SC4.

457 Moreover, density is related to the porosity ϕ according the saturation state by:

$$458 \quad \rho_{sat} = (1 - \phi)\rho_0 + \phi\rho_w \quad (5)$$

$$459 \quad \rho_{dry} = (1 - \phi)\rho_0 \quad (6)$$

460 Where ρ_0, ρ_{dry} and ρ_{sat} are the densities of the matrix, the dry rock and the saturated rock
 461 respectively.

462 Then, ΔK can be expressed as a function of porosity and variation in velocities (noted ΔK_{VP} due to
 463 the use of P-wave velocities):

$$464 \quad \Delta K_{VP}(\phi) = (1 - \phi)\rho_0(VP_{sat}^2 - VP_{dry}^2) + \phi\rho_w VP_{sat}^2 \quad (7)$$

465 Besides, the second Biot-Gassmann equation relates the saturated and the dry bulk moduli as:

$$466 \quad K_{sat} = K_{dry} + \frac{\beta^2 K_f}{\phi + (\beta - \phi)\frac{K_f}{K_0}} \quad (8)$$

467 Where β is the Biot coefficient, K_f and K_0 the water and matrix bulk modulus respectively. Besides,
 468 the Biot coefficient is equal to:

$$469 \quad \beta = 1 - \frac{K_{dry}}{K_0} \quad (9)$$

470 Then the variation in bulk modulus can be expressed in a different way as a function of porosity
 471 (noted ΔK_{BG} due to the use of Biot-Gassmann theory):

$$472 \quad \Delta K_{BG}(\phi) = \frac{\beta^2 K_f}{\phi + (\beta - \phi) \frac{K_f}{K_0}} \quad (10)$$

473 No assumption is made on nature of porosity inclusions in the Biot-Gassmann equations: it is a
 474 macroscopic approach using the total pore space. We keep in mind that for water catchment the
 475 effective porosity is need. Our approach could be coupled with a structural geological field work to
 476 analyse precisely the fracture network. The next step would be to calculate the porosity proportion
 477 identified as crack porosity and introduce it in the effective medium modelling.

478 Finally from (7) and (10) we have a relationship between the difference of P-wave velocities,
 479 between saturated and dry states, and the porosity. The leading idea consists in minimizing a given
 480 objective function to determine the porosity. The objective function J is define as:

$$481 \quad J(\phi) = \left(1 - \frac{\Delta K_{VP}(\phi)^2}{\Delta K_{BG}(\phi)^2} \right)^2 \quad (11)$$

482 It is a one-term function, which quantifies the data mismatch in a least-squares sense. The
 483 minimization process is iterative; the process is repeated until the objective function is small enough.
 484 The optimization parameter is the porosity. Other parameters remain constant (Table 5), especially
 485 the Biot coefficient which is fixed to 1 in a first approach, *i.e.* we assume that K_{dry} is much smaller
 486 than K_0 . Matrix modulus is taken equal to 25.6 GPa from experimental data performed in laboratory
 487 on Santa Cruz basalts as both islands present the same general lithology [Loaiza, 2012].

488
 489 **Table 35 - Constant parameters**

ρ_{matrix} (kg/L)	ρ_{water} (kg/L)	K_{water} (GPa)
2.7	1	2.25

490
 491 Table6 summarizes input data (dry and saturated P-wave velocities) and output data (porosities) for
 492 the different sites on which we have both velocities. Note that SC3 and SC4 are respectively close to
 493 scoria cone and pyroclastic debris.

494 **Table 46 – Input P-wave velocities and calculated porosity with constant Biot coefficient**

sites	SZ1	SZ2	SZ3	SC1	SC2	SC3	SC4
VP_sat (km/s)	2.39	2.33	2.39	2.69	2.72	2.53	2.43
VP_dry (km/s)	1.30	1.36	1.35	1.34	1.38	1.33	1.38
J evaluations	10	11	9	13	13	11	10
J minima	1.44E-13	3.02E-12	7.12E-11	2.12E-11	4.31E-11	1.25E-10	7.62E-12
inverted porosity	0.15	0.18	0.16	0.08	0.08	0.11	0.15

495
 496 Galapagos lava flows are described as riches in vacuoles due to gas trapping inside magma [Loaiza,
 497 2012]. Inverted porosities are in range of acceptable values for such effusive volcanic material

498 [Adelinet, 2010; Schaefer et al., 2015; Siratovich et al., 2014]. Laboratory porosity measurements
 499 made on fresh Santa Cruz basalts provide values between 10 and 12 % [Loaiza, 2012]. We can classify
 500 results of table 4 according three porosity facies: low porosity on basaltic San Cristobal sites (SC1 and
 501 SC2), intermediate porosity for scoria San Cristobal coastal site (SC3), and high porosity of Santa Cruz
 502 sites and mid-slope San Cristobal pyroclastic site(SZ1, SZ2, SZ3 and SC4). According to geological
 503 interpretation made before, the lowest porosity is associated with coastal basaltic sites (SC1 and
 504 SC2).

505 In order to discuss much precisely the absolute values of porosity we need to have a sensitivity
 506 approach on the parameters introduced in the objective function. We identified two major sinks of
 507 errors on porosity computations: the values of Biot coefficient arbitrary fixed to 1 and the matrix bulk
 508 modulus, which has been chosen from experimental laboratory data. Thus we perform simulations
 509 with different couples of Biot coefficient and matrix bulk modulus whereas other parameters
 510 remaining constant. We choose velocity values of site SC1 as representatives of good quality data.
 511 Figure 11 presents the sensitivity results. The range of variation for tested parameters is 0.6 – 1 for
 512 Biot coefficient and 10 – 50 GPa for matrix bulk modulus in order to see the influence of both
 513 parameters on porosity. The computed porosity range is between 0 (computed for very low matrix
 514 bulk modulus, not realistic with volcanic rocks) and 0.17. The dependence of porosity with bulk
 515 modulus is the highest for Biot coefficient equal to 1. For realistic values of Biot coefficient and
 516 matrix bulk modulus (respectively 0.8-1 range and 20-40 GPa range, white square on Figure 9), the
 517 porosity is more dependent on the variation in Biot coefficient than on the matrix bulk modulus.
 518 Note that porosity increases with higher values of bulk modulus, which could be incoherent at the
 519 first glad. However, in this sensitivity approach the macroscopic field velocities remain constant (data
 520 from SC1 profile). Then, if the matrix is stiffer (high bulk modulus), the effective medium modelling
 521 needs to increase the porosity in order to fit with velocities which remains the same all over the
 522 tested values of bulk modulus.

523 In order to reduce this range of variability we introduce a variable Biot coefficient into our inverse
 524 modelling. For that we need to express the dry bulk modulus (K_{dry} of eq. 9) as a function of known
 525 parameters. As we have only measure P-wave velocities on field, we assume a constant Poisson's
 526 ratio (noted ν) which is a more stable coefficient. In this case the dry bulk modulus (K_{dry}) is expressed
 527 from dry P-wave velocity and ν :

$$528 \quad K_{dry} = \frac{1+\nu}{3(1-\nu)} \times \rho_{dry} \times VP_{dry}^2 \quad (12)$$

529 Injecting the dependency of ρ_{dry} with porosity we obtain:

$$530 \quad K_{dry} = \frac{1+\nu}{3(1-\nu)} \times (1 - \phi) \times \rho_0 \times VP_{dry}^2 \quad (13)$$

531 We can now reformulate the objective function by introducing the new K_{dry} expression within the
 532 Biot coefficient (eq. 9). Table 7 presents the new porosities calculated from minimization of the new J
 533 function and with a Poisson's ratio of 0.25 accordingly with literature data [Schultz, 1995; Adelinet,
 534 2010; Loaiza, 2012]. This table presents also the post-calculation of the Biot coefficient and the K_{dry}
 535 values for each site.

536 | [Table 57 – Porosity calculations using variable Biot coefficient and constant Poisson's ratio \(0,25\)](#)

sites	SZ1	SZ2	SZ3	SC1	SC2	SC3	SC4
VP_dry (km/s)	1.30	1.36	1.35	1.34	1.38	1.33	1.38
new_porosity	0.11	0.14	0.12	0.05	0.05	0.08	0.11
K_dry (GPa)	2.25	2.40	2.42	2.55	2.71	2.44	2.55
Biot coefficient	0.91	0.91	0.91	0.90	0.89	0.90	0.90

537

538 Inverted porosities are smaller than the previous ones computed with a Biot coefficient equal to 1, in
539 agreement with the sensitivity approach given in Figure 9. Moreover, the post-processed Biot
540 coefficient is relatively constant between sites, with a mean value of 0.90 and a standard deviation of
541 0.007.

542 Finally we plot the porosity in the map dry P-wave velocities versus saturated P-wave velocities
543 (Figure 12) using the last optimization process with variable Biot coefficient. We show three domains.
544 The first one is the low porosity area (porosity less than 8 %) in which basalts of coastal San Cristobal
545 sites are present (SC1 and SC2). This area is interpreted as the domain of basaltic rocks weakly
546 weathered. The second porosity area concerns intermediate values (between 8 and 13 %) in which
547 SZ1, SZ3, SC3 and SC4 are present. Due to the presence of SC3 and SC4, we interpret this area as the
548 domain of scoria and pyroclasts. The limit between the two areas could also be a limit of weathering:
549 a weathered basaltic lava flow could have the same porosity. A third domain is also recognizable with
550 higher porosity (more than 13 %). It could be attributed to very weathered or fractured rocks. The
551 lowest computed porosity is the one of SC1 and SC2 with 5 %. It is the site closest the seashore with
552 evidence of basaltic lava flows as underground. The most similar site on Santa Cruz is SZ1 with a
553 porosity of 11 %. The difference between porosities should rely once again on the age of the islands.
554 Lava flows on San Cristobal are older than on Santa Cruz. Porosity had time to be filled with
555 secondary material, especially into the pores and fractures. On Figure 12, we notice that all the three
556 sites of Santa Cruz are close and the highest value of porosity is obtained for SZ2 (14 %) which is the
557 closest to the coast. Then we can assume that lower velocities recorded on Santa Cruz interpreted as
558 high porosity values could be due to the high degree of fracturing of the young basaltic lava flows
559 forming this island.

560

561 **5. Conclusion**

562 Seismic-refraction has been successfully used on Santa Cruz and San Cristobal Islands. It was a
563 challenge to obtain acoustic information in the subsurface in such complex structural area.
564 Moreover, penetration depths are enough to image different hydrogeological structures, salted
565 wedge and a freshwater perched aquifer especially. Even if obtained P-wave velocity values obtained
566 remains low we are able to distinguish different velocity layers and interpret them in terms of water
567 saturation state. One step further should be the acquisition or the specific processing [Foti et al.,
568 2003; Williams et al., 2003; Grelle & Guadagno, 2009; Pasquet et al., 2015; Uhlemann et al., 2016] to
569 have access to shear-wave tomography, specially using the surface wave processing (Multi-Channel
570 Analysis of Surface Waves, [Park et al., 1999]). Nevertheless, our study provides the mapping of low
571 and high velocity layers in different geological context (basaltic lava flow or pyroclastic deposits) and
572 at different altitudes. We went a step further by interpreting differences between dry and water-
573 saturated P-wave velocities in terms of porosity thanks to the poroelasticity theory. From this work,

574 absolute porosity values could be attributed to Galapagos subsurface material according elevation
575 and geological facies: unweathered and weathered basaltic lava flows, scoria and pyroclast materials.
576 This data could be very helpful in the building of flow models for the Galapagos Islands.

577

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579

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589 **Bibliography**

- 590 Adelinet, M., Fortin, J., d'Ozouville, N., & Violette, S. (2008). The relationship between hydrodynamic
591 properties and weathering of soils derived from volcanic rocks, Galapagos Islands
592 (Ecuador). *Environmental geology*, 56(1), 45-58.
- 593 Adelinet, M. (2010). *Du terrain au laboratoire, étude des propriétés élastiques du basalte* (Doctoral
594 dissertation, Université du Maine).
- 595 Adelinet, M., Dorbath, C., Le Ravalec, M., Fortin, J., & Guéguen, Y. (2011). Deriving microstructure
596 and fluid state within the Icelandic crust from the inversion of tomography data. *Geophysical
597 research letters*, 38(3).
- 598 Adelinet, M., & Le Ravalec, M. (2015). Effective medium modeling: How to efficiently infer porosity
599 from seismic data?. *Interpretation*, 3(4), SAC1-SAC7.
- 600 Anderson, M. G., & Burt, T. P. (1978). The role of topography in controlling throughflow
601 generation. *Earth Surface Processes*, 3(4), 331-344.
- 602 ASTM D2845-08, (2008). Standard Test Method for Laboratory Determination of Pulse Velocities and
603 Ultrasonic Elastic Constants of Rock, ASTM International, West Conshohocken, PA,
604 2008, www.astm.org
- 605 Auken, E., Violette, S., d'Ozouville, N., Deffontaines, B., Sørensen, K. I., Viezzoli, A., & De Marsily, G.
606 (2009). An integrated study of the hydrogeology of volcanic islands using helicopter borne transient
607 electromagnetic: Application in the Galápagos Archipelago. *Comptes Rendus Geoscience*, 341(10),
608 899-907.
- 609 Ayers, J. F., & Vacher, H. L. (1986). Hydrogeology of an atoll island: a conceptual model from detailed
610 study of a Micronesian example. *Ground Water*, 24(2), 185-198.
- 611 Banda, E., Dan, J. J., Surin, E., & Ansorge, J. (1981). Features of crustal structure under the Canary
612 Islands. *Earth and Planetary Science Letters*, 55(1), 11-24.
- 613 Bear, J. (1972). Dynamics of fluids in porous media. *American Elsevier, New York*.
- 614 Biot, M. A. (1956). Theory of propagation of elastic waves in a fluid-saturated porous solid. II. Higher
615 frequency range. *the Journal of the Acoustical Society of America*, 28(2), 179-191.
- 616 Bosshard, E., & MacFarlane, D. J. (1970). Crustal structure of the western Canary Islands from seismic
617 refraction and gravity data. *Journal of Geophysical Research*, 75(26), 4901-4918.
- 618 Bow, C. S. (1979). *Geology and petrogeneses of the lavas of Floreana and Santa Cruz Islands:
619 Galápagos Archipelago*. Oregon Univ., Eugene (USA).
- 620 Cleary, M. P. (1978). Elastic and dynamic response regimes of fluid-impregnated solids with diverse
621 microstructures. *International Journal of Solids and Structures*, 14(10), 795-819.

622 Descloitres, M., Ritz, M., Robineau, B., & Courteaud, M. (1997). Electrical structure beneath the
623 eastern collapsed flank of Piton de la Fournaise volcano, Reunion Island: Implications for the quest
624 for groundwater. *Water resources research*, 33(1), 13-19.

625 Domínguez Gonzalez, C. G. (2016). Integrated hydrogeological study of San Cristobal Island,
626 Galapagos. *Doctoral dissertation, Ph. D. thesis, Université Pierre et Marie Curie, Paris.*

627 Dominguez Gonzalez, C., Pryet, A., Garcia Vera, M., F., Gonzalez, A., Chaumont, C., Tournebize, J.,
628 Villacis, M. J., D'ozouville, N., Violette, S., (2016). Comparison of deep percolation rates below
629 contrasting land covers with a joint canopy and soil model. *Journal of Hydrology*, 532, 65-79,
630 doi:10.1016/j.jhydrol.2015.11.022

631 d'Ozouville, N. (2007). Étude du fonctionnement hydrologique dans les îles Galápagos:
632 caractérisation d'un milieu volcanique insulaire et préalable à la gestion de la ressource. *Doctoral*
633 *dissertation, Ph. D. thesis, Université Pierre et Marie Curie, Paris.*

634 d'Ozouville, N., Deffontaines, B., Benveniste, J., Wegmüller, U., Violette, S., & De Marsily, G. (2008a).
635 DEM generation using ASAR (ENVISAT) for addressing the lack of freshwater ecosystems
636 management, Santa Cruz Island, Galapagos. *Remote Sensing of Environment*, 112(11), 4131-4147.

637 d'Ozouville, N., Auken, E., Sorensen, K., Violette, S., De Marsily, G., Deffontaines, B., & Merlen, G.
638 (2008b). Extensive perched aquifer and structural implications revealed by 3D resistivity mapping in a
639 Galapagos volcano. *Earth and Planetary Science Letters*, 269(3), 518-522.

640 Feroci, M., Orlanda, L., Balia, R., Bosmann, C., Cardarelli, E. & Deidda, R. (2000) Some consideration
641 on shallow seismic reflection surveys. *Journal of Applied Geophysics*, 45, 127-139

642 Foti, S., Sambuelli, L., Socco, V. L., & Strobbia, C. (2003). Experiments of joint acquisition of seismic
643 refraction and surface wave data. *Near surface geophysics*, 1(3), 119-129.

644 Garambois, S., Sénéchal, P. & Perroud, H. (2002). On the use of combined geophysical methods to
645 assess water content and water conductivity of near surface formations. *Journal of Hydrology*, 259
646 (1), 32-48.

647 Gassmann, F. (1951). Elasticity of porous media. *Vierteljahrsschrder Naturforschenden*
648 *Gessellschaft*, 96, 1-23.

649 Geist, D. J., McBirney, A. R., & Duncan, R. A. (1986). Geology and petrogenesis of lavas from San
650 Cristobal Island, Galapagos archipelago. *Geological Society of America Bulletin*, 97(5), 555-566.

651 Geist, D., Naumann, T., & Larson, P. (1998). Evolution of Galápagos magmas: Mantle and crustal
652 fractionation without assimilation. *Journal of Petrology*, 39(5), 953-971.

653 Grab, M., Zürcher, B., Maurer, H., & Greenhalgh, S. (2015). Seismic velocity structure of a fossilized
654 Icelandic geothermal system: A combined laboratory and field study. *Geothermics*, 57, 84-94.

655 Grelle, G., & Guadagno, F. M. (2009). Seismic refraction methodology for groundwater level
656 determination: "Water seismic index". *Journal of Applied Geophysics*, 68(3), 301-320.

657 Haeni, F. P. (1988). *Application of seismic-refraction techniques to hydrologic studies*. US Government
658 Printing Office.

659 Ingebritsen, S. E., & Scholl, M. A. (1993). The hydrogeology of Kilauea volcano. *Geothermics*, 22(4),
660 255-270.

661

662 Izquierdo, T., Dominguez, C., Violette, S. and Villacis, M. (2015). Volcanic island evolution and their
663 implications for the groundwater conceptual model development in San Cristóbal (Galápagos).
664 *In 42nd IAH Congress 2015*.

665

666 Kearey, P., Brooks, M., & Hill, I. (2013). *An introduction to geophysical exploration*. John Wiley &
667 Sons.

668 Keiswetter, D. A., & Steeples, D. W. (1995). A field investigation of source parameters for the
669 sledgehammer. *Geophysics*, 60(4), 1051-1057.

670

671 Khalil, M. H., & Hanafy, S. M. (2008). Engineering applications of seismic refraction method: A field
672 example at Wadi Wardan, Northeast Gulf of Suez, Sinai, Egypt. *Journal of Applied Geophysics*, 65(3),
673 132-141.

674 Krivochieva, S., & Chouteau, M. (2003). Integrating TDEM and MT methods for characterization and
675 delineation of the Santa Catarina aquifer (Chalco Sub-Basin, Mexico). *Journal of Applied*
676 *Geophysics*, 52(1), 23-43.

677 Lienert, B. R. (1991). An electromagnetic study of Maui's last active volcano. *Geophysics*, 56(7), 972-
678 982.

679 Loaiza Ambuludi, S. (2012). *Étude des propriétés physiques et du comportement mécanique des*
680 *Basaltes: étude cinétique, mécanistique et toxicologique de l'oxydation dégradante de l'Ibuprofène*
681 *par l'oxydation avancée électrochimique et photochimique* (Doctoral dissertation, Paris Est).

682 Mari, J. L. (1999). *Geophysics of reservoir and civil engineering*. Editions Technip.

683 McBirney, A. R., & Williams, H. (1969). Geology and petrology of the Galapagos Islands. *Geological*
684 *Society of America Memoirs*, 118, 1-197.

685 Murphy, W. F. (1985). Sonic and ultrasonic velocities: theory versus experiment. *Geophysical*
686 *Research Letters*, 12(2), 85-88.

687 Palmason, G. (1965). Seismic refraction measurements of the basalt lavas of the Faeroe
688 Islands. *Tectonophysics*, 2(6), 475-482.

689 Pryet, A. (2011a). Hydrogeology of volcanic islands: a case-study in the Galapagos Archipelago.
690 *Doctoral dissertation, Ph. D. thesis, Université Pierre et Marie Curie, Paris*.

691 Pryet, A., Ramm, J., Chilès, J. P., Auken, E., Deffontaines, B., & Violette, S. (2011b). 3D resistivity
692 gridding of large AEM datasets: a step toward enhanced geological interpretation. *Journal of Applied*
693 *Geophysics*, 75(2), 277-283.

694 Pryet, A., d'Ozouville, N., Violette, S., Deffontaines, B., & Auken, E. (2012a). Hydrogeological settings
695 of a volcanic island (San Cristóbal, Galapagos) from joint interpretation of airborne electromagnetics
696 and geomorphological observations. *Hydrology and Earth System Sciences*, 16(12), 4571-4579.

697 Pryet, A., Dominguez, C., Tomai, P. F., Chaumont, C., d'Ozouville, N., Villacís, M., & Violette, S.
698 (2012b). Quantification of cloud water interception along the windward slope of Santa Cruz Island,
699 Galapagos (Ecuador). *Agricultural and forest meteorology*, 161, 94-106.

700 Pasquet, S., L. Bodet, L. Longuevergne, A. Dhemaied, C. Camerlynck, F. Rejiba, and R. Guérin (2015),
701 2D characterization of near-surface V P/V S: surface-wave dispersion inversion versus refraction
702 tomography, *Near Surf. Geophys.*, 13(2089), 315–331.

703
704 Revil, A., Naudet, V., & Meunier, J. D. (2004). The hydroelectric problem of porous rocks: inversion of
705 the position of the water table from self-potential data. *Geophysical Journal International*, 159(2),
706 435-444.

707 Revil, A., Finizola, A., Piscitelli, S., Rizzo, E., Ricci, T., Crespy, A., ... & Bolève, A. (2008). Inner structure
708 of La Fossa di Vulcano (Vulcano Island, southern Tyrrhenian Sea, Italy) revealed by high-resolution
709 electric resistivity tomography coupled with self-potential, temperature, and CO₂ diffuse degassing
710 measurements. *Journal of Geophysical Research: Solid Earth*, 113(B7).

711 Saar, M. O., & Manga, M. (1999). Permeability-porosity relationship in vesicular basalts. *Geophys.*
712 *Res. Lett*, 26(1), 111-114.

713 Schaefer, L. N., Kendrick, J. E., Oommen, T., Lavallée, Y., & Chigna, G. (2015). Geomechanical rock
714 properties of a basaltic volcano. *Frontiers in Earth Science*, 3, 29.

715 Schultz, R. A. (1995). Limits on strength and deformation properties of jointed basaltic rock
716 masses. *Rock Mechanics and Rock Engineering*, 28(1), 1-15.

717 Siratovich, P. A., Heap, M. J., Villeneuve, M. C., Cole, J. W., & Reuschlé, T. (2014). Physical property
718 relationships of the Rotokawa Andesite, a significant geothermal reservoir rock in the Taupo Volcanic
719 Zone, New Zealand. *Geothermal Energy*, 2(1), 1.

720 Uhlemann, S., S. Hagedorn, B. Dashwood, H. Maurer, D. Gunn, T. Dijkstra, and J. Chambers (2016),
721 Landslide characterization using P- and S-wave seismic refraction tomography — The importance of
722 elastic moduli, *J. Appl. Geophys.*, 134, 64–76.

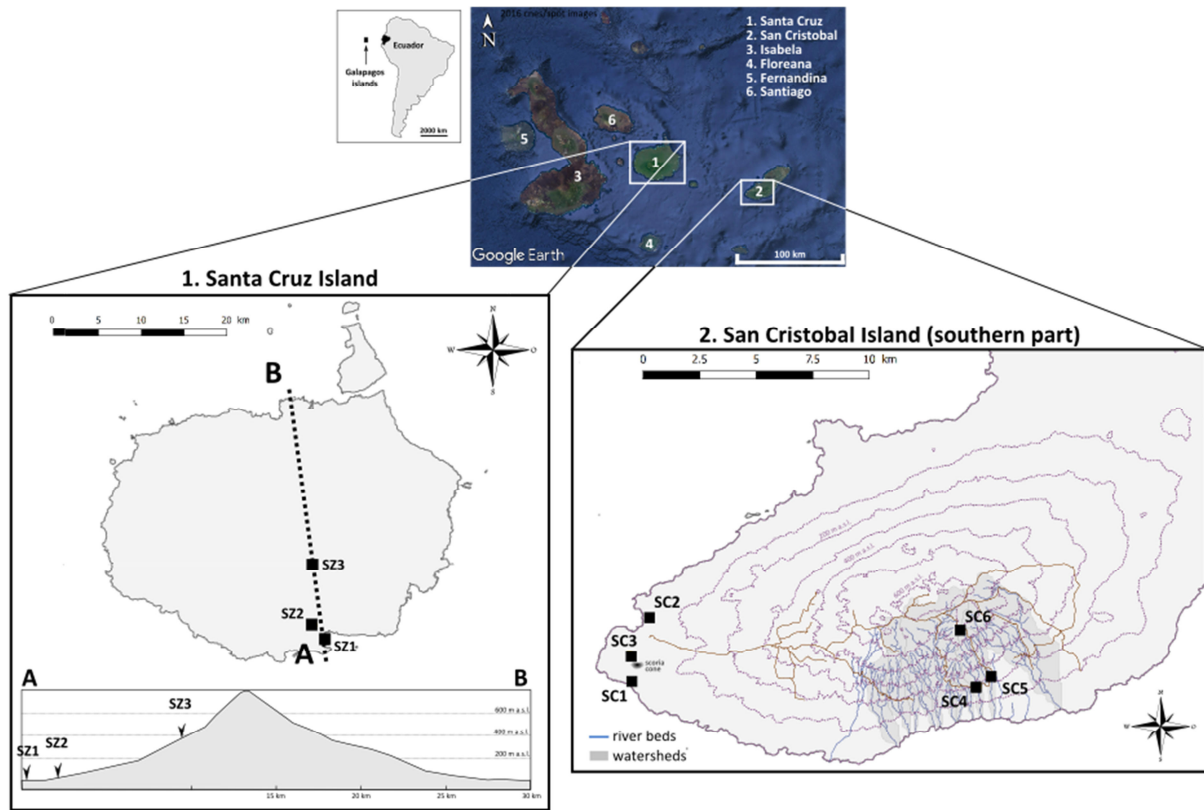
723 Violette, S., Ledoux, E., Goblet, P. & Carbonnel, J.-P., (1997). Hydrologic and thermal modelling of an
724 active volcano: the "Piton de la Fournaise, La Réunion Island". *Journal of hydrology*, 191, 37-
725 63
726 Violette, S., d'Ozouville, N., Pryet, A., Deffontaines, B., Fortin, J., & Adelinet, M. (2014).
727 Hydrogeology of the Galapagos Archipelago: an integrated and comparative approach between
728 islands. *The Galapagos: A Natural Laboratory for the Earth Sciences*, 204, 167.

728 Vittecoq, B., Deparis, J., Violette, S., Jaouen, T., & Lacquement, F. (2014). Influence of successive
729 phases of volcanic construction and erosion on Mayotte Island's hydrogeological functioning as
730 determined from a helicopter-borne resistivity survey correlated with borehole geological and
731 permeability data. *Journal of Hydrology*, 509, 519-538.

- 732 Vittecoq B., Reninger, P.-A., Violette, S., Martelet, G., Dewandel, B., Audru, J.-C., (2015).
733 Heterogeneity of hydrodynamic properties and groundwater circulation of a coastal andesitic
734 volcanic aquifer controlled by tectonic induced faults and rock fracturing - Martinique Island (Lesser
735 Antilles - FWI). *Journal of Hydrology*, 529, 1041-1059, doi:10.1016/j.jhydrol.2015.09.022
- 736 White, W. M., McBirney, A. R., & Duncan, R. A. (1993). Petrology and geochemistry of the Galápagos
737 Islands: Portrait of a pathological mantle plume. *Journal of Geophysical Research: Solid
738 Earth*, 98(B11), 19533-19563.
- 739 Williams, R. A., Stephenson, W. J., & Odum, J. K. (2003). Comparison of P-and S-wave velocity profiles
740 obtained from surface seismic refraction/reflection and downhole data. *Tectonophysics*, 368(1), 71-
741 88.
- 742 Zhang, J., and Toksoz, M. (1998) Non-linear refraction travel-time tomography. *Geophysics*, 63, 1726–
743 1737.
- 744

745 **Figures**

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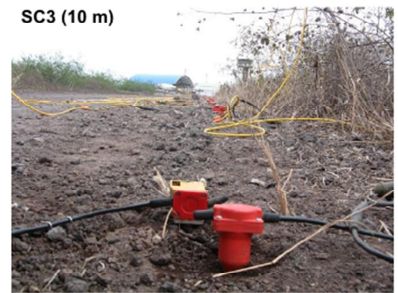
748 **Figure 1 - Location of seismic site surveys (background of top picture: ©Google Earth image). We**
749 **investigated three sites on Santa Cruz Island (2 near the coast and 1 in the highlands) and six sites**
750 **on San Cristobal Island split into three coastal, two mid-slope and one highland sites.**

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Santa Cruz sites

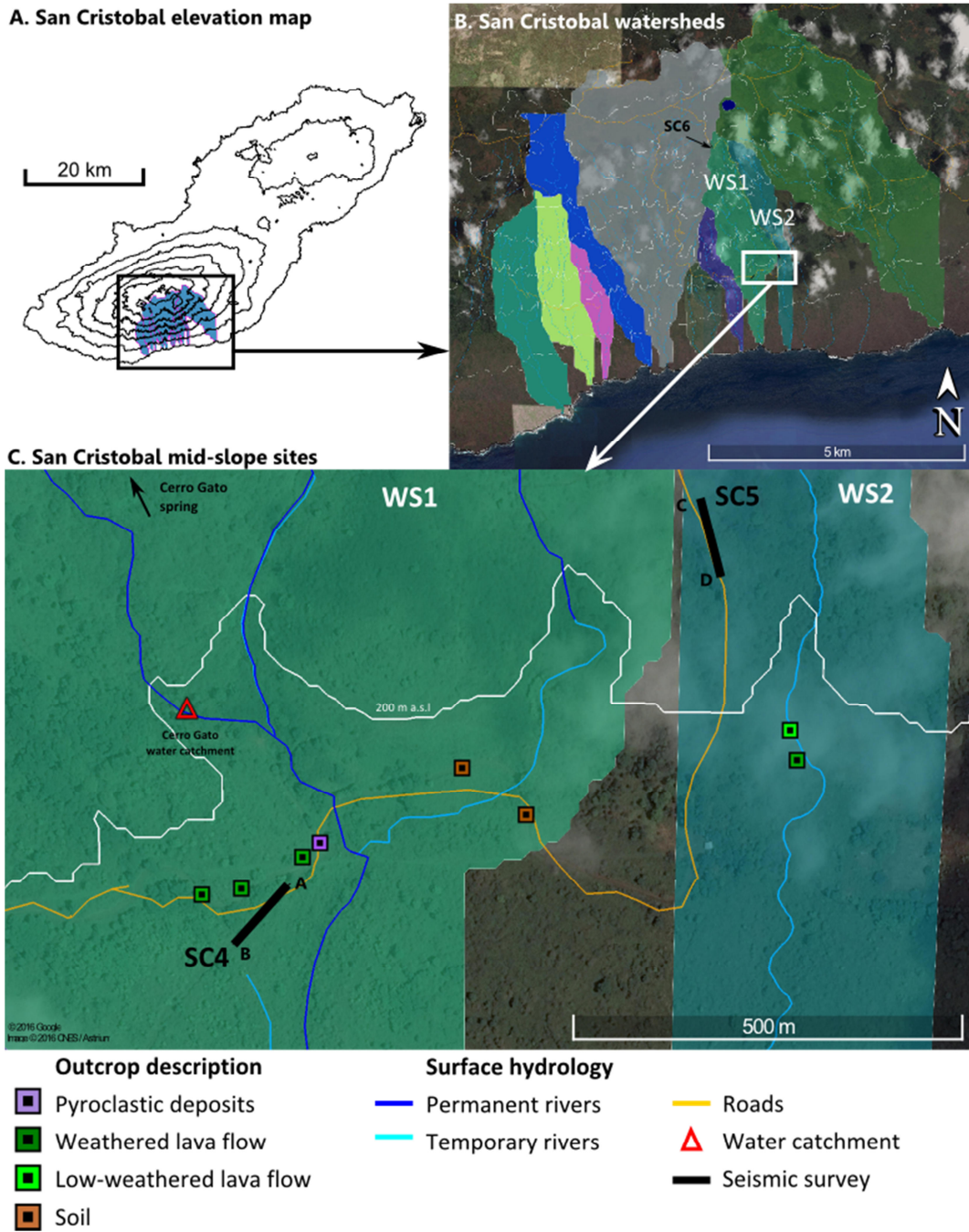


San Cristobal sites



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753 **Figure 2 – Pictures of investigated sites according altitude.**

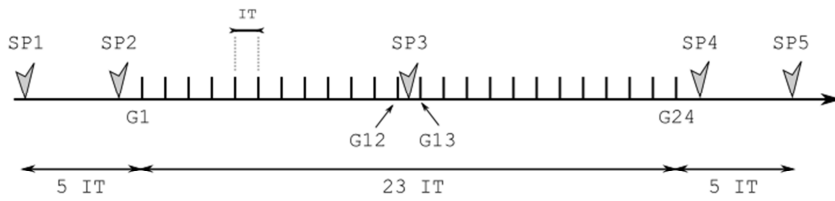


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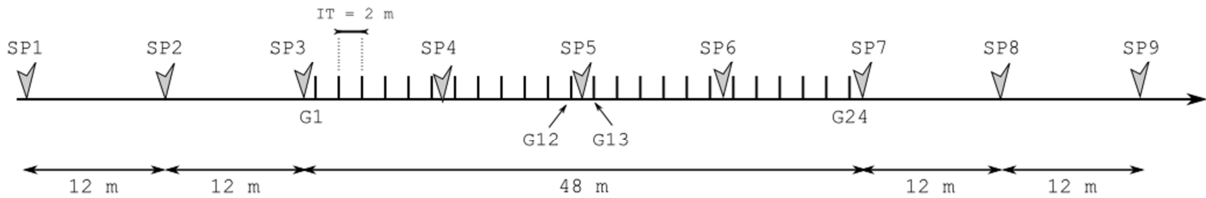
755 **Figure 3 - Spatial configuration of seismic-refraction layouts for mid-slope sites on San Cristobal**
 756 **Island (background: ©Google Earth image)**

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A. Santa Cruz layout



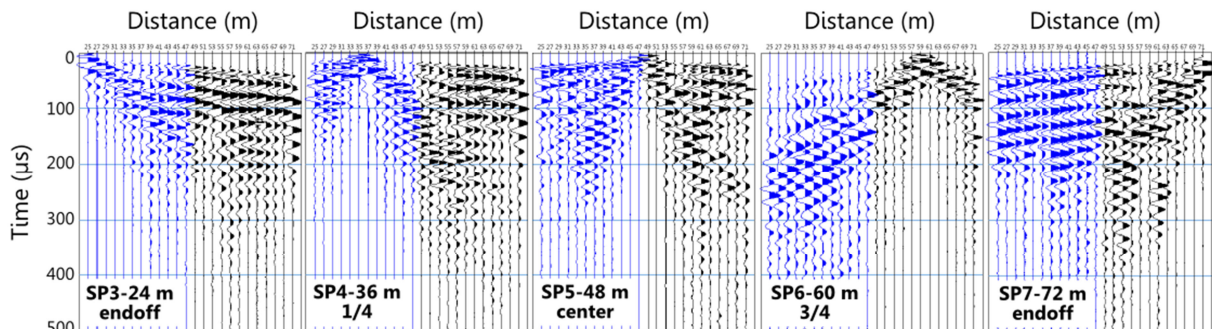
B. San Cristobal layout (96 m seismic spread)



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759 **Figure 4 - Seismic-refraction survey layouts on both islands. On Santa Cruz, the intertrace is**
 760 **variable according the depth of the expected refractor target: 1 m (SZ1), 2 m (SZ2), 5 m (SZ3). Shot**
 761 **points (SP) for Santa Cruz sites are spread as follows: 1 central (SP3) and 4 end-off shots. On San**
 762 **Cristobal, the intertrace is always the same for the 6 sites (2 m) and 9 SP are equally distributed on**
 763 **the lines (each 12 meters).**

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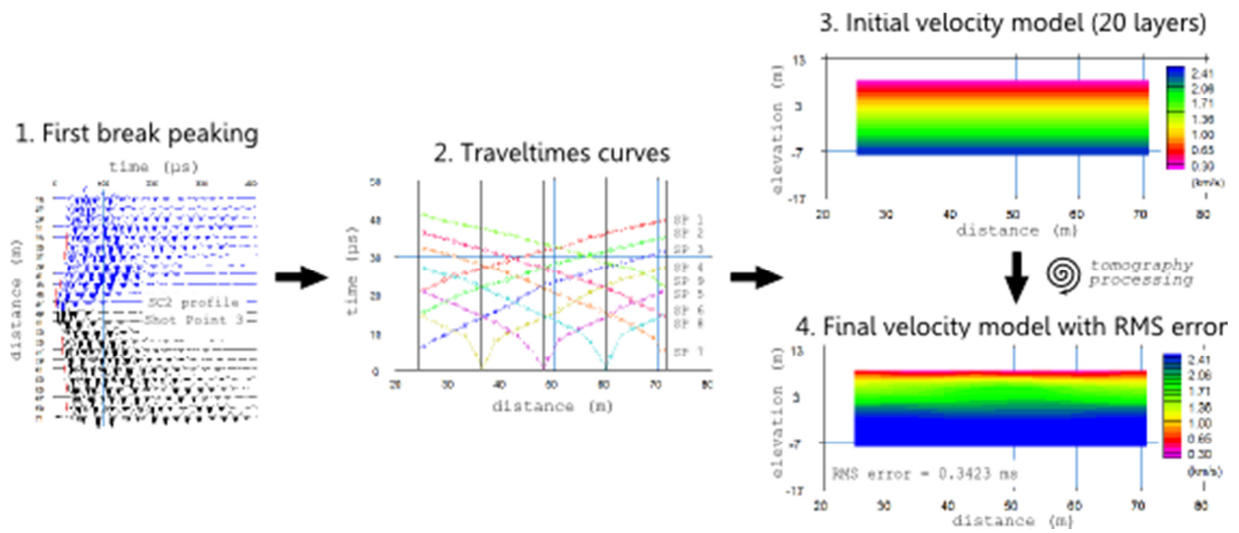


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766 **Figure 5 - Shot gathers recorded for profile SC3. Trace amplitudes are normalized for display**
 767 **purpose.**

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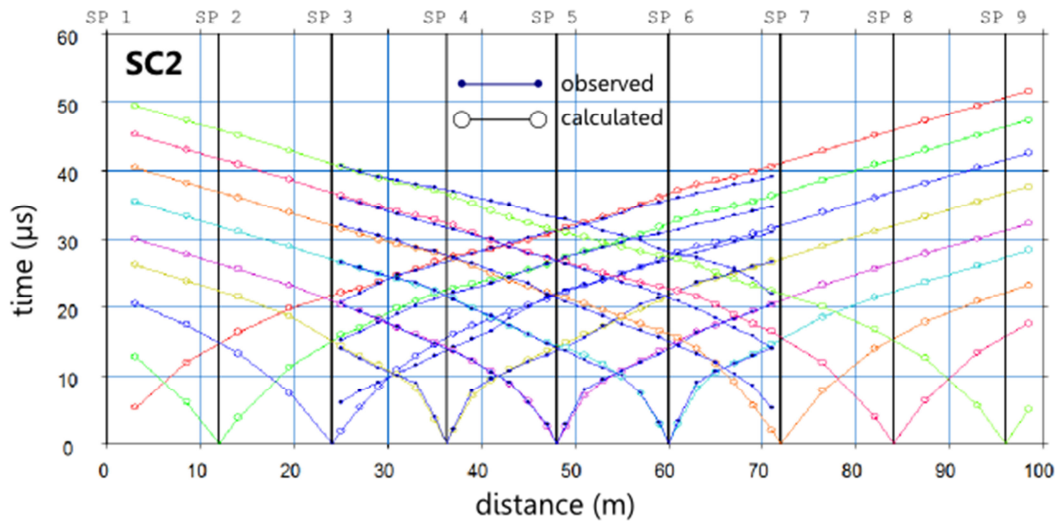


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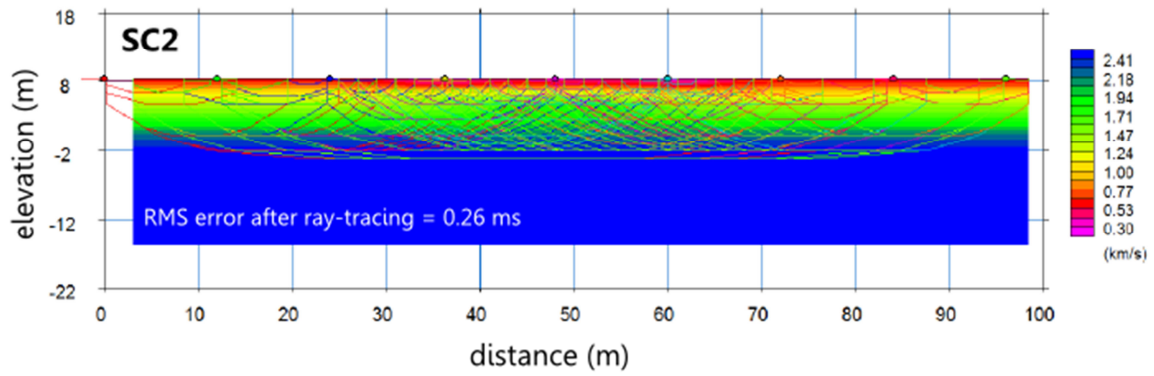
771 Figure 6 - General methodology of seismic-refraction processing made on the Galapagos data.
 772 SeisImager Geometrics softwares were used for first break picking (Pickwin module) and
 773 tomography iterative process (PlotRefra module).

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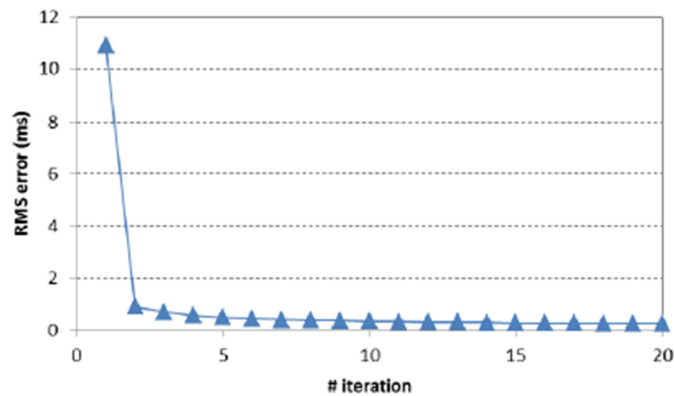
A. Comparison between observed and calculated traveltimes



B. Best tomography model and associated ray-paths



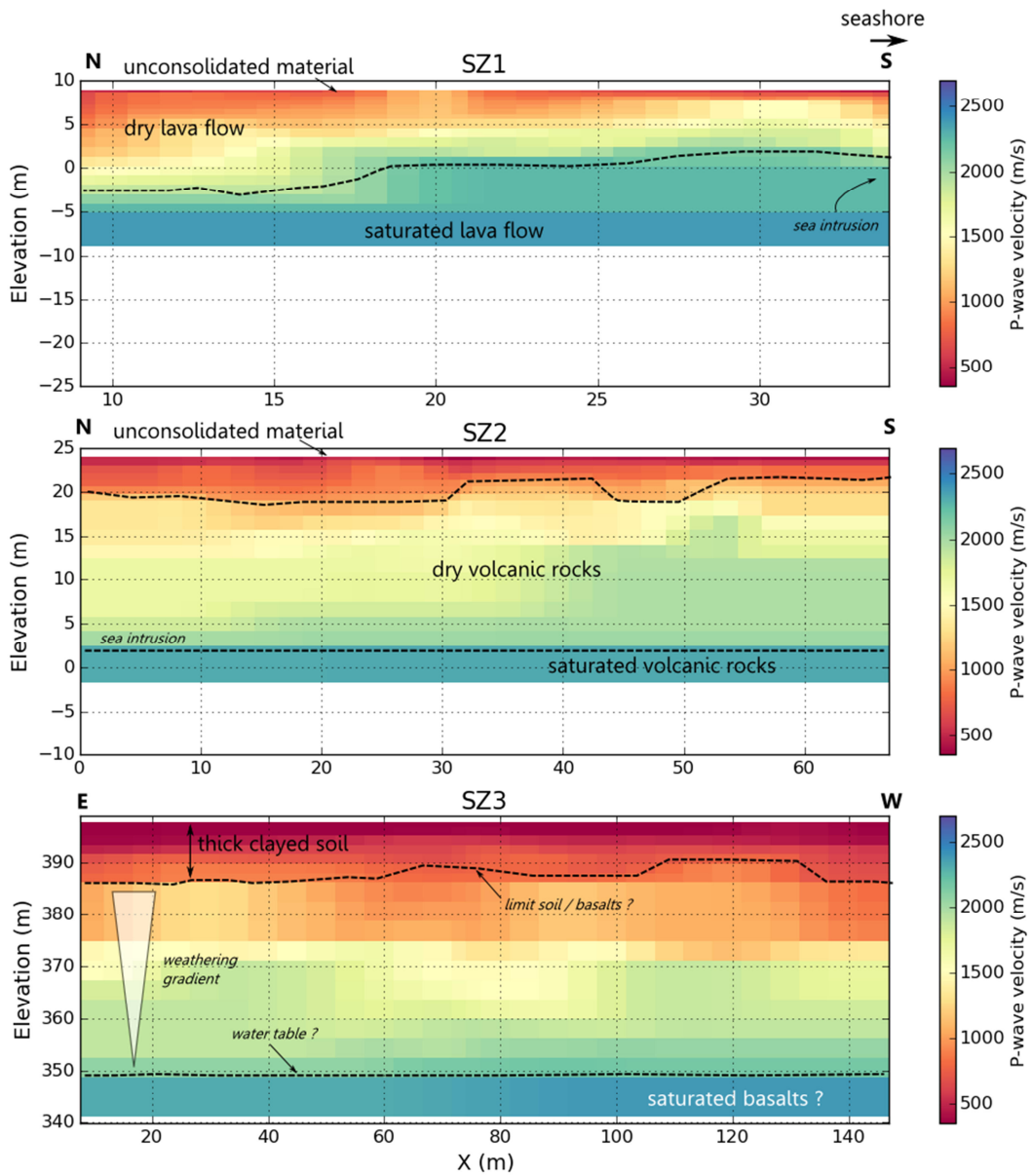
C. Root mean square (RMS) error curve for the 20 iterations



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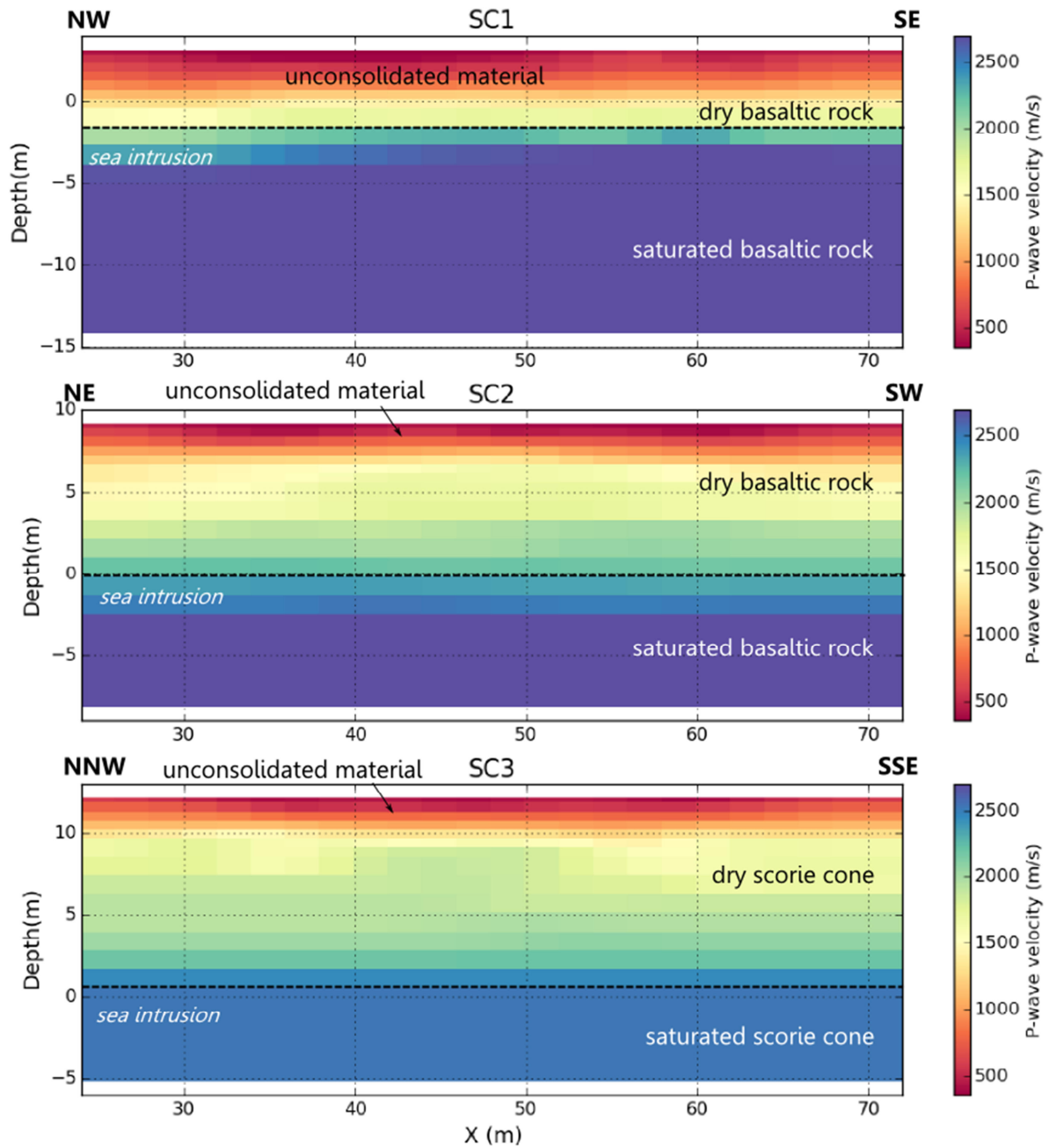
776 Figure 7 - Example of raypath processing to check the tomography inversion quality. Example of
 777 SC2 profile.

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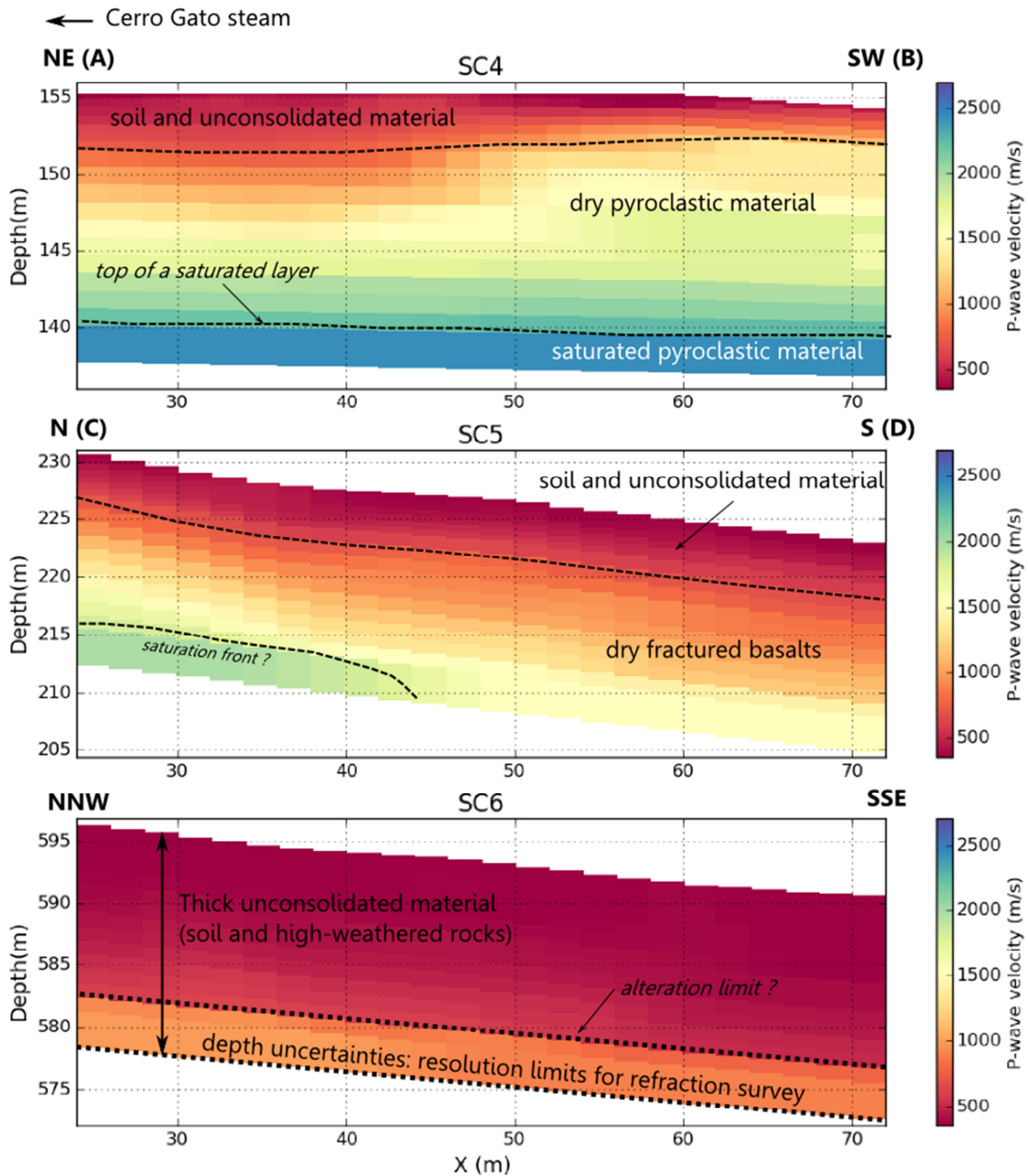
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780 **Figure 8 - Results obtained on Santa Cruz Island. Contrast between dry and water-saturated layers**
 781 **is observed. The interface is interpreted as the salted wedge near from the coast. For the highland**
 782 **site SZ3, the transition is smoother and can be interpreted more as a progressive water saturation**
 783 **profile in weathered material.**



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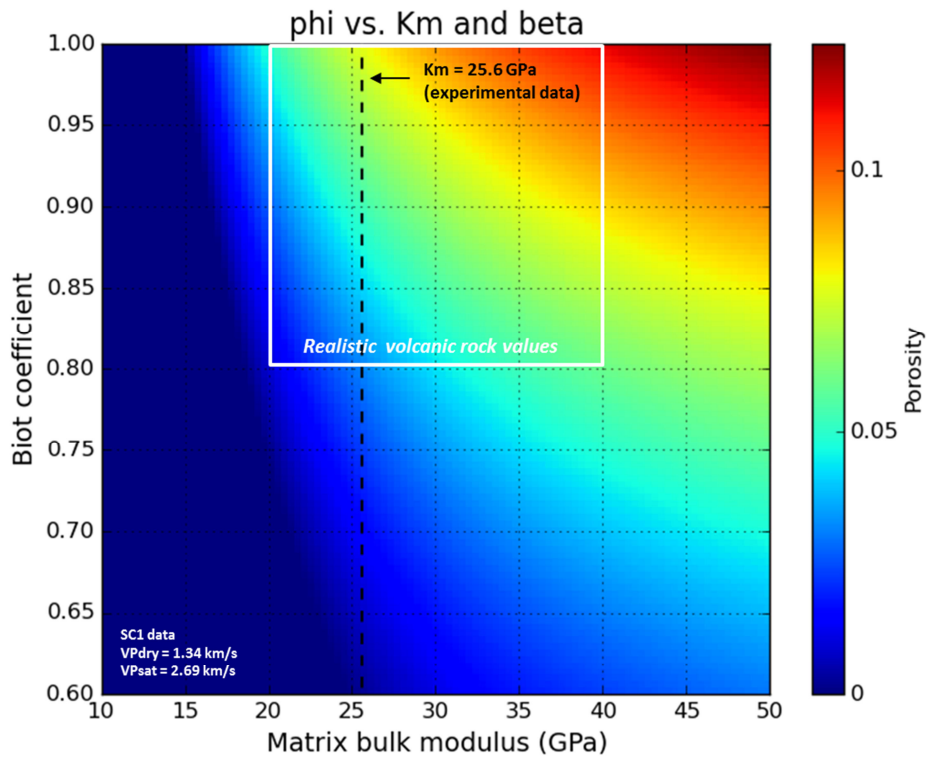
785 **Figure 9 - Velocity profiles obtained for coastal sites on San Cristobal Island. As for Santa Cruz**
 786 **profiles, a sharp contrast between low and high-velocity layer is observed corresponding to the**
 787 **contrast between dry and saturated layers in depth. The scoria site (SC3) presents velocities lower**
 788 **than basaltic sites (SC1 and SC2).**



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790 **Figure 10 - Velocity profiles obtained for land sites on San Cristobal Island. SC4 presents both dry**
 791 **and saturated velocity layer. The interface is interpreted here as the top of a freshwater saturated**
 792 **aquifer. Whereas SC5 is located also in the mid-slope of the island, it presents only dry velocities in**
 793 **depth. Limits of refraction resolution are achieved for highland site SC6 without any refractor in**
 794 **depth. Only unconsolidated material has been investigated (probably soil and highly weathered**
 795 **volcanic material).**

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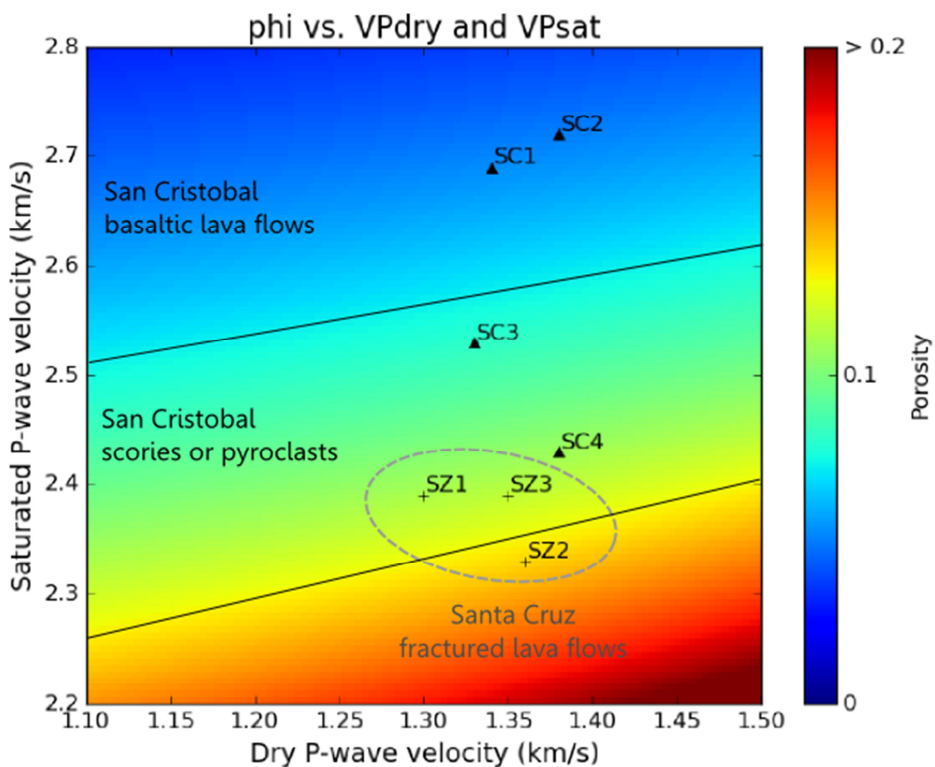


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Figure 11 - Sensitivity approach on the effect of Biot coefficient and matrix bulk modulus on inverted porosities using SC1 input velocity data.



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Figure 12 - Modelling porosity from field P-wave velocities. Different San Cristobal lithologies are identified according inverted porosities: basaltic bedrocks (SC1 and SC2) or scoria / pyroclast cones (SC3 and SC4). The three sites of Santa Cruz are close, probably due to high fracturation in the bedrock.