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1 **Rupture Segmentation of the August 14, 2021 Mw7.2 Nippes, Haiti, Earthquake Using**
2 **Aftershock Relocation from a Local Seismic Deployment**

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14
15 **Key Points:**

- 16 ● Aftershocks detected by local seismic deployment are used to delineate the geometry of
17 the faults that ruptured during the Mw 7.2 Haiti earthquake
18 ● Aftershocks delineated three clusters with slightly variable dip
19 ● First motion focal mechanisms are primarily composed of left-lateral both strike-slip and
20 thrust motions consistently with geodetic observations.

21
22 **0. Abstract:**

23 The 14 August 2021 M_w 7.2 Haiti earthquake struck 11 years after the devastating 2010 event
24 within the Enriquillo Plantain Garden Fault Zone in the Southern peninsula of Haiti. Space
25 geodetic results show that the rupture is composed of both left-lateral strike-slip and thrust motion,
26 similar to the 2010 rupture, but aftershock locations from a local short-period network are too
27 diffuse to precisely delineate the segments that participated in this rupture. A few days after the
28 mainshocks, we installed 12 broadband stations in the epicentral area. Here we use data from those
29 stations in combination with 4 local Raspberry Shakes stations that were already in place as part
30 of a citizen seismology experiment to precisely relocate 2528 aftershocks from August to
31 December 2021 and derive one-dimensional P and S crustal velocity models for this region. We
32 show that the aftershocks delineate three north dipping structures with different strikes, located to
33 the north of the Enriquillo Plantain Garden (EPG) fault. Additionally, two smaller aftershock
34 clusters occurred on the EPG fault near the hypocenter area, indicative of triggered seismicity.
35 Focal mechanisms are in agreement with coseismic slip inversion from InSAR data with nodal
36 planes that are consistent with the transpressional structures illustrated by the aftershock zones.

41 **1. Introduction**

42 The 14 August 2021 Mw7.2 Nippes, Haiti, earthquake is the second major event to strike
43 southern Haiti this century, 11 years after the devastating 2010 Mw7.0 event. These two
44 earthquakes struck a fault zone that encompasses the Enriquillo Plantain Garden fault (or EPG
45 fault for short), that cuts through the southern peninsula of Haiti in the E-W direction and
46 accommodates part of the relative motion between the Caribbean and North American plates.
47 Geological mapping shows that the EPG fault is a left-lateral strike-slip fault with geomorphic
48 evidence for Quaternary activity (Mann et al., 1995; Saint Fleur et al., 2015) and a geodetically-
49 determined slip rate of 7 to 9 mm/yr (Benford et al., 2012; S. Smithe et al., 2015). Historical
50 archives show that southern Haiti was struck by 4 significant earthquakes in the 18th century in
51 1701, 1751, 1751, and 1770 and a sequence of moderate earthquakes in 1860 (Bakun et al., 2012;
52 Scherer, 1912; Vogt, 2004, 2005), followed by a long period of relative quiescence until 2010. To
53 the north, the remainder of the relative motion between the Caribbean and North American plates
54 is taken up by the Oriente-Septentrional strike-slip fault and, further north, by the North Hispaniola
55 thrust fault, continuous to the east with the Puerto Rico Trench (Figure 1).

56
57 The 2010 earthquake occurred near Léogâne with an epicenter less than 25 km from the
58 capital city of Port-au-Prince (Nettles & Hjörleifsdóttir, 2010). The rupture was initially believed
59 to have initiated on the EPG fault, on the basis of the proximity of the mainshock epicenter to that
60 fault. Most subsequent finite-fault inversions using geodetic (interferometric synthetic aperture
61 radar (InSAR) and GPS), seismological (teleseismic data) and geological data (coral uplift)
62 concluded that more than 80% of the seismic moment was released on a north dipping fault,
63 different from the EPG fault, referred to as the Léogâne fault (Calais et al., 2010; Hayes et al.,
64 2010). The 2010 earthquake ruptured at least two fault segments, a first one in the east with mostly
65 reverse motion, then propagated westward to a second, strike-slip, segment but did not transfer to
66 the nearby EPG fault (Douilly et al., 2013; Smithe et al., 2013). Dynamic rupture models show
67 that the two rupture is well explained by the successive rupture of two fault segments oriented
68 favorably with respect to the rupture propagation, while the geometry of the EPG fault did not
69 allow shear stress to reach failure (Douilly et al., 2015).

70
71 While a detailed analysis of the 2010 earthquake aftershocks – hence a direct
72 characterization of the rupture geometry – had to wait for the analysis of data from the deployment
73 of a temporary seismic network (Douilly et al., 2013), a rapid preliminary analysis of the 2021
74 earthquake was made possible thanks to low-cost, citizen-hosted seismic stations that operated
75 during and after the mainshock (Calais et al., 2022a). Their real-time data allowed for the rapid
76 identification of two aftershock clusters that coincide with the two areas of coseismic slip
77 identified in inversions of conventional seismological and geodetic data. The 2021 rupture bears
78 similarities with its 2010 counterpart as the event is transpressional, initiated on a mostly reverse
79 fault segment, then propagated westward onto a purely strike-slip segment. Though the presence
80 of citizen-hosted seismic stations proved invaluable for a rapid assessment of the 2021 earthquake

81 source, much remains to be understood as the low-cost stations used in this preliminary analysis
82 have a limited dynamic range (Anthony et al., 2019) and are sparsely distributed. A rapid field
83 response led by the Haiti State University in collaboration with other institutions from France and
84 USA however allowed for the deployment of 12 broadband seismic stations in the epicentral area
85 within 6-10 days of the mainshock.

86
87 Ground deformation from InSAR interferogram images indicates that the eastern half of
88 the rupture is dominated by reverse motion while the western half has mostly left-lateral motion,
89 with coseismic ground displacement limited to the north of the EPG fault (Calais et al., 2022a;
90 Maurer et al., 2022). This implies that the 2021 rupture occurred on a secondary unmapped fault,
91 as in 2010, or that it ruptured the EPG fault proper, but with a curved geometry at depth. To test
92 these possibilities, and considering that well located early aftershocks tend to better delineate the
93 ruptured segments that participated in the mainshock (Douilly et al., 2013; Ratchkovski et al.,
94 2004; Shelly, 2020), we used a subset of the aftershocks detected from August to December 2021
95 to infer a 1D P and S crustal velocity model for this region and to precisely relocate those
96 aftershocks to resolve the geometry of the fault segments involved in the rupture.

97 98 **2. Data and methods**

99 **2.1. Station deployment**

100 A few days following the August 14, 2021 mainshock, we deployed 10 Nanometric and 2
101 Guralp broadband seismic stations in the epicentral area to complement the 4 local 4-component
102 (3-component accelerometer and 1-component velocimeter) Raspberry Shake (RS) stations that
103 were installed during the citizen seismology experiment in southwestern Haiti (Calais et al.,
104 2022a). The real-time aftershock detection from the ayiti-séisme platform allowed us to optimize
105 the geographic distribution of broadband stations. Each Nanometric station consists of a Trillium
106 Compact 120 s posthole broadband seismometer, a 24 bit Centaur digital recorder and the
107 remaining accessories such as GPS receiver, 12 V battery, solar panels, and a deployment box.
108 The Guralp systems, installed three days after the earthquake, were each composed of a 24 bit
109 Minimus recorder associated with CMG40T broadband sensor and other accessories such as a GPS
110 receiver, a 12 V battery, and a solar panel. All the stations were fully operational starting August
111 25, 2021 and we plan on leaving them in the field for at least a year to continuously record the
112 seismic data. The first service maintenance and data collection took place in early October 2021
113 but two stations had stopped working. Station PAST had a battery problem that was later fixed.
114 The solar panel at station LBOR was stolen, so we decided to move it to a more secure location
115 and rename it SALO. This renamed station was operational on October 10. The complete list of
116 all broadband and short period Raspberry Shake stations with their deployment date is given in
117 Table 1.

121 **2.2. Event detection and magnitude calculation**

122 In this study, we used continuous waveforms recorded between August 20 and December
123 31st 2021. In total, 63 GB of recordings were collected by the temporary stations over the studied
124 period. The waveforms were stored in standard miniseed format in a database organized by daily
125 continuous files (24 h), completed with data from the four RS of the HY Haiti network. Such a
126 database allows for direct access to the data with the processing software, and for verifying data
127 availability via the fdsn web service. We use SeisComp3, a tool for real-time monitoring, to
128 analyze the data. The realtime stream is simulated with records collected by injecting time-ordered
129 multiplexed data (playback) in blocks of 24 hours.

130
131 The data is processed in two steps. The first one is a phase detection based on a standard
132 STA/LTA analysis (0.5-60s) (Allen, 1982) on filtered data (4-20Hz). These parameters have been
133 defined in such a way that the algorithm is sensitive to rapid increases in amplitude over time,
134 characteristic of local earthquakes. For S phases, we use the AIC (Akaike Information Criterion)
135 (Maeda, 1985) detection algorithm implemented in SC3. The second step is the association of the
136 automatic picks. This is performed by the SC3 scanloc module, which uses DBSCAN (density-
137 based spatial clustering of applications with noise; Ester et al., 1996), a machine learning algorithm
138 for clustering tasks. To limit false detections, a minimum of 6 associated phases is required to
139 create an event. In total, the automatic catalog contains 5560 events detected and located during
140 the time interval considered here. We calculate the magnitude of these events and compare the
141 event detection from the playback catalog with the ayiti-séisme catalog (Figure 2). With the
142 addition of the local broadband stations, we were able to detect significantly more daily events and
143 with lower magnitude compared to the original catalog.

144 145 **2.3. Velocity and hypocenter determination**

146 To properly delimitate the structures involved in the 2021 earthquake, we selected a subset
147 of well located aftershocks within the original catalog described above. We decided to only use
148 local stations in our analysis since a 1D velocity model would not be able to fully accommodate
149 the phase delays from the distant regional stations considering the heterogeneity of the crustal
150 structure over the Hispaniola island (Corbeau et al., 2017; Douilly et al., 2016; Possee et al., 2019;
151 Quiros et al., 2018). We retain a total of 2877 aftershocks with 22249 P-wave arrivals and 9652 S-
152 wave arrivals that have an RMS < 0.7 s and that are only located on land and inside the area
153 covered by our stations. Therefore all the events that occurred offshore near the town of Jérémie
154 or near the 2010 rupture by Léogâne are not considered in the analysis below. We then used the
155 location software Velest (Kissling et al., 1994, 1995) to jointly invert those arrivals for the 1D P&S
156 velocity models, hypocenter locations, and station corrections. After performing the joint-
157 hypocenter inversion, we incorporated the final velocity model and hypocenter locations from
158 Velest into the HypoDD double-difference software (Waldhauser, 2001; Waldhauser & Ellsworth,
159 2000, 2002) to reduce the first order scattering effect due to regional heterogeneities and to further
160 improve the aftershock locations. The double-difference method iteratively minimizes the residual

161 between the observed and calculated travel times for pairs of earthquakes observed at common
162 stations by changing their hypocenter vector. This approach cancels common errors when the
163 distribution of seismicity is sufficiently dense and can better delineate the active structures. As an
164 example, for the 2010 Haiti earthquake, the relocations from hypoDD were more tightly clustered
165 compared to the Velest locations and the ruptured segments were better defined (Douilly et al.,
166 2013). However, the hypoDD earthquake catalog will have fewer events compared to the Velest
167 catalog. This is due to the fact that by fixing the maximum event separation to 10 km and the
168 number of links to define a neighbor to 6, the reweighting process after each iteration will cause
169 some events to exceed the separation criteria and be removed in the process (Waldhauser, 2001).
170 Thus, after computing the inversion with hypoDD, the number of aftershocks is reduced to 2528
171 events and those high-precision location events are then used to identify the structures that were
172 activated by the mainshock.

173

174 **2.4. P-wave first motion focal mechanisms**

175 To investigate the deformation patterns of the ruptured segments delineated by the
176 aftershock relocations, we manually picked two hundred events from the hypoDD catalog with at
177 least 10 P-wave first motion polarities to compute their preferred fault plane solution using the
178 HASH software (Hardebeck & Shearer, 2008). Given the limited number of local stations in our
179 study, we also incorporate the manual picks from regional stations with the purpose of increasing
180 the station distribution ratio and reducing the misfit to obtain a reliable set of focal mechanisms.
181 We use the 1D velocity model obtained from the Velest joint inversion to compute the take-off
182 angles and determine the best focal mechanisms. Following Hardebeck & Shearer (2008), we only
183 consider focal mechanisms with a misfit less than 0.3 and a station distribution ratio greater than
184 0.3. This results in a focal mechanism dataset of 53 events.

185

186 **3. Results**

187 **3.1. Minimum 1D Velocity structure and station corrections**

188 To derive the best fitting velocity structure, we first select a subset of events that have the
189 most recordings and an azimuthal gap less than 180° . We chose station BFIN as the reference (i.e.
190 P station correction is set to zero) because it is located near the center of the aftershock zone and
191 has the most recordings. We tested a range of starting velocity models including the recent one
192 from Douilly et al., (2016) that was derived in the southeastern part of the peninsula near the 2010
193 mainshock. After several iterations, the residuals and average Root Mean Square (RMS) decrease
194 from 0.40 and 0.16 s to 0.22 and 0.05 s respectively. Figure 3 shows the results considering only
195 two input velocity models (dashed lines). The velocities after the iterations are shown with solid
196 lines where the black solid line is the final model used in this study. Despite the differences with
197 the input velocities, the final models are consistent with each other, implying a good stability of
198 our velocity models. We observe that the final P and S velocities for almost all the layers are
199 consistently smaller compared to ones obtained further east near Léogâne by Douilly et al., (2016)
200 (gray dashed lines in Figure 3). In the upper 5 km, the decrease in velocity is on the order of 0.4

201 km/s for the P and ~ 0.1 km for the S. For the layers between 8-18 km, the decrease is ~ 0.2 km/s
202 for both P and S. This suggests that there is a lateral heterogeneity for both P and S velocities in
203 the Southern Peninsula.

204
205 To further assess the sensitivity of the inversion to the initial parameters, we performed
206 two additional tests. For the first test, we split the dataset equally into two groups with similar
207 spatial distribution of aftershocks. Using the same initial model shown in black dashed line in
208 Figure 3, we inverted both groups individually and compared their final velocities. Figure 4
209 compares the final velocity model from Figure 3 to the velocities for the two separate datasets. The
210 velocities for the two datasets appear to converge towards our final velocity model for this region.
211 Finally, similarly to Douilly et al., (2016), we used different starting model magnitudes with low
212 and high values for the P and S models (dashed lines in Figure 5). After inverting each of them,
213 we observe that all models are converging to the final velocity model (solid lines in Figure 5 and
214 Table 2) that we will refer to as the minimum 1D velocity model for this region. Those two tests
215 show high convergence and stability of our minimum 1D velocity model.

216
217 Using Velest, we also invert for the P and S station corrections which are the average time
218 residuals that the 1D velocity model could not fully accommodate due to a number of factors such
219 as lateral heterogeneity of the velocity structure. The corrections are initially set to zero and vary
220 during the inversion with respect to the reference station. Table 1 and Figure 6 show the final P
221 and S station corrections. Considering that RS stations SPRIV, SJER2, SAQUI and SMESL have
222 only one vertical velocity component and no horizontal velocity components, their S station
223 corrections are by default set to zero and should not be interpreted. RS stations SPRIV and SJER2
224 have ~ 8 times fewer P-arrivals compared to the other two RS stations (SAQUI and SMESL) and
225 thus their P-station corrections are not well constrained. For the P-wave station correction
226 distribution, we observe that the outermost stations (TROU, HASL, LBOR, CHAR) have positive
227 station corrections on the order of $+0.2-0.3$ s while stations in the center of the network have either
228 nearly zero (e.g. CAVA, PEST) or negative anomalies (e.g. HBAR). Stations SMESL and SALO
229 are located on the same site and as expected their P corrections are nearly the same, which further
230 showcases the high accuracy and stability of the results. The S-wave station corrections show
231 similar distribution as for the P corrections, where stations TROU, HASL, LBOR and CHAR have
232 positive corrections while the center stations such as PEST, HBAR, CAVA and PBEA have
233 negative corrections. This variability in station correction distribution is most likely due to a
234 change in velocities, which further supports the argument of a lateral heterogeneity of the velocity
235 model in the Southern Peninsula.

236 237 **3.2. Spatial distribution of aftershocks**

238 After identifying the best fitting 1D velocity model (Table 2) from the joint inversion
239 described above, we run the Velest program one last time to relocate the entire set of 2820
240 aftershocks by keeping the final P&S velocities and station corrections fixed. While doing so, we

241 incorporate the final hypocenter locations from Velest to hypoDD to further refine the locations
242 using the catalog of phase arrival picks only. For the reasons explained above, the hypoDD catalog
243 is reduced to 2528 total events, and their locations, coded by hypocenter depth and magnitude, are
244 shown in Figure 7a (see Table S1 in the electronic supplement for a complete list of the earthquake
245 locations). Similar to the results of Calais et al. (2022a), the aftershocks cluster north of the EPG
246 fault has a spatial distribution that seems to follow the topography. Overall, the aftershock
247 distribution illustrates several zones, or clusters, with slightly different behavior and orientation.
248 The eastern one, which is located between the longitudes of -73.35° and -73.65° , shows a
249 northwest-southeast striking feature that has significantly more events compared to the other two
250 clusters. Furthermore, events in this zone reach greater depth (up to ~ 25 km) while events in the
251 other zones are shallower (maximum depth ~ 15 km). In the center zone (longitudes -73.65° to $-$
252 73.8°), we observe a slight rotation in the strike of the aftershock cluster, to a southwest-northeast
253 strike with shallower events. As one moves west, aftershocks transition to an east-west direction
254 (longitudes -73.8° and -74.10°) which is in agreement with the orientation and surface trace of the
255 Ravine du Sud fault (Saint Fleur et al., 2020). To better understand the vertical distribution of
256 aftershocks, we represent them along different depth slices of ± 2 km (Figure 8). The structures
257 described above are well expressed at different depth slices where the eastern, central and western
258 zones dip to the north with a strike of $N60^\circ W \pm 5^\circ$, $N60^\circ E \pm 5^\circ$ and $N85^\circ E \pm 5^\circ$ respectively.
259

260 For all clusters, we observe very few near-surface events, *i.e.* located in the upper 4 km.
261 The shallowest events are primarily located in the western cluster near the intersection with the
262 central one, which is consistent with the sharp transition in the InSAR data indicative of surface
263 rupture along the Ravine du Sud fault (Calais et al., 2022a; Maurer et al., 2022). Figures 7b, c and
264 d show the aftershock locations coded by hypocenter depth but for different time intervals. While
265 more than 50% of the events occurred between August 20th and September 30th, for the remaining
266 days in the catalog, the aftershocks still display the same behaviors where the central and western
267 cluster have significantly fewer events compared to the eastern one, while the deeper events are
268 clustered in the eastern zone. We did not observe a clear migration of the aftershocks during either
269 time slice, events were continuously occurring on all clusters (Figures 7 and S2). We also observe
270 a small cluster of shallower aftershocks, less than 15 km-long, outside of the mainshock area and
271 to the east (longitude -73.25°) with events that occurred primarily during the first month after the
272 mainshock. They are likely related to shallow triggered afterslip along the EPG fault, as
273 documented by Maurer et al. (2022) and Yin et al. (2022).
274

275 The P-wave first motion focal mechanism nodal planes match the overall pattern of the
276 aftershock distribution (see Table S2 in the electronic supplement for a complete list of the focal
277 mechanisms). Figure 9 shows the focal mechanisms sorted by the plunge of their principal axes
278 (following Zoback, 1992) where the red focal mechanisms indicate primarily thrust motion, the
279 green ones strike-slip events, and the black ones are the rest. The events within the eastern cluster
280 are primarily composed of thrust and left strike-slip motion consistently with the coseismic rupture

281 models (Calais et al., 2022a; Maurer et al., 2022; Okuwaki & Fan, 2022). Most importantly, one
282 of the nodal planes for most of these events is parallel to the NW-SE as illustrated by the
283 aftershocks. Furthermore, the western cluster is mostly composed of left lateral strike-slip
284 mechanisms with nodal planes that are aligned with the direction of the Ravine du Sud fault,
285 consistent with the aftershock distribution. Nevertheless, a more detailed analysis of the focal
286 mechanisms is necessary to confirm this assertion.

287

288 **4 . Discussion**

289 **4.1 Was the EPG fault part of the main rupture?**

290 The Mw7.2 2021 Nippes, Haiti, earthquake can now be added to a long list of complex
291 branch fault earthquakes involving rupture along multiple fault segments such as the 1979 Imperial
292 Valley (Archuleta, 1984), the 1980 El Asnam (Cisternas et al., 1982; Yielding, 1985), the 1980
293 Irpinia (Bernard et al., 1993), the 1992 Landers earthquake (Sowers et al., 1994), the 1999 Hector
294 mine earthquake (Treiman et al., 2002), the 2002 Denali earthquake (Frankel, 2004), the 2010
295 Darfield earthquake (Beavan et al., 2012), the 2010 El-Mayor Cucapah earthquake (Hauksson et
296 al., 2011), the 2010 Haiti earthquake (Douilly et al., 2013; Meng et al., 2012; S. J. Smithe et al.,
297 2013) and the 2016 Kaikoura earthquake (W. Xu et al., 2018). This event ruptured several north
298 dipping segments close to the EPG fault in a pattern that is similar to the 2010 rupture further east
299 (Douilly et al., 2013). It is important to note that the dip angle of the EPG fault is not directly
300 constrained in the area of the 2021 rupture, though this fault is believed to be primarily vertical or
301 south-dipping near the 2010 mainshock (Prentice et al., 2010). However one cannot rule out a
302 variable dip along strike for the EPG fault in accordance with the spatial distribution of the
303 topography. Near the 2010 rupture, the high topography is located to the south of the rupture,
304 consistent with the south dipping configuration of the EPG fault inferred by Prentice et al. (2010)
305 further east. However, near the 2021 mainshock, the high topography is located to the north of the
306 rupture (Pic Macaya) and thus, without the presence of other north-dipping secondary faults, a
307 north-dipping EPG fault could explain the high topography north of the surface trace. This warped
308 fault configuration with laterally-variable dip has also been inferred for the San Andreas fault (Fuis
309 et al., 2012), another plate boundary fault in a similar tectonic setting. Using potential field data,
310 active source imaging and seismicity, Fuis et al., (2012) indicate that the SAF dips to the southwest
311 north of the Big Bend area but immediately rotates to a northeast dip after the bend, consistent
312 with the asymmetric topography in that region. However, considering the lack of evidence for a
313 dipping EPG fault in our study area, in the following we will assume the EPG fault to be purely
314 vertical.

315

316 Considering the proximity of those ruptured segments to the nearby EPG fault, it is worth
317 investigating whether the latter did participate in this earthquake, as the outcome could alter
318 seismic hazard estimates for this region following the 2021 rupture. Therefore, to further
319 understand the geometry of the structures and investigate the likelihood for the main structures to
320 coincide with the EPG fault, we display on Figure 10 a series of cross sections perpendicular to

321 the orientation of each aftershock cluster. Events in cross section A-A' located outside of the
322 rupture zone delineate a vertical structure which is in agreement with the assumption of a vertical
323 EPG fault. These events coincide with the zone of afterslip that has been observed using InSAR
324 data (Maurer et al., 2022; Yin et al., 2022). In cross section B-B', which is perpendicular to the
325 NW-SE striking direction of the eastern cluster, we observe that the aftershocks delineate primarily
326 a north dipping segment ($\sim 60^\circ$ - 65°), though its dip angle seems to be steeper below 18 km depth.
327 Moreover, we find aftershocks along the vertical projection of the EPG surface fault trace (vertical
328 gray line in Figure 10) near 10 km depth. This suggests that the eastern cluster occurred on a fault
329 north of – and separate from – the EPG fault, a pattern similar to with the Léogâne fault rupture
330 during the 2010 earthquake (Calais et al., 2010; Mercier de Lépinay et al., 2011; Smithe et al.,
331 2013). Aftershocks within the central cluster in cross section C-C' define a dip angle down to
332 18 km that is consistent with the eastern cluster, but appear to dip at a slightly shallower angle
333 below that depth. Finally, aftershocks in cross section D-D' show a clear $\sim N75^\circ$ dip angle on a
334 fault segment that coincides with the Ravine du sud fault, parallel to the EPG fault but separate
335 from it, in accordance with slip inversion from InSAR data (Calais et al., 2022a; Maurer et al.,
336 2022).

337

338 We also display north-south, NE-SW and NW-SE directed cross sections on Figures 11,
339 S1, S2. Cross section A-A' in Figures 11 and S2 clearly shows events on the EPG fault (assumed
340 to be vertical) that may have been triggered by the mainshock. Events within cross section B-B'
341 and C-C' show a north-dipping structure adjacent to the EPG fault. We observe a rotation in strike
342 between the eastern and central clusters in cross sections E-E' in Figures 11 and S2. Overall, our
343 favored interpretation of the 2021 Nippes earthquake involves the rupture of north-dipping faults
344 separate from the main EPG fault, with a compressional bend configuration.

345

346 This raises the question as to why would the rupture favor secondary, compressional faults
347 rather than the perhaps more mature EPG fault? This was observed during the 1989 Loma Prieta
348 earthquake in California where the ruptured occurred on a steeply dipping thrust fault near the
349 main San Andreas fault (Dietz & Ellsworth, 1990). This was also the case for the 2010 Haiti
350 earthquake, where Douilly et al., (2015) argued that the geometry of the faults and particularly a
351 weak (lower friction) eastern Léogâne fault were necessary for the rupture to break both north
352 dipping segments and bypass the EPG fault. We hypothesize that this could also be the case for
353 the 2021 rupture. Also, that the EPG fault did not rupture, does not imply that the 2021 rupture
354 had no impact on the that fault. In the case of the 2010 Haiti earthquake, the Léogâne fault rupture
355 intersected the EPG fault at depth, causing an increase in stresses in the upper part of the EPG fault
356 and a decrease below the intersection (Douilly et al., 2015; Smithe et al., 2013). Given the
357 similarity in rupture pattern between the 2010 and 2021 events, and the fact that the surface
358 projection of the ruptured segments intersect the EPG fault near the surface and not at depth, one
359 would expect the 2021 rupture to cause a slight decrease in shear stress on the EPG fault segments
360 adjacent to the ruptured structures. Future Coulomb stress change calculations on nearby faults

361 and dynamic rupture studies are needed to clarify this hypothesis about the shear stress variation
362 on the EPG fault.

363

364 **4.2. Activation of secondary faults**

365 Following major crustal earthquakes, aftershocks can sometimes occur on secondary
366 structures (Douilly et al., 2013; Hauksson et al., 1993; Shearer et al., 2003; Shelly, 2020), *i.e.* fault
367 segments that did not slip coseismically during the mainshock but were activated or triggered due
368 to mechanisms such as creep, postseismic deformation, static or dynamic stress change etc. Such
369 secondary faults were observed following the 2019 Ridgecrest sequence. This earthquake involved
370 two main events of magnitude 6.4 and 7.1 with complex rupture on nearly parallel and nearly
371 perpendicular fault segments (DuRoss et al., 2020; Ponti et al., 2020; Shelly, 2020). The Mw6.4
372 event occurred on a set of left-lateral faults and the Mw7.1 one took place nearly 36 hours later on
373 a right-lateral fault that crossed the left-lateral fault system. This event triggered significant
374 seismicity on the Garlock fault, particularly on the segment close to the rupture area (Shelly, 2020)
375 where shallow creep and shear stress increase have been observed (Ramos et al., 2020; Toda &
376 Stein, 2020). Furthermore, the aftershock distribution delineated numerous cross-cutting faults
377 perpendicular to the right lateral fault (Shelly, 2020). The activation of these secondary cross-
378 cutting structures was also corroborated by phase gradient analysis with InSAR where those
379 surface fractures showed slip polarity in retrograde with the background tectonic stress (Xu et al.,
380 2020). Secondary structures were also observed during the 2010 Haiti earthquake. The offshore
381 Trois Baies fault experienced significant seismicity following the mainshock (Douilly et al., 2013),
382 consistent with coseismic Coulomb stress change calculations (Symithe et al., 2013). In addition,
383 the aftershocks also delineated antithetic and cross-cutting structures with respect to the fault
384 segments that ruptured during the main event (Douilly et al., 2013).

385

386 Consistent with those crustal earthquakes, the aftershock sequence that followed the 2021
387 Nippes earthquake activated several secondary structures. Similar to the 2010 earthquake, the 2021
388 rupture also triggered significant seismicity along offshore faults (see ayiti-séismes), though we
389 did not incorporate these events in this analysis as their locations are not well constrained because
390 they occurred outside of the footprint of our network. In addition, the aftershocks seem to delineate
391 some north-south striking secondary structures. In map view, these structures are for the most part
392 buried within the central cluster of seismicity. But if we analyze the catalog between November
393 and December (Figure 7d), the aftershocks show alignments different from the orientation of the
394 central cluster described above. While the presence of these structures in map view is debatable,
395 there are some focal mechanisms within that region that have one of their nodal planes parallel to
396 the orientation of these secondary structures, which further support this hypothesis (Figure 8).
397 These structures can also be seen in cross sections B-B' and C-C' in Figure S3 and C-C' in Figure
398 10 where the aftershocks delineate some south-dipping fault planes. Moreover, phase gradient
399 analysis of InSAR images (Sandwell et al., 2000; Sandwell & Price, 1998; Xu et al., 2020), applied

400 to the 2021 Nippes earthquake, revealed the presence of some secondary fault features (Yin et al.,
401 2022) in agreement with our interpretation.

402

403 **5. Conclusion**

404 In this study, we used data from a local seismic station deployment from August 20 to
405 December 31, 2021 to perform a high-resolution aftershock relocation for the 2021 Mw 7.2 Nippes
406 earthquake in southern Haiti. We find two small clusters of events located on the EPG fault. The
407 first one is located just to the east of the rupture area, coincident with afterslip observed in InSAR
408 data. The second one is located in the near vicinity of the hypocenter, where some events delineate
409 a vertical structure that coincides with the vertical projection of the surface trace of the EPG fault.
410 However, the majority of the seismicity is located on structures that are adjacent to the EPG fault,
411 which indicates that the EPG fault proper likely did not rupture during the Nippes earthquake and
412 remains a source of significant regional hazard.

413

414 The majority of the aftershocks form three separate clusters with slightly different strike
415 and dip. The eastern one defines a fault segment north of the EPG fault with a strike of $N60^{\circ}W \pm$
416 5° and a dip of $\sim 60^{\circ}$ towards the north. The central one has a similar dip as the eastern one but the
417 strike rotates to $\sim N60^{\circ}E$. The western one follows the surface trace of the Ravine du Sud fault,
418 with an east-west strike and northward dip of about $\sim 75^{\circ}$. The spatial distribution of aftershocks
419 is not uniform, as the eastern cluster has significantly more events compared to the central and
420 western ones, with deeper events in the eastern cluster as well (greater than 18 km depth). We did
421 not investigate the Moho depth in this study. Variable Moho depth was observed on a north-south
422 configuration near the capital Port-au-Prince from receiver function analysis where the Moho was
423 imaged at 22 km in the south and increased to 41 km in central Haiti (Corbeau et al., 2017). Future
424 receiver function studies should be considered to investigate whether the Moho depth is also
425 variable throughout the Southern Peninsula.

426

427 We also invert for a 1D P&S velocity structure for this region. In general, the final P and
428 S velocities for almost all the layers are consistently smaller compared to the velocities near the
429 2010 Haiti mainshock. This suggests the presence of lateral velocity heterogeneity near the 2021
430 mainshock area. Prominent low and fast velocity anomalies were observed near the 2010 ruptured
431 area and bimaterial interfaces were observed along all the fault segments (Douilly et al., 2016).
432 Bimaterial interfaces can sometimes generate dynamic dilatation at one end of a rupture and
433 dynamic compression at the other end which could cause the rupture to die in the direction of
434 compression and facilitate the rupture to propagate in the dilational direction (Shi & Ben-Zion,
435 2006). Therefore bimaterial interfaces along the EPG fault and the 2021 ruptured segments could
436 potentially explain the unilateral nature of this event where the rupture only propagates west of the
437 hypocenter. Local earthquake tomography and ambient noise tomography with the existing data
438 should be considered in the future to not only define a 3D crustal structure for this region but also
439 to investigate the likelihood of bimaterial interfaces.

440

441 **Data and Resources**

442 The seismic data was collected by a temporary broadband stations following the 2021 Nippes
443 earthquake in Haiti and will be available through the IRIS Data Center. Additional data from RS
444 stations are obtained from the Webservice FDSN of the Ayiti-séismes platform
445 (<https://ayiti.unice.fr/ayiti-seismes/fdsnws/>) and the IRIS Data Center. The stations used in this
446 study are composed of four RS of the HY Haiti network (DOI: <https://doi.org/10.7914/SN/HY>)
447 and twelve broadband stations of the Z2 Haiti network (https://doi.org/10.7914/SN/Z2_2021).
448 SeisComp3 (SC3, <https://www.seiscomp.de/>) is used for the real-time monitoring of the seismic
449 data. The figures in study are plotted with Generic Mapping Tools (Wessel and Smith, 2001;
450 Wessel et al., 2019). This article includes supplemental material that consists of (1) a figure (Figure
451 S1) showing cross sections with respect to time perpendicular to the orientation of the main
452 aftershock clusters, (2) a figure (Figure S2) showing NE-SW cross sections illustrating possible
453 fault structures, (3) a figure (Figure S3) showing NW-SE cross sections illustrating possible fault
454 structures, (4) a table (Table S1) with the Final hypoDD catalog for the 2520 events shown in
455 Figures 7,8,10 and 11 and (5) a table (Table S2) with the P-wave first motion focal mechanisms
456 for the 53 events used in this study.

457

458 **Declaration of Competing Interests**

459 The authors declare no competing interests.

460

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485
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492

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706

707 **List of figure captions**

708 Figure 1: The upper panel shows the seismotectonic context of the Caribbean – North America
709 plate boundary at the longitude of Hispaniola. Main active faults are shown with black lines. Stars
710 indicate major destructive historical (white) and instrumental (red) earthquakes (Scherer, 1912;
711 Bakun et al., 2012). Large arrows show the relative motion between the Caribbean and North
712 American plates. The black dashed rectangle displays the area shown in the lower panel. Top right
713 inset shows the large-scale tectonic setting of the study area, with arrows showing the GPS-derived
714 velocity of the surrounding plates with respect to the Caribbean. Numbers are in cm/yr. The lower
715 panel shows the active faults with red lines from Calais et al., (2022b) in the southern peninsula of
716 Haiti. The white circles mark the aftershock distribution for the 2010 Haiti earthquake (Douilly et
717 al., 2013) and the yellow circles indicate the aftershock relocation for the 2021 Nippes rupture
718 from this study. The dashed blue rectangle shows the area encompassed in figures 6 and beyond.
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742 function of their magnitudes. The black triangles show the local seismic station distribution. The
743 top left is a map view of seismicity, the right and bottom panels are with respect to depth; (a)
744 Complete catalog of 2520 events between the period of August 20th to December 31st, 2021; (b)
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752 principal stresses based on the classification of Zoback, (1992). Thrust mechanisms are
753 represented in red, strike-slip mechanisms are in green, and the black mechanisms indicate the
754 unclassified type of faulting.

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756 Figure 10: Cross sections color coded by hypocenter depth perpendicular to the orientation of the
757 main aftershock clusters. Hypocenters included within a box are projected into the corresponding
758 cross sections. Gray curve above each cross section indicates the surface topography. The vertical
759 gray lines mark the location of either the EPG fault (EF) or the Ravine du Sud fault (RF).

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761 Figure 11: North-South cross sections illustrating the correlation of the fault structures with respect
762 to the EPG fault. Hypocenters within the rectangular box are projected into the corresponding cross
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765
766 **Electronic Supplement**

767 Figure S1: Cross sections with respect to time perpendicular to the orientation of the main
768 aftershock clusters. Hypocenters included within a box are projected into the corresponding cross
769 sections. The vertical gray lines mark the location of either the EPG fault (EF) or the Ravine du
770 Sud fault (RF).

771
772 Figure S2: NE-SW cross sections illustrating possible fault structures. Hypocenters within the
773 rectangular box are projected into the corresponding cross sections. The vertical gray lines mark
774 the location of either the EPG fault (EF) or the Ravine du Sud fault (RF).

775
776 Figure S3: NW-SE cross sections illustrating possible fault structures. Hypocenters within the
777 rectangular box are projected into the corresponding cross sections. The vertical gray lines mark
778 the location of either the EPG fault (EF) or the Ravine du Sud fault (RF).

779
780 Table S1: Final hypoDD catalog for the 2520 events shown in Figures 7,8,10 and 11

781 Table S2: P-wave first motion focal mechanisms for the 53 events used in this study

782 **Table 1: Station information with their P and S time corrections obtained from the joint**
 783 **inversion**
 784

Name	Code	Long. (deg.)	Lat. (deg.)	Elev (m)	P-wave station correction (s)	S-wave station correction (s)	Date installed (yyyy/mm/dd)	Date recovered (yyyy/mm/dd)	Station Type
CHARD	Z2	-74.166	18.275	8	0.38	0.39	2021/08/27	—	Nanometrics
HBAR	Z2	-73.643	18.481	19.2	-0.08	-0.41	2021/08/18	—	Guralp
PBEAU	Z2	-73.957	18.477	600	0.11	-0.24	2021/08/26	—	Nanometrics
CAMPP	Z2	-73.386	18.325	215	0.15	-0.12	2021/08/26	—	Nanometrics
SALO	Z2	-73.616	18.227	0	0.12	-0.15	2021/10/02	—	Nanometrics
CAVA	Z2	-73.656	18.415	784	0.06	-0.19	2021/08/26	—	Nanometrics
BFIN	Z2	-73.612	18.394	454	0.00	-0.29	2021/08/17	—	Nanometrics
HASL	Z2	-73.415	18.384	157	0.46	0.72	2021/08/17	—	Guralp
ROCH	Z2	-73.016	18.180	24	0.09	-0.23	2021/08/26	—	Nanometrics
STTHE	Z2	-73.993	18.534	204	0.21	-0.10	2021/08/26	—	Nanometrics
LBOR	Z2	-73.804	18.280	66	0.23	0.03	2021/08/27	2021/09/21	Nanometrics
TROU	Z2	-73.474	18.513	31	0.17	0.04	2021/08/25	—	Nanometrics
PEST	Z2	-73.799	18.541	39	0.01	-0.41	2021/08/25	—	Nanometrics
SPRIV	HY	-73.244	18.477	1	0.93	0.00	2021/08/18	—	Raspberry Shake
SAQUI	HY	-73.397	18.283	26	0.11	0.00	2021/08/18	—	Raspberry Shake
SMESL	HY	-73.616	18.227	0	0.17	0.00	2020/12/10	—	Raspberry Shake
SJER2	HY	-74.121	18.650	19	0.51	0.00	2019/09/10	—	Raspberry Shake

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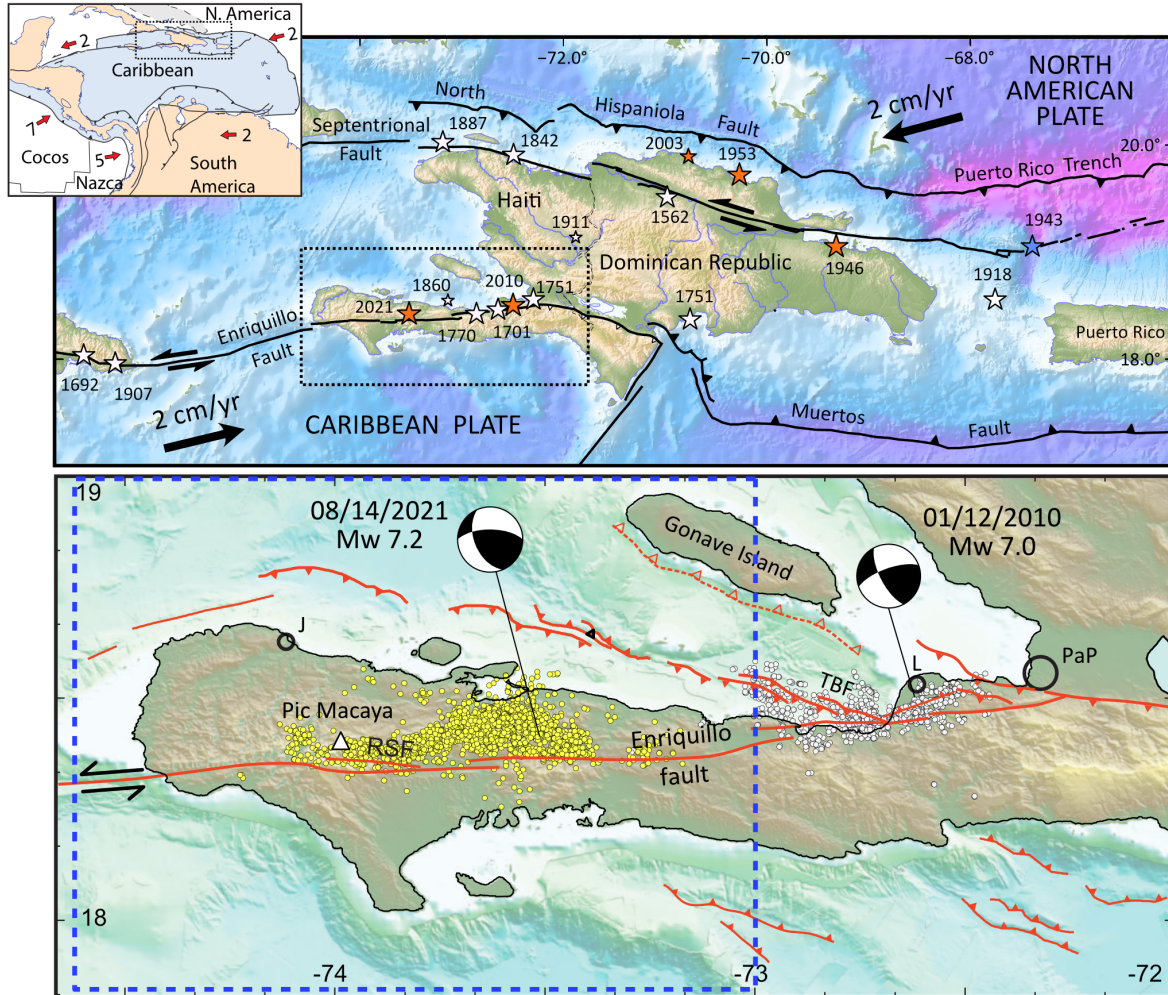
787 **Table 2: Best fitting 1D model for the P-Wave and S-Wave velocity structure**

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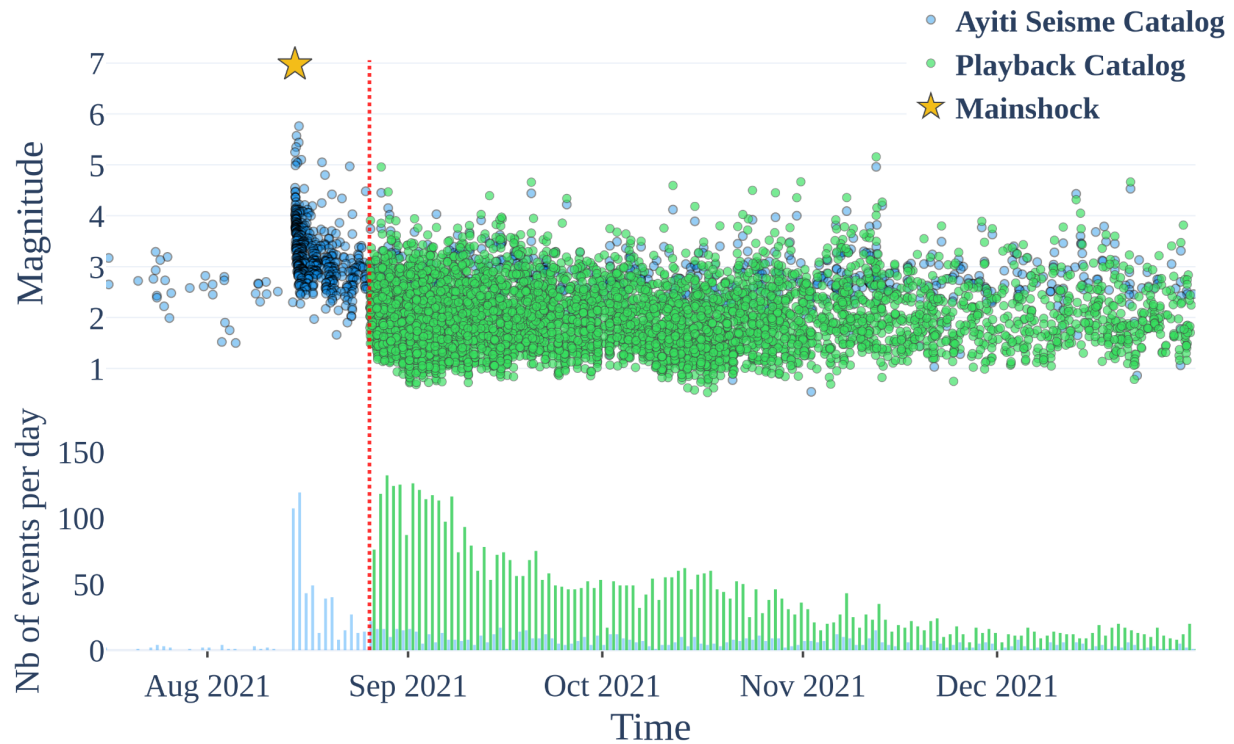
Depth (km)	V_p (km/s)	V_s (km/s)	V_p/V_s
0	4.90	2.42	2.02
3	5.16	2.85	1.81
6	5.91	3.20	1.85
9	6.16	3.41	1.81
12	6.43	3.60	1.79
15	6.46	3.69	1.75
18	6.78	3.80	1.78
22	7.11	3.90	1.82
25	7.33	4.01	1.83
30	8.04	4.49	1.79

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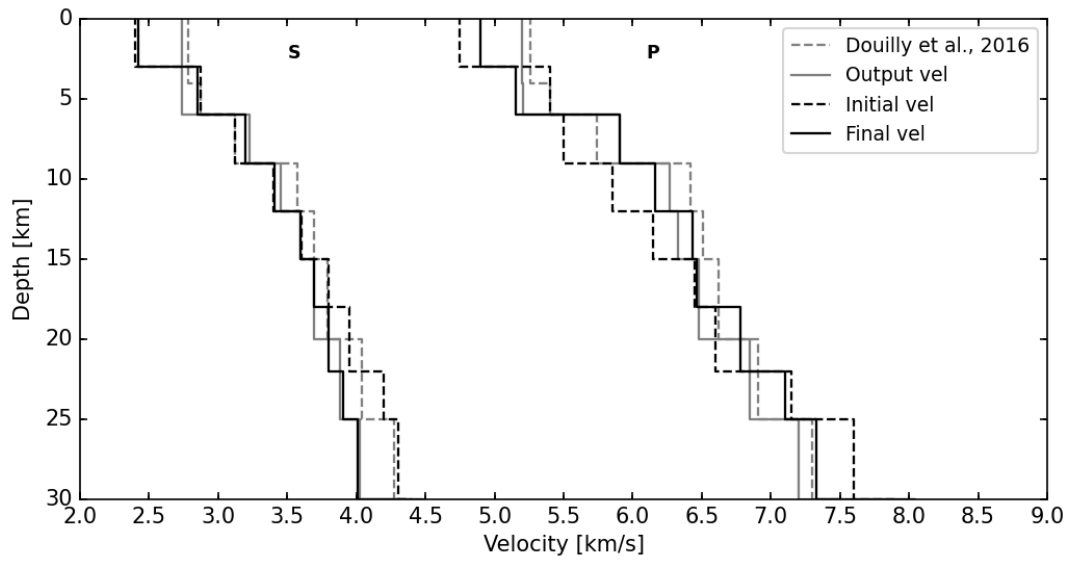
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 793 **Figure 1: The upper panel shows the seismotectonic context of the Caribbean – North**
 794 **America plate boundary at the longitude of Hispaniola. Main active faults are shown with**
 795 **black lines. Stars indicate major destructive historical (white) and instrumental (red)**
 796 **earthquakes (Scherer, 1912; Bakun et al., 2012). Large arrows show the relative motion**
 797 **between the Caribbean and North American plates. The black dashed rectangle displays**
 798 **the area shown in the lower panel. Top right inset shows the large-scale tectonic setting of**
 799 **the study area, with arrows showing the GPS-derived velocity of the surrounding plates**
 800 **with respect to the Caribbean. Numbers are in cm/yr. The lower panel shows the active**
 801 **faults with red lines from Calais et al., (2022b) in the southern peninsula of Haiti. The**
 802 **white circles mark the aftershock distribution for the 2010 Haiti earthquake (Douilly et al.,**
 803 **2013) and the yellow circles indicate the aftershock relocation for the 2021 Nippes rupture**
 804 **from this study. The dashed blue rectangle shows the area encompassed in figures 6 and**
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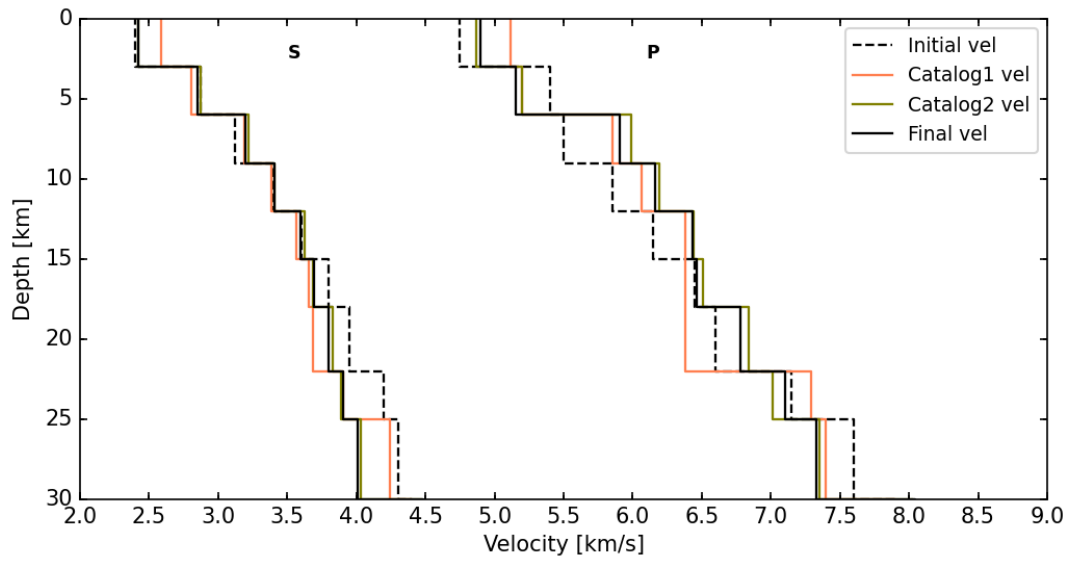


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 810 **in blue) and the playback catalog (green) with temporary stations. The top panel is the**
 811 **distribution with respect to magnitude and the bottom panel is with respect to the number**
 812 **of events per day. The yellow star marks the mainshock and the red dash line indicates the**
 813 **installation date of the temporary stations. Significant more daily events are detected with**
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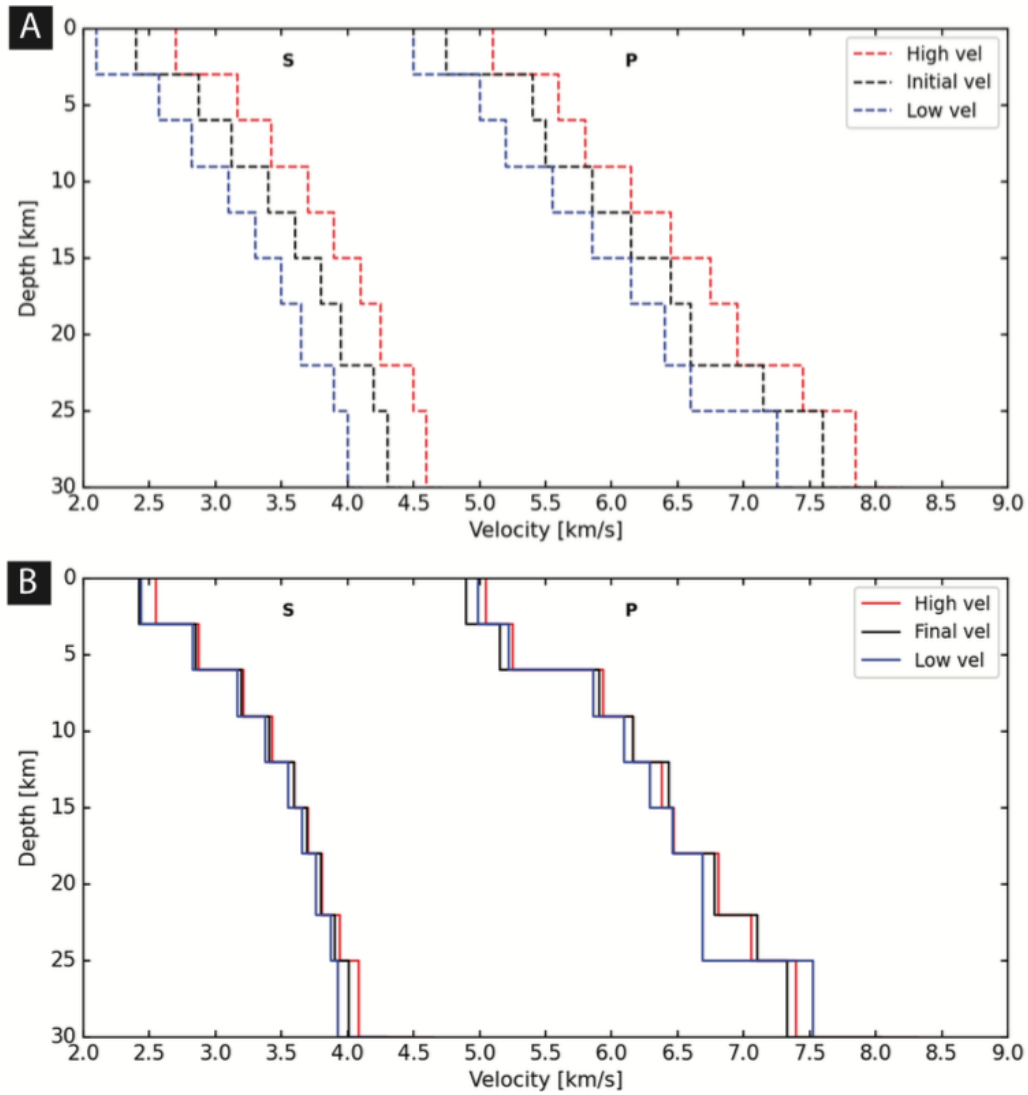
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Figure 3: 1D P and S velocity profiles considering two input velocities. Initial models are shown with dashed lines and final models after several runs are shown with solid lines.

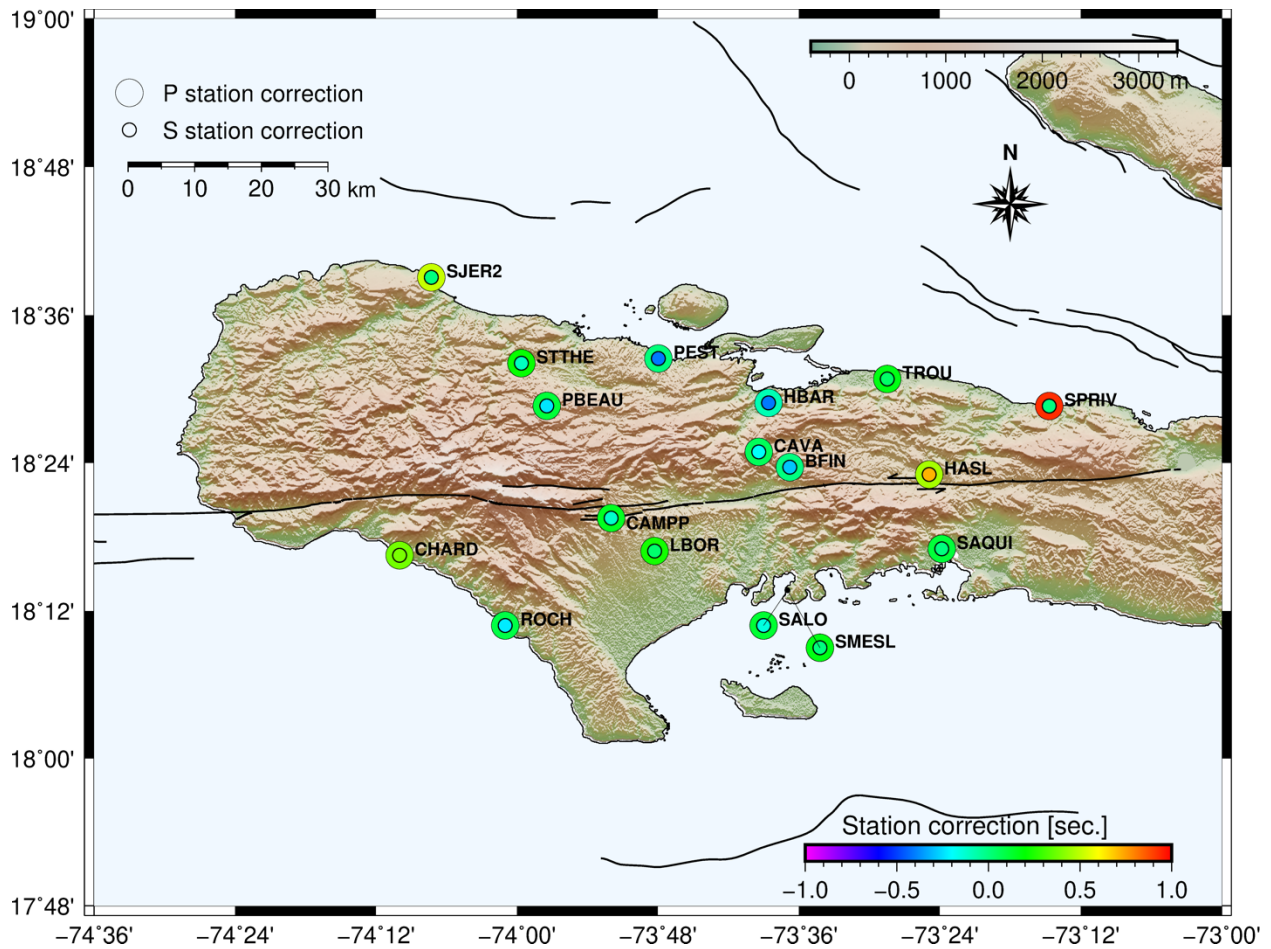


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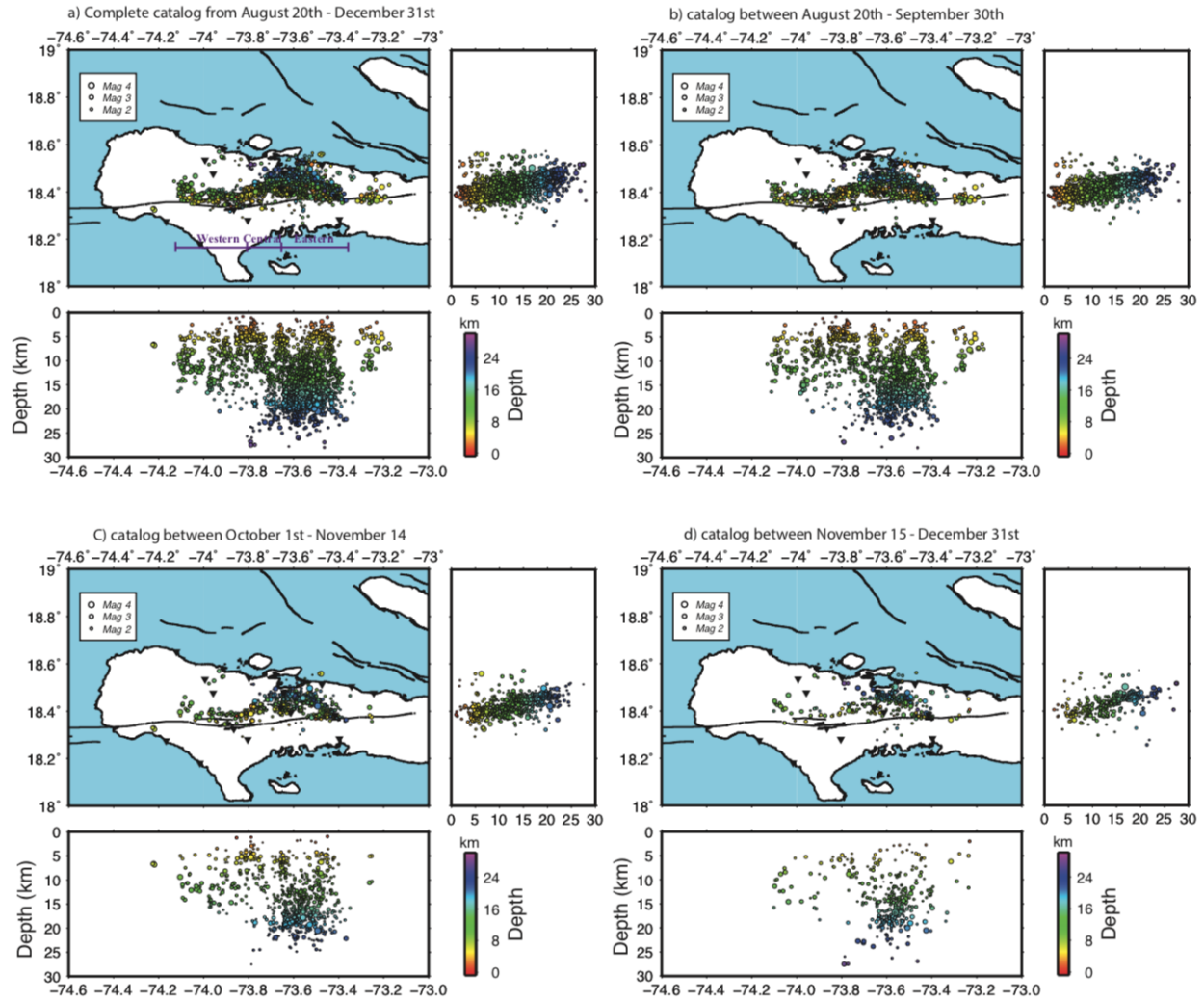


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 826 **Their corresponding final velocity models (solid lines) for each model in A. The black**
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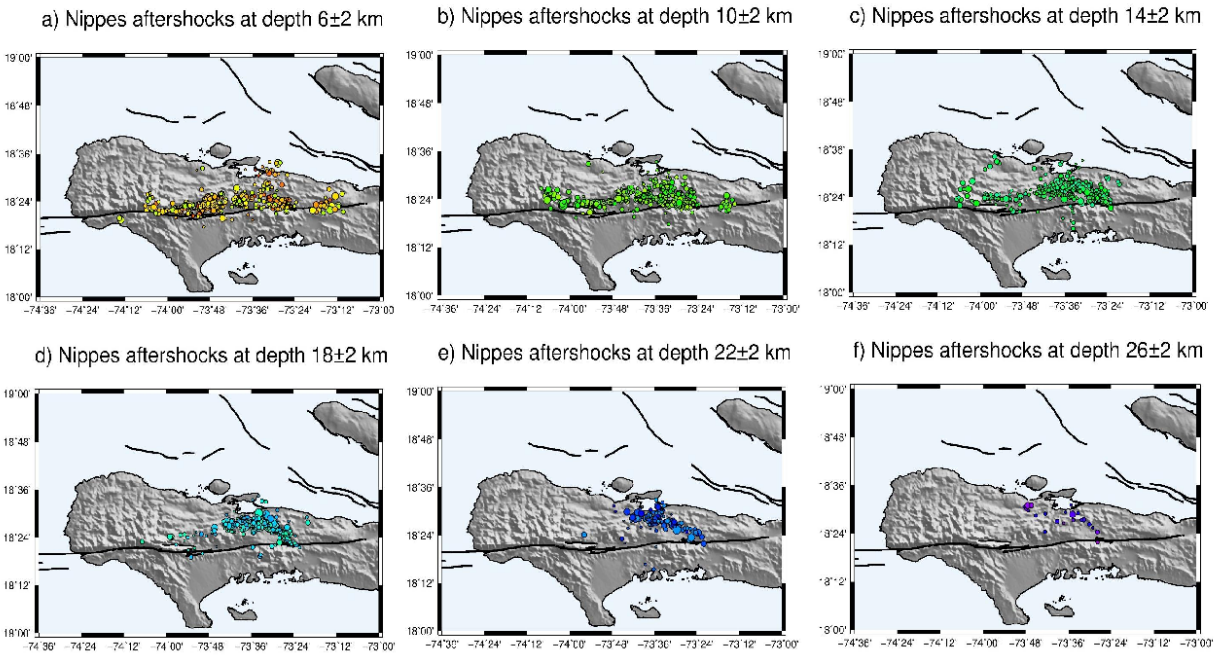
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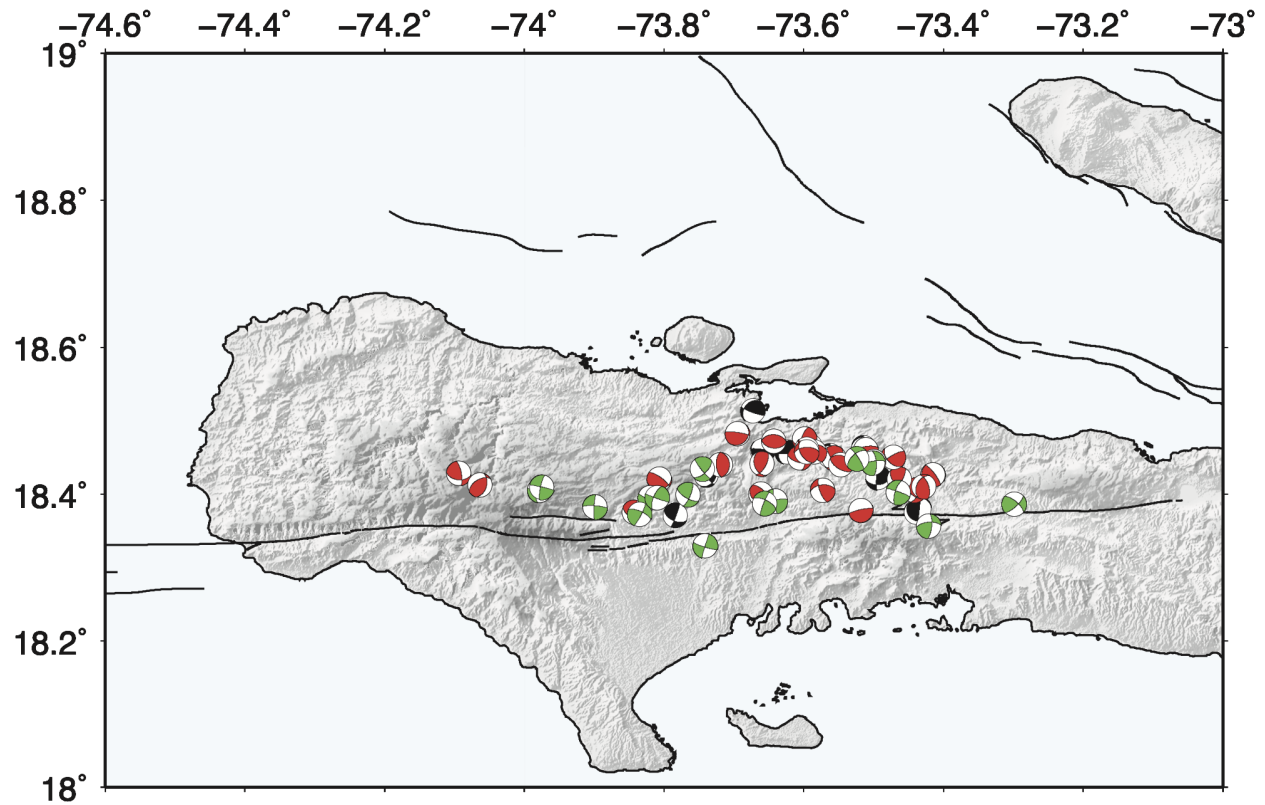


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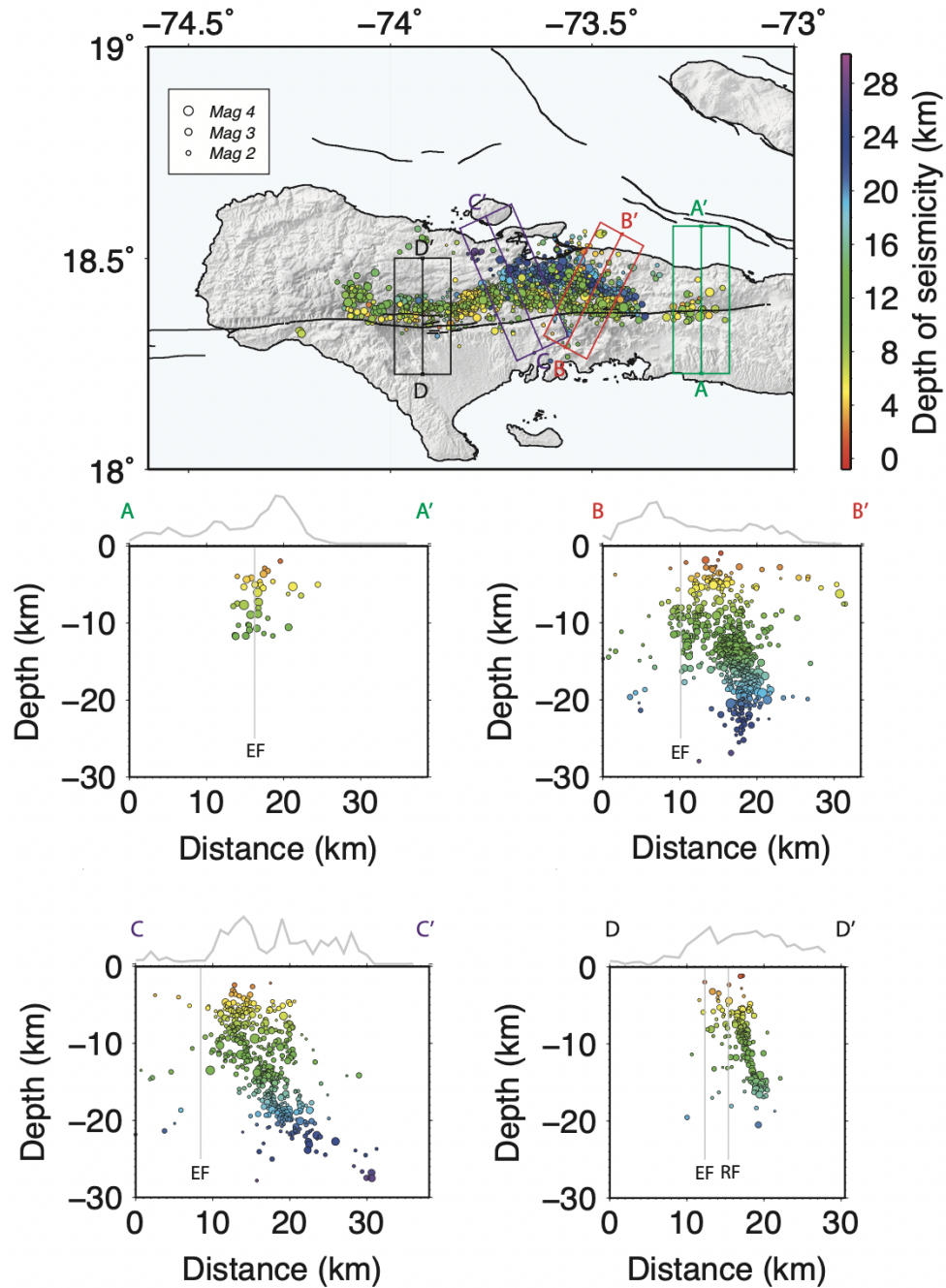
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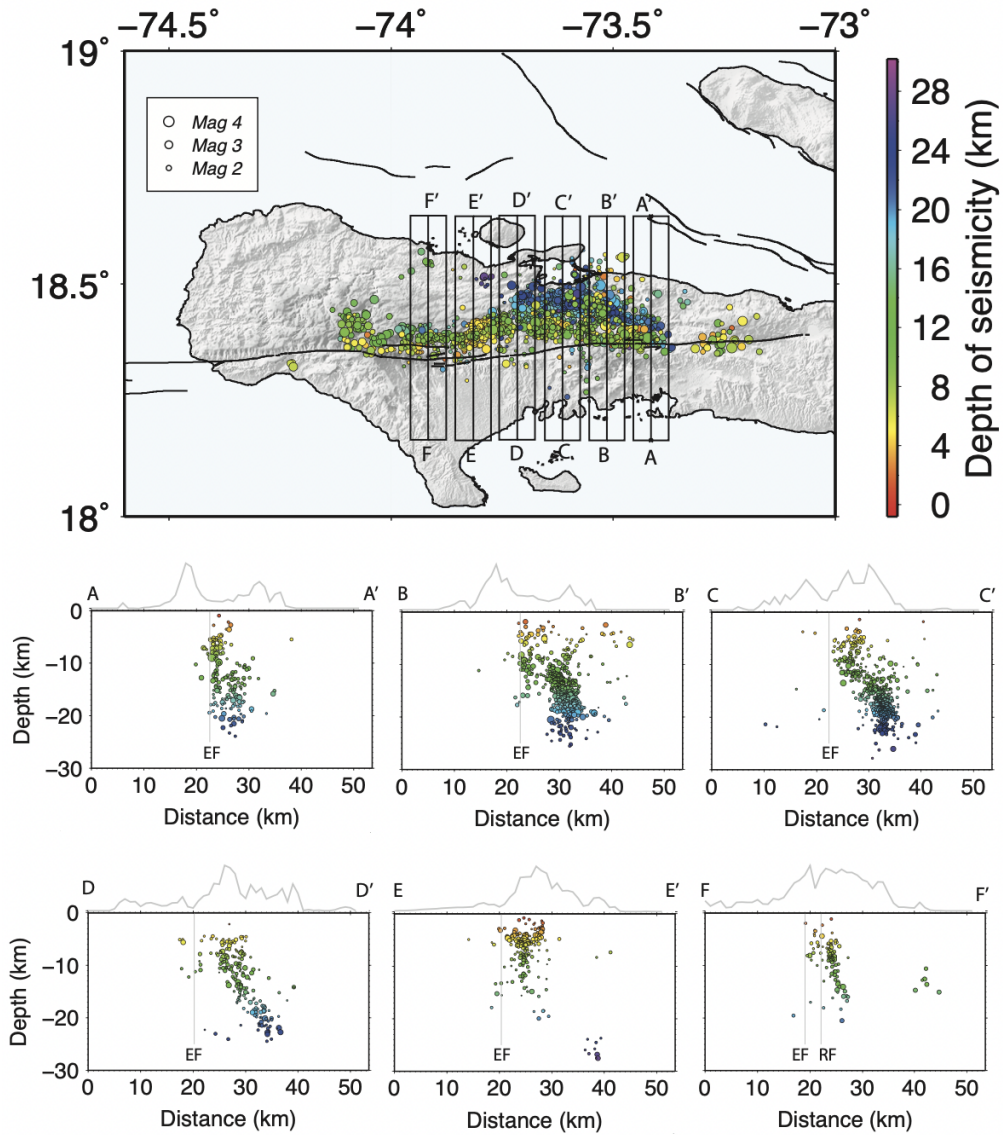


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Figure 10: Cross sections color coded by hypocenter depth perpendicular to the orientation of the main aftershock clusters. Hypocenters included within a box are projected into the corresponding cross sections. Gray curve above each cross section indicates the surface topography. The vertical gray lines mark the location of either the EPG fault (EF) or the Ravine du Sud fault (RF).



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